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THE NEW INJECTION REGION OF THE CERN PS BOOSTER

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Abstract

During the Long Shutdown 2 (LS2) at CERN, the new Linac4 (L4) accelerator will be connected to the PS Booster (PSB) to inject 160 MeV H^- beam into the 4 superposed PSB rings. In order to achieve this, we have designed, built and pre-assembled a completely new H^- charge-exchange injection chicane system, with a carbon stripping foil unit to convert the negative hydrogen ions into protons by stripping off the electrons. In parallel, we have built and installed a test stand in the L4 transfer line enabling us to gain valuable experience with operation of the stripping foil system and to evaluate different foil types during the L4 reliability runs. This paper describes the final design of the new PSB injection region and reports on the important test results obtained with the stripping foil test stand.

INTRODUCTION

A massive improvement program of the Large Hadron Collider (LHC) injector chain is presently being conducted under the LHC Injectors Upgrade (LIU) project [1, 2] with the aim of producing the challenging High Luminosity LHC (HL-LHC) beam parameters [3, 4]. The project comprises a new Linac, so-called Linac4 (L4), as well as major upgrades and consolidation of the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS).

L4 is a linear accelerator [5] intended to deliver from 2020 a beam of 160 MeV energy to the 4 superposed synchrotron rings of the PSB. L4 will deliver negative hydrogen ions (H^-) instead of protons (H^+) to the PSB, at higher injection energy than the 50 MeV of Linac2, therefor the PSB is equipped with an H^- charge-exchange injection system during the Long Shutdown 2019-2020 (LS2).

H^- CHARGE-EXCHANGE INJECTION

Charge-exchange injection can achieve higher particle density providing an extremely flexible way to load particles into the PSB, making the accumulation of many turns possible with a tight control of the beam density [6]. In the new injection system, H^- will be progressively injected horizontally into the PSB and converted into H^+ by passing through a 200 μg/cm^2 carbon foil to strip them of the electrons, aiming to convert at least 98% of the beam to protons [7]. To achieve this, the local orbit of the PSB circulating beam is horizontally displaced by a set of 4 pulsed dipole magnets (BSW) [8] in order to merge with the injected beam (see Fig. 1). Four horizontal kickers (KSW) [9], outside the injection region, are used to paint the beam into the required horizontal emittance. Partially stripped H^0 and ~1% H^- missing the foil are directed to an internal H^0/H^- dump located inside chicane magnet BSW4 [10]. An image of the new H^- injection region equipment is given in Fig. 2.

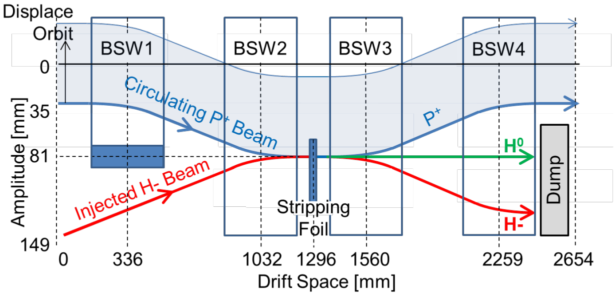

Figure 1: Configuration of the PSB injection region.

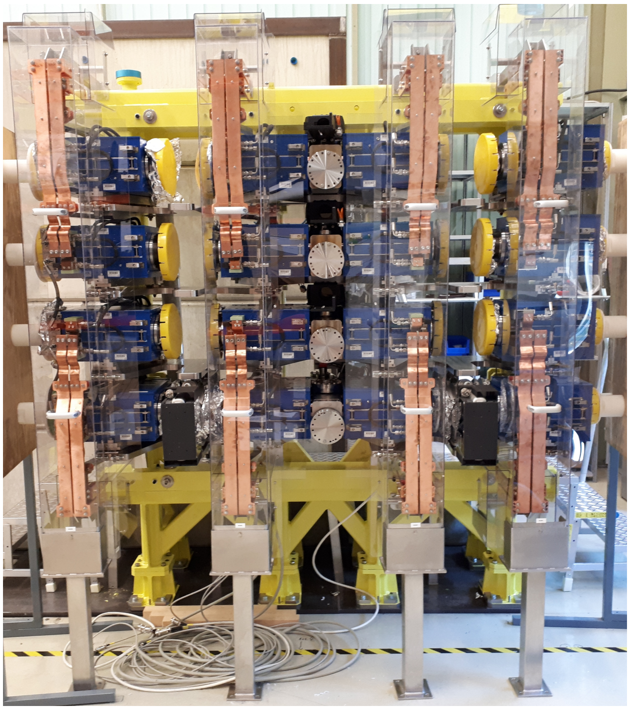

Figure 2: Mockup assembly of the new H^- injection region.

Injection Chicane

Considering a symmetric injection bump, the strength of the BSW magnets [8] is determined by the 66 mrad injection angle from L4 transfer line and an integral field of 126 mTm will be required to achieve this deflection. For each of the 4 PSB rings, the chicane consists of a septum magnet (BSW1), only deflecting the orbiting circulating beam providing a field-free region for the injected H^- beam, followed by 3 bumper magnets (BSW2-4). The magnet apertures are adapted to the dimensions of the corrugated Inconel vacuum

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chambers located inside the gap of the chicane magnets. To fit all elements in the limited 2.654 m space of injection straight section, the BSW magnets are only 0.38 m in length having a magnetic length of 0.316 m. The vertical space available for each magnet and its support is limited by the PSB ring separation of 360 mm. Following this, the main parameters of the BSW magnets are given in Table 1.

Table 1: Main BSW Magnet Parameters

Parameters	Unit	BSW1	BSW2-4
$\int B_y dl$ at magnet centre	mTm	126	126
Electric peak current	kA	6.7	3.4
RMS current	A	463	231
Resistance	mΩ	3.5	7
Inductance	µH	13	77
Number of turns		4	8
End Plate thickness	mm	13.6	12
Aperture H×V	mm	162x85	242x85
Good field region 1%	mm	140x85	220x85

During injection, the chicane magnets are powered and the H^- beam is injected into the PSB at the flat top. After injection the chicane is ramped down linearly in 5 ms.

Painting Bump

A series of 4 horizontal kickers (KSW) [9], positioned outside the injection region, will produce a 35 mm closed orbit bump, see Fig. 1, with falling amplitude during injection, uniformly filling the horizontal phase space (transverse painting) [11] moving the circulating beam away from the stripping foil; this allows reduction of the emittance (ϵx) blow-up induced by space charge effects and scattering processes. Since these magnets are not symmetrically distributed around the stripping foil, each magnet has to give a slightly different kick to perfectly close the bump and prevent any orbit leakage around the ring (see Table 2). All magnets will be individually powered, a multiple-linear waveform [9] is chosen for the KSW generators to have a highly flexible KSW current decay to fulfill the requirements of the different users (LHC, nTOF, ISOLDE, etc.).

Table 2: Main KSW Magnet Parameters per Magnet Position

Parameter	Unit	1L4	2L1	16L1	16L4
Kick	mrad	1.15	5.41	5.85	0.83
Magnetic field	mT	6	28	30	4
Gap height/width	mm	132	132	132	132
Length	mm	370	370	370	370
Inductance	µH	390	39	39	390
Number of turns		48	16	16	48
Repetition rate	Hz	1.1	1.1	1.1	1.1

Foil Exchange Mechanism

The stripping foil handling and exchange mechanism consists of a stainless steel belt, rotating over two pulleys, to which a maximum of six foil holders can be attached by use of quick disconnect sliders [12, 13]. This allows moving a foil into the beam aperture, with a perpetual rotation; each of the six foils can be re-selected into the nominal beam position, with a precision of ±0.1 mm, from which a foil movement in the horizontal plane of ±2 mm is possible in order to find the optimum position. To this extend the mechanism is equipped with ultra-high vacuum (UHV) compatible microswitches and membrane potentiometers, doubled for redundancy, allowing calibration of the stepping motor, precise measurement of the foil position and detection of the foil IN and foil OUT positions over the 4 mm range [14].

Instrumentation

Each ring in the injection region is equipped with a retractable optical beam observation system (BTV), consisting of a 1 mm thick Chromox (Al_2O_3 doped with CrO_2) scintillating screen, which can be placed 6 mm in front of the foil [15]. The image of the screen, or of the stripping foil, is recorded by a radiation-hard camera, allowing checking either the beam position or the integrity of the foil [13].

Each BSW4 magnets has an internal, in-vacuum, H^0/H^- Titanium beam dump [10]. These dumps are equipped with a set of 4 Titanium plates, designed to measure the amount and position of residual H^0 and H^- beam currents [16]. The 1 mm thickness of the plates is sufficient to strip all remaining electrons, while leaving the resulting protons easily penetrate and reach the dump. This system will monitor the efficiency of the stripping foil and protect the dump from a high intensity beam impacts, providing an interlock signal in case of stripping foil failure.

STRIPPING FOIL EFFICIENCY

In order to gain experience with these very fragile foils, test different foil materials and thicknesses, evaluate the lifetime of the foils and foil holders and test the foil exchange mechanism as well as the interlocking functions, a stripping foil test stand was installed in the L4 transfer line [17]. From 2016 beam commissioning of L4 took place in steps of increasing energy to reach 160 MeV [18] followed by reliability runs [19]. Throughout the L4 reliability run, stripping foil efficiency measurements took place during night-shifts and weekends, the day shift being dedicated to machine development and beam diagnostics.

Foil Characteristics

The stripping foils used for the beam tests are commercially available and the characteristics are shown in Table 3. The required foil thickness for PSB injection is 200 $\mu g/cm^2$ (~1 µm) to ensure a theoretical stripping efficiency >99% while keeping the emittance increase below ~0.1 mm mrad for the LHC beam (required <2 mm mrad rms normalised emittance at injection) and the uncontrolled beam losses below the 10^{-4} level [20]. The 32 mm wide foils are glued, on identical 58 mm vertical beam aperture stainless steel

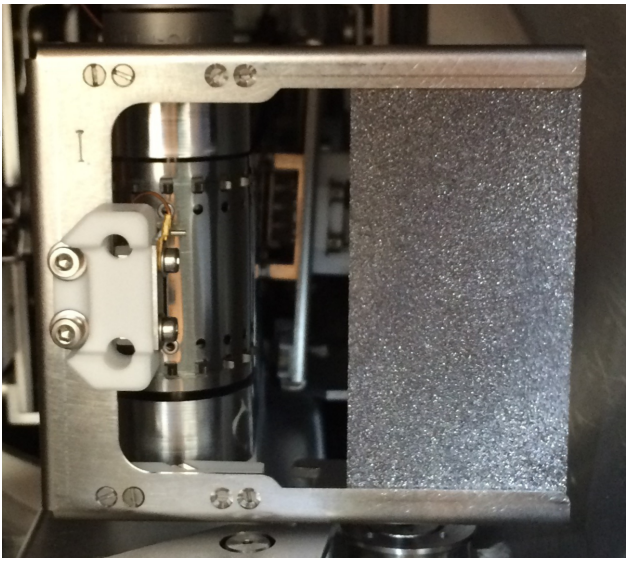

Figure 3: A 32 mm wide MLG-251 stripping foil mounted on the stainless steel foil holder. The vertical beam aperture of the holder is 58 mm.

frames, with a mixture of 50% demineralised water and 50% Aquadag® 18% solution [13], as shown in Fig. 3.

Table 3: Characteristics of the different foil types tested.

Description	Weight	Name	
Amorphous carbon	200 μg/cm^2	XCF-200	[21]
Amorphous carbon	199 μg/cm^2	GSI-199	[22]
Diamond-like carbon	200 μg/cm^2	DLC-200	[23]
Multilayer graphene	200 μg/cm^2	MLG-200	[24, 25]
Multilayer graphene	233 μg/cm^2	MLG-233	[24, 25]
Multilayer graphene	251 μg/cm^2	MLG-251	[24, 25]

Test Parameters

During nominal L4 operation, a peak current of 26 mA is expected. Four pulses, one per ring, of up to 150 μs, will have to be produced with a flatness in current of ±5%. But for each foil also multiple crossings have to be considered for the circulating beam, at slightly different locations of the foil due to the transverse painting. The beam conditions used during the tests, as summarized in Table 4, allowed to evaluate both the stripping efficiency and extrapolate the lifetime of each foil type during standard operation. All the foils at the test stand were tested with 160 MeV H$^-$ beam with a transverse r.m.s. emittance of 0.4 μm mainly defined by the acceptance of the L4 RFQ. During the tests, a source current of 30-35 mA was reached and up to 20 mA could be transported to the foil.

Test Results

Dedicated L4 runs took place to determine the stripping efficiency of the foils mentioned in Table 3. Taking into account data from several runs, and discarding measurements outside the 98-100% data range, the stripping efficiency was calculated and is presented in Fig. 4. One can observe that the efficiency of all foils is well above the theoretical value of >99% with the exception of MLG-200. According to experts [24, 25], the observed behavior in terms of stripping efficiency and losses is as expected for multi-layer graphene foils, despite the same thickness of 200 μg/cm^2 as the other carbon-based foils. Since Graphene foils have interesting mechanical properties, which make them relatively easy to handle, it was decided to test thicker graphene foils (MLG-233 and MLG-251) and assess their stripping efficiency [26]. Unfortunately the emittance blowup induced by the different foils cannot be measured with the present installation since the effect of a single passage across the foil is below the resolution of the available diagnostics.

Table 4: Characteristics of the Beam Used for the Tests

Parameters	Unit	Value
Ion Species		H$^-$
Energy	MeV	160
Repetition Rate	s	1.2
Pulse Length*	μs	200-600
Mean pulse Current	mA	5-20
Transverse emittance	π μm (rms)	0.4

*200μs to 600μs pulses with 50μs to 150μs batches

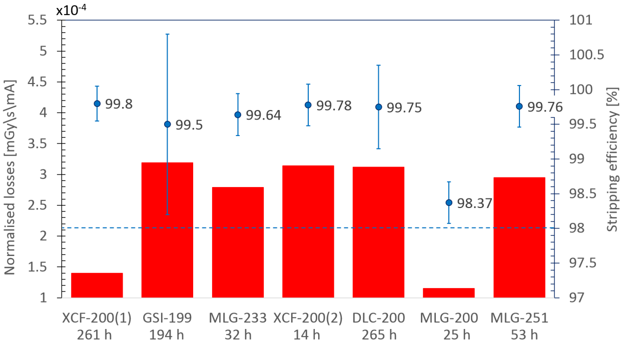

Figure 4: Measurements in the L4 test stand with 600-μs beam pulses, showing the stripping efficiency [%], the normalised beam losses [mGy/s/mA] and the beam-time [h] of each foil.

CONCLUSION

A complete new H$^-$ charge exchange injection system comprising of chicane magnets, painting bump kickers, stripping foil exchange mechanisms, internal beam dumps and dedicated instrumentation will be installed in the 4 superposed PSB rings during LS2. Furthermore, a stripping foil test stand is installed in the L4 transfer line and several types of foils have been evaluated, showing the expected theoretical efficiency >99%. For beam commissioning of the new PSB injection region, each type of tested foil will be installed in the exchange mechanism.

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