SNS STRIPPER FOIL FAILURE MODES AND THEIR CURES*

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Abstract

The diamond stripper foils in use at the Spallation Neutron Source worked successfully with no failures until May 3, 2009, when we started experiencing a rash of foil system failures after increasing the beam power to ~840 kW. The main contributors to the failures are thought to be 1) convoy electrons, stripped from the incoming H^- beam, that strike the foil bracket and may also reflect back from the electron catcher, and 2) vacuum breakdown from the charge developed on the foil by secondary electron emission. In this paper we will detail these and other 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. 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 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. In this paper we will discuss the causes of the foil system failures, and the modifications made to prevent them.

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. When in use, the foil is positioned inside a strong (~0.25 T) magnetic field to control the beam loss caused by H^0 excited states [3]. The magnetic field causes the convoy electrons stripped from the H^- beam to circle with a gyroradius of 12 mm, but the field is tilted longitudinally by ~200 mrad so that the electron trajectories drop ~16 mm in the first revolution, which is ideally enough to miss the foil and thus avoid depositing more energy into the foil [4]. 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.

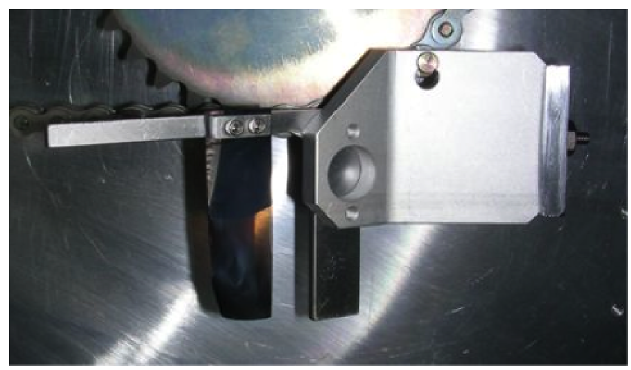

Figure. 1. A first generation foil bracket mounted on the foil-changer mechanism. The long arm and leg of the L-shaped bracket are designed to stretch carbon fibers across the span to support foils if needed (not used in this case).

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 photo of a second generation bracket (the type in use at the times 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 counterweight was attached before the material around the mounting hole melted, causing the counterweight to fall off.

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Reflected convoy electrons

The second failure mechanism is reflected convoy electrons. If the electrons are not properly captured by the electron catcher, some may reflect back up into the vacuum chamber and strike the foil and/or the bracket. The electron catcher material is a carbon-carbon composite (since carbon has a relatively low reflection coefficient), with angled undercut faces where the electrons are supposed to hit in order to aim any reflected electrons in the downward direction.

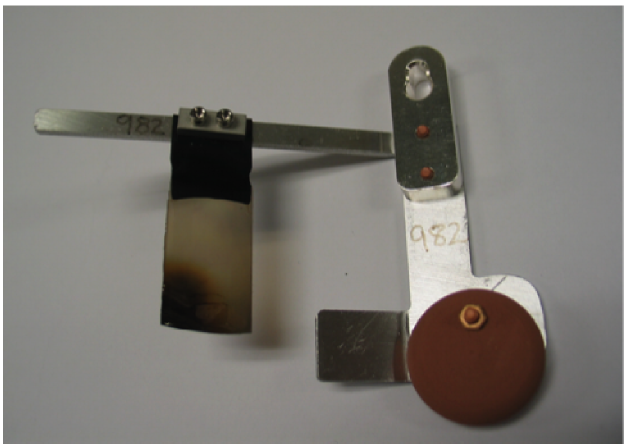

Figure. 2. A used second-generation foil bracket. The beam power in this case was only 400 kW, so this foil and bracket show very little damage.

Figure. 3. A failed second-generation foil and bracket. This foil lasted for a few hours at a beam power of ~840kW.

Figure. 4. A used third-generation foil bracket

However, some electrons can hit the upward-facing surfaces of the electron catcher and reflect back up toward the foil and bracket. Figure 4 shows a 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. We believe that the melting on the lower left corner is due to reflected convoy electrons. Although some of these reflected electrons also strike the foil and the bracket arm, they cannot explain all the damage to this part of the bracket.

Vacuum breakdown

The third failure mechanism is cathode-spot in-vacuum breakdown. This form of electrical breakdown 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 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 develop. Figure 5 shows a close up photo of the same bracket as in Fig. 4. Several holes can be seen where the 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.

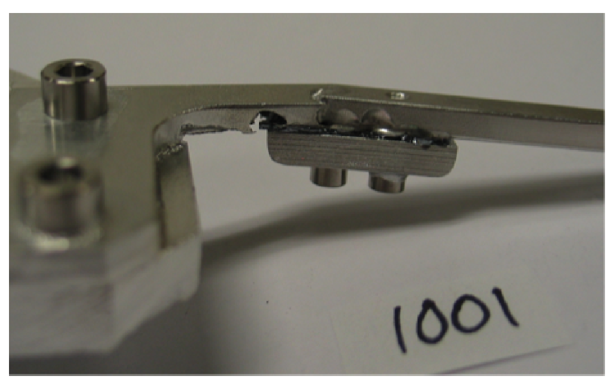

Figure. 5. A close-up view of the foil clamp for the bracket shown in Fig. 4.

In addition to damage to the bracket, cathode-spot in-vacuum breakdown can also cause damage to the foil, if the breakdown events start and/or end on the free-hanging portion of the foil. We have not observed strong evidence of this type of damage to the foil.

Bracket pinching

The foil bracket will get hot simply because the foil itself gets hot enough to emit visible light. 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 relatively high coefficient of thermal expansion, so that as the temperature increases it pinches the stripper foil between the clamp and the bracket arm and at same time applies tension along the width of the foil. This can cause the silicon substrate that supports the upper portion of the foil 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.

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 supports 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 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 [5]. 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 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 strong 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 are machined flat, and before clamping the foil to the bracket, both the bracket arm and the clamp are carefully polished to remove any sharp points that can 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 will 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 up to a 35-mm free-standing length (shorter silicon substrate) to prevent beam halo and reflected convoy electrons from striking the 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. 6. For the present February to June 2010 run cycle, we are using a foil mounted without gold, and to date it has also functioned well.

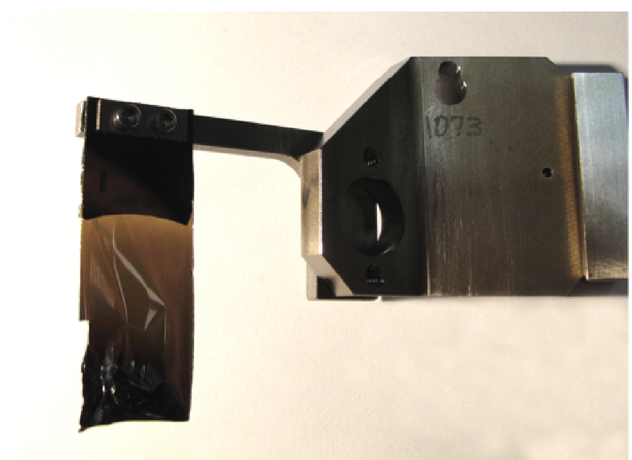

Figure 6. Photo of the foil and bracket that lasted the entire Sept. – Dec. 2009 run cycle at high beam power.

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