Workshop on LHC Interaction Region Correction Systems, BNL, Upton, New York, 1999

BNL-66796

# LHC INTERACTION REGION CORRECTION IN HEAVY ION OPERATION*

V. Ptitsin, W. Fischer, J. Wei, BNL, Upton, NY

*Abstract*

In heavy ion operation the LHC interaction region at IP2 will have a low-$\beta$ optics for collisions. The dynamic aperture is therefore sensitive to magnetic field errors in the interaction region quadrupoles and dipoles. We investigate the effect of the magnetic field errors on the dynamic aperture and evaluate the effectiveness of local interaction region correctors. The dynamic aperture and the tune space are computed for different crossing angles.

## 1 INTRODUCTION

The LHC heavy ion collision lattice uses a low-$\beta$ insertion at IP2 in addition to low-$\beta$ insertions at IP1 and IP5 [1]. This produces large values of the $\beta$ functions in corresponding interaction region triplet quadrupoles and D1 dipoles. Furthermore, all interaction regions utilize orbit separation and crossing angle schemes. Such schemes lead to large orbit excursion inside the interaction region quadrupoles and dipoles, thus shifting the beam into the field regions with larger nonlinear fields. The basic parameters for the LHC proton and ion operation are listed in Table 1.

Table 1: Basic LHC parameters for proton operation at injection and collision and heavy ion operation at collision. $E$ denotes the particle energy, $\nu_x/\nu_y$ the horizontal and vertical tunes, $\xi_x/\xi_y$ the horizontal and vertical chromaticities, $\epsilon_N$ the normalized transverse emittance, and $\sigma_p$ the rms momentum spread.

| Quantity | p injection | p collision | ion collision |
|---|---|---|---|
| E [GeV] | 450 | 7000 | 7000/charge |
| $\nu_x/\nu_y$ | 63.28/59.31 | 63.31/59.32 | 63.31/59.32 |
| $\xi_x/\xi_y$ | 2/2 | 2/2 | 2/2 |
| $\epsilon_N$ [rad] | $3.75 \times 10^{-6}$ | $3.75 \times 10^{-6}$ | $1.5 \times 10^{-6}$ |
| $\sigma_p$ | $4.7\times10^{-4}$ | $1.1\times10^{-4}$ | $1.14\times10^{-4}$ |

We use tune footprints and the dynamic aperture (DA) to evaluate the magnetic multipole error impact and the effectiveness of correction schemes. The dynamic aperture target is set at a $12\sigma$ average over a number of random multipole error selections with a minimum of $10\sigma$, determined after 100,000 turns. We aim at tune spreads of less than $10^{-3}$ for particles with amplitudes of up to $6\sigma$.

## 2 TRACKING SETUP

The Fortran version of the TEAPOT code was used for the tracking studies. We restricted our investigation to 1,000 turns. Previous studies indicate that tracking up to $10^5$ turns further reduces the dynamic aperture by $0.5 - 1.0\sigma$ [2].

For every case we use 10 sets of randomly generated multipole errors, based on the error tables (version 2.0 for the FNAL built quadrupoles, version 2.0 and 3.0 for the KEK built quadrupoles, version 1.0 for the warm and cold D1 magnets) [2]. We excluded orbit and coupling errors from our simulations. Particles are started with $2.5\sigma$ of the momentum distribution and tracked in 6 dimensions.

## 3 RESULTS FOR LIMITING CROSSING ANGLE

The interaction region configuration of the lattice for heavy ion operation used at the tracking studies is shown in Table 2. In this section we investigate the case with the maximum crossing angle in all interaction points.

Table 2: Interaction region configuration parameters.

| | IP1 | IP2 | IP5 | IP8 |
|---|---|---|---|---|
| separ. [mm] | 0 | 0 | 0 | 1.5 hor |
| angle[$\mu$rad] | ±150 v | ±150 v | ±150 h | ±100 v |
| $\beta_x^*/\beta_y^*$ [m] | 0.5/0.5 | 0.5/0.5 | 0.5/0.5 | 33/33 |

We investigated two possible schemes of interaction region quadrupole arrangements. In the *unmixed* scheme KEK-built magnets are installed at IP1, IP2 and FNAL-built magnets at IP5, IP8. In the *mixed* scheme each interaction region contains both KEK-built (Q1,Q3) and FNAL-built (Q2A,Q2B) quadrupoles. The majority of our cases is for the mixed scheme. Table 3 presents a summary of the tracking results.

The beam dynamics is mainly determined by the magnetic field errors in the interaction region quadrupoles. However, the cold D1 magnets at IP2 reduce the dynamic aperture further by up to $2\sigma$.

An important observation is the dynamic aperture of $10.2\sigma$ average and $6\sigma$ minimum when when errors were only installed in the IP2 quadrupoles and dipoles. This is below the target dynamic aperture.

In the cases where errors were only installed at IP2 the dynamic aperture rms values are quite large. In these cases we found a vertical dynamic aperture which is about 4.5σ smaller than the the horizontal one.

* Work performed under the auspices of the US Department of Energy.

Table 3: Comparison of dynamic aperture (DA) for various triplet arrangements ($10^3$-turn DA in units of $\sigma_{xy}$ with $1\sigma_{xy}$ step size).

| Case | DA mean | DA rms | DA min |
|---|---|---|---|
| UNMIXED | | | |
| all errors | 8.3 | 1.8 | 5 |
| errors at IP2 only | 9.7 | 2.4 | 6 |
| quad error at IP2 only | 11.8 | 3.7 | 6 |
| MIXED | | | |
| all errors | 8.5 | 1.5 | 5 |
| all errors, no X-angle | 13.1 | 2.1 | 9 |
| quad errors only | 8.9 | 1.6 | 6 |
| errors at IP2 only | 10.2 | 2.3 | 6 |
| quad error at IP2 only | 11.7 | 3.5 | 6 |
| systematic errors only | 9.5 | 0.8 | 8 |
| random errors only | 12.4 | 2.2 | 8 |
| without $n = 3, 4$ errors | 9.1 | 1.8 | 6 |
| without $n = 5, 6$ errors | 11.4 | 1.4 | 7 |
| without $n = 7, 8$ errors | 8.1 | 2.5 | 5 |
| without $n = 9, 10$ errors | 9.0 | 1.7 | 6 |
| D1 dipole errors only | > physical aperture | | |

## 4 RESULTS WITH VARYING CROSSING ANGLE

In the last section we reported on tracking results for crossing angles of $\pm150\mu$rad at IP3. However, one can adopt a smaller value for the crossing angle. In such a situation the effect of the nonlinear field errors is reduced since the orbit is closer to the central axis of the interaction region magnets. We used the *mixed* arrangement for the interaction region quadrupoles and installed errors only at IP2 and IP8. No local interaction region correction has been applied.

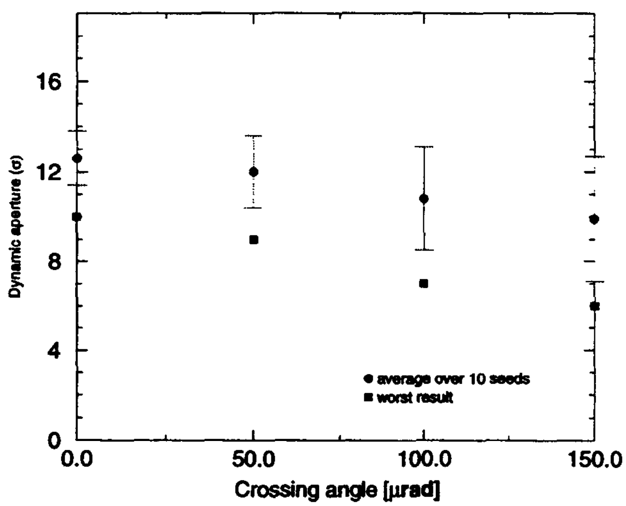


Figure 1: The 1,000 turn dynamic aperture as a function of the crossing angle at IP2.

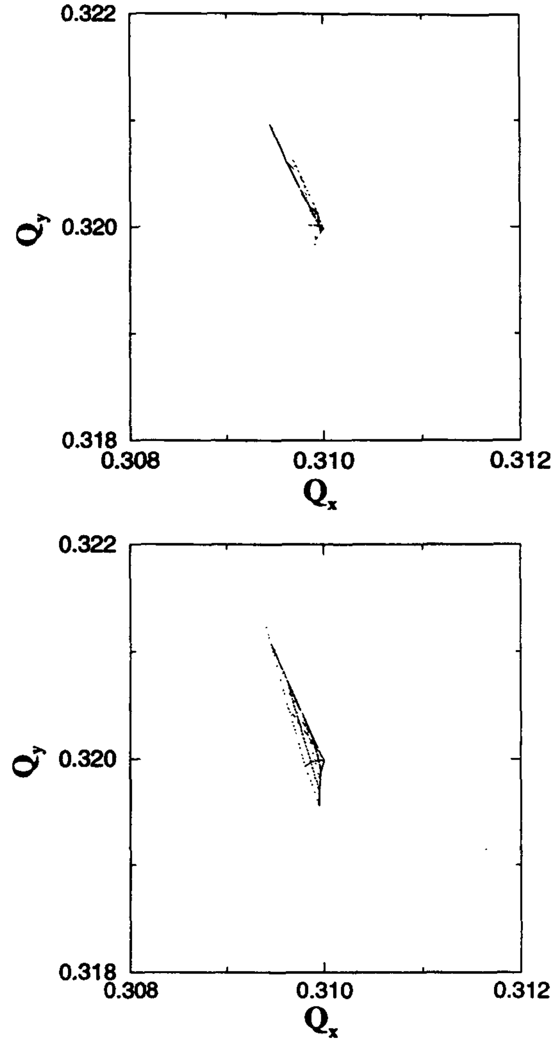


Figure 2: Tune footprints at $\pm50\mu$rad (top) and $\pm100\mu$rad (bottom) crossing angle.

Fig. 1 shows the dynamic aperture as a function of the crossing angle. The dynamic aperture increases almost linearly with an decreasing crossing angle. The target dynamic aperture of $12\sigma$ is reached at an crossing angle of about $\pm30\mu$rad.

Fig. 2 and Tab. 4 show the transverse tune space needed for a $6\sigma$ beam for different crossing angles. The results in Tab. 4 were obtained from 10 random error distributions. At $\Phi = \pm50\mu$rad the average tune space reaches the target value of $10^{-3}$.

Our results indicate that with a crossing angle larger $30-50\mu$rad interaction region correctors are required at IP2 to reach the target values for tune space and dynamic aperture.

## 5 INTERACTION REGION CORRECTION

We use the same correction scheme that is applied at IP1 and IP5 (see Ref. [3, 4], scheme 2). The local correction

Table 4: Transverse tune space needed for a $6\sigma$ beam as a function of the crossing angle $\Phi$. The average, rms and maximum value of the tune space is computed from 10 random distributions.

| $\Phi$ [$\mu$rad] | average [$10^{-3}$] | rms [$10^{-3}$] | max [$10^{-3}$] |
|---|---|---|---|
| ±150 | 2.7 | 1.5 | 4.9 |
| ±100 | 1.2 | 0.7 | 2.1 |
| ±50 | 0.8 | 0.4 | 1.5 |

Table 5: Comparison of dynamic aperture (DA) for without and with local correction at IP2.

| Case | DA mean | DA rms | DA min |
|---|---|---|---|
| correctors IP1,IP5 only | 10.5 | 3.0 | 6 |
| correctors IP1, IP2, IP5 | 17.0 | 1.7 | 13 |

at IP2 improves the dynamic aperture by $7\sigma$ at a crossing angle of $\pm 150\mu$rad (see Tab. 5).

The Fig. 3 shows the required and available corrector strengths at IP2. All strength are well within the technical limits.

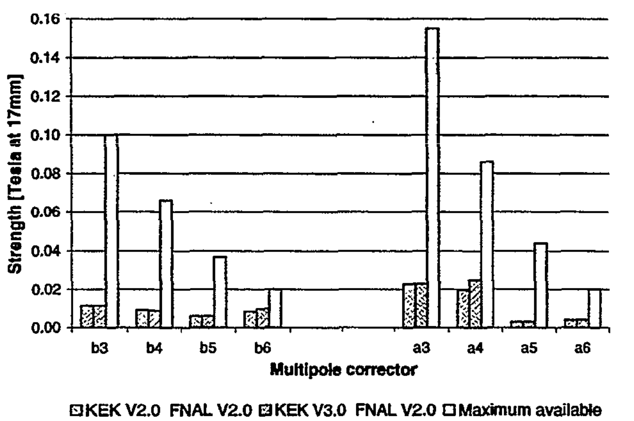


Figure 3: Available and needed corrector strength at IP2. The needed corrector strength shows the maximum out of a distribution of 10 machines.

## 6 SUMMARY

The magnetic field errors in the cold D1 magnets at IP2 reduce the dynamic aperture by 1.5–$2\sigma$. To reach the target values for the maximum tune space and the dynamic aperture the crossing angle must be smaller than $\pm 30\mu$rad if no local nonlinear correction is applied. With local correctors the crossing angle can be safely increased to $\pm 150\mu$rad. The required corrector strength is well within the limits that are technical achievable.

## 7 ACKNOWLEDGMENTS

We thank J.-P. Koutchouk, O. Brüning and R. Ostojic for lattice assistance and discussions, and many others, including A. Jain, M. Harrison, S. Peggs, S. Plate, J. Strait, R. Talman and E. Willen.

## 8 REFERENCES

[1] V. Ptitsin, S. Tepikian, J. Wei, "BNL-Built LHC Magnet Error Impact Analysis and Compensation", PAC 1999 proceedings, p. 1575.

[2] W. Fischer et al., "LHC interaction region quadrupole error impact studies", these proceedings.

[3] W. Fischer et al., "LHC interaction region correction scheme studies", these proceedings.

[4] J. Wei, "Principle of interaction region local correction", these proceedings.