⟨S|P|S⟩
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SPG Mitteilungen
Communications de la SSP

Annual Meeting of the
Swiss Physical Society
9 - 13 September 2024, ETH Zürich

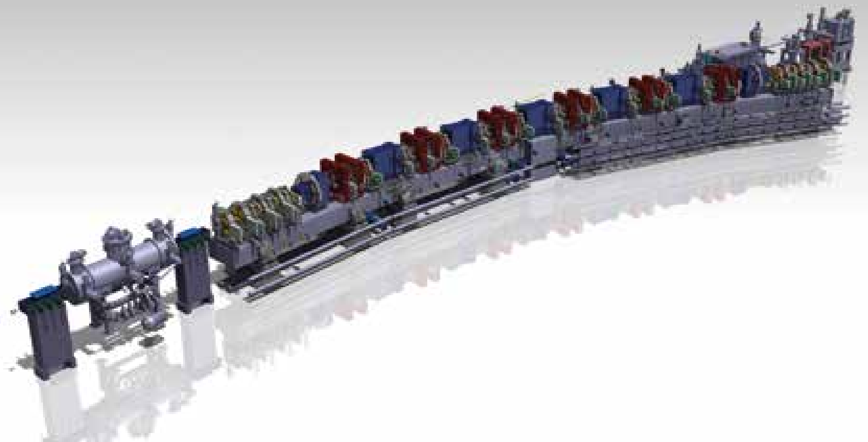
in collaboration with

CHIPP, SGN, SSPh, Departement Physik - ETH Zürich

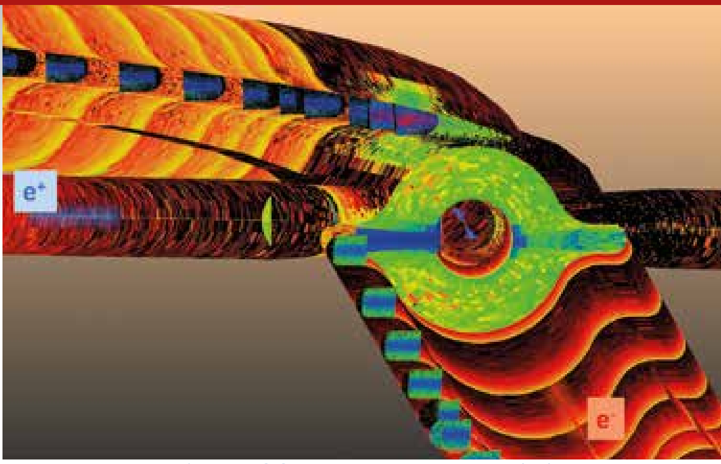
Photo: © ETH Zürich / Kuster Frey

Call for Abstracts: Submission Deadline 1 May 2024

More information on page 7.



Arc 2 and Straight 2 of the new SLS ring lattice, including the HTSU10 superconducting undulator (far left) that will serve the new I-TOMCAT beamline. More on the upgrade of the Swiss Light Source at PSI on p. 18.



Inclined view of the FCC-ee interaction point (IP), showing the SR photon flux density, which will determine the local molecular outgassing rate. More on the FCC-ee vacuum system on p. 26.

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Editorial

A Call for a New Commission on Gender Diversity in Physics

Alice Kohli

Switzerland has long been celebrated for its commitment to excellence in education, innovation, and research, particularly in the field of physics. The country boasts a rich scientific heritage, with groundbreaking discoveries and contributions that have shaped the global scientific landscape.

However, as we navigate the 21st century, it becomes increasingly evident that to sustain and enhance this legacy, we must address the gender disparity within the field of physics. Research has consistently shown that diverse teams are more productive and successful in solving complex problems [1] [2] [3]. Thus, fostering diversity is essential for achieving true scientific excellence.

As of today, Switzerland does by no means lead as an example in terms of equal opportunities. According to the World Economic Forum's Global Gender Gap Report, the disparities between men and women in positions of power – both in economy and in academia – are glaring in our country [4].

Some effort has been made to address these issues. Switzerland has implemented measures to promote gender equality, such as parental leave policies [5], anti-discrimination laws [6] [7], and initiatives to increase the representation of women in the work force [8]. Progress has been gradual and this can easily be mistaken for overall equality.

Some employers these days prefer women when filling new positions in order to improve the gender balance. Nonetheless, particularly in the Science, Technology, Engineering and Mathematics (STEM) field, the gender gap is statistically remarkable. As more women enter and excel in the workforce, the burden of managing both professional and domestic responsibilities has created an unsustainable imbalance. Current findings also imply a relevant salary difference as well as a dominance of part-time jobs for female employees. The path to gender equality does not end with the hiring process, it involves challenging traditional norms and roles.

Breaking down societal expectations around gender roles requires a collective effort and includes teaching children that responsibilities – both professional and domestic – are not inherently tied to gender.

Regarding physics, it is important to remember that the gender gap in STEM starts very early in the educational pipeline. According to data aggregated by the World Bank, Swiss women rank at 120 out of 137 in the share of graduates in STEM fields [9]. With only 22 % female graduates, Switzerland marks the tail end of all countries in Europe.

Swiss schools should be encouraged to address the stereotypes and biases that dissuade young girls from pursuing STEM subjects. Encouraging girls to engage with science and mathematics from an early age, providing access to STEM-related extracurricular activities, and implementing inclusive teaching practices are essential steps in dismantling the barriers that hinder girls' interest in STEM fields.

It is crucial that women are given opportunities to network and to support each other, as they cannot rely on alliances that have grown over centuries. On the contrary, women have been denied their place in the scientific spotlight for generations, just like members of minority groups.

Many female researchers and researchers of colour have not been able to publish their work, let alone present it as their own. Establishing mentorship programs, offering scholarships to pursuing STEM degrees, and conducting regular diversity audits in STEM organizations are actions that can catalyze change.

In face of all these challenges, 20 years ago, the International Union of Pure and Applied Physics (IUPAP) adopted a resolution on Enhancing the Role of Women in Physics [10] and established a Working Group on Women in Physics [11]. The European Physical Society has a Committee on Equal Opportunities [12], the German Physical Society formed an equal opportunities working group [13], and so did the Austrian Physical Society [14].

At the last board meeting of the SPS, it was decided to propose the implementation of a *Commision for Diversity, Equity and Inclusion* (DEI) within the Swiss Physical Society as well. The scope of the new commission is to promote gender and equity, nourish diversity and foster inclusion in all fields of physics and working environments.

Switzerland has the potential to be a global leader not only in technological innovation but also in equal opportunities. By addressing diversity and inclusion in STEM with urgency and commitment, Switzerland can create an environment where every individual can contribute to and benefit from the nation's scientific and technological advancements.

The time for action is now, and the benefits of a more inclusive STEM landscape will undoubtedly reverberate throughout Swiss society for generations to come.

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[1] https://www.science.org/doi/abs/10.1126/science.1193147

[2] https://www.pnas.org/doi/10.1073/pnas.2200841119

[3] https://www.mckinsey.com/featured-insights/diversity-and-inclusion/diversity-wins-how-inclusion-matters

[4] https://www.weforum.org/publications/global-gender-gap-report-2023/in-full/benchmarking-gender-gaps-2023/

[5] https://www.bsv.admin.ch/bsv/de/home/sozialversicherungen/eo-msv/reformen-und-revisionen/eo-vaterschaftsurlaub-200927.html

[6] https://www.fedlex.admin.ch/eli/cc/1999/404/de#a8

[7] https://www.fedlex.admin.ch/eli/cc/1996/1498_1498_1498/de

[8] https://www.ebg.admin.ch/en

[9] https://genderdata.worldbank.org/indicators/se-ter-grad-fe-zs/?fieldOfStudy=Science%2C%20Technology%2C%20Engineering%20and%20Mathematics%20%28STEM%29

[10] http://wgwip.df.uba.ar/

[11] https://iupap.org/who-we-are/internal-organization/working-groups/wg5-women-in-physics/

[12] https://www.eps.org/members/group.aspx?id=84913

[13] https://www.dpg-physik.de/vereinigungen/fachuebergreifend/ak/akc

[14] https://oepg.at/de/about/fachausschuesse/ak-chancengleichheit-in-der-physik

Extraordinary General Assembly of the Swiss Physical Society

The SPS Board invites the SPS members to an extraordinary General Assembly (GA) on Monday, **26 February 2024, 8:30h - 10:30h**. The GA will be performed online as video conference via *Zoom*.

Agenda

1. Welcome
2. Approval of the minutes of the General Assembly from 4 September 2023
3. Vote on closing the section *Earth, Atmosphere and Environmental Physics* and opening the section *Energy and Sustainability* and election of its chairs
4. Vote on establishing a new commission for *Diversity, Equity and Inclusion* (DEI) and election of its chair
5. Vote on the relocation of Medical Physics from the *Biophysics, Soft Matter and Medical Physics* section to the *Applied Physics* section, combined with renaming the section to *Biophysics and Soft Matter*
6. Candidates for other section chairs and vice president, to be elected at the Annual Meeting in September
7. Varia

Motivation

Ad 3.: For over 5 years, all attempts to find a leader for the section *Earth, Atmosphere and Environmental Physics* have been unsuccessful. The SPS Board decided to propose to the GA the closure of this section. Simultaneously the SPS board proposes the opening of a new section on *Energy and Sustainability (Energie und Nachhaltigkeit; Energie et durabilité)*. The vote on closure and opening will be coupled. In addition, two chairs for the new section need to be elected, who have been nominated by the SPS Board.

After having produced successfully *SPS Focus* 1 on Nuclear Energy Generation, a further issue is planned on *Energy Science and Solutions* leading to a carbon-free world by 2050.

Recent global crises led to severe uncertainties among the population and politics concerning the reliable supply of energy. The SPS engages in fostering a multi-strategic approach towards the solution of the energy crisis by contributing to the dissemination of news on the current progress in various fields of energy science and by engaging in policies on sustainable research, to influence actors in research, politics, education, and society.

Ad 4.: The scope of the new commission for *Diversity, Equity and Inclusion* (DEI; Kommission für *Vielfalt, Chancengleichheit und Inklusion*; commission pour *diversité, égalité des chances et inclusion*) is to promote gender equity and equality of opportunities, nourish diversity and foster inclusion in all fields of physics and working environments. The DEI commission should have a horizontal nature through all SPS sections by including members from various fields of work. The commission should also institutionalize within the SPS the organization of the *Women in Physics Career Symposium* (WiP), which was successfully held in the past two years at the Annual Meetings. The organizers have set up a mentoring program for female physicists.

The SPS DEI would also establish relations with similar initiatives of neighbor societies, such as the EPS Equal Opportunities Committee (*https://www.eps.org/members/group.aspx?id=84913*), the Women Portraits of SCNAT (see, i.e., p. 46), the SATW Tech Ladies, and others. More details on the motivation are presented in the Editorial of this issue.

Ad 5.: The section *Applied Physics* should host all those disciplines where results from fundamental physics research are mature enough to start soon industrial product development. This includes plasma physics, which is more than nuclear fusion and accelerator technology, material sciences and others. With this proposal, "physics applied to medicine" would be included, thereby with a focus on modern diagnostic tools such as X-ray imaging and in-vivo spectroscopy and therapeutic tools such as treatment by particle beams. The section is open to include further fields of physics with relevance to application.

How to participate

Only SPS members can participate in the extraordinary GA. In order to do so, go to *https://indico.cern.ch/event/1348883/* and register. Explanations are included in the registration form.
Once you are confirmed as member, you will get access to the event. The link to the *Zoom* conference will be provided there together with further information.

Registration deadline: 25 February 2024, 20:00h

If you are not yet familiar with the *Zoom* software (*https://www.zoom.us/*), we recommend to have a look at the help pages (*https://support.zoom.us/hc/de*) The client application can be installed freely without any subscription.

Protokoll der Generalversammlung vom 04. September 2023
Protocole de l'assemblée générale du 4ème septembre 2023

Agenda

1. Approval of the Minutes of the General Assembly held in Fribourg on 27 June 2022
2. New Code of Conduct
3. Revision of the Statutes
4. Brief Report from the President
5. 2022 Finances and Auditors' Report
6. Elections
7. New Honorary Member
8. Varia

The President opens the General Assembly 2023 at 18:20, following the symposium dedicated to the 400th birthday of Blaise Pascal.

1. Approval of the Minutes of the General Assembly held on 27 June 2022 in Fribourg

The protocol of the last General Assembly, published in the *SPG Mitteilungen* Nr. 70 on p. 5, is approved.

2. New Code of Conduct

The new code of conduct has been published in the *SPG Mitteilungen* Nr. 70 on p. 15 and is briefly presented. In order to pass, a 2/3 majority is needed, as it is related to the statutes of our Society. One member asks for a remission of vote as the code of conduct was not published in German. However, given that English is one of the official languages of the Society, this request is being rejected. As reaction the member leaves the assembly. In the following vote, the code of conduct is approved unanimously with no abstentions.

3. Revision of the Statutes

The board proposes a revision of the Society's statutes, which have been published in the *SPG Mitteilungen* Nr. 70, pp. 10 - 14. The main changes are summarized by the President: there is an increase in the membership fees to 100 CHF per year (last increase 2011), the introduction of the possibility to announce general assemblies electronically and, finally, it includes the possibility to exclude members, e.g. based on the code of conduct. The passing needs a 2/3 majority. The changes in the statutes are passed unanimously with no abstentions.

4. Brief Report from the President

The President reports that the number of members of our Society remains at 1093 members, including 19 honorary and 24 associated members. One new honorary member was elected at the 2022 General Assembly.

He reminds the General Assembly of the main activities of the Society in organizing meetings, particularly the annual meeting, and workshops, awards prizes, and engages in public outreach, particularly fostering the interest in Physics in the next generation.

The President then recalls the activities of the Society towards these aims, starting with the youngest target audience, the event "Physik im Advent". There is a steady increase in participating school children carrying out funny and interesting Physics experiments every day during the weeks before Christmas, reaching more than 1500 pupils in 2022. Continuing to older students, the SPS sponsors an award for *Schweizer Jugend forscht*, for research projects of high school students. For this age group, SPS also supports the *Swiss Physics Olympiad*, the *International Young Physicists Tournament*, and organises an annual "Young Talents Day", a special day devoted to the most excellent participants in these various national and international physics competitions. In 2022 it was held in conjunction with the Clausius memorial symposium at EPFL. This symposium was along the tradition of the SPS to organize historical symposia in conjunction with other societies and took place on 8 October 2022.

The SPS supports also the activities of the *Young Physicists Forum*.

In order to promote the careers of women in Physics, the SPS has supported a symposium dedicated to the subject organised by Prof. Marc Janoschek in conjunction with the annual meeting, which took place the first time on 1 July 2022.

Individual physicists are promoted by the Society through its dedicated awards. Six young physicists are awarded in 2023 with the SPS Prizes sponsored by ABB, IBM, Oerlikon Surface Solutions, METAS, COMSOL, and Hitachi Energy Switzerland.

The Society publishes 3 issues per year of the *SPG Mitteilungen*. In parallel, a monthly electronic newsletter is provided.

In addition, the second edition of our series *SPS Focus* was sent to all our members and to nearly 160 international decision makers and institutions. General reactions were broad and very positive, and the *Focus* essence has been summarized into a fact sheet published by SCNAT.

5. 2022 Finances and Auditors' Report

The Society’s treasurer, Dr. Dirk Hegemann, presents the 2022 financial report (see also page 8 of the *SPG Mitteilungen* Nr. 70). Prof. Dr. Claude Monney and Dr. Pierangelo Gröning, the auditors of the Society, have approved the numbers and their statement can be found on page 9.

A net loss of 32705 Swiss Francs is accounted for. The treasurer explains that this loss can be attributed to several exceptional circumstances. One reason are major expenses associated with production and distribution of the Society's publications. On the other hand, the member numbers have reduced in recent years leading to an imbalance of income and expenses.

The annual financial report is approved unanimously by the General Assembly.

6. Elections

Two members of the board have reached the end of their term and are up for re-election. The General Assembly unanimously renews these board members for their 2nd two-year term:

- Condensed Matter: Prof. Ilaria Zardo
- Atomic Physics & Quantum Optics: Prof. Jean-Philippe Brantut

Teresa Montaruli is elected as new president from 2023 - 2025 unanimously and Johan Chang as new vice president from 2023 - 2024.

Dr. Andreas Fuhrer and Dr. Tilo Stöferle have reached the end of their last term as section heads of Physics in Industry. The President thanks them warmly for their long and valuable service for the Society.

As new heads of the section Physics in Industry, Dr. Valeria Bragalia and Dr. Gian Salis are elected unanimously.

The President informs that the search for a new vice president is starting soon. The search for a chair for the section “Earth, Atmosphere and Environmental Physics” has been unsuccessful so far. The board therefore intends to redefine this section with a stronger focus on “Energy and Sustainability”, thus raising the chances of getting an active chair for the section.

7. New Honorary Members

Two proposals for honorary membership have been received this year by the President. He introduces Dr. Bernhard Braunecker as new honorary member nominated by Hans Peter Beck, Ulrich Claessen and Christophe Rossel. The nomination is approved with one abstention.

Bernhard Braunecker shall be elected as a new honorary member *for his outstanding scientific work in the field of applied optics, his strong commitment to optimizing the exchange of knowledge between academia and industry, and for his numerous voluntary activities in support of our society*.

Second, the President introduces Prof. Ruth Durrer, nominated by Camille Bonvin, Laura Baudis, and Maurice Bourquin. The nomination is approved with one abstention.

Ruth Durrer shall be elected as new honorary member *for her comprehensive contributions covering major involvements and outstanding scientific achievements related to cosmology.*

The President thanks the General Assembly and congratulates Ruth Durrer and Bernhard Braunecker warmly.

8. Varia

No topics are discussed.

The President closes the meeting at 19:00

Kurzmitteilungen - Short Communications

Editor's note: "Milestones of the Future"

What's better for a child at Christmas, helping to build the electric train or riding it? Some of them prefer to build the infrastructure because they enjoy the progress step by step, others prefer to take the job to transport goods. Both activities are necessary, equivalent and ultimately satisfying.

This is also the case with large-scale physics facilities at CERN or at PSI, where future accelerator variants are being technically advanced and where a lot of physical know-how is necessary besides all the engineering efforts to build, maintain or drive the big machines.

Two articles in this issue put these upcoming pioneering tasks into perspective, one (p. 18) dealing with the coming upgrade of the Swiss Light Source SLS at the Paul Scherrer Institute and the second one (p. 26) with the planning of the vacuum system of the Future Circular Collider FCC at CERN.

The first article about the SLS upgrade presents the general features of diffraction-limited storage rings (DLSRs), the characteristics of the new SLS 2.0 machine, and the scientific opportunities in more detail.

The second article from CERN reaches even further into the future. Since the LHC collider and its large detector units ATLAS, CMS, ALICE and LHCb will reach the limit of their discovery potential in the coming years, the planning of a "Future Circular Collider" FCC has already started. We report on this complex beam guidance technique and the vacuum physics behind it.

Both articles appear in our article series *Milestones in Physics*, which reports traditionally on retrospective events. They expand, however, the series to considerations about "Milestones of the Future".

Annual Meeting of the Swiss Physical Society
Zürich, 9 - 13 September 2024

The next annual meeting will take place from 9 - 13 September 2024 at the Campus Zentrum of the ETH Zürich.

The conference will open this year on Monday, 9 September with the third edition of the ***Physics Funding in Switzerland*** session.

In the afternoon we will continue with the General Assembly, followed by a symposium acknowledging ***Louis de Broglie: 100 years of wave-particle duality*** (see p. 9).

After the symposium, **Anne l'Huillier**, Lund University (Sweden), Nobel Laureate 2023 (see also p. 13), will give a public lecture, jointly organised by the SPS and the SSPh:

The route to attosecond pulses.

The ***Women in Physics Career Symposium***, also with its third edition, will become an integral part of the annual meeting and take place on Tuesday, 10 September (see p. 11).

On Friday, 13 September the new section ***Energy and Sustainability*** will have its inaugural session with a special program, as described on page 9.

From Tuesday to Thursday, renowned speakers will address latest advancements in different research fields in the plenary session, while the parallel sessions will allow in-depth discussions in several topical fields. A poster exhibition on Tuesday and Wednesday will complement the scientific program.

The *Swiss Institute for Particle Physics* (CHIPP), the *Swiss Neutron Science Society* (SGN) and the *Swiss Society for Photon Science* (SSPh) will again contribute to the program. Thanks to all these collaborations, our annual meeting will offer again an exciting program, covering latest advancements of physics in a wide range of fields at its best.

Scientific Program

Plenary Session

- **Giacomo Indiveri,** Universität & ETH Zürich:
  Neuromorphic Intelligence: spiking neural network and on-line learning circuits for brain-inspired technologies
- **Matthias E. Lauer,** Roche Innovation Center Basel:
  Structure Biology and Interaction Analysis in Drug Discovery
- **Kirsten Moselund,** PSI Villigen & EPF Lausanne:
  Advances in nanotech/integrated photonics
- **Sven Reiche,** PSI Villigen:
  Attosecond Pulses from X-ray Free-electron Lasers: Status and Outlook
- **Leonardo Senatore,** ETH Zürich:
  Questions in Theoretical Cosmology
- **Mikhail Shaposhnikov,** EPF Lausanne:
  Physics of the early universe and the intensity frontier of particle physics
- **Andreas Wallraff,** ETH Zürich:
  (Title not yet available)

Topical Sessions

The following parallel sessions will be scheduled from Tuesday to Friday:

- Accelerator Science and Technology
- Applied Physics, Plasma Physics
- Atomic Physics and Quantum Photonics
- Biophysics and Soft Matter
- Condensed Matter Physics
- Electron and photon spectroscopies of quantum materials
- Gravitational Waves
- History and Philosophy of Physics
- Magnetic fields for materials research *
- Neutron Science **
- Nuclear, Particle- & Astrophysics ***
- Photon Science ****
- Spintronics and Magnetism at the Nanoscale
- Startups: The role of physics and physicists in developing a product?

* sponsored by the EU project ISABEL; ** in collaboration with the Swiss Neutron Science Society (SGN); *** in collaboation with CHIPP; ****organised in collaboration with the Swiss Society for Photon Science (SSPh)

Depending on the number and contents of the contributed papers, each topical session may be split into special thematic subsessions.

Poster Session

The poster session will start on 10 September evening with an apéro and will continue on 11 September with a lunch buffet. **All** posters are presented on both session days.

The three most outstanding posters will be awarded with a "Best Poster Prize". It is required that at least the first author of the poster is personally present at the conference in order to be eligible for the award.

The maximum poster size is A0 (portrait).

General Assembly

The general assembly is scheduled for 9 September in the afternoon. The agenda will be published in the next issue of the *SPG Mitteilungen*. We encourage all members to actively participate and contact the committee if special points of interest should be discussed at the assembly.

Award Ceremony

As in every year, outstanding scientific work will be honored with the SPS awards in the fields of General Physics (sponsored by ABB Research Center), Condensed Matter Physics (sponsored by IBM Zürich Research Laboratory), Metrology (sponsored by METAS), Computational Physics (sponsored by COMSOL) and Energy Technology (sponsored by Hitachi Energy). Each award is granted with CHF 5000.-.

Furthermore the winners of the Charpak-Ritz award and the SGN award will also be honored.

The award ceremony will be held on 10 September at 09:45h.

Conference Dinner

A conference dinner is scheduled for the evening of 12 September. Information on the location and more details will be available on our website soon.

Vendors Exhibition

A vendors exhibition will be organized in addition to the scientific program. An invitation letter will be mailed within the next weeks to interested companies. If your company would like to join the exhibition, but did not receive the invitation letter, please contact: *sps@unibas.ch*

Abstract Submission

You can submit abstracts to all topical sessions. The choice between an oral or a poster presentation of your contribution is possible. Due to the limited number of time slots the session organizers might, however, have to change some oral presentations into posters. If possible, please mark both options in your submission, indicating that you are flexible regarding the presentation mode. Abstracts shall not be longer than ca. 100 words, and pictures are not allowed.

The submission of abstracts must be done online. Visit our webpage *www.sps.ch* and follow the link to the submission form. Further explanations are available there. The submission form will be activated shortly.

The conference program will be available in July 2024 on *www.sps.ch*. Please check the web regularly for further information and updates.

Submission Deadline: 1 May 2024

Conference Fees, Registration and Payment

The conference fees cover the participation to all sessions, including coffee breaks (all days), poster-apéro (Tuesday) and lunch buffet (Wednesday). The conference dinner on Thursday evening will be charged separately.

Pay your conference fee in time and save money !

The regular fees, as shown in the table below, hold for payments reaching us before 15 August 2024.

Category:	*CHF*
Individual Members of SPS, CHIPP	150.-
Students before Master/Diploma degree (*)	100.-
Other persons	190.-
Plenary speakers, invited speakers, awardees	0.-
Conference Dinner	90.-

(*) Students licence required

For payments done later than 15 August a surcharge of CHF 20.- will be added. This applies also for participants paying cash at the conference.
For registration just follow the link on *www.sps.ch*. Payment information is available directly during the registration process. Please make sure that your name and the purpose of the payment are indicated.

Attention: Fees are not refundable in case of individual cancellation. In the case the entire conference needs to be cancelled, we will contact participants who have already paid for the refunding process.

Registration Deadline: 15 August 2024

Special offer for non-members:

Do you plan to participate in our meeting and want to become a member of the SPS ? Take advantage of our special offer of CHF 200.- covering the conference fees and the membership for 2024 (CHF 220.- after 15 August) !

Fill out the online-registration form, choose the option "Special offer", then download, fill and sign the admission form for new members, and return it as soon as possible to the SPS Secretariat. The membership admission form is available on *www.sps.ch/fileadmin/doc/Formulare/anmeldeformular_d-f-e.pdf* .

*(This offer does **not** apply for students and Ph.D. students. They still profit from the free membership in the first year and have only to pay the conference fee shown above.)*

Symposium: Louis de Broglie: 100 years of wave / particle dualism

After the success of last year's historical symposium on Blaise Pascal (and several former symposia we organised either in conjunction with an annual meeting or as stand-alone events) we embed this year again such a symposium in the program of our annual meeting.

The years 1920 - 1930 are regarded as an important decade in modern physics, in which every year epoch-making discoveries in quantum physics occurred. This prompted Unesco to proclaim 2025 as the Year of Quantum Science and Technology (see also p. 11). One of the highlights of this decade was Louis de Broglie's formulation of the duality of matter.

Louis de Broglie (1892 - 1987) is considered one of the most important physicists of the 20th century. In 1924, de Broglie completed his studies with the famous dissertation *Recherches sur la théorie des Quanta*, in which he suggested that wave-particle duality could be applied to all matter. This bold idea was honored by the Institut de France in 1926 and 1927. In 1929, the discovery of the wave nature of electrons was followed by the Henri Poincaré Medal of the Académie des Sciences and the Nobel Prize in Physics.

Four lectures addressing the history and the impact of de Broglie's work will be given.

- **Friedrich-Karl Thielemann,** Universität Basel: *Matter and Light: Louis de Broglie and our current understanding of physics*
- **Tilman Esslinger,** ETH Zürich: *Waves of Quantum Matter*
- **Philipp Treutlein,** Universität Basel: *Wave-particle duality in atom interferometers: precision measurements at the quantum limit*
- **Henning Stahlberg,** EPFL: *Single electron imaging vs. coherent electron beam diffraction: Optimization of image contrast in cryo-electron microscopy*

The abstracts of the four talks will be published in the next issue of the *SPG Mitteilungen*.

This symposium will take place on 9 September 2024 in the afternoon, and is free of charge, no registration needed.

The SPS considers this symposium also as "warm up" for our IYQ 2025 activities. In 2025, we plan a similar symposium at our joint annual meeting with the colleagues of the Austrian Physical Society. This conference will take place at the University of Vienna in September 2025. The historical symposium will then focus on the scientific work of Wolfgang Pauli and Erwin Schrödinger, performed in the years between 1920 and 1930. Both physicists were born in Austria, but had close relation to Switzerland as professors of Physics in Zürich.

Additional information for selected sessions

Energy and Sustainability (Inaugural session)

The Energy and Sustainability section is driven by a commitment to tackle the world’s urgent challenge: create a sustainable energy future with access for all. Beyond just advancing our understanding, this new section aims to make a real-world impact by focusing on cleaner energy and environmental sustainability. In our first session, we'll discuss practical physics-based research strategies, highlighting examples within the context of the Switzerland Energy Strategy 2050. For this purpose, both long-term strategies of relevant Swiss research organisations and today’s grass-roots actions will be presented. Join us in this effort to actively contribute to a future where responsible energy practices and environmental awareness are top priorities for researchers. Let's work together to make a meaningful difference in our world.

Contact: Tomoko Muranaka (tomoko.muranaka@epfl.ch), Thomas Christen (thomas.christen@hitachienergy.com)

Startups: The role of physics and physicists in developing a product?

Physics and engineering have often played a major role in the development of new technologies and products. For instance, the birth of semiconductor technology led to nowadays ubiquitous products such as radios, televisions, computers and smartphones. In the Physics in Industry session of the annual meeting, we want to collect examples of how physics contributed to the development of a new product and bring together presentations from companies in Switzerland focusing on Quantum, AI and Optics. This session will be of interest to the attending young physicists because they can learn about their professional role after university. For the speakers from industry, it will be a great opportunity to get in touch with young talents.
If you are interested in presenting a talk in this session please contact the section heads.

Contact: Valeria Bragaglia (vbr@zurich.ibm.com), Gian Salis (gsa@zurich.ibm.com)

Theoretical Physics

As in the previous years, theoretical contributions are highly encouraged and will be included directly in a corresponding topical session. This way, the sessions will profit from a broad range of experimental, phenomenological, and theoretical advancements that are relevant in the specific topical field and thus can engage in broader and deeper discussions.
Please submit your abstract to the session which best matches your topic. You can optionally mark your contribution as "theoretical" in the submission interface.

Contact: Philippe Jetzer (jetzer@physik.uzh.ch)

Gravitational Waves

For this special session contributions covering all aspects of gravitational wave physics are welcome, in particular those connected with the Einstein Telescope (ET), the LISA mission, and the ongoing LIGO-Virgo detectors.
Relevant topics include data analysis, theoretical aspects, and experimental challenges of ET and / or LISA.
We particularly encourage PhD students and postdocs to submit abstracts and to join the meeting. Depending on the number of proposed contributions, the session will take place on one or two afternoons. Poster contributions are also welcome.

Contact: Steven Schramm (steven.schramm@cern.ch), Philippe Jetzer (jetzer@physik.uzh.ch)

Accelerator Science and Technology

Particle accelerators play an important role in high energy physics, materials and life sciences. They are used to create a very special state of matter — beams of particles (protons, electrons, photons, neutrons, muons, neutrinos etc.). Contributions are encouraged on all aspects of accelerator development for future high energy frontier electron, proton and muon colliders, high brightness synchrotron light sources as well as high intensity neutron sources.

Contacts: Leonid Rivkin (leonid.rivkin@psi.ch), Mike Seidel (mike.seidel@psi.ch)

Photon Science

This session is devoted to the application and technology of large-scale photon science infrastructures and related laboratory based efforts for research in all fields of physics where photon science tools take a center stage. Examples include the physics and application of free-electron lasers and synchrotron sources, the development and application of ultrafast photon science methods and many more.
The session is organised in collaboration with the SSPh.

Contact: Lukas Gallmann (gallmann@phys.ethz.ch)

Condensed Matter (KOND)

The condensed matter program welcomes contributions from all topics within Condensed Matter Physics, including magnetism, superconductivity, semiconductors and more. Investigations by advanced experimental techniques, e.g. by using synchrotron radiation, are highly welcome. Where relevant, we encourage participants to submit their abstracts to the respective focus sessions described below.

Contact: Henrik M. Rønnow (henrik.ronnow@epfl.ch), Ilaria Zardo (ilaria.zardo@unibas.ch)

Electron and photon spectroscopies of quantum materials

Angle-resolved photoemission spectroscopy (ARPES) and resonant inelastic x-ray scattering (RIXS) are powerful techniques to measure the momentum-resolved electronic structure of materials. In the recent years, the development of high brilliance synchrotron facilities, X-ray free electron lasers, as well as stable laser technology, have allowed new possibilities like micro- and nano-ARPES and in-operando experiments on tiny devices, as well as versatile time-resolved studies to cite a few of them.
This session is dedicated to highlight recent results in the field of quantum materials, correlated systems, and complex devices. It will bring together research groups using photoelectron, x-ray and optical spectroscopies, and serve to elaborate novel perspectives and collaborative development.

Contact: Claude Monney (claude.monney@unifr.ch), Felix Baumberger (felix.baumberger@unige.ch), Luc Patthey (luc.patthey@psi.ch)

Neutron Science

Neutrons produced at large-scale research facilities offer valuable insights into a wide array of subjects, spanning from particle physics and quantum materials to food science. The Swiss Neutron Science Society invites abstract submissions covering any topic where neutron experiments have played or may play a significant role. We are excited about creating an excellent program for this session, and eagerly anticipate your contributions.

Contact: Viviane Lutz-Bueno (viviane.lutz-bueno@psi.ch), Romain Sibille (romain.sibille@psi.ch)

Spintronics and Magnetism at the Nanoscale

This focus session concerns the latest advancements in the fabrication, measurement, and exploitation of novel functionalities in spintronic and nanomagnetic materials. We aim to showcase recent work conducted by experimentalists and theorists from Switzerland who are researching the magnetic properties of thin films, interfaces, and nanostructures. Pietro Gambardella (ETHZ), Alberto Morpurgo (Uni Geneva), Cinthia Piamonteze (PSI), and Martino Poggio (Uni Basel) will present invited talks during this session.

Contact: Jeffrey Brock (jeffrey.brock@psi.ch), Lauren Riddiford (lauren.riddiford@psi.ch) Laura Heyderman (laura.heyderman@psi.ch)

Magnetic fields for materials research

The generation and use of high magnetic fields enable the investigation of novel materials ranging from superconductors to 2D van der Waals compounds. The European Magnetic Field Laboratory (EMFL) extends the range of fields,

both continuous and pulsed, accessible to researchers, by developing state-of-the-art facilities in several European laboratories and in collaboration with large scale facilities, like the Paul Scherrer Institute. This session aims to present advances in the generation and use of high magnetic fields in materials research.
The session is sponsored by the EU project ISABEL (*https://emfl.eu/isabel/*)

Contact: Stefano Gariglio (stefano.gariglio@unige.ch)

Women in Physics Career Symposium

With the third-edition of the women-in-physics career symposium, we aim to institutionalize this event and make it an integral part of the SPS annual meeting. Our focus remains on improving our professional and mentoring network in physics for female early-career undergraduate and postdoctoral scientists. The event will feature a series of career talks, which will provide information on navigating a career in physics from the personal perspective of invited speakers covering several career levels. Here speakers pursuing successful careers both in and outside academia provide insights about key moments of their careers. Ample networking opportunities, exchange of experiences and ideas will be provided in the breaks.

Although the event is focused on connecting mentees from the undergraduate up to postdoctoral career level with experienced mentors, we invite female participants from all career levels to register for this event to contribute and benefit from the networking. In addition, we are asking interested colleagues willing to act as mentors to register (a list of last year's mentors can be found here: *https://www.sps.ch/en/events/sps-annual-meeting-2023/satellite-event-women-in-physics-career-symposium/mentors*). Following our inherent belief in diversity and inclusion, we also encourage people of all genders, backgrounds and ethnicities to participate in sharing this experience and learning from each other.

The event is sponsored by the University of Geneva, University of Zurich, the Paul Scherrer Institute, the Swiss Academy of Sciences (SCNAT) and SPS. Further contributions are most welcome. More details will be made available soon.

Contact: Tobias Golling (Tobias.Golling@unige.ch), Marc Janoschek (marc.janoschek@psi.ch)

Kurzmitteilungen - Short Communications

International Year of Quantum Science and Technology 2025

An international group of major scientific institutions and academies drafted a resolution in 2020 to declare 2025 the *International Year of Quantum Science and Technology* (IYQ 2025) to recognize the profound impact of quantum science on technology, culture and our understanding of the natural world (*https://quantum2025.org/*). The resolution was endorsed by the International Union of Pure and Applied Physics (IUPAP) at its 30th General Assembly in October 2021 and was approved by the General Conference of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in November 2023 [1]. It will be submitted next to the United Nations General Assembly to be put on the agenda of the 78th plenary session on one of their session days in spring 2024. Once approved, IYQ 2025 can be officially proclaimed.

The year 2025 has been proposed for this International Year, as it marks the 100th anniversary of the development of quantum mechanics. Over the last century, quantum science and technology have become increasingly important in a variety of scientific and technical fields such as physics, chemistry, materials science, biology and computer science.

The IYQ 2025 campaign is very similar in its definition, goals and organization to the IYL 2015, the International Year of Light, where actions were called for worldwide to demonstrate the role of modern photonics in science, technology, culture and education. The successful campaign led to the organization of an International Day of Light every year, always centered around 16 May, the day the first laser was introduced by T. Maiman in 1960. Switzerland participated from the front row, and the SPS organized colloquia, seminars and publications, which were well accepted by the public. We were also active in the following years, for example in 2020 with a report 'Laser Research in Bern', summarizing the pioneering work in laser physics and laser technology in the 1960s, particularly at the University of Bern [1].

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[1] *SPG Mitteilungen* Nr. 61, p. 22 - 31, 2020

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[1] On November 13, the 42nd General Conference of all member states of UNESCO recommended that the United Nations General Assembly (UNGA) proclaim 2025 as the International Year of Quantum Science and Technology. The resolution was put forward by an impressive 60 member states — led by Mexico.

Frédéric Mila wins the Charpak-Ritz Award 2024

The Charpak-Ritz Prize 2024 is awarded to **Frédéric Mila** *for his contributions to the theory of strongly correlated systems, in particular for the successful analysis of several experimental results in systems ranging from high-temperature superconducting cuprates to frustrated quantum magnets thanks to a thorough investigation of various strongly correlated models and to a close collaboration with experimental groups.*

Frédéric Mila is a condensed matter theory professor who taught at the University of Lausanne from 2000 to 2003 and since then at the EPFL and is widely considered a leading figure in the field of frustrated magnetism. His work is often in lose synergy with leading-edge experiments – either being inspired by experimental results or predicting phenomena motivating new experiments. Thanks to extensive collaborations with experimental groups in France, Switzerland, Japan and the US, he has contributed to the identification and explanation of several new quantum phases in magnetic models and materials and more recently also in cold atom quantum simulators. His remarkable achievements have not only advanced our understanding of complex materials but also fostered close collaborations with experimental groups, enhancing the bridge between theoretical and experimental physics.

One cornerstone of his achievements is a remarkable series of contributions to understanding a paradigmatic model of frustrated quantum magnetism known as the Shastry-Sutherland model, and the properties of the compound $SrCu_2(BO_3)_2$, which is a physical realization of this fundamental model. This led to the of discovery of new quantum phases such as fractional magnetization plateaus, spin-supersolid phases, and a spin-nematic phase that can be seen as a condensate of bosonic Cooper pairs. He also showed that there is a critical point in the phase diagram of this compound under pressure that is a quantum magnetic analogue to the critical point of water.

Beyond that specific system, he has made pioneering contributions to the magnetic properties of Mott insulators. He has worked on this topic throughout his whole career, first as a post-doc (Rutgers and Neuchâtel), then as a chargé de recherche at CNRS in Toulouse, and later in Lausanne. He came up with a microscopic theory of the low-lying singlets of the kagome spin-1/2 Heisenberg model, supporting the scenario of a resonating-valence bond (RVB) ground state in that system. He also showed that the spin-1/2 ladder has a 1/2-magnetisation plateau if the inter-dimer coupling is frustrated, opening the way to the experimental investigation of magnetization plateaus in Mott insulators such as $SrCu_2(BO_3)_2$.

He has also extensively worked on Mott insulators with orbital degeneracy, in particular on their connection with lattice SU(N) models. Over the years, he has contributed to the development of several theoretical approaches to investigate these models including tensor-network simulations, which led to the first concrete example of a spin-orbital algebraic quantum liquid for the SU(4) model on the honeycomb lattice, symmetry-based formulations in terms of Young tableaux that opened the way to the investigation of these models for large values of *N*, and a field-theory approach in 1D which led, in collaboration with a colleague from Canada, Ian Affleck, to a generalisation of Haldane's conjecture to SU(3).

More recently he got interested in quantum simulators realised with Rydberg atoms and came up with strong evidence in favour of an unconventional chiral transition first predicted four decades ago by Huse and Fisher in the context of adsorbed layers, and with a road map towards its detection in Rydberg chains through precise measurements of the Kibble-Zurek exponent across the transition.

In addition to his research achievements, Frédéric Mila has largely contributed to the broader scientific community. In 2005, he took part in the creation of the "Highly Frustrated Magnet" program of the European Science Foundation and sat on its steering committee until 2011. In 2007, he organised a summer school and workshop on Highly Frustrated Magnets at ICTP Trieste. In 2011, with two French colleagues, he co-edited the reference book on Highly Frustrated Magnets (Springer).

Finally, I would like to mention one of his first achievements, obtained as a postdoc at ETH Zürich in collaboration with Maurice Rice, where he developed a model of the hyperfine coupling between the spins located at the copper site and the neighbouring oxygen ions in high-temperature superconducting cuprates. This model led to predictions that were shortly after confirmed by NMR experiments done in the group of Charles Slichter, a result that landed direct support to the one-band description of these materials, and to the role of magnetic fluctuations.

The SPS Board congratulates Frédéric Mila for these impressive achievements and bright career.

Teresa Montaruli

The Nobel Prize in Physics 2023: The birth of attosecond science

Lukas Gallmann, ETH Zürich

1. Introduction

The 2023 Nobel Prize in Physics was awarded to ***Anne l'Huillier***, ***Pierre Agostini*** and ***Ferenc Krausz*** "*for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter*". With their contributions, the three laureates pioneered the field of attosecond science. In this article, I will describe the history behind the development of this field, the underlying physics and the technology that made all of this possible. Some background on the generation of attosecond pulses, the experimental techniques in attosecond time-resolved spectroscopy and their application for studying ultrafast dynamics in solids can be found in an earlier article in the *SPG Mitteilungen* Nr. 57 [1].

2. Of atoms and photons

Attosecond science has one of its roots in a sub-domain of atomic physics that studied the interaction of intense laser pulses with atoms. In the late 1970s and throughout the 1980s an intense field of study (also in the literal sense) was the ionization of atoms through the simultaneous absorption of multiple photons. The investigation of such processes was made possible by laser amplifiers now reaching focused peak intensities on the order of 10^{13} - 10^{14} W/cm^2. Researchers observed that under irradiation with intense laser pulses, atoms can absorb tens of photons simultaneously and highly charged ion species can be produced with photons that individually possess only a fraction of the energy needed to overcome the ionization threshold of the neutral atom.

The laser technology of that time mainly relied on Nd^{3+} doped materials, emitting radiation around 1064 nm. Instead of the fundamental, many multi-photon ionization studies used frequency-doubled, -tripled, or even -quadrupled light. This is because the nonlinear optical frequency-conversion improves pulse contrast and focusability of the beam while at the same time fewer photons are needed to bridge the ionization threshold.

However, such powerful lasers were too large and expensive for regular university-scale laboratories and available only at specialized research facilities. Both, Pierre Agostini and Anne l'Huillier spent their early careers at the same leading center for intense laser science in Gif-sur-Yvette near Paris. An example of Pierre Agostini's work from that time is his report of the first observation of electrons absorbing one photon more than they needed to overcome the ionization threshold of xenon [2]. Later it was found that in the underlying process of above-threshold ionization large numbers of excess photons can be absorbed simultaneously. An example of Anne l'Huillier's early work, on the other hand, is an experiment where she showed how the absorption of additional photons above the single-ionization threshold can lead to the formation of multiply charged krypton ions [3].

An important step towards the development of attosecond science happened, when researchers shifted their attention from the ions and electrons to the electro-magnetic radiation being generated in these interactions. In 1987, McPherson and co-workers reported the production of vacuum-ultraviolet light at odd-order harmonics of the 248-nm driving laser wavelength [4]. The highest observed harmonic was the 17th, corresponding to a wavelength of 14.6 nm. Probably the most important result of that paper was that the authors found a significant change in the intensity-scaling of the associated conversion efficiencies around harmonics 9 and 11. This was an early indication that the mechanisms responsible for the generation of low and high harmonic orders are not the same.

Only a year later, Anne l'Huillier and co-workers observed all the hallmark features of the process soon-to-be-known as high-harmonic generation (HHG) [5]. This work reported the first clear evidence of the so-called plateau and cut-off of the HHG spectrum. This was possible because the team used a longer driving laser wavelength of 1064 nm compared to earlier studies, which is also more representative of how HHG is performed today. Why this is the case, is explained below.

Figure 1 displays the typical structure of a HHG spectrum. Conversion efficiencies into the lowest harmonics drop exponentially with harmonic order. Above a certain harmonic

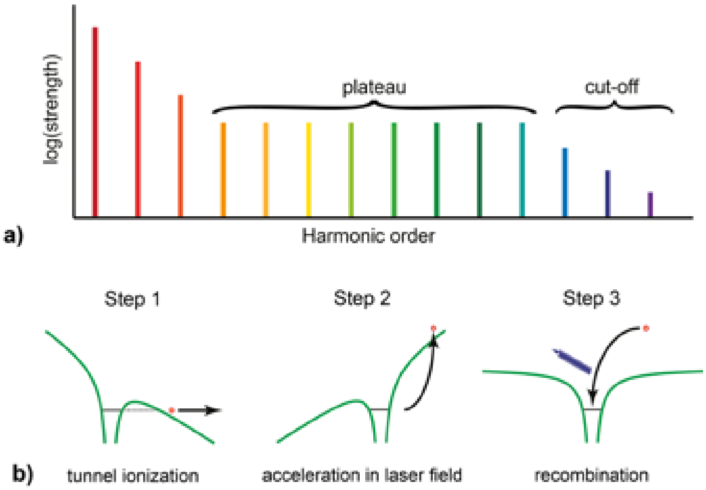

Figure 1: a) Typical structure of a high-harmonic spectrum. At a given laser intensity, the strength of the lowest harmonics drops exponentially with harmonic order. Above harmonics 9 to 11, however, their strength only weakly changes – a clear sign for a non-perturbative interaction. On the high-energy side again a rapid drop of the harmonic signal is observed. This is called the cut-off region. b) Semi-classical three-step model of high-harmonic generation. The strong electric field of the laser distorts the Coulomb potential of an atom and creates a tunnel barrier for the most weakly bound electron. The liberated electron is then accelerated in the oscillating light field and may eventually return to the parent ion. The returning electron can recombine with the ion and emits excess energy as a high-energy photon. The periodic oscillation of the light field results in a periodic repetition of these steps, which results in the formation of discrete odd harmonics in spectral domain.

order, conversion efficiencies remain almost constant over a large number of harmonics. This region is known as the plateau. At the highest observed harmonics, another rapid drop in efficiency occurs. This region of harmonic orders or photon energies is known as the cut-off.

In traditional nonlinear optics, harmonic generation is understood as a perturbative process. The different orders of nonlinear processes are obtained through a Taylor expansion of the time-dependent polarization with respect to the driving electric field. Such a perturbative approach is only justified if the importance of the different terms of the Taylor expansion drops rapidly with their order. The appearance of a plateau in the HHG spectrum is a clear sign for the breakdown of perturbative nonlinear optics.

The early 1990s brought rapid progress in the theoretical understanding of the phenomena observed by experimentalists in prior years. It was found that HHG can be described successfully as a single-electron effect [6] and that it is based on re-scattering of this laser-driven electron wavepacket with its parent ion [7, 8]. The cut-off energy was found – aside from a constant offset given by the ionization energy of the irradiated atom – to be proportional to the driving laser intensity and its wavelength squared [9]. This wavelength scaling explains why clear evidence for the existence of a plateau and cut-off was found in the work by l'Huillier and co-workers using a 1064-nm laser [5], but not in the earlier papers on harmonic generation using shorter-wavelength drivers. A full quantum-mechanical model introduced by Maciej Lewenstein in 1994 confirmed the main findings of the earlier semi-classical models [10].

A particularly popular model for describing the HHG process is the semi-classical three-step model [8], which intuitively explains many of the important properties of this effect. It describes HHG as a tunnel-ionization event resulting from the distortion of the atomic potential due to the strong laser field, followed by a Newtonian acceleration of the liberated electron in that field. If the ionization step is timed correctly with regards to the accelerating field, the electron can return to its parent ion and recombine. Upon recombination it releases excess energy in the form of an energetic photon. As the process periodically repeats with each half oscillation cycle of the driving laser field, these photons are emitted as odd-order harmonics of the original laser frequency.

In parallel to the development of theoretical frameworks describing HHG, first proposals for using HHG for the generation of attosecond pulses appeared [11, 12]. These ideas were motivated by the extremely large optical bandwidths covered by the plateau harmonics, which could be used to synthesize short field transients in time domain. However, it took another decade until these proposals were made a reality [13].

3. A technology-enabled route

The invention of chirped-pulse amplification by Strickland and Mourou in 1985 [14], which was awarded with the 2018 Nobel Prize in Physics, was a game-changer (see also *SPG Mitteilungen* Nr. 57, p. 40). On one hand, it allowed to increase the peak intensities that can be reached by laser amplifiers by many orders of magnitude. More important for the field of attosecond science, it made the laser intensities that are needed for HHG and related phenomena accessible with compact and relatively inexpensive table-top laser systems.

Around the same time, Ti:sapphire was discovered as a new laser gain material [15, 16]. Due to its extremely large amplification bandwidth (still the broadest to date), Ti:sapphire supports pulses with durations down to a few femtoseconds (10^{-15} s) from laser oscillators or down to about 20 fs from amplified systems [17]. This is orders of magnitude shorter than what the Nd-based systems were able to offer. With shorter pulses, a given peak intensity can be reached with much less energy per pulse. This therefore represented another important step for reducing size and cost of laser systems capable of HHG. Pulses from Ti:sapphire oscillators typically have energies on the order of few nJ and can reach peak powers approaching 1 MW. Compact table-top amplifiers easily produce mJ level pulse energies and tens of GW peak power.

The discovery of Ti:sapphire and a number of important related technologies triggered a 'rush for the shortest pulse' in the 1990s [17]. The third 2023 Nobel Laureate in Physics, Ferenc Krausz, was one of the leading contributors to these developments.

In this context, Krausz' group invested significant efforts into shortening the energetic pulses from amplified systems. While the finite gain bandwidth of the Ti:sapphire gain material makes it difficult to produce pulses shorter than about 20 fs with amplifiers, nonlinear optical pulse compression schemes allowed to shorten them to the few-fs regime [18], otherwise only accessible with low-energy oscillators. Applying such intense few-cycle pulses for HHG lead to the generation of quasi-continuous extreme ultraviolet spectra already in 1997 [19] – an early hint at the possibility of producing isolated attosecond bursts of radiation from a single driving pulse.

With the shortest generated pulses now lasting only a few oscillation cycles of the underlying electro-magnetic field, the phase of these field oscillations with regards to the pulse envelope started to matter (Figure 2). If, for example, the electric field maximum coincides with the maximum of the pulse envelope (a 'cosine pulse'), higher peak field strengths are reached than if a zero-crossing of the field occurs at the envelope maximum ('sine pulse'). For field-dependent physical phenomena, such as HHG, the outcome of the process may depend on this phase between the field (carrier) and its envelope.

Control of this so-called carrier-envelope offset phase became possible around 2000 [20-22]. This was not only an enabling step for attosecond science as we'll see below, but its frequency domain incarnation also laid the foundation for the application of frequency combs in high-precision frequency metrology, which was a key aspect of the 2005 Nobel Prize in Physics that was awarded to Theodor W. Hänsch and John L. Hall.

The ability to control the electric field of intense few-cycle laser pulses was a prerequisite for the successful demonstration of isolated attosecond pulses – the approach pursued

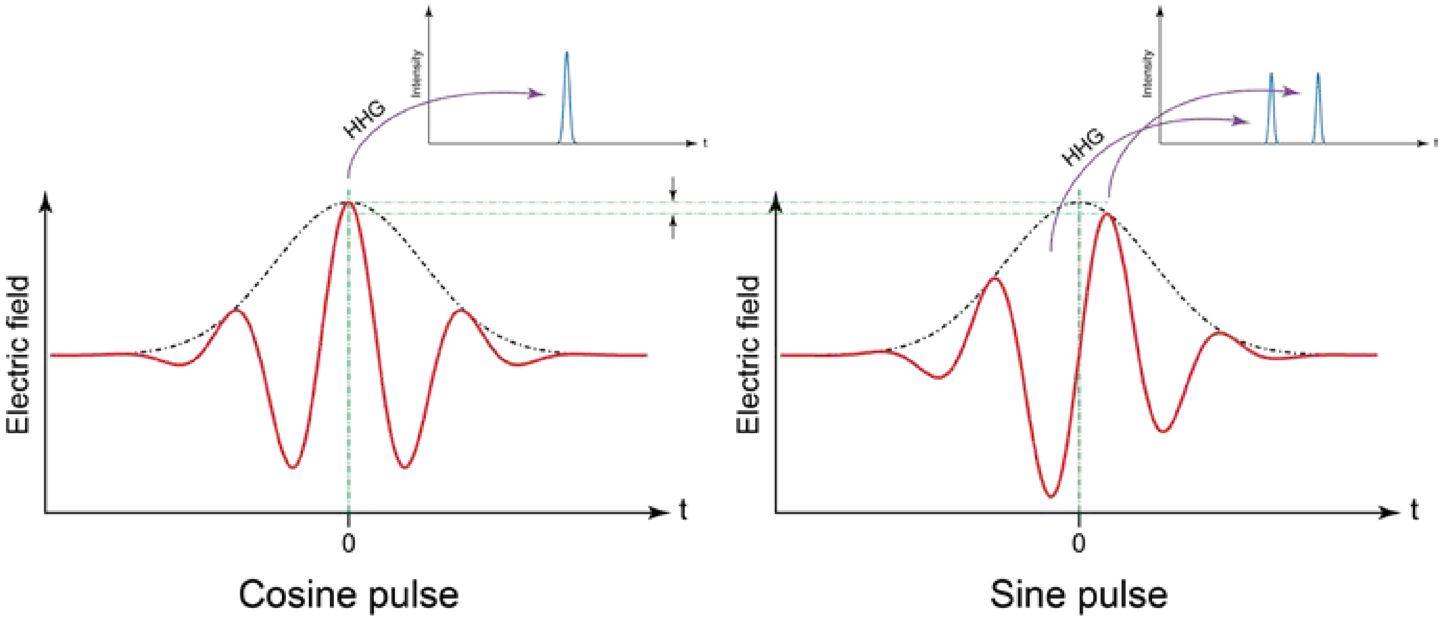

Figure 2: Importance of carrier-envelope offset phase control for isolated attosecond pulse generation. For very short laser pulses, the phase between their envelope (black dash-dotted line) and their electric field (red line) matters in field-driven processes such as high-harmonic generation. A 'cosine pulse' reaches a higher maximum electric field strength than a 'sine pulse'. The former may produce an isolated attosecond pulse (blue) whereas the latter may yield a double pulse under the same conditions (with appropriate spectral filtering), as the highest field strengths are now reached in two half-oscillation cycles. Without external control, the carrier-envelope offset phase would fluctuate randomly from pulse to pulse and along with this the temporal structure of the generated attosecond bursts.

by Krausz. With such short driving pulses, the cut-off region of the high-harmonic spectrum and the temporal structure of the emission sensitively depend on the carrier-envelope offset phase (Figure 2).

4. Attosecond pulses, finally

Shortly after the turn of the millennium, everything finally came together for the first experimental demonstration of attosecond pulses – interestingly almost at the same time for the two different approaches pursued by Agostini and Krausz [13, 23].

While it was expected that HHG can indeed give rise to the formation of attosecond pulses in the time domain, suitable methods for measuring them needed to be devised.

The approach chosen by the team around Pierre Agostini used longer, multi-cycle pulses (~40 fs) to drive the HHG process [13]. These relatively long pulses give rise to narrow, well-defined harmonics in the plateau that are insensitive to the carrier-envelope offset phase of the fundamental. Control of this parameter was therefore not required. A superposition of a set of these odd-order harmonics synthesizes a train of evenly spaced attosecond pulses in the time domain, with two attosecond pulses being emitted per field oscillation cycle of the fundamental.

For their temporal characterization, the team sent the attosecond pulse train into a gas target containing argon atoms. Due to the high photon energy of the individual harmonics forming the pulse train, they could easily single-photon ionize the atoms. The spectrum of the photo-emitted electrons now essentially mimics the energetic structure of the harmonics (minus the energy needed to ionize argon). If one now superimposes a fraction of the original fundamental beam with the attosecond pulse train in the argon target, the resulting interaction can lead the photoelectrons to absorb or emit a fundamental photon in addition to the already absorbed harmonic photon. From this, quantum path interference can occur between photoelectrons created by odd harmonic (2N-1) and the absorption of an additional fundamental photon and photoelectrons created by the next higher odd harmonic (2N+1) and the emission of a fundamental photon (N being an integer number). Both possible paths originate from the same ground state and end in the same final state: a photoelectron energy in a sideband between the electrons that were created by the two neighboring harmonics alone.

In this scheme called Reconstruction of Attosecond Beating by Interference of Two-photon Transitions (RABBITT, [24]), the quantum path interference encodes the relative phases of neighboring harmonics. Together with the easily measured optical power spectrum of the high-harmonic radiation, this is everything that is needed to reconstruct the temporal structure of an average of the pulses forming the pulse train. Using this method, Paul et al. reported the generation of a train of 250 as pulses in the June 2001 issue of Science [13].

The approach pursued by the team of Ferenc Krausz called for a different characterization technique. They created isolated attosecond pulses from a field-controlled, few-cycle fundamental, building on the fact that the most energetic high-harmonic radiation is generated only by the strongest electric-field half-cycle in such a short pulse. By definition, this radiation forms the cut-off region of the HHG spectrum. Using a spectral band-pass filter, they extracted this spectral component from the rest of the emission.

Similar to the technique used by Agostini, the attosecond pulse was used to single-photon ionize a rare gas target (krypton in the first demonstration) and, again, the attosecond pulse beam was superimposed with a fraction of the fundamental laser beam. Due to the temporal structure of the attosecond pulse, emission of photoelectrons is confined to an equally short time interval. From the instant of ionization onwards, the electrons will be accelerated by the superimposed fundamental field. Their final kinetic energy thereby becomes modulated by the electric field of the fundamental. By recording electron spectra as a function of the relative time delay between attosecond pulse and fundamental, one traces out this modulation, which essentially represents a cross-correlation between an electron wavepacket that mimics the time structure of the attosecond pulse and the fundamental field (or, more precisely, its vector potential). The duration of the attosecond pulse can now be inferred from the resulting cross-correlation. The first successful measurement of an isolated attosecond pulse of 650 as duration using this so-called ‘attosecond streak camera’ was reported in the last November issue of Nature in 2001 [23].

More details on attosecond pulse generation, the related measurement techniques and their applications can be found in [1].

5. Attosecond pulses, what are they good for?

The attentive reader may have spotted that the measurement methods used to characterize the first attosecond pulses – isolated or trains – should also encode information about the photoemission process that forms the foundation of these techniques. Indeed, the very same methods allowed for the first time to study the dynamics of the photoemission process itself.

For example, in 2010, the Krausz group measured a relative delay of 20 as between electrons emitted from 2s and 2p orbitals of neon using ~90 eV photons and the attosecond streak camera technique [25]. Shortly after, the l’Huillier group reported delays of 110 as between 3s and 3p electrons from argon using the RABBITT method with harmonics between 30 and 40 eV photon energy [26]. Such studies of the dynamics of photo-ionization phenomena remained at the focus of attosecond science for many years.

It can be noted that atomic nuclei are generally too heavy to exhibit a significant dynamical response on sub-femtosecond scales. Attosecond science therefore studies the response of the electrons and associated phenomena. How does charge redistribute in a molecule following the removal of an electron? How is energy flowing on atomic scales after absorption of a photon? How do the electrons in a solid respond to a strong laser field? These are just a few example questions that can be addressed in modern attosecond science.

During the first years after the first successful demonstrations of attosecond pulses, only very few groups managed to perform experiments with them and even for the groups that mastered the techniques, intervals between successive publications remained long. This was not due to a lack of interest as almost all first papers were published in high-profile journals, but it reflected how technically challenging these experiments were. In addition, while the theory of HHG and attosecond pulse generation was already mature by the time the experimentalist groups succeeded, the same thing cannot be said about the theories describing the studied attosecond phenomena – not least because of the time-resolved nature of the experiments.

However, during the last decade the field gained significant momentum and has expanded to a wide range of physical systems of increasing complexity. These systems now include molecules of sizes up to amino acids in gas phase or solution, liquids and a wide range of solid-state materials. As the experimentalists push the frontiers, theorists are quickly catching up with their models and descriptions of these systems on the involved scales.

As a detailed discussion of the capabilities of attosecond science and recent developments in the field goes well beyond the scope of this article, the reader is referred to some of the many excellent review articles on the topic (e.g., [27-30]).

6. Conclusion and outlook

At first sight it may have been surprising that the Nobel Committee awarded the 2023 edition of its physics prize to three experimentalists. Looking at the historical development and the technical challenges that needed to be overcome to turn the vision and early prediction of attosecond-scale time-resolved spectroscopy into a reality, this becomes understandable. Furthermore, the instant at which attosecond pulses became available, experimentalists produced a wide range of observations, which challenged the understanding of physics and the methods used by theorists. Overall, attosecond science is a beautiful example of the fruitful interplay of theory and experiment in physics.

Based on paradigms of traditional ultrafast time-resolved spectroscopy, the initial suspicion was that isolated attosecond pulses would prove to be more useful than the attosecond pulse train approach. However, from today’s perspective, more than 20 years after the first experimental demonstrations of the respective techniques, we know that pulse trains are equally powerful for attosecond spectroscopy. In short, since pulse trains are perfectly phase-locked to their generating fundamental wave, in many experiments that use the very same fundamental to drive a process and the pulse train to probe it, each individual pulse in the train probes essentially the same dynamics, yielding in sum the same information a single pulse would (but often with better statistics). The fact that both approaches are equally useful in practice was honored by the Nobel Committee by awarding the prize to Krausz and Agostini, who essentially represent these two incarnations of attosecond pulses.

Anne l’Huillier, on the other hand, is a pioneer of the entire field going back to its early days in intense laser – atom interactions. She not only significantly contributed to the discovery and understanding of high-harmonic generation, which forms the foundation of attosecond science, but since those early days continued to consistently make important contributions to the field. Her group, for example, was responsible for a range of essential contributions to our understanding of the attosecond dynamics of single-photon ionization processes.

The above discussion provides a glimpse of how the field spread from studies of simple atoms into other domains of physics, today including investigations on condensed-phase systems. On the other hand, with its extension towards increasingly complex molecules in gas phase or even in solution, the field also became relevant for chemists and even biologists. While most of the chemistry and biology happens on comparably slow time scales, these often complex chains of inter-linked processes may start with a very fast one: e.g., the absorption of a photon in a photoreceptor in our eye, followed by a fast redistribution of charge and energy on atomic scales.

At the same time, the exclusivity of HHG as a source of attosecond pulses comes to an end, with more and more XUV or x-ray free-electron lasers (such as SwissFEL at PSI) becoming capable of producing such short flashes of light. Free-electron lasers (FELs) can produce orders-of-magnitude more photons per pulse and generate light at considerably higher photon energies than what HHG will ever be able to. However, FELs will not render the more traditional table-top, lab-based HHG sources obsolete, but rather expand the parameter space for experimental attosecond science in a complementary way. Cost and size of HHG sources, and the coherence and level of control over the generated light fields are difficult to beat. On the other hand, pulse and photon energies from FELs are out of reach for HHG setups. In particular, these high light intensities attainable with FELs open a new route for studying nonlinear optical phenomena with attosecond resolution, further expanding the tool set of attosecond science.

With the scientific scope and technological capabilities of attosecond science still growing, also the number of research groups in this field keeps increasing at a fast pace. Many new insights into fundamental processes and breakthrough results can be expected for years to come. The Nobel Prize in Physics 2023 is therefore not expected to mark the culmination of a research area, but rather celebrates its pioneers, acknowledges that attosecond science has shown its potential and implies that this field is expected to have a lasting impact also for our future.

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Milestones in Physics (26)

SLS 2.0 – The upgrade of the Swiss Light Source

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The Swiss Light Source (SLS) has been operational since 2001. In the last two decades, unique and groundbreaking scientific programs and methods have been developed at the SLS in fields as diverse as macromolecular biology, imaging, and the electronic structure and behaviour of novel and complex materials. These achievements have been largely underpinned by the excellent performance of the electron accelerator and storage ring, which was considered the benchmark in this field until well into the second decade of this century. Nonetheless, with the advent of novel technologies in accelerator physics and the consequent emergence of the next generation of storage-ring facilities, known as diffraction-limited storage rings (or DLSRs), it has now become imperative to upgrade the SLS in like manner. The general features of DLSRs, the characteristics of the new SLS 2.0 machine, and the scientific opportunities it will offer are the subject of this in-part didactic article.

I. Introduction

The Swiss Light Source (SLS) has been serving the international scientific community since 2001 in scientific endeavours as diverse as bioimaging, macromolecular biology, novel electronic materials, nanomagnetism, catalysis and energy research, and cultural heritage, to name just some examples. Indeed, two Nobel prizes were awarded for discoveries enabled by experimental data obtained at the SLS [1–4].

The SLS has been a highly attractive research tool for many reasons, including the reliability and stability of the performance of the storage ring. A decade after its inauguration, the horizontal electron emittance value of 5.6 nm rad (the concept of emittance is described below) was considered to be a benchmark for storage-ring facilities, boasting horizontal and vertical electron emittances that approached the theoretical limit, given the machine parameters and contemporary magnet-lattice technology [1]; moreover it was with the SLS that regular so-called 'top-up' operation was first implemented – this allows small injections of the order of a percent of the total current at intervals measured in a few minutes, instead of the previous approach of letting the electron beam current decay by a few tens of percent over hours before injection. This has the advantage of maintaining an almost constant thermal load on the beamline components, in particular mirrors and monochromators, thereby permitting much more stable operation.

Nonetheless, a quantum leap in storage-ring performance was promised by innovations in beam dynamics theory, magnet fabrication and vacuum technologies that emerged in the first decade of this century [7], resulting in the emergence of fourth-generation storage-ring facilities known as diffraction-limited storage rings (DLSRs). There are already three operational DLSRs, namely MAX-IV in Lund, Sweden, the ESRF-EBS in Grenoble, France, and SIRIUS, in Campinas, Brazil, while several more are in the planning or active upgrade stage.

To appreciate the approximately two orders of magnitude improvement in performance promised by these developments, the concept of the figure-of-merit for synchrotrons called the 'brightness', or 'brilliance', must be understood. We thus begin with a short exposition on machine physics.

II. Some Basic Storage-Ring Machine Physics

A. Brightness and emittance

Brightness encapsulates the most important parameters of synchrotron radiation in a single figure of merit (see Figure 1). It is defined as the flux of photons produced per unit time and in a defined bandwidth from a source exhibiting a certain source area and divergence. It is specifically given by

$$\mathcal{B}(h\nu) = \frac{\text{ph / s}}{\sigma_x \sigma_y \times \sigma'_x \sigma'_y \times 0.1\%\,\text{BW}} \qquad (1),$$

where by $\sigma_{x,y}$ (in mm) and $\sigma'_{x,y}$ (in mrad) are the standard deviations of the beam profiles of the source size and divergence, respectively, in the x- and y-directions. An undulator source at third-generation synchrotron facilities can expect to deliver brilliances of the order of 10^{19} to 10^{20} ph / (s · mm^2 · mrad^2 · 0.1 % BW).

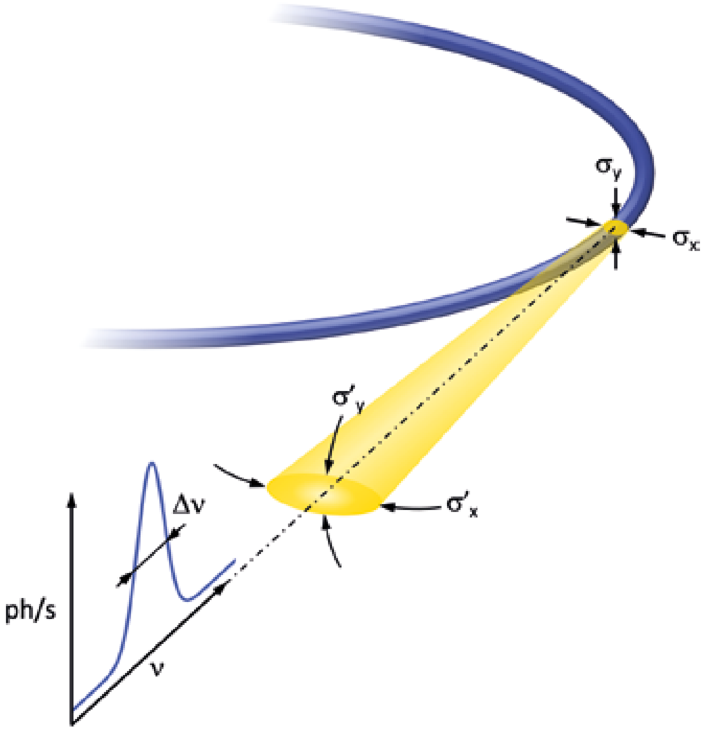

Figure 1. Schematic of the parameters determining brilliance, see Equation 1. The root-mean-square (RMS) source sizes $\sigma_{x,y}$ and divergences $\sigma'_{x,y}$ in the planes perpendicular to the direction of radiation define the emittance; the relative bandwidth is given by the bandwidth $\Delta\nu$ divided by the central frequency ν, delivering a flux given in ph s^{-1}. Adapted from [8], with permission of John Wiley & Sons.

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[1] The original SLS design was in fact what today is called a multibend achromat lattice. This design was developed between 1993 and 1996 [5, 6]. The final design was changed to a triple-bend achromat, as no suitable multibend solution could be found at the time.

The combined quantity of source size and divergence found in the denominator of the expression for brilliance is referred to as emittance, ε. The horizontal emittance in the orbital plane, $\varepsilon_x = \sigma_x \sigma'_x$ is generally larger than the emittance in the vertical plane $\varepsilon_y = \sigma_y \sigma'_y$.

The total emittance in any one plane is a convolution of the electron emittance, ε^e, which can be tuned according to the storage-ring design, and the photon emittance, ε^p, which is a fundamental property defined solely by the photon energy. It can be shown that the source size and divergence of radiation from an undulator source of length L, ignoring contributions from the electron beam, are given by

$$\sigma^p = \frac{\sqrt{\lambda L}}{4\pi} \quad (2);$$

$$\sigma'^p = \sqrt{\lambda / L} \quad (3),$$

and hence

$$\varepsilon^p = \frac{\lambda}{4\pi} \quad (4).$$

The ratio σ^p / σ'^p is referred to as the photonic beta function $\beta^p = L/4\pi$, which has units of length and is independent of the radiation wavelength. Analogously, the beta function of the electron beam is given by $\beta^e = \sigma^e / \sigma'^e$; this can, however, be manipulated using electron optics.

It is thus important to match the storage ring parameters at each source point to that source's design. The flux of a beamline is simply the brilliance multiplied by the total emittance, and thus has dimensions of [ph/s/0.1 % bandwidth]. It is briefly noted that for some synchrotron techniques, flux on the sample is more important than the brilliance, particularly for those that do not require the smallest focus, or don't exploit the coherent properties of the beam.

In the hard x-ray regime, for which $\lambda \sim 1$ Å (12-keV photons), the photon emittance, according to Equation 4 is of the order of 10 pm rad. Even for photon energies in the regime of 1 keV, $\varepsilon^p \sim 100$ pm rad, and hence the photon emittance is between one and two orders of magnitude smaller than the electron emittance in third-generation facilities. The performance of third-generation facilities is thus primarily determined by the electron emittance.

B. Multibend achromats and the diffraction limit

The electron emittance is determined by the so-called radiation equilibrium: like in a spectrometer, the bending magnets forming the storage-ring lattice deflect particles depending on their energy spread – an effect called dispersion. The quantum nature of photon emission introduces a stochastic spread of individual electron energies, which is then translated into a spatial spread in the orbital plane through dispersion.

On the other hand, continuous energy loss to radiation in combination with acceleration of the electrons in the radio frequency cavities of the storage ring provides damping of the energy fluctuations [8]. Finally, the emittance of the electron beam is given by the competing effects of radiation damping and quantum excitation, forming an equilibrium, which is dictated by the structure of the magnet lattice.

Obviously, in order to adjust the equilibrium beam emittance to low values requires that the dispersion remains small inside the bending magnets. This means one should rather use many small bending magnets instead of a few big ones, in order to prevent the dispersion growing to large values inside the magnet.

Thus, the defining feature of fourth-generation synchrotron facilities is the employment of so-called multibend achromats (MBAs) in the arc sectors of the storage ring. What is meant by this term? Classically, the arc sectors of synchrotrons, that is, the regions which are responsible for bending the electron beam into a closed path, are served by so-called double-bend achromats [2].

A double-bend achromat (DBA), as depicted in Figure 2, uses two bending-magnet dipoles separated by focusing quadrupole magnets. This has in the past been the standard system to suppress dispersion in the straight sections at third-generation synchrotrons. A multibend achromat is similar, but uses several small DBAs in a row, typically between 5 and 9, to execute a given arc angle. An MBA with M dipoles contains (M – 1) DBA cells (Figure 2 bottom).

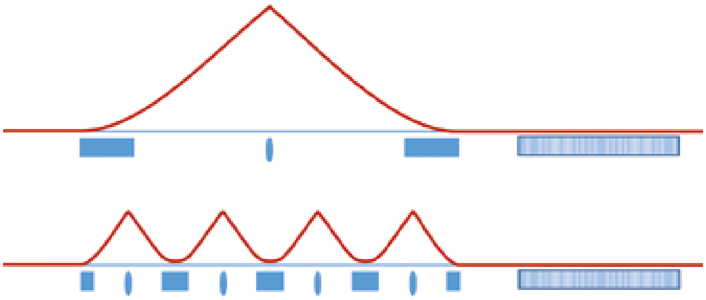

Figure 2. Schematics of a double bend achromat (DBA) and multibend achromat (MBA). The red line indicates the dispersion, which is refocused by magnetic lenses (quadrupoles) in order to minimize it inside the dipoles and to suppress it in the straight sections, where the undulators are located. From [9], with permission from the Swiss Society for Photon Science.

Limiting the dispersion growth inside the bending magnets enables a dramatic reduction in emittance: the *minimum* horizontal electron emittance theoretically attainable by an MBA structure is found to be proportional to the third power of the bending angle θ of the dipoles used in the MBA [8]. Precisely,

$$\varepsilon_x^e = \frac{C_q \gamma^2}{12\sqrt{15}\, J_x} \theta^3 \quad (5),$$

where $\gamma = \mathcal{E} / m_e c^2$ is the ratio of the storage ring energy to the electron rest-mass energy, and $C_q = 3.832 \times 10^{-13}$ m. The parameter J_x in the denominator depends on the distribution of radiation damping to transverse and longitudinal dimensions and typically has values between 1 and 2.

Note that ε_x^e depends on the square of the storage-ring energy. Despite this, the upgrade of the SLS includes an *increase* in this parameter from $\mathcal{E} = 2.4$ to 2.7 GeV [10, 11], as this will facilitate access to photon energies well in excess of 40 keV, which is especially interesting for both imaging and chemical spectroscopies, two areas of research in which the SLS has historically been a leading player.

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[2] Some third-generation facilities, notably the SLS until its upgrade, use a triple bend achromat, but this is a detail that need not concern us here.

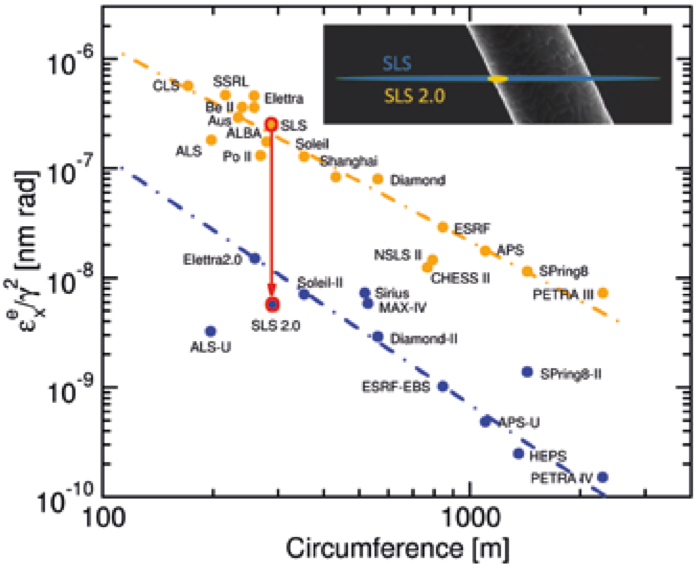

Figure 3. Plot of horizontal electron emittances weighted by the square of the storage-ring energy as a function of ring circumference (see Equation 5), for both a selection of third- (orange data points) and fourth-generation (blue) synchrotrons. Note the approximately fortyfold improvement in the weighted emittance for the SLS 2.0 upgrade, highlighted in red. The inset shows the cross-sections of the electron beams at SLS and SLS 2.0 compared to a typical human hair. *From [9], with permission from the Swiss Society for Photon Science.*

The path to low emittance by building a lattice from many small magnets became viable once miniaturization of accelerator components became feasible, in particular with regards to the precision of magnet construction and distributed pumping via so-called 'nonevaporable getter' (NEG) coatings on the inner surfaces of the narrow-cross-section vacuum vessels containing the circulating electrons.

For a storage ring containing N arcs of M dipoles each, the bending angle per dipole is simply $\theta = 2\pi/N(M-1)$, and Equation 5 becomes

$$\varepsilon_x^e = \frac{2C_q\gamma^2\pi^3}{3\sqrt{15}\,J_x}\frac{1}{N^3(M-1)^3} \qquad (6)$$

$$\Rightarrow \varepsilon_x^e\,[\text{nm rad}] = 7834\frac{(\mathcal{E}\,[\text{GeV}])^2}{J_x}\frac{1}{N^3(M-1)^3} \qquad (7).$$

Therefore, SLS 2.0, for which $N = 12$ and $M = 7$, has a theoretical ultimate horizontal electron emittance of 153 pm rad (for $J_x = 1$). The actual goal is $\varepsilon_x^e = 157$ pm rad (Figure 3) [11].

From our expression given in Equation 4, we can calculate that radiation with the same emittance ε^p as ε_x^e will, for SLS 2.0, have a wavelength of 19.73 Å, equating to a photon energy of approximately 630 eV; these are referred to as the 'diffraction-limited wavelength' λ_{DL} and 'diffraction-limited energy' $h\nu_{\mathrm{DL}}$, respectively. For photon energies much lower than this, the photon contribution to the total emittance dominates, and no substantial gain is made by attempts to improve the electron emittance further[3]. This is the meaning of diffraction-limited storage rings – their performance is limited, at least for photon energies below that for which $\varepsilon^p = \varepsilon_x^e$, by fundamental diffraction phenomena associated with the x-ray sources. We summarize this in Figure 4.

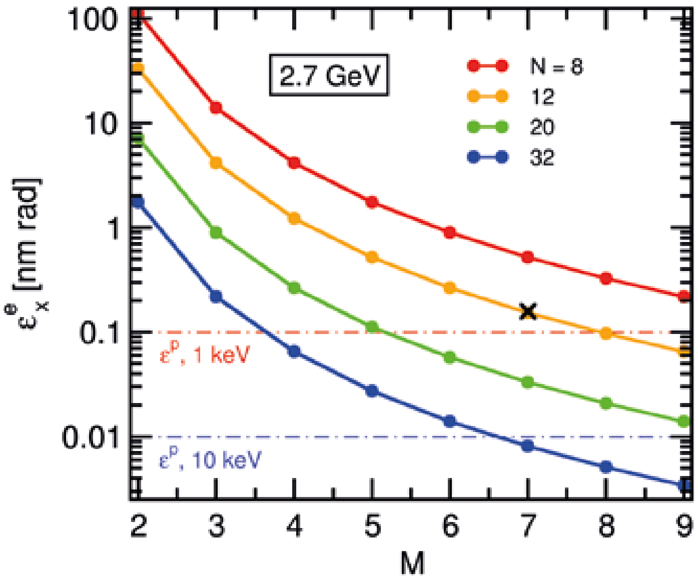

Figure 4. Plot of the theoretically optimal horizontal electron emittance ε_x^e as a function of the number of straights N in a 2.7-GeV synchrotron ring and number of dipoles M within a single arc sector, according to Equation 6. Values for N = 12, 20, and 32 were selected, as these correspond to SLS 2.0, MAX-IV, and ESRF-EBS, respectively. Also included as dot-dash lines are the fundamental photon emittances for 1 and 10-keV photons, given by Equation 4, and the position of SLS 2.0, labelled as the black X. *From [9], with permission from the Swiss Society for Photon Science.*

The electron emittance is a constant around the storage ring for a given magnet lattice. In the above, however, we have not considered how this is distributed between divergence and electron-beam size – do we want the electron beam to be very small but highly divergent (low β^e), or larger and more parallel (high β^e)? Importantly, although the electron emittance remains constant for a given ring, one can manipulate β^e using the electron optics such as the quadrupole magnets and the combined function magnets, which are magnets providing focusing and bending simultaneously. Now, because the total emittance is the convolution of the electron- and photon contributions, it is easy to demonstrate that the beta function of the electron emittance is optimized, and thereby the total emittance is minimized, when it equals that of the photon emittance, i.e., $L/4\pi$, that is, of the order of a few tens of cm, depending on the undulator length.

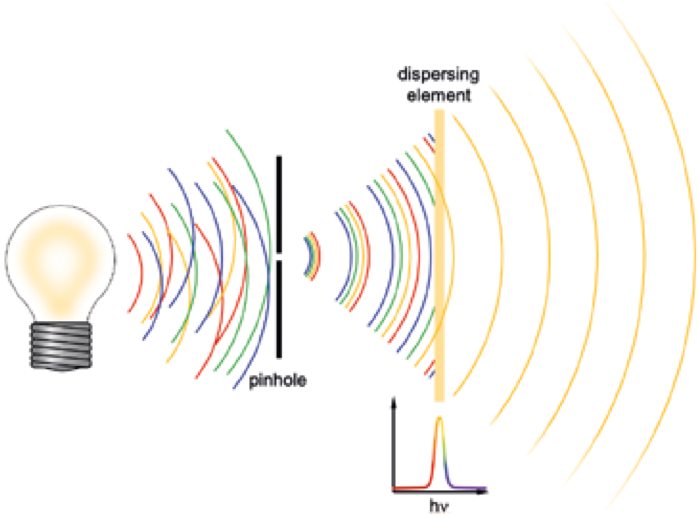

Figure 5. Coherent radiation can be extracted from a broadband, spatially extended source by the use of a pinhole and a dispersive element that selects a narrow band of wavelengths. *Adapted from [8], with permission of John Wiley & Sons.*

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[3] Note that, for third-generation facilities, the 'diffraction-limited photon energy' is of the order of 20 eV.

C. Coherence

To conclude this whistle-stop précis of the most important aspects of storage-ring and radiation parameters, we briefly discuss coherence. Within the figure of merit of brightness are the parameters that quantitatively define coherence – the emittance and the relative spectral bandwidth. Consider a broadband and spatially distributed source such as an incandescent light bulb (Figure 5). The source emittance can be reduced by placing a slit or pinhole in front of the source. This determines the ‘spatial’, or ‘transverse’ coherence. In the case of synchrotrons, the slit (or source) size is given by the transverse spatial extent of the beam. Even for soft x-ray sources below a few keV, this is dominated by the size of the electron beam, as this will be of the order of tens of microns or more, much larger than the radiation’s wavelength, measured in nanometers or angstroms. The divergence is given by the Fourier transform of the source profile; accordingly, the full-width half-maximum (FWHM) subtended angle is approximately equal to the ratio of the wavelength to the beam FWHM, of the order of 10^{-4} rad for soft x-radiation. Secondly, a dispersive element such as a monochromator suppresses all radiation apart from a narrow bandwidth. Now, the radiation is both spatially and longitudinally (or temporally) coherent. Both the emittance and relative spectral bandwidth are included in the definition of brilliance.

The transverse coherence length at a distance R from a source of width D is given by

$$l_c^{(t)} = \frac{\lambda R}{2D} = \frac{\lambda R}{2\sqrt{\pi}\,\sigma_{x,y}} \qquad (8).$$

Hence, in the orbital plane of the synchrotron, DLSRs have transverse coherence lengths of several hundred microns, up to two orders of magnitude larger than those typically found at third-generation facilities. This has a huge benefit both for lensless-imaging techniques such as ptychography [12, 13] that exploit the coherent part of the beam, and also those techniques that require both small divergence and a tight focus, such as in serial crystallography [14].

The ‘temporal’, or ‘longitudinal’ coherence length, determined by the degree of monochromacity, is given by

$$l_c^{(l)} = \frac{\lambda^2}{\Delta\lambda} \qquad (9).$$

The temporal coherence length thus depends on any dispersive element in the beamline, particularly monochromators. A Si(111) double-crystal monochromator has an intrinsic relative bandwidth of approximately 1.4×10^{-4}, which, for 1-Å-radiation leads to $l_c^{(l)} \sim 1\,\mu$m. Note that DLSR technologies do not in themselves provide advantages in longitudinal coherence compared to third-generation facilities.

III. Sources at the SLS 2.0 Upgrade

A graphical summary of the expected brilliances of the x-ray sources at SLS 2.0 is provided in Figure 6, while further details of their parameters are listed in Table 1.

The six hard x-ray undulator beamlines are served by four U17s, one cryogenically-cooled U14 (also operational at the original SLS), and one high-temperature superconducting U10, while four hard x-ray bending-magnet beamlines have two warm superbends (2.1 T) and two superconducting superbends (5 T). The five remaining straights produce soft and tender x-rays, and are served by combinations of the elliptical undulators (UEXX).

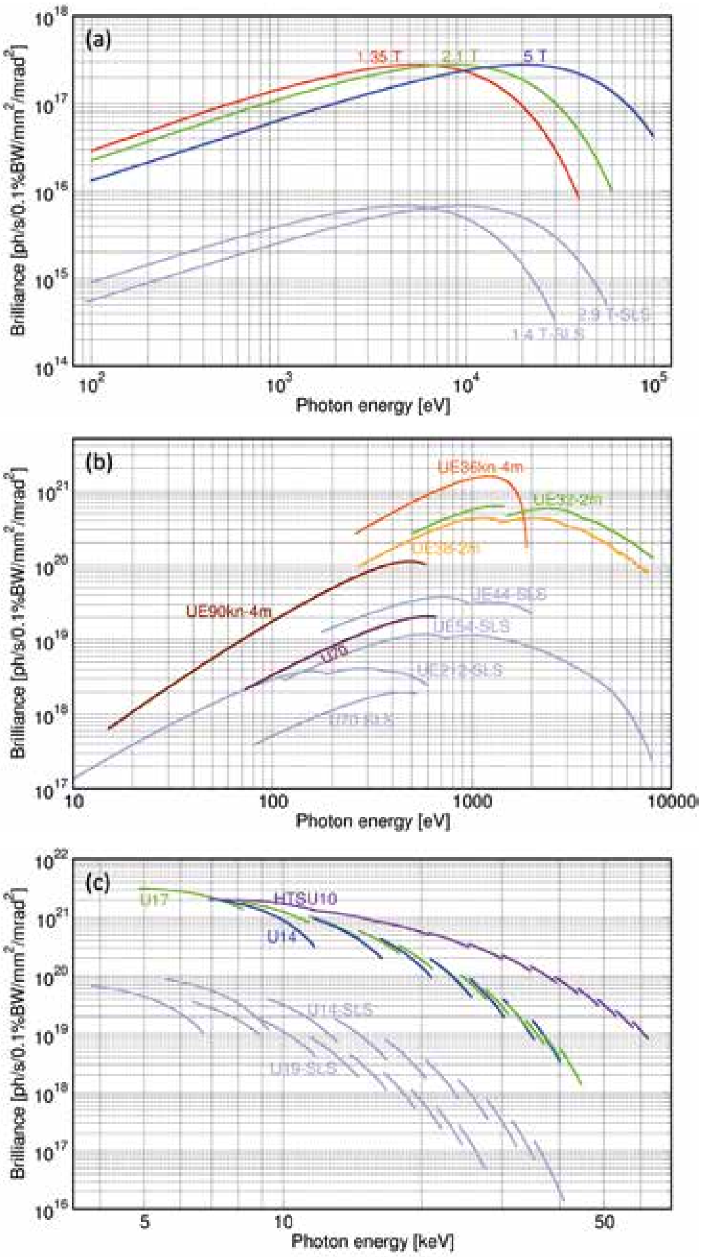

Figure 6. Brilliance curves of the SLS 2.0 sources for (a) bending magnets and superbends, (b) soft x-ray undulators, and (c) hard x-ray undulators. -kn suffix = knot magnet design; HTSU = high-temperature superconducting undulator; UE = elliptical undulator; two-digit suffices = undulator periodicity in mm. The performance of the previous sources installed in the 2.4-GeV storage ring are also shown in grey.

An exciting aspect of the upgrade is that improvements in the brilliance also enable other innovations further down the technological chain, notably in the field of undulator development.

A. Hard x-ray undulators

The description of the interference phenomena that lead to the spectral output from undulators is given by

$$m\lambda_m(\theta) = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad (10),$$

whereby λ_m is the wavelength of the m^{th} harmonic, λ_u is the

ID name	λ_u [mm]	$h\nu$-range [eV]	Length [m]	Polarization modes	ID beamlines
UE90kn	90	30 – 600	4.0	LH, LV, CL, CR	QUEST, XIL
U70	70	70 – 660	1.54	LH	XIL
UE38	38	250 – 8000	2.0	LH, LV, CL, CR	PHOENIX/X-Treme
UE36kn	36	270- 1900	4.0	LH, LV, CL, CR	SIM, ADRESS, QUEST
U17	16.8	4900 – 34000	3.0	LH	cSAXS, PXI, PXII, microXAS
CPMU14	14	7000 – 40000	1.68	LH	MS (ADDAMS)
HTSU10	10.5	7000 – 62000	1.0	LH	I-TOMCAT

Table 1. List of insertion devices, their relevant parameters, and the beamlines they serve. Insertion device names ending in 'kn' indicate knot-magnet configurations. LH = linear horizontal, LV = linear vertical, CL = left-circularly, CR = right-circularly.

periodicity of the undulator magnet array (typically measured in cm), and

$$K = 0.934\,\lambda_u[\text{cm}]\,B_0[\text{T}] \sim 1 \qquad (11)$$

is the magnetic deflection parameter describing the ratio of the maximum angular excursion of the electron beam as it passes through the undulator's magnet array to the natural opening angle of the synchrotron radiation, which is itself equal to $1/\gamma$. The second term in the brackets, $\gamma^2\theta^2$, describes the contribution from off-axis radiation. This results in broad lobes on the low-energy flanks of the main undulator maxima (see the curve for the undulator spectrum for third-generation facilities in Figure 7).

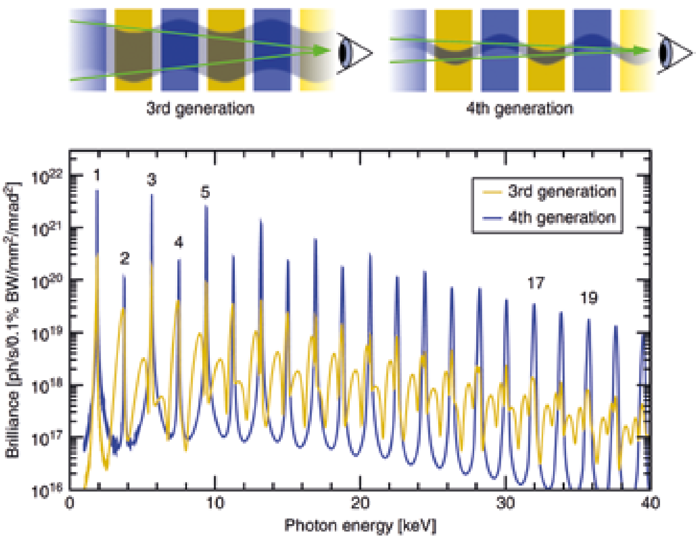

Figure 7. Comparison of the brilliance of hard x-ray undulator spectra at third- and fourth-generation facilities. Top: the width of the electron beam passing through an undulator at third-generation facilities is approximately two orders of magnitude larger than the oscillation amplitude, while at DLSRs, it might only be approximately ten times, or even less. Bottom: consequently, less off-axis radiation (given by Equation 10) is produced by undulators at DLSRs. Note also the enhanced brilliance at the spectral peaks for the DLSR. Both simulated spectra were generated for a U12 undulator (that is, λ_u = 12 mm) containing 120 magnet periods, for K = 1.6, 400 mA, and a storage-ring energy of 2.4 GeV. Adapted from [8] with permission from John Wiley & Sons.

Importantly, the ratio of the horizontal width of the electron beam to the amplitude of its oscillations induced by the undulator is, for third-generation facilities approximately 100. The reduced horizontal emittance and quasi-on-axis injection of SLS 2.0 produce an electron beam which is significantly narrower, especially in the small-beta short straights occupied by the hard x-ray ID beamlines. Consequently, the ID magnets and poles need only have a width of 15 mm (in contrast to the previous value of 40 mm) to ensure a sufficiently homogeneous magnetic field.

This reduced lateral extent and increased 'elbow room' permits two developments. Firstly, the reduced off-axis excursions of the narrower beam reduces off-axis harmonics and hence these contributions are largely suppressed, as summarised in Figure 7. This narrower electron beam presents several technological opportunities. Firstly, entire undulator maxima can be used for those experiments that do not require a very small relative bandwidth but do require as many photons per unit time on the sample as is possible. At SLS 2.0, these might include certain types of diffraction techniques such as serial crystallography [14–18], lensless imaging that relies primarily on the transverse coherence [12], and imaging techniques such as phase-contrast tomography [19, 20].

Secondly, the reduced oscillations of the electron beam due to the improved injection scheme from the booster means that as it passes along the undulator, the width of the magnets needed to produce a homogeneous field across the central axis can be reduced. The forces acting on the undulator support structure become concomitantly smaller. Moreover, the additional space won by making the magnets narrower also allows the incorporation of two additional sets

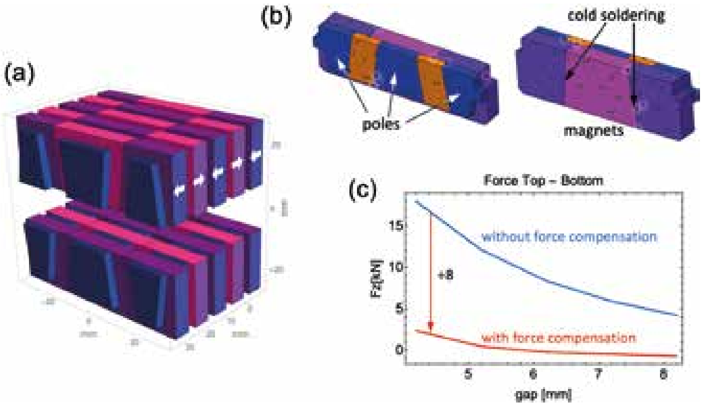

Figure 8. Novel developments in hard x-ray insertion devices. (a) The central Halbach array of poles and magnets can be made to be significantly narrower, thanks to the reduced lateral extent of the electron beam in the orbital plane as it passes through the ID in DLSRs compared to third-generation facilities. Consequently, the forces for a given central magnetic-field strength will be lower. Moreover, the central magnet array can be flanked by arrays in which the poles are opposed (N-N or S-S), thus reducing the total forces even more. The configuration is shown in (b). The reduction in force is typically a factor of eight or more (c), allowing for far more compact and inexpensive mechanical designs. From [9], with permission from the Swiss Society for Photon Science.

of magnets, one on each side of the central array, which, in contrast to the central array, are poled so that they repel (Figure 8). This reduces the net forces on the undulator frame by well over an order of magnitude compared to standard devices used today, and makes them cheaper and much more compact and reliable.

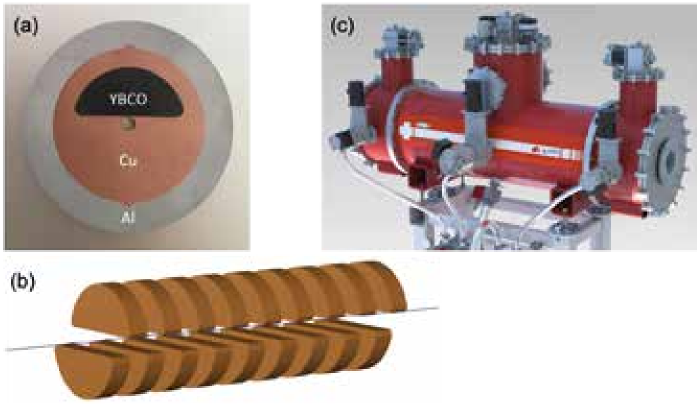

Figure 9. The new HTSU10 superconducting undulator at SLS 2.0. (a) the magnetic elements are half-moons of bulk rare-earth-cuprate superconductors. (b) They are configured in a staggered array to produce the core magnet field. (c) the expunged Meitner field is activated using a 12 T superconducting solenoid in which the HTSC core array is placed.

Another R&D project being pursued concerns a novel insertion device exploiting high-temperature superconducting bulk material (Figure 9). The goal is to generate undulators with ultra-short-period (10.5 mm) and high-strength magnetic fields. Because of the moderate storage-ring energy of SLS 2.0 of 2.7 GeV, high K-values are required in order to enhance the intensities of higher-harmonic radiation, which in turn means that magnetic-field strengths are required that can only be generated using superconducting materials (Equation 11) [21]. For medium-energy synchrotron storage rings such as SLS 2.0, this is a promising route to significantly extend the photon flux to energies beyond 50 keV [Figure 6(c)]. The so-called ‘HTSU10’, with a 1-m magnetic length, will be installed at the new I-TOMCAT beamline in the second planned shutdown [22].

B. Soft x-ray undulators

The brilliance curves for the soft x-ray insertion devices are shown in Figure 6(b).

The APPLE X undulator design was adopted and developed for the SwissFEL Athos beamline. These insertion devices provide an identical photon-energy range in all major polarization modes (linear horizontal, linear vertical, and circular), with full symmetry over the entire range. This is achieved by using independently controllable radial and longitudinal movements for all four magnet arrays. The radial design is suited to small, round, vacuum chambers used in FELs or other single-pass accelerators, and, importantly, also to DLSRs such as SLS 2.0. By exploiting the latest grade of permanent-magnet material, the magnetic period length can be significantly reduced, which means that the desired soft x-ray photon-energy range can be covered by the fundamental harmonic alone. Undulators with many periods and high magnetic fields are, however, problematic because of the associated high and variable heat load on x-ray optical components. High heat loads require aggressive active cooling solutions that can induce unwanted vibrations that are deleterious to ultimate spectral resolutions and, in the case of micro- and nanofocussing and scanning techniques, also spatial resolution.

The so-called ‘APPLE knot’ design [23, 24] will be used at ADRESS (UE36kn), QUEST/XIL (UE36kn and UE90kn), and SIM (2 × UE36kn). This ‘knot’ concept features an additional subharmonic field component (with a period three times longer than that of the main undulator period, see Figure 10). With this magnetic configuration, only the fundamental has its maximum intensity on axis, while the higher harmonics have a cone-like form and are shifted outwards to larger angles. They therefore have a ring-like power-density cross-section. As the fundamental covers the desired energy range for these beamlines, these higher harmonics can then be blocked in the front end using a water-cooled aperture. The load on the optics (mirrors and monochromators) in terms of power density is therefore reduced by a factor of approximately 4, depending on the photon-energy range, allowing more modest cooling and significantly reduced associated vibrations of critical x-ray optical components.

IV. SLS 2.0 Beamline Portfolio and Science Program

The future scientific mission of photon science at SLS will be founded firmly on already established fields of excellence at the Paul Scherrer Institute (PSI). Among others, the SLS to date has produced world-leading research in activities as varied as scanning lensless imaging (ptychographic

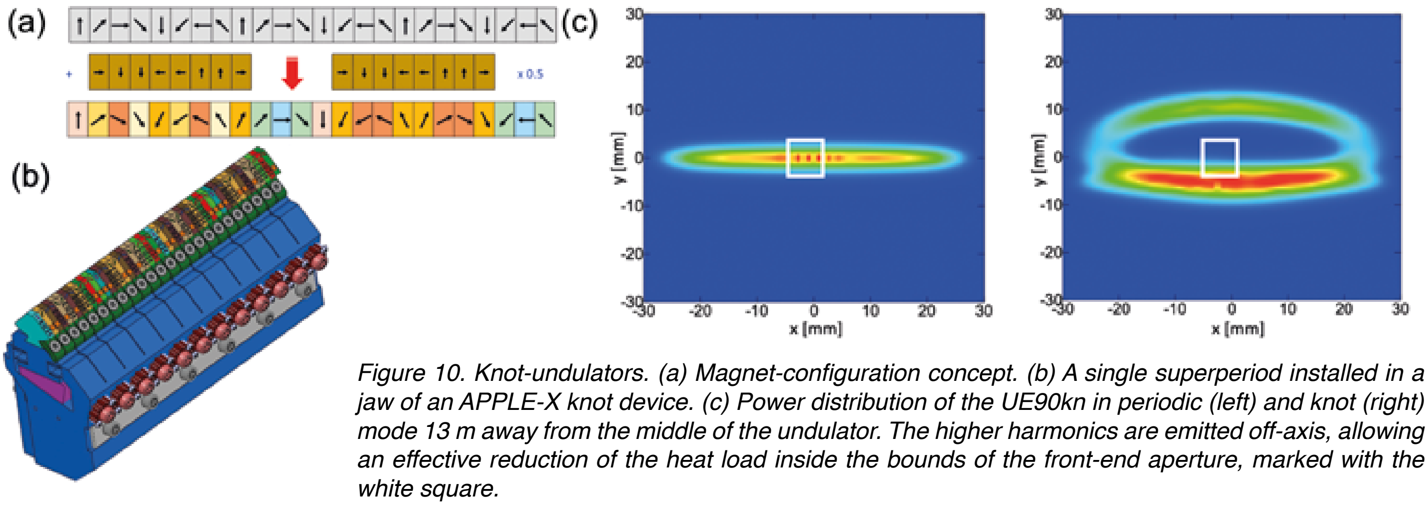

Figure 10. Knot-undulators. (a) Magnet-configuration concept. (b) A single superperiod installed in a jaw of an APPLE-X knot device. (c) Power distribution of the UE90kn in periodic (left) and knot (right) mode 13 m away from the middle of the undulator. The higher harmonics are emitted off-axis, allowing an effective reduction of the heat load inside the bounds of the front-end aperture, marked with the white square.

tomography), diffraction of macromolecular molecules, full-field tomography, soft x-ray angular-resolved photoelectron spectroscopy (ARPES), and resonant inelastic x-ray scattering (RIXS). All of these techniques will profit considerably from the upgrade, which we summarise in this section.

An overview of the beamlines planned for SLS 2.0 is shown in Figure 11.

The main upgrade phase, or 'dark time', to dismantle the existing storage ring and to install the new ring began on 30th September 2023 and will continue until December 2024. For resource reasons, the beamline upgrades have been divided into two phases; first pilot users after the first phase are expected in the Summer of 2025, followed by a further shutdown at the beginning of 2026 and pilot users in Summer 2026.

All already existing beamlines are undergoing upgrades, especially regarding their optics. Moreover, some beamlines have moved, and there are two entirely new beamlines. Changes beyond optics and endstation upgrades include:

- Debye: a new chemistry-focused, hard x-ray spectroscopy/scattering beamline, a sister to the SuperXAS beamline, has already been built.
- I-TOMCAT: a new tomography undulator beamline utilizing the novel HTSU10 is being constructed in Straight 2S, and is complementary to the upgraded TOMCAT beamline, now called S-TOMCAT because of the upgrade of its superbend source from 2.9 T to 5 T.
- The PEARL beamline will amalgamate with the SIS beamline at Straight 9L to create the new QUEST beamline.
- PXIII has been completely rebuilt with new optics and experimental hutches.
- microXAS moves from Straight 5L (which has, in SLS 2.0, an electron beam cross-section incompatible with hard x-ray undulators) to Straight 8S.

Most of the beamlines will benefit from a significant optics upgrade program. The hard x-ray monochromators and mirrors will be redesigned with the reduced horizontal breadth of the photon beam at SLS 2.0 in mind. New crystal and multilayer monochromators will scatter and disperse the incident radiation in the horizontal plane; the minor loss in intensity due to polarization factors will be more than offset by the benefit of horizontal rotational movements, allowing more compact and stable designs. Horizontally deflecting and focusing mirrors will also be able to be made significantly shorter and thereby gain in stability.

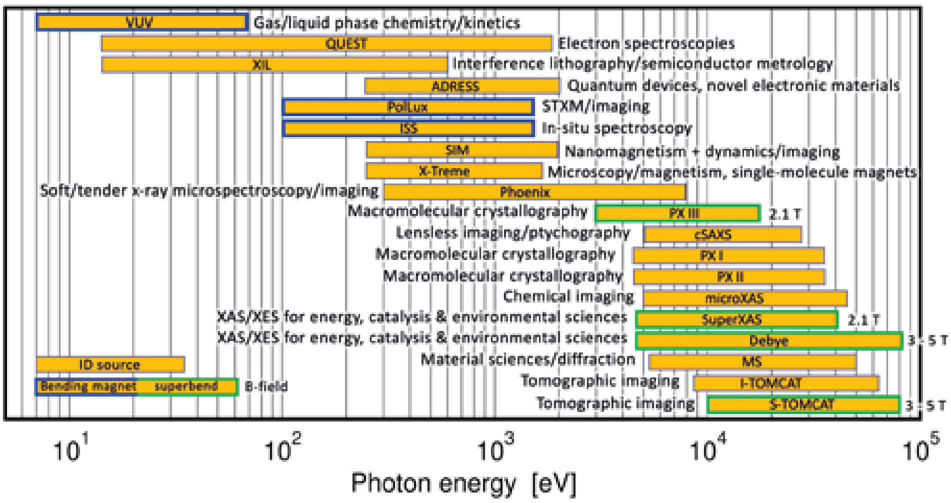

Figure 11. Overview of beamlines in user operation after the upgrade. The source type, the beamline name, areas of major applications, and energy range are shown.

V. Concluding Remarks

Electron-accelerator photon sources have a remarkable track record in science, technology and biomedicine. The SLS has been a leading player in this field since the turn of the century. The underlying physics as well as a demand for seeing matter at the atomic and nanoscale ensure that synchrotrons will continue to be essential for scientific and technical progress in the future. Therefore, most third-generation electron storage rings are either considering or actively undergoing an upgrade to a DLSR. At the Paul Scherrer Institute, the plans for the upgraded SLS 2.0 extend beyond simple improvements of the emittance (and thereby also the brilliance), including novel magnet-lattice elements and x-ray sources pioneered at the PSI, plus an aggressive x-ray optics and endstation upgrade program [25]. This will maintain the pre-eminence of PSI, the ETH Domain, and Switzerland in photon science, which has been established by the current SLS and SwissFEL for the foreseeable future.

The machine upgrade [11] in conjunction with novel source technologies will increase the most relevant experimental parameters at the endstations by well over two orders of magnitude in the hard x-ray regime (Figure 12), which will have very substantial benefits to many methods [25], including ptychography [13], full-field tomography [19, 20], macromolecular crystallography [14, 15], soft x-ray ARPES [26], and resonant inelastic x-ray scattering [27].

Indeed, even greater improvements by up to another factor of 100 are anticipated through adaptations in x-ray optics, most notably in the use of multilayer monochromators instead of crystal monochromators at hard x-ray beamlines, and the substitution of hitherto more conventional but lossy refractive and diffractive focussing elements such as compound refractive lenses and Fresnel zone plates with reflecting elements such as Kirkpatrick-Baez mirrors, which can be made to be more compact than previously possible, thanks to the reduced source sizes.

The design, construction and exploitation of SLS 2.0 will enable not only advanced research and education, but also the continued excellence of technology transfer demonstrated by SLS these last two decades, especially in partnership with InnovAare, the node of the Swiss Innovation Park, located next to SLS 2.0.

SLS 2.0 has been designed to be highly synergistic with SwissFEL [28], co-located at PSI, to create a unique centre for accelerator-based photon science in Switzerland. The people and expertise which enabled the recent completion of SwissFEL

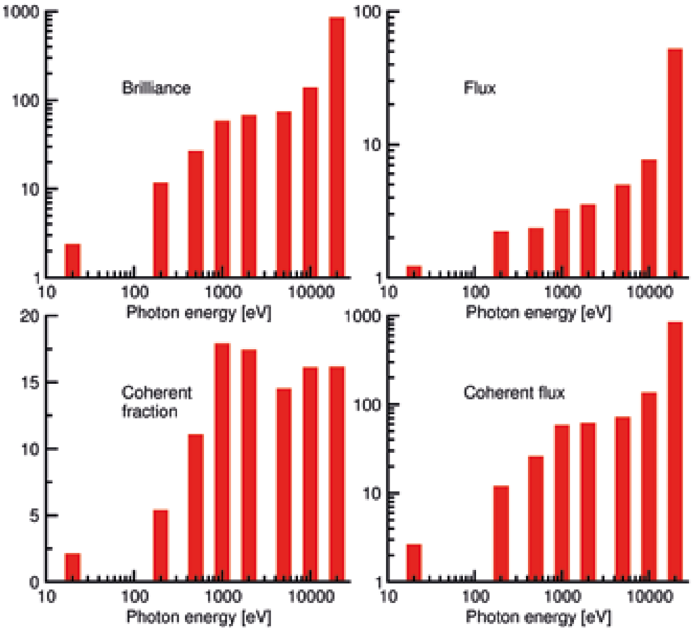

Figure 12. Improvement factors in brilliance, flux, coherent fraction, and coherent flux for the SLS 2.0 upgrade compared to the present SLS, with the new storage-ring energy of 2.7 GeV, for selected photon energies. The undulators assumed in the original SLS are UE212 (8.4 m) for 20 and 200 eV, UE56 (3.6 m) for 500, 1000, and 2000 eV, and U19 (1.8 m) for higher photon energies. The corresponding undulators in SLS 2.0 are UE90 (4.4 m), UE36 (4.4 m), and CPMU15 (3 m).

are now deployed for SLS 2.0. Many of the technologies developed for the SwissFEL project, ranging from serial crystallography to APPLE-X undulators, are now being exported to SLS 2.0; we expect similar fertilization of the Porthos upgrade of SwissFEL which will follow SLS 2.0.

Acknowledgements

Many thanks go to the PSI staff who contributed to the building and operation of the SLS and the planning for the SLS 2.0 project, from the accelerator department, through support and logistics, IT, to the many beamline staff and the user community. Special thanks go to Alun Ashton, Romain Ganter, Juri Honegger, Markus Jörg, Roland Kobler, Frithjof Nolting, Jörg Raabe, Thomas Schmidt, Andreas Streun, Johan Wickström, and Elmar Zehnder for their intimate involvement in the project.

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Milestones in Physics (27)

Developments for the FCC-ee vacuum system

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Abstract

The Future Circular Collider (FCC), the proposed next large CERN's accelerator, would realize a groundbreaking high-energy physics research initiative following the Large Hadron Collider (LHC) successes. This study emphasizes the vacuum system's pivotal role in reducing radiation effects, beam instabilities, and maintaining low-pressure conditions, essential for optimal electron-positron collider performance. Intense optimization and prototyping efforts are required in the future years, together with tight collaboration with the industry.

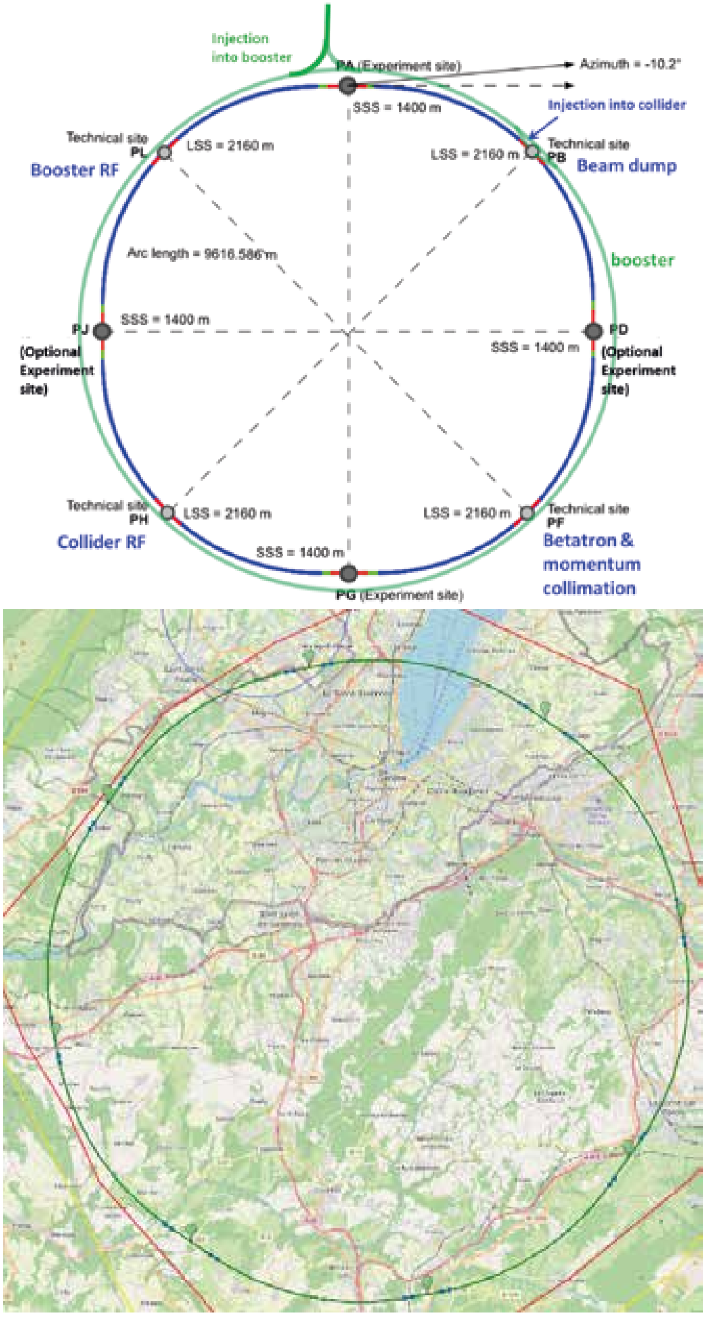

Fig. 1: Schematic views of the FCC-ee accelerator (90.7 km long) and its indicative geographical implantation. The scheme shows in green the booster (not to scale), where the electron and positron bunches are accelerated, and in blue the storage rings, where the two beams circulate in opposite direction in separate beampipes except in the four interaction points where collisions take place. Courtesy of M. Benedikt, J. Gutleber and V. Mertens (CERN).

1. Introduction

CERN's Large Hadron Collider (LHC) is presently full steam in its third operational run (run-3) colliding two beams of protons at 13.6 TeV at the centre of mass and Pb ions at 2.7 TeV/nucleon. At the end of this run, planned in 2026, the world largest accelerator will undergo a major upgrade that aims to increase the proton collision rate, namely its luminosity [1]. This improvement will be attained by installing new equipment, notably new Nb_3Sn superconducting final focusing magnets, during the Long Shutdown 3 (LS3) that will last three years. The final goal of this project (High Luminosity LHC, HL-LHC) is to accumulate by the early forties an integrated luminosity of 3000 fb^{-1} (i.e., ten times more than that obtained in an equivalent time of operation from 2010 to 2023)[1] [2]. When such a high collection of events will be available, the discovery potential of the LHC will be exhausted, therefore requiring a new facility to pursue the quest of fundamental laws of the Universe.

As high-energy particle accelerators need at least two decades from the conceptual proposal to start of operation, CERN and several worldwide collaborators are already working on design and feasibility studies for a new 91 km circumference (see Fig. 1) accelerator featuring in a first step an electron-positron collider, and then a hadron-hadron one with a centre-of-mass energy of 100 TeV (i.e., 7 times that of the LHC) [3]. This study is named *Future Circular Collider* (FCC); today, it is considered as the highest-priority next collider by the European Strategy for Particle Physics (ESPP) [4].

The FCC feasibility study should be completed in 2025 for the next ESPP update around 2026. It mainly focusses on the civil engineering infrastructure and its impact on the local area. Moreover, it aims to optimize the design of the main ring and its injection chain, including the development of crucial equipment and their environmental and sustainability aspects. Finally and importantly, a consolidated cost estimate is being prepared together with a funding model [5].

Staging electron-positron collisions (FCC-ee) first and then hadron-hadron ones (FCC-hh) in the same tunnel is the best option. In addition to the physics prospects, this choice optimizes the cost of the infrastructure, as was the case with the Large Electron Positron collider, LEP, which was later replaced by the LHC in the same tunnel [5]. Furthermore, this choice gives enough time for the development of new affordable superconducting magnets (e.g., using Nb_3Sn and

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[1] An integrated luminosity of 1 fb^{-1} is equivalent to roughly 10^{14} proton-proton collisions [6].

high-T_c superconducting cables) delivering magnetic fields in the range 16 to 20 T to steer 50 TeV protons in the FCC-hh.

Contrary to FCC-hh, FCC-ee is technologically mature. Despite that, dedicated development is mandatory to optimize essential systems, like normal-conducting magnets, collimation, vacuum, and RF acceleration, and to minimize costs and electricity consumption. In this latter respect, a ceiling to the maximum power lost per beam in synchrotron radiation is limited to 50 MW, which in turn sets boundaries to the maximum beam current at a given beam energy.

In the present projected schedule, the civil engineering work for the FCC would start in the thirties for beginning of operation with electrons and positrons about 15 years later.

The FCC-ee operation involves four phases (see Tab. 1), each targeting a defined scientific objective. The first phase, the one at the lowest energy, aims to generate as much as possible Z bosons[2]. The beam energy and current are 45.6 GeV (≈ 91 GeV at the centre of mass) and 1.27 A, respectively, carried by 11200 bunches of 2.14 × 10^{11} electrons or positrons. The last phase, with the most energetic beams (182.5 GeV, 4.9 mA), is dedicated to the study of top quarks. In the two intermediate energy steps, FCC-ee runs as a $W^\pm$ and H(ZH) facility. Recently, some experimentalists have proposed an alternative operation scenario where FCC-ee would start its operation at the ZH energy, as shown in Fig. 2.

In the present design, the FCC-ee accelerator consists of two rings, where positrons and electrons counter rotate, placed side-by-side at a distance of 350 mm along the arcs. A full-energy booster ring capable to inject into the two rings e^- and e^+ in opposite directions is placed 1300 mm above the two storage rings. Four interaction points, IP, where the two beams cross their path and collide at a small angle (30 mrad), and related detectors are presently expected.

2. Vacuum requirements

The main objective of the vacuum system is to ***ensure that the beam-gas scattering lifetime*** is large enough not to be detrimental to the integrated luminosity. This criterium fixes a limit to the average pressure in the low 10^{-9} mbar range in the beampipe of the storage rings of the FCC-ee when beams circulate. The residual gas species should be mostly H_2, with CH_4, CO and CO_2 about one order of magnitude lower. The partial pressures of gas species with molecular masses above 44 must be negligible.

Another important objective of the vacuum system is ***reducing or even eliminating the electron cloud*** [8] ***and ion-trapping effects*** [9] and related beam instabilities and losses. The first detrimental mechanism affects positively charged beams. As bunched high-energy particle beams traverse the vacuum chamber, electrons can be emitted from and accelerated towards the beampipe walls. If the secondary electron yield of the inner surfaces is higher than a given threshold, a multipacting mechanism is generated with possible impact on beam dynamics. Photoelectrons emitted by synchrotron radiation also contribute significantly to the electron cloud formation. Ion-trapping instabilities impact the quality of negatively charged beams. They occur when positively charged ions, generated by beam-gas interactions, get trapped in the beam's potential, leading to an accumulation around the beam itself. These trapped ions can cause significant beam degradation. In both cases, instabilities can result in beam loss, emittance growth (beam size and divergence), and other undesirable effects, that could spoil the performance of such a complex accelerator.

While the first two objectives apply in all positions of the main FCC-ee ring, a third fundamental one concerns the interfaces between the four particle detectors and the accelerator, i.e. the fraction of accelerator nearby and inside the detectors, frequently referred to as Machine-Detector Interfaces (MDI). In these specific cases, the vacuum chambers must be designed to reduce as much as possible the radiation background reaching the detector. As it is explained in detail in the next chapters, five sources of radiation background can be accounted for, including inelastic beam gas scattering and beam emitted synchrotron radiation.

3. Synchrotron radiation

Synchrotron radiation (hereafter SR), a relativistic effect resulting in the emission of electromagnetic waves by a

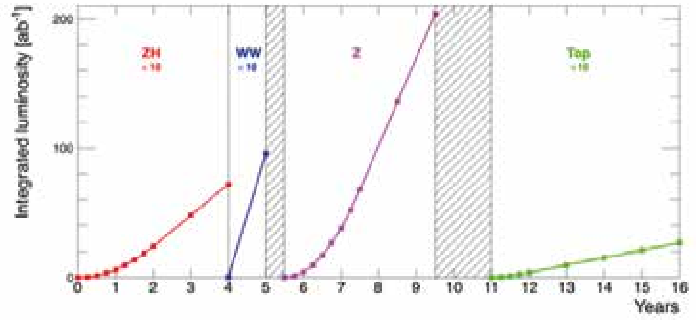

Fig. 2: Integrated luminosity, expressed in inverse attobarn, along the operational years of the FCC-ee. In this scenario, the FCC-ee would initially operate as a Higgs boson facility [7].

Parameters	**Z**	**W^+W^-**	**H (ZH)**	**t - t̄**
Beam energy [GeV]	45.6	80	120	182.5
Beam current [mA]	1270	137	26.7	4.9
Number of bunches / beam	11200	1780	440	60
Bunch intensity [× 10^{11}]	2.14	1.45	1.15	1.55
Luminosity per detector [× 10^{34} $cm^{-2}s^{-1}$]	140	20	5.0	1.25
Years of operation	4	2	3	5
Particle produced	5 × 10^{12}	> 10^8 W^+W^-	2 × 10^6 H	2 × 10^6 tt̄ pairs
FCC-ee / LEP [10]	10^6	10^4	/	/

Table 1: Main parameters of the FCC-ee beams in the four different energy phases [5]. FCC-ee / LEP gives the figures of the FCC-ee with respect to the LEP. 't̄ ' is the antimatter counterpart of the top quark 't'.

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[2] The Z and $W^\pm$ bosons are fundamental particles that carry the weak nuclear force. The weak force is responsible for certain types of radioactive decays and interactions involving particles like electrons and neutrinos. H indicates the Higgs boson. Z bosons generated by proton collisions can interact with the Higgs field, giving rise to the creation of a Higgs boson because of this interaction (ZH).

charged particle moving in a magnetic field [10], characterizes so strongly the design and performance of the FCC-ee vacuum system that, in this context, it deserves particular consideration.

SR has been observed first by astrophysicists who called it “magnetic breaking radiation”, or “magnetic bremsstrahlung”. In accelerators it was first noticed in a small tabletop synchrotron run by the General Electric Corp. in Schenectady, NY, USA, in the early 50s. Its physical explanation has been given by Julian Schwinger, Nobel prize in physics for studies in quantum electrodynamics, in the western world, and independently by Sokolov and Ternov in the USSR. The generation and use of SR has been greatly enhanced later by a class of accelerators known as “light sources”, which nowadays constitute a large fraction of the research accelerators worldwide (for example, the Swiss Light Source at the Paul Scherrer Institute).

SR is characterized by a continuous spectrum ranging from microwaves to hard gamma rays, depending on the energy of the charged beam, its charge, mass, and magnetic field strength. One of the main figures of merit of SR is the critical energy, ε_c, which divides the spectrum in two parts, equally splitting the emitted power. The critical energy depends on the third power of the beam energy and is inversely proportional to the radius of curvature of the orbit. Typically, SR is generated along dipole magnets, where the beam trajectory follows an arc of circumference. Along the ring, dipoles are separated by straight sections where quadrupole magnets are inserted, in order to focus the electron (or positron) beams. Quadrupoles too generate SR emission, but with lower intensity as compared to dipoles, except in the very particular area of the MDI where stronger superconducting quadrupoles are used to squeeze the colliding beams. In those four locations, the strength of the focusing quadrupoles is very high, the so called “gradient” (units are T/m). Higher order magnets, like sextupoles and octupoles, although needed, they generate a negligible amount of SR.

SR can induce desorption of gas molecules from the inner beampipe surfaces whenever the critical energy raises above the few eV range [11]. This effect is called “photon-stimulated desorption” (PSD). In FCC-ee, as in modern synchrotron light sources, it is the main source of gas in the accelerator’s vacuum system. Protons generate SR as well, even if the total emitted power is inversely proportional to the fourth power of the mass of the particle (1836^4 times lower as compared to electrons on the same orbit and energy). This is well known at CERN from LHC operation: as soon as the proton beam energy is ramped up above 2 TeV, pressure rises in locations where photons are expected to impinge [12].

Fig. 3 shows the SR flux spectra of the FCC-ee in four operational phases compared to a known light source, the European Synchrotron Radiation Facility in Grenoble, a 6 GeV 200 mA electron storage ring. One table on the figure gives the value of the critical energy ε_c of each spectrum. The other table gives the linear photon flux generated by 1 m of beam trajectory along a dipole.

We can see that the ESRF has a larger SR photon flux at low photon energies, while the FCC-ee has larger critical photon energies above the Z phase at 45.6 GeV beam energy. The ESRF has also a larger linear photon flux density and power. To deal with this, the ESRF intercepts in a very efficient way most of the dipole SR using so called “crotch absorbers”, which unfortunately cannot be implemented in a twin-ring accelerator like the FCC-ee due to geometrical constraints.

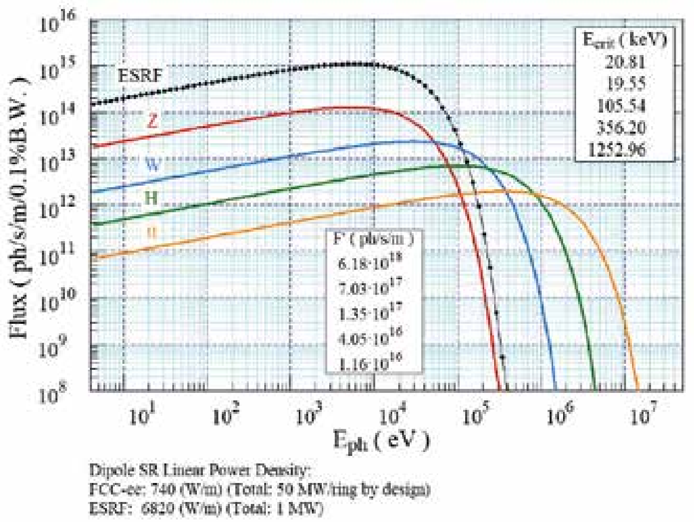

Fig. 3: SR spectra for four FCC-ee energies and the ESRF; B.W. means “Band Width”. The two embedded tables report the critical energies and the number of photons generated per metre of orbit per second in the five cases, from ESRF to FCC-ee $t\bar{t}$ energy. The linear flux density are also reported in the bottom part of the figure.

One can immediately notice that as soon as the energy of the FCC-ee is increased from 45.6 GeV the corresponding critical energy ε_c raises immediately above 100 keV. This photon energy range corresponds to very penetrating gamma rays, which can easily pass through any material over rather large thicknesses, in addition to creating diffuse electron and photon showers via Compton scattering. In fact, such photons can be used to carry out industrial gammagraphies, e.g. looking through thick metal sheets. For accelerators, this is very detrimental, as it can generate a large “leaking” field of hard photons outside of the vacuum chamber, which can irradiate the tunnel and all its components, activating materials and damaging them.

The design of the FCC-ee arc vacuum system must therefore consider this in order to assure the multi-decade-long experimental program and guarantee an acceptable integrated radiation dose to personnel accessing the tunnel.

4. The FCC-ee arc vacuum system

Since the inception of the FCC study program, many different versions and options of the FCC-ee arc vacuum system have been considered. After close scrutiny of the unique high-intensity and high-energy spectrum of the SR fan generated along the orbits, we have concluded that the most efficient way to deal with it is to implement a series of SR photon absorbers placed at carefully studied locations so as to intercept all primary SR photons (i.e. those which are not reflected or scattered). This solution guarantees the fastest beam conditioning, namely the fastest reduction of gas molecules desorbed per impinging photon. This is regularly experienced in all existing SR light sources where short localized SR photon absorbers have been used for dec-

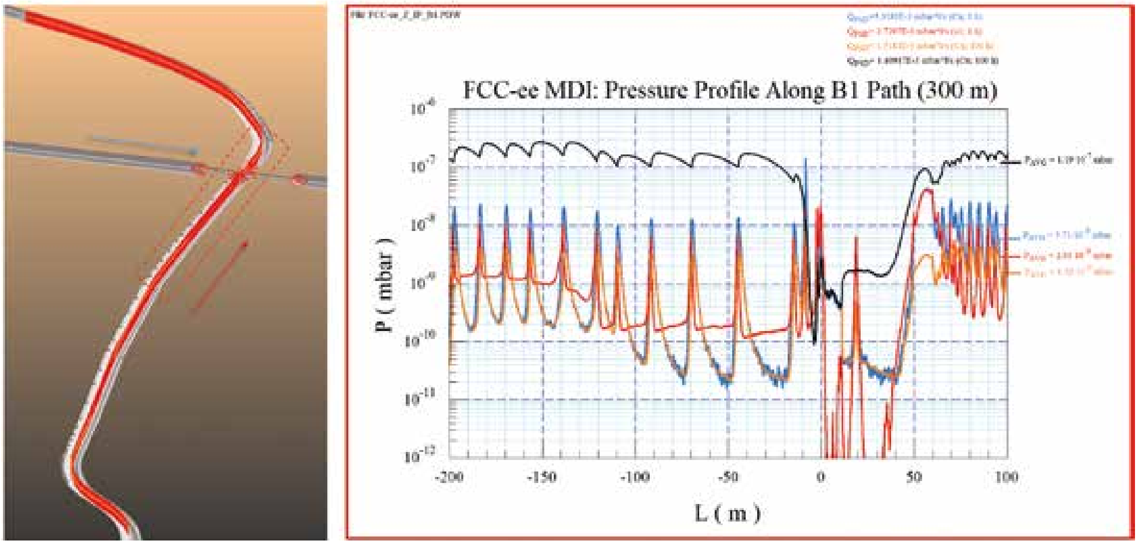

Fig. 4: Pressure profiles in the FCC-ee main rings nearby a collision point. Black line: uncoated beampipe; other colours: NEG coated beampipe. The curves are calculated for four different gas flows extracted by SR from the adsorbers. The pressure peaks correspond to the position of the SR adsorbers. The average pressures are reported on the right side of the graph. On the left, a schematic of the two colliding rings. In red: e⁻; in grey: e⁺. Only the area inside the dashed rectangle is shown on the pressure plots.

ades. This also helps in localizing the source of high-energy Compton electron and photon cascades, as identified by detailed beam-material interaction modelling [13]. Without SR absorbers, the SR fan would hit the internal wall of the vacuum chamber along a continuous strip, as it happened to LEP, and this would require a continuous shielding with lead or other high atomic-number material, such as tungsten for instance. For an accelerator with 2 rings of ~ 91 km this would call for a large amount of shielding material, with attendant tunnel integration issues (e.g., supports).

Detailed ray-tracing montecarlo simulations [14] have been carried out on 3D models of the vacuum chamber with SR absorbers; the location of SR absorbers along a sample 130 m-long section of the arcs, taken as representative, have been optimized. The resulting average longitudinal spacing of the absorbers is 5.5 m. The corresponding pressure profiles stemming from the SR-induced degassing have been calculated for various impinged photon doses, i.e. the integrated SR photon irradiation onto each point around the ring. The same pressure profiles, calculated for different gas species (typically H_2, CO, CO_2 and CH_4) have been iteratively used as input in calculation of bremsstrahlung due to inelastic collisions between high-energy electrons and residual gas atoms [13].

Fig. 4 shows the results of pressure profile simulations along 300 m of one of the two colliding beam paths (the other one is symmetric) for CO gas, under different assumptions for the vacuum chamber material and its conditioning time.

The pressure bumps corresponding to the position of the SR adsorbers are clearly visible. The black curve represents the case when the material of the inner surface is a copper alloy and pumping is localized at the position of the adsorbers. If the beampipe surface is coated with a non-evaporable getter (NEG) thin film, the corresponding pressure values (curves with the other colours) are much lower than for the uncoated cases. The average pressure is around 80 times lower (compare black and orange curves). NEG coatings were developed at CERN in the late nineties to ensure uniformly distributed pumping speed in the LHC; such a coating is made of Ti, Zr and V co-sputtered from intertwisted elemental cathodes, and their typical thicknesses are in the range 0.1 to 2 μm [15]. Heating at temperatures above 180 °C during the bakeout results in the dissolution of the coating oxide layer which, consequently, enable chemisorption on the film surface. The oxide reduction, in addition to pumping, ensure a very low SR-induced desorption [16] and a reduced secondary electron emission [17]. The industrial implementation of NEG coatings in 180 km of beampipes is a real challenge and requires an intense technological development.

A strong program of design, prototyping and testing for the SR absorbers has been already set up: after trying several versions, we have come up with a novel design based on 3D printing technology, which allows us to optimize the cooling efficiency and keep the surface temperature at the location where the SR fan intercepts the absorber within safe limits

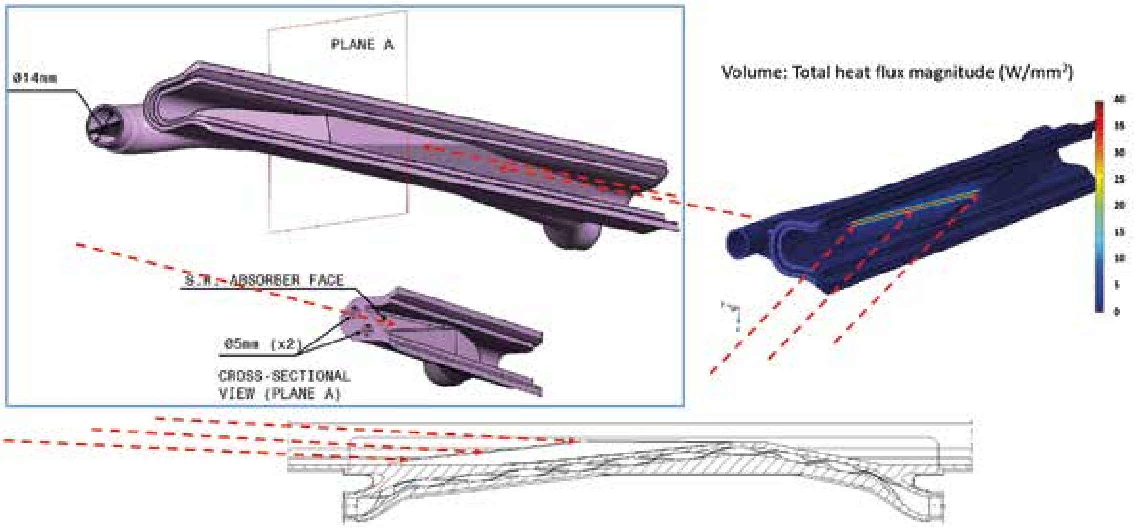

Fig. 5: 3D model of the SR adsorber. The SR light strikes on the inner face of the adsorber that is cooled by water. Such an element is welded to the beampipe. The 3D drawing on the right show the temperature distribution on the surface of the adsorber; the maximum temperature is around 40 °C. Courtesy of M. Morrone, S. Rorison, C. Garion, and F. Santangelo (CERN).

for the material chosen. The material we are considering is a copper alloy, either OFE Cu or CuCrZr. A 2 m-long prototype of extruded chamber with one SR absorber joined to it via electron-beam welding is under fabrication: it will be tested on the BESTEX SR beamline [18] of the 2.5 GeV KARA light source at the Karlsruhe Institute of Technology, Karlsruhe, Germany.

Different views of the 3D-printed SR adsorber are shown on Fig. 5. The dashed red arrows represent the SR fan. On the right a thermal analysis based on the raytracing of SR.

As we plan to apply NEG coating to all the chambers, only a small number of pumps for H_2, CO, CO_2 are necessary. Pumping CH_4 and any other 'non-getterable' gas specie (e.g., argon given off by TIG welds or small air leaks) will be left to ancillary sputter ion pumps placed along the arcs and connected via carefully designed pumping domes. We plan to minimize the number of these sputter ion pumps because they need high-voltage coaxial cables which are known to be subject to radiation damage in the tunnel of accelerators such as FCC-ee. Preliminary calculations done by a dedicated working group, R2E "Radiation to Electronics", show that all sputter ion pump power supplies and other electronics must be placed in dedicated alcoves dug along the tunnel. The preliminary design calls for an alcove spacing of 1.6 km, i.e. each alcove will collect cables and host electronics for equipment 800 m upstream and 800 m downstream of its position.

The proposed FCC-ee vacuum chamber is a 70 (or 60) mm circular tube with two small "winglets" in the plane of the orbit, with 10 mm height and total horizontal width of 115 mm (see Fig. 6), to install the SR absorbers and intercept SR. This vacuum chamber is made of cold-extruded OFE copper in up to 12 m long units. Our present development focuses on three key subjects for cost containment: the flanges and their vacuum tightness, the incorporation of heating elements for the bakeout, and the integration of beam position monitors (BPM).

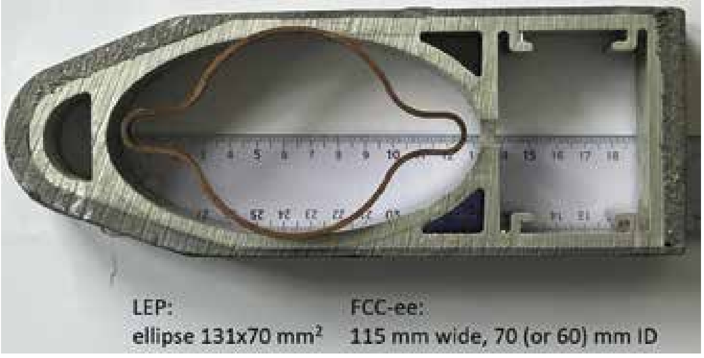

Fig. 6: The proposed FCC-ee vacuum chamber extrusion placed on top of the extruded aluminium cross-section used for LEP (with external Pb shielding to stop high-energy radiation leakage). Courtesy of S. Rorison (CERN).

In the first development we profit of a recent development that successfully introduced shape-memory alloys (SMA) in vacuum technology for particle accelerators [19]. The properties of such materials, shaped as rings, can be utilized to tighten circular flanges simply by heating them; the unclamping is obtained by cooling the SMA rings to temperatures well below 0 °C. The circular flanges at the extremities of the chambers would be friction stir welded to the beampipe.

The second development concerns bakeout, which is an essential step in the process of achieving ultrahigh vacuum. However, the preparation for the bakeout is time consuming and represents an important workload; furthermore, standard heating jackets are expensive and can be deteriorated by radiation. To circumvent such hindrances, cold spray of heating circuits on the vacuum chamber are studied. This additive manufacturing comprises first the deposition of a thin electrical insulator and then of a resistive metal.

Finally, in the third development, the integration of about 8000 BPM is addressed. The present study considers BPM blocks directly added and finely machined on the vacuum chamber by additive technologies. Each BPM electrode would be tightly connected to the BPM block by a SMA ring.

5. The FCC-ee machine-detector interfaces and their vacuum system

The proper design of the vacuum system within the MDI (Machine Detector Interface) is critical for the FCC-ee collider. Its significance lies in ensuring minimal detector background, reducing radiation damage to detectors, accelerator components, and tunnel structures. This also includes mitigating radioactive activation to facilitate safe intervention by technical personnel in line with the ALARA principle (As Low As Reasonably Achievable).

The design of the MDI area leverages on prior experience with LEP, up to 104 GeV, and with data from more recent high-intensity B-factories such as the KEKB and SuperKEKB e^-e^+ colliders in Japan [20]. Given the extremely high beam energies, the FCC-ee's MDI is affected by various forms of radiation, as well as collision debris. The former include bremsstrahlung, radiative Bhabha-scattered gamma rays, beam-gas scattering (elastic and inelastic), beam-thermal radiation scattering, SR from focusing/defocusing quadrupole doublets, and SR from intense solenoidal fields (2 T) within the detector. Most of the electromagnetic radiation generated by these five different effects is concentrated in a rather narrow conical space of $1/\gamma$ radians angular aperture, where γ is the relativistic factor of the beam. For the Z-energy phase, at 45.6 GeV, $\gamma = 89237$; for the $t\bar{t}$ it is 4 times higher. These values correspond to opening angle of the emission cone of about 1 cm diameter at 50 m distance. The total power contained within this narrow cone is of the order of several hundred kW (Z phase): it will require a very detailed study of a dedicated radiation beam dump line, similar to the one installed on each of the LHC beams, with a large-volume photon absorber inside a heavy radiation-shielded bunker. Due to the very large radius of curvature of the machine, about 10 km, a suitable horizontal separation of the e^-e^+ rings and the radiation beam dump will be attained only at about 500 m distance from the IP, meaning that the tunnel over this distance will have to be much larger than the regular arc tunnel, about 18 m wide horizontally instead of 5.5 m diameter along the arcs.

SR from the dipoles immediately upstream of the IP are taken care of by placing discrete absorbers at relevant positions, of the same type as described earlier for the arc vacuum system, plus one last mask absorber in front of the first superconducting focusing quadrupole. A small fraction of this SR hits the internal part of the beryllium chamber, 180 mm long, around which the “vertex” detector layers are placed. These vertex detectors determine with high precision the exact point of impact of the colliding e^- and e^+ bunches. Only very low-energy SR photons are able reach the Be chamber, namely those generated at large angles. A thin layer of gold will be deposited on the internal wall of the Be chamber in order to prevent these SR photons from reaching the vertex detector.

Detailed ray-tracing simulations of the SR fans have been carried out with the SYNRAD+ Montecarlo code [21], to determine the distribution of the SR photons finally being absorbed along the MDI. These photon maps are then imported into the other raytracing Montecarlo code Molflow+ where the molecular flow stemming from photon-stimulated desorption is used as an input. Detailed 3-D models generated by CAD programs can be imported into both SYNRAD+ and Molflow+. These two software tools are being used since a decade or so by basically all accelerator laboratories and projects. They have been tested and validated within reasonable accuracies over a number of recent accelerators, most notably the 4th-generation light sources MAX-4 and SIRIUS.

Some codes used to design the MDI trace not only the SR photons but also all other forms of radiation, like scattered high-energy e^- and e^+, plus the collision debris coming out of the interaction point. The multi-purpose code GEANT4 is usually used, in addition to FLUKA: these codes use models not only of the vacuum chamber but also of all detector components, estimating the radiation dose delivered to them.

For the design of the vacuum system of the MDI, we consider applying the same vacuum chamber cross-section concept with localised SR adsorbers as adopted along the arcs. A number of pumping ports are also placed either in front of each adsorber or immediately before it. Emphasis is placed into the design of the “X”-shaped central chamber, where the e^- and e^+ beams’ paths cross at the 30 milliradians crossing angle (see Fig. 7), and eventually collide inside the short central beampipe.

This chamber is entirely placed inside the detector, and therefore needs to be transparent enough to the collision debris so as not to intercept and absorb too much of it. For this reason, the central ± 2 m long part is made of beryllium and its alloy Albemet, an Al-Be metal matrix composite [22]. The mechanical tolerances of this chamber are very stringent, in particular there is a very narrow space available for the chamber of the outgoing beam and the internal wall of the toroidal luminometer (LumiCal on Fig. 7), a very important device which measures the instantaneous luminosity of the collider. A close collaboration with the experimental physicists designing the detector components placed near the IP chamber is therefore mandatory. A dedicated series of meetings has been set up and run for several years already.

Moving away from the IP, in both directions, the central chamber is welded to aluminium-to-stainless steel transitions which allow welding of stainless steel-made bellows with RF contact fingers. The internal surface of these chambers is carefully designed and studied using sophisticated numerical modelling of its electromagnetic properties, using codes such as CST Studio, to avoid trapping of standing waves generated by the electromagnetic interaction of the intense e^-e^+ beams and the conductive chamber walls. Around the IP, over few meters of their length, both the e^- and e^+ beams transit inside the same chamber, in opposite directions, therefore doubling the beam current and complicating the image current calculations. Very small grid meshes are needed for these calculations, and this pushes to the limit the electromagnetic computations that sometimes require days of continuous processing prior to converging to a solution.

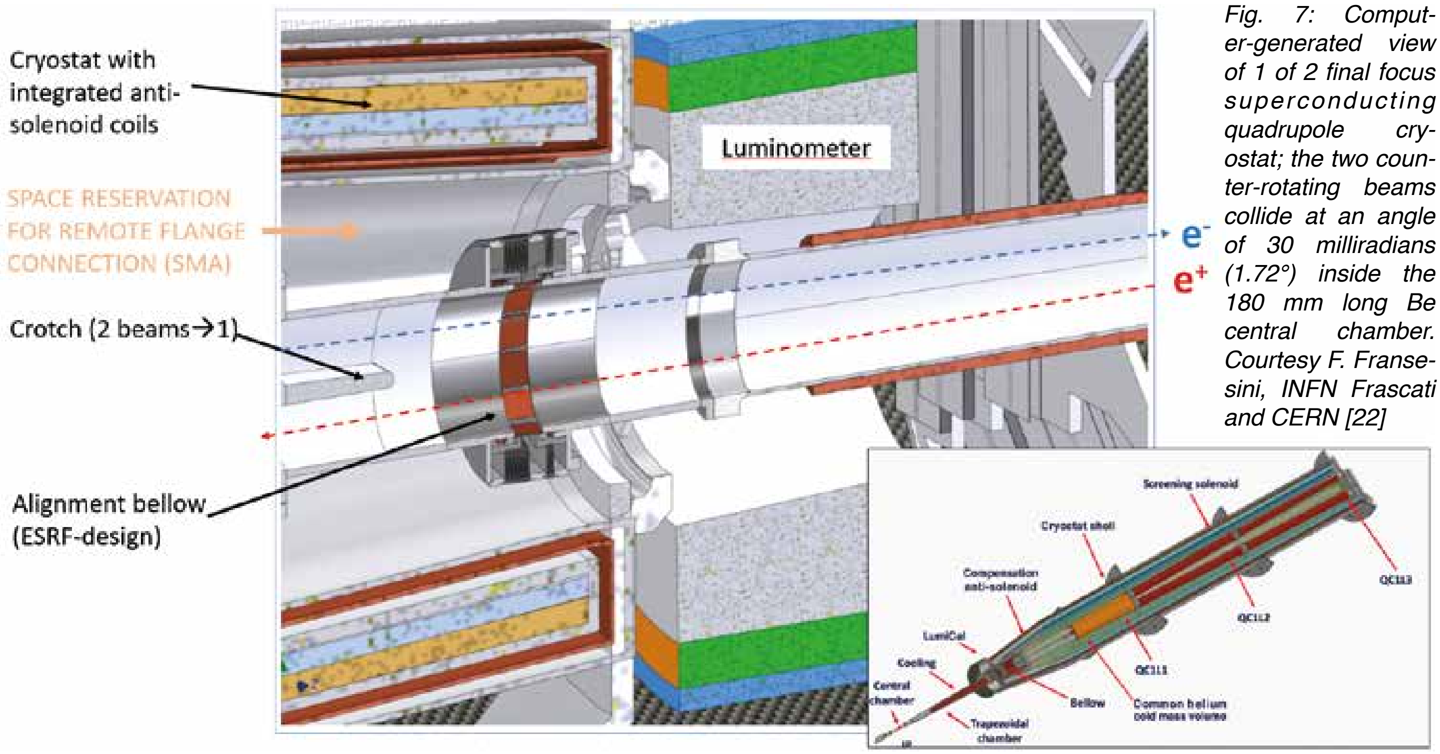

Fig. 7: Computer-generated view of 1 of 2 final focus superconducting quadrupole cryostat; the two counter-rotating beams collide at an angle of 30 milliradians (1.72°) inside the 180 mm long Be central chamber. Courtesy F. Fransesini, INFN Frascati and CERN [22]

6. Conclusions

The Future Circular Collider (FCC-ee) highlights the indispensable nature of advanced vacuum technology in driving the frontiers of particle physics. Even if we have already identified conceptual solutions for the vacuum system of this accelerator, the unprecedented scale of this potential project underlines the necessity for a tight collaboration with the industry, emphasizing the critical role it plays in developing manufacturing processes. The success of FCC-ee relies on employing cutting-edge technology to mitigate radiation effects and ensure reliable operational standards while optimizing production processes to ensure affordable costs and realistic planning. This alliance aims to address the complex challenges posed by big science equipment, necessitating a harmonized effort between scientific activities and industrial expertise.

Acknowledgments

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Appendix

Physics case:

Precision Measurements of the Higgs Boson Properties:

One of the primary goals of the FCC-ee is to conduct precise measurements of the properties of the Higgs boson. By colliding electrons and positrons at extremely high energies, scientists can study the Higgs boson with unparalleled precision. This includes measuring its mass, spin, and interaction strengths, providing deeper insights into the fundamental nature of this elusive particle and its role in the Standard Model of particle physics.

Testing the Standard Model and Searching for New Physics:

The FCC-ee serves as a powerful tool to scrutinize the predictions of the Standard Model of particle physics. While the Standard Model has been remarkably successful in explaining the known particles and their interactions, it is not a complete theory and leaves questions unanswered. By precisely measuring known particles and their behaviours, FCC-ee aims to identify any deviations from the Standard Model predictions, which could be indicative of new, previously undiscovered physics.

Study of Electroweak Processes:

Electroweak processes, which involve the interplay of electromagnetic and weak nuclear forces, are of particular interest in understanding the fundamental forces governing particles. FCC-ee's high-luminosity collisions provide an ideal environment for studying these processes with unprecedented precision. This includes investigations into electroweak symmetry breaking and the properties of W and Z bosons.

Tau-Charm Physics and Flavour Factories:

The FCC-ee is designed to be a "flavour factory," producing copious amounts of tau leptons and charm quarks. By focusing on the study of these particles, scientists can delve into the realm of flavour physics, exploring the subtle differences in the behaviour of particles and their antimatter counterparts. This research can contribute to our understanding of CP violation and the matter-antimatter asymmetry observed in the universe.

Energy consumption:

To gauge the electrical energy usage per person among CERN Member States, we analyse the overall electricity consumption of the FCC and allocate it based on the total population. Assuming the FCC consumes 1 TWh annually and the collective population of CERN Member States is around 540 million. Hence, roughly 1.85 kWh per person would support the FCC annually. In comparison, household electricity consumption per person in the EU in 2021 averaged 1.7 MWh (sourced from Eurostat 2021). Thus, the electricity utilized per person for the FCC constitutes a relatively small portion of an individual's usual electricity usage. When spread across Member States, the FCC's electricity consumption stands as a reasonable and justified investment considering its contributions to global scientific, technological, and educational advancements.

Paolo Chiggiato serves as the head of the Vacuum, Surfaces, and Coatings group at CERN. With 35 years of experience at CERN, he has specialized in vacuum and material technology for high-energy particle accelerators, encompassing surface treatments. Currently, he is actively engaged in overseeing the operation of CERN's accelerator vacuum systems, contributing to the LHC upgrade, and participating in CERN's forthcoming initiatives such as FCC and muon colliders. Simultaneously, he participates in the design and prototyping of future gravitational wave telescopes. Specifically, he leads CERN's efforts on the Einstein Telescope's laser beampipes. Additionally, he frequently provides valuable counsel on projects where vacuum systems hold critical significance.

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Neue Serie "Energie und Nachhaltigkeit"
Nouvelle série "Energie et durabilité"
New Series "Energy and Sustainability"

Die SPG hat sich in den letzten Jahren sporadisch auch mit Beiträgen zur Energiepolitik positioniert. Mit der geplanten Gründung der neuen Sektion "Energie und Nachhaltigkeit" (siehe S. 4) wird der zunehmenden Wichtigkeit beider Themen zur Eindämmung des Klimawandels und der Sicherstellung der Energieversorgung Rechnung getragen. Wissenschaftlich fundierte Erkenntnisse sollen in Zukunft in Artikeln unserer neuen Serie "Energie und Nachhaltigkeit" in den *SPG Mitteilungen*, aber auch als Schwerpunktsthemen in der *SPS Focus* Reihe, oder in speziellen Sitzungen an der SPG Jahrestagung gebündelt behandelt werden. Auf den folgenden Seiten finden Sie den ersten Artikel, verfasst von Eduard Kiener, dem früheren Direktor des Bundesamtes für Energie (BfE).

Ces dernières années, la SSP s'est également positionnée de manière ponctuelle sur la politique énergétique. La création prévue de la nouvelle section "Énergie et durabilité" (voir page 4) tient compte de l'importance croissante de ces deux thèmes en vue de l'atténuation du changement climatique et de la sécurité de l'approvisionnement énergétique. À l'avenir, les connaissances scientifiques seront regroupées dans des articles de notre nouvelle série "Énergie et durabilité" dans les *Communications de la SSP*, ainsi qu'en tant que thèmes prioritaires dans la série *SPS Focus*, ou lors de sessions spéciales à la réunion annuelle de la SSP. Dans les pages suivantes, vous trouverez le premier article rédigé par Eduard Kiener, l'ancien directeur de l'Office fédéral de l'énergie (BfE).

In the last years the SPS has sporadically taken position on topics related to energy politics. The proposed creation of the new section on "Energy and Sustainability" (see page 4) reflects the growing importance of both issues for climate change mitigation and energy supply security. In the future, scientifically sound findings will be presented in articles of our new series "Energy and Sustainability" in the *SPG Mitteilungen*, but also as key topics in the *SPS Focus* series, or in special sessions at the SPS Annual Meeting. On the following pages you will find the first article, written by Eduard Kiener, former Director of the Federal Office of Energy (BfE).

Energie und Nachhaltigkeit (1)

Sichere Stromversorgung mit erneuerbaren Energien?

Eduard Kiener, ehem. Direktor des Bundesamtes für Energie

1 Hochgestecktes energiepolitisches Ziel

Mit der 2017 vom Volk angenommenen Energiestrategie 2050 wurde der Ausstieg aus der Kernenergie beschlossen. Der vom Parlament 2022 verabschiedete Netto-Null-Beschluss verlangt den Ausstieg auch aus den fossilen Energien, die weitgehend durch Strom ersetzt werden. Die Energiezukunft ist deshalb elektrisch; Strom wird für Gesellschaft und Wirtschaft noch wichtiger. Die bisherigen Stromanwendungen werden weiterhin zu befriedigen sein, dazu kommt die Dekarbonisierung.

Die heutige energiepolitische Doktrin will eine Stromversorgung, die einzig auf der Wasserkraft und den sogenannten *neuen erneuerbaren Energien* Fotovoltaik, Wind, Biomasse und Geothermie (den *nEE*) beruht. Dies soll mit dem in der Herbstsession 2023 verabschiedeten "Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien", dem sogenannten *Mantelerlass*, möglich werden. Wie der Gesetzestitel verlangt, muss die künftige Stromversorgung erneuerbar sein und den (inländischen) Bedarf jederzeit sicher decken; die Strom-Versorgungssicherheit ist das zentrale energiepolitische Kriterium, dessen Bedeutung weiter steigt. Bekanntlich ist dabei die Versorgung im Winter massgeblich. Eine Energiepolitik, die diese nicht gewährleisten könnte, wäre gescheitert.

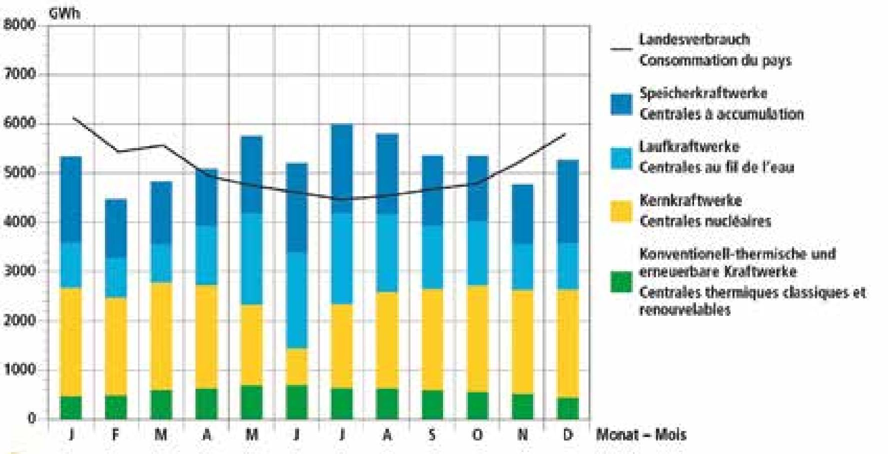
Bundesrat und Parlament orientieren sich an den optimistischen Energieperspektiven 2050+ (EP 2050+) [1], in denen für 2050 eine in der Jahresbilanz durch erneuerbare Erzeugung gedeckte Stromversorgung errechnet wurde. Für den Winter zeigen die EP 2050+ dagegen mindestens bis zur Jahrhundertmitte eine starke Importabhängigkeit. Zu hinterfragen ist die angepeilte voll erneuerbare Stromversorgung auch bezüglich Wirtschaftlichkeit, Umwelt- und Klimaschutz.

2 Stromversorgung mit erneuerbaren Energien: was braucht es dazu?

Die Stromerzeugung steht seit Jahren im Zentrum der Energiepolitik. Parallel dazu ist der Ausbau des gesamten Stromsystems nötig, dies wird jedoch von der Politik verkannt oder verdrängt. Die Grundzüge der Transformation hin zur angestrebten erneuerbaren Stromversorgung sind durch die physikalisch-technischen und teils auch die ökonomischen Gesetze vorgegeben:

- Der Stromverbrauch wird deutlich zunehmen, die erneuerbare Stromerzeugung muss massiv ausgebaut werden. Von den Potentialen her steht dafür primär die sommerlastige Fotovoltaik zur Verfügung, die Möglichkeiten der Windkraft sind beschränkt, jene von Wasserkraft, Biomasse und erst recht von Geothermie bescheiden. Im Jahr 2050 sollen nEE gemäss dem Mantelerlass 45 TWh Strom produzieren. Daraus lässt sich aufgrund der EP 2050+ ein PV-Bedarf von mindestens 40 TWh abschätzen.
- Trotz Förderung seit 2009 betrug die Stromerzeugung durch nEE 2022 erst 6,02 TWh oder 9,8 % des Landesverbrauchs [2]. Der aktuelle PV-Produktionszubau von etwa 1 TWh/a ist erfreulich, der Ausbau der nEE aber trotzdem viel zu gering, um die Versorgungssicherheit innert nützlicher Frist zu gewährleisten. Damit die im Mantelerlass verlangten 45 TWh erreicht werden könnten, müssten ab sofort jährlich 1,4 TWh installiert werden.
- Für die sichere, eigenständige Versorgung im Winter würde dies jedoch immer noch nicht genügen. In den EP 2050+ wird 2050 ein Winterverbrauch von 44 TWh erwartet und eine Wasserkrafterzeugung von 20 TWh angenommen. Die nEE müssen dann also 24 TWh bringen, wenn man effektiv eine ausgeglichene erneuerbare Stromversorgung will und nicht einfach, wie in den EP 2050+ und im Mantelerlass, auf Importe ausweicht. Davon muss die Fotovoltaik schätzungsweise 22 TWh Winterstrom produzieren. Da der Winteranteil etwa 30 % der PV-Jahreserzeugung beträgt, muss diese bis 2050 auf 69 TWh steigen und der PV-Jahreszuwachs auf durchschnittlich 2,5 TWh/a. Das scheint trotz Solar- und Windexpress wenig realistisch.
- Schon bisher war die Schweiz im Winter Strom-Nettoimporteur, im Sommer Exporteur. Der weitgehend auf der sommerlastigen Fotovoltaik beruhende Ausbau der

Fig. 10 Monatliche Erzeugungsanteile und Landesverbrauch im Kalenderjahr 2022
Quotes-parts mensuelles et consommation du pays durant l'année civile 2022



BFE, Schweizerische Elektrizitätsstatistik 2022 (Fig. 10)
OFEN, Statistique suisse de l'électricité 2022 (fig. 10)

Figur 10 aus der Schweizerischen Elektrizitätsstatistik zeigt wesentliche strukturelle Aspekte der Stromversorgung: Verbrauch Winter > Sommer, Erzeugung Winter < Sommer, deshalb Winterdefizit und Sommerüberschuss. Kurve Landesverbrauch wird im Winter stärker steigen als im Sommer, wegen Dekarbonisierung der Wärmebereitstellung. Ausbau Stromerzeugung v.a. PV, führt zu immer höheren Sommerüberschüssen. Aktuell hoher Kernenergieanteil im Winter.

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[1] Bundesamt für Energie: Energieperspektiven 2050+, November 2020

[2] Bundesamt für Energie: Gesamtenergiestatistik 2022

Stromproduktion vergrössert dieses Ungleichgewicht zwischen Erzeugung und Bedarf. Es werden sich steigende, schlecht verwertbare Sommerüberschüsse ergeben. Die Fotovoltaik weist neben der saisonalen Problematik weitere Eigenheiten auf, die das Stromsystem beherrschen muss: sie produziert wetterabhängig und nachts gar nicht.

- Dann muss bei voll erneuerbarer Stromerzeugung primär die Wasserkraft die Versorgung sicherstellen. Die Laufkraft bringt im Winter aktuell eine Leistung von etwa 1 GW, im Sommer etwa 3,5 GW. In den Dunkelzeiten beträgt die Verbrauchslast im Winter jedoch bis 10 GW, im Sommer mindestens etwa 5,5 GW. Die Laufkraftwerke decken den Verbrauch also nicht einmal in Sommernächten. Einen gewissen Beitrag können stationäre und Autobatterien liefern, allerdings mit Umwandlungsverlusten. Die Speicherkraftwerke werden deshalb den Grossteil des nächtlichen Bedarfs decken müssen, es sei denn, die Schweiz verlasse sich weiterhin darauf, dann importieren zu können, was immer weniger gesichert ist, besonders natürlich im Winter.
- Die aktuell nutzbare Speicherkapazität der Wasserkraftwerke beträgt 8 TWh; sie genügt schon nicht für den Ausgleich der Sommer-/Winterbilanz und erst recht nicht für weitere Anforderungen wie die Netzregelung und das Nachtmanko der Fotovoltaik. Deshalb ist der massive Ausbau der Saison- und Tagesspeicherung unverzichtbar.
- Zunehmend wird temporär überschüssige PV-Produktion abzuregeln sein. Dazu braucht es gesetzliche Massnahmen.
- Eine weitere Herausforderung entsteht durch die künftig hohe Einspeiseleistung, vor allem durch die Fotovoltaik. Anstelle von 1 GW Bandenergieleistung aus Kern- oder Gaskraftwerken muss für die gleiche Winterenergie eine PV-Leistung von etwa 13 GW installiert werden. Schon für die im Mantelerlass verlangten 40 TWh PV ist, wenn man optimistisch von umgerechnet jährlich 1000 Volllaststunden ausgeht, eine installierte Leistung von 40 GW nötig. Das ist viermal mehr als die bisherige Winter-Verbrauchshöchstlast von 10 GW, im Sommer ist dieses Verhältnis noch ungünstiger. Wenn wirklich 2050 die rein erneuerbare Versorgung angestrebt werden sollte, mit 69 TWh PV, würde das Leistungs-/Lastverhältnis noch extremer. Auch wenn nicht gleichzeitig alle PV-Anlagen mit voller Leistung produzieren, werden hohe temporäre Leistungsüberschüsse auftreten und die Netzregelung wird technisch und organisatorisch immer schwieriger. Auch dazu braucht es gesetzliche Massnahmen.
- Solaranlagen speisen überwiegend auf tiefer Spannungsebene ins Netz, deshalb muss vielerorts das Verteilnetz verstärkt werden, etwa wenn die Fotovoltaik in einem Quartier ausgebaut wird. Bei verschiedenen alpinen Solarparkprojekten müssen die erforderlichen Leitungen zum Abtransport der Energie erst erstellt werden, was bekanntlich Bewilligungs- und Baudauern von Jahren bis Jahrzehnte bedeutet. Es ist auch zu beachten, dass die Netzkapazität aufgrund der installierten Leistung dimensioniert werden muss, die nur selten erreicht wird.
- Die Energiezukunft ist wie erwähnt elektrisch. Dies wird durch eine Empa/EPFL-Studie untermauert, die ergab, dass eine erneuerbare Energieversorgung über einen stromdominierten Pfad sehr viel kostengünstiger möglich wäre als mit Wasserstoff oder synthetischen Brenn- und Treibstoffen[3]. Fast alle Energiedienstleistungen - Kraft, Licht, Kommunikation, Wärme, Mobilität - können ganz oder teilweise durch Strom erbracht werden. Wärmepumpen ersetzen Öl- und Gasheizungen, Automobile werden durch Elektro- statt durch Verbrennungsmotoren angetrieben. Ausnahmen sind einige industrielle Prozesse, der Flug- und vermutlich auch der Fernlastverkehr. Dafür sind künstliche Brenn- und Treibstoffe erforderlich, die überwiegend mit Strom hergestellt werden (PtX: Power to Gas und Power to Liquids). Auch für PtX braucht es gesetzliche Massnahmen.

Soweit die energiewirtschaftlichen Fakten und Notwendigkeiten für ein auf erneuerbaren Quellen beruhendes Stromsystem. Wo steht die Schweiz auf diesem Weg?

3 Versorgung nicht gesichert

Spätestens im letzten Jahr wurde klar, dass es um unsere Stromversorgungssicherheit schlecht bestellt ist. Dies zeigten die Notfallmassnahmen drastisch, die der Bundesrat aufgrund der im vergangenen Winter drohenden Strommangellage ergreifen musste. Auch für die kommenden Winter sieht es nicht grundsätzlich besser aus, obwohl sich die europäische Versorgungslage dank dem weniger kritischen Gasmarkt und der steigenden Verfügbarkeit der französischen Kernkraftwerke etwas entspannt hat.

Hohe Importabhängigkeit im Winter

Jahrzehntelang wurde viel zu wenig in das Stromsystem investiert, vor allem in die für die Versorgung entscheidende Winter-Stromerzeugung, deshalb bleibt unsere Versorgung auf Importe angewiesen, mit steigender Tendenz.

In den letzten zehn Wintern betrug der Einfuhrüberschuss fünfmal mehr als 4,5 TWh, also mehr als die Winterproduktion eines grossen Kernkraftwerks. Im Winter 2021/22 wurden netto gar 7,8 TWh importiert; dies waren 23 % des Landesverbrauchs. Die Auslandabhängigkeit war im Winter 2022/23 wegen den milden Temperaturen zwar etwas geringer, tendenziell steigt sie jedoch wegen der Dekarbonisierung.

Es muss also weiterhin viel Winterstrom importiert werden. Woher kann er kommen? Deutschland hat seine Kernkraftwerke abgestellt und will aus der Kohleverstromung aussteigen, was nicht recht gelingen will, Frankreich hat Mühe, seinen Kernkraftwerkpark zu erneuern und von der EU kann keine Hilfe erwartet werden, im Gegenteil.

Auch mit Mantelerlass: Importe langfristig nötig

Wir dürfen uns also immer weniger darauf verlassen, den benötigten Strom einführen zu können. Die aktuelle Politik sieht dies anders, sie nimmt hohe strukturelle Importe inkauf. In den Energieperspektiven 2050+ wird für die Wintermonate 2035 mit einem Importüberschuss von 15 TWh oder 38,5 % des Landesverbrauchs gerechnet; für 2050 sind es immer noch 9 TWh oder 20,5 % des Landesverbrauchs. Das war dem Parlament offenbar zu viel, im Mantelerlass

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[3] A. Züttel *et al.*, Future Swiss Energy Economy: The Challenge of Storing Renewable Energy, März 2022

legte es einen Richtwert - was dies auch immer sein soll - für die zulässigen Winter-Stromimporte fest. Diese sollen auf 5 TWh beschränkt werden; damit wird eine Auslandabhängigkeit akzeptiert, die in etwa der zu hohen heutigen entspricht. Eine Stromversorgung mit einem strukturellen Importbedarf von 5 TWh ist alles andere als sicher. Zudem würde eine Mangellage nicht nur das Inland betreffen, sondern wäre eine europäische Krise. Ungeschmälerte Importmöglichkeiten wären dann nicht gegeben.

4 Die Schweiz muss sich selber versorgen können

Ausbau des ganzen Stromsystems nötig

Es gibt deshalb nur eine verantwortbare Politik: Die Stromversorgung muss möglichst rasch auch im Winter wieder eigenständig werden, mit einer ausgeglichenen Strombilanz, also Richtwert null oder höchstens 1 TWh. Dazu braucht es eine starke Erhöhung der Stromerzeugung; weil diese aber aus erneuerbaren Quellen stammen soll, wird auch ein entsprechender Ausbau der Speicherung, des Netzes und der Netzregelung unverzichtbar. Politische Massnahmen dazu fehlen weitgehend.

Den Verbrauch mit hoher Wahrscheinlichkeit selber decken zu können und von Importen unabhängig zu sein bedeutet nicht Autarkie. Die Schweiz soll weiterhin möglichst aktiv am europäischen Stromverbund mitwirken. Dies wird allerdings immer schwieriger, einerseits aufgrund neuer Strom-Binnenmarktregeln, anderseits weil die EU wegen fehlenden Rahmen- und Stromabkommen die schweizerischen Akteure gezielt behindert, selbst auf der technischen Ebene der Netzgesellschaft Swissgrid. Eines ist klar: Das Ausland löst unsere Versorgungsprobleme nicht.

Gas- oder Kernkraftwerke?

Der Zubau an erneuerbarer Stromerzeugung ist und bleibt zu gering, um den steigenden Winterverbrauch zu decken und zudem die künftig wegfallende Kernenergie zu ersetzen. Die Winterstromlücke wird sich absehbar weiter öffnen und die Auslandabhängigkeit steigt. Allein mit Erneuerbaren lassen sich Versorgungssicherheit und Netto-Null nicht innert nützlicher Frist realisieren. Ohne Kern- und/oder Gaskraftwerke wird es nicht gehen. Aber auch mit solchen besteht noch lange ein Importbedarf, weil der Zubau neuer Kernkraft genauso wie jener der Erneuerbaren viel Zeit erfordert und beide Produktionsschienen starke politische Widerstände zu überwinden haben.

Gaskraftwerke belasten das Klima, widersprechen dem Netto-Null-Ziel und sind keine nachhaltigen Elemente der Stromversorgung. Trotzdem musste der Bundesrat - wegen der drohenden Winter-Mangellage - teure Not-Gaskraftwerke mit einer Leistung von aktuell 336 MW einrichten und Notstromanlagen reservieren. Die ElCom empfiehlt gar eine Reservekapazität von 400 MW für 2025 und von 700 - 1400 MW für die Jahre 2030/2035. Damit wird aber bloss möglichen kurzfristigen Mangellagen Rechnung getragen, nicht aber ein Beitrag zu einer zukunftsfähigen Stromversorgung geleistet.

Zur Beseitigung der strukturellen Winter-Importabhängigkeit ist viel gesicherte Erzeugung nötig. Sie kann klimaschonend nur von zusätzlicher Wasserkraft - diese leider mit beschränkten Ausbaumöglichkeiten - und von Kernenergie stammen. Die Bandenergie liefernde Kernkraft durch fluktuierenden Strom aus Fotovoltaik und Wind ersetzen zu wollen, ist schlicht unsinnig. Die Beschlüsse, aus der Kernenergie auszusteigen und erst noch Projekte für Ersatz-KKW ohne Grund vorzeitig abzulehnen, waren die bisher gravierendsten energiepolitischen Fehlentscheide, besonders bezüglich der Versorgungssicherheit. Es braucht die erneuerbaren Energien und die Kernkraft.

Kernenergie bleibt Versorgungsstütze

Im Winter 2022/23 haben die schweizerischen KKW 45 % zur Netto-Stromerzeugung beigetragen und damit 40 % des Landesverbrauchs gedeckt. Aktuelle Studien der ElCom[4] und der ETH[5] haben die grosse Bedeutung des Weiterbetriebs der noch funktionierenden KKW für die Winterversorgung aufgezeigt. Betriebsverlängerungen auf 60 Jahre (Gösgen 2039, Leibstadt 2044) würden die Versorgungsprobleme wesentlich reduzieren. Weitere Verlängerungen wurden ebenfalls untersucht. Sicherer und auf Dauer energetisch und wirtschaftlich sinnvoller wäre der Bau neuer KKW-Kapazität, ihre Planung sollte umgehend begonnen werden. Behauptungen, man könne die KKW rasch ohne Versorgungsprobleme stilllegen, sind schlicht abstrus.

Importabhängigkeit ist teuer

Würde Strom länger als bei üblichen Unterbrüchen fehlen, also Tage oder gar Wochen, wären gewaltige Schäden für die Gesellschaft unausweichlich. Die Kosten für Wirtschaft und Haushalte wären rasch viel höher als jene für eine sichere Eigenversorgung. Gegen die Forderung, die Stromversorgung solle eigenständig sein, also nicht importabhängig, werden wohl Einwände kommen, das koste viel zu viel. Importe seien günstiger als Eigenerzeugung. Solche Zeiten sind vorbei, die Marktpreise sind nach dem Allzeithoch vom August 2022 zwar zurückgegangen, liegen aber deutlich über jenen vor wenigen Jahren und eine neue Tiefpreisphase ist nicht in Sicht. Die Stromkosten steigen für die meisten Verbraucher. Stromversorger, die auf tiefe Marktpreise und Importe statt auf Eigenerzeugung gesetzt haben, konfrontieren ihre Abnehmerinnen und Abnehmer nun mit teils exorbitanten Preiserhöhungen.

Der letzte Winter hat gezeigt, wie teuer Auslandabhängigkeit werden kann. Der Bund hat für Notfallmassnahmen Ausgaben von rund 900 Mio. Fr. verpflichtet; dies belastet alle Endverbraucher zusätzlich mit 1,2 Rp./kWh. Allein die Wasserkraftreserve von 400 GWh kostete 296 Mio. € oder 74 ct/kWh – ein stattlicher Betrag für eine Versicherung, die glücklicherweise nicht beansprucht wurde. Die für den Winter 2023/24 kontraktierten 400 GWh sind mit 13,9 ct/kWh deutlich günstiger, liegen aber immer noch höher als die Jahresproduktionskosten neuer Solaranlagen und erstrecht neuer Kernkraftwerke.

Bis Anfang dieses Jahrhunderts konnte sich unser Land selbständig mit Strom versorgen, war dabei auf dem europäischen Strommarkt konkurrenzfähig und konnte stets einen beachtlichen Aussenhandelssaldo erzielen. Dies war

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[4] Eidgenössische Elektrizitätskommission: Winterproduktionsfähigkeit, Juli 2023

[5] ETHZ, Energy Science Center: Swiss electricity supply after the "Mantelerlass" - quo vadis ? September 2023

nur möglich dank weitsichtig getätigten Investitionen, mit welchen die damalige Elektrizitätswirtschaft eine sichere Stromversorgung anstrebte. Es ist zu erwarten, dass auch eine künftig wieder eigenständige Stromversorgung wirtschaftlich und wenig von Marktpreisschwankungen abhängig sein wird.

Niemand fühlt sich für Versorgungssicherheit verantwortlich

Im früheren Monopol sorgten die Elektrizitätswerke, insbesondere die sogenannten Überlandwerke, für die sichere Versorgung, ohne dass dazu gesetzliche Vorgaben nötig waren. Mit der Liberalisierung änderte sich dies, heute will niemand für die Versorgungssicherheit zuständig sein. Das Stromversorgungsgesetz verlangt zwar von den Endversorgern, dass sie ihre Verbraucher jederzeit beliefern können, was aber in Mangellagen gar nicht möglich ist. Deshalb muss festgelegt werden, wer für die Versorgungssicherheit zuständig sein soll und welche organisatorischen Vorkehren erforderlich sind. Es drängt sich m.E. auf, analog zur nationalen Netzgesellschaft Swissgrid eine nationale Energiegesellschaft zu errichten, die mit den erforderlichen Kompetenzen ausgerüstet die nötigen Kraftwerke bauen könnte, soweit die traditionelle Stromwirtschaft dazu nicht in der Lage oder willens ist.

Die Umwelt- und Klimafrage

Die Energiegesetzgebung ist nicht nur daran zu messen, ob sie eine sichere Versorgung ermöglicht. Netto-Null ist ein ebenso wichtiges Ziel. Dabei besteht weitherum der Glaube, dieses lasse sich am besten mit erneuerbaren Energien erreichen. Dem ist aber nicht so. Die neuen erneuerbaren Energien weisen alle eine geringe Energiedichte auf und verlangen deshalb einen hohen spezifischen Investitionsaufwand, mit viel grauer Energie. Der künftige globale Rohstoffbedarf für Fotovoltaik- und Windanlagen, Batterien, PV-Aufständerungen und dergleichen ist riesig. Die oft knappen Materialien stammen grossenteils aus China und aus Entwicklungsländern, wo sie unter ökologisch und sozial problematischen Bedingungen abgebaut werden. Der ökologische Fussabdruck wird erst in einer fernen Zukunft abgebaut sein, wenn der ganze Materialkreislauf geschlossen und nurmehr mit erneuerbaren Energien betrieben wird.

Das Paul Scherrer Institut hat mit umfangreichen, den technischen Fortschritt berücksichtigenden und bisher nie bestrittenen Lebenszyklusanalysen die Umwelt- und Klimabelastungen der verschiedenen Stromproduktionstechnologien ermittelt [6]. Sie zeigen, dass die Wasserkraft die geringsten spezifischen Treibhausgasemissionen aufweist, gefolgt von Kernenergie und Wind, Fotovoltaik ist bereits deutlich klimabelastender. Noch wesentlich schädlicher sind fossile Kraftwerke, also auch die installierten Gasturbinen. Die Stromerzeugung aus neuen erneuerbaren Quellen belastet das Klima mehr als jene aus Kernenergie. Dazu kommen die Klima- und Umweltauswirkungen, die sich aus dem Systemaus- und Umbau ergeben, der nicht zuletzt wegen dem steigenden Anteil des Sonnenstroms erforderlich wird.

5 Sichere Versorgung mit Strom aus erneuerbaren und aus nuklearen Quellen

Um es vorwegzunehmen: Der Mantelerlass geht in die richtige Richtung, aber die hehren, hochgesteckten Ziele werden verfehlt. Sein Titel "Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien" besagt eindeutig, dass die künftige Elektrizitätsversorgung allein auf erneuerbaren Quellen beruhen soll und sicher sein muss, also die Bedürfnisse der Stromkonsumenten jederzeit decken kann. Die vorstehenden Ausführungen zeigen, dass dies nicht der Fall sein wird und eine sichere, erneuerbare Stromversorgung bis 2050 nicht gewährleistet werden kann.

Positiv ist, dass die Rahmenbedingungen für den Ausbau der erneuerbaren Stromerzeugung verbessert werden und die vorgesehene Solarpflicht bei Neubauten ist politisch massvoll. Bis 2040 soll mit Speicherkraftwerken zusätzlich eine sicher abrufbare Winter-Stromproduktion von 2 TWh zugebaut werden. Damit würde das durch wissenschaftliche Studien ermittelte zusätzliche Potential [7] ausgeschöpft, was aber bis 2040 wenig realistisch erscheint. Ebenso wenig wahrscheinlich ist, trotz umfassender Subventionswirtschaft, dass die oben aufgezeigten nötigen Zubauraten der erneuerbaren Stromerzeugung, insbesondere von Winterstrom, erreicht werden können.

Die grössten Mängel der Energiegesetzgebung sind das Fehlen der erforderlichen Bestimmungen für den erwähnten Systemausbau (Speicherung, Netz inklusive intelligente Netze und Netzregelung, Bereitstellung synthetischer Brenn- und Treibstoffe) und der Festlegung, wer für die Versorgungssicherheit verantwortlich sein soll. Ferner erhalten Haushalte und KMU weiterhin keinen Marktzugang. Zudem ist der Abschluss eines Stromabkommens mit der EU für die Versorgungssicherheit und auch aus wirtschaftlichen Gründen unerlässlich.

Die Energiewende wurde nie zu Ende gedacht, auch mit dem Mantelerlass nicht. Es wird deshalb noch lange dauern und massive Anstrengungen erfordern, bis die Stromversorgung wieder krisenfest ist. Die Kernenergie muss eine Säule der Stromproduktion bleiben; sie ist nicht nur energiewirtschaftlich und für die Versorgungssicherheit vorteilhaft, sondern auch für das Klima günstiger und zudem wirtschaftlicher als die neuen erneuerbaren Energien, trotz anderslautenden Behauptungen.

Die Kernenergie darf nicht weiterhin ein Tabu bleiben. Eine sinnvolle Energiewende würde den Ausstieg aus den fossilen Energien ermöglichen und nicht aus der klimafreundlichen Kernenergie. Das sollte die Politik endlich erkennen, auch wenn es Populäreres gibt als das Einstehen für die lange verteufelte Kernkraft. Konkret muss deshalb das Verbot für neue KKW-Rahmenbewilligungen im Kernenergiegesetz aufgehoben werden.

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[6] Paul Scherrer Institut und Bundesamt für Energie: C. Bauer (ed) *et al.*, Potentials, costs and environmental assessement of electricity generation technologies – An update of electricity generation costs and potentials, 2019

[7] ETH Zürich: R. Boes *et al.*, Swiss Potential for Hydropower Generation and Storage, 2021

Physics Anecdotes and Personal Recollections (28)

Optical Wavefront Sensing

Bernhard Braunecker

Introduction

We described in No. 71 of this journal the measurement of the internal centering state of e.g. lithographic lenses, a rather special task in optical factories. In the following we focus more on questions of daily industrial business how to control the wavefront (WF) shape of optical beams. This could concern laser power systems for micro-machining applications, where the beam profile of the laser has to be modified appropriately either to drill holes or to polish surfaces or to anneal the material to relax internal tensions. Or WF measurements in astronomy when the image of a star is blurred by the turbulence of the earth atmosphere. To get rid of this distortion modern telescopes include a so called adaptive optical mirror which reflection surface can be mechanically shaped to compensate the distortion of the star WF. This is controlled by a WF sensor and allows to retrieve full image resolution. We will describe WF-sensors which are either commercially available or still in development or even just an idea. Each method has its pros/cons, and the user has to find his optimal solution.

We will start with the simplest approach, the Hartmann sensor, and extend its concept to more efficient, smaller and faster versions.

WF measuring Concept

Most WF sensors work with a 2f-optics (Fig. 1), where the light wave in the lens entrance pupil (EP) located at $z = -f$ is transferred to its Fouriertransform in the image plane (IM) at $z = +f$, where f is the lens focal length. The lens characterized by its F-Number $\equiv f/D_{EP}$, where D_{EP} is the EP diameter, should be designed that a plane wave with a preset tilt angle α still leads to a diffraction limited spot at position $r = f \cdot \tan(\alpha)$ in IM. To measure the full profile of an incident WF, one divides first the EP in many small sub-apertures and second inserts a position sensitive detector PSD in the image plane IM.

The PSD measures both, the spot intensity I and the centroid vector of the light distribution $\boldsymbol{R}(x,y)$. It will be shown next that $\boldsymbol{R}$ is directly proportional to the WF-gradient in EP, which is the average slope of the WF across all open sub-apertures. As a first approach, the classical method, one moves a single hole across the beam cross section D_{EP}, which delivers enough information to retrieve the complete WF from all averaged local WF slopes. But there are more efficient strategies which we will explain next.

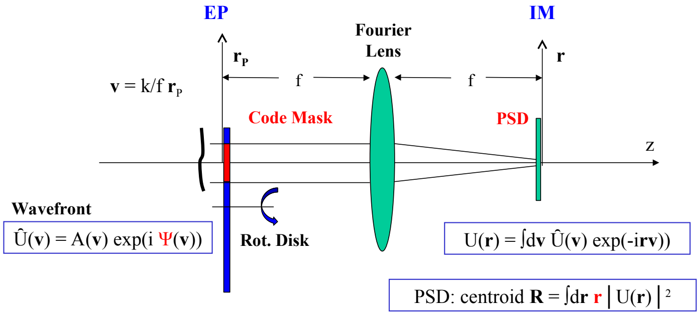

Fig. 1: Hartmann sensor using a 2f System. The WF in the entrance pupil EP is fouriertransformed in the image plane. The EP is covered by a rotating code mask. The position sensitive detector PSD measures the intensity centroid.

Theory

The WF in the entrance plane is described by the complex amplitude $\hat{U}(\boldsymbol{v}) = A(\boldsymbol{v})\,exp(\mathrm{i}\psi(\boldsymbol{v}))$, where the WF error ψ is the deviation from a perfect plane wave expressed as phase term[1]. If the lens works diffraction-limited, as we assumed, the complex amplitude $U(\boldsymbol{r})$ in IM is up to irrelevant phase factors equal to the Fourier transform $U(\boldsymbol{r}) = \int dv\,\hat{U}(\boldsymbol{v})\,exp(-\mathrm{i}\boldsymbol{rv})$. The measured quantities at the PSD are the intensity

$$I = \int d\boldsymbol{r}\,|\,U(\boldsymbol{r})\,|^2 \qquad (1a)$$

and the intensity centroid

$$\boldsymbol{R} = \int d\boldsymbol{r}\,\boldsymbol{r}\,|\,U(\boldsymbol{r})\,|^2 \qquad (1b)\,.$$

The sampling of the WF in the EP is performed by a code mask F of one or many small holes, called sub-apertures. Then $F(\boldsymbol{v})$ is multiplied with $\hat{U}(\boldsymbol{v})$. Inserting the Fourier transform in (1a) and (1b) leads to

$$I = \int d\boldsymbol{v}[\,F(\boldsymbol{v})\,A(\boldsymbol{v})\,]^2 \qquad (2a)$$

and

$$R = \int d\boldsymbol{v}\ \mathrm{Im}\{F(\boldsymbol{v})\,A(\boldsymbol{v})\cdot\nabla[F(\boldsymbol{v})\,A(\boldsymbol{v})] \\ +\mathrm{i}\,(F(\boldsymbol{v})\,A(\boldsymbol{v}))^2\cdot\nabla[\psi(\boldsymbol{v})]\} \qquad (2b)$$

where we applied the Fourier theorem of differentiating and the integration by parts. It will be shown that measuring I_m and $\boldsymbol{R}_m$ for a complete set of filters F_m (m = 1...M) allows to determine $A(\boldsymbol{v})$ and the WF-gradient function $\nabla[\psi(\boldsymbol{v})]$. The latter can be integrated across the whole aperture to obtain $\psi(\boldsymbol{v})$ up to an additive constant. In most cases the phase function ψ can be developed to K = 24 or 36 Zernike polynomials $Z_k(\boldsymbol{v})$, k = 1...K, leading to $\psi(\boldsymbol{v}) = \sum c_k Z_k(\boldsymbol{v})$. The measurement goal is to determine the Zernike coefficients c_k.

If the full aperture is scanned at N sampling positions $\boldsymbol{v}_n$ by M measurements of I_m and $\boldsymbol{R}_m$, the unknown amplitude values A_n and the Zernike coefficients c_k are obtained by solving the set of M linear equations (3a) and (3b), written in matrix notation

$$F^2_{M,N} \bullet A^2_{N,1} = I_{M,1} \qquad (3a)$$

leading to

$$A^2_{N,1} = (F^{\mathrm{T}}_{N,M} \bullet F_{M,N})^{-1} \bullet F^{\mathrm{T}}_{N,M} \bullet I_{M,1}$$

and to

$$F^2_{M,N} \bullet \mathrm{diag}\,(A^2)_{N,N} \bullet \nabla Z_{N,K} \bullet c_{K,1} \equiv L_{M,K} \bullet c_{K,1} = \boldsymbol{R}_{M,1} \qquad (3b)$$

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[1] It is usual to express the EP-coordinates $\boldsymbol{r}_P$ by the spatial frequencies $\boldsymbol{v} = k/f\,\boldsymbol{r}_P$ using $k = 2\pi/\lambda$, λ the wavelength and f the focal length.

resulting in

$$c_{K,1} = (L^{\mathrm{T}}_{K,M} \bullet L_{M,K})^{-1} \bullet L^{\mathrm{T}}_{K,M} \bullet \boldsymbol{R}_{M,1} \qquad \text{(3c)}$$

where we ignored here the first term with $\nabla[F(\boldsymbol{v})\,A(\boldsymbol{v})]$ in (2b, 3b) as of minor importance.

Single Hole Hartmann WFS

The most simply WF sensor is the historical Hartmann sensor where the beam cross section, illustrated by the red circle in Fig. 2, is scanned in polar coordinates by a rotating Nipkow-disk [2] with several holes. In our example seven holes are arranged in such a way, that when one hole enters the red circle, its adjacent radial neighbor just leaves it. This assures that at any time only one hole is inside the circle, and the measured WF is directly the corresponding local one, so $M = N$ in (3a, 3b) and function $F_n = \mathrm{circ}(\boldsymbol{v} - \boldsymbol{v}_n, \boldsymbol{r}_{Hole})$.

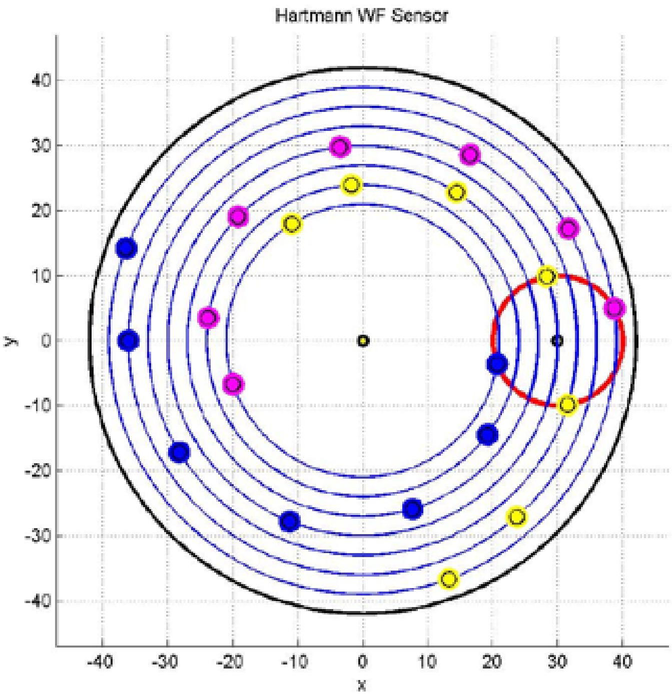

Fig. 2: Example of a Hartmann disk with seven scanning holes. The red circle is the beam cross section in the EP. The hole arrangement in magenta shows start of scan, in yellow at scanning halftime and in blue at end of scan. At any time there is only one hole inside the red EP area.

Hadamard coded Hartmann WFS

The main disadvantage of the Hartmann single hole method is its inefficiency. The low intensity transmitted through the small hole requires long integration times to achieve an acceptable signal to noise ratio (SNR) [3]. The solution is to encode the WF by a set of code masks that about 50 % of the incident intensity is permanently measured (Fig. 3). The price to pay, however, is the numerical decoding after the measurements.

The code should be a) binary (hole or no hole), b) cyclic, meaning when the code pattern is rotated by one code element, a new pattern appears, c) orthogonal d) should have a fast decoding algorithm similar to the Fast Fourier transform FFT and e) the code length should be a product of two nearly equal numbers m_a and m_b to fold the pattern in two dimensions to cover the beam cross section.

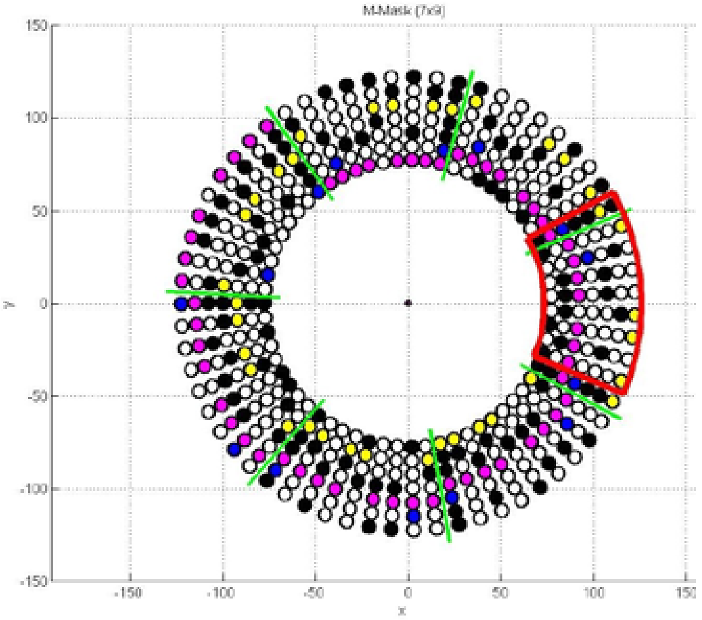

Fig. 3: Hartmann disk with M-sequence code of N = 63 elements. The red segment is the area where the WF is measured. The same color e.g. magenta, shows how the code elements 1 … 63 are arranged in 7 segments (separated by green lines) of 9 elements each. When rotating the disk by one hole step, a new orthogonal 2D-code pattern covers the WF in the red segment.

A good choice as code mask is the S-matrix, derived from so called M-sequences [4]. The decoding algorithm is based on the Fast Hadamard Transform FHT, faster than the FFT since binary, which, however, needs two permutations of the input and output vector. But there are clever possibilities to make both permutations equal to reduce the computation effort. We applied in many industrial applications M-sequences of length $N = 2^m - 1$ with m even as $N = 63 = 7 \times 9$, or $255 = 15 \times 17$, or $1023 = 31 \times 33$, but also $N = 65535 = 255 \times 257$ and larger would be possible. This, however, would need a lot of computing power and be more the case for big astronomical applications.

Then (3b) is rewritten as

$$S_{N,N} \bullet \mathrm{diag}\,(A^2)_{N,N} \bullet \nabla Z_{N,K} \bullet c_{K,1} \equiv S_{N,N} \bullet \boldsymbol{x}_{N,1} = \boldsymbol{R}_{N,1} \qquad (4)$$

where $S_{N,N}$ is the S-matrix and solve for

$$\boldsymbol{x}_{N,1} = (S_{N,N})^{-1} \bullet \boldsymbol{R}_{M,1} \qquad (5)$$

to obtain

$$c_{K,1} = (\nabla Z^{\mathrm{T}}_{K,N} \bullet \nabla Z_{N,K})^{-1} \bullet \nabla Z^{\mathrm{T}}_{K,N} \bullet \mathrm{diag}\,(A^2)_{N,N} \bullet \boldsymbol{x}_{N,1} \qquad (6)$$

by using the known values of $A_{N,N}$ and the Zernike gradient functions $\nabla Z_{K,N}(\boldsymbol{r})$.

When we developed some years ago such an encoded WF sensor for ESA, we chose a code of $N = 63$ elements folded

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[2] The Nipkow disk was used as first scanner for TV images in the 1920 years.

[3] The spatial encoding of an aperture (red circle in Fig. 2) with masks of about 50% transmittance is necessary if the aperture is the human thyroid gland enriched with the isotope iodine-131. Then all emitted gamma quanta (364 keV) should be permanently measured to keep the injected dose small.

[4] E E Fenimore 'Large symmetric Pi transformations for Hadamard transforms', Applied Optics, Vol. 22, No. 6, 15 March 1983

in circular segments of 7 × 9 elements (Fig. 3), together with a PSD characterized by a noise equivalent displacement NeD = 25 nm/Hz$^{-1/2}$ which value was experimentally verified at an incident power of 1 µW. Since we measured each code pattern 80 ms, the NeD was 25 nm / Hz$^{-1/2}$ / $\sqrt{80\,\text{ms}}$ = 88 nm. Using a Fourier optics of $F\# = 6.25$ and $\lambda = 0.6$ µm led to a noise equivalent WF error $\partial x = \text{NeD}/(2\,F\#) = 0.0064$ µm, i.e. $\lambda/100$ rms.

The WF resolution was verified with a test laser beam of 0.611 λ pV (0.104 λ rms) WF error. The total measurement time was however 63 × 80 ms = 5 s.

Both Hartmann versions based on rotating disks are very accurate, but large scaled and slow in operation. This is not a problem when testing the image quality of optical systems in the lab or in the factory. In those cases, however, where WF measurements in real time are required, one needs other configurations of the Hartmann method.

Shack-Hartmann WFS

This is the most used technical version today. The incident WF of diameter D_{Beam} is imaged by an array of lenslets (diameter $d_{Lenslet}$) on a 2D-CMOS sensor of diameter $D_{CMOS} = D_{Beam}$ and pixel diameter d_{Pixel}. Therefor each lenslet adresses $m = d_{Lenslet} / d_{Pixel}$ pixels which determines the measurement range.

Example: For D_{Beam}= 25 mm and $d_{Lenslet}$ = 0.1 mm we have 250 lenslets in one direction. If the focal length f is 25 mm, then the maximum WF angular range is ± 2 mrad. Measuring with a wavelength $\lambda = 0.5\,\mu$m yields a maximum WF tilt range of ± 5 λ. If the CMOS pixel size is 10 µm, the WF resolution is about $\lambda/25$ rms, which is sufficient for most industrial tasks.

Hartmann WFS with Digital Light Projector®

If one needs the high WF resolution of the Hadamard-Hartmann sensor but with shorter measurement times, then the following idea might be interesting. It still keeps the modern 2-step concept (physical encoding by masks plus numerical decoding), but substitutes the mechanical disk by MEMS technology which significantly increases the speed and reduces the size. The code disk is replaced by a digital light projector (DLP) which is used more and more in TV and display applications[5]. It consists of a 2D-MEMS array of switchable mirror pixels of about 10 µm width and pitch that can be electrically deflected about 20° with video or even higher frame frequencies.

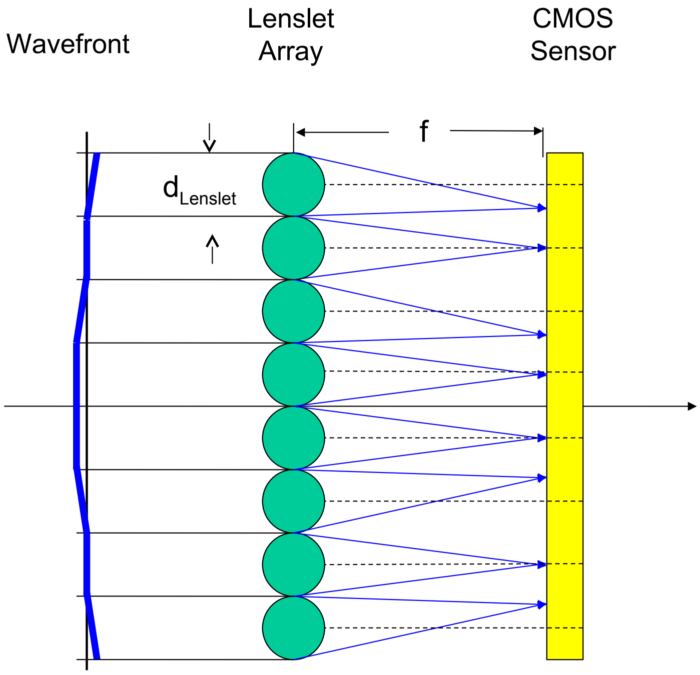

Fig. 4: The incident WF (blue line) is imaged as a dentered spot array on the CMOS sensor. This allows to calculate the WF tilt angle across each lenslet aperture and to reconstruct the total WF error.

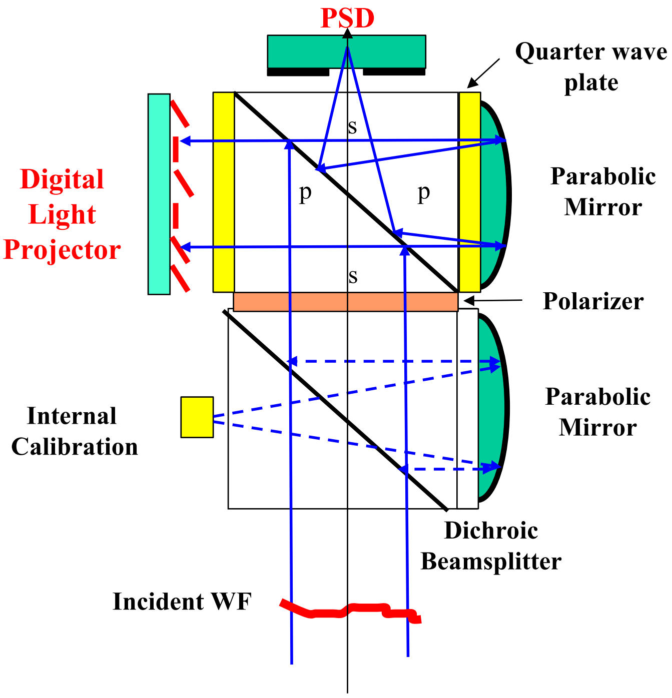

Fig. 5: Concept of a DLP - WFS. The incident WF is reflected from the DLP switching elements (left) and focused by the mirror optics (right) on the PSD (top).
The light from a not-deflected DLP element corresponds to a code bit 'one' and is recorded by the PSD, otherwise stopped at the PSD-aperture as code bit 'zero'. In the lower part the perfect WF of a laser diode is used for autocalibration on demand.

In Fig. 5 we sketch the idea of such a compact Hadamard WF sensor with a beamsplitter cube as the central optical element. The incoming WF is reflected from the DLP and Fourier-transformed by a parabolic mirror on the PSD. The PSD is covered with a field stop with an aperture wide enough to accept the diffraction pattern arising from a not-deflected mirror element of some degrees plus some margin for the expected WF tilt angle range. A not-deflected mirror pixel corresponds to a '1' in our coding mask scheme and is registered by the PSD, while a code element '0' is implemented as a mirror pixel deflecting of 20° and thus not registered. To minimize the intensity loss, the beamsplitting layer is polarization sensitive, i.e. highly reflecting s-polarized light, but fully transmitting p-polarized light. The necessary change of polarization is accomplished by a linear polarizer at the entrance side and two $\lambda/4$ waveplates (orange and yellow plates in Fig. 5).

The idea to use a DLP for multiplex signal coding of light is getting more and more attractive for imaging tasks in microscopes and cameras, using only one pixel sensor according

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[5] https://www.ti.com/de-de/dlp-chip/products.html

to equation (1a) [6]. But the version here with a PSD is much more powerful since it measures intensity and phase. We presented the idea in 2010 using a DLP D4X00Kit of Texas Instruments (1920 x 1080) pixels of 10 µm pitch [7], but unfortunately could never experimentally realize it. Especially the trade-off between the DLP's fast switching speed and the frequency dependent NeD of the PSD needs to be better understood, but also how exactly returns each mirror element after deflection back to a reflection angle zero ? This potential error source, however, could be eliminated by adding a on-line calibration module, as shown in the lower part of Fig. 5. A laser diode with slightly different wavelength produces a perfect plane wave and thus can measure the true zero-deflection angle of each pixel element whenever needed. To minimize the intensity loss in the operating mode the beamsplitter coating of the calibration cube is dichroic [8].

Space Communications

Such a fast, accurate and robust WFS is best suited for real-time space applications. In the future the data transfer between satellites is performed by laser light, which includes the up- and down link from satellite to ground stations (Fig. 6). The laser WF is, however, blurred by turbulences in the atmosphere which led to an intensity loss at the receiver telescopes. To keep a certain SNR necessary for a preset bit error rate would need longer integration times resulting in smaller data rates. But installing an adaptive optical element in one or both telescopes controlled by the measurement signals of a WF sensor - as described in the introduction above - would allow to compensate the actual WF distortion and to maintain the full data rate [9].

Fig. 6: Ground station on Tenerife for up- and down link to satellites using laser light as data carrier. Image: GA-Synopta GmbH.

Summary

WF sensors are nowadays integrated parts of many optical systems as on-line control elements of the emitted or received optical information. Which variant is selected, depends on the task: for robust industrial purposes the use of the Shack-Hartmann version is meanwhile standard, while for special work in science as astronomy or in technology as space applications modifications as the Hadamard types with higher resolution and much higher measurement speed are interesting. In the next issue of the *SPG Mitteilungen* we describe how to apply WF sensors to test large space telescopes.

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[6] Laser Focus World, No. 48 (July 2010), p 48. www.laserfocusworld.com

[7] Darmstädter Kolloquium für optische Messtechnik (Dakom), 11.03. 2010

[8] Even there is no need to use a (cyclic) M-sequence as code pattern as in the case of the rotating disk, the advantage is the nearly same signal intensity of all M-transforms. This is different to Fourier or Hadamard transformations with their large DC peak, and results in a better use of the dynamic range of the PSD sensor.

[9] See *SPG Mitteilungen* Nr. 50, p. 57 - 59 (2016)

The Jost Bürgi Future Forum 2024

Bernhard Braunecker

In 2015, the Jost Bürgi Initiative was founded in Lichtensteig in the canton of St. Gallen, the birthplace of the famous watchmaker and co-inventor of the logarithm Jost Bürgi (1552 - 1632). Since then the SPS is co-organizing an annual symposium for historians presenting new details of life and work of Bürgi and his time. This is also of special importance for physicists, since Bürgi collaborated around 1600 in Prague at the court of Emperor Rudolf II with the famous astronomers, the German Johannes Kepler and the Dane Tycho Brahe. The cooperation culminated some years later in the formulation of the three Kepler laws of planet motion.

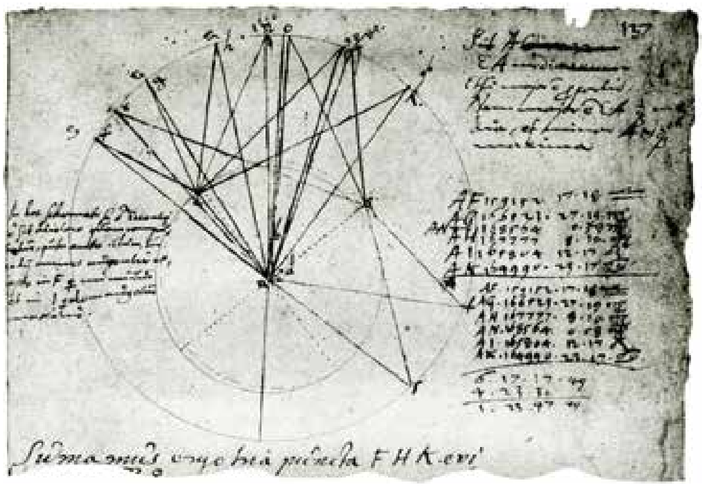
Since 2020 part of the symposium is a *Future Forum*, where modern cutting-edge technology with strong relation to Physics is explained by experts at first hand, in analogy to the fact that Bürgi, Brahe and Kepler were pioneers at their time with revolutionary achievements in science. Whenever possible, historical recourse is made to them, since their scientific-technical legacy can still be found in many fields as today's astronomy, but also in modern navigation and surveying concepts.

Das wissenschaftliche Erbe Keplers und Bürgis

Die Prägung der Moderne durch Präzision, Zeitmessung und Ellipsen.

Sonderheft der Jost-Bürgi-Stiftung Lichtensteig (SG) zur Ausstellung "Schlüssel zum Kosmos - Jost Bürgi (1552 - 1632) bringt den Himmel in Ordnung" im Kulturmuseum St. Gallen 2023/2024.

In Kepler's case, he also had a decisive influence on the development of modern physics, more than has been perceived



Sketch from Kepler's handwritten studies of various positions of Mars observed by Tycho Brahe, shown in relation to the circular orbit of the Earth's orbit. They then led him to the assumption of elliptical orbits.
From: Gesammelte Werke Keplers, Band XX, Teilband 2, Seite 132.

by the public up to now. This is explained in a special issue of the Jost Bürgi Foundation ***Das wissenschaftliche Erbe Keplers und Bürgis*** in four articles with examples from economics, theoretical physics (from *Kepler*, *Newton*, *Lagrange*, *Hamilton* to *Emmy Noether*), astronomy and industrial surveying [1].

From Bürgi's "Small Data" to Modern "Big Data" Applications

The next Future Forum will be held on Saturday, 2 March 2024 in Lichtensteig on the eve of the closing event of the Bürgi special exhibition in the Kulturmuseum St. Gallen "Schlüssel zum Kosmos – Jost Bürgi (1552 – 1632) bringt den Himmel in Ordnung" [2].

When regarding the achievements of Kepler and Bürgi, mainly the correct description of planetary orbits by ellipses, one should remember that Kepler had only 12 special observations to trace the elliptical orbit of Mars, a typical case of "Small data" (Figure). Today astronomical data are collected in star catalogues as *Hipparcos*, *Tycho* and *Gaja* in huge amounts (see Box), a typical example of "Big data". They require in many cases a preprocessing by artificial intelligence methods before scientists can evaluate them.

In the scientific part of the Future Forum, the opportunities and risks of "big data" will be discussed in the following three lectures:

The exploration of Mars with robots

Robin Phillips, maxon international ag

The immense progress towards ever more powerful computer concepts, communications channels and software technology makes it possible to carry out large-scale, cross-national and even space-wide actions in real time. Just as we may control large telescopes around the world from our office using a tablet, operators will soon be able to control instruments on Mars. In the presentation by Dr. Robin Phillips of maxon international ag, the status of activities in the Mars 2020 rover project 'Perseverance' will be reported, in which the company is involved with its special motor drives. The instruments deliver huge amounts of image and scientific measurement data to Earth permanently and on-line (with a time delay).

Hunting Outbursting Young Stars (HOYS), Project for amateur astronomers

Dirk Froebrich, University of Kent, UK

Dr. Dirk Froebrich from the University of Kent (UK) will present the HOYS project, in which amateur astronomers, but also school classes from all over the world, participate in a joint project on the formation of stars and planets, exchange their extensive measurement results with each other every night and publish them together at the end of a measurement campaign. Participating in a large-scale international project is exciting and of great didactic value, especially for school classes. https://hoys.space/

Wann ist Messen vermessen?

Gerd Folkers, former President of the Swiss Science Council

Even in Bürgi's days, measurement data had to be accurate, unambiguous and reproducible so that theories could be tested and decisions made. Since then, this has usually not been a problem, since the data volumes have been manageably large ("small data") and suitable control procedures were always available to clearly identify wrong information or targeted data manipulation. Nowadays, in the age of "Big data", this is different, as in almost all areas of daily life huge amounts of data are generated at such a high rate that only artificial intelligence (AI)-based programs can control, for example, industrial activities in real time. But are the manipulated images, artworks, scientific analyses, and machine controls trustworthy? How can their relevance, i.e. their truthfulness, be recognized and verified? This difficult problem will be addressed in the lecture by Prof. Gerd Folkers.

After the scientific lectures there will be a cultural evening program, including a guided tour through the Wakker Prize-winning Lichtensteig by the Mayor Mathias Müller, a delicious dinner with selected regional cheese specialities, and a concert visit. For details and how to register please use https://www.jostbuergi.com/symposium/ .

The Gaia catalogue

The European Space Agency's Gaia science satellite will record the position, proper motion, distance and brightness of about two billion celestial bodies, or about one percent of our galaxy. From the observations, the astrophysicists of the Gaia 'Data Processing and Analysis Consortium' DPAC are creating the largest star catalog to date. Until its final completion, the scientists will use huge systems of equations to determine around ten billion parameters from 1000 billion observations and process more than a petabyte of data. The first two partial catalogs were already published in September 2016 and April 2018, and another part was added in December 2020. The complete catalog should be available in 2027.

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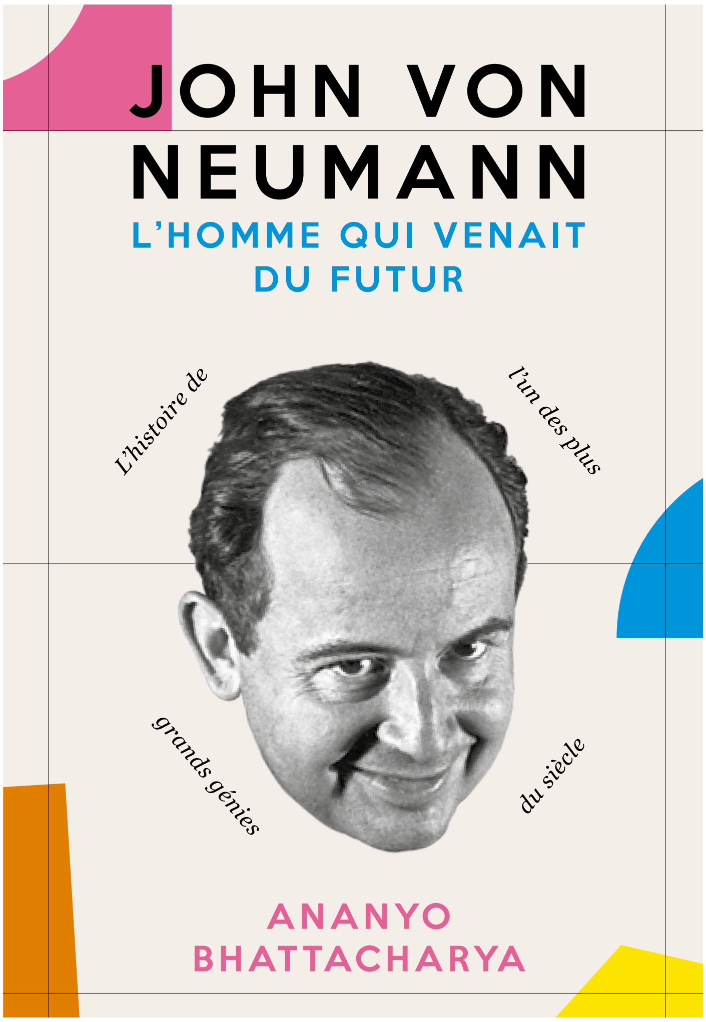
[1] The report can be ordered free of charge from *https://www.jostbuergi.com/kontakt/*

[2] The full program including a cultural part is here: *https://www.jostbuergi.com/symposium/*

Bücherecke - Le coin aux livres - Book Corner

Ananyo Bhattacharya
John von Neumann
L'homme qui venait du futur
Quanto, édit., PPUR, Première édition française 2023, ISBN 978-2-88915-507-1



Wunderkind, martien, extraterrestre, ce sont les mots prononcés par les contemporains de János Neumann, John von Neumann, né à Budapest au début du XXe siècle (1903 - 1957). La première chose sur laquelle tous ses contemporains s'accordent, c'est la vitesse phénoménale avec laquelle il pensait. Il n'avait pas besoin de se souvenir des choses, il les calculait. Si quelqu'un lui posait une question dont il ne connaissait pas la réponse, il réfléchissait pendant trois secondes, puis il avait la réponse. Mais sa mémoire quasi photographique n'était cependant pas en reste : enfant, il avait dévoré une histoire du monde en quarante-cinq volumes dont il était capable de réciter mot à mot des chapitres entiers plusieurs décennies plus tard ou d'en réciter la traduction à la même vitesse. Un professeur d'histoire byzantine, invité à l'une de ses réceptions, accepta de s'y rendre contre la promesse que le sujet ne serait pas abordé : « Je passe généralement pour le plus grand spécialiste en la matière, confia-t-il à l'épouse de von Neumann, et j'aimerais que cela ne change pas ».

Si John von Neumann est bien connu des spécialistes, il l'est en revanche moins du grand public, à la différence d'un Einstein ou Feynman. Le nombre de sujets auxquels il s'est attaché est tout simplement hors normes : théorie des ensembles, mécanique quantique, recherche nucléaire, théorie des jeux, économie, géopolitique, intelligence artificielle, architecture d'ordinateur, découverte de l'ADN. Il a défriché ces domaines en pionnier ou en contributeur essentiel en y laissant une empreinte structurante. Sans les multiples innovations dont il est à l'origine, le monde serait bien différent de celui que nous connaissons aujourd'hui.

János voulait devenir mathématicien. Pour satisfaire son père il va étudier la chimie à l'ETHZ mais commence en parallèle les mathématiques à Berlin. En 1925, à vingt-deux ans, il entreprend la formalisation mathématique de la mécanique quantique qui aboutit à son chef d'œuvre, « Fondements mathématiques de la mécanique quantique », publié en 1932 en allemand.

Descendant d'une famille d'origine juive, il a vite compris le danger nazi et fuit l'Europe à temps vers les Etats-Unis. Ce danger a joué un rôle permanent dans sa stratégie de choix de domaines de travail, pour viser au plus utile et au plus urgent.

On ne sera donc pas étonné que cet homme - plaçant son inventivité dans le domaine le plus utile du moment - ait aussi introduit la notion quantitative d'*utilité* des intervenants dans le domaine du jeu économique ou social. Il développait là la théorie des jeux, qui cherche à établir les meilleures stratégies gagnantes. Il a fondé et ensemencé ce domaine qui a par la suite profité à plusieurs prix Nobel d'économie qui ont reconnu en John von Neumann leur mentor. Et à cette époque de guerre froide, la théorie des jeux était au coeur de la logique de l'utilisation du bouton nucléaire.

Comment faire le tour d'un personnage aussi multiple, touchant avec brio tant de sujets en profondeur ? C'est le pari qu'a brillamment réussi Ananyo Bhattacharya - rédacteur en chef de la revue Nature pendant 4 ans – qui a fait le choix de décrire le personnage de John von Neumann dans le contexte de son époque et des collègues scientifiques et techniques avec lesquels il interagissait. C'est un livre accessible à tous, foisonnant de récits et d'anecdotes qui nous fait rencontrer des personnes comme David Hilbert, Werner Heisenberg, Erwin Schrödinger à Göttingen ou Zürich; Albert Einstein, Kurt Gödel, Eugene Wigner, Edward Teller à l'IAS à Princeton; Robert Oppenheimer, Richard Feynman, Stanislaw Ulam à Los Alamos; et Lloyd Shapley, John Nash au think tank de la Rand Corporation, pour ne citer que ces quelques points de repère. Un livre passionnant qui rend justice à cette figure étonnante et légendaire.

Et cette phrase emblématique du personnage de John von Neumann : « Si les gens ne trouvent pas que les mathématiques sont simples, c'est juste qu'ils ignorent à quel point la vie est compliquée ».

Antoine Pochelon

Version originale: **The Man from the Future: The Visionary Life of John von Neumann**, Allen Lane Editor, GB, 2021

Science Gateway - CERN

Margherita Boselli, Martina D'Arco, Université de Genève

On 7 October 2023, CERN officially inaugurated a new space for science education and outreach: the ***Science Gateway***.

Designed by world-renowned architect Renzo Piano, the new iconic building is located next to the “Globe of Science and Innovation”, the previous focal point for groups of visitors and one location of the old permanent CERN exhibition. In recent years, the overwhelming demand for visits has exceeded CERN's capacity to accommodate all requests. The newly inaugurated Science Gateway aims to address this problem. CERN’s goal is to reach a capacity of 300,000 to 500,000 visitors per year, with activities suitable for preschool children and older. It is accessible free of charge and open six days a week, from Tuesday to Sunday.

This project has been exclusively funded through donations, with no contribution from taxpayers' money. The primary contributor was the Stellantis Foundation, and additional financial support came from Swiss entities including the Ernst Göhner Foundation, Loterie Romande, Fondation Hans Wilsdorf, Fondation Gelbert, and various other local foundations.

The distinctive structure of the building is divided into three pavilions and two imposing tubes connected by a suspended walkway. The profound symbolism embodied by the two suspended tubes above the road is unmistakable: Renzo Piano designed them to echo the LHC tunnel situated 100 meters below. In another homage to the scientific universe, when viewed from above, the silhouette of the Science Gateway resembles that of a space station touching down in a forest. This forest, featuring 400 specially planted trees, stands as a key element of the project, emphasizing the inherent connection between science and nature.

Chroma VII (2023) by the artist Yunchul Kim, installation view Exploring the Unknown, CERN Science Gateway. Photo: Marina Cavazza.

Furthermore, the transparent glass panels and bridges symbolize CERN's dedication to fostering collaboration across international boundaries and diverse cultures, as well as its commitment to make open science accessible to everyone. In a final nod to its industrial identity, the selected materials and the overall aesthetic of the building, featuring raw forms and exposed concrete, openly celebrate CERN's unique character rather than trying to conceal it.

The structure features also a shop at the entrance and a restaurant named "Big Bang Café". The restaurant offers space-themed items that can be conveniently ordered from the tables using a QR code. Additionally, visitors have the option to store personal belongings in lockers located beneath the entrance, enhancing their overall experience during the visit.

Furthermore, the Science Gateway features a new area for events and conferences—a 900-seats theater that can be cleverly divided into multiple sections during regular periods, creating three separate spaces where multiple activities can take place at the same time. These function like small cinemas, screening educational films and videos on CERN's physics or offering science shows for both adults and children.

There are five exhibitions in total at the Science Gateway. Once past the entrance, the visitors are in the first section of the suspended corridor. The first tube encountered along the way hosts two exhibitions dedicated to particle acceleration and detection at CERN. Visitors learn about the various physical processes that occur within a particle detector like those built around the LHC. For example, they can play with a particle tracking system or understand how magnetic dipoles and quadrupoles work. The exhibition also includes a real accelerator that soon will be available for science experiments that visitors can witness. Components of the LHC accelerator and the various particle detectors built along the ring complete the exhibition. All along the museum, visitors can learn more through infographics and video explanations specifically created by CERN scientists.

Continuing along the suspended corridor, this time crossing the road and enjoying the panorama of snow-covered mountains on the horizon, visitors reach the second tube. Here, they embark on a journey backward through time, traveling all the way to the Big Bang and passing through the formation period of stars and galaxies, up to inflation. In this section, visitors can learn how scientific research conducted by CERN can contribute to a better understanding of the history of our cosmos. This includes the discovery of the Higgs boson, showcased with the opened champagne bottle commemorating the event in 2012, and the subsequent mechanism that imparts mass to the particles constituting the matter around us.

On the other side of the tube, the Science Gateway celebrates the union of art and science with an exhibition highlighting the creative aspect of physics and the mysteries of the unknown. This showcase features works created by artists invited to the CERN artist residency. For instance, visitors can enjoy an artistic representation of multidimensional rotation, envisioned as a large and intricate serpent coiled upon itself. This serpent elongates and compresses as if it were breathing, achieved through a special polymer that changes color based on the pressure applied to it.

Components of a particle detector installed in the Discover CERN exhibition, CERN Science Gateway. Photo: Teresa Montaruli

The final exhibition encountered at the end of the building is an enlightening showcase on the quantum realm. Attempting to explain quantum mechanics in a simple and clear manner has always been a challenge for science communicators and science museums. However, the Science Gateway shows its innovation in this regard. Here visitors can understand some aspects of quantum mechanics through a series of interactive exhibits. For example, they can learn about the quantum indeterminacy principle by playing tennis or discover the Casimir effect using a manual vacuum pump.

All of this is possible thanks to one of the main features of this new museum: the possibility of carrying out interactive experiments built around the fundamental concepts of physics they want to convey. Indeed, each section offers a wild range of simple activities, experiments and games designed for both children and adults.

Thanks to this, for instance, it’s possible to experience in the first exhibition the entire process of data acquisition through a game divided into three parts, designed to simulate the operation of a trigger, the sorting of data into different channels, and the analysis of results. Another intriguing experiment in the accelerator section involves vacuum physics, where one can observe firsthand how a wooden ball and a feather, in the absence of air, fall to the ground simultaneously. This is achieved using a rotating cylinder and a vacuum pump, which visitors can activate to witness the differences in the behavior of the two objects with or without air.

In the exhibition about the Universe, interactive activities include, for example, creating your own star, where visitors can choose the quantity of heavy and light elements and its rotation speed, and then launch it into space to observe its evolution. Alternatively, one can learn more about the gravitational lensing effect through an interactive activity demonstrating how the image of a galaxy changes when observed through dark matter using a telescope.

Understanding quantum mechanics is not easy, but it becomes more enjoyable when visitors can engage in "quantum tennis," where they experience the challenge of hitting a ball when the precise position or velocity is unknown. Another game in this part of the exhibition aims to illustrate the phenomenon of interference. It involves a table with a digital screen and blocks of various sizes simulating slits through which photons pass.

To make the visit even more interactive and diverse, the Science Gateway offers visitors the opportunity to take part in interactive workshops and laboratories where visitors can learn firsthand what it truly means to detect a particle or explore the secrets of electromagnetism through experiments conducted by CERN volunteers. During the week the laboratories are usually booked in advance by school groups, but during the weekend individuals and families can register to the activities an hour before the scheduled time.

In general, the activities on offer at the Science Gateway can be enjoyed by both children and adults - not an easy task, but this new centre succeeds extremely well. It is easy to make mistakes by designing activities that are either too complex for the younger audience or too simple for the older one. However, the extensive variety of experiments and explanations in the museum exhibits makes the visit enjoyable for the entire family. Moreover, many exhibits have been created to be fully accessible for people with disabilities. For example, the mock-up of the LHC dipole has been developed to be disassembled and touched by blind visitors.

The fact that it is open on Sundays makes the museum an excellent alternative for spending a family day during rainy autumn days, when finding indoor activities in a city like Geneva can be challenging, especially considering that everything is closed on Sundays. With the expansive spaces available and numerous activities such as workshops or short films, it's easy to get lost for hours in the corridors of knowledge.

While the museum has impressive interactive features, there's room for improvement. Indeed, the high number of visitors has led to a series of issues, which will undoubtedly be resolved thanks to the experience gained during this initial opening period and in the coming months.

In conclusion, the Science Gateway can be compared to the Louvre in a way: it may not be fully appreciated on the first visit due to the variety of activities on offer. It is necessary to return several times and allow yourself to be continually captivated by the beauty of the physics behind simple experiments. This is the key to fully grasping its essence.

Bestrahlungsraum, Parlamentssaal, Museum – wohin ein Physik-Studium führen kann

Anina Steinlin, SCNAT

Einen Beruf ausüben, der das Leben finanziert, gleichzeitig einen Mehrwert für die Gesellschaft bietet und persönlich erfüllend ist – das ist für viele Gymnasiast:innen und Student:innen die Idealvorstellung. Ein Studium der Mathematik, Astronomie und Physik (MAP) macht genau das möglich. Das zeigt eine Porträtserie der Plattform MAP der Akademie der Naturwissenschaften (SCNAT).

Je abstrakter das Studium, desto undeutlicher sind die Vorstellungen, was man künftig ausserhalb der Hochschule Konkretes damit machen kann - dann wenn man merkt, "dass die Forschung nicht die Berufung ist", wie es Emmanuelle Giacometti in ihrem Porträt verdeutlicht. Deshalb zeigt die Plattform MAP in zwölf Folgen, welche Möglichkeiten es in der Privatwirtschaft, Verwaltung oder Bildung nach einem Hochschulstudium oder Doktorat in Mathematik, Astronomie oder Physik gibt. Dies ist eine Erweiterung der Serie von 2021, in der die Karrierewege innerhalb der Forschung im Zentrum standen. Da nach wie vor weniger Frauen ein Studium aus den MAP-Bereichen wählen, trotz gleicher Begabung, beschreiben die Porträts die Karrierewege von zwölf Frauen.
Es zeigt sich, dass die ehemaligen Mathematikerinnen, Astronominnen und Physikerinnen in ihrem aktuellen Beruf eine Vielzahl an Stärken und Vorlieben ausleben können:

Komplexe Systeme verstehen
Silvia Steila arbeitet im Post Price Ticketing bei der SBB. Post Price bedeutet, dass der Preis für eine zurückgelegte Strecke erst am Ende der Reise berechnet wird. Der Mathematikerin kommt ihre Fähigkeit und ihr Durchhaltewille, komplexe Systeme im Detail zu verstehen, zu Gute um das bestehende Angebot zu verbessern. "In der Mathematik lernt man, ein Problem logisch zu analysieren und eine einfache Lösung zu finden – Mathematiker wollen elegante Lösungen." Auch Shiva Farghar, Astrophysikerin, liebt es an Problemen zu knobeln. Sie ist Data Science Consultant – ihre Kunden wollen aus gesammelten Daten Erkenntnisse gewinnen und Mehrwert generieren und holen sich dazu Unterstützung durch Farghar. "Manchmal erwache ich in der Nacht mit Ideen, weil ich ein Problem unbedingt lösen will."

Im Einsatz für die Gesellschaft sein
Stephanie Tanadini-Lang ist die leitende Medizinphysikerin am Universitätsspital Zürich. Sie und ihr Team planen die Bestrahlung von Krebspatienten und forschen, wie man die Behandlungen noch effizienter und ärmer an Nebenwirkungen machen kann. "In unserer alternden Gesellschaft hat die Krebstherapie einen wichtigen Stellenwert", führt sie aus. Immer mehr Menschen erkranken einmal im Leben an Krebs und sind auf entsprechende Behandlung angewiesen.
Die Nationalrätin Barbara Schaffner hat ebenfalls einen Hintergrund in Medizinphysik, setzt sich aber heute vor allem fürs Klima ein. Sie vertritt die Anliegen ihrer Wähler:innen im nationalen Parlament. Dank eines Doktorats, einer Anstellung in einem KMU, einer Weiterbildung in Energiewissenschaften und der Gründung eines eigenen Unternehmens "bringe ich Lebenserfahrungen aus verschiedenen Bereichen mit", erklärt sie.

Kreativität und Weltoffenheit ausleben
Emmanuelle Giacometti hat ein Doktorat in Materialphysik und leitet den "Espaces des Inventions" in Lausanne. Sie und ihr Team überlegen sich immer wieder neu, wie sie wissenschaftliche Themen der Öffentlichkeit vermitteln. "Es verlangt Kreativität und Ideen, unser Publikum für Wissenschaft, Technik und Kultur zu begeistern." Valerie Koller hat Mathematik und Astronomie studiert und darf als wissenschaftliche Beraterin im Swiss Space Office mit ganz unterschiedlichen Ansprechpartnern zusammenarbeiten. Sie ist zuständig für die Forschungsförderung der Weltraumwissenschaften und besucht dafür die Hochschulen und Universitäten in der Schweiz, und "da wir mit der ESA zusammenarbeiten, bin ich sehr oft im Ausland für Meetings und Workshops.", so Koller.

Ausblick
Die Videos und Texte entstehen in Zusammenarbeit mit dem Wissenschaftsjournalisten Benedikt Vogel. Die Serie dauert noch bis ins Frühjahr. Nebst den bereits veröffentlichten Porträts, die im Text erwähnt sind, sind noch sechs weitere vorgesehen:

- Hanna Wick – Physikerin und Gymnasiallehrerin
- Cristina Poretti – Mathematikerin und wissenschaftliche Mitarbeiterin im Bereich Radioaktivität bei der Nationalen Alarmzentrale NAZ des Bundes
- Martina Nieswand – Physikerin und Patentanwältin bei Hepp Wenger Ryffel
- Anne-Thérèse Morel – Mathematikerin und Head of Capability Management bei Swisscom
- Miriam Gantert – Physikerin und Managing Partner bei Superloop Innovations
- Stefanie Hayoz – Statistikerin und Head of Statistics bei der Schweizerischen Arbeitsgemeinschaft für klinische Krebsforschung

SATW Industrial Advisory Board: One Year of Operation

Ulrich Claessen, President SATW Industrial Advisory Board

The Swiss Physical Society (SPS) and the Swiss Academy of Engineering Sciences (SATW) decided rightly and independently to strengthen the connection between research and industry (see editorial in the *SPG Mitteilungen* Nr. 69 on page 3 [1]). In line with this strategy SATW set up an *Industrial Advisory Board* which became officially installed at the SATW Annual Meeting in April 2023.

From SPS side Andreas Fuhrer of IBM, formerly responsible for the section ‘Physics in Industry‘ at the SPS Executive Board, is a valuable member. Other members are R&D heads of large and small companies as well as start-up companies. Members are from various branches of industry: medical devices, sensors, communication, photonics, biotechnology, laboratory automation, actuators, and machine industry. The board also includes executive board members from Swissmem, Swiss Engineering and Switzerland Innovation Park.

The SATW Industrial Advisory Board is complementary to the SATW Scientific Advisory Board. It brings in the perspective of Swiss companies competing on the world market by innovation.

New technology is a prime driver of product innovation. However, it takes time from technology development to the launch of the mature product on the market. Machines and production technology have to be developed, and quality standards and market regulations to be fulfilled. This is the engineering process and it is here where companies are good at.

In its first year the Industrial Advisory Board worked on 3 focal points.

The first point is the *Technology Outlook* of SATW, a very valuable document which describes latest technologies and their importance in relation to Switzerland. The Industrial Advisory Board pointed out that the needs of Small and Medium Enterprises (SMEs) have to be covered as well. SMEs have limited R&D means and have to apply new technology in a mature state.

The second focal point is to rank the importance of various technologies for industry. In the first place all companies are interested to get an understanding of the possibilities of new groundbreaking technologies, like artificial intelligence and quantum technologies, and to find out what type of products can be derived from these new technologies. It is indispensable for almost all SMEs to deal with the possibilities of digitalized and automated processes, advanced manufacturing technologies, internet of things, data handling and cybersecurity, semiconductor sourcing, as well as the reduction of waste, water and energy consumption.

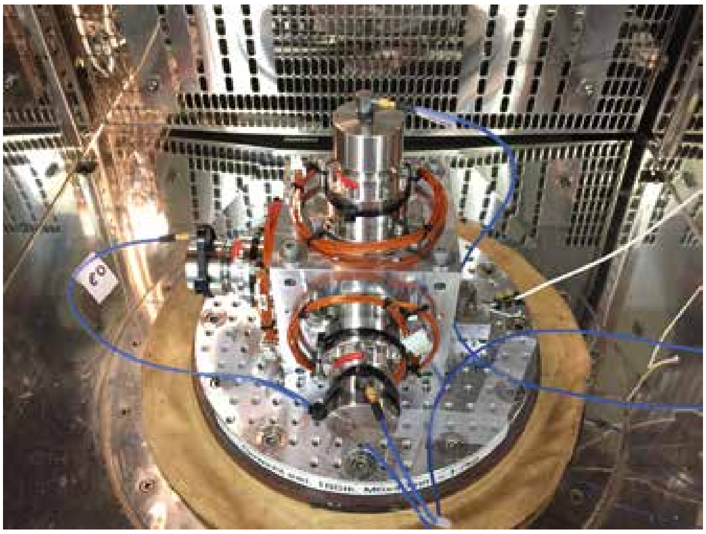
The third focal point is to get an understanding of the large Swiss public research landscape. Swiss companies have a clear advantage in that they have access to internationally leading institutions like ETHZ, EPFL, EMPA, PSI, CSEM, universities, universities of applied sciences, and Innosuisse. Start-up companies have first rate access to Innosuisse, Venturekick, and important foundations and investors. Nevertheless the Industrial Advisory Board sees a lot of possibilities to further improve the interaction of the Swiss public research network and industry.

The physics-based industries (PBI), or in general hightech-based industries play an important role in the Swiss economy, comparable to that of the manufacturing or trade sectors. The economic efficiency of PBIs even exceeds that of manufacturing (see ***SPS Focus*** No. 2 [2]). The SATW Industrial Advisory Board is therefore ideally suited to optimize the flow of knowledge from and to the SATW member societies.

To conclude: The Industrial Advisory Board proposes two action items, one for research institutions and one for industry:

1) Research institutions should consider to have industry representatives in steering committees of large research projects, for example quantum technologies. This helps to generate a better understanding of the research part and of the engineering part and to accelerate innovation.

2) Industry companies should continuously work on the assessment of new technologies, as part of their yearly R&D budget (the main part of R&D budget is product development and maintenance). Although this is risk investment and often subject to cost cutting in economic downturns it is an investment in company growth 10 years ahead.



Vibration test of Mars 2020 DC motors at maxon Space Lab in Sachseln / Obwalden. The development of the motors took several years due to extensive qualification tests. The motors drive robot arms inside the rover Perseverance filling rock samples into caches. The caches are presently deposited on Mars for later sample return missions.

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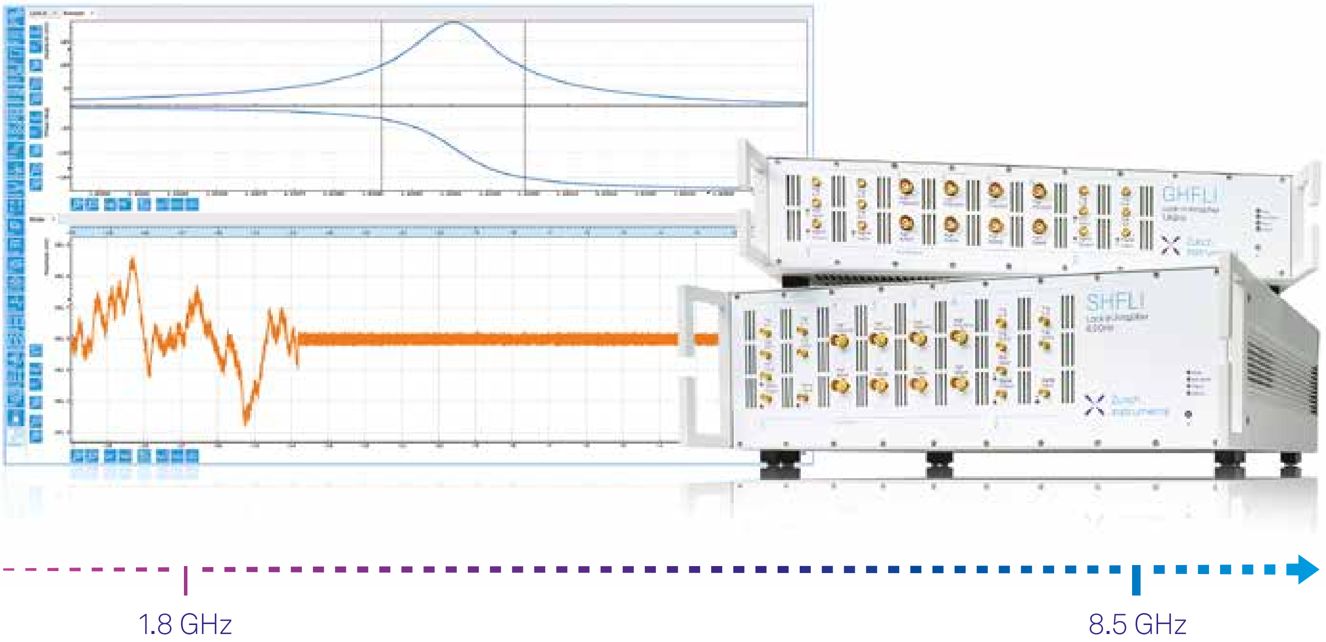
[1] https://www.sps.ch/fileadmin/doc/Mitteilungen/Mitteilungen.69.pdf

[2] https://www.sps.ch/artikel/sps-focus/sps-focus-2


GHFLI
SHFLI
Zurich Instruments
1.8 GHz
8.5 GHz