WIRE GRID AND WIRE SCANNER DESIGN FOR THE CERN LINAC4

F. Roncarolo[(a)], E. Bravin[(a)], B. Cheymol[(a,b)], C. Dutriat[(a)],
M. Duraffourg[(a)], G.J. Focker[(a)], U. Raich[(a)], C. Vuitton[(a)]

[(a)] CERN, Geneva, Switzerland [(b)] Université Blaise Pascal, Clermont-Ferrand, France

Abstract

As part of the CERN LHC injector chain upgrade, LINAC4 [1] will accelerate H^- ions from 45 KeV to 160 MeV. A number of wire grids and wire scanners will be used to characterize the beam transverse profile. This paper covers all monitor design aspects intended to cope with the required specifications. In particular, the overall measurement robustness, accuracy and sensitivity must be satisfied for different commissioning and operational scenarios. The physics mechanisms generating the wire signals and the wire resistance to beam induced thermal loads have been considered in order to determine the most appropriate monitor design in terms of wire material and dimensions.

INTRODUCTION

In order to measure beam profiles along the linac, several SEM grid and wire beam scanner (WS) monitors will be installed between the RF cavities from 50 MeV to 160 MeV. Two wire scanners will also be installed at the chopper located in the 3 MeV MEBT line.

The SEM grids are retractable devices that will be inserted into the beam in a single step, while WS are driven by stepping motors that will allow slow scans of the particle distribution over multiple beam pulses. More details about the monitor locations and characteristics can be found in [2]

NET CHARGE DEPOSITED ON THE WIRE

One the phenomena providing the wire signal is Secondary Emission (SE), a surface effect generating escaping electrons as i) the H^- ions enter the wire and ii) the same ions or their dissociated products exit the wire. Depending on the ion energy, the wire material and diameter, the signal can have a contribution from direct charge deposition of the ions or their dissociated products. If for N_I ions hitting the wire, N_p protons escape after the ion stripping and N_e stripped electrons are stopped into the wire, the charge created on the wire is given by [3]:

$$Q = Ye + \eta Ys + (1-\eta) - 2\mu \qquad (1)$$

where Ye and Ys are the SE Yield (SEY) of H^- ions and of protons traversing the wire surface, $\eta=N_p/N_I$ and $\mu=Ne/N_I$. Above 50 MeV, $\eta\cong 1$ and $Ye\cong Ys=Y$. Thus, the net charge results:

$$Q \cong 2 * Y - 2\mu \qquad (2)$$

The parameter μ depends on the electron energy E and on the electron range in the wire material at that energy, which is given by [4]:

$$r(E) = 412\frac{13}{27}\frac{A}{Z}E^n \qquad (3)$$

where $n = 1.265 - 0.0654\ln(E)$. For H^- ions with energy E_I , neglecting any electron energy loss due to ionization after stripping, one can assume $E=E_I/1836$.

For the LINAC4 SEM grid and WS monitors, two types of wires are presently considered: 40 μm diameter Tungsten wires and 33 μm diameter Carbon wires.

Signal at 3 MeV

Since for H^- ions below 50 MeV the electron range in Carbon and Tungsten is well below the wire diameter, the ions are fully stripped and each ion contributes with two electron charges to the signals. At 3 MeV the range of protons in tungsten is about 30 μm and 73 % of the protons are stopped inside the 40 μm tungsten wire, while the remaining produce SE exiting the wire. The average kinetic energy of the outgoing protons is 1.52 MeV. Therefore, the contribution to the signal is about -0.18 electrical charges (q) per H^-.

For Carbon the range of protons is about 100 μm and all protons will exit the wire. Consequently, the wire signal is given by SE of entering H^-, SE of exiting protons and direct charge deposition of electrons. This results in about -1.259 q per H^- ion hitting the wire, considerably higher than the one for Tungsten.

Signal Between 50 MeV and 160 MeV

For H^- ions between 50 and 160 MeV, the electron range is below the wire diameter for Tungsten, while it becomes of the order of the wire diameter for Carbon for ion energies of about 100 MeV. For both Carbon and Tungsten the proton range is well above the wire diameter and all protons will escape generating SE. The expected net charge left on the wire at the different LINAC 4 energies is shown in Table 1. As expected, above 110 MeV the Carbon wire signal changes polarity and is reduced by at least a factor 50. For Tungsten, the signal polarity is always negative and the net charge almost constant with energy.

Table 1: Net Charge Left on the Wire by each H^- Ion as Function of Energy and for the Two Wire Types

E [MeV]	Carbon 33 µm	Tungsten 40 µm
50	-1.934	-1.762
60	-1.943	-1.791
70	-1.949	-1.812
80	-1.954	-1.829
90	-1.958	-1.842
100	-1.961	-1.854
110	-1.964	-1.863
120	0.034	-1.871
130	0.032	-1.877
140	0.030	-1.883
150	0.029	-1.888
160	0.028	-1.893

Since SE electrons have energy of few eV, biasing the wire can neutralize the SE effect on the wire signal. With a relatively low bias (e.g. +100 V) such electrons can be attracted back on the wire. Applying such a bias to Tungsten wires would result in having a net charge equal to -2 q (from the stripped electrons) at all energies.

The same applies for 33 µm Carbon wires only below about 100 MeV. For higher energies, when the electron range is larger than the wire diameter the bias would result in a zero net charge on the wire. Choosing larger diameter wires would imply the bias effectiveness also for Carbon wires. For H^- above 110 MeV, the range of stripped electrons in Carbon is of the order of 50 µm and a 100 µm diameter wire would be enough.

In addition, the wire bias would minimize the signal variation with time due to the SE effect changes with the wire aging. Avoiding electron SE would allow comparing the absolute charge deposition at different energies, even though the ultimate accuracy could be perturbed by the creation of high energy electrons (δ rays) for which a reasonably low bias would not be sufficient.

WIRE CURRENT

Ion Energy Equal to 3 MeV

The two WS monitors in the 3 MeV line are supposed to measure a maximum average beam current from 40 to 65 mA. The beam sizes at the wire beam scanner locations are summarized in Table 2. For these two monitors, Carbon is preferable to Tungsten. This is due to the higher signal at 3 MeV as discussed above, and to the higher sublimation temperature as discussed below. Table 3 gives the maximum expected current for a 33 µm Carbon wire at the two locations, while sampling the beam core.

Table 2: Beam Sizes at the Chopper WS

	WS 1	WS 2
σ_x [mm]	3.52	3.77
σ_y [mm]	3.07	1.77

Table 3: Expected Maximum Current at the Chopper WS

I beam [mA]	40	65
I_max WS 1 [mA]	-0.35	-0.57
I_max WS 2 [mA]	-0.6	-0.97

Ion Energy Between 50 and 160 MeV

The average beam current foreseen for the LINAC 4 nominal operation is 40 mA, while the transverse RMS beam sizes are expected to be 1 mm in one plane and 2 mm in the other in most of the inter-tank regions where SEM grids and WS will be installed [5].

Starting from such parameters, the expected wire current has been calculated for a wire sampling the beam core and for the plane where the beam size is minimum (i.e. maximum wire signal). Four possible wire types have been simulated: a 33 µm or 100 µm Carbon wire and a 40 µm or 100 µm Tungsten wire, every time with a 100 V bias.

As discussed above, for biased 100 µm wires, the signal is constant with energy and its maximum, after applying the beam parameters results to be -3.2 mA. For the smaller wire diameters, the maximum expected current depends on energy and is shown in Table 4.

Table 4: Expected Maximum Current for a 33 µm Carbon Wire and 40 µm Tungsten Wire

Energy [MeV]	Carbon	Tungsten
50	-1.053	-1.276
57	-1.053	-1.276
79	-1.053	-1.276
86	-1.053	-1.276
100	-1.053	-1.276
115	0.0025	-1.276
129	0.0023	-1.276
145	0.0022	-1.276
160	0.0021	-1.276

Considering that the monitors need to sample the beam halo down to the electronics noise level (few nA), the values of the maximum current gives an indication of the required system dynamic range. The table confirms that small diameter Carbon wires give a very small signal for energies above 100 MeV.

THERMAL LOAD

The thermal load on wire induced by the beam can produce thermo ionic emission of electrons that would perturb the measurement. If the wire temperature increases further, the wire can break due to melting or sublimation. The increase in temperature for one pulse can be calculated as [6]:

$$\Delta T = \frac{\mathrm{Npart}}{\mathrm{Cp}} * \frac{\mathrm{dE}}{\mathrm{dz}} * \frac{1}{2\pi\sigma_x\sigma_y} e^{-\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)} \quad (4)$$

where N_{part} is the number of particles per pulse, Cp the material specific heat capacity, dE/dz the stopping power of the particles in the material and σ_x ,σ_y beam RMS beam size. SRIM [7] has been used to calculate dE/dz and an analytical model to estimate Cp [8]. The cooling of the wire has been simulated by black body radiation only, assuming that other processes, like thermal conductivity, are negligible. In the calculation, we assume that the wire stays at the same position during 10 pulses.

Thermal Effects at 3 MeV.

At low energy the power deposition varies along the wire depth. Consequently, the wire has been divided in slices along which the energy deposition can be considered constant. Since at 3 MeV Carbon is expected to give a higher signal, only this material has been simulated, assuming a 33 μm wire. Table 5 shows the calculated maximum wire temperature, considering different average beam currents and pulse lengths.

Table 5: Maximum Carbon Wire Temperature at 3 MeV.

Intensity [mA]	**65**	**65**	**65**	**40**	**40**
Pulse length [μs]	**50**	**100**	**400**	**100**	**400**
T_{max} WS 1 [K]	1359	2175	6983	1550	4520
T_{max} WS 2 [K]	1871	3178	∞	2174	7000

Since Carbon sublimation occurs at about 3900 K, both wires would not survive to the full pulse length. Therefore the pulse length during the WS measurements should be reduced to 100 μs. For WS 2, a maximum average current of 40 mA is also advisable.

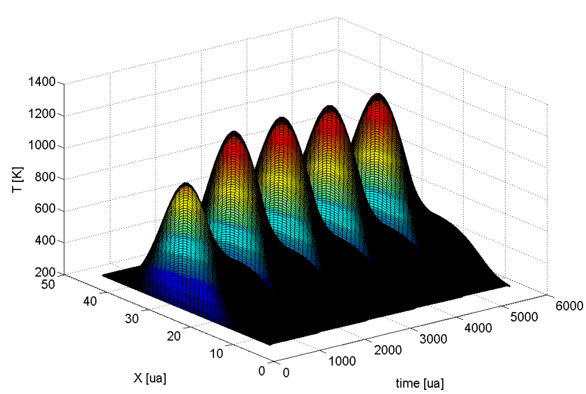

Figure1: Evolution of the temperature along several pulses for the WS1 in case of a 65 mA and 50 μs beam.

Figure 1 shows the evolution of the wire temperature during several pulses, for WS1 and a 65 mA, 50 μs beam. The equilibrium is reached after 3 pulses and the temperature decreases to 600 K between two pulses. This has been verified also for the other cases of Table 5.

Thermal Effects Above 50 MeV.

The LINAC 4 average beam current after chopping will be 40 mA, with a pulse length of 400 μs and a repetition rate of 1 Hz.

Figure 2 shows the maximum expected temperature for 100 μm wires, when assuming σ_x=1 mm and σ_y = 2 mm. The figure also shows the materials damage temperature. If Carbon would survive at all energies, a 100 μm Tungsten wire would exceed its melting point in all cases. When considering a 33 μm Carbon wire or a 40 μm Tungsten wire, the temperature is reduced by about 200 K at each energy.

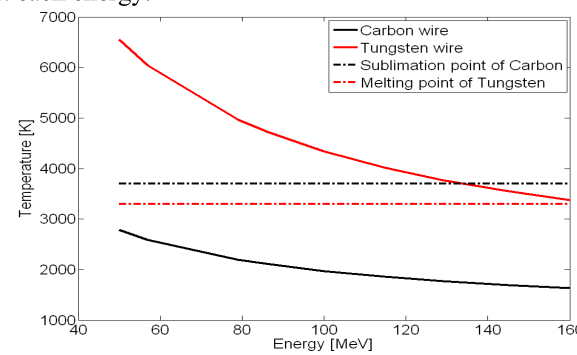

Figure 2: Temperature evolution for 100 μm diameter Carbon and Tungsten wire as function of beam energy, for a LINAC4 40 mA, 400 μs pulse and typical beam sizes at the monitors locations.

CONCLUSION AND OUTLOOK

The WS and SEM grid wire materials presently considered are Carbon and Tungsten. For the 2 WS monitors to be used at 3 MeV, it is convenient to use Carbon wires, due to their higher sublimation temperature and higher expected signal after studying the net charge deposition. However, the wire is expected to sublimate with a full 400 μs beam pulse at both 65 and 40 mA. The pulse length should be reduced to 100 μs during the measurements. For all measurements above 50 MeV, it is efficient to bias the wires in order to minimize secondary emission of electrons. With nominal beam parameters Tungsten would exceed its melting temperature in almost all cases. Carbon would survive, but with a wire diameter smaller than about 100 μm, the signal results very poor even when biasing the wires.

REFERENCES

[1] "Linac4 technical design report", CERN-AB-2006-084 ABP/RF.
[2] F. Roncarolo et al., "Overview of the LINAC4 instrumentation", these proceedings.
[2] B.Cheymol et al. "Design of the Emittance Meter for the 3 and 12 MeV LINAC4 H$^-$ Beam", IPAC 2010.
[4] R.E. Shafer, SNS Technical Note, SNS-104050000-TD0001 - R00, 2000.
[5] A. Lombardi, K. Hanke, "Beam measurements for LINAC4 and its transfer lines", CERN EDMS L4-B-ES-0002
[6] E.Bravin et al., "OTR studies for the high charge CTF3 beam", PAC 2003.
[7] F.Ziegler, J.P. Biersack, SRIM, URL: www.srim.org
[8] C.J. Liaw, P. Cameron, "Carbon Wire Heating due to Scattering in the SNS", PAC 2001.