AN ELECTRON BEAM SNS FOIL TEST STAND

R.W. Shaw, D.P. Bontrager, L.L. Wilson, ORNL, Oak Ridge, TN 37831, U.S.A.
C.S. Feigerle, University of Tennessee, Knoxville, TN 37996, U.S.A.
C.F. Luck, M.A. Plum, Spallation Neutron Source, Oak Ridge, TN 37831, U.S.A.

Abstract

Nanocrystalline diamond foils are now in use for injection stripping at the SNS. Typical dimensions are 17x25 mm x 300-350 μg/cm^2 physical thickness. Corrugations of the foil help to maintain flatness, but after ca. 300 C of injected charge curling is observed. We continue to experiment with foil preparation techniques. To allow independent stripper foil testing without impacting SNS neutron production, we have assembled a 30 keV electron beam foil test facility to investigate foil lifetimes. At 30 keV energy, a 1.6 mA/mm^2 electron beam imparts the same peak heating load to a carbon foil as the injected and circulating current of the 1.4 MW SNS. At this energy the electron stopping distance is approximately six-fold longer than the foil thickness. The electron gun is capable of 5 mA current in a focal spot less than 1 mm FWHM diameter. Two foil stations are available for sequential tests, and foils can be rotated relative to the beam to vary their effective thickness. A 6 μs risetime optical pyrometer records instantaneous foil temperatures over the 60 Hz heating profile. A CCD camera captures foil images over time. Results using this test stand are described.

BACKGROUND

Since 2003 we have prepared diamond stripping foils as a replacement for conventional carbon foils at high-power accelerators.[1-3] The mechanical strength of diamond allows 350 μg/cm^2 (1 μm thickness) foils as large as 17 x 25 mm that are supported on only a single edge to be grown and mounted without the use of supporting carbon fibers. Nanocrystalline diamond is preferred and is grown on semiconductor grade (100) silicon by plasma-assisted chemical vapor deposition using a 2:8:90 methane:hydrogen:argon gas mixture. Chemical etching of a portion of the Si wafer results in a free standing foil with a convenient Si mounting handle. There is stress in the foil, and spontaneous curling of the foil is overcome by incorporating corrugations in the diamond. However, curling is a common failure mechanism when the foil is heated in a high intensity proton beam. For example, at the SNS, where the beam power will ultimately be 1.4 MW and is now ~850 kW, we have subjected nanocrystalline diamond foils to ~2.6x10^{13} p/mm^2/(670x10^{-6} s) pulses at 60 Hz peak current. To-date, no diamond foils have failed at this power level, which is approximately 60% of the SNS design value. These diamond foils have also been evaluated in the Proton Storage Ring (PSR) at LANL, where the foil hits per second are approximately 50% of that for the SNS full design power.[4] Additional lifetime tests have been conducted using a dc H$^-$ beam at KEK in Japan.

A bottleneck in our development program has been the poor availability of intense ion beams to determine the effective foil lifetime corresponding to different beam currents and pulse timing. In our early work, tests were performed at the front end injector for RHIC at BNL during times when RHIC was in a scheduled shutdown. Tests exceeding 100 hours of beam time were required for diamond foil failure. Only four foil stations are available at the PSR, and the majority of those must be reserved for LANL foils of known performance to provide a reliable production schedule neutron flux for users. At the SNS, the foil changer has eleven useful stations, but the scheduled shutdown cycle only allows for foil re-loading on a quarterly basis. A variety of foil materials that would be candidates for testing, given sufficient beam time, include mCADAD foils (Sugai/LANL), diamond like carbon foils (TRIUMF), hybrid boron carbon foils (Sugai), carbon nanotube foils (Yamane), and additional diamond formulations.

In order to permit more flexible foil tests without the need to perturb accelerator run cycles, we have assembled an electron beam test stand. The primary goal is to measure foil temperatures for a variety of foil materials and for controlled loadings that match the SNS design value. Thirty keV electron beams of sufficient intensity to mimic the SNS foil load are available and have been used for some preliminary foil tests. The facility design and our early test results are described here

TEST STAND REQUIREMENTS AND DESIGN

The SNS design values corresponding to the foil load include a 1.4 MW, 1 GeV beam with 60 Hz/1 ms pulse timing. The design peak current in the SNS ring is 70 A (corresponding to 1.5x10^{14} protons/pulse). The circulating beam comprises the majority of the foil load due to the nominally seven to ten proton hits per pulse.

The peak foil hit density for a well-tuned full-design-power SNS beam is 4.5x10^{13} protons/mm^2, including the contribution from the convoy electrons ($H^- = H^+ + 2e^-$) as well as both the injected and circulating beam contributions.[3] This is for a ~1 ms duration, and the hits per unit time are approximately the same over the 1 ms accumulation and storage cycle. To simulate the SNS case, a peak proton beam density of (4.5x10^{13} p/mm^2)/(1x10^{-3} s) = 4.5x10^{16} p/mm^2/s is needed, with the beam on for 1 ms, off for 15 ms, on for 1 ms, etc. In units of amps, this is 7.2 mA/mm^2 peak. Thirty keV electrons

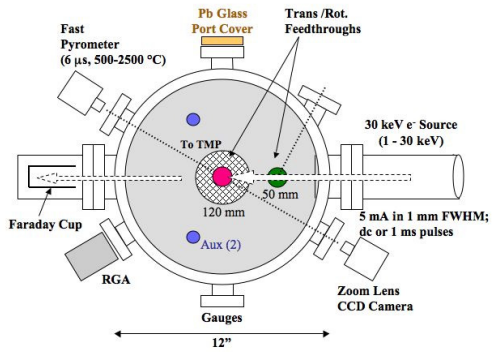

Figure 1: Top view schematic of the test stand apparatus. TMP, turbomolecular pump; RGA residual gas analyzer.

have a 4.43-fold higher stopping power than 1 GeV protons. The range of 30 keV electrons is 1.966×10^{-3} g/cm^2, which is ~6x the nominal SNS foil thickness, so this electron energy is suitable for simulating the SNS case. Thus for 30 keV electrons, one would need 1.6 mA/mm^2. A foil test facility should be able to deliver at least 2x more peak density to account for modeling errors.

Ideally we would like to heat a spot larger than 1 mm^2. The SNS beam spot is about 3 mm rms in both the x and y directions, for an rms area of ~27 mm^2. The peak electron current would then be (1.6 mA) x (2) x (27 mm^2) = 86 mA. This value is unrealistic for laboratory electron sources, and thus it was decided to match the SNS power density, but for a smaller spot size.

A custom electron source was manufactured by Kimble Physics, Inc. (Wilton NH), based on their Model EMG-4215. Pre-production ion simulations indicated that 5 mA of electron current was possible in a 1 mm diameter (FWHM) spot, if the working distance is constrained to be no more than 50 mm. In fact, the measured beam diameter is as small as 0.5 mm. A LaB_6 filament with thousands of hours expected life is incorporated. Beam pulsing is accomplished by a dual grid technique and the inter-pulse leakage is expected to be no more than pA. Beam deflection and rastering up to 2 degrees is provided.

A test chamber was constructed based on a 12" diameter base well design; a top view schematic is shown in Fig. 1. The chamber is pumped from below using a 300 l/s turbomolecular pump backed by a dry mechanical scroll pump; the typical chamber base pressure is 5×10^{-9} Torr. There are two foil stations at 50 mm and 120 mm distance from the electron source output aperture. The foil stations are equipped with rotation/translation feedthrough actuators that allow us to position two foils, or more commonly, a phosphor screen (at 50 mm) and a test foil (120 mm). The phosphor screen is removed from the beam path when a foil test is in progress. Opposing the electron source is a water-cooled Faraday cup detector for measuring the electron beam current. The Faraday cup has a 3-mm entrance aperture that is electrically isolated from the body of the detector. A 1 kΩ resistor from that aperture plate to ground allows us to measure the fraction of the electron current that strikes the aperture plate. By comparing the plate and cup currents we can gauge the focal spot size at that location (187 mm from the source output).

Other chamber ports are available as shown in Fig. 1. These are used for optical diagnostic equipment. Each viewport is shielded with a lead glass window (2 mm Pb equivalent) to block X-rays that may be generated within the chamber. A CCD video camera with a 12X zoom lens is positioned at a port 30 degrees off the source port for viewing the foil; it records either black body light due to the electron beam spot on the foil or a photograph of the foil after the beam has been turned off. The zoom feature allows us to fill the ½" camera chip (0.410 MP) with the test spot or alternately to view the overall foil. The scene was illuminated using a small filament lamp that was connected through the chamber top plate 1.33" CFF feedthrough; however the bulb envelope has been removed, as it was found that the glass shell charged-up during beam operation, resulting in a deflection of the electron beam.

A fast, one-color pyrometer (Mikron Infrared, KG740-LO, Oakland NJ) was positioned at the port opposing the CCD camera. This device detects 1.7 μm light and was factory calibrated for 500 to 2500 °C. The response time is specified as 6 μs. The detection spot diameter is adjustable down to slightly below 1 mm at our working distance and is indicated by a projected LED spot for careful alignment of the pyrometer viewing location with the electron beam heated spot. The pyrometer (emissivity setpoint 0.5) was standardized against a calibrated disappearing tungsten filament pyrometer, both of which observed a tungsten filament lamp coil; the infrared pyrometer viewed the filament through leaded glass to match the eventual experimental conditions. A satisfactory correspondence between the measured result and the factory calibration resulted, with a maximum 150 °C temperature difference observed.

PRELIMINARY MEASUREMENTS

The foil test stand was recently brought into service and some preliminary test data have been recorded. Figure 2a shows a contour plot derived from a CCD image of the luminous spot on an electron-irradiated 385 μg/cm^2 thick nanocrystalline diamond foil. The peak beam current was 0.24 mA (60 Hz and 1 ms) and the spot diameter is less than 0.5 mm. Figure 2b is a CCD image of the foil after the test. It is shown in false color to improve the clarity; it is difficult to photograph near-transparent objects within a vacuum chamber. Two damage spots are visible and were created because the beam position was relocated during the test. The vertical lines on the right hand side of the CCD image are reflections from the foil corrugations (100 lines per inch) that were used as a standard for spatial calibration. The damage spots have a nominal diameter of 0.45 mm.

The corresponding pyrometer output voltage is plotted in Fig. 3. As expected for the low thermal inertia foil, the temperature fluctuates with the incoming 60 Hz pulses,

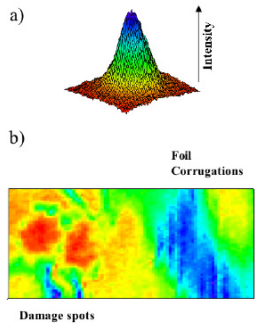

Figure 2: a) Contour plot created from an electron beam spot-on-foil photograph taken through a 10% transmission filter; b) Post test damage spots on the diamond foil.

with a rapid rise time and a slower decay to an inter-pulse value above ambient. Using the pyrometer calibration emissivity setting of 0.5, the indicated peak and trough temperatures were 1070 and 580 °C, respectively. When the beam current was increased to the nominal 1.5 mA corresponding to the SNS foil simulation, the pyrometer peak temperature approached 1700 °C; recall that our design loading was calculated for a 1 mm spot, not the <0.5 mm spot measured here. Thus the current density for this 1.5 mA test was approximately four-fold higher than the SNS foil loading. Precise pyrometry is difficult, as the foil emissivity certainly changes as the diamond foil converts to a more graphite-like material within the heated spot at temperatures above about 1500 °C. At present, our measured temperatures are thought to be accurate within about 150 °C with the maximum error at the high temperature end of the range. Further investigation of methods to minimize thermometry errors is required. One possibility is to irradiate the diamond foil with sufficient flux to quickly accomplish the diamond to graphite conversion; then further measurements can be made with a stabilized emissivity.

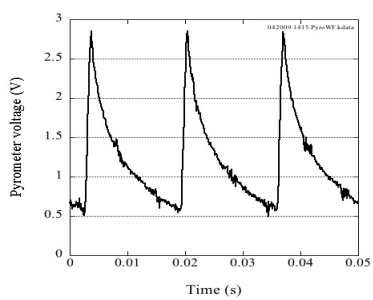

Figure 3: Time-dependent pyrometer voltage output corresponding to the foil trial in Figure 2. The peak beam current is 0.24 mA. The temperature extremes correspond to approximately 1070 and 580 °C.

SUMMARY

We have assembled a 30 keV electron beam apparatus for evaluating stripping foils. A foil loading in excess of the SNS design value can easily be attained, but only for a 1 mm reduced foil area. The test stand is equipped with a fast pyrometer to determine instantaneous foil temperatures and a camera to record beam-on-foil luminous spots and post-test foil damage. Initial tests indicated that for nanocrystalline diamond foils, foil temperatures approaching 1700 °C result and can be measured with reasonable accuracy. Improved pyrometry techniques are required and are under development. Foil tests for a variety of candidate foil materials are possible using this apparatus.

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