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SCL wire scanner signal wire choice

The choice of wire for the SCL wire scanners deserves careful consideration. Wire failure has high consequences. If the wire fragments or ablates and contaminates a superconducting cavity, the cavity must be replaced at high cost. Repairing a SCL wire scanner actuator is also very difficult due to cleanliness and high vacuum considerations. Any type of wire used will present a risk to the superconducting cavities. We must choose the wire that will be the most reliable and least likely to fail.

Three wire materials have been selected as the most promising – tungsten, silicon-carbide, and carbon. All have been successfully used in other accelerator facilities, and some work[1] has already been done for their application at the SNS. Niobium was once considered[2] for the SNS, but rejected due to it's unimpressive thermal characteristics, high vapor pressure, and because wire fragment deposition on the niobium superconducting cavities was judged to be no better for this wire than any other.

We reject SiC (silicon-carbide) wire due to the experience at LEDA. The SiC wire is made by depositing SiC on a carbon wire core, and although the wire appeared to work well, later inspection showed that during operations the SiC flaked off the carbon core. This leaves two wire types consider – tungsten and carbon. Smaller diameter wires tend to not get as hot as larger wires, but the wire should be large enough to be strong and readily handled. The thickest carbon wire that can be purchased is 32 micron (1.2 mil) diameter. It is already somewhat fragile at this thickness, so this is typically the diameter used for profile monitors. For the tungsten wires we chose to investigate 25 micron (1 mil) and 20 micron (0.8 mil) diameter wires.

The SCL accelerates H^- beam from 186 to 1000 MeV (low beta section to 380 MeV, high beta section to 1000 MeV). The beams in the SCL tend to be round at the wire scanner locations. The most challenging wire locations will be where the beam is the smallest and the energy deposition is the greatest. The minimum beam size in the low beta section (<380 MeV) is 0.16 cm rms. The minimum beam size in the high beta section (>380 MeV) is 0.12 cm rms.

The worst case beam energy is where the electrons from the H^- beam just stop in the wire. This will result in the maximum energy deposition (once we're past 100 MeV or so, where the protons no longer stop in the wire). As shown in

[1] R. Shafer, "Performance of a Tungsten-Wire Profile Scanner in the SNS Superconducting Linac," SNS00_TCM_0190, 30/April/2000.
[2] R. Shafer, "Performance of a Niobium- Wire Profile Scanner in the SNS SCL," SNS00_TCM_0203, 24/May/2000.

Figs. 1 – 3, computer model calculations predict that the worst case beam energy for 32 micron carbon wire heating is about 108 MeV. The worst case beam energy for 25 micron tungsten wire is about 310 MeV, and the worst case beam energy for 20 micron tungsten wire is about 265 MeV. In these figures note that the abrupt transitions in the curves at the point of maximum energy deposition are not in reality as sharp as shown in the graphs. This is because the wires are round and not square as modeled in the program, and because of electron range straggling.

The maximum useful wire temperature depends on how the wire scanner is used. If beam loss is measured as a function of wire position then the wire must simply not melt and sag. In the SNS linac, where the secondary electron emission (SEM) current is used to measure the profile, the wire must stay cool enough to keep the thermionic electron emission currents less than 1% or so of the SEM current. The maximum useful temperature of a carbon wire used in the SEM mode has been measured[3] to be 1500 deg. K. The maximum useful temperature of a tungsten wire used in the SEM mode also depends on the thermionic emission, but we shall defer this discussion until later.

Wire scanner requirements call for measurements to be made with 100 us beam pulses. We shall consider the cases of 1 and 10 Hz beams. Since it is simplest to commission the linac with unchopped beam, both chopped (26 mA) and unchopped (38 mA) beam will be considered.

Eleven cases corresponding to potential worst cases for the wires are:

Case 1: 1 Hz, 100 us beam pulse, 186 MeV, 38 mA, 0.16 cm rms round beam.
Case 2: 10 Hz, 100 us beam pulse, 186 MeV, 38 mA, 0.16 cm rms round beam.
Case 3: 1 Hz, 100 us beam pulse, 380 MeV, 38 mA, 0.12 cm rms round beam.
Case 4: 10 Hz, 100 us beam pulse, 380 MeV, 38 mA, 0.12 cm rms round beam.
Case 5: 1 Hz, 100 us beam pulse, 310 MeV, 38 mA, 0.16 cm rms round beam.
Case 6: 10 Hz, 100 us beam pulse, 310 MeV, 38 mA, 0.16 cm rms round beam.
Case 7: 1 Hz, 100 us beam pulse, 265 MeV, 38 mA, 0.16 cm rms round beam.
Case 8: 10 Hz, 100 us beam pulse, 265 MeV, 38 mA, 0.16 cm rms round beam.
Case 9. 1 Hz, 90 us beam pulse, 310 MeV, 26 mA, 0.16 cm rms round beam.
Case 10. 1 Hz, 90 us beam pulse, 265 MeV, 26 mA, 0.16 cm rms round beam.
Case 11. 1 Hz, 90 us beam pulse, 380 MeV, 26 mA, 0.12 cm rms round beam.

Cases 1 – 4 are the worst cases for carbon; Cases 3, 4, 5, and 6 are the worst cases for 25-micron tungsten; and Cases 3, 4, 7, and 8 are the worst cases for 20-micron tungsten. Cases 9 – 11 are for the absolute minimum operating requirements for the two tungsten wires.

[3] D. Gilpatrick, proceedings of the LHC Emittance Workshop. CERN, July 3-4, 2001.

A computer model was developed[4] to calculate wire temperatures. It calculates the energy deposition in the wire, raises the temperature using a variable specific heat, and radiatively cools the wire with a variable emissivity. Figures 4 to 6 show example graphs from the program. The peak temperatures for the various cases are as follows:

32 micron (1.2 mil) carbon wire
Case 1: 447 deg. C.
Case 2: 863 deg. C
Case 3: 509 deg. C
Case 4: 917 deg. C

25 micron (1 mil) tungsten wire
Case 3: 2554 deg. C
Case 4: 3100 deg. C
Case 5: 2110 deg. C
Case 6: 2673 deg. C
Case 9: 1578 deg. C
Case 11: 2005 deg. C

20 micron (0.8 mil) tungsten wire
Case 3: 2462 deg. C
Case 4: 2974 deg. C
Case 7: 2279 deg. C
Case 8: 2798 deg. C
Case 10: 1678 deg. C
Case 11: 1925 deg. C

Discussion

For 25 micron tungsten wire, Case 3 (380 MeV, 1 Hz, un-chopped beam), the maximum temp is 2554 deg. C. A conservative assumption for the thermionic emission current is that electrons are emitted over a length of wire equal to 4 times the rms beam size (4 * 0.12 cm = 0.48 cm). The surface area is 2*pi*r*l = 3.8E-3 cm^2, and the electron emission at 2827 deg. K is about 4 amp/cm^2. The thermionic electron emission current is therefore estimated to be 4 * 0.0038 = 15 mA. The SEM coefficient is[5] 0.41 and the SEM current is 0.21 mA. The SEM current should be many times the thermionic electron emission current for an effective beam profile measurement. The 25 micron tungsten wire is therefore not a good choice, even at 1 Hz. What about the absolute minimum operating conditions of Case11?

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[4] Enhanced version of program originally written by R. Shafer. Private communication.
[5] M. Plum, "Wire scanner and harp signal levels in the SNS," SNS01_TCN_1507, 13/Dec/2001.

For 25 micron tungsten wire, Case 11 (380 MeV, 1 Hz, chopped beam), the maximum temperature is 2005 deg. C. The electron emission at 2278 deg. K is about 0.03 amp/cm^2, so the thermionic electron emission 0.03 * 0.0038 = 0.11 mA. The SEM current is 0.14 mA. This is an improvement over Case 3, but not enough to warrant further consideration of this wire type.

For 20 micron tungsten wire, Case 3 (380 MeV, 1 Hz, un-chopped beam), the maximum temperature is 2462 deg. C, or 2735 deg. K. The wire area is 0.003 cm^2, and the thermionic electron emission is about 2.5 amp/cm^2, for a current of 0.003 * 2.5 = 7.5 mA. The SEM coefficient is 0.38 (different from the 25 micron diameter case because of the different energy of the exiting electrons), and the SEM current is 0.15 mA. Therefore 20 micron tungsten will not work.

For the absolute minimum operating conditions for the 20 micron tungsten wire, Case 11 (380 MeV, 1 Hz, chopped beam), the maximum temperature is 1925 deg. C, or 2198 deg. K. The thermionic electron emission is 0.013 amp/cm^2, so the thermionic emission current is 0.013 * 0.003 = 0.39 mA. The SEM signal is 0.10 mA. Therefore the 20-micron wire would not work, even for 1 Hz chopped beams.
Tungsten wires 10 and 5 micron in diameter were also investigated for Case 3, but the peak temperatures (2289 deg. C and 2177 deg. C respectively) were not a big enough improvement to warrant further consideration. In addition to the thermal problems of the tungsten wire, there are concerns[2] with the vapor pressure. Tungsten vapor could deposit onto the superconducting cavity surfaces and interfere with their performance.

In contrast to the tungsten wire, the carbon wire performs well for even for 10 Hz, un-chopped beams. It does not appear to have any vapor pressure problems. However, it is a fragile wire, and there is anecdotal evidence that the wire may ablate carbon fragments. Some of this evidence comes from LAMPF, where a rotating carbon wheel was used for a pion production target. It was found that there was a strong correlation between wheel lifetime and poor vacuum. Lifetimes of the SiC harp wires were also limited by poor vacuums. However, in good vacuums, and when the wires are not overheated, I do not know of any ablation problems.

Carbon wires were studied[6] in detail for the LEDA experiment. The wires performed well for about five months. No wire problems were observed except those related to off-normal beam events. In one such event a wire broke and provided a convenient specimen for further investigation. Microscope photographs and SEM images showed that near the broken end where the wire failed from overheating there were many points of evidence for ablation. However, just one or two millimeters away from the broken end there was very little evidence for ablation. Based on these observations and the above explanations for the anecdotal evidence for ablation, it appears that ablation

[6] D. Gilpatrick and J. O'Hara, private communication.

concerns can be minimized by ensuring that the carbon wires do not overheat and are always used in high vacuum systems (such as the SCL, where the vacuum environment is expected to be 1E-9 Torr).

There are also concerns with the fragility of the carbon wire. Experience at LEDA showed that the carbons wires never failed (except for the off normal beam events discussed above) over roughly a five month operating period. Also, an actuator with carbon wires was recently shipped from BNL to LBL and then to LANL, and the wires arrived intact, in spite of the rough handling incurred during shipping.

Conclusions

Choosing wires for the SCL wires is primarily a matter of exclusion. There is no perfect wire for this application. We must choose the wire with the fewest shortcomings. Of the three wire types investigated, 32 micron diameter carbon wires appear to be the best.

Figures

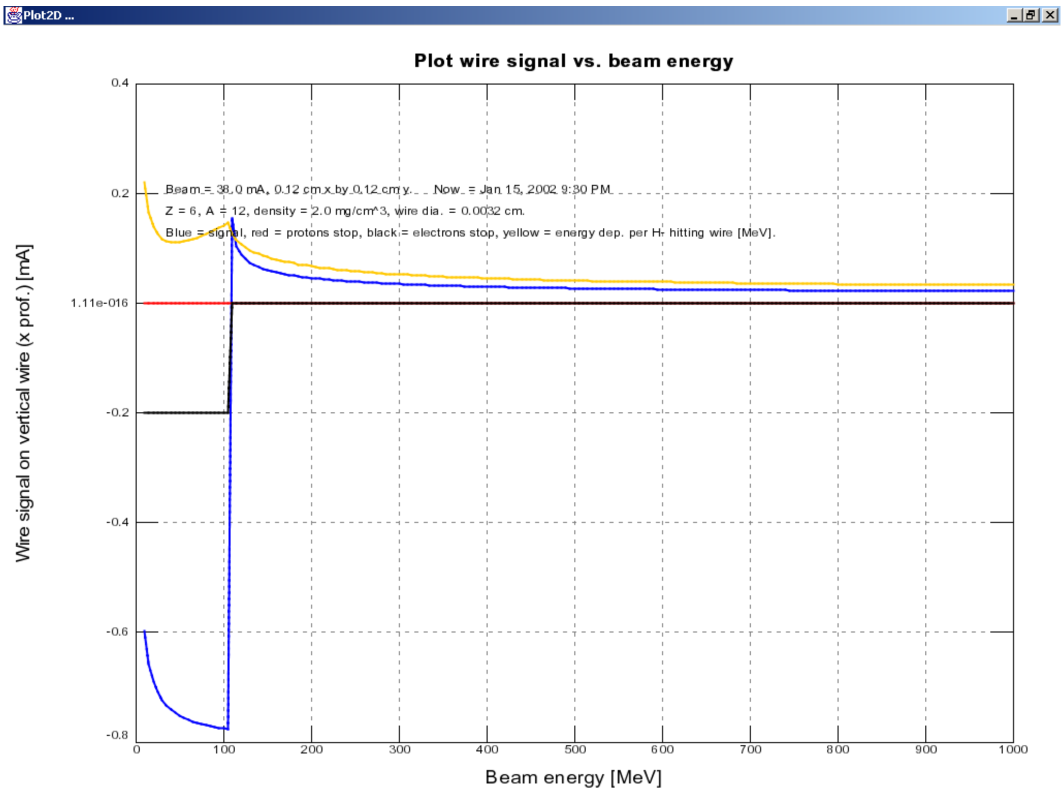

Fig. 1. Carbon wire, 32 micron dia. The blue line is the wire scanner signal in units of mA. The red line, when non-zero, indicates that protons are stopping in the wire. The black line, when non-zero, indicates that electrons are stopping in the wire. The yellow line indicates energy deposited in the wire per H^- particle, in units of MeV. Note that above 20 MeV, the most wire heating occurs at about 108 MeV.

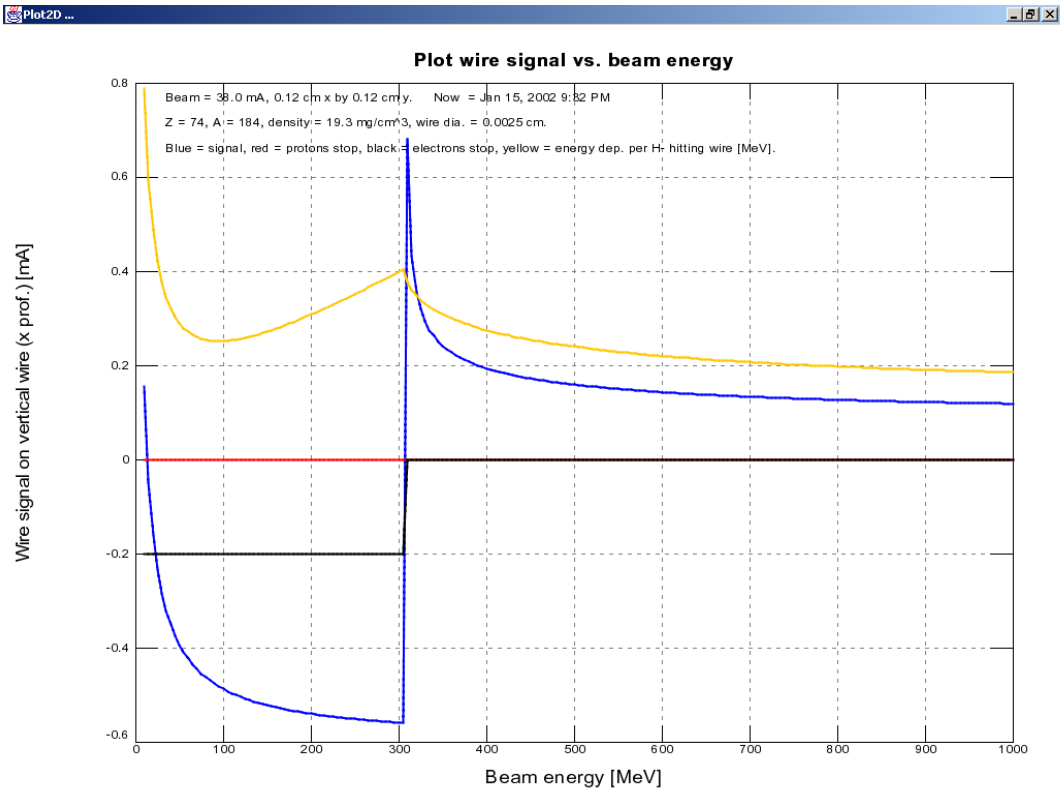

Figure 2. Same as Fig. 1, but 25 micron dia. tungsten wire.

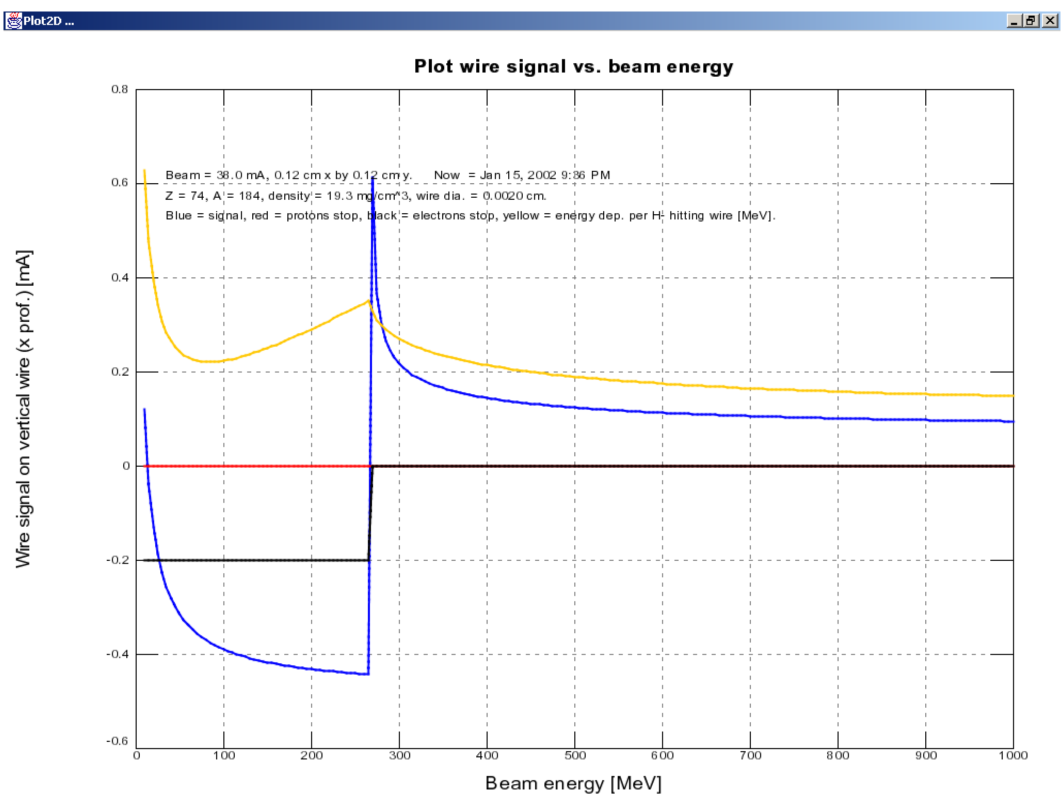

Figure 3. Same as Fig. 1, but 20 micron dia. tungsten wire.

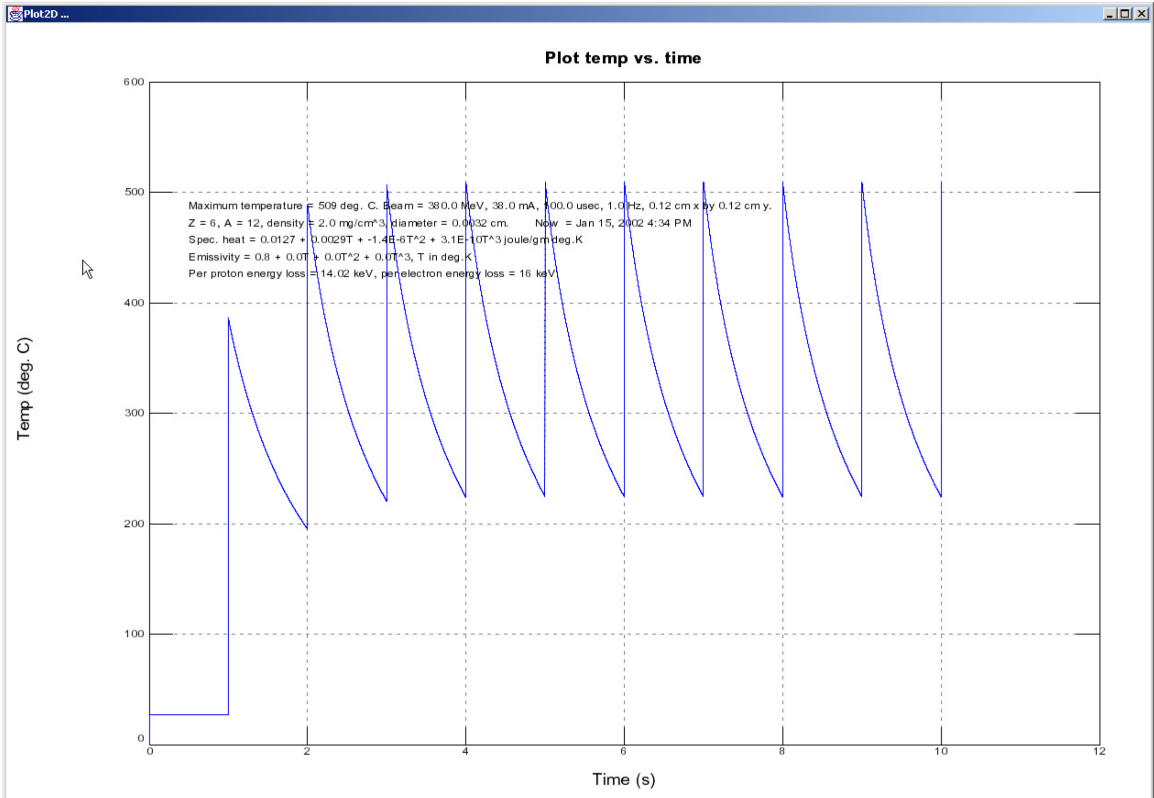

Figure 4. Plot of temperature vs. time for the case of 380 MeV beam, 38 mA (un-chopped), 1 Hz.

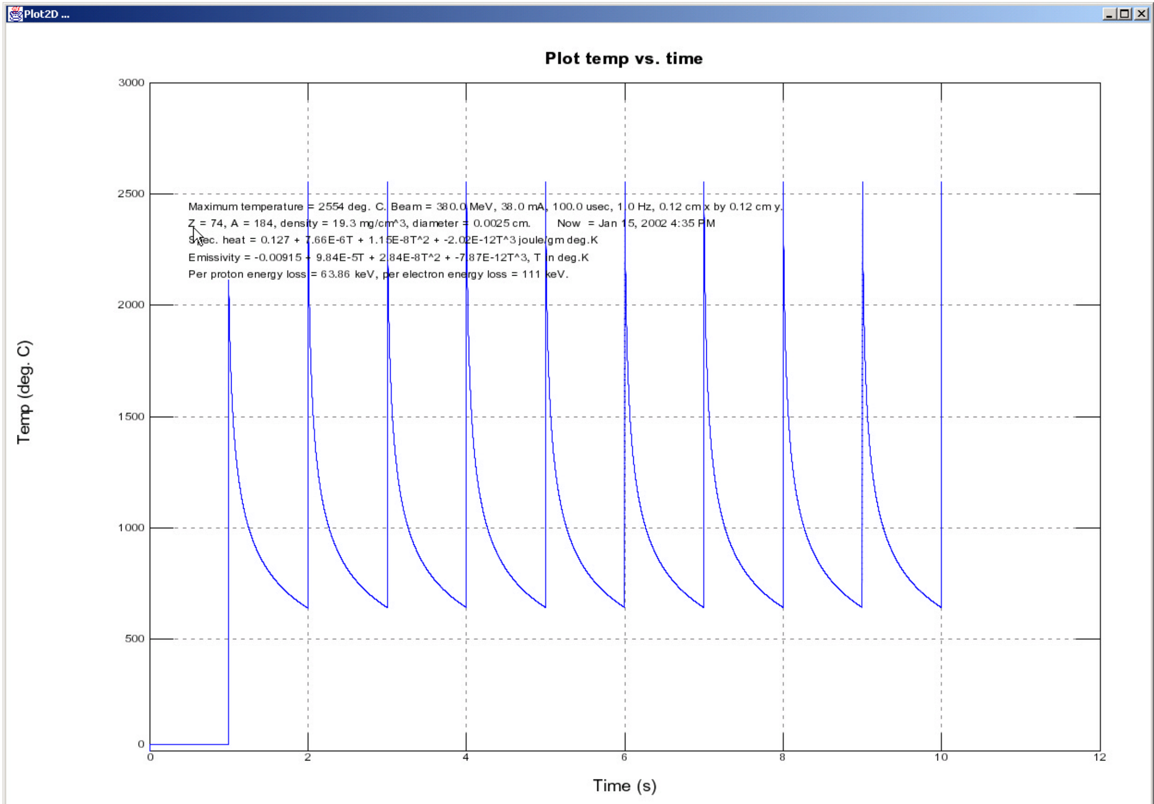

Figure 5. Same as Fig. 4, but 25 micron tungsten wire.

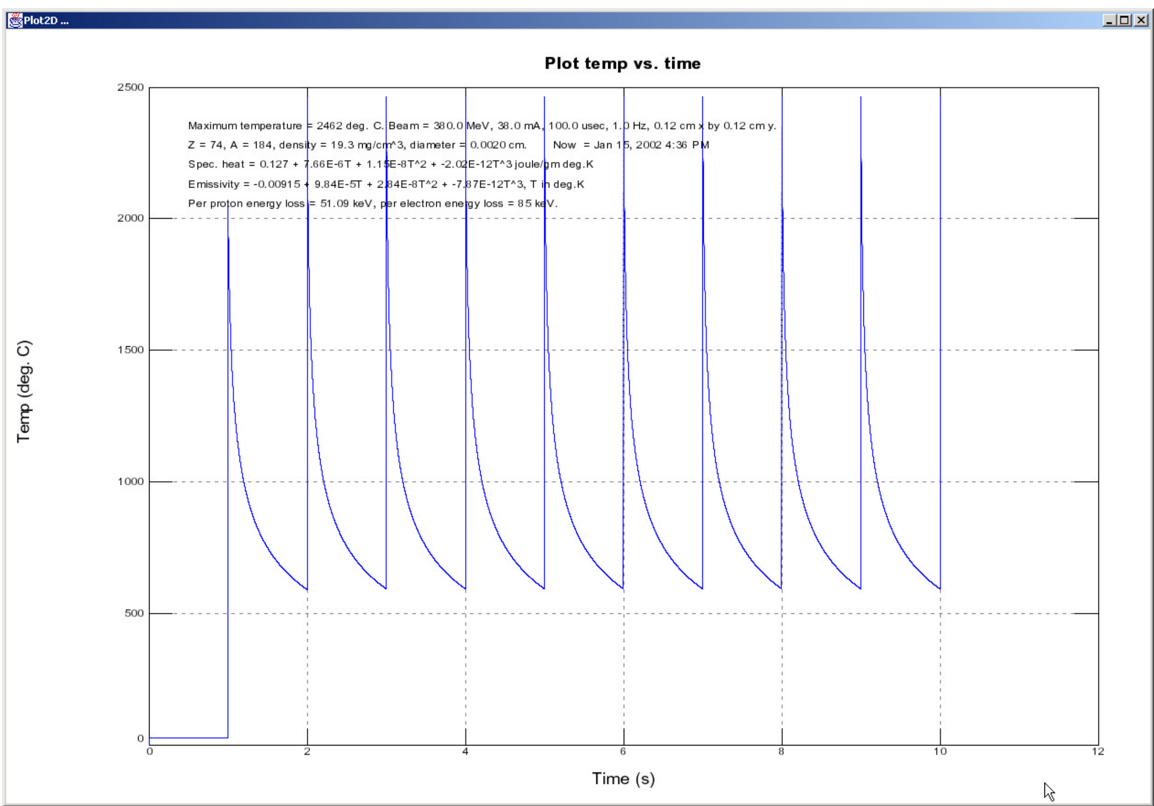

Figure 6. Same as Fig. 4, but 20 micron tungsten wire.