A VERY HIGH-β OPTICS TO BE USED FOR AN ABSOLUTE LUMINOSITY DETERMINATION WITH FORWARD DETECTORS IN ATLAS

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Abstract

The Atlas experiment at the LHC pursues a number of different approaches to obtain an estimate of the absolute luminosity [3]. Measuring elastic scattering at very small angles (3 μrad) represents a different and complimentary approach that will improve the precision of the final luminosity estimate. In this paper we show the required very high-β optics and the detector acceptance studies.

METHODS FOR ABSOLUTE LUMINOSITY DETERMINATION

Different methods for absolute luminosity determination exist:

Elastic Scattering at Small Angles

This method uses the fact that the rate of elastic scattering is linked to the total interaction rate through the optical theorem, which states that the total cross section is directly proportional to the imaginary part of the forward elastic scattering amplitude extrapolated to zero momentum transfer squared,$-t$. This implies that by measuring the total interaction rate R_{tot}, and the elastic rate $dR_{el}/dt|_{t=0}$ in the forward direction simultaneously, both the luminosity L and the total cross section σ_{tot} can be determined:

$$L = \frac{1}{16\pi} \frac{R_{tot}^2 (1+\rho^2)}{\frac{dR_{el}}{dt}|_{t=0}} \tag{1}$$

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{\frac{dR_{el}}{dt}|_{t=0}}{R_{tot}} \tag{2}$$

where ρ is the ratio of the real to imaginary part of the elastic scattering forward amplitude. This method requires a precise measurement of the inelastic rate with a good coverage in $|\eta|$. To make an accurate extrapolation over the full phase space an $|\eta|$-coverage up to 7-8 is needed, and the ATLAS coverage is not good enough for this purpose. This method is pursued by the TOTEM experiment [1].

Coulomb Scattering

A different approach is to measure elastic scattering down to such small t-values that the cross section becomes sensitive to the electromagnetic amplitude via the Coulomb interference term. Luminosity and total cross section may then be obtained without the need of any inelastic detector. The technique relies on the measurement of elastic scattering in the part of the t-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 [2], it implies $-t_0 \simeq 6.5 \times 10^{-4}$ GeV ^{2}. Scattering angles, $\theta \simeq \sqrt{-t}/p$, are then of the order of 3.5 μrad. To indicate the scale of the difficulty: at the SPS collider the Coulomb region was reached at scattering angles of 120 μrad.

Alternative and Complementary Methods

In addition, there are several alternative and complementary methods for the determination of the absolute and relative luminosity. These methods are:

The use of the LHC beam monitors to determine the bunch densities and the bunch-bunch effective overlap region at the IP. Based on experience at previous machines, the determination of luminosity from machine monitor information is far from trivial and further complicated by the fact that the beam profiles at the IP cannot be directly accessed but must be extrapolated from measurement outside the experimental area. The precise limits to the accuracy of a machine derived luminosity are currently not well known, with estimates ranging between 5-10 %.

Other well-calculable physics processes as luminosity monitors. The most promising example of a QED process is the production of a muon pair by double photon exchange.

Another process that has been proposed, and has been studied in some details by ATLAS, is the QCD production of W and Z gauge bosons, and the measurement of their production rate times leptonic branching ratio.

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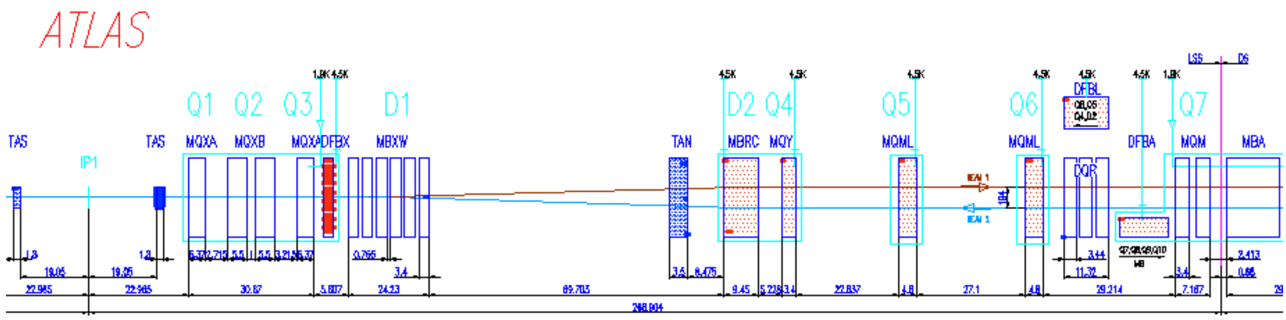

Figure 1: Schematic layout of the LSS1 near ATLAS with the proposed location for the detectors (one side).

REQUIRED BEAM PROPERTIES

The most suitable method to reach the Coulomb region employs a so-called parallel-to-point focusing optics from the IP to the detector. In this type of optics the betatron oscillation between the IP and the detector position has a 90^o phase difference (in at least one of the two transverse plane), such that all particles scattered with the same angle are focused on the same locus at the detector, independent of the position of their interaction vertex position.

In this kind of optics the beam is quasi parallel at the IP and must have an intrinsic beam divergence significantly smaller that the smallest scattering angle to be observed. The divergence at the IP equals $\sqrt{\epsilon/\beta^*}$, where ϵ is the emittance and β^* the betatron function at the IP. Thus, a small emittance ϵ and a large β^* are required. In order to reach the Coulomb region we need a normalized emittance ($\epsilon_N = \epsilon\gamma$) of the order of 10^{-6} m rad and a β^* in the range 2000-3000 m.

Requirement on the Optics

Protons are emitted at the IP with an angle θ given by: $\theta = \sqrt{t}/p$ where p is the momentum of the proton beam. Using a parallel-to-point focusing optics with a phase advance of $\pi/2$ and the derivative of the β-functions , $\alpha^* = 0$ gives us an effective lever arm between the IP and the detector equal to: $L_{eff} = \sqrt{\beta^* \beta_d}$, where β_d is the betatron function at the detector location. The minimum t_{min} reachable will the be given by: $-t_{min} = (p\theta_{min})^2 = p^2 n_d^2 \epsilon/\beta^*$ where n_d is the smallest possible detector distance to the beam center expressed as a multiple of the r.m.s. beam size. Using a ϵ_N of 10^{-6} m rad, which we hope is reachable and a minimum distance to the detector corresponding to $n_d = 15$, we see that a t_{min} of 0.0006 Gev^2 can be reached for $\beta^* \geq 2600$ m.

In case the closest beam approach is limited by to closed orbit instabilities instead of the beam halo considerations, the minimum distance will be an absolute number independent of the beam size. This implies that t_{min} will be proportional to $1/(\beta^* \beta_d)$. Thus we have an additional requirement on the optics: that β_d should not be too small. Putting in realistic numbers we find $\beta_d \geq 70$ m.

As mentioned above, the detectors will be in a location with 90^o phase advance relative to the IP at least in one of the two transverse planes. The LHC has two separate beams in the horizontal plane with the two beam pipes separated only 194 mm. This gives a considerable technical advantage to approaching the beam from above and below the beam axis compared to approaching from the the sides. Thus we require the optics to have 90^o phase advance in the vertical plane at the detector location.

In the horizontal plane it is not necessary to have a 90^o phase advance. This is due to the fact that there is a total symmetry with respect to the IP for elastic scattered events and in this case the smearing contribution from the horizontal vertex position cancels.

Optics Solution

Several high-β and very high-β optics have been studied for LHC Version 6.4 [4].

Optics solution for very high-β optics. A solution fulfilling the requirements above has been found, with the required phase advance in the vertical plane with the detectors located between $Q6 - Q7$ (240 m from IP) see Fig.1.

This solution does not require any hardware changes but it requires that $Q4$ works with reversed polarity compared to the standard optics. Fig.2 shows the solution which has β^*=2625 m. The most significant parameters are summarized in Tab.1. The beam sizes are calculated for an emittance $\epsilon_N = 1.0$ μm rad. The vertical displacement at the detector y_d has been calculated taking as vertical vertex coordinate the r.m.s. beam size at the IP, σ_y^* and the scattering angle 3.5 μrad. $|\theta_{min}| = s_{min}/M_{12_d}$ where M_{12_d} is the Twiss transfer matrix element from the IP to the detector and s_{min} = 1.5 mm. The value of the theoretical acceptance of the detector is calculated as: $A_{y,d} = \frac{2}{\pi} \arccos \frac{d_{min}}{y_d}$.

Injection and transition optics. Due to the aperture limitation at injection energy, the injection requires a special optics. A new injection optics has been found, with the same power supplies and keeping the reversed polarity

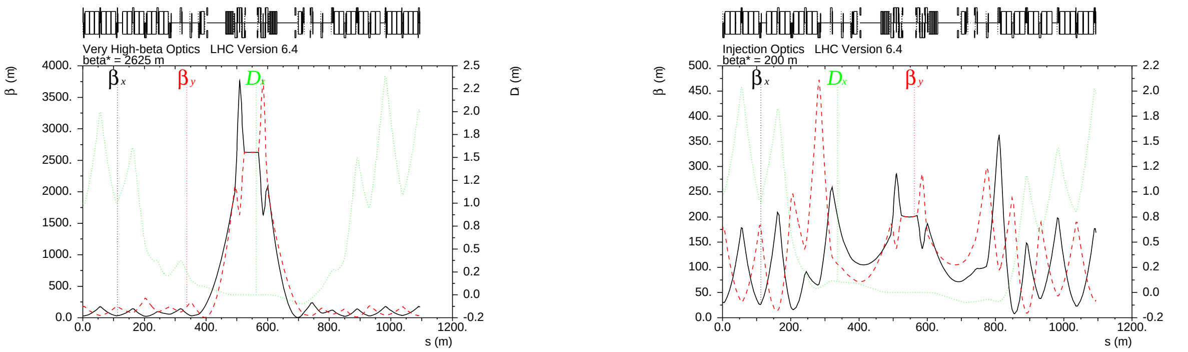

Figure 2: Very High-β (β^*=2625 m) and Injection optics (β^*=200 m) in Ring 1 around $IP1$, Version 6.4.

Table 1: Performance of very high-β (β^*=2625 m) symmetric triplet optics Version 6.4, at 7 TeV.

ϵ_n	1.0	μm rad
σ_ϵ	0.111	10^{-3}
IP		
β^*	2625.0	m
α^*	0.0	
D_x^*	0.0	m
$D_x^{'*}$	0.0	
σ^*	0.61	mm
$\sigma^{'*}$	0.23	μrad
π/2 location (239.6 m)		
β_{y_d}	119.1	m
$\Delta\mu_{y_d}$	0.25	2π
$M_{y,11_d}$	0.0	
$M_{y,12_d}$	559.2	m
β_{x_d}	84.0	m
$\Delta\mu_{x_d}$	0.549	2π
$M_{x,11_d}$	-0.2	
$M_{x,12_d}$	-142.3	m
y_d	1.96	mm
$\|y_d/\sigma_{y_d}\|$	15.0	
$\|\theta_{y_{min}}\|$	2.682	μrad
A_y	0.444	

for $Q4$. A solution for injection optics with β^*=200 m is shown in Fig.2.

DETECTOR ACCEPTANCE STUDIES

In order to estimate the performance of the proposed small-angle scattering detector we used a simple simulation. The simulation is a FORTRAN-based program based on the machine emittance and beam momentum dispersion, a vertex location and initial four momenta of the colliding protons are generated. Using the standard small-angle elastic scattering formula, containing both electromagnetic and nuclear amplitudes, a t-value is generated and a flat azimuthal angle under the assumption that the initial states are unpolarized. The resulting four-vectors of the scattered protons are transformed back to the laboratory system and traced to the detectors. For the simple tracing, we have taken the formalism of optics transfer matrices, from the IP to the detector location. Only one detector unit after $Q6$ at 239.6 m form the IP has been implemented in the simulation. Furthermore we have considered the aperture limitations of the beam pipes for all the elements between the IP and $Q6$. The calculated intersection of the elastically scattered protons with the detector planes are converted to detector hits. The simulation results are shown in Fig.3

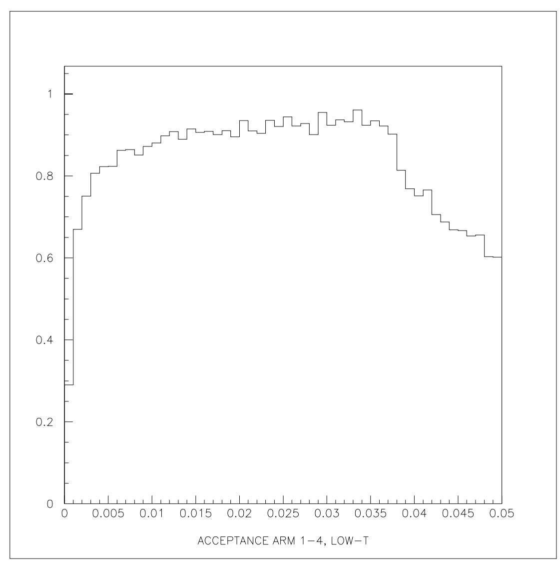

Figure 3: Acceptance of the detectors (one side).

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