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SHAPING HIGH BRIGHTNESS AND FIXED TARGET BEAMS WITH THE CERN PSB CHARGE EXCHANGE INJECTION

C. Bracco*, S. Albright, F. Asvesta, G.P. Di Giovanni, F. Roncarolo, CERN, Geneva, Switzerland

Abstract

CERN adopted the charge exchange injection technique for the first time in the PS Booster after the Long Shutdown 2. This allowed to overcome space charge limitations, tailor high brightness beams for the LHC and deliver a high intensity flux of protons to fixed target experiments. Details about the concept, physics, hardware and diagnostic tools are presented while retracing the exciting steps of the successful commissioning period and the first years of operation with this system. A look to the future is taken by explaining the next stages to achieve the ambitious Luminosity targets foreseen for the HL-LHC era.

INTRODUCTION

One of the main upgrades implemented in the Large Hadron Collider (LHC) injectors during the Long Shutdown 2 (LS2) [1] was the replacement of a conventional multi-turn injection system with an H$^-$ charge exchange in the PS Booster (PSB). This, combined with an increase of energy at injection, allowed to overcome previous limitations in the achievable beam brightness and intensity due to both the very nature of the old injection system and to space charge phenomena. The first year after LS2 was dedicated to recommissioning the PSB and reestablishing pre-LS2 operational conditions. The following years were instead devoted to beam production and optimisation studies to finally reach the targeted brightness and intensity for the High Luminosity LHC (HL-LHC) [2] and experimental area (ISOLDE [3], nTOF, North Area, East area, etc.) beams respectively. The full process was impressively smooth and the performance reached by the produced beam, time- and quality-wise, was beyond expectations. In the following, the main highlights of the first years of operation of the new charge exchange injection system are described. Ways to further increase the stored intensity to maximize the flux of particles towards fixed target experiments are being investigated and the first promising results are mentioned.

THE NEW CHARGE EXCHANGE SYSTEM

Originally, 50 MeV protons were injected from Linac2 into the PSB by using a conventional multi-turn injection system. Four slow horizontal bumpers where used to move the closed orbit towards the injection septum that was used to merge the injected with the circulating beam. The injection bump amplitude was reduced at each turn to paint the beam and fill the horizontal phase space. The presence of the septum implied high losses (up to 30-40%) from the circulating beam hitting the septum blade, a limited number of injection turns (10-20 turns) and thus of the achievable stored intensity plus a linear increase of the emittance at each turn translating in a limited brightness.

* chiara.bracco@cern.ch

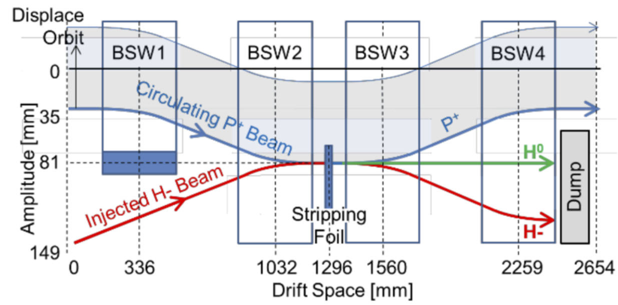

Figure 1: Schematic view of the new PSB H$^-$ charge exchange injection system

All these constraints could be overcome by modifying the injection region of each of the four superposed PSB rings to host an H$^-$ charge exchange system. This consists of four chicane dipoles (BSW1,2,3 and 4, Fig. 1) which move the closed orbit of the circulating beam by 46 mm towards the 160 MeV H$^-$ beam coming from Linac4. A thin Carbon stripping foil, located in the middle of the chicane, is used to strip the two electrons from the H$^-$ ions to convert them into protons which follow the PSB closed orbit. This allows to accumulate particles in the same phase space area and hence increase the charge density. Four horizontal kickers (KSW), installed in the ring lattice, are used to further move the closed orbit by 35 mm and for the transverse phase space painting. The painting, together with the higher injection energy with respect to pre-LS2 operation, mitigate space charge effects and allow to keep the emittance growth under control. Partially (H^0) and unstripped (H$^-$) ions are dismissed on a 70 mm thick Ti beam dump. A current monitor, installed in front of the dump, allows to measure the amount of H^0 an H$^-$ particles and thus the stripping efficiency of the foil. Charge exchange injection is a multi-turn process that can be performed over hundreds of turns and is characterized by very low losses. In the PSB up to 150 turns injections can be performed and losses can be kept at the order of a percent. Moreover, the controlled decay of the painting bump permits to tailor the beam emittance and make it suitable to the requirements of the different PSB users [4].

The Chicane

The BSWs are rectangular pulsed magnets, independently powered, which apply a kick of 66 mrad to the beam. BSW1 acts as a septum to divide the high-field region for the circulating beam from the field-free region for the

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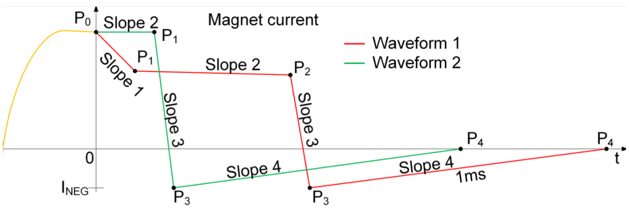

Figure 2: KSW current decay for the two mainly used types of waveforms.

injected beam. The H^0H^- dump and current monitor are integrated in BSW4. The magnets are water cooled and are installed around Inconel® corrugated chambers. The chicane amplitude stays constant for 150 µs (the longest injection time, being the PSB revolution time at injection 1 µs) and then decays to 0 mm in 5 ms. Quadrupolar field perturbations are generated in the vertical plane due to the strong edge focusing. Moreover, eddy currents induced in the metallic chambers during the decay of the field create sextupolar field components. Both effects translate in a vertical β-beating which can be corrected with k-modulation [5].

The Painting

The PSB provides a variety of beams satisfying the diverse needs and constaints of users in terms of intensity and emittance. LHC beam operation aims at keeping the transverse emittance ($\epsilon_{x,y}$) under control in order to reach the design peak luminosity at the experiments collision points while storing the required intensity. For fixed target experiments (e.g. ISOLDE) instead, the goal is to maximize the beam intensity and minimize the losses during the full machine cycle to keep them to a $\leq$10 % level. In this case, the constraints on the emittance are mainly driven by the need of fitting the beam in the available machine aperture ($\epsilon_x < 15$ µm, $\epsilon_x < 9$ µm). The painting process, together with an accurate choice of the working point along the full PSB cycle, allow to fulfill all these requirements. The painting bump is produced by the KSWs and six interposed quadrupoles installed outside the injection region of the four PSB rings. A multiple-linear waveform generator was developed to ensure the necessary high flexibility. The waveform amplitude, length and shape depend on the aimed final intensity and PSB ring optics, which vary between the users, as well as the uniformity and flatness of the pulse coming from Linac4 and on the steering of the injected beam at the injection point. Small differences between the rings require applying slightly modified waveforms even for the same user. For all these reasons, each magnet is independently powered to allow the fine tuning of the transverse painting and to homogenize the characteristics of the beam produced by the four rings.

Two main types of waveforms are used and are defined by determining amplitude and time at key points (P_0, P_1 and P_2 in Fig. 2). A flat waveform is applied for the LHC beams (Waveform 2). Different decay times in the current of the magnets is instead used for ISOLDE like beams (Waveform 1) and this allows to tailor the transverse shape of the beam and fit the aimed number of protons in an area that easily accommodates within the machine aperture. The number of injection turns depends on the requested final stored intensity and, in general, it corresponds to the length of the waveform flattop. The system is nevertheless designed to allow decoupling the actual number of injection turns and the KSW waveform duration. At the end of injection, a fast decay is applied to all waveforms to remove the circulating beam from the foil.

Table 1: Stripping foils

Foil #	Reference	Thickness [µg/cm^2]	Description
1-4	XCF-200	200	Amorphous C
2-5	GSI-200	200	Amorphous C
3-6	MLG-250	240	Graphene

The Stripping Foil System

Up to six stripping foils are attached to an exchange mechanism, consisting of a rotating stainless steel belt placed between the BSW magnets (see Fig. 3). Three different types of foils are installed, in pairs, in each ring (see Table 1). These are all Carbon-based foils, produced by different manufacturers, and their thickness was chosen in order to guarantee a $\geq$ 98 % stripping efficiency while minimizing emittance growth and losses induced by the scattering processes due to multiple-crossings of the circulating beam. The rotating mechanism allows to remotely change the operational foil when needed (e.g. in case of reduced stripping efficiency or foil breakage) and also to select a “no foil” position. Furthermore, a fine transverse adjustment of up to ±2 mm is possible. A BTV screen, installed right in front of the stripping foil, can be inserted and used to steer the injected beam onto a reference position. The BTV camera is also employed for an online monitoring of the status of the foil.

The H^0H^- monitor

The H^0H^- current monitor consists of four 1 mm-thick adjacent Ti plates (H0L, H0R, HML and HMR) installed in front of the dump as shown in Fig. 4. The signal from each plate is calibrated using Beam Current Transformers (BCT) installed in the injection lines and is independently acquired. This allows not only a continuous monitoring of the foil stripping efficiency but also, by comparing the signal from the different plates, to obtain a qualitative information about the injected beam position at the foil. In fact, when the stripped beam is centered, with respect to the expected reference (position 2 in Fig. 4), the currents measured from the H0L and H0R plates should be the same.

Higher currents measured on the HM rather than the H0 plates are instead indicative of a mis-steering of the injected beam corresponding to H^- ions missing the foil and being

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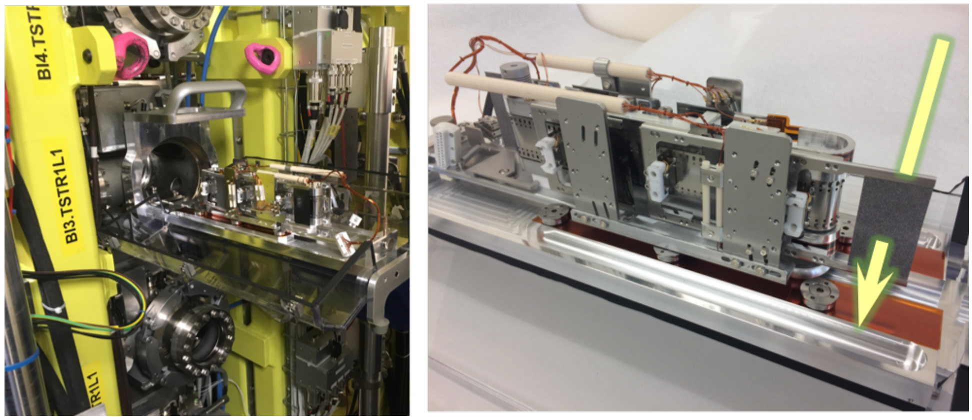

Figure 3: The stripping foil exchange mechanism, which is installed in the middle of the BSW chicane magnets, is shown.

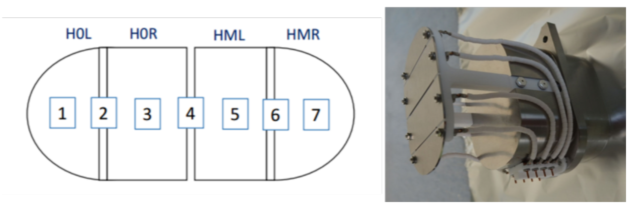

Figure 4: The H^0H^- monitor consists of four plates and is installed in front of the dump. The plates signal calibration is performed using a BCT at the end of the TL and moving the injected beam on the seven sketched positions.

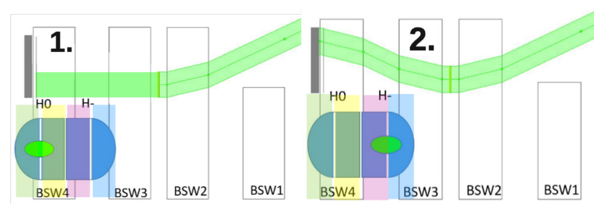

Figure 5: Schematic representation of the two steps for the horizontal angular alignment of the beam at the injection point.

directly dismissed. The H^0H^- current signals are connected to an interlock system that blocks the injection process in case of heavy degradation or breakage of the foil, which could damage the dumps.

FROM COMMISSIONING TO OPERATION

The PSB commissioning started in December 2020 and the first low intensity beam was captured and accelerated after only a few weeks. The production of all user-specified beams could be achieved according to the injectors schedule and with no major difficulties. At the end of 2021, pre-LS2 conditions were fully reestablished and the PSB performance is now constanlty improved through Machine Development (MD) studies. The full recommissioning after each winter stop takes now less than one week and all operational beams are put into operation and optimized in a few days.

The following sections discuss the initial beam setup, the challenges encountered, and the lessons learnt from 2020 until now regarding the injection system.

Steering and Injection Setup

The beam coming from Linac4 was steered through the transfer lines (TL) up to the four relative injection points. Two pairs of horizontal and vertical correctors, installed at the end of each line, were used for the orthogonal steering (i.e. the setup of the position and angle) of the injected beam at the stripping foils. The unstripped H^- beam ("no foil" position) was first centered at the reference point on the BTV and then the horizontal angle was adjusted by centering the beam at the H0 plates with the BSW3 and 4 magnets off (step 1 in Fig. 5). In theory, when powering all the BSWs at nominal current, the H^- beam should have been also centered at the HM plates (step 2 in Fig. 5 and position 6 in Fig. 4) but this was not the case.

Moreover, when inserting the stripping foil and thus injecting protons in the ring, a large horizontal orbit leakage (r.m.s = ±5.5 mm) was measured before the BSW decay. Calculations proved that the nominal current of BSW2,3 and 4 (3400 A) had to be reduced by 3 % and BSW1 current (6700 A) increased by 2.5 % for Ring1,3 and 4 and 3 % for Ring2 to minimize the orbit leakage. This change further allowed the correct centering of the H^- beam at the H0 and HM plates in both configurations with the magnets respectively turned off and on. The vertical position and angle could only be adjusted by minimizing injection oscillations, through orthogonal steering, with respect to the closed orbit established with all the bumps switched off. Despite the applied corrections and with the BSWs on, the vertical orbit of Ring2 was showing a leakage four times larger than the other rings. This behavior was compatible with a ~6 mrad roll angle of the magnets while an accuracy of 1-2 mrad was specified. Survey measurements confirmed that three magnets had an angle larger than 5 mrad and they were re-aligned at the following winter stop. The measurement of the roll angle from the vertical orbit leakage is now systematically used after any intervention on the BSWs to ensure that they are correctly aligned. Turn-by-

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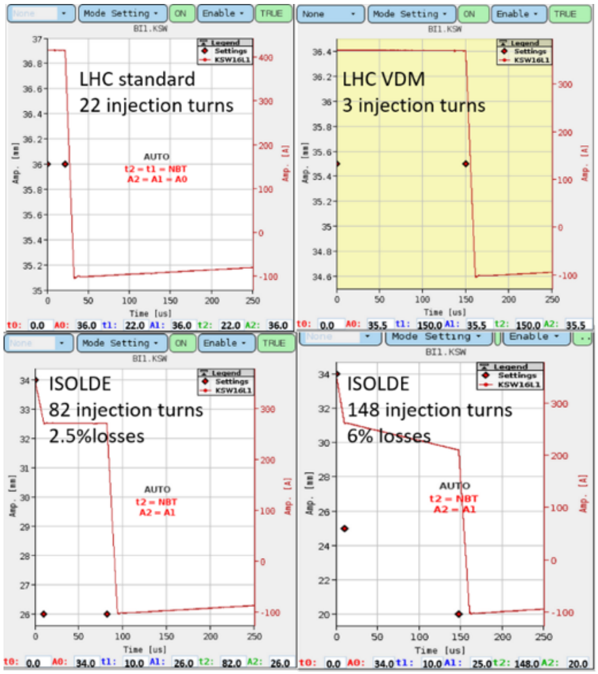

Figure 6: Ring3 KSW waveforms applied in operation for different PSB users. The dots represent the amplitude of the bump in mm (left y-axis) while the solid line corresponds to the KSW current (right y-axis).

turn orbit measurements permitted also to identify the wrong polarity of the internal KSWs in all rings. After all these corrections, the expected $\leq \pm 2$ mm closed orbit at injection was finally achieved.

Because of the tight scheduled for recommissioning after each winter break, not all steps performed during the initial beam commissioning are conducted. The injection setup is limited to the steering of the TLs to previously defined references, a preliminary centering of the beam on the BTV and then the minimisation of the injection oscillations while verifying that the current at the H^- monitor is lower than that at the H^0 monitor. The TL and orthogonal steering are then periodically performed to compensate for natural drifts, equalize the emittances in the four rings and rematch them to the requirements of the different users.

Injection Painting Setup and Optimisation

Theoretical KSW waveforms, as calculated through tracking simulations, were initially set up for the transverse painting. A fine tuning was then performed to obtain the target intensity and emittance while minimizing the losses. The initial amplitude (P_0 in Fig. 2) was adjusted to adapt to the applied working point and also to ensure that the full injected beam could cross the stripping foil when centered on the bumped closed orbit. Through orthogonal steering, offsets were applied in some cases to “paint” in the vertical plane as well. Figure 6 shows examples of the waveforms presently used for LHC standard, Van Der Meer (VDM) and

Table 2: Target and achieved beam parameters

	Target		Achieved	
	Intensity [10^{10} ppr]	$\epsilon_{x,y}$ [µm]	Intensity [10^{10} ppr]	$\epsilon_{x,y}$ [µm]
LHC	250	1.5-1.5	250	1.2-1.3
VDM	1	2.5-2.5	1	2.3-2.6
ISOLDE	800	10-6	800	10.5-7.2

ISOLDE beams production. Typically achieved parameters are presented in Table 2 and compared with target values.

For standard LHC beams, the brightness which is regularly obtained in operation is beyond specifications. This result is particularly promising in view of the production of the High Luminosity (HL-LHC) beams which require 40% higher intensities in <1.7 µm and which could be already successfully prepared during dedicated MD time. The possibility of decoupling number of injection turns and the KSW flattop duration is particularly useful for the production of the beams for VDM scans at the LHC experiments. The target transverse emittance is, in fact, particularly large for such low intensity beams, and it is reached by keeping the KSW flattop up to 150 µs even if the full beam is injected in only three turns. Beam particles are scattered by interaction with the stripping foil and the emittance is slightly blown up at every turn. This procedure allows to reach an emittance which closely approximates the design values in both the horizontal and vertical plane.

The same intensity achieved before LS2, losing 30-40 % of the beam at injection, can now be systematically reached for ISOLDE beams while keeping the losses at ~2.5 % over the full cycle up to the end of the acceleration process. Moreover, MDs were performed to assess the intensity that can be stored by injecting over 148 turns (a safety margin was kept with respect to the maximum length of the KSW waveform). In this case, the beam was also painted longitudinally by varying the energy of the Linac4 bunches to optimize the filling of the PSB RF bucket [6]. Studies performed using a derivative-free optimization algorithm demonstrated that losses could be further reduced by increasing the gradient of Slope2 [7]. This outcome was experimentally confirmed and the unprecedented intensity of 1.25×10^{13} protons per ring (ppr) was accelerated maintaining losses at ~6 % in all rings. Further optimization is still possible, and the ultimate desirable intensity reach of 1.6×10^{13} ppr can be envisaged.

Stripping Foils Performance

All foil types installed in the PSB were previously checked in a test stand, located at the end of Linac4, to ensure that the aimed ≥98 % stripping efficiency requirement was fulfilled.

Information on emittance growth and lifetime could not be retrieved and only the operational experience with the nominal PSB beams allowed the full validation of the foil performance. The status of the foils used in operation in

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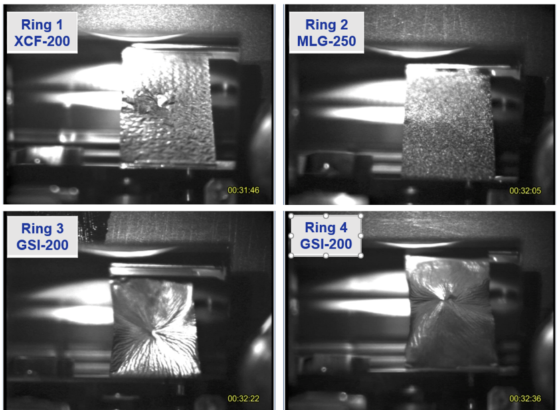

Figure 7: Live image of the four stripping foils used in the PSB after almost three years of operation.

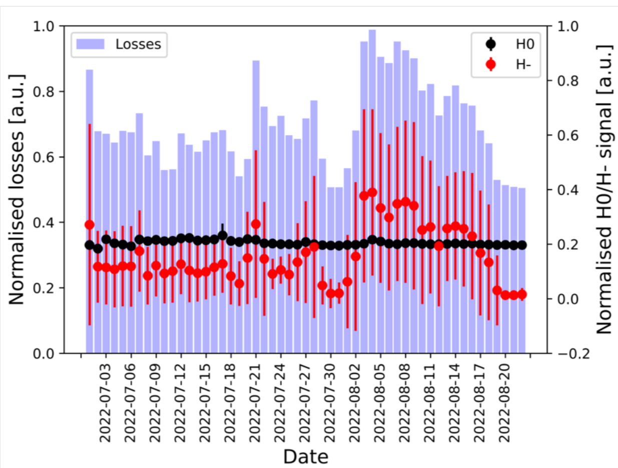

Figure 8: Normalized H^0/H^- signals (dots) and losses (bars) at injection. A re-steering of the TL on September 19^{th} allowed to reduce the number of H^- ions missing the foil.

the four PSB rings is shown in Fig. 7. Despite some foils show a large plastic deformation, their stripping efficiency stays ≥99.8 % and no measurable degradation was observed over the years. Visible variations were all attributed to mis-steering of the TLs resulting in H^- ions missing the foil.

One example is shown in Fig. 8 for Ring3 where large fluctuations and a clear increase in the number of detected H^- at the H^0H^- monitor was observed while the H^- signal staid constant. Correspondingly, higher losses were recorded by the Beam Loss Monitor (BLM) installed in the injection region. A careful check allowed to confirm that, for one PSB user, the steering of the injected beam on the foil was not ideal and, after correction, the original stripping efficiency could be restored. None of the installed foils was broken until now by the beam during operation. Ruptures occurred only as a consequence of mechanical problems with the loader, wrong manipulations or during vacuum pump down. In particular, an intervention on Ring2 loader during last winter stop caused the breakage of the MLG-250 foil used in operation. This is the only non-original foil presently used in the PSB. According to the present knowledge, it is

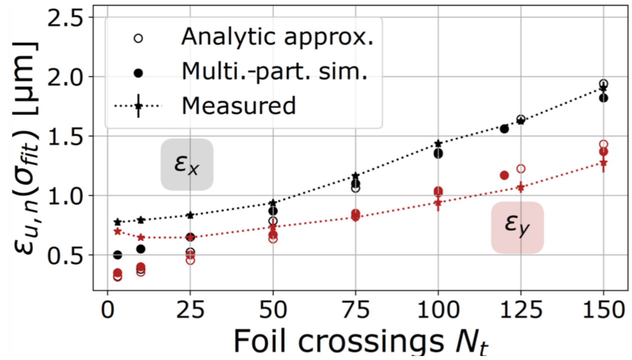

Figure 9: Transverse emittance growth as a function of the number of foil crossings for a GSI-200 foil [7]. Measurements, analytical and tracking simulations results are compared.

still not possible to estimate the lifetime of the PSB foils and a constant monitoring of their stripping efficiency is performed to identify the first signs of degradation.

Also from the point of view of the emittance growth induced by multiple crossings of the circulating beam, the selected foils behave according to specifications. The typical emittance increase, measured as a function of the number of foil crossing for a GSI-200 foil, is shown in Fig. 9 and compared with analytical calculations and tracking simulations proving a good agreement. No significant degradation is visible for up to the 35 turns which are needed to store the required intensity for the HL-LHC high brightness beams. Equivalent results apply to all types of used foils.

FUTURE DEVELOPMENTS

As already mentioned, a number of MDs were dedicated to fully exploit the potential of the PSB in the production of beams with brightness and intensity even higher than specifications. Using a longitudinal painting or a triple harmonic to optimize the filling of the PSB RF bucket, reduce the line density and thus the space charge-related effects proved to be effective [6]. Preliminary studies indicate that a fine optimisation of the transverse painting, based on numerical optimisation algorithms, could contribute to further improve the achieved results [7]. Moreover, automatic tools capable of constantly survey the injection quality (e.g. checking the losses, injection oscillations and TL steering) and react to compensate for drifts and changes in the operational conditions would push the reliability and efficiency of the system.

These are challenging goals requiring a non negligible amount of studies and beam time. Therefore, supervized machine learning algorithms are considered as the most promising means to explore the universe of all possible additional improvements to apply to the injection system.

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CONCLUSION

The new PSB H^- charge exchange system has been successfully commissioned and has been in operation for the past three years with no major issue. The results achieved up to now in terms of beam quality meet the upgrade goals. Nonetheless, relentless endeavors persist in pushing the boundaries to assess the ultimate levels of the achievable intensity and brightness.

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