Design Status of Medium-energy Electron-Ion Collider at JLab

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for
Jefferson Lab EIC Study Group

Outline

- Introduction
- MEIC conceptual design
  - High luminosity concept
  - Polarized beam design
- Detector integration and performance
- Electron cooler
- Outlook

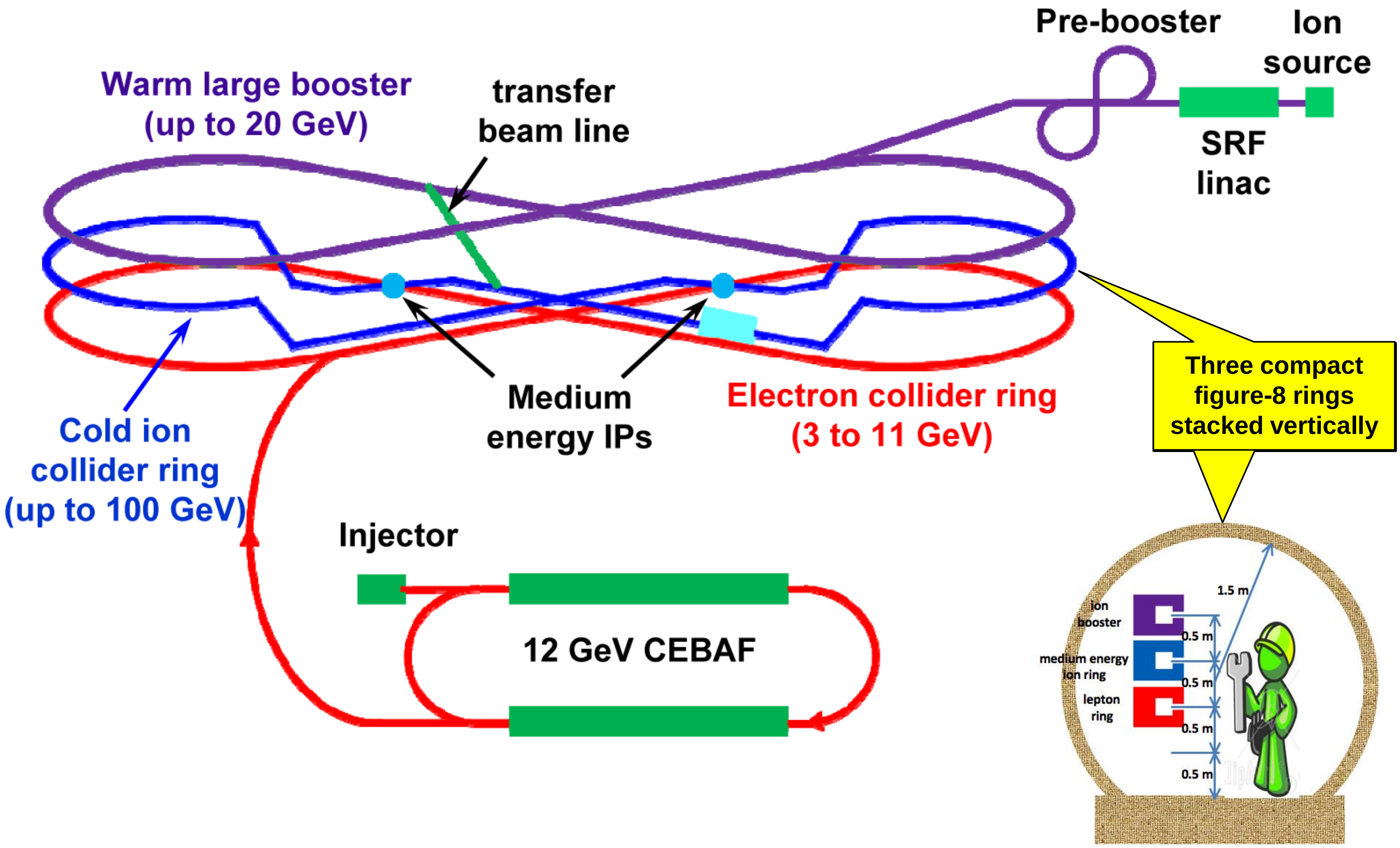
EIC as JLab's Future

- JLab's fixed target program after 12 GeV CEBAF upgrade will be world-leading for at least a decade.
- A *M*edium-energy *E*lectron-*I*on *C*ollider (MEIC) at JLab will open new frontiers in nuclear science.
- The timing of MEIC construction can be tailored to match available DOE-NP funding while the 12 GeV physics program continues.
- MEIC parameters are chosen to optimize science, technology development, and project cost. We maintain a well defined path for future upgrade to higher energies and luminosity.
- A conceptual machine design has been completed, providing a base for performance evaluation, cost estimation, and technical risk assessment

MEIC Design Parameters

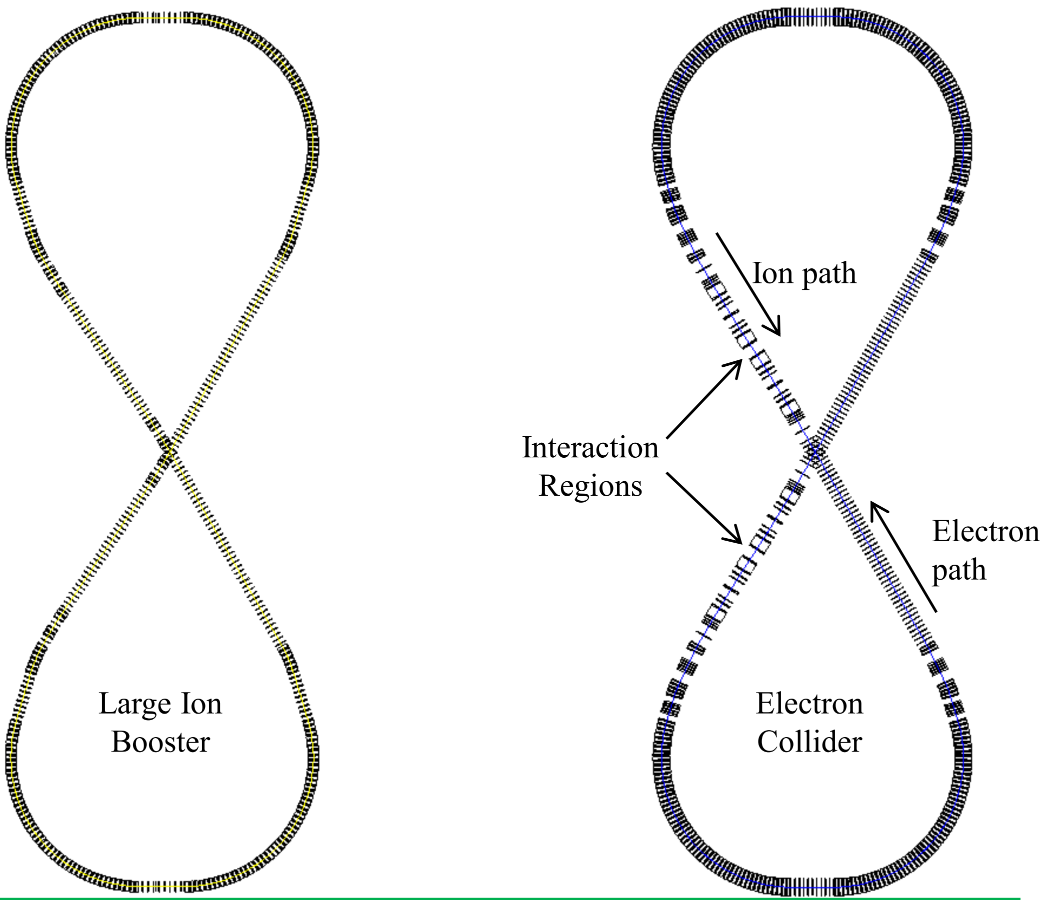
- **Energy** *(bridging the gap of 12 GeV CEBAF & HERA/LHeC)*
  - **Full coverage of *s* from a few 100 to a few 1000 GeV^2**
  - **Electrons 3-11 GeV, protons 20-100 GeV, ions 12-40 GeV/u**
- **Ion species**
  - **Polarized light ions: p, d, ^{3}He, and possibly Li**
  - **Un-polarized light to heavy ions up to A above 200 (Au, Pb)**
- **Up to 3 detectors**
  - **One optimized for full acceptance, another for high luminosity**
- **Luminosity**
  - **Greater than 10^{34} cm^{-2}s^{-1} per interaction point**
  - **Maximum luminosity should optimally be around $\sqrt{s}$=45 GeV**
- **Polarization**
  - **At IP: longitudinal for both beams, transverse for ions only**
  - **All polarizations >70% desirable**
- **Upgradeable to higher energies and luminosity**
  - **20 GeV electron, 250 GeV proton, and 100 GeV/u ion**

MEIC Layout



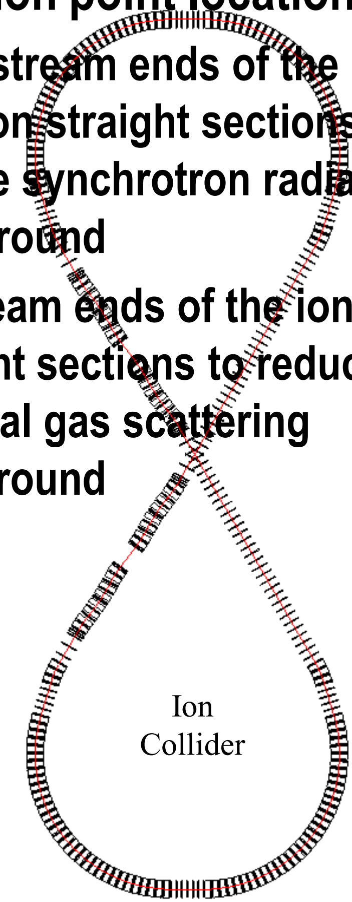
Pre-booster
Ion source
SRF linac
Warm large booster (up to 20 GeV)
transfer beam line
Medium energy IPs
Electron collider ring (3 to 11 GeV)
Cold ion collider ring (up to 100 GeV)
Three compact figure-8 rings stacked vertically
Injector
12 GeV CEBAF
ion booster
medium energy ion ring
lepton ring
1.5 m
0.5 m
0.5 m
0.5 m
0.5 m

Stacked Figure-8 Rings



Interaction point locations:

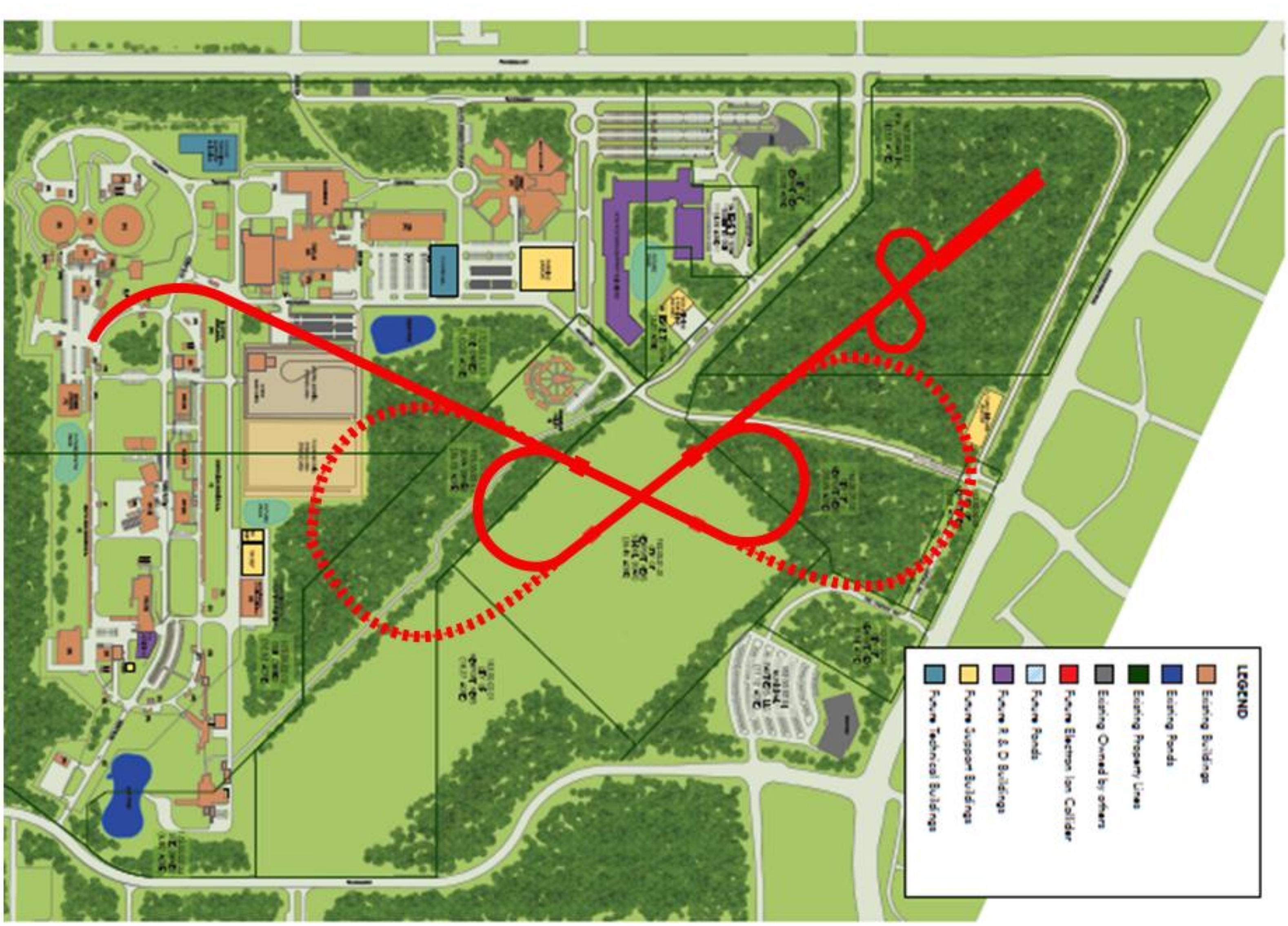
- Downstream ends of the electron straight sections to reduce synchrotron radiation background
- Upstream ends of the ion straight sections to reduce residual gas scattering background



- Vertical stacking for identical ring circumferences
- Horizontal crab crossing at IPs due to flat colliding beams
- Ion beams execute vertical excursion to the plane of the electron orbit for enabling a horizontal crossing

- Ring circumference: 1340 m
- Maximum ring separation: 4 m
- Figure-8 crossing angle: 60 deg.

MEIC and Upgrade on JLab Site Map



Design Features: High Luminosity

- **Based on the following concepts**
  - Very short bunch length
  - Small transverse emittance
  - Very high bunch repetition rate
  - Very small bunch charge
  - Very small β*
  - Crab crossing
- **A proved concept: KEK-B @ 2×10^{34} /cm²/s**
- **JLab will replicate the same success in colliders w/ hadron beams**
  - The electron beam from CEBAF possesses a high bunch repetition rate
  - Ion beams from a new ion complex can match the electron beam

		KEK-B	MEIC	eRHIC
Repetition rate	MHz	509	748.5	13.1
Particles per bunch (e^-/e^+) or (p/e^-)	10^{10}	3.3 / 1.4	0.42 / 2.5	20 / 2.4
Beam current	A	1.2 / 1.8	0.5 / 3	0.42 / 0.05
Bunch length	cm	0.6	1 / 0.75	8.3 / 0.2
Horizontal & vertical β*	cm	56 / 0.56	10/2 to 4/0.8	5 / 5
Beam energy (e^-/e^+) or (p/e^-)	GeV	8 / 3.5	60 / 5	250 / 10
Luminosity per IP, 10^{34}	$cm^{-2}s^{-1}$	2	0.56 ~ 1.4	0.97

Parameters for ***Full Acceptance*** Interaction Point

		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	MHz	750	750
Particles per bunch	10^{10}	0.416	2.5
Beam Current	A	0.5	3
Polarization	%	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1
RMS bunch length	mm	10	7.5
Horizontal emittance, normalized	µm rad	0.35	54
Vertical emittance, normalized	µm rad	0.07	11
Horizontal β*	cm	10	10
Vertical β*	cm	2	2
Vertical beam-beam tune shift		0.014	0.03
Laslett tune shift		0.06	Very small
Distance from IP to 1st FF quad	m	7	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6	

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		Proton	Electron
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RMS bunch length	mm	10	7.5
Horizontal emittance, normalized	µm rad	0.35	54
Vertical emittance, normalized	µm rad	0.07	11
Horizontal β*	cm	4	4
Vertical β*	cm	0.8	0.8
Vertical beam-beam tune shift		0.014	0.03
Laslett tune shift		0.06	Very small
Distance from IP to 1st FF quad	m	4.5	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	14.2	

Design Features: High Polarization

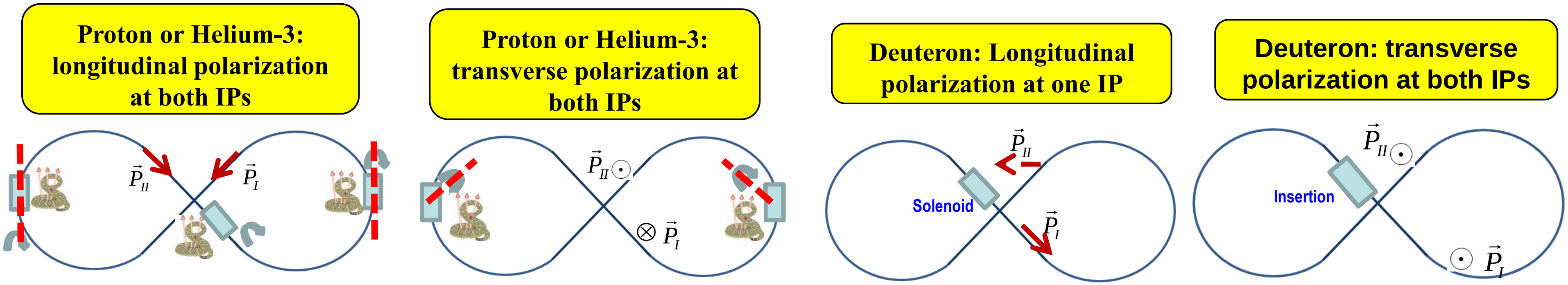
- **All ion rings (two booster, collider) have a figure-8 shape**
  - **Spin precessions in the left & right parts of the ring are exactly cancelled**
  - **Net spin precession (spin tune) is zero, thus energy independent**

  - **Ensures spin preservation and ease of spin manipulation**
  - **Avoids energy-dependent spin sensitivity for ion all species**
  - **The only practical way to accommodate polarized deuterons**

  This design feature promises a high polarization for all light ion beams

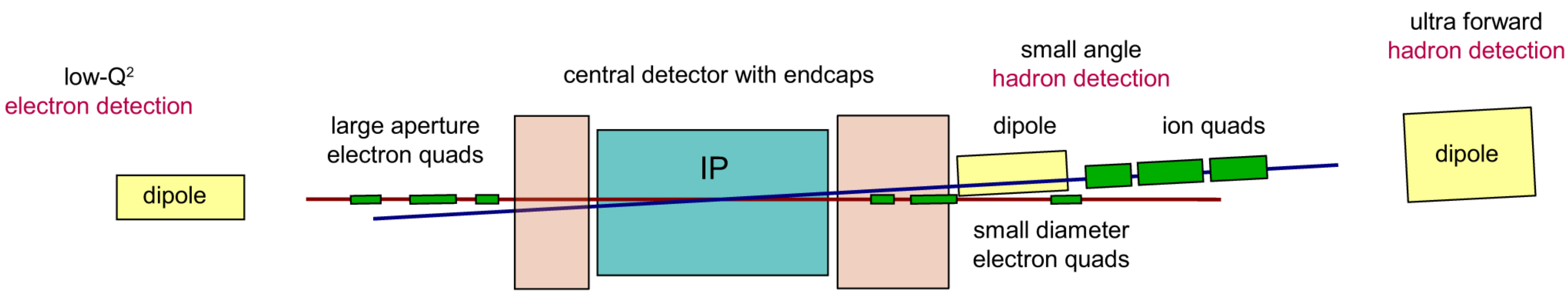
(The electron ring has a similar shape since it shares a tunnel with the ion collider ring)

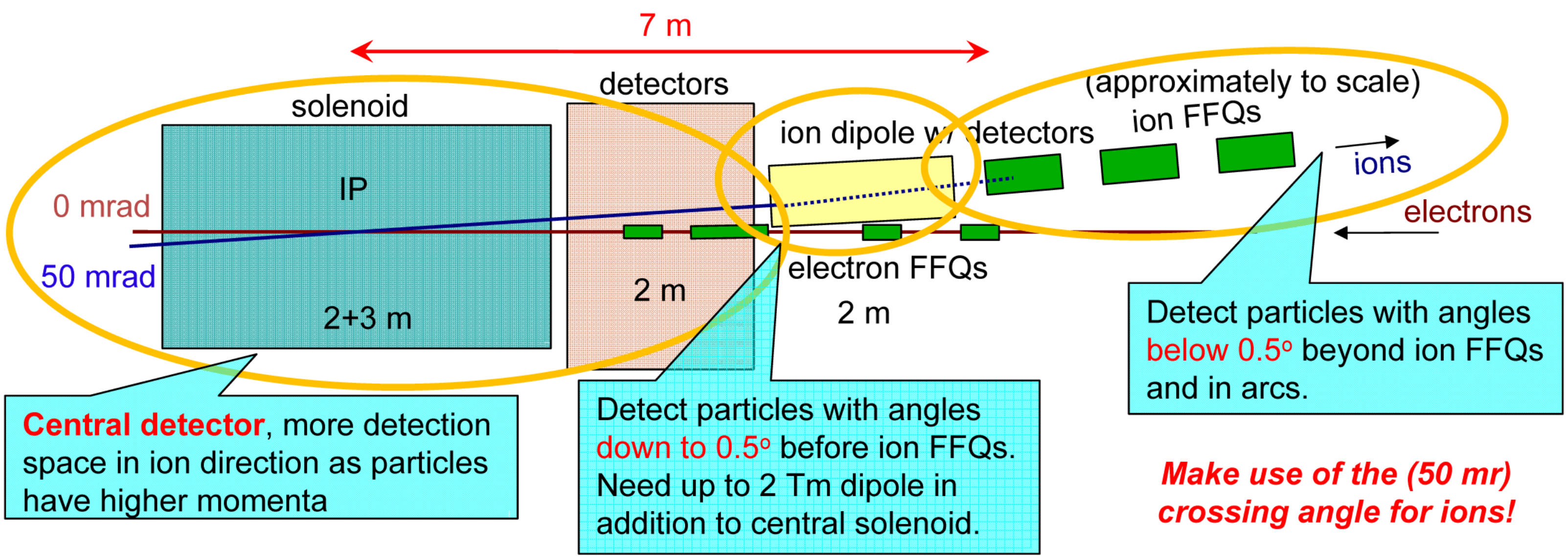
- **Use Siberian Snakes/solenoids to arrange polarization at IPs**



MEIC Primary *Full-Acceptance* Detector

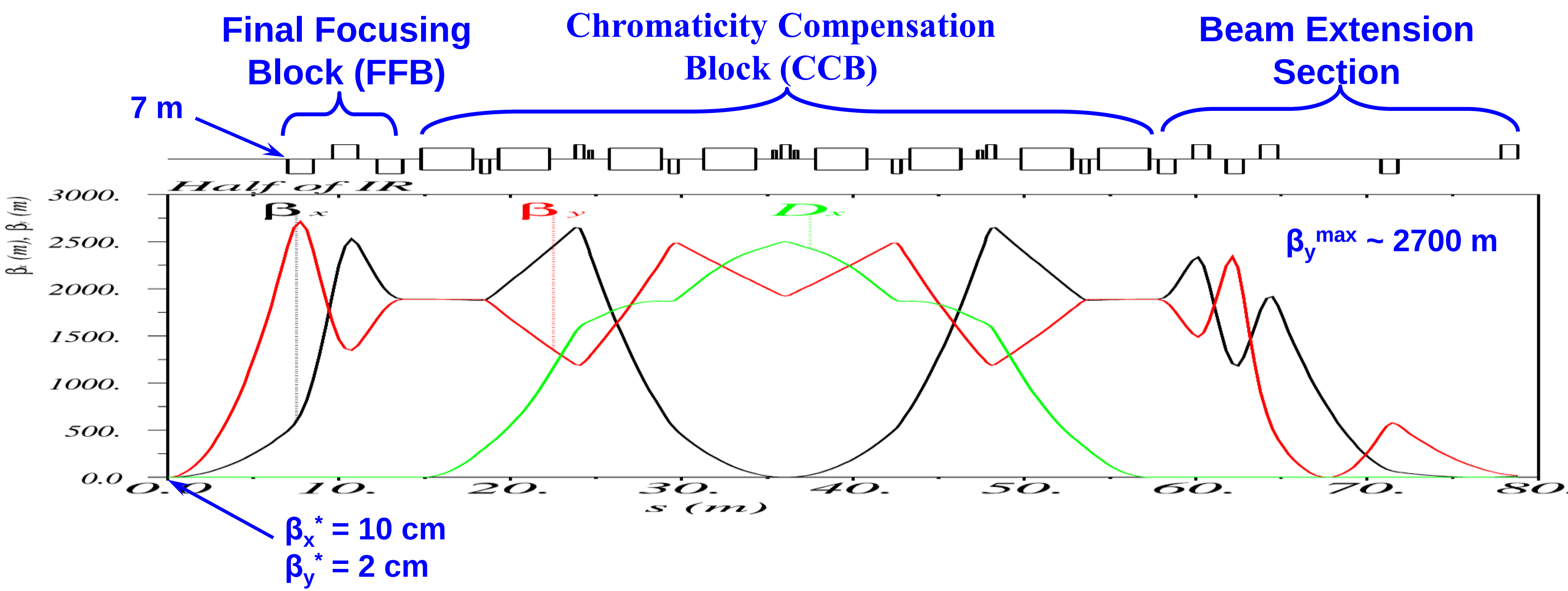
- Large 50 mrad crossing angle: no parasitic collisions, improved detection, fast beam separation
- Forward small-angle hadrons pass through large-aperture FFB quads before detection
- FFB / spectrometer dipole combo optimized for acceptance and detector resolution





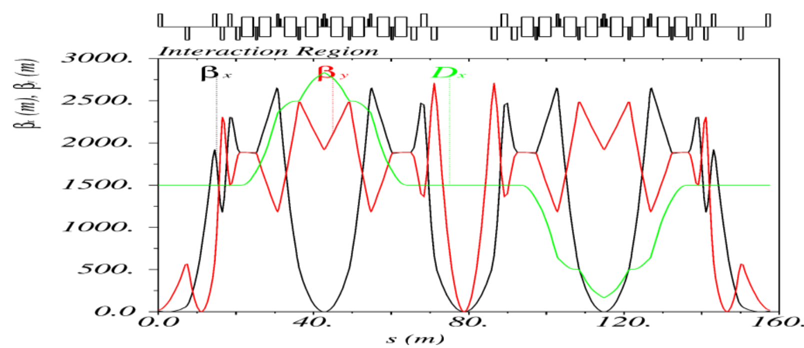
Make use of the (50 mr) crossing angle for ions!

Interaction region: Ions



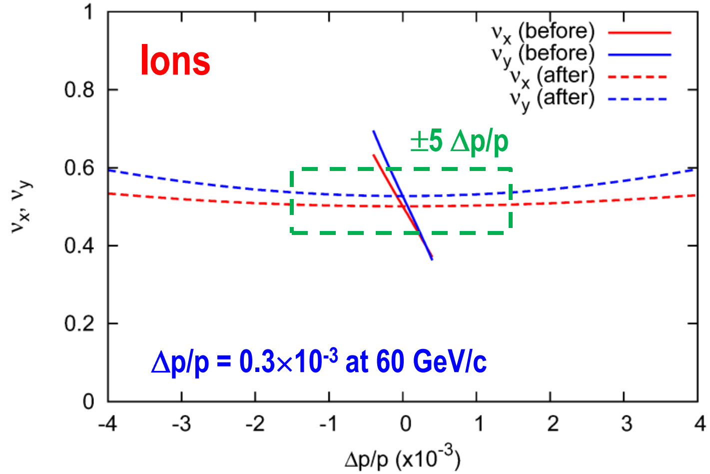
- Distance from the IP to the first FF quad = 7 m
- Maximum quad pole tip field at 100 GeV/c = 6 T
  - Allows ±0.5° forward detection
  - Evaluating detailed detector integration and positions of collimators
- Symmetric CCB design for efficient chromatic correction

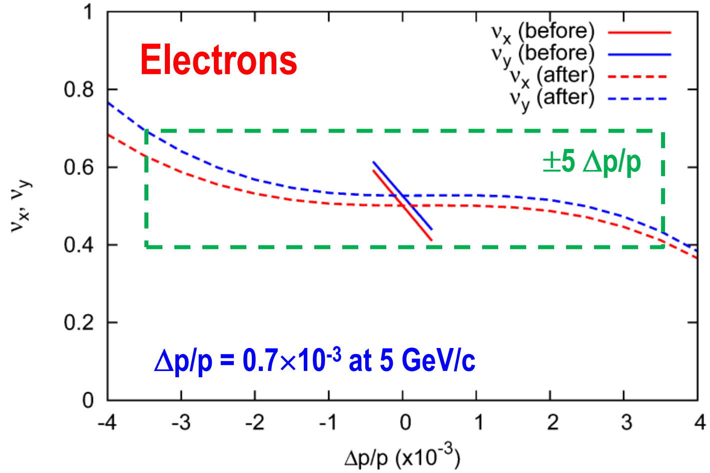
Whole Interaction Region: 158 m



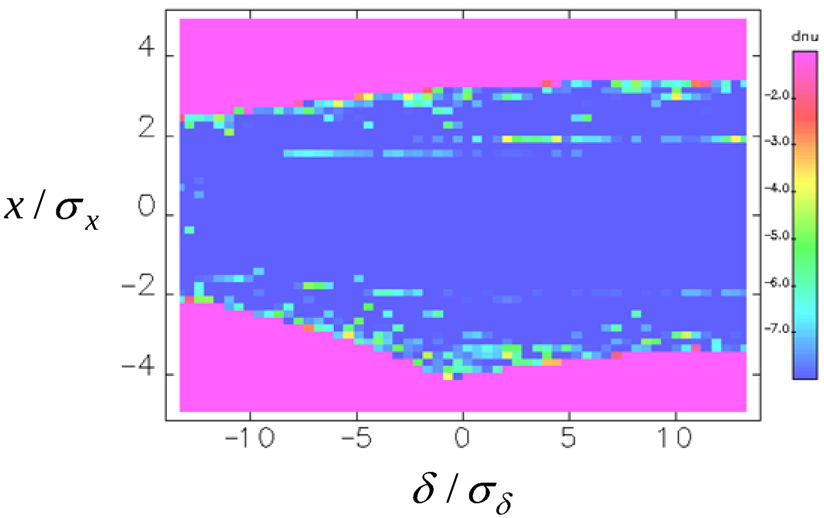
Chromaticity and Dynamic Aperture

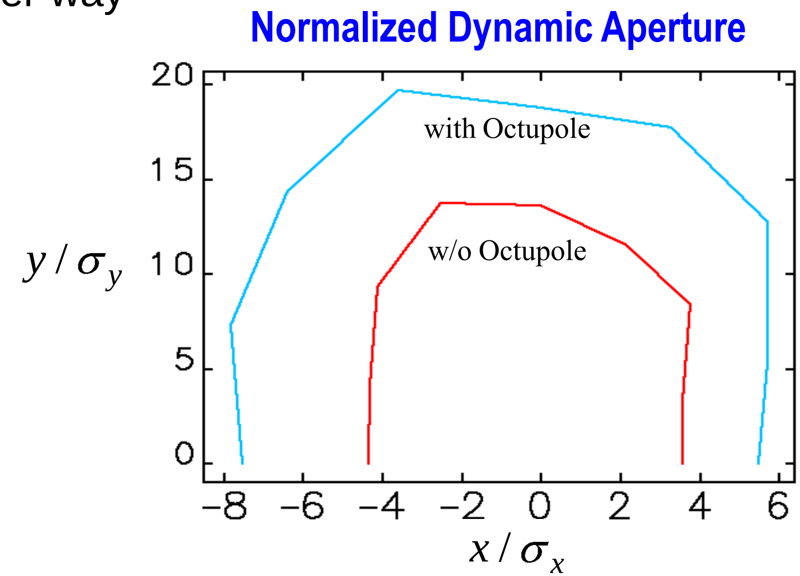
- Compensation of chromaticity with 2 sextupole families only using symmetry



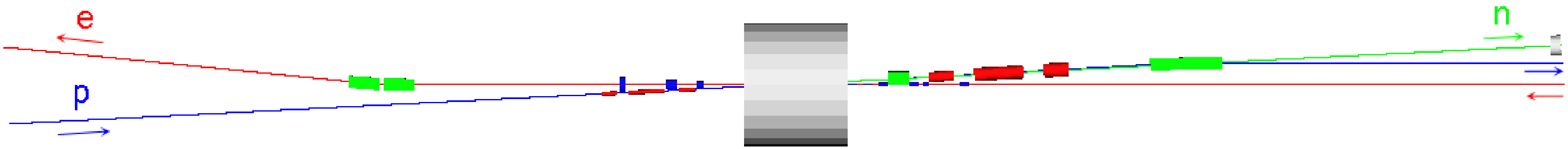


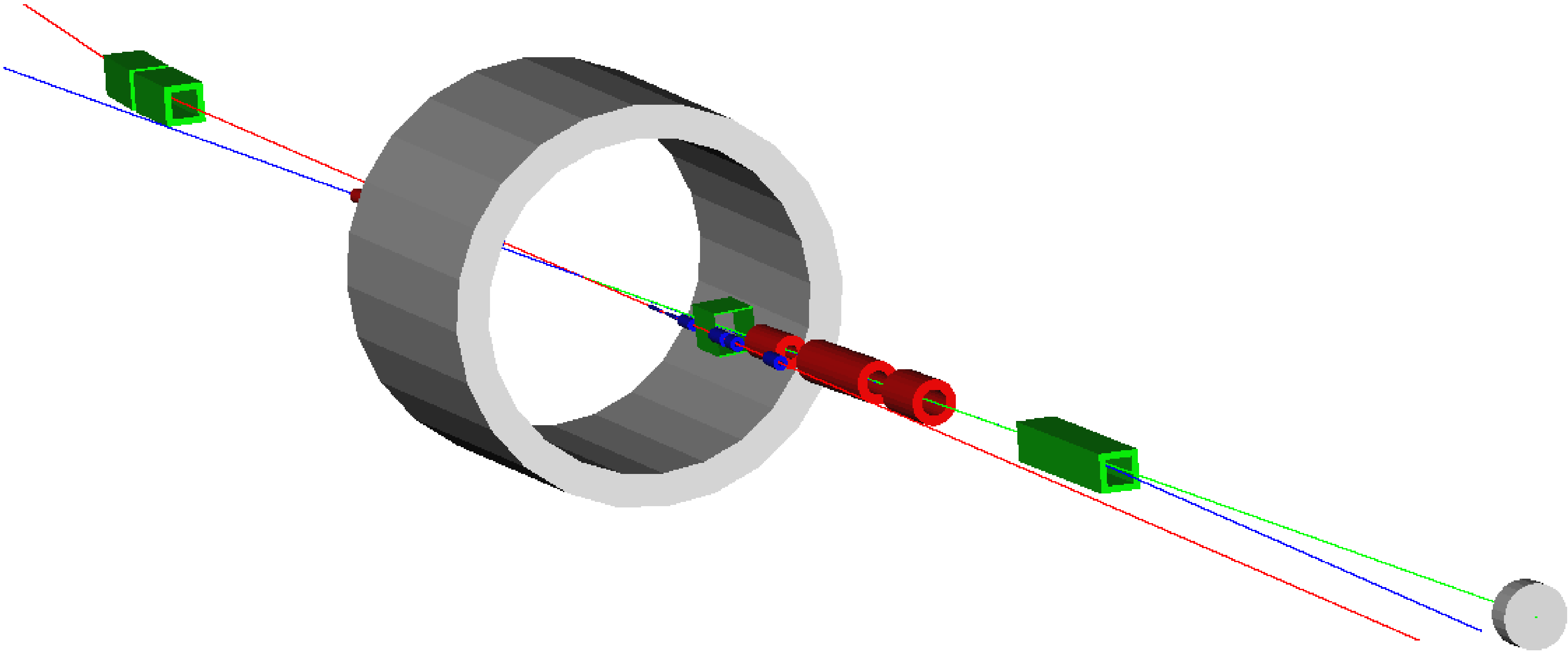
- Non-linear dynamic aperture optimization under way





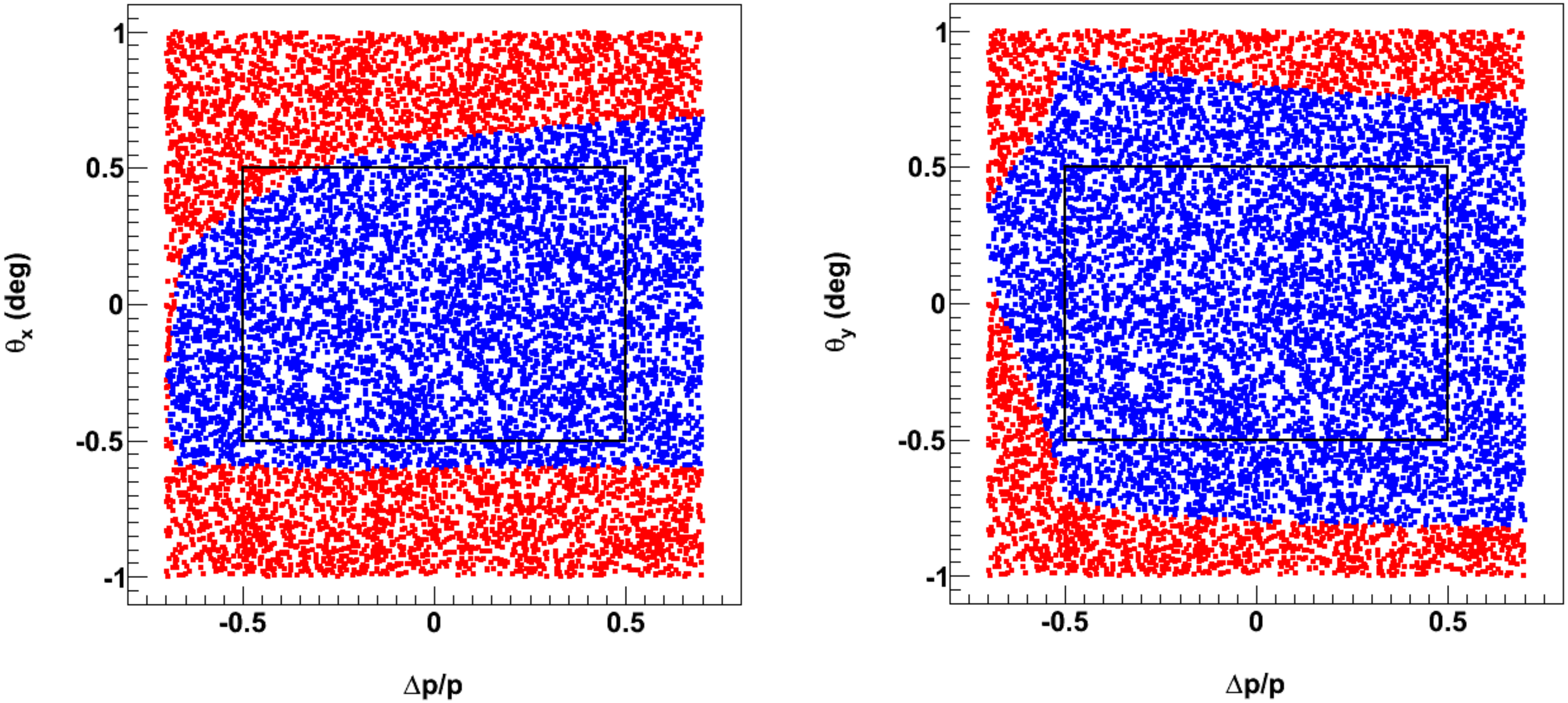
3D Detector Model





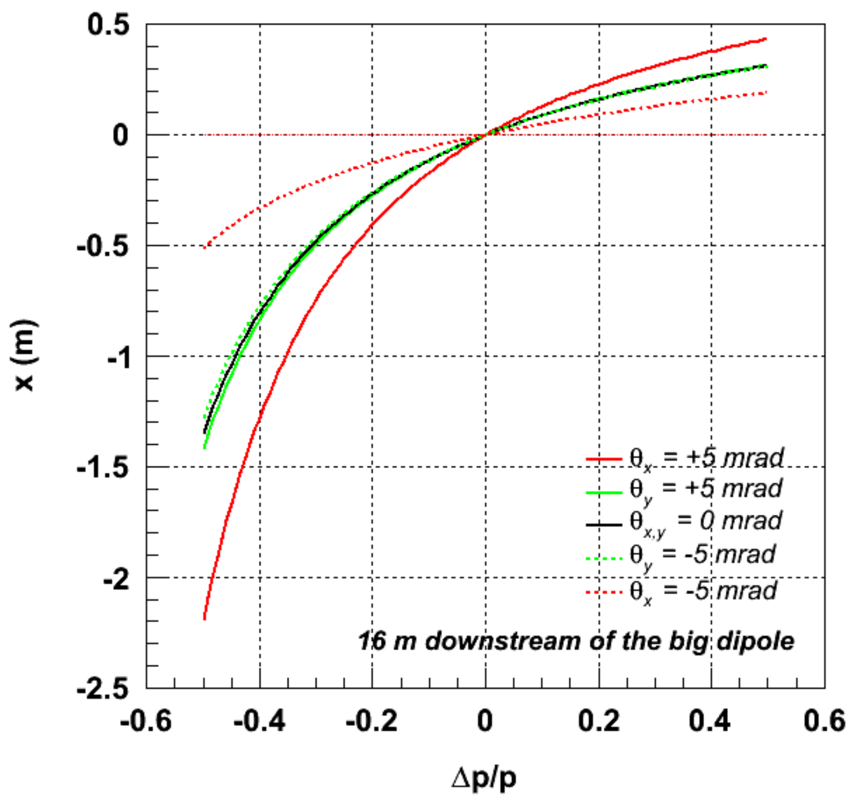
Acceptance of Downstream Ion FFB

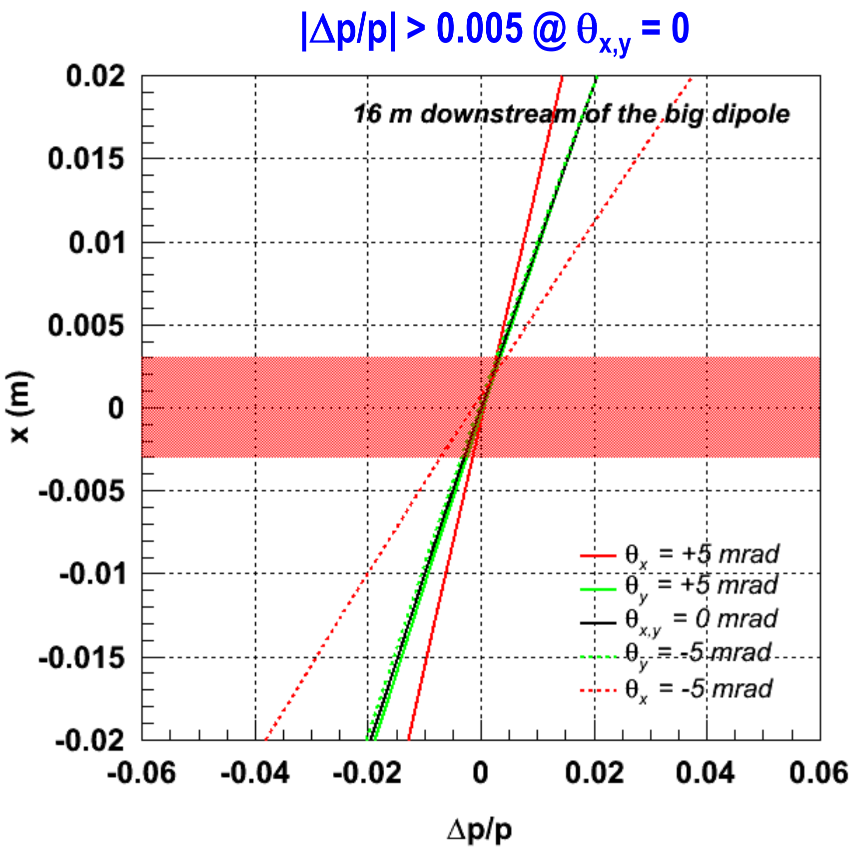
- 60 GeV/c protons, uniform spreads: ±0.7 in $\Delta p/p$ and ±1° in horizontal/vertical angle
- Apertures: Quads = 9, 9, 7 T / ($\partial B_y / \partial x$ @ 100 GeV/c)



Momentum & Angle Resolution

- Protons with Δp/p spread launched at different angles to nominal 60 GeV/c trajectory
- Red hashed band indicates ±10σ beam stay-clear





Electron Cooling

- Essential to achieve high luminosity for MEIC
- Traditional electron cooling, not Coherent Electron Cooling
- MEIC *cooling* scheme

Pre-booster: *Cooling* for assisting accumulation of positive ion beams

(Using a low energy DC electron beam, existing technology)

Collider ring: *Initial cooling* after injection

Final cooling after boost & re-bunching, for reaching design values

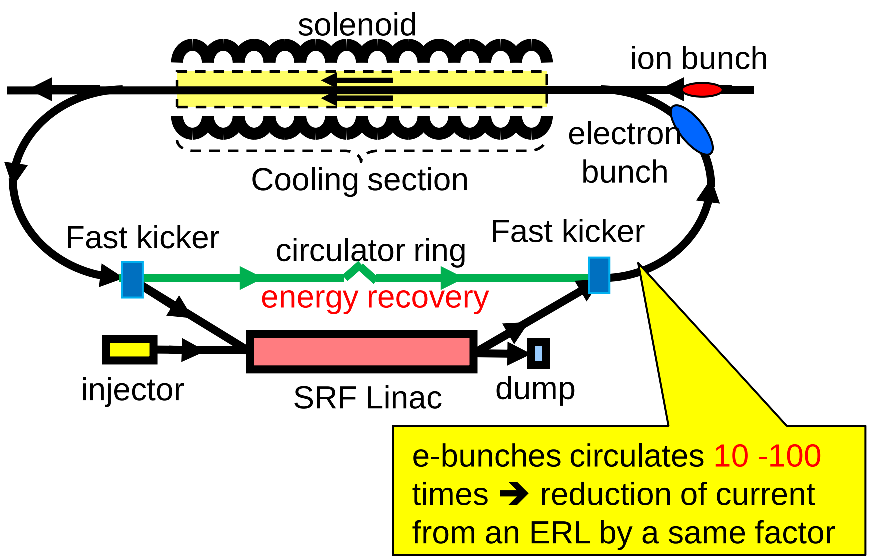
Continuous cooling during collision for suppressing IBS

(Using new technologies)

- Challenges in cooling at MEIC collider ring
  - High ion energy

    (*State-of-the-art: Fermilab recycler, 8 GeV anti-proton, DC e-beam*)
  - High current, high bunch repetition rate CW cooling electron beam

ERL Circulator Electron Cooler



Design challenges

- Large RF power (up to 81 MW)
- Long gun lifetime (average current 1.5 A)

Proposed solution

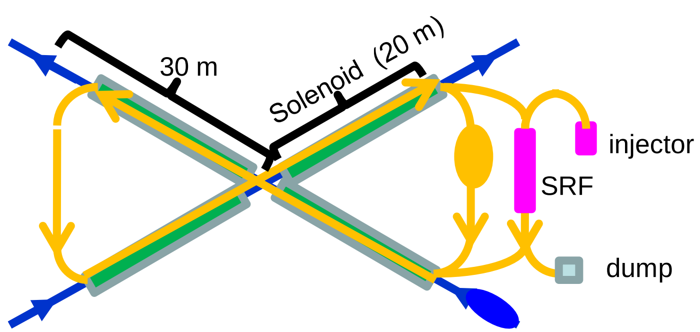
- Energy Recovery Linac (ERL)
- Compact circulator ring

Required technologies

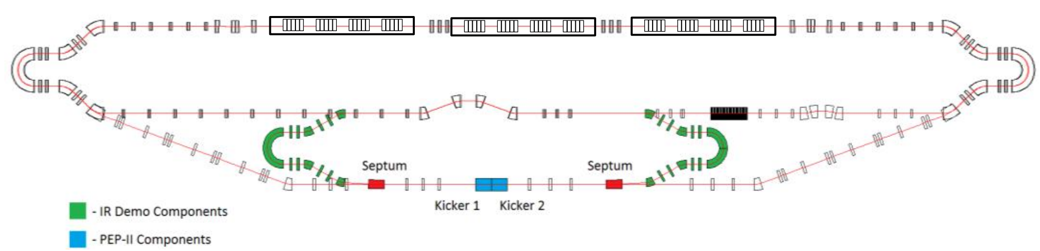
- High bunch charge magnetized gun
- High current ERL (55 MeV, 15 to150 mA)
- Ultra fast kicker

Optimization

- reduce return path to improve cooling rate and beam dynamics



Proposal: A technology demonstration using JLab FEL facility



Immediate Outlook and R&D

- **Electron cooling**
  - Electron cooling of medium energy ion beam (by simulations)
  - ERL circulator cooler design optimization, technology development
  - ERL-circulator cooler demo (using JLab FEL facility)
- **Interaction region**
  - Detector integration
  - Sufficient dynamic aperture with low beta insertions
- **Polarization**
  - Demonstrate superior ion polarization with figure-8 ring
  - Electron spin matching
- **Collective beam effects**
  - Beam-beam with crab crossing
  - Space charge effects in pre-booster
  - Electron cloud in the ion rings and mitigation
- **Ion Injector complex optimization and beam studies**

JLab EIC Study Group

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Crab Crossing

- Restore effective head-on bunch collisions with 50 mrad crossing angle $\Rightarrow$ Preserve luminosity
- Dispersive crabbing (regular accelerating / bunching cavities in dispersive region) vs. Deflection crabbing (novel TEM-type SRF cavity at ODU/JLab, very promising!)