**Installation and commissioning of the stripping foil system in the new CERN PS booster 160 MeV H⁻ injection region**

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**Abstract.** During Long Shutdown 2 (LS2) at CERN, the new Linac4 (L4) accelerator was connected to the PS Booster (PSB) to inject 160 MeV H⁻ beam into the 4 superposed PSB rings. In order to achieve this, a completely new H⁻ charge-exchange injection chicane system, with 200 μg/cm² carbon stripping foil units, to convert the negative hydrogen ions into protons, by stripping off the electrons, has been installed. Beam commissioning of this system started in December 2020 and different types of foils have been used for this purpose. In parallel, stripping efficiency measurements, of different foil types, continued to take place with the stripping foil test stand in the L4 Transfer Line. This paper briefly recalls the final design, and installation of, the main components in the PSB injection region, before reporting on the important results obtained during measurements and commissioning with beam.

1 Introduction

The CERN Proton Synchrotron Booster (PSB) is the first synchrotron in the CERN injector complex and is used for tailoring the wide range of transverse beam characteristics requested by the various users at CERN. To produce the challenging High Luminosity Large Hadron Collider (HL-LHC) beam parameters, a massive improvement program of the injector chain was completed in 2021, under the LHC Injectors Upgrade (LIU) project [1]. The project included a new Linac, so-called Linac4 (L4) [2], 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 delivering negative hydrogen ions (H⁻) to the PSB at a higher injection energy of 160 MeV than the previous 50 MeV protons (H⁺) beam of Linac2. Therefore, the PSB was upgraded in 2019/2020 during the Long Shutdown 2 (LS2), a major aspect of this upgrade was the connection of the L4 to the PSB, with an H⁻ charge-exchange injection system [3], replacing the conventional H⁺ multi-turn injection.

Commissioning of the upgraded PSB started in December 2020 and was completed in Q1 2021 [4].

2 PSB injection modifications

The PSB consists of 4 superposed synchrotron rings and, in the new configuration, the 160 MeV H⁻ beam from L4 is distributed to the four rings by a vertical bending magnet (DVT30), a system of 5 kicker magnets (DIS), a vertical bend (DVT40) and 3 septum magnets (SMV) [5]. The beam is subsequently injected horizontally into the PSB by a H⁻ charge-exchange injection system, one for each ring.

Charge-exchange injection can achieve higher particle density providing an extremely flexible way to load particles into the PSB, which has a revolution period \( \tau \approx 1 \mu s \) at 160 MeV, making the accumulation of many injected turns possible with a tight control of the beam density [6]. In the new injection system, H⁻ are progressively injected horizontally into the PSB and converted into H⁺ by passing through a 200 μg/cm² carbon foil to strip off the electrons, aiming to convert at least 98% of the beam to H⁺ [7]. Partially stripped H⁺ and ≤ 1% H⁻ missing the foil are directed into internal TiAl₅V dumps, one per ring, equipped with H⁺/H⁻ monitors [8] to measure the stripping efficiency and interlock the injection on any foil degradation or failure.

During injection, the local orbit of the PSB circulating beam is displaced 46 mm horizontally by a set of 4 pulsed dipole magnets (BSW) [9] to merge with the injected beam (Fig. 1).

![Schematic representation of PSB H⁻ injection system.](image)

**Fig. 1.** Schematic representation of PSB H⁻ injection system.

Four horizontal kicker magnets (KSW) [10], outside the injection region, produce during injection a 35 mm
closed orbit bump, with falling amplitude, to paint the beam into the required horizontal emittance and move the circulating beam away from the stripping foil.

3 Foil exchange mechanism

The stripping foil handling and exchange mechanism, presented in detail in [11, 12], 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 (Fig. 2). This allows moving foils into the beam aperture, with a perpetual rotation; each of the six foils can be re-selected into the nominal beam position with a possible horizontal foil adjustment of ±2 mm, and a precision of ±0.1 mm, to find the optimum position, while having precise measurement of the foil position of over this 4 mm range [13].

4 PSB Beam commissioning

Beam commissioning of the upgraded PSB and new $H^−$ charge-exchange injection region started in December 2020, including foil efficiency measurements and optimisation of the beam production schemes for tailoring the various user-defined beam requirements.

4.1 Stripping efficiency measurement

In 2018/2019 foils of different manufactures have been qualified regarding gluing & manipulation and stripping efficiency & lifetime in a test stand [11] installed in the L4 transfer line [14, 15], described in more detail in § 6. The selected stripping foils for PSB beam commissioning are shown in Table 1.

Table 1. Characteristics of foil used for PSB commissioning.

<table>
<thead>
<tr>
<th>Foil #</th>
<th>Description</th>
<th>Thickness</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 4</td>
<td>Amorphous Carbon 200 µg/cm²</td>
<td>XCF-200</td>
<td>[16]</td>
</tr>
<tr>
<td>2, 5</td>
<td>Amorphous Carbon 200 µg/cm²</td>
<td>GSI-200</td>
<td>[17]</td>
</tr>
<tr>
<td>3, 6</td>
<td>Multilayer Graphene 240 µg/cm²</td>
<td>MLG-250</td>
<td>[18]</td>
</tr>
</tbody>
</table>

By comparing the Beam Current Transformers (BCT) positioned in the L4 transfer line and the PSB ring, the beam transmission can be calculated, which is dependent on the foil efficiency as well as other loss mechanism such as resonance crossing, instabilities, aperture bottlenecks, etc. Figure 3 shows the average BCT signal, for each PSB ring, considering all beam types, with a 98% target below which alerts, or beam interlock might take place. Beam Loss Monitors (BLM) values, localised in the injection region, are also shown.

The degradation and large standard deviation of the beam transmission at Ring 3 was analysed in detail by looking at the signals from the $H^+/H^−$ monitor [8] for different PSB beam types. All foils showed a stripping efficiency of at least 99.5%, but large signal fluctuations were measured for the different beams at the $H^+$ plates while $H^−$ remained constant (Fig. 4). In general, one would expect a higher signal of $H^+$ than $H^−$, but since this was not the case, there was a clear indication that the stripping efficiency was influenced by the steering of the beam, thus $H^−$ ions not intercepting the foil. The stripping efficiency could indeed be brought back to the original ~99.5% value by adjusting the trajectory of all beams at the foil.

4.2 Emittance measurement

The choice of 200 µg/cm² stripping foil is based on providing sufficient stripping efficiency, while minimizing the emittance blow-up, and hence the degradation of the beam brightness, induced by foil scattering [6]. The foils installed in the PSB were qualified by single foil passages in the L4 test stand [11], verification of the predicted scattering properties was thus not possible.

During PSB commissioning, the flexibility to customize the number of foil crossings enabled the assessment of the emittance increase induced by
multiple passages through the foils [4]. Figure 5 (left) illustrates the emittance increase, measured for a varying number of foil crossings ($N_f$) of the GSI-200 foil. Analytical and simulation results show good agreement with the measurements for $N_f > 30 − 50$. Figure 5 (right) also shows the measurements for $N_f = 150$ for the different foil types as listed in Table 1.

For all tested foils, the measured emittance increase is consistent with the model. No significant foil induced beam degradation is expected for any foil type to produce high brightness beams (10 to 35 injected turns).

![Fig. 5. Left: Transverse emittances for varying number of foil hits $N_f$ for foil #2 GSI-200. Right: Different foil types, as described in Table 1 for $N_f = 150$ [4].](image)

### 5 Observations

In [14], we described the sudden GSI-200 foil deformation, towards the centre of beam impact, after only one pulse in the L4 test stand. The same phenomenon was also observed during PSB beam commissioning, but only at higher injected intensities, and dedicated beam time was used to investigate.

While increasing in small steps the injected intensity, whilst recording with the BTV camera [11, 12], increasingly small local deformation was observed at the beam spot. Reaching up to 70 injected turns, a sudden light wave was seen, during which the foil deformation took place, see Fig. 6, but this had no influence on the stripping efficiency.

![Fig. 6. GSI-200 foil before (top-left) and after (bottom-right) beam impact with images of light wave observed on foil surface at ms intervals (left to right). Event took place with 330 ns, 25 mA beam pulses, 70 injected turns with $5 \times 10^10 H^+$ per turn and 150 foil crossings (~6.7E12 $H^+$ foil passages).](image)

One hypothesis is that residue of the betaine-sucrose paring agent, left on the foil surface, ignites and burns off creating this effect [19], but other experts [20] mentioned that this is observed on other foils and thought to be linked to grain friction reaching the carbon diffusion temperature.

### 6 L4 test stand

A stripping foil test stand [11] is installed in the L4 transfer line allowing measurement, at the % level, of the stripping efficiency for different foils by measuring the decrease in current between two cross-calibrated BCTs installed upstream and downstream of the test stand. To qualify suppliers for possible future orders, measurements were done during weeks 38 & 48 2020.

The beam characteristics during the tests are shown in Table 2, and the foils used are shown in Table 3.

#### Table 2. Characteristics of the beam used for the tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
<td>$H^+$</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>160</td>
<td>MeV</td>
</tr>
<tr>
<td>Current</td>
<td>25</td>
<td>mA</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>500*</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>Repetition</td>
<td>1.2</td>
<td>s</td>
</tr>
</tbody>
</table>

*4 x 125 $\mu$s batches, 1 $\mu$s gap

#### Table 3. Characteristics of foils used in L4 test stand.

<table>
<thead>
<tr>
<th>Foil #</th>
<th>Description</th>
<th>Thickness</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Amorphous Carbon</td>
<td>200 $\mu$g/cm$^2$</td>
<td>XCF-200 [16]</td>
</tr>
<tr>
<td>2</td>
<td>Amorphous Carbon</td>
<td>200 $\mu$g/cm$^2$</td>
<td>GSI-200 [17]</td>
</tr>
<tr>
<td>3</td>
<td>Multilayer Graphene</td>
<td>200 $\mu$g/cm$^2$</td>
<td>NAL-200 [21]</td>
</tr>
<tr>
<td>4</td>
<td>Graphene</td>
<td>200 $\mu$g/cm$^2$</td>
<td>AGP-200 [22]</td>
</tr>
<tr>
<td>5</td>
<td>Graphene</td>
<td>200 $\mu$g/cm$^2$</td>
<td>SHT-200 [23]</td>
</tr>
<tr>
<td>6</td>
<td>Graphene rGO</td>
<td>185 $\mu$g/cm$^2$</td>
<td>ARC-200 [24]</td>
</tr>
</tbody>
</table>

Arc evaporated amorphous Carbon

The transmission data of the tests are shown in Fig. 7. In comparison to reference foils #1 & #2, also installed in the PSB injection, #3 & #6 have a very good transmission with a comparable 99% efficiency. The performance of #5 is slightly less, about 98%, and #4 only has a 94.5% efficiency. Improved samples of #4 have been received for further testing and #6 was identified as a possible future (European) supplier.

![Fig. 7. Stripping efficiency of the six tested foils shown with the corresponding normalised beam losses.](image)

### 7 Conclusion

A completely new $H^+$ charge exchange injection system comprising of chicane magnets, painting bump kickers, stripping foil exchange mechanisms, internal beam dumps and dedicated instrumentation has been installed,
and successfully commissioned, in the 4 superposed PSB rings. The installed stripping foils were qualified using the L4 test stand and all show the expected theoretical efficiency > 98%. Measurements of emittance increase, caused by multiple beam passages through the foils, show that no significant foil induced beam degradation is expected to produce high brightness beams.

Observed sudden visual degradation of foils was studied in detail and is thought to be linked to sudden combustion of residue left on the foil or inter-grain friction reaching the carbon diffusion temperature.

Furthermore, additional stripping efficiency tests with the L4 test stand yielded in encouraging results to qualify possible new suppliers.

The authors would like to thank everybody involved in the successful installation and commissioning of the PSB 160 MeV $H^-$ injection region for their valuable contribution, but in particular R. Noulibos for his continuous engineering efforts and ingenious ideas, M. Plum for initiating us to the world of stripping foils, the INTDS members for sharing their valuable expertise and knowledge and the CERN Control Centre (CCC) operators for giving support and input during hardware and beam commissioning.

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