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A report on 30 years of a multitude of activities in physics, chemistry, biology, medicine and engineering with a fair coverage of all the achievements in these scientific and technical disciplines, requires more space than was allotted to us. We therefore decided to concentrate on PSI's development to a multidisciplinary, internationally competitive user laboratory. Although some external experts were very sceptical that this strategy would succeed, we intend to show below that they were wrong.

The beginning is tedious

The Paul Scherrer Institute (PSI) officially went into operation on January 1, 1988. It was a merger of the two previously individual Institutes of the ETH domain, then termed Annexanstalten des Bundes, namely the *Schweizerische Institut für Nuklearforschung* (SIN) [1] and the *Eidgenössisches Institut für Reaktorforschung* (EIR), both situated on opposite banks of the river Aare near Villigen and Würenlingen, respectively. Its first director was Jean-Pierre Blaser, professor of physics at ETH Zürich and director of SIN, who had lead the project of the merger, strongly assisted by his deputy Dr. Wilfred Hirt.

The research areas were represented by specific departments. The two dominating units were dedicated to particle physics (ex SIN) and nuclear energy and –safety (ex EIR), respectively. Distinctly smaller units hosted biology and medical applications, solid-state and materials physics, and activities in non-nuclear energy and environment (see Fig. 1). From its beginning it was intended that PSI should have close ties to Swiss universities by directly involving scientists based at these institutions but also acting as research leaders of the respective research departments. It was clear from its beginning that PSI needed to define its mission as a multidisciplinary institute with high academic and technical standards and the different visions were discussed, starting on January 15, 1988, in so called Direktionskonferenzen (DIRK), assembling all the department heads and important representatives of the administration with respect to finances and human resources. Under the leadership of Blaser and Hirt, various options for future developments were considered and debated.

It was agreed that PSI should, to a large extent, develop into an internationally competitive user laboratory, serving scientists from Switzerland but also, for obvious reasons, in significant numbers, attract users from abroad. This was already the case for particle physics with the environment around SIN's proton facility and muon factory. In this respect, the already existing and singled-out project, the realization of the spallation neutron source (SINQ) based on SIN's proton accelerator, played the role of an incubator for extending this trend. After the approval of the construction of SINQ by the Swiss parliament in 1986, the project was launched under the auspices of PSI as an interdepartmental enterprise and was, as all the other units, heavily relying on the department of technical support. The design of the source itself comprised a number of innovations that required a lot of work in developing the necessary technical components including their design. At the same time it was clear that, in order to obtain an internationally competitive neutron source dedicated to using neutron scattering for investigating static and dynamic properties of condensed matter, the proton current extracted from the proton accelerator had to be enhanced significantly. It was thus decided that, in parallel with the construction of the source itself, the project termed *current enhancement* proceed with high priority.

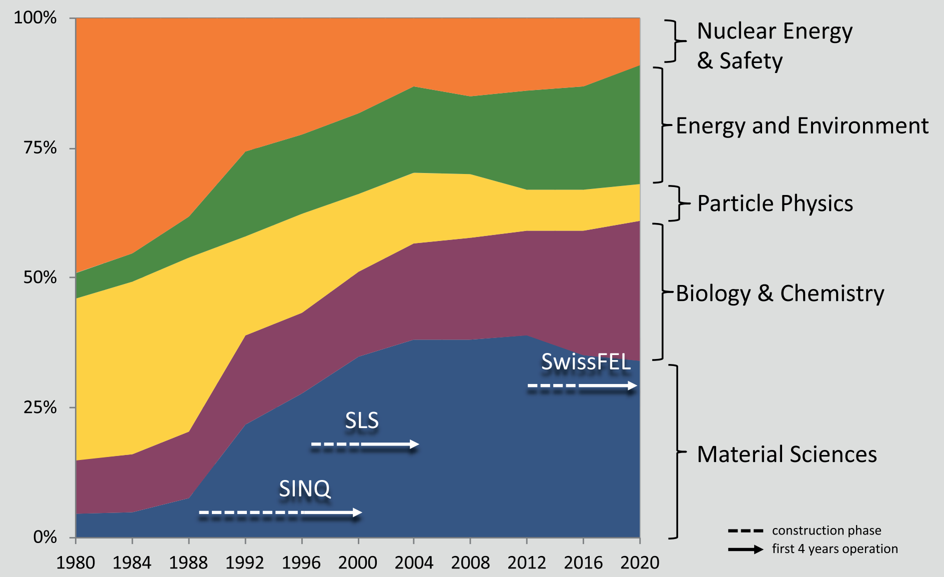

Fig. 1: History of research activities at PSI

Another early and important task to be tackled was to develop a clear vision on the content of activities concerning energy research and its balance between nuclear and non-nuclear energy. At the same time, ideas on new developments for securing PSI's long-term future were considered. An intention that was favoured by some was to extend PSI's program in particle physics by installing a so called B-factory (see this issue of *SPG Mitteilungen* on p. 40). Although a promising project scientifically, it did not get much support from the ETH Schulrat and finally, in mid September of 1989, was abandoned. Already at the end of that month, the condensed-matter fraction of the DIRK came up with an alternative option, the construction of an electron synchrotron acting as a light source; even more courageous actors envisioned the installation of a free-electron laser (FEL). This idea, of course, came not out of the blue. After recognizing the potential of electron synchrotrons as intense light sources, such installations were established in many countries, in particular in the USA, Germany, France and England, later

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[1] The history of SIN and its legacy are well documented in Andreas Pritzker, Geschichte des SIN, munda Verlag, Küttigen, Schweiz, 2013

also in Italy, Japan and Sweden. Various opinion leaders in the field were then convinced that for the benefit of future cutting-edge Swiss-based research in physics, chemistry and specifically also biology, the availability of a national and internationally competitive installation of this kind was highly desirable. Subsequently through 1991 the option of an electron-synchrotron light source was further developed under the lead of interims director Hirt as a *Direktionsprojekt* as the discussions in the DIRK regarding new developments of activities of the institute got stuck because no convincing conclusion was reached.

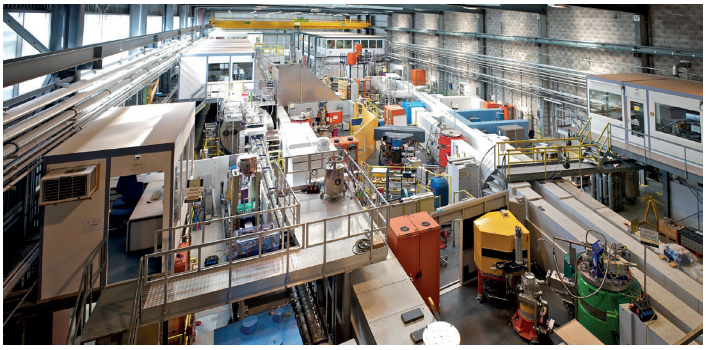

Fig. 2: The SINQ experimental hall

In this difficult situation, Meinrad Eberle, professor for combustion technology at ETH Zürich, stepped in as the new director of PSI in spring 1992. He faced a number of problems including a slower than anticipated progress in the implementation of SINQ. As usual for projects with pioneering character, some technical difficulties in the realization process arose and their solutions were not easy to achieve. The subsequent 3 years were characterized by significant financial strains and detailed screenings of the then current department programs. Even activities regarding the extension of PSI's experimental infrastructure were questioned. A newly established research committee consisting of internal stakeholders and internationally renowned experts in their field helped to evaluate existing and planned activities and to advise the management accordingly. Although dimmed down for a while, the light of prosperity and innovation never quite went out. In October 1994, a national hearing on the appropriateness of a light source at PSI marked the turning point and within one month, the project was back on the agenda of the Schulrat, now renamed to ETH Rat. Meanwhile also the construction of SINQ had taken up speed and PSI's future as an attractive user lab looked again much brighter.

New large facilities: Full steam ahead

Indeed the project plans and the concept of the Swiss synchrotron light source SLS were ready by September 1995. The Swiss Federal Council agreed to support the construction of SLS in November 1996. The Swiss parliament finally approved its execution in 1997 and the foundation stone was laid in June 1998. Concerning SINQ, the first neutrons left the source in 1996 and regular user operation at the then worldwide strongest spallation neutron source started in 1997. Initially four experimental stations in the form of spectro- and diffractometers were available but the planning for new instruments had started 2 years earlier and their implentation was on track. The efficiency of SINQ was significantly enhanced by an in-house development of so-called neutron mirrors which, after an intense in-house R&D activity, proved to be so effective that their production ended up in an industrial spin-off enterprise.

The success in enhancing the strength of the proton beam to the range of 2 mA also had consequences regarding the current density and brightness of muon beams serving as sensors for probing internal magnetic fields in solids in μSR experiments. This experimental method was already in use at the former SIN, but the new conditions offered innovations in its application. A particularly attractive new possibility in form of an intense low-energy muon beam was realized and used in the first operational instrument of its kind worldwide. It opened the way for this experimental technique to study thin films and layered materials, both rapidly gaining importance in technical applications.

As may be seen from Fig. 1, these efforts to create new experimental opportunities had a strong impact on PSI's investment of resources in the field of materials sciences and enhanced the benefit of a large number of users from Switzerland and abroad. After 1997, Swiss researchers had the privilege to profit from the access to different experimental methods for investigating microscopic properties of condensed matter at internationally competitive or, in parts even leading, large facilities at the same location in their own country. With the SLS under construction this situation promised to improve further. The implementation of the facility and the building hosting it proceeded according to plan and the first experimental stations went into test phase at the end of 2001.

Fig. 3: The SLS experimental hall

As expected, its performance parameters emittance and brightness proved to be excellent. The first user meeting was attended by more than 100 participants involved in research in physics, chemistry, materials-, surface- and environmental sciences. Initially, experienced users tested the beamlines and their endstations with experiments employing spectroscopy or microscopy of surfaces, tomographic microscopy with x-rays, microscopy with photoemitted electrons and protein crystallography. The regular operation for users began in 2002 and all first results turned out to be very promising. In particular the outstanding spatial and time stability of the resulting x-ray beams was responsible for the fact that in a very short time, SLS became the installation of choice for innovative studies in protein crystallography. In parallel to the operation of the facility, specialists responsible for the installations engaged in design and construction of innovative detectors and new sources for extremely short x-ray pulses extending the range from picoseconds down to femtoseconds. Particularly satisfying was the rapidly growing interest of industrial firms to finance and use part of the instruments for their proprietory research.

The rapid successes during the first years of SLS' operation, induced new ideas with respect to a further extension of PSI's role as a user lab responding to new scientific developments. The aim to create opportunities for investigations of condensed matter, i.e., solids, soft matter and liquids, employing coherent radiation soon turned the focus on the implementation of continuously tunable, laser-like radiation in the UV and x-ray spectral range. The progress in accelerator technology, involving very bright electron sources and advanced undulator magnets resulted in the likely possibility to obtain coherent radiation around 1 Ångstrom wavelength by controlling the motion of free electrons in free-electron lasers (FEL). At around 2000, the first installations in Asia, the USA and Europe were at early stages of planning. For Swiss-based stakeholders it was soon clear that in order to again play a significant role in that field, the construction of a corresponding source in Switzerland was mandatory.

Fig. 4: The SwissFEL undulator magnets

Ralph Eichler, who succeeded Meinrad Eberle as PSI Director in 2002, encouraged the development of innovative technical ideas that finally resulted in the design of a compact and cost-effective, i.e., affordable installation under the name of SwissFEL. It was after Joël Mesot became PSI Director in 2008, that the usual application procedure involving the federal administration and political establishment started in 2010 and the realization of the SwissFEL was approved by the parliament in 2012.

By the time SwissFEL was inaugurated in 2017 four short wavelength FELs were lasing: LCLS at Stanford, SACLA in Japan, PAL-XFEL in South Korea and European XFEL in Hamburg. Compared to the storage ring based light sources these facilities produce 10 orders of magnitude more coherent photons in a pulse of femtosecond duration. Continuously tunable wavelength hard x-rays extend the powerful experimental techniques developed with the short pulse conventional lasers to atomic resolution. By the end of May 2019 SwissFEL was producing attosecond x-ray pulses.

PSI's role as a base laboratory for particle physics

In parallel to the efforts of *extending* the attempted user-lab function of PSI, the nucleus of this type of mission, the program covering particle physics at medium energies, continued to attract researchers from Swiss universities and from abroad to this date. The enterprise stays based on the already mentioned existing proton beam and to a large extent involves high-precision experiments searching, for instance, for the limits of so-called rare events that would violate the existing and seemingly sturdy standard model of particle physics. The very nature of these studies requires highest experimental and technical skills as well as a long-term commitment to the cause. One example for such projects is the search for the forbidden μ-eγ decay which is active since the early days of PSI. Another long-term enterprise is dedicated to investigating the properties of muonic hydrogen which, only recently, resulted in a value of the proton radius that is in conflict with results from spectroscopy-type experiments and awaits further clarifications. Likewise, a search for the electric dipole moment of the free neutron turns out to require an ongoing and non-trivial refinement of the experimental set-up and a lot of patience.

From its start, PSI also contributed, and still does, to supporting the build-up of experimental infrastructure related to particle physics by the respective Swiss research community at other user labs such as CERN. A particularly important and successful contribution is the design, construction and implementation of the innermost silicon pixel detector of the CMS detector at the large hadron collider (LHC) and its recent upgrade. This development resulted in a very successful industrial spin-off that uses this technology to produce fast x-ray pixel cameras that are used at synchrotron light sources all over the world.

Benefits of PSI's accelerator based advanced technologies

These advances in detectors and light sources allowed PSI researchers to develop pioneering imaging techniques. Phase-contrast 3-D tomography methods with nanometer resolution play a revolutionary role in such diverse fields as medical applications and computer micro-chip inspection. The Swiss industry stands to profit from similarly impressive neutron based imaging methods developed at PSI. Key areas in this context are advanced manufacturing and digitalisation.

Interestingly, the advanced accelerator technology expertise being developed at PSI for the light sources is proving highly relevant to the ambitious future collider CERN projects.

Physics and accelerator technology in the service of human health

Just after the merger, human health became an applied research priority at PSI based on the knowledge and experience in accelerator technology and particle physics at SIN and the nuclear chemistry and radiochemistry research used for nuclear technology developments at EIR. Innovative projects on cancer therapy using elementary particles have been running already at SIN with the development of the PIOTRON facility, using negative pi-mesons for the treatment of deep seated tumors, and with the construction of the OPTIS facility for treatment of eye melanoma with high energy protons. The EIR had projects running for accelerator based isotope production for cancer diagnostics in collaboration

Fig. 5: The first compact proton therapy PSI gantry (Gantry 1)

with the SIN since middle of the 80's. The cancer treatment activities had been strengthened and extended at PSI over the last 30 years. OPTIS was the first facility for eye tumor treatment with protons in Europe. To today, close to 8000 patients with ocular melanoma have been treated at PSI in collaboration with the Ophthalmic Institute "Jules Gonin" in Lausanne. This is the highest number of eye tumors treated with protons in a single facility worldwide. A tumor control rate of > 98 percent was achieved.

Based on the successful first clinical results using protons at the OPTIS program PSI started a proton therapy project for the treatment of deep-seated tumors with a new innovative technology. A low intensity beam of 5-10 μA was separated with an electrostatic splitter from the > 1 mA proton beam of the 590 MeV isochronous cyclotron. The beam was degraded to energies below 250 MeV and injected into a 360° rotational compact gantry, using a dynamic parallel pencil beam delivery technique. The irradiation method - called "discrete spot scanning" – has several advantages: most conformal dose delivery with an optimal spearing of health tissue, improved treatment efficiency and potential for intensity-modulated treatment. The innovative treatment method is used for patient treatment at PSI since end of 1996 and established itself over the past 10 years as the beam delivery and irradiation standard for most of the proton therapy facilities worldwide. More than 60 proton therapy facilities are using the PSI technology today.

In 2001 PSI decided to expand the activities by launching the PROSCAN project. A dedicated compact superconducting 250 MeV proton cyclotron was developed in close collaboration with industry and a second gantry (Gantry 2) with advanced beam scanning features was realized. In parallel OPTIS was replaced by an upgraded version (OPTIS2). In 2012 PSI decided together with the University Hospital Zurich to expand the PSI proton therapy facility by an additional gantry (Gantry 3) for intensifying the clinical research. Gantry 3 came into clinical operation middle of 2018.

Summing up

In this review on *30 Years of PSI* we hope to have demonstrated that with talent and determination even a small country like Switzerland may succeed in building up an internationally competitve multidisciplinary user lab that not only serves a substantial part of the Swiss natural-science community including medicine but also attracts top researchers from abroad. In this sense, PSI has turned into a real asset of Swiss science. Finally, it should not be forgotten that this achievement would not have been possible without the trust, courage and will of political decision makers and funders to support the development outlined above.

Fig. 6: The PSI campus consisting of the former SIN (west bank) and EIR (east bank). 1: SINQ, 2: SLS, 3: SwissFEL