# OPTIMIZED HIGH-$\beta$ INSERTION OPTICS FOR IR1 AND IR5 FOR THE TOTEM EXPERIMENT AT DIFFERENT ENERGIES OF THE LHC V6.0*

A. Faus-Golfe, IFIC-University of Valencia, Spain

*Abstract*

In this paper we present an optimized high-$\beta$ insertion optics for IR1 and IR5 for Ring 1 and Ring 2 of the LHC Version 6.0 at different running energies. The transition optics from collision (7 TeV) to injection (450 GeV) are investigated. Furthermore these optics allow the minimization of the cost of the special infrastructure by simple modification of the triplet powering. A dedicated study of the running conditions at 900 GeV per beam (Tevatron energy) is also included. The performances of the experiment and its implications from the experimental point of view are also revisited.

## 1 INTRODUCTION

The main differences of insertions IR1 and IR5 in Version 6.0 with respect to Version 5.0 are the individual powering of the quadrupoles of the dispersion suppressor. The new insertions are described in detail in [1]. As a result of this modification we have additional flexibility in the matching of these insertions. Taking advantage of this flexibility we redesigned the optics for the TOTEM experiment at high-$\beta$ ($\beta^*$ = 1100 m) and furthermore we incorporate its requirements (see [2]) for all the optics of the transition from collision to injection ($\beta^*$= 18 m) if possible. This property allows the optics to be adapted to the beam conditions, as they evolve during the operation of the LHC.

## 2 DESIGN REQUIREMENTS FOR TOTEM OPTICS

The geometrical layout of the right part of IR5 is shown in figure 1. In the following only vertical Roman pots arrangements are considered.

The optics requirements for the TOTEM experiment at collision energy of 7 TeV for a measurement in the vertical plane with the nominal normalized emittance $\epsilon_n = 3.75\ \mu$ m rad, are summarized as follows [2]:

- At the IP, $\beta_z^* \geq$ 1100 m where $z = x, y$, $\alpha_z^* \ll$ 0.4 and $D_x^{'*} \ll$ 0.13. Nevertheless it is desirable to have $\alpha_z^*$=0, $D_x^*$= 0 and $D_x^{'*}$= 0.

- At the detector place ($RP1$), $(\phi_{y_d} - \phi_y^*) = \pi/2,\ 3\pi/2, ...$ and $\beta_{y_d} \geq$ 20 m i.e. $M_{y,12} = L_{y,eff}$= 150 m. Furthermore it is very desirable to have the twiss matrix elements $M_{x,12} \approx M_{y,12}$.

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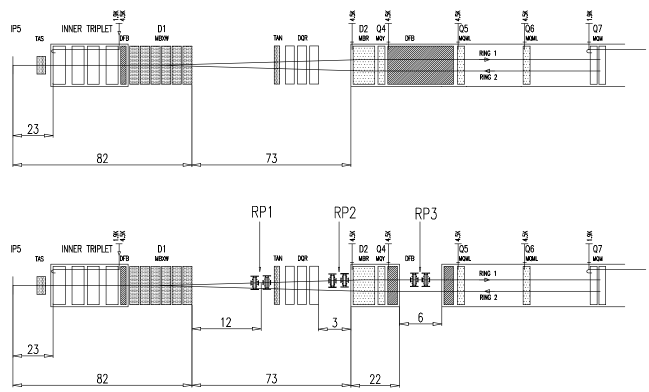


Figure 1: Layout of the insertion 5, Version 6.0. The upper part reproduces the standard insertion while the lower part shows the location of the three Roman pot stations $RP1$, $RP2$ and $RP3$. The layout is symmetric with respect to the IP.

## 3 TOTEM OPTICS FOR RING 1 AND 2 AT 7 TEV COLLISION ENERGY

### 3.1 Collision optics with $\beta_z^*$= 1100 m

The best solution is found, as in Version 5.0, assuming that the low-$\beta$ triplet could be independently powered but strictly antisymmetric. To match properly Ring 2 we are obliged to double some of the trim power supplies of the dispersion suppressor quadrupoles. $Q4.L5$ of Ring 2 is exceeding the nominal maximum gradient by 7.8%. However this value could be acceptable without requiring new equipment [3]. Figure 2 shows the solution for high-$\beta$ optics with $\beta_z^*$=1100 m, for Ring 1 calculated with MAD8 [4].

Furthermore by increasing the gradient of the low-$\beta$ trim power supplies until 4000 A ($\sim\ \pm$73.3 T/m) if we have only one polarity, [5], we have a high-$\beta$ optics equivalent to the high-$\beta$ optics described before with:

- one main power supply of 12000 A, powering $Q2$ and $Q3$, i.e. $Q2.L5$=$QM2.L5$ and $Q3.L5$=$-QM2.L5$ + $QT3.L5$.

- two trims power supplies of a maximum of 4000 A, for $Q1$ and $Q3$, with the same polarity i.e. $Q1.L5$=$QT1.L5$ and $Q3.L5$=$-QM2.L5$ + $QT3.L5$.

This solution seems the most economic way to implement the requirements of TOTEM in IR1 and IR5.

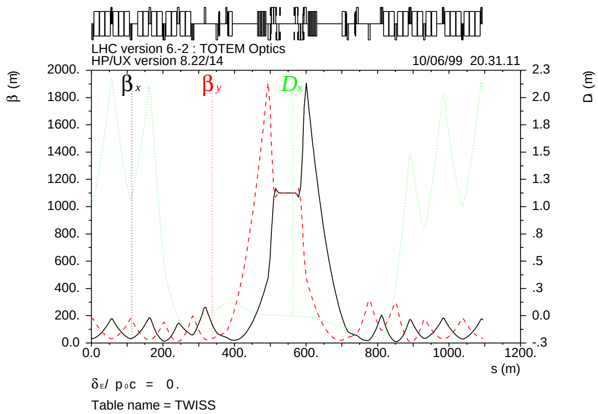


Figure 2: High-$\beta$ optics with $\beta^*$=1100 m in Ring 1 around IP5, Version 6.0.

The measurement in the vertical plane is feasible without serious disturbances for the cryogenics by placing the Roman pots before $D2$. The most significant parameters for the experiment in Ring 1 are summarized in table 1. Due to the antisymmetry of the triplet the situation for Ring 2 is completely equivalent. The beam sizes are calculated taking the nominal normalized emittance $\epsilon_n = 3.75$ $\mu$m rad. The displacement at the detectors place $y_d$ has been calculated taking $y^* = \sigma_y^*$ and $\theta_y^* = 14\mu$rad. The $\theta_{y_{min}}$ and $\theta_{y_{max}}$ have been calculated for an opening of the Roman pots of $\pm$1.5 mm and $\pm$25.0 mm that correspond to the radius of the vacuum chamber from [6] respectively. The $|t_{y_{min}}|$ and $|t_{y_{max}}|$ have been calculated for $p$= 7000 GeV.

We have calculated the geometrical acceptance around IR1 and IR5. The procedure to estimate the maximum acceptance at a given place as well as the aperture parameters for the LHC magnet classes are described in detail in [6]. The minimum acceptance for optics occurs in $TAS1$ absorbers and is equal to $n_1$=9.09. From the point of view of the measurement this element is not imposing a limit in our measurement.

### 3.2 Injection optics with $\beta_z^*$ = 18 m

A solution could be matched by keeping the same power principles for the low-$\beta$ trim power supplies, if we double some of the trim power supplies of the dispersion suppressor quadrupoles and we could increase the strength of $Q8.R5$ and $Q8.L5$ by 14%. By relaxing the conditions $\alpha_z^* = 0$ and $Dx^* = Dx^{'*} = 0$ we could matched an optics without increasing the strength of $Q8.R5$ and $Q8.L5$. $Q4.L5$ and $Q6.R5$ of Ring 1 and $Q6.L5$ and $Q4.R5$ of Ring 2 are exceeding the nominal maximum gradient less than 4%. These values are acceptables without requiring new equipment [3].

The geometrical acceptance is 9% below the specifications but the value is compatible with the recommended value due to the fact that we are running without crossing angle and with a reduced number of bunches [7].

### 3.3 Transition optics at collision energy with measurement for $\beta_z^*$ going from 1100 m to 150m

A continuous transition in quadrupole excitation from $\beta_z^*$ = 1100 m to 150 m could be found by keeping the same powering principles for the low-$\beta$ trim power supplies and the possibilities of measuring in all the range of $\beta_z^*$. Note that in that case we also need to double the trim power supplies of some of the dispersion suppressor quadrupoles. Some quadrupoles are exceeding by less than 3 % the nominal maximum gradients but the values are acceptables without requiring new equipment [3].

The geometrical acceptance is sufficiently large and is not imposing a limit in the measurement.

### 3.4 Transition optics at collision energy for $\beta_z^*$ going from 150 m to 18 m

A continuous transition in quadrupole excitation from $\beta_z^*$ going from 150 m to 18 m could be found by keeping the same powering principles for the low-$\beta$ trim power supplies, although the slope of the gradient transition changes its signs. These problems could be avoided by injecting at $\beta_z^*$ = 150 m. For this last injection optics the geometrical acceptance is 16% below the specifications but the value is compatible with the recommended value due to the fact that we are running without crossing angle and with a reduced number of bunches [7].

## 4 TOTEM OPTICS FOR RING 1 AND 2 AT 900 GEV COLLISION ENERGY

In the TOTEM Technical Proposal [8] it was mentioned the interest of running at 900 GeV per beam (Tevatron energy), because the optics with $\beta^*$= 1100 m would make possible the measurement of Coulomb interference (momentum transfer $|t_{min}|$ = 0.0005 GeV$^2$) feasible at that energy.

Taking the high-$\beta$ optics of IR1 and IR5 Version 6.0 ($\beta^*$=1100 m) described before, we have calculated the performance of the experiment and the geometrical acceptance [6] at 900 GeV for different values of normalized emittances [9].

The most significant parameters for the experiment in Ring 1 are summarized in Table 2. Due to the antisymmetry of the triplet the situation for Ring 2 is completely equivalent. The displacement at the detector place $y_d$ has been calculated taking $y^* = \sigma_y^*$ and $\theta_y^* = 24.8$ $\mu$rad, that corresponds to $|t_{min}|$ = 0.0005 GeV$^2$ at 900 GeV. The $\theta_{y_{min}}$ and $\theta_{y_{max}}$ have been calculated for an opening of the Roman pots of $\pm$1.5 mm and $\pm$25.0 mm that correspond to the radius of the vacuum chamber [6].

We have calculated also the geometrical acceptance around IR1 and IR5. The minimum acceptance values occurs in $TAS1$ absorbers in all cases. At the nominal nor-

| | | |
|---|---|---|
| $\epsilon_n$ | 3.750 | $\mu$m rad |
| $\beta_z^*$ | 1100.0 | m |
| $\alpha_z^*$ | 0.0 | |
| $D_x^*$ | 0.0 | m |
| $D_x^{'*}$ | 0.0 | |
| $\sigma_\epsilon$ | 0.111 | $10^{-3}$ |
| $\sigma_z^*$ | 0.74 | mm |
| $\sigma_z^{'*}$ | 0.68 | $\mu$rad |
| detector before $D2$ | | |
| $\beta_{x_d}$ | 210.2 | m |
| $\Delta\mu_{x_d}$ | 0.032 | $2\pi$ |
| $M_{x,12_d}$ | 96.0 | m |
| $\beta_{y_d}$ | 20.1 | m |
| $\Delta\mu_{y_d}$ | 0.25 | $2\pi$ |
| $M_{y,11_d}$ | 0.0 | |
| $M_{y,12_d}$ | 148.6 | m |
| $y_d$ | 2.08 | mm |
| $\lvert y_d/\sigma_{y_d}\rvert$ | 20.7 | |
| $\lvert\theta_{y_{min}}\rvert$ | 14.3 | $\mu$rad |
| $\lvert\theta_{y_{max}}\rvert$ | 168.3 | $\mu$rad |
| $\lvert t_{y_{min}}\rvert$ | 0.010 | GeV$^2$ |
| $\lvert t_{y_{max}}\rvert$ | 1.387 | GeV$^2$ |

Table 1: Performance of the experiment at the IP and at the detector place ($RP1$) in Ring 1 for high-$\beta$ optics with $\beta^*$=1100 m, Version 6.0 at 7 TeV.

malized emittance (3.75 $\mu$m rad) the acceptance limit occurs in the low-$\beta$ triplet. The minimum geometrical acceptance $n_1$=2.77, is 60.4% below the specification. The problem could be solved if we reduced the nominal normalized emittance.

When the nominal emittance is reduced by two, the acceptance limit occurs in $Q1$ and in $TAS1$. The minimum geometrical acceptance $n_1$=3.92, is 44.0% below the specification. This value is not acceptable. When the nominal emittance is reduced by four, i.e. the normalized emittance in the early days, the acceptance limit occurs only in $TAS1$. The geometrical acceptance for this element $n_1$=5.55, is 20.7% below the specification. This value is probably unacceptable from the point of view of machine acceptance but a possible increase of the $TAS1$ aperture is now under consideration.

## 5 CONCLUSION

Flexibility of the insertions is limited. The requirements of a high-$\beta$ insertion could be met with some modifications of the nominal LHC insertion hardware. A vertical measurement is possible before $D2$ by powering independently the quadrupoles of the triplet in the two rings. The transition from $\beta^*$=1100 to 18 m is also possible with the same powering principles. From $\beta^*$=1100 to 150 m the optics fulfills all the conditions for the experiment.

Running at Tevatron energy seems feasible.

Future lines of work are : feasibility study for Coulomb

| | | | | |
|---|---|---|---|---|
| $\epsilon_n$ | 3.750 | 1.875 | 0.938 | nm rad |
| $\beta_z^*$ | 1100.0 | | | m |
| $\alpha_z^*$ | 0.0 | | | |
| $D_x^*$ | 0.0 | | | m |
| $D_x^{'*}$ | 0.0 | | | |
| $\sigma_\epsilon$ | 0.443 | | | $10^{-3}$ |
| $\sigma_z^*$ | 2.07 | 1.48 | 1.04 | mm |
| $\sigma_z^{'*}$ | 1.89 | 1.35 | 0.94 | $\mu$rad |
| detector before $D2$ | | | | |
| $\beta_{x_d}$ | 210.2 | | | m |
| $\Delta\mu_{x_d}$ | 0.032 | | | $2\pi$ |
| $M_{x,12_d}$ | 96.0 | | | m |
| $\beta_{y_d}$ | 20.1 | | | m |
| $\Delta\mu_{y_d}$ | 0.25 | | | $2\pi$ |
| $M_{y,11_d}$ | 0.0 | | | |
| $M_{y,12_d}$ | 148.6 | | | m |
| $y_d$ | 3.69 | 3.69 | 3.69 | mm |
| $\lvert y_d/\sigma_{y_d}\rvert$ | 13.2 | 18.4 | 26.4 | |
| $\lvert\theta_{y_{min}}\rvert$ | 14.3 | 14.3 | 14.3 | $\mu$rad |
| $\lvert\theta_{y_{max}}\rvert$ | 168.3 | 168.3 | 168.3 | $\mu$rad |
| $\lvert t_{y_{min}}\rvert$ | 0.00017 | 0.00017 | 0.00017 | GeV$^2$ |
| $\lvert t_{y_{max}}\rvert$ | 0.0229 | 0.0229 | 0.0229 | GeV$^2$ |

Table 2: Performance of the experiment at the IP and at the detector place ($RP1$) Ring 1 for high-$\beta$ optics with $\beta^*$=1100 m, Version 6.0 at 900 GeV for different emittance values.

scattering measurements at 7 TeV collision energy and a detailed study of the acceptance of the detectors.

## REFERENCES


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