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First Experience with Carbon Stripping Foils for the 160 MeV H⁻ Injection into the CERN PSB

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Abstract

160 MeV H^- beam will be delivered from the new CERN linear accelerator (Linac4) to the Proton Synchrotron Booster (PSB), using a H^- charge-exchange injection system. A 200 µg/cm^2 carbon stripping foil will convert H^- into protons by stripping off the electrons. The H^- charge-exchange injection principle will be used for the first time in the CERN accelerator complex and involves many challenges. In order to gain experience with the foil changing mechanism and the very fragile foils, in 2016, prior to the installation in the PSB, a stripping foil test stand has been installed in the Linac4 transfer line. In addition, parts of the future PSB injection equipment are also temporarily installed in the Linac4 transfer line for tests with a 160 MeV H^- commissioning proton beam. This paper describes the foil changing mechanism and control system, summarizes the practical experience of gluing and handling these foils and reports on the first results with beam.

Keywords: Charge stripping; H^- injection; Charge exchange; Stripping foil; Solid stripper

1. Introduction

At CERN, the European Organization for Nuclear Research, a massive improvement program of the Large Hadron Collider (LHC) injector chain is put in place, aimed at producing beams with the challenging High Luminosity LHC (HL-LHC) parameters [1]. This LHC Injectors Upgrade (LIU) project [2] 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 an H^- linear accelerator [3] intended to deliver a beam at 160 MeV energy to the 4 superposed synchrotron rings of the PSB. The beam will be injected horizontally into the PSB by means of a H^- charge exchange injection system, one for each ring, through a graphite foil aiming to convert ~98 % of the beam to protons [4]. Partially stripped H^0 and ~1% H^- missing the foil will be directed to an internal H^0/H^- dump [5].

Beam commissioning of L4 is taking place in steps of increasing energy, to reach the final 160 MeV in 2016. An extended beam measurement phase, including a test stand of the foil handling and exchange mechanism for the PSB [6] and a half sector test (HST), with parts of the future PSB injection equipment and chicane magnets (BSW) to qualify the new injection scheme, will be finalised and ready by beginning of 2017. This will make the connection to L4 possible in the unlikely case that LHC has to stop for an extended time before the planned connection during the next LHC long shutdown (LS2) in 2019-2020 [2].

2. Stripping foil exchange mechanism

2.1. Foil loader

The conceptual design of the stripping foil handling and exchange mechanism, so-called TKSTR, has been presented in [6]. It 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. This allows moving a foil into the beam aperture, with a perpetual rotation, so that each of the six foils can be reselected 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 for operation.

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 microstepping driven which yields a higher positioning resolution and smoother holder movement to avoid foils being damaged by vibration. Inside the tank, ultra-high vacuum (UHV) compatible microswitches and membrane potentiometers, for redundancy twice the required amount, allow for 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 [7]. An illustration of the TKSTR is given in Fig 1.

2.2. Instrumentation

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. A mirror is positioned below the beam line to reflect the images of the screen, or of the stripping foil, towards an observation viewport on top of the vacuum chamber, which is made of fused silica to avoid the browning that occurs for normal glass in radiation environments. The system is equipped with a radiation-hard camera and the field depth of the focusing lens makes the use of a single, fixed, optical system possible to observe the screen and the stripping foil with the same camera, allowing either the beam position or the integrity of the foil to be monitored. To prevent BTV screen and foil holder collisions, no foil movement will be allowed when the BTV screen is in BEAM position and at the same time any BTV movement is interlocked when the foil holder is not in the IN or OUT positions.

The TKSTR is positioned inside the vacuum tank on insulating supports and, in order to have an indication of degrading stripping efficiency and the lifetime of the foils, measurement of the stripping foil current can be made by means of taking the electrical signal from the foil holder; a signal loss would indicate a broken foil.

Inspired by systems used at other institutes [8], an infrared fiberscope has been installed for continuous monitoring of the beam-spot temperature on the foil. The system consists of an infrared fibre optic radiation thermometer near the control room, with a range of 170°C to 450°C, connected by 23 m of fibre optic cable to a dedicated lens assembly, on the vacuum tank in the L4 tunnel, capable of measuring a beam-spot of 5 mm at ~150 mm distance [9].

3. Stripping foils

3.1. Characteristics

The stripping foil material is carbon, having the advantage of good thermal and mechanical stability, high sublimation temperature and radiation resistance. Several types of carbon foils are commercially available and the foils used for the beam tests are shown in Table 1. The foil thickness is 200 $\mu g/cm^2$ (~1 μm) to ensure a theoretical stripping efficiency > 99 %, yet to control the emittance increase below 0.1 $\pi \cdot \mu rad$, for the ~2 $\pi \cdot \mu rad$ requirements of the LHC beam at injection and to keep the uncontrolled beam loss below the 10^{-4} level [10].

Table 1. Characteristics of the different foil types used.

Description	Thickness	Remark	Reference	Dimension	
Arc evaporated amorphous Carbon	200 $\mu g/cm^2$	Collodion coated	XCF-200	32*68 mm	[12]
Arc evaporated amorphous Carbon	400 $\mu g/cm^2$		XCF-400	32*68 mm	[12]
Diamond-like Carbon	200 $\mu g/cm^2$	Boron doped 10%	DLC-23-1000-S	32*68 mm	[13]
Hybrid type boron mixed Carbon	200 $\mu g/cm^2$		HBC	21*68 mm	[14]

The PSB has to provide beam to several users with different requirements in terms of beam intensity and emittance. For this reason, using foils with two different dimensions was initially considered, a larger foil (32*68 mm) for beams with matched dispersion (Dx= -1.4m) and longitudinal painting as well as a smaller foil (21*68 mm) for beams with zero or matched dispersion but no longitudinal painting. For operational reasons, changing the two different foils depending on the users turned out not be feasible and studies [11] have shown that the use of the large foil for LHC beams does not influence much the emittance at the end of the injection process. An illustration of the stripping foil holder, attached to the rotating belt with foil dimensions for the PSB injection, is given in Fig 2.

3.2. Foil handling

The team responsible for the TKSTR had no previous experience in handling and attaching these fragile foils to frames and a period of trial and error was required to become familiar with this process. Some foils very easily curl when removed from the storage box and for this reason they are carefully manipulated between protective paper to avoid this. Doing so, they can be adjusted and cut to the required length if needed. The foil is then correctly positioned onto the frame by delicately moving it with a cotton stick before it can be glued. This is done by applying, with a syringe in the dedicated grove milled into the frame, a drop of solution of 50% demineralised water and 50% Aquadag® 18%, which is an aqueous-based colloidal dispersion of ultra-fine graphite in ammonium hydroxide. The whole intervention is done on a special purpose position board, in which the contours of the holder are machined to keep it firmly into place, and holes have been drilled in the surface below the foil to avoid foil damage due to suction when lifting the finished holder from the board. This foil handling process is illustrated in Fig 3.

4. Test results with beam

The first beam tests took place in October 2016, in parallel with the beam commissioning of L4 to reach the final energy of 160 MeV. This meant that, prior to this conference, only limited beam time was available for evaluating the behaviour of the foils under these beam conditions. Nevertheless, some interesting initial findings have been made. The characteristics of the beam used for the tests is shown in Table 2.

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

Parameter	Value	Unit
Energy	160	MeV
Current	12	mA
pulse Length	100	µs

4.1. Setting up

Correct position of the foil with respect to the beam is important for optimizing the stripping efficiency and for this reason the use of the BTV camera has shown to be very useful. The ideal beam impact, or stripping point, is at ~14 mm from the edge of the foil, as illustrated in Fig 2, and with the BTV screen placed in front of the foil a single beam pulse is shot on the screen to determine its position. Subsequently the foil edge can be moved ±2 mm, or the beam optics need to be adjusted, in order to achieve the stripping point position of the beam on the foil. The image from the BTV camera and a screen shot of the control interface for the BTV is given in Fig 4.

4.2. Stripping efficiency measurements

Two beam current transformers (BCT), located upstream and downstream of the foil, are used to measure the stripping efficiency by looking at their relative current decrease. A cross-calibration of these BCTs at the percent level is needed for a reliable evaluation of the number of protons with respect to the original H^-. At the half sector test there is also the possibility of measuring the partially or totally unstripped particles by means of an H^0/H^- current monitor placed in front of the dump.

4.2.1. Stripping foil test stand measurements

Preliminary measurements were performed without the foil to check the cross-calibration between the BCTs around the TKSTR test stand. A 20% higher signal was measured at the downstream monitor and this correction factor was taken into account to qualify the different foils. A stripping efficiency of about 75.5% was measured and no significant difference could be observed when moving from amorphous to hybrid or diamond like carbon nor when using a thicker foil (400 µg/cm^2 instead of the nominal 200 µg/cm^2) as shown in Fig 5. Possible reasons for such a low efficiency are being investigated knowing that an improved and more accurate calibration of the BCTs is the preliminary requisite for any clearer understanding. Calculations showed that the low energy stripped electrons can escape the foil and thus contribute to the current measured at the downstream BCT mimicking a lower stripping efficiency. A vertical corrector, located downstream of the stripping foil, was powered with an increasing current and used as a spectrometer to bend the electrons away from the main beam. The stripping efficiency increased by up to 3% when powering the corrector with 6 A (Fig 5). The current was not further increased since non negligible losses started appearing in the line. This confirms that a method has to be developed to bend, collect and measure the stripped electrons at the TKSTR. Another possible explanation for the reduced efficiency could be the presence of pinholes or a non-full interception of the beam by the foil. The beam was steered 4 mm away from its nominal position to check if this had any impact on the measured efficiency. A 0.5% reduction was indeed observed but this was clearly due to a factor of 3 increase of the losses in the line. A larger scan was not performed to limit irradiation.

4.2.2. Half sector test measurements

The stripping efficiency of a 200 µg/cm2 thick DLC-23-1000-S foil was measured also at the half sector test. The second BCT is installed after the half-chicane and a cross-calibration of the transformers without the foil would only be possible by inverting the polarity of the BSW. No correction factor was used in this case to evaluate the stripping efficiency shown in Fig 6. An increase by 20% to 90% was measured after steering the beam to the ideal position on the foil. In this case the stripped electrons are cleaned by the BSW magnets and do not pollute the signal at the BCT. Unfortunately the H^0/H^- current monitor was not yet calibrated and could not be used. A clear reduction in the stripping efficiency and a systematic increase of the local losses are seen when the BTV screen is placed in front of the foil.

4.2.3. Foil breakage

Two foils at the TKSTR test stand got broken. In order to calibrate the measurement of the stripping foil current, continues beam pulses were send on the BTV during a 1 minute period and after removing the screen, the foils appeared broken. In the first case a XCF-200 foil was only partially broken and no effect was observed at the foil current monitor nor in the measured stripping efficiency afterwards. In the second case a DLC-23-1000-S foil was completely disrupted and some foil debris was seen attached to the edge of the BTV screen, the foil current monitor showed an abrupt current fall to zero and this allowed to correlate the moment of the breakage with a movement of the BTV screen. The mechanism which caused the foil disruption is not clear yet. A hypothesis is that the BTV screen is statically charged during beam impact, causing foil attraction and subsequent breakage, or continuous exposure to the secondary showers produced at the screen causing direct heating of the frame and foil and dilatation damage. FLUKA and ANSYS calculations will be performed to assess the energy deposition on the foil and the frame in different configurations.

5. Conclusion

A new H^- charge exchange injection system needs to be installed when Linac4 is connected to the PSB with a 160MeV injection energy. We successfully designed, built and installed a stripping foil handling and exchange mechanism, including a BTV beam observation system and the team responsible for this TKSTR has gained valuable experience in handling and attaching fragile foils to frames. Only limited time was available for evaluating the behaviour of the foils under beam conditions and only qualitative measurements on the efficiency of different stripping foils have been made since the BCTs used for the measurements need more accurate calibration. Foil breakage is observed in case continues beam pulses are send on the BTV screen in front of the foil but the mechanism which caused this foil disruption is not clear yet.

6. Acknowledgement

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7. References

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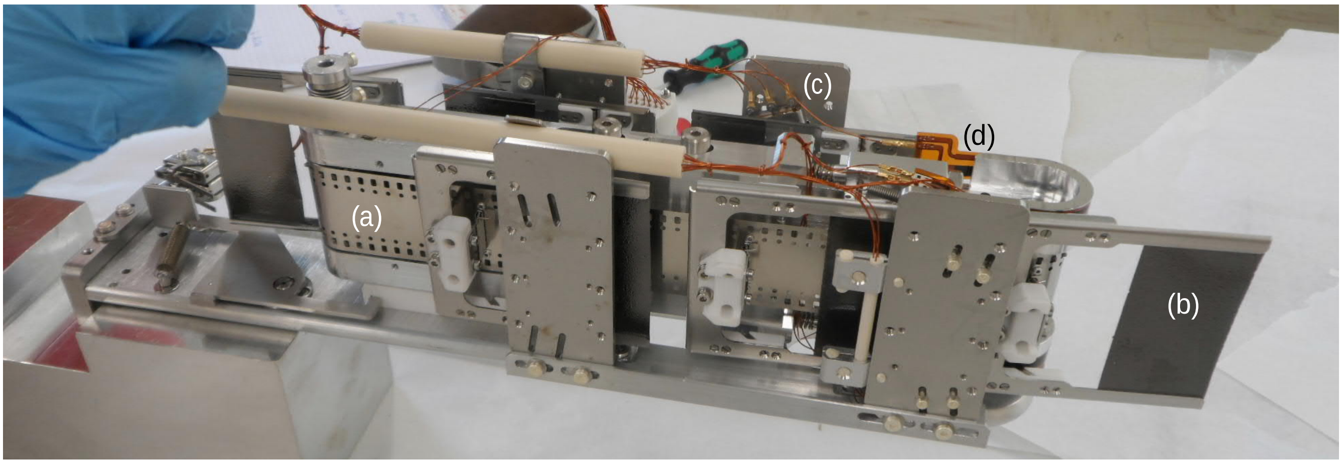


Fig. 1. The stripping foil exchange mechanism showing the rotating stainless steel belt (a), the holders with stripping foils attached (b), the UHV compatible microswitches (c) and the membrane potentiometers (d).

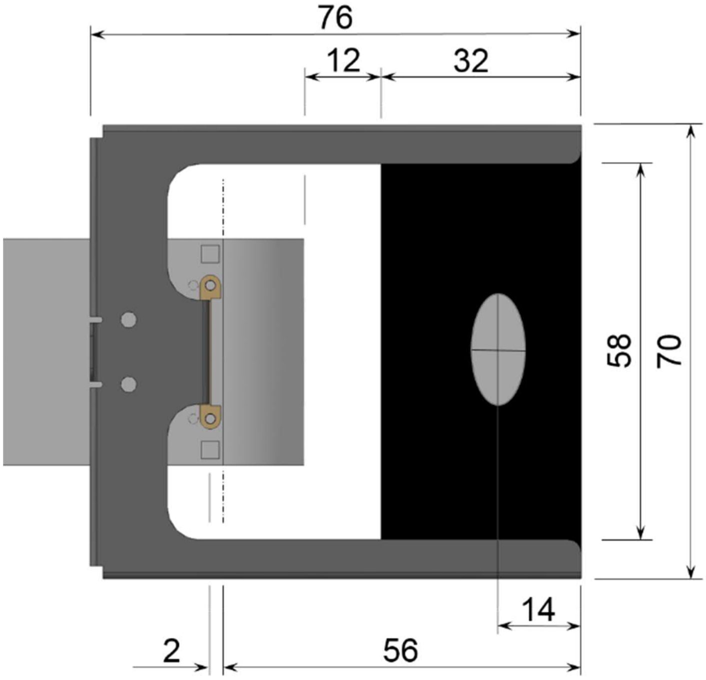


Fig. 2. Back view of the stripping foil holder attached to the rotating belt with foil dimensions for the PSB injection and an illustration of the beam stripping point.

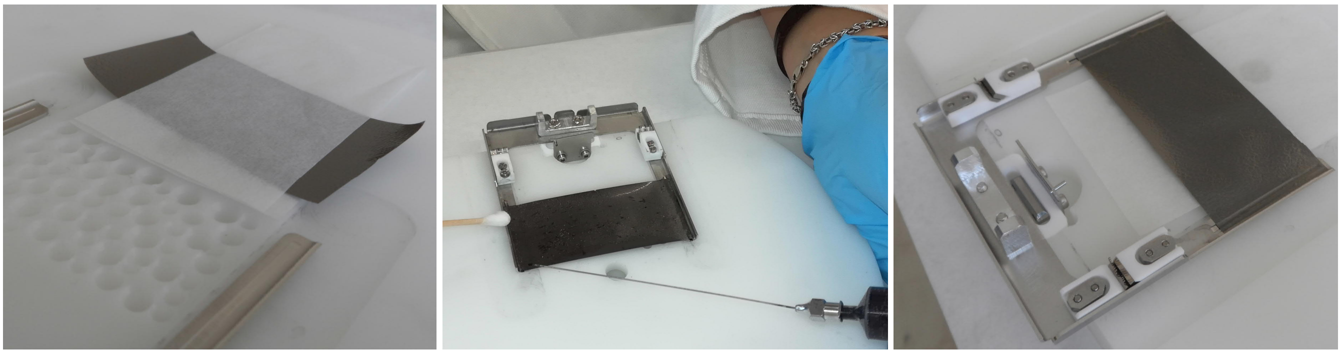
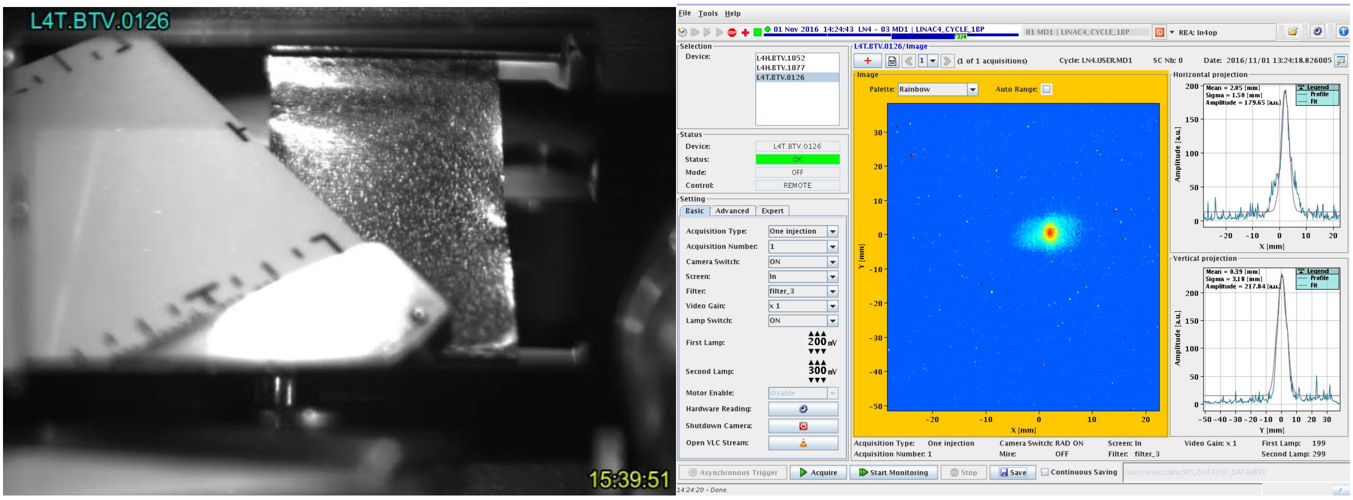


Fig. 3. Applied solution for handling and attaching foils to the holder showing the careful manipulation of the foils with protective paper on the left. The correct placement of the foil on the frame and applying a drop of Aquadag® solution in the dedicated grove is shown in the middle. The finished holder with the foil attached is shown in the picture on the right. This image also shows the wipers used for the membrane potentiometers to determine the precise position of the foil holder on the exchange mechanism.



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L4H.BTV.1077
L4T.BTV.0126

Status

Device: L4T.BTV.0126
Status: OK
Mode: OFF
Control: REMOTE

Setting

Acquisition Type: One injection
Acquisition Number: 1
Camera Switch: ON
Screen: In
Filter: filter_3
Video Gain: x 1
Lamp Switch: ON
First Lamp: 200 mV
Second Lamp: 300 mV
Motor Enable: disable
Hardware Reading:
Shutdown Camera:
Open VLC Stream:

L4T.BTV.0126/Image

1 (1 of 1 acquisitions) Cycle: LN4.USER.MD1 SC Nb: 0 Date: 2016/11/01 13:24:18.826005

Image

Palette: Rainbow Auto Range: ☐

Mean = 2.05 [mm]
Sigma = 1.50 [mm]
Amplitude = 179.65 [a.u.]

Mean = 0.39 [mm]
Sigma = 3.18 [mm]
Amplitude = 217.84 [a.u.]

Acquisition Type: One injection
Acquisition Number: 1
Camera Switch: RAD ON
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Screen: In
Filter: filter_3
Video Gain: x 1
First Lamp: 199
Second Lamp: 299

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Fig. 4. Image from the BTV camera on the left, showing the combined view of the stripping foil in the background and the Chromox scintillating screen of the BTV moving in front of it. The image on the right shows a screenshot of the BTV GUI control interface for operation and acquisition, showing a single bunch beam impact.

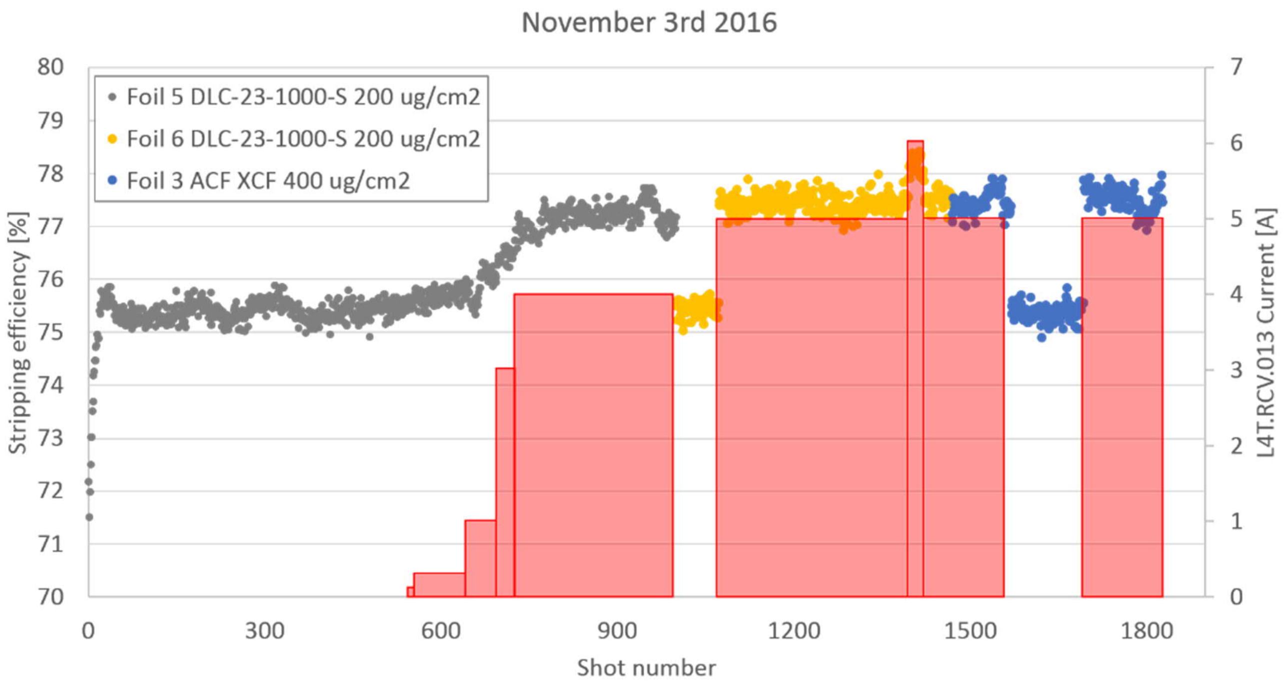

Fig. 5 Stripping efficiency for different foils and current of the vertical corrector (red squares) used as a spectrometer to remove the stripped electrons from the main beam

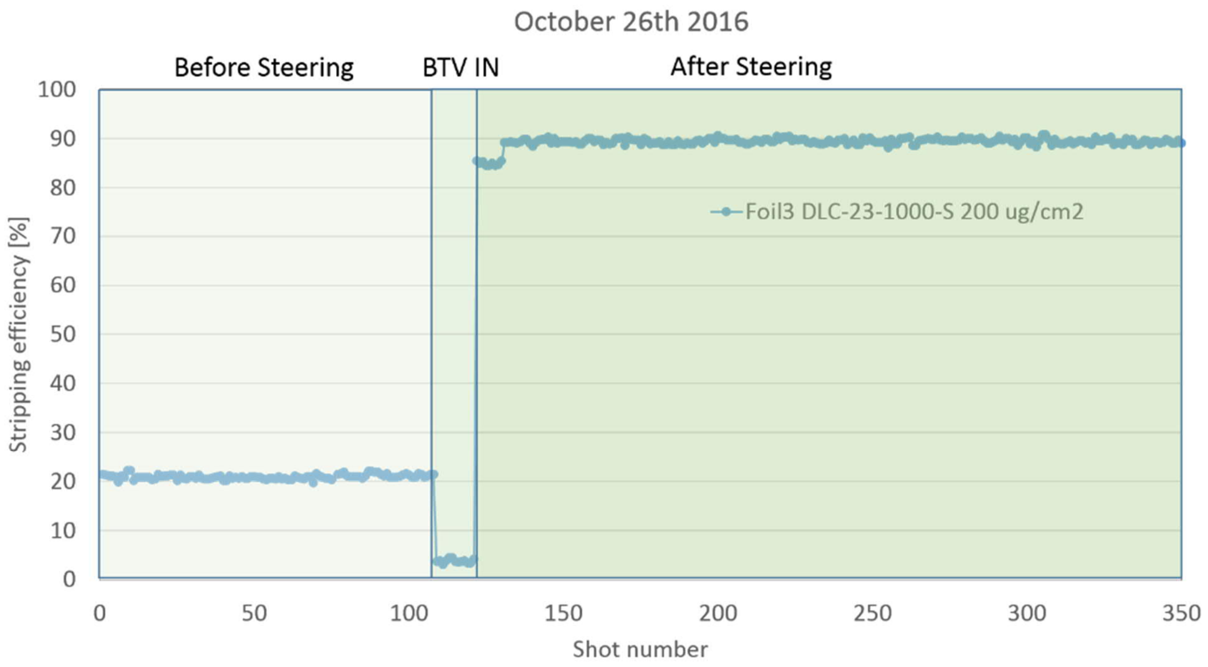

Fig. 6. Stripping efficiency for a foil in the half sector test. Three areas are highlighted and indicate the data before, after the steering and with the BTV intercepting the foil.