SYSTEMATIC UNCERTAINTIES FOR HIGH BETA OPTICS

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Abstract

For luminosity and proton-proton total cross section measurement, the standard LHC Physics optics has been modified for TOTEM [1] and ATLAS-ALFA experiments [2] in the so-called High Beta optics with β^* = 2625 m as an ultimate optics for ALFA. The high beta optics takes into account the whole LHC ring. Protons are tracked from the interaction point to the detectors.

Intermediate optics of β^* = 90 m have been simulated and tested on LHC in year 2011 with datas taking for both experiments. The knowledge of the optics parameters precision has an effect on the final measurement and leads to systematic uncertainties. The goal is to determine and quantify how much systematic uncertainties impact on the measurement.

INTRODUCTION

Measurement description

For the ATLAS experiment at LHC the absolute luminosity will be measured by the ALFA detectors which consist of Roman Pots (RPs) on each part of the interaction point (IP1) in the forward direction at 240 m distance (see Fig. 1). The RPs are compact detectors designed to operate very close to the beam when it is stable and to be extracted during setting up phases.

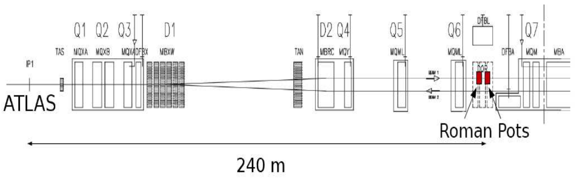

Figure 1: Beam line for the Roman Pots around IP1 (ATLAS)

To perform the measurement, the proton-proton elastic scattering interactions occurring at the IP must be tagged. The typical diffusion angle at 7 TeV is 3.5 $\mu\mathrm{rad}$. However protons cannot be intercepted with such small angles before the inner focusing triplet. As a consequence, a parallel to point focusing optics is set in the vertical plane providing a 90 ° phase advance between the IP and the RPs.

This leads to the fact the transversal position in the RPs is related to the scattering angle at the IP. Another requirement to reach such small angles is to minimize the angular dispersion at the IP. This has been done using a special high- beta optics ($\beta^* = 2625\,\mathrm{m}$) for the design beam energy of LHC of 7 TeV.

The 2625 m optics also requires a normalized emittance close to 1 $\mu\mathrm{m}$ which is smaller than currently achieved and an inversion of the polarity of the Q4 magnet which is not compatible with the present LHC operation.

An intermediate 90 m β^* optics has been provided and tested to give a first opportunity to perform forward scattering measurements with the Roman Pots with relevance for the total cross-section and elastic scattering cross section determination. Also it has given the opportunity to test new high β optics in the LHC.

The 90 m β^* optics parameters are listed in table 1.

Table 1: 90 m optics parameters for beam 1. When two values are given, they correspond to two successive RPs

LHC version V6.503

IP1		**RPs**	
$\epsilon_n(\mu\mathrm{mrad})$	2.0	β_x (m)	133.92-119.24
$\epsilon_{x,y}(\mu\mathrm{mrad})$	5.36×10^{-10}	β_y (m)	856.21-779.37
β^*_x (m)	86.39	σ_x (μm)	0.268-0.253
β^*_y (m)	90.16	σ_y (μm)	0.678-0.646
σ^*_x (mm)	0.215	$\Delta\mu_x$ (2π)	0.515-0.521
σ^*_y (mm)	0.220	$\Delta\mu_y$ (2π)	0.252-0.253
$\sigma^{*'}_x$ (μrad)	2.49	$\mathrm{L_{eff,x}}$	277.804-265.023
$\sigma^{*'}_y$ (μrad)	2.44	$\mathrm{L_{eff,x}}$	-10.293 -13.018

The corresponding β-functions and dispersion functions are shown in Fig. 2

All these parameters are computed with MadX [3] taking into account the tune compensation. The 90 m β^* optics is used for both IP1 and IP5 without crossing angle but by cons crossing angles have been added in IP2 and IP8.

The systematic uncertainties consists of studying the impact of optics parameters errors on what is called the Lever arm $\mathrm{L_{eff}}$ using MadX simulations and taking into account first results from LHC High β optics runs.

Lever arm definition

The lever arm can be found using the matrix beam formalism as in Eq. 1.

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \tag{1}$$

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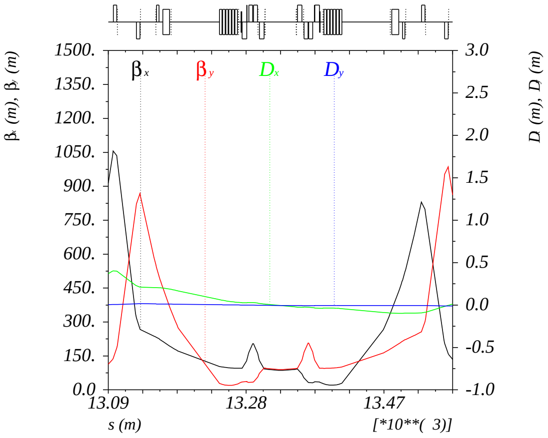

Figure 2: 90 m β^* optics parameters for beam 1

with:

$$
\begin{aligned}
M_{11} &= \sqrt{\frac{\beta_{y(s)}}{\beta_{y0}}}(\cos\phi(s) + \alpha_{y0}\sin\phi(s)) \\
M_{12} &= \sqrt{\beta_{y0}\beta_{y(s)}}\sin\phi(s) \\
M_{21} &= -\frac{1}{\sqrt{\beta_{y0}\beta_{y(s)}}}[(\alpha_{y(s)} - \alpha_{y0})\cos\phi(s) \\
&\quad + (1 + \alpha_{y(s)}\alpha_{y0})\sin\phi(s) \\
M_{22} &= \sqrt{\frac{\beta_{y0}}{\beta_{y(s)}}}(\cos\phi(s) - \alpha_{y(s)}\sin\phi(s))
\end{aligned}
$$

The matrix formalism allows to retrieve the position at the Roman pots from the position and slope at IP1 taking into account the M11 term.

Inserting all the previous optics parameters from the 90 m β^* optics into the matrix equations, we find that the position u corresponding to transverse coordinates x or y is directly linked to the scattering angle at the IP as can be seen in Eq. 2.

The scattering angle (Eq. 3) depends then on the left and right positions at the Roman Pots and on the lever arm as defined in Eq. 4. The lever arm is then completely dependant on the optics parameters.

$$u_{RP} = \sqrt{\beta_{RP}\beta^*}u'^* \qquad (2)$$

$$\theta_u^* = \frac{u_L - u_R}{2L_{\mathrm{eff,u}}} \qquad (3)$$

with

$$L_{\mathrm{eff,u}} = \sqrt{\beta_{RP}\beta^*}\sin\psi \qquad (4)$$

The description of the lever arm shows that systematic uncertainties on the global elastic proton measurement can appear from the optics. This optics systematic uncertainties study has been done using the first results provided by the first LHC runs on the 90 m β^* optics.

The fill that has been studied here is the fill number 2232, from the 20th October 2011. Systematic uncertainties are expected to originate in quadrupoles gradient errors, quadrupoles misalignments and beam-beam effects. We will now more closely look into these effects.

SYSTEMATIC UNCERTAINTIES ON THE LEVER ARM

Gradient field differences

Quadrupoles are defined by their magnetic fields and more over their gradient k (see Eq. 5). A modification of the gradient is directly linked to a modification of optics parameters ie a modification on the Lever arm. The interest here concerns the quadrupoles located in IR1 around the Roman Pots.

$$k = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} \qquad (5)$$

As already shown in Fig 1, six quadrupoles are located before the RPs : the triplet Q1,Q2,Q3 and three more Q4, Q5, Q6. Quadrupoles up to Q13 are included to match the whole insertion to the rest of the LHC ring.

In order to estimate the errors on the k gradient for quadrupoles from Q1 to Q13, a JAVA interface has been provided. The JAVA interface allows to find the gradient k values for each quadrupoles taking into account the real magnet currents used during the run.

These values are then compared with the ones used in MadX to obtain the optics parameters listed in table 1. The gradient difference $\Delta k/k$ found are listed in table 2.

The largest gradient error is close to 0.7×10^{-4} and located in the triplet.

These new gradient values have been implemented in MadX. Firstly, only quadrupoles in front of the Roman Pots ie quadrupoles Q1 to Q6 have been modified with the new k values and the impact on $\mathrm{L}_{\mathrm{eff,y}}$ estimated (table 3).

The uncertainty goes from -0.2×10^{-4} and -0.9×10^{-4}.

Then, the same has been done with quadrupoles Q11 to Q13, which as can be seen in table 2, have a larger gradient error than previous quadrupoles. But nevertheless, the ratio on the Lever arm uncertainty stays between 0.2×10^{-4} and 0.9×10^{-4}.

This allows to conclude that in this case, the impact of gradient errors on $\mathrm{L}_{\mathrm{eff,y}}$ is negligible.

Misalignments

Misalignments or orbit distortion can affect the β functions used to calculate the lever arm.

The orbit is being corrected using orbit correctors so as the effect on magnet misalignments on the beam. But still,

Table 2: Gradient values used during an LHC run

MadX strengths names	$\frac{\Delta k}{k}$
kqx.l1	-0.11×10^{-4}
ktqx.l1	-0.66×10^{-4}
ktqx2.l1	-0.1×10^{-4}
kqx.r1	-0.12×10^{-4}
ktqx1.r1	-0.67×10^{-4}
ktqx2.r1	-0.12×10^{-4}
kq4.r1b1	-0.11×10^{-4}
kq5.r1b1	-0.11×10^{-4}
kq6.r1b1	-0.11×10^{-4}
kqtl11.r1b1	0.06
kqt12.r1b1	-0.02
kqt13.r1b1	-0.17
kq4.l1b2	-0.15×10^{-4}
kq5.l1b2	-0.11×10^{-4}
kq6.l1b2	-0.11×10^{-4}
kqtl11.l1b2	0.14
kqt12.l1b2	-0.01
kqt13.l1b2	-0.01

Table 3: $\mathrm{L_{eff}}$ uncertainty at each roman pots taking beam-beam effect into account

Roman Pots	$\frac{\Delta L_{\mathrm{eff,x}}}{L_{\mathrm{eff,x}}}$ (%)	$\frac{\Delta L_{\mathrm{eff,y}}}{L_{\mathrm{eff,y}}}$ (%)
XRPV.A7R1.B1	0.9×10^{-4}	0.2×10^{-4}
XRPV.B7R1.B1	0.7×10^{-4}	0.2×10^{-4}
XRPV.A7L1.B2	0.9×10^{-4}	0.2×10^{-4}
XRPV.B7L1.B2	0.7×10^{-4}	0.2×10^{-4}

the orbit correction is not completely perfect. As we can see on Fig. 3 for beam 2, the RMS orbit is about 0.053 mm in horizontal and 0.061 mm in vertical.

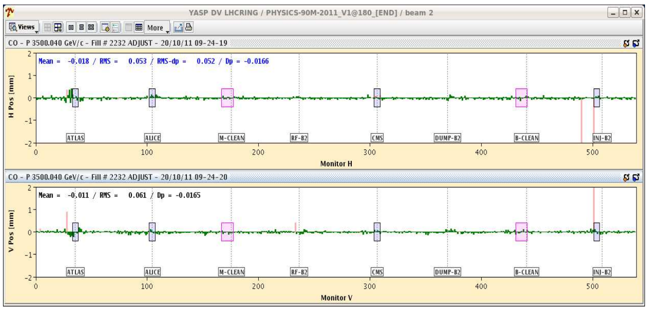

Figure 3: Orbit RMS from LHC elogbook for beam 2

Table 4: Impact of quadrupoles misalignements on $\mathrm{L_{eff,y}}$

	$\mathrm{L}_{eff,y}$
Without misalignments	277.804266
Q1 to Q6	277.804265
$\frac{\Delta L_{\mathrm{eff,y}}}{L_{\mathrm{eff,y}}}$	$< 10^{-4}$ negligible
Q1 to Q13	277.8042614
$\frac{\Delta L_{\mathrm{eff,y}}}{L_{\mathrm{eff,y}}}$	$< 10^{-4}$ negligible

Table 5: Linear tune shift parameter for different bunch population and a normalized emittance of $2\,\mu\mathrm{m.rad}$

N	ξ
4×10^{10}	-0.00246
7×10^{10}	-0.00432
1.5×10^{11}	-0.00926

To ensure that orbit errors won't affect the lever arm and leads to systematic uncertainties, an arbitrary value has been chosen, higher than the RMS value. Quadrupoles will have a misalignment of 1 mm. This misalignement is not really achievable but if this quite high misalignment value doesn't give significant errors, no realistic misalignments will give significant errors.

Misalignements have been firstly applied on several quadrupoles from Q1 to Q6 and then, for more precise results with all quadrupoles in IR1, from Q1 to Q13. The results are summarized in table 4.

Even for the high quadrupole misalignements value of 1 mm, the impact on the $\mathrm{L_{eff,y}}$ value is still negligible.

Beam-beam effect

The last effect which was thought to impact on systematic uncertainties is the beam-beam effect. Beam-beam effect is quantified by the tune shift induced by a linear kick (Eq. 6).

$$\Delta Q_x = \frac{-\beta_x}{4\pi} \frac{\Delta x'}{x} \tag{6}$$

For round beams, the linear beam-beam parameter defined in Eq 7 is equal to the tune shift.

$$\xi = -\frac{N r_0}{4\pi\epsilon_N} \tag{7}$$

N is the bunch population and r_c the classical proton radius. Table 5 summarized the linear tune shift parameter for the emittance of $2\,\mu\mathrm{m.rad}$ used during the runs.

The beam-beam effect can be replaced by adding an equivalent quadrupole in the beam line. The $\mathrm{L_{eff,y}}$ is recalculated taking into account the new optics parameters.

Table 6: $\mathrm{L}_{\mathrm{eff}}$ uncertainty at each roman pots taking beam-beam effect into account

Roman Pots	$\left\|\frac{\Delta L_{\mathrm{eff,x}}}{L_{\mathrm{eff,x}}}\right\|$ $(\%)$	$\left\|\frac{\Delta L_{\mathrm{eff,y}}}{L_{\mathrm{eff,y}}}\right\|$ $(\%)$
XRPV.A7R1.B1	0.1198	0.3015
XRPV.B7R1.B1	0.1664	0.3016
XRPV.A7L1.B2	0.1198	0.3015
XRPV.B7L1.B2	0.1664	0.3016

Table 7: Systematic uncertainties summary

k values compared with TIMBER	$\frac{\Delta L_{\mathrm{eff,y}}}{L_{\mathrm{eff,y}}}$
From Q1 to Q6	0.2×10^{-4}
From Q11 to Q13	0.6×10^{-4}
Misalignments	negligible
Beam-beam effect	0.3%

The results obtained with a bunch population of 7×10^{10} similar to the bunch population during the fill 2232 are in table 6.

The beam-beam effect on L_{eff} is of about 0.3 %. It seems to be the dominant effect for the time being. Nevertheless, this effect can be corrected during a run.

Global summary

Table 7 summarizes the systematic uncertainties that have been studied.

These are first investigations concerning the uncertainties, more are needed to check if other effects can also impact on $\mathrm{L}_{\mathrm{eff}}$. However, from these first results we can conclude that $\mathrm{L}_{\mathrm{eff}}$ seems to be a robust quantity.

TRACKING AND ACCEPTANCE RESULTS

An important parameter for the measurement is the acceptance which is the ratio between the elastic protons collected after the tracking at the RPs and the generated elastic protons at the IP.

This acceptance is determined by the simulation. Indeed, when elastic protons are collected at the RPs, the way to know the initial t-spectrum goes through the acceptance value.

The simulation for ATLAS/ALFA beam line example is made of three different steps.

- the generation of elastically scattered protons using the Monte Carlo generator PYTHIA [4], defining also vertex smearing, emittances and angular divergence from the 90 m β^* optics measured during the run.
- the tracking of these elastic protons with MadX using 90 m β^* optics from IP1 to the RPs.
- the collection of the data at the RPs and acceptance calculation

Table 8: Unexpected crossing angle impact at IP1 on the beam position

	10 μrad crossing angle in y	
Roman Pots	$\Delta x(\mu\mathrm{m})$	$\Delta y(\mathrm{mm})$
XRPV.A7R1.B1	2.4	2.7
XRPV.B7R1.B1	3.5	2.6
XRPV.A7L1.B2	-5.9	-2.7
XRPV.B7L1.B2	-6.9	-2.6

Table 9: Emittances measurements and errors during fill 2232 for bunch population of 7×10^{10}

	$\epsilon_{x,N}$	$\epsilon_{y,N}$	Error_x	Error_y
Beam1	2.302	1.748	0.22	0.064
Beam1	2.362	1.999	0.236	0.022

Crossing angle and emittances can be a source of errors for the acceptance therefore it has to be studied.

Crossing angle

Collisions for the measurement with the Roman Pots are head-on. But if an unexpected crossing-angle is added, the beam is shifted at Roman Pots location which can provide alignement considerations problems. The values for 10 μrad crossing angle (value measured by BPMs during the run) are listed in table 8.

The mean offset found at the Roman Pots for a 1 μrad crossing angle in vertical y position is close to 0.3 mm whereas for 10 μrad the offset is close to 3 mm. This confirm that the knowledge of the crossing angle value with a good precision is rather important.

Emittances

During the run, the emittances have been measured using Wire Scanners. The emittances values measured for colliding bunches with 7×10^{10} protons are shown in table 9.

To take into account the emittances errors, proton elastic generation used for acceptance calculation has been changed applying an error of ± 0.2 μm.rad. Then protons are tracked and the acceptance is computed. The

Table 10: Emittances measurements and errors during fill 2232 for bunch population of 7×10^{10}

	$\left\lvert \frac{\Delta Acc}{Acc}(total) \right\rvert$ $(\%)$	$\left\lvert \frac{\Delta Acc}{Acc}(8\sigma) \right\rvert$ $(\%)$
Beam1	0.002	0.20
Beam1	0.001	0.20

final acceptance has been compared to the acceptance result without any emittance errors. Both acceptance are shown in Fig. 4 and numerical acceptance parameters are summarized in table 10.

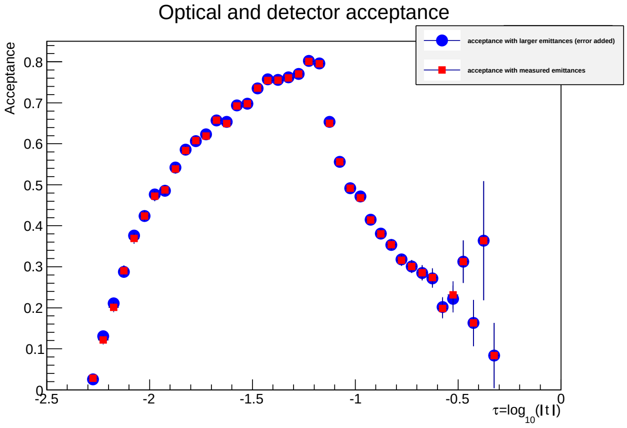

Figure 4: Acceptance results with and without emittances error

If the emittance increases of about 0.2 $\mu\mathrm{m.rad}$, looking only at the elastic protons that have hitten the sensitive area of the detectors and when the detectors are placed at 8 σ, the error generated on the acceptance is about 0.2 $\%$.

PRELIMINARY CONCLUSION

L$_{\text{eff}}$ is a very robust quantity. Nevertheless, the acceptance and alignment corrections determined with full simulation leads to about 1 $\%$ uncertainties. For the moment, no major known optics leads to large uncertainties.

Furthermore, large unknown effect would have been seen in β-measurements. The largest effect found, up to now, is the beam-beam effect with 0.3 $\%$ uncertainties compared to the optics ones of less than 1 $\%$. But this effect could be possibly corrected.

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