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Milestones in Physics (4)

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PSI's High Intensity Proton Accelerator - A Versatile Facility Celebrates its 40th Anniversary

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Typically large cyclotron based facilities have a broad range of applications and over a long lifespan their utilization can be adapted to new research directions. Living examples for this hypothesis are the Gustav Weber Cyclotron in Uppsala (1951), the 88-Inch Cyclotron in Berkeley (1962) or the large TRIUMF Cyclotron in Vancouver (1975). Also the Ring cyclotron (1974) at Paul Scherrer Institut in Villigen, which is optimized for high beam power, belongs to this line of successful cyclotron facilities. Today the facility produces muons and neutrons as secondary particles. The high beam power of HIPA, beyond a megawatt, results in a high flux of these secondary particles. The flux is of essential importance for the efficiency and even the feasibility of many experiments. As a result PSI is in a leading role in certain areas of particle physics and science with muons and neutrons.

The accelerator was built by the Schweizer Institut für Nuklearforschung (SIN), founded in 1968 with J. P. Blaser acting as the first and only director. In 1988 SIN and the federal institute for reactor research merged into the Paul Scherrer Institut (PSI). The HIPA facility was originally designed as a

meson factory with the purpose to generate intense pion-beams and to study their interactions with protons and neutrons. The proton beam, delivered by the Ring cyclotron at a kinetic energy of 590 MeV, hits solid targets and produces the pions. The plans for the facility assumed a proton beam intensity around 100 μA , or a beam power of 60 kW. The accelerator consisted of an injector cyclotron, built by the company Philips and the Ring cyclotron which followed a revolutionary new concept. H. Willax (Fig. 1, Willax, 1963) was leading this effort and introduced new ideas. While classical cyclotrons contain a single magnet with large poles, the Ring cyclotron is split into separated sectors



Fig. 1: Hans Willax was a driving force during design and construction of the Ring cyclotron.

that contain eight individual dipole magnets with spiral pole shapes. Four box-like aluminum resonators were placed in-between the magnets to accelerate the beam at 50 MHz. The new concept allowed building a large cyclotron with an extraction radius of 4.5 m and with effective high voltage RF acceleration. Both properties are the key for low beam losses at extraction and thus the ability to accelerate very high intensity beams. The disadvantage of the separated sector concept is the need of an external injector at intermediate energy, in this case 72 MeV. The first beam was extracted from the cyclotron in January 1974. Shortly later on February 24 the first pions were detected and it is this date that was recently celebrated at PSI with a colloquium for the 40th anniversary of the facility. Over its history the facility was significantly upgraded in several steps. A first major improvement was the introduction of a third harmonic resonator, operating at 150 MHz. This "Flattop" resonator reduces the variation of the effective accelerating voltage the individual particles experience as a function of longitudinal position within a beam packet. The reduction of the overall energy spread of the beam allows reducing beam losses.

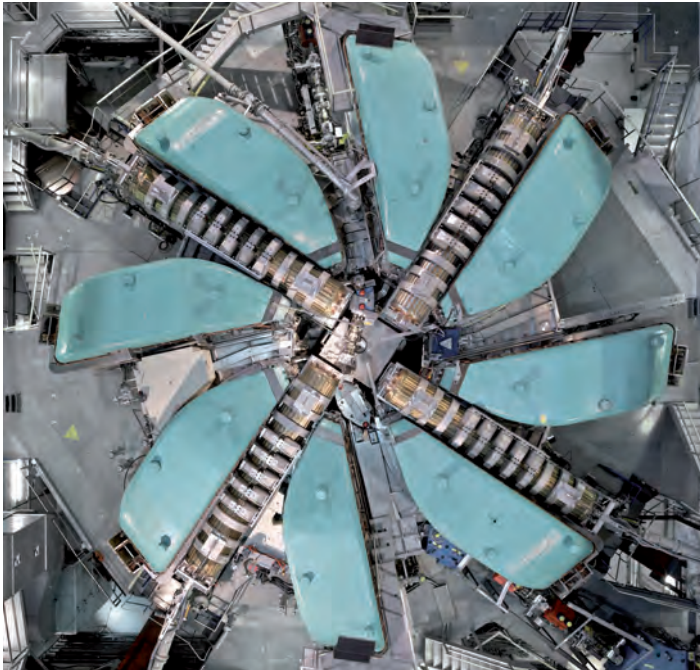


Fig. 2: The PSI Ring cyclotron, a separated sector cyclotron for the acceleration of very intense proton beams.

In the early eighties a new injector cyclotron was built to overcome another limitation of the beam current. It was also realized as a separated sector cyclotron with four magnets, two accelerating and two third harmonic resonators. The new injector II marks another milestone for cyclotron development since the high charge density in the beam packets cause a new operating regime, which was not achieved in any other cyclotron. The repelling space charge forces together with the bending forces of the magnets lead to a spiral roll-up of the phase space and the formation of compact, circular particle packets that are stable during the course of acceleration. No tails are produced and flattop resonators are no longer needed for these short packets.

Further upgrade steps of the Ring cyclotron involved the installation of more powerful accelerator chains and the replacement of the original aluminum resonators against cop-

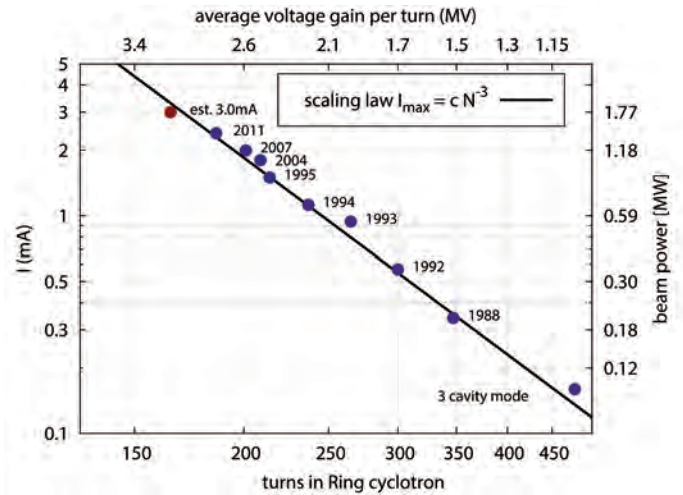


Fig. 3: Beam intensity over the history of HIPA and as a function of turn number.

per resonators. Theoretical estimates on the beam losses caused by space charge effects were performed by the accelerator physicist W. Joho and showed that beam losses scale as a cubic function of the number of turns the beam needs for acceleration to the final energy. In accordance with this relation the main intensity upgrades were achieved through higher voltages in the resonators, resulting in lower relative losses (Fig. 3). With 1.4 MW peak power the accelerator of HIPA is still at the forefront of high intensity accelerators worldwide. Only the spallation neutron source (SNS) in Oak Ridge/USA, equipped with a superconducting linear accelerator, delivers a beam power at similar level (Fig. 4). For the future it is planned to exchange the Flattop resonators in the injector cyclotron against new accelerating resonators, and to improve certain collimators to withstand higher heat loads. With these upgrades the reliability of the facility will be improved and even higher beam intensities will be possible.

The development of HIPA in the late seventies and early eighties is remarkable, considering that most other countries closed their small accelerator facilities for particle physics. Instead the efforts were focused on large international facilities like CERN. Switzerland and PSI decided to be heavily involved in CERN and to realize an aggressive upgrade of HIPA. The neutron scattering program with a focus on condensed matter physics was at the same time

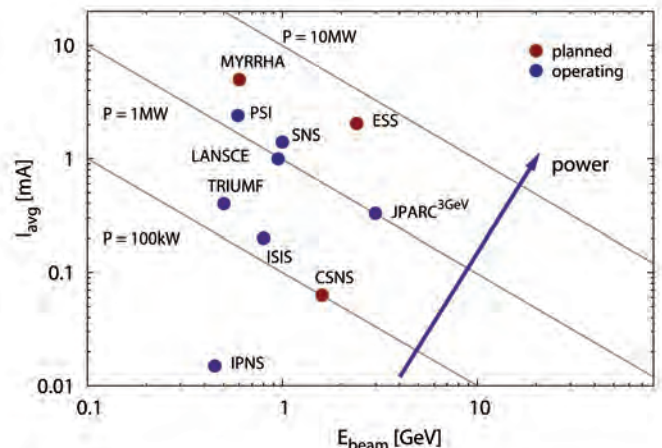


Fig. 4: Operating and planned high power proton accelerators. The black diagonal lines of constant beam power correspond to 0.1, 1 and 10 MW.

transferred from an old reactor (Saphir) on the east side of PSI to the new high power "beam dump" for HIPA, which was named SING.

With the increased beam power of HIPA the Muon facilities in the Muon experimental hall (Fig. 5) became world leading, both for Particle Physics and condensed matter science. The neutron spallation source SING with one megawatt of protons on a lead spallation target and a large guide hall, delivers a neutron performance comparable to a modern 10-15 MW research reactor and is an internationally competitive neutron scattering facility. The neutron and muon facilities around HIPA are now well established user facilities. Annually a total of 1000 scientists perform their experiments at PSI (Fig. 6). Half of these users are from Switzerland. The annual number of peer reviewed publications is around 280.

The very intense Muon beams enable particle physics experiments at the high intensity (precision) frontier that is complementary to the experiments at international high energy facilities like LHC at CERN. The current flagship experiment at PSI is the MEG experiment: The search for an upper limit for existence of the $\mu^+ \rightarrow e^+ \gamma$ decay. The analysis of a combined data set, totalling 3.6×10^{14} stopped muons on target, yield a new upper limit on the branching ratio of this decay of 5.7×10^{-13} (90% confidence level, Adam et al 2013). These findings have dramatically reduced the available parameter space for SUSY type models as explanation for physics beyond the standard model.

Another experiment currently only possible at PSI is the measurement of the positive Muon lifetime with a precision of one ppm. The experiment utilizes a time-structured, low-energy muon beam and a segmented plastic scintillator array to record more than 2×10^{12} Muon decays. The result $\tau_{\mu^+} = 2\,196\,980.3(2.2)$ ps represents the most precise particle lifetime ever measured. From the muon lifetime the most precise value for the Fermi constant can be found $G_F = 1.166378(7) \times 10^{-5} \text{ GeV}^{-2}$ (0.6 ppm). It is also used to extract the μ -p singlet capture rate, which determines the

proton's weak induced pseudoscalar coupling g_p (Webber et al, 2011).

Lately a second spallation neutron source has been added to HIPA (Fig. 5), the ultra-cold neutron source UCN. Every few hundred seconds the full beam from HIPA is sent to the UCN source for a few seconds (1% duty cycle), thereby filling a container with ultra-cold neutrons with typical energies of 200 neV. These ultra-cold neutrons are used in another key precision experiment of particle physics: the search for a non-zero electric dipole moment of the neutron (EDM). The experiment represents currently the most sensitive search for a neutron EDM and the goal is to detect a signal down to 5×10^{-28} e-cm in a few years time.

Muons are not only useful for particle physics, but also for condensed matter and materials science. Muons provide a sensitive local probe to measure very small magnetic fields or moments ($0.001 \mu_B$), magnetic homogeneity, superconductivity etc. The possibility to stop Muons in a cold moderator and to re-accelerate polarised muons and implant them locally at a controllable depth in a material (Low Energy MuSr) is a unique capability at PSI, only possible due to the very high Muon beam intensity.

This Low Energy MuSr technique is the only method which can directly measure the magnetic field penetration into a superconductor with nm depth resolution, and thereby also the depth dependent superconducting properties or quality of a material. The latter has recently been used to examine s.c. cavities for use in linear accelerators. The cost of a high power s.c. linear accelerator scales almost linearly with its length, i.e. inversely with the achievable accelerating gradient. It has been somewhat dark magic to surface treat the Nb metal for the cavities in order to achieve low losses and high accelerating gradients. With low energy muons one has been able to establish that surface treated Nb has a dead top layer which dominates the loss. Baking and f.i. N doping the surface leads to a poorer superconductor in general, but a lower loss dead layer. With this knowledge, more predictable performance of s.c. niobium cavities with

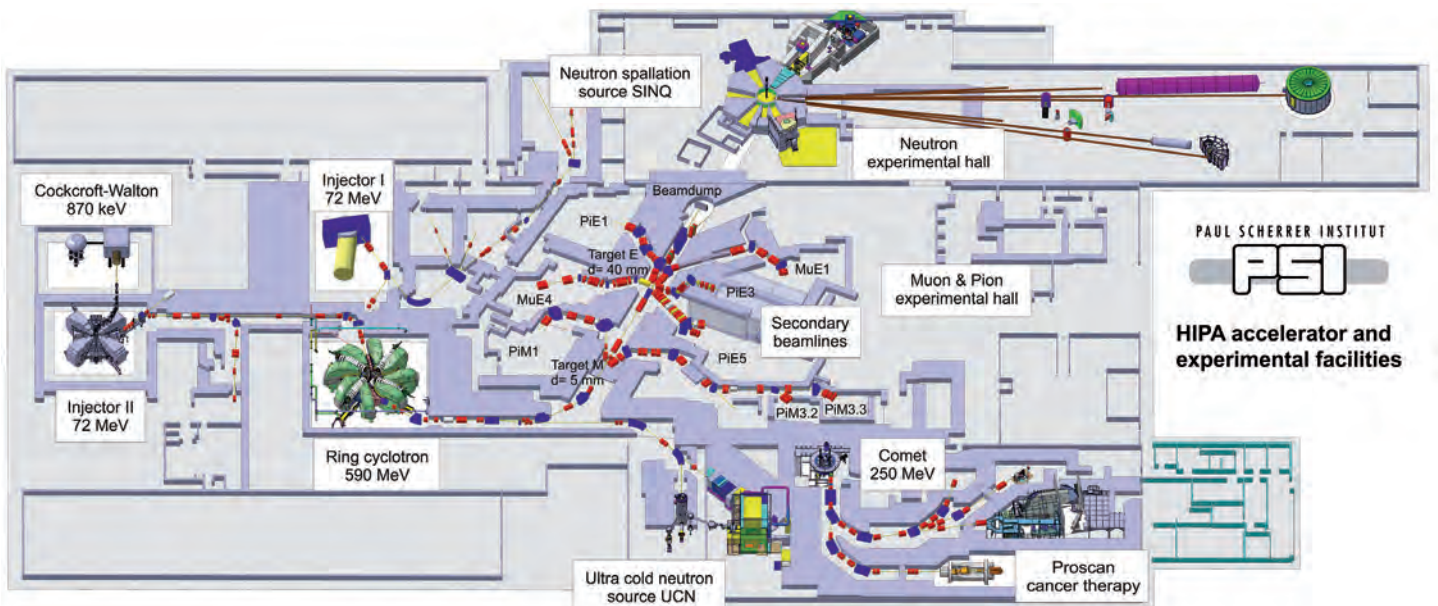


Fig. 5: The HIPA accelerator complex, with accelerators and the two main experimental areas for neutrons (top) and muons middle right. The Ultra Cold Neutron source (UCN) and the proton irradiation cancer treatment facility is shown lower right.

higher quality factor, and the possibility to operate them with a higher accelerating gradient, has been achieved (Romanenko 2014).

The neutrons from the SINQ source have the broadest range of application. Neutrons are the tool of choice for investigating magnetic ordering and excitations, and almost all we know about magnetic structures has been learned from neutrons. In this paper we will however mention a couple of other areas where the use of neutrons is less well known.

Electrodes are extremely important for battery materials. Sustainable use of batteries requires that the electrode materials are built from abundant and environmentally friendly materials. At present most electrode materials are based on Li as the conducting ion. At PSI a substitute electrode material ($\text{Na}_{0.7}\text{CoO}_2$), where rare Li ions are replaced by abundant Na ions, has been studied. In this material neutron diffraction experiments have shown that the melting and diffusion of the Na^+ ions appear in a stepwise manner. At low-temperatures the Na^+ sub lattice has a large number of static vacancies, above $T_1 \approx 290$ K quasi one dimensional diffusion of Na^+ is observed, and above $T_2 \approx 400$ K the Na^+ ions in the electrode layer can move in two dimensions. These results shed new light on previous, seemingly incompatible experimental interpretations regarding the relationship between Na vacancy order and Na dynamics in this material (Medarde 2013).

gases from entering the environment. However, within the automotive industry little knowledge existed on the exact mechanism how the soot particles are deposited inside these filters. With neutron tomography the movement of soot inside filters can be observed in situ and non-destructively, creating a foundation from which these filters can be optimised and developed further (Grünzweig et al 2012). The final example we present here is a small angle neutron scattering study (SANS) of a drug delivery system. The ideal nanoscale drug delivery vehicle allows control over the released dose in space and time. With SANS it is possible to follow how stealth liposomes – like small spheres filled with the active ingredient and surrounded by a lipid membrane containing super paramagnetic iron oxide nanoparticles - can be made to release their cargo by the application of an alternating magnetic field. The coupling of the field to the magnetic nanoparticles results in local heating and opens or closes the membrane (Amstad 2011).

The 40th anniversary celebration started with reminences from the last 40 years. This session was concluded by a guest speaker Prof. Michael Craddock of the University British Columbia and TRIUMF. In his "External View of the PSI Proton Accelerator" he summarized his presentation in two words: "*admiration* mixed with *envy*", and this statement was of course well received by PSI colleagues in the audience.

In the afternoon focus shifted towards the future – with forward looking presentations from the current heads of the HIPA accelerator, particle physics, MuSr and neutron scattering. With planned upgrades to instrumentation, beam optics and sample environment the fields of science and technology where PSI's research with neutrons and muons can be internationally competitive is still expanding. To maintain the lead also in 15 years time, larger investments must be anticipated on a 10 year time scale. We are currently looking into different options that could lead to significant, i.e. order of magnitude improvement of the HIPA based facilities, upgrade projects that will further extend the life of HIPA.

The authors would like to acknowledge past and present staff and the management of PSI for making HIPA and the facilities around HIPA a success, and we look forward to join forces to secure an equally bright future.

References:

- H. Willax, Proposal for a 500 MeV Isochronous Cyclotron with Ring Magnet, Proc. intl. Conf. on Sector-Focused Cyclotrons, 386 (1963).
- J. Adam et al (MEG collaboration), Physical Review Letters **110**, 201801 (2013).
- D. M. Webber et al, Physical Review Letters **106**, 041803 (2011)
- A. Romanenko et al., Applied Physics Letters **104**, 072601 (2014).
- M. Medarde et al, Physical Review Letters **110**, 266401 (2013)
- Grünzweig et al, MTZ Motortechnische Zeitschrift **73**, 326 (2012)
- E. Amstad et al, Nano Letters **11**, 1664 (2011)

2013	SINQ	SμS	LTP	HIPA total
Beamlines	13	5	8	26
Instrument Days	1841	633	600	3074
Experiments	431	219	8	658
User Visits	870	289	597	1756
Individual Users	486	170	350	1006
New Proposals	438	233	6	677

Fig. 6: Key numbers for the user facilities at HIPA: SINQ (neutrons for condensed matter research), SμS (Muons for condensed matter research and LTP (particle physics). The number of experiments is inversely proportional to their average duration and differs dramatically between the different probes. However, the number of individual users per beam line is almost the same ≈ 40 . The publication rate is also roughly proportional to the number of beam lines, 10-12 publications per beam line per year.

Neutron imaging and tomography have developed strongly over the last few years. Most metals are almost transparent to neutrons but hydrogen strongly scatters neutrons. Thus neutrons can be effectively used to study the performance of fuel cells in situ. Specifically it is possible to observe how water/steam is generated and transported out of an operating fuel cell. Another area where the penetrating power of neutrons can be used are studies of particle filters, which all diesel engines utilize to fulfil the emission standards. These filters prevent the harmful soot and ash particles in exhaust