# Beam Stay Clear Issues in the Far-Forward Tracking Region

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The placement of the Far-Forward tracking detectors ($20\,\mathrm{m} < z_{\mathrm{ion}} \leq 36\mathrm{m}$) must be compatible with a full range of ion species from hydrogen to lead, and must be compatible with both the fully accelerated, cooled beam in collision mode and the injected beam before cooling and acceleration. The tentative conclusion of this discussion is that the beam stay clear during injection should be a constant 3 cm radius in the Far-Forward tracking region. Following acceleration and cooling, specialized tracking detectors in 'Roman Pots' can be brought closer to the beam near the secondary focus.

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## I. INTRODUCTION

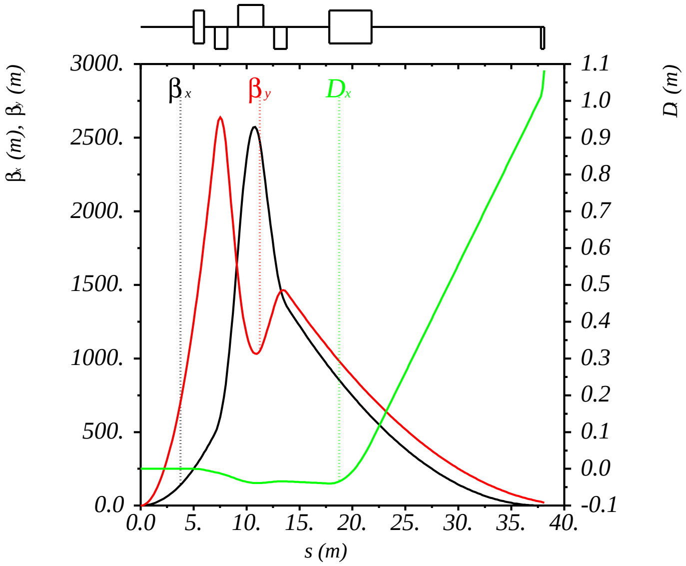

FIG. 1. MEIC Interaction Point optics for the ion beam. Left axis is $\beta_X(s)$ (black) and $\beta_Y(s)$ (red). Right axis is the Dispersion $D_X(s)$ (green).

The JLab MEIC design calls for electron cooling of the fully accelerated ion beams in order to achieve and maintain a small emittance, and therefore high luminosity. Concomitant with the small emittance is a very small $\beta^*$ at the interaction point (IP). The ion optics in the vicinity of the IP are illustrated in Fig. 1. Table I summarizes the beam parameters in fully accelerated collision mode [1].

## II. BEAM ENVELOPE AND BEAM-STAY-CLEAR

The r.m.s. beam envelope (1-$\sigma$) is defined by

$$\sigma_{x,y}(s) = \sqrt{\epsilon_{x,y}\beta_{x,y}(s)} = \sqrt{\epsilon_{N;x,y}\frac{M}{P}\beta_{x,y}(s)} \tag{1}$$

The exact Beam-Stay-Clear (BSC) is an engineering choice, but is currently set at $10\sigma$. Thus no obstruction is allowed to be closed to the beam line than:

$$\mathrm{BSC} = 10\sigma_{x,y}(s) = 10\sqrt{\epsilon_{N;x,y}\frac{M}{P}\beta_{x,y}(s)} \tag{2}$$

One of the purposes of this note is to explore the limitations the BSC imposes on the detector design.

TABLE I. JLab MEIC beam parameters for full acceptance detector. Values from Table 5.2 of 2012 EIC White Paper [1].

| Description | Units | Protons | Electrons |
|---|---|---|---|
| Momentum | (GeV/c) | 60 | 5 |
| Collision frequency | (GHz) | 0.75 | |
| Particles per bunch | $10^{10}$ | 0.416 | 2.5 |
| Beam current | (A) | 0.5 | 3 |
| Polarization | (%) | 70 | 80 |
| RMS bunch length | (mm) | 10 | 7.5 |
| Normalized emit. | ($\epsilon_{N,x}$ / $\epsilon_{N,y}$) ($10^{-6}$ m) | 0.35/0.07 | 53.5/10.7 |
| Horizontal: $\beta_x^*$ | (cm) | 10 | |
| Vertical: $\beta_y^*$ | (cm) | 2 | |
| Vert. beam-beam tune-shift | (rad) | 0.015 | 0.03 |
| Laslett tune-shift | (rad) | 0.06 | Small |
| Detector space at IP | (m) | ±7 | ±3.5 |
| Luminosity | ($10^{33}$ cm$^{-1}$s$^{-1}$) | 5.6 | |

## III. FAR FORWARD SPECTROMETER

The downstream ion optics are designed to have full acceptance for scattering angles up to 0.5 degrees, and to produce a secondary focus with high dispersion at $s \approx 36$ m. The focus and dispersion are illustrated in Fig. 1. The dispersion is achieved with a large (60 mrad bend angle) dipole at $s \approx 20$ m. In a drift space around a focal point $s_0$, the beta-function has the form

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*} \tag{3}$$

From a data table of the beta-functions [2] at the secondary focus (SF),

$$\beta_x^*(\mathrm{SF}) = 0.425\,\mathrm{m}, \qquad s_{0,x}(\mathrm{SF}) = 37.80\,\mathrm{m}, \tag{4}$$

and

$$\beta_y^*(\mathrm{SF}) = 0.525\,\mathrm{m}, \qquad s_{0,y}(\mathrm{SF}) = 41.48\,\mathrm{m}. \tag{5}$$

Similarly, the horizontal dispersion ($dx/d\delta$) in this region is well described by:

$$D_x(s) = [0.0586/(100\%)]\,[s - (20.53\,\mathrm{m})]\,. \tag{6}$$

In a region of high dispersion, the envelope equation 1 must be modified by the contribution of the intrinsic momentum spread of the beam:

$$\sigma_{x,y}^2(s) = \epsilon_{N;x,y}\frac{M}{P}\beta_{x,y}(s) + [D(s)\sigma(\delta)]^2 \tag{7}$$

The ion rms momentum spread is

$$\sigma(\delta) = \frac{\sigma(\delta P)}{P} = 5 \cdot 10^{-4} \tag{8}$$

The beam envelopes for 20, 60, and 100 GeV/c protons are plotted in Fig. 2. With 6 Tesla peak fields, the quadrupoles are designed to have a line-of-sight aperture to the IP of 10 mrad (not including the 6 mrad bend of the first dipole) Thus at the maximum horizontal spread of the beam at $s \approx 7.5$ m, the $10\sigma$ BSC is still within the quadrupole aperture, even for 20 GeV/c protons. (cooled to the normalized emittance of Table I).

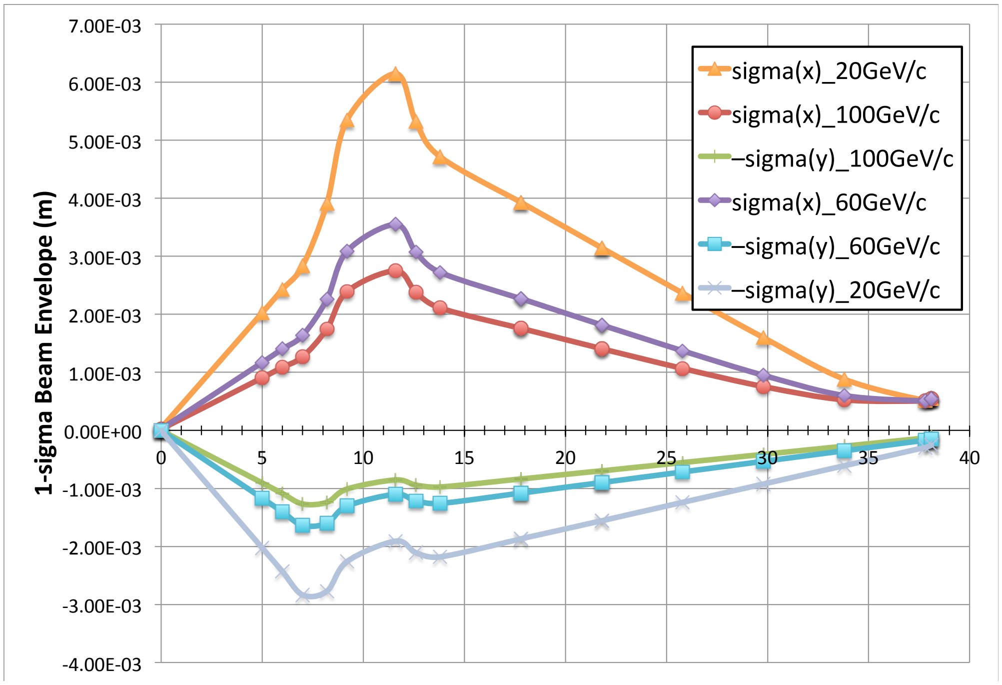

FIG. 2. Beam envelope (1-$\sigma$) for protons, as a function of distance $s$ (m) downstream of the full acceptance IP. The curves are distorted by the discreteness of the points in $s$. The $x$- and $y$-envelopes are displayed as + and − values, respectively, for clarity. The normalized emittance is the fully cooled value of Table I. At the secondary focus of $s \approx 38$ m, the $x$-envelope is dominated by the dispersion (at least for $P \geq 60$ GeV/c).

Downstream of the large dipole ($22\,\text{m} < s < 38\,\text{m}$), the $10\sigma$ BSC of Fig. 2 is $\leq 2$ cm for $P \geq 60$ GeV/c. However, if we want to consider high luminosity collisions for proton momenta as low as 20 GeV/c, then the BSC at the exit of the large dipole must be increased to 3 cm.

## IV. INJECTION

The proton beam is injected into the MEIC ring at 20 GeV/c with a normalized emittance (symmetric in $x$ and $y$?):

$$\epsilon_N(\text{injection}) = 4 \cdot 10^{-6}\,\text{m} \tag{9}$$

This is slightly more than a factor of 10 worse than the normalized emittance of the final cooled beam, tuned for collisions. Obviously, at this emittance, the IP cannot be configured with the short $\beta^*$ for *ep* collisions – the beam would be $\sqrt{11}$ times bigger in horizontal size and would scrape on the quadrupole apertures. Instead, the entire IP region must be tuned to a much 'flatter' design, closer to the standard FODO cells of the arcs.

In general, if the strengths of the Final Focus Quadrupoles (FFQ) are adjusted, the product of the minimum and maximum $\beta$ values will be a constant. Thus for the $x, y$ values at the IP

$$\left.\begin{array}{l}\beta_x^*\beta_x^{\mathrm{Max}}\\ \beta_y^*\beta_y^{\mathrm{Max}}\end{array}\right\} = \left\{\begin{array}{l}(0.10\,\mathrm{m})(2301\,\mathrm{m}) = 230\,\mathrm{m}^2\\ (0.02\,\mathrm{m})(2450\,\mathrm{m}) = 490\,\mathrm{m}^2\end{array}\right. \tag{10}$$

A conservative choice would reduce the $\beta^{\mathrm{Max}}$ values by a factor of 20 at injection. This would increase the $\beta^*$ values by the same factor of 20 at injection. At the IP, this would produce an injected beam spot size of

$$\sigma_x^{IP}(\text{injection}) = \sqrt{(4\cdot 10^{-6}\mathrm{m})\frac{0.938\,\mathrm{GeV}}{20\,\mathrm{GeV}}(2\,\mathrm{m})} = 0.6\,\mathrm{mm} \tag{11}$$

This will likely have no effect on the IP design.

For the Far-Forward tracking region, applying the same scaling to the minimum $\beta^*$ at the secondary focus:

$$\beta^*(\text{SF, Injection}) \approx 20\beta^*(\text{SF}) \tag{12}$$

yields

$$\beta_x^*(\text{SF, Injection}) \approx 8.5\,\mathrm{m}, \qquad \text{and} \quad \beta_y^*(\text{SF, Injection}) \approx 10.5\,\mathrm{m}. \tag{13}$$

The 1-$\sigma$ beam envelope at injection is illustrated in Fig. 3 for the Far-Forward region.

## V. ION OPTICS SCALING WITH $Z$ AND $A$

The design of the beam optics and apertures must accommodate ions from H to Pb. A full study of ion beams in the MEIC has not been completed. However, a number of scaling laws can be inferred, and are implicit in the MEIC white paper [3] and the earlier ELIC ZDR report [4] (see particularly Section VI, Table 3.3.1, p. 116).

In this discussion of ion scaling, I am comparing a proton beam of momentum $P_0$ to to an ion beam of fully stripped species $^{A}Z$ of momentum $ZP_0$. Thus all dipoles and quadrupoles in the lattice have the same settings for the two beams, the $\beta$-functions, *etcetera* are identical.

### A. Ion Beam Current Scaling

The intra-beam beam-beam tune shift determines the scaling of the total current in the ion beam. For a given current $I$ in the beam, the intra-beam force on an ion will scale as $ZI$. Therefore, the beam disruption $F/P$ scales as $ZI/(ZP_0) = I/P_0$, or independent of beam

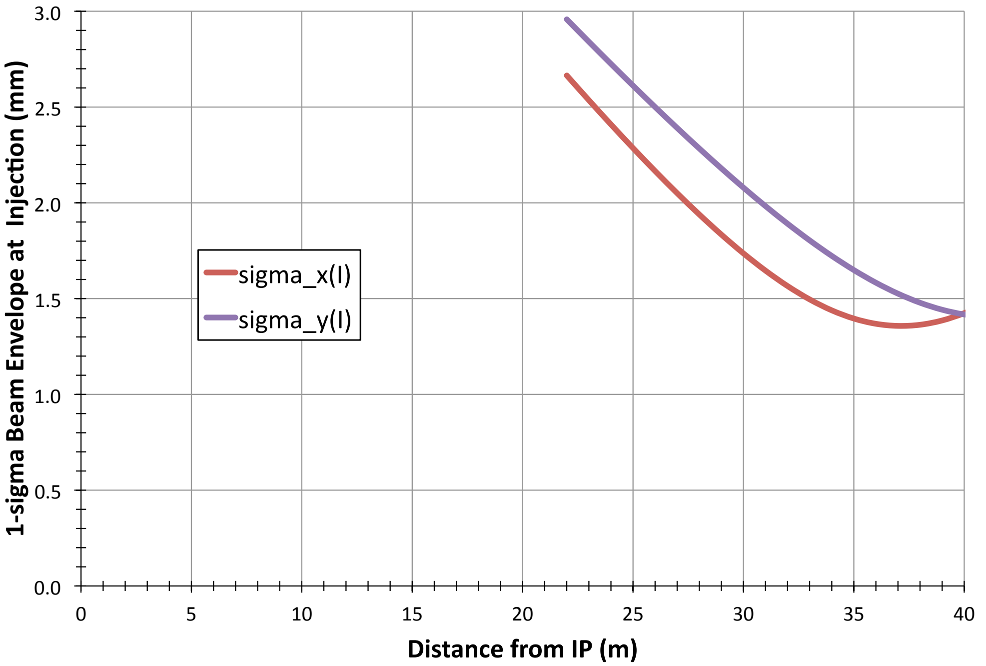

FIG. 3. Beam envelope (1-$\sigma$) for protons, at injection in the MEIC ring at 20 GeV/c and $\epsilon_N = 4\,\mu$m in the Far-Forward tracking region.

species. This implies that all beams will have the same current, as indicated in Table 3.3.1 of the ELIC ZDR [4]. *There may be a small fallacy in this argument. The net disruption of the beam scales as $FT$, where $T$ is the orbital period. The period scales inversely with the velocity, and therefore scales as*

$$T \sim \frac{1}{v} = \frac{E}{P} \sim \frac{\sqrt{(ZP_0) + (AM)^2}}{ZP_0} = \sqrt{1 + \left(\frac{A}{Z}\frac{M}{P_0}\right)^2} \tag{14}$$

*Thus there may be a requirement to reduce the ion beam by the factor $[1 + AM/(ZP_0)]^{1/2}$. For the fully accelerated ions with $P_0 = 100$ GeV/c, this is an almost negligible correction. However, if this scaling must be applied in the pre-booster at much lower energies, then the effect will be greater. For the time being, however, we will ignore this issue, and assume constant currents.*

## B. Ion Beam Emittance Scaling

For a given electron cooling beam, the cooling force on each ion scales as $Z$. If the primary beam heating is electron-ion beam tune shift, then if the ion beam has the same *geometrical* emittance as the proton beam, then the individual ions (on the same trajectories as the protons) will experience heating forces $Z$ times greater. This is an argument that electron cooling will achieve the same geometrical emittance for protons and ions, and therefore the normalized emittance of ions will scale as:

$$\epsilon_{N;x,y}(^{A}Z) \approx \frac{Z}{A}\epsilon_{N;x,y}(p) \tag{15}$$

This is the scaling proposed in Table 3.3.1 of Section VI of the ELIC ZDR [4]. The beam injected into the MEIC ring at $Z$20 GeV/c has been cooled in the pre-booster. Therefore this $Z/A$ scaling of the normalized emittance should apply to injected beam (proton normalized emittance $4\,\mu$m) as well as the fully accelerated beam.

In conclusion, the best estimate is that for a given lattice tune, the beam envelope is independent of ion species:

$$\text{Envelope}\left(^{A}Z\right) \sim \sqrt{\epsilon_N(^{A}Z)\frac{M_A}{P}\beta} \sim \sqrt{\frac{Z}{A}\epsilon_N(p)\frac{AM}{ZP_0}\beta} = \sqrt{\epsilon_N(p)\frac{M}{P_0}\beta} = \text{Envelope}\,(p) \tag{16}$$

Thus all of the arguments presented above regarding the BSC of proton beams during injection, acceleration, cooling, and collisions, will remain unchanged for ion beams.

## VI. CONCLUSION

In conclusion, the beam pipe at the exit of the 60 mrad bend dipole should have a radius of 3 cm. This can be inferred from both Figs. 2 and 3. This will accommodate $10\sigma$ Beam-Stay-Clear for all ion species (H to Pb) and for both the the injection beam at $P_0 = 20$ GeV/c and the fully cooled beam at proton equivalent momenta $P_0$ from 20 to 100 GeV/c (ion beam momenta $P = ZP$). At some point in the Far-Forward drift space, the vacuum pipe should expand to larger radius, to allow the installation of movable 'Roman Pot' style trackers. To achieve full acceptance tracking, these detectors must with be moved into position with high-precision after the cooling and acceleration. Depending upon the final accelerated momentum, the leading edges of the tracking elements should just clear the $10\sigma$ BSC. As can be seen in Fig. 2, the horizontal (x) BSC at $s = 38$ m is only 5mm, nearly independent of final momentum.

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[1] A. Accardi, J. L. Albacete, M. Anselmino, N. Armesto, E. C. Aschenauer, A. Bacchetta, D. Boer and W. Brooks *et al.*, arXiv:1212.1701 [nucl-ex].

[2] V. Morozov, MEIC Optics Table, Private Communication, 2 Oct 2013.

[3] S. Abeyratne, A. Accardi, S. Ahmed, D. Barber, J. Bisognano, A. Bogacz, A. Castilla and P. Chevtsov *et al.*, arXiv:1209.0757 [physics.acc-ph].

[4] JLab ELIC Zero Design Report (ZDR) prepared for NSAC, 2007 (draft): `http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/NSAC2007/070118_elic_zdr.pdf` also, `http://www.jlab.org/elic/reports.html`