Particle Physics and Related Topics at the Paul Scherrer Institute

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Abstract

We highlight the specific and unique opportunities that PSI offers for particle physics. The input outlines mid- and longterm projects and asks for support and cooperation of the international community. It exemplifies the benefits of the particle physics activities for other fields and also the return from developments elsewhere into the particle physics program. Sharing of facilities, e.g., with material science applications broadens the scope. Spin-offs from developments, e.g., in detector technology and electronics are beneficial to many applications. Radio chemistry enables unique experiments, irradiations using shared accelerator infrastructure and new developments in accelerator and magnet technology present opportunities for a broad variety of applications.

1 Introduction

As a Swiss National Laboratory, the mission of the Paul Scherrer Institute (PSI) includes the operation of large scale facilities for Switzerland, with access also for the international community: The High Intensitiy Proton Accelerator complex (HIPA) with its pion and muon beams, the Swiss Muon Source (SμS), the neutron sources (SINQ, UCN), the Swiss Light Source (SLS), and the X-ray free electron laser (SwissFEL). Access to and use of these facilities is usually granted based on scientific excellence of the proposed research, scrutinized by international advisory committees. Groups from all Swiss universities and from a broad European and world-wide community are involved in projects and collaborations at the facilites at PSI.

An integral and important part of PSI's mission is to cover particle physics. Its facilities offer unique opportunites to the field. In particular, HIPA with its 1.4 MW proton beam provides the highest intensities world-wide of low momentum pions, muons and ultra-cold neutrons. The Laboratory for Particle Physics at PSI runs a program 'precision and discovery physics at low and high energies', addressing fundamental questions in experimental and theoretical accelerator-based particle physics. The research is structured in three pillars with many interconnections: collider physics with the CMS experiment at the LHC and muon and ultracold neutron physics in international collaborations at PSI. The theory group provides PSI specific support.

This document outlines activities and opportunities in particle physics at PSI, including high precision, highest intensity experiments, sensitive to multi-TeV mediators as well as to very weakly coupled, very light ones. This research is complementary to the exploration of the high energy frontier and very timely to be strongly pushed. Searches for new physics should be pursued with a broad approach using the most sensitive tools. Leading searches for charged Lepton Flavor Violation in the muon sector and for CP Violation with the neutron electric dipole moment are pursued at PSI, along with other high-impact precision experiments which can be performed best, or even only, at PSI.

PSI particle physics' developments in electronics, detector physics and chip design allowed major contributions to the CMS pixel detector and to other projects. On various occasions technology is being transferred to other research institutions and industry.

Naturally, there is a strong connection between particle physics and accelerator science. Similarly, detector technology, magnet R&D, irradiation facilities, production of radio-isotopes, and proton therapy benefit from developments in particle physics. Likewise, today, return from R&D for other applications, e.g., for electronics, magnets or beams, is coming back to particle physics, meaning real mutual benefits. We encourage technological developments and exchange with other communities to move our field, other fields and applications forward.

We invite the European particle physics community to take note of the outstanding opportunities offered at the HIPA facility at PSI, to recommend pursuing projects with unique discovery potential at high priority, and to actively participate in it. The European Strategy for Particle Physics should emphasize the need for a broad and complementary search program for new physics, including low energy searches with unique reach as an essential component.

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2 PSI facilities

2.1 The PSI ring cyclotron

As part of the HIPA facility, the PSI Ring cyclotron accelerates a continuous wave (CW) proton beam with 50 MHz time structure to proton kinetic energies of 590 MeV. Due to the specific characteristics of this cyclotron with a diameter of 15 m, the beam losses can be kept very low, at a relative level of 10^{-4}. Very high beam powers of up to 1.4 MW are generated in this way. As a result, intense secondary pion, muon and neutron beams can be generated for a variety of experiments. For this kind of facility the conversion efficiency of grid power to beam power is an important parameter, and with 18% efficiency for the accelerator alone the performance of HIPA is excellent in comparison to other high intensity facilities in the world [1]. Plans for the future of the HIPA accelerator chain include moderate upgrades of both cyclotrons. In the 72 MeV injector cyclotron two new resonators are installed and the RF amplifier chains of all 4 resonators will be exchanged till 2021. In the Ring cyclotron a new 3rd harmonic cavity is being designed since the present one with an aluminum surface suffers from plasma excitations. These measures will improve the reliability of the facility and also open options to further increase the intensity. As it was shown by Joho [2], the attainable intensity in the Ring cyclotron, under the assumption of constant losses, scales with the third power of the energy gain per turn. The circumference voltage is limited today by the third harmonic cavity that has to be adjusted at a certain ratio relative to the accelerating resonators. Thus, with the replacement of the third harmonic cavity the accelerating resonators can be operated at higher voltage, allowing to accelerate higher beam intensities. Roughly 30% of the 1.4 MW beam power is lost after the passage of the beam through the two meson production targets. A large part of these beam losses are deposited on a set of three high power collimators. These collimators are presently replaced by newly designed ones, allowing an increase of the beam power. If a new harmonic cavity including a driver amplifier chain can be realised, beam intensities up to 3mA, corresponding to 1.8 MW beam power, seem achievable.

2.2 The target stations and secondary beamlines

It is a major advantage of the HIPA facility that its proton beam serves many beamlines, user instruments and experiments simultaneously. The beam is going through the pion production targets M and E before it is dumped in the spallation target of the neutron source SINQ. With that it allows the operation of more than 25 simultaneous measurements with $\pi^{\pm}$, $\mu^{\pm}$, $e^{\pm}$ (momenta up to 400 MeV/c, but most experiments today use low momentum muons) and fast, thermal and cold neutrons at different beamlines. For 1-3% of the time the full proton beam is redirected to hit the spallation target of the UCN source.

In passing we mention that the unique muon beams at PSI and the R&D towards higher intensities and small phase space volume, see below, may also present a potential developing ground for ideas and techniques towards a possible future muon collider.

2.2.1 Meson production targets M and E

Pion and muon beams The pion and muon beams of PSI are generated within two target stations TgM and TgE located in the path of the high-power proton driver. The normally operated targets have a length of 5 and 40 mm in beam direction, respectively, and are made out of polycrystalline graphite. They are built as wheels turning at around 1 Hz in order to radiatively cool of the deposited heat from the proton beam. Despite this measure the longer target TgE is operated at a temperature of 1700 K, which – together with the harsh radiation environment – poses a formidable challenge in their design to achieve a reliable operation. The two highest intensity muon beam lines (μE4 and πE5) feature low-energy muon rates of 5×10^8 and 2×10^8 μ^+/s at a proton beam current of 2.4 mA available for materials science and particle physics, respectively.

High intensity Muon Beam – HiMB The next generation of searches for charged lepton flavour violation in rare muon decays detailed below will need muon intensities in excess of the 10^8 μ^+/s currently available at PSI. For this reason we have started a program to investigate the possibility of delivering at PSI muon beams of the order 10^{10} μ^+/s using the existing proton driver. As the existing target stations are already now producing low-energy muons in excess of 10^{11} μ^+/s, the key to higher muon rates lies in a more efficient capture and transport of these muons. Initial studies have shown that a beam line based on large-bore, normal-conducting solenoids and large-aperture dipoles can indeed capture and transport 10^{10} μ^+/s to an experimental area. A potential location for such a beam line could be at the current TgM station which, however, will need to be completely redesigned and rebuilt.

High brightness, slow muon beam – muCool In addition to increasing the intensity of the existing muon beams, we also pursue a program to increase their brightness with the goal of decreasing their phase space by a factor 10^{10} at an efficiency of 10^{-3}. For this a muon beam is stopped inside a cryogenic helium gas target at a few mbar. Once stopped, a position-dependent drift velocity engineered by the appropriate combination of electric and magnetic fields allows to compress the muons into a point and extract them through a 1-mm diameter hole back into vacuum where the muons can be reaccelerated [3]. While the compression in longitudinal and transverse directions have been shown separately [4, 5], work is currently ongoing on the combination of the two and the subsequent extraction into vacuum.

2.2.2 The Swiss Muon Source SμS

PSI operates the world-leading μSR (which stands for Muon Spin Rotation, Relaxation, Resonance or Research) user facility, called SμS, with six permanently installed instruments at five separate secondary muon beamlines located around the M and E targets of the HIPA proton cyclotron complex. Muon spin spectroscopy typically uses positive muons as highly sensitive local magnetic probes to study a broad range of research topics in solid-state physics, chemistry and materials science. The experimental techniques referred to as μSR are universally applicable since muons can be implanted in any material. The spin 1/2 muons are produced in pion decays at rest with 100% spin polarization, providing μSR with a great advantage compared to other local probes like NMR or ESR which rely upon a usually tiny thermal equilibrium spin polarization.

The different instruments of the SμS facility provide the users with a wealth of different experimental capabilities with respect to *e.g.* temperature, magnetic field, pressure, time resolution, measurement geometry, probing depth and minimal sample size to fulfill the various requirements for the broad scientific spectrum addressed by the Swiss and international user community. SμS has different world-wide unique μSR instruments as the Low-Energy Muon (LEM) spectrometer for the study of thin films, layers and surfaces; the high-field instrument (HAL-9500) equipped with specially designed detectors to perform studies in fields up to 9.5 Tesla and at very low temperatures; the high-energy muon instrument GPD with the combination of very-high pressures (up to 2.8 GPa) and sub-Kelvin temperatures.

Typical applications of μSR comprise a large variety of topics in condensed matter research with a focus on the investigation of novel and unconventional magnetic and superconducting materials. As a local probe, μSR is a powerful tool in this context since it allows *e.g.* studying the exact nature of magnetic and superconducting phases as a function of control parameters like doping, magnetic field or pressure on a microscopic level. Thereby, it is of special advantage that μSR is sensitive to both the superconducting and magnetic volume fractions and to the respective order parameters. Due to the volume sensitivity of μSR, the technique is often used in complement to scattering probes like X-ray diffraction and neutron scattering where this information cannot be obtained. In addition to the traditional application of μSR in magnetism and related subjects, it can also be used to investigate molecular dynamics, charge transport phenomena such as polaron motion in conducting polymers, electron and spin transport as well as ion conduction in technology relevant battery materials. As a 'light isotope' of the proton the μ^+ can form the hydrogen-like 'exotic' atom Muonium (Mu $= \mu^+ e^-$) which may substitute for hydrogen in insulators, semiconductors and organic materials and provide technologically relevant spectroscopic information on hydrogen levels in these materials. In addition, the muon can serve as a test model for light particle diffusion, radical formation, and chemical reactions with the largest known kinetic isotope effect.

For high intensity beams of slow muons and especially also for Muonium, there are considerable common interests with particle physics, see 3.1.2. Detailed studies to improve the production of Mu in vacuum and to spatially confine it have recently been performed in collaborative efforts [6, 7].

2.2.3 The Spallation Neutron Source SINQ

The SINQ continuous spallation source is driven by HIPA with a power of up to 1 MW, and is thus one of the two most powerful neutron spallation sources worldwide. The neutrons produced at SINQ are moderated to thermal ($\sim$300 K) and cold energies (<200K) where they can be used to study materials or the properties of slow neutrons themselves. Because the interaction of neutrons with matter is fundamentally different from that of X-rays, neutrons allow the study of materials with a completely different elemental contrast, even for samples with industrial dimensions. Due to the magnetic moment of the neutron, neutron scattering and imaging is well suited to study magnetic properties of materials, particularly for the determination of magnetic structures on the microscopic scale or magnetic fluctuations in the important sub 50meV energy range.

SINQ features 17 neutron instruments that are optimized for different kinds of neutron scattering or imaging measurements. An important class of instruments is that of diffraction instruments. These are used to study atomic and magnetic structures on a microscopic scale, allowing the determination of the atomic positions with a pico-meter resolution, even for light elements such as Li and H that give only small contrast with other techniques. Neutron diffraction instruments are often used to determine atomic structures of novel materials, to determine chemical disorder and the symmetry of magnetic structures. Neutron diffraction allows thus to understand the structure of materials and how it changes through magnetic and structural phase transitions. Applications include the study of novel multifunctional materials, battery materials, chemical hydrogen storage and the structure of biological materials with applications in the personalized medicine.

Another important class is that of inelastic instruments, that are optimized to measure magnetic fluctuations as a function of wave-vector and energy. These allow measurements of atomic vibrations, and such studies were crucial for our understanding of first- and second-order structural phase transitions. Unique are magnetic inelastic neutron scattering measurements that allow the direct measurement of spin-spin correlations on a microscopic scale, and remain the only technique where this can be done for energies below about 50meV. Such measurements are crucial to understand quantum entangled and coherent phases such as quantum spin liquids or magnetic superconductors.

A third class of neutron instruments are imaging or tomography instruments. Because neutrons are only weakly absorbed in most materials, neutron imaging allows the non-destructive measurement of large samples. This includes completely metallic materials that can often not be well studied using other techniques. Today, neutron imaging measurements can be performed with a spatial resolution as good as 1 micrometer. Imaging techniques are used in various fields: for purely industrial applications with the goal to optimize the design of a product, but also for study of archeological artefacts and more recently also for the imaging of phase separation of complex electronic materials.

Finally, from time to time SINQ hosts fundamental particle physics experiments at one of its beamlines [8, 9, 10, 11]. High cold neutron rates, high degrees of polarization, very special instrumental equipment and sample environment, and very flexible area management can permit pursuing unique ideas or developing novel techniques for more intense sources like at the ILL or at the ESS.

2.2.4 The Source of Ultracold Neutrons UCN

The ultracold neutron (UCN) source is the second target end station of the proton beam. It can use the full beam intensity of HIPA at up to 3% duty cycle with macro-pulses of several seconds length. Initially neutrons are produced via spallation when the proton beam hits a high power lead target. The neutrons are thermalized in heavy water and further cooled and downscattered to the nano-eV regime in 5 kg of solid ortho-deuterium at a temperature of about 5 K. In regular operation since 2011, the source provides UCN 24/7 during proton beam operation at three different beamports. Standard operation is pulsed with 8 s long proton pulses of the full HIPA beam delivered every 300 s. Beamports West-1 and South provide several hundreds of kHz UCN with decreasing intensity over the delivery period, up to 50 Million UCN integrated over the pulse period, and with UCN densities of presently around 30 UCN/cm^3 at the beam port, presenting a world-leading UCN facility [12]. Beamport West-2 has a factor 10 lower intensity, but allows for a certain UCN energy spectrum adjustment via gravitational acceleration. Beamport South is providing with priority UCN to the world-leading search for the electric dipole moment of the neutron. Since startup the UCN intensity has been improved by almost 2 orders of magnitude and vigorous research is ongoing to further increase the output for high sensitivity fundamental physics experiments.

3 PSI Particle Physics

3.1 Muon physics

3.1.1 The search for charged lepton flavor violation

Charged lepton flavour violating decays (cLFV) are unobservably small in the Standard Model. The three golden channels of muon physics are the decays $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ and the $\mu \rightarrow e$ conversion in atoms. These decays are possible in the SM through neutrino mixing, with a tiny branching ratio of ($< 10^{-54}$). Many extensions to the SM predict, however, branching ratios that are accessible to high precision experiments at PSIs highest intensity muon beams. All present best limits have been obtained in experiments at PSI [13, 14, 15].

The MEG experiment was proposed in 1999 by an international collaboration from five countries searching for the $\mu \rightarrow e\gamma$ decay. It features a novel liquid xenon calorimeter with unprecedented energy, time and position resolutions, a timing detector with sub-100 ps resolution and a low mass drift chamber. It utilises the πE5 beamline at PSI with a muon stopping intensity of 3×10^7 muons per second. After an extensive R&D phase, the experiment pursued measurement campaigns in the period 2009-2013 with totalling 7.4×10^{14} stopped muons. These measurements resulted in an improvement of the previous limit on the $\mu \rightarrow e\gamma$ branching ratio from 1.2×10^{-11} by the MEGA experiment down to 4.2×10^{-13} (90% confidence level) which has been published in 2016. No signal was found, but significant constraints on the parameter space of BSM theories have been set. At that point, the systematic limit of the measurement was approached due to the growing accidental background from normal muon decay. To improve the measurement even further, all resolutions of the detector had to be improved. This led to the proposal of the MEG II experiment in 2013, which aims at a further improvement of the sensitivity by roughly one order of magnitude [16]. This will be achieved by increasing the muon stopping rate by about a factor of three and at the same time improving the energy, time and position resolutions of all detectors. The liquid xenon calorimeter has been equipped with silicon photomultipliers being much smaller than the original 2-inch photomultipliers and therefore giving a superior resolution in detecting gamma showers induced in the xenon. The scintillator bars of the positron counter have been replaced by pixelated detectors. The particular geometric layout causes each positron from a muon decay hit several of these pixels, which improves the time measurement down to 35 ps. A new cylindrical drift chamber has been developed which improves the momentum measurement of the positrons significantly. The number of data channels has been increased from about 3000 to 9000, which required a complete redesign of the trigger and data acquisition systems. A first full engineering run is expected in 2019, with physics data taking following in 2020-2023.

The second golden channel $\mu \rightarrow eee$ is addressed by the Mu3e experiment [17], which has been proposed in 2012 by an international collaboration. It aims to improve the current limit of the branching ratio $\mu \rightarrow eee$ from 1×10^{-12} by the SINDRUM experiment established in 1991 down to 1×10^{-15} in a first phase pushing the sensitivity by three orders of magnitude. It will be performed in the πE5 area of PSI as well and features a 2 T solenoidal magnet containing the muon stopping target and a set of detectors. The key element of the detectors are novel high voltage monolithic active pixels (HV-MAPS) which can be thinned down to 50 μm per layer to minimise multiple scattering of the through-going electrons and positrons. Two inner layers of HV-MAPS measure the vertex point of the two positrons and one electron supposedly originating from the same stopped muon, while two outer layers measure the bending radii of the particle tracks and therefore determine their momentum. Scintillating fibres between the layers measure the track timing to better than one nanosecond, which gets improved by scintillating tiles at the end of the tracks to below 100 ps. A high-speed trigger-less online system moves all hit information from the detectors into a computer farm consisting of graphical processing units (GPU), where all hits are combined to tracks and events are sought where three tracks originate from the same location on the target. The excellent momentum resolution of the tracking system of 0.5 MeV/c distinguishes signal events from irreducible background events coming from $\mu^+ \rightarrow e^+e^+e^-\nu_e\bar{\nu}_\mu$ events. Intensive studies of the design of the HV-MAPS with many prototypes have been performed, and promising results have been produced. It is expected that the first engineering run will be performed in 2020, followed by several years of data taking. The second phase of the Mu3e experiment will require a higher intensity muon beam. The High-Intensity Muon Beam (HiMB) project has been started at PSI which seeks for ways to improve the muon stopping rate. A modified muon production target and solenoidal muon beamlines are expected to deliver increased muon stopping rates by two orders of magnitude, which will be to the benefit of several experiments at PSI and allow the Mu3e experiment to push its sensitivity to 1×10^{-16}.

3.1.2 Muonic atoms

Laser spectroscopy of light muonic atoms Laser spectroscopy of the 2S-2P tranistion in light muonic atoms has been used recently by the CREMA collaboration to deduce precise values of the rms charge radii of the proton, deuteron, ^{3}He and ^{4}He nuclei [18, 19, 20]. From muonic hydrogen a proton charge radius 20 times more precise than obtained from electron-proton scattering and hydrogen high-precision laser spectroscopy has been extracted but at a variance of 7σ from these values. This discrepancy which is known as the "proton radius puzzle" has initiated a variety of theoretical and experimental investigations in the field of bound-state QED, proton structure at low energy, electron scattering, atomic spectroscopy and beyond standard model explanations. At PSI, the MUSE collaboration is comparing simultaneous electron and muon (both polarities $e^{\pm}$, $\mu^{\pm}$) scattering on hydrogen at low momentum transfer in the same experiment with the goal to resolve the proton radius puzzle. Production runs will start in 2019.

As a next step, the CREMA collaboration is pursuing a measurement of the ground state hyperfine splitting of muonic hydrogen with 1 ppm accuracy by means of pulsed laser spectroscopy at 6.8 μm. From this measurement the two-photon exchange contribution, which is the sum of Zemach radius and nuclear polarizability constributions, will be deduced with 10^{-4} relative accuracy. The obtained value can be compared with the theoretical predictions based on dispersion relation and chiral perturbation theory. This measurement also impacts active programs being run at MAMI (Germany), JLab (US) and elsewhere investigating the spin-independent and spin-dependent structure of the proton at low energy.

muX Muonic atom spectroscopy has been used to extract information on nuclear properties such as charge radii and quadrupole moments on almost all stable and a few radioactive elements. However, no measurements so far could be performed with elements that are only available in microgram quantities either due to their radioactivity or availability. To this end we have developed a method that is based on muon transfer reactions inside a high-pressure hydrogen target with a small admixture of deuterium. In the target the muons are stopped forming muonic hydrogen. Subsequently they transfer to the deuteron and due to the Ramsauer-Townsend effect [21] are able to travel at energies of a few eV over large distances. A sizeable fraction then reaches the radioactive target where they transfer again. With the method established, we are preparing for the measurements of the charge radii of ^{248}Cm and ^{226}Ra, which is relevant for the ongoing experiment on atomic parity violation in a radium ion [22] and aiming at a precision measurement of $\sin^2\theta_W$ at low momentum transfer.

Muonium Muonium is the bound state of a positive muon with an electron. As such it is an analogue of the hydrogen atom with the advantage of being free of finite-size effects and thus a perfect candidate for precision measurements. We have two projects that aim to profit from these unique properties. In the first we are aiming at measuring the free-fall of a horizontal muonium beam – generated by the emission of muonium from a thin film of superfluid helium – in a three-grating interferometer [23]. With the mass of muonium dominated by the positive muon, this will give access to the gravitational interaction of a second-generation anti-particle, which has never been tested. As a second project we are pursuing an improved measurement of the $1s-2s$ transition frequency [24] by a factor 1000. This will allow for a stringent test of bound state QED and result in a much improved measurement of the muon mass, which together with the muon magnetic moment is needed as an input for the ongoing muon $g-2$ measurement.

3.1.3 The muon EDM

In order to measure the electric dipole moments (EDM) of charged particles a storage ring method with 'frozen spin' has been proposed [25]. This method can be adapted to low momentum muons. With an almost table-top ring the present limit could be improved by 3-4 orders of magnitude to a sensitivity of 5×10^{-23}ecm [26]. Attention to this approach was re-triggered by the recent flavor anomalies in B physics [27]. A feasibility study is ongoing.

3.2 UCN physics

PSI's UCN source is primarily used to search for an electric dipole moment of the neutron (EDM) with unprecedented sensitivity. EDMs are time reversal violating quantities and, assuming CPT conservation, CP violating. The neutron EDM could be due to CP violation in the strong interaction or from BSM contributions. The regular CKM CP phase generates unobservably small contributions. Limits on or discoveries of finite EDMs will contribute to the understanding of the processes involved in generating the matter-antimatter asymmetry of our Universe. PSI's phased approach to the experiment builds on the unique experience established in the last decade running the up-to-now most sensitive nEDM search within an international collaboration of 15 institutions. A new apparatus, n2EDM, is currently being constructed and will be commissioned towards the end of 2020. With a baseline goal of a factor 10 improvement in sensitivity and envisioned later upgrades it aims at pushing the sensitivity into the 10^{-28}ecm regime. With previous measurements, the neutron EDM experiment has contributed to the search for possible constituents of the Dark Matter in our Universe. Several limits have been recently set with measurements at PSI on axion like particles [28, 29] and mirror matter. Improving the neutron EDM sensitivity requires considerable technological R&D. Dedicated studies on UCN production and transport [30], and UCN surface coatings are being pursued to further enhance the UCN source intensity. Research on laser optically pumped atomic magnetometers aims at improving ultra-high precision magnetic field measurements and long-term monitoring on the femtoTesla scale in the experiment and dedicated magnetometry laboratory setups.

4 Synergies with other fields

4.1 Proton Irradiation Facility

The Proton Irradiation Facility PIF at PSI allows for realistic simulations of accelerator and space particle radiation environments. It is therefore invaluable for the research on radiation induced effects in electronic components and devices prior to their dedicated application, e.g. the flight in space. For more than a decade PIF is actively used for testing of newly developed radiation hard electronics and beam line dosimetry systems applied in the CERN LHC and future accelerator systems. The facility is furthermore intensely used for testing and calibrating of modern particle detectors and radiation monitors used on space missions. It encompasses qualification and assessment of the radiation hardness of sub-systems for either long term high cost missions or short time application on nano-satellites. The facility has been in operation since 1992. Currently it is connected to the COMET medical cyclotron and uses an experimental area of the Proton Therapy Center. PIF experiments are outside of the medical treatment periods, i.e. typically during weekends and night shifts. The facility provides various mono-energetic proton beams with energies ranging from 6 to 230 MeV with maximal intensities between 2 nA (for $E > 200$ MeV) and 10 nA (for $E < 100$ MeV). The PIF facility offers user-friendly conditions concerning experimental setup, operating procedures and data acquisition system and uses adaptable monitoring of flux and dose. About 70 exposure and measuring campaigns with more than 130 users are performed each year at the facility. The Proton Irradiation Facility PIF is a member of the ESA supported European Component Irradiation Facilities (ECIF).

4.2 Detector developments and detector spin-offs

The Laboratory for Particle Physics (LTP) carries detailed knowledge and long-standing experience in the fields of development, design, construction, commissioning, operation and repair work of detectors for ionizing radiation, especially for charged particles and neutrons, and maintains dedicated infrastructure needed for these tasks. The relevant groups consist of scientific and technical staff, a great strength in the phase of design, construction and installation of the detector systems. Detector systems using gaseous or scintillation detectors are mainly used in particle physics experiments operated at the HIPA accelerator at PSI. The rising demands in particle physics experiments give stimuli for new and innovative developments in detectors and electronics that allow further applications in μSR or neutron scattering instrumentation. Some developments were successfully commercialized or are in the phase of a feasibility study for industrial application. A spin-off company dealing with detectors for fast neutrons in the field of homeland security and nuclear industries is in the course of formation.

In the field of silicon detectors the main activity takes place around the continuing developments of pixel detectors for the CMS/LHC experiment. The pixel detectors planned for the HL-LHC period will be of the "classical" hybrid style with the readout chip bump-bonded to a sensor. The module design is progressing well including the high-density interconnect circuit. The scientists from LTP will have to build about 500 such modules to be ready for 2026. In parallel the group is also performing R&D for future detectors. One project is silicon detectors with very good timing resolution, which would allow a much better separation of the simultaneous interaction points in LHC collisions. Another project concerns monolithic sensors, which do not require the bump-bonding step and would make pixel detectors much simpler and less expensive. As in the past, the silicon detector development is pursued in close collaboration with the detector developments for photon detection done by the SLS/SwissFEL groups at PSI. The collaboration is very close, sharing technologies and designs. In 2007 the spin-off company DECTRIS has emerged out of this activity, which fabricates and sells x-ray counting pixel detectors all over the world. Know-how in several areas was transferred to this company, e.g. radiation tolerant chip design. The company with its PSI particle physics trained CEO has been very successful and is employing more than 100 people today.

4.3 Isotopes, Radiochemistry, Radiopharmacy

Research topics of radiochemistry and nuclear chemistry are in the focus of the Laboratory of Radiochemistry at Paul Scherrer Institute. Radiochemistry uses radionuclides with their specific decay properties to assess physico-chemical problems. The other way around Nuclear Chemistry uses chemical methods involving radionuclides to determine physical properties related to nuclear data of these nuclides, i.e. the production, the decay, and their nuclear reaction properties. Three main research directions involve the accelerator infrastructure at PSI, which is used for the production of tracers for fundamental radiochemical research, for the production of rare isotopes e.g. of astrophysical interest, and for the production and separation of novel isotopes for radiopharmaceutical research.

The fundamental radiochemical research focuses on the chemical identification of superheavy transactinide elements. The fundamentality arrives from the experimental proof of relativistic influences on the atomic structure due to the high nuclear charges in the atoms and thus on chemical properties of the heaviest elements of the last row of the periodic table. Thus, this research challenges one of the most fundamental ordering schemes of chemistry. Rapid gas phase chemical separation schemes are developed merging chemistry with the sophisticated detection of single atomic amounts of transactinides, which are artificially produced in heavy ion induced nuclear fusion processes [31]. Therefore, innovative detector developments based on materials apart from semiconductors, such as diamond and silicon carbide are pursued. The successfully developed setups are tested using radionuclide tracers produced at PSI and subsequently applied in experimental campaigns for transactinide research in large international collaborations at heavy ion accelerator facilities available worldwide, such as FLNR Dubna, RIKEN, and GSI.

The operation of large particle accelerator facilities at PSI is inevitably accompanied by the production of radioactive isotopes in interactions of high energy particle beams with various materials (e.g. beam stops, collimators, muon production targets, SINQ targets, STIP samples within the SINQ targets etc.). From the safe-operation point of view, the long-lived products have to be identified and specified for their safe disposal. However, some of these by-products have greatest scientific value to astrophysical sciences and a broad community in fundamental physical and chemical research, just to name a few: Fe-60, Mn-53, Be-7, Si-32, Ti-44 etc. These isotopes are available in worldwide uniquely large amounts. Nuclear irradiation targets can be prepared out of the chemically separated isotopes. This work is performed in close collaboration with the Hotlaboratory of PSI. National and international collaborations e.g. with the UCN and ICON beam lines at PSI as well as with the $\mathrm{n_{TOF}}$ community at CERN have proven successful in determining fundamental nuclear data of these nuclides with great outreach [32, 33]. To secure this success an advanced target manufacturing is being established at PSI for which radiochemical know-how is a prerequisite. Collaborations with other European nuclear physics communities are evaluated on these topics within the Euratom Research and Training Program.

The isotope production at PSIs IPII at the HIPA Injector 2 cyclotron and at the SINQ-Neutron Irradiation Facilities (NIS) driven by HIPA is heavily used to generate innovative isotopes for radiopharmaceutical research. Here, the concept of matched-pair theragnostic isotopes is pursued. This means, isotopes of one element with hours up to days half-lives suitable for either therapy (beta minus, Auger emitters) or diagnosis (beta plus, low energy gamma emitters) are being prepared. Featuring the same chemical properties, these isotopes can be radiochemically purified and chemically attached to the same biomolecules and transported by the same mechanisms to the targeted cancer cells. Thus, the therapy can be well prepared and its success can be directly monitored. Several Tb and Sc isotope matched pairs have shown great promise in this regard [34, 35]. Established collaborations with CERN ISOLDE, ILL Grenoble and other European production facilities facilitate the availability of these isotope pairs. The development of fast and clean radiochemical separation schemes together with the strong collaboration with the Center for Radiopharmaceutical Research (CRS) at PSI is prerequisite to the final goal of developing these isotopes from-bench-to-bedside. All together the Radiochemistry at PSI is strongly involved in exciting cutting-edge multidisciplinary fundamental sciences, which appears ideal for its educational academic endeavors to maintain radiochemical competence in the future.

4.4 Accelerator Research and Development

Accelerator R&D has been the backbone of development of large accelerator driven research facilities at PSI. Switzerland is home to two world leading accelerator centers, CERN and PSI, and it is only natural that there exists a close collaboration between the laboratories in the field of accelerator science and technology.

Linear collider designs can benefit from advancements in light source technology. Recent developments in accelerator technology allow to design diffraction limited light sources with even smaller horizontal beam emittance. Worldwide several new light sources utilizing these concepts are under construction or being designed. The PSI design of SLS2.0 achieves a horizontal emittance around 100 pm with a circumference of less than 300 m. The lattice concept involves longitudinally varying bending magnets and small reverse bends to suppress dispersion at the location of the maximum bending strength in the arc.

Technology developed for accelerating structures of the free electron laser SwissFEL has been applied for the production of high gradient CLIC structures in a collaboration PSI/CERN. Outstanding gradients up to 120 MV/m where achieved at the X-band frequency of CLIC. In view of damping rings and linear acceleration both advancements may contribute to performance enhancements of electron/positron linear collider designs.

4.4.1 CHART

PSI is the host organisation for CHART, the Swiss Center for Accelerator Research and Technology, that was founded to support the Future Circular Collider (FCC) at CERN and the development of advanced accelerator concepts in Switzerland beyond the existing technology for synchrotron light and neutron sources as well as medical applications.

The CHART partners at the moment include the two Swiss Federal Institutes of Technology (EPFL and ETHZ), University of Geneva and CERN.

CHART FCC studies The goal is to design, build, and test 16 Tesla Nb3Sn superconducting-magnet models according to strategic needs of the FCC Study.

CHART High Gradient Acceleration R&D The work on high gradient structures for future FELs, FCC-ee injector and CLIC linear accelerators is based on the experience gained at PSI during the construction of the SwissFEL facility.

PSI and EPFL also investigate advanced high gradient THz acceleration of relativistic electrons. A structure for laser-based acceleration, scaled to the needs of the THz acceleration has been used to accelerate electrons, excited by the wake fields of a high-current drive beam. CHART partners are working in close collaboration with the University of Bern and FAU Erlangen in the context of the ACHIP project funded by the Gordon and Betty Moore Foundation.

4.5 High-field and special magnets

4.5.1 Superconducting Gantry

The center for proton therapy at PSI is Switzerland's treatment center for the irradiation of tumours with proton beams. Besides treatment of patients it is pursuing research and development in various directions which are not further elaborated here. A beam of protons from an accelerator can be used for precise and minimally invasive treatment of tumours in the human body. A gantry is an arrangement of beam guiding magnets that can be rotated around the patient in order to direct the proton beam precisely to the location of the tumour. Classical gantries use conventional electromagnets with iron cores, resulting on the one hand in a large weight of the rotatable part. On the other hand the position tolerance of the magnets is small, and the mechanical support structure must be heavy and rigid as well. The superconducting magnet technology will allow very significant reductions in weight and footprint of such systems. PSI works on a development program to design a superconducting magnet prototype, suitable for future light and compact iso-centric gantries. Superconducting magnets can generate stronger and more complex magnetic fields. The superposition of dipole, quadrupole and sextupole fields allows realising an achromatic bending section with small aberrations. The energy of the beam can be varied quickly without changing the magnet field, while the beam is constantly pointing to the same location of the tumour. This enables new treatment scenarios for cancers, not possible with normal conducting magnets. The development of magnets for these medical applications has synergies with the magnet development program for high energy colliders.

4.5.2 High field magnets for the Swiss Light Source SLS2.0 and undulators for a third beamline at SwissFEL

A development program on high field magnets and superconducting insertion devices using the Nb3Sn and HTS superconducting technology is pursued at PSI. These two projects involving Nb3Sb and HTS technologies are grouped under the umbrella of CHART (Swiss Center for Accelerator Research and Technology). These PSI projects will indeed benefit from the infrastructure developed for the coil manufacturing of the CCT magnet models and from the hands-on expertise in several fields like the quench protection systems or the magnet construction. For the upgrade of the Swiss Light Source (SLS 2) a novel lattice concept is developed that results in an emittance reduction by a factor 45 as compared to the present design. Longitudinal gradient bend magnets (LGB) are placed in the center of the cells where the magnetic field reaches its maximum to minimize the dispersion. At three locations around the machine, three superconducting super-bends working at 4T and 6T are proposed to extend the photon energy range of SLS2.0 to up to 100 keV. The space constraints, the low field integral and the required quasi-hyperbolic field profile lead to a conduction cooled magnet design, with an inner solenoidal coil made of Nb3Sn superconducting High Jc strands as a base line [36]. In parallel a HTS coil development based on high Jc (600 A) YBCO tapes will be carried out at PSI as alternative option for the conductor in the inner coil and for a possible superbend upgrade. The other project related to HT superconductors concerns a possible additional hard X-ray line at SwissFEL, Porthos, planned for the 2025-2029 period to extend the photon energy of Aramis, reaching wavelength down to 0.03 nm. In that case, the undulator period length must decrease to 10 mm while the deflection parameter value (K) has to increase to 2.4 with a vacuum gap above 4 mm. These parameters could neither be achieved with conventional technology, nor with advanced permanent magnet cryogenic undulators. The use of the superconducting technology to produce a 2.5 T magnetic field in the axes of the undulator is required. An R&D program up to 2020 focused in a high field, short period undulator design and construction is ongoing in the Insertion Device group with the support of the magnet section. The preliminary design considers the use of HTS bulks of GdBCO, field cooled (4.2K) in a 10 T solenoidal field. The goal of the PSI program is:

- to validate the design by building a 10 period prototype using GdBCO bulks and measure it in the +/-12 T solenoid at the test facility of J.Durrel (Cambridge University);
- to improve, if needed, the uniformity of the produced field along the magnetic axis by substituting the HTS bulks by a stack of High Jc HTS tapes

5 Summary and Points addressing the Strategy Group

As a national laboratory, the Paul Scherrer Institute, PSI, offers unique facilities also to the international communities in various research fields. The co-existence of diverse communities leads to the exchange of ideas and common developments, beneficial to all. Important R&D with broad potential concerns detectors, electronics, specialized magnets, and accelerator technology.

Of particular relevance for particle physics is the high intensity proton accelerator complex HIPA driving simultaneously secondary beamlines of pions, muons and neutrons. The intensities of low momentum particles are world-leading and permit highly attractive precision measurements and searches for new physics complementary to the ones that can be obtained at the highest energies.

The international MEG, Mu3e, nEDM collaborations at PSI are leading the field in charged lepton flavor violation searches with muons and in the search for the CP violating electric dipole moment of the neutron. The international CREMA collaboration at PSI has successfully initiated the laser spectroscopy of light muonic atoms with highly relevant results for the proton structure at low momentum transfer. All projects have challenging midterm goals ahead where they aim at considerably pushing their sensitivities.

These projects, together with several other experiments that are being pursued in particle physics at PSI, offer unique discovery potential for physics beyond the Standard Model. They also offer excellent training conditions for students at all levels. The broad education in all aspects of experimental particle physics is very attractive and should be highly appreciated as qualification for the next generations of experimentalists in the field. This is even more important as the time scales of future large-scale projects span several decades.

We invite the international particle physics community in this European Strategy process to consider and support the following statements:

- National laboratories play a major role for achieving the highest priority goals of the community through significant contributions to the high energy frontier at CERN. At the same time, they themselves offer important infrastructures to the European particle physics community. Various experiments with unique reach, complementary to collider physics, can be best perfomed at these facilities. They should become visible in the strategy process and should receive the full support of the community.
- The European Strategy for Particle Physics should emphasize the need for a broad and complementary search program for new physics, including searches and precision measurements at low energies with unique reach as an essential component.
- The HIPA facility at PSI sends the world-wide most powerful DC (50 MHz) proton beam to targets. Studying the feasibility of further improving its capabilities, e.g., with higher proton intensities, improved and new target systems, novel beamline concepts, and improved isotope production capabilities should be strongly encouraged.
- HIPA today produces the world-leading intensities of slow muons and ultracold neutrons. Precision measurements with these particles present highly competitive opportunities to the European particle physics community. These capabilities should be maintained and further improved. A new, high intensity, DC muon beam HiMB could boost the rates of slow positive muons by two orders of magnitude.
- Searches for charged lepton flavor violation (cLFV) with muons represent some of the tightest constraints on new physics. All present best limits on muon cLFV come from experiments in Europe at PSI. The projects MEG II and Mu3e at PSI aim at considerable improvements in sensitivities to the searches of $\mu \to e\gamma$ and $\mu \to eee$ and should be strongly supported.
- The measurement of CP violating permanent electric dipole moments (EDM) of particles with spin offers a unique opportunity for the discovery of new physics. The nEDM collaboration at PSI is leading the field. The n2EDM project at PSI will measure the neutron EDM with another order of magnitude improved precision. Beyond that, further improvements to the ultracold neutron source and to the neutron EDM search should be strongly supported.
- The measurement of the muon EDM in a compact storage ring at PSI with 3-4 orders of magnitude improved sensitivity should be studied in detail. Depending on the further development of the various flavor puzzles, this could present another promising and unique search for new physics. The demonstration of the 'frozen spin' technique for EDM measurements in storage rings could be done with such a setup and should be strongly encouraged.
- The precision laser spectroscopy of light muonic atoms and of Muonium offers complementary information, via measuring fundamental constants, testing of QED and searching for light new physcis. The interactions of the particle physics, the nuclear physics, the atomic physics and the laser physics communities are very fruitful and should be intensified also for developing new low energy tests of the Standard Model.
- R&D on accelerator and magnet technology, on detector technology and on electronics should be pursued at high priority, and in cooperation of national labs, universities and CERN.
- The diverse communities present at national laboratories, besides particle physics, e.g., material science, radio chemistry and medical applications allow for fruitful and mutually beneficial interactions and cooperations. Exchange with neighbouring fields should be used to realize ambitious projects. Application of new technologies and the generation of spin-offs should be further encouraged.

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