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UPGRADE OF THE PS BOOSTER-TO-ISOLDE BEAM TRANSFER LINE TO FACILITATE AN INCREASE IN PROTON DRIVER ENERGY

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Abstract

Following the successful completion of the LHC Injectors Upgrade (LIU) project, since 2021 the Proton Synchrotron (PS) Booster has served the LHC injector chain with protons at an increased kinetic energy of 2 GeV. An upgrade of the ISOLDE (Isotope Separator On-Line DEvice) facility has long been considered to produce radioactive ion beams with a higher energy proton driver beam. A Consolidation and Improvements programme is presently underway to maintain ISOLDE's position as a world-leading ISOL facility in the decades to come, with activities planned during the upcoming Long Shutdown 3 (LS3) (2026 - 28) and beyond. This contribution details a study to upgrade the beam line from the PS Booster to ISOLDE to operate between 1.4 and 2 GeV, and to increase the power of the proton driver in the future, assuming the replacement of the two beam dumps behind the facility's production targets.

ISOLDE CONSOLIDATION & IMPROVEMENTS PROGRAMME

The ISOLDE radioactive ion beam facility has a long history at CERN since it started operation in 1967 at the Synchro-Cyclotron. It has been continuously evolving to maintain its present-day position at the forefront of radioactive beam science. Today, more than 30 years after its move to the PS Booster, its proton driver beam energy of 1.4 GeV makes it a unique facility worldwide. It serves a large variety of beams to a community of over 1000 users from more than 45 countries, receiving annually some 500 - 600 visitors carrying out a rich and diverse scientific programme by undertaking 45 - 55 experiments per year using approximately 15 different instruments. Consolidation is underway to maintain the reliability of the facility, with the Consolidation and Improvements programme exploiting the opportunity to enhance the performance of the facility. It has identified several problems, limitations and risks for systems that are reaching obsolescence and has identified opportunities where consolidation today can improve performance in the future [1].

BEAM POWER LIMITATIONS

Presently, the facility is operated below an average beam current limit of 2 μA at 1.4 GeV (2.8 kW) to respect the integrity of the beam dump systems and radiation protection limits. The beam dumps behind the two target front-ends are presently operating at their limits in terms of temperature and mechanical stresses and are a critical part of the Consolidation and Improvement programme. The ISOLDE Beam Dump Replacement (IBDR) Study has prepared a proposal [2], which, if approved, will replace the dumps during LS3 with a safe and reliable solution that complies with CERN's Host State regulations as a starting block for a future increase in proton driver beam power already available from the PS Booster after the successful completion of the LIU project [3].

PROTON DRIVER ENERGY UPGRADE

An upgrade of the energy of the proton beam driving radioactive beam production at ISOLDE was given strong endorsement by the INTC [4] and the most recent NuPECC Long Range Plan [5] also identified and supported the upgrade to 2 GeV. The past assertions that increasing the beam

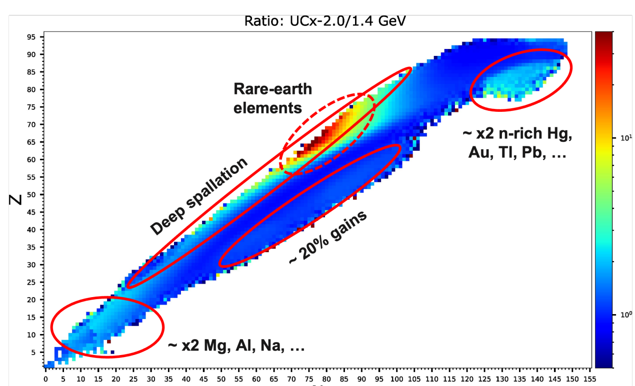

Figure 1: FLUKA simulations of the relative production yield at 2 GeV to 1.4 GeV on a UCx target [8].

energy to 2 GeV would increase the yield of fission fragments by a factor of ~ 1.4 on average, of fragmentation products by a factor $\sim 2-6$, and for exotic spallation products by $\gtrsim 6$, were recently validated using FLUKA v4-2.2 [6, 7], as shown in Fig. 1. The relative yield calculations were successfully benchmarked with an experimental measurement campaign at an increased proton beam energy of 1.7 GeV, which was carried out by operating the existing beam transfer line magnets from the PS Booster to ISOLDE at their limit [8]. Although the PS Booster and its transfer lines are capable of delivering protons at up to 1.7 GeV today, such

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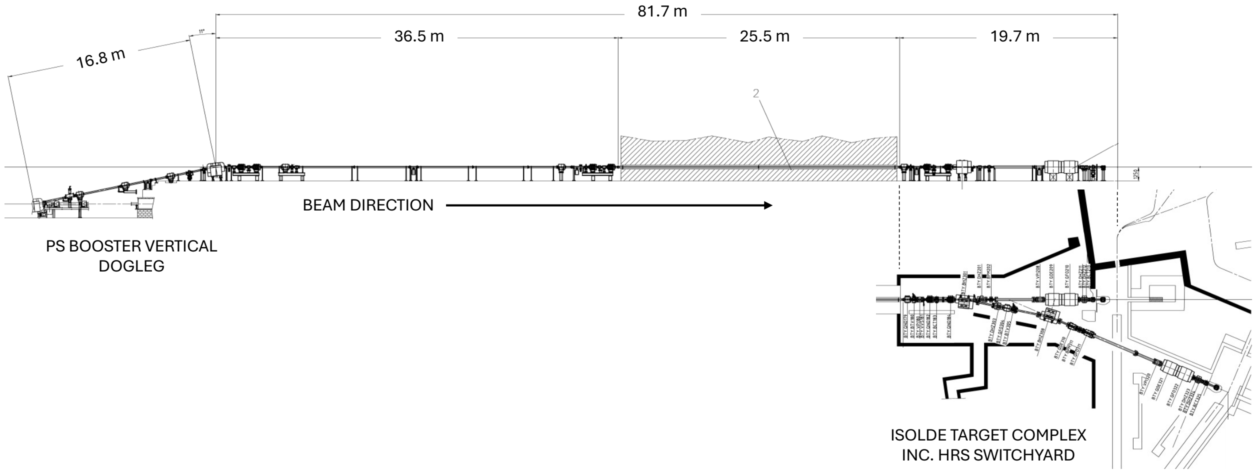

Figure 2: BTY transfer line: starting with the vertical dogleg from the PS Booster level and rising above the beam dump, before a transfer section to ISOLDE and the horizontal switch from the GPS to HRS front-end target stations.

scenarios are not operational and are used only occasionally within the prescribed limits of the beam dumps to study the change in production yields.

The increase in yield will allow some experiments to be performed quicker, whilst allowing others to collect higher statistics for more detailed or precise spectroscopy. Where enhancements are larger, the capability of the facility will be increased by allowing measurements on new isotopes. Whilst the yields of nuclei far from stability are improved, the yields of other isotopes closer to stability of interest for condensed matter, biological and medical experiments may decrease. Therefore, the possibility of delivering 1.4 GeV protons will be retained in order to support a broad science programme.

BEAM TRANSFER TO ISOLDE

The transfer line connecting the PS Booster with ISOLDE was designed for the 1 GeV protons available at the time of its construction. It is composed of magnets recuperated from the former Intersecting Storage Rings (ISR) and their transfer lines. The transfer line, named BTY, switches and translates the beam vertically upwards in a dogleg before transferring it about 60 m to the ISOLDE facility where it is switched horizontally between the two production targets serving the General Purpose Separator (GPS) and High Resolution Separator (HRS), as shown in Fig. 2. Today, the transfer line is operated at 1.4 GeV and is limited to a kinetic energy of 1.7 GeV by the ISR HB4 dipole magnets [9] that compose the dogleg and switch to the targets. The feasibility of upgrading the BTY transfer line to transport a 2 GeV proton beam was investigated over 10 years ago [10, 11] under the assumptions that the transfer line geometry and optics remains the same. It is planned to ensure all future magnets on the transfer line are laminated to give the option in the future to change the optics and energy to the different target stations via pulse-by-pulse modulation (PPM) operation. Recently, the upgrade effort was revived after the IBDR Study indicated the possibility of replacing the beam dumps during LS3.

Beam Parameters

The assumed beam parameters used for the design work of the transfer line upgrade can be found in Table 1 and are consistent with those used for the IBDR Study [12]. The present emittance is achieved today for an intensity of $\sim 8 \times 10^{12}$ protons per ring at a kinetic energy of 1.4 GeV at extraction from the PS Booster and up to a total intensity of $\sim 3.2 \times 10^{13}$ protons.

Table 1: Beam Parameters at PS Booster Extraction Assumed for the Upgrade of the BTY Transfer Line

Kinetic Energy [GeV]	ϵ_x / ϵ_y (rms, norm.) [mm mrad]	ϵ_z (matched area) [eV s]	$\Delta p/p$ (rms) $\left[10^{-3}\right]$
2.0	9 / 6	2.1	1.1
1.4	9 / 6	1.8	1.1

Recent studies exploiting LIU upgrades have been able to push the maximum cycle intensity even higher in the PS Booster and well above 1.0×10^{13} protons extracted per ring [13]. The maximum cycle intensity that will be available for ISOLDE in the future will depend on the brightness of the extracted beam, the population of the tails and the resulting beam loss on the tight aperture restrictions present in the kickers and septa of the PS Booster's recombination line, which cause induced radioactivation of the machine. The vertical aperture between the beam and the blades of the recombination septa is only $\sim 2.5\sigma_y$ with $\epsilon_y = 6$ mm mrad, including dispersion and assuming a Gaussian beam distribution [14].

Improved Operational Flexibility

With the need for improved operational flexibility, the transfer functions of the BTY transfer line magnets were

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implemented into the LHC Software Architecture (LSA) control system, as has become standard nowadays at CERN. The optics applied in the transfer line can now be versioned, updated using a MADX optics model, the trajectory steered using the model and the beam rigidity scaled automatically.

Transfer Line Magnets

Vertical Dogleg Dipoles Designing and producing new dipole magnets would have required longer yokes to avoid operating in a saturated region. Instead, it was decided to modify the geometry of the achromatic vertical dogleg to allow the continued use of the existing HB4 dipole magnets at up to 2 GeV. The dipoles were spaced further apart and their bending angle reduced by 1.3 deg to allow 2 GeV operation at a maximum integrated dipole field strength of 1.645 Tm. Magnetic measurements were recently carried out to understand the effect at the increased excitation current, showing an acceptable degradation of about 10 units of 10^{-4} of the main field at a reference radius of 27 mm [15]. Spare coils will be produced for the dipoles to safeguard future operation of the old magnets. The optics was rematched to fit the beam size in the tight 80 mm horizontal gap of the dipoles using the existing quadupoles placed symmetrically inside the stretched achromat. The horizontal aperture restriction of the transfer line remains upstream in the recombination kickers of the transfer line where the bunches from the different PS Booster rings are vertically combined onto the same trajectory. The vertical beam size is kept small in the dipoles to avoid the relatively large degradation in field quality as the magnet is pushed into saturation.

The integration of the modified geometry is relatively simple without significant impact on the transfer line used for measurements and diagnostics located underneath the BTY line. Only minor civil engineering modifications are needed to allow the beam line to pass into the transfer tunnel via the partial demolition of a non-load bearing wall, along with modifications to the beam line infrastructure such as the location of the magnet supports, vacuum chambers, careful transport and handling in the confined space of the transfer tunnel, alignment and zone sectorisation, including fire safety doors.

HRS Switchyard Dipoles For the switch to the High Resolution Separator target station, two small dipoles with an integrated field of up to 0.25 Tm were added symmetrically about the centre of the achromatic bend to correct for the missing strength of the HB4 dipoles and respect the geometry of the existing front-ends and beam dumps. The modifications required moving the quadrupole at the symmetry point of the achromat outwards by ~ 80 mm. The perturbation to the optics of this modification is negligible.

Transfer Line Quadrupoles The optics solution at 2 GeV is compatible with the ratings of the existing transfer line quadrupole magnets (Q130 [16]), which are laminated and can be operated up to 300 A in pulsed mode with a pulse length of 100 ms. Magnetic measurement have been carried out recently to validate that stable operation is possible in pulsed operation [17].

Final Focus Quadrupoles The final focus before each production target consists of two quadrupoles (Q100 [18]) that have a large aperture of 200 mm diameter to focus the beam down into a tight focus as small as ~ 1 mm to maximise the radioactive beam yield. It was decided to upgrade these magnets and laminate them to allow pulsed operation. A magnet design being developed for the Antimatter Decelerator target zone will be adapted with a modified pole profile and an aperture diameter of 196 mm.

Corrector Dipoles The last corrector magnets are used to steer the beam on target and push the beam onto a neutron converter placed below the target, if requested. These correctors will need upgrading with the 2 GeV upgrade.

Power Converters

The BTY power converters will be consolidated in LS3 as they reach their end of life and replaced with technology used in all of the CERN injector complex transfer lines. Extra budget has been made available to guarantee that the new powering solution is also compatible with the 2 GeV upgrade proposal, capable of energy recovery operation for energy economy and PPM operation [19].

Beam Stopper

The beam stopper that acts as part of the safety system when downstream areas are in access is also undergoing consolidation and will be replaced with a device compatible with 2 GeV beams. It will be removed from the vertical dogleg and replaced by new standard PS complex beam stoppers of modular design after the dogleg [20].

BEAM TESTS AT 1.7 GEV

To validate the operation of the HB4 dipoles at higher current, as well as to collect data for energy dependence of the production yield a 1.7 GeV test campaign was carried out in 2022. To circumvent limits on the old power converters for a couple of quadrupoles in the transfer line at the higher beam energy the optics needed slightly rematching. The tests showed no issues with transmission or beam spot size at the production target stations and radioactive beam production yields could be measured at 1.7 GeV [8].

TIMELINE & OUTLOOK

A costed and integrated solution for the 2 GeV upgrade of the proton beam transfer from the PS Booster to ISOLDE has been prepared and submitted for approval for implementation in LS3 at CERN. The hope is that after LS3 the ISOLDE facility will be able to produce radioisotopes up to 2 GeV and start to increase the beam power on its production targets as the other necessary facility upgrades continue as part of the ISOLDE Consolidation and Improvements programme.

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REFERENCES

[1] S.J. Freeman *et al.*, "ISOLDE Consolidation and Improvements", CERN, Geneva, Switzerland, Letter of Intent, CERN-INTC-2023-028, Jan 2023. `https://cds.cern.ch/record/2846021`

[2] A-P. Bernardes *et al.*, "IBDRS Summary Report", CERN, Geneva Switzerland, Rep. EDMS#2875087, to be published.

[3] H. Damerau, M. Meddahi and G. Rumolo, "LHC Injectors Upgrade, Technical Design Report", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, 2014. `doi:10.17181/CERN.7NHR.6HGC`

[4] M. Borge, M. Kowalska and T. Stora, "Motivations to receive a 2 GeV proton beam at ISOLDE / HIE-ISOLDE: Impact on radioisotope beam availability and physics program", CERN, Geneva, Switzerland, Rep. CERN-INTC-2012-06, 2012. `https://cds.cern.ch/record/1482729`

[5] NuPECC Long Range Plan 2017: Perspectives of Nuclear Physics, `https://www.nupecc.org/pub/lrp17/lrp2017.pdf`

[6] C. Ahdida *et al.*, "New Capabilities of the FLUKA Multi-Purpose Code", *Frontiers in Physics*, vol. 9, p. 788253, 2022. `doi:10.3389/fphy.2021.788253`

[7] G. Battistoni *et al.*, "Overview of the FLUKA code", *Annals of Nuclear Energy*, vol. 82, pp. 10-18, Aug. 2015. `doi:10.1016/j.anucene.2014.11.007`

[8] S. Stegemann, "Radioactive ion beam production yields using 1.4 and 1.7 GeV protons at CERN-ISOLDE", presented at the 19th International Conference on Electromagnetic Isotope Separators and Related Topics EMIS 2022, Daejeon, South Korea, 3 - 7 Oct 2022. `https://indico.ibs.re.kr/event/469/contributions/3670`

[9] B. de Raad *et al.*, "Specification for the bending magnets for the ISR beam transfer system", CERN, Geneva, Switzerland, Rep. I-5010-ISR EDMS#1100428, Nov 1967. `https://edms.cern.ch/document/1100428/1`

[10] D. Voulot *et al.*, "2 GeV upgrade of ISOLDE", CERN, Geneva, Switzerland, Rep. EDMS#1357395, Mar 2013. `https://edms.cern.ch/document/1357395/1`

[11] K. Hanke *et al.*, "A Possible Scheme to Deliver 2 GeV Beams from the CERN PS Booster to the ISOLDE Facility", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWO079, pp. 3942–3944.

[12] M.A. Fraser, J.M. Martin Ruiz, J. Vollaire, "Functional Specification for the ISOLDE Beam Dump Upgrade", CERN, Geneva, Switzerland, Rep. IBDRS-ES-0001 EDMS#2891725, May 2023. `https://edms.cern.ch/document/2908818`

[13] F. Asvesta *et al.*, "Pushing High Intensity and High Brightness Limits in the CERN PSB after the LIU Upgrades", in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, pp. 458–461. `doi:10.18429/JACoW-HB2023-THBP09`

[14] J. L. Abelleira, "Beam dynamics study on LIU high intensity beam in the BT line", CERN, Geneva, Switzerland, Rep. PSB-MSMI-EN-0001 EDMS#1537199, Nov 2015. `https://edms.cern.ch/document/1537199`

[15] R. Chritin and C. Petron, "Magnetic measurement results of the dipole PXMBXFBCWP-01000032", CERN, Geneva, Switzerland, Rep. EDMS#2908818, Jun 2023. `https://edms.cern.ch/document/2908818`

[16] P. Bossard *et al.*, "Technical specification for the supply of quadrupole magnets (type 130) for the beam transfer booster-isolde", CERN, Geneva, Switzerland, Rep. AT-MA/90-19 EDMS#1084379, Aug 1990. `https://edms.cern.ch/document/1084379/1`

[17] M. Liebsch and C. Petrone, "Magnetic measurement results of the Q130 quadrupole magnet", CERN, Geneva, Switzerland, Rep. EDMS#2909943, Mar 2024. `https://edms.cern.ch/document/2909943/2`

[18] M. Chassard, J. Delaprison, G. Granger, "Les aimants des zones experimentales du PS", CERN, Geneva, Switzerland, Rep. PS/EA/NOTE 87-11 EDMS#1103521, 19 Nov 1987. `https://edms.cern.ch/document/1103521/1`

[19] G. Le Godec *et al.*, "Sirius S and 2P Power Converters for Magnets of the PSB-BTY Transfer Line in the Framework of the Accelerator Consolidation Project", CERN, Geneva, Switzerland, Rep. PSB-RP-ES-0002 EDMS#2907443, Jul 2023. `https://edms.cern.ch/document/2907443/3.0`

[20] A. Pilan Zanon *et al.*, "Engineering and Design of the New PS Complex Beam Stopper", CERN, Geneva, Switzerland, Rep. EDMS#1979131, Oct 2018. `https://edms.cern.ch/document/1979131/0.01`