# BEAM PERFORMANCE REACH AT THE CERN PSB FOR THE ISOLDE FACILITY

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*Abstract*

The Proton Synchrotron Booster (PSB) at CERN is the first synchrotron of the proton accelerator chain and provides beam not only to the LHC and the rest of the injector complex, but also directly serves ISOLDE. This facility is one of the most demanding users in terms of beam intensity, receiving more than 60% of the overall protons produced at CERN. To further optimise beam delivery while accommodating new beam users at CERN, systematic studies are conducted to identify the performance reach. Current efforts focus on maximizing the achievable intensity in the PSB and assessing the impact on the isotope production at the facility.

## INTRODUCTION

The Isotope Separator OnLine Detector (ISOLDE) is a radioactive ion beam facility at CERN, exploiting GeV energy protons to access the full range of production mechanisms, spallation, fission, and fragmentation, for the creation of exotic nuclei [?]. The facility is hosting up to 60 experiments per year across a broad physics programme spanning nuclear structure, nuclear astrophysics, fundamental interactions, condensed-matter physics, and medical applications. Consequently, ISOLDE places unique and growing demands on the CERN accelerator complex and in particular on the Proton Synchrotron Booster (PSB).

Protons for ISOLDE are delivered by the PSB, the first synchrotron in the CERN injector chain, currently operating at 1.4 GeV and providing intensities of $3.2 \times 10^{13}$ protons per pulse (ppp), i.e. $0.8 \times 10^{13}$ protons per ring (ppr) in each of the four rings of the PSB. The average beam current delivered to ISOLDE, and consequently the protons on target (PoT), depends on the intensity per pulse and the number of pulses that PSB can allocate to ISOLDE, while serving the other users of the complex, such as LHC or any of the fixed target experiments. The beam delivery is organized using a supercycle, which is essentially a sequence of beam users linked in all accelerators that define the facilities that are served. During Run 3 (operations from 2021 to 2026), typical operation at 40% occupancy of the supercycle yielded average currents of 1.6 µA to 2.0 µA to ISOLDE.

The beam allocation at CERN, however, is set to face new challenges in Run 4 (operations from 2028 to 2033) with the introduction of the new Beam Dump Facility dedicated to the Search for Hidden Particles (BDF/SHiP) experiment at the Super Proton Synchrotron (SPS) [?]. In particular, dedicated beam sharing studies conducted in recent years have shown that accommodating SHiP in the supercycle substantially increases SPS demands, thereby reducing the number of slots available to upstream users, including ISOLDE [?]. Depending on the specific supercycle configuration and the proton flux requirements of other facilities such as EAST, n_TOF, and AD, ISOLDE's share of PSB pulses could drop from ~47% to as low as 30-35%, leading to a potential PoT reduction of up to 15-20% relative to Run 3, in the absence of any mitigation measures. One such measure would be an increase in the number of protons delivered per PSB pulse to ISOLDE, partially compensating for the reduced slot occupancy.

In parallel, the ISOLDE improvement programme is preparing a set of infrastructure upgrades during the Long Shutdown 3 (LS3), from 2026 to 2028 for ISOLDE, to extend the facility's capabilities [1]. These include an upgrade of the PSB to ISOLDE transfer line to transport protons at up to 2.0 GeV [2] together with the replacement of beam dumps, ventilation upgrades, and improvements to low-energy beam delivery systems. These upgrades open up the facility to a new regime of exploitation due to the higher beam energy and the option of higher intensities reaching up to 6 µA.

In this context and in order to assess the performance reach and propose suggestions for further improvements, the Injectors Performance for Fixed Target (IP-FiT) study was launched in 2025 [3]. Under the IP-FiT study, the systematic studies of the achievable PSB intensity for ISOLDE are coordinated, serving both as a mitigation strategy for reduced slot availability during BDF/SHiP operation and as input to long-term design choices for the ISOLDE infrastructure. The present contribution reports on the performance reach of the PSB for ISOLDE beam delivery and the implications for isotope production at the facility.

## PSB INTENSITY REACH

To assess the intensity reach of the PSB in the LIU era [4, 5], dedicated studies for the ISOLDE user have been conducted since the PSB restart in 2021. In particular, intensities up to $1.6 \times 10^{13}$ ppr at 1.4 GeV have been demonstrated during dedicated Machine Development (MD) studies at the end of 2023 [6]. Furthermore, higher intensities up to $1.7 \times 10^{13}$ ppr at 1.4 GeV were achieved in 2024 [7]. Finally, the highest intensities were reached in 2025, exceeding $1.8 \times 10^{13}$ ppr and $1.45 \times 10^{13}$ ppr at 1.4 GeV and 2 GeV respectively, as shown in Fig. 1. Note that the reduced inten-

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sities achieved at 2 GeV beam energy is caused by the higher DC current demand on the FineMet RF cavity amplifiers.

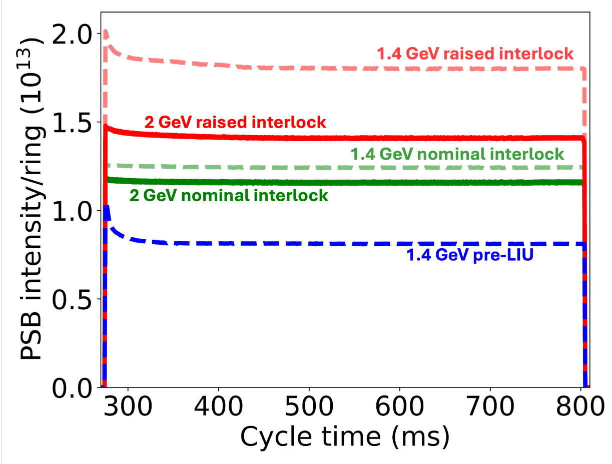


Figure 1: PSB demonstrated intensities in a single ring for 2 GeV (solid lines) and 1.4 GeV (dashed lines) for different settings of the interlock thresholds on the maximum current provided by the amplifiers of the FineMet RF cavities.

Pushing towards these intensities can only be possible by careful tuning of the full parameters in the PSB, like the $H^-$ injection system, optimization of the tune evolution along the cycle, resonance compensation as well as employing a triple harmonic capture [9]. These MD studies have also revealed a number of constraints that can limit the operational intensities, like losses in the machine due to limitations of the resonance compensation at high energy [10], losses at the transfer line due to the larger beam size, and instabilities [8]. However the main constraint is the aforementioned high DC current demand on the RF system. The interlock thresholds on the maximum current that can be provided by the amplifiers of the FineMet RF cavities required adjustment to sustain high intensity beam conditions. Figure 1 showcases the impact of the increased interlock thresholds on the intensity. Namely, the intensities of $1.8 \times 10^{13}$ ppr and $1.4 \times 10^{13}$ ppr at 1.4 GeV and 2 GeV, respectively can only be achieved with increased interlocks that imply reduced margins in the PSB RF system redundancy, and a potential degradation of machine availability. The safe intensities for current operations in the PSB were identified as $1.25 \times 10^{13}$ ppr and $1.1 \times 10^{13}$ ppr at 1.4 GeV and 2 GeV, respectively. Efforts are ongoing to better understand these limitations and fully characterise the RF operational conditions for higher intensities. Measurements have shown that a faster acceleration ramp can reduce the DC current requirement on the FineMet amplifiers, thereby providing additional margin within the existing interlock settings.

A key milestone of the ongoing MD programme is the demonstration of $5 \times 10^{13}$ ppp delivered to ISOLDE under fully operational conditions with transmission exceeding 99%. This represents a significant step beyond the nominal operational intensity of $3.2 \times 10^{13}$ ppp and establishes a new benchmark for the facility. The $5 \times 10^{13}$ ppp were delivered to ISOLDE for measurements concerning the target yield. In particular, two different configurations were prepared as shown in Fig. 2. In the nominal configuration, the increased intensity results in larger emittances due to space charge effects, while a variant with constant emittances was prepared using the $H^-$ injection system to blow up the beam at low intensities. The constant emittance configuration was used to study the target yield independently of the beam size variation.

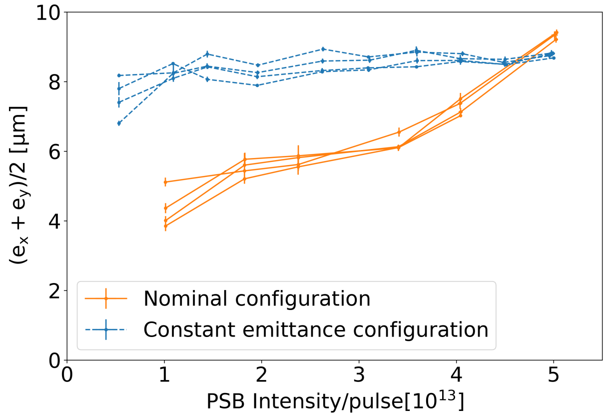


Figure 2: PSB brightness for intensities delivered to ISOLDE, up to $5 \times 10^{13}$ ppp at 1.4 GeV. Brightness curve (emittance vs. intensity) in the 4 PSB rings for the nominal configuration (solid lines) and the constant emittance variant as prepared for target tests (dashed lines).

PSB operations to ISOLDE have already profited of the high intensity studies allowing nominal current delivery to the facility even with lower duty cycle. Furthermore, the facility was able to conduct three higher current runs at the end of 2025 with intensities up to $4 \times 10^{13}$ ppp [11].

## PSB TO ISOLDE TRANSFER

To support the operational delivery of maximum target yield, an online optimiser has been developed for the PSB-to-ISOLDE transfer line. The optimiser is built within *Geoff* [12], a Python framework for accelerator optimisation that integrates with the CERN controls infrastructure. Its goal is to maximise the isotope yield at the ISOLDE tape station by autonomously tuning the proton beam position and size on the target. To this end, the optimiser acts on the dipole correctors and quadrupole magnets in the final section of the transfer line. Brightness constraints required for target protection will also be included.

The single-objective optimisation problem is formulated as the minimisation of the negative tape-station count, using the BOBYQA (Bound Optimization BY Quadratic Approximation) derivative-free algorithm [13–15]. The observables include the tape-station count, beam sizes from upstream profile monitors, and the beam current transformer readings.

The initial beam tests of the optimisation tool were conducted in 2025 with reduced intensity ($100 \times 10^{10}$ ppp) to ensure target safety, since beam-size constraints were not yet implemented. The aim of the tests was to demonstrate that the machinery functions correctly and is capable of recovering optimal beam delivery conditions from sub-optimal starting points in a small number of iterations. Furthermore, they allowed identifying missing features that will be included in future developments, such as incorporating beam-size constraints to allow safe operation at full intensity and evaluating alternative algorithms. The full functionality of the tool can only be explored after the completion of the ISOLDE improvement programme in Run 4.

## CHARACTERISATION OF TARGET ISOTOPE YIELD

The isotope yield at ISOLDE is a function of the delivered proton intensity. The intensity at the target is governed by:

$$I_{\text{ion}} = \sigma \cdot j \cdot N_t \cdot \varepsilon = \text{Yield}\,[\mu\text{C}^{-1}] \cdot I_p, \quad (1)$$

where $\sigma$ is the nuclear cross section, $j$ the proton flux at the target, $N_t$ the number of exposed target atoms, $\varepsilon$ the overall efficiency, and $I_p$ the average proton current. The yield depends on the spatial distribution of the proton beam on the target material, which is in turn a function of the beam optics in the transfer line. Hence, maximising production requires optimising both the delivered intensity and the proton beam position and size on the target, while respecting brightness constraints.

A systematic campaign of MD studies has been carried out to characterise the dependence of isotope yield on proton intensity, covering the range from $50 \times 10^{10}$ ppp to $5 \times 10^{13}$ ppp and the two distinct beam production scenarios in Fig. 2. The isotope yields are measured using the ISOLDE fast tape station via the $^{26}$Na release curve, which records the decay of the radioactive ion beam as a function of time after each proton impact, as shown in Fig. 3.

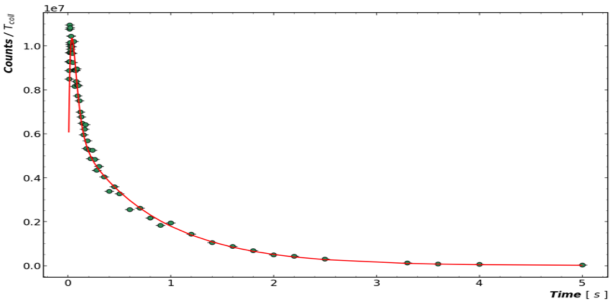


Figure 3: $^{26}$Na release curve used to measure the isotope yields.

Early measurements in 2022 showed a declining relative yield with increasing intensity, suggesting that the proton beam size at the target was exceeding the physical container aperture. The recommended beam size constraint of $\sigma_{x,y} \leq 3.5$ mm at the target was identified as a key boundary condition, and it was noted that simply compensating a larger beam with higher intensity is not an acceptable strategy [16].

The 2025 measurement campaign addressed this assumption with an improved programme, measuring yields for the full intensity range, separately for the nominal (increasing emittance) and constant-emittance beam variants. The measurements, shown in Fig. 4, exhibit a decreasing trend at high intensities for the nominal configuration consistent with the previous hypothesis of the proton beam exceeding the target container aperture. An improvement was observed when operating at constant emittance, highlighting the need to fully control the beam size on the target. In that respect, studies will continue in Run 4, including intensity measurements as part of commissioning and a systematic mapping and monitoring of the beam size at the target.

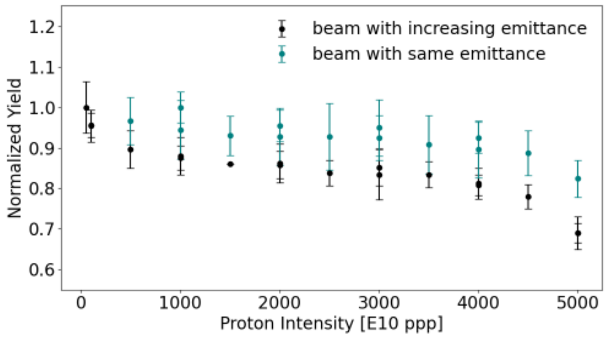


Figure 4: Normalized isotope yield versus delivered intensity with the nominal (black) and constant emittance (cyan) variants.

## CONCLUSION

The PSB intensity reach for the ISOLDE facility is being explored within the IP-FiT study, in view of the new beam users that will be introduced at CERN in Run 4. Ongoing studies have demonstrated that $5 \times 10^{13}$ ppp can be delivered to ISOLDE under operational conditions at 1.4 GeV, with MD beams reaching intensities of $1.8 \times 10^{13}$ ppr at 1.4 GeV and $1.4 \times 10^{13}$ ppr at 2 GeV. The operational intensity is currently kept at lower values due to the FineMet cavity amplifier constraints, as well as the current facility limitations to accept higher intensities. On the target side, high-intensity studies on the relative isotope target yield have been conducted. The studies show that the relative yield can decrease at higher intensities, possibly linked to larger beam size reaching the limits of the target container aperture. Hence, an online optimisation framework for the PSB-to-ISOLDE transfer line is under development to provide better control of the beam size on the target. The studies form an integrated programme that aims to maximise the scientific output of ISOLDE in Run 4, combining PSB performance studies, target response characterisation, and online optimisation tools into a coherent strategy for high-intensity operation.

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