Chapter 3

Beam optics and running conditions

For the luminosity independent total cross-section measurement TOTEM has to reach the lowest possible values of the squared four momentum transfer $-t \sim p^2\Theta^2$ in elastic pp scattering.

Scattered particles close to the beam can be detected downstream on either side of the Interaction Point (IP) if the displacement at the detector location is large enough (at least $10\sigma_{\text{beam}}$ away from the beam center) and if the beam divergence ($\sim 1/\sqrt{\beta^*}$) at the IP is small compared to the scattering angle. In order to achieve these conditions special high beta optics are required: the larger the β^*, the smaller the beam divergence will be.

Two optics have been proposed: the ultimate one with $\beta^* = 1540\,\text{m}$, probably foreseen at a later stage, and another one with $\beta^* = 90\,\text{m}$. The latter uses the standard injection optics and the beam conditions typical for early LHC running: zero degree crossing-angle and consequently at most 156 bunches together with a low number of protons per bunch.

3.1 Properties of the high-β^* Optics

The properties of the optics can be expressed by the two optical functions L (effective length) and v (magnification) which, at a distance s from the IP, are defined by the betatron function $\beta(s)$ and the phase advance $\Delta\mu(s)$:

$$\begin{aligned} v(s) &= \sqrt{\frac{\beta(s)}{\beta^*}}\cos\Delta\mu(s) \\ L(s) &= \sqrt{\beta(s)\beta^*}\sin\Delta\mu(s) \\ \text{with}\ \ \Delta\mu(s) &= \int_0^s \frac{1}{\beta(s')}ds' \end{aligned} \tag{3.1}$$

The transverse displacement $(x(s), y(s))$ of a proton at a distance s from the IP is related to its transverse origin (x^*, y^*) and its momentum vector (expressed by the horizontal and vertical scattering angles Θ_x^* and Θ_y^* and by $\xi = \Delta p/p$) at the IP via the above optical functions and the dispersion $D(s)$ of the machine:

$$\begin{aligned} y(s) &= v_y(s)\cdot y^* + L_y(s)\cdot\Theta_y^* \\ x(s) &= v_x(s)\cdot x^* + L_x(s)\cdot\Theta_x^* + \xi\cdot D(s) \end{aligned} \tag{3.2}$$

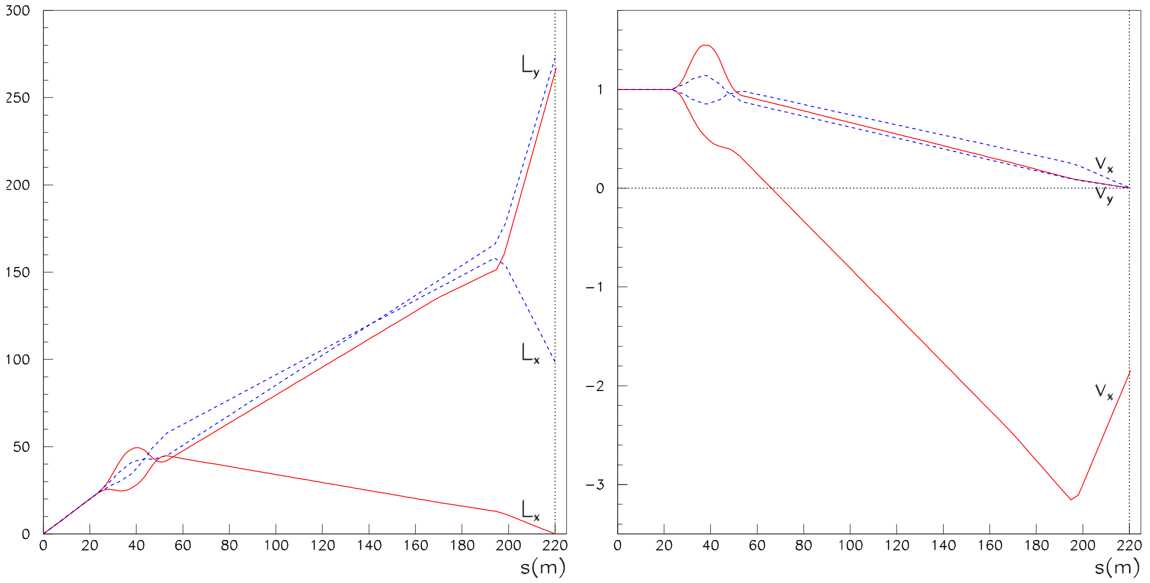

Figure 3.1: The optical functions for β^*=90 m (solid) and 1540 m (dashed) as function of the distance s to IP5: effective length L [in m] (left) and magnification v (right).

As a consequence of the high β^*, the beam size at the IP is large ($\sigma^*_{\text{beam}} \propto \sqrt{\beta^*}$). To eliminate the dependence on the transverse position of the proton at the collision point, the magnification has to be chosen close to zero (parallel-to-point focussing, $\Delta\mu = \pi/2$). At the same time, a large effective length ensures a sizeable displacement from the beam centre.

Having in mind the above optimisation for the position of the RP station RP220, two scenarios have been studied. Their optical functions are compared in figure 3.1. For $\beta^* = 1540$ m, the parallel-to-point focussing is achieved in both projections whereas for $\beta^* = 90$ m only in the vertical one. In both cases, the large L_y pushes the protons vertically into the acceptance of the RP detectors.

The minimum distance of a detector from the beam is proportional to the beam size:

$$y_{\text{min}} = K\sigma_y^{\text{beam}} = K\sqrt{\varepsilon\,\beta_y(s)}\,, \tag{3.3}$$

where ε is the transverse beam emittance and K is around 10–15. Assuming perfect parallel-to-point focussing, the smallest detectable angle is:

$$\Theta^*_{y\ min} = K\sqrt{\frac{\varepsilon}{\beta^*_y}}. \tag{3.4}$$

The parallel-to-point focussing condition allows the measurement of both t components (t_x, t_y) for elastically scattered protons at $\beta^* = 1540$ m but only the vertical component at $\beta^* = 90$ m.

Both optics also offer the possibility of detecting diffractive protons almost independent of their momentum loss. To be able to measure the momentum loss ξ with an acceptable resolution, L_x has to vanish to eliminate the dependence on the horizontal scattering angle Θ^*_x (cf. eq. (3.2)). This condition can only be achieved with the $\beta^* = 90$ m optics (figure 3.1).

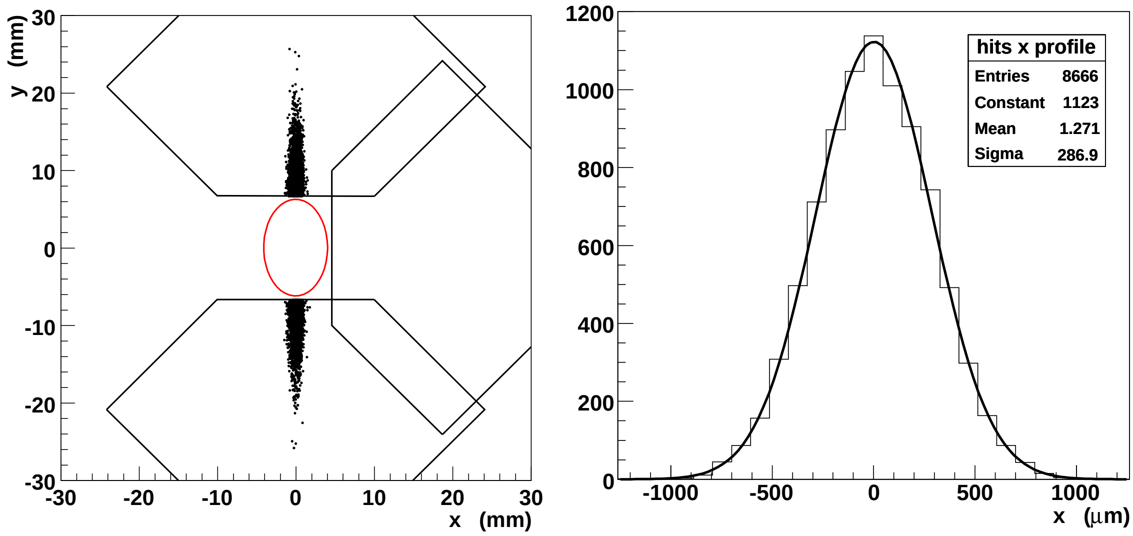

Figure 3.2: Left: hit distribution for elastic-scattering events in the detectors of RP220 with the $\beta^* = 90\,\mathrm{m}$ optics; the $10\,\sigma_{\mathrm{beam}}$ beam envelope is also shown. Right: hit distribution in the horizontal projection (x) at RP220.

3.2 Beam diagnostics

In addition to the luminosity measurement via the Optical Theorem, TOTEM can contribute more information to beam diagnostics, in particular with the $\beta^* = 90\,\mathrm{m}$ optics. There, the horizontal hit positions of elastically scattered protons in the RP 220 m station depend only on the vertex position and not on the horizontal scattering angle. Thus the narrow hit distribution (figure 3.2) reflects well the horizontal beam position at the Roman Pot which can be used for an absolute calibration of the Beam Position Monitors on the micrometre level. Furthermore, this hit distribution gives access to the horizontal vertex distribution which can furthermore – assuming round beams — be exploited for an independent luminosity measurement based on beam parameters.

3.3 Running scenarios

The versatile physics programme of TOTEM requires different running scenarios that have to be adapted to the LHC commissioning and operation in the first years. A flexible trigger can be provided by the Roman Pot detectors and the T1 and T2 telescopes as discussed in chapter 8. TOTEM will take data under all optics conditions, adjusting the trigger schemes to the luminosity. The DAQ will allow trigger rates up to a few kHz without involving a higher level trigger.

The high-β^* runs (table 3.1) with 156 bunches, zero degree crossing-angle and maximum luminosity between 10^{29} and $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, will concentrate on low-$|t|$ elastic scattering, total cross-section, minimum bias physics and soft diffraction. A large fraction of forward protons will be detected even at the lowest ξ values.

Low-β^* runs (table 3.2) with more bunches and higher luminosity (10^{32} – $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) will be used for large-$|t|$ elastic scattering and diffractive studies for $\xi > 0.02$. Hard diffractive events come within reach.

Table 3.1: Running Scenarios for high β^* (k: number of bunches, N: number of protons per bunch). The t ranges given correspond to the $\geq 50\%$ acceptance intervals.

β^* [m]	k	$N/10^{11}$	$\mathscr{L}$ [cm^{-2}s^{-1}]	$\lvert t\rvert$-range [GeV^2] @ $\xi = 0$	ξ-range
1540	$43 \div 156$	$0.6 \div 1.15$	$10^{28} \div 2\times 10^{29}$	$0.002 \div 1.5$	< 0.2
90	156	$0.1 \div 1.15$	$2 \times 10^{28} \div 3 \times 10^{30}$	$0.03 \div 10$	<0.2

Table 3.2: Running Scenarios for low β^* (k: number of bunches, N: number of protons per bunch)

β^* [m]	k	$N/10^{11}$	$\mathscr{L}$ [cm^{-2}s^{-1}]	$\lvert t\rvert$-range [GeV^2] @ $\xi = 0$	ξ-range
11	$936 \div 2808$	1.15	3×10^{32}	$0.6 \div 8$	$0.02 \div 0.2$
$0.5 \div 2$	$936 \div 2808$	1.15	10^{33}	$1 \div 10$	$0.02 \div 0.2$