Project of the Electron-Ion Collider at Jefferson Laboratory

Ya. Derbenev for EIC @ JLab Design Team

POETIC 2013

Physics Opportunities at an Electron-Ion Collider

4-8 March 2013

Universidad Técnica Federico Santa María, Valparaíso, CHILE

MEIC project

MEIC design collaboration

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[2] Argonne National Laboratory
[3] Brookhaven National Laboratory
[4] Catholic University of America
[5] College of William and Mary
[6] DESY
[7] Hampton University
[8] Idaho State University
[9] Joint Institute for Nuclear Research, Dubna
[10] Moscow Institute of Physics & Technology
[11] Muons Inc.
[12] Northern Illinois University
[13] Old Dominion University
[14] Paul Scherrer Institute
[15] SLAC National Accelerator Lab
[16] Science and Technique Lab Russia
[17] Universidad de Guanajuato
[18] University of Wisconsin-Madison

MEIC Project

- Electron-Ion Collider* for Nuclear Science
- Medium-Energy Electron Ion Collider (MEIC) Layout
- MEIC Basic Design Choices
- Integrated Detector and Interaction Region
- Polarized Beams in MEIC
- Electron Cooling

* EIC is the generic name for the Nuclear Science-driven Electron-Ion Collider, presently considered in the US

Into the “sea”: the EIC

(“Medium-Energy”) MEIC@JLab energy choices driven by:

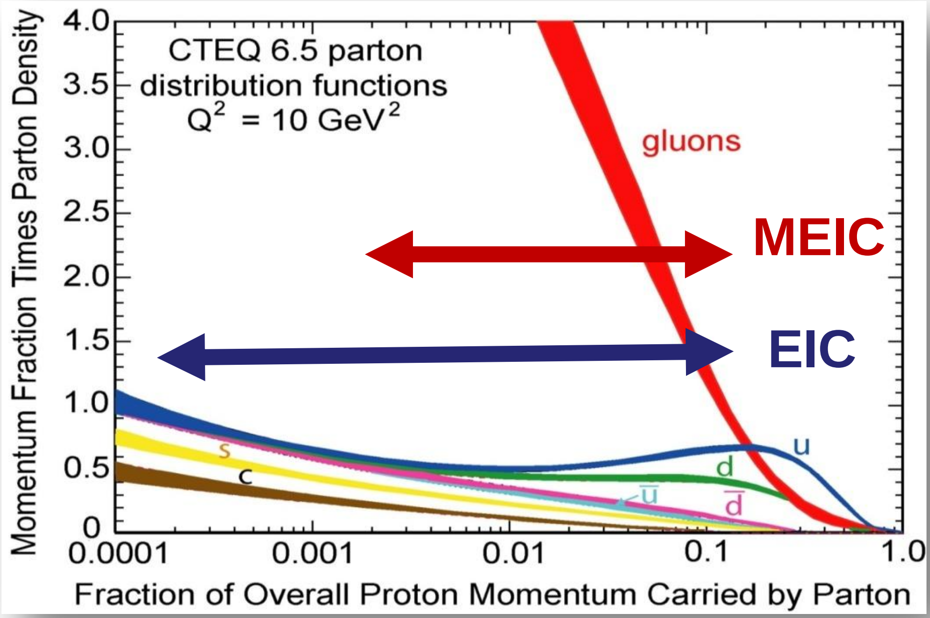
access to sea quarks and gluons

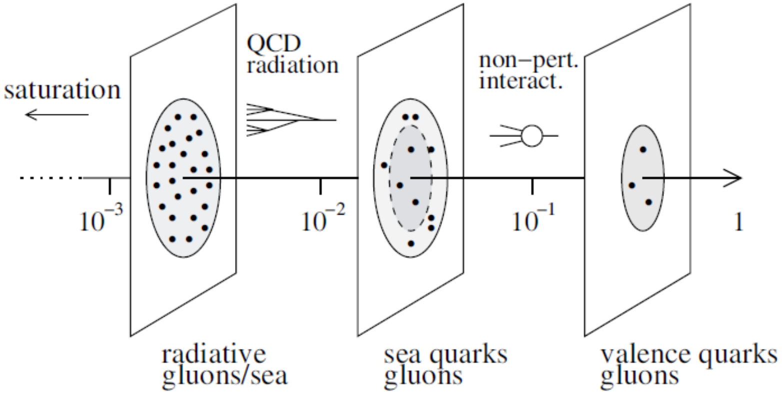
→ s = few 100 - 1000 seems right ballpark

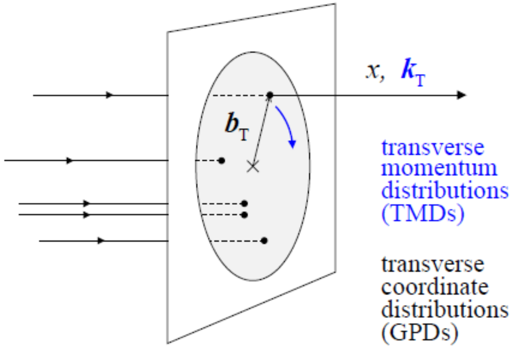
→ s = few 1000 allows access to gluons, shadowing

Polarization + good acceptance to detect spectators & fragments

An EIC aims to study the sea quarks and gluon-dominated matter.

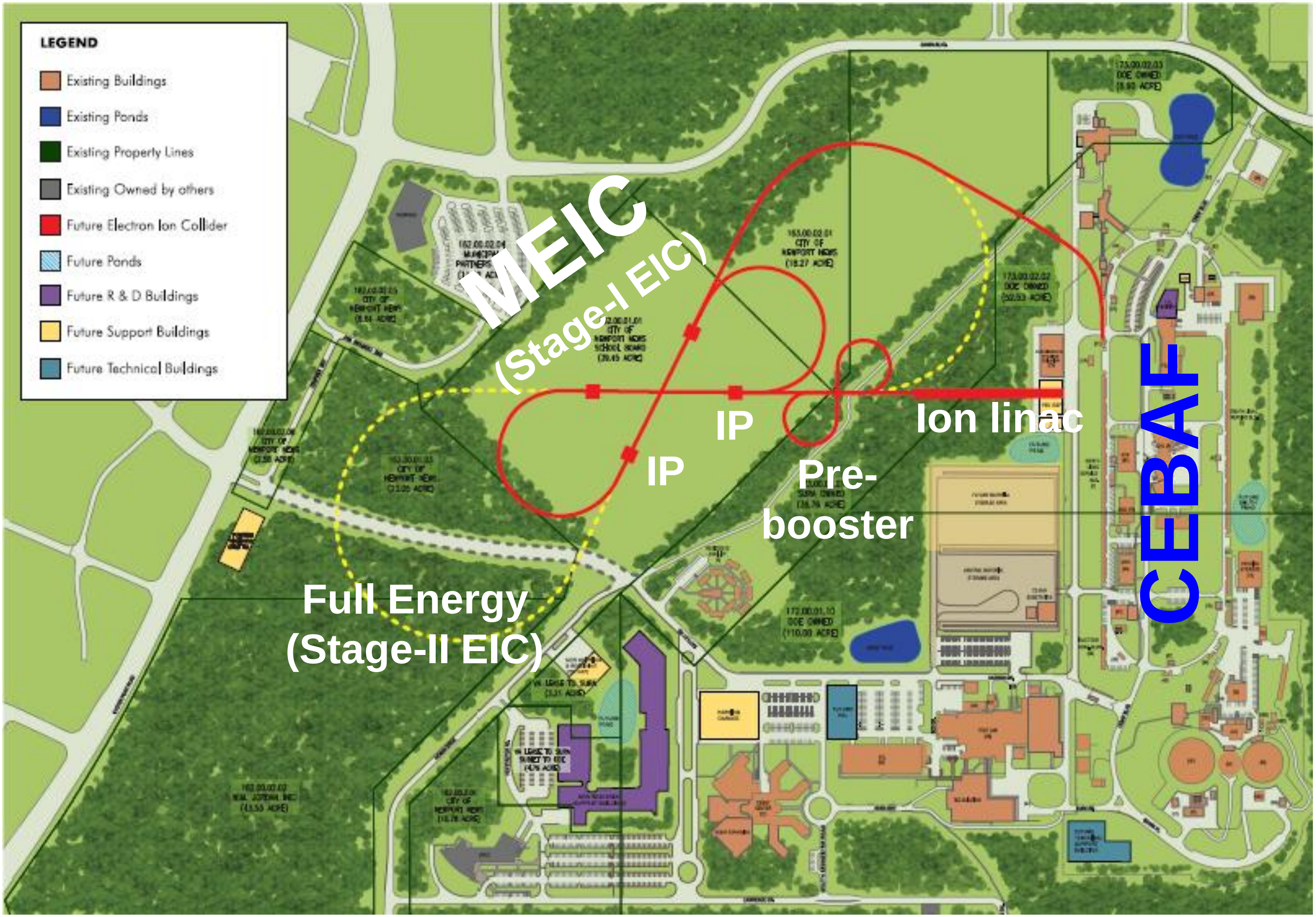




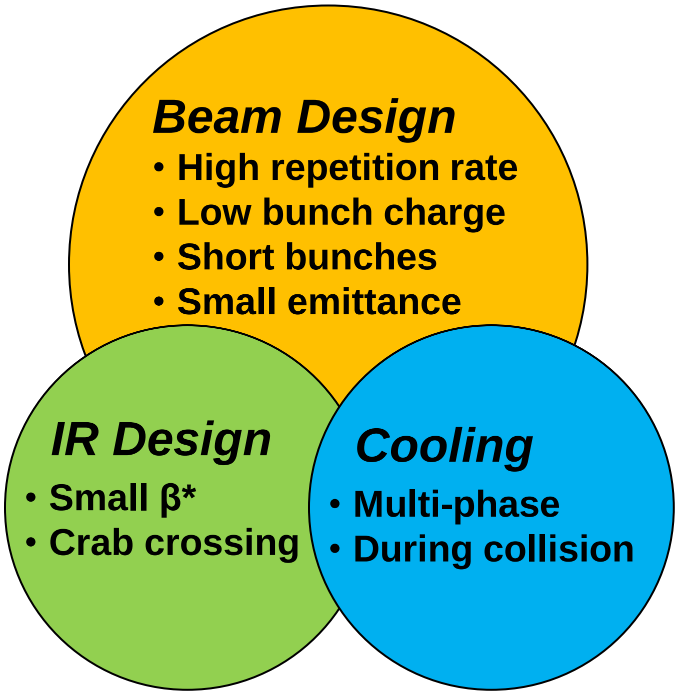


Jefferson Lab

MEIC/EIC Layout



MEIC Design Features: High Luminosity, Stable Spin, Full Acceptance Detection + Forward Tagging



JLab is poised to design a ring-ring EIC taking the advantages of:

- **CEBAF** as a **full energy injector** for electron storage ring
- Multi-phase ERL-based *regular electron cooling* to obtain **very short, low charge, small emittance** ion bunches
- A high luminosity design based on ***short bunches*, *high repetition rate, crab-crossing*** colliding beams by use of ***HF SC cavities***
- ***Twisted Spin*** dynamics in ***figure 8*** MEIC booster and collider rings providing for spin stability and manipulation for all polarized species ***including deuterium***
- A novel **full acceptance + forward tagging detector** design suitable for ***crab-crossing*** beams and corresponding to the EIC aims to study the **sea quarks and gluon-dominated matter**

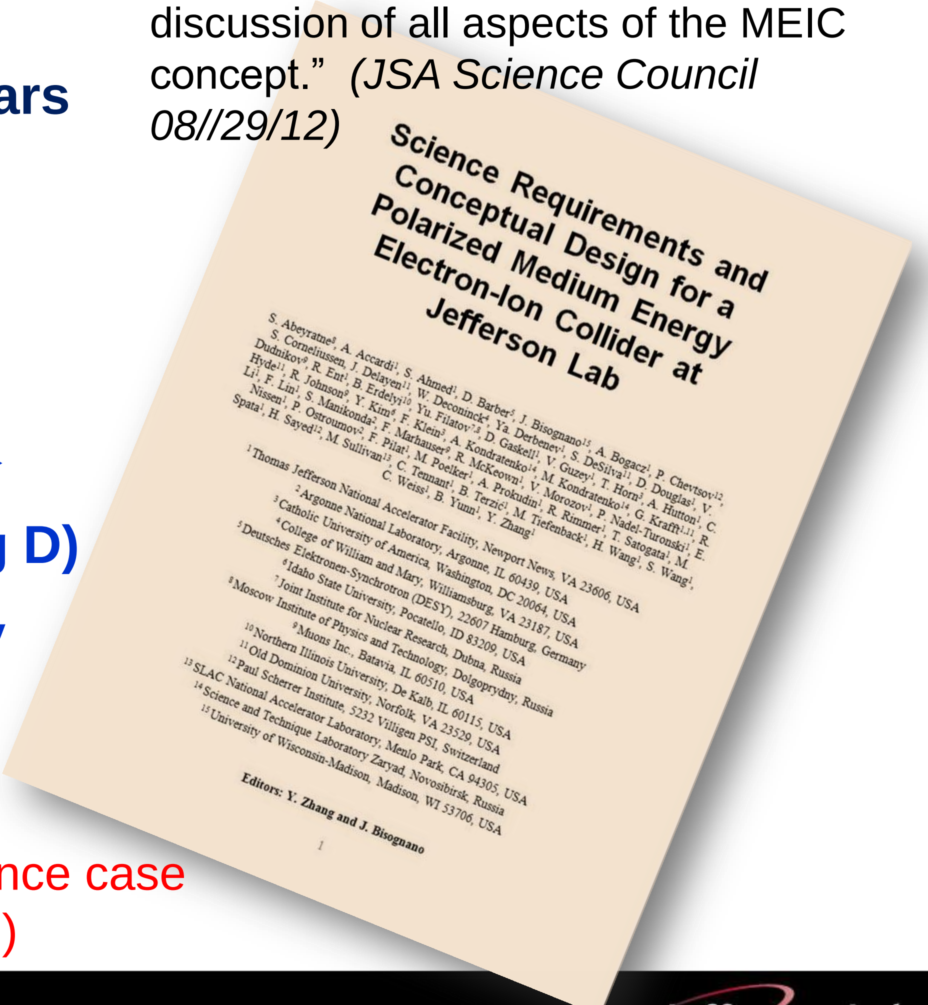
MEIC Design Report

- [Posted: arXiv:1209.0757]
- **Stable CEBAF-based principal layout and operation concept for 7 years**
- **Stable IR/detector concept for 3 years**

"… was impressed by the outstanding quality of the present MEIC design"
"The report is an excellent integrated discussion of all aspects of the MEIC concept." *(JSA Science Council 08//29/12)*

Overall MEIC design features: →

- **Highly polarized beams (including D)**
- **Full acceptance & high luminosity**
- **Minimized technical risk and R&D**


Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

S. Abeyratne[8], A. Accardi[1], S. Ahmed[1], D. Barber[5], J. Bisognano[15], A. Bogacz[1], P. Chevtsov[12], S. Corneliussen, J. Delayen[11], W. Deconinck[4], Ya. Derbenev[1], S. DeSilva[11], D. Douglas[1], V. Dudnikov[9], R. Ent[1], B. Erdelyi[10], Yu. Filatov[7,8], D. Gaskell[1], V. Guzey[1], T. Horn[3], A. Hutton[1], C. Hyde[11], R. Johnson[9], Y. Kim[6], F. Klein[3], A. Kondratenko[14], M. Kondratenko[14], G. Krafft[1,11], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[9], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], M. Spata[1], H. Sayed[12], M. Sullivan[13], C. Tennant[1], B. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

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Editors: Y. Zhang and J. Bisognano

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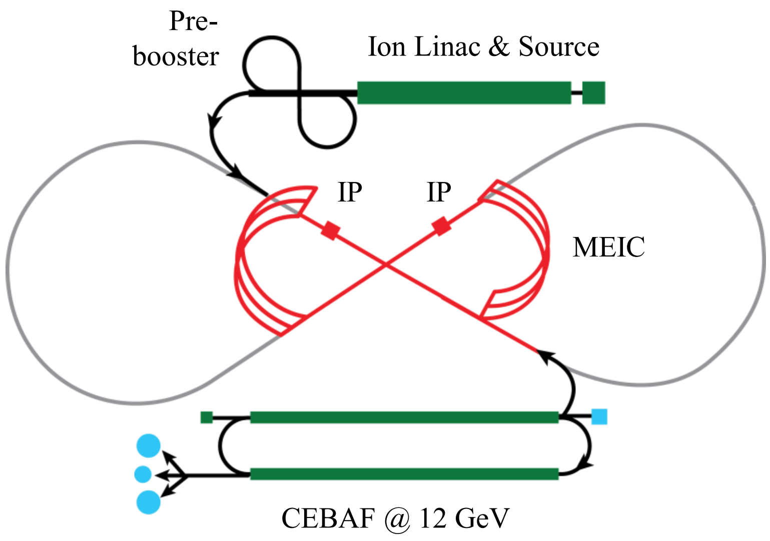
- EPJA article by JLab theory on MEIC science case
  (arXiv:1110.1031; EPJ A48 (2012) 92)

What this design makes possible

- Simultaneous use of two full-acceptance detectors
  - total beam-beam tune shift < 0.03
- Longitudinal and *transverse* polarization of light ions
  - protons, *deuterium*, ^{3}He, ...
- Longitudinally polarized leptons
  - electrons and *positrons*
- Reduced R&D challenges
  - Regular electron cooling
  - Regular electron source
  - No need in a new high energy e-accelerator (ERL)
  - Modest ion space-charge



- **Running fixed-target experiments in parallel with collider**

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Detector/IR in pocket formulas

- Luminosity ~ $1/\beta^*$
- β_{max} ~ 2 km = l^2/β^* (l = distance IP to 1st quad)

  Example: l = 7 m, β^* = 20 mm → β_{max} = 2.5 km
- IP divergence angle ~ $1/\mathrm{sqrt}(\beta^*)$

  Example: l = 7 m, β^* = 20 mm → angle ~ 0.3 mr

  Example: 12 σ beam-stay-clear area

  → 12 x 0.3 mr = 3.6 mr ~ 0.2°
- FFQ gradient ~ $E_{p,max}$ /sqrt(β^*) (for fixed β_{max}, magnet length)

  Example: 6.8 kG/cm for Q3 @ 12 m @ 60 GeV

  → 7 T field for 10 cm (~0.5°) aperture

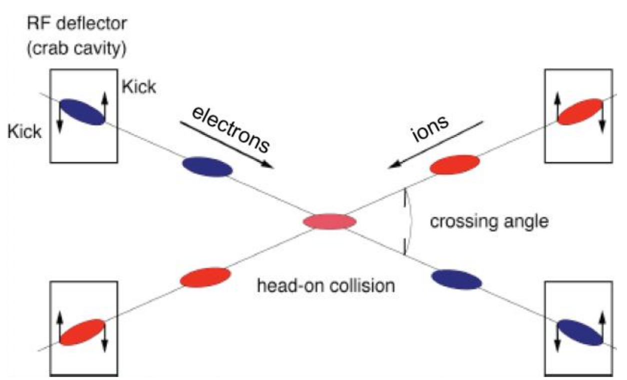
Making β^* too small complicates small-angle (~0.5°) detection before ion Final Focusing Quads, and would require too high a peak field for these quads given the large apertures (up to ~0.5°). But: **β^* = 1-2 cm and E_p = 20-100 GeV ballpark right!**

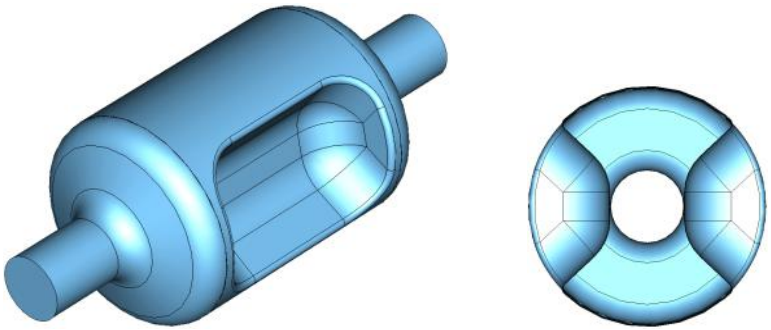
MEIC Point Design Parameters

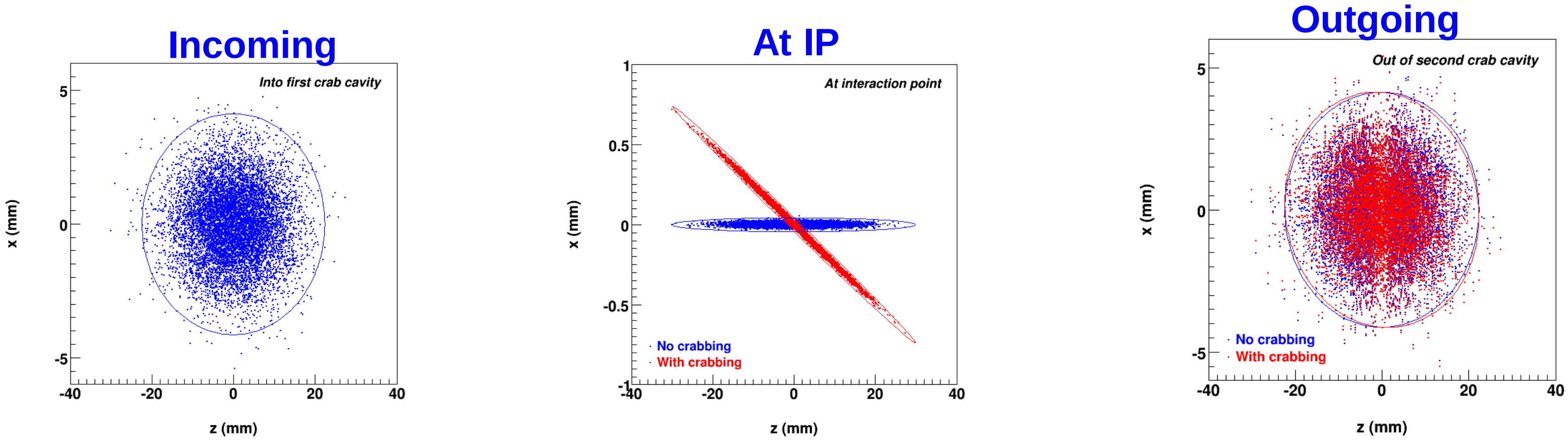
Detector type		Full acceptance		high luminosity & Large Acceptance	
		Proton	Electron	Proton	Electron
Beam energy	GeV	60	5	60	5
Collision frequency	MHz	750	750	750	750
Particles per bunch	10^{10}	0.416	2.5	0.416	2.5
Beam Current	A	0.5	3	0.5	3
Polarization	%	> 70	~ 80	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1	~ 3	7.1
RMS bunch length	mm	10	7.5	10	7.5
Horizontal emittance, normalized	µm rad	0.35	54	0.35	54
Vertical emittance, normalized	µm rad	0.07	11	0.07	11
Horizontal and vertical β*	cm	10 and 2	10 and 2	4 and 0.8	4 and 0.8
Vertical beam-beam tune shift		0.014	0.03	0.014	0.03
Laslett tune shift		0.06	Very small	0.06	Very small
Distance from IP to 1st FF quad	m	7	3.5	4.5	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6		14.2	

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!)
- **Feasible for short bunches with HF SC cavities!**







EIC@JLab (MEIC) Technical Design Strategy

Limit as many design parameters as we can to *within or close to* proven technology in order to *minimize technical uncertainty and R&D tasks*

- Stored electron current should not be larger than 3 A
- Stored proton/ion current should not be larger than 0.5 A
- Maximum synchrotron radiation power density is 20 kW/m
- Maximum peak field of warm electron magnet is 1.7 T
- Maximum peak field of ion superconducting dipole magnet is 6 T
- Maximum betatron value (β^{max}) at FF quad is 2.5 km

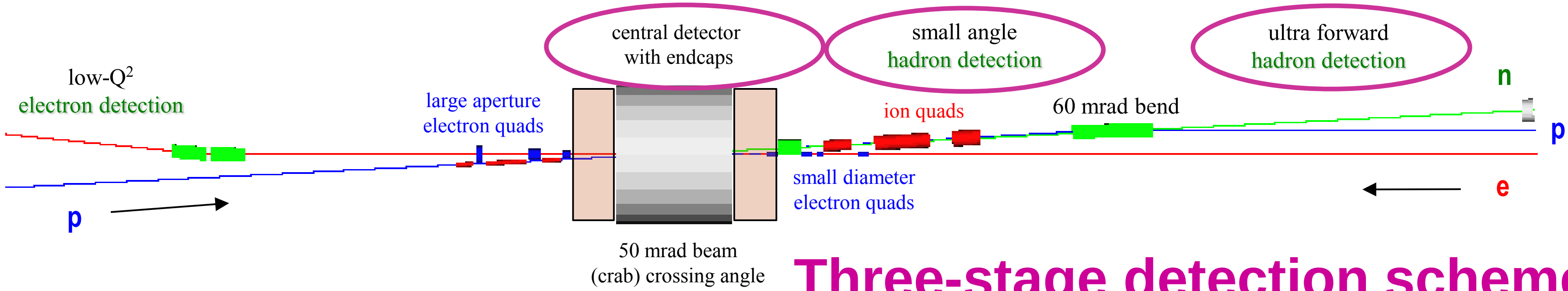
- Choose beta-star appropriate to detector requirements

2.5 km β^{max} + 7 m → $\beta_y^* = 2$ cm	Full acceptance
2.5 km β^{max} + 4.5 m → $\beta_y^* = 0.8$ cm	Large acceptance

(beta-star requires electron cooling of proton/ion beams → R&D)

Design Feature: Full-Acceptance Detector

In general, e-p and even more e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams… spectator quark or struck nucleus remnants will go in the forward (ion) direction → this drives the **integrated** detector/interaction region design



Three-stage detection scheme

Full acceptance detector

- Demonstrated excellent acceptance & resolution
- Completed the detector-optimized IR optics
- Fully integrated detector and interaction region
- Working on hardware engineering design

Addressing accelerator challenges

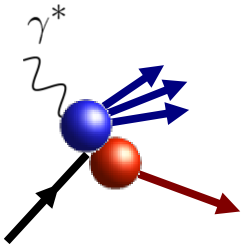
- Demonstrated chromaticity compensation

- *Neutron* detection in a 25 mrad cone *down to zero degrees*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2-3 mrad for *all momenta*
- Momentum *resolution < 3x10^{-4}*
  - limited by intrinsic beam momentum spread

Ultra-forward hadron detection – requirements

1. Good acceptance for ion fragments (rigidity different from beam)

- Large downstream magnet apertures
- Small downstream magnet gradients (realistic peak fields)

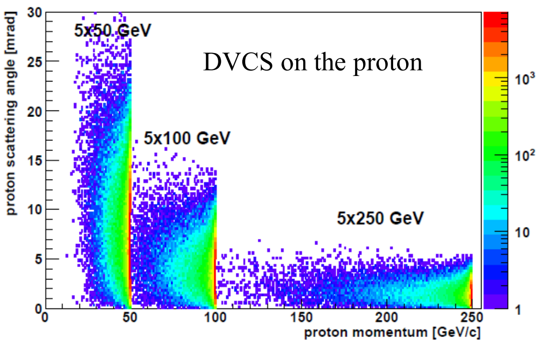


2. Good acceptance for recoil baryons (rigidity similar to beam)

- Small beam size at second focus (to get close to the beam)
- Large dispersion (to separate scattered particles from the beam)

3. Good momentum- and angular resolution

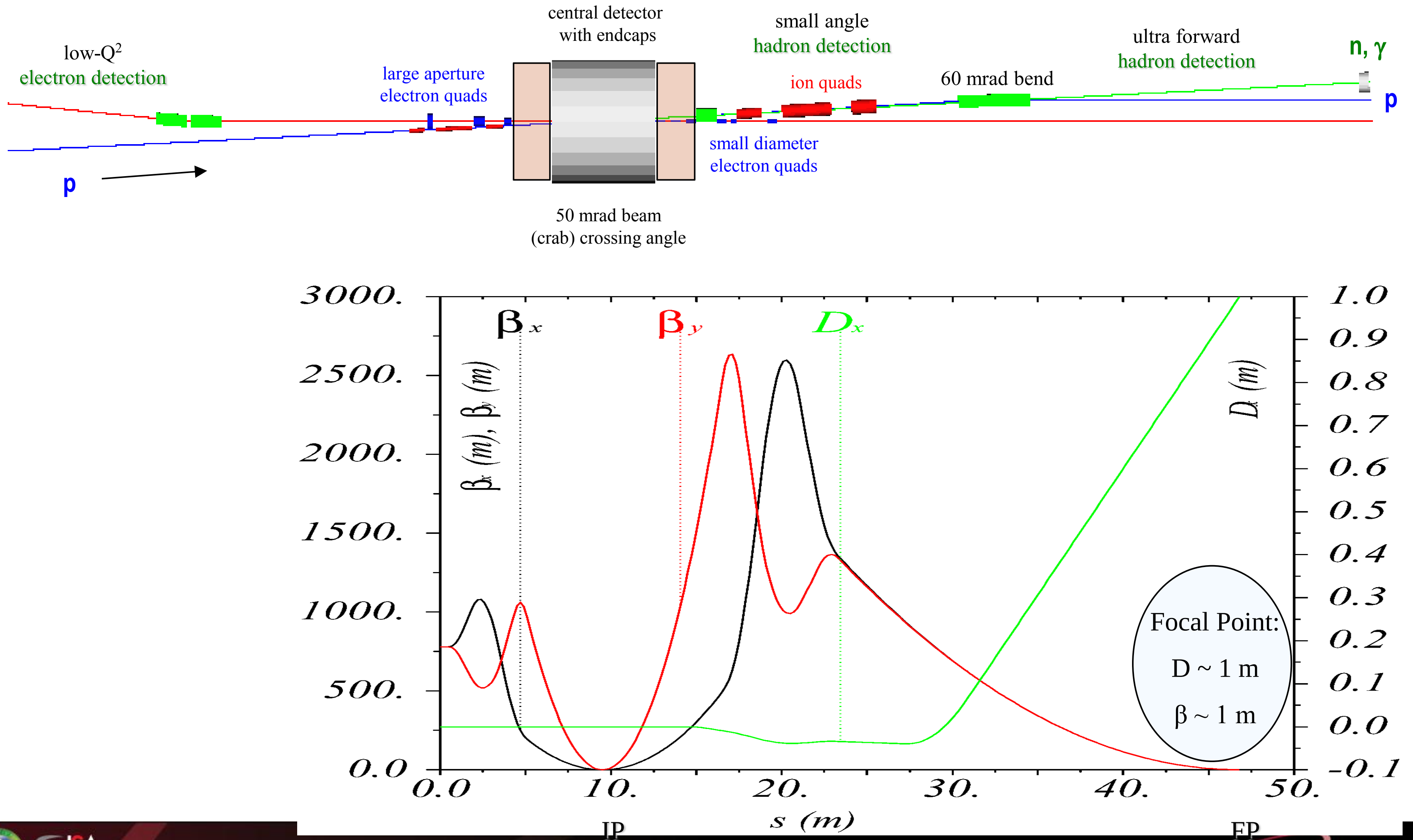
- Large dispersion (*e.g.*, 60 mrad bending dipole)
- Long, instrumented magnet-free drift space



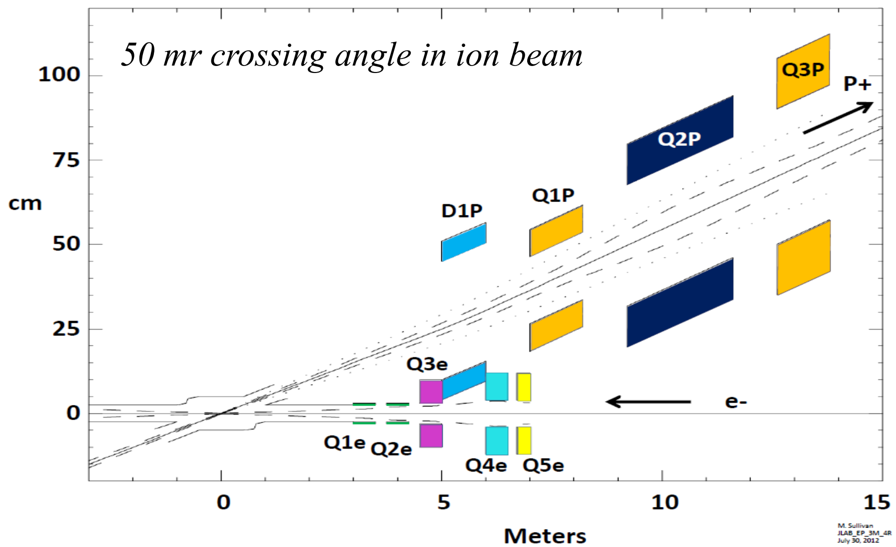
4. Sufficient separation between beam lines (~1 m)

Accelerator optics – fully integrated interaction region

No other magnets or apertures between IP and FP!



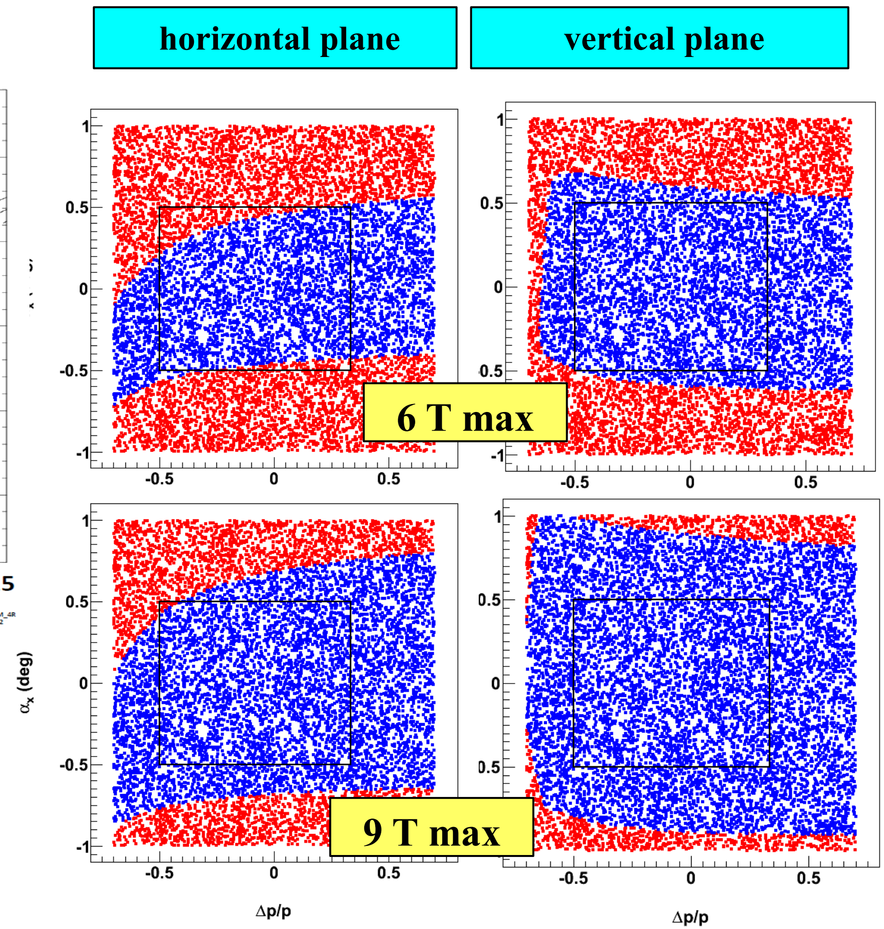
Ultra-forward charged-hadron acceptance



Red: Detection before ion quadrupoles

Blue: Detection after ion quadrupoles

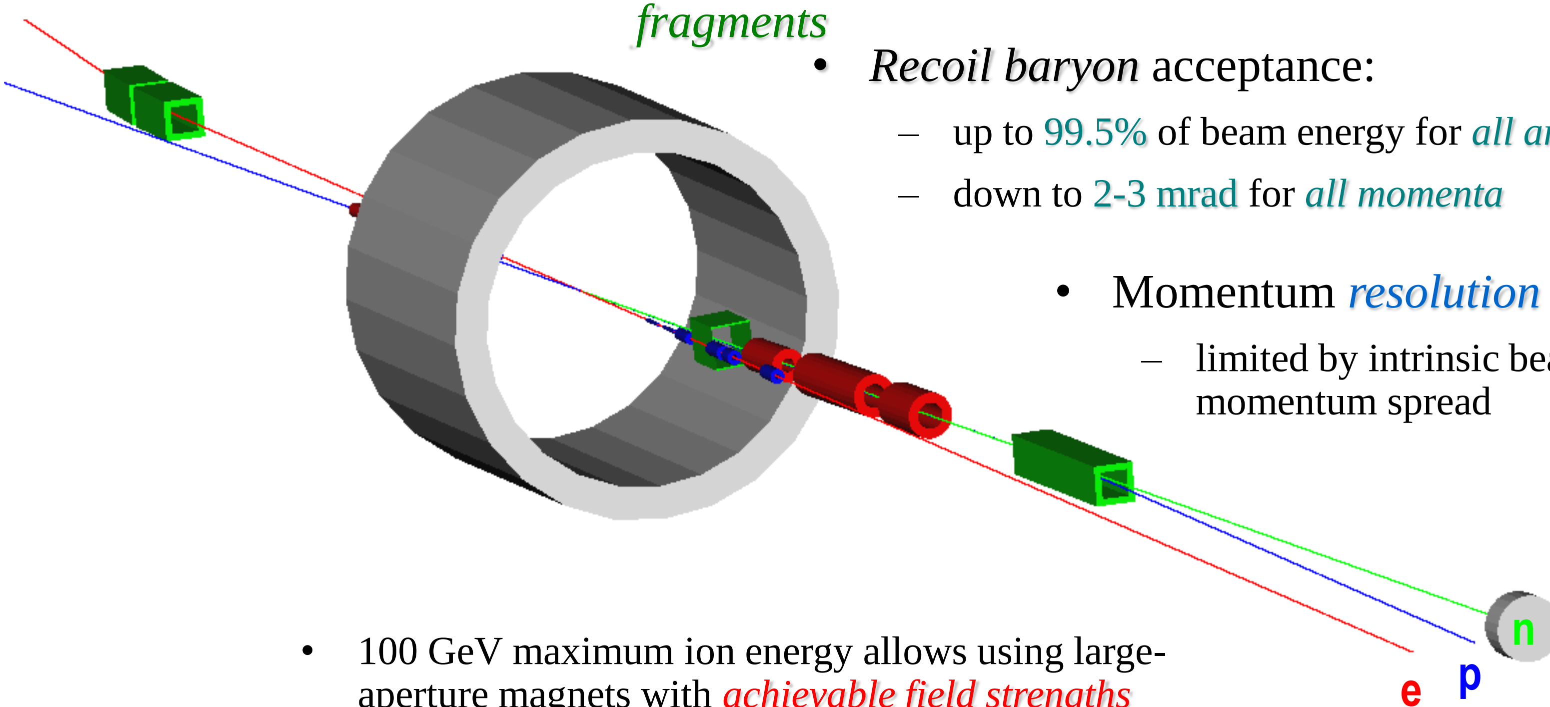
Forward acceptance vs.magnetic rigidity



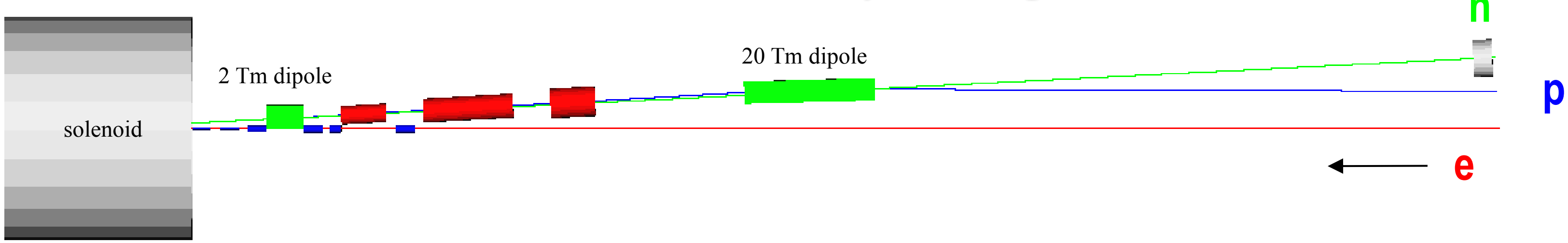
Tagged d beam: dp/p = -0.5
Tagged ^{3}He beam: dp/p = +0.33

Ultra-forward hadron detection – summary

- *Neutron* detection in a 25 mrad cone *down to zero degrees*
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2-3 mrad for *all momenta*
- Momentum *resolution < $3x10^{-4}$*
  - limited by intrinsic beam momentum spread

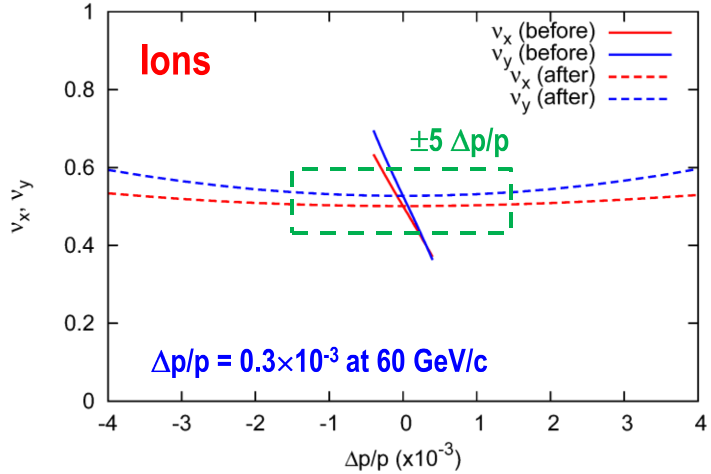


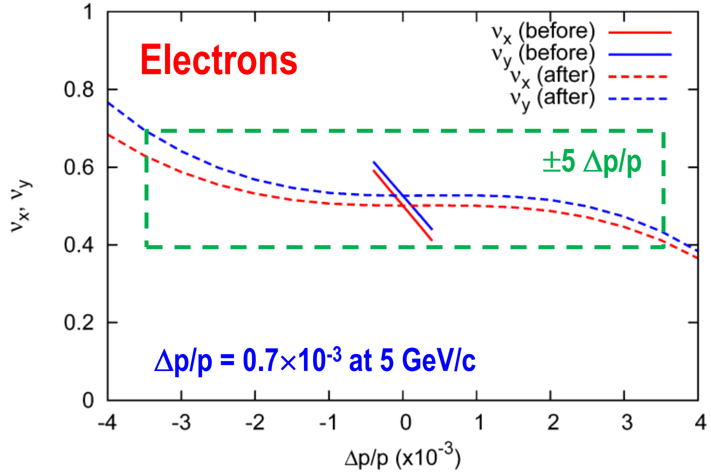
- 100 GeV maximum ion energy allows using large-aperture magnets with *achievable field strengths*



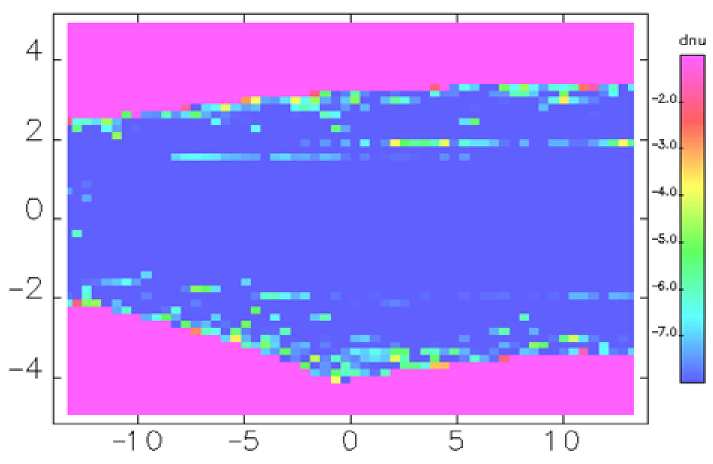
Chromaticity Compensation and Dynamic Aperture

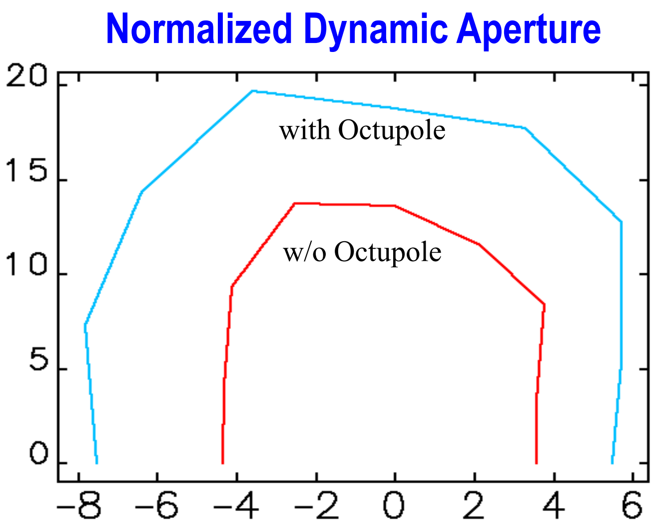
- Compensation of chromaticity with 2 sextupole families only using symmetry





- Non-linear dynamic aperture optimization under way





Backgrounds and detector placement

Synchrotron radiation

- From arc where electrons exit and magnets on straight section

Random hadronic background

- Dominated by interaction of beam ions with residual gas in beam pipe between arc and IP
- **Comparison of MEIC (at s = 4,000) and HERA (at s = 100,000)**
  - Distance from ion exit arc to detector: 50 m / 120 m = 0.4
  - Average hadron multiplicity: $(4000 / 100000)^{1/4} = 0.4$
  - p-p cross section (fixed target): σ(90 GeV) / σ(920 GeV) = 0.7
  - At the same ion current and vacuum, MEIC background should be about 10% of HERA
    - Can run higher ion currents (0.1 A at HERA)
    - Good vacuum is easier to maintain in a shorter section of the ring
- **Backgrounds do not seem to be a major problem for the MEIC**
  - Placing high-luminosity detectors closer to ion exit arc helps with both background types
  - Beyond arcs proton/ion beams get manipulated (crab crossing angle), electron beam stays straight to go through detector → minimizes synchroton radiation
  - Signal-to-background will be considerably better at the MEIC than HERA
    - MEIC luminosity is more than 100 times higher (depending on kinematics)

Ion Polarization in Twisted Rings

All ion rings (two boosters, collider) have a figure-8 shape

- Spin precession in the left & right parts of the ring are exactly cancelled
- Special insertions invented to provide energy independent spin tune off 0 at constant orbit
- Ensures spin preservation and manipulation by ***easy means***
- Avoids energy-dependent spin sensitivity for ion all species
- ***The only practical way to accommodate medium energy polarized deuterons***

which allows for "clean" neutron measurements

This design feature offers *a* ***firm no-pain long term operation runs*** for all polarized beams at low and high energies, since:

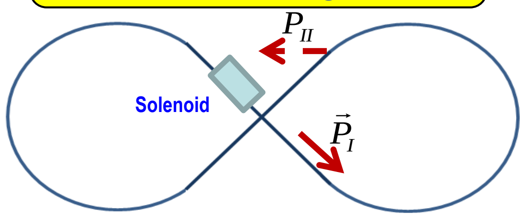
- Intrinsic spin resonances stay away
- High order intrinsic effects are diminished with *cooled emittance*

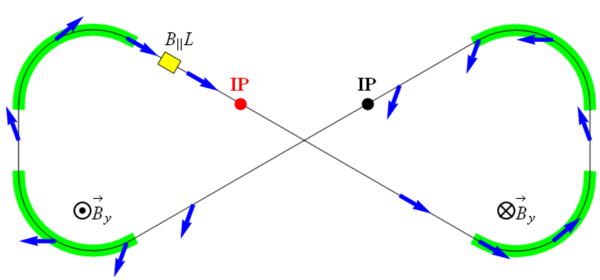
Ion Spin Acceleration and Manipulation

Special insertions provide <u>energy independent spin tune</u> off zero – at <u>constant orbit</u>

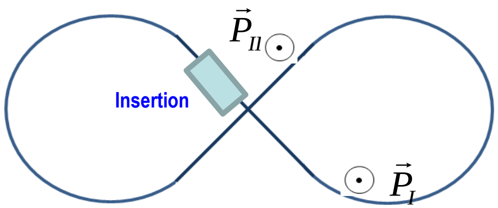
- Acceleration of all species in boosters
- <u>Deuterium</u> in Collider Ring
- Spin manipulation for all species in CR of Phase I MEIC

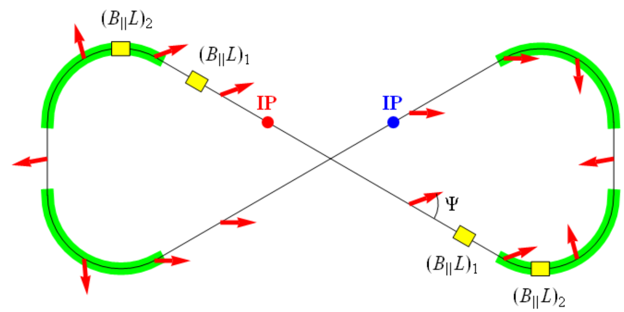
Longitudinal polarization in one straight

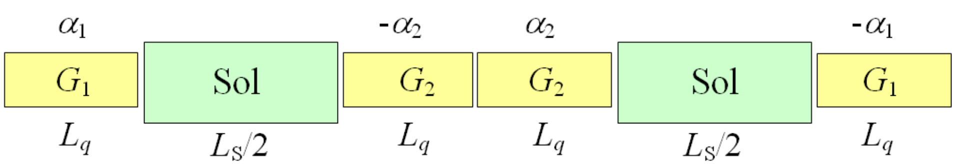




Vertical polarization over all ring







Proton and He-3 spin in Phase II CR

“Strong solutions” based on:

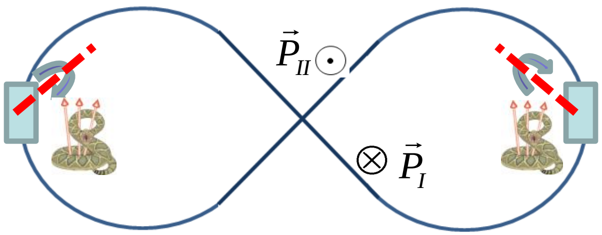
two RHIC type helical snakes in arcs, switching axis

Transverse polarization at both IPs

45 degrees snake axis

Spin tune ½

Inject vertical spin



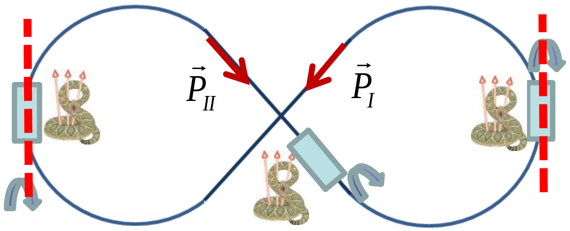
Longitudinal polarization at both IPs

Longitudinal RHIC snakes + Compact single helix snake in one of two straights

Spin tune ½

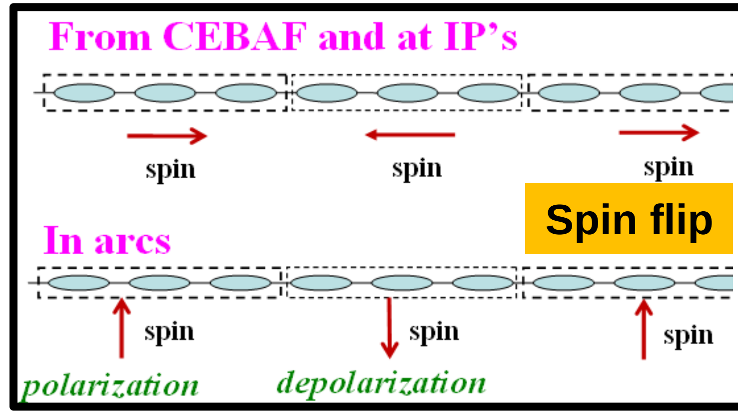
No spin rotators at IPs

Inject longitudinal spin

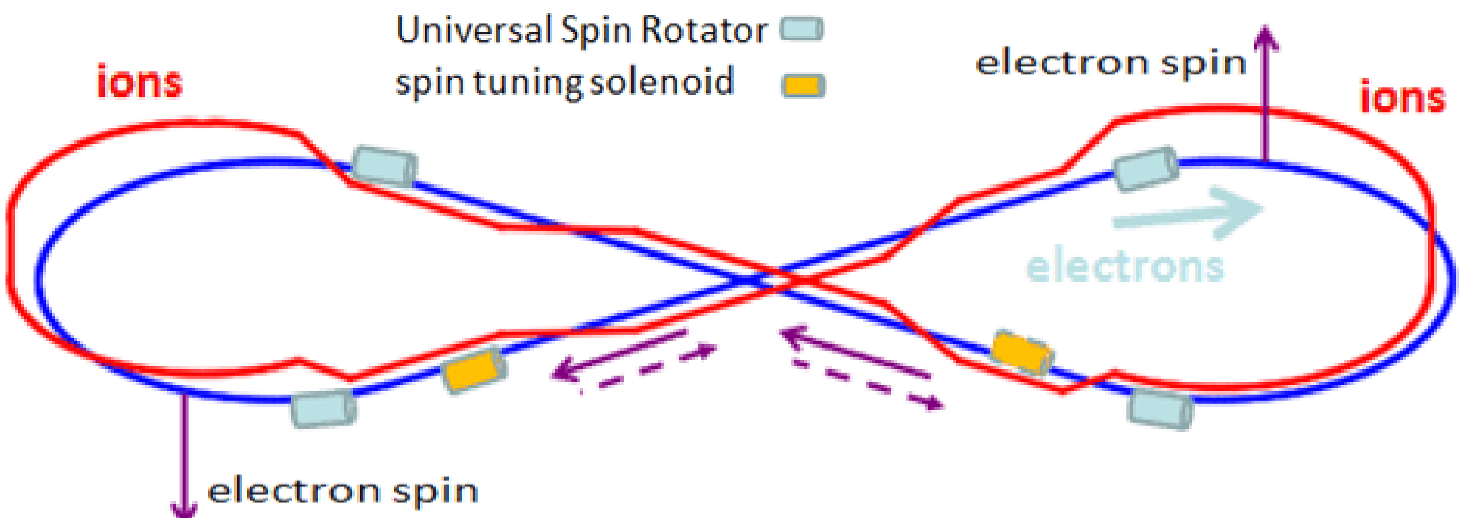


- **New /easier and more flexible/ solutions based on <u>compact helixes</u> and <u>Universal Spin Rotators</u> – in design process**

Polarized e-Beam in the Storage Ring



- **MEIC Physics program demands**
  - High polarization (>70%) and long life-time (>10 min.)
  - Longitudinal direction at all collision points
  - Spin flip capability for improving data statistics
- **MEIC electron polarization design**
  - CEBAF polarized electron source (>85%)
  - Inject e-beam with vertical spin in arcs
  - Using ***universal spin rotators*** for longitudinal spin at IP
  - Employing ***spin matching*** to minimizing quantum depolarization

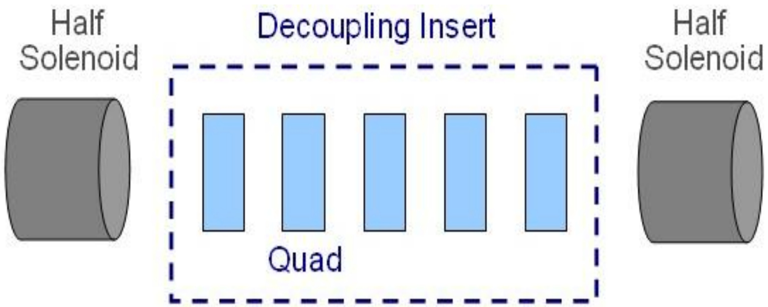


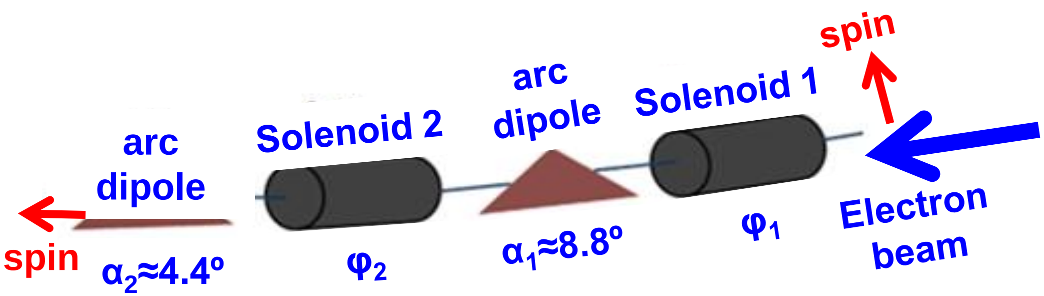
Universal Spin Rotator

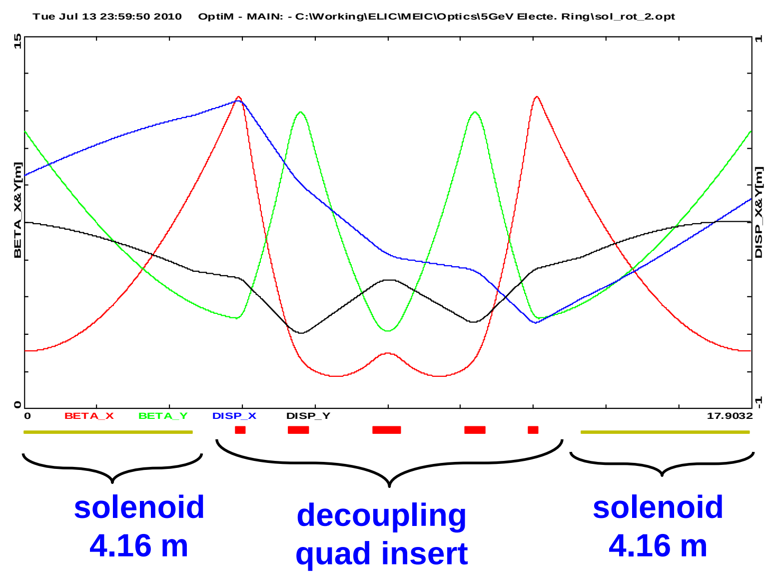
- Rotating spin from vertical to longitudinal
- Consists of 2 solenoids & 2 (fixed angle) arc dipoles
- ***Universal***
  - ➔ ***energy independent***
    works for all energies (3 to 12 GeV)
  - ➔ ***orbit independent***
    does not affect orbital geometry

Compensation of solenoid x-y coupling

V. Livinenko &
A. Zholents, 1980







E (GeV)	φ_1	BL_1 (Tm)	α_1	φ_2	BL_2 (Tm)	α_2
3	$\pi/2$	15.7	$\pi/3$	0	0	$\pi/6$
6	0.62	12.3	$2\pi/3$	1.91	38.2	$\pi/3$
9	$\pi/6$	15.7	π	$2\pi/3$	62.8	$\pi/2$
12	0.62	24.6	$4\pi/3$	1.91	76.4	$2\pi/3$

Study for Polarized Positrons in MEIC

- Use CEBAF beam to generate unpolarized positrons
  (working out an optimum scheme in process)
- Accelerate, inject and stack in the storage ring
- Arrange and wait for possibly fastest ST polarization
  (at 10-12 GeV, perhaps , and (or) by use special wigglers)
- Ramp energy down to a reasonable minimum for experiment
- Use spin-resonance SC cavities for *spin flip* (***frequent*** flip for the ***whole*** beam or ***one-time*** flip for ***half*** beam***)***

  / techniques by A. Krisch – V. Morozov – A. Kondratenko and collaborators/

Electron Cooling in MEIC

- Essential to achieve high luminosity for MEIC
- Based on traditional electron cooling
- ***Multi-phase cooling* scheme**

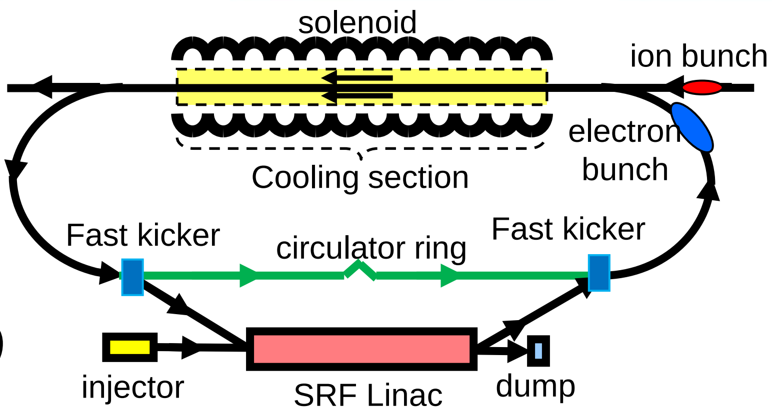
Pre-booster: *Cooling* for assisting accumulation of positive ion beams
(Using a low energy DC electron beam, existing technology)

Collider ring: *Initial cooling* after injection
Final cooling after boost & re-bunching, reaching design values
Continuous cooling during collision for suppressing IBS
(Using new technologies)

Energy (proton / electron)	GeV / MeV	20 / 10.9	100 / 54
Cooling length/circumference	m	60 / 1350	
Current and Particles/bunch	A and 10^{10}	0.5 / 1.5 and 0.417 / 1.25	
Bunch frequency	MHz	~ 1 / 748.5	748.5
Energy spread	10^{-4}	10 / 3	5 / 3
Ion bunch length	cm	coasted	coasted → 1
Electron bunch length	cm	2	
Proton emittance, horiz. /vert.	μm	4	4 → 0.35/0.07
Cooling time	min	10	~ 0.4

Staged Electron Cooling In Collider Ring

To achieve desired hadron beam properties requires ERL-based regular electron cooling



Design choices:
- *energy recovery linac*
- *circulator ring (~100 turns)*
- *fast kicker*

- **Initial cooling:** after injection for reduction of longitudinal emittance < acceleration
- **Final cooling:** after boost & rebunching, for reaching design values of beam parameters
- **Continuous cooling:** during collision for suppressing IBS & preserving luminosity lifetime

FNAL:
8 GeV/4 MeV

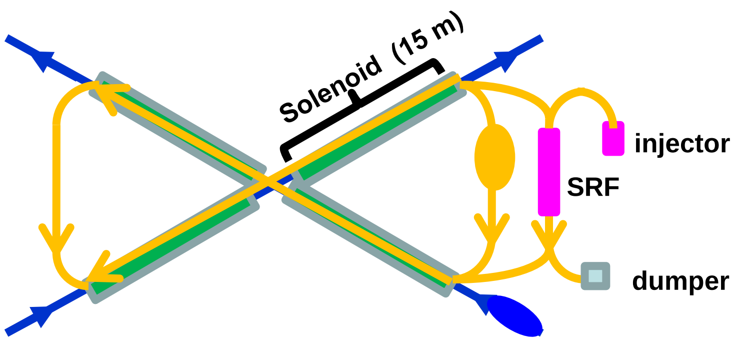
		Initial Cooling	after boost & bunching	Colliding Mode
Energy	GeV/MeV	20 / 8.15	60 / 32.67	60 / 32.67
Beam current	A	0.5 / 3	0.5 / 3	0.5 / 3
Particles/Bunch	10^{10}	0.42 / 3.75	0.42 / 3.75	0.42 / 3.75
Ion and electron bunch length	cm	(coasted)	1 / 2~3	1 / 2~3
Momentum spread	10^{-4}	10 / 2	5 / 2	3 / 2
Horiz. and vert. emitt, norm.	µm	4 / 4		0.35 / 0.07
Laslett's tune shift	(proton)	0.002	0.006	0.07
Cooling length /circumference	m/m	15 / 1000	15 / 1000	15 / 1000

MEIC Accelerator R&D: Electron Cooling

- **Electron Cooling in Collider – proof of principle of concept & techniques**
  - Cooling simulations are in progress (collaboration with Tech-X established through an SBIR grant)
  - ERL circulator cooler (linear optics and ERL) design has been completed
  - Fast RF kicker concept has been developed, plan to test with two kickers from SLAC
  - Test of beam-beam kicker concept at FNAL/ASTA facility and collaboration are in planning
  - Optics design of a cooler test facility based on JLab FEL ERL has been completed

MEIC Electron cooler

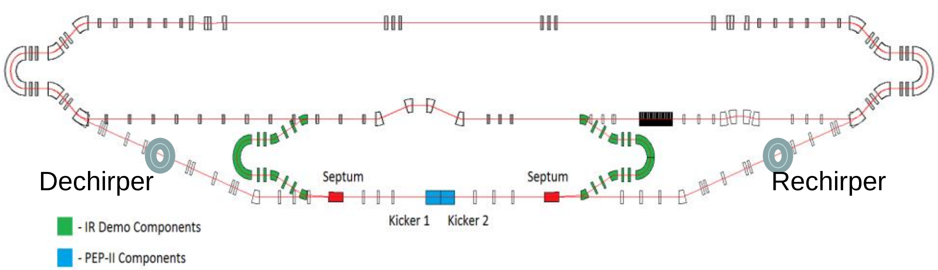
(in center of figure-8)



- eliminating a long return path could double the cooling rate

A technology demonstration possible using JLab FEL facility

e-Cooler Test Facility @ FEL



Required R&D: demonstrate ERL-based cooler concept by 2016 (at FEL/ERL conditions)

Further ongoing MEIC Accelerator R&D

(not discussed, only for reference of committee)

- **Space Charge Dominated Ion Beam in the Pre-booster**
  - Simulation study is in progress by Argonne-NIU collaborators
- **Beam Synchronization**
  - A scheme has been developed; SRF cavity frequency tunability study is in progress
- **Beam-Beam Interaction**
  - Phase 1 simulation study was completed
- **Interaction Region, Chromaticity Compensation and Dynamic Aperture**
  - Detector integration with IR design has been completed, offering excellent acceptance
  - Correction scheme has been developed, and incorporated into the IR design ✓
  - Tracking simulations show excellent momentum acceptance; dynamic aperture is increased
  - Further optimization in progress (*e.g.*, all magnet spaces/sizes defined for IR +/- 100 m)
- **Beam Polarization**
  - Electron spin matching and tracking simulations are in progress, achieving acceptable equilibrium polarization and lifetime (collaboration with DESY) ✓
  - New ion polarization scheme and spin rotators have been developed (collaboration with Russian group) – numerical demonstration of figure-8 concept with misalignments ongoing ✓
- **Electron Cloud in Ion Ring**
- **Ion Sources (Polarized and Universal)**

Summary

- EIC is the ultimate tool to study sea quarks and gluons
- EIC allows a **unique opportunity** to make a breakthrough in nucleon structure and QCD dynamics
- Collider environment provides tremendous advantages
  - Kinematic coverage (low to high center-of-mass energy)
  - Polarization measurements with excellent Figure-of-Merit
  - Detection of spectators, recoil baryons, and target fragments

- The MEIC concept has been stable for 3 years
  - Allowing for refinement of the design
  - MEIC design report completed and available on the arXiv
  - Phased options including use of 25 GeV booster under consideration
  - Some accelerator R&D funds have been allocated
  - Joint detector R&D projects have started

- The MEIC design is based predominantly on proven technology & our immediate goal is full validation of the MEIC design with R&D