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WIRE SCANNERS FOR LHC

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SUMMARY

LEP wire scanners will be of great help in LHC where they can be used to measure beam sizes with a great precision. In order to preserve the wire from overheating and to avoid creating too much secondaries background, partial filling will be used with, at most, a tenth of nominal intensity. These measurements will allow a direct measurement of beam profiles and insure an absolute calibration of non destructive beam size monitors like synchrotron light telescopes.

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1. INTRODUCTION

The aim of this paper is to discuss the conditions in which wire scanners developed for LEP [1] could be used at LHC [2]. On the one hand the large beam density will pose a problem for the wire survival, on the other hand the interaction of the wire (even if it is thin and fast) will produce many secondary particles which will be lost downstream of the detector and might endanger machine components.

In the following evaluation, nominal bunches of $n_0=10^{11}$ protons with a normalised emittance : $\varepsilon_n = 3.75 \mu\text{m}$ are taken into account. The betatron functions at the wire position are taken as $\beta = 100 \text{ m}$ which is certainly pessimistic because values in the range 500 m to 1500 m are likely to be reached in physics (squeezed optics) but all results presented here can be easily scaled for other β -values. Carbon wires with a diameter of $36 \mu\text{m}$ have been used in the SPS for many years. They will be considered here as a safe option, although thinner wires could be envisaged. But thinner wires will not stand higher intensities, they will only reduce the production of secondary particles and the beam blow-up.

2. BEAM AND WIRE

2.1 Beam size and divergence

The rms radius of the proton beam and its divergence are given by :

$$\sigma = \sqrt{\frac{\varepsilon_n \beta E_0}{E_p}} \quad , \quad \text{and} \quad \sigma' = \sqrt{\frac{\varepsilon_n E_0}{\beta E_p}} \quad , \quad (1)$$

where $E_0 = 0.938 \text{ GeV}/c^2$ is the proton rest mass and E_p the energy of the circulating protons. Some values are given in Table 1, col. b) and e).

2.2 Wire speed and equivalent thickness

As the wire has a diameter d far smaller than the beam size and a speed v such that it will meet the beam several times, whatever the number of bunches n_b , the wire-beam interaction will be characterised by an equivalent wire thickness given by :

$$d_{\text{eq}} = \frac{\delta d^2}{4vt_{\text{rev}}} \quad . \quad (2)$$

In what follows we assume $d=36 \mu\text{m}$, $v=2 \text{ m/s}$, therefore the corresponding value for the wire equivalent thickness is $d_{\text{eq}}=5.7 \mu\text{m}$.

2.3 Wire temperature

The proton energy loss, when traversing the wire, is dominantly due to ionisation characterised by dE/dx . The total loss induced by one wire traversal of the beam can be expressed as :

$$\Delta E = n_o n_b \frac{dE}{dx} \rho d_{eq} \quad . \quad (3)$$

This energy is dissipated along the wire with a distribution corresponding to the transverse beam profile since the wire traversal time through the beam is shorter than the heat diffusion time over a length σ_{\perp} (sigma perpendicular to the measuring direction thus along the wire). Therefore the temperature increase ΔT , reached at the hottest point (centre of the Gaussian distribution) can be computed as:

$$\Delta T = \frac{4\Delta E}{3\pi d^2 \ell_{eq} \rho c_v} \quad , \quad (4)$$

where $\ell_{eq} = \sqrt{2\pi} \sigma_{\perp}$ stands for the Gaussian distribution normalisation and the factor 3 at the denominator has been put to match experimental results obtained at the SPS [3] and studies made for LEP [1].

If a maximum temperature increase of say $\Delta T = 1000$ K is tolerable to preserve the carbon wire integrity, this will put a limit to the beam intensity as a function of proton energy, which can be expressed in number of nominal bunches. Using equations (2) to (4) and replacing all fixed parameters by their numerical values^{+) one gets :}

$$n_o n_b = 6.9 \times 10^{10} \sigma_{\perp} [\mu\text{m}] \quad . \quad (5)$$

Values for n_b , given in Table 1, col. c) show that wire scans cannot be done at LHC with a full circulating beam (in order to preserve the ΔT limit), but only when the machine is partially filled. (Note that provided $\beta_{\perp} > 300$ which will always be the case with squeezed optics, the allowed n_b will be larger than 243 which means that a calibration MD, using wire scanners can be done with a normal filling of one batch instead of twelve.)

When the beam current $n_o n_b$ reaches the maximum value given by (5) then the wire speed cannot be reduced for fear of burning the wire and the number of points measured per sigma of the bunch profile is given by:

$$n_m = \frac{\sigma}{vt_{rev}} = \frac{\sigma}{178 \mu\text{m}} \quad . \quad (6)$$

Values for n_m are shown in Table 1, col. d). It is important to know that the r.m.s. beam size can be determined with high accuracy provided $n_m \cdot 1$. The only condition is

^{+) As a reminder, for carbon we have: $A=12$, $\rho=2.3 \text{ g cm}^{-3}$, $cV=1.2 \text{ J g}^{-1} \text{ K}^{-1}$ at $600 \text{ }^{\circ}\text{C}$, $X_o=18.8 \text{ cm}$, $dE/dx=1.45 \text{ MeV g}^{-1} \text{ cm}^2$.}

that the measurements should be of high precision which will be the case at LHC because the number of secondaries produced during the wire scans is very large (see chap. 3) and therefore the counting statistics will be particularly stable. Even with a partial filling there will be many bunches and their profile measurements can be made simultaneously, compared and averaged if necessary.

2.4 Beam blow-up

The rms angle (in a plane) resulting from multiple Coulomb scattering is given by [4]:

$$\theta_{\text{msc}} [\text{mrad}] = \frac{13.6}{\beta c p [\text{GeV}]} \sqrt{\frac{d_{\text{eq}}}{X_0} \left[1 + 0.038 \ln \left(\frac{d}{X_0} \right) \right]} \quad , \quad (7)$$

where d_{eq} is the equivalent thickness traversed by all particles and d is the real traversal made by those particles which hit the wire. Values for θ_{msc} are listed in Table 1, col. f). The beam blow-up after filamentation due to this effect is given by:

$$\frac{\Delta \varepsilon}{\varepsilon} = \frac{\theta_{\text{msc}}^2}{\sigma'^2} \quad , \quad (8)$$

and the values listed in Table 1, col. g) show that several measurements can be done before any significant blow-up will be noticed.

Table 1. Beam parameters relevant to wire scanner use

E_p [TeV]	σ [μm]	n_b	n_m	σ' [μrad]	θ_{msc} [nrad]	$\Delta \varepsilon / \varepsilon$ %
0.45	884	610	5.0	8.8	113	.2
1	593	409	3.3	5.9	62	.11
2	419	289	2.4	4.2	37	.08
4	295	204	1.7	3.0	22	.05
7	224	155	1.3	2.2	13	.04
a)	b)	c)	d)	e)	f)	g)

3. FLUX OF SECONDARIES

It is important to evaluate the number of secondary particles produced during the wire scan i) to make sure that the measurable signal will be abundant and ii) to evaluate the energy spread on the downstream magnets. This chapter is a summary of the more elaborate analysis presented in [2].

3.1 Inelastic collisions

From Ref. 4, the nuclear inelastic cross section for carbon is $\sigma_{in} = 0.231$ barn. Therefore the number of inelastic collisions for one wire traversal with n_b bunches is :

$$N_{in} = n_0 n_b \sigma_{in} d_{eq} \rho N_{Av} / A = 1.5 \times 10^6 n_b , \quad (9)$$

where the numerical values discussed above⁺⁺⁾ have been used.

For central collisions the average number of charged particles produced n_{ch} is approximately given by [2] :

$$n_{ch} = 7.6 s^{0.125} - 7.4 , \quad (10)$$

where s is the square of the energy in the centre of mass system :

$$s [\text{GeV}^2] = (E_{cm})^2 \cong 2 E_o E_p , \quad (11)$$

and neutral particles amount to one third of that number. The total number of secondaries n_{tot} , per wire traversal, is given in Table 2, col. b). Hence the momentum of charged or neutral nucleons or pions is on average equal to $p_l = E_p / cn_{tot}$, see Table 2, col. c). Furthermore the average production angle of nucleons and pions is given by $\theta_{n,\pi} = p_{\perp} / p_l$, where $p_{\perp} = 0.3$ GeV/c is the mean momentum transfer. Values for $\theta_{n,\pi}$ are listed in Table 2, col. d).

Table 2. Characteristics of secondaries

E_p [TeV]	n_{tot}	p_l [GeV/c]	$\theta_{n,\pi}$ [mrad]	L [m]	θ_{ela} [μrad]
0.45	13.7	33	9.1	2.4	253
1	16.1	62	4.8	4.6	114
2	18.5	108	2.8	7.9	57
4	21.0	190	1.6	13.8	28
7	23.3	301	0.9	24.4	16
a)	b)	c)	d)	e)	f)

3.2 Statistics for data taking

According to Eq. 9 and the values of n_{tot} (Table 2, col.b)) each bunch will produce 2×10^7 secondaries which will hit the vacuum chamber between 2.4 and 24 m downstream of the wire and produce a shower with high multiplicity. A detector, even of small acceptance, will receive a signal with negligible statistical fluctuations.

⁺⁺⁾ $n_0 = 10^{11}$, $d_{eq} = 5.7 \mu\text{m}$, $\rho = 2.3 \text{ g cm}^{-3}$, $N_{Av} = 6 \times 10^{23}$, $A = 12$.

3.3 Irradiation of equipment

A high flux of secondaries might be dangerous for some equipment and should be compared, for instance, to the quench limit set for supra conducting magnets. This limit, according to Ref. 6 is of 2.7×10^9 protons/m at injection energy and of 1.2×10^6 protons/m at top energy. Not more than a quarter of the cone of secondaries will hit a given coil and the losses will be spread over a typical length L [m] = $22 / \theta_{n,\pi}$ [mrad] whose values are listed in Table 2, col.e). Therefore the maximum number of bunches is of 17300 at injection and of 78 at top energy. In reality no super conducting dipole is expected to be located in the 40 m downstream of a wire scanner and there will be no limitation to the beam intensity for wire scanner measurements due to the flux of secondaries hitting equipment.

3.4 Elastic collisions

The cross section for elastic scattering on carbon is 0.100 barn [4] giving a number of elastic collisions of 100/231 times the number of inelastic events calculated in (9).

From Ref. 5, the rms scattering angle θ_{ela} is given by :

$$\theta_{\text{ela}} = b/p , \quad (12)$$

with $b = 0.114$ GeV/c and p is the proton momentum. Values for θ_{ela} are shown in Table 2, col. f) and when they are compared to the beam divergence σ' (Table 1, col. e)) it is clear that most scattered particles will populate the tail of the beam and be lost in the cleaning section on the minimum aperture collimators, since their rms angle is of the order of $10 \sigma'$.

4. CONCLUSIONS

Wire scanners of the type developed for LEP can be very useful at LHC, particularly for cross calibration of other beam profile monitors. If robust carbon wires of 36 μm diameter are scanned through the beam at the maximum speed of 2 m/s then the beam blow-up is small enough not to perturb the measurement. Beams of at least 1/4 of nominal intensity can be handled up to 2 TeV, and of 1/8 of nominal intensity up to top energy, in order to cross calibrate synchrotron light monitors with an adequate intensity overlap.

5. REFERENCES

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