IONISATION LOSSES AND WIRE SCANNER HEATING: EVALUATION, POSSIBLE SOLUTIONS, APPLICATION TO THE LHC.

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Abstract

Harmful heating mechanisms, resulting in wire breakage, limit the utilisation of wire scanner monitors to below a given beam intensity. This threshold depends on the accelerator design parameters. In lepton colliders, the short beam bunches generate strong wake-fields inside the vacuum pipe which are sensed by the wire and are the predominant current limit. These effects can be minimised by a smooth design of the monitor cross section and by choosing a wire made of an insulating material [1].

A second source of energy deposition inside the wire, also present in hadron machines, and even when the wire material is insulating, results from collision and ionisation of the wire material atoms by the incident beam particles. Calculations are presented to evaluate the efficiency of this process and a possible solution is suggested which may reduce this limitation. An example is given for the case of the LHC.

1. INTRODUCTION

In wire scanner monitors, excessive heating may result in wire breakage. The main heating mechanism in proton accelerators results from energy deposition inside the wire due to ionisation of the wire material atoms by the incident beam. Calculations will first be developed in a view to evaluate the efficiency of this process. The two cases of 55 GeV leptons and 450 GeV protons are considered. The resulting limitations in the use of wire scanner monitors in LEP and in the future for the LHC [2] are discussed. A solution is suggested which, by using a special mechanical design of the monitor, permits to increase the beam current limit. An application is then made in the case of the LHC beam parameters.

2. HEATING FROM COLLISION LOSSES

2.1 Collision losses

For a high energy particle, ionisation losses are [3]:

$$\frac{1}{\rho}\frac{dE}{dx} = \frac{0.1535}{\beta^2}\frac{Z}{A}\left(F(\beta) - 2\ln I - \delta(X)\right) [\text{MeV cm}^2\ \text{g}^{-1}] \quad \textbf{(1)}$$

Z and A are the atomic and the mass numbers of the material atoms and ρ is the material density. The expression of *F(β)* depends on the incident particle rest mass and energy [3], [4]. *F (β)* =19.032 and 10.920 respectively for 55 GeV electrons and 450 GeV protons. The binding atomic electron energy into Carbon is I = 78 eV and δ(X), describing the density effect of the medium, is given by:

$$\delta(X) = 4.605\, X + C, \text{ with } X = \log(\beta\gamma).$$

For high energy particles, C = 2.868. Hence, density effects decrease the ionisation losses by respectively 39 % and 22 % for either type of particle mentioned above such that 1/ρ. dE/dx is equal to 2.41 MeV $cm^2\ g^{-1}$ for an electron at 55 GeV and 2.56 MeV $cm^2\ g^{-1}$ for a proton at 450 GeV.

2.2. Energy transferred to knock-on electrons

By collision with an incident particle of charge z, some atomic electrons are ejected from the wire material lattice. The number of these knock-on electrons with energy E is [4]:

$$\frac{d^2N}{dEdx} = 0.153\frac{Z}{A}\frac{z^2}{\beta^2}\rho\frac{F}{E^2}$$

for I<< E ≤ $T_{max.}$, with T_{max}, the maximum energy transfer. For leptons, T_{max} is one half of the incident particle energy, and for 450 GeV protons T_{max} is given by [4]:

$$T_{max} \cong 2m_0 c^2\beta^2\gamma^2 / (1+2\gamma\, m_0/M)$$
$$= 154.4 \text{ GeV}$$

with m_0 and M the electron and proton rest mass. F is a spin dependent factor nearly equal to 1 in our case and ρ = 2.2 g/cm^3 for Carbon. The energy transferred between E and E + dE at a depth x by a particle is:

$$dW = \frac{d^2N}{dEdx} ExdE$$
$$= 0.153\,(Z/A)\,\rho\, x\, dE/E$$

and between I, the binding electron energy, and T_{max}, each particle will deposit:

$$W = \int_I^{T\,max} dW$$

$$W = 0.153\, x \ln(T_{max} / I), \text{ with x in cm.} \quad \textbf{(2)}$$

For a complete scan, x is the average wire thickness seen by each particle of the beam, and is given by:

$$<x> = \frac{\pi D^2}{4D}\frac{D}{vT}$$
$$= \frac{\pi D^2}{4vT}$$

where D is the wire diameter, v the wire speed and T the beam revolution period, 88.9 µs for LEP or the LHC and 22 µs in the SPS.

The energy transmitted to knock-on electrons by a beam of N particles during a scan is:

$$\Delta W_{scan} = N <x> W$$

whereas the energy actually lost by the incident beam through the wire is:

$$\Delta E_{scan} = \frac{1}{\rho}\frac{dE}{dx}\rho < x > N \qquad \textbf{(3)}$$

Hence the fraction η_1 of energy transmitted to knock-on electrons can be determined:

$$\eta_1 = \Delta W_{scan} / \Delta E_{scan}$$

However, all knock-on electrons will not contribute to the wire heating. Some of them escape the wire with a given momentum. The fraction η_2 of electrons leaving the wire must now be evaluated.

2.3 Escaping knock-on electrons

The practical range of an electron with energy E is [5],

$$r_{[g/cm^2]} = 0.71\ E^{1.72}_{[MeV]}$$

hence, the corresponding electron energy is:

$$E_{[MeV]} = (\rho \quad r_{[cm]} / 0.71)^{0.581}$$

At a depth x, the energy threshold allowing an electron to leave the wire is:

$$E_{thresh.} = (\rho \quad (t-x) / 0.71)^{0.581}$$

with t, the material thickness, which is in average $<t>=\pi D/4$ for particles traversing the wire. The energy threshold averaged through the wire thickness is therefore:

$$< E_{ion} >= \frac{1}{< t >}\int_0^{<t>} E_{thresh}\, dx$$

$$= \frac{1}{<t>}\left(\frac{\rho}{0.71}\right)^{0.581}\left[\frac{(x-<t>)^{1.581}}{1.581}\right]_0^{<t>}$$

or, $\quad <E_{ion}>_{[MeV]} = 0.772\ (\rho \ <t>_{[cm]})^{0.581}$

$$= 0.038 \text{ MeV}.$$

Out of all the generated knock-on electrons, the fraction getting enough energy to escape the wire is then, referring to Equation. (2):

$$\eta_2 = \frac{\ln(T_{max} / < E_{ion.} >)}{\ln(T_{max} / I)}$$

Results for electrons and protons are summarised in Table 1

2.4 Overall heating efficiency

Finally, the energy actually deposited inside the wire is:

$$E_d = \Delta E_{scan}\ \eta$$

with η, the overall wire heating efficiency given by:

$$\eta = (1-\eta_1) + (1-\eta_2)\ \eta_1 \qquad \textbf{(4)}$$

The first term of Equation 4 represents the fraction of energy lost by incident particles by other processes than knock-on electrons, and which is supposed to remain within the wire. The second one is the contribution of non escaping knock-on electrons. Applying the previous calculations to the LEP and SPS wire scanners, using 36 µm diameter Carbon wires, one get the results of Table 1. Values of η between 30 % and 35% have been quoted in the past [6].

Particles	Energy (GeV)	σ_{orth} (mm)	Wire speed (m/s)	η_1	η_2	η
$3.2.10^{12}$ $e^{\pm}$	55	0.4	0.4	**58%**	62%	68%
$2\ 10^{13}$ p	450	1	5	**55%**	64%	71%

Table 1

Other calculations performed in the case of LEP [1], with quartz and Carbon wires of various diameters lead to about the same results, showing a tendency of η_2 to increase to around 75% for wire diameters of 10 µm.

These data can be checked, considering the restricted energy loss rate, i.e. collisions with energy transfer smaller than a given threshold T_{thresh}. This restricted energy loss can be expressed as [4]:

$$\frac{dE}{dx} = 0.1534\left[\ln\left(\frac{2m_0c^2\beta^2\gamma^2T_{thresh.}}{I^2}\right)^{0.5} - \frac{\beta^2}{2} - \frac{\delta}{2}\right][\text{MeVcm}^2\ \text{g}^{-1}]$$

with $T_{thresh.} << T_{max.}$, all parameters having their previous definition. Taking $T_{thresh} = <E_{ion}>$, restricted energy loss rates dE/dx of 1.35 MeV cm^2 g^{-1} and 1.36 MeV cm^2 g^{-1} are obtained respectively for 55 GeV electrons in LEP and 450 GeV protons in the SPS. Comparing these numbers with the global energy losses calculated in section 1 in presence of the density effects, provides an efficiency η within the wire of 56 % for an electron and 53 % for a proton. The agreement with the data of Table 1 is quite good.

2.5 Wire heating

The energy actually deposited inside the wire during a complete scan is given by Equ. (3) weighed by the heating efficiency η. The wire volume heated in the dense part of the beam , ($\pm\ \sigma_{orth.}$), is:

$$V = (\pi\ D^2 /4)\ 2\ \sigma_{orth}$$

with $\sigma_{orth.}$, the rms beam dimension perpendicular to the scan direction. The temperature increase when scanning this wire region is then:

$$\Delta T = 0.683\ \eta\ \Delta E_{scan} / (V\ \ \rho\ \ c_p).$$

The Carbon specific heat c_p, averaged from 300 K to 1300 K, is 1.65 J $g^{-1}K^{-1}$ and with the other parameters taken from Table 1, then ΔT = 1000 K and 820 K after a scan performed respectively in LEP and in the SPS.

These results do not consider effects like thermal conduction within the wire, they could account for a few per cent of beneficial cooling, nor eventual small contribution from radiation inside the wire. It must also be remembered that in LEP, the main contribution to heating Carbon wires comes from electromagnetic fields [1].

However when Quartz wires used in LEP are considered, these results lead to temperature increases between

1600 K to 1700 K [1], for beam currents of 7mA. This is very close to the Quartz melting point. An experimental verification was possible. When inspecting a 30 µm wire, it was found thinned down to a few microns in the part interacting with the beam. At the bottom a pearl of melted material was observed, as shown in Figure 1. Hence this effect sets a current limit for the utilisation of wire scanners in LEP.

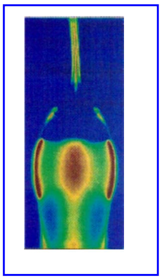

Figure 1: A 30 µm Quartz wire, used in a LEP wire-scanner monitor, after scans through 7mA beams. The thickness of the top part, traversed by the beam, is a few microns.

2.6 The case of the LHC:

In the LHC, the nominal beam intensity will be larger than in LEP by nearly two orders of magnitude. For an adequate measurement precision, the wire speed cannot be increased by more than a factor of 5 and at top energy, (7 TeV), the highest possible rms beam dimensions are smaller than one millimetre. At nominal current, the safest threshold to avoid destroying a Carbon wire by temperature increase is exceeded by more than one order of magnitude. This problem has been investigated in [2].

From the computation of the temperature rise, (section 5), it is obvious that the effect is proportionally reduced if the wire volume heated is increased. One solution is to act on the wire length interacting with the beam. In practice, this means that the wire must move not only in the direction of the scan but also in the orthogonal transverse direction. This is possible by combining the movement of a tilted sustaining mechanism, with the same tilt of the wire on its support such as to maintain it perpendicular to the transverse direction to be scanned. This is represented in Figure 2.

For a speed v_m of the mechanism, the angle θ determines the speed of the wire v_t in the scan direction, hence the distance $\Delta x = v_t T$ between consecutive measurements, with T the revolution period. The value of v_m gives the speed v_l in the direction of the wire and therefore its longitudinal displacement $\Delta l = v_l.T$ between two acquisitions; Δl can be chosen to be of the same order as the dense part of the beam distribution hitting the wire, i.e. $\Delta l = 2\sigma_{orth}$. Considering a round beam with rms dimensions of 0.5 mm, Δl = 1mm is achieved with v_l = 11 m/s. With a tilt θ of 10 degrees, v_t = 2 m/s, which provides a suitable spacing of 178 µm between consecutive points. This sets v_m = 11,2 m/s for the mechanism.

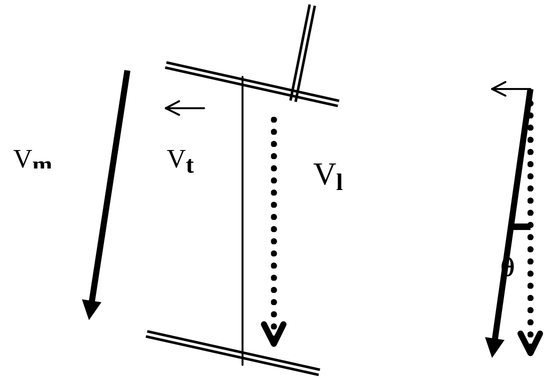

Figure 2: Proposed principle of a wire displacement in both transverse directions and for an horizontal scan.

The portion of wire interacting with the beam is different at each acquisition, and, over the dense part ± σ, it is increased by a factor $f = 2\sigma / v_t T$, i.e. f = 6 in this case. The total wire longitudinal displacement over a complete scan, (5 mm), is 30 mm in this case.

This discussion only sets principles. A refined mechanical study is needed before implementation, the acceleration and deceleration phases of the mechanism must in particular be carefully investigated. In this scheme, the wire diameter variation over its active length during a scan must be limited in order to minimise the error made on the signal amplitude.

3. CONCLUSION

These calculations show that in wire scanner monitors, an efficiency of about 55% is to be considered for the heating of the wire by energy deposition from collision losses. The observation of a Quartz wire used in LEP seems to corroborate these figures. For the LHC the limiting current could be increased considerably using the technique described, provided that a proper mechanical movement can be designed.

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