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ANALYSIS OF PRIMARY STRIPPER FOILS AT SNS BY AN ELECTRON BEAM FOIL TEST STAND

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Abstract

Diamond foils are used at the Spallation Neutron Source (SNS) as the primary strippers of hydride ions. A nanocrystalline diamond film, typically 17 x 45 mm with an aerial density of 350 μg/cm^2, is deposited on a corrugated silicon substrate using plasma-assisted chemical vapor deposition. After growth, 30 mm of the silicon substrate is etched away, leaving a freestanding diamond foil with a silicon handle that can be inserted into SNS for operation. An electron beam test facility was constructed to study stripper foil degradation and impact on foil lifetime. The electron beam capabilities include: current up to 5 mA, 0.300 mm^2 focused spot size, and rastering in the x- and y-directions. A 30 keV and 1.6 mA/mm^2 electron beam deposits the same power density on a diamond foil as a 1.4 MW SNS beam. Rastering of the electron beam exposes a similar area of the foil as SNS beams. Experiments were conducted using the foil test stand to study: foil flutter and lifetime; effects of corrugation patterns, aerial densities, foil crystallite size (micro vs. nano), and boron doping; temperature distributions and film emissivity; and conversion rate of nanocrystalline diamond into graphite.

BACKGROUND

Diamond stripper foils have been developed at Oak Ridge National Laboratory (ORNL) for use within the SNS since 2003 [1-2]. The foils are grown on a semiconductor grade (100) silicon wafer using plasma-assisted chemical vapor deposition, and include nanocrystalline diamond, microcrystalline diamond, and occasionally boron-doped nanocrystalline diamond. The design size and aerial density of the foils have varied greatly over the years, with the current size and aerial density being a 17 mm x 45 mm and 350 μg/cm^2. This aerial density corresponds to a diamond film of approximately 1.0 μm thick. Once the foils are grown, 30 mm of the silicon substrate is chemically etched away to leave a free-standing portion of diamond at the bottom of the foil that is 17 mm x 30 mm and a silicon handle at the top that is 17 mm x 15 mm. A variety of lithography patterns are implemented on the silicon growth surface that transfers into the conformal to help give the needed rigidity and flatness when the silicon substrate is etched away. The growth and processing of these diamond foils has been optimized and routinely produces high quality stripper foils for use within the SNS.

The current status of SNS is providing researchers with a pulsed beam of 0.94 GeV, 1.0 to 1.4 MW, at a pulse rate and width of 60 Hz/975 μs. In the past few years, several obstacles have delayed the progress of SNS to provide a constant design value of 1.4 MW. These obstacles are the result of growing pains of a decade old machine. Some examples that SNS employees have faced in recent months include multiple mercury target failures; water contamination in various portions of the linac; multiple components that have either failed completely or have limited operation; issues with foil brackets; and the rare foil failure. Despite these issues, SNS employees have been able to successfully diagnosis and resolve these problems.

In order to further develop the foil program at ORNL and meet the growing needs of SNS, a team of researchers from ORNL, SNS, and the University of Tennessee (UTK) formed the Foil Development Team (FDT) in 2001. This group consists of both highly skilled technicians in foil growth and development, experts in chemical vapor deposition, and experts in accelerator physics. The mission of this group is to design and develop foils for use in the SNS to maintain current operating conditions of 1.0 to 1.4 MW, along with developing foils for future SNS upgrades to 2.0 and 3.0 MW. One aspect of this team that is of particular interest to this work is developing and characterizing a variety of foils to determine how well the foils will perform under SNS operating conditions. This includes the use of an electron beam test stand to help determine how foils will perform under various thermal loads experienced in the SNS.

FOIL TEST STAND

Since the SNS started full operation in 2006, it has been desirable to provide high reliability the various users coming from around the world. Therefore it was difficult to experiment with the different foil composition and types that were being developed, and it severely limited the foil development program. In 2009 the FDT deemed it necessary to develop a table top test stand that would allow a more adaptable approach to testing foil properties than what could be done during normal operation at SNS. This test stand would allow a variety of foils to be examined, along with determining the various properties that influence the success of a foil within the SNS. Since having an accelerated H$^-$ beam was not feasible as a table top source, a source was required that would both meet the size restriction but still apply the same thermal load that the foils experience actual operation. Therefore it was calculated that a 30 keV beam could apply a high enough current density to simulate the thermal load of the SNS. This device became known as the Electron Beam SNS

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Foil Test Stand, or more commonly the Foil Test Stand (FTS) [3].

The SNS was designed to produce a 1.0 GeV beam with a power of 1.4 MW. This beam is pulsed at 60 Hz, at 1 ms width. This corresponds to the beam to cycle between being on for 1 ms and off for 15 ms. This design parameter corresponds to a pulsed beam containing 1.5 x 10^{14} protons per pulse (ppp). In addition to the foil being impacted by the 1.5 x 10^{14} ppp from the linear accelerator, the foil also experiences a foil load from the circulating beam within the accumulator ring. On average for each pulse coming from the linear accelerator, the foil will experience each proton seven to ten times. This accounts for the majority of the load that the foils experience. With this all in mind, a well-tuned SNS beam that is at the design-power of 1.4 MW, both the injected and circulating beams, will have a peak hit density on the foil of 4.5 x 10^{13} protons per square millimeter (p/mm^2). Since the pulse width of the SNS beam is 1 ms, then the peak proton beam density per unit time is approximately:

$$4.5 \times 10^{13}\ \text{p/mm}^2 \div 1 \times 10^{-3}\ \text{s} = 4.5 \times 10^{16}\ \text{p/mm}^2\text{/s}$$

To better understand this number of 4.5 x 10^{16} p/mm^2/s, it can be converted to Ampere units. This number corresponds to a 7.2 mA/mm^2 beam peak. In order to compare the thermal load the foil will experience from the SNS beam to that of the FTS electron beam, the stopping powers of the two different particles were compared. At 1.0 GeV the proton's stopping power in amorphous carbon (density is ~2.0 g/cm^3) is approximately 1.946 MeV*cm^2/g. On the other hand, the stopping power of an electron at 30 keV in amorphous carbon is 8.575 MeV*cm^2/g. The stopping power of 30 keV electrons is ~4.43 times higher than that of a 1 GeV protons. Since the stopping power is much greater for electrons than for protons, it requires a lower power to achieve the same thermal effect. Therefore to have a comparable power density to that of a 7.2 mA/mm^2 proton beam, it is necessary to have an electron beam that can produce a power density of 1.6 mA/mm^2.

$$1.4\ \text{MW SNS Beam} \approx 1.6\ \text{mA/mm}^2\ \text{Electron Beam}$$

The FTS consists of several different components, including a 30 keV electron gun, a Faraday cup and limiting aperture, a residual gas analyzer, various vacuum components, an actuator and bracket that allows up to four foils to be attached, an infrared camera, a high definition video recorder, and a stainless steel vacuum chamber that houses several of these components. The FTS is a very dynamic tool that is used to analyze and characterize a variety of foils that have the potential to be used within the SNS. The FTS has the capability to replicate the present, and future, thermal loads that the foils experience within the SNS. In order to meet the necessary spot size requirement, it is required that the beam from the electron gun be rastered in both the x- and y-direction. Rastering of the electron beam allows for a larger, but still uniform, illumination spot on the foil. In order to compare the FTS to the SNS, it is necessary to determine what energy and current the electron gun from the FTS must achieve to reach an equivalent SNS thermal load.

EXPERIMENTS

The FTS was optimized for each experiment to allow for reproducible and consistent results. Table 1 shows the parameters of the electron gun.

Table 1: Electron Gun Settings

	Minimum	**Maximum**
Energy	1.00 keV	30.00 keV
Grid Voltage	0.0 V	300.0 V
Source Voltage	0.000 V	3.000 V
Emission Current	1 x 10^{-6} mA	5.000 mA
Spot Size	0.300 mm^2	25.000 mm^2
Raster Freq. (X & Y)	0.00 Hz	15,000 Hz
Pulse Width	1 μs	1 x 10^6 μs
Pulse Frequency	1.00 Hz	5000.0 Hz

In order to use the FTS as a device to simulate the thermal load on a foil, it was first necessary to determine the actual spot size from the SNS beam on the foil and the corresponding electron gun settings. Since the foil experiences both the injection and circulation beams, it was decided that the FTS would be configured for the peak beam intensity. Using irradiated foils from the SNS, the peak beam spot size was found to have a diameter of 3.0 mm, giving an area of 7.07 mm^2. Since the electron gun gives a focused spot size of 0.300 mm^2, it was necessary to raster the beam in both the X- and Y-directions to achieve the necessary spot size. Additionally, it was important to determine how each electron gun emission current corresponded to the SNS beam intensity. Similar to the SNS, the FTS uses a pulsed beam with frequency of 60 Hz and width of 1 ms. By using a smaller spot size of 0.0265 cm^2, the FTS was able to produce beam current densities similar to those experienced within the SNS. The electron beam was rastered with a raster size to produce a 0.0265 cm^2 spot and a raster frequency high enough to limit the amount of cooling between cycles of the beam. In Table 2, the corresponding FTS settings are compared to the corresponding SNS power levels, along with the calculated emissivity and temperature of foils within the FTS.

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Table 2: FTS/SNS Correspondence

FTS 2.65 mm^2	SNS 7.07 mm^2	Emissivity	Temperature K
0.272 mA	0.090 MW	0.1794	710.9
0.640 mA	0.211 MW	0.2414	926.0
1.120 mA	0.370 MW	0.3378	1176.0
1.600 mA	0.528 MW	0.4875	1376.0
2.160 mA	0.713 MW	0.6588	1534.6
2.720 mA	0.898 MW	0.8059	1635.3
3.200 mA	1.057 MW	0.8146	1714.8
3.760 mA	1.242 MW	0.8150	1775.8
4.320 mA	1.426 MW	0.8350	1883.5
4.800 mA	1.585 MW	0.8296	1889.1

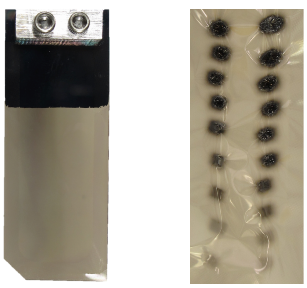

Figure 1: Primary Stripper before beam (left) and after seeing multiple beams at different currents (right) as indicated in Table 2.

The emissivity was calculated by measuring the optical transmission for the series of spots using a blackbody source. The measurements were made at four different blackbody source temperatures to confirm that there was no dependence of emissivity on temperature. The spots experienced differing amounts of beam as shown in Table 2 and Figure 1. The lowest spot, received 5 minutes of a pulsed and rastered beam at a current of 0.272 mA. The second lowest spot received the same 5 minutes of current exposure as the lowest spot, plus an addition 5 minutes at 0.640 mA, for a total beam exposure of 10 minutes. This method was carried out for the remaining spots, with the last spot receiving a maximum current of 4.800 mA and total beam time of 50 minutes. Once the emissivity was calculated, it allowed the calculation of the foil temperature at each of the beam spots. This data is important because not only does define the temperatures that the foils are experiencing within the FTS, but also indicates the temperature that the foils are experiencing within the SNS. Raman analysis has been used to follow temperature dependent phase changes in the foil, evident by the darkening seen in the film [4]. The results of this analysis will be reported elsewhere. These results demonstrate that the foils potentially capable of surviving future power upgrades planned for the SNS.

In addition to determining the temperature and emissivity of the foil at different settings, it is also necessary to determine what foil properties and characteristics are essential to their longevity. In a series of tests, multiple foils were loaded into the FTS that varied in corrugation patterns, aerial densities, crystal size (micro vs. nano), and boron doping. The foils were tested for the ability to withstand high beam current densities and their prevalence to foil flutter. The lithography patterns that have been currently tested within the FTS include those that cover the outer edge of the foil (checkerboard, U-shape) and those that cover the entire foil surface (U-shaped, random ellipses, concentric rings, diagonal lines). Within the FTS, it was found that the two patterns used along the outer edge of the foil performed similarly. It may be noted however, that the checkerboard pattern is more susceptible to more drastic tears that tend to increase foil flutter. Of the full foil lithography patterns, the concentric ring and full U performed very well whereas the random ellipses and diagonal lines had severe foil flutter. The outcome of the lithography pattern tests gave important preliminary data to the SNS on how certain foils would perform at the SNS ring. A variety of polycrystalline diamond films were tested, including nanocrystalline, microcrystalline, and films doped with boron. Similar to the lithography pattern tests, all foil types performed very well and were limited more by extrinsic effects (tears or rips from processing) than by their intrinsic effects (crystal size and distribution). These results confirm what has been seen within the SNS, where there have been several champion foils with various intrinsic properties. The foils with a larger aerial density performed slightly better because of their increased rigidness, but had slightly higher peak temperature than the thinner foils.

CONCLUSION

The FTS has been a key resource for determining how new lithography patterns and foil types would perform within the SNS, the causes of foil flutter, and the maximum temperature foils can experience before failure.

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