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Phase Space Painting and H$^-$ Stripping Injection

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Abstract
The achievable hadron beam density at injection can be limited by space charge or by the capacity of the injectors. Conventional multiturn injection allows the total intensity to be augmented but also determines a linear increase of the beam emittance with the number of injected turns and is characterized by high losses at the septum. These limits can be overcome with the H$^-$ charge exchange injection technique and high-power beams can be produced. Combination with transverse or longitudinal phase space painting allows for control of the size and distribution of the injected particles and minimizes the number of foil hits for the circulating beam. In the following, the H$^-$ charge exchange technique is described in detail, together with the related hardware, main achievements, and complications.

Keywords
Multiturn injection; charge exchange; high power; stripping foil; phase space painting.

1 Introduction

As explained in Ref. [1], the beam density in hadron storage rings can be limited at injection by space charge or by the injector capacity. A way to overcome this limitation and attain higher bunch current is to accumulate particles by injecting several beam pulses, generally from a linac, into the same RF bucket. This method is called multiturn injection and can be applied when the acceptance of the receiving machine is larger than the delivered beam emittance. The injected and circulating beam cannot be overlapped in phase space. Multiturn injection is then often also described as ‘phase space painting’, since the injected bunches are positioned in different spots of the transverse or longitudinal phase space of the ring to generate the desired beam distribution. Conventional multiturn injection employs a septum with a programmed orbit bump, which brings the circulating beam close to the septum blade. The closed orbit is then adiabatically (i.e., slowly with respect to the synchrotron oscillations) moved away from the septum so that the early beam occupies the central region and the later beam the outer part of the acceptance. The main disadvantages of this technique consist in high beam losses due to the circulating beam hitting the septum and the small number of injected turns due to the limited acceptance. The achievable brightness is then restrained by the total accumulated intensity and the fact that the final emittance increases linearly with the number of injection turns.

In addition to conventional multiturn schemes, there are several more exotic injection techniques, devised to control and improve the properties of the stored beam. Charge exchange injection allows the injected (H$^-$) and circulating (p$^+$) beam to be overlapped in the same phase space area and then provides the only way to achieve low-loss multiturn injections (from 10% in the best case with conventional multiturn injection down to 0.02% for charge exchange injection) and stack many small bunches over several turns without a linear increase of the emittance, e.g., allowing the production of high-density beams.

2 H$^-$ charge exchange injection

Charge exchange injection was applied for the first time at the end of the 1960s; examples of pioneering experiments can be found in Refs. [2–4]. The roadmap of the achieved and target beam powers for the

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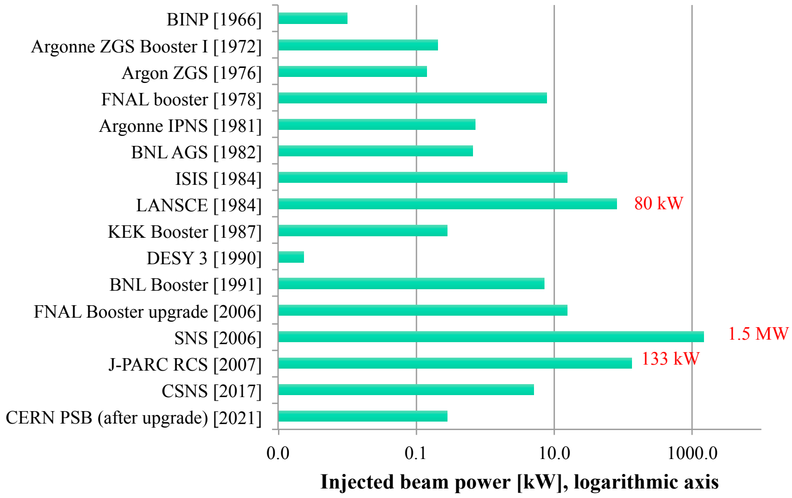

Fig. 1: Roadmap of the achieved and goal beam power for the main facilities using H^- charge exchange injection

main facilities that use H^- charge exchange injection is shown in Fig. 1. In particular, the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory leads, with 1.5 MW power beams.

In general, the charge exchange is performed by stripping two electrons, by means of thin stripping foils, from an H^- ion and transforming it into a proton (p^+). The closed orbit of the circulating beam is bumped onto the injection orbit using a set of chicane magnets located around the stripping foil, as shown in Fig. 2. The fully stripped p^+ follows the closed orbit while the partially (H^0) and unstripped (H^- ions are dismissed. Additional fast bumpers, installed in the ring lattice, are used to perform transverse phase space painting by changing the closed orbit, in a programmed way, during the injection process. This allows the size and the distribution of the beam to be controlled. The final size of the beam is defined by the distance between the injected H^- beam and the closed orbit at the location of the foil: the closer the foil, the smaller the beam. Ideally, in the absence of space charge, perfectly hollow, very dense, or smooth and uniform distributions could be obtained. In reality, the final particle distribution is determined by both the painting and the filamentation due to space charge. The fact of being able to overlap the injected and circulating beams in phase space and the space charge mitigation obtained by painting the beam in an almost uniform way allow much higher densities to be achieved than with conventional multiturn injection. The closed-orbit bump decay is also important to minimize the foil hits, which could determine foil heating, losses, or emittance blow-up due to scattering. Longitudinal painting can also be performed by modulating the energy and the energy spread of the injected beam to further reduce the charge density.

In the following, two examples of H^- charge exchange injection systems are described: those of the SNS and the future CERN Proton Synchrotron Booster (PSB).

2.1 SNS injection system

The SNS accelerator complex comprises an H^- source, a 1 GeV linac, an accumulator ring, and a liquid mercury target for spallation neutron production [5]. The accumulator ring delivers 0.7 μs pulses of $\sim 2\times 10^{14}$ particles and delivers them at a rate of 60 Hz to the target. Owing to the high power of the beam, care must be taken to ensure hands-on maintainability of the ring components by minimizing uncontrolled losses of the proton beam. The H^- beam is transferred from the linac, stripped by the foil, and then injected into the ring. A fixed horizontal chicane is installed around the stripping foil and assures adequate clearance during the full injection process. Eight symmetrically placed horizontal (four) and vertical (four) dynamic kickers are installed, in pairs, immediately upstream and downstream of the

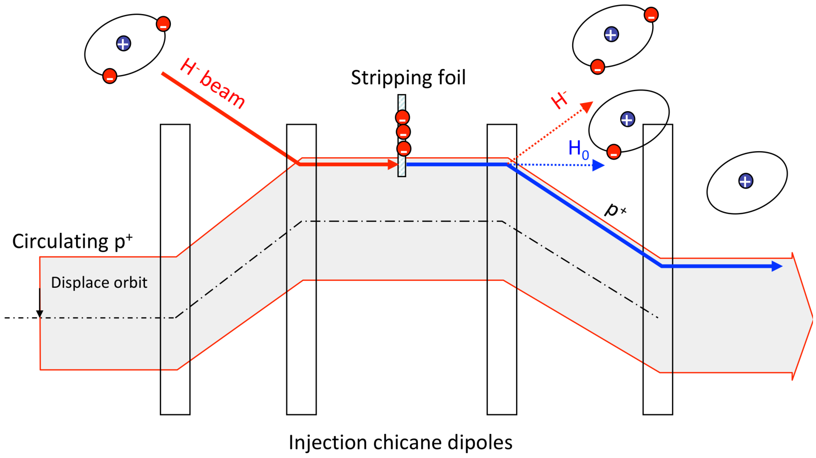

Fig. 2: Magnetic chicane installed around stripping foil. Varying the amplitude of the orbit bump during the injection process enables transverse phase space painting while avoiding excessive crossings, which might induce losses, foil heating, or emittance blow-up.

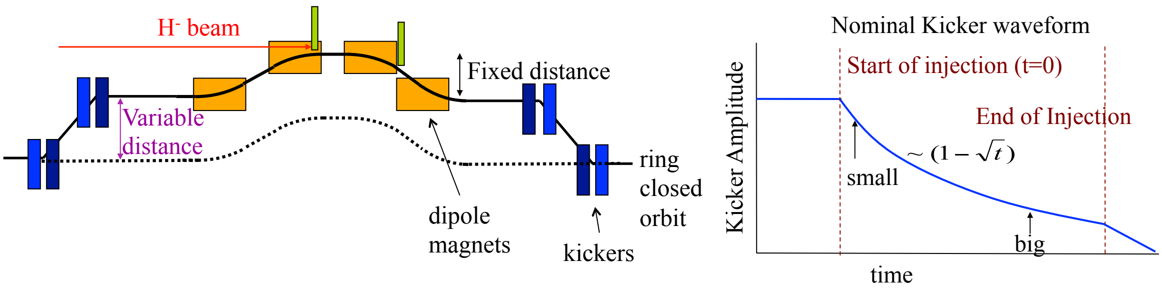

Fig. 3: Layout of the H$^-$ charge exchange injection system used at SNS (left). Four dipoles (orange) are used to create the fixed injection chicane. Four horizontal and four vertical fast bumpers (light and dark blue) are powered with a current decaying in time proportionally to $1-\sqrt{t}$ (right) and provide a correlated transverse painting in both planes.

chicane, as shown in the left panel of Fig. 3. They provide the variable amplitude bump (Fig. 3, right) to perform the transverse phase space painting, in both planes, which gives the desired transverse density and beam profile at the target. The painting allows an average of eight foil hits per particle to be achieved during the full accumulation (>1000 turns). Longitudinal painting is also performed, by manipulating both the energy and the energy spread, to fill the phase space as uniformly as possible and reduce the longitudinal halo [6]. The SNS system separates transverse and longitudinal phase space, since injection occurs in a dispersion-free section of the ring.

2.2 PSB injection system

The PSB at CERN has to provide beams with different emittance and intensity to several users. The goal is to produce, after the upgrade, which will occur during the 2019–2021 long shutdown [7], high-brightness beams for the LHC (1.7×10^{12} p$^+$ in <1 µm r.m.s. normalized emittance) and high-intensity beams for fixed-target experiments (up to 2×10^{13} p$^+$ in 8×13 µm r.m.s. normalized vertical and horizontal emittance respectively). Linac2, which is currently injecting 50 MeV p$^+$ into the PSB, will be replaced with Linac4, with the goal of providing 600 µs pulses of up to 5×10^{13} 160 MeV H$^-$ ions. The PSB consists of four superimposed rings and, for each ring, the present conventional multiturn injection

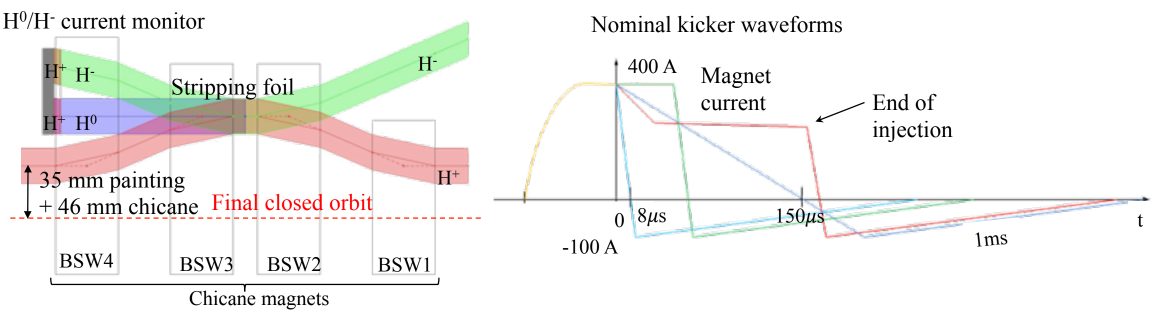

Fig. 4: Layout of the future H^- charge exchange injection system for the PSB (left). In this case, the injection bump is defined, only in the horizontal plane, by the chicane magnets and four kickers installed in the ring lattice. Different painting schemes can be obtained, by variable modulations of the current of the kickers, for the various users (right).

system will be replaced with charge exchange injection. This will contain a horizontal fixed chicane and a stripping foil (Fig. 4, left). A current monitor will be installed in front of the injection dump to measure the stripping efficiency of the foil. Four horizontal kickers, installed in the ring lattice, will be used for the transverse phase space painting [8]. No painting will be applied in the vertical plane but the injected beam will be steered, in the transfer line, to a fixed vertical offset. Different waveforms will be used for the horizontal painting, according to the requirements of the various users (Fig. 4, right). The bump will stay constant for small-emittance beams, while a multilinear decay will be applied for the fixed-target experiments. An initially fast decay must be followed by an almost constant slope to fill first the centre and then the outer area of the phase space, reducing the charge density in the core and thus the space charge effects. The accumulation will be completed in a maximum of 150 turns. Once injection is finished, the circulating beam must be moved away from the foil, as quickly as possible. A negative bump is implemented to limit the interactions with the foil during the slow decay of the injection chicane. Longitudinal painting will be performed only for the high-intensity beams. The dispersion is non-zero in the PSB injection region; the longitudinal painting affects the transverse painting and constrains the minimum size of the stripping foils [9].

3 Stripping foils

Stripping foils are the best technology available today for charge exchange injection into storage rings and synchrotrons. Standard foils are commercially available but, in some cases, as for SNS, owing to the extremely high power of the handled beams, special designs are needed, which require in-house fabrication. The foils must be at the same time thick enough to ideally strip off all the electrons from the H^- ions but also thin enough to minimize the effect on the circulating beam (i.e., minimize scattering and energy loss). Foils can sometimes get very hot so they should be made of materials with a high melting point. When foils can be supported only from one side, to avoid any extra material that might be intercepted by the beam, they must be self-supporting. Amorphous or diamond carbon, with a density range of $\rho = 1.7–2\ \mathrm{g/cm^2}$, provides a good material for stripping foils, owing to its thermal stability, high sublimation temperature, and radiation and mechanical resistance. The stripping efficiency of a carbon foil depends on the energy of the H^- ions and the foil thickness. The absolute yield of H^-, H^0, and p^+ can be calculated as [10]:

$$H^-(x) = \exp[-n(\sigma_{-0} + \sigma_{-+})x]; \tag{1}$$

$$H^0(x) = \frac{\sigma_{-0}}{\sigma_{-0} + \sigma_{-+} - \sigma_{0+}}\{\exp(-n\sigma_{0+}x) - \exp[-n(\sigma_{-0} + \sigma_{-+})x]\}; \tag{2}$$

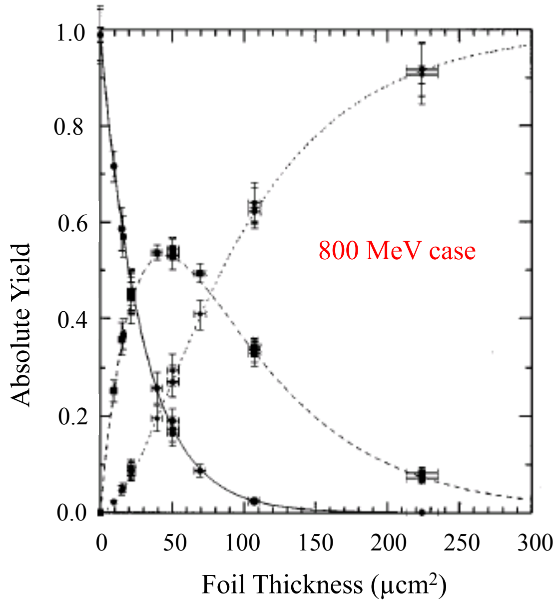

Fig. 5: Absolute yield of H$^-$, H^0, and p$^+$ as a function of the carbon foil thickness for an 800 MeV beam [10]

$$H^-(x) = 1 - H^-(x) - H^0(x)\ . \tag{3}$$

Here, x is the foil thickness and σ_{-0} and σ_{-+} are the cross-sections for one- and two-electron stripping of H$^-$ respectively, σ_{0+} is the cross-section of one-electron stripping for H^0 and $n = \rho N_0/A$ is the foil density in atoms per unit volume, N_0 being Avogadro's number and A the atomic mass number of the foil atoms. The relative curves, for an 800 MeV beam, are shown in Fig. 5. In the PSB, owing to the lower energy, 200 µg/cm^2 thick foil should guarantee that ~100% of the electrons are stripped. Foils with a thickness of 300 µg/cm^2 are used at SNS and provide ~97% stripping efficiency for the 1 GeV beam. Despite the lower stripping efficiency, thicker foils are not used, since they would increase the foil temperature and the radio-activation. Both inelastic and elastic nuclear scattering processes are assumed to result in uncontrolled loss of the impacting protons. The probability of scattering per foil traversal is:

$$P = \left(\frac{2Zm_\mathrm{e}r_\mathrm{e}}{\gamma M\beta^2}\right)^2 N_0\left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]; \tag{4}$$

where Z is the atomic number, t the foil thickness, m_e and r_e the electron mass and classical radius, respectively, and M the rest mass of the incident particles. In this formula, θ_{xl}^2 and θ_{yl}^2 define the limiting angles above which a scattered particle is lost and can be written as:

$$\theta_{xl}^2 = \left(\frac{X_A}{\beta_{fx}}\right) \tag{5}$$

and

$$\theta_{yl}^2 = \left(\frac{Y_A}{\beta_{fy}}\right). \tag{6}$$

X_A and Y_A are the horizontal and vertical acceptance of the machine and $\beta_{fx,fy}$ the β-functions at the foil. For very thin foils, losses due to single large-angle scattering have a significant probability (much higher than from a Gaussian distribution).

Beside the losses, thick foils might induce unwanted emittance blow-up through multiple-Coulomb scattering (mainly an issue for high-brightness beams, such as those at LHC) and foil heating

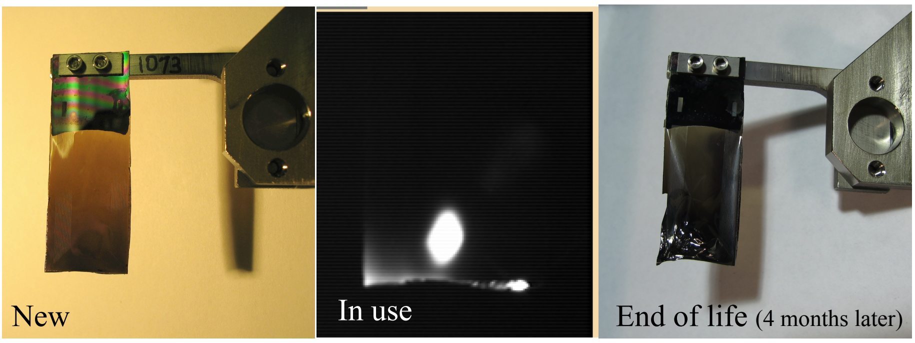

Fig. 6: Nanocrystalline diamond foil used at SNS when new, during, and after 4 months of operation

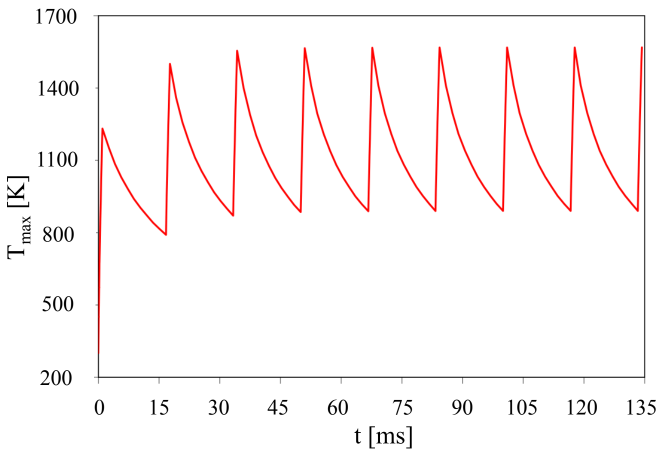

Fig. 7: Calculated temperature fluctuations at the SNS foil when operating with a 1 GeV, 1.5 MW beam

via ionization and electron excitation energy loss of the impacting protons and stripped electrons [10]. High temperature and thermal stress constitute two of the biggest issues for the foil lifetime and pose limits to the maximum achievable beam power. Figure 6 shows images of a nanocrystalline diamond foil, new, during, and after four months of operation in the SNS facility. It is calculated that temperature fluctuations of the order of 600 K can be achieved when operating with the 1.5 MW SNS beam (Fig. 7). In reality, foil temperatures are very hard to model, calculate, or measure. In fact, emissivity, heat capacity, and thermal conductivity are not well known at these high temperatures. The energy deposition is not well known either. The exact number of foil hits per injected proton, the deposited energy when H^- particles break up while passing through the foil, and effects such as knock-out electrons (delta rays) caused by relativistic p^+ striking the foil need to be known to correctly evaluate the total energy deposition. Measurement techniques are under development but are also challenging, since the heating process is very fast (the peak temperature only lasts for tens of microseconds). It was possible to observe, while operating at 800 kW, that the SNS foil was turning white, indicating a temperature >1700 K, i.e., higher than calculations. Sublimation is one of the biggest risks for stripping foils. At 2200 K, carbon sublimates at a rate of about 1 µm/h and foils have a typical thickness of 1–2 µm. The sublimation rate is a strong function of the temperature and small increases determine a dramatic change in the foil lifetime (four orders of magnitude for a 300 K temperature increase).

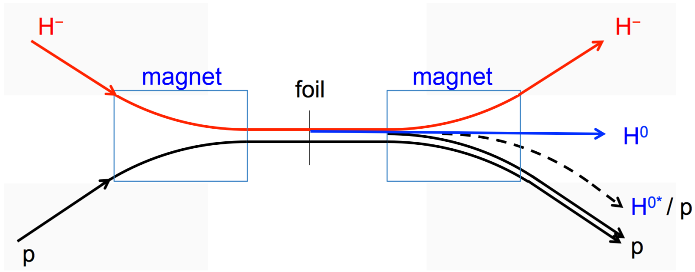

Fig. 8: Possible trajectories of H^{0*} atoms when then decay into p^+, owing to the effect of the magnetic field. If their trajectory is outside of the ring acceptance, these particles are lost [11].

4 Beam losses caused by H^0 excited states

The neutral hydrogen atoms emerging from the foil are in a distribution of excited quantum states H^{0*} according to the $n^{-2.8}$ law where $n = 1, 2, 3, \ldots$ is the principle quantum number of the H^0 atoms. When they pass through a magnetic field, for example of the injection chicane dipoles, they see an electric field due to the relativistic transformation $E = \gamma\beta c B_{\mathrm{lab}}$ (Fig. 8). This electric field can strip off the electron and, if the newly created proton is outside of the acceptance of the machine, it will create beam losses. This phenomenon was observed for the first time in 1993 by Hutson and Macek at the Los Alamos Proton Storage Ring (PSR) [12] and causes, at present, 15–20% of the total beam loss, corresponding to 23–40 W. Such a loss level would be catastrophic for the SNS, since it would correspond to 2.85 kW. The SNS design was made taking this process into account; the stripping foil is located in the falling fringe field of a magnet. In this way, high n states ($n \geq 6$) are short-lived and are Lorentz-stripped immediately after the foil and captured into the ring acceptance, along with the fully stripped protons. The low n states ($n \leq 3$) are long-lived; they can be transported along with the ground state H^0 into the injection dump and are controlled losses. The intermediate, $n = 4$ and $n = 5$, states have the potential of decaying, in the magnetic field, far enough downstream from the injection foil that their resultant deflection puts them on trajectories that do not lie within the ring acceptance. About 0.01% of them are lost. For these considerations, the choice of foil thickness should also take into account the H^0 excited states [10].

5 Control of 'convoy' electrons

Positioning the foil inside the fringe field of a magnet also has the advantage of directing the stripped, also called 'convoy', electrons to a dedicated electron catcher (Fig. 9) [11]. At J-PARC the convoy electrons carry a design power of about 145 W; these are directed to a water-cooled block of graphite by the fringe field of one of the chicane dipole magnets. At the SNS, these particles carry 1.6 kW and hence must be properly controlled to avoid damaging the equipment surrounding the foil. A water-cooled carbon–carbon electron collector is installed at the bottom of the vacuum chamber to intercept and trap these electrons. In reality, owing to a combination of fabrication errors and modifications of the foil mount position, in the original design some electrons were reflected back up and hit the foil and the bracket, which, after 3 months of operation, was damaged (Fig. 10). Evidence of softening, sag, and sputtering of the titanium bracket were observed. A new design was proposed, with brackets made of titanium-zirconium-molybdenum alloy. This alloy has a high sublimation temperature, low sputtering yield, and high sputtering threshold; no damage was observed after 16 days of operation with 1.3–1.4 MW beams. The main disadvantage of this material is a higher residual radioactivity. The electron catcher also showed signs of damage, confirming the hazard of the convoy electrons; a new upgraded design is presently under development.

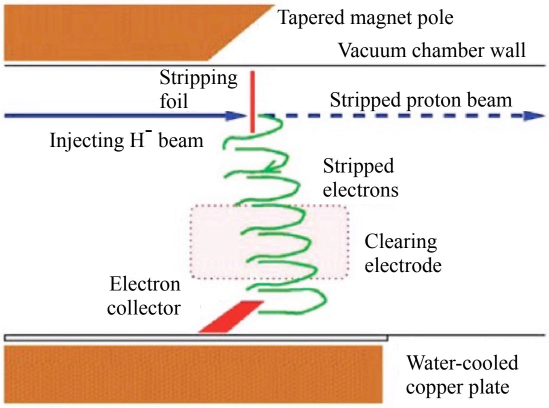

Fig. 9: The SNS stripping foil is installed inside one of the injection chicane magnets to drive the convoy electrons towards an electron catcher [13].

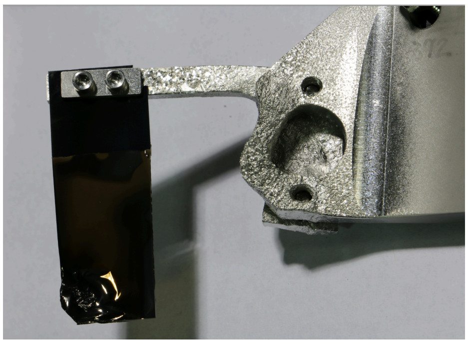

Fig. 10: Foil and bracket damaged by convoy electrons reflected back up from the catcher after 3 months of operation at 1.1–1.4 MW [11].

6 Main lessons

For hadrons, the beam density at injection can be limited by space charge or by the injector capacity. Transverse phase space painting allows the total stored intensity to be augmented but the final emittance increases linearly with the number of injected turns and high losses occur at the septum unless charge exchange injection is used. The combination of charge exchange injection and transverse phase space painting enables control of the size and distribution of the injected particles and the production of high-intensity and high-brightness beams while minimizing the foil hits for the circulating beam. Longitudinal painting, performed by modulating the energy during the injection, permits further reduction of the charge density and thus the space charge effects.

Stripping foils are the best technology available today for charge exchange injection. They need to be thick enough to maximize the stripping efficiency but, at the same time, thin enough to minimize losses and energy loss through scattering processes. The robustness and lifetime of the foils determine the main limitation to the presently achievable beam power. Other complications include need of a careful handling of the stripped electrons and H^0 excited states to avoid damage of the equipment surrounding the stripping foil.

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