ACHROMATIC LOW-BETA INTERACTION REGION DESIGN FOR AN ELECTRON-ION COLLIDER*

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Abstract

An achromatic Interaction Region (IR) design concept is presented with an emphasis on its application at an electron-ion collider. A specially-designed symmetric Chromaticity Compensation Block (CCB) induces an angle spread in the passing beam such that it cancels the chromatic kick of the final focusing quadrupoles. Two such CCB's placed symmetrically around an interaction point (IP) allow simultaneous compensation of the 1^{st}-order chromaticities and chromatic beam smear at the IP without inducing significant 2^{nd}-order aberrations. Special attention is paid to the difference in the electron and ion IR design requirements. We discuss geometric matching of the electron and ion IR footprints. We investigate limitations on the momentum acceptance in this IR design.

INTRODUCTION

In order to achieve the highest possible luminosity in a collider [1,2], the colliding beams should be focused to a small spot at the interaction point. This tight focusing is unavoidably accompanied by a large transverse beam extension before it enters the final focusing block. The size of the required beam extension is determined by the focal length of the focusing block and is closely related to the space between the Interaction Point (IP) and the nearest focusing quadrupole. The larger this distance, the greater the beam extension must be. Since the focal length of the final focusing block depends on the particle's momentum, large beam size inside the focusing quadrupoles leads to a large correlation between the particle's phase advance and its momentum. The problem with such a correlation is two-fold. First of all, it induces a large chromatic betatron tune spread. Since the available betatron tune space is limited by beam resonances, the chromatic betatron tune dependence limits the ring's momentum aperture. Secondly, the chromatic dependence of the focal length causes chromatic beam smear at the collision point, which can even dominate over the beam size due to the emittance, significantly increasing the beam spot size at the interaction point and resulting in luminosity loss. Thus, an interaction region design must employ sextupole magnets to compensate the chromatic effects [3,4]. However, the non-linear sextupole fields generate 2^{nd}- and higher-order non-linear aberrations at the interaction point, introduce non-linear phase advance and limit the ring's dynamic aperture.

The Interaction Region (IR) design approach [5] described below involves installation of a dedicated Chromaticity Compensation Block (CCB) next to the Final Focusing Block (FFB). In the CCB, certain symmetries of the beam orbital motion and dispersion are created using a symmetric arrangement of dipoles and quadrupoles. Two such CCB's are placed symmetrically around the IP. The symmetries of the beam orbital motion and dispersion in the CCB's then allow simultaneous compensation of the 1^{st}-order chromaticities and chromatic beam smear at the collision point without inducing significant 2^{nd}-order aberrations and therefore largely preserving the ring's dynamic aperture.

A schematic of the IR design is shown in Fig. 1. The Beam Extension Section (BES) first expands the beam from its regular size in the arcs to the size required for final focusing. The beam next passes through the CCB, which creates in it an angle spread negatively correlated with the chromatic kick of the FFB, so that FFB's chromatic effect is cancelled. The FFB then focuses the beam to the required spot size at the IP.

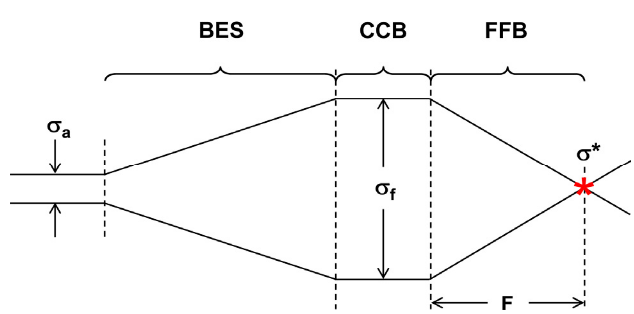

Figure 1: Schematic of the Interaction Region (IR) design consisting of the Beam Extension Section (BES), Chromaticity Compensation Block (CCB), and Final Focusing Block (FFB).

CCB

Interaction region design requirements up to 2^{nd} order can be expressed analytically by the following five nonlinear equations [5]:

$$2\int_0^* Dn_s x^2 ds = \int_0^* nx^2 ds \quad (1), \qquad 2\int_0^* Dn_s y^2 ds = \int_0^* ny^2 ds \quad (2),$$

$$2\int_0^* D(Dn_s - n)x ds = 0 \quad (3), \qquad \int_0^* n_s x^3 ds = 0 \quad (4),$$

$$\int_0^* n_s x y^2 ds = 0 \quad (5),$$

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Supported in part by Muons, Inc.

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where n and n_s are the normalized quadrupole and sextupole strengths, respectively, D is the dispersion, and x and y are the dominant *parallel* ("cos"-like) components of the particle *betatron* trajectory at the entrance into the CCB. The integration is performed from the start of the beam extension to the IP. These equations are an analytic representation of the common interaction region design constraints. However, by imposing certain symmetries with respect to the center of the CCB, namely,

$$\begin{aligned} &x(s) = \mp x(-s), \quad y^2(s) = y^2(-s), \quad D(s) = \pm D(-s), \\ &n(s) = n(-s), \quad n_s(s) = \pm n_s(-s), \end{aligned} \tag{6}$$

the conditions of Eqs. (1)-(5) are reduced to just the first two, (1) and (2). While creating chromatic kick, the CCB does not generate the non-linear aberrations associated with the 2nd-order effects of the dispersion and transverse beam sizes in sextupole fields. All these terms corresponding to Eqs. (3), (4) and (5) are automatically compensated inside the CCB due to the symmetric dispersion and betatron motion design and lattice symmetry.

The conditions of Eqs. (1)-(5) ignore the effect of the beam angular spread, which is admittedly small since the beam is assumed to be greatly extended and almost parallel at the entrance into the CCB. However, this effect may adversely affect the ring's dynamic aperture. A conceptual drawing of a CCB with an even symmetry of the dispersion and an odd symmetry of the horizontal betatron trajectory is shown in Fig. 2. If one then uses an even symmetry of the sextupole fields, Eqs. (3), (4) and (5) are automatically satisfied. The two remaining "original" chromaticity compensation conditions of Eqs. (1) and (2) are satisfied by adjusting the sextupole fields. This can be achieved by using the difference in behavior of the horizontal and vertical beta-functions.

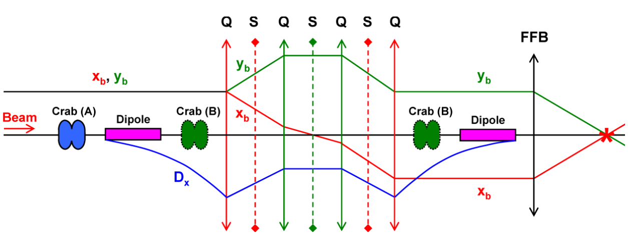

Figure 2: A conceptual drawing of a CCB with an even-symmetry dispersion and an odd-symmetry horizontal betatron trajectory.

In Fig. 2, there are two identical bends at the beginning and at the end of the CCB, which generate and then suppress the dispersion while quadrupole optics ensures the appropriate symmetries of the betatron and dispersive orbital components with respect to the center of the CCB. In an electron ring, since the CCB dipoles are located in regions with large beta function values, their maximum bending fields and therefore the maximum practical dispersion value are limited due to the emittance degradation impact of the bending magnets. In an ion ring, on the other hand, it is advantageous to have strong bends to produce large dispersion thus reducing required sextupole fields and their non-linear effects. These contradicting bend requirements complicate geometric matching of the footprints of the electron and ion interaction regions. The solution presented below involves use of alternating bends in the ion CCB. Also for the purpose of the electron and ion rings' geometric matching, both the electron and ion CCB's located on the opposite sides of the IP have their bends reversed. The resulting layout of the electron and ion interaction regions together is shown in Fig. 3. The IR geometries in Fig. 3 were adjusted to produce a 60 mrad beams' crossing angle at the IP.

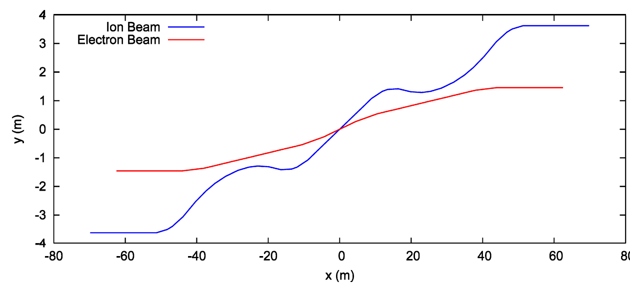

Figure 3: Scaled layout of the electron and ion interaction regions together, produced using MAD-X survey output.

Since the chromaticity scheme is independent of particular BES and FFB implementations, below we will focus on the CCB design. Figure 4 shows the optics of the electron CCB. The bends are chosen to keep electron emittance increase caused by the bends at an acceptable level. Seven quadrupoles are placed symmetrically between the bends. The quadrupoles' positions and strengths are adjusted to attain a CCB transfer matrix that meets the symmetry requirements of Eq. (6). Because of the weak bends the maximum value of the dispersion is only about 25 cm.

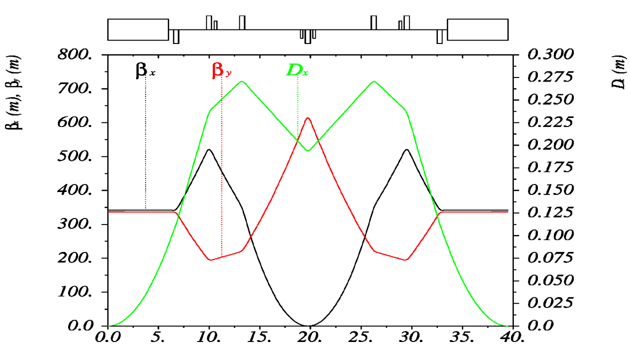

Figure 4: Optics of the electron CCB.

Optics of the ion CCB is shown in Fig. 5. The design concept of the ion IR is the same as of the electron IR;

therefore, only the main differences need to be pointed out. The CCB bends are made much stronger producing the maximum dispersion of about 1.25 m. Each ion CCB contains alternating bends to ensure geometric footprint matching with the electron IR. However, the ion CCB still satisfies all of the symmetry requirements. For the ion FFB, the distance from the IP to the front face of the nearest quad is 7 m. Since the beta functions grow as a square of the distance from the IP, the maximum beta functions for ions are a factor of 4 greater than those for electrons.

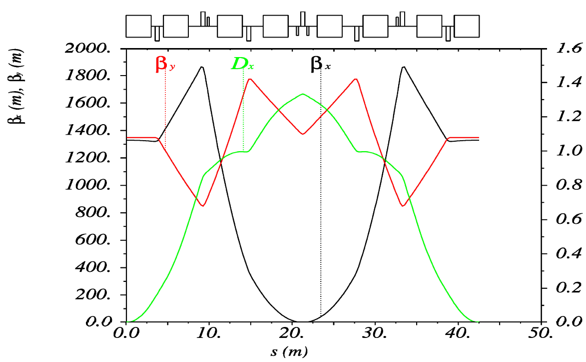

Figure 5: Optics of the ion CCB.

CHROMATICITY COMPENSATION

In accordance with the chromaticity compensation concept discussed above, two sextupole pairs are inserted in each CCB. The sextupoles in each pair are identical and are placed symmetrically with respect to the center of the CCB. Placement of sextupoles is shown by the shorter bars in Figs. 4 and 5 for the electron and ion CCB's, respectively. The sextupole positions are chosen at the points where the dispersion is near maximum and there is a large difference between the horizontal and vertical beta functions. The two parameters corresponding to the strengths of the sextupole pairs are adjusted to compensate the horizontal and vertical linear chromaticities.

The horizontal/vertical chromaticity values before the chromaticity compensation were $\xi_{x,y} = -226\,/\,-218$ for electrons and $\xi_{x,y} = -320\,/\,-397$ for ions. The two sextupole families in each ring are used to adjust the slopes of the chromatic horizontal and vertical betatron tune curves to zero. The chromatic tune dependence before and after the compensation is shown for the electron collider ring in Fig. 6. Figures 7 show a similar graph for the ion collider ring. Chromatic correction for the electron ring needs optimization. It does not work as well as for ions because the dispersion is relatively small in the electron CCB's. Modifying the electron CCB's to raise their dispersion should improve the electron ring's chromatic tune dependence. This can be done, for instance, by placing a relatively strong dipole in the middle of the electron CCB where the horizontal beta function is small and the dipole would not significantly affect the equilibrium emittance but where it could still be used to manipulate the dispersion increasing its value. Another possible path for raising the dispersion is to focus the electron beam in the horizontal plane towards the end of the CCB dipoles while preserving the CCB's symmetry properties. This would greatly reduce emittance degradation inside the dipoles allowing one to make them stronger. Making the CCB longer would also help increase the dispersion. Octupole compensation of the 2nd order chromaticities can be explored.

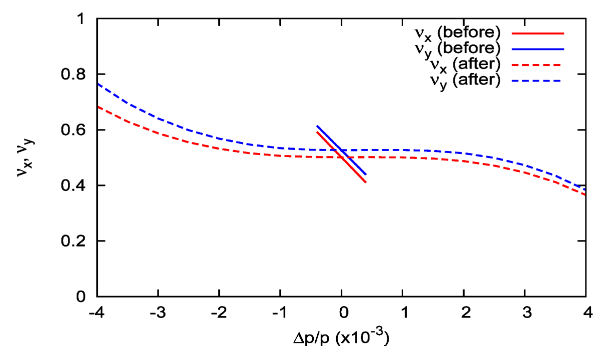

Figure 6: Chromatic dependence of the fractional betatron tunes for the electron ring before and after the sextupole chromaticity compensation.

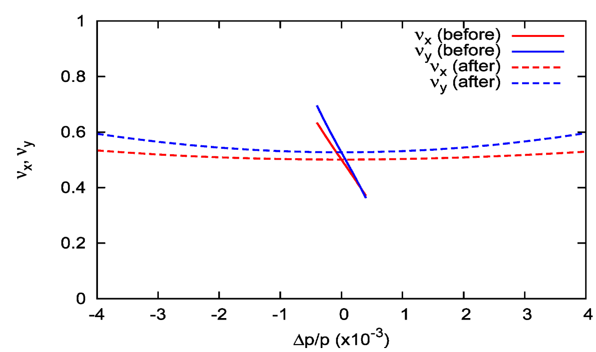

Figure 7: Chromatic dependence of the fractional betatron tunes for the ion ring before and after the sextupole chromaticity compensation.

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