COMMISSIONING OF THE STRIPPING FOIL UNITS FOR THE UPGRADE OF THE PSB H⁻ INJECTION SYSTEM

C. Bracco*, S. Burger, V. Forte, B. Goddard, G. Guidoboni, L.O. Jorat, B. Mikulec, A. Navarro Fernandez, R. Noulibos, F. Roncarolo, P. Van Trappen, W. Weterings, CERN, Geneva, Switzerland

Abstract

The PSB will be extensively upgraded during the next long shutdown of the CERN accelerator complex, to double the brightness of the stored beams. The existing multi-turn injection will be replaced by a charge exchange system designed for the 160 MeV hydrogen ions provided by Linac4. Part of the injection equipment has been temporarily installed along the Linac4-to-PSB transfer line and tested with beam. This allowed to gain experience with the system, test the related diagnostics and benchmark calculations with measurements. An additional permanent stripping foil test stand is also installed right after the Linac and will be used to characterise new foils for possible future applications. The main outcomes, issues and applied or planned mitigations are presented for both installations.

INTRODUCTION

The luminosity goals of the HL-LHC require major modifications of the LHC injectors complex (LIU project [1]) in order to double the brightness of the delivered beams. Among other upgrades, Linac4 will be connected to the PSB and will supply it with 160 MeV H^- ion beams. Consequently, the present PSB injection region will be modified by installing an H^- charge exchange injection system [2] consisting of a horizontal chicane and a thin stripping foil converting the hydrogen ions into protons by removing the electrons. The chicane will be made up of four dipole magnets (BSW) located symmetrically around the stripping foil.

The fully stripped H^+ will be bent onto the PSB closed orbit while the partially stripped H^0 and the unstripped or non-intercepted H^- will be dumped. A current monitor [3] will be installed in front of the dump to measure the H^0/H^- current and hence the stripping efficiency of the foil. The monitor consists of four Ti plates: H^0 Left, H^0 Right, H^- Left and H^- Right. Such partition will provide information about the position of the unstripped beams on the monitor and might be used to improve the steering of the injected beam with respect to the foil.

To gain experience with the new injection system before the final installation in the PSB, part of the equipment (the stripping foil unit, the second half of the chicane including the dump and the H^0/H^- monitor) was temporarily placed in the Linac4-to-PSB transfer line, at the so called Half Sector Test (HST) [4], and tested with beam. This allowed to check different foils, the foil changing mechanism, the related diagnostics and interlock logic providing fundamental information in view of the future commissioning and operation in the PSB. A permanent stripping foil test stand is also installed right after the last cavity of Linac4 [5] and can be used to characterise new foils for possible future applications.

The main characteristics of the stripping foil units from the mechanical and control point of view are presented in this paper together with the main outcomes of the gained operational experience. First measurements of stripping efficiency for different foils are also given.

STRIPPING FOIL UNITS

A schematic view of the stripping foil unit and some pictures of the main components are shown in Fig. 1.

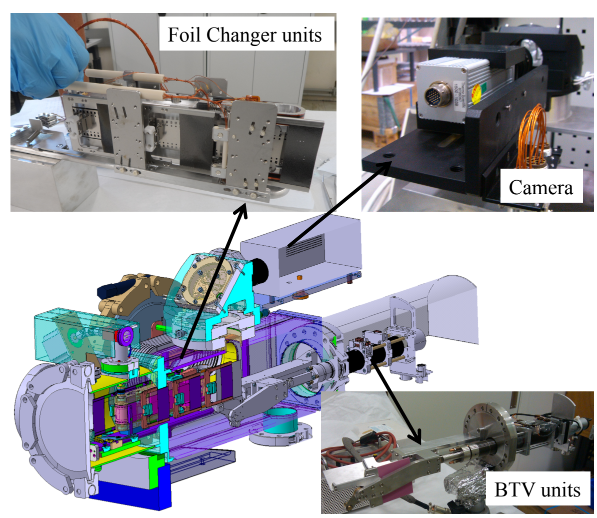

Figure 1: The stripping foil unit including the integrated BTV screen and camera.

The design of the stripping foil handling and exchange mechanism, the so-called TKSTR, was extensively presented in [5, 6]. It consists of a stainless steel belt, rotating over two pulleys, to which a maximum of six foil holders can be attached by using quick-disconnect sliders. This allows moving a foil into the beam aperture and each of the six foils can be reset to the nominal beam position with a precision of ±0.1 mm. A foil displacement of ±2 mm in the horizontal plane is also possible for a fine adjustment of the foil with respect to the beam during operation. The TKSTR is positioned inside the vacuum tank on insulating supports to measure the stripping foil current by taking the electrical signal from the foil holder.

* chiara.bracco@cern.ch

ISBN 978-3-95450-182-3

Table 1: Stripping Foil Characteristics. The identification number of the foils used for the stripping efficiency measurements presented in Fig. 3 is also shown. Foil 3* was broken and replaced in January 2017.

Description	**Thickness [μg/cm^2]**	**Size [mm]**	**Foil number**
XCF-200, arc evaporated amorphous Carbon, collodion coated [11]	200	32×68	1-4
XCF-400, arc evaporated amorphous Carbon [11]	400	32×68	3*
DLC-23-1000-S, diamond-like Carbon, boron doped 10% [12]	200	32×68	2-3
HBC, hybrid type Boron mixed Carbon [13]	200	21×68	5-6

Furthermore, a retractable optical beam observation system (BTV), consisting of a 1 mm thick Chromox (Al_2O_3 doped with CrO_2) scintillating screen, can be placed 6 mm in front of the foil. The image of the screen, or of the stripping foil, is recorded by a radiation-hard camera, allowing to either check the beam position or the integrity of the foil.

The carbon stripping foils used for the beam tests are commercially available and shown in Table 1. The required foil thickness for PSB injection is 200 μg/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 [7]. Experience was gained in handling and attaching these fragile foils to frames.

Controls

The rotation of the belt is done by an outside vacuum stepping motor, connected through a 10:1 worm and wheel gearbox, to a mechanical vacuum feedthrough. The 1.8° stepping motor is micro-stepping driven which yields a higher positioning resolution of ~5 μm/step and a smoother holder movement to avoid the foils to be damaged by vibration. Inside the tank, ultra-high vacuum (UHV) compatible microswitches and membrane potentiometers, doubled for redundancy, allow the calibration of the stepping motor, the precise measurement of the foil position and the detection of the foil IN and foil OUT status over the 4 mm range. The selection of these components was an important part because of the stringent vacuum pressure and radiation dose constraints [8, 9].

The remote control was kept simple so that the operator can request any of the six foils, the foil IN and foil OUT positions and perform the fine adjustment to optimise the beam interception and thus the stripping efficiency.

The commands are passed to the Programmable Logic Controller (PLC) using the Injector Controls Architecture (InCA) and Front-End Software Architecture (FESA3) CERN frameworks. All developed controls code will be reused for the final PSB units.

An important part of the controls is the connection to the BTV equipment to avoid collisions between the BTV screen and the stripping foil frames. A collision would require a manual intervention, breaking of the vacuum, thus unacceptable. Hard-wired position switches of both the BTV screen and the stripping foil frame implement proper interlocking functionality.

An optical fiber radiation temperature meter [10] was installed for foil temperature measurements. During the performed measurements, the foil temperature never surpassed the bottom limit of 170 °C so no useful foil temperatures were measured. Nevertheless, correct operation of the thermometer was validated by using the BTV screen.

OPERATIONAL EXPERIENCE

The first checks consisted in verifying that the main functionalities of the stripping foil units in terms of mechanical movements, achievement and reproducibility of the requested position within the design tolerances worked as expected. Initially the reproducibility was found out of specifications. The requested ±0.1 mm could be reached by using a micro-switch for calibrating the band on each full turn and the membrane potentiometers for mechanical imperfection corrections.

The interlock logic was then validated by checking that the rotation of the foil holder was inhibited when the BTV screen was in front of the foil while the fine position tuning was still allowed. The correct reaction of the pre-chopper, which has to cut the beam for any foil movement request, was also probed.

The BTV was used both to define the position of the beam with respect to the foil and monitor the status of the foil. This allowed to detect partial ruptures which did not affect the current measured at the foil nor the intensity transmission (see Fig. 2). Three foils, two at the permanent test stand and one at the HST, got broken during operation but never due to a direct beam impact, as expected according to previous calculations [7]. In all the cases the foils were found broken when moving the BTV screen to the OUT position after a few minutes of operation with beam. An interlock was implemented which cut the beam in case of screen movement request but this did not solve the issue. At present the most likely explanation seems to be the beam induced charging of the screen and probably of the foil, which causes the rupture when the screen is moved. The improvement of the electrical contacts of the foil and the application of a conducting layer on the backside of the screen are taken into account as possible mitigations. Studies and lab tests are foreseen to further investigate this phenomenon.

ISBN 978-3-95450-182-3

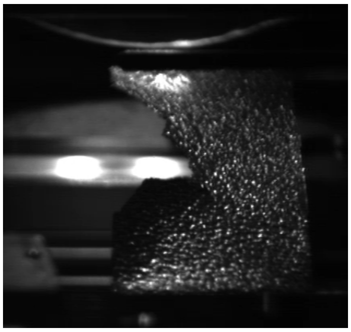

Figure 2: Image of a partially broken foil (Foil 4) as recorded by the BTV camera. The H^- beam was hitting the right part of the foil so that the intensity transmission was not affected by the foil rupture.

In another occasion a foil frame got stuck behind a microswitch at the permanent test stand. The system could be unblocked by reversing the movement of the band but this manoeuvre caused the rupture of the foil.

Apart from the few mentioned issues, globally the system proved to perform according to the expectations. Further improvements are foreseen in particular also to reduce the time needed to mount/dismount the loader and thus minimise the radiation exposure of the personnel.

STRIPPING EFFICIENCY

The same type of foils were mounted on the loaders at the permanent test stand and at the HST. Stripping efficiency measurements were performed, at both installations, with a typical current of 10-12 mA and a pulse length of ~100 μs.

The stripping efficiency at the test stand could be evaluated only by comparing the signals of two cross-calibrated Beam Current Transformers (BCT) located at each side of the unit. No H^0/H^- monitor was installed at this location and the foil current measurement proved to be useless since the stripped electrons were not stopped by the 1 μm thin foils. Measurements with the BTCs were particularly challenging. Initially an unrealistic 120% transmission was measured, without foil, at the downstream monitor preventing reliable measurements. Nevertheless the same transmission was calculated for all the foils including the 400 $\mu g/cm^2$ thick one; this seemed to indicate a stripping efficiency close to 100%. A possible influence of the stripped electrons escaping the foil on the current measured at the downstream BCT was checked. A vertical corrector, downstream of the stripping foil, was powered with an increasing current to bend the electrons away from the main beam. The transmission increased by up to 3% when powering the corrector with 6 A. The current was not further increased since non negligible losses started appearing in the line. This confirmed that a method has to be developed to bend, collect and measure the stripped electrons for future operation. The problem with the BCTs was cured by installing a filter for high-frequency components only close to the end of the test period [4]. Unfortunately no further measurement was possible due to the mechanical problem encountered with the loader and described in the previous section.

At the HST the stripping efficiency was measured by using two cross-calibrated BCTs and the H^0/H^- monitor. The second BCT was installed after the half-chicane; in this way the stripped electrons were cleaned by the BSW magnets and did not affect the signal. The current transmission measured with the BCTs for different foils is shown in Fig. 3. About

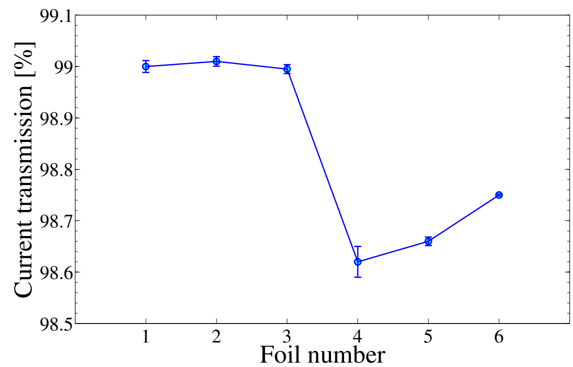

Figure 3: Current transmission between the downstream and upstream BCT for different foils (see Table 1).

99% transmission was measured for all the amorphous and diamond-like Carbon foils with the exception of Foil 4 which was partially broken (see Fig. 2). For the Boron mixed carbon foils the transmission was ~98.6% and measurements with the H^0/H^- monitor confirmed this difference [3]. In particular a current above the noise level could be measured only by the H^0 monitor for Foil 5 and 6 pointing to partially stripped beam. This hypothesis was validated by steering the beam to the right first with a horizontal corrector located upstream of the foil and then with the first downstream BSW magnet. In the first case the signal on the monitor moved as expected from the H^0 Left to H^0 Right plate while in the second case no effect could be seen confirming the charge-less nature of the escaping particles.

Measurements with the H^0/H^- monitor and the comparison with thicker foils seem to indicate a stripping efficiency between 99.6% and 100% and that the missing 1% transmission recorded by the BCTs was due to losses probably due to a non-perfect steering of the beam at the entrance of the chicane as explained in [3].

CONCLUSION

The operational experience gained with the stripping foil units and the related diagnostics represent a fundamental step in view of the future commissioning of the new PSB injection system. All the main functionalities were checked and validated. A few weaknesses could be found; some were fixed and further improvements are being developed.

First stripping efficiency measurements could be performed, after having solved some diagnostics issue, and confirmed the expected >99% for 200 $\mu g/cm^2$ thick Carbon based foils fulfilling the design specifications.

REFERENCES

[1] H. Damerau *et al.*,“LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons”, CERN note number CERN-ACC-2014-0337, CERN, Geneva, Switzerland, 2014.

[2] M. Aiba *et al.*, “Layout considerations for the PSB H^- injection system”, sLHC Project Note 0004, CERN, Geneva, Switzerland, 2017.

[3] F. Roncarolo *et al.*, “Beam Instrumentation for the CERN Linac4 and PSB Half Sector Test”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper MOPAB120, this conference.

[4] B. Mikulec *et al.*, “Commissioning and Results of the Half Sector Test Installation with 160 MeV H^- Beam from Linac4”, presented at IPAC’17, Copenhagen, Denmark, May 2017, paper MOPIK047, this conference.

[5] W. Weterings *et al.*, “The stripping Foil Test Stand in the Linac4 Transfer Line”, J Radioanal Nucl Chem, vol. 305, no. 3, 2015, pp. 831-835.

[6] Wim Weterings *et al.*, “First Experience with Carbon Stripping Foils for the 160 MeV H^- Injection into the CERN PSB”, in Conference Proceedings of INTDS2016, Cape Town (South Africa), 2016.

[7] A. Aiba *et al.*, “Stripping Foil Issues for H^- Injection into the CERN PSB at 160 MeV”, in Conference proceedings of IPAC10, Kyoto, Japan, 2010.

[8] IEEE Editorial Style Manual, IEEE Periodicals, Piscataway, NJ, USA, Oct. 2014, pp. 34-52.

[9] P. van Trappen *et al.*, “Stripping Foil Displacement Unit Control for H^- Injection in PSB at CERN”, in Conference Proceedings of ICALEPCS2015, MOPGF121, Melbourne (Australia), 2015, pp. 363-366.

[10] IR-FAINNU Thermometer (170 °C to 450 °C), IR-ZFL5 lens, IR-ZFH23 Fiber optic cable, CHINO, http://www.chino.co.jp/.

[11] ACF-Metals, 2239 E. Kleindale Road, Tucson, Arizona, U.S.A.

[12] MICROMATTER, Unit #1, 8333 - 130th Street, Surrey, BC V3W 7X4, Canada.

[13] Courtesy I. Sugai, KEK, Tsukuba, Ibaraki, Japan.

ISBN 978-3-95450-182-3