FEASIBILITY STUDY FOR A HIGH-β INSERTION OPTICS IN THE LHC V5.0 FOR THE TOTEM EXPERIMENT

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Abstract

The TOTEM experiment is intended to measure the total cross section, elastic scattering and diffraction dissociation at the LHC energies. For those measurements, we have to detect particles emitted in the very forward region. The experimental method, techniques and optics layout which are involved are very special and quite different from those used in the large general purpose detectors. From the optics point of view a high-beta insertion (1100 m) is needed. In this paper we present a feasibility study for an experiment to be installed in IR1, IR2, IR5 or IR8. Our first objective is to made it with no special infrastructure and minimum cost.

1 REQUIREMENTS FOR THE INSERTION OPTICS.

A measurement of the total cross section at LHC energies requires the observation of elastically scattered particles at very small angles (14 μrad, $-t\ \leq$0.01GeV^2). In practice this is achieved by placing the detectors into special units, known as "Roman pots", mounted in the vacuum chamber of the accelerator.

The detectors are placed in a long straight section of the accelerators on both sides of the IP. On each beam, downstream of the crossing point, there will be a telescope of two Roman pots placed a few meters apart and therefore able to measure both the position and the direction of the scattered protons. Roman pots can in principle be placed either in the horizontal or in the vertical plane as long as the beam motion in the two planes is equally stable [1]. Between the detectors and the crossing point there will be magnetic elements of the machine in order to make the beams collide.

The best configuration, as already pointed in [2], corresponds to the optics with parallel-to-point focusing from the crossing to the detectors. This has the convenient property that particles scattered in the same direction are brought together to the same point on the detector independently of their position at the IP. Using the standard notation and taking z for x or y, we write the transverse displacement at the detector as a function of the displacement z^* at the IP and of the scattering angle θ_z^*:

$$z_d = M_{z,11}\ \ z^* + M_{z,12}\ \ \theta_z^* \tag{1}$$

where $M_{z,11}$ and $M_{z,12}$ are the twiss element matrix.

From equation (1) we may deduce that the condition of parallel to point focusing is satisfied when the twiss matrix element $M_{z,11} = 0$. This is achieved when the elastic detectors are placed at the position where the phase advance is $(\phi_{z_d} - \phi_z^*) = \pi/2,\ 3\pi/2, ...$ and α_z^*=0. Insertions are usually designed with α_z^*=0. This is not, however, a strictly necessary requirement and it is possible that by relaxing this condition one might gain some additional flexibility which could be used for an optimized design of the insertion [3]. The limit for the value of α_z^* is given by the condition that on the right hand side of the expression (1), the first term should always be substantially smaller than the second one [4]. Supposing that the phase advance is $(\phi_{z_d} - \phi_z^*) = \pi/2,\ 3\pi/2, ...$ and taking $z^* = \sigma_z^*$ the limit in α_z^* is given by:

$$\alpha_z^* \ll \frac{\beta_{z_d}\theta_z^*}{\sigma_z^*} \tag{2}$$

In the case of the parallel-to-point focusing optics, the twiss matrix element $M_{z,12}$ represents the effective distance of the detectors from the crossing point, $L_{z,eff}$.

The minimum distance of approach of the inner edge of the detectors to the beam axis, z_d, is proportional to the r.m.s. beam size at the detector position, σ_{z_d}. At the SPS collider it was empirically found by the UA4 experiment that the constant of proportionality, k, had the numerical value between 15 and 20, depending on the machine conditions.

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

$$\theta_{z_d} = k\sqrt{\frac{\epsilon_z}{\beta_z^*}}\ \ ,\ \ |t_{z_d}| = p^2k^2\frac{\epsilon_z}{\beta_z^*} \tag{3}$$

where ϵ_z is the emittance. We notice that the angle θ_{z_d} corresponds to a zero value of the acceptance of the detector which reaches useful values for $\theta_{z_{min}} \simeq \sqrt{2}\theta_{z_d}$.

For a given emittance, small values of the momentum transfer are reached for large β_z^* and small k. Assuming $k = 15$, the nominal emittance value of $\epsilon_z = 5.0\ \ 10^{-10}$ m rad [5] at the momentum p= 7 TeV with $\theta_{z_{min}} \simeq 14$ μrad corresponding to $|t_{z_{min}}| = 10^{-2}$ GeV^2, we have from equation (3) that

$$\beta_z^* \geq 1100 \text{ m}$$

An additional requirement comes from the fact that the actual distance z_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 position instabilities. A too small value of z_d would also put unrealistic constraints on the mechanical construction of the Roman pots and of the detectors. Assuming a minimum acceptable value for z_d of 1.5 mm [2] this requirement can be written as

$$L_{z,eff}\theta_{z_d} \geq z_{d_{min}} = 1.5 \text{ mm} \quad (4)$$

A priori it is desirable to have $D_x^* = D_x^{'*}$=0, however this is not a strict requirement and we could relax this condition in order to gain some flexibility in optics. D_x^* is behaved like an orbit and it is not a problem. For $D_x^{'*}$ the limit occurs when the value of the r.m.s beam divergence $\sigma_x^{'*}$ is similar in magnitude to the scattering angle θ_z^*. The limit condition is given by:

$$D_x^{'*} \ll \frac{\theta_z^*}{\sigma_\epsilon} \quad (5)$$

where σ_ϵ is the r.m.s energy spread.

Taking $\theta_z^* \simeq 14\mu$rad, $\epsilon_z = 5.0 \;\; 10^{-10}$ m rad, $\beta_z^* \simeq 1100$ m and $\sigma_\epsilon = 0.111 \;\; 10^{-3}$ from [5] we have from equations (4), (2) and (5)

$$L_{z,eff} \geq 150 \text{ m}, \;\beta_{z_d} \geq 20 \text{ m}, \alpha_z^* \ll 0.4, \; D_x^{'*} \ll 0.13$$

When we are measuring in one transverse plane, there is no additional requirement for the other plane, once the basic condition of a left-right anti-symmetric optics is implemented. It is very desirable, however, to have the twiss matrix elements $M_{x,12} \approx M_{y,12}$. The reason is related to the fact that the scattering angle is determined by measuring the displacement at the detector in the two transverse planes; then we should not have very different resolutions in the two planes of the detector.

Different optics designs taking into account these requirements are described in the following section.

2 EXPERIMENTAL LAYOUT AND DESIGN TECHNIQUE.

A simplification of the experiment arises from the left-right anti-symmetry of the LHC insertions [5]. By locating the detectors in the right part of Ring 1 and in the left part of Ring 2, one obtains the same transport from the IP to either detector.

There are in principle three possible locations for the detectors, one just before the dipole $D2$, the second one between $Q5$ and $Q6$ and the third one between $Q6$ and $Q7$.

There is some incentive to find a solution where the Roman pots are vertical, which would ease the mechanical design.

3 TOTEM IN IR1 AND IR5.

Using the low-β triplet quadrupoles in a standard way (non-independent gradients) [5] and all the other independent quadrupoles of the IR8 with the corresponding limitations in gradients, no solution could be found.

If the quadrupoles of the low-β triplet were assumed to be independently powered, it is then possible to match an optics that fulfills nearly all the conditions before $D2$ for the vertical plane, except for β_{y_d} which is 35% too small. However all the conditions can be fulfilled to place a detector for an horizontal measurement between $Q5$ and $Q6$. If the strength of $Q6$ can be increased by 10 % the ideal solution is obtained for a vertical measurement at $D2$.

The results for the ideal optics are summarized on figure 1 and in table 1. In table 1 we have summarized the performances corresponding to the two possible locations for the two detectors (vertical and horizontal). The displacements x and y have been calculated with equation (1) taking $z^* = \sigma_z^*$ and $\theta_z^* = 14\mu$rad. The $\theta_{z_{min}}$ and $\theta_{z_{max}}$ have been calculated for an opening of the Roman pots of ±1.5 mm and ±25.0 mm that correspond to the radius of the vacuum chamber from [6] respectively. The optics have been calculated with MAD8 [7].

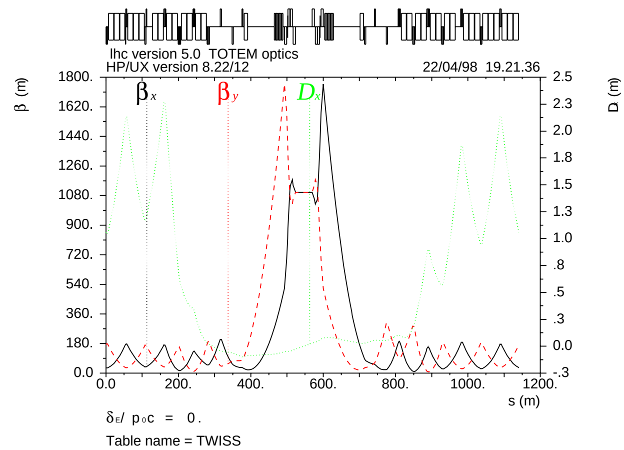

Figure 1: β-functions and dispersion around IP5 for the ideal high-β optics adapted to vertical and horizontal Roman pots with fully independent low-β triplet quadrupoles.

Table 1: Performances at the IP and at the detectors place for a high-β optics in IR5 with fully independent low-β triplet quadrupoles (nominal Version 5.0).

	high-β optics in IR5		units
requirements	**Indep. Q1/Q2/Q3, 10 % Q6**		
β_x^*/β_y^*	1100.0 /1100.0		m
α_x^*/α_y^*	0.0 /0.0		
D_x^*	0.0		m
$D_x^{'*}$	0.001		
σ_x^*/σ_y^*	0.74 /0.74		mm
$\sigma_x^{'*}/\sigma_y^{'*}$	0.69 /0.68		μrad
measure	**vertical** $\mathbf{z = y}$	**horizontal** $\mathbf{z = x}$	
detec. position	**before D2**	**between Q5-Q6**	
β_{z_d}	20.1	20.6	m
μ_{z_d}	0.249	0.251	2π
$M_{z,11_d}$	0.000	0.000	
$M_{z,12_d}$	148.7	212.3	m
$\lvert z_d/\sigma_{z_d}\rvert$	20.7	20.7	
$\lvert\theta_{z_{min}}\rvert$	14.3	10.0	μrad
$\lvert\theta_{z_{max}}\rvert$	168.1	117.7	μrad

4 TOTEM IN IR2 AND IR8.

Using the low-β triplet quadrupoles in a standard way (non-independent gradients) [5] and all the other independent quadrupoles of the IR8 with the corresponding limitations in gradients, no solution could be found to place a detector before $D2$. An optics that fulfills all the conditions for a measurement in the vertical plane between $Q5$ and $Q6$, close to $Q6$, could be matched. Furthermore this optics could be used to place a detector for an horizontal measurement between $Q5$ and $Q6$, close to $Q5$, but β_{x_d} is 32% too small. The situation could be improved taking fully independent low-β quadrupoles but only 10 % difference between the strengths, corresponding to the capabilities of the trim power supplies. The results are summarized on figure 2 and in table 2.

Two similar solutions could be found for IR2. The minor changes are due to the different locations of $Q5$ and $Q6$ in the two insertions.

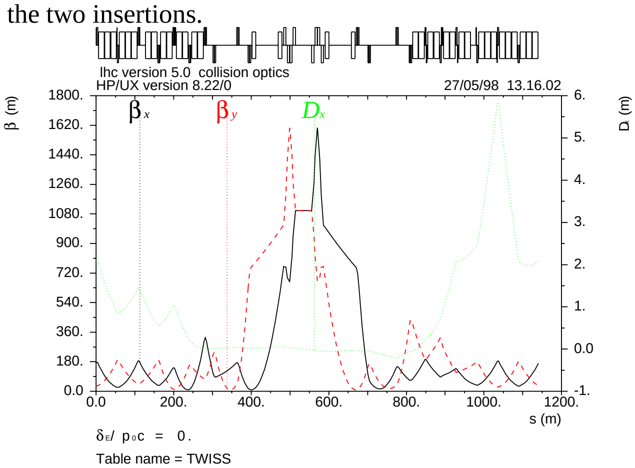

Figure 2: β-functions and dispersion around IP8 for a high-β optics adapted to vertical and horizontal Roman pots with fully independent low-β triplet quadrupoles but only 10 % difference between the strengths of the quadrupoles.

5 CONCLUSION

In this study, we analysed first the requirements of the TOTEM experiment at the LHC for installation in IR1/IR5. These requirements could be met with some modifications to the nominal LHC Version 5.0. The best solution is found by powering the low-β triplet quadrupoles independently without any limitation in their strength differences and thereby being able to operate the Roman pots in the vertical plane before $D2$ or in the horizontal plane between $Q5$ and $Q6$. In both cases the $Q6$ quadrupole strength should be increased by 10 %. According to [8], the extra ripple due to the separated powering of the low-β quadrupoles is negligible.

Finally, we analysed the requirements of the TOTEM experiment at the LHC for installation in IR2/IR8. A measurement in the vertical plane between $Q5$ and $Q6$ could be met with the nominal LHC Version 5.0. By powering independently the quadrupoles of the low-β triplet, but with only 10 % difference between the strengths of the low-β quadrupoles corresponding to the capabilities of the trim power supplies, the horizontal measurement is also possible.

The next step of this work is to study the possibility to increase the β^* for the measurement of the Coulomb scattering.

Table 2: Performances at the IP and at the detectors place for a high-β optics in IR8 with standard low-β triplet quadrupoles and with fully independent low-β triplet quadrupoles but only 10 % difference between the strengths of the quadrupoles (nominal Version 5.0).

	high-β optics in IR8		units
requirements	**10 % Indep. $Q1/Q2/Q3$**		
β_x^*/β_y^*	1100.0 /1100.0		m
α_x^*/α_y^*	0.0 /0.0		
D_x^*	0.0		m
$D_x^{'*}$	-0.001		
σ_x^*/σ_y^*	0.74 /0.74		mm
$\sigma_x^{'*}/\sigma_y^{'*}$	0.68 /0.68		μrad
measure	**horizontal** **z = x**	**vertical** **z = y**	
detec. position	**between Q5-Q6**		
β_{z_d}	15.8	30.0	m
μ_{z_d}	0.272	0.750	2π
$M_{z,11_d}$	-0.016	0.0	
$M_{z,12_d}$	130.9	-181.7	m
$\lvert z_d/\sigma_{z_d}\rvert$	20.1	20.7	
$\lvert\theta_{z_{min}}\rvert$	16.3	11.7	μrad
$\lvert\theta_{z_{max}}\rvert$	191.7	137.6	μrad

6 REFERENCES

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