COMPARISON OF CARBON AND CORRUGATED DIAMOND STRIPPER FOILS UNDER OPERATIONAL CONDITIONS AT THE LOS ALAMOS PSR*

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Abstract

To accumulate high-intensity proton pulses, the Los Alamos Proton Storage Ring (PSR) uses the charge-exchange injection method. H$^-$-ions merge with already circulating protons in a bending magnet and then are stripped of their two electrons in a carbon stripper foil. The circulating protons continue to interact with the foil. Despite efforts to minimize the number of these foil hits, like “painting” of the vertical phase space, they cannot be eliminated totally. As a result, foil heating and probably also radiation damage limit the lifetime of these foils. In recent years LANL has collaborated with KEK to improve the carbon foils in use at PSR, and these foils now typically last for several weeks. Recently an alternative in the form of corrugated diamond foils has been proposed for use at SNS. We have tested these foils in the PSR. Here we compare their performance in a PSR production beam to that of the LANL carbon foils during the 2005 run cycle. First results from the 2006 run cycle will also be presented.

INTRODUCTION

Repeated foil hits by circulating protons cause excessive heating and radiation damage of the stripper foil and thus limit the lifetime of the foil. The carbon foils in use at PSR in recent years were developed at KEK [1] to improve the durability of stripper foils under these conditions. These “LANL foils” have proven to be far superior to commercially available carbon foils. Recently, at ORNL and the University of Tennessee a diamond foil has been developed for use in the SNS ring [2]. It was deemed useful to test these foils in PSR before the SNS ring commissioning.

Here we give a brief description of the injection process used in PSR as it is necessary to understand the stresses that the stripper foils endure. We then briefly introduce the LANL carbon foils as well as the SNS diamond foils. We report on the results of the test of the SNS foils during the 2005 run cycle as well as on first results from the 2006 run cycle where a diamond foil has been used in production from the start. Finally we provide an outlook on upcoming foil studies at PSR.

PSR INJECTION

H$^-$-ions are injected into PSR via a merging dipole. Charge exchange occurs in a carbon stripper foil downstream of the dipole. Since the transverse emittances of the injected beam are much smaller than the acceptance of the ring, the injection is done at a horizontal and vertical offset. In the vertical plane, where the β-function at the foil is about 4.5 times larger than in the horizontal plane, a closed-orbit bump is used to fill in the acceptance of the ring and to reduce the number of stripper foil hits by circulating protons. The injected beam is matched to the circulating beam. Figure 1 shows the ellipses of the injected and the circulating beams in horizontal and vertical phase space for nominal injection offsets. Smaller values for the offsets are typically used in normal operating conditions.

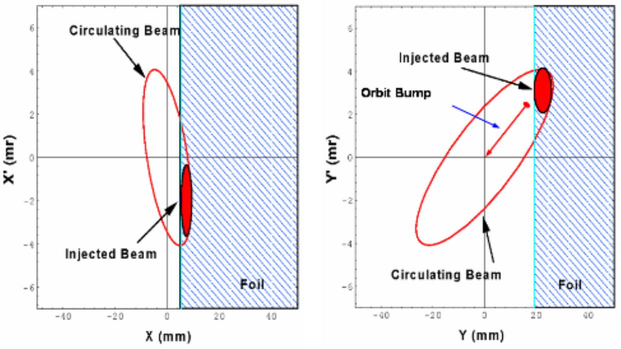

Figure 1: Transverse phase space ellipses of the injected and circulating beam for nominal injection offsets. A vertical closed orbit bump is used to fill in the ring acceptance and reduce the number of foil hits by circulating protons.

Despite these efforts to minimize the number of foil hits by circulating protons they cannot be completely eliminated. For 125 μA at 20 Hz or 6.25 μC/pulse, injected over 725 μs, a proton hits the foil on average up to 80 times. These foil hits are a dominant source of losses in PSR [3]. They also limit the lifetime of the stripper foil due to rapid cycling of the foil temperature [4] and probably also due to radiation damage.

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LANL CARBON FOILS

The foils are produced in an *arc evaporation* process, developed by one of the authors (I. Sugai) and referred to as *modified Controlled AC/DC Arc Discharge* (mCADAD) [1]. This method allows one to produce layers of up to 130 µg/cm^2 thickness. In PSR the optimum thickness was determined to be about 450 µg/cm^2. This number is a compromise between beam losses due to foil scattering, which increase with increasing foil thickness, and beam losses due to inefficient stripping. The latter, most importantly the production of excited H^0 atoms that are field-stripped in downstream magnets, become the dominant source for foil related losses for foil thicknesses below 400 µg/cm^2. Hence it is necessary to stack several layers (typically 4) produced with the mCADAD method to make one LANL carbon stripper foil. To ensure the integrity of the foil during beam operation it is necessary to support the foil with 4 µm thick carbon fibers. Applying these microfibers is a major step in the procedure to produce the LANL carbon foils which is now performed at LANL. Other major steps involve chamber preparation, annealing, stacking of layers, mounting of the foil and fibers onto the frame. The time spent to produce one LANL carbon foil is estimated to be about 1 man-week [5]. Figure 2 shows a photograph of a LANL carbon foil newly mounted on a frame as well as a foil after several weeks of beam exposure.

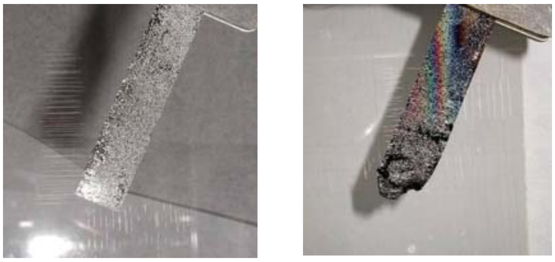

Figure 2: Photograph of a LANL carbon foil newly mounted on the frame (left), and of a foil after several weeks of beam exposure (right). Note the microfibers that are necessary because these foils are composed of several layers (typically 4) to achieve optimum thickness.

These foils usually reach the end of their useful life when wrinkling or curling leads to excessive losses due to foil scattering. Up to four foils can be simultaneously installed in PSR. Foil lifetimes are typically several weeks. With run cycles now lasting 8-10 months , at least one foil change is normally necessary during a short outage (e.g. for ion source recycling, 2-3 days) rather than at the end of an extended maintenance outage. Because of high radiation dose levels at and near the foil box, workers typically receive dose in excess of 100 mrem when they perform a foil change during a short outage [6]. It would thus be highly desirable to obtain foils that last long enough to render these intermediate foil changes obsolete.

SNS DIAMOND FOILS

These foils are produced by *Chemical Vapor Deposition* (CVD) from a microwave driven plasma. The method was developed by two of the authors (R. W. Shaw, C. S. Feigerle) [2]. Grain size is of the order of 1 µm, i.e. of the same order as the thickness of the foil. Shaw and Feigerle refer to this foil as *microcrystalline*. Recently they increased the argon content in the plasma to over 90 % to allow them to grow films with grain sizes of 5-50 nm. These are referred to as *nanocrystalline*. The nanocrystalline foils appear to be mechanically stronger and easier to handle than the microcrystalline ones. It takes 1-2 days to produce a foil of either type, the shorter time assuming that one produces more than one sample at a time [7].

One limitation for the diamond foils is that they tend to curl up when they are released from their silicon growth substrate. Corrugating the foils seems to help, but even so the length is limited to about 20 mm, about half the length of the LANL foils. Use of microfibers is not an option for SNS because of their expected high beam intensity. The usefulness of the fibers in connection with the diamond foil is also questionable. In PSR the shorter foil length was instead made up by an aluminum plate. Concerns that this may lead to excessive beam losses in PSR due to scattering in the plate have been allayed during beam development.

A microcrystalline foil was first tested in PSR in August 2005, but catastrophically failed before production beam intensities were reached. The foil also had very poor stripping efficiency which would have prohibited its use in production. A nanocrystalline foil was installed in October 2005 and was used in production continuously until the end of the 2005 run cycle in late December. Figure 3 shows a photograph of the foil before installation in PSR. Note the corrugation pattern which follows the outline of the foil. This pattern has proven most successful in preventing curling of the corners. The picture also shows the aluminum plate as well as the remainder of the silicon wafer from the foil production process and is left in place for mounting.

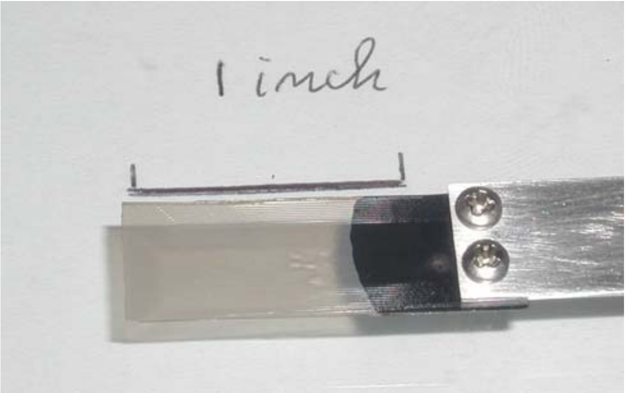

Figure 3: Photograph of the nanocrystalline diamond foil used in PSR production during the last months of the 2005 run cycle. Notice the U-shape corrugation pattern that follows the outline of the foil. The aluminum plate is used to make up for the shorter length of the foil, compared to LANL carbon foils. The black region is remaining silicon wafer.

SNS NANOCRYSTALLINE DIAMOND FOIL IN 2005 PRODUCTION

Ring Charge

Figure 4 shows the total charge injected into PSR via the nanocrystalline SNS diamond foil, compared to the three LANL carbon foils that were used in the 2005 run cycle. One should note that a more accurate comparison of the foil performance would have to consider the total number of foil hits by both injected H^- and circulating protons. This number can vary tremendously if the foil is moved, even if that movement brings about only a small change in injected current [3]. Care was taken, though, throughout the run cycle, to adjust the foil positions to achieve a compromise between number of foil hits and injected current, by allowing about 4 % of the injected beam to go to the injection beam stop (this number includes ~ 1-2 % of the beam not completely stripped).

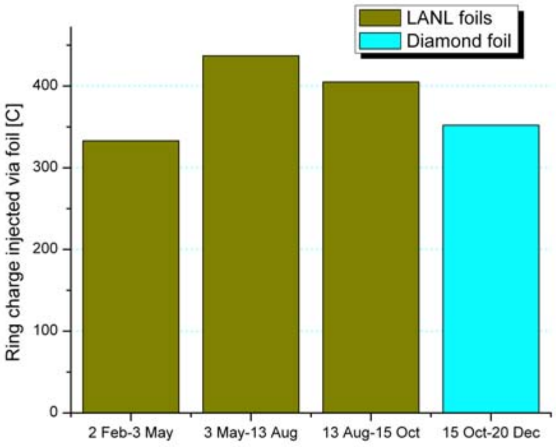

Figure 4: Total charge injected into PSR via the three LANL foils and the nanocrystalline SNS diamond foil used in the 2005 run cycle. Note that unlike the diamond foil the LANL foils had reached the end of their useful lives.

One also needs to mention that while the LANL foils had reached the end of their useful lives the diamond foil had shown no sign of deterioration when the end of the 2005 run cycle was reached.

Foil shape

During beam exposure the foil was observed with a radiation hard black and white camera [8]. A frame grabber allowed digitizing the images. The corner where the beam hit the foil (lower right) is most intense because there the foil temperature reaches 2000 K or more ("white hot"). Figure 5 shows that area over a period of time (corresponding to roughly similar beam exposure) for the diamond foil (top) and one of the LANL foils (bottom). While the corner of LANL file has curled over, the diamond foil shows no such deterioration.

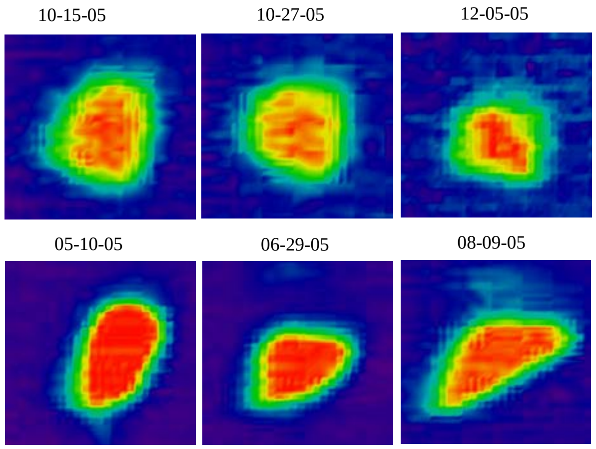

Figure 5: Digitized camera images of the foil corner where the beam hits the foil. Top: SNS diamond foil. Bottom: LANL carbon foil. In the case of the carbon foil the peculiar change in shape is explained by curling of the corner. The diamond foil shows no such deterioration.

At the end of the extended outage following the 2005 run cycle the foils were removed from the ring. Figure 6 shows that some slight curling had actually occurred for the diamond foil. Also visible is the darkened area hit by the beam.

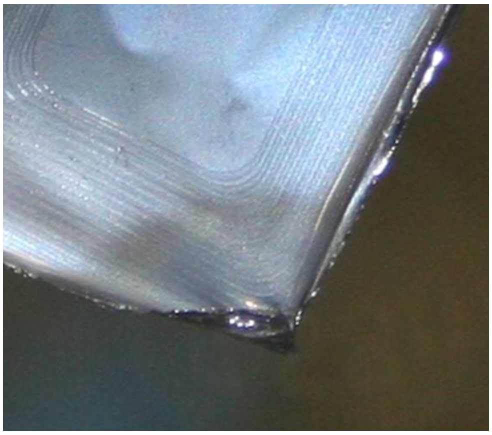

Figure 6: Photograph of the SNS nanocrystalline foil after removal from PSR. Some slight curling had indeed occurred with beam exposure.

First-Turn Losses

Excited states of H^0 are produced with some probability in the stripper foil [9] and field-stripped to H^+ in downstream magnets. The H^+ are typically lost in the first quarter of the ring before completing even one turn (hence the name "First-Turn" losses).

First-turn losses occur only while beam is injected into the ring. Their contribution to the overall loss rate can thus be determined by extending the storage of the beam beyond the end of injection and measuring the drop in the sum of the ring loss monitor signals as shown in figure 7 for the diamond foil.

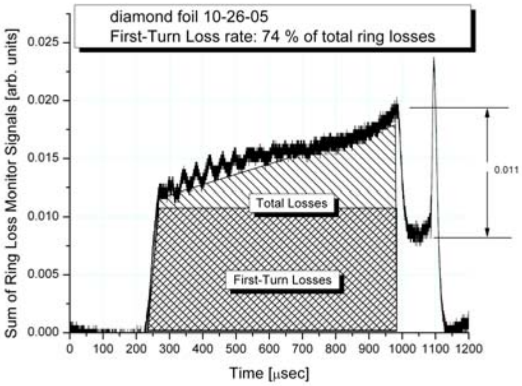

Figure 7: Measurement of first-turn losses for the diamond foil. The peak to the right is due to extraction losses.

Losses in the first ring quadrant (but past the injection area, "section 0") were dominated by first-turn losses as demonstrated in figure 8 for a loss monitor in section 2.

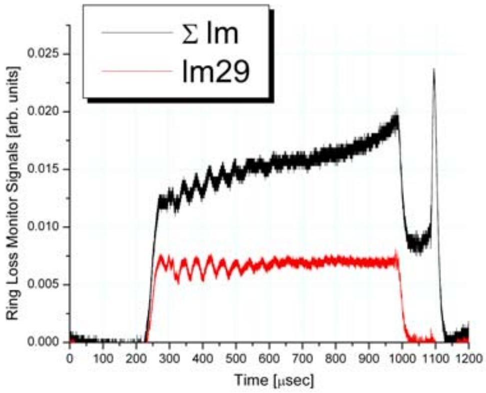

Figure 8: LM29, a loss monitor in section 2 of the ring is clearly dominated by first-turn losses for the diamond foil.

LANL foils normally start with first-turn loss rates on the order of 25-50 % which then drop over typically two weeks to 10-20 % or less due to curling or wrinkling of the foil which increases its thickness and thus the stripping efficiency. The much higher first-turn loss rate in the diamond foil may be due to variations in thickness [10]. An overall thicker foil will likely cure this problem. We also observed a slow decline in the first-turn loss rate with the diamond foil, though slower and less pronounced than in the LANL foils. Only slight curling was observed in this foil, however, a thickness change can also be expected from a phase transition from diamond to a more carbon-like structure during exposure to beam [11].

Foil current

For similar beam conditions (i.e. same number of foil hits) we observed a foil current signal with the diamond foil about a factor 5 smaller than with the LANL foils. We suspect that this has to do with a smaller secondary emission yield, but more studies are needed to clarify this point.

We also observed a significant change in the diamond foil current when the foil was returned to service after a LANL foil was used during a different operational mode.

This was not accompanied by a similar increase in foil related losses. A possible explanation might be a change in the secondary emission yield due to increased carbon-like defects in the diamond structure of the foil.

Further clarification may be gained from tests on a different diamond foil in 2006.

FIRST RESULTS FROM THE 2006 RUN CYCLE

Because of the relatively high first-turn loss rate associated with the diamond foil in 2005 we decided to replace this foil with thicker foils in 2006. The 2005 foil had a thickness (measured by weighing [12]) of 450 $\mu g/cm^2$. Since the startup in May 2006, a nanocrystalline diamond foil with a 480 $\mu g/cm^2$ thickness has been continuously used in production. The first-turn loss rate has indeed improved, although the optimum has not yet been achieved.

The total charge injected into the ring via the 2006 diamond foil has not yet reached the value achieved with the diamond foil in 2005, nor that achieved with any of the LANL foils in that year. The foil is still in use, however, and is approaching those values.

The foil current signal is lower by a factor of ~1.5 than with LANL carbon foils under similar beam conditions, as opposed to the factor of 3-5 that was the observed with the 2005 diamond foil.

Under certain beam conditions (small injection offset, high density) that are used in a different operational mode we find that the beam tends to be unstable in the first pulse after a long waiting period. This *first-pulse instability* is discussed in greater detail in [13]. It is accompanied by a significant increase in foil current, even early in the pulse before the instability occurs. The foil current also increases with increasing waiting time. This led us to suspect that adsorption of residual gases, water or even dust on the foil may change the secondary emission yield of the foil. This in turn may lead to an increase in seed electrons for the e-p instability. We recently had a chance to look for the first-pulse instability with the diamond foil that has been in use since the start-up in 2006. Unlike in the case of stable beam where the foil current signal is significantly lower for the diamond foil than for the LANL carbon foils, we do not observe a similar difference in the unstable first pulse.

OUTLOOK

As mentioned above, we are presently testing another nanocrystalline diamond foil in PSR production. Our primary interest is to determine the lifetime of the foil (in terms of charge injected into the ring). Once we are confident that these foils are indeed candidates to replace the LANL carbon foils in PSR production, we also need to determine if they are suitable for use in more extreme beam conditions. Occasionally we are asked to provide a smaller and denser beam with high charge per pulse for a specific type of experiment. The higher density leads to increased foil hits and thus increased foil temperatures. We typically observe a peak in the foil current signal at the end of the pulse from thermionic emission.

The LANL carbon foils do not normally break under these conditions; however, it does speed up the process of wrinkling or curling and leads to a reduction in their lifetime. Based on previous experience we expect the diamond foils to fail in a more violent fashion, but we need to know under what precise conditions this failure will occur.

We also hope to gather more insight into issues such as electron emission from the foil, adsorption of water or gases on the foil, and what exact role the foils play in the first-pulse instability.

Nanocrystalline diamond foils are now in use at SNS, and other laboratories are testing them (RIKEN) or will be in the near future (J-PARC).

An interesting new foil concept has been presented by Sugai at this workshop: a Hybrid-Boron-Carbon foil (HBC) with much improved durability [14]. We are discussing tests of these foils in PSR, probably during the 2007 run cycle.

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