Luminosity Calibration

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Abstract

The experiments do not only require high collision rates and integrated luminosity, but also an absolute normalization of the observed cross sections. This normalization can be derived from theoretical predictions or the determination of the absolute luminosity. During the 2010 proton run, the Van Der Meer scan method was used to provide a first measurement of the absolute luminosity from machine parameters. Based on the outcome of the Lumi Days workshop [1], future requirements, prospects and alternative methods (vertex, high-β) will be summarized. Implications on machine operation and protection will be discussed.

INTRODUCTION

For particle colliders, the most important performance parameters are the beam energy and the luminosity. High energies allow the particle physics experiments to study and observe new effects and the luminosity is used as a measure of the number of collisions. It is defined as the proportionality factor between the event rate, measured by the experiments, and the cross section of the process observed.

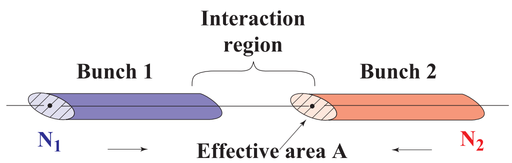

Figure 1: Luminosity from particles flux and geometry.

We consider two bunches of N_1 and N_2 particles colliding in an interaction region as shown in Figure 1. For bunches crossing head-on at a frequency f (revolution frequency in the case of a circular collider) the luminosity $\mathcal{L}_0$ is expressed as:

$$\mathcal{L}_0 = \frac{N_1\, N_2\, f}{A_{\text{eff}}} = \frac{\dot{N}}{\sigma}. \tag{1}$$

$\dot{N}$ is the event rate observed by the experiments. σ is a visible cross section which depends on the energy, the physics process and the acceptance and efficiency of the detector. A_{eff} which is the effective transverse area within which the collisions take place is determined by the overlap integral and depends on the beam shape, crossing angle and offsets. For Gaussian beams colliding head-on without crossing angle we have:

$$A_{\text{eff}} = 2\,\pi\,\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\,\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}, \tag{2}$$

where σ_{iu} ($i = 1, 2$ and $u = x, y$) are the individual beam sizes.

MOTIVATION AND TARGET PRECISION

An essential ingredient in the characterization of a particle physics process is the knowledge of the absolute cross section. Recalling Equation 1 we have:

$$\mathcal{L}_0 = \frac{\dot{N}}{\sigma}. \tag{3}$$

The determination of the absolute luminosity therefore allows the particle physics experiments to normalize their data. In addition, for particle colliders the most important performance parameters are the beam energy and the luminosity. The absolute knowledge of these quantities is therefore very important to understand the performance of the machine.

The target precision for luminosity calibration is driven by the accuracy of the particle physics theoretical predictions. As of today, the W and Z production cross section is the most accurately known elementary cross section which could be determined with a precision of 2% [3]. While a measurement to better than 5% would already start challenging the models, this naturally defines the ultimate target for absolute luminosity determination.

METHODS

In $e^+ e^-$ colliders, the theoretically well known Bhabha scattering is generally used for this purpose. In the LHC the W and Z production which cross section could be calculated to a few percents could be used for such purpose. These normalizations however rely on the fragmentation model and it is desirable to cross check the theoretical expectations with an independent measurement.

The methods used in 2010 for luminosity calibration are based on the measurement of the effective area A_{eff} defined in Equation 1.

Van Der Meer Method

The Van Der Meer method is the main source of luminosity calibration used in 2010 and measurements were performed at the four interaction points. It was pioneered by S. Van Der Meer at the ISR [4] and uses the dependency of the luminosity on transverse offsets:

$$\mathcal{L} = \mathcal{L}_0 \exp\left[-\frac{\delta x^2}{2(\sigma_{1x}^2+\sigma_{2x}^2)} - \frac{\delta y^2}{2(\sigma_{1y}^2+\sigma_{2y}^2)}\right], \quad (4)$$

where δx and δy are the transverse offsets in the horizontal and vertical planes. Integrating under the curve obtained by measuring interaction rates as function of the separation will therefore allow to determine the effective beam size as well as the maximum achievable collision rate.

The main potential sources of uncertainty for this method are:

- **Bunch intensity measurements**: the LHC is a bunched beam machine and the total luminosity is given by the sum of the bunch luminosities. A precise bunch by bunch analysis is therefore required and an uncertainty on the intensity measurement would directly apply to the luminosity.
- **Beam displacement**: the knowledge of the absolute beam displacement is essential for the measurement of the beam size. Any uncertainty or error on the scale factor will directly translate in an error on the beam size.
- **Non stable beam conditions**: the precision of the method relies on the fact the beam parameters remain constant during the measurement. Emittance or orbit drifts could affect the measurement.

Other effects such as coupling or the hourglass effect could also have an impact on the measurement but are small in the LHC or could easily be minimized [5]. Generally speaking the Van Der Meer scans are best performed in the simplest possible configuration regarding beam dynamics i.e. with small beam-beam parameter.

Beam-gas Imaging

This method was initially introduced by LHCb [6] and uses the beam-gas vertices to reconstruct the individual beam sizes. The luminosity measurement using beam gas imaging does not require transverse scans and can therefore be performed parasitically. Only LHCb uses this method.

The main potential sources of uncertainty for this method are:

- **Bunch intensity measurements**: for the same reasons as for the Van Der Meer scans.
- **Non stable beam conditions**: this condition is even more relevant for this method due to the low rate of beam gas events. It is foreseen to introduce a pressure bump in order to increase the beam gas rates and reduce the time required to reconstruct the profile. The residual gas profile could also contribute to the uncertainty.
- **Vertex resolution**: the vertex resolution limits the precision with which the beam sizes can be reconstructed. This uncertainty can be decreased by increasing the IP beam sizes.

A low beam-beam parameter would also be desirable but the requirement for large beam sizes and high rates makes it difficult to accommodate. The only source of systematic uncertainty shared with the Van Der Meer scans is the beam intensity measurement. It would therefore be interesting to combine these two methods in the same fill in order to cross check the results.

An alternative to this method, also taken by CMS, is to use the proton-proton vertices during the separation scans. The same uncertainties as for the Van Der Meer scans therefore apply. The Van Der Meer method gives a direct measurement of the overlap area while this method requires to reconstruct it from the individual beam sizes which might introduce some bias in the analysis. It should therefore be seen as a complementary analysis of the Van Der Meer scans but not a primary calibration source.

Optical Theorem

This technique has been used since ISR in a number of machines and consists of determining the luminosity via an extrapolation to zero scattering angles in combination with a measurement of the total inelastic rate using the optical theorem:

$$\frac{1}{\mathcal{L}} = \frac{1}{16\,\pi}\frac{\sigma_{tot}^2\,(1+\rho^2)}{dR_{el}/dt|_{t=0}}, \quad (5)$$

where

$$\rho = \left.\frac{Re\, f_{el}(t)}{Im\, f_{el}(t)}\right|_{t=0}. \quad (6)$$

R_{tot} is the total interaction rate and R_{el} the elastic rate and f_{el} is the scattering amplitude. It is foreseen to use this method in TOTEM [7] and ATLAS [8] using dedicated high-β^* optics.

2010 MEASUREMENTS AND RESULTS

Calibration scans were performed in the four LHC interaction points [9]. The experiments first published results and latest offline analysis can be found in [11, 10], [12], [13, 14] and [15, 16]. Two sets of measurements were performed. The first measurements, in spring 2010, were performed early in the commissioning phase of the LHC and the beam conditions and instrumentation were not optimal. The final uncertainty on the measurement was found to be of 11% from which 10% came from the preliminary determination of the beam intensity [19]. A more detailed offline analysis of the beam current data improved the overall uncertainty to about 6 %. The earlier measurements also suffered from a larger emittance blow-up due related to instrumental noise picked-up by the beam [17]. The second set of measurements was performed in October 2010. Significant progress in the calibration of the LHC instrumentation and better beam conditions and stability helped reducing the overall systematic uncertainty to about 5% for these measurements. An excellent agreement was found between the different methods. The precision of 5% obtained during the first year of operation of a machine as complex as the LHC represents a significant achievement and could be further improved with dedicated beam conditions.

An example of a scan performed in CMS is shown in Figure 2.

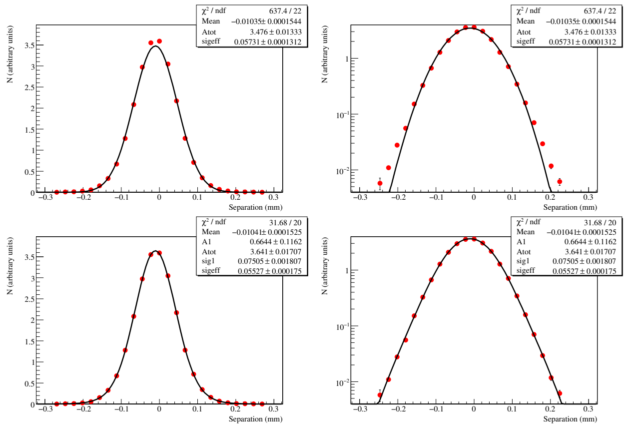

Figure 2: Example of a scan performed in CMS in the horizontal plane. The four plots show the same data, displayed with linear scale on the right, logarithmic scale on the left and single Gaussian in the top and double Gaussian in the bottom plots. A small excess of non-Gaussian tails is visible with logarithmic scale in the top right plot, which is well taken into account by the double Gaussian fit shown on the bottom.

In order to extract the correct beam size from the overlap profile it is important to know the absolute displacement generated with the closed orbit bump. An error on the relative scale of the beam position would directly translate in an uncertainty on the fitted beam size. A measurement of this error was done at the four interaction points by displacing the two beams transversally in the same direction, which results in a displacement of the luminous region, and compare the values given by the magnet settings with the position of the luminous region reconstructed by the experiments.

An excellent agreement of the order of 1% was observed between the theoretical value as given by the magnet settings and the measured luminous region centroid given by the experiments as shown in Figure 3. Different methods were used to perform this measurement in 2010. All were performed fully manually. In 2011, it would be desirable to agree on a standard procedure and implement it in an automated routine in order to avoid errors such as wrongly trimmed magnets. This measurement needs to be performed only once for the optics that are used for the scans. Using different optics for the calibration scans will result in overhead due to the requirement to perform new

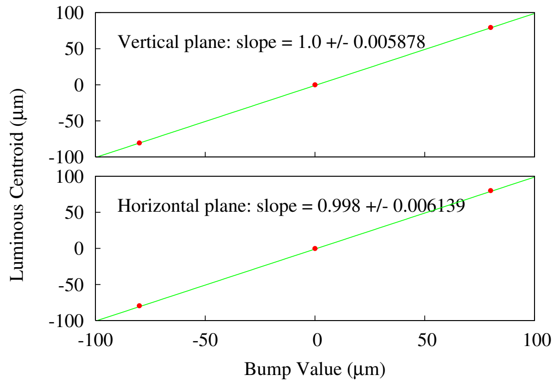

Figure 3: Bump calibration measurement done in IP5. Each scan consists of three acquisition points at -100 μm, 0 μm and +100 μm. The bump value is in excellent agreement with the vertex position.

scale calibration measurements.

INSTRUMENTATION

The most important observable for luminosity calibration is the intensity measurement done with Beam Current Transformers (BCT) as it directly enters the luminosity formula. They are are capable of integrating the charge of each LHC bunch. The precision of these measurements for the nominal LHC beams is expected to be of the order of 1% [18]. An additional uncertainty could come from the longitudinal bunch distribution; unbunched particles or non colliding bunches would be counted in the average beam intensity while not fully contributing to the luminosity. A careful bunch by bunch analysis combined with an intensity calibration at the end of the ramp where no unbunched beam component exists, provides a good monitoring of this uncertainty. The first measurements were performed in the early stage of the commissioning of the LHC at very low intensity (2 bunches of 2.0×10^{10} p /bunch per beam). In these conditions, an initial 10% uncertainty was derived for the determination of the beam intensity. This error was later decreased to about 3 % as the understanding of the system and the knowledge of the related systematic uncertainties was improved [19]. Increasing the overall beam intensity while keeping the bunch intensity relatively small to avoid other effects such as beam-beam and pile-up to become significant, should ultimately allow to reduce this uncertainty to 1 % per beam in the current configuration [20].

The challenge for 2011 is to reduce this error to the specifications of 1% per beam. This requires a better understanding of the satellite bunches and unbunched components which could be provided by the Longitudinal Density Monitor (LDM).

Other instruments such as the BPM system or the emittance measurements devices were used during luminosity calibration runs for verification purposes. They are not essential but proved to be very useful especially in the case of the emittance measurements. Providing automated bunch to bunch emittance acquisition and logging would help in the analysis of the calibration scan data.

MACHINE PROTECTION

The beams are displaced at the IP via a closed orbit bump that consists of four magnets and allows to control the beams independently.

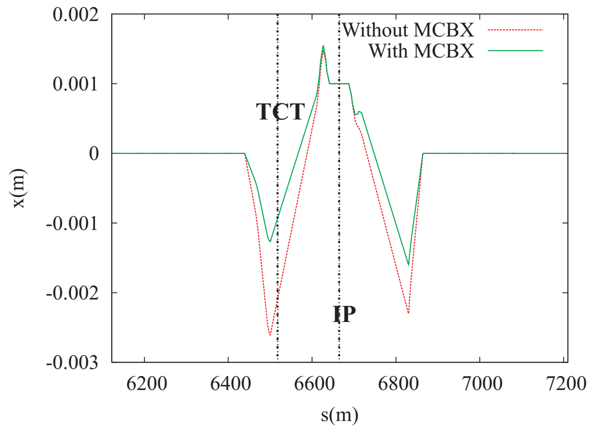

Figure 4: Example of closed orbit bumps using different orbit correctors at IP5. Displacing the beam at the IP also changes the orbit at the tertiary collimator location.

One can see in Figure 4 that a four magnet separation bump extends over a large fraction of the straight section around the IP. More specifically, displacing the beams at the IP will result in a change of orbit at the tertiary collimators (TCT). Given the non-negligible offset at the TCT introduced by the bumps, one has to ensure that while performing a separation scan the beams remain far enough from the aperture set by the collimators and that the displacement does not compromise the machine protection. In 2010, the displacement at the TCT was minimized by splitting the amplitude of the corrections required to find the optimum collision point between the two beams. In addition a re-qualification of the collimation system was done with the TCTs closed by 2σ with respect to their nominal settings to ensure that the margins were sufficient to safely perform the full scan.

In 2011, it was decided to move the TCTs together with the beam [21] in order to provide more flexibility and operation efficiency and ensure that the aperture margin between the dump protection and the TCTs remains large enough. It does not guarantee, that the safety margin between the TCTs and the triplet magnets is always respected. A complete assessment of the aperture reduction due the scans, especially in the crossing angle plane, should therefore be performed in order to ensure safe operation.

2011 SPECIAL FILLS FOR CALIBRATION SCANS

A dedicated joint machine experiments workshop was held at CERN in January 2011 [1]. The details of the discussion and proposal from the experiments can be found in [22]. The four experiments have different wishes in terms of beam conditions which can be summarized as follows:

- **ATLAS**: $\mu \approx 1.5 - 2$ driven by low acceptance detector.
- **ALICE**: $\mu \approx 0.1 - 0.5$.
- **CMS**: $\mu \approx 1$ and large beam sizes to use the proton - proton beam imaging method.
- **LHCb**: $\mu \approx 1$ and large beam sizes to use the beam - gas imaging method.

μ is the number of events per bunch crossing. It was generally agreed that these special measurements should be performed with the crossing angle on and no bunch trains. The knobs to accommodate these condition are β^*, the emittance and the bunch intensity. Some limitations apply both from the machine and operation overhead:

- Use standard optics, either physics or injection.
- Stay below or well above the BPM calibration switch to avoid crossing during the fill.

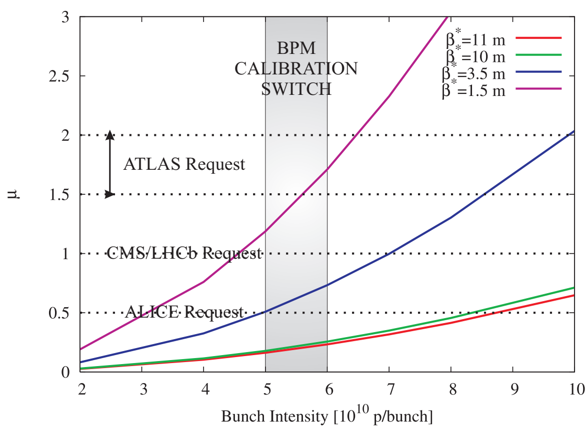

Figure 5: μ as a function of the bunch intensity for different β^* and an emittance of 3.0 μm. The experiments request are illustrated by the dashed lines.

Figure 5 shows the evolution of μ as a function of the bunch intensity for different β^* and an emittance of 3.0 μm. It is clearly seen on this picture that all the experiments requests cannot be fulfilled in a single fill unless the LHC is operated in a non-standard configuration i.e. intermediate β^*, different bunches with different intensities or emittances. This would result in significant operation overhead which could become unreasonable with respect to the time required for the measurements. It is however possible to accommodate almost all the requests in two fills using standard configuration:

- **High Precision**: optimal conditions for Van Der Meer scans. Physics optics with low bunch intensity $< 5.0 \times 10^{10}$ p/bunch. Minimal setup time.
- **Beam Imaging**: large beam sizes and high rates. Use injection optics with highest possible μ. Van Der Meer analysis could still be performed even if the conditions are not optimal. Need to assess the time required to qualify the injection optics for STABLE BEAM.
- **Reproducibility**: a few end of fill scans could be performed almost parasitically.

Given the excellent results obtained in 2010 at an energy of 3.5 TeV an early luminosity calibration is not necessary as long as the energy is not changed.

HIGH-β^* EXPERIMENTS

Two experiments, TOTEM [7] and ATLAS [8], are foreseen to study diffractive and elastic scattering at the LHC in the very forward region. They use dedicated movable detector, the Roman Pots (RP), situated on each of the IP. Ultimately these experiments should provide a cross section measurement with a precision of about 1%. The TOTEM experiment started commissioning in 2010 and is now ready for physics and expects to reach a precision of 3% on the cross section in 2011 [23]. The ATLAS experiment finished installing the RP during the 2010 winter shutdown and expects to be ready for physics in summer 2011 and to reach a precision of 5-7% on the cross section [24]. About 4 fills were requested for physics.

Both experiments require special high-β^* optics with a phase advance of $\pi/2$ in at least one plane between the IP and a roman pot detector. The details of the implementation of these optics can be found in [25].

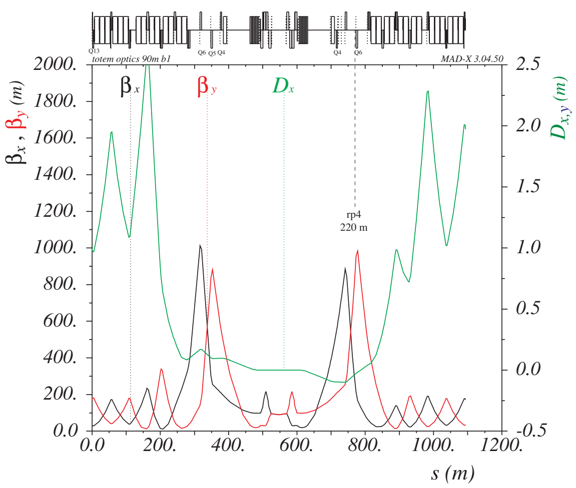

Figure 6: 90 m TOTEM optics for beam 1.

The nominal high-β^* optics have β^* of 1540 m for IP5 and 2632 m in IP1. These optics are not compatible with the actual LHC configuration. An intermediate optics solution has been found with β^* of 90 m which is illustrated in Figure 6. This optics is fully compatible with the actual LHC and is ready for commissioning in 2011 [26].

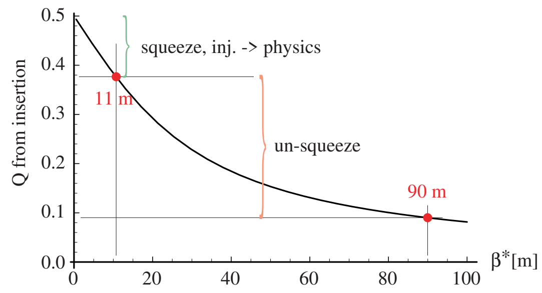

Figure 7: Tune contribution from the insertion ± 26 m from the IP as relevant for the LHC.

A low-β insertion with $\beta^* \ll \ell$, where ℓ is the distance from the IP to the triplets, contributes with a phase advance of π and tune of 0.5. For $\beta^* \gg \ell$ instead, the phase advance and tune contribution drops to zero. This is illustrated in Figure 7. We see that the local tune change from the IR for the squeeze from 11 m to 0.55 m is approximately +0.1 and about -0.3 for the un-squeeze from 11 m to 90 m. The tune changes in the un-squeeze are too large to be fully compensated internally.

Other constraints such as maintaining a phase advance of $\pi/2$ between the IP and a roman pot detector and high precision optics measurement ($\Delta\beta/\beta \approx 1\%$) make this optics very challenging for operation and the commissioning should start as soon as possible. The following strategy was discussed at the LHC Lumi Days workshop:

- Cold check-out, drive the magnets without beams
- MDs: first try to un-squeeze IP1 and IP5 at the same time, tune compensation done with the arc quadrupoles
- Beam conditions: 1 bunch per beam at low intensity, measure optics during the un-squeeze

If no major issues are found a total of 5 shifts are expected to fully commission these optics including machine protection qualification.

SUMMARY

The luminosity calibration measurements done in 2010 were very successful and a precision of 5% is expected in view of the latest results. Several methods have been developed and used which show an excellent agreement. The precision could be improved to below 5% providing dedicated beam conditions.

- **Separation Scans**: two fills are required to fulfill all the experiments wishes. As long as the energy remains at 3.5 TeV, the measurements done in 2010 remain valid and no early calibration is necessary. New developments were requested by the experiments [27] out of which the priority should be set on improving the knowledge of the bunch current normalization (BCT and LDM) and developing an automated procedure for the scale calibration. Time could be gained by performing the scans simultaneously at the four interaction points, but it remains to be demonstrated that this can be done without increase in systematic uncertainties due to beam-beam effects and leakage from the closed orbit bumps.

- **High-β^* Experiments**: TOTEM is ready for physics and ATLAS expects to be ready in summer 2011. About 4 fills were requested for physics. The 90 m optics is ready commissioning. The constraints and requirements in terms of precision represent a real challenge for LHC operation and the high-β^* goes in opposite direction with respect to the squeezed optics. Commissioning should start as soon as possible to be able to react in case of problems.

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