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Abstract. The Low Energy Demonstration Accelerator (LEDA), located at Los Alamos National Laboratory, utilizes a slow wire scanner to measure beam profiles. The beam energy is 6.7 MeV and the peak current is 100 mA. This wire scanner profile measurement is located in the High Energy Beam Transport (HEBT) section of the LEDA beam line. This section of beam line is used to expand the proton beam coming out of the LEDA Radio Frequency Quadrupole (RFQ) prior to impacting the beam-stop. The purpose of the scanner is to provide horizontal and vertical beam profiles. The wires or fibers are a Silicon Carbide (SiC) material, and are attached to an actuator driven by a stepping motor. The actuator drives the fibers through the beam in incremental steps. At each step, the amount of secondary electrons generated by the interactions of the proton beam and the wire are measured. From these incremental measurements the beam profile is constructed. This paper will discuss the operation of the scanner, two of the experiments conducted to understand the capability of the SiC wire to survive and some of the different uses of the beam profile data acquired during the ongoing commissioning of LEDA.

Scanner Operation

The wire scanner is used to measure beam profiles produced by the LEDA[1] at Los Alamos National Laboratory. The instrument is located in the HEBT[2] section of beamline directly down-stream of the RFQ[3]. The wire scanner is controlled through the Experimental & Physics Industrial Control System (EPICS)[4] accelerator control system. Control software is a combination of EPICS databases programming for actuator motion control, sequences (written in State Notation Language) for overall system coordination, and PADL[5] routines to link EPICS data to Interactive Data Language (IDL)[6] analysis routines. The operator has the ability to set the scanning parameters for profile start and stop as well as the distance between acquisition points. The scanner will move to the position specified, acquire data, move the prescribed distance, and again acquire data. Data acquisition consists of obtaining a waveform depicting the integrated charge caused by the fiber intercepting the accelerated protons. Since the scanner is moving relatively slowly, a beam profile is actually acquired over the course of many beam macro-pulses.

The charge on the wire is integrated over the course of a beam macro-pulse. Since we are constructing the profiles over the course of many beam macro-pulses it is necessary to normalize the charge detected at a particular location by the total charge detected at the nearby upstream AC toroid [7]. So when data is acquired, the charge on the wire and the total current in the macro-pulse are both recorded as waveforms. These waveforms are then stored into an array in the SNL and at the end of the scan are passed through the PADL software to IDL for final processing. Figure 1 shows the results of a typical profile measurement. The points on the graph indicate a data point of normalized charge vs. position along the X and Y-axes. The line through the points is the result of a fit done to the data based on Gaussian distribution.

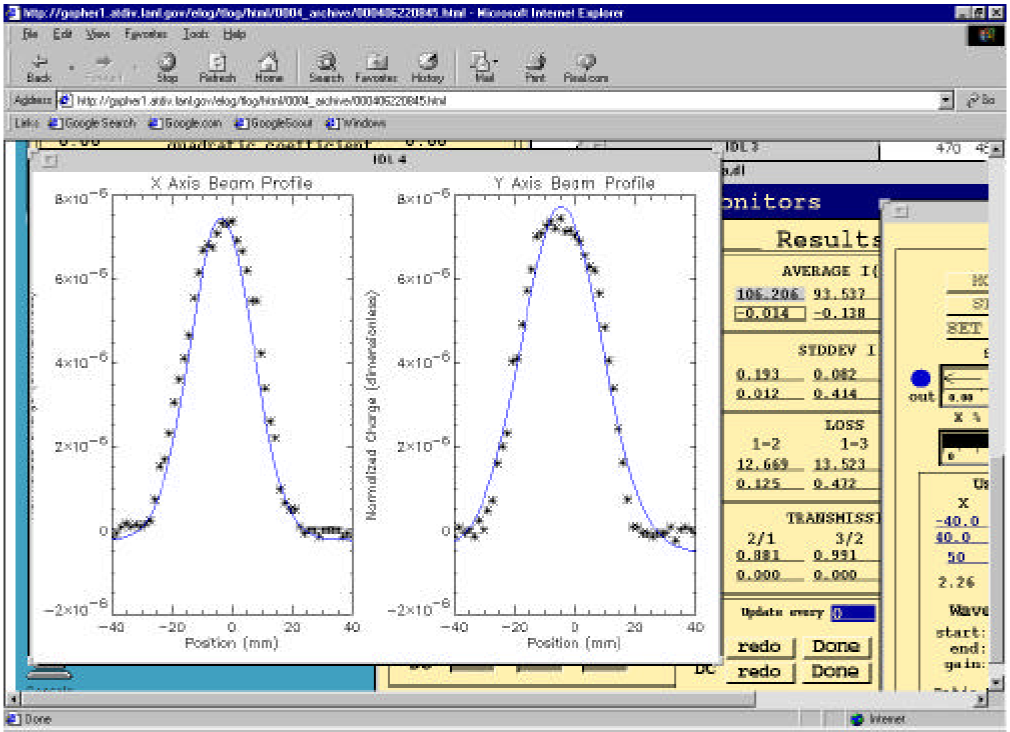

Figure 1. Typical beam profile

In addition to the two plots, the system reduces the data in two different ways. The first method is to calculate the first four moments of the distribution: mean, variance (standard deviation), skew, and kurtosis. The second method is to use a Gaussian distribution to fit the data. This Gaussian fit is a routine provided by IDL, which returns a mean, standard deviation, and other parameters to improve the fit. The profile data is written to two different files. The first file contains the raw waveform data from the wire scanner and toroid as well as the position data for each point in both profiles. This is a fairly large and cumbersome file, but has proved to be an extremely important source of information for system de-bugging. The second file contains just the position and normalized charge information as well as the data reduction parameters from both the calculated moments and the Gaussian fit.

Wire Survivability Experiments

One of the key issues with this diagnostic is to determine how much beam power the detection fiber can be subjected to without destroying it. Two different experiments were conducted to attempt to verify the theoretical calculations and to investigate exactly how much beam power the wire could safely absorb. Silicon Carbide fibers were selected for this diagnostic because of their successful prior use at the Los Alamos Neutron Science Center (LANSCE)[8] facility and their proven durability. The SiC material is in the form of a monofilament or fiber. The particular fiber being tested is similar to SCS-6 made by Textron System Inc. and is 100 micron (0.004 inch) in diameter. There is an inner core of the fiber that is carbon (33 micron). Figure 2 shows how the fiber is mounted to the actuator with the use of a crimped copper fitting, a tensioning spring, and an isolating post.

Figure 2. Wire tensioning system

The testing of the fiber was accomplished by placing the fibers in the 6.7 MeV, 100 mA, H^+ beam and subjecting them to increasingly longer beam pulses. The first test consisted of increasing the beam pulse until the wire eventually failed. Failed in this instance means that the wire no longer transmitted a detectable signal. The second experiment was similar to the first except that the wires were not tested to failure. Both tests utilized a spectrometer to measure the light emitted from the fiber due to the fiber/beam interaction. From this spectrometer data, the average fiber temperature was extracted. The results of the initial experiment showed that the wires were able to survive well past the predicted limitations. The second test was done to try to understand the mechanisms that allowed the wire to survive beyond the predicted limit and to see if the limitations could be extended without degrading the performance of the diagnostic.

Fiber heating

As the H^+ particles encounter the fiber, they are slowed down by the interactions with the orbiting electrons in the SiC molecules. The energy lost by the H^+ particles takes the form of heat in the fiber material. The only cooling mechanism considered is radiative cooling to the surroundings. The wire is in a vacuum so there is no convection, and conduction along the wire is assumed to be negligible. An energy balance is done on the system and the following first-order differential equation for the change in temperature over time in the fiber is derived:

$$\frac{dT}{dt} = \frac{\rho V \frac{dE}{dx} I_{avg} - \varepsilon\sigma\left(T^4 - T_{surr}^4\right)A_{surf}}{\rho V c(T)} \quad \text{. (Eq 1)}$$

This equation is numerically integrated to determine the fiber temperature as a function of time. Equation 1 was used to predict the fiber temperature for the experimental conditions. Figure 3 is a plot of the predicted peak temperatures for various beam pulse lengths based on the following beam conditions: 100 mA average current, 6 Hz, 6.7 MeV beam energy, σ_x = 10 mm, and σ_y = 14 mm. This beam size corresponds to a peak current density of 0.01137 A/cm^2 at the beam centroid.

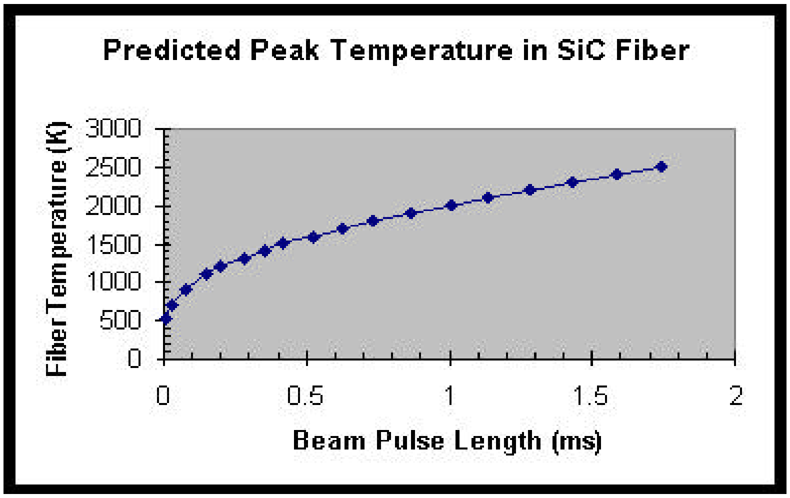

Figure 3. Peak calculated wire temperature vs. beam pulse length

Temperature Measurement of the Fiber Using a Spectrometer

An Ocean Optics fiber optic spectrometer was used to measure the temperature of the wire. The 2048 channel spectrometer had a 1200 groove/mm grating, which provided a spectral response from 450-750 nm. Light from the HEBT was collected by a 60-mm Nikon lens, coupled into a 300', 600-micron quartz fiber, and brought into the control room where the spectrometer was located. A channel-by-channel intensity calibration of the entire system, lens, fiber, and spectrometer, was carried out using a lamp with a 2800 K color temperature.

The power per unit area per unit wavelength from a blackbody is given by Plank's equation:

$$P/A = 2\pi \times 10^{-9} \frac{hc^2}{\left[\lambda^5\left(e^{\frac{hc}{\lambda kT}} - 1\right)\right]}. \text{ (Eq 2)}$$

For temperatures less than about 4000 K, the spectrometer, which is only sensitive in the visible, will not see the peak of the emission distribution. We are working in the short wavelength limit where emission is proportional to $\lambda^{-5} e^{-hc/\lambda kT}$. This function's shape has a relatively weak dependence on T, but the intensity of the emission is a very strong function of T.

The emission from the wire varies both temporally and spatially along the wire. Because of the strong temperature dependence of the emission, the measured temperature is close to the peak temperature. Our simulations indicate that, if the temperature is determined from the shape of the emission with wavelength, the time and spatially averaged temperature should be within 200 K of the peak temperature.

Experimental Setup and Procedure

The SiC fibers being studied are mounted on an aluminum fork attached to an actuator. The actuator moves on a line that is 45° off the vertical. The fibers are mounted so that the actuator moves the fibers across the beam parallel to the horizontal (X) and vertical (Y) axes. The secondary electron signal is taken from the fiber in the middle. There are two outer fibers (also SiC) biased to 24 volts. This voltage is used to attract the secondary electrons leaving the signal fiber, thereby preventing the secondary electrons from returning to the signal fiber and affecting the signal. The accelerator is capable of producing beam pulses from 0.010 ms at 10 Hz up to continuous wave (CW). The beam parameters for this experiment were 90-100 mA beam current, 6 Hz repetition rate, 10-mm by 14-mm rms width beam, and the beam pulse length was the parameter to be varied.

The first step in the experiment was to acquire the beam profile in order to determine the beam centroid and the current density at the centroid. This was done using the LEDA slow wire scanner system. Once the beam centroid was found, the "Y-axis" signal wire was moved into the center of the beam. The initial beam pulse was set at 0.015 ms, which corresponded to a calculated temperature of 500 K. The spectrometer was used to collect the light emitted from the wire as a way to determine the wire temperature. Vacuum pressure in the HEBT was monitored in the event a fiber was destroyed, because it was expected the pressure would possibly increase. The signal from the wire scanner was also monitored on an oscilloscope. This signal provided the verification that the wire was still intact and functioning. Once all data was acquired, the beam pulse length was incremented and the data acquisition process repeated. It was determined that the experiment would continue until the signal from the wire scanner was no longer detected, meaning the fiber had been destroyed.

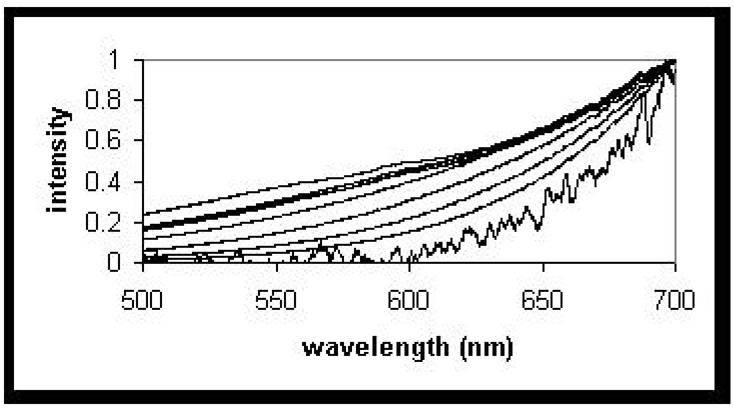

Figure 4. Normalized spectrometer data, corrected for intensity. Lines are for pulse lengths of 0.15, 0.52, 1, 1.72, 2.8, 3.8, 5, 7.5, 10, and 19 ms.

Spectrometer data at short pulse length was acquired for integration times of 64 s. Measurable light was first seen at a pulse length of 0.15 ms. As the pulse length was increased, the signal got stronger, and the integration time was decreased to keep the detector from saturating. For pulse lengths greater than 3.6 ms the integration time was 5 s. The raw data was corrected for the intensity calibration, normalized, and then fit to the short wavelength approximation of Plank’s equation. The corrected and normalized data for a representative set of the data is shown in figure 4.

Test Results

The results of the first experiment were quite surprising. Figure 5 shows the calculated temperature and the experimentally extracted temperature determined from the spectrometer data. The surprise was that we were able to detect a signal from the fiber out to a pulse length of 20 ms (at 6 Hz this represented 12% duty factor), well past the point where we expected the fiber to have melted. The theoretical values begin to diverge from the experimental values after about 150 microseconds.

Another interesting feature was that the measured temperature leveled off at approximately 2200 K. Not all the fibers survived to the 20-millisecond pulse length; there was evidence that a bias wire failed at approximately the 7-millisecond pulse length. At a pulse length of about 4 ms, the temperature reached a plateau, and at that pulse length, the signal level, which had been rapidly increasing with pulse length, began to fall. After reaching 5.2 ms, the pulse length was reduced to 4 ms. The signal level had permanently decreased by a factor of 5, indicating either a change in emissivity or the window had been coated. When the actuator was removed from the beam line it was evident that some material had been lost from the fiber.

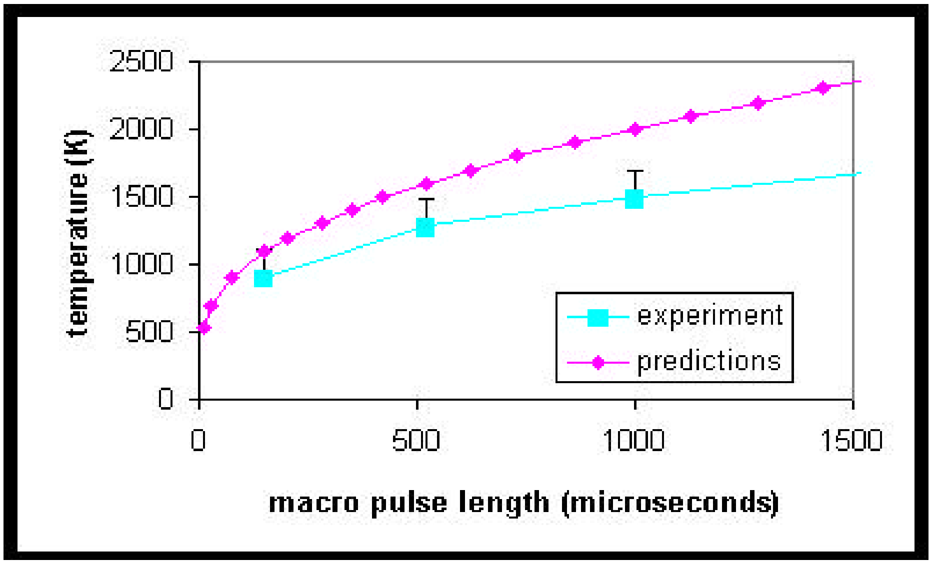

Figure 5. Calculated peak temperature and experimental temperature

The result of this experiment led to questions concerning the modeling of the temperature. There is some effect that is not being modeled. There were two main theories concerning this question. One is that the wire temperature was high enough to cause thermionic emission of electrons. This would cause thermally excited electrons to leave the wire and cause additional current. This would explain the additional cooling mechanism but would cause a detrimental effect by interfering/combining with the desired measurement signal. The second theory was that the temperature was high enough and the pressure low enough for the SiC material to sublimate off the carbon wire core. This phase change would require additional heat with no additional increase in temperature. This theory would explain the loss of SiC material from the fibers as well as why the temperature appeared to plateau above 2200K. The detrimental effect of this phenomenon is that the wire loses material and therefore loses strength.

Based on the findings from the first experiment it was decided that a second experiment should be conducted. It was hypothesized that if thermionic electrons were being generated it should be determined at what temperature this effect was occurring. It was expected that if thermionic electrons were being generated, a non-linear signal would be generated since the secondary electron and the thermionic electrons would combine. The objective of this second experiment was then to see if this non-linearity was being produced and when it began affecting the secondary electron signal. This testing was done using shorter pulse lengths compared to the first experiment.

The second experiment was conducted in the same manner as the first. The beam parameters were the same: 90 – 100 mA beam current, 6 Hz repetition rate, 10 mm by 14 mm rms width beam, and the beam pulse length was the parameter to be varied. The longest pulse length used was 2 millisecond because it was believed that this would not cause enough heat in the wire to do any damage. In fact, there was a visible change in the slope of the secondary electron signal[9], which became more pronounced with increasing pulse length. The pulse length at the suspected onset of thermionic electron emission is at approximately 1.2 – 1.4 milliseconds. This pulse length corresponds to a predicted temperature of 2025 –

2143 K. Even though the intent of this experiment was to not cause failure of the fiber, there was an apparent failure of one of the bias wires. A visible flash was seen toward the latter portion of the experiment, although a signal was still detected. The maximum predicted temperature at the 2 ms beam pulse length was 2451 K. After the experiment was concluded and access to the beam line was allowed, the wire scanner was removed and a bias wire was found to be broken. Again, close examination of the fibers showed the same thinning of material in the area where the core of the beam was impinging on the fiber that occurred on the first experiment.

Based on these two experiments the safe operating temperature for the remainder of the LEDA commissioning was set at a calculated value of 1800 K. By establishing this parameter a guideline has been determined for every subsequent scan. Depending upon the beam conditions, i.e., beam current, beam rms size, beam pulse length, and repetition rate, an analysis can be run to determine if the beam conditions will damage the wire.

Conclusion

The LEDA wire scanner beam profile measurement has been used extensively in the commissioning of LEDA. It has been utilized to verify the HEBT focusing lattice, verified the functionality of the steering magnets, provided data for quad scan style emittance measurements, and helped to verify beam position diagnostics. The two experiments discussed above have enabled the establishment of a maximum temperature guideline for all subsequent scan operations. There still remains work to be done to fully understand the ability of the fiber to survive beyond expectations. Two different effects were discussed and, in fact, a combination of both effects is likely occurring. The development of a better mathematical model is continuing. The work done with the LEDA wire scanner has been incorporated into the development of the APT Beam Halo experiment, the next phase of the LEDA commissioning.

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