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PROGRESS ON OPTIMIZATION OF THE NONLINEAR BEAM DYNAMICS IN THE MEIC COLLIDER RINGS*

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Abstract

One of the key design features of the Medium-energy Electron-Ion Collider (MEIC) proposed by Jefferson Lab is a small beta function at the interaction point (IP) allowing one to achieve a high luminosity of up to 10^{34} cm^{-2}s^{-1}. The required strong beam focusing unavoidably causes large chromatic effects such as chromatic tune spread and beam smear at the IP, which need to be compensated. This paper reports recent progress in our development of a chromaticity correction scheme for the ion ring including optimization of dynamic aperture and momentum acceptance.

INTRODUCTION

Design of the Medium-energy Electron-Ion Collider (MEIC) [1] at Jefferson Lab is aimed at reaching high luminosity of up to 10^{34} cm^{-2}s^{-1}. The latter requires a small beam size and, therefore, small beta function (β^*) at the interaction point (IP). As a result, beta functions in the nearest to IP final focusing quadrupoles (FFQ) become very large ($\propto 1/\beta^*$) making the FFQ the main source of chromaticity in the ring. Since the FFQ linear chromaticity (i.e. first order tune shift with momentum deviation $\delta_p = \Delta p/p$) is straightforward to cancel with conventional two-family sextupoles in the ring arcs, the main concern is the large non-linear chromaticity. The latter is driven by a large perturbation of momentum dependent beta function created by the FFQ chromatic kick. This perturbation could lead to a strong non-linear momentum dependence of tune and the β^*. The increased tune spread could excite stronger effects of betatron resonances on dynamic aperture, thus limiting the momentum acceptance; and the IP chromatic beam smear would increase the effective beam size resulting in a lower luminosity. To compensate the FFQ non-linear chromaticity, a dedicated correction system is required. This paper presents a study of two correction options for the ion ring including the results of dynamic aperture optimization.

LATTICE

The MEIC ring circumference has been recently increased to $\simeq 2.2$ km [1]. This allows the re-use of the PEP-II High Energy Ring [2] components in the electron ring and the use of super-ferric magnets [3] in the ion ring. The two rings are stacked vertically in the same tunnel and have a figure-8 layout, as shown in Fig. 1, which optimizes preservation of the ion polarization [4]. The design collision beam energies are: 3-10 GeV for electrons, 20-100 GeV for protons, and up to 40 GeV per nucleon for ions. Each ring consists of two 90° FODO arcs and two long straight sections. One straight contains the interaction region (IR), a polarimeter, a cooling section and tune trombone, while the other FODO straight houses accelerating cavities and can be upgraded to a second IR in the future. The beams collide at 50 mrad horizontal angle at the IP.

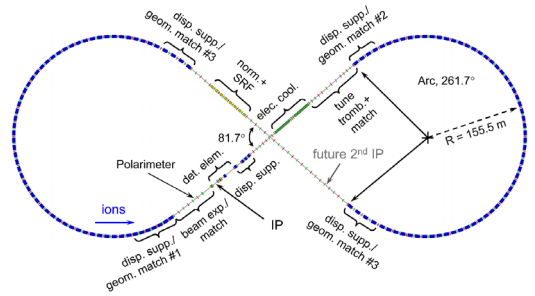

Figure 1: Top view layout of the ion ring.

The ion ring lattice (before chromaticity correction adjustment) is shown in Fig. 2, where the machine natural chromaticity is $\xi_{x,y} = [-101.1, -111.6]$. The two FODO arcs are the only dispersive regions suitable for the chromaticity correcting sextupoles. The IR optics is shown in Fig. 3, where $\beta^*_{x,y} = 10 \times 2$ cm corresponding to the IP rms beam size of $\sigma^*_{x,y} = 18 \times 3.6\ \mu$m for 100 GeV protons. Due to the detector requirements, the IR optics is made asymmetric with 7 m free space downstream of IP versus 3.6 m on the upstream side. This results in a factor of 3 higher beta functions in the downstream FFQ leading to stronger chromatic perturbation. The downstream side also includes a detector spectrometer optics with a second focal point which further increases the IR chromatic asymmetry.

CHROMATICITY CORRECTION

As pointed out, the large non-linear chromaticity generated by the FFQs requires a dedicated correction. Due to the $\simeq \pi$ phase advance between the upstream and downstream FFQs their chromatic contributions add up. If not locally cancelled, the chromatic beta perturbation would propagate around the ring giving rise to large non-linear momentum dependence of the tune. A conventional solution is to use local sextupoles generating a chromatic beta wave opposite to the one from FFQ, so they cancel each other. A separate local correction is needed on each side of IP in order to avoid the IP chromatic beam smear. Desired conditions at

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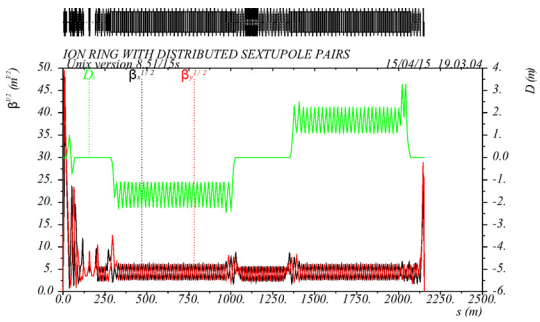

Figure 2: The ion ring lattice starting from IP.

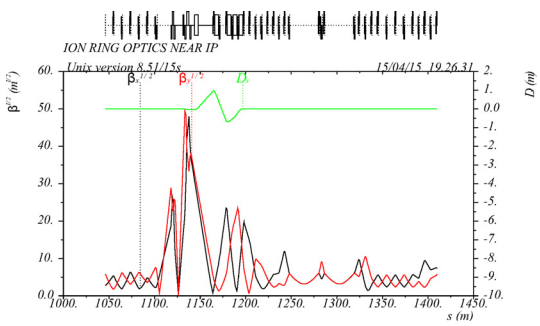

Figure 3: The ion ring IR and adjacent lattice.

the sextupoles for an efficient correction are: 1) large dispersion and beta function to achieve compensation with a reasonable sextupole field; 2) $\simeq n\pi$ phase advance between the FFQ and the sextupoles (in the correcting plane); 3) large β_x/β_y and β_y/β_x ratio at the x and y sextupoles for orthogonal correction; 4) minimal optics between the sextupoles and FFQ for minimal distortions due to chromaticity from other quadrupoles in this region.

Unfortunately, the sextupole non-linear fields also generate the 2nd and higher order geometric (amplitude dependent) aberrations resulting in non-linear tune shift and excitation of the 3rd and higher order resonances. These effects can significantly limit the beam dynamic aperture (DA). A common way to compensate these aberrations is to use non-interleaved pairs of identical sextupoles with $-I$ separation between them. As demonstrated at KEKB [5], a pseudo $-I$ separation can be also used which differs from $-I$ in that the matrix terms (2,1) and (4,3) are not zero. The latter adds flexibility to the sextupole optics. The geometric effects can be also suppressed by applying special optics conditions at the sextupoles such as in the compact chromaticity compensation block (CCB) [6] developed for the earlier MEIC design.

Several non-linear chromaticity correction options are currently under study for the MEIC ion ring. These include: 1) non-interleaved $-I$ sextupole pairs with large beta functions; 2) distributed interleaved $-I$ pairs with nominal FODO beta functions; 3) distributed interleaved $-I$ pairs with large beta functions (as e.g. in Ref. [7]); 4) compact CCB design as described in Ref. [6]. In all options the FFQ correcting sextupoles are placed in the arc sections nearest to the IP. The other part of the arcs is reserved for correction of the remaining linear chromaticity using periodic two-family sextupoles. Below we discuss performance of the first two correction options including DA optimization.

Non-interleaved $-I$ Sextupole Pairs

Schematic of the non-interleaved $-I$ sextupole pairs on one side of IP is shown in Fig. 4. In this case we use a pseudo $-I$ separation as it gives more optical flexibility. Two pairs on each side of IP correct the x and y FFQ non-linear chromaticity. The quadrupole strengths were adjusted to create high beta functions and large beta ratio at these pairs as shown in Fig. 5. The remaining machine linear chromaticity is canceled using two-family sextupoles in twelve 90° cells of each arc. The use of multiple of four cells in this case provides compensation of the sextupole second order geometric and chromatic effects [8].

The correcting sextupole strengths were obtained using MAD [9]. First, the $-I$ sextupole strengths were set to cancel the chromatic beta perturbation (W-function in MAD) at the IP and minimize its amplitude in the rest of the ring. This way both the IP chromatic beam smear and the 2nd order term of chromatic tune shift are minimized. Note that the sextupoles downstream of IP are stronger due to the higher FFQ beta functions and additional optics on this side. Secondly, the two-family periodic sextupoles were set to cancel the remaining linear chromaticity. The required sextupole strengths are quite modest even at the top proton energy (<0.4 T at 4 cm radius). As shown in Fig. 6, the momentum dependence of tune and β^* are well corrected for the shown range of $\delta_p = \pm 10\sigma_p$, where the tune and linear chromaticity are $\nu_{x,y} = [24.22, 23.16]$ and $\xi_{x,y} = +2$.

The choice of the above tune is based on a dynamic aperture tune scan (at $\delta_p = 0$) performed in LEGO [10], as shown in Fig. 7, where the tune adjustment was done using a thin lens trombone. One can see that the maximum DA occurs in the first quarter above integer. The final selection also took into account the impact on chromatic tune shift.

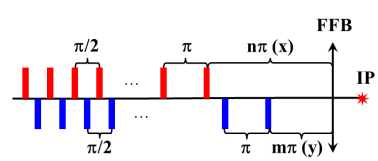

Figure 4: Two non-interleaved $-I$ sextupole pairs near IP.

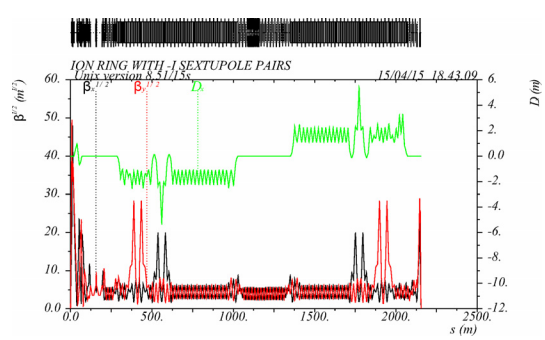

Figure 5: Modified ion ring optics with high beta at non-interleaved x and y correcting sextupole pairs.

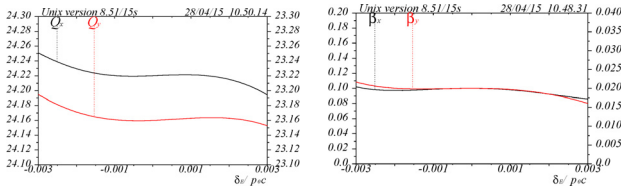

Figure 6: Tune (left) and β^* (right) versus δ_p with non-interleaved $-I$ sextupole pairs.

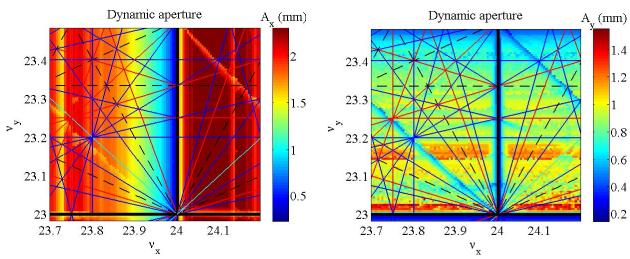

Figure 7: Horizontal (left) and vertical (right) DA at IP versus tune with non-interleaved $-I$ sextupole pairs.

Tune shift with amplitude was also calculated in LEGO tracking and found to be relatively small (<0.03), thus confirming the self-compensation of the geometric effects. The corresponding frequency map of the tune footprint is shown in Fig. 8 (left), where some impact of high order resonances can be seen, for example $3\nu_x+2\nu_y$ and $6\nu_y$ resonances. Dynamic aperture at IP for the ring without errors is shown in Fig. 8 (right). The on-momentum DA is sufficient ($\simeq 40\sigma$) even for a large beam size at 20 GeV proton energy. The momentum range of ±0.4% is also sufficient ($13\sigma_p$).

Distributed Interleaved $-I$ Sextupole Pairs

The scheme of interleaved distributed $-I$ sextupole pairs is shown in Fig. 9. Here, the relatively low periodic FODO beta functions are used at the sextupoles, as in Fig. 2. Therefore, more sextupole pairs are needed for the FFQ correction. Total of 8 and 10 pairs were used upstream and downstream of IP, respectively. The two additional downstream pairs are included due to the higher FFQ beta functions on this side. Since the $-I$ pairs are interleaved, this can lead to higher order aberrations. The small beta ratio makes the x and y corrections less orthogonal resulting in stronger sextupoles and contribution to out-of-phase chromaticity. Linear chromaticity is cancelled with two-family sextupoles in

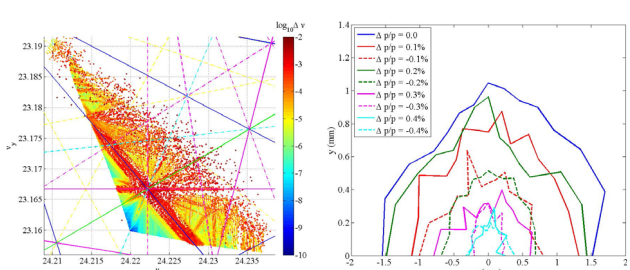

Figure 8: Left: Tune footprint with non-interleaved $-I$ sextupole pairs. The color reflects tune diffusion ($\log\sqrt{(\Delta\nu_x)^2+(\Delta\nu_y)^2}$). Right: DA at IP for δ_p up to ±0.4%.

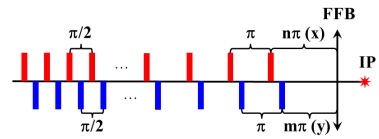

Figure 9: Distributed interleaved $-I$ sextupole pairs.

8 other cells of each arc. The sextupole strengths are a factor of 2.5 higher than in the non-interleaved scheme, but still acceptable. The betatron tune was not yet optimized and set at [24.625, 24.320]. The momentum dependent tune and β^* for $\xi = 0$ are shown in Fig. 10. The stronger non-linear dependence, as compared to Fig. 6, is due to less local and less orthogonal compensation. Figure 11 shows a slightly larger geometric tune spread (0.04) and a factor of 2 reduced vertical DA as compared to Fig. 8. This may be due to the stronger non-linear geometric effects in this scheme as well as not yet optimized tune. The momentum range is also reduced to δ_p<0.3%, consistent with larger non-linear chromaticity.

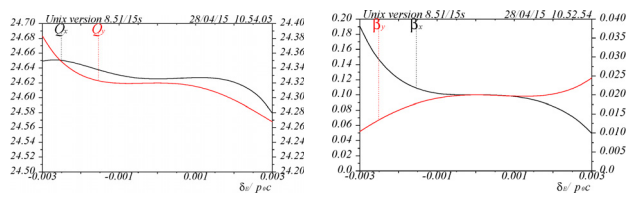

Figure 10: Tune (left) and β^* (right) versus δ_p with distributed interleaved $-I$ sextupole pairs.

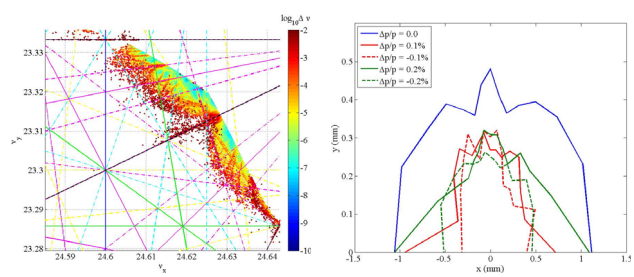

Figure 11: Tune footprint (left) and dynamic aperture (right) with distributed interleaved $-I$ sextupole pairs.

CONCLUSIONS

The study of two chromaticity correction options for the MEIC ion ring showed that the scheme with non-interleaved $-I$ sextupole pairs provided a better performance as compared to the one based on distributed interleaved $-I$ pairs. This is due to the more local and orthogonal x and y correction, as well as better compensation of sextupole geometric effects in the first scheme. The corresponding dynamic aperture and momentum range are sufficient. Further improvement to both schemes can include a fine tuning of the sextupole phase advance relative to the FFQ [11]. The second scheme performance can be also improved by optimizing the betatron tune. Two other correction options will be

studied in the future which will allow us to make a comparison and select the best scheme.

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