COMMISSIONING AND RESULTS OF THE HALF-SECTOR TEST INSTALLATION WITH 160 MeV H^- BEAM FROM LINAC4

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Abstract

During the Long Shutdown 2 (LS2) at CERN in 2019/20, the Proton Synchrotron Booster (PSB) will undergo a profound upgrade in the framework of the LHC Injector Upgrade (LIU) project involving also the connection to the new Linac4 injector. The 160 MeV Linac4 H^- injection entails a complete replacement of the PSB injection section, including a stripping foil system, injection chicane, an H^0/H^- dump and novel beam instrumentation. The equivalent of half of this new injection chicane was temporarily installed in the Linac4 transfer line to evaluate the performance of the equipment and prepare controls, interlocks and applications for the connection. Outcomes of this so-called Half-Sector Test (HST) are presented in this paper.

INTRODUCTION

In the framework of the LIU project a vast effort is ongoing at CERN to upgrade all LHC injectors before the end of LS2 (2020) in order to provide the required beam parameters for the LHC luminosity upgrade [1]. The PSB upgrade consists of the connection to the new Linac4 H^- injector and an extraction energy upgrade from 1.4 to 2 GeV [2]. The Linac4 connection requires a complete renewal of the PSB injection section due to the energy upgrade from 50 to 160 MeV and the injection of H^- ions instead of the current proton injection from Linac2 [3]. At present, protons are injected in a multi-turn injection process using injection kickers and an injection septum, whereas after Linac4 connection the H^- ions will be injected onto a stripping foil (charge-exchange injection), which is located in the centre of the injection bump. Fast kicker magnets will be used for horizontal phase-space painting, and the chopped Linac4 beam will directly be injected into the PSB rf buckets. This new injection scheme will have the following advantages:

- Reduced space-charge effects and therefore lower transverse emittance blow-up thanks to the energy increase from 50 to 160 MeV,
- Reduced injection losses (from the current ~50% injection losses to ~2% losses due to unstripped or partially stripped particles),
- Tailoring of the emittance due to horizontal phase-space painting and tuneable vertical injection offset,
- Possibility to apply longitudinal phase-space painting through Linac4 energy modulation for reduction of longitudinal space-charge effects [4].

THE HALF SECTOR TEST

Within the LIU project the future new PSB injection section has been identified as a high-risk item in terms of technical risk (novel beam instrumentation, stringent requirements on the injection chicane parameters, reliability of stripping foil system) and planning risk (commissioning time). The design of this injection system for the four PSB rings, consisting of 16 chicane magnets, 4 stripping foil units with BTV cameras, 8 pumping modules and quite some instrumentation, was very complex because of the lack of space in the existing PSB tunnel; this meant for example that the H^0/H^- dump had to be integrated with the last chicane magnet instead of constructing a separate dump line, and that a compact stripping foil loader system had to be designed allowing maintenance and foil exchange in situ. A 3D integration model shows the complexity of this section with the four superposed PSB rings (see Fig. 1).

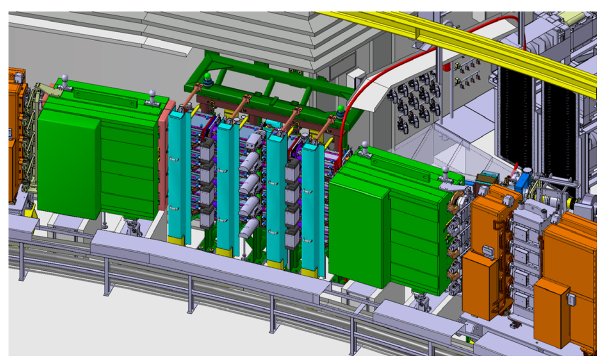

Figure 1: 3D integration drawing of the future PSB injection section, inserted between two main PSB bending magnets (green large structures) [5]. The injection line is barely visible in the middle at the right edge of the picture.

To reduce the risks of installation problems and commissioning delays as well as assuring that the new equipment works according to specification at the start-up after LS2, it was proposed to install half of the PSB injection chicane corresponding to one PSB ring in the Linac4 transfer line.

The HST installation consisted of the following main elements (see Fig. 2):

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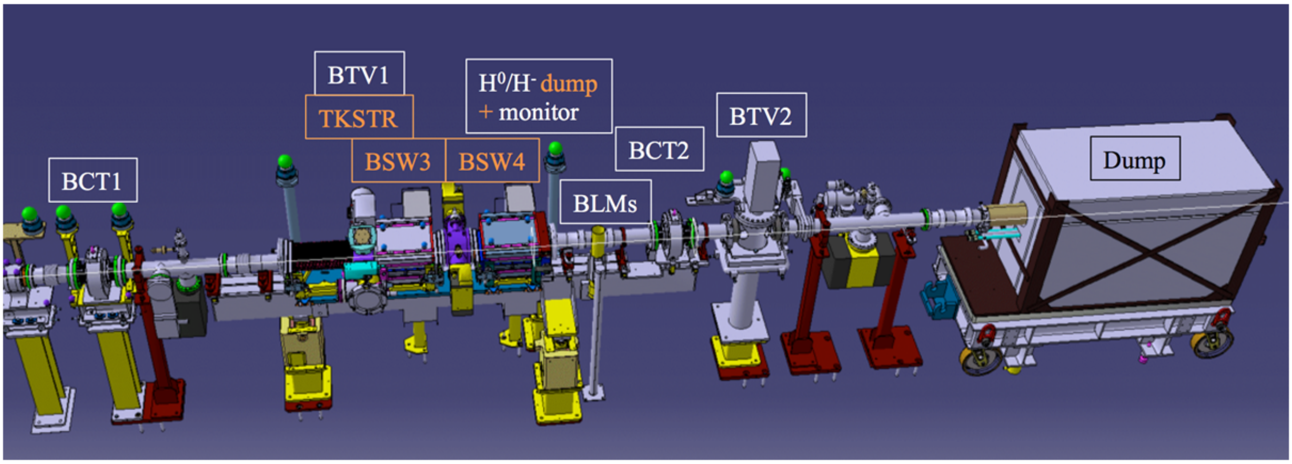

Figure 2: 3D drawing of the HST installation in the Linac4 transfer line (beam from left to right) [5].

- The stripping foil system with a loader containing max. 6 foils (TKSTR) and a screen with radiation-hard camera (BTV1),
- Half of the injection chicane, (BSW3 and BSW4 magnets) with the final undulated vacuum chambers,
- The monitor measuring the partially and unstripped particles (H^0/H^- monitor) and the H^0/H^- dump integrated with BSW4,
- Beam loss monitors (BLMs) in vicinity of the H^0/H^- dump, one ionisation chamber and one diamond BLM for fast time-resolved measurements,
- One beam current transformer upstream (BCT1) and one downstream (BCT2) of the HST for transfer efficiency measurements,
- A second screen (BTV2) for beam profile and steering to the final (temporarily installed) dump,
- Vacuum equipment and services.

From the material and density the stripping foils were expected to strip 98-100% of the electrons from the 160 MeV H^- beam. The BSW3 and BSW4 magnets would then bend the proton beam to the left and the unstripped H^- particles to the right. The partially stripped or unstripped particles were measured with the newly designed H^0/H^- monitor (the H^0 and H^- monitor consists of two plates each for basic position information in the horizontal plane) and dumped on the H^0/H^- dump, a water-cooled Titanium block fixed to the BSW4 chicane magnet. Beam loss monitors were surveying the losses on this dump, and with the upstream and downstream BCTs the transfer efficiency could be measured. The proton beam was finally dumped on the temporarily installed external dump.

HST INSTALLATION

The installation of the HST in the Linac4 transfer line took place during summer 2016. During the preparation and installation phases, a few issues were identified:

- Non-conformities in the fabrication of the undulated BSW vacuum chamber; could be solved with the manufacturer,
- Planarity non-conformity of the magnet support plate; was in a region where it could finally be accepted,
- Outgassing and contamination of the stripping foil loader unit; took several iterations of cleaning and re-assembling before vacuum acceptance; cabling improvements were made (to improve vacuum performance and signal quality and for space optimisation),
- Vacuum chamber flange supports had to be removed (modification of electrical properties of chicane magnets),
- Connectivity issue of the H^0/H^- monitor; slight reworking of the H^0/H^- dump was sufficient.

HST BEAM MEASUREMENTS

The HST received first beam on 26 October 2016 and stopped operation on 6 April 2017. In total, about 3 months of beam operation were accumulated.

Chicane Magnets and Power Converters

Operation with the chicane magnets was flawless. The controls and stability of the magnets was improved along the run; at the HST the final pulse shape for the PSB with a flat top of around 2 ms and a ramp-down function within 5 ms was used (injection into the first PSB ring will happen at the start of the ramp-down). After several improvements a flat top and ramp-down reproducibility of ±150 ppm and ±60 ppm could be reached with the prototype converters (to be compared to the specified ±50 ppm and ±500 ppm), respectively.

Stripping Foil System

The stripping foil loader has up to six foils mounted that can be remotely interchanged and fine-adjusted to avoid lengthy machine interventions and unnecessary dose to the intervening personnel in case of a foil breakage (see Fig. 3) [6]. A camera can view the foil (Fig. 4) or can visualise the beam spot on a screen that can be inserted in the vicinity of the foil. In the HST and in a separate stripping foil test stand installed permanently at the beginning of the Linac4 transfer line, foils from various manufacturers and with different material and density were mounted and tested. Following up on some minor mechanical issues during HST running, fine-adjustments will be implemented for the final design of the system. During operation, a few foil breakages were observed. They are mostly believed to be related to charging up of the foil during screen movement after observation of the beam spot with the screen. This is still under investigation, and more details are published in [7].

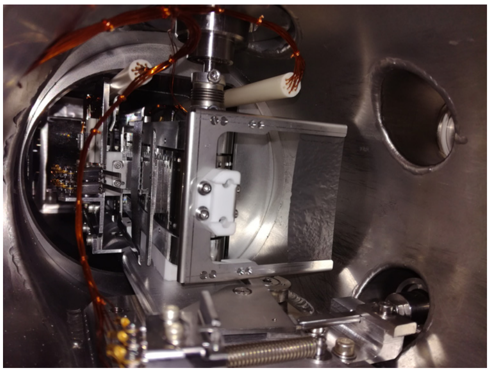

Figure 3: Stripping foil loader installed at the stripping foil test stand with a mounted foil.

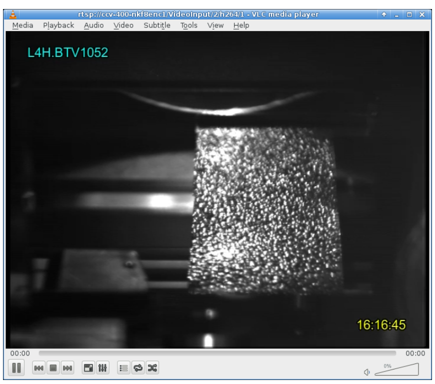

Figure 4: Online camera image of a 200 µg/cm^2 coated amorphous carbon foil installed at the HST.

H^0/H^- Monitor

This novel instrument with its readout electronics is composed of 2x2 ~1 mm thick titanium plates, which strip off the remaining electrons that survived the passage through the stripping foil or from non-intercepted beam halo (see Fig. 5). The system has successfully measured H^0 and H^- beams of varying beam current and pulse length; stripping inefficiencies of the installed foils between 0.2% and 0.4% were shown as well as good linearity with beam current and good stability of the calibration factors of the four plates [8]. After first data it was evident that a redesign of the readout board was necessary, mainly to suppress noise and to be usable for the required interlocking functionality. First tests with the new version of the board could be performed in the last days of HST beam operation.

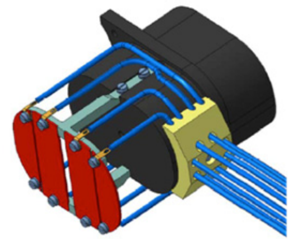

Figure 5: 3D drawing of the H^0/H^- monitor mounted on the H^0/H^- dump [8]. The two left plates will intercept the H^0 beam and the right two plates the H^- beam; some basic position information is provided through the separation of the plates.

Other Beam Instrumentation

During several months it was impossible to measure the stripping inefficiency with the Linac4 beam current transformers until finally it was found that the high-frequency component of the beam was leading to erroneous measurements. This could in the end be corrected by installing filters in the head amplifiers and will benefit Linac4 operation.

Beam losses could be adequately monitored with the ionisation chamber and the new acquisition system. On the other hand, the measurements with the diamond BLM were dominated by noise, and thus the analogue signal transmission has to be improved in the final system deployment.

CONCLUSIONS

Half of the future PSB injection chicane of one ring was installed in the Linac4 transfer line. Beam measurements with 160 MeV H^- beam allowed an evaluation of the new equipment, preparation of applications and controls as well as experience with its operation. During installation and beam operation a few design and manufacturing issues were discovered and have been or will be resolved for the final system. Furthermore, valuable experience has been gained in intervention procedures, e.g. for broken foil exchanges. The HST outcome will make sure that the new injection equipment will fulfil the final specifications and will contribute to minimise the commissioning time of the new PSB injection after Linac4 connection.

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