LUMINOSITY DETERMINATION USING COULOMB SCATTERING AT THE LHC

A. Faus-Golfe, J. Velasco, IFIC-Univ. of Valencia, Spain
M. Haguenauer, LLR, Palaiseau, France

Abstract

A precise determination of the luminosity will be a crucial issue for the experiments at the LHC. Several methods have been proposed with the aim to achieve at least 5% precision. In this paper we proposed to obtain the luminosity as a by product of the determination of the proton-proton total cross section through the measurement of Coulomb scattering. Precisions of the order of 1-2 % could be reached.

1 INTRODUCTION

Luminosity, L, relates the cross section σ of a given physical process to its corresponding event rate, R:

$$R = L \times \sigma \tag{1}$$

Therefore by definition L is a process-independent quantity which is completely determined by the properties of the colliding beams. Typically a $5 - 10\%$ precision for the luminosity determination is assumed in experiments at LHC, as obtained from previous hadron-collider experiments. However, there are cases which would benefit from a luminosity precision of $1 - 2\%$.

There are roughly three different types of luminosity measurement. The most direct one is from the machine parameters, but usually the precision is poor at the beginning of a Collider operation. The second method relies in accurately measuring the rate of a well-known and sizeable cross section, whereupon L is determined from the expression (1). Here we concentrated in the third one, which uses the optical theorem and it also serves for calibrating the absolute scale of the luminosity measurement,

$$L = \frac{dR_{el}}{dt} \times \frac{R_{tot}^2(1+\rho^2)}{16\pi} \tag{2}$$

where ρ is the ratio of the real to imaginary part of the elastic scattering forward amplitude. In this way precisions of the order of 2 % had been obtained at the CERN $S\bar{p}pS$ Collider at 541 GeV and at the Fermilab Tevatron at 1.8 TeV. In this method is necessary a dedicated detector of protons which scatter at very small angles, to measure the elastic rate, R_{el}, as well as a good detection and high efficiency of pp inelastic interactions to determine the inelastic rate, R_{inel}. The elastic detector has to be able to reach values of $-t$, the square momentum transfer, as low as $-t \simeq .01$ GeV^2 which, at the energies of the LHC, correspond to angles of 14 μrad. This possibility is the one contemplated by the TOTEM experiment [2].

However if still smaller angles of elastic scattering are reached, i.e. a few μrad, then the measurement of pp Coulomb scattering becomes possible. Luminosity and pp total cross section, σ_{tot}^{pp}, may then be obtained without the need of any inelastic detector. The technique relies in the measurement of elastic scattering in the part of the Coulomb region where the interference between the nuclear, f_N, and Coulomb , f_C, scattering amplitudes

$$\frac{d\sigma_{el}}{dt} = \pi |f_C + f_N|^2 \tag{3}$$

is maximum. This happens at $-t_0 \simeq 8\pi\alpha/\sigma_{tot}$. At the LHC energy, $\sqrt{s} = 14$ TeV, where σ_{tot} is predicted to be 110 mb [1], it implies $-t_0 \simeq 6 \times 10^{-4}$ GeV ^{2}. Scattering angles, $\theta \simeq \sqrt{-t}/p$, are then of the order of 3 μrad. As a comparison, these angles are smaller that the intrinsic angular divergence of the beam in high luminosity operation, which is $\Delta\theta = \sqrt{\epsilon/\beta^*} \geq 35\mu rad$.

2 REQUIREMENTS FOR THE INSERTION OPTICS

The optics requirements for a measurement of the elastic proton scattering at collision energy of 7 TeV in the LHC are derived from the physics requirements. Protons elastically scattered with a value of t equal to t_{min}= 0.0006 GeV^2 must be measurable with good efficiency [2].

These protons are emitted at the IP with an angle θ given by : $\theta = \sqrt{t_{min}/p}$ where p is the momentum of the proton beam. In order to be detected, their distance from the beam axis downstream of the insertion must be larger than n_σ r.m.s. beam size.

The value of n_σ is determined as follows. The edge of the detectors close to the beam must be at a distance from the beam centre such that an accidental triggering of the beam dump does not send the bunches into the detectors. In the LHC this value is about 15-20 [3].

A proton emitted from the IP with an angle θ will be at a distance from the beam axis equal to $L_{eff} = \theta\sqrt{\beta^*\beta}$ at a place where the betatron phase is $(n + 1/2)\pi$. Specifying that this distance is equal to n_σ r.m.s. beam size, we obtain the value of t_{min} : $t_{min} = n_\sigma^2 \epsilon_n m_0 cp/\beta^*$ where ϵ_n is the normalised r.m.s. emittance, m_0 the proton mass and c the speed of light. For the commissioning period the beam intensity will be reduced to 2.7 10^{10} p/bunch and ϵ_n will have the value of 10^{-6} m rad. Thus in order to obtain a maximum value of t_{min} of 0.0006Gev^2, the minimum value of β^* has to be 2300 m. The nominal parameters are [4]:

- At the IP, $\beta^* \geq 2300$ m, $\alpha^* \ll 0.4$ and $D_x^{'*} \ll 0.03$. To this end the design parameters are : α^*=0, D_x^*= 0 and $D_x^{'*}$= 0.
- At the detector place supposing an horizontal measurement, $(\mu_{x_d} - \mu_x^*) = \pi/2,\ 3\pi/2, ...$ and $\beta_{y_d} \geq$ 80 m i.e. $M_{x,12} = L_{x,eff}$= 500 m. Furthermore it is very desirable to have the transfer matrix elements $M_{y,12} \approx M_{x,12}$.

3 OPTICS SOLUTION FOR VERY high-β OPTICS

Assuming the standard conditions of Version 6.2 no solution could be matched which fulfills the requirements of parallel to point focusing optics.

A solution for measuring Coulomb scattering in the horizontal plane with the Roman pots stations between $Q6$ and $Q7$ could be found if $Q4$ is doubled in strength and $Q8$ is exceeding 12.2%. Figure 1 shows the solution for β^*=3500 m in Ring 1 calculated with MAD8 [5]. The most significant parameters are summarized in table 1. The beam sizes are calculated taking the commissioning emittance $\epsilon_n = 1.0\ \ \mu$m rad. The displacement at the detectors place x_d has been calculated taking $x^* = \sigma_x^*$ and $\theta_x^* = 3\mu$rad. The $n_{x,\sigma}$ has been calculated as $|x_d/\sigma_{x_d}|$. The $\theta_{x_{min}}$ and $\theta_{x_{max}}$ have been calculated for an opening of the Roman pots of $\pm$1.5 mm and $\pm$25.0 mm that correspond to the radius of the vacuum chamber from [6] respectively. The $|t_{x_{min}}|$ and $|t_{x_{max}}|$ have been calculated for p= 7000 GeV.

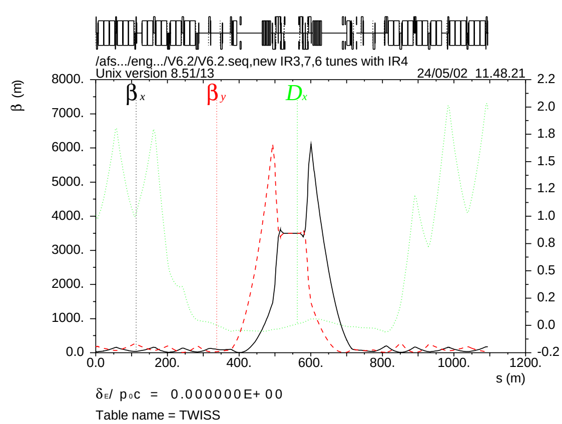

Figure 1: Very high-β optics with β^*=3500 m in Ring 1 around IP1, Version 6.2.

We have calculated the geometrical acceptance at collision energy around $IR1$ and $IR5$ as follows. For a given shape of the vacuum chamber, the inscribed secondary halo is estimated and the position of the associated primary collimator is deduced. If this position is larger than n_1=7σ, the situation is safe as the primary collimators in the cleaning insertion are at n_1=6σ[6].

ϵ_z	1.258 10^{-10}	m rad
β^*	3500.0	m
α^*	0.0	
D_x^*	0.0	m
$D_x^{'*}$	0.0	
σ^*	0.66	mm
$\sigma^{'*}$	0.19	μrad
horizontal measurement		
detector between $Q6 - Q7$		
β_{x_d}	168.5	m
$\Delta\mu_{x_d}$	0.750	2π
$M_{x,11_d}$	0.0	
$M_{x,12_d}$	767.9	m
$M_{y,12_d}$	-217.1	m
x_d	2.5	mm
$n_{x,\sigma}$	16.8	
$\|\theta_{x_{min}}\|$	2.8	μrad
$\|t_{x_{min}}\|$	0.0004	GeV^2
$\|\theta_{x_{max}}\|$	32.6	μrad
$\|t_{x_{max}}\|$	0.052	GeV^2

Table 1: Performance of a Coulomb measurement at the IP and at the detector place of Ring 1 for optics with β^*=3500 m, Version 6.2 at 7 TeV for commissioning emittance with the Roman Pots between $Q6$ and $Q7$. $|\theta_{x_{min}}| = \sqrt{2}x_d/M_{x,12_d}$ with x_d = 1.5 mm.

The minimum value of n_1 for the very high-β optics at commissioning emittance occurs in $TAS1$ absorbers and is equal to 8.35 as shown on figure 2. On the other hand, from the measurement point of view this element $TAS1$ does not set an unacceptable upper limit to the maximum value of t which is in the range of 1.4 GeV^2.

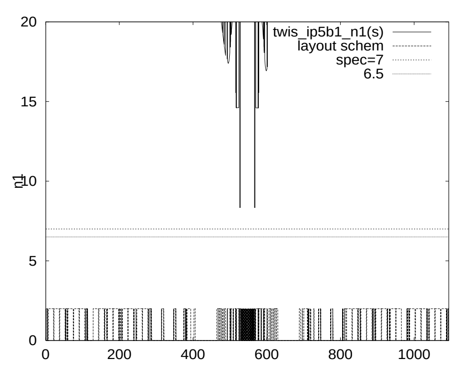

Figure 2: Geometrical acceptance at collision energy for very high-β optics with β^*=3500 m in Ring 1 around $IP5$, Version 6.2.

4 DETECTOR ACCEPTANCE

The crucial point for Coulomb scattering is to be able to reach down values well beyond $-t_0$. Figure 3 represents the geometrical acceptance of a detector 2.0 mm x 2.5 mm with the parameters of table 1, as a function of the minimal distance of approach to the beam: 10, 15 and 20 σ_{x_d}, where $\sigma_{x_d} = 0.149$ mm is the horizontal beam size (rms) at the detector place.

As it can be seen , with a minimal approach distance of 2.2 mm (15 σ_{x_d}), an efficiency better than 40% is reached at $-t = 6 \times 10^{-4}$ GeV^2.

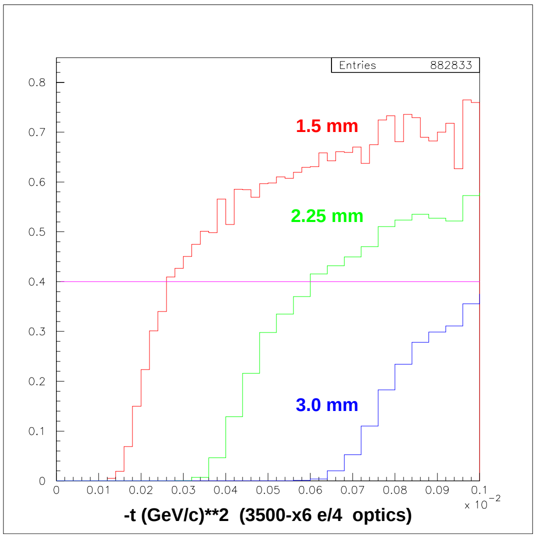

Figure 3: Acceptance for Coulomb scattering.

5 CONCLUSION

A very high-β optics ($\beta^* = 3500m$), for a precise determination of luminosity through the measurement of the Coulomb scattering at the LHC has been studied. It requires some minor hardware modifications of the present LHC set up. With realistic assumptions as to the minimum beam distance approach, an acceptance good enough is obtained. The goal of a luminosity known to a 2% seems achievable.

6 REFERENCES

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