1 Luminosity uncertainty

In this section we summarise the methods for luminosity determination and associated uncertainties expected in the start-up phase of the LHC and the accuracy which might ultimately be reached for the high luminosity phase after calibration of the luminosity detectors. We don't consider here the absolute luminosity calibration using W/Z counting and theoretical cross section calculations, which are treated in a dedicated section.

It is a safe assumption that the uncertainty of total integrated luminosity needed for cross section measurements is dominated by the uncertainty of the absolute calibration of the various relative luminosity monitors. The relative luminosity at IP1 is directly monitored by the LUCID [1] detector by sampling the number of charged particles per bunch crossing. LUCID is instrumented with projective Cerenkov tubes at 17 m from the interaction point and will cover a pseudo-rapidity range from $5.4 \leq |\eta| \leq 6.1$ in its full version (a reduced prototype set-up will be used at start-up). The dynamic range of LUCID covers luminosities from $10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with a non-linear uncertainty below 1 %. Other ATLAS detectors can also be used for luminosity monitoring, such as the minimum bias counters (in the initial phase), the ZDC, the Tile calorimeter (minimum bias rate) and the currents of high voltage power supplies for the Liquid Argon calorimeter. The LHC in addition has the BRAN luminosity monitors which instrument the TAN absorbers located 141 m from the interaction point. The BRAN measures the flux of showers from photons and neutrons originating from the collisions in four quadrants of each 4×4 cm^2 size. These monitors provide a bunch-by-bunch rate for the luminosity and in addition a measurement of the crossing angle at the interaction point.

1.1 Absolute Luminosity from beam parameters

A comprehensive review of machine parameter determinations is given in [2]. In the start-up phase the only luminosity measurement will be derived from machine parameters. We recall for completeness the well know principle. For round beams with Gaussian transverse profile of width σ circulating with a revolution frequency f and two bunches with N_1 resp. N_2 particles the instantaneous luminosity is given by:

$$\mathscr{L} = \frac{N_1 N_2 f}{4\pi\sigma^2} \,. \tag{1}$$

The frequency is determined with high accuracy and the beam current can be measured accurately with beam current transformers to a precision of better than 1%. This does not necessarily mean that the number of particles contributing to the luminosity can be measured with the same accuracy. Still the dominant source of uncertainty is expected to come from the knowledge of the beam profiles. In the start-up phase an uncertainty of 20-30 % is expected [2]. The precision can be improved by performing special runs and calibrations.

Luminosity calibration runs are best performed with an optics with a β value of 2 meters or larger and with a few bunches colliding without crossing angle. A crossing angle always leads to a reduction of the luminosity and those simplified conditions will minimise the uncertainty. Moreover any residual crossing angle will be measured by the BRAN and special strip line coupler beam position monitors (BPMSW) installed close to Q1. A loss in luminosity is also encountered for beams not colliding head-on. The separation of the two beams can be studied with separation scans and are further directly measured with the BPMSW to keep the separation at the level of 0.1 σ. The transverse bunch shapes are measured with profile monitors and can also be studied with separation scans. The main uncertainty is expected to arise from the tails of the transverse distributions, which fully contribute to the intensity but marginally to the luminosity [3]. Special wire scanners will allow the detection of these tails, which can be eliminated with scraping procedures. Further information on beam profiles can be gained from beam-gas interaction [4]. The longitudinal beam charge distribution must be monitored to eliminate extra non-colliding bunches or particles outside bunches. Further effects such as beam-beam effects and hour glass effects have been studied [2] and are believed to not contribute sizably to the luminosity calibration. Upon completion of these systematic studies an absolute luminosity accuracy of better than 5% is within reach.

1.2 Luminosity calibration from elastic scattering

The traditional method for luminosity measurements at hadron colliders uses small-angle elastic scattering. In ATLAS the ALFA Roman Pot detectors [5] will perform elastic measurements at very small scattering angles in the Coulomb-Nuclear Interference (CNI) region. This measurement requires a special beam optics with low emittance and large β^* at a very low luminosity of $10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in order to approach the beam as close as possible. Under these conditions the t-spectrum can be measured and the absolute luminosity is extracted from a fit to the spectrum according to:

$$\frac{dN}{dt} = \mathscr{L}\left(\frac{4\pi\alpha^2(\hbar c)^2}{\mid t\mid^2} - \frac{\alpha\,\rho\,\sigma_{tot}}{\mid t\mid}\cdot\exp\frac{-B\mid t\mid}{2} + \frac{\sigma_{tot}^2}{16\pi(\hbar c)^2}\left(1+\rho^2\right)\cdot\exp -B\mid t\mid\right)\,. \tag{2}$$

In addition to the luminosity, the total cross section σ_{tot}, the nuclear slope B and the ratio of the real and imaginary nuclear scattering amplitude ρ can be extracted simultaneously. The performance of this method has recently been evaluated [6]. For a calibration run of 100 hours a statistical uncertainty for $\mathscr{L}$ of 1.8% is reached. Sources of systematic uncertainty are related to the beam parameters, in particular the optical functions, the detector acceptance and alignment and the background originating mostly from beam-gas interaction. Using currently available simulation tools a total experimental uncertainty of about 2.6% is obtained, yielding a total uncertainty of 3%. Luminosity measurements using LUCID under collision optics have to account for an extrapolation uncertainty from the calibration point, which is estimated to be about 1%.

In case the beam conditions are not favourable for a measurement in the CNI region the ALFA detector can still be used to measure the t-spectrum at larger t and use other determinations of the total cross section to extract the luminosity.

Ultimately and anticipating future model improvements also the Optical Theorem can be used to determine the luminosity. This requires an extrapolation of the nuclear part of the t-spectrum to zero and an estimate of the total inelastic rate over all η. Combinations of measurements using machine parameters and elastic scattering are conceivable and allow for cross-calibrations of different systems.

In conclusion we expect in the start-up phase a rough luminosity determination to 20-30% accuracy using machine measurements. Once a good understanding of the LHC operation is obtained a number of calibration runs will be performed in order to improve the absolute luminosity calibration, which ultimately can reach a precision of 3%.

References

[1] *Forward Detectors for Luminosity Measurement and Monitoring*, ATLAS LoI, CERN/LHCC/2004-010 (22 March 2004)

[2] H. Burkhardt and P. Grafstrom, *Absolute Luminosity from Machine Parameters*, LHC Project Report XX

[3] H. Burkhardt and R. Schmidt, *Intensity and Luminosity after Beam Scraping*, CERN-AB-2004-032

[4] M. Ferro-Luzzi, *Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions*, Nucl. Instrum. Meth. **A 553** (2005) 388-399.

[5] *ATLAS Forward Detectors for Measurement of Elastic Scattering and Luminosity Determination*, ATLAS TDR CERN/LHCC/2007-XXX in preparation

[6] H. Stenzel, *Luminosity calibration from elastic scattering*, ATL-LUM-PUB-2007-001