SNS INJECTION FOIL EXPERIENCE

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Abstract

The Spallation Neutron Source comprises a 1 GeV, 1.4 MW linear accelerator followed by an accumulator ring and a liquid mercury target. To manage the beam loss caused by the H^0 excited states created during the H^- charge exchange injection into the accumulator ring, the stripper foil is located inside one of the chicane dipoles. This has some interesting consequences that were not fully appreciated until the beam power reached about 840 kW. One consequence was sudden failure of the stripper foil system due to convoy electrons stripped from the incoming H^- beam, which circled around to strike the foil bracket and cause bracket failure. Another consequence is that convoy electrons can reflect back up from the electron catcher and strike the foil and bracket. An additional contributor to foil system failure is vacuum breakdown due to the charge developed on the foil by secondary electron emission. In this paper we detail these and other interesting failure mechanisms and describe the improvements we have made to mitigate them.

INTRODUCTION

The Spallation Neutron Source accelerator [1] comprises a 1 GeV, 60 Hz, H^- ion beam linac with a 1.5 MW design beam power, followed by an accumulator ring with charge-exchange injection to compress the 1 ms long pulses from the linac to ~700 ns. The present beam power is typically about 1 MW at 925 MeV. Corrugated nanocrystalline diamond stripper foils [2] have been in use from the beginning of formal operations in 2006. These foils were successfully used with no failures until May 3, 2009, shortly after increasing the beam power to ~840 MW. The first failure was quickly followed by two more, and the beam power was reduced to ~430 kW to prevent further foil system failures, and then to ~400 kW two days later after another failure. A mid-cycle foil change (a first for SNS) was executed on May 19, 2009 using a modified foil bracket, but the foil system continued to fail.

A team was assembled to investigate the failures and recommend modifications, which were put in place for the next run cycle starting in September 2009. The modified foils and brackets performed very well, and a single foil lasted for the entire September – December production run, which included operating at a beam power of 1 MW. A single foil was also used for the subsequent February – June 2010 run cycle, with even more charge delivered to the neutron production target.

In this paper we discuss the causes of the foil system failures, and the modifications made to prevent them.

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SNS STRIPPER FOIL SYSTEM

The nominally 17 mm x 45 mm x 0.30 mg/cm^2 stripper foils have three free edges and are mounted on L-shaped brackets that hang from pins on the foil changing mechanism. A photo of a first generation foil and bracket is shown in Fig. 1. The long arm and leg of this bracket style were designed to accommodate stripper foils that require support from thin carbon fibers that can be stretched across the arm and the leg. The diamond foils do not require fiber support.

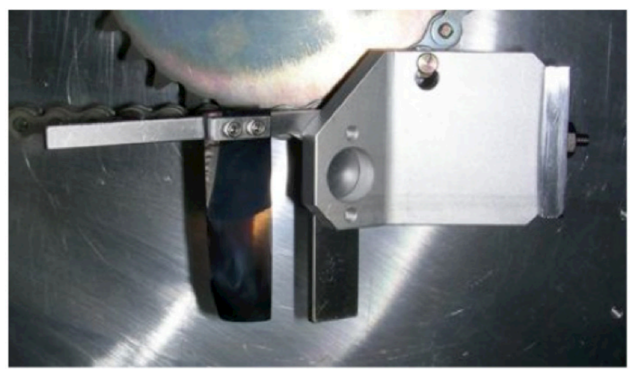

Figure 1: A first generation foil bracket mounted on the foil-changer mechanism. The long arm and leg of the L-shaped bracket were designed to stretch carbon fibers across the span to support foils if needed (not used in this case). (Figure reproduced from Ref. 3.)

When in use, the foil is positioned inside a strong (~0.25 T) magnetic field to control the beam loss caused by the partially stripped H^0 excited states created by the foil that, if not properly controlled, could strip to H^+ at some point downstream of the foil and outside the ring acceptance [4]. The magnetic field at the foil causes the excited states with $n \geq 5$ to strip within about a mm of the foil. Also, the foil is located in the falling field (downstream end) of the magnet, and the peak field of the next downstream magnet is less than the field at the foil, so that the surviving $n<5$ states will not strip until they reach the secondary stripper foil, whereupon they can be properly transported to a beam dump.

The magnetic field causes the convoy electrons stripped from the H^- beam to circle with a 12 mm gyroradius. To prevent these electrons from circulating repeatedly through the foil and causing it to overheat, the field is tilted longitudinally by ~200 mrad so that the electron trajectories drop ~16 mm in the first revolution, which is enough to miss the foil [5].

It is important to properly control the convoy electrons since, e.g., for a 1.4 MW proton beam power there is 1.5 kW of electron power. A water-cooled electron catcher is mounted to the bottom of the vacuum chamber to intercept the electrons and prevent them from reflecting back up into the path of the beam. The electron catcher is comprises carbon-carbon composite wedges that have undercut faces. By design the convoy electrons strike these faces so that any reflected electrons will be aimed downward and away from the path of the proton beam.

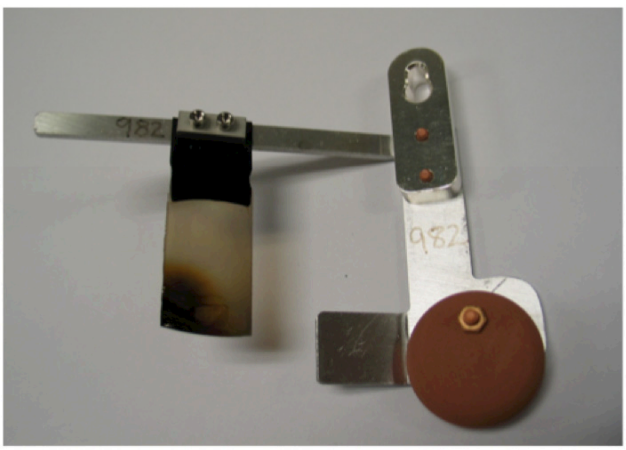

Figure 2: A used second-generation foil bracket. The beam power in this case was only 400 kW, so this foil and bracket show very little damage. (Figure reproduced from Ref. 3.)

FOIL SYSTEM DAMAGE MECHANISMS

Convoy Electrons Strike the Bracket

The first failure mechanism is simple – the lower portion of the L-shaped bracket was too close to the foil, so the convoy electrons struck the bracket on their first revolution around the magnetic field lines. It should be stressed that this failure mechanism is actually a bracket failure, not a foil failure. A photograph of a second generation bracket (the type in use at the time of the first set of failures) is shown in Fig. 2. An example of a failed bracket is shown in Fig. 3. The bottom-left corner of the bracket shows the melting that occurred from the convoy electrons striking the bracket. The large melted area on the lower right shows where a circular counterweight was attached before the material around the mounting hole melted, causing the counterweight to fall off.

Reflected Convoy Electrons

The second failure mechanism is reflected convoy electrons. If the electron catcher is not properly positioned relative to the stripper foil, the convoy electrons can miss the undercut faces and instead strike the tops of the wedges, which would make it much more likely for convoy electrons to be reflected back up toward the beam and stripper foil. In February 2010 the electron catcher and stripper foil positions were measured, and they are in fact not positioned according to design, so it is likely that there is a surplus of reflected electrons.

Figure 3: A failed second-generation foil and bracket. This foil lasted for a few hours at ~840 kW beam power. (Figure reproduced from Ref. 3.)

The trajectories of the reflected convoy electrons were simulated [6] using a particle tracking code and magnetic fields from a detailed 3-D model of the magnet [7]. An example result is shown in Fig. 4, where it can be seen that the reflected electrons will strike both the stripper foil and the bracket.

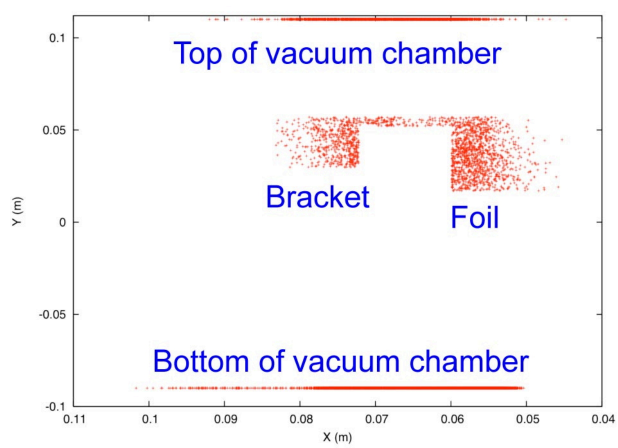

Figure 4: The results of a particle tracking simulation showing the locations where the reflected convoy electrons strike the stripper foil, the bracket, and the top of the vacuum chamber.

Figure 5 shows a used third-generation foil and bracket. The lower leg on this bracket was removed so that the convoy electrons would not hit it as they travel down to the electron catcher, yet it still shows melting damage on the lower left corner, and the arm of the bracket has also softened enough to allow the arm to droop down. This damage is consistent with the tracking results in Fig. 4.

However, these simulations do not explain all the damage to this bracket. There is also a vertical hole created in the bracket along the inner edge of the foil substrate (see next section).

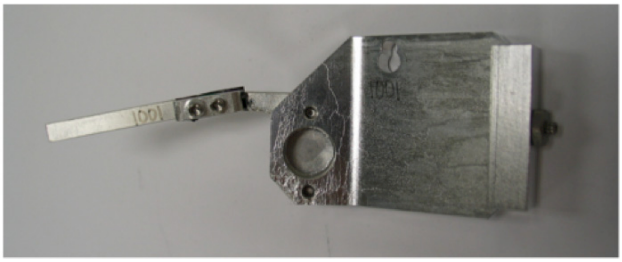

Figure 5: A used third-generation foil bracket. (Figure reproduced from ref. 3.)

Vacuum Breakdown

The third failure mechanism is cathode-spot in-vacuum breakdown. This is a form of electrical breakdown that can take place in a perfect vacuum. To initiate the breakdown, the anode (foil) first develops a positive electrical charge due to secondary electron emission. If the foil is hot enough, thermionic electron emission can further charge the foil. The next step is evaporation of sharp points on the cathode (bracket) that become hot from field emission due to the strong electric field that has been created between the bracket and the foil. The evaporated cathode material then provides the gaseous environment needed to sustain the breakdown. Each breakdown event creates a small crater in the bracket, and over time large holes can develop. Figure 6 shows a close up photo of the same bracket as in Fig. 5. Several holes can be seen where the silicon foil substrate was clamped to the bracket. One hole passes completely through the bracket arm. The top of the bracket also shows similar material erosion at locations where the foil substrate had sharp edges that helped initiate the vacuum breakdown events.

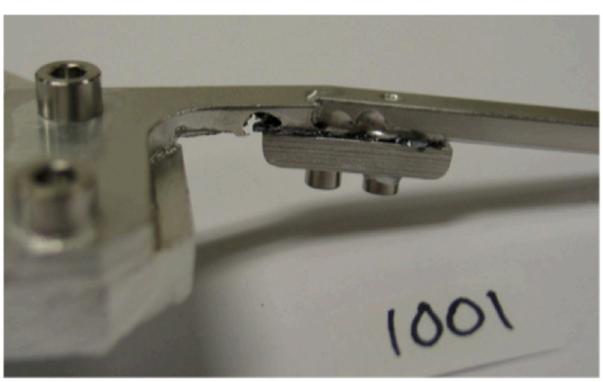

Figure 6: A close-up view of the foil clamp for the bracket shown in Fig. 5. (Figure reproduced from ref. 3.)

Bracket Pinching

Even in the absence of reflected convoy electrons and vacuum breakdown, the foil bracket will get hot due to conduction of heat from the irradiated foil. The generations 1 through 3 foil brackets were made of aluminium due to its ease of machining, good conductivity, light weight, and low radioactivation. However, aluminium also has a low melting point and a high coefficient of thermal expansion (CTE) which is approximately 8 times higher than that of the Silicon foil substrate. Titanium screws were used at one point creating an additional CTE mismatch between the fastening components. As the temperature increases in this arrangement, it pinches the stripper foil between the clamp and the bracket arm because the aluminum between the screw head and nut expands more than the titanium. The clamping of the foil to the holder in combination with the expansion of the holder induces significant tensile stresses in the silicon substrate. This can cause the silicon to fracture, which can then lead to rips and tears in the free-standing portion of the foil, and also create sharp edges that contribute to the vacuum breakdown. Some of the failed foils exhibited this symptom, such as the one shown in Fig. 7, where most of the right half of the silicon substrate is missing.

Figure 7: An example of a fractured foil substrate on a third-generation foil bracket.

Other Mechanisms

In addition to the foil system damage mechanisms already discussed, there are others that probably contribute to at least a minor degree.

The silicon substrate that mounts the diamond foil, and some portions of the bracket, are located inside the beam aperture of the ring. Particle tracking simulations do not predict that any particles will be this far away from the closed orbit, yet beam halo is certainly present at a low level (otherwise there would be no beam loss).

Trailing edge multipacting is also likely to be present at some level in the ring, due to the triangular nature of the longitudinal beam profile. This phenomenon has been detailed at the Los Alamos PSR [8]. These electrons could strike the foil and bracket and cause additional heating.

Sudden beam excursions in the ring, caused by momentary equipment failure, can cause large beam loss in the ring injection area. Some of the beam loss is likely to be due to beam striking the stripper foil and/or bracket. An example of this type of phenomenon occurred every few minutes and lasted for several days in 2009 due to problems with the Ring rf system.

Another heating mechanism that we investigated was eddy current heating due to the pulsed nature of the electric fields of the beam, causing electrical currents to flow in the foil bracket. We have not observed evidence for this type of heating.

SOLUTIONS

During the summer of 2009 several modifications were made to the foil and the bracket. The bracket material was changed from aluminium to titanium, since the thermal expansion coefficient of titanium is much better matched to that of silicon. Also titanium has a relatively high melting point, good electrical conductivity, and it is lightweight. However, the radioactivation properties are not as good as aluminium due to its high atomic number. The bracket and clamp were machined flat, and before clamping the foil to the bracket, both the bracket arm and the clamp were carefully polished to remove any sharp points that could contribute to cathode-spot in-vacuum breakdown. Some of the foils we installed in September 2009 were also sandwiched between layers of gold foil ~0.025 mm thick to help improve the large-area electrical contact between the foil and the bracket.

The foils were also moved 1 cm further out on the arms of the brackets to improve the clearance for the circulating convoy electrons, and the arms and legs of the brackets were made as short as possible to remove any excess material that could be struck by beam halo or reflected convoy electrons. Note that some additional length would need to be added to both the arm and the leg in order to mount fiber-supported foils.

The foil itself was modified to have a longer free-standing length, increased from 25 mm to 30 – 35 mm (i.e. shorter silicon substrate), to prevent beam halo and reflected convoy electrons from striking the opaque substrate.

A new set of foils, half with the gold foil mounting and half without, were installed for the September to December 2009 run cycle. The first foil selected was one with the gold foil mounting method, and it lasted the entire run cycle, even after increasing the beam power to 1 MW. The total charge delivered to the target using this foil was 4820 C, to be compared to the previous high-power record of 978 C. The used bracket shows no signs of damage, although there is an unknown coating on the upstream side of the bracket and foil substrate that is not understood at this time. The foil itself is blackened, twisted, and wrinkled, but it was still performing well at the end of the run cycle. A photograph of this foil, taken after it was removed in February 2010, is shown in Fig. 8.

For the next run cycle, from February to June 2010, we selected a foil mounted without the gold, and that foil also survived the entire run cycle, with an even higher integrated charge to the target of 7,359 C. It seems that the gold foil is not necessary. For comparison, at full design beam power, 95% availability, and 2,500 hours per run cycle, the integrated charge to the target would be 12,300 C.

FUTURE PLANS

The foil lifetime is no longer an issue at the present operating power of ~1 MW. However, we are working to continue to ramp up the beam power to the design value of 1.4 MW. We are also working on a beam power upgrade to 3 MW at 1.3 GeV. These higher beam powers will place even greater demands on the stripper foil, so we will continue to improve the foils.

To help with the foil charging issue we are developing more conductive nanocrystalline diamond foils using boron doping. Also, as the foil ages, it tends to develop a curl. We plan to try different corrugation patterns to alleviate this problem. Another issue is that the edge of the foil often has an over-hang due to the way the foil is grown on the substrate, where some of the growth occurs on the sides of the substrate rather than just the top. One way to cure this problem is to cut off the edge of the foil prior to etching away the substrate material. The bottom edge of the foil in use at the time of this writing has been cut off.

As we accumulate more experience with this stripper foil technology we anticipate that we will be able to fabricate stripper foils that will be even better than the ones we have today.

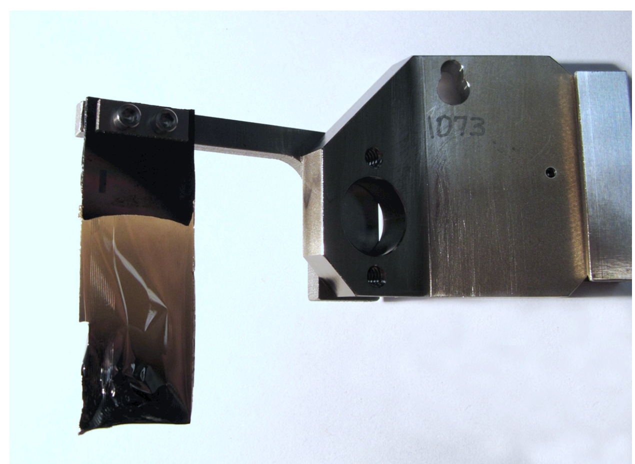

Figure 8: Photo of the foil and bracket that lasted the entire Sept. – Dec. 2009 run cycle at high beam power. (Figure reproduced from ref. 3.)

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