INTERACTION REGION DESIGN AND DETECTOR INTEGRATION AT JLAB'S MEIC

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Abstract

The Electron Ion Collider (EIC) will be a next-generation facility for the study of the strong interaction (QCD). JLab's Medium-energy Electron Ion Collider (MEIC) is designed for high luminosities of up to 10^{34} $cm^{-2}s^{-1}$. This is achieved in part due to an aggressively small beta-star, which imposes stringent requirements on the collider rings' dynamical properties. Additionally, one of the unique features of MEIC is a full-acceptance detector with a dedicated, small-angle, high-resolution detection system, capable of covering a wide range of momenta (and charge-to-mass ratios) with respect to the original ion beam to enable access to new physics. The detector design relies on a number of features, such as a 50 mrad beam crossing angle, large-aperture ion and electron final focusing quads and spectrometer dipoles as well as a large machine-element-free detection space downstream of the final focusing quads. We present an interaction region (IR) design developed with close integration of the detection and beam dynamical aspects. The dynamical aspect of the design rests on a symmetry-based concept for compensation of non-linear effects. The optics and geometry have been optimized to accommodate the detection requirements and to ensure the interaction region's modularity for easiness of integration into the collider ring lattices. As a result, the design offers an excellent detector performance combined with the necessary non-linear dynamical properties.

INTRODUCTION

The MEIC accelerator complex at Jefferson Lab is designed to pursue a high luminosity to understand QCD in the nuclear physics programs [1]. As an interface between the beam acceleration/transport system and the detector, the interaction region (IR) is one of the most challenging parts of the MEIC design and largely determines the performance of the detectors and colliders. To achieve the required physics goals, the IR design should go through an optimization process between the physics requirements and accelerator performance. Besides, as part of the optics design of the complete accelerator complex, the IR design should also consider the modularity for its integration into the collider rings. This paper provides an overall consideration from the detection and accelerator performance points of view in the IR design and demonstrates a well-developed multi-function MEIC IR layout.

IR DESIGN REQUIREMENTS AND CONSTRAINTS

Detector Requirements

The primary full-acceptance detector has a sufficiently large magnet-free space near the interaction point (IP) for detection of particles down to about 0.5° in front of the final focus blocks. In addition, to allow detection of particles scattered between 0-0.5°, the hadrons and electrons need to pass through the large-aperture final focusing quadrupoles and are detected by the further downstream (up to 37 m) detector components. To maximize the detector's acceptance to the forwarding-scattered hadrons and electrons, both the ion and electron beams are focused downstream of the forward final focus so that small beam sizes at the focal points allow one to place the detectors closer to the beam centers. In combination with ~1 m dispersion at those points, this allows detection of particles with small momentum offset *Δp/p*. This optics was optimized to maximize its angular and momentum acceptance and detector resolution [2].

The considerations of detection performance in the IR design can be comprehensively described as follows,

1. large detector space (-4.4m / +7m) for a full-acceptance detector,
2. detection of forward scattered hadrons down to 0° achieved by
   - large aperture downstream ion final focusing quadrupoles,
   - strong spectrometer dipole,
   - large machine-element-free drift space after the spectrometer dipole,
   - secondary focus after the spectrometer dipole combined with large dispersion for better momentum resolution,
3. detection of low-Q^2 electrons and electron momentum analysis,
4. large 50 mrad crab crossing angle for faster beam separation to
   - reduce parasitic collisions due to high repetition rate,
   - increase space for magnets,
   - obtain better detector resolution,
5. IP locations
   - close to exit from ion arcs to reduce the residual gas scattering background,
   - far from exit from electron arcs to reduce synchrotron radiation background.

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Beam Dynamic Requirements

To achieve the required high luminosity, the colliding beams are strongly focused to a small spot at the IP, associated with a large transverse beam expansion before its focusing. This unavoidably induces a large chromatic betatron tune spread and chromatic beam smear at the collision point. The betatron tune spread is limited by the beam resonances and therefore restricts the ring's momentum aperture. The chromatic beam smear increases the beam spot size at the IP, resulting in a luminosity loss. A dedicated compensation approach to the chromatic effects has been reported and studied systematically by using a symmetric Chromaticity Compensation Block (CCB) [3,4,5,6,7]. The symmetries of particle's orbital motions and dispersion in the CCB allow simultaneous compensation of the 1st-order chromaticities and chromatic beam smear at the collision point without inducing significant 2nd-order aberrations and therefore preserving the ring's dynamic aperture.

In addition, the IR design was performed to consider a simultaneous optimization of chromatic compensation and detector requirements. Such an optimized optics is asymmetrically detector-optimized, with the upstream final focusing elements placed much closer to the IP than those on the downstream side, as shown in Figs. 1 and 2 for the MEIC ion and electron collider rings. This will be beneficial in reducing both the maximum betatron functions on the upstream side and the contribution to the chromaticity.

The layout of magnets in this detector-optimized optics is shown in Fig. 3, a complete 3D model of the detector region implemented using G4beamline/GEANT4 [7]. Special attention was paid to sizes and positions of the detector region elements to avoid interference with each other and with the detector functionality. For example, i) two permanent magnetic quadrupoles were used in the electron upstream final focusing block so that they are very close to the IP to maximize the detector acceptance by reducing the solid angle blocked by the final focusing quadrupoles; ii) the upstream ion final focusing block was designed using standard ring elements as much as possible and its layout was adjusted to minimize its interference with the forward electron detection; iii) the apertures and position of the downstream electron final focusing block were optimized to maximize the forward electron acceptance while ensuring proper fit of the electron and ion quads.

Geometric Constraints

The figure-8 MEIC collider rings are designed to have two collider rings' arcs vertically stacked in the same underground tunnel. Each arc bends the beam by 240° in the horizontal plane and two arcs in one ring are connected by straights with 60° crossing angle. With the 50 mrad crab crossing angle between the two collider rings at the IP, the geometry of the IR affects the overall ring geometry. The optics design decouples this dependence of the ring geometry from the IR design by imposing the following constraints to both electron and ion ring.

1. Electron ring
   - IR
     - zero net bend and zero transverse beam shift on each side of the IP,
   - Arcs
     - 240° bending angle including the spin rotators,

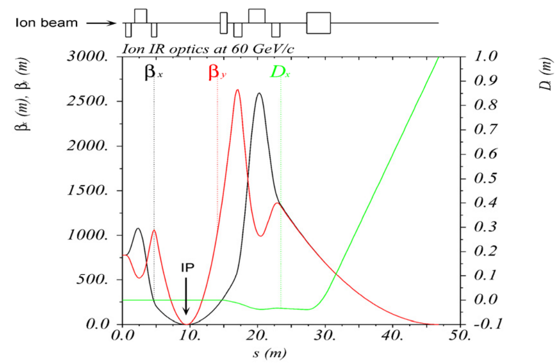

Figure 1: Detector region optics in the MEIC ion collider ring.

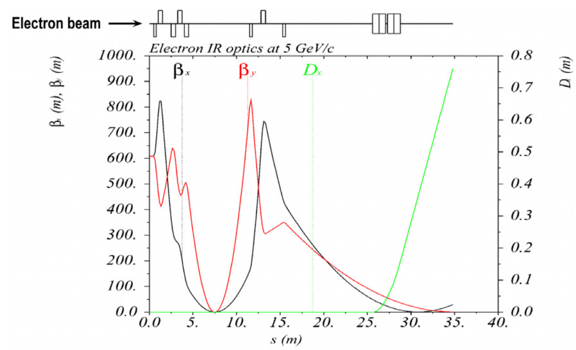

Figure 2: Detector region optics in the MEIC electron collider ring.

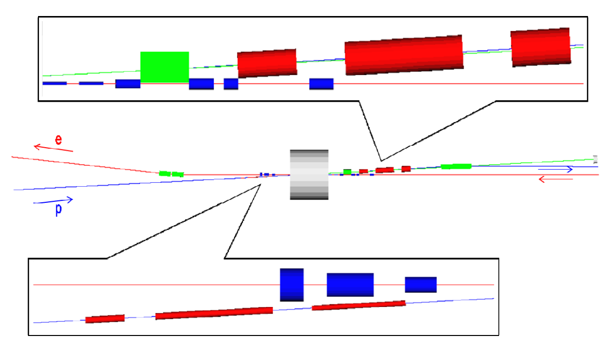

Figure 3: Layout of magnets in the detector region of MEIC collider rings.

2. Ion ring
   - IR
     - 50mrad net bend on each side of the IP to compensate the crossing angle (opposite bends on two sides of the IP),

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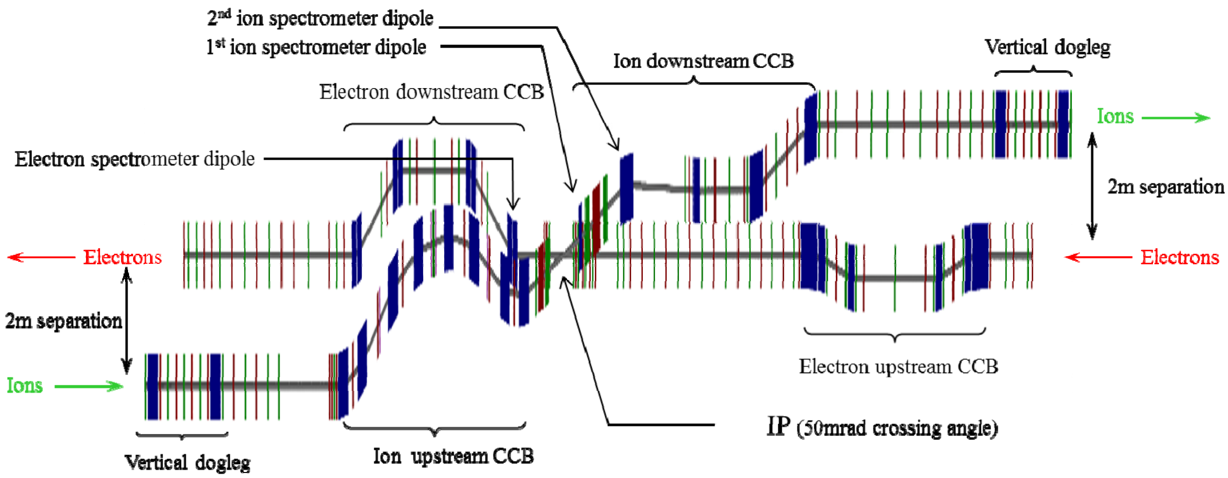

Figure 4: MEIC interaction region components and layout.

- ◦ 2m transverse beam shift on each side of the IP with respect to the electron ring,
- – Arcs
  - ◦ 240° arc bend,
  - ◦ 2m transverse separation from the electron ring at the arc ends.

These geometric constraints to the optics promise that the IR design is modular and any lattice changes in the IR will not interfere with the rest of the collider rings' configuration.

Combining all these considerations of detection, beam dynamics and geometry requirements, the interaction region components and its layout are shown in Fig. 4. Note that the two beam lines are parallel at the entrance and the exit of the interaction region with 2 m separation on each side. In order to compensate the chromatic aberrations at the IP and in the ring, each collider ring has two CCBs located upstream and downstream of the IP. The ion upstream and downstream CCBs produce a 50 mrad net bending angle for the crab crossing. The electron upstream CCB is moved away from the IP to avoid synchrotron radiation background in the detector.

CONCLUSIONS

An asymmetric detector-optimized IR optics design was developed for a full-acceptance detector simultaneously considering the detection requirements, chromatic compensation and rings' geometric constraints. The design provides the necessary properties of both the physics detection and beam dynamical aspects. In addition, such optics and geometry guarantee that the interaction region is modular and can be easily integrated into the collider ring lattices. We next plan to validate the design by tracking simulations.

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