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MACHINE PROTECTION SYSTEM FOR THE PROPOSED TATTOOS BEAMLINE AT HIPA

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Abstract

IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target Technology) is a proposed upgrade project for the High Intensity Proton Accelerator (HIPA) at the Paul Scherrer Institute (PSI). As part of IMPACT, a new radioisotope target station, TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions) is planned. The TATTOOS beamline and target will be located near the UCN (Ultra Cold Neutron source) target area, branching off from the main UCN beamline. In particular, the 590 MeV proton beamline is designed to operate at a beam intensity of 100 μA (60 kW), requiring a continuous splitting of the main beam by an electrostatic splitter. The philosophy of the machine protection system (MPS) for the TATTOOS beamline will not differ significantly from the one already implemented for HIPA. However, it is particularly important for TATTOOS to avoid damage to the target due to irregular beam conditions. We will show the diagnostic systems involved and how the requirements of the machine protection system can be met. Emergency scenarios and protective measures are also discussed.

INTRODUCTION

The High Intensity Proton Accelerator facility (HIPA) at the Paul Scherrer Institute (PSI) delivers a 590 MeV proton beam with up to 1.4 MW beam power (2.4 mA) to spallation and meson production targets serving particle physics experiments and material research [1].

IMPACT (Isotope and Muon Production using Advanced Cyclotron and Target technologies) is a proposed upgrade project envisaged for HIPA [2]. IMPACT proposes two new target stations: HIMB (High Intensity Muon Beamline) replaces an existing target and focuses on increasing the rate of surface muons while TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions), an online isotope separation facility, will allow to produce promising radionuclides for diagnosis and cancer therapy in doses sufficient for clinical studies. The TATTOOS facility includes a dedicated beamline intended to operate at a beam intensity of 100 µA (60 kW beam power), requiring continuous splitting of the high-power main beam via an electrostatic splitter [3, 4]. A realistic model of the complete TATTOOS beamline from splitter to target was established [5, 6].

OVERVIEW HIPA

An overview of the HIPA facility with the foreseen TATTOOS installation is shown in Fig. 1. HIPA consists of a Cockcroft-Walton pre-accelerator (870 keV) followed by two isochronous cyclotrons, the Injector II (72 MeV) and the Ring cyclotron (590 MeV). After extraction from the Ring cyclotron the high intensity, up to 2.4 mA, proton beam interacts with two rotating graphite target wheels, target M and E, to produce pions and muons. After collimation the remaining beam with roughly 1 MW power is used to produce neutrons in a spallation target (SINQ). In addition, a pulsed source for ultracold neutrons (UCN) is in operation as well. A fast kicker magnet can divert the full intensity beam to the UCN beamline and target for up to 8 seconds. Finally, an electrostatic splitter (EHT) located downstream of the kicker magnet in the PK1 beamline can peel off a fraction of the main beam and send it continuously to the UCN target. Another electrostatic splitter (EXT) [7, 8] can peel off a few tens of microamperes from the main 72 MeV (2.4 mA) beam to produce radionuclides in the IP2 irradiation station [9].

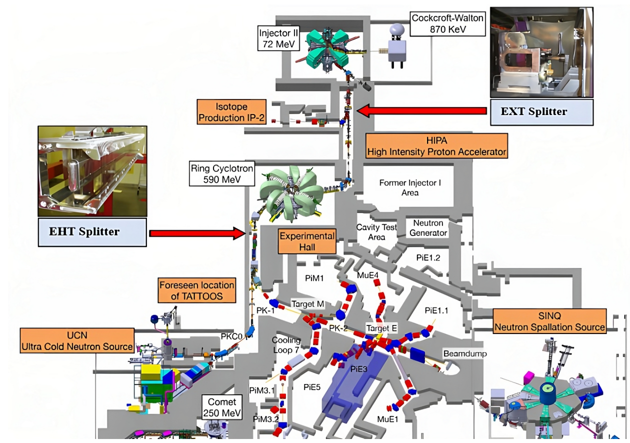

Figure 1: Overview of the high intensity proton accelerator HIPA. The proposed TATTOOS beamline and the location of the EHT splitter is also indicated.

Machine Protection System

When handling a beam of over 1 MW power, the protection and control of the facility become crucial and require reliable protection mechanisms as well as appropriate diagnostics and controls. In particular the high dynamic range needed for currents between less than 1 and up to 2400 µA is a big challenge for the beam diagnostics and has to be accounted for by the control system.

The well established HIPA machine protection system (MPS) [10–13] guarantees safe operation of the accelerator facility protecting the machine from severe instantaneous beam losses and from prohibitive activation generated by large integrated losses.

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TATTOOS BEAMLINE

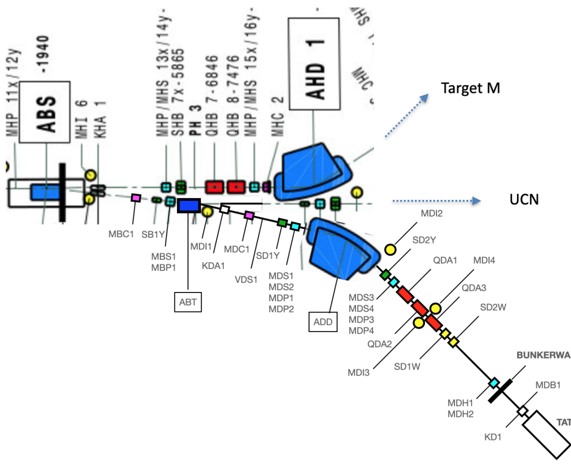

Figure 2: Main components along the proposed TATTOOS beamline. Beam loss ionisation chambers are depicted with yellow circles; bending magnets in blue; steerer corrector magnets in green; quadrupole magnets in red; beam position and profile monitors in cyan; beam current monitors in pink; wobbler magnets in yellow; collimator MDB1 in white.

Figure 2 illustrates the proposed TATTOOS beamline. Upstream, the beamline starts with the EHT splitter (see Fig. 1) peeling off a small portion (up to 100 μA) from the main beam. The EHT consists of two cathodes at a fixed voltage of about -172 kV and a thin septum. The septum is located equidistant from the cathodes and consists of 175 tungsten alloy strips. The two cathodes are on ground potential, the incoming protons of the main beam are thus steered away by 3 mrad from the strips at the end of the splitter for both sides. Two identical steering magnets on each side of the splitter compensate for the effect of the electrostatic field on the main beam and increase the deflection of the split beam to a total of 6 mrad.

Downstream the EHT splitter a septum magnet (ABS) separates the main beam and the TATTOOS beam into individual beamlines. The first section of the TATTOOS beamline is common with the UCN beamline. At the next dipole magnet (ABT) the UCN and TATTOOS beamline are separated. Both magnets ABS and ABT bend by 6.5 degrees for a combined 13 degree bend. Further downstream, an additional dipole magnet (ADD) will bend the beam a further 32 degrees for a total of 45 degrees towards the TATTOOS beamline. Finally, a quadrupole triplet will be used to shape the beam on target. To distribute the beam more uniformly on the target, the beam will be wobbled in two dimensions. A complete description of the beamline is given in Refs. [2, 5].

The beam is delivered towards a target containing a high atomic-number element, initially tantalum. The high-energy nuclear reaction (spallation) occurs, the radioisotopes are produced, and the beam energy is degraded from an initial 590 MeV to roughly 300 MeV. The remainder of the beam goes to the beam dump. The target operates in vacuum in a high but narrow temperature range, high enough to achieve good radionuclide release efficiencies, but below the material melting point. The operational temperature close to the melting point puts strong constraints on the machine protection system to protect the target from overheating. The target is described in more detail in [2, 14].

Operation

Since the first part of the beamline is shared with UCN, TATTOOS cannot be operated whenever a beam pulse is being delivered to UCN. In order to switch from TATTOOS to UCN operation, it is necessary to retract the splitter from the beam, while the ABT dipole magnet will change its polarity to bend the beam from the TATTOOS to the UCN beamline. Once this is done the kicker will be activated for the usual UCN operation. After that the ABT's polarity is changed back, and the splitter is moved into the beam.

Diagnostics

The TATTOOS beamline has the following diagnostic elements relevant for the MPS:

- Two beam current monitors, one relative RF resonator [15] and one absolute Bergoz monitor [16]. The absolute measurement is used to calibrate the relative monitor, which provides a faster measurement.
- Beam loss monitors, distributed along the beamline in the vicinity of the beam pipe. Air-filled ionization chambers will be used, sensitive enough to detect beam losses in the sub-nA level [17, 18].
- A harp for each plane before the target chamber measures both the beam profile and the position in a continuous manner.
- A four segment aperture foil in front of and after the target. The collimator and beamdump will be equipped at the front with four segments of thin-sheet metal (100 µm nickel) that provide beam halo measurements in four directions. Aperture foils are in use for several collimators and beam dumps in HIPA.

In all cases, signal evaluation is done in the diagnostics electronics. Interlock requests to the MPS are generated according to implemented rules. The new loss monitor electronics under development will allow a broader variety of tailored algorithms.

Machine Protection System

The philosophy of the TATTOOS MPS will not differ substantially from the one already implemented at HIPA. The MPS should prevent material damage and operational interruptions, and also excessive activation of accelerator components. The HIPA MPS is an extensive system that processes thousands of signals that represent the status of single elements, both active elements like magnets and HF systems, and passive elements like collimators and ionization chambers. These signals are evaluated and, if outside of the acceptable range, the beam is turned off within a few milliseconds. It is essential that this time is being kept to an absolute minimum to reduce the chances of damage.

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Most important for TATTOOS is to prevent target damage. The target can be overheated or harmed in case the beam is off-centered, over-focused or too much current is peeled off by the splitter. Such beam properties must be detected fast enough. Also the TATTOOS beamline components as, e.g., the collimators, can be damaged or overly activated by accidental beam loss, caused by an off- axis or broad beam or misplaced components. Large beam loss must be detected, while lower beam losses can be tolerated temporarily, but the beam has to be switched off after some time to limit the dose for service personnel.

The target protection will be achieved by:

- The four-segment aperture foil in front of the collimator will detect if the beam is off-centered or has an asymmetry. This system will also be able to detect if the beam is over-focused by comparing the beam current to the expected halo.
- Until the MPS responds, the collimator in front of the target will act as a shielding for the target in case the beam is off-center.
- The harps measurement before the target will provide the measurement for the beam trajectory feedback to keep the beam position stable Beam width and center position will be evaluated and compared to expected values. An interlock signal is generated if needed.
- The beam current monitors will provide a fast measurement that will trigger the interlock system if too much current is peeled off by the splitter.

To protect the TATTOOS beamline components from being destroyed in case the beam window breaks during target exchange, a valve between the target and the harps will close and protect the beamline from a possible shockwave.

With a 5 kHz measurement frequency the harps could resolve the beam rotation generated by the wobbler, currently foreseen at 30 Hz. However, for the MPS there is no specific need to resolve the beam rotation generated by the wobbler. Since the rotation will have a time scale that the target does not react to, it is sufficient to measure the average beam profile and position.

The protection of the beamline itself is less stringent. The BPMs and the beam trajectory feedback system will keep the beam position stable within 0.2 mm and will transport the beam with low losses to the target. In addition, the beam loss monitors will provide a fast and sensitive measurement that is connected to the MPS, in case losses occur. These measures will also prevent activation of the beamline area. In addition, each power supply will be connected to the MPS, as is already currently the case in HIPA.

The thin strips of the splitter will break in case of too much power is deposited on it. For TATTOOS, the beam optics will be adapted to ensure a large beam size in both planes at the splitter location to reduce the power deposit. Even with this enlarged beam, according to simulations the 100 µA is close to the ~20 W limit of what the strips can handle. To avoid a large power deposit the energy deposit on the first few strips is monitored by measuring the current through the strip. In addition, the beam current monitor will guard the maximum amount of split beam.

To ensure the correct operational procedure from switching between splitter operation for TATTOOS and kicker operation for UCN, the logic in the interlock system needs to be rigorously implemented:

- There should be no beam while the ABT dipole magnet is ramping, meaning that the kicker is disabled and the splitter is in park position.
- There should be no UCN kick to TATTOOS, meaning that the kicker is disabled when ABT bends towards TATTOOS.
- There should be no split beam to UCN, meaning that the splitter is in park position when ABT bends towards UCN.
- To ensure the correct ABT polarity short UCN test pulses are sent before the 8 seconds long UCN kick, and the split beam is slowly ramped up.

Emergency Scenarios

The following emergency scenarios and protective measures are considered:

- In case one of the splitter strips, typically the one in front, breaks due to overheating or mechanical wear, the two ends of the strip will be pulled out by the tensioning system. The splitter can still function correctly by increasing the applied voltage slightly.
- If so many strips break that the splitter voltage cannot be increased anymore, the splitter will need to be exchanged with the available spare splitter, and the broken strips can be replaced. After about 8 broken strips the splitter needs to be exchanged.
- If the movement mechanism of the splitter fails, the motor repair or exchange can be done with an exchange flask.
- In case the wobbler system is not functioning, the beam shape can be widened by the quadrupoles and the target can be radiated with a reduced current.
- Almost all diagnostic devices have a redundant partner system and it is expected that with operational experience the breakdown of a single diagnostic sensor will not cause downtime.

CONCLUSION

The operation and the machine protection system of the proposed TATTOOS beamline have been described. Although the beam power of 26 kW is relatively small compared to the rest of HIPA, TATTOOS has a few pecularities, which must be considered. Special attention to the electrostatical beam splitter to split off an unprecedented 100 µA beam, the operational switching between the UCN and TATTOOS beamlines and the target has been given, and the diagnostic devices that will be used to ensure their safe operation have been outlined. The most important emergency scenarios have been mentioned and protective measures are taken.

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