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# HIGH-POWER TARGETRY AND THE IMPACT INITIATIVE AT PAUL SCHERRER INSTITUTE

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*Abstract*

The main challenges to operate a high power target include heat dissipation and radiation damage. The latter refers to the damage of the material. Since the breakdown of the material depends on the operation temperature and other conditions, like the material treatment before irradiation, it is difficult to predict.

To reduce failures, target operation parameters and beam properties have to be monitored carefully. After the failure of the neutron spallation target (SINQ) in 2016, several improvements at the HIPA (High intensity Proton Accelerator) beam line at Paul Scherrer Institute (PSI), as well as the target installation, were implemented.

MW beams are not a prerequisite for the need of high power targets. This is the case at one of the two new target stations within the IMPACT initiative at PSI. One target station will produce radionuclides for research in cancer therapy, while the other will improve the surface muon rate by a factor of 100 for experiments in particle and material physics.

In this report, strategies for successful operation of high-power targets are shown. Furthermore, the IMPACT initiative at PSI, with focus on the two planned target stations, will be presented.

## MOTIVATION AND CHALLENGES

Most experimental target stations are overbooked, i.e., the demand for beam time based on proposals submitted far exceeds the beam time available. In addition, measurements are repeated, aiming for better statistics, which means that the time for data taking would increase significantly without an increase of particle fluxes. The worldwide experimental quest for new physics beyond the standard model, which aims to lower the upper cross-section limit of forbidden reactions, is a good example thereof. Nowadays, state-of-the-art detectors and electronics are capable to process high data rate efficiently, with small dead time, and data analyses on high-performance computers can cope with the large amount of data collected.

The demand for higher particle fluxes leads to the development of more powerful accelerators, planned from the beginning or later as an upgrade. Figure 1 illustrates this trend. Many accelerators worldwide announced a major upgrade or provide increased power with respect to its initial design value. SNS was originally targeted to 1.4 MW, however, recently reached 1.7 MW, a world record [1]. Further, SNS envisaged a challenging power upgrade towards 2.8 MW in the PPU project (Proton Power Upgrade) [2]. While J-PARC and CSNS are in the process of gradually

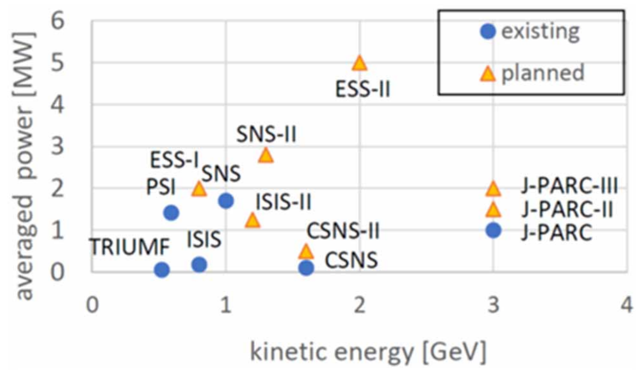


Figure 1 Accelerators with high-power targets.

ramping up their power, ISIS, too, has major plans for a upgrade. According to the ISIS-II roadmap, it might be a new stand-alone facility or a facility upgrade which reuses as much existing ISIS infrastructure as possible [3].

High-power accelerators require high-power targets (HPT) for efficient use of the power. The operation of such HPTs is a challenge. As these targets are operating at the limit of feasibility, the beam properties have to be carefully monitored to avoid target failure due to deviation from the nominal beam power distribution. Such a situation could likely lead to overheating and damage of the target. If a critical deviation is detected, a fast interlock system (machine protection system = MPS) has to quickly stop the beam to avoid damage. At HIPA [4, 5], PSI, the time between detection of a beam state outside predefined boundaries and switching off the beam takes less than 10 ms [6]. Reliable beam diagnostics is also needed, as well as enough additional monitors to ensure redundancy, such that monitors, which fail completely or show wrong signals, are detected at an early stage. HPTs also often require a wider distribution of the beam power on the target to reduce the power deposition per surface area. The simplest method is to enlarge the Gaussian beam profile, which is the default beam shape provided by most accelerators, using two quadrupoles. However, the Gaussian is not optimal due to its power concentration in the centre. A rectangular profile is ideal, however, it requires space for a couple of higher-order magnets like sextupoles, octupoles or a combination of them to form the Gaussian beam to a rectangular profile. An alternative is wobbling or painting a beam of small or medium size. For this, two magnets are needed to bend the beam in horizontal and vertical directions, respectively. Often, Lissajous figures are used to fill a profile as homogenously as possible. In Fig. 2 an example is shown. Depending on the size of the beam and the target

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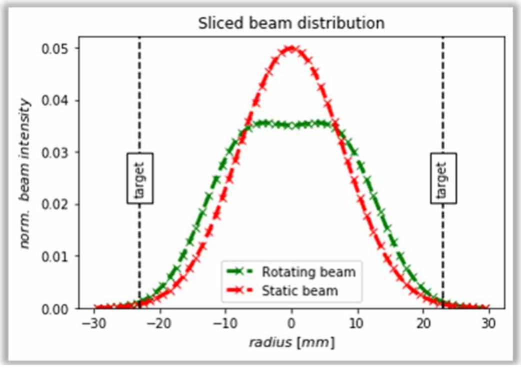


Figure 2: Red: Gaussian beam enlarged by quadupoles. Green: Wobbling of the beam (size: s = 9 mm) by two fast magnets. Courtesy of M. Hartmann, PSI.

requirement, the beam must be moved so fast over the surface that the temperature is not affected by its frequency, often several 10th Hz, sometime several kHz are used. The difference between wobbling and painting is that painting describes a line-by-line movement of the beam on a given surface. It is often used in proton therapy where the target is the tumour.

The challenges on the target side are mainly caused by the high power deposition and radiation damage. Even if the power distribution of the beam on the target surface is as homogeneous as possible, temperature gradients are caused by the heat sink, which dissipates the power deposited by the beam out of the target. Also, when the beam penetrates the target the power deposition along the beam varies. Both effects lead to temperature gradients, causing mechanical stress. In pulsed sources the materials are heated and cooled many times. This can lead to material fatigue and, subsequently, cracks, if the number of the cycles are above the so-called fatigue damage cycle limit. However, the exact number, even an estimated one, is difficult to evaluate. It depends not only on the material, but also of its treatment, i.e., rolled, forged, annealed etc. as well as on the operating temperature and the particular stress occurring during the pulse. The number of cycles until failure are often in between $10^5$ and $10^9$ cycles. While this appears a lot, $10^9$ cycles are already reached after 5000 h for a 60 Hz beam, which is easily achieved over one year of operation.

Like the accelerator, the target parameters during operation must be monitored carefully to cease target operation before a failure causes significant damage. Important parameters to detect are the temperatures at different locations of the target and the cooling medium as well as its flow (if a fluid is used). Temperature and flux sensors must be mounted inside the target for this purpose. Therefore, such sensors suffer from strong temperature gradients and/or radiation damage, i.e., they are susceptible to malfunctions. To avoid stopping target operation due to a malfunctioning sensor, the number of redundant sensors have to be chosen carefully at the stage of the target design. Due to the high residual radiation level of the HPT, replacement of sensors might be not possible at all or may require a major downtime of beam operation. Repairing, if possible, has to be performed in a shielded cell by remote handling.

## RADIATION DAMAGE

Radiation damage of HPTs can occur due to electromagnetic or nuclear reactions. The first type, usually caused by gamma- or electron-particles, break molecular joints, which leads to embrittlement or hardening of organic materials like epoxies and lubricants. For organic materials that are called "radiation hard", the manufacturer specifies a limit in Gray, i.e., the energy absorbed per kg from the charged particles penetrating the material. However, at the high level of radiation in high power targets, organic materials cannot be used.

Nuclear reactions lead to two main effects that change the properties of solid materials organized in a lattice, namely, defects in the lattice due to the knock-out of atoms from their lattice position and the production of isotopes, which were not part of the original lattice. Since the resulting isotopes usually do not fit into the lattice, the lattice structure is disturbed in both cases.

Due to defects in the lattice, vacancies and also interstitials (i.e., atoms including impurities in between the original lattice positions) occur, with the material losing its elasticity. The hardness increases, the material gets brittle and, depending on the local stress, this could lead to cracks.

Many interstitials can lead to swelling of the material, i.e. the dimension of the material increases. This is often accompanied by cracks, due to additional stress on the already brittle material when it presses against the next component. The probability of swelling is increased if hydrogen and, particularly, helium is produced in large quantities, e.g., due to high-energy reactions (spallation).

Further, the thermal conductivity of the material can decrease significantly. This is mainly due to defects in the lattice, with a minor contribution due to the impurities produced. The thermal conductivity in graphite already decreases after a short irradiation period [7]. Since HPTs rely on good cooling, this could quickly lead to overheating and melting.

However, due to annealing or evaluated temperatures during the operation, some of the defects heal, because the additional thermal energy shakes the lattice and interstitials, for example, find their right position in the lattice. Therefore, the thermal conductivity increases at higher temperature after the often significant decrease due to irradiation, since there are now fewer defects in the lattice than before. While charged particles from the accelerator also heats the material, healing of radiation damage in some parts of the target during irradiation is possible. The effect is enhanced due to the so-called radiation-induced (self-) diffusion, which can increase by several orders of magnitude [8]. This is related to the fact that atoms often change lattice places. If there is a pure material consisting of just one kind of atom, diffusion has no side effect. However, different types of atoms can undergo junctions and form

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new molecules. The atoms might belong to the original material composition or be produced by nuclear reactions. For example, when hydrogen is produced in large quantities via spallation reactions it can form $H_2$ or $H_2O$, if the original material composition contains a notable oxygen contribution. At elevated temperatures, cracks can be formed by internal pressure due to gas bubbles. Blisters might be visible close to the surface. Other than hydrogen, helium can induce these effects as well.

The main technical problem of radiation damage is that prediction is almost impossible. It not only depends on the operation temperature and the primary particle type and energy, but also on the specific material, its impurities as well as the fabrication process (rolled, forged, annealed etc.). Therefore, the only way to predict accurately is to perform many irradiation experiments, comparing different types of material, and to select the one with the best performance. However, such tests are elaborate and usually the conditions in the later HPT can be only approximated at best. Nevertheless, it is important to build up experience and a database of tested material, as done by the RaDIATE collaboration [9] and HiRadMat at CERN [10].

## STRATEGIES FOR HPT

### *Fluid Target Material*

Fluids have the advantage that they have no structure and, therefore, they cannot be destroyed by irradiation. If the fluid can be used not only as target material but also as coolant, the target is particularly efficient, because no extra coolant agent in the target is needed, which otherwise dilutes the effective target density. In addition, a target container with a window is needed, which likely has to be exchanged regularly due to radiation damage. However, the fluid can usually be reused. This reduces the operational radioactive waste significantly. The disadvantage is that a fluid target is difficult to handle and often requires an extra shielded cell for maintenance for this purpose only. Furthermore, containment of the fluid has to be ensured in case of failure and the final disposal of the fluid needs solidification first. This will require chemical treatment and likely produce additional waste. For these reasons, obtaining approval from the authorities for operating such a target is more difficult and, depending on the quantity and activity of the fluid as well as the country, it is not approved.

Fluid targets are often used for pulsed high-power sources, because fluids resist radiation and fatigue is not an issue. The spallation targets at J-PARC [11] and SNS [12] use both mercury as target material. After high-power operation, both facilities observed an unexpected effect, namely, the damage of the inner vessel at the beam entry. Joint effort from both institutes traced the effect to cavitation. The large energy deposit in the fluid creates bubbles, which eject during collapsing high-energy jets of drops towards the vessel. The vessel wall erodes due to pitting, which is also known from tubes guiding liquids with negative pressure. J-PARC introduces first a helium flow as buffer layer between the mercury and the vessel, which

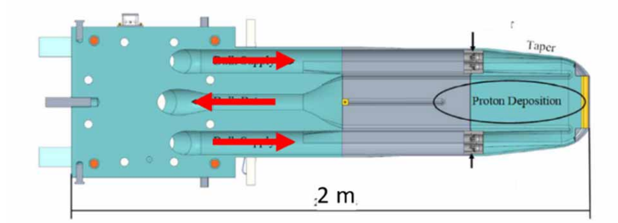


Figure 3: New SNS target design for 2 MW [12]. Beam enters from the right. The red arrows indicate the mercury flow.

mitigated the effect of cavitation to a large extent after experimentally optimizing the helium flow. To the knowledge of the author the mitigating effect of the helium flow on cavitation damage cannot be simulated yet. In the new design for the PPU at SNS, up to 10 l/min helium is foreseen at the nose of the target [12].

The SNS target design for the 2 MW proton beam after the PPU is shown in Fig. 3. The helium gets distributed with swirl bubblers at the positions of the two black arrows. Importantly, the mercury flows into the vessel along its walls to cool them first. The flow is guided back towards the centre of the target and passes the region with the highest power deposition. The flow directions in Fig. 3 are indicated by the red arrows. The vessel is a double shell, in between it is cooled using mercury. In the J-PARC spallation target, it is cooled with water. One obvious change in the geometry of the PPU target is the tapered nose, which was close to a rectangular shape in previous target designs. Due to the tapered form, the corners of the target are cooled better and the flow increases towards the entry window. In addition, the mercury flow is guided towards the centre for the flow-back. The J-PARC targets in operation are also equipped with the tapered nose [13,14]. Due to the high proton power pulse and the localized power deposition a pressure wave is formed, which travels through the target. Its peak values at 1 MW beam power is 40 MPa, according to Ref. [15]. This causes mechanical stress on the vessel walls.

### *Segmentation of Target Material*

A block of (target) material, which is exposed to high power deposition, can often not be cooled sufficiently without segmentation. The latter increases the surface-to-volume ratio and, thus, the contact surface for the coolant medium. Since the segments are separated from each other, enough space for thermal expansion have to be provided reducing mechanical stress.

The extra space required for the coolant medium around the segments is disadvantageous. An alternative is to use coolant channels in the target material instead of segmentation. If the resulting temperature distribution in the target is close to homogeneous and the temperature low enough that expansion is not an issue, segmentation because of stress reduction is not necessary.

Since the choice of the target material is driven by target performance and less from the technical or operational point of view, the target material often requires cladding. This may be due to reaction between the material and the

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coolant medium or a low melting point of the target material becoming liquid during irradiation by power deposition. The latter is the case for SINQ at PSI, where lead is clad in zircaloy tubes. Zircaloy was chosen because of its well-known use in highly radioactive environments as cladding for fuel rods. In addition, it has a much lower neutron absorption cross section compared to steel. To allow for thermal expansion, the tube volume is filled with only 90 % lead. In the region of high-power deposition, the lead completely or partly melts. However, since the failure of the target in 2016 [16], this region is equipped by full zircaloy rods, since molten lead flowing out of a cracked tube can plug the cooling channels between the tubes, which leads to local boiling and partial meltdown of the target. This measure reduces the target performance of about 10 % for the benefit of a safer operation. In addition, thermocouples were installed in the target to monitor the shape of the beam and quickly detect anomalies. Furthermore, the beam instrumentation in front of the target was improved [17]. Altogether, the SINQ target contains about 300 rods and can be operated at 1 MW. The window is a double shell made from AlMg3 and it cooled with water ($D_2O$) in between.

At ISIS, tungsten is chosen as target material, which has to be protected from corrosion from the cooling water. Irradiated water is particularly reactive due to radicals formed by radiolysis like OH- or its products like hydrogen peroxide ($H_2O_2$) [18]. For tungsten, a 2-mm tantalum cladding is used in the TS1 target station. It is crucial that a good thermal contact between cladding and material exists for effective cooling and avoiding hot spots. The cladding should also stay intact, despite the harsh operating environment. ISIS has almost 40 years' experience with such targets and the tantalum-cladding technique [19]. The segments in the TS1 target station are chosen according to the power deposition, small at the entry of the beam and increasing in thickness towards the end of the target. In the smaller blocks, the heat can be dissipated faster - keeping temperature and stress at acceptable levels. The cooling channels in between the segments are 2 mm. TS1 operates successfully at 0.2 MW. Using the same design but thinner segments the maximum acceptable power could be doubled. The limit is given by the thinnest possible plate that can be manufactured, including cladding. Beyond this, in preparation for a possible upgrade it is concluded either a molten heavy metal target (see above) or a rotating solid (see below) is required [20].

### *Rotating Targets*

If the power is so high that no (solid) material would stand it and if enlarging the beam profile is not sufficient or cannot be done to the size needed (e.g., in case the target does not act as beam dump), a rotating target is a good and sometimes only choice. The advantage of a rotating target is that the power is distributed on the rim of the target, which reduces the power density. Additionally, the beam can be spread in the direction perpendicular to the rotational movement if needed. At the same time, the effect of radiation damage is also distributed on a larger surface, which leads to a longer lifetime of the target. Usually, the power density is significantly reduced, as the larger circumference of the target increases the reduction factor. However, this could require large targets. In general, a rotating target is significantly larger than a fixed one. This leads to more radioactive waste and manufacturing costs. Due to size and weight, it is also more difficult to exchange the target, particularly, if there are components that have to be removed first or mounted around the rim (like a moderator).

The main challenge is the bearing. The challenge increases with the size and weight of the target. Since the bearing has to work reliably in a harsh radioactive environment, lubricants like oil and grease made from organic materials cannot be used. It would soon get brittle and solidify. Therefore, the bearings are often operated without lubricant, i.e. dry steel or ceramic balls rolling in a steel cave. Since the balls suffer from mechanical damage without lubrication, the lifetime of the bearings is drastically reduced.

The ESS spallation target designed for 5 MW has a diameter of 2.6 m and a shaft of about 5 m [22, 23]. Scheduled to begin operation in 2025, it will be likely the largest and heaviest target. The outer part of the circular target steel shell, 48 cm from the beam entry, is filled with 7000 blocks of tungsten (without cladding). Between the blocks are pathways for the helium cooling agent as well as slits for thermal expansion. The helium is supplied through the shaft to target and bends back at the beam window. Helium removes 3 MW of heat deposited in the target by the 5-MW proton beam. At full power each beam pulse leads to a temperature increase of 100ºC, which corresponds to 100 MPa. The maximum temperature is 450ºC, with predicted lifetime of the target estimated at 5 years.

At J-PARC, the meson production target was changed from a fixed target to a rotating target while increasing the beam power from 300 kW to 1 MW [24]. The beam spot was moved every 700 h on the fixed target to mitigate radiation damage. The targets consist of graphite with an effective target thickness of 20 mm. Since the beam energy is high, the beam power deposited in the target is moderate at 12 kW. The rotating target operates at 940 K. It is cooled by thermal radiation and a cooling jacket located in close proximity. The wheel consists of three parts to allow for thermal expansion [25]. Due to the target rotation at 15 Hz, the lifetime could be increased from 6 years (fixed target) to more than 30 years. In collaboration with industry, J-PARC developed [26] Koyo bearings, whose lifetime is predicted to be more than 22 years. They used a sintered compact of disulfide tungsten ($WS_2$) as lubricant. The bearings also dissipate their heat to the water-cooling jacket. Maximum temperature at the bearings is 390ºC.

At PSI a similar target, called Target E [27, 28], is in operation producing pions and, subsequently, muons. The proton beam of 2.4 mA and 590 MeV deposits about 50 kW on the target with an effective thickness of 40 mm. The graphite wheel has a diameter of 450 mm and rotates at 1 Hz. It is cooled by thermal radiation and operates at about 1500ºC. Cooling by radiation has the advantage that its effectiveness is independent of the thermal conductivity,

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which is known to degrade with high-energy particle bombardment. Thermal radiation becomes an effective cooling method if the temperature is above 1000°C and the emissivity ε is high, as is the case for graphite (ε ~ 0.7). Materials that do not have a high emissivity can be coated, e.g., copper with $Al_2O_3$-$TiO_2$ as it is done for the local shielding at Target E.

To reduce the heat on the bearings in the centre of the graphite wheel, the spokes between the graphite and the hub are hollow, which reduces thermal conduction. The rim of the wheel is segmented into twelve parts to allow for thermal expansion. Polycrystalline graphite is used to reduce anisotropic thermal expansion. Instead of the slab-like target a new target type, called slanted, has been in operation since 2021. The beam passes the target at a small angle, thereby, increasing the effective surface. Therefore, the surface muons, which are produced by decaying pions close to the surface of the target, increase by 30 – 50% [29].

At FRIB, a graphite wheel rotating at 5000/60 Hz is in operation to produce rare isotopes from oxygen to uranium at 200 MeV/u (400 MeV/u after upgrade). Depending on the ion range, the thickness of the target varies from mm to cm with a maximum thickness of 5 cm. Since FRIB is ramping up the power gradually, starting at 1 kW to presently 10 kW, to 400 kW in 2028 [30], the target design has to keep pace. Up to 50 kW the graphite wheel consists of one slice, similar to Target E at PSI or the J-PARC meson production target. However, from 100 kW a multi-slice target (Fig. 4) has to be used to increase the surface area for radiation cooling. Between 100 kW and 400 kW the number of slices will be increased from two to nine, keeping the maximum temperature below 1900°C to mitigate evaporation of the graphite [31]. Many tests with electron beams [32] were performed, as well as simulations [33] and radiation damage examinations [34] to improve the design for such extreme conditions.

Since the FRIB target is inserted horizontally, the bearings rotating the long horizontal axis with the fixed wheel at the end are well shielded. A similar design is used for Target M, the thinner meson production target at PSI. The bearings in Target M last much longer compared to Target E where, due to the vertical insert, the bearings have to be placed close to the wheel. However, using the KoYo bearings in Target E, the bearings do not need to be ex changed during operation from April to December [35]. Target M is foreseen to be replaced as part of the IMPACT initiative in 2027.

Figure 4: Left: Multi-slice graphite target with part of the cooling jacket out of copper. Right: Sketch showing the stacked targets at the rim [21].

## IMPACT

IMPACT, Isotope and Muon Production with Advanced Cyclotron and target Technology, consists of two target stations including beamlines, infrastructure and end stations [36]. HIMB, High Intensity Muon Beams, aims to upgrade Target M, originally installed in 1985, to achieve 100-fold more surface muon rate compared to the muon beamline MuE4 - providing a rate of the order of $10^8$ surface muons per second [37], the world's highest intensity to date. HIMB will ensure particle physics and material science (μSR) will remain competitive for the foreseeable future. TATTOOS, Targeted Alpha Tumour Therapy and Other Oncological Solutions, will provide promising radionuclides for cancer therapy and diagnostics (theragnostics) in quantities needed for clinical research.

In 2027, where HIPA will be in shutdown for the entire year, Target M will be dismantled using remote handling, due to the high radiation of up to 8 Sv/h, and the new Target H installed. However, the installation of the new MuH2 beamline for particle physics requires a major rearrangement of several user areas and service installations. The beam is planned to return in mid-2028 for users of all other user facilities except for the two HIMB beamlines MuH2 and MuH3, which are then in pilot operation. For TATTOOS a new building is necessary, which also requires removal and reinstallation of infrastructure at PSI, particularly for UCN, which presently uses the location foreseen for the new building. Installation of the TATTOOS target station, including ion beamline and infrastructure for radionuclide separation will take place two years after HIMB, with first beam planned in 2030.

Dedicated beamline simulations for MuH2 could confirm an increase of the muon rate of more than $10^{10}$ μ/s [38]. The key components making this vast increase possible are:

- A capture solenoid with a large diameter and an optimized magnetic field (~0.45 T) for surface muons in close proximity (250 mm) to and on both sides of the target [39].
- Large transmission for low-energy muons in a series of solenoids with large aperture and a minimum number of bends.
- Increase of target thickness from 5 to 20 mm.
- Slanted target type already tested at Target E (see above).

The capture magnet provides a special field with a longitudinal gradient, which is strong at the entrance, to maximize muons capture, and lower at the exit to have the right focusing for further transport. The maximum field is limited by current allowed in the radiation-hard coils [40]. Therefore, the capture solenoid consists of three "pancakes" driven by independent power supplies. The increase of the target thickness, as well as the small number of bends, only two, in combination with a large diameter of the beamline, is a challenge for the shielding. In addition, losses along the main proton beamline have to be reduced and under control [41].

The target design and insert will be similar to Target E. Since the space between the two capture solenoids is limited to +/- 250 mm, there is not enough space for the beam in front of the target wheel. The beam has to pass the water-cooled local copper shielding. To avoid melting in case the beam is missteered, a tungsten collimator with an aperture at the entrance will be inserted. Both components measure the current induced by the proton beam and shut off the beam via fast interlock.

For TATTOOS, 100 µA protons will be split from the main 590 MeV beam from HIPA. The splitter dates back to the 1980s [42, 43] and was used for the early proton cancer therapy when <100 µA was obtained. Recently, a test with broadened beam optics was performed and 80 µA could be split [44, 45]. Further tests will be performed using cooled quadrupoles that allow for an even broader beam profile. TATTOOS will be operated in quasi-parallel with UCN, i.e., UCN receives the full beam for a few seconds using a fast kicker while the beam is continuously delivered to TATTOOS [46, 47]. This results in loss of only 15 % of the beam. Since the split beam is almost pencil-like, it will be wobbled in horizontally and vertically to reduce the maximum power deposition on the target (see Fig. 2). Since TATTOOS will focus on $^{152}$Tb (imaging with PET=Proton Emission Tomography), $^{149}$Tb (α-therapy) in the first phase, a 10-cm thick tantalum target is chosen. The 100 µA proton beam will deposit 26 kW on the target, while the remaining beam power and scattering in the shielding surrounding the target will be absorbed by the beam dump. Although the operation temperature of the target is above 2000 ºC to allow for a fast diffusion of the radionuclides to the nozzle, it is challenging to keep the target temperature below melting point and to provide a temperature distribution as homogeneously as possible. Since the radionuclides have to diffuse freely, active cooling using an agent like helium or water cannot be applied. Therefore, the target will dissipate the power by thermal radiation. For tantalum, the emissivity is about 0.35 and the surface for radiating increases with the radius of the target. However, since it should be possible to heat the target not only by the beam but also by ohmic heating in case the beam current is low, the required electrical current also increases with the target radius. A diameter of 20 mm requires about 2000 A and a diameter of 60 mm 6000 A. The target design for TATTOOS is still under development [48].

The separation of the isotopes are done by the ISOL (Isotope Separator On Line) and RILIS (Resonance Ionization Laser Ion Source) [49] methods combined with chemical processing in the shielded cells.

At TRIUMF, the effective emissivity was increased with the installation of 90 fins, 55 mm x 55 mm, along the cylindrical target shell 20 mm in diameter (Fig. 5). This increases the effective emissivity from 0.35 to 0.92 [50]. This target design is able to dissipate 25 kW to a copper shield cooled by water. Therefore, such a target design would be an option for the TATTOOS target.

ISOLDE [51], CERN, in operation for more than 50 years, continuously improves its performance and applications. Its ion source and target installation served as a model for many similar facilities. An upgrade of the proton beam from 2 µA at 1.4 GeV to almost 7 µA at 2 GeV as well as an improved secondary beam quality is envisaged in the near future (HIE-ISOLDE design study) [52].

## CONCLUSION

In this report, strategies for the design of HPTs were shown by means of working examples all over the world as well as damage caused by radiation, which cannot be predicted without experimental efforts. Of course, not every HPT could be mentioned. Many strategies applied to high power targets are also applicable to collimators [53] and beam dumps [54]. Today, many targets operate on the brink of the feasibility. The trend to increase the power of the accelerator leads to huge targets (e.g., ESS wheel) or to a second target station fed simultaneously to the first (e.g., ISIS, SNS).

At PSI, the IMPACT initiative aims to upgrade Target Station M from 1985, as well as to extend radionuclide production to 590 MeV for cancer theragnostics. The pre-project is underway, with the preparation of the CDR in 2021.

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