HIGH-β AND VERY HIGH-β OPTICS STUDIES FOR LHC

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Abstract

New high-β and very high-β optics have been sought in order to find the best possible configuration for measuring elastic scattering at the LHC. They are based on the nominal powering scheme of the low-β triplet. A list of the various possible solution is given in this report. A particularly interesting solution has been found for a case where the phase advances in both planes at the detector are close to π/2.

INTRODUCTION

Several high-β and very high-β insertions have already been studied for measuring elastic scattering at the LHC.

The last proposals done for this kind of optics featured a quasi doublet optics (gradient of $Q1$ one order of magnitude smaller than that of $Q2$ and $Q3$). Its drawback is that it needs one main power supply of 12 kA powering $Q2$ and $Q3$ and two trims power supplies of a maximum of 4 kA, for $Q1$ and $Q3$, with the same polarity [1].

The present powering scheme of the triplet allows a quasi-symmetric triplet solution. This powering scheme is imposed by the difference in construction of the triplet quadrupoles. The FNAL quadrupoles, which are used for $Q1$ and $Q3$, have a nominal current of 6 kA. The KEK quadrupoles, which are used for $Q2A$ and $Q2B$, have a nominal current of 10 kA. The present powering scheme consists of a single power supply of 6 kA nominal current for all quadrupoles which are connected in series and two trim power supplies. One bipolar trim power supply of 0.6 kA is connected to $Q1$. One unipolar trim power supply of 4 kA is connected to $Q2$.

The basic feature of a high-β insertion used for elastic scattering measurements is a detector placed at a phase advance of π/2 from the IP, i.e. a parallel to point focusing optics. The constraints imposed by this condition are examined in the next section. Then the various optics are discussed in the next following sections.

$(2N+1)\pi$/2 IN AN INSERTION

Using the standard notation and taking z for x or y, we write the transverse displacement at the point labeled i as a function of the displacement z_0 and of the scattering angle θ_{z_0} at the point labeled 0:

$$z_i = m_{z,11}\ z_0 + m_{z,12}\ \theta_{z_0} \tag{1}$$

where:

$m_{z,11} = \sqrt{\frac{\beta_i}{\beta_0}}\,[\cos(\mu_i-\mu_0)+\alpha_0\sin(\mu_i-\mu_0)]$

$m_{z,12} = \sqrt{\beta_0\beta}\sin(\mu_i-\mu_0)$

are the transfer matrix $m_{i,j}$ elements in a machine section between the point labeled 0 and the point labeled i.

A physics insertion is usually designed with $\alpha_0 = 0$. Under this condition the matrix element $m_{1,1}$ associated with the place in the insertion where the phase advance is $(2n+1)\pi$/2 is equal to zero (zero magnification). For case where the transfer matrix is kept constant, the product $\beta_0\beta$ stays equal to $m_{1,2}^2$ when the initial value β_0 is changed.

In the case of LHC, the detectors for elastic scattering measurements must be installed between the interaction point and the dispersion suppressor as there is no space to install them neither in the dispersion suppressor nor in the arc. As there are few quadrupoles in this region ($Q1$-$Q6$), there is little freedom to match the insertion. If the phase advances and the α's are matched, there is no parameter to adjust the β's. Consequently the product $\beta_0\beta$ is about constant, i.e. the effective length which is equal to $m_{1,2}$ is approximately constant at a given location in the insertion, when the value of the β-function at the IP is varied albeit being above 1km.

HIGH-β AND VERY HIGH-β SYMMETRIC TRIPLET OPTICS

High-β with π/2 at 147 m from IP in vertical plane

With the nominal triplet polarities it is possible to reproduce an optics equivalent to quasi-doublet solution described in [2] and [3]. However the value of β_y at the point with a vertical phase advance of π/2 is 11.37 m, i.e. about half the value which was obtained with the quasi-doublet solution. This explains clearly why the quasi-doublet solution was chosen. The value of β_x at the point with an horizontal phase advance of π/2, at 220 m, is 38.4 m, i.e.much larger than the value of 20 m obtained with the quasi-doublet optics. However the serious drawback is the vertical value.

With polarities of the triplet opposite to the nominal ones, the situation is similar. The value of β_y at the point with a vertical phase advance of π/2 is 10.0 m.

High-β with π/2 at 220 m from IP in vertical plane

As the horizontal β value at 220 m is larger than the vertical one at 147 m for the optics described in section , it is natural to swap the plane phases.

Doing this, the maximum value of β_0 is in the range of 1400 m. It is limited by the maximum normalized gradi-

* Financial support FPA2003-01425

ents of 6.85 10^{-3} m^{-2} of the quadrupoles $Q4-Q6$ in the downstream part of the insertion. The phase advances in this insertion can be set to the nominal ones. This has the advantage that this optics can be substituted to the nominal optics without changing anything else in the machine.

The maximum value of β_y at 220 m is obtained with a zero gradient in $Q4$ and a maximum gradient in $Q5$. This is why this optics has the serious drawback that the horizontal phase advance at 220 m is close to π. This is not convenient to identify the scattering angle of the protons at the IP. As this angle has to be restricted to small values, which reduces the efficiency of the detector. This is why another solution was sought.

High-β with π/2 at 220 m from IP in both planes

Such a solution would have the advantage that both horizontal and vertical proton tracks can be processed by the same detector. This increases significantly the efficiency of the detector. Therefore an emphasis has been put on such solutions. These solutions have been matched for version 6.4 of LHC. It has been checked that they are compatible with the new triplet layout of LHC version 6.5.

If the quadrupole gradients are maintained below their maximum values, the maximum possible value of β^* is 1270 m.

$Q6$ gradient 3.4% above nominal Allowing the gradient of the upstream $Q6$ to go 3.4% above nominal, it is possible to set the value of β^* to 1540 m. This gain was estimated to be substantial by the TOTEM collaboration so that this solution was considered as the nominal one [5]. The optics functions and the performance for this optics solution are shown on figure 1 and table 1. The beam sizes are calculated for the commissioning emittance $\epsilon_n = 1.0$ μm rad. The displacement at the detectors place z_d ($z = x, y$) has been calculated with (1) taking $z_0 = \sigma_y^*$ and $\theta_{z_0} =$ 14.3 or 3.5 μrad for total cross section and Coulomb measurement respectively. $|\theta_{min}| = d_{min}/m_{12_d}$ with d_{min} = 1.5 mm. The value of the theoretical acceptance of the detector $A_{z,d} = \frac{2}{\pi} acos \frac{d_{min}}{z_d}$ associated with these conditions is given in table 1.

Quadrupoles at ultimate If the quadrupole gradients are allowed to increase to ultimate values, i.e. 8% above the nominal (the only quadrupoles in this configuration being $Q6$ upstream and $Q8$ downstream), the value of β^* can be increased up to 2480 m. However, as pointed in section , the matrix element $m_{1,2}^2$ between the IP and the detector (the effective length) changes very little compared with the situation with nominal K's.Such an optics could be used in case the LHC energy is smaller than the nominal by more than 8%.

Very high-β with π/2 at 224 m from IP in vertical plane

Taking as starting point the optics described in sections and we have studied the possibility of increasing the value of β_0 and β_y with π/2 at approximately 220 m from IP in vertical plane. We added another degree of freedom which is the location of the point with a π/2 phase in the vertical plane lies between $Q5$ and $Q6$, i.e. 198.890 m to 225.990 m from IP.

Taking as starting point the optics described in sections and we tried to increase the value of β_0 and β_y with an additional degree of freedom which is the location of the point with a π/2 phase. Eventually we allowed the maximum gradients of quadrupoles $Q5$ and $Q6$ in the downstream and upstream part of the insertion to exceed the maximum value.

Allowing the detector to be between $Q5$ and $Q6$, i.e. 198.890 m to 225.990 m from IP, the maximum value of β_0 is 2625 m and the value of β_y is 59 m at 224 m from IP. This small value of β_y is due the vertically focusing $Q6$. For space reasons we considered a minimum distance to $Q6$ of 1.990 m, i.e. a point 224 m from IP.

The phase advances in this insertion can be set to the nominal ones by reducing slightly β_y to 51.6 m and by exceeding the ultimate limits (1.08 of maximum limits) of $Q5$ and $Q6$ by 1.215 for $Q5$ and 1.123 for $Q6$ of the upstream of the insertion and 1.151 for $Q5$ and 1.103 for $Q6$ of the downstream of the insertion. The maximum value of β_y at 224 m is 56.4 m. In this case the phase advances in the insertion deviate from the nominal values by 0.02 and the maximum gradients of $Q5$ and $Q6$ exceed the nominal values by a factor 1.250 and 1.113 respectively in the upstream part of the insertion and 1.210 and 1.135 respectively in the downstream part.

All these three optics has the serious drawback that the horizontal phase advance at 224 m is close to π so the effective length in the horizontal plane is much smaller than the vertical one. This is why another solution was sought.

Keeping the values of the maximum limits of $Q5$ and $Q6$ below the ultimate limits the maximum β_y at 224 m is 31.7 m with a ratio between the vertical and horizontal effective lengths of 3.3.

These studies showed that the maximum value obtained for β_y at a point upstream of $Q5$ with π/2 phase advance is not sufficient to perform a Coulomb measurement, the angles we have access being close to 3.5 μrad. In order to do so with β_0 close to 2625 m, the value of β_y at the detector has to be at least 70 m. This is why another solution was sought.

Very high-β with π/2 at 240 m from IP in vertical plane

Following the ideas in [4] the poinrt with a π/2 phase advance has to be set further from the IP, i.e. between $Q6$ and $Q7$ (230.79 m to 260.004 m from the IP). The

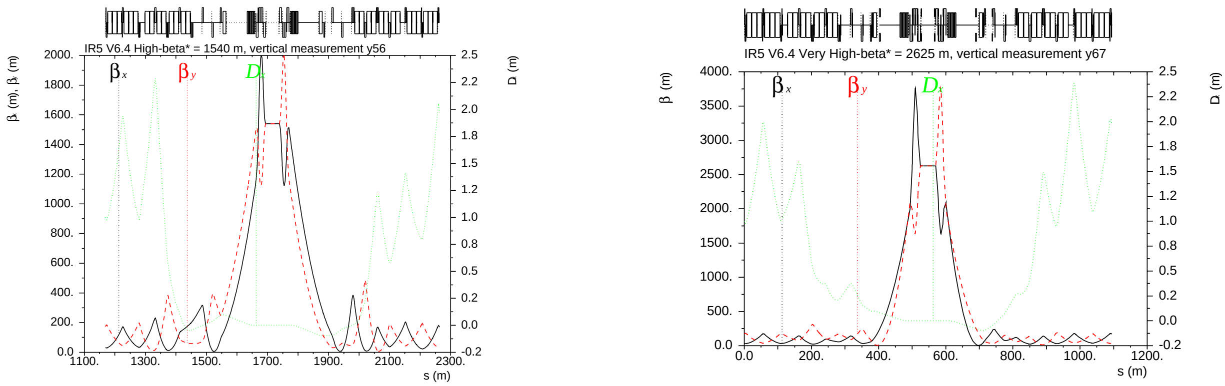

Figure 1: High-β (β^*=1540 m) and Very High-β (β^*=2625 m) symmetric triplet optics in Ring 1 around $IP5$, Version 6.4.

situation close to $Q6$, with focusing in the vertical plane, is rather similar to the situation found at 224 m. As there is not much free space in that region, the only available space not to close to $Q6$ is at 239.6 m from the IP. The maximum value of β_y, with $\pi/2$ in vertical plane is 70.9 m. In order to achieve this, the gradients of $Q5$ of the upstream and downstream part of the insertion have to exceed the ultimate values by a factor 1.242 and 1.246 respectively.

A possible solution to this problem is to reverse the polarity of $Q4$, which is possible [6] (it was turned off for the previous optics). Doing this, we found a solution with a value of β_y with $\pi/2$ in vertical plane of 76.4 m. The gradient of all quadrupoles is below the maximum limit.

These two optics solution has the serious drawback that the horizontal phase advance at 239.6 m is close to π so the effective length in the horizontal plane is much smaller than the vertical one. The ratio between the vertical and horizontal effective lengths is 9.6 and 12 respectively. This is why another solution was sought. This solution is shown on figure 1 and table 1. The ratio between the vertical and horizontal effective lengths is 3.9.

With this optics the maximum value of β_h with $\pi/2$ beyond $Q6$, at 239.6 m from the IP, is largely enough to perform a Coulomb measurement. The value of β_y of 119 m at this location is limited by the maximum gradient in $Q4$.

Table 1: Performance of high-β (β^*=1540 m) and very high-β (β^*=2625 m symmetric triplet optics Version 6.4, at 7 TeV.

ϵ_n	1.0	1.0	μm rad
σ_ϵ	0.111	0.111	10^{-3}
IP			
β^*	1540.0	2625.0	m
α^*	0.0	0.0	
D_x^*	0.0	0.0	m
$D_x^{'*}$	0.0	0.0	
σ^*	0.47	0.61	mm
$\sigma^{'*}$	0.30	0.23	μrad
$\pi/2$ location			
	total	Coulomb	m
d_{IP}	220.0	240.0	m
elements	$Q5-Q6$	$Q6-Q7$	
β_{y_d}	48.4	119.1	m
$\Delta\mu_{y_d}$	0.25	0.25	2π
$m_{y,11_d}$	0.0	0.0	
$m_{y,12_d}$	272.9	559.2	m
β_{x_d}	6.4	84.0	m
$\Delta\mu_{x_d}$	0.240	0.549	2π
$m_{x,11_d}$	0.004	-0.2	
$m_{x,12_d}$	98.8	-142.3	m
y_d	4.69	1.96	mm
$\lvert y_d/\sigma_{y_d}\rvert$	46.8	15.0	
$\lvert\theta_{y_{min}}\rvert$	5.496	2.682	μrad
A_y	0.749	0.444	

CONCLUSION

A large variety of optics has been considered for the elastic scattering measurements in LHC. An optimized solution has been found as the result of a tight collaboration between experimentalists and machine physicists.

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