DESIGN STUDIES FOR MEIC: Medium Energy Electron -Ion Collider at Jlab

Hisham Sayed
(JLAB/ODU)
A. Bogacz

For the JLab (CASA) MEIC Study Group
Outline

• Introduction to the MEIC
• Machine Design
• Electron Ring
• Chromaticity Correction
• Universal spin rotator
• Summary
ELIC: JLAB’s Future Nuclear Science Program

- JLab has been developing a design of an electron-ion collider (ELIC) based on the CEBAF recirculating SRF linac for nearly a decade.

- Requirements of the future nuclear science program drives ELIC design efforts to focus on achieving
  - ultra high luminosity per detector (up to $10^{35}$ at high energy) in multiple detectors
  - very high polarization (>80%) for both electrons & light ions

- **Medium-energy Electron Ion Collider (MEIC) project.**
  - A stage to be a good compromise between science, technology and project cost
    - Energy range is up to 60 GeV ions and 11 GeV electrons
  - A well-defined upgrade capability to higher energies is maintained
  - High luminosity & high polarization continue to be the design drivers
Jefferson Lab Now
Luminosity

General luminosity formula for any e-p collider

\[ L = \frac{N_e N_p N_B f_{rev}}{2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2} \sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}} \]

\( N_p \) (\( N_e \)) Number of protons (electrons) per bunch
\( N_B \) Number of bunches
\( f_{rev} \) revolution frequency
\( \sigma_p \) (\( \sigma_e \)) rms beam sizes
ELIC considerations

• Luminosity is dominated by proton beam parameters
  – Minimum achievable $\epsilon$ (space-charge & IBS fundamental limits –cooling solution ?)
  – Minimum achievable $\beta^*$
    • limited by FF quad aperture at $\beta_{\text{max}}$ (LHC magnet aperture 70 mm)
    • ability to correct chromaticity specially with 7 m focal length)
    • Hour glass effect - Bunch length ( $\beta^* \sim \sigma_s$ )

Electron FF parameters are then matched to achieve values of proton beam ($\sigma_{p,x}^* = \sigma_{e,x}^*$ & $\sigma_{p,y}^* = \sigma_{e,y}^*$)
1. Beam cross sections of proton & leptons have to match to limit the nonlinearity of the beam-beam interaction
\[ \sigma^*_{p,x} = \sigma^*_{e,x} \quad \sigma^*_{p,y} = \sigma^*_{e,y} \]

2. The total beam current of lepton beam is limited by the available rf power
\[ N_e = \frac{I_e}{(e \cdot N_B \cdot f_{rev})} \]

3. \( N_p \) limited by space charge effects in the injector chain.

4. The beam size at IP limited by \( \beta^{\text{max}} \) of protons at IR FF quads

\[ L = \frac{I_e N_p \gamma_p}{4\pi e \sqrt{\beta_{xp}^* \beta_{yp}^* \sqrt{\epsilon_x N \epsilon_y N}}} \]
Luminosity beam-beam tune-shift relationship

- **Linear beam-beam tune shift**
  \[ \xi_x^i = \frac{N_i r_i}{2\pi \gamma_i} \frac{1}{\varepsilon_x^i \left(1 + \frac{\sigma_y}{\sigma_x}\right)} \quad \xi_y^i = \frac{N_i r_i}{2\pi \gamma_i} \frac{1}{\varepsilon_y^i \left(1 + \frac{\sigma_y}{\sigma_x}\right) \left(\sigma_x / \sigma_y\right)} \]

- Express Luminosity in terms of the (larger!) vertical tune shift (i either 1 or 2)
  \[ L = \frac{f N \xi_y^i \gamma_i}{2 r_i \beta^*} \left(1 + \frac{\sigma_y}{\sigma_x}\right) = \frac{I_i \xi_y^i \gamma_i}{e 2 r_i \beta^*} \left(1 + \frac{\sigma_y}{\sigma_x}\right) \]

- Necessary, **but not sufficient**, for self-consistent design

- Expressed in this way, and given a “known” limit to the beam-beam tune shift, the only variables to manipulate to increase luminosity are the stored current, the aspect ratio, and the $\beta^*$ (beta function value at the interaction point)

- Applies to ERL-ring colliders, stored beam (ions) only
Energy Recovery Linac – Storage Ring (ERL-R)
ERL with Circulator Ring – Storage Ring (CR-R)
Back to Ring-Ring (R-R) – by taking advantage of CEBAF as full energy polarized injector
Challenge: high current polarized electron source
  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA

12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of ring-ring design
CEBAF-based R-R design preserves high luminosity and high polarization (+polarized positrons…)
Medium Energy EIC

Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)
Detailed Layout

- Prebooster
- Ion source
- SRF Linac
- 60 GeV/c proton collider ring

- Big booster (up to 12 GeV/c)
- Warm ring
- 3 Figure-8 rings stacked vertically
- Ion ring jump
- Medium energy IP with horizontal crab crossing
- Cold ring
- Electron ring
- Injector
- 12 GeV CEBAF

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JSA
**Stage** | **Max. Energy (GeV/c)** | **Ring Size (m)** | **Ring Type** | **IP #**
---|---|---|---|---
Medium | 96 | 11 | 1000 | Cold, Warm | 3
High | 250 | 20 | 2500 | Cold, Warm | 4

Serves as a large booster to the full energy collider ring
MEIC

Ring-Ring Design Features

- Ultra high luminosity
- Polarized electrons and polarized light ions
- Up to three IPs (detectors) for high science productivity
- "Figure-8" ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
- Present CEBAF injector meets MEIC requirements
  - 12 GeV CEBAF can serve as a full energy injector
    - Simultaneous operation of collider & CEBAF fixed target program possible
- Experiments with polarized positron beam would be possible
Figure-8 Ion Rings

• Figure-8 optimum for polarized ion beams
  – Simple solution to preserve full ion polarization by avoiding spin resonances during acceleration
  – Energy independence of spin tune
  – $g$-2 is small for deuterons; a figure-8 ring is the only practical way to arrange for longitudinal spin polarization at interaction point
  – Transverse polarization for deuteron looks feasible
  – Long straights can be useful
    • Allows multiple interactions in the same straight – can help with chromatic correction
  – Only disadvantage is relatively small cost increase
Adopts Proven Luminosity Approaches

High luminosity at B factories comes from
• Very small $\beta^*$ (~6 mm) to reach very small spot sizes at collision points
• Very short bunch length ($\sigma_z \sim \beta^*$) to avoid hour-glass effect
• Very small bunch charge which makes very short bunch possible
• High bunch repetition rate restores high average current and luminosity
• Synchrotron radiation damping

⇒ KEK-B and PEPII already over $2 \times 10^{34} / \text{cm}^2/\text{s}$

<table>
<thead>
<tr>
<th></th>
<th>KEK B</th>
<th>MEIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition Rate</td>
<td>MHz</td>
<td>509</td>
</tr>
<tr>
<td>Particles per Bunch</td>
<td>$10^{10}$</td>
<td>3.3/1.4</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1.2/1.8</td>
</tr>
<tr>
<td>Bunch length</td>
<td>cm</td>
<td>0.6</td>
</tr>
<tr>
<td>Horizontal &amp; Vertical $\beta^*$</td>
<td>cm</td>
<td>56/0.56</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>20</td>
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</tbody>
</table>

JLab believes these ideas should be replicated in the next electron-ion collider
### Design Parameters for a Full Acceptance Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Electron</th>
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<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
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<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
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<tr>
<td>Beam Current</td>
<td>A</td>
<td>1</td>
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<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
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<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
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<tr>
<td>RMS bunch length</td>
<td>mm</td>
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<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
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<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
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<tr>
<td>Horizontal $\beta^*$</td>
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<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>2</td>
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<tr>
<td>Vertical beam-beam tune shift</td>
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<td>0.007</td>
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<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
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<tr>
<td>Distance from IP to 1$^{\text{st}}$ FF quad</td>
<td>m</td>
<td>7</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>5.6</td>
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Luminosity Vs. CM Energy

https://eic.jlab.org/wiki/index.php/Machine_designs
**MEIC** Electron Figure-8 Collider Ring

- **Spin Rotator**
  - $(8.8^\circ / 4.4^\circ, 50 \text{ m})$
- **IR**
  - $(60 \text{ m})$
- **RF Straight**
  - $(20 \text{ m})$
- **1/4 Electron Arc**
  - $(106.8^\circ, 117.5 \text{ m})$
- **Experimental Hall**
  - (radius $15 \text{ m}$)
- **Figure-8 crossing angle**: $2 \times 30^\circ$
- **Polarimetry**
- **Injection from CEBAF**
Electron Collider Ring

Electron ring is designed in a modular way

- two long (140 m) straights (for two IPs)
- two short (20 m) straights (for RF module), dispersion free
- four identical (106.8°) quarter arcs, made of 135° phase advance FODO cell with dispersion suppressing
- four 50 m long electron spin rotator blocks

<table>
<thead>
<tr>
<th></th>
<th>Length</th>
<th>Field</th>
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<tr>
<td>Dipole</td>
<td>1.1 m</td>
<td>1.25 T (2.14 deg)</td>
</tr>
<tr>
<td>Quad</td>
<td>0.4 m</td>
<td>9 kG/cm</td>
</tr>
<tr>
<td>Cell</td>
<td>4 m</td>
<td></td>
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135° FODO Cell for arc

One quarter arc

2 dis. sup. cells

26 FODO cells

2 dis. sup. cells

Figure-8 Collider Ring - Footprint

circumference ~1000 m
MEIC ring

A. Bogacz
Arc Cells

- 135 phase advance per cell for minimum equilibrium emittance
- Dispersion is well tailored to add chromatic correction sextupoles

Arc dipoles:
Lb=1.10 m
B=1.25 T
ang=2.14 deg.
rho = 29.4 meter

Arc quadrupoles
Lq=0.40 m
G= 0.99 T

135° FODO offers emittance preserving optics
– ⟨H⟩ minimum for FODO lattices

Synchrotron radiation power per meter less than 20 kW/m
Interaction Region

- ‘Relaxed’ IR Design:
- Beam Stay Clear and FF quad apertures
- Chromaticity Compensating Optics
  - Uncompensated dispersion in the straights
  - Anti-symmetric dispersion pattern across the IR
  - Dedicated Symmetric Inserts around the IR
- Forward detection/tagging, low $Q^2$ tagging

\[ \beta_x^* = 10 \text{ cm} \]
\[ \beta_y^* = 2 \text{ cm} \]
Detector and IR layout

- low-$Q^2$ electron detection
- dipole
- large aperture electron quads
- central detector with endcaps
- dipole
- ion quads
- small diameter electron quads
- ~50 mrad crossing
- 5 m solenoid
- ultra forward hadron detection
- ultra forward hadron detection
- central detector with endcaps
- dipole
- ion quads
- small diameter electron quads
Interaction Region

\[ \ell^* = 3.5 \text{m} \]

FF doublets

\[ D = \frac{3.5^2}{2 \times 10^{-2}} \approx 6.5 \times 10^2 \text{m} \]

\[ \beta^\text{ff} = \ell^* \frac{\beta^*}{\beta} = \frac{3.5^2}{2 \times 10^{-2}} \approx 6.5 \times 10^2 \text{m} \]

\[ \xi_{\text{IR}} \sim \frac{\ell^*}{\beta^*} \frac{\beta^*}{f} = \frac{f}{\beta^*} \]

\[ \zeta_1 := \frac{1}{4 \pi} \int_0^l \beta_x (-g_0 + \eta_0 g_1) \, ds \]

Natural Chromaticity:

\[ \zeta_x = -47 \quad \zeta_y = -66 \]
Two Interaction Region

Two Symmetric IP’s at the same straight with antisymmetric dispersion Phase between IP1-IP2 adjusted to cancel second order chromaticity.

Matching to Arc

Matching to second IR
Reduce Luminosity

Smearing of image at IP \( \beta \)-chromaticity

Phase advance change with \( \delta p/p \)

Reduce momentum acceptance

Chromatic Aberration

Tune dependence on \( \delta p/p \) Chromaticity

Particle loss ring stability

concerns for the final focusing in a storage ring

Reduce Touschek lifetime

concerns for the final focusing in a linear collider

ELIC \( \rightarrow \) fix both problems
Montague Chromatic function

Sextupoles off
The Hamiltonian of a particle moving in a circular accelerator

\[ H(x, y, p_x, p_y) = -(1 + x K_x) \sqrt{(1 + \delta)^2 - p_x^2 - p_y^2 + \frac{1}{2} (1 + x K_x)^2} + \sum_{n=0}^{\infty} \frac{g_n}{(n+2)!} \sum_{m=0}^{(n/2)+1} (-1)^m \times \text{Binomial}[n + 2, m] x^{n+2-2m} y^{2m} \]

Expansion of the tune with momentum deviation \( \delta_p \)

\[ \zeta = \sum \delta^n \zeta_n \]

**First Order Chromaticity**

\[ \zeta_{1x} = \frac{1}{4\pi} \int_0^s \left( -\beta_x \left( K^2 + g_0 - g_1 \eta_0 \right) - 2\alpha_x K \eta'_0 + \gamma_x K \eta_0 \right) ds \]

\[ \zeta_{1y} = \frac{1}{4\pi} \int_0^s \left( \beta_y \left( g_0 - g_1 \eta_0 \right) + \gamma_y K \eta_0 \right) ds \]

\[ \gamma = \left( K^2 + g_0 \right) \beta + \frac{1}{2} \beta'' \]

**Radius of curvature**

**Quadrupole field**

**Dispersion**

**Sextupole field**

\( \alpha \) & \( \beta \) twiss parameters
Chromaticity
Analytical Approach

• Second Order Chromaticity:

\[
\zeta_{2x} = \frac{1}{4\pi} \left( \int_0^l \beta(s) G_2(s) ds - \frac{1}{16} \mu_0 a_1^2(0) - \sum_{n=1}^{\infty} \frac{\mu_0^3}{8\mu_0^2 - \pi^2 n^2} (a_1^2[n] + b_1^2[n]) \right)
\]

Where

\[
a_{x,1}[n] = \frac{2}{\mu_x} \int_0^l \left( \left( G_{1,x} - \frac{1}{2\beta_x} \left( \frac{2\pi n}{\mu_x} \right)^2 K_x \eta_0 \right) \cos \left[ \frac{2\pi n}{\mu_x} \phi_x \right] + \frac{2\pi n}{\mu_x} \left( \frac{\alpha_x}{\beta_x} K_x \eta_0 - K_x \eta_0' \right) \sin \left[ \frac{2\pi n}{\mu_x} \phi_x \right] \right) ds
\]

\[
b_{x,1}[n] = \frac{2}{\mu_x} \int_0^l \left( \left( G_{1,x} - \frac{1}{2\beta_x} \left( \frac{2\pi n}{\mu_x} \right)^2 K_x \eta_0 \right) \sin \left[ \frac{2\pi n}{\mu_x} \phi_x \right] - \frac{2\pi n}{\mu_x} \left( \frac{\alpha_x}{\beta_x} K_x \eta_0 - K_x \eta_0' \right) \cos \left[ \frac{2\pi n}{\mu_x} \phi_x \right] \right) ds
\]

\[\Phi\] betatron phase

\[G_{1,x} = -\beta_x \left( K_x^2 + g_0 - g_1 \eta_0 \right) - 2\alpha_x K_x \eta_0' + \gamma_x K_x \eta_0\]
Manipulating Chromaticity
Analytical Approach

– Assuming straight section (MEIC IR case)

\[ \zeta_1 = \frac{1}{4\pi} \int_0^l \beta_x \left( -g_0 + \eta_0 g_1 \right) ds \]

\[ \zeta_1 \sim 0 \quad \text{for Sextupole field} \quad g_1 \sim g_0/\eta_0 \]

\[ \zeta_2 = \frac{1}{4\pi} \int_0^l \left( \beta_x \frac{g_0 \eta_1}{\eta_0} + \frac{3}{2}\beta_x g_0 \eta_0^2 + \frac{3}{4} \eta_0^2 \beta_x''' + \frac{\beta_x}{2} g_2 \eta_0^2 \right) ds \]

\[ \zeta_2 \sim 0 \quad \text{for octupole field} \]

\[ g_2 = \frac{-2}{\beta_x \eta_0^2} \left( \beta_x g_0 \left( \frac{\eta_1}{\eta_0} + \frac{3}{2} \eta_0^2 \right) + \frac{3}{4} \eta_0^2 \beta_x''' \right) \]
Six Sextupole pairs placed semi-symmetrically around IP
- the closest pair to IP was applied to eliminate the \( W_{x,y} \) at IP
- five pairs confine chromatic functions within the IR

\( \beta \) correction sextupoles around IP reduced \( W \)'s from \( 10^3 \) to \( 10^{-4} \) range and be confined to acceptable values at end of IR

Second order chromaticity arising from IRs final focus quadrupoles and correcting sextupoles was mitigated by fixing the phase advance between the two symmetric IR to be \( \pi(1/2 + n) \) (where \( n \) is an integer number)
Local Chromatic Correction

Sextupoles off

Sextupoles on
Local Chromatic Correction

Sextupoles off

Sextupoles on
Global Chromatic Correction

- Families of sextupoles in the arcs & IP free straight

- Arc:
  - Four interleaved sextupoles families
  - Every family member at $(3\pi) - I$ transformation from each other to cancel second order aberrations from those sextupoles.

- IP free straight with special symmetric insertion blocks, the sextupoles were placed in a non-interleaved families with -I transformation apart as well.
Global Chromatic Correction

![Graph showingGlobal Chromatic Correction](image)
Tune Variation with $\delta p/p$
Touschek Lifetime

\[ \frac{1}{\tau_{\text{Touschek}}} \approx \frac{N r_0^2 c}{8\pi \gamma^3 \sigma_s L} \sum_{i=1}^{N} \frac{D(\xi) \Delta s_i}{\sigma_x(s_i)\sigma_y(s_i)\sigma_{x'}(s_i)\delta_{\text{acc}}^2(s_i)} \]

- Accurate estimate of the Touschek effect is obtained by estimating the integral equation as a sum over all N elements in the lattice.
- The beam parameters (\( \alpha, \beta, \eta \)) are all assumed constant at end of each of the N lattice elements.
- Momentum acceptance for the lattice:
  - Constant across the whole lattice

0.003 momentum acceptance for the lifetime to reach 3 hours
• Polarized electron beam is injected at full energy from 12 GeV CEBAF
• Electron spin is in vertical direction in the figure-8 ring, taking advantage of self-polarization effect
• Spin rotators will rotate spin to longitudinal direction for collision at IP, than back to vertical direction in the other half of the ring
The last two arc dipole sections interleave with two solenoids.

The rotator works by adjusting spin rotation angles in solenoids depending on the beam energy.

X-Y betatron coupling introduced by solenoids must be compensated.
Optics Coupling Compensation

- X-Y beam coupling introduced by solenoids is compensated locally
- Each solenoid is divided into two equal parts and a set of quadrupoles is inserted between them to cancel coupling

Emma rotator
More general solution (Litvinenko)

**Challenges:**
1. Work at all energies
2. Independent of solenoid strength
3. Space economy (we need at least four of USR)
4. Modular to be easily matched and implemented at different places along the ring

\[ M_{\text{sol}} = \begin{pmatrix} \cos^2 \Phi & \frac{\sin 2\Phi}{2} & \frac{\sin 2\Phi}{2} & \frac{2\sin^2 \Phi}{S} \\ -S \sin 2\Phi & \frac{S}{\cos^2 \Phi} & -\frac{S}{\sin 2\Phi} & -S \sin 2\Phi & \frac{2}{\cos^2 \Phi} \\ -\frac{S}{\cos^2 \Phi} & \frac{2}{S} & -\frac{2\sin^2 \Phi}{2} \end{pmatrix} \]

\[ \Phi = \frac{B}{L/2} \]
\[ B \text{ solenoid field strength} \]
\[ L \text{ length respectively} \]
Emma Rotator

\[ M_{\text{COMP}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \]

\[ M_{\text{sol}} \cdot M_{\text{COMP}} \cdot M_{\text{sol}} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \]
Emma Rotator

Disadvantages:
1. Very long
2. Requires 8 quads with different strengths
3. Require 8 quads for matching (un-modular)
General Case

\[ M_{\text{COMP}} = \begin{pmatrix} M & 0 \\ 0 & -M \end{pmatrix} \quad M_{\text{sol}} \cdot M_{\text{COMP}} \cdot M_{\text{sol}} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \]

- Three required optimization parameters to fulfill four conditions (\( M_{\text{COMP}} \)) minus simplicity of the system.
A set of two symmetric doublets separated by one quadrupole is designed to meet the three conditions.

The compactness incorporated in the optimization process yielding relatively short drifts in between quadrupoles.

\[
M = \begin{pmatrix}
an & b & 0 & 0 \\
c & d & 0 & 0 \\
0 & 0 & -a & -b \\
0 & 0 & -c & -d
\end{pmatrix}
\]
Locally decoupled solenoid

\[
M = \begin{pmatrix}
C & 0 \\
0 & -C
\end{pmatrix}
\]
The symmetric insert: requires only four parameters to match the insert to the end of the arc and to the FODO cells of the straight. This will reduces number of matching quadrupoles to only four.
Spin Rotator in Arc

Half-solenoid  Compensating quads  Dipole

$\beta_x$  $\beta_y$  $D_x$  $D_y$

$\Lambda (m)$  $\psi (m)$  $Z (m)$

$0$  $10$  $20$  $30$  $40$  $50$  $60$

$-6$  $-5$  $-4$  $-3$  $-2$  $-1$  $0$

$0.0$  $0.1$  $0.2$  $0.3$  $0.4$  $0.5$  $0.6$
MEIC

ELIC Study Group

M. Sullivan - SLAC
W. Fischer, C. Montag - Brookhaven National Laboratory
D. Barber - DESY
V. Danilov - Oak Ridge National Laboratory
P. Ostroumov - Argonne National Laboratory
B. Erdelyi - Northern Illinois University and Argonne National Laboratory
V. Derenchuk - Indiana University Cyclotron Facility
A. Belov - Institute of Nuclear Research, Moscow, Russia
V. Dudnikov, R. Johnson - Muons Inc.
A. Kondratenko - Novosibirsk