H^- CHARGE EXCHANGE INJECTION ISSUES AT HIGH POWER*

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Abstract

At low beam powers H^- charge exchange injection into a storage ring or synchrotron is relatively simple. A thin stripper foil removes the two "convoy" electrons from the H^- particle and the newly-created proton begins to circulate around the ring. At high beam powers there are complications due to the heat created in the stripper foil, the power in the H^0 excited states, and the power in the convoy electrons. The H^- injected beam power at the Oak Ridge Spallation Neutron Source is the highest in the world. Although the SNS ring was carefully designed to operate at this level there have been surprises, primarily involving the convoy electrons. Examples include damage to the foil brackets due to reflected convoy electrons and damage to the electron collector due to the primary convoy electrons. The SNS Second Target Station project calls for doubling the beam power and thus placing even more stress on the charge-exchange-injection beam-line components. In this presentation we will compare charge-exchange-injection designs at high-power facilities around the world, discuss lessons learned, and describe the future plans at SNS.

INTRODUCTION

Charge exchange injection (CEI) is important because it is the only way to achieve low-beam-loss multi-turn injection into a storage ring or synchrotron. Accelerators that do not use CEI for multi-turn injection lose about 10% of the beam due to injection inefficiency. This may not be a problem for low injected beam powers, but for today's high-power storage rings and synchrotrons it makes anything other than CEI infeasible. Additionally CEI allows the newly injected beam to be deposited inside the phase space of the circulating beam, thus reducing the final emittance. Without CEI, $\varepsilon_{TOTAL} > N * \varepsilon_{INJECTED}$, where N is the number of turns injected. With CEI, $\varepsilon_{TOTAL} << N * \varepsilon_{INJECTED}$.

The only practical way today to achieve CEI is by using stripper foils. Alternative technologies such as a flowing sheet of mercury, or gas jets, are only applicable in special cases. Laser stripping is a promising technology but it is not ready yet.

At the Oak Ridge Spallation Neutron Source the injected H^- beam power is 1.5 MW – more than a factor of 10 higher than any other H^- injection system. The SNS has a unique arrangement of stripper foils and bending magnets to mitigate the inevitable complications of high power injection. Overall the SNS CEI system works well, but we have encountered some surprises as we have been working to increase the beam power to the design value of 1.4 MW on target.

BRIEF HISTORY OF CEI

Multi-turn CEI was invented and first demonstrated at BINP in Novosibirsk in 1966 [1]. A 1 MeV H^- ion beam was first stripped to H^0 by a CO_2 gas jet, then drifted through one of the ring dipole magnets, then stripped to H^+ by a hydrogen gas jet. The first experiments with this technique were amazingly productive and innovative, and produced results that impacted both proton beam injection and high intensity proton beam dynamics for many years.

The first use of a stripper foil for CEI was at the ZGS Booster project at ANL in Argonne in 1972. The stripper foils were 36 x 100 mm^2 pieces of 35 μm-thick polyparaxylene mounted to a disk rotating at 1800 rpm, with the rotation synched to the booster injection cycle such that the foil was only in the path of the beam during injection. It is ironic that the world's first stripper foil mechanism was also the most complicated – but it worked very well. The expected lifetime of these foils was just two hours – so even from the very first use of stripper foils lifetime was an issue. A graphical history of CEI beam powers around the world is shown in Fig. 1. The three highest H^- injected beam powers are for the Los Alamos PSR (80 – 100 kW), J-PARC RCS (133 MW design), and SNS (1.5 MW design).

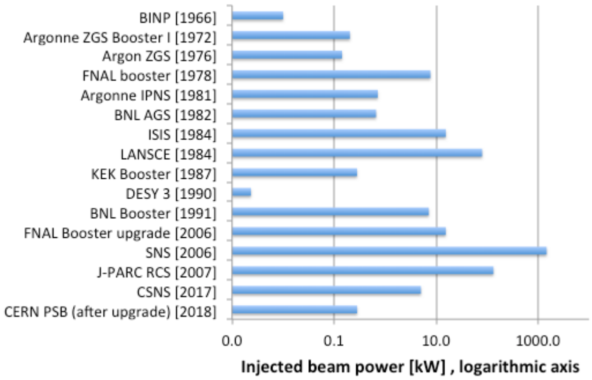

Figure 1: Summary of H^- beam powers used for CEI, from the first use of CEI to future facilities.

COMPLICATIONS OF CEI

Complications of CEI include 1) beam loss caused by foil scattering, 2) stripper foil lifetime, 3) control and disposal of un-stripped and partially stripped beam, 4) beam loss caused by H^0 excited states, 5) control of the stripped (convoy) electrons. The first three complications have been well addressed by other authors and so they will be only briefly mentioned here.

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Beam Loss Caused by H^0 Excited States

When the H^- beam passes through the stripper foil, some of the beam emerging from the foil will be only partially stripped to H^0 particles if the foil is not thick enough to achieve 100% stripping efficiency. It is usually desirable to not have 100% efficiency because the foil would have to be so thick that it would cause excessive beam loss due to foil scattering, and because the foil might become too hot. Some of the H^0 particles will be in excited states (H^{0*}), with the electrons more loosely bound to the nucleus. The problem is that when these particles enter the magnetic fields of the storage ring or synchrotron the field is Lorentz-transformed to an electric field ($E = \gamma\beta B$) in the rest frame of the H^{0*} particles, and this E-field can cause the electrons to be stripped off. If this process occurs more than a few millimeters away from the stripper foil, the newly-created protons are likely to be outside the dynamic aperture of the ring, and they will be subsequently lost. If the beam power lost is more than a few Watts it can damage beam line components and cause excessive residual radiation. The excited state populations are distributed according to $n^{-2.8}$, where n is the principle quantum number of the H^0 state [2]. Figure 2 illustrates this process, and Fig. 3 shows the lifetimes of the excited states as a function of the electric field.

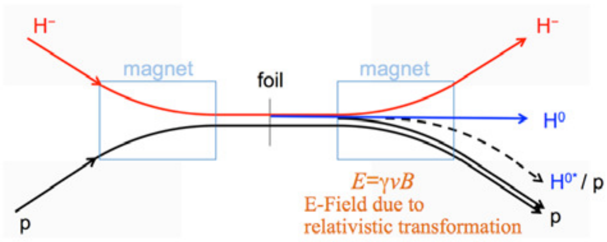

Figure 2: Illustration of H^{0*} states being created and then causing beam loss.

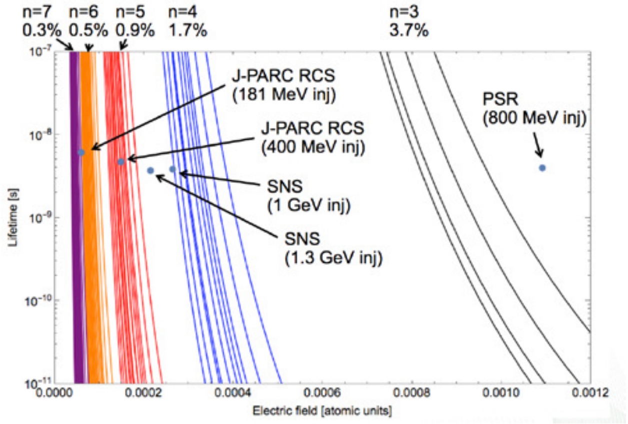

Figure 3: The H^0 excited state lifetimes vs. electric field, colored according to the principle quantum number n, with the relative populations also indicated. The operating points of today's highest power CEI injection systems are also indicated.

Beam loss caused by H^{0*} states was first discovered at the Los Alamos Proton Storage Ring [3]. Even after redesigning the PSR injection system beam loss due to H^{0*} states today still contributes 15 - 20% of the total beam loss (i.e. it causes 23 – 40 W beam loss), which is high enough to be barely tolerable. If the SNS did not take special measures to mitigate the H^{0*} beam loss we could expect about 2,300 W of loss, which is clearly intolerable.

Figure 3 illustrates the advantage of CEI at low beam energy. The J-PARC RCS is a nice example. Before the J-PARC linac was upgraded from 181 to 400 MeV, the only concern was H^{0*} states with $n > 6$, and after the upgrade the only concern is $n > 4$. Therefore only a small fraction of the H^{0*} states are susceptible to stripping. Low injection beam energy is a triple win because 1) the lower beam velocity leads to a smaller Lorentz transformation factor, 2) the B-fields are lower because the beam is less stiff, and 3) there is less power in the H^0 beam to start with. At J-PARC, even after the 400 MeV upgrade, the H^{0*} states cause less than 8 W of beam loss [4].

The SNS injection system was carefully designed to mitigate beam loss caused by H^{0*} states [5]. The key innovation [6] was to place the stripper foil inside one of the injection chicane magnets, as shown in Fig. 4. The field at the foil Lorentz transforms to an E-field high enough to immediately strip all the $n > 4$ states, and the following magnetic fields are, by design, too low to strip the $n < 5$ states. The net result is H^{0*} beam loss that is too low to accurately measure.

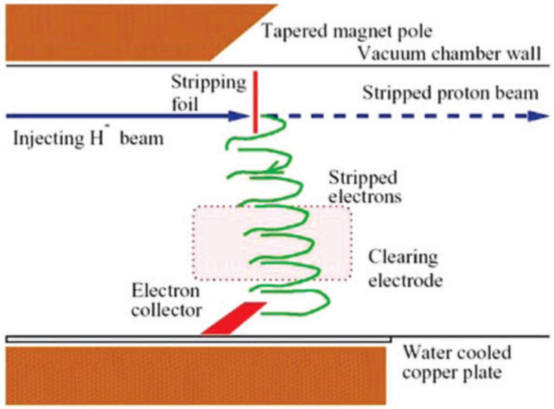

Figure 4: The SNS stripper foil inside one of the injection chicane magnets. Reproduced from ref [7].

Convoy Electrons

There are, however, some unintended consequences of placing the foil in a B-field. The most important one involves the convoy electrons stripped off the incoming H^- beam. At the design proton beam power of 1.4 MW on target, the convoy electrons carry 1.6 kW, and must therefore be carefully controlled. By design a water-cooled electron collector at the bottom of the vacuum chamber intercepts and traps these electrons, but in practice, due to a combination of fabrication errors and modifications to the injection point [8], the convoy electrons do not strike the electron collector at the optimum point. This results in reflected convoy electrons (RCE), which are trapped by the magnetic field and can travel back up to strike the stripper foil, the stripper foil bracket, and the vacuum chamber [9]. The initial consequences of this were not realized [9,10] until the SNS beam power was increased to about 840 kW. At that time the solution was to redesign the stripper foil bracket, with the biggest modifications being a material change from Aluminum to titanium, and moving the foil 1 cm further out on the bracket arm.

This solution worked well until the beam power was increased to more than 1.2 MW proton power on target, when new issues were discovered with the electron collector and the stripper foil brackets. Figure 5 shows a stripper foil and bracket removed in July 2014, after being used for three months at beam powers of 1.1 to 1.4 MW, including ~20 days at 1.3 to 1.4 MW. The reflected convoy electrons heated the titanium enough to cause it to soften and sag, and there is also evidence of the titanium material being sputtered off.

Figure 5: An SNS stripper foil bracket showing damage due to reflected convoy electrons. Photo by Chris Luck.

The long term solution involves replacing the electron catcher and the associated vacuum vessel, but until this can be done we are testing a new type of bracket made of TZM (an alloy of 0.50% Titanium, 0.08% Zirconium and 0.02% Carbon with the balance Molybdenum). We chose this material after expanding our requirements to include 1) high sublimation temperature, 2) high sputtering threshold, and 3) low sputtering yield. The high sublimation temperature means the material can withstand higher operating temperatures. The high sputtering threshold means that the electrons striking the bracket must be very high energy before they can cause any sputtering, and the low sputtering yield means that in the event any sputtering does occur there will not be very much of it.

Of course there are also some drawbacks. TZM has a high density (10.2 g/cm^3) and high atomic numbers. It is therefore relatively heavy, which presents some difficulties for our stripper foil changer. The residual radioactivity will also be greater than for our light-weight, low-atomic-number titanium brackets.

Figure 6 shows a photograph of the TZM bracket that has seen our highest beam powers to date. It was used for about 16 days at 1.3 to 1.4 MW proton beam powers on target. There is almost zero damage to the bracket. We are now in the process of expanding our use of this bracket type, and we plan to install four of them this summer.

Figure 6: A TZM bracket used at 1.3 to 1.4 MW for about 16 days. Photograph by Chris Luck.

The electron catcher is also showing signs of damage due to convoy electron impact. It is made of carbon-carbon, and it showed very little signs of damage until we increased our beam powers to above about 1 MW on target. Figure 7 shows a photograph of the electron collector in 2012 (highest beam power before this photo was 1.08 MW). The electron collector comprises five undercut wedges. By design the convoy electrons should strike the undercut face of the middle wedge, such that any reflected electrons will be directed down on to another wedge, and also such that the low-energy secondary electrons will have very small gyro-radii and will consequently be trapped underneath the wedge.

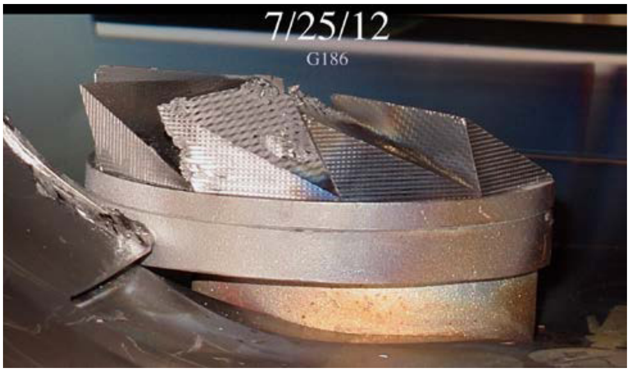

Figure 7: A photograph of the electron collector in 2012. Photograph by Chris Luck.

As we alluded earlier, due to a combination of fabrication errors and modifications to the injection point, the convoy electrons tend to strike center wedge on the top rather than the undercut face. This increases the probabil-

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ity that reflected convoy electrons will travel back up into the vacuum chamber to cause problems.

Figures 8 and 9 show two more photographs of the electron collector taken in July 2015 and January 2016. From these photographs it is evident that substantial damage occurred in just six months. During those months the beam power on target was typically in the 1.3 to 1.4 MW range.

Figure 8: The electron collector in July 2015. Photograph by Chris Luck.

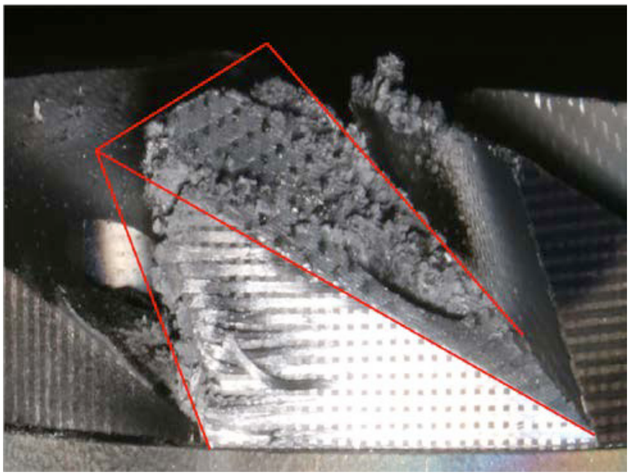

Figure 9: The electron collector in January 2016. The red lines show the approximate outline of the original undamaged wedge. Photograph by Chris Luck.

We are now in the process of redesigning the electron collector and the vacuum chamber that it sits in. The new vacuum chamber will have an additional view port to illuminate the stripper foil, and there will be provisions to allow the relative positions of the foil and the collector to be adjusted for optimum efficiency. The electron collector itself may also be redesigned to accommodate a wider range of convoy electron trajectories and to function with a higher electron power.

The SNS is the only accelerator that suffers from high convoy electron power. At the Los Alamos PSR the electron power at the primary stripper foil is 90 W, and no special accommodation was made for them during the design process. The electrons happen to strike the side of the vacuum chamber a short distance downstream of the foil, near the midline of the beam pipe, and they have created some discoloration in the pipe but there does not seem to be any other bad consequences. At the J-PARC RCS the convoy electrons carry a design power of about 145 W, they are directed to a water cooled block of graphite by the fringe field of the dipole magnet just upstream of the stripper foil, and this is working well.

Of course there are also the electrons stripped off by the secondary stripper foil (and tertiary foil at J-PARC). These foils strip any H^- beam that misses the primary foil, and any H^0 beam that does not get Lorentz-stripped as H^{0*} states. At PSR there is typically only ~2 W in these electrons, and at J-PARC there is just ~0.2 W. Their powers are too low to be of much concern. At SNS the power in the convoy electrons at the secondary stripper foil is about 64 W, which is high enough to be of concern. However, no special measures are taken to dump these electrons in a controlled location, and they have not caused any obvious problems to date. They probably strike the beam pipe a short distance downstream of the secondary foil after being deflected in the weak fringe field of the downstream chicane magnet.

SECOND TARGET STATION UPGRADE

The Second Target Station (STS) upgrade calls for increasing the beam energy to 1.3 GeV and increasing the beam power at the exit of the ring to 2.8 MW (the beam current also increases). These parameters will place additional demands on the ring injection section. The modifications for the injection section magnets are discussed in [11]. The convoy electron power will increase to ~3.2 kW at the primary stripper foil and ~130 W at the secondary stripper foil. This further increases the urgency of redesigning the primary electron collector to function with greater efficiency and also to be able to withstand higher power.

The STS design calls for carefully placing the secondary foil in the fringe field of the downstream chicane magnet. The field at the foil must be weak enough that the convoy electrons do not circle back and repeatedly pass through the foil. This could cause overheating of the foil in a manner similar to the charge-exchange extraction issues at TRIUMF [12]. Due to the limited space available for the chicane magnets in the upgraded design there is magnetic field overlap at the location of the secondary foil. Hence a few centimeters either upstream or downstream is enough to have a significant impact on the convoy electron trajectories at the secondary stripper foil.

The STS primary foil will have to be about 8% thicker to strip with the same efficiency at the higher beam energy. The optimum thickness of the nanocrystalline diamond foils in use today is ~0.38 mg/cm^2, so the new foils will be ~0.41 mg/cm^2. The operating temperature will therefore increase for two reasons – the higher beam current and the thicker foil. The higher beam energy is actually a mitigating factor since the proton stopping power is about 5% less at 1.3 GeV compared to 1.0 GeV.

Based on finite element analysis simulations [13] we expect the maximum temperature of the hottest place on the stripper foil to increase by ~300 K. It is an open question about the impact of this temperature increase because absolute temperature simulations contain so many uncertainties (e.g. the effect of knock-on electrons, emissivity and specific heat at very high temperatures, the thermal parameters of nanocrystalline diamond vs. natural diamond, etc.). The relative temperatures are however more reliable. Figure 10 shows a plot of the sublimation rate for carbon as a function of temperature. Sublimation is the most important limiting factor for the SNS stripper foil lifetime. If the foil becomes too hot its thickness will decrease until it is too thin to achieve high stripping efficiency. The nominal STS stripper foil has an areal density of 0.41 mg/cm^2, corresponding to a physical thickness of ~1.3 μm. After a thickness decrease of about 10%, or ~0.13 μm, the stripping efficiency will drop off enough that the foil will need to be replaced. Our best estimates today predict a maximum foil temperature of ~1850 K, and the corresponding sublimation rate is ~0.001 μm/h, so the predicted lifetime is about 130 hours if the foil temperature is constant in time. However due to the 60 Hz pulse structure of the beam the temperature of the foil at the hottest location fluctuates by hundreds of degrees K.

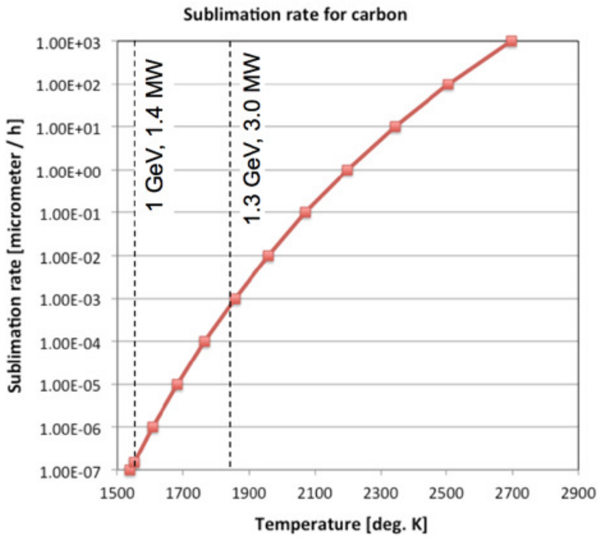

Figure 10: Sublimation rate for carbon as a function of temperature. Also indicated are the approximate expected foil temperatures at 1.0 GeV, 1.4 MW and 1.3 GeV, 3.0 MW beam parameters.

As shown in Fig. 10 the sublimation rate is a sharp function of temperature. A 100 K temperature change causes the sublimation rate to change by about one order of magnitude. We therefore expect that our STS stripper foils will last much longer than 130 hours. However we must keep in mind that this estimate has a large error bar.

To improve the accuracy of our simulations we are working to make an absolute temperature measurement of the stripper foils in use today, and then use the results to benchmark our simulations. Once this is done we will be able to confidently predict what the SNS-STS foil temperature will be.

SUMMARY

Multi-turn charge-exchange injection is a necessary and important component in today's storage rings and synchrotrons. CEI at high power has challenges with beam loss, stripper foil survival, and convoy electron damage. Today's accelerators have addressed these challenges, but complications continue to arise as beam powers are increased. The Second Target Station project at SNS will provide further interesting challenges.

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