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OPERATIONAL EXPERIENCE WITH NANOCRYSTALLINE INJECTION FOILS AT SNS

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Abstract

The Spallation Neutron Source (SNS) uses 300-400 μg/cm^2 nanocrystalline diamond foils grown in-house at the Center for Nanophase Materials Sciences to facilitate charge exchange injection (CEI) from the 1 GeV H- linac into the 248 m circumference accumulation ring. These foils have performed exceptionally well with lifetimes of thousands of MW·hrs. This contribution shares some experience with the operation of these foils during 1.4 MW operation, and discusses current operational concerns including injection related losses, foil conditioning, deformation, and sublimation due to high temperatures. The implications for the SNS Proton Power Upgrade are also discussed.

INTRODUCTION

The Spallation Neutron Source is a 1.0 GeV short-pulse accelerator that operates at 60 Hz to produce an average power on target of 1.4 MW. Linac pulses are approximately 1 ms long, and are compressed by roughly a factor of 1000 in the accumulator ring. Injection into the ring is achieved via charge exchange injection using approximately 30x17mm, 300-400 μg/cm^2 thick nanocrystalline diamond foils grown on a Silicon substrate, a portion of which serves as a 'handle' for mounting. Figure 1 shows the various parts of the foil, including the conditioned corner on the bottom left. Foils are mounted at a 30° angle relative to injected and recirculating beams which increases the effective thickness determining stripping efficiency. The optimal foil thickness balances stripping efficiency, foil heating, beam scattering, and mechanical stability which can contribute to the stability of losses, and power to the injection dump. A foil changer mechanism, or 'chainsaw', allows the installation of up to 12 foils which are changed roughly once per year. In a typical year between 4 and 6 foils will be used and replaced, with one conditioned foil often left in to accommodate high-power target studies done immediately upon start up.

Early in the design of SNS the survivability of foils at the high average power of SNS operation was a major concern. Although there were problems with charge exchange injection at high power, the worst fears about foil failure have not been realized, and many issues discussed previously have been mitigated [1], [2]. After several years of routine operation at the SNS design power of 1.4 MW the foils have performed exceptionally well, with the best foils lasting an entire run cycle of 2500 MW·hrs or more.

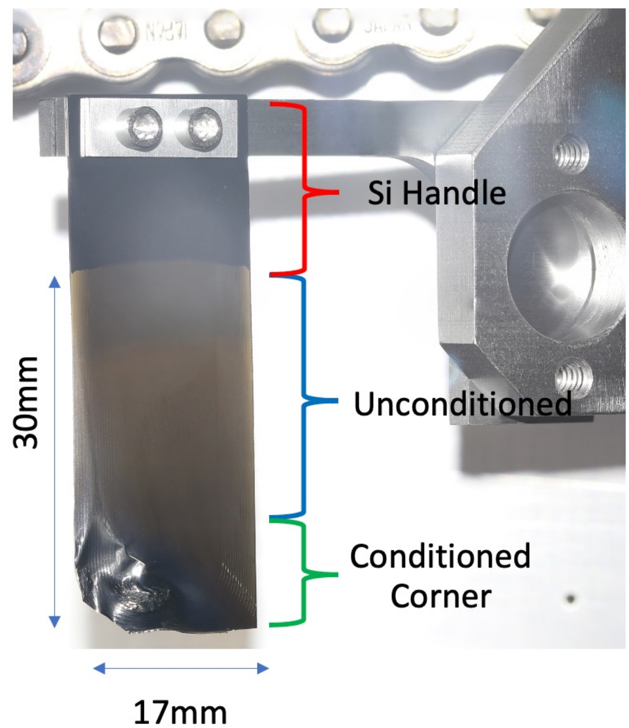

Figure 1: A used, mounted foil.

The Proton Power Upgrade will increase the power capability of the SNS accelerator from 1.4 MW to 2.8 MW by increasing kinetic energy from 1.0 GeV to 1.3 GeV, and the charge per pulse from 24 μC to 33 μC by increasing the peak current in the linac. The 60 Hz repetition rate, and number of accumulated turns will remain the same. However, the actual power at which the accelerator will operate will be staged over several years as the First Target Station(FTS) will only be capable of handling 2.0 MW, with the remaining power eventually destined for the Second Target Station(STS). Key parameters affecting the foils are summarized in Table 1, where SNS refers to current operation, PPU/FTS the first stage of operation to the first target station after the completion of PPU, and STS the 2.8 MW era currently planned for the early 2030's. These upgrades have renewed interest in the limits of nanocrystalline foils for high power charge exchange injection.

Currently the primary challenges for operation are: beam loss, foil conditioning time, foil deformation, and foil sublimation. With the exception of foil sublimation, these are mainly an annoyance to operation, but do not represent single-point failures. Foil sublimation due to heating, how-

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Table 1: Key SNS Upgrade Parameters

	SNS	PPU/FTS	STS
Charge(μC)	24	25	33
Energy(GeV)	1.0	1.3	1.3
Power(MW)	1.4	2.0	2.8
Rep Rate(Hz)	60	60	60

ever, does represent a possible single-point failure for increased power. The following sections will describe these concerns and their effect on operations.

BEAM LOSS

Beam loss induced activation is one of the primary concerns in high power accelerators, and the interaction of injected beam with stripping media represents an unavoidable source of beam loss. The ring injection region represents the highest loss, and residual activation by roughly an order of magnitude, and is the only section of the machine that does not meet the 1 W/m loss design specification. Even under ideal conditions, simulations show losses in this region to be on the order of a part in 10^{-5}, about an order of magnitude above the 1 W/m limit.

Beam loss is grouped into two categories: first turn losses, and recirculating beam hits. Without considering exotic stripping methods (e.g. laser-assisted charge exchange injection) a certain fraction of first turn losses (due to coulomb, and nuclear scattering of the injected protons with the stripping medium) are intrinsic to the process of charge exchange injection and represent a lower limit on losses for a given stripping medium. In the current painting scheme each injected particle hits the foil between 4 and 5 times, based on realistic ORBIT simulations of the entire injection process. Recirculating beam hits can be minimized, but currently there is no scheme to maintain the required phase space distribution while eliminating recirculating hits entirely.

Losses and stripping efficiency, increase with foil thickness. However, Mike Plum noticed in 2015 [3] a distinct lack of correlation between foil thickness and losses. Archived data for operating powers above 1.35 MW over the last several years shown in Fig. 2 clearly demonstrates this. Of course, we are not suggesting that the foil thickness is not related to losses, this seems to be a consequence of operational procedure.

Operators are instructed to keep the current to the dump constant at 1 mA (≈ 60 kW) desipte the dump limit of 150 kW, partly out of concern for the longevity of the dump window. As foils become thicker stripping efficiency is increased and the beam is moved closer to the edge of the foil to maintain constant dump power, and the waste beam consists of a larger proportion of H- beam. Moving the beam toward the edge of the foil also reduces the number of recirculating beam hits. Our current hypothesis is that the reduction in losses from recirculating hits the increase in losses due to the thicker foil, but this has not been definitively established.

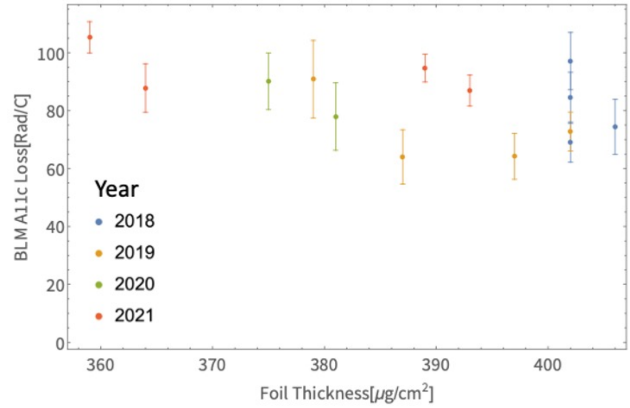

Figure 2: Beam loss at a representative loss monitor vs. foil thickness for operation above 1.35 MW.

FOIL CONDITIONING

Nano-crystalline diamond foils used for CEI discolor, deform, and change composition when subjected to high temperatures. This process known as 'graphitization' was investigated by Barrowclough using an electron beam to heat foils to similar temperatures as those expected in the SNS [4]. The emissivity of the graphitized regions has been measured to be about 0.85 compared to 0.17 for unexposed foils. Because of the higher emissivity, more energy can be deposited in the foil while maintaining a favorable temperature. (Though there is no hard limit, for temperatures above 2000 K we expect foil lifetimes to decrease as described in the following section.)

Figure 3 illustrates the beam power ramp used during operation to graphitize the region of the foil that will be subjected to full power. This process is called 'conditioning'. A one hour rep-rate ramp up to 400 kW which allows the vacuum systems time to clear any products of outgassing from the foil, then a roughly 12 hour ramp up to 850 kW in steps of 40 kW/hr during which the foil is moved at each step to position the injected beam on one of the two 45° angles at the edge of the foil that sits in the beam, and finally a ramp up to 1.4 MW in steps of 20 kW/hr during which the foil is not moved.

This procedure was developed conservatively based on knowledge gleaned from the foil test stand, and has not been optimized. We know from test stand experiments that the actual process of graphitization is very quick once foils reach temperatures of ≈1500 K [4], but the variability of the beam position on the foil because of deformation, beam jitter, or operator tuning means large areas must be conditioned for use at high power. While tests using a conditioning ramp almost twice as fast have been successful, a new procedure has not been implemented for routine operation.

FOIL DEFORMATION

During conditioning the density of the material changes causing deformation of foils. This deformation is unpredictable and can cause the foil to curl, pucker, tear or distort

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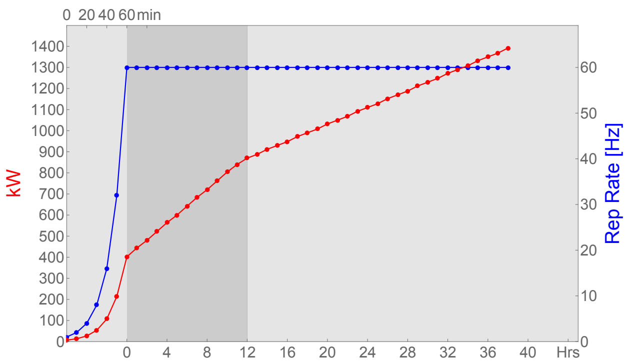

Figure 3: Current conditioning schedule.

in ways that adversely affect operation. Figure 4 shows a small area that has been graphitized using a 30 keV electron gun that simulates the heat load of the SNS ion beam on the foil test stand [5]. The graphitized region is at the center of the image with sub-mm puckering around the edge of the beam spot where the change in density distorts the foil. Larger scale deformation can also be seen as creases in the foil not subjected to beam, a new foil would be very flat by comparison.

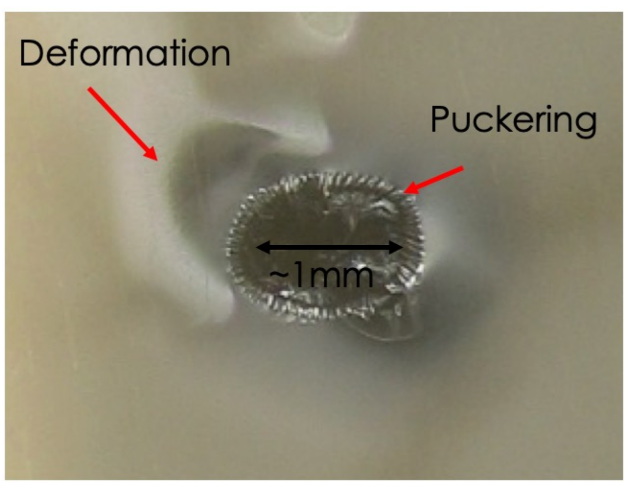

Figure 4: A small region graphitized on the foil test stand.

Figure 5 shows two foils after conditioning, and operation in the SNS. The foil on the right has significantly more distortion along the perimeter which can cause a change in the makeup of the waste beam, requiring operators to move the foil to maintain constant power. Additionally, the twisting and puckering which is particularly evident in the left foil can change the effective thickness of the foil which can also lead to changes in the stripping efficiency, losses, and heating.

The random nature of this deformation means a foil may be fully conditioned and still be unsuitable for operation. One solution to this problem may be to pre-condition foils using an electron beam similar to the one on the foil test stand mentioned above to better control the distortion, or just to reject poorly conditioned foils before they are used for operation. Because conditioned foils are very fragile, this would likely have to be done in the tunnel with an in-situ electron gun, and would require a redesign of the foil changer.

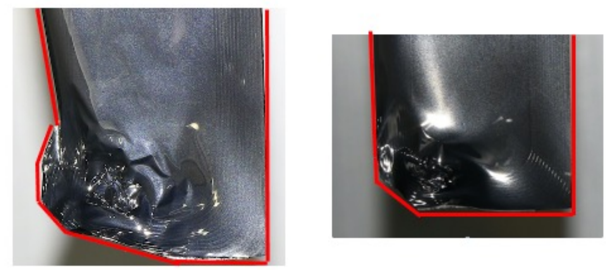

Figure 5: Two foils after conditioning demonstrating the unpredictable deformation.

Foils can also experience tears, which tend to form at the interface of the Si handle and the free foil. Figure 6 shows the result of a massive tear in foil #3111 during operation that formed sometime between Feb. 7-8, 2020. An outline of the extent of the foil has been added to the image taken from the online video foil monitor on the top left. The beam spot can be seen as a bright circle in the lower left corner of the foil. On Feb 8^{th}, 2020 operators noticed another bright feature, but no difference in performance. The foil was left in for another 10 days without incident. Only after post-mortem images were taken was the source of the bright spot appreciated. The tear that formed appears to have been contained by the fine-scale U-shaped corrugations, details of which are described elsewhere [6]. This foil was run for 2967 MW·hrs.

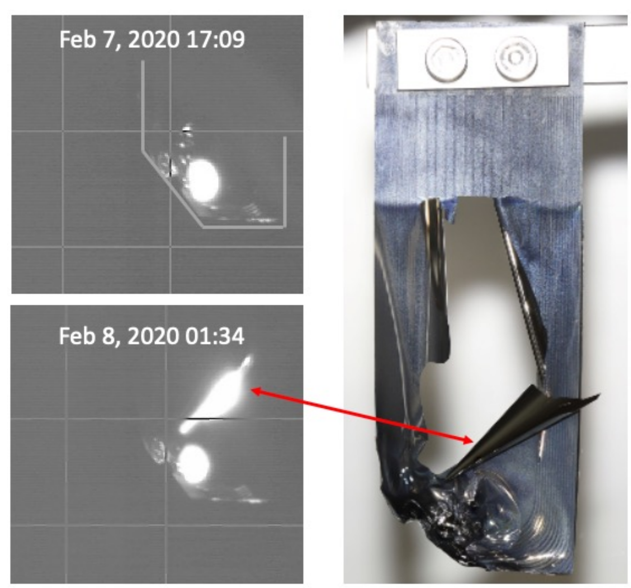

Figure 6: Foil exhibiting a large tear during operation. Foil outline has been added on top left image.

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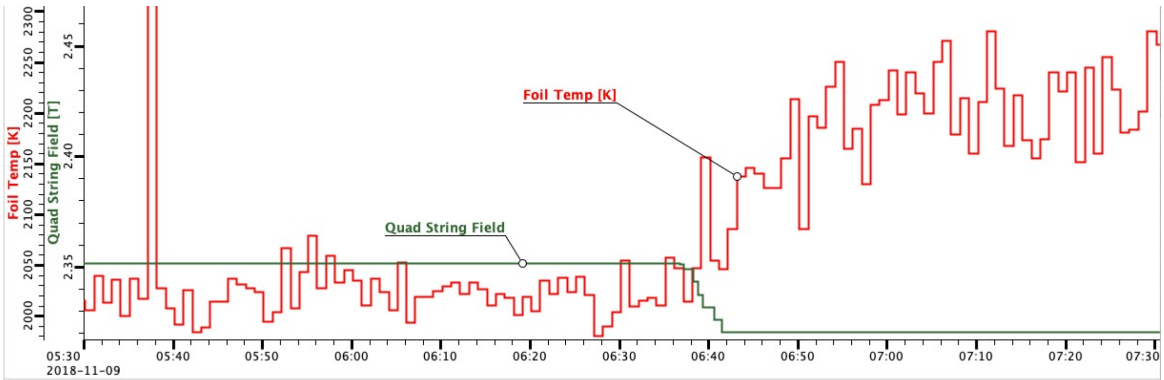

Figure 7: HEBT quad field and foil temperature during quad tuning.

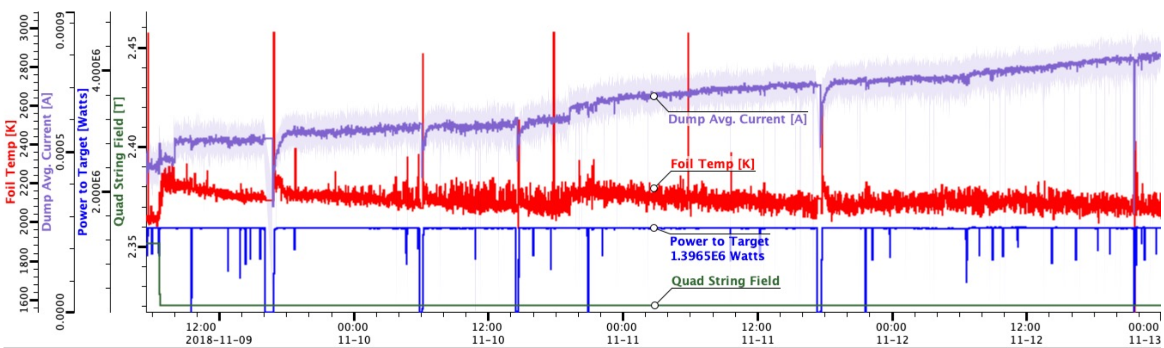

Figure 8: Injection dump current, foil temperature, power to target, and quad field immediately after tuning event in Fig. 7.

FOIL SUBLIMATION

Of the concerns presented here, foil sublimation is potentially the most disruptive, representing the possibility of a single-point failure at high power. As mentioned in the previous sections, radiative cooling dominates and is proportional to the emissivity of the material, near 0.9 after foil conditioning. Even so, at high power the temperature of the foil can get very high, leading to sublimation of the foil. As the foil sublimates it thins and the stripping efficiency declines. This process can be fast enough that the foil is effectively destroyed as the beam burns a hole in the material. Approaching this limit of catastrophic failure, however, the sublimation rate can be much slower and still detrimental to operation. Once the stripping efficiency drops below 90% at 1.4 MW, or 95% at 2.8 MW the foil would need to be retired as the waste beam would necessarily exceed the 150 kW limit of the injection dump. If this situation were to occur with a frequency of 1 week, SNS would spend roughly 25% of it's operational time conditioning new foils with the current conditioning ramp. (A key reason the foil conditioning time itself is under investigation, despite long foil lifetimes.)

A prototype foil pyrometer [7] provides a real-time measurement of the foil temperature, allowing us to correlate suspected thinning with temperature. Upgrades to this system are being implemented now that will make it easier to use as part of routine operation. Figure 7 shows data from operations as a quad string in the High Energy Beam Transport(HEBT) line just upstream of the foil is being tuned to reduce losses, squeezing the beam on the foil and increasing the temperature by about 180 K to just over 2200 K. Figure 8 shows the foil temperature slowly decreasing and the dump current slowly increasing over the next several days with constant beam power to the target. While this is circumstantial evidence for foil thinning, the temperature range is consistent with slow sublimation, and this observation was accompanied by counter-intuitive behavior of the dump current in response to foil position adjustments consistent with thinning, e.g. moving the foil to position the injected spot closer to the edge of the foil decreased dump current.

FOILS AND SNS UPGRADE PLANS

Noting that current operation sometimes puts foils near the failure point would seem to bode poorly for SNS upgrade plans, but there are several mitigating factors to consider.

First, the foils currently used in operation are thicker than is strictly required because the mechanical stability offered by thicker foils means less tuning of the foil position to maintain desirable dump power, and the lack o correlation between foil thickness and losses means there is no pressure to reduce foil thickness. In the future, the temperature of the foils will provide additional constraints.

Second, for the PPU-FTS case shown in Table 1, the beam current will not increase significantly, and while an $\approx 8\%$ thicker foil would be required to maintain the same stripping efficiency at 1.3 GeV the foils we currently use are thick enough for operation at 1.3 GeV. In addition, the stopping

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power in graphite decreases by about 5% for both protons and electrons [8], which means the energy deposition should decrease if the foil thickness is not changed.

Finally, the spot size on the foil is much smaller than the design - horizontal and vertical beta functions as small as 3.93 m, 2.97 m with emittances of 0.29 mm·mrad, 0.33 mm·mrad have been calculated at the foil using wirescans upstream and loss-tuned production optics, compared to 10.44 m and 12.12 m, and 0.3 mm·mrad design values, giving a beam density about 3× design. No constraints are imposed on the beam size today. We plan to use feedback from the pyrometer as an additional constraint on optics tuning in the injection region once it is reliable enough for routine operation, and if necessary magnet interlocks to restrict changes to the beam size on the foil after machine set up prior to a run, similar to the protection of the mercury target.

In the STS era, beam current will increase by about 50%, which we believe can be easily compensated by increasing the beam size closer to design values once gains from reduced foil thickness have been exhausted. We are currently working to understand the tuning pressures that lead operators to reduce the beam size on the foil and address them through other means, such as beam collimation in the HEBT line.

Combining data from operations shown here, and foil test stand data in preparation for publication, we are confident that with design beam sizes at the foil, nanocrystalline foils should easily survive above 4-5 MW for a 1.3 GeV SNS. Higher powers may be possible.

CONCLUSION

Experience over the last several years at the design energy of 1.4 MW has shown that the nanocrystalline diamond foils used for charge exchange injection at the SNS perform exceptionally well. Typical foil lifetimes are measured in thousands of MW·hrs. Still some problems cause operational headaches, notably beam losses related to interaction with the foils - for which a clear correlation with foil thickness is surprisingly absent, a disruptively long 'conditioning' procedure that requires continuous operator intervention, and possible foil sublimation.

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