COMPARISON OF CARBON STRIPPER FOILS UNDER OPERATIONAL CONDITIONS AT THE LOS ALAMOS PROTON STORAGE RING*

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Abstract

At the 39th ICFA Advanced Beam Dynamics Workshop HB 2006 and the 23rd INTDS World Conference we reported on first results of a test of nanocrystalline diamond foils developed at ORNL under operational conditions at the Los Alamos Proton Storage Ring (PSR) [1]. We have continued these tests during the 2006 and 2007 run cycles and have been able to compare the diamond foils with the foils that are normally in use in PSR, which were originally developed by Sugai at KEK. We have gathered valuable information regarding foil lifetime, foil related beam losses and electron emission at the foil. Additional insight was gained under unusual beam conditions where the foils are subjected to higher temperatures. In the 2007 run cycle we also tested a Diamond-like-Carbon foil developed at TRIUMF. A Hybrid-Boron-Carbon foil, also developed by Sugai, is presently in use with the PSR production beam. We will summarize our experience with these different foil types.

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 foils in use at PSR in recent years were developed at KEK and LANL to improve durability under these conditions. These LANL foils have proven to be far superior to commercially available carbon foils. During the 2005 run cycle we started to test other carbon foil types in PSR to determine whether they may be a suitable alternative to the LANL foils. While long lifetime is desirable since it reduces the number of foil changes and worker exposure to radiation, another important aspect is how the use of a particular foil type affects foil related losses in PSR. The lifetime of a foil is not necessarily bound by complete failure. In most cases a foil is deemed to have reached the end of its usefulness when changing to a new foil significantly reduces losses in PSR.

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LANL CARBON FOILS

LANL foils are produced in an *arc evaporation* process, referred to as *modified Controlled AC/DC Arc Discharge* (mCADAD) [2]. This method allows one to produce layers of up to 130 μg/cm^2 thickness. At least 4 layers are needed in PSR to achieve the optimum thickness of 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 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 stripper foil. To ensure the integrity of the foil during beam operation it is necessary to support the foil with 5 μm thick carbon fibers. Figure 1 shows a photograph of a LANL foil newly mounted on a frame as well as a foil after several weeks of beam exposure.

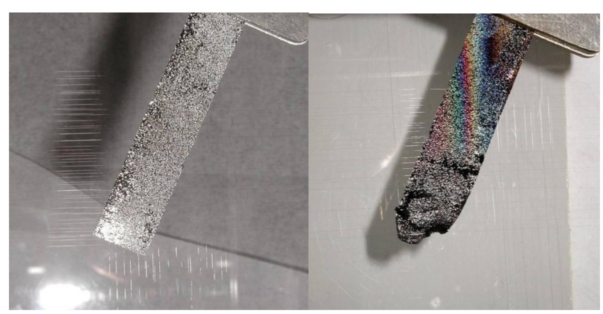

Figure 1: Photograph of a LANL foil newly mounted on the frame (left) and of a foil after several weeks of beam exposure (right).

SNS NANOCRYSTALLINE DIAMOND FOILS

SNS Nanocrystalline (NC) diamond foils are made by *Chemical Vapor Deposition* in a microwave driven plasma [3]. Grain sizes are about 50 nm. It takes 1-2 mandays to produce a foil. The thickness required in PSR can be achieved in one layer and microfibers are not needed. However, because the foils tend to curl up in the production process they are limited in length to ~25 mm when they are only mounted on one edge as in PSR and SNS. A corrugation pattern is added to further strengthen the foils against curling. Figure 2 shows a foil before installation in PSR, as well as a foil after several weeks of beam exposure.

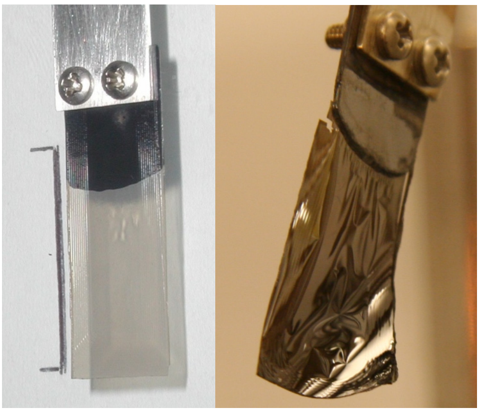

Figure 2: Photograph of an NC foil before installation in PSR (left) and of a foil after several weeks of beam exposure (right).

As shown in figure 3 the lifetime of the SNS NC foils in PSR is comparable to that of LANL foils. The third and fourth NC foils installed in PSR had been exposed to very intense beam and deteriorated much more rapidly under these conditions than LANL foils typically do.

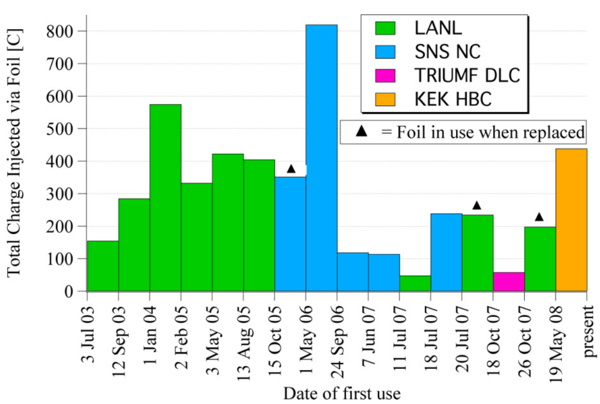

Figure 3: Total charge injected into PSR via various foils. Note that the HBC foil is still in use as of the writing of this article.

Another concern with SNS NC foils in PSR is the elevated First-Turn Loss (FTL) rate due to incomplete stripping of H^--ions. The resulting excited states of H^0 are field-stripped in magnets downstream of the stripper foil and many are lost in the first quadrant of the ring. The FTL rate can be determined by extending the storage time of the beam beyond injection and measuring the drop in ring losses. Figure 4 shows an FTL measurement for an SNS NC foil.

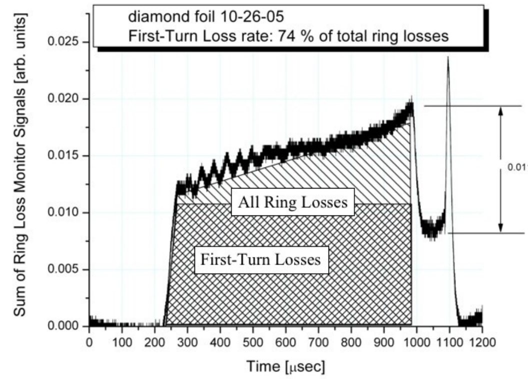

Figure 4: Extending storage time beyond injection allows determining the *First-Turn Loss* (FTL) rate by measuring the drop in ring losses. SNS nanocrystalline diamond foils have significantly higher FTL rates than LANL foils.

In subsequently tested foils the FTL rate could be reduced by increasing the foil thickness, however, even with a thickness of 600 $\mu g/cm^2$ the FTL rate is still significantly higher than with LANL foils. The reason for this is not yet understood, but may have to do with the higher density of the nanocrystalline diamond foils.

TRIUMF DIAMOND-LIKE CARBON FOILS

Diamond-Like Carbon (DLC) foils are produced by *Pulsed Laser Deposition* [4]. They contain a nearly isotropic distribution of nanocrystals and a certain fraction of sp^3 bonds. The foil tested in PSR was a multi-layer foil, where all layers are pure DLC, albeit with different densities. Co-authors Zeisler and Jaggi at TRIUMF can vary the process to produce foils of different strengths, at the cost of higher brittleness. They can now also produce single-layer DLC foils of the thickness required in PSR [5].

We chose to apply microfibers to the foil tested in PSR to protect it against damage from handling.

The foil tested in 2007 started with fairly low losses, which rapidly increased. Within less than two weeks the losses had become intolerable and the foil had to be replaced. An ion chamber close to the foil is dominated by losses due to (nuclear) scattering in the foil. The signal depends on the number of foil hits by circulating protons and foil thickness. The foil current depends also on the number of hits, but not the thickness, since secondary emission is a surface effect. The ratio of the two can be used to monitor relative changes in the foil thickness due to a) wrinkle or curling which will increase thickness or b) evaporation which will decrease thickness. Figure 5 shows the change in this foil "thickness" variable as a function of the total charge injected into the ring via the foil (over two weeks).

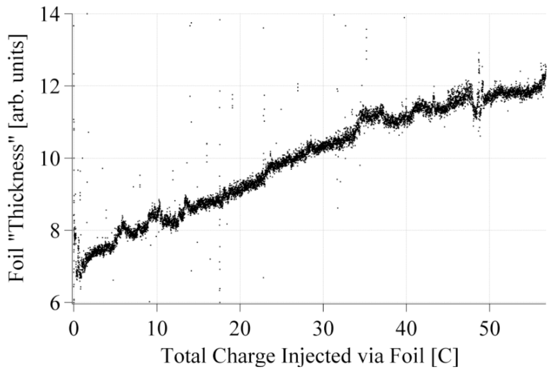

Figure 5: The foil “thickness” variable, obtained by dividing a foil scattering loss signal by the foil current, changed dramatically within two weeks for the DLC foil, indicating strong wrinkling or curling.

Figure 6 shows a picture of the foil after removal from the ring. Strong curling, leading to increased scattering losses, is clearly evident in the picture.

Figure 6: Curling, indicated by the strong change in the foil “thickness” variable (see figure 4), is evident in the DLC foil, which was removed from the ring after only two weeks of production beam exposure.

It is too early to judge the performance of the DLC foils after testing just one foil. For example, during the same 2007 run cycle one LANL foil had become unusable after less than two weeks, because one piece had completely detached from the foil. We intend to continue testing DLC foils as our schedule permits.

KEK HYBRID-BORON-CARBON FOILS

Like LANL foils, Hybrid-Boron-Carbon (HBC) foils are produced via Sugai’s CADAD method, but with the addition of about 25 % of boron to the carbon rods [6]. Measurements with 3.2 MeV Ne^+ and 650 keV H^- DC beams indicate a large lifetime improvement over original CADAD foils as well as SNS NC foils [7].

An HBC foil has been in use from the start of the 2008 run cycle. Figure 3 shows the total charge injected via this foil in comparison to LANL, SNS NC and the DLC foils.

The foil thickness variable discussed above does not yet indicate any foil deterioration, as shown in figure 7.

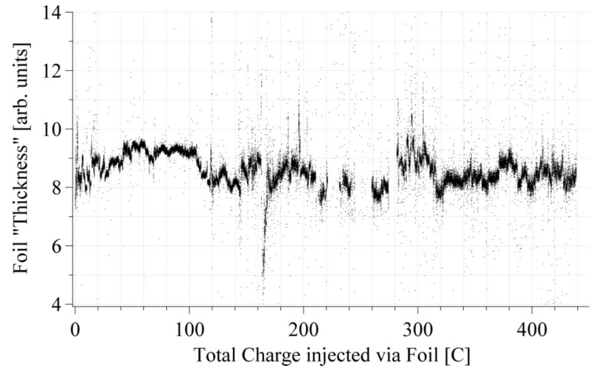

Figure 7: The foil “thickness” variable for the HBC foil does not yet indicate any deterioration.

Some problems, like pin-holes, are still being addressed by Sugai et al., and HBC foils tested in the future may prove yet superior to the one that is presently being tested.

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