THE TOTEM EXPERIMENT AT LHC

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Abstract: The TOTEM experiment will measure the total cross section, elastic scattering and diffraction dissociation at the LHC. The aim is to obtain accurate information on the basic properties of proton-proton collisions at the maximum accelerator energy detecting particles emitted in the very forward region.

1.Introduction

The TOTEM Collaboration [1] aims at the following experimental programme [2] :

1) The **total cross section** with absolute error of about 1 mb.

2) Elastic scattering from ($-t \sim 5 * 10^{-4}$GeV^2) up to at least $-t \sim 10$ GeV^2.

3) Diffraction dissociation : $p + p \rightarrow p + X$

The experimental set-up consists of (fig.1):

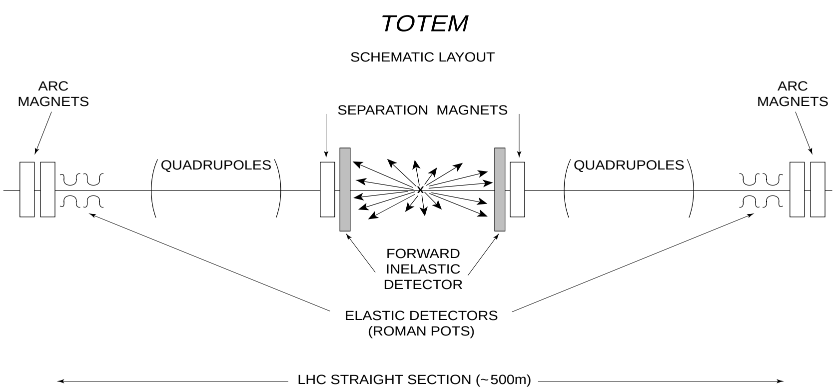

Figure 1: Sketch of the experimental apparatus of TOTEM

1) *Elastic scattering detectors* of small size and high spatial resolution, placed symmetrically on both sides of the crossing region. They will also be used to detect the proton which is scattered quasi-elastically in diffraction dissociation.

2) *A forward inelastic detector* for the measurement of the inelastic rate including events of diffractive type with full azimuthal acceptance. An electromagnetic calorimeter near the forward direction will complement the “inelastic detector”.

2. Total Cross Section and Real Part of the Amplitude

A much debated question is whether σ_{tot} increases as $\log s$ or $(\log s)^2$. The solid line in Fig.2 represents the result of a recent dispersion relation fit[3] which is based on measurements of σ_{tot} and of the parameter ρ (ratio of the real to the imaginary part of the forward amplitude) in the c.m.s. energy interval 5$\leq \sqrt{s} \leq$546 GeV. The high-energy dependence of the total cross section was described by the term $(\log s/s_0)^\gamma$ with $s_0 = 1$ GeV^2. The best fit gives $\gamma = 2.2 \pm 0.3$. This analysis seems to favour a $(\log s)^2$ dependence ("Froissart-Martin" bound [4]) with respect to the linear rise as $\log s$.

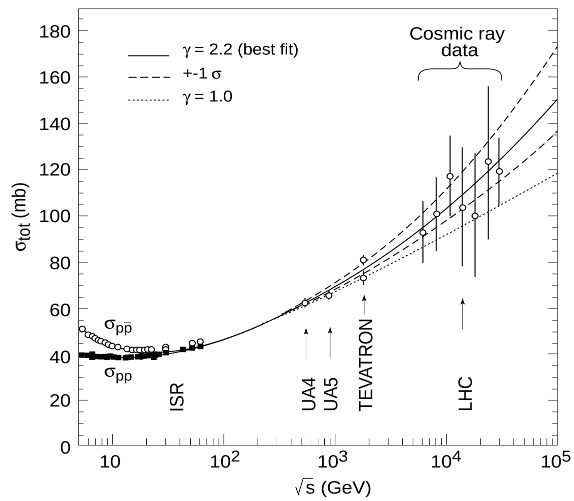

Figure 2: The total cross section for $\bar{p}p$ and pp scattering is shown together with the prediction of the dispersion relations fit of ref.[5].

At $\sqrt{s} = 14$ TeV the fit predicts $\sigma_{tot} = 109 \pm 8$ mb while extrapolating as $\log s$ one would obtain $\sigma_{tot} \simeq 95$ mb. The measurement of TOTEM will have accuracy of about 1 mb, clearly sufficient to discriminate between the two possibilities.

In practice the analysis of the data on σ_{tot} and ρ is performed with the standard dispersion relations. The correlation between σ_{tot} and ρ has been exploited to predict the behaviour of the total cross section at energies higher than those at which the measurements were actually performed.

An unconventional and exciting possibility was discussed recently by Khuri [5]. The presence of a fundamental length R would imply a breakdown of Quantum Field Theory and as a consequence also of the dispersion relations. At present from QED and the results on the muon magnetic moment one may set a limit and rule out the existence of a fundamental length R such that R^{-1} >1 TeV. The model calculation of ref.[18] shows that, if $R^{-1} \simeq 10 - 15$ TeV, the actual value of ρ at the LHC might differ substantially from that calculated with the standard dispersion relations.

The measurement of the real part of the amplitude near the forward direction requires to reach values of the the momentum transfer t_0 where the Coulomb and the strong interaction amplitudes are equal in magnitude, $|t_0| \simeq 8\pi\alpha/\sigma_{tot}$, At the LHC one expects $|t_0| \simeq 7 * 10^{-4}$ GeV^2 corresponding to an angle of only 4 μrad. To find a way to detect events at such small scattering angles is a very serious challenge.

3. Elastic Scattering and Diffraction Dissociation

The Tevatron data confirm the trend already observed at the SPS Collider that the ratio σ_{el}/σ_{tot} increases with energy. This implies that the effective "opacity" of the two colliding particles increases with energy, and puts important constraints on the models of high-energy scattering.

The measurement of σ_{el}/σ_{tot} can be made with quite high precision because it essentially corresponds to a ratio of counting rates and therefore some systematic errors disappear. TOTEM plans to measure this ratio at the 1% level.

Near the forward direction ($|t| < 0.1$ GeV^2) the differential cross section is well described by the simple exponential $e^{-B|t|}$. On the other hand the overall forward peak for $|t| < 0.5$ GeV^2 in general does not show the simple exponential shape $e^{-B|t|}$. In the energy range of the ISR[6] and SPS Collider[7] the shape is concave. At the Tevatron the curvature seems to have disappeared and the shape of the t-distribution can be described by a single exponential[8].

The LHC will accumulate high statistics in a short running time and therefore small structures of the forward peak should be observed experimentally.

Of great interest is the large momentum transfer region where at present energies a diffraction-like structure is observed which is followed by a smooth behaviour. The pp and $\bar{p}p$ data differ considerably in the region of the structure because pp scattering shows a pronounced dip[9] while $\bar{p}p$ shows no dip but only a shoulder [10, 11]

The large design luminosity of the LHC allows elastic scattering to be measured up to large values of the momentum transfer, i.e. in the range 10 - 15 GeV^2. The question of whether pp scattering at very large energy and large momentum transfer has a smooth behaviour or a diffraction-like structure will be resolved experimentally.

The process of *diffraction dissociation* is closely related to elastic scattering. To be diffractively produced, the system X, with mass M, must have the same intrinsic quantum numbers as the incoming proton while spin and parity may be different because some orbital angular momentum can be transferred to X in the collision. In a high-energy collision if p_0 is the beam momentum and p the momentum of the final state proton, the mass M is given by $M^2 = (1-x)\,s$ where $x = p/p_0$. High-energy data provide clear evidence for diffractive production up to $M^2/s \sim 0.05$.

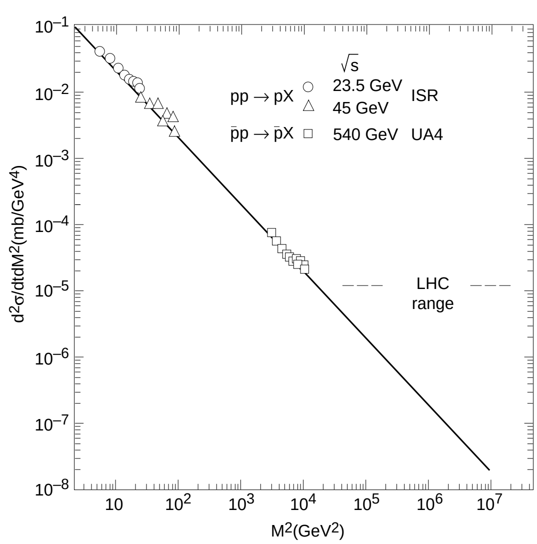

Figure 3: The observed mass spectrum of the diffractively excited system.

An important feature about diffraction dissociation to be investigated is the mass dependence of the double differential cross section $\frac{d^2\sigma}{dtdM^2}$. The data from the ISR[12] and the SPS Collider[13], shown in Fig.3 for -t = 0.5 GeV^2, indicate that the mass spectrum has a $1/M^2$ behaviour in agreement with the classical prediction of triple Pomeron exchange.

At LHC when $M^2 \sim 0.05\ s$, the mass M is as large as 3 TeV.

We are also planning to measure the production of π^0 in the near forward direction. This allows studying *scaling in the fragmentation region* at rapidities very close to the beam rapidity and it is of special interest in connection with the interpretation of very high-energy cosmic ray interactions.

4. Measurement of Elastic Scattering

The measurement of elastic scattering at the LHC requires observation of particles at angles which are a small fraction of a *mrad*. This is achieved by placing the detectors into special units mounted on the vacuum chamber of the accelerator, known as "Roman pots" and first used at the CERN ISR. Once the final energy is attained and the circulating beams are stable, the "Roman pot" is moved toward the machine axis until the inner edge of the detector reaches a distance of the order of one *millimeter* from the beam.

The momentum transfer resolution is given by $\Delta t = 2p\sqrt{|t|}\Delta\vartheta$ where $\Delta\vartheta$ is the error on the scattering angle.

The displacement y at the detector as a function of the displacement $y^\star$ at the crossing point and of the scattering angle ϑ is

$$y = \sqrt{\beta_d/\beta^\star}(\cos\Delta\psi + \alpha^\star \sin\Delta\psi)y^\star + (\sqrt{\beta^\star\beta_d}\sin\Delta\psi)\vartheta \tag{1}$$

where $\beta^\star$ and β_d are the values of the betatron function (in the vertical plane) at the crossing point and at the detector respectively. The beam size σ_y and the beam angular divergence σ_ϑ are written in terms of the emittance ϵ (defined at the one r.m.s. value) as $\sigma_y = \sqrt{\epsilon\beta}$ and $\sigma_\vartheta = \sqrt{\epsilon/\beta}$. The quantity $\sqrt{\beta^\star\beta_d}\sin\Delta\psi$ represents the effective distance L_{eff} of the elastic detectors from the crossing point.

The best configuration for elastic scattering is achieved when the elastic detectors are placed at the position where the phase advance is $\Delta\psi = \pi/2$, $y = L_{eff}\theta$, $L_{eff} = \sqrt{\beta^*\beta_d}$. The minimum distance of approach of the inner edge of the detectors to the beam axis, y_d, is proportional to the r.m.s. value of the beam size at the detector position σ_y. We may write

$$y_d = K\sigma_y = K\sqrt{\epsilon\beta_d} \tag{2}$$

At the SPS Collider it was empirically found by the experiment UA4 that the parameter K had numerical values between 15 and 20, depending on the machine conditions.

For the protons which hit the detector just on its inner edge, the scattering angle and the corresponding momentum transfer will be

$$\vartheta_d = \frac{K\sqrt{\epsilon}}{\sqrt{\beta^*}} \quad , \quad |t_d| = K^2p^2\frac{\epsilon}{\beta^*} \tag{3}$$

The parameter K may be controlled by the system of collimators which will protect the detectors from being hit by particles of the beam halo. For the design of the present experiment it appears safe to assume $K = 15$. Using $\epsilon = 5 * 10^{-10}$ m at the nominal beam momentum, $p = 7$ TeV, we have :

1) *Extrapolation of the elastic rate to the optical point for the measurement of* σ_{tot}.

For $|t_{min}| \simeq 10^{-2}$ GeV^2, $\beta^* \simeq$ *1100 m.*

2) *Measurement of Coulomb scattering.*

For $|t_{min}| \simeq 5 * 10^{-4}$ GeV^2, $\beta^* \simeq$ *20000 m .*

An additional requirement comes from the fact that the actual distance y_d of the inner edge of the detectors from the machine axis should not be too small, in order to avoid problems from possible beam instabilities. If we assume a minimum acceptable value for y_d of 1.5 mm :

$$L_{eff}\,\vartheta_d \geq y_d(min) = 1.5\ mm \tag{4}$$

For the two options mentioned above it gives **1)** $L_{eff} \geq 150$ m and **2)** $L_{eff} \geq 650$ m.

For a given value of β^*, already fixed by the requirement of minimum t, eq.(4) can be translated into the following condition on the value of the β-function at the detectors

$$\beta_d \geq 20m$$

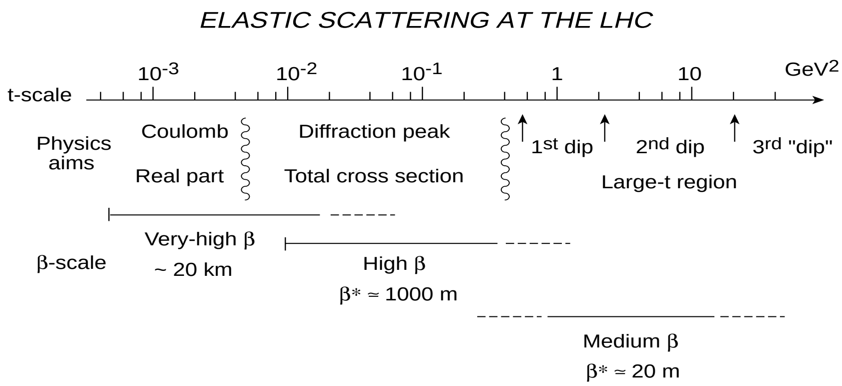

Figure 4: The proposed scheme for a complete study of elastic scattering at LHC.

The insertion for TOTEM should be designed with a tunable β^* to allow measurement of elastic scattering also in the large momentum transfer region [14]. A possible scheme is presented in Fig.4.

Running at L $\sim 10^{28}$ cm^{-2} s^{-1} would yield $\sim 10^7$ elastic events per day assuming $\sigma_{tot} = 110$ mb (28% elastic) and an overall running efficiency of $\sim$ 50%.

5. Measurement of the Total Cross Section

The total cross section is measured by the "luminosity independent method" based on the simultaneous detection of elastic scattering at low t and of the number of the inelastic interactions :

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{N_{el}+N_{inel}}$$

The elastic scattering t-distribution dN_{el}/dt is measured at small t using the "Roman pot" system and extrapolated to $t = 0$, i.e. to the so called "optical point", assuming the simple exponential dependence $e^{-B|t|}$ which is known to describe the data adequately in the very small t region.

At LHC we expect $B \approx 20\ GeV^{-2}$. In order to measure the total cross section, one has to extrapolate the elastic scattering distribution dN_{el}/dt to the optical point. If we want to extrapolate by not more than 20%, the minimum value of t should be $|\ t_{min}\ | \approx 10^{-2} GeV^2$.

The contribution to the final error on σ_{tot} coming from the uncertainty Δp on the absolute value of the beam momentum is $\frac{\Delta\sigma_{tot}}{\sigma_{tot}} = 2\frac{\Delta p}{p}$.

The total number of inelastic events N_{inel} will be measured by the *forward inelastic detector* which has to fulfill two basic requirements.

- A "fully inclusive" trigger, sometimes called "minimum bias trigger".
- Identification of beam-beam events against background.

At present collider energies, a sizeable fraction of the inelastic events (about 15 %) are of diffractive type, where the recoil proton, scattered at very small angles, remains inside the vacuum pipe while a few particles are emitted in the opposite hemisphere in the angular region known as fragmentation region. Events of this kind will be observed with a "single arm" trigger using the *inelastic detector* which provides the reconstruction of the interaction vertex from the observed charged tracks. In order to reduce the background, the recoil proton can be detected in coincidence by means of the "Roman pots" in the opposite hemisphere.

The angular coverage which is needed for a fully inclusive trigger can be estimated on the basis of previous experience at the SPS collider and at the Tevatron and are presented in Table 2.

	$\sqrt{s}(TeV)$	y_{beam}	η_{min}	η_{max}	$\Delta\eta$	$y_{beam}-\eta_{max}$	ΔN_{inel}
UA4	0.55	6.4	2.5	5.6	3.1	0.8	$1.0 \pm 0.3\%$
E710	1.8	7.6	5.2	6.5	1.3	1.1	$3.2 \pm 1.6\%$
CDF	1.8	7.6	3.2	6.7	3.5	0.9	$1.3 \pm 0.4\%$

Table 2. The pseudorapidity coverage of the inclusive trigger is listed for previous experiments together with their own estimates of the loss of inelastic events.

A Monte Carlo simulation of the efficiency of the trigger was performed using the standard program PYTHIA[15]. The results of the simulation for the efficiency of the inclusive trigger used in previous experiments (UA4, E710 and CDF) are presented in Table 3. They agree qualitatively with the estimates made by the experiments themselves, which were shown in Table 2. These results show that in order to keep the loss of inelastic events to the level of 1%, the coverage has to be of at least 3 pseudorapidity units close to the beam rapidity.

	$\sqrt{s}(TeV)$	$\sigma_{SD}/\sigma_{inel}$	Eff_{NSD}	Eff_{SD}	$\mathrm{Eff}_{overall}$	ΔN_{inel}
UA4	0.55	0.18	0.999	0.900	0.981	1.9 %
E710	1.8	0.16	0.975	0.729	0.936	6.4 %
CDF	1.8	0.16	0.999	0.926	0.987	1.3 %

Table 3. Results of the simulation for the loss of inelastic events, ΔN_{inel} in previous experiments. Partial and overall efficiencies for single diffraction and non single diffraction events are given.

6. Measurement of Diffraction Dissociation

The detectors needed to measure the total cross section and elastic scattering will be used also to measure the basic properties of the single diffraction dissociation. The proton scattered quasi-elastically which recoils against the system X will be detected by the telescope of Roman pots of one arm in coincidence with the inelastic detector of the opposite hemisphere.

The overall sequence of magnetic elements between the crossing point and the Roman pot telescope represents in fact a *powerful magnetic spectrometer* that will select protons with momentum close to the beam momentum, i.e. those which are scattered quasi-elastically in single diffraction dissociation.

7. Technical Aspects

A complete study of a high-β insertion with $\beta^* = 1100$ m (the same in the horizontal and vertical plane) has been made recently [17],[18]. The effective distances are $L^V_{eff} = 150$ m and $L^H_{eff} = 150$ m.

With $y_d = 1.5$ mm, from eq.(3,4) the minimum reachable momentum transfer is $|t_{min}| = 10^{-2}$ GeV^2 (angle of 14 μrad), good enough for the measurement of σ_{tot}.

The main technical problem is the need for having the detectors efficient even very close to the physical edge of the detector itself. At present we are considering the following options :

- Silicon detectors with (x,y) strips or (x,y,u) strips.
- Silicon detectors with combination of pads and strips.
- Hodoscopes of scintillating fibers of the UA4/2 type[16].

Of crucial importance for a Roman pot experiment is the control of the absolute geometrical alignment of facing detectors (up-down). The final systematic error depends on that measurement and on the uncertainty on the beam momentum. We need an absolute uncertainty less than $10\mu m$.

The *forward inelastic detector* has to obey the following requirements:

- Fully inclusive trigger also for single diffractive events with expected loss on N_{inel} at the 1% level
- Capability of reconstruction of the collision vertex in order to disentangle beam-beam events from background.

We choose the pseudorapidity coverage from η_{min}= 5 up to η_{max} = 8.5 which corresponds to the range of polar angles from about 0.5 mrad up to 13 mrad. For this angular range, the Monte Carlo simulation indicates that the loss of inelastic events is at the 1% level. The simulation also shows that the average number of charged tracks per event in this angular range is about 15 on each side. For L = $10^{28} cm^{-2} s^{-1}$, we expect on the average about 10^4 charged particles/s traversing each telescope. There is no problem of rate or radiation damage.

A possible configuration could be made of four arms, two on each side of the crossing point. Each arm consists of a telescope of two planes of scintillation counters placed 5 m apart with 3 gas chambers in between. Each telescope will be placed at about 50 m from the crossing. The shape of each detector could be hexagonal with inner radius of 2.5 cm and outer radius of about 65 cm. The distance from the crossing point is determined by the minimum polar angle and by the radius of the standard vacuum chamber (2.2 cm).

The scintillation counters of each telescope will discriminate outgoing from ingoing particles by timing. The gas chambers will provide reconstruction of the charged particle tracks and extrapolation to the collision point. Their basic requirement is a resolution of few tenths of mm. This will allow extrapolation to the centre of the intersection region with an error on the transverse coordinate of few mm which is sufficient.

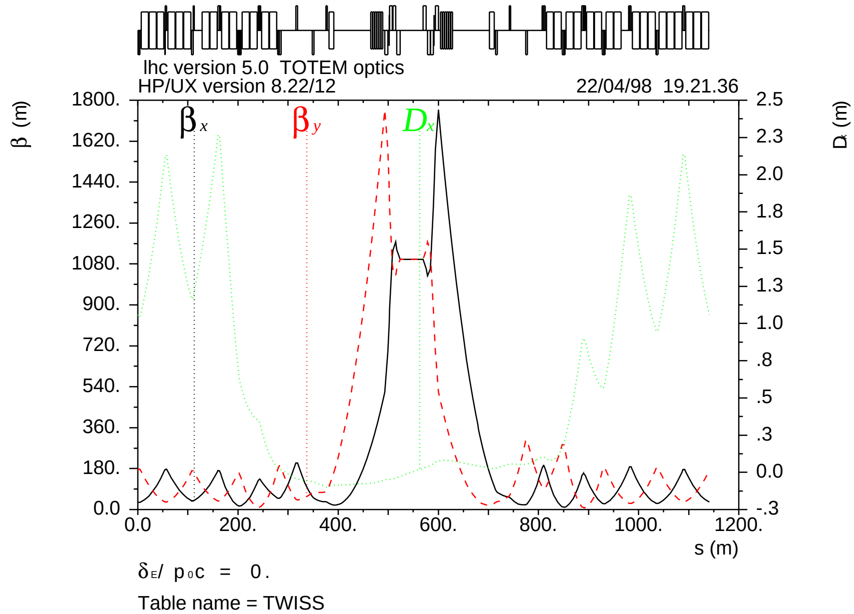

Figure 5: β-functions and dispersion around IP5 for the ideal high-β optics adapted to vertical and horizontal Roman pots with low-β triplet quadrupoles with three parameters, from [17].

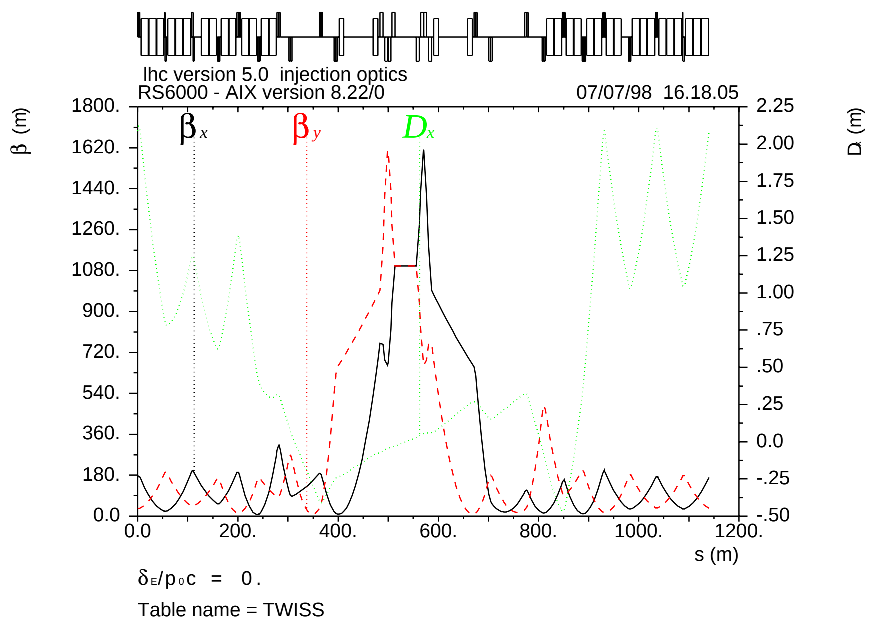

Figure 6: β-functions and dispersion around IP8 for a high-β optics adapted to vertical and horizontal Roman pots taking into advantage of the low-β triplet trim power supplies available in the standard design (10 %), from [18].

It is clear that there is no severe condition on the gas chambers, neither from the expected rate nor from the required spatial resolution.

8. Background and Radiation Damage

A detailed simulation [19] gives the background profile as a function of the distance from the beam axis. The results of this calculation demonstrate the effectiveness of the collimators in reducing the background rate at distances from the beam axis above $10 \times \sigma_{beam}$.

At nominal intensity, the average loss in one ring all around the machine should be about 3×10^9 protons s^{-1}. If this loss is uniformly distributed around the ring the local loss is about 10^5 protons m^{-1} s^{-1}. The collimators are expected to provide a reduction factor of about 100.

Therefore, assuming the closest part of the pot placed at a distance of $15 \times \sigma_{beam}$, this would lead to a background rate of the order of magnitude of 10^3 Hz as seen by the detectors at the maximum beam intensity. This rate is very similar to that observed during the UA4/2 run and can be easily faced by the TOTEM experiment.

Contrary to what is expected for the Roman pots, the background in the "inelastic" detector is mainly induced by the showering of the very forward particles produced in beam-beam interactions.

At a luminosity of 10^{28} cm^{-2} s^{-1}, the average number of interactions will be 1000 Hz, i.e. 10^{-2} interactions per crossing at reduced number of bunches. The measurement will not be affected by multiple interactions during the same crossing.

The background comes essentially from beam-gas events simulating Single Diffractive (SD) events. For the total cross section measurement assuming the luminosity given above and reduced intensity, the ratio of SD to background events in the interaction region is about 10. With this factor the SD rate could also be determined with sufficient precision to get the inelastic cross section at the 1% level. On the other hand the ratio of the SD events to all inelastic could be determined at higher luminosity, thus lowering the background.

From the previous discussion on the expected rates, it is clear that for the TOTEM operation we do not expect problems of radiation damage.

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