1. The Roman Pots of the TOTEM experiment

Proton-proton elastic scattering has been measured by the TOTEM experiment at the CERN Large Hadron Collider at √s = 7 TeV in dedicated runs. The small scattering angle (down to a few degrees) are detected with the movable near-beam insertions (Roman Pots) equipped with stacks of silicon microstrip detectors, installed on the outgoing LHC beams.

![Roman Pot detector](image)

Side view of an elastic event at IP5

2. How to transport protons from the interaction point to the detectors?

At IP5 they are characterized by transverse vertex position (x, y) and scattering angle (θx, θy). They are observed with transverse positions (x, y)IP and angles (θx, θy)IP. Proton trajectories are described by a transport matrix:

\[ T(x, y, θx, θy) = T(x, y, θx, θy) \]

with \( x \) and \( y \) magnification and \( L \) effective length being particularly important, which can be expressed in terms of betatron amplitudes:

\[ \frac{dL}{ds} = \frac{1}{x} \left( \frac{dL}{ds} + \frac{1}{x} \right) \]

In case of a perfect machine at \( x \) would be 0. In reality, they are close to zero and approximately \( \theta_y = \frac{v}{x} \approx 0 \), \( \theta_x = \frac{v}{y} \approx 0 \), where \( v \) is the beam energy. Therefore, the vertical contributions are cancelled due to the anti-symmetry between the beams. For elastically scattered protons the four momentum transfer is given by:

\[ q^2 = -p^2 \left( A_p + \delta_p \right) \]

As the values of the reconstructed angles are directly depend on the optical functions, the accuracy of optics defines the systematic errors of the final physics results.

3. Optics errors induced by LHC Imperfections

Proton transport matrix

The proton transport matrix \( T(x, y, θx, θy) \) is defined by the machine settings \( x \). Therefore it is calculated with the MAD-X code for each group of runs with identical optics based on several data sources:

- TIMBER: actual currents of the magnets
- FIDEL: LSA curvature to strength conversion curves
- WISE: measured imperfections (harmonics, displacements, rotations)

The lattice is subject to additional \( ΔA \) imperfections, not measured well enough (so far), which alter the transport matrix \( T(x, y, θx, θy) \rightarrow T(x, y, θx, θy) + ΔT \), \( \DeltaT \) biasing measurement with 5–10% accuracy is not enough for the TOTEM physics program.

4. Constraints for optics estimation from distributions measured with Roman Pots for \( β_p = 3.5 m \)

Elastically scattered proton collinearity constraints

Vertical and horizontal angle vs. position constraints

X,Y coupling estimation and constraints

The coupling components of the transport matrix can be estimated:

\[ R_x = \frac{L_{rad} \theta_y}{R_{beam}} \]

and \( R_y \) follow this pattern for beam 2. Their precision is 0.5%.

5. Real optics estimation: matching the machine parameters for \( β_p = 3.5 m \)

From detailed sensitivity studies it is known that there are 6 relevant parameters per beam segments between IP5 and Roman Pots:

- the inner triplet (2 MQXA and 2 MQXB magnets)
- the MQML, MQY magnets (less important, but not negligible)

In total 36 constraints were applied:

- 10 constraints \( x \) from measurements
- 42 constraints \( y \) from measurements
- 2 constraints strength, rotation, 26 parameters optimized, magnet strengths, rotations, beam momenta.

The phase space is \( x = \beta_p \theta \), and the \( x^3 \rightarrow x \) function is minimized, where

\[ x_0 \cdot \sum \theta_{ref} + \frac{1}{2} \frac{1}{ΔT^2} \left( \sum \frac{x_0}{ΔT^2} \right) \]

The design point defines the nominal machine as an attractor \( x \) \( θ \), while the measured point "pushes" the place of minimum from \( A \) to a nearby \( P \) to meet with the measured constraints. In practice both the CERN MINUIT package and Windows Solve were used to estimate. Finally, \( \theta_x, \theta_y \) and \( L \) were used for data analysis.

6. Monte-Carlo validation of the method for \( β_p = 3.5 m \)

In the study the following LHC parameters were perturbed to simulate the effect of \( ΔA \):

- The strength of relevant magnets
- Beam momenta
- Magnet displacements, rotations
- Risers, harmonics
- Scattered protons angular distribution

Distribution of optical function errors resulting from imperfections:

- Bias: \( |ΔA| \leq 0.5 % \), RMS: \( |ΔA| \leq 1.1 % \)
- Bias: \( |ΔA| ≤ 0.77 % \), RMS: \( |ΔA| ≤ 3.0 % \)
- Other optics imperfections after matching with Roman Pot data:

\[ |ΔA| ≤ 0.12 \%, \text{ RMS: } |ΔA| ≤ 0.21 \% \]

\[ |ΔA| ≤ 0.057 \%, \text{ RMS: } |ΔA| ≤ 0.10 \% \]

Conclusion: for \( β_p = 3.5 m \) TOTEM can measure the transfer matrix between IP5 and Roman Pots with a precision 0.2%.

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