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IMPACT: A SUBSTANTIAL UPGRADE TO THE HIPA INFRASTRUCTURE AT PSI

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Abstract

The High Intensity Proton Accelerator (HIPA) complex at the Paul Scherrer Institute (PSI), Switzerland, delivers a 590 MeV CW (50.6 MHz) proton beam with currents up to 2.4 mA (1.4 MW) to several user facilities and experimental stations. In addition to the two spallation targets for thermal/cold neutrons (SINQ) and ultracold neutrons (UCN), the beam feeds two meson production targets, Target M and Target E, serving particle physics experiments and materials research via seven secondary beam lines.

IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target technologies) aims to expand the infrastructure at HIPA in two ways: by HIMB (High-Intensity Muon Beams), increasing the surface muon rate by a factor 100, and TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions), producing promising radionuclides for diagnosis and therapy of cancer in doses sufficient for clinical studies. HIMB and TATTOOS are located close to each other. HIMB has to fit into the existing main proton beam line towards Target E and SINQ, while TATTOOS will occupy an area in a new, adjacent building using 100 µA, 590 MeV protons split from the main beam. TATTOOS will be a perfect complement to the existing radionuclide production using 72 MeV, adding a smorgasbord of nuclides at a large scale for potential medical purposes. At HIMB, the current Target M will be replaced by a four-fold thicker Target H consisting of a graphite wheel optimized for surface muon production. In addition, both muon beam lines feature optimized transmission from target to experiment. Due to the thicker Target H, the proton beam line has to be tuned to reduce the losses to an acceptable level and to maximize the transmission at the same time.

Installation towards the implementation of IMPACT is foreseen from 2027.

MOTIVATION

At the High Intensity Proton Accelerator (HIPA) [1], protons are accelerated using two cyclotrons, namely, Injector II to 72 MeV followed by the Ring cyclotron to 590 MeV. Up to 2.4 mA current is possible and has been demonstrated in routine operation. The 72 MeV beam also feeds the Isotope Production target station (IP2). The beam from the Ring cyclotron serves four target stations, two spallation targets (UCN for ultracold neutrons and SINQ for cold and thermal neutrons) and two meson production targets called Target M and Target E [2]. Before the beam reaches SINQ, it passes through Target M and Target E, whereas the full beam is kicked to UCN every five minutes for a few seconds.

IMPACT will add a new target station (TATTOOS) adjacent to UCN, providing innovative and otherwise not accessible radionuclides for research in nuclear medicine, and to replace the Target M station (built in 1985) with a new Target H(IMB) to increase the surface muon rate to 10^{10} µ/s. Figure 1 shows the close location of HIMB in the so-called experimental hall and TATTOOS in a new building.

The IMPACT collaboration at PSI consists of more than 100 people in 35 working groups. At the beginning of 2022, the Conceptual Design Report (CDR) [3] was submitted to support the project proposal for the Swiss Roadmap for Research Infrastructure, a joint application of PSI, University of Zurich (UZH) and University hospital Zurich (USZ). IMPACT was well received and reviewers gave the highest scientific evaluation in 2022.

In this paper, the purpose and concepts for HIMB and TATTOOS are described with focus on beam transport.

HIMB

The present Target M station consists of an effective 5 mm thick graphite target-wheel with two beam lines called PiM1 and PiM3 for secondary particles, both aligned in a forward direction. As a consequence, these beam lines are optimized for particles of higher momentum, originally pions of momenta larger than 100 MeV/c. The beam lines are used for different purposes: PiM1 for particle physics and PiM3 for material physics. While PiM3 already uses surface muons exclusively with the µSR technique, particle physics experiments aim for large rates of surface muons as well. A two orders of magnitude larger surface muon rate will boost the attractiveness for users as well as the competiveness of future experiments, both in the hunt for forbidden muon decay channels as stress test of the standard model and for the investigation of magnetic properties deeper below the surface.

To optimize the future target station H and its two beam lines for surface muons, the new concept comprises several improvements: Two large capture solenoids, one at each side of the target, with inner diameters of up to 500 mm are placed in a close distance of 250 mm to the interception of beam and target, perpendicular to the proton beam to guide a large fraction of the muons from the target to the second-

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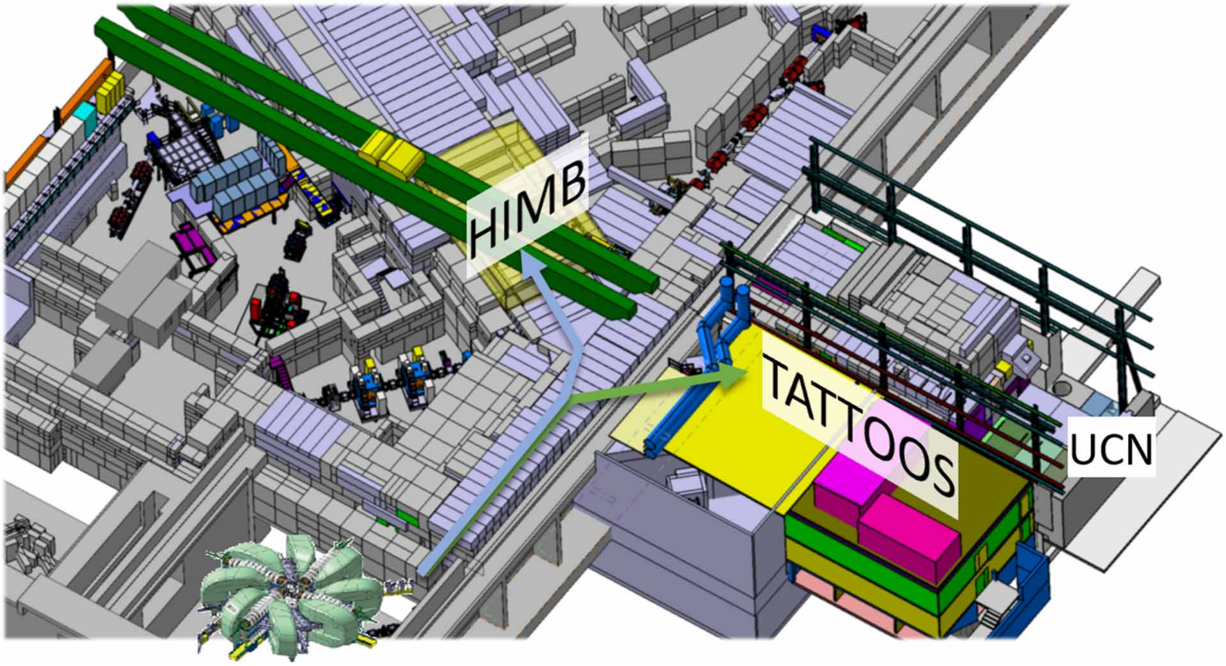

Figure 1: This CAD model shows the location of the target station H(IMB) under the yellow concrete bars with the secondary beam line MuH2 on the left. In close proximity, TATTOOS, adjacent to UCN, is located in a new building. Courtesy of M. Kalt, PSI.

ary beam lines (Fig. 2). The solenoidal beam lines are optimized for large transmission of surface muons. More information about the beam line design for the new MuH2 and MuH3 experimental areas can be found in [4]. For the capture solenoid a graded-field design is favoured with approximately 0.45 T in its centre. The graphite target itself is optimized for the production of surface muons by using a so-called slanted target design. The proton beam passes through the target rim of the rotating wheel at a small angle. The target rim is extended in the beam direction, significantly increasing the muon production surface. This type of target was already successfully tested in the target E station, increasing surface muon rates by up to 50% [5]. In addition, the effective target H thickness is increased from 5 to 20 mm compared to target M, leading to larger beam spread and, consequently, thicker shielding. It also requires a new collimator system and careful beam transport studies up to the SINQ target to match the beam profile for safe operation. Further, the fringing field at the target, due to the capture solenoids, has to be taken into account and corrected for.

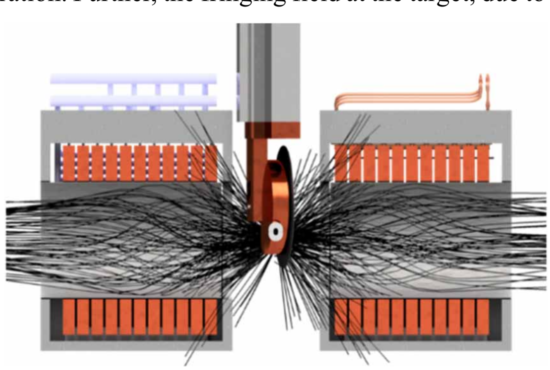

Figure 2: On both sides of Target H the capture magnets with particle trajectories from simulation are shown.

The complete beam line from the Ring cyclotron to the SINQ target was modelled by building Geometry Description Markup Language (GDML) files [6] and partly importing CAD models for important components, such as collimators and targets. Before the beam optics for the new Target H was optimized for small losses, the simulation software BDSIM [7] was benchmarked against the current optics using various techniques [8]. For example, very good agreement was obtained between the simulated losses on the collimators and the measured temperature increase of the cooling water. It was recognized that the losses do not scale linearly with the current. This was traced back to the dependence of the beam size with current, which was finally determined and confirmed by measurements with a profile monitor located just after the Ring cyclotron. Using this beam size–current dependence, the beam envelope obtained by BDSIM with the current 5-mm Target M could be well matched to the beam profile measurements from the Ring to the SINQ target.

For the proposed 20 mm Target H, a collimator system was designed, minimizing losses and maximizing transmission up to the SINQ target. The quadrupoles after Target H had to be tuned to larger focussing to accommodate the larger beam spread. The simulations with BDSIM revealed that the energy spread after Target E is twice as large with the 20-mm Target H compared to the 5-mm Target M. Therefore the losses in the AHL dipole, which bends the beam down on its way to SINQ, are higher compared to the present situation. With the optimized optics a transmission of 67 % can be kept compared to the current 70 %. Replacing the present collimator system KHE2/3 after Target E

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with an existing new design for 3 mA beam [2], the transmission could be increased back to 70 % while keeping the required beam profile for SINQ.

TATTOOS

Several radionuclides are already produced at PSI for research towards cancer therapy and diagnostics, using the 72 MeV proton beam at the IP2 station [9] or thermal neutrons at the irradiation station close to the SINQ target [10]. Particularly interesting are the radioisotopes belonging to the same element, which can be used for therapy as well as diagnostics (theragnostics). This approach allows better and personalized therapy planning for cancer. Promising radioisotopes in this regard are those of terbium, with ^{155}Tb and ^{161}Tb, already produced at IP2 and SINQ, respectively. The aim of TATTOOS is to extend the list of radionuclides for theragnostics to the region of neutron-deficient isotopes such as ^{152}Tb and ^{149}Tb, the latter a promising agent for α-particle therapy [11]. In Phase 1, TATTOOS will focus its production on these nuclides using a tantalum (Ta) target; later, targets containing uranium or thorium are planned.

For the efficient production of sufficient quantities at PSI a 100 µA proton beam at 590 MeV on target, containing effectively 10 cm Ta, is proposed. This beam has to be split from the main beam. Due to space limitations, the first part of the UCN beam line will also be used for TATTOOS. Therefore, TATTOOS cannot be operated whenever a beam pulse is being delivered to UCN. This quasi-parallel operation mode results in 15 % loss of beam time, which is anticipated as acceptable. To switch from TATTOOS to UCN operation the splitter needs to be retracted from the beam, while a dipole magnet changes its polarity to bend the beam from the TATTOOS to the UCN branch of the beam line.

The splitter, already installed in the late 1990s for proton therapy, was developed and tested for 20 µA [12]. It consists of 175 stripes, 2 mm wide with a thickness of 50 µm. A high voltage is applied at two cathodes to achieve a deflection of 6 mrad. The current of the colliding protons is measured on the first three stripes and restricted to 1 µA for safe operation. This limit was deduced from comparison of simulation and operation of the splitter used for 72 MeV beam. To split a large fraction of the beam and, at the same time, respect the current limit, the beam optics was broadened in the horizontal direction in a recent beam study under the condition that beam operation up to SINQ as well as UCN kicks were still feasible. Since the TATTOOS beam line does not yet exist, as part of a demonstration, 80 µA of the beam could be successfully split with these optics onto the UCN target. However, the beam losses after the splitter were increased with respect to the operation without splitter, which was expected. Further studies and measures to reduce losses are needed as this part of the beam line is maintained hands-on.

To better distribute the heat on the target more uniformly, the beam will be wobbled in two dimensions. Further, the beam profile will be broadened to about 60 mm diameter for an optimal distribution on the target. The produced isotopes diffusing out of the hot target are preselected by Resonance Ionization Laser Ion Source (RILIS) [13, 14]. Another selection occurs on the way from the target to the three shielded cells by mass separation (ISOL technique). Finally, the desired nuclide is chemically purified and isolated from potential isobars in the shielded cells. The radionuclides shall be used for preclinical as well as clinical studies. The radiopharmaceutical manufacture needed for clinical applications are done in GMP (Good Manufacturing Practice) laboratories.

The free space between the experimental hall, where the Ring cyclotron, the two meson production targets and later Target H are located (Fig. 1), and the UCN office/laboratory building is only 14 m by 16 m. This is quite small for the shielded target station, the three shielded cells for chemistry separation, an extra one for target exchange, the access lock for personnel and material, as required for an area handling α-emitting nuclides as well as the needed infrastructure for operation. Therefore the UCN office/laboratory building will be rebuilt and extended to the experimental hall. Part of the space of the former office building will be used by TATTOOS in addition. However, it requires the relocation and rebuilding of infrastructure to free the space for the new building.

SCHEDULE

The installation of HIMB is planned for 2027, with first beam after the regular winter-spring shutdown of HIPA in 2028. Since Target Station M of the main beam line to SINQ has to be removed and rebuilt, there will be no operation of HIPA in 2027. In the same year, the building for TATTOOS will be constructed and finished in 2028, such that the TATTOOS facility can be installed in 2029 with first beam after the regular HIPA shutdown in 2030. This schedule avoids the installation of two target facilities in parallel, with the advantage that more PSI resources and more storage space are available at a given time. In addition, the building construction will not be particularly constrained by the operation of HIPA and UCN. A lot of preparation work will be carried out before the start of the installations in 2027.

CONCLUSION

IMPACT covers a broad field of applications, particle and solid state physics as well as life sciences. Realization of the two target stations for HIMB and TATTOOS is planned from 2027, for completion in 2030. The conceptual design presented in the CDR was refined in 2022. The feasibility to operate a four-fold thicker target at the location of the target M station was shown, a prerequisite for the realization of HIMB. Further, good progress was made in simulation as well as beam studies to demonstrate that the fraction of the beam, almost the full current proposed for TATTOOS, could be peeled off from the main beam using the existing splitter.

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