Performance of a Niobium-Wire Profile Scanner in the SNS SCL

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Introduction

Because of the possibility of ablation or vaporization of wire-scanner wires, niobium wires are probably the most suitable for use in wire scanners adjacent to superconducting RF cavities. The assumption here is that vaporized niobium is less harmful to the superconducting cavities than would be for example tungsten.

This note examines the thermal response of niobium wires for use in stepping wire scanners. Specific properties of the niobium wire used in this note are:

Density	8.57 grams/cm^3
Specific heat	0.33 Joules/gram-°K
Thermal emissivity	0.2
Diameter	100 μm (4 mil)
Melting point	2468 deg. C

The beam properties used in this note are

Beam energy	185 MeV
Peak beam current	56 mA
Beam size	1-mm by 2-mm rms width
Beam pulse length	150 μsec
Pulse repetition rate	1 Hz
dE/dx (for protons)	3.63 MeV-cm^2/gram at 185 MeV

The thermal heating of the wire with H^- is expected to be higher than that for protons, because the two valence electrons on H^- very quickly separate from the proton in the wire, and produce additional dE/dx heating. For 185 MeV H-, the valence electron energy is 100 keV. Its range in niobium is roughly 0.015 grams/cm^2, equivalent to about 18 microns. Thus the valence electrons will probably stop in the wire. The proton energy loss is roughly 310 keV, and the additional heating by two valence electrons increases this to roughly 510 keV, a 65% increase.

A plot of the peak wire temperature vs. time is shown in Figure 1. The maximum wire temperature is about 1780º C. Only thermal radiation heat loss ($\varepsilon\sigma T^4$) is included. At very high temperatures, thermionic-emission electrons will carry away some thermal energy, resulting in additional cooling.

For a 1-mm rms width beam hitting a 100-micron diameter wire, about 4% of the incident beam (i.e., 2 mA) is stripped to protons. These protons are poorly matched to the doublet focusing lattice in the SCL, and are not accelerated, and are probably lost, either in the warm insertions, or in the cryomodules. For the above beam parameters, this loss represents about 60 watts of average beam power. If this loss is distributed over 50 meters (this needs to be checked), it represents about 1 watt per meter. This represents a significant beam loss (ionizing radiation) signal, and should be distinguishable from other losses; e.g., stripping by residual gas [1]. It also represents a significant (but probably acceptable) increase on the cryomodule heat load. Because the warm insertions have an aperture diameter of 3”, while the cryomodules have an aperture diameter of 4”, most of the lost protons probably will not lead to a heat load on the cryomodules.

The wire-current signal includes

a) Secondary emission from the wire surfaces. This signal is probably about 4% of the H- current hitting the wire.
b) Valence electrons that stop in the wire (opposite sign to secondary emission). This is probably about 200% of the H- current hitting the wire.
c) Thermionic emission (very nonlinear with temperature). This may be significant at 1800º C. See Appendix.

The valence electron signal (about 200% of the proton current hitting the wire) is probably very significant relative to the secondary emission signal, which is probably only about 4% of the proton current. By biasing the wire positive relative to its environment, the secondary and thermionic emission signals can be inhibited, leaving the valence electron signal as the most significant. At 1800º C, the thermionic emission signal is about 14 times lower [see appendix]

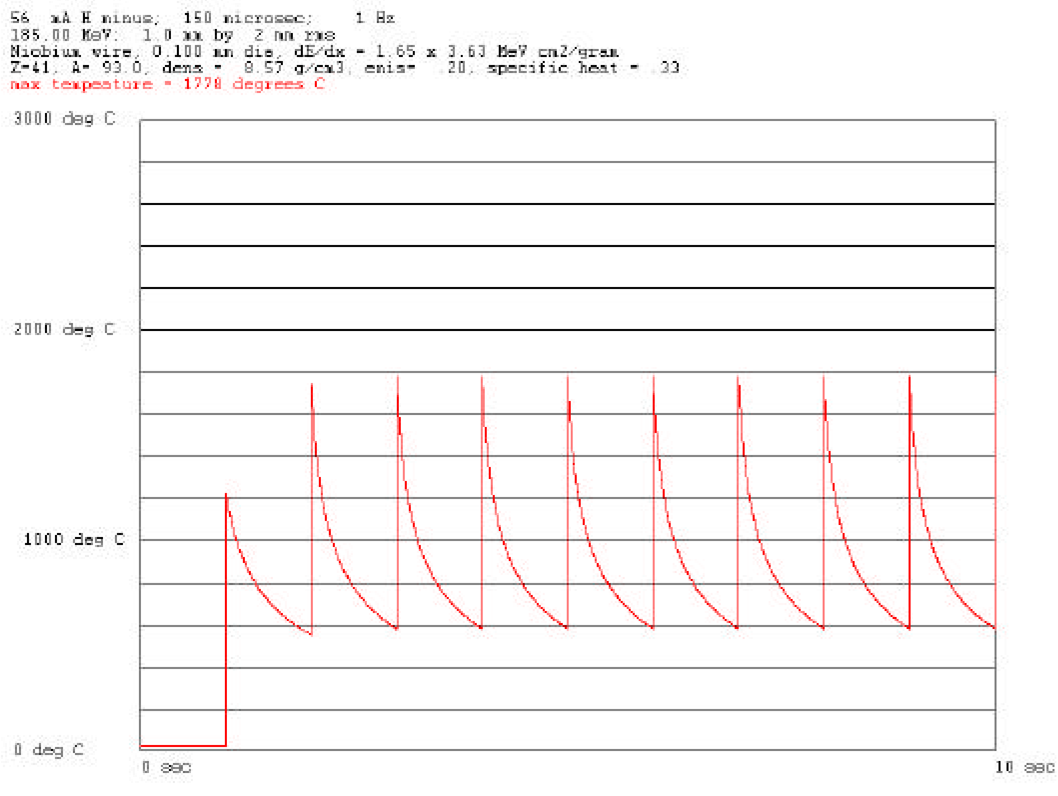

Figure 1. Wire temperature vs. time for 185-MeV H- on a 100-µm niobium wire.

The evaporation rate of niobium is about 2000 times higher than tungsten at the same temperature, amounting to about 10^{-8} grams/cm^2-s at 1800º C. This decreases about 1 order of magnitude for every 100º of temperature drop. For a 2-mm length of 100-micron wire, this corresponds to about $6x10^{-14}$ grams per beam pulse, assuming 1 ms of evaporation per beam pulse. This evaporation leads to both loss of wire mass and deposition of niobium ions on the accelerator structure. This is equivalent to less than 10^{-9} of the wire mass per beam pulse, so the wire should last for more than 10,000,000 pulses (115 days of continuous operation at 1 Hz).

It is clear that the 100 µm diameter niobium wire will work at 185 MeV with the baseline parameters shown above. However, because the melting point is 2468º C, the niobium wires will not survive for even a single full 1000-µsec beam pulse at full beam current. Thus the control system must be programmed to limit the beam macropulse length and pulse repetition rate to the prescribed values while the wire scanner is being used.

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[1] For a 2-MW beam, the residual gas stripping loss is about 1 watt per meter, equivalent to $<10^{-6}$ of the beam per meter. This is negligible compared to 4% of the beam lost over 50 meters.

Appendix: Thermionic Emission from Hot Niobium Wire

Using Richardson's equation

$$J = A \cdot T^2 \cdot \exp\left[-11{,}605 f / T\right] \quad \text{amps/cm}^2$$

with the constants A=60.2 and f=4.00 eV (work function), the thermionic emission current at 1800º C is about 50 mA/cm^2. For 2 mm length of 100-micron diameter niobium wire, this is equivalent to 0.3 mA. For a 150 µsec period, this is 50 nC of charge. The valence electron signal, assuming both stop in the wire, is about 700 nC.