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BRINGING THE FIRST LHC BEAMS INTO COLLISION AT ALL 4 IPs

E. Bravin, CERN, Geneva, Switzerland

Abstract

Collision rate monitors are essential in bringing particle beams into collision and optimizing the performances of a collider. In the case of LHC the relative luminosity will be monitored by measuring the flux of small angle neutral particles produced in the collisions. The LHC rate monitors (BRAN) are being developed by Berkeley National Laboratory (USA) in the framework of the LARP collaboration and consist of a fast ionization chamber that will be installed on both sides of each IP and at about 140m from it. The monitors aim at measuring the relative luminosity of LHC bunch by bunch with a few percent resolution.

INTRODUCTION

The ultimate aim of LHC is producing collisions inside the four experimental detectors: ATLAS, CMS, ALICE and LHC-b. This will allow the further understanding of the nature of matter and of the forces holding it together.

Looking more in details there are differences in the way this should be done. ATLAS and CMS will profit from the highest collision rate possible while ALICE and LHC-b require the collision rate to be set and controlled at optimal levels. In the case of ALICE the radiation damage sustained by the sub-detectors in case of long terms p-p luminosities above 10^{30} cm^{-2}s^{-1} is dangerous. For LHC-b the upper limit is defined by the requirement of not having more that one p-p interaction during the same bunch crossing. This limits the “bunch” luminosity to 1.8×10^{29} cm^{-2}s^{-1} and thus the maximum luminosity to 5×10^{32} cm^{-2}s^{-1} for 2808 bunches.

LUMINOSITY

In order to express the collision rate in a univocal way the concept of “Luminosity” is normally used as collisions can be of many different kinds and shades.

Luminosity is defined as the ratio between the collision rate of any particular process and the respective cross section. Cross sections of known processes have been calculated, measured or estimated and are available.

$$L = \frac{\dot{N}_x}{\sigma_x} \tag{1}$$

Luminosity can also be expressed as a relation between the parameters of the colliding beams:

$$L = \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi\sqrt{(\sigma_{x1}^2+\sigma_{x2}^2)(\sigma_{y1}^2+\sigma_{y2}^2)}} \cdot \exp\left[-\frac{(\bar{x}_1-\bar{x}_2)^2}{2(\sigma_{x1}^2+\sigma_{x2}^2)} - \frac{(\bar{y}_1-\bar{y}_2)^2}{2(\sigma_{y1}^2+\sigma_{y2}^2)}\right] \tag{2}$$

Where: N_{bi} are the bunch populations, f_{rev} is the revolution frequency, k_b is the number of bunches per beam, σ_m are the transverse beam sizes and x_i and y_i are the transverse centre positions of the two beams.

The term on the left gives the maximum theoretical luminosity with the given beam parameters. The term on the right indicates the reduction of the luminosity due to the transverse offset between the two beams.

As explained before the luminosity of the machine at all four interaction points must be known with certain accuracy [1]. Eq. 2 could be used to calculate the luminosity if all parameters were known with the same accuracy. Unfortunately this is not the case, especially for the offset between the two beams. Assuming, equal, round beams, an offset of one beam size will reduce the luminosity by 20%. At nominal luminosity the incertitude on the beams position at the IP will be of several sigmas.

For this reason the luminosity must be monitored using a dedicated, robust and reliable device, independent of the incertitude on the beam parameters and optics.

COLLISION RATE MONITORS (“LUMINOSITY MONITORS”)

In the tuning of the machine the most important information will be the relative impact of the different trims on the luminosity. Devices that measure the rate of a particular group of events are sufficient for this task, even if the value of the “equivalent” cross section for these events is not known; these will in fact be constant and not influenced by the trims. These devices will of course not allow measuring directly the absolute value of the luminosity. It is however possible to periodically calibrate the readings of these monitors with the results of the experiments and thus obtain a sufficiently accurate absolute knowledge of the luminosity.

In the p-p collisions at LHC many particles will be generated, in particular there will be neutral particles like neutrons and photons arising from “soft” interactions. These particles will in general follow the trajectories of the protons they descend from. Tacking advantage of the geometry of the IPs it is possible to intercept these neutral particles at a location where the two proton beams have been sufficiently deviated by the bending magnets D1 and D2. At about 140 m from the IP the two proton beams are separated by about 160 mm. This leaves a space of about 100mm between the two vacuum chambers where a detector can be placed. The straight trajectory of the neutral particles coming from the IP will intercept the detector in the centre. In fact the flux of neutral particles is expected to be sufficient to damage the magnet D2 in IP1 and IP5 where the luminosity can reach 10^{34} $cm^{-2}s^{-1}$. For this reason an absorber made of copper of several meters of length, the TAN, is foreseen just in front of D2 [2][3]. This absorber is built in a way that a detector can be inserted at the location of the shower maximum of the neutral particles. A layout of the IP can be seen in Fig. 1.

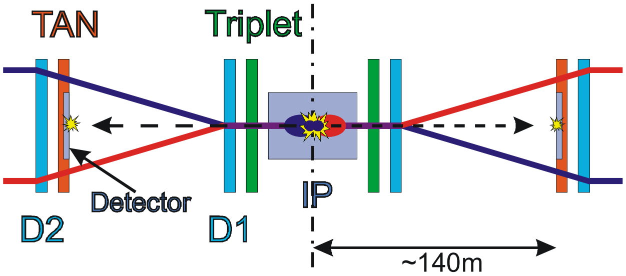

Figure 1: Typical layout of a high luminosity IP in LHC.

REQUIRED PERFORMANCES

Table 1 shows the luminosity values for the different machine conditions. In particular the values expected at the start up of LHC where two un-squeezed pilot bunches will be collided first.

Table 1: Different p-p luminosity scenarios

N_b	k_b	IP	L
Collision studies with single pilot bunch **(Initial condition)**			
5×10^9	1	IP1, IP5 β=18 m	2.5×10^{26}
		IP1, IP5 β=1.2 m	3.7×10^{27}
		IP2, IP8 β=10 m	4.4×10^{26}
Collision studies with single bunch			
2.75×10^{10}	1	IP1, IP5 β=1.2 m	1.1×10^{29}
1.15×10^{11}		IP1, IP5 β=0.55 m	4.3×10^{30}
		IP2 β=10 m	2.4×10^{29}
		IP8 β=35 m	6.7×10^{28}
Early p-p luminosity run			
2.75×10^{10}	43	IP1, IP5 β=1.2 m	4.8×10^{30}
1.15×10^{11}			8.4×10^{31}
4.0×10^{10}	2808		6.5×10^{32}
1.15×10^{11}	936		1.8×10^{33}
Nominal p-p luminosity run			
1.15×10^{11}	2808	IP1, IP5 β=1.2 m	1.0×10^{34}
		IP8 β=35 m	1.9×10^{32}
		IP2 β=10 m	3.0×10^{30}

Table 2: Requirements for the luminosity monitors

Luminosity $[cm^{-2}\ s^{-1}]$	**resolution**	**Integration time [s]**
$10^{26} \rightarrow 10^{28}$	±10% (beam)	~ 60
$10^{28} \rightarrow 10^{34}$	±1% (beam)	~ 1
$10^{33} \rightarrow 10^{34}$	±10% (bunch) (machine)	~ 10
	±1% (bunch) (experiment)	~ 100

The performances required for the luminosity monitors are presented in Table 2. The absolute accuracy of the measurement is not specified, it has already been mentioned that the main aim of these detectors is to monitor variations of the luminosity in a fast and reliable way [1].

Table 3: Estimated integration times

Luminosity $[cm^{-2}\ s^{-1}]$	**Rate of p-p events $[s^{-1}]$**	**Int. time [s]** (10% error)	**Int. time [s]** (1% error)
1.0×10^{26}	8.0	50	5.0×10^{3}
1.0×10^{28}	800	0.5	50
1.0×10^{30}	8.0×10^{4}	5.0×10^{-3}	0.5
1.0×10^{32}	8.0×10^{6}	5.0×10^{-5}	5.0×10^{-3}
1.0×10^{34}	8.0×10^{8}	5.0×10^{-7}	5.0×10^{-5}

Table 3 indicates the expected integration times for different luminosity levels and different resolutions (1% and 10%). These values are calculated solely from the statistical point of view, not considering the effects of an eventual background field.

THE MONITORS

There are two different types of detectors being developed for the luminosity monitors of LHC. On one side LBNL is committed to deploy four fast ionization chambers (IC) in the TANs around IP1 and IP5 in the framework of the US-LARP collaboration [4]. On the other side CERN is aiming to install solid state Cadmium Telluride (CdTe) detectors [5][6] developed by CSA-LETI [7] in the remaining two points. The reasons for the two different types arise from the two main challenges for the detectors. The most difficult requirement is to stand the high radiation dose, of the order of ~1 GGy for IP1 and IP5 [2], a bit lower for IP2 and IP8. The second complexity arises from the requirement of performing bunch by bunch measurements, or in other words to have a measurement speed higher that 40 MHz. The two technologies are each good with one of these requirements. The IC is sufficiently radiation hard, but will have difficulties meeting the 40 MHz requirement. The CdTe can easily comply with the 40 MHz requirement, but can only stand the lesser dose foreseen at IP2 and IP8.

History of the project

Back in 1997 W. Turner of Berkeley proposed to install an IC in the TANs for measuring the average luminosity. A year later he modified the proposal for a fast IC in order to achieve the bunch-by-bunch measurement. In 1999 CERN (SL/BI) endorsed the project and in the following years a prototype was built and tested on the SPS. The limitations in terms of speed became evident and as a consequence CERN started to consider the CdTe technology it had previously used in the Synchrotron light monitors of LEP as an alternative. A collaboration was established with LETI to develop further the technology and validate it.

THE IONIZATION CHAMBER

The detector developed by LBNL consists of a pressurized ionization chamber depicted in Fig. 2 whose parameters are summarized in Table 4. The gas mixture is Ar + 6%N_2 at 6 bar. It is composed of 4 square quadrants in order to measure the centre of gravity of the impinging neutral flux in the transverse plane (*x-y*), this will allow the calculation of the crossing angle at the IP. Each quadrant has 6 gaps connected in parallel with a gap width of 1mm [4].

Fig. 2 shows a 3D model of the detector. In the picture the lower grey part represents the chamber itself while the upper brown part is a copper support/shielding. In fact the detector mimes one of the copper bars used as central absorbers in the TANs. It is foreseen to replace each third bar in the TAN with a detector.

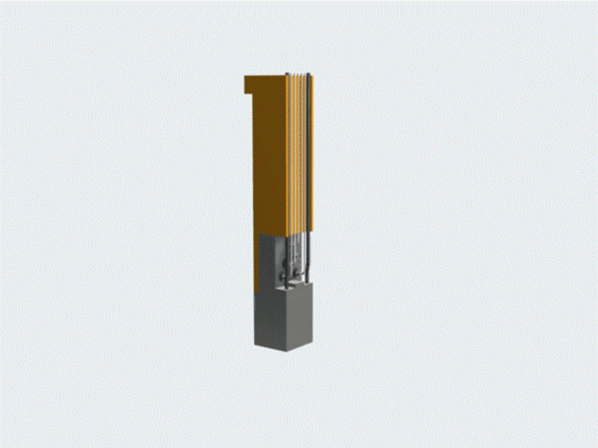

Figure 2: 3D model of the Ionization chamber.

Table 4: Parameters of the Ionization Chamber

Quadrant area	1600 mm^2
Gap between electrodes	1 mm
No. of gaps in parallel	6
Gas mixture	Ar + 6%N_2
Gas pressure	6 bar (abs)
Ioniz. Pairs / MIP mm	58
E / P	200 V/mm bar
Gap voltage	1200
e^- drift velocity	45 mm/µs
Amplifier gain	0.16 µV/e^-
Noise (RMS)	1.24 mV

Status of the detector

A prototype of the chamber exists and has been tested on different beam lines. The final design of the detector that will include all the modifications suggested by the various tests will be ready soon. The production of the four chambers will start soon after and the first detector will be delivered by end 2006. The remaining 3 detectors will only be delivered by mid 2007, mainly due to the profile of budget allocations.

The front-end electronics consists of a very low noise preamplifier followed by a rather complicated shaper. The first component has been initially developed by the University of Pavia (Italy) and is now being refined in Berkeley. The second is entirely developed at LBNL. Both components are keystone to this project as their performances will determine the ultimate speed of the detectors. The designs are well advanced and on track.

Test performed on an X-ray test beam at ALS indicate that the 40 MHz feature is right at the edge of what the system can do. The rest of the acquisition system is based on the DAB-IV card developed by TRIUMF and CERN for the BPM project [8] and the integrators mezzanine developed for the fast beam transformers [9]. The programming of on-board FPGA of the DAB-IV has not started yet and is on the critical path. The gas distribution system required to flow the chamber has still to be designed and installed. LBNL is seeking help from CERN (TS+PH) on this matter. Contacts have already been established and the task is advancing although slowly still. For the time being this is in the hands of AB-BI.

THE CdTe DETECTOR

The Cadmium Telluride detector is the result of two years of collaboration between CERN and LETI. By mid 2003 the prototype detector shown in Fig. 3 was ready. In order to validate the technology sample CdTe disks were irradiated in nuclear reactors up to equivalent doses of 10^{17} n/cm^2 [5][6]. This showed that the maximum dose they could stand was ~10^{16} n/cm^2, which is enough for IP2 and IP8 but not for IP1 and IP5. The detectors consists of an aluminium housing of about 10cm width containing 10 polycrystalline CdTe disk of 17 mm diameter and 300 µm thickness. The CdTe disks are polarized to 300 V, when an ionizing particle traverses it e^-/holes pairs are created and drifted to the collection electrodes. The signal is then fed to a linear preamplifier that does not require special development as the S/N ratio is not as vital here as for the IC. Finally the signal can be treated by the same acquisition system developed for the IC (DAB-IV etc.).

Figure 3: Picture of the CdTe prototype.

This detector is very simple both from the mechanical point of view and also from the electronics point of view. This is one of the key points that lead to the decision of adopting this technology.

Status of the CdTe detector

The design of the detector has been ready since 2003. Financial problems and the initial proposal of having the same detectors in all 4 IPs (then discarded as non necessary) caused the temporary freezing of this development. In the mean time LETI has improved further the technology and the required founds have been obtained at CERN. Seen also the question marks left on the IC performances, at the end of 2005 AB-BI decided to diversify and revise this option. A purchase contract is being placed with LETI for the delivery of 4 detectors, this will have to go trough the upcoming finance committee of March. After the signature of the contract LETI will take 12 months to deliver. The four detectors will thus be available at the beginning of 2007. The preamplifier will have to be procured or manufactured, although this is not expected to be a lengthy or complicated task it is however undermanned at the moment and actions need to be taken soon. As mentioned the remaining part of the acquisition system will be a copy of the system developed by LBNL for the IC.

THE QUEST FOR A PLACE IN THE TAN

It has already been mentioned that the initial plan was to install the IC as replacement of the 3rd copper bar of the TANs; at least this was the plan up to 2003.

In the last 3 years several other detectors have been proposed inside the TANs replacing more copper bars. In fact at the moment there is no more space left for Cu bars in the TANs as all space has been reserved for experimental detectors.

These detectors are: ATLAS-ZDC (Zero degree Calorimeter) + LHC-f (forward physics studies) at IP1 and CMS-ZDC at IP5. Not all detectors are in a design state suited for integration. Interferences with the operation of the luminosity monitors are expected, especially with LHC-f and this requires some coordination.

COLLIDING BEAMS “The final approach”

Once the machine will have been commissioned and the two beams will be smoothly circulating around the two rings the moment will come to bring them into collision.

In principle the beam position monitors could be used to overlap beam 1 on beam 2. In fact the resolution of these devices will leave an uncertainty of about 200 μm on their transverse overlap. This is equivalent to 13 beam sizes (σ) separation at β= 0.5 m (squeezed optics) and 2 σ separation at β= 18 m (un-squeezed optics). First collisions will be carried out with very little beam current, probably only one pilot bunch per beam. This means that the p-p event rate will be very low. At this point the only way to overlap the two beams will be scanning one beam against the other while monitoring the collision rate. The four experiments could deliver signals proportional to the collision rate, but their reliability, resolution and above all measurement speed will probably not be sufficient at this point. This is the reason why the machine luminosity detectors have been included from the beginning in the LHC design.

Background effects

At very low luminosity the probability of having a p-p interaction in one bunch crossing is very small. In this condition the integration of the analogue signal generated in the detector could be heavily influenced by noise sources. A better approach is to count the rate of events that generate signals above a certain threshold. In this case only background events that generate high signals need to be considered such that beam losses or beam gas interactions. Table 5 reports the estimations for the rate of events used to measure the collision rate as well as the background events that could perturb the measurement. In the same table the scaling factor for these sources is given. In the calculation of the values a residual gas pressure of 10^{-10} torr has been assumed as well as a cleaning efficiency of 1:6500.

As can be seen the major difference between the wanted and the unwanted events is that while the firsts depend quadratically on the bunch charge the seconds only depend linearly, moreover the background is virtually independent from the squeeze. This means that at very low luminosity the effect of background sources is much more important, even more if the luminosity is reduced acting on the geometry of the collision (beam sizes and separation). Detecting coincident events on both sides of the IP could improve the measurement if the cross section for such events is sufficiently big. This option is currently being investigated.

Table 5: Rates for the different types of events

Process	**Scaling**	**Rate [s^{-1}]** $L= 10^{34}$	**Rate [s^{-1}]** $L=2.5\times 10^{26}$
p-p inelastic collisions	I_b^2, N_b, β, L	8.0×10^8	16
Beam-gas collisions	I_b, N_b	3.5×10^4	0.6
Beam -Halo scraping	I_b, N_b	8.0×10^4	1.3

CONCLUSIONS

Measuring the collision rates at the four IPs will be fundamental for the LHC setting up and operation. For this reliable and fast monitors capable of measuring small variations in luminosity are needed. Two different technologies are being used: a fast ionization chamber developed by LBNL for IP1 and IP5 and solid state CdTe detectors developed by CERN and LETI for IP2 and IP8. Currently the limitations of resources on both sides of the Atlantic have delayed the project to the point that there is no more slack left.

The TAN absorbers where the IC should be installed, once a lonely and awkward place, are becoming more and more crowded with different detectors. This requires an accurate orchestration for the installations and also for avoiding or at least reducing the interferences during their operation.

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