EXPERIENCE AT CERN WITH LUMINOSITY MONITORING AND CALIBRATION, ISR, SPS PROTON ANTIPROTON COLLIDER, LEP, AND COMMENTS FOR LHC…

WERNER HERR, RÜDIGER SCHMIDT, CERN, Geneva, Switzerland

Abstract

There is a long history of luminosity calibration at CERN. Already at the ISR, operating during 1968–1983, luminosity calibrations were performed. Beams were crossing at a large angle, to calibrate the luminosity a scan in only one plane (vertical) measuring the beam height overlap was required. Such "Van der Meer" scans were performed by beam displacements with magnets. In the SPS Proton Antiproton collider, operating during 1984-1991, Van der Meer scans were performed by beam displacement with electrostatic separators in both planes. For LEP, operating from 1989-2001, scans were performed in both planes by beam displacement with electrostatic separators, not to precisely measure the luminosity, but to optimise luminosity. From the experience with Van der Meer scans at these very different accelerators some lessons were learned that might be considered when discussing luminosity calibration at the LHC.

PARAMETERS AND LUMINOSITY CALIBRATION AT THE ISR

The ISR was a 2-ring proton-proton collider, but also proton antiproton beams were brought into collision. The beam energy of the ISR was up to 31 GeV. Beams were circulating in two separate vacuum chambers with different orbits for the two beams. The ISR operated with coasting beams (no bunches). The collisions between the beams were at large angle in horizontal plane and the maximum beam current was up to 40 Amperes. Van der Meer scans were performed with reduced beam current of a few Amperes. The transverse beam size at the ISR was very large, in the order of cm. The beams were separated with magnets.

The luminosity calibration was performed for both, proton-proton and proton-antiproton collisions. At the interaction point a wire scanner was installed to measure the beam profile.

The proposal for calibration of the beam height in ISR came from S. van der Meer [1]. The main challenge was the calibration of the beam displacement during the scan. In his paper S. van der Meer wrote: *Of course, this method suffers from all the disadvantages connected with beam displacements outlined in [2]. On the other hand, it might be suitable for somewhat less precise measurements in cases where the experiments requires that the interaction region remains without the obstructions inherent to the wire method.* It seems that S. van der Meer did not expect that his method would turn out to be the most accurate method for calibrating the luminosity of hadron colliders.

The largest challenge was the calibration of the beam displacement at the collision point [3] when the magnet currents were changed. A measurement of the beam displacement was later performed using beam scrapers installed at the collision point. There was a large effort to understand systematic errors.

The results that were finally reported for the total luminosity had an error of 0.7% for proton-proton collisions and 1.1% for proton-antiproton collisions [4], different techniques were used to obtain these results.

PARAMETERS AND LUMINOSITY CALIBRATION AT THE SPS

The SPS was build as a proton synchrotron and later transformed into a proton-antiproton collider with a beam energy of up to 315 GeV. The beams were bunched. The SPS had one beam pipe and both beams had the same orbit when operating with a few bunches colliding head-on. In order to increase the luminosity, electrostatic separators were installed to separate the beams, that allowed to increase the number of bunches. The beam current was less than 0. 1 A. Luminosity calibrations were performed with a special optics (high beta optics, with beta = 2500 m).

The luminosity at the SPS was calibrated with different methods, using the optical theorem, direct coulomb scattering and Van der Meer scans [5][6].

A generalisation of the Van der Meer scan for luminosity calibration in the case of bunched beams was proposed for the SPS in 1977 [7]. Taking into account the difference between ISR (coasting beams, scan in only one plane, and SPS (bunched beams, scans in both planes) the calibrations in the SPS were more challenging.

The technique using Van der Meer scans is not the only method to calibrate the luminosity. Another method for luminosity determination is from beam profile measurements. The horizontal and vertical beam profiles of both beams are measured with a scraper or a wire scanner. With the knowledge of the beta function, the beam size at the collision points can be calculated. The estimated accuracy is about 5–10%.

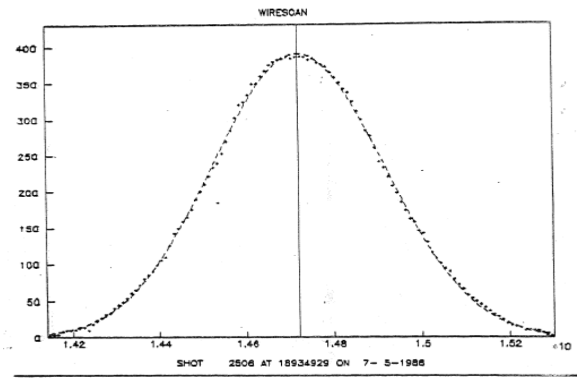

Fig. 1: Profile measured with the linear wire scanner at the SPS proton antiproton collider

In general, Gaussian beams are assumed. This was shown to be very accurate [8] – the r.m.s. beam size is an excellent assumption for any realistic beam distribution. For precise measurement of the beam profile at the SPS with an error better than 0.5% a linear wire scanner was developed. The result of such a scan is shown in Fig.1. The same type of (linear) wire scanner is also used in LHC. It should also be possible to use these instruments for luminosity calibration at LHC.

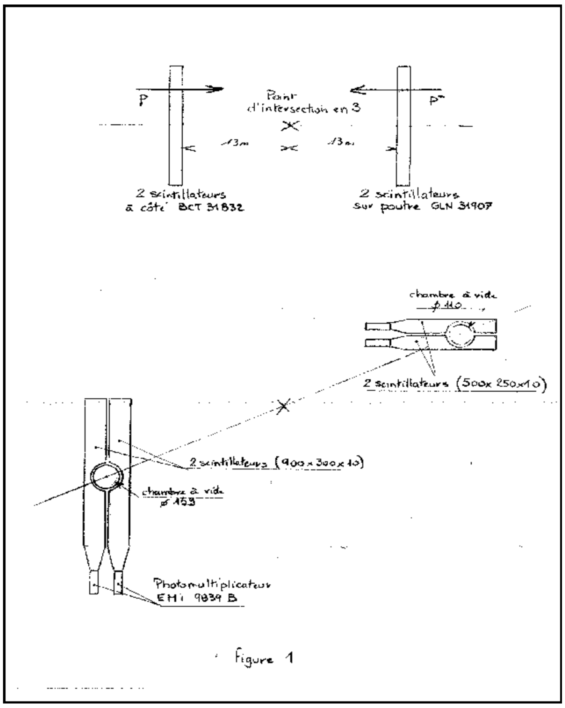

Fig. 2: Schematic drawing of a "poor mans" monitor to measure the overlap integral at the SPS

Fig.2 shows that Van der Meer Scans can be performed with very simple instrumentation. In order to measure the overlap integral of both beam at a collision point without experiments, two sets of scintillation counters were installed and the beams were displaced with electrostatic separators (see fig. 2). The beams were displaced with electrostatic separators, and the counting rate in the monitors was recorded. The results of such a scan in the SPS are shown in fig. 3.

PARAMETERS AND LUMINOSITY CALIBRATION AT LEP

To calibrate the luminosity for an electron positron collider other methods than Van der Meer scans are more accurate, essentially Bhabha scattering. Van der Meer scan for e+e- luminosity calibration do not work correctly due to strong beam-beam effects (much stronger than for hadron colliders). Because of the small cross section the counting rate is very low and the statistical error much larger than for scans at hadron colliders.

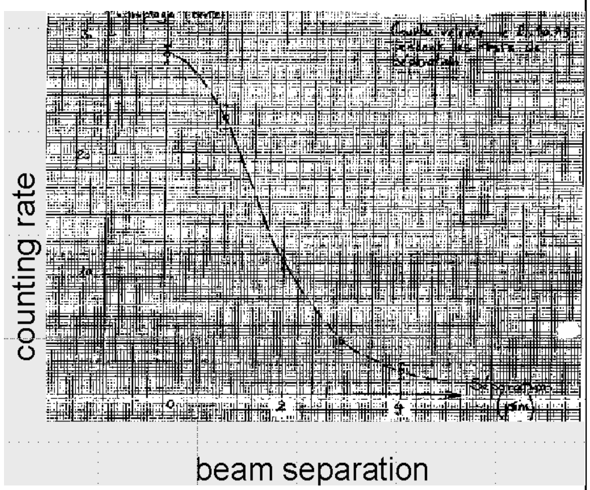

Fig. 3: Result from a Van der Meer scan in the SPS proton antiproton collider, measured with the instruments shown in fig.2.

Both, the beta function and orbit changes during the scan (dynamic beta). The beam sizes are dominated by the balance between damping and quantum excitation due to synchrotron light emission PLUS excitation of resonances driven by the beam-beam effect. The beam size and emittance changes, in general the beam is blown up during a scan. This is very different from beam dynamics at hadron colliders.

Still, at LEP scans were done frequently to optimise the luminosity. This can be done by measuring the counting rate as a function of separation, but for LEP operating at 100 GeV with very low cross-section this method is very lengthy. An alternative is to measure the beam-beam deflection during the scan [9].

At LEP, a large effort went into the precision measurement of the beam energy. The techniques to calibrate the energy are very different from luminosity calibrations, but from the way to approach precision measurement lessons for the LHC can be derived. On of the lessons is the need for close collaboration between machine and experiments during many years.

IDEAS FOR LUMINOSITY CALIBRATION AT LHC

There are several options for luminosity calibration. The most accurate method is expected to come from the TOTEM and ALFA experiments but need a specific optics with high beta function at the collision points. The calibration based on Van der Meer scans can be performed during normal luminosity operation and it is expected to achieve results with an error of about 5 %. Other methods that use the knowledge of beam parameters rely on measuring the beam sizes at the interaction point. This can be done using direct measurement by LHC experiments using proton-proton collisions (measuring the overlap integral) and collisions with gas molecules (measuring single beam profiles).

Indirect measurement of the beam size at the IP use precise wire scan data and calculating the beam size at the IP with the knowledge of the beta function (the SPS micro wire scanner was invented for very precise measurements of the beam size).

Beta function measurements are performed by exciting beam oscillations with an AC dipole and measuring the beam response. Today, the beta function measurement can be performed with an error of about 5%, in the future it might be possible to reduce the error to about 1% for dedicated studies, but this needs to be demonstrated [10]. This would result in a beam size error of 0.5%.

It is always required to precisely measure the bunch current. Bunch current measurements are not obvious and precise calibration is needed. For utmost precision, an independent measurement of the bunch current is recommended.

When performing Van der Meer scans, the beams are displaced by magnets. The displacement needs to be calibrated, by measuring . The displacement can also be derived from the knowledge from the machine optics and magnetic fields. Both methods should be used and the results should be compared.

Orbit effects when beams are separated need to be considered. This depends on the beam-beam parameter, on the number of bunches and on the number of long range interactions.

Very important are simulations – programs exist and should be used to simulate the entire measurement process with MAD and other programs (to understand possible errors of the measurements and to understand detail of the LHC machine).

Calibration of the luminosity with different methods is recommended since the total cross section is an absolute value to be measured. For the most precise scans it is proposed to operate the LHC in a simple configuration:

- Avoid too many bunches
- Avoid parasitic crossing
- No crossing angle

The luminosity calibration is a precision experiment – the more precise the more difficult. If ultimate accuracy is required this is a long term effort, possibly requiring new ideas, in particular for monitoring of the beam parameters. Precise calibration will take machine time and will have an adverse effect on the integrated luminosity.

It is proposed to use different calibration principles, in order to get confidence in the results and to better understand systematic error (of possibly unknown nature).

The question to the physics community: Is if the physics motivation strong enough to justify such effort and is a (moderate) loss in integrated luminosity acceptable?

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