# The Electron-Ion Collider Project at Jefferson Lab

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**Jefferson Lab**

Seminar at Argonne National Lab

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# Outline

1. Introduction
2. MEIC Baseline Design
3. Electron and Ion Complex
4. Electron Cooling
5. Interaction Region
6. Outlook and Summary

# 1. Introduction

# Electron-Ion Collider on World Map

# Science Goals

## The High-Energy/Nuclear Science of LHeC

***Overarching Goal: lepton-proton at the TeV Scale***

Hunt for quark substructure & high-density matter (saturation)

High precision QCD and EW studies and possible implications for GUT

## The Nuclear Science of eRHIC/MEIC

***Overarching Goal: Explore and Understand QCD***:

Map the spin and spatial structure of quarks and gluons in nucleons

Discover the collective effects of gluons in atomic nuclei

*(role of gluons in nuclei & onset of saturation)*

***Emerging Themes:***

Understand the emergence of hadronic matter from quarks and gluons & EW

## The Nuclear Science of ENC/HIAF(?)

***Overarching Goal: Explore Hadron Structure***

Map the spin and spatial structure of valence & sea quarks in nucleons

**R. Ent**

# Electron-Ion Collider Physics

- JLab theory paper on MEIC science (EPJA 48 (2012) 92)
- EIC White Paper (arXiv:1212.17010)

## Map the spin and spatial structure of quarks and gluons in nucleons

Needs high (polarized) luminosity and range of energies: s ~ 500-5000

- How much spin is carried by gluons?
- Does orbital motion of sea quarks contribute to spin?
  - Generalized Parton Distribution (GPDs)
  - Transverse Momentum Distributions (TMDs)
- What do the partons reveal in transverse momentum and coordinate space

## Discover the collective effects of gluons in atomic nuclei

- What is the distribution of glue in nuclei?
- Are there modifications as for quarks?
- Can we observe gluon saturation effects?

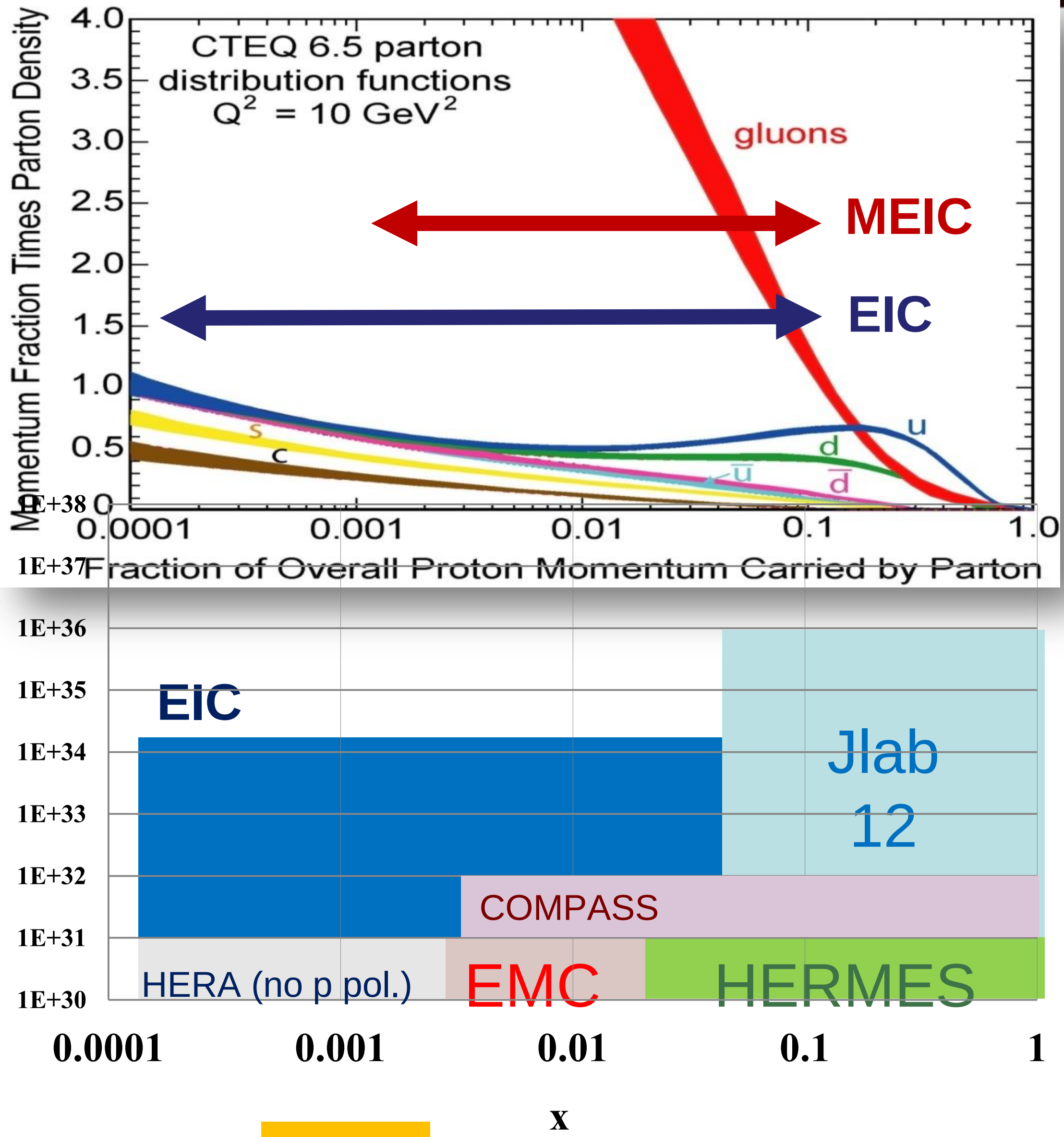
## Understand the emergence of hadronic matter from color charge

- How do color charges evolve in space and time?
- How do partons propagate in nuclear matter?
- Can nuclei help reveal the dynamics of fragmentation?

## Opportunities for fundamental symmetry measurements

**R. Ent**

# The Reach of EIC – into the “sea”



- **High Luminosity**
  **→ $10^{34}cm^{-2}s^{-1}$**
- **Low x regime**
  **x → 0.0001**
- **High Polarization**
  **→ 70%**

***Discovery Potential!***

**R. Ent**

# JLab Nuclear Science: 12 GeV CEBAF

## CEBAF fixed target program

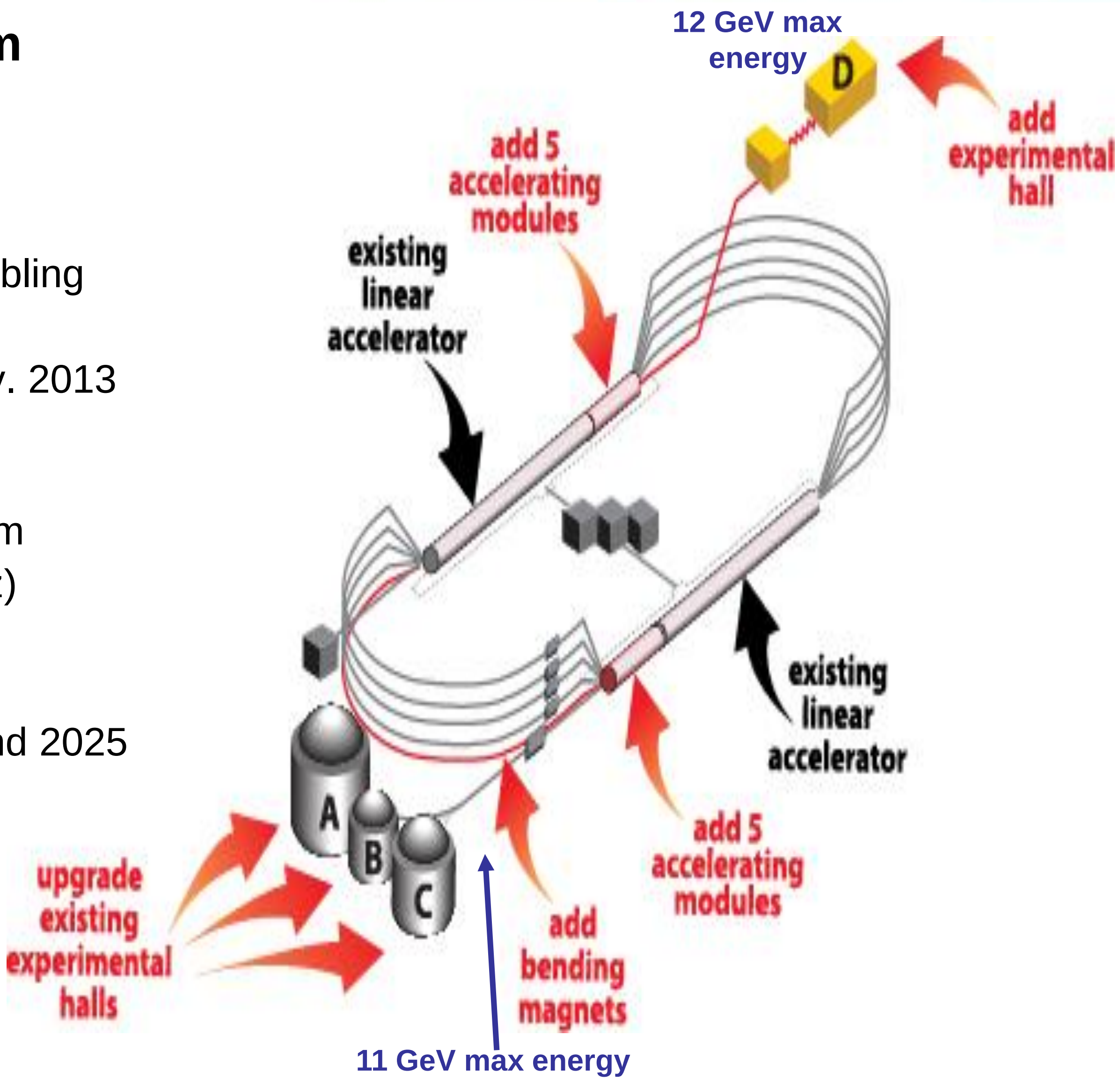
- 5-pass recirculating SRF linac

## 12 GeV CEBAF Upgrade

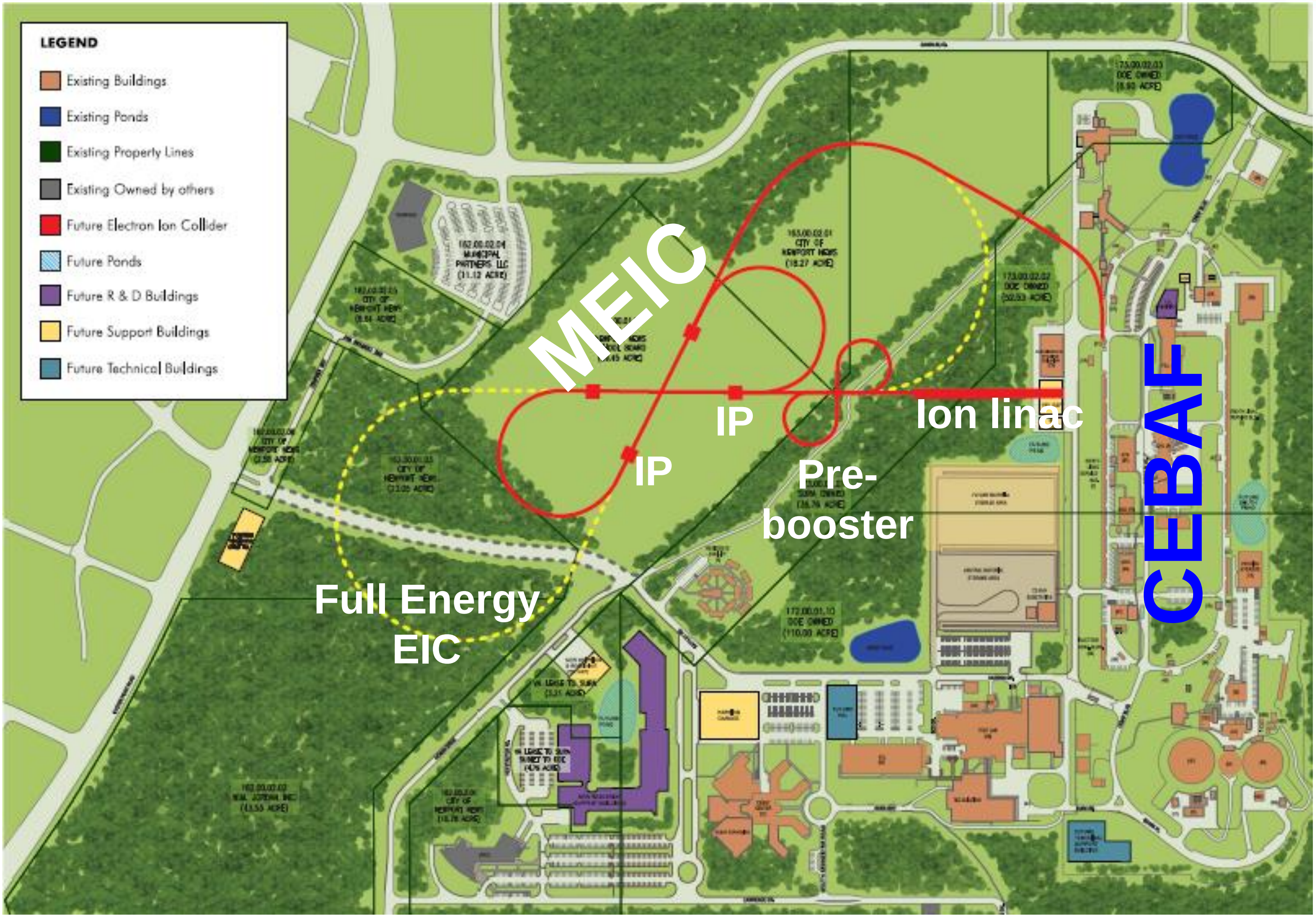
- A $340M project for energy doubling
- Construction near completion
- Commissioning will start on Nov. 2013

## New CEBAF will provide

- Up to 12 GeV CW electron beam
- High repetition rate (3x499 MHz)
- High polarization (>80%)
- Very good beam quality
- Exciting science program beyond 2025



# Future Nuclear Science at JLab



# Introduction

- JLab’s fixed target program after the 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-ONP 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 luminosities.
- A conceptual machine design has been completed recently, providing a base for performance evaluation, cost estimation, and technical risk assessment.
- A design report was released on August, 2012.

# MEIC Design Report Released!

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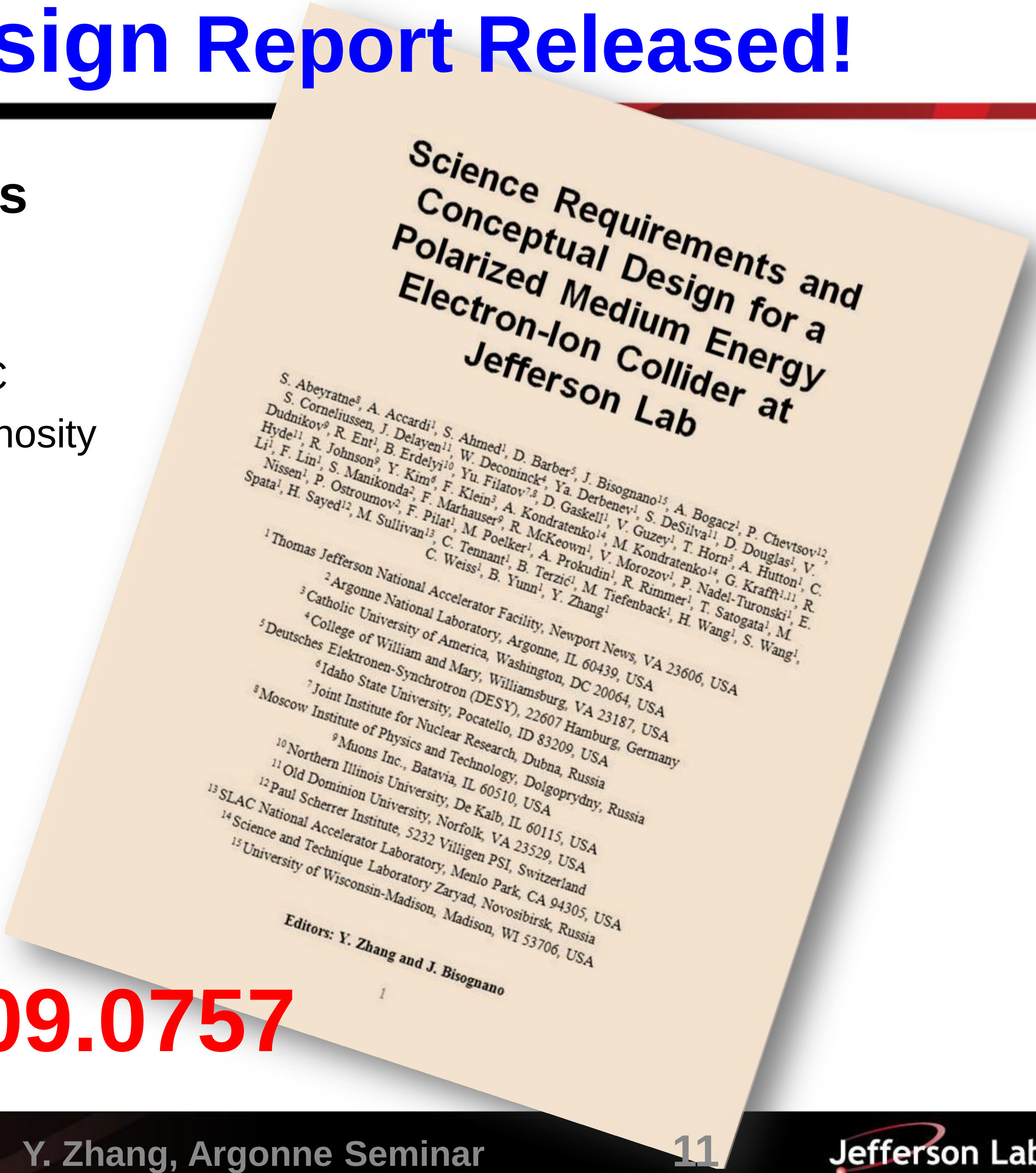

### Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

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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**arXiv:1209.0757**

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- **RF systems** R. Rimmer, H. Wang, S. Wang (SRF Institute, JLab)
- **Ion injector complex**
  source: V. Dudnikov (Muons, Inc)
  Linac: P. Ostroumov, S. Manikonda (Argonne Lab)
  Pre-booster: B. Erdelyi (Northern Illinois Univ.)
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  ERL-CR cooler demo: D. Douglas and C. Tennant (FEL, JLab)
  Magnetized gun: R. Geng (SRF JLab), S. Kondrashev, P. Ostroumov (Argonne)
  Simulations: David Bruhwiler, Ilya Pogorelov (Tech-X)
- **Interaction regions**
  Detector integration: C. Hyde (Old Dominion Univ.), P. Nadel-Turonski (NP, JLab)
  SR background: M. Sullivan (SLAC)
  Crab cavity: A. Castilla, J. Delayen, S. DeSilva (Old Dominion Univ.)
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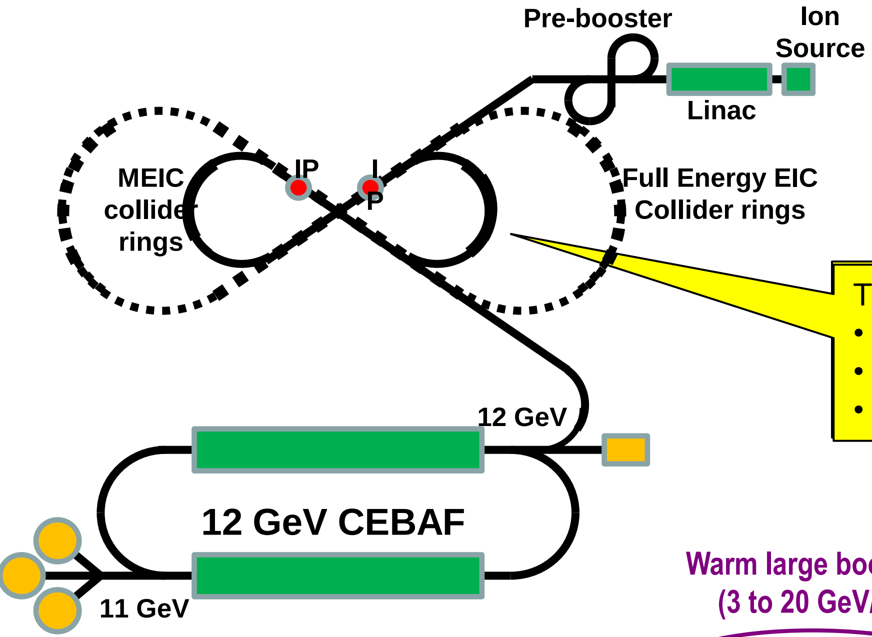
- **Beam-beam simulation** J. Qiang (LBL)
- **Feedback** Y. Kim (Idaho State Univ.)

# 2. MEIC Baseline Design

# MEIC Design Goals

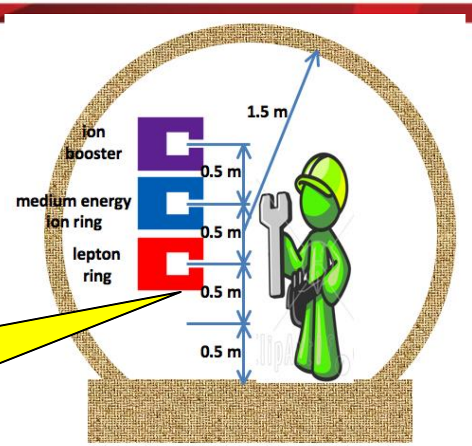
- **Energy** *(bridging the gap of 12 GeV CEBAF & HERA/LHeC)*
  - – Full coverage of *s* from a few 100 to a few 1000 GeV$^2$
  - – Electrons **3-12** GeV, protons **20-100** GeV, ions **12-40** GeV/u
- **Ion species**
  - – Polarized light ions: p, d, $^3$He, and possibly Li
  - – Un-polarized light to heavy ions up to A above 200 (Au, Pb)
- **Up to 2 detectors**
- **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

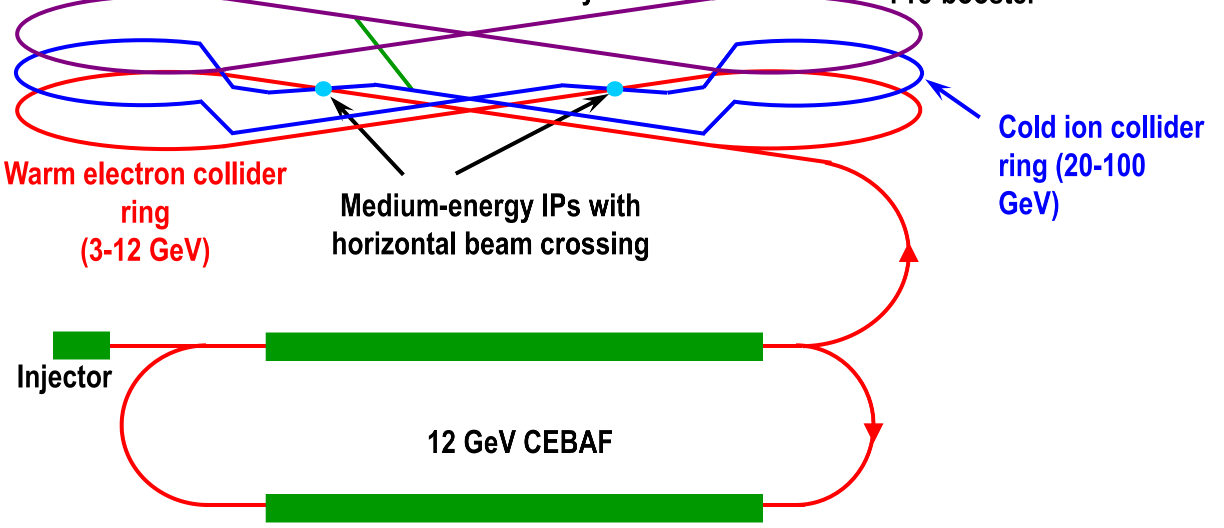
# MEIC Layout



Three compact rings:

- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)





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

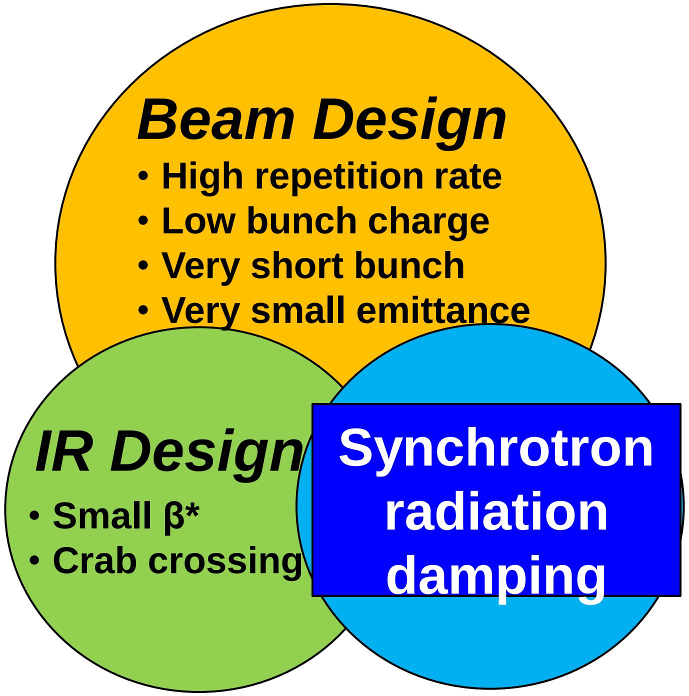
| | | Proton | Electron |
|---|---|---|---|
| Beam energy | GeV | 60 | 5 |
| Collision frequency | MHz | 750 | 750 |
| Particles per bunch | $10^{10}$ | 0.416 | 2.5 |
| Beam Current | A | 0.5 | 3 |
| Polarization | % | > 70 | ~ 80 |
| Energy spread | $10^{-4}$ | ~ 3 | 7.1 |
| RMS bunch length | cm | 1 | 0.75 |
| Horizontal emittance, normalized | µm rad | 0.35 | 54 |
| Vertical emittance, normalized | µm rad | 0.07 | 11 |
| Horizontal $\beta^*$ | cm | 10 | 10 |
| Vertical $\beta^*$ | 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 |
| Luminosity per IP, $10^{33}$ | $cm^{-2}s^{-1}$ | 5.6 | |

# Parameters for ***High Luminosity*** 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 | cm | 1 | 0.75 |
| Horizontal emittance, normalized | µm rad | 0.35 | 54 |
| Vertical emittance, normalized | µm rad | 0.07 | 11 |
| Horizontal $\beta^*$ | cm | 4 | 4 |
| Vertical $\beta^*$ | 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 |
| Luminosity per IP, $10^{33}$ | $cm^{-2}s^{-1}$ | 14.2 | |

# Design Feature: High Luminosity

- MEIC design concept for high luminosity is based on *high bunch repetition rate CW colliding beams*, specifically



**Beam Design**

- **High repetition rate**
- **Low bunch charge**
- **Very short bunch**
- **Very small emittance**

**IR Design**

- **Small β***
- **Crab crossing**

**Synchrotron radiation damping**

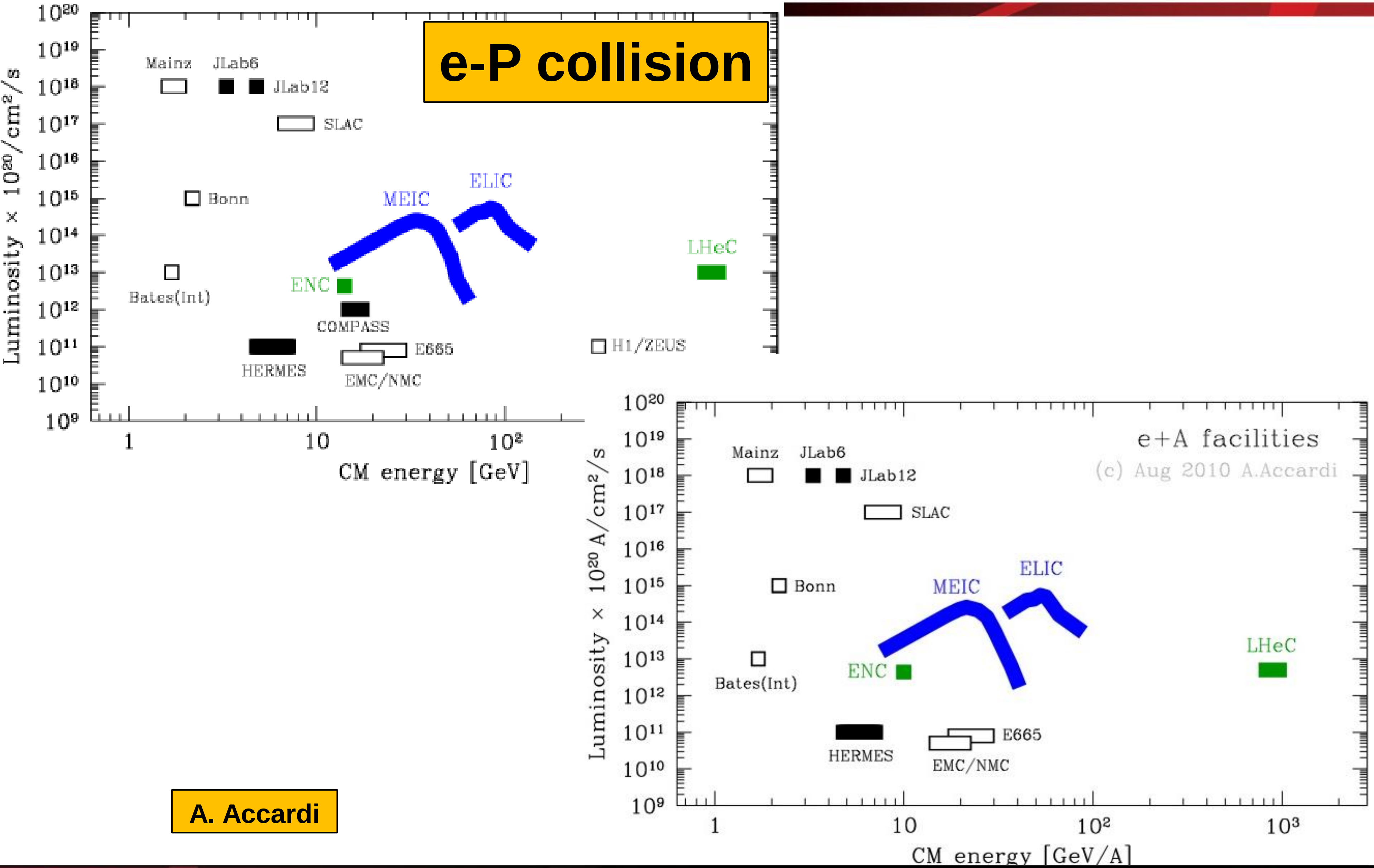
**KEK-B already reached above $2\times10^{34}$ /cm$^2$/s**

**JLab is poised to replicate same success in electron-ion collider:**

- A high repetition rate electron beam from CEBAF
- A new ion complex specifically designed to match e-beam
- Multi-phase electron cooling of ion beams

| | | KEK-B | MEIC | eRHIC ring-ring |
|---|---|---|---|---|
| Repetition rate | MHz | **509** | **748.5** | **13.1** |
| Energy ($e^-/e^+$ or $p/e^-$) | GeV | 8/3.5 | 60/5 | 250/10 |
| Particles/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 |
| Horiz. & vert. β* | cm | 56/0.56 | 10/2 ~ 4/0.8 | 5/5 |
| Luminosity/IP, $10^{34}$ | /cm$^2$s | 2 | 0.56 ~ 1.4 | 0.97 |

# MEIC/ELIC Luminosity Plot



**e-P collision**

**A. Accardi**

# MEIC Design Feature: High Polarization

**All ion rings (two boosters, 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

**Advantage 1: Ion spin preservation during acceleration**

- Ensures spin preservation
- Avoids energy-dependent spin sensitivity for ion all species
- promises a high polarization for all light ion beams

**Advantage 2: Ease of spin manipulation w/ small B-field**

- Delivering desired polarization at multiple collision points

**Advantage 3: The only practical way to accommodate polarized deuterons** (ultra small *g-2*)

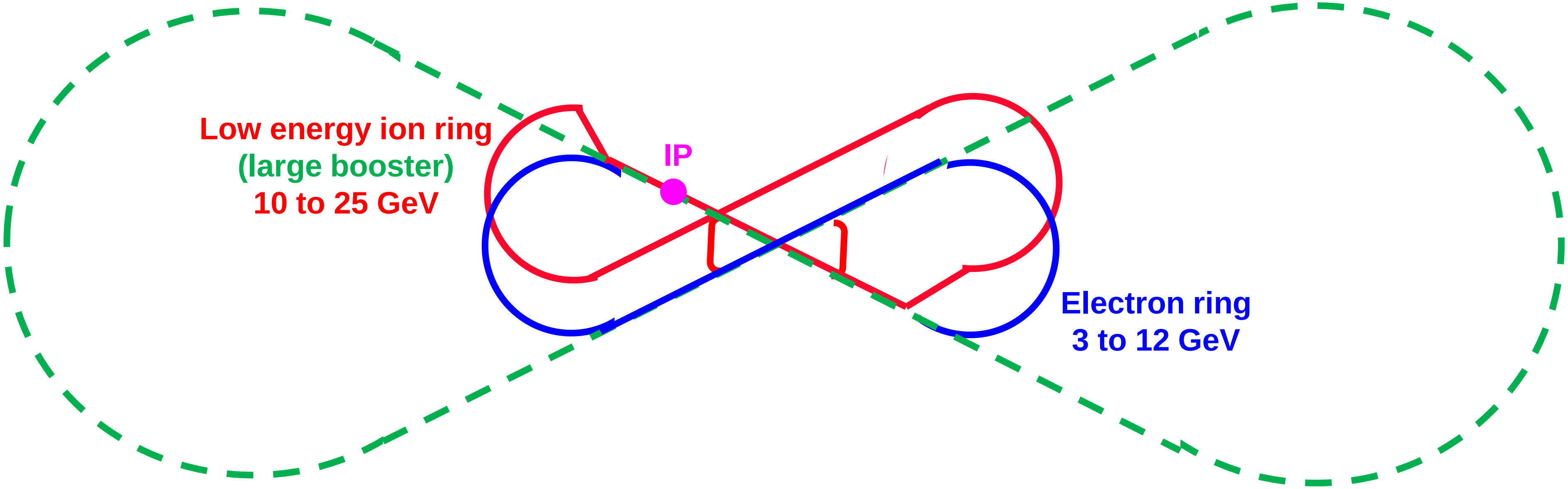
(The electron ring has a similar shape since it shares a tunnel with the ion ring)

# LEIC: *L*ow Energy *E*lectron-*I*on Collider

**MEIC+LEIC has large advantage**

- Design flexibility
- Detector interchangeable between MEIC and LEIC
- No SC ring for LEIC
- Low initial project cost
- Low technology R&D challenges
- Reduce risk

| | Electron ring | Ion Collider Ring | |
|---|---|---|---|
| | GeV | GeV | Magnet |
| LEIC | 3 - 12 | 10 – 25 | warm |
| MEIC | 3 - 12 | 20 – 100 | Cold |
| Full Energy EIC | 3 - 20 | 50 - 250 | Cold |



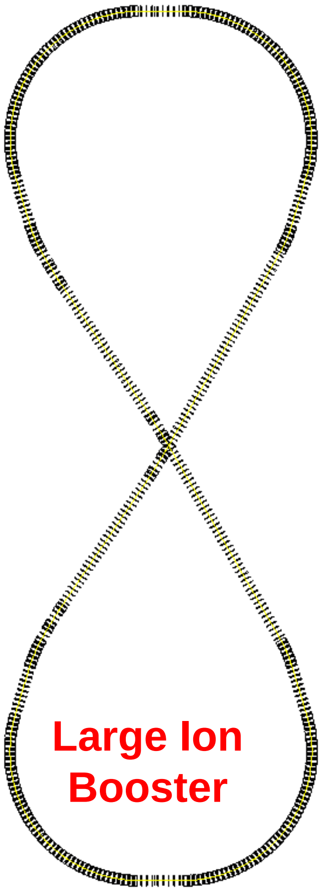
# LEIC Design Parameters

| | | p | e | P | e | p | E |
|---|---|---|---|---|---|---|---|
| Beam energy | GeV | 25 | 5 | 25 | 7.5 | 25 | 10 |
| Collision frequency | MHz | 748.5 | | | | | |
| Particles per bunch | $10^{10}$ | 0.25 | 2.5 | 0.25 | 0.76 | 0.25 | 0.24 |
| Beam current | A | 0.3 | 3 | 0.3 | 0.91 | 0.3 | 0.29 |
| Polarization | % | >70 | ~ 80 | >70 | ~ 80 | >70 | ~ 80 |
| Energy spread | $10^{-4}$ | ~ 3 | 7.1 | ~ 3 | 7.1 | ~ 3 | 7.1 |
| RMS bunch length | cm | 2 | 0.75 | 2 | 0.75 | 2 | 0.75 |
| Emittance, normalized | µm rad | 0.24 | 53.5 | 0.24 | 110 | 0.2 | 250 |
| Horizontal & vertical β* | cm | 2 | 3.3 | 2 | 2.3 | 2 | 1.4 |
| Beam-beam tune shift | | 0.013 | 0.011 | 0.004 | 0.005 | 0.001 | 0.002 |
| Laslett tune shift | | 0.053 | Small | 0.053 | small | 0.053 | small |
| Luminosity per IP, $10^{33}$ | $cm^{-2}s^{-1}$ | 2.1* | | 0.63* | | 0.2* | |

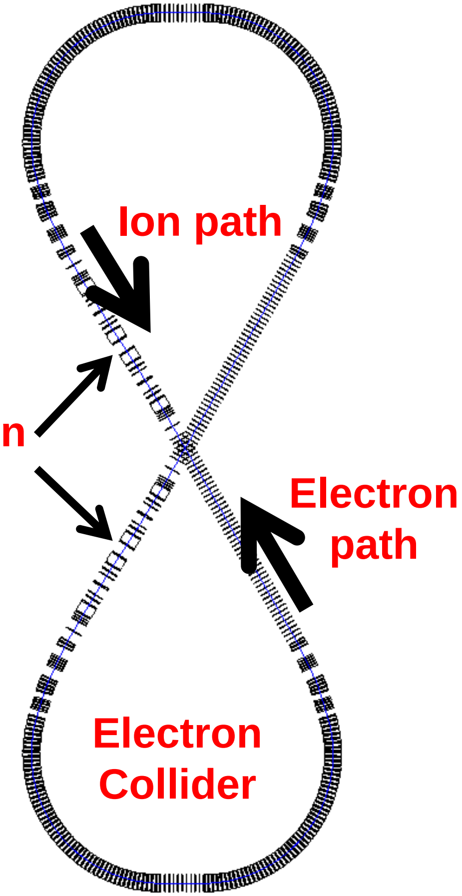
- There is a small hour glass effect, causing 13.5% luminosity loss
- Total tune-shift (space-charge + beam-beam) ≤ 0.066 for ion beams
- Round ion beams due to low energy

# 3. Electron and Ion Complex

# MEIC Collider Ring Layout



Large Ion Booster

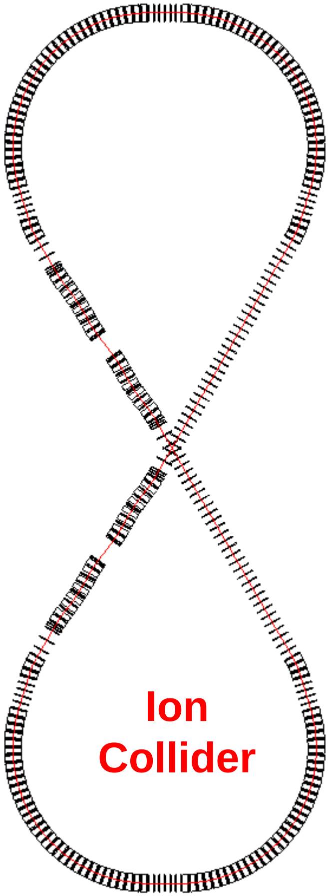


Ion path

Interaction Regions

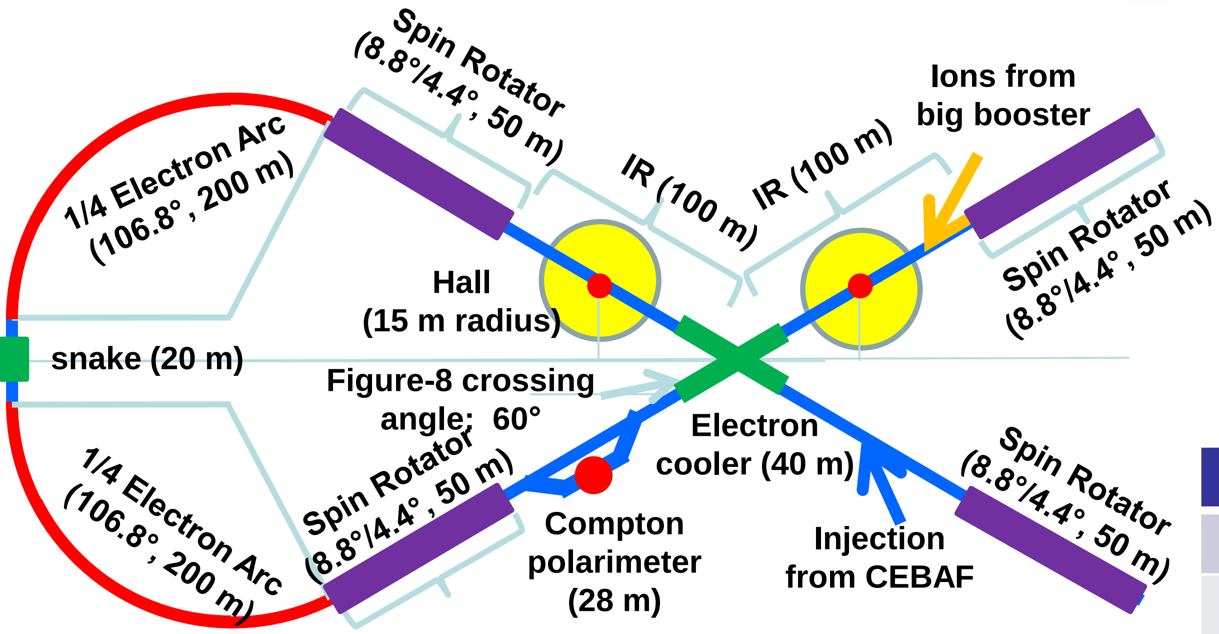
Electron path

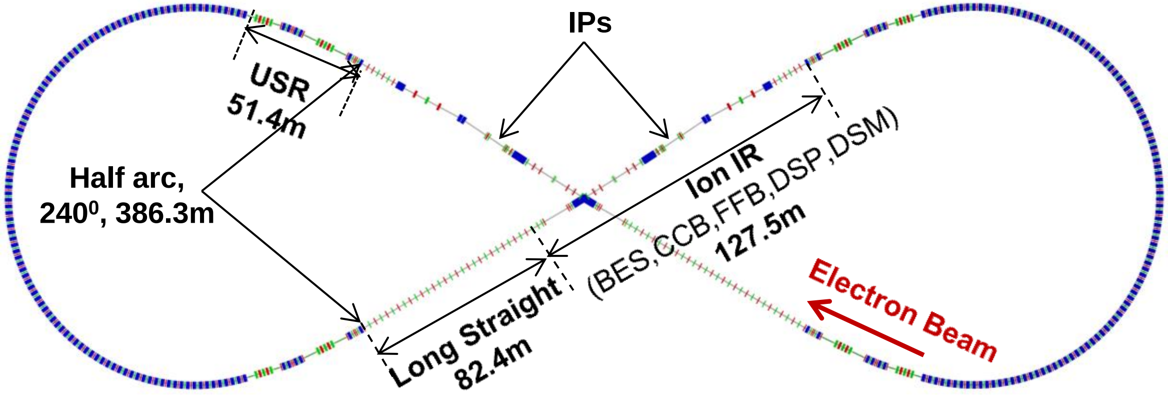
Electron Collider



Ion Collider

# Figure-8 Electron Collider Ring



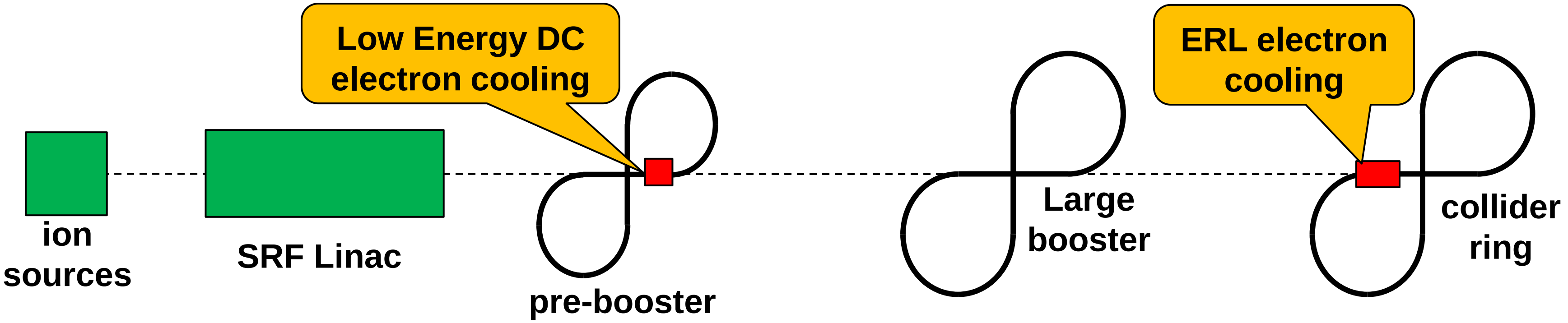


- Normal conduct magnets
- FODO lattice (60$^o$ phase/cell)
- Utilizing dispersion suppressor (varying quad strength)
- High transition energy

| Circumference | m | ~1340 |
|---|---|---|
| Figure-8 crossing angle | deg | 60 |
| Symmetric arc sections | | 4 |
| Quarter arc length | m | ~200 |
| Quarter arc angles | deg | 106.8 |
| Length of Long straights | m | 260 |
| Length of short straight | m | 25 |
| Length of spin rotator | m | 50 |
| Bending in spin rotator | deg | 13.2 |
| Interaction region | m | 100 |
| Compton Polarimetry | m | 28 |

# Formation of Ion Beams in a New Complex

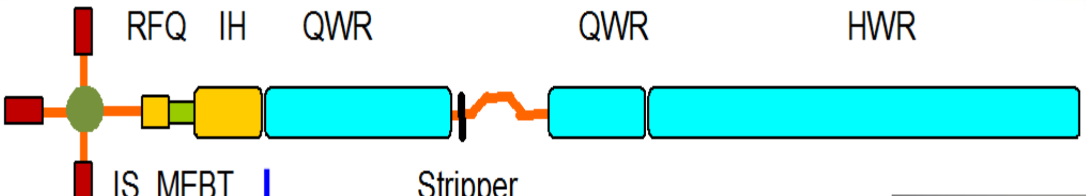
- Goals: covering all required ion species & energies, matching phase-space structures
- Challenges: beam formation ← *space charge effect at low energy*
  maintaining beam phase density ← *intra-beam scatterings*
- Low energy DC electron cooling for assisting accumulation of heavy ions
- SRF linac and boosters. No transition energy crossing in all rings
- High energy electron cooling

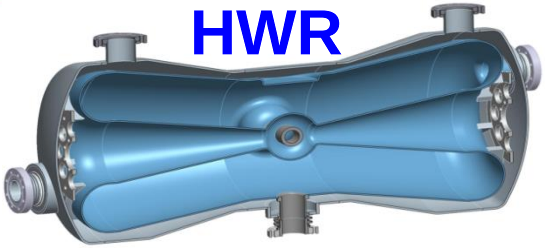


| | Max. energy (GeV/c) | Electron Cooling | Process |
|---|---|---|---|
| SRF linac | 0.2 (0.08) | | Stripping |
| Pre-booster | 3 (1.2) | DC | Accumulating |
| Large booster | 20 (8) | | Stacking |
| collider ring | 100 (40) | Multi-phased/ERL | Coasting/rebunching |

* Numbers in parentheses repre

# Ion Linac





- Pulsed linac, peak power 680 kW
- Consists of quarter wave and half wave resonators
- Originally developed at ANL as a heavy-ion driver accelerator for ***Rare Isotope Beam Facility***
- Adopted for MEIC ion linac for
  - Satisfying MEIC ion linac requirement
  - Covering similar energies, variety of ion species
  - Excellent and matured design
- All subsystems are either ***commercially available*** or based on ***well-developed technologies***

**P. Ostroumov, ANL**

| Parameters | Unit | Value |
|---|---|---|
| Species | | p to lead |
| Reference Design | | $^{208}$Pb |
| Kinetic energy | MeV/u | 100 |
| Max. pulse current<br>Light ions (A/q≤3)<br>Heavy ions (A/q≥3) | <br>mA<br>mA | <br>2<br>0.5 |
| Pulse repetition rate | Hz | 10 |
| Pulse length | ms | 0.25 |
| Max. beam pulsed power | kW | 680 |
| Fundament frequency | MHz | 115 |
| Total length | M | 150 |

# Ion Pre-booster

## Purpose of pre-booster

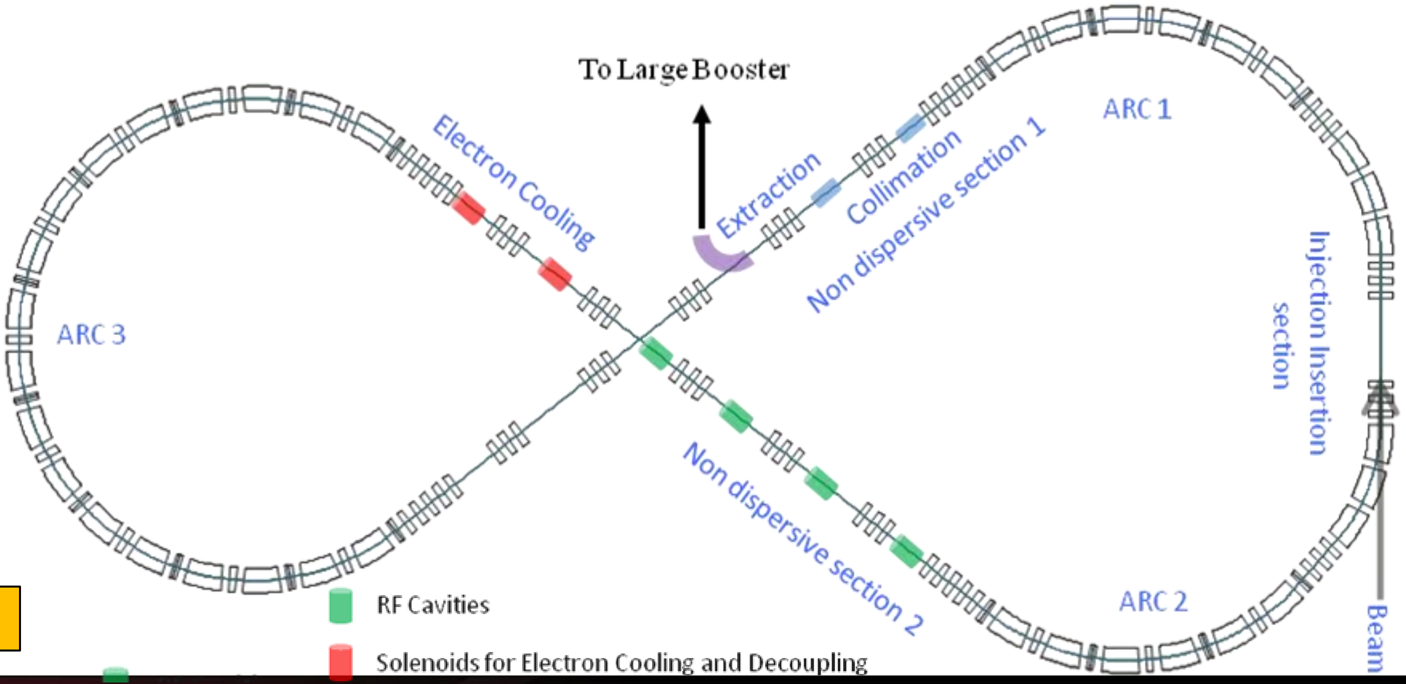
- Accumulating ions injected from linac
- Accelerating ions
- Extracting/sending ions to the large booster

## Design Concepts

- Figure-8 shape
- (Quasi-independent) modular design
- FODO arcs for simplicity and ease optics corrections

## Design constraints

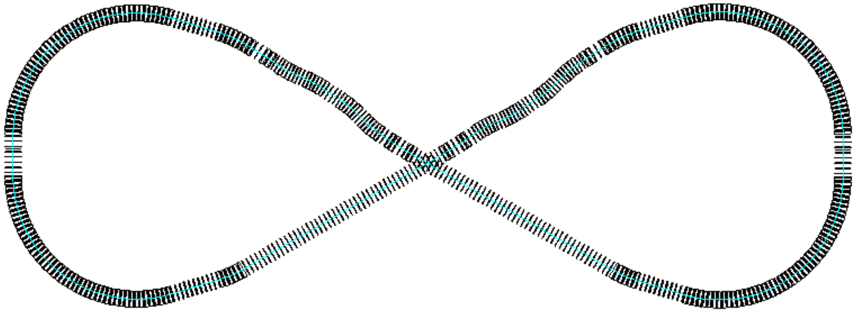
- Maximum bending field: 1.5 T
- Maximum quad field gradient: 20 T/m
- Momentum compaction smaller than 1/25
- Maximum beta functions less than 35 m
- Maximum full beam size less than 2.5 cm,
- 5m dispersion-free sections for RF, cooling, collimation and extraction.

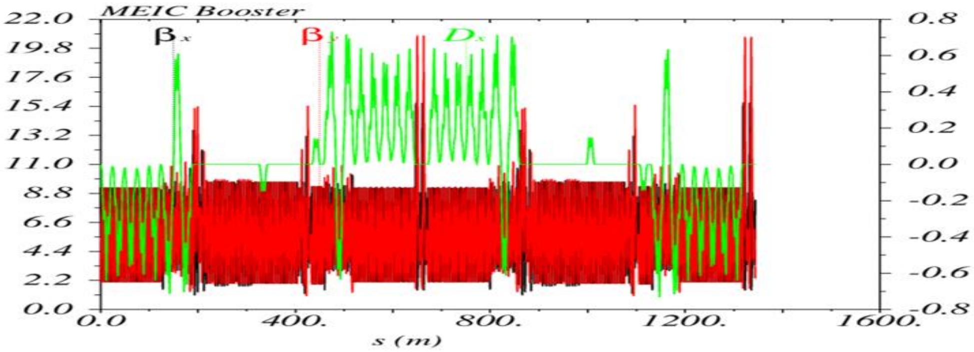


**B. Erdelyi, NIU**

# MEIC Ion Large Booster/LEIC Collider Ring

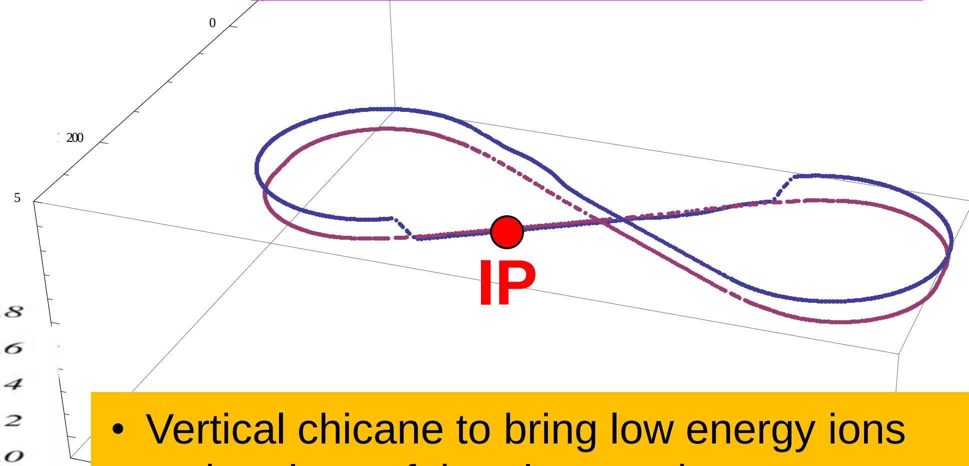
- Accelerating protons from 3 to 20 GeV (and ion energies with similar magnetic rigidity)
- Follow electron/ion collider ring footprints, housed in same tunnel
- Made of warm magnets and warm RF
- No transition energy crossing (always below $\gamma_t$=25.03)
- Quadrupole based dispersion suppression.
- Tuneable to any working point.





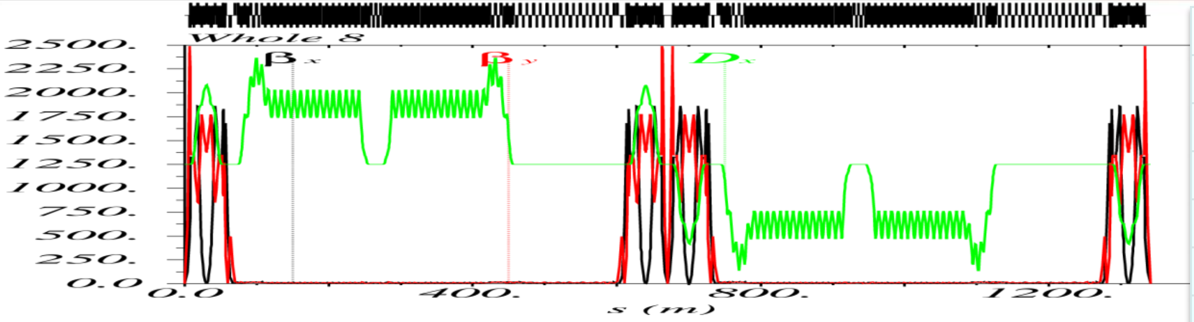
**Nissen**

**Large booster converted to a low energy collider ring**



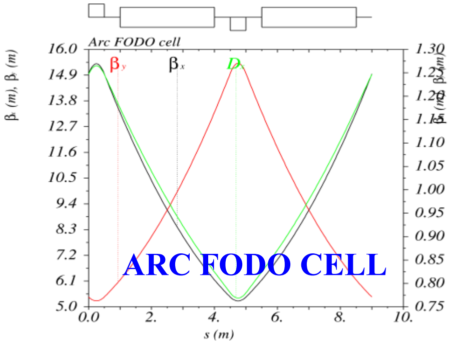
- Vertical chicane to bring low energy ions to the plane of the electron ring
- Add electron cooling and SRF
- Share detector with MEIC

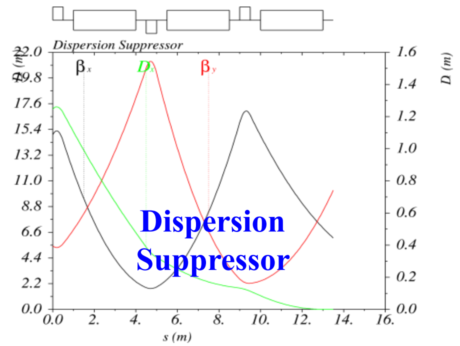
# MEIC Ion Collider Ring

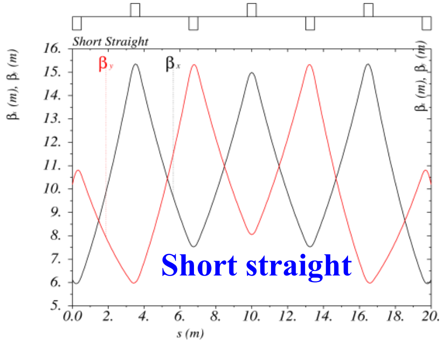


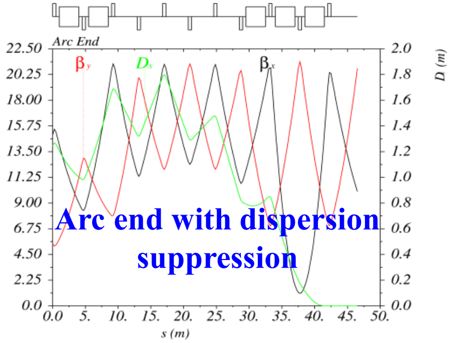
| | | |
|---|---|---|
| **Dipole** | | 144 |
| Length | m | 3 |
| Bending radius | M | 53.1 |
| Bending Angle | deg | 3.236 |
| Field @ 60 GeV | T | 3.768 |
| **Quad** | | 298 |
| Length | M | 0.5 |
| Strength @ 60 GeV | T/m | 92 / 89 |

| Circumference | m | 1340.92 |
|---|---|---|
| arc radius / length | m | 93.34 / 391 |
| Long & short straight | m | 279.5 / 20 |
| Lattice base cell | | FODO |
| Cells in arc / straight | | 52 / 20 |
| Arc/straight cell length | m | 9 / 9.3 |
| Phase advance per cell | m | 60 / 60 |
| Betatron tunes ($\nu_{x,}\ \nu_y$) | | 25.501 /25.527 |
| Momentum compaction | $10^{-3}$ | 5.12 |
| Transition gamma | | 13.97 |
| Dispersion suppression | | Adjusting quad strength |


ARC FODO CELL

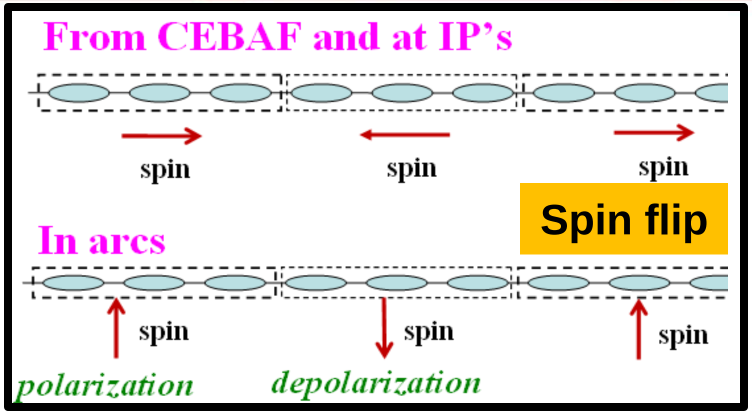

Dispersion Suppressor


Short straight

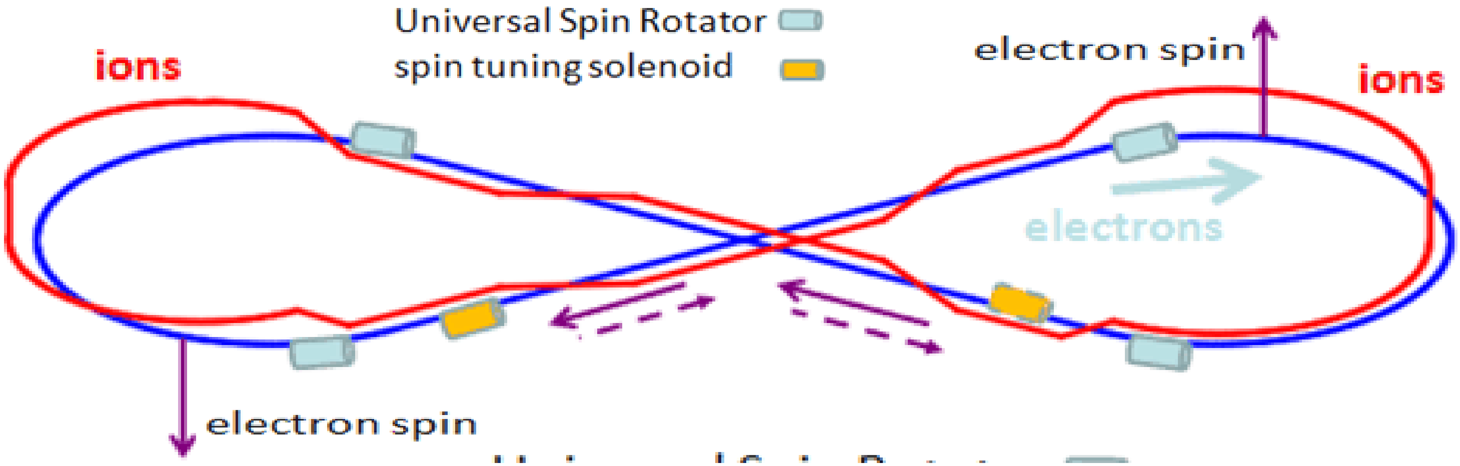

Arc end with dispersion suppression

**Lin, Morozov**

# Polarized Beam in the Electron 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%)
  - Utilizing Sokolov-Ternov effect for preserving polarization (vertical, anti-parallel to B-field in arc)
  - Using universal spin rotators for aligning spin in longitudinal direction at the interaction points
  - Employing spin matching to suppressing depolarization



# Universal Spin Rotator

- Rotating spin from vertical to longitudinal
- Consists of 2 solenoids & 2 (fixed angle) arc dipoles
- ***Universal***

  ➔ ***energy independent***

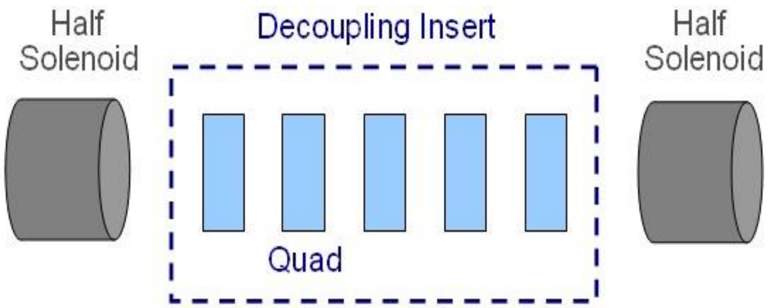
  works for all energies (3 to 12 GeV)

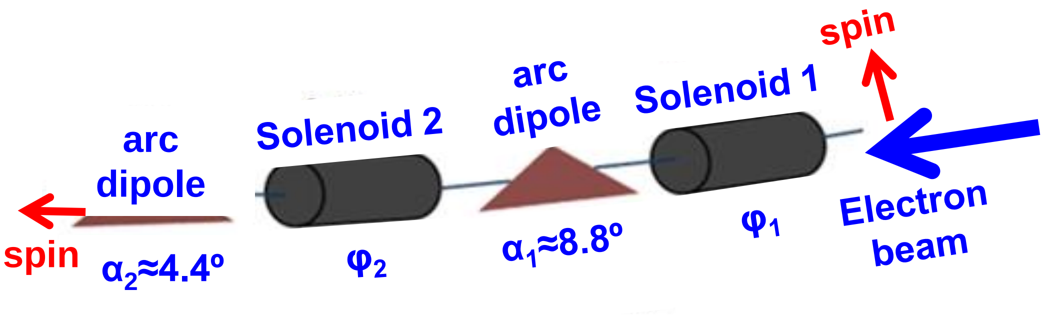
  ➔ ***orbit independent***

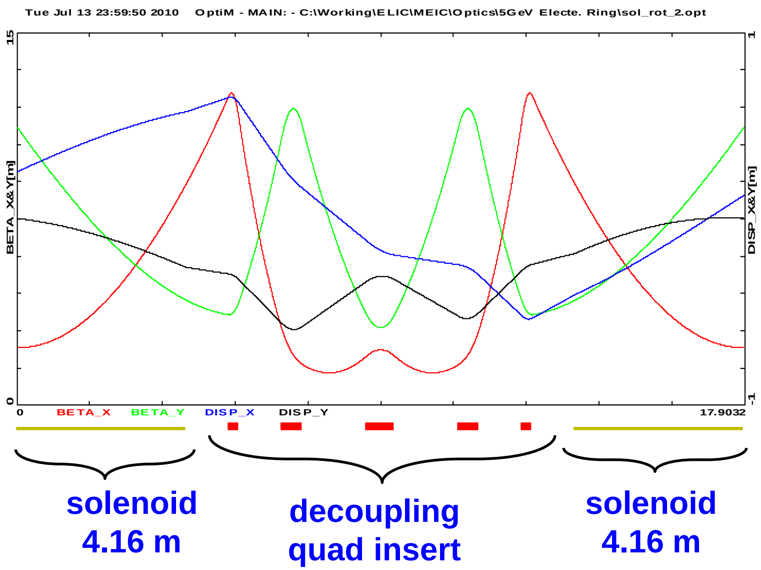
  does not affect orbital geometry

## Compensation of solenoid x-y coupling

**V. Livinenko &**
**A. Zholents, 1980**





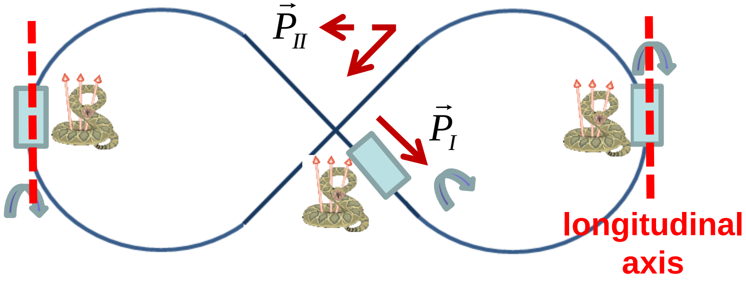


| E (GeV) | $\varphi_1$ | BL$_1$ (Tm) | $\alpha_1$ | $\varphi_2$ | BL$_2$ (Tm) | $\alpha_2$ |
|---|---|---|---|---|---|---|
| 3 | $\pi/2$ | 15.7 | $\pi/3$ | 0 | 0 | $\pi/6$ |
| 6 | 0.62 | 12.3 | $2\pi/3$ | 1.91 | 38.2 | $\pi/3$ |
| 9 | $\pi/6$ | 15.7 | $\pi$ | $2\pi/3$ | 62.8 | $\pi/2$ |
| 12 | 0.62 | 24.6 | $4\pi/3$ | 1.91 | 76.4 | $2\pi/3$ |

**Chetsov, Derbenev**

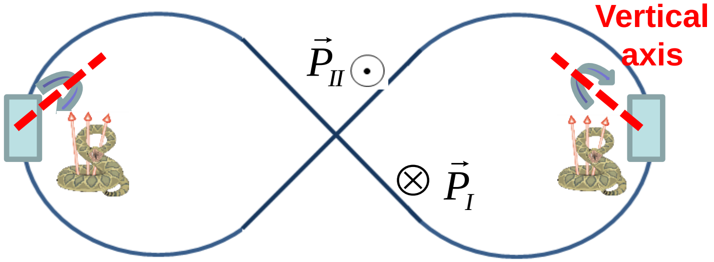
# Proton/He-3 Polarization at IPs

## Case 1: Longitudinal Proton Polarization at IP’s



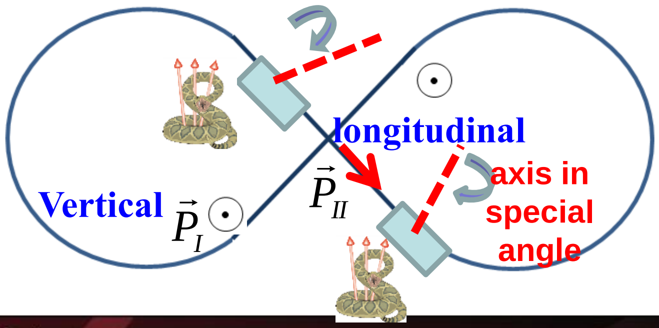
- Three Siberian snakes, all longitudinal-axis
- Third snake in straight is for spin tune
- Spin tune: 1/2

## Case 2: Transverse proton polarization at IP’s



- Three Siberian snakes, both in horizontal-axis
- Vertical polarization direction periodic
- Spin tune: 1/2

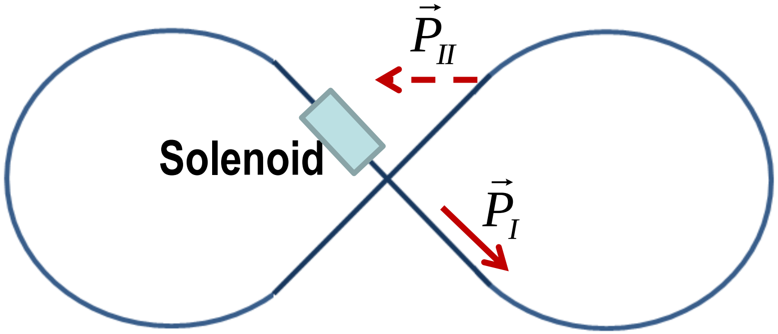
## Case 3: Longitudinal & transverse proton polarization on two straights



- Two Siberian snake, with their parameters satisfying certain requirements
- Spin tune: 1/2

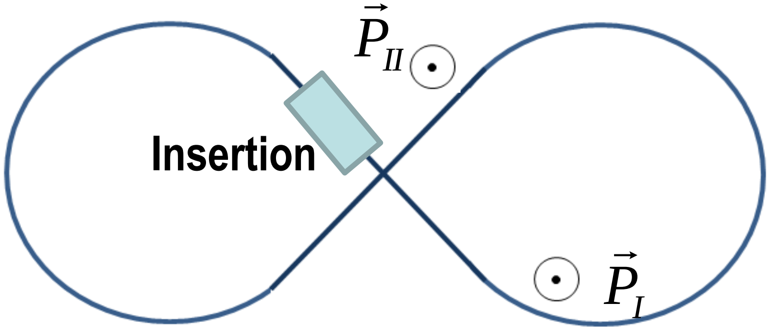
# Deuteron Polarizations at IPs

## Case 1: Longitudinal Deuteron Polarization at IP's



- Sable spin orientation can be controlled by magnetic inserts providing small spin rotation around certain axis and shifting spin tune sufficiently away from 0
- Polarization is stable as long as additional spin rotation exceeds perturbations of spin motion
- Polarization direction controlled in one of two straights
- Longitudinal polarization in a straight by inserting solenoid(s) in that straight

## Case 2: Transverse Deuteron Polarization at IP's



- Magnetic insert(s) in straight(s) rotating spin by relatively small angle around vertical axis (Prof. A. Kondratenko)

# 4. Electron Cooling

# Electron Cooling in MEIC

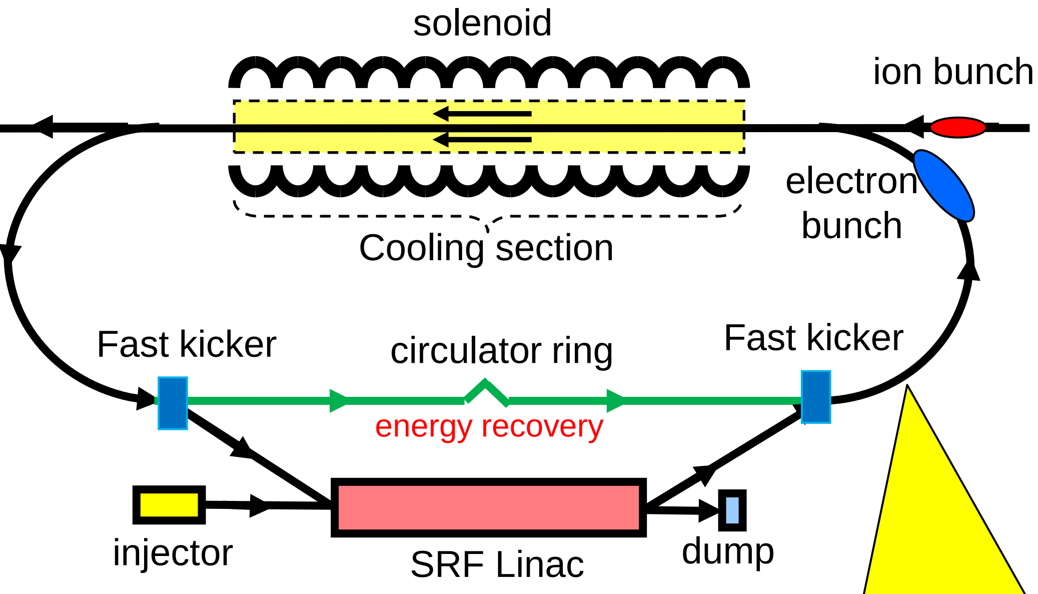
- Essential to achieve high luminosity for MEIC
- Based on traditional electron cooling
- ***Multi-phase cooling* scheme**

**Pre-booster:** DC *cooling* for assisting accumulation of positive ion beams
(Using a low energy DC electron beam, existing technology)
*Initial DC cooling* at top energy
***(within state-of-art)***

**Collider ring**: *Final cooling* after boost & re-bunching, reaching design values
*Continuous cooling* during collision for suppressing IBS
***(Beyond stat-of-art, 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. | $\mu$m | 4 | 4 → 0.35/0.07 |
| Cooling time | min | 10 | ~ 0.4 |

# ERL Circulator Cooler for MEIC Collider Ring



e-bunches circulates 10+ turns
➔ reduction of current from an ERL by a same factor

## Design Choices

- Energy Recovery Linac (ERL)
- Compact circulator ring

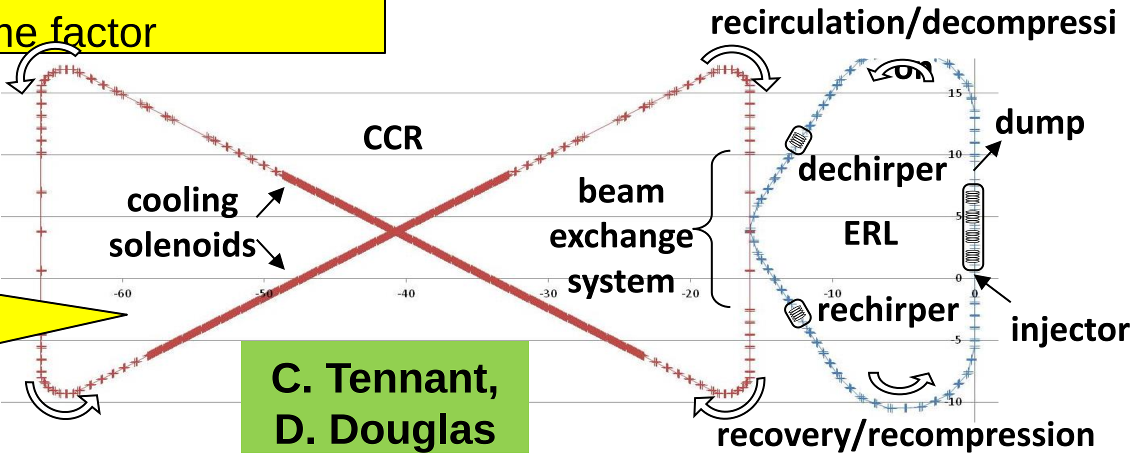
to meet design challenges

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

## Required technologies

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

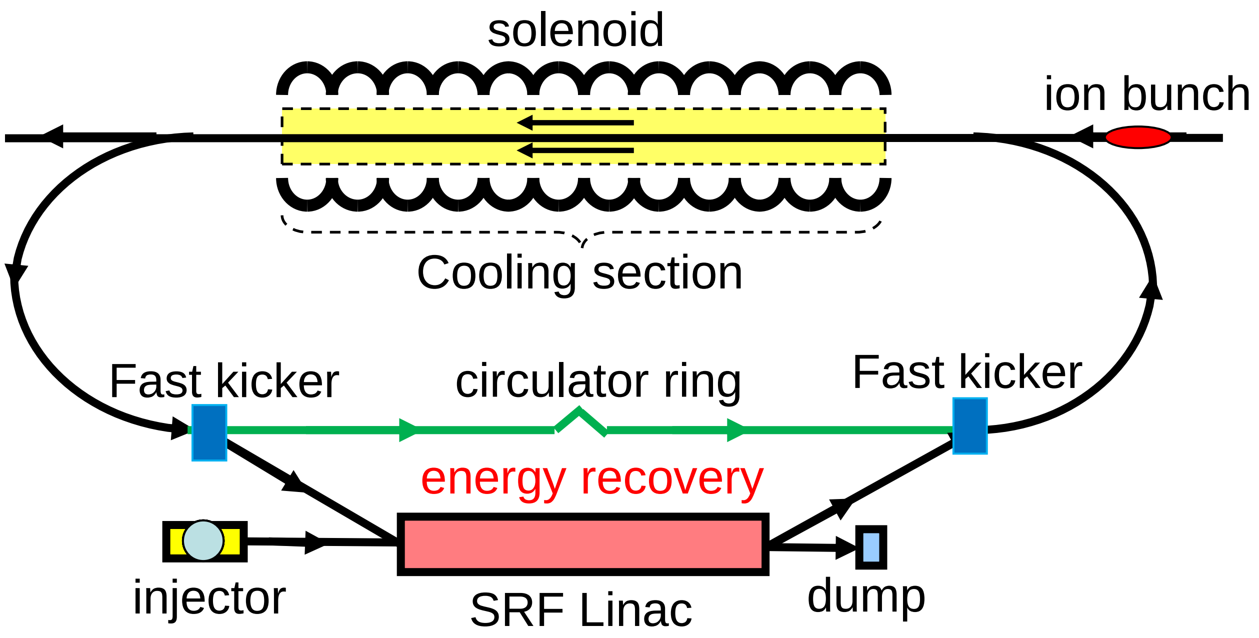
**Optimization:**
Put it at center of the Figure-8 ring, for eliminating the long return path doubles the cooling rate



**C. Tennant, D. Douglas**

# Fast Bunch Replacement in a Circulator Cooler

- Needs faster kicker technology
- Enabling large number turns in the circulator ring

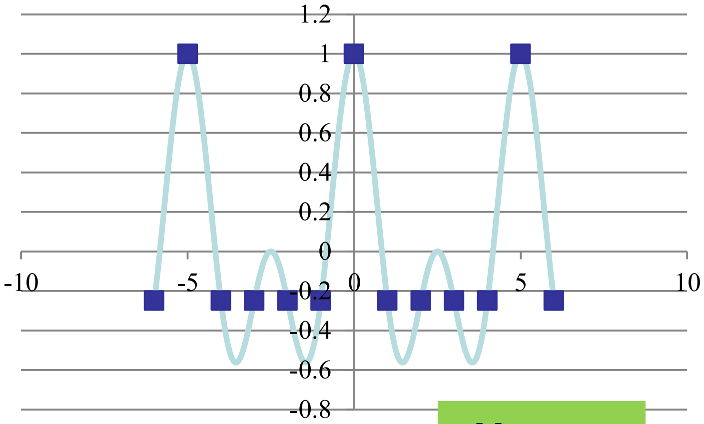


**Nissen**

# RF Kicker and Beam-Beam Kicker

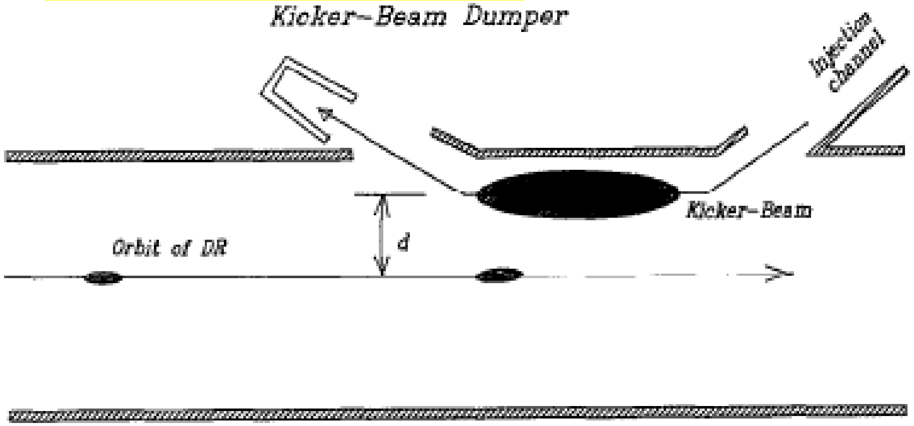
- Uses resonant RF similar to an RF separator
- Very high duty factor, especially with a small number of survivable turns.
- Low power requirements
- Requires multi-harmonic signal amplifier

**A proof-of-concept experiment supported by Jlab LDRD (pending)**



**Hutton**

**Head-on Scheme**



**Shiltsev**

- Kicking time: *τ=l/c*
- For a transversely round Gaussian beam

kicking angle $\theta_0[\mu\mathrm{rad}] = 250\frac{N[10^{11}]}{\sigma_r[\mathrm{mm}]E[\mathrm{GeV}]}$

kicking strength $P_{\mathrm{BBK}}[\mathrm{Gs\ m}] = 8.4\frac{N[10^{11}]}{\sigma_r[\mathrm{mm}]}$.

**A proof-of-principle experiment at ASTA, Fermilab?**

# A Test Facility for an ERL Circulator Cooler

## A Test Facility based on JLab ERL-FEL

- Similar energy range, reduced bunch charge
- Reuses the existing hardware, reducing the cost

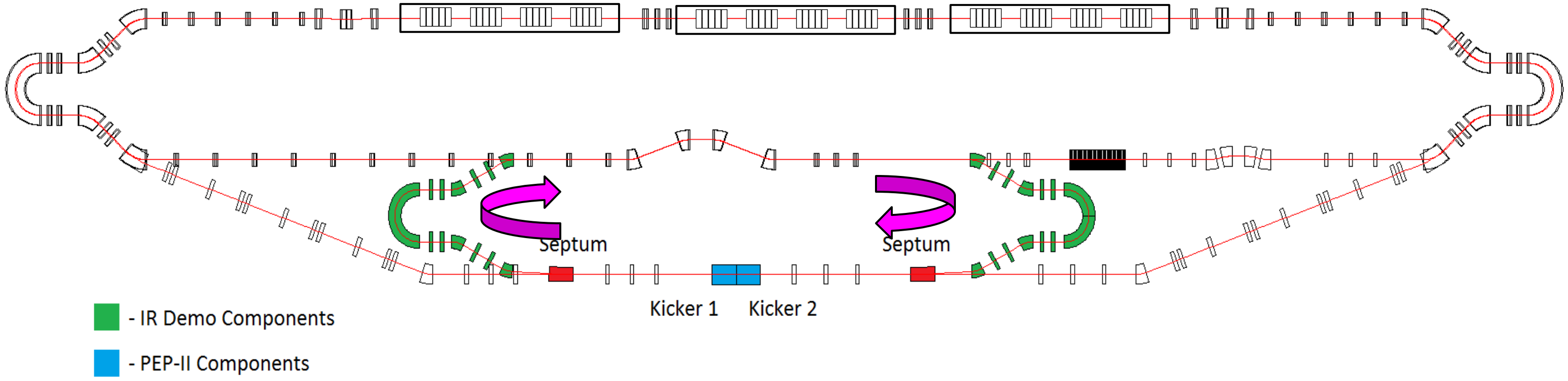
| | | FEL ERL | ERL-CR |
|---|---|---|---|
| Energy | MeV | 80-210 | 10-54 |
| Bunch charge | nC | 0.135 | 2 |
| Turns in CR | | | 10-100 |
| Bunch frequency | MHz | 75 | 75-7.5 |
| Gun current | mA | 10 | 150–15 |
| Trans. emit., norm. | µm | 10 | 1-3 |
| Long. emittance | keV-ps | 25-75 | 150 |
| Energy spread | % | 0.4 | 0.01 |
| RMS bunch length | ps | 2 | 100 |

## Proof-of-Principle experiment

- Demonstrate bunch exchange between ERL and circulator ring
- Demonstrate bunch decompression/compression
- Test bed for collective beam effect studies
- Develop supporting technologies

## Status (expected completion 2015)

- Circulator ring optics design completed
- Initial tracking shows CSR could be a problem



# Proof-of-Principle Experiments

- Bunch Exchange Experiments
  - Demonstrate proper functioning of bunch train and fast replacement exchange methods
  - Demonstrate resonant replacement of the bunches
- Beam Lifetime Experiment
  - Measure the beam over varying numbers of turns
  - Maintain proper phase space conditions over these turns
- Longitudinal Manipulation Experiment
  - Use the $M_{56}$ of the Bates bends to properly manipulate the longitudinal phase space
  - Use a set of de-chirping and re-chirping cavities to manipulate longitudinal phase space

# 5. Interaction Region

# Interaction Region Requirements

## Detector requirements

- **Hermeticity** **(*full acceptance*)** ➔ allows for the detection of scattered electrons, mesons and baryons without holes in the acceptance, even in forward directions
- **High luminosity** ➔ operates in a high-luminosity environment with moderate event multiplicities and acceptable background conditions

## Accelerator/beam dynamics requirements (& considerations)

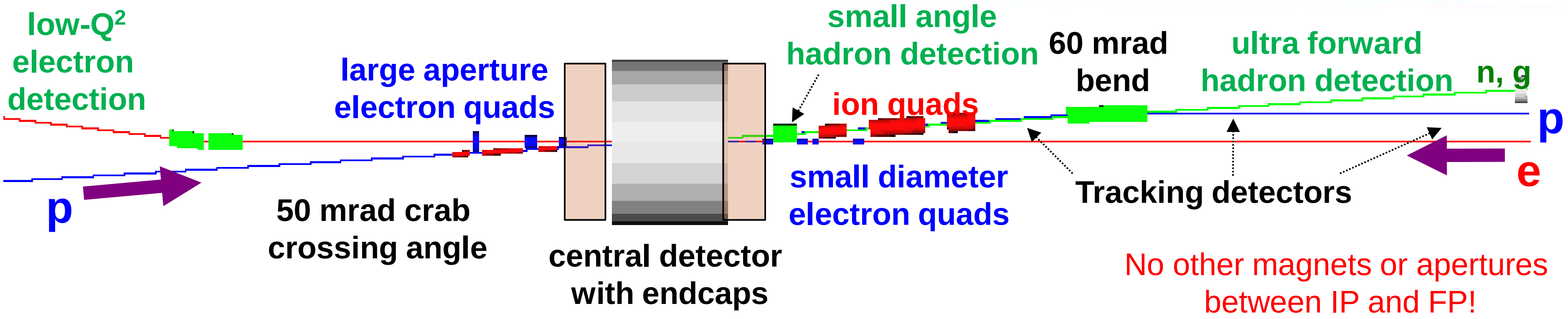
- **High luminosity**
  - ➔ pushing final focusing of the beams (squeezing down β*)
  - ➔ not so demanding machine elements (e.g., max. field & gradient)
  - ➔ crab crossing for high bunch repetition rate colliding beams
- **Nonlinear dynamics**
  - ➔ chromaticity compensation
  - ➔ momentum acceptance and dynamic aperture
- **Collective effect limit** ➔ beam-beam (flat beam, etc.)

**Interaction region design rules**

#1: Detector requirements & accelerator requirements, though they usually conflict, must coexist

#2: Compromises must be made on both sides without jeopardizing either side's design goals

# Interaction Region w/ Integration of Detector



low-Q² electron detection

large aperture electron quads

small angle hadron detection

60 mrad bend

ultra forward hadron detection

n, g

ion quads

p

e

p

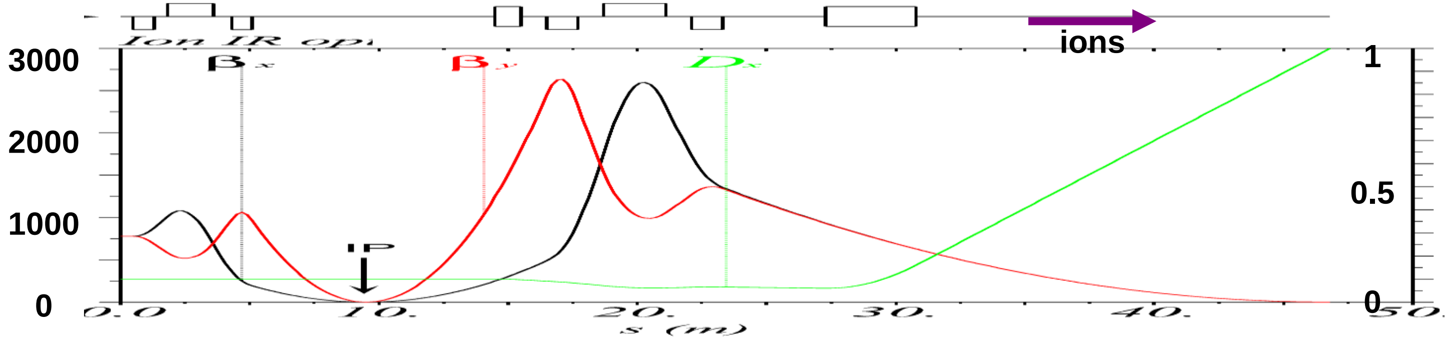
50 mrad crab crossing angle

central detector with endcaps

small diameter electron quads

Tracking detectors

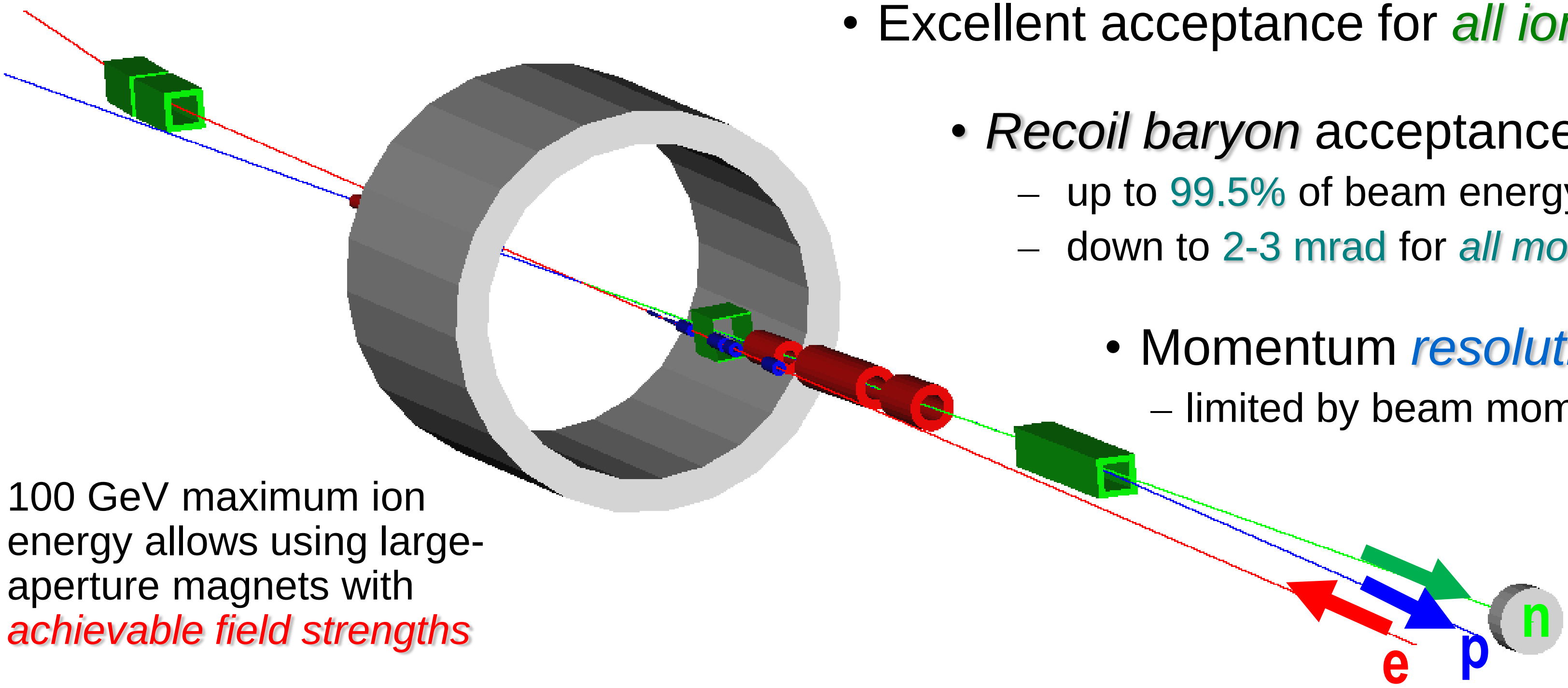
No other magnets or apertures between IP and FP!



- ***A major victory*** for producing a preliminary optics design which satisfies all the requirements
  - element location, size and apertures
  - maximum fields or field gradients
  - Beam stay-clear
  - Small beta final focusing, crab crossing
- Make use of crab crossing for enhancing detector acceptance
- Adopted permanent magnets for smaller sizes of electron FFQs

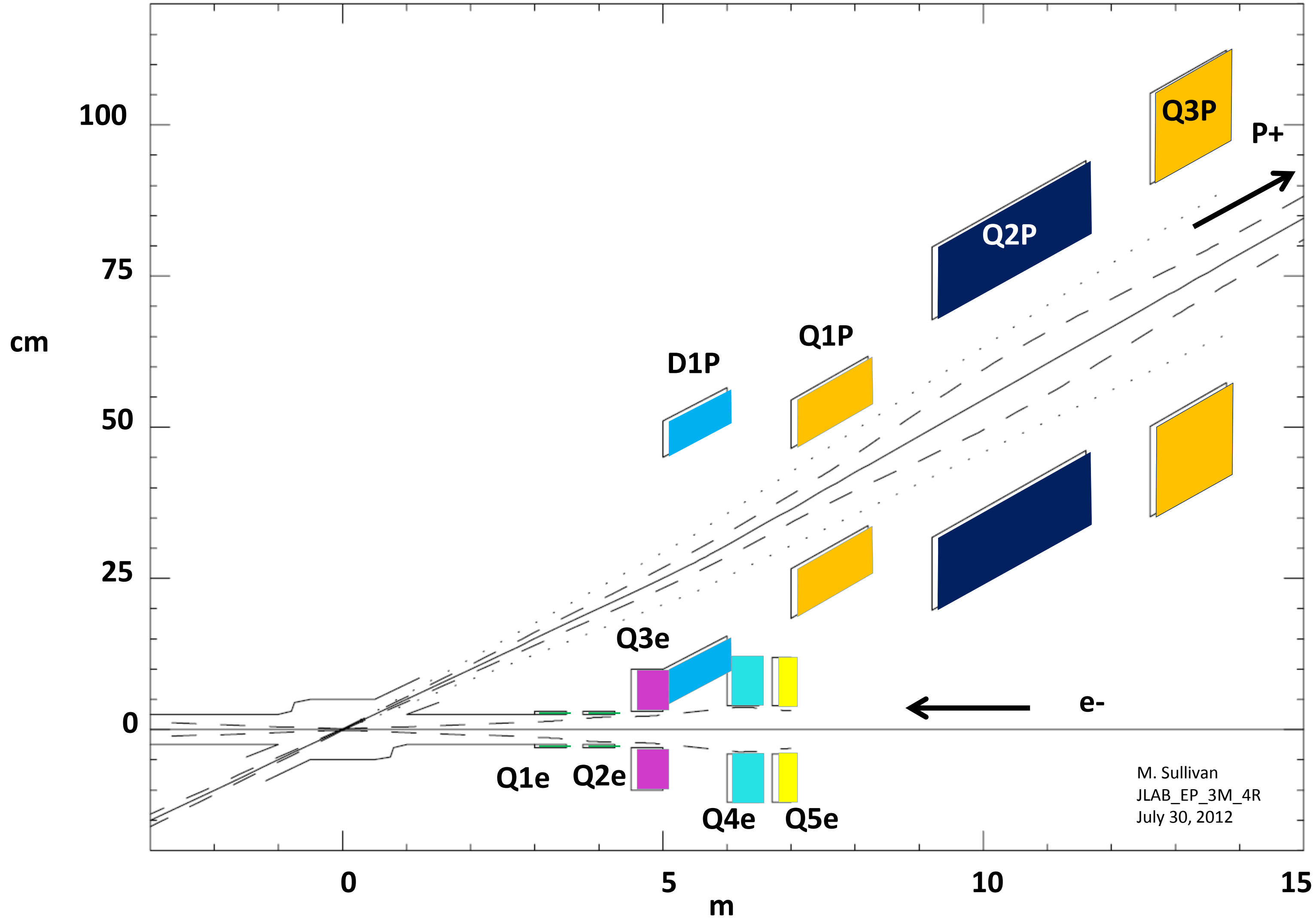
# A 3D View of Detector & Small-angle Ion Detection

- *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 beam momentum spread



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

# Another View of MEIC Interaction Region

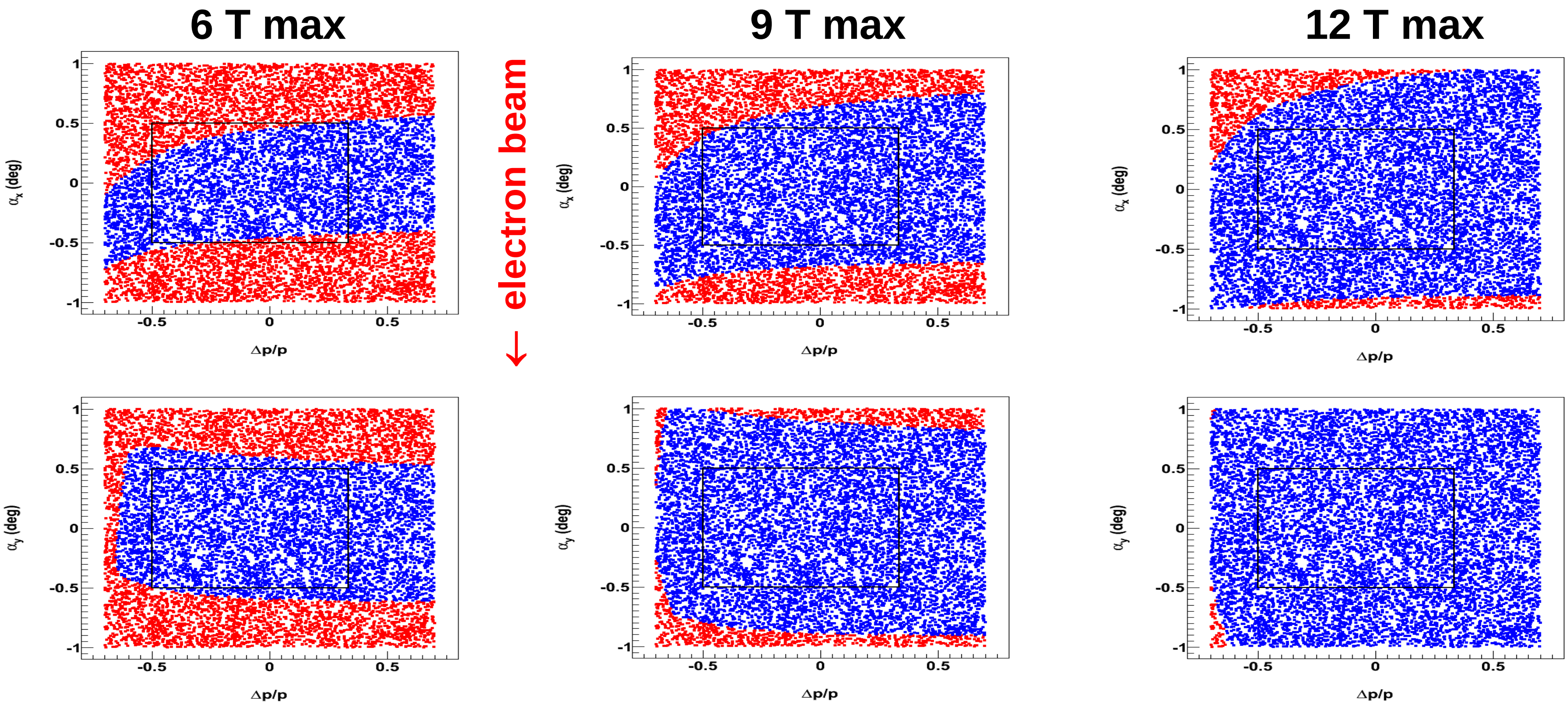


M. Sullivan
JLAB_EP_3M_4R
July 30, 2012

# Proton Acceptance at Downstream Ion FFB

- **Quad apertures = B max / (field gradient @ 100 GeV/c)**

**G4Beamline/GEANT4 Model**



**Red**: Detection between the 2 Tm upstream dipole and ion quadrupoles

**Blue**: Detection after the 20 Tm downstream dipole

**V. Morozov's talk at the 2nd Detector/IR Mini-workshop**
**V. Morozov, *et al*, IPAC2012 paper**

# Nonlinear Beam Dynamics

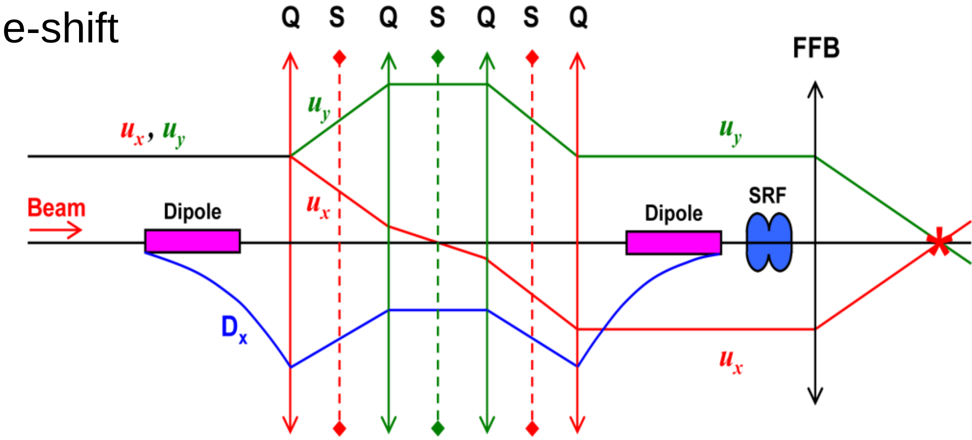
## Chromaticity is an issue in MEIC design, particularly due to the low-β insertions

- Chromatic turn spread
- Chromatic beta-smear at IP

| | Ion ring ($\xi_x/\xi_y$) | Electron ring ($\xi_x/\xi_y$) |
|---|---|---|
| Contribution from whole arc | 17.4 / 16.1 | 68.8 / 70. 1 |
| Contribution per IR | 130 / 126 | 47.3 / 54.0 |
| Whole ring (2IP+arc) | 278 / 268 | 188 / 202 |

## MEIC chromaticity compensation scheme

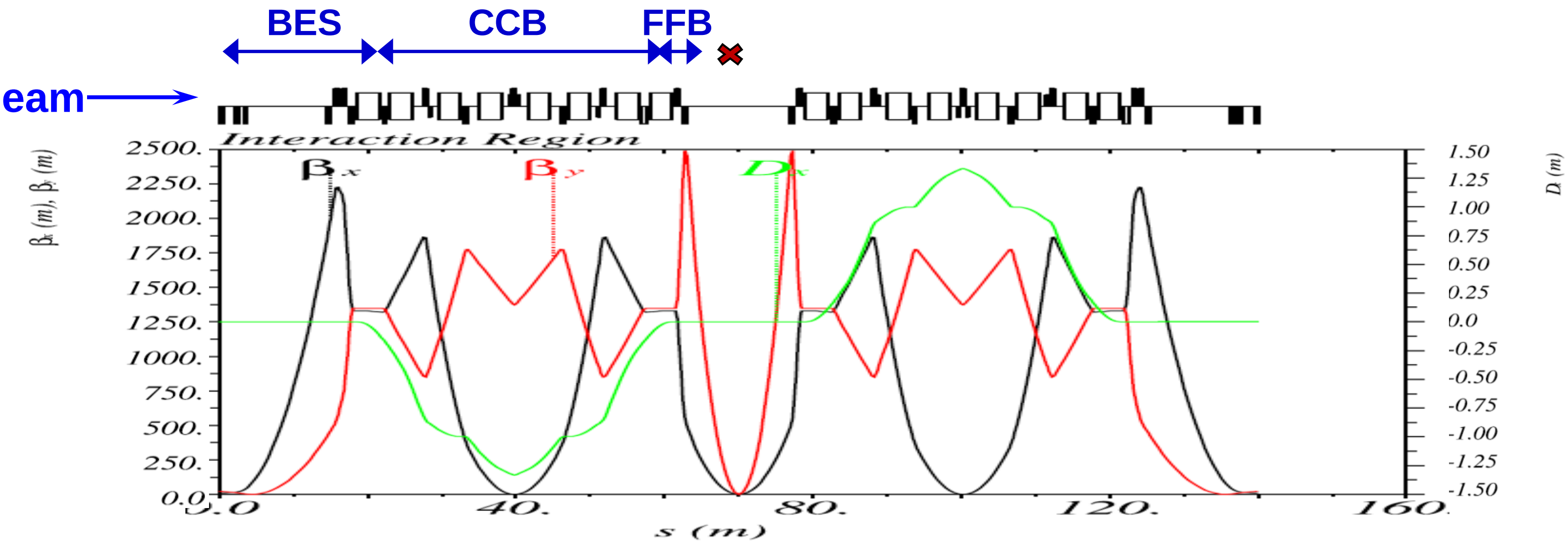
- Local compensation scheme: dedicated chromaticity compensation blocks (CCB) near an IP
- Using families of sextupoles and octupoles
- simultaneous compensation of chromatic tune-shift and beam smear at IP
- Symmetric CCB (with respect to its center)
  - – $u_x$ is anti-symmetric, $u_y$ is symmetric
  - – $D$ is symmetric
  - – $n$ and $n_s$ are symmetric



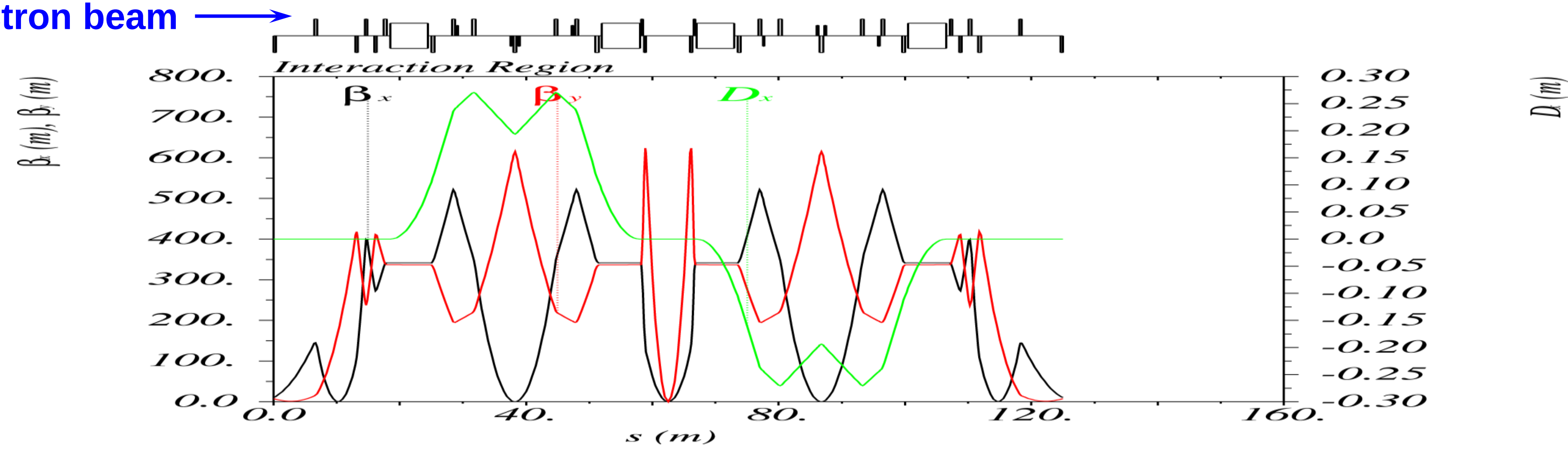
**MEIC design report Section 7.4**

# IR Optics Optimized for Chromaticity Compensation

**Ion beam** →

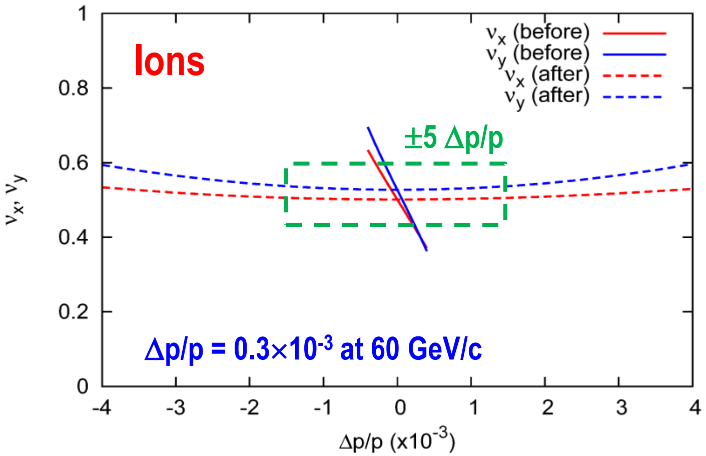


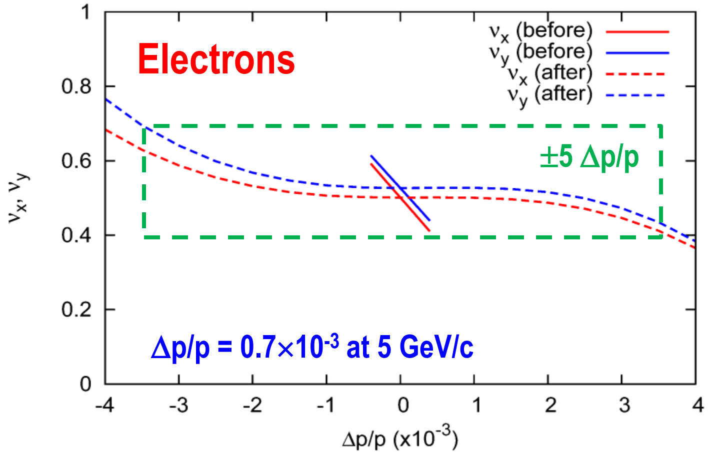
**Electron beam** →

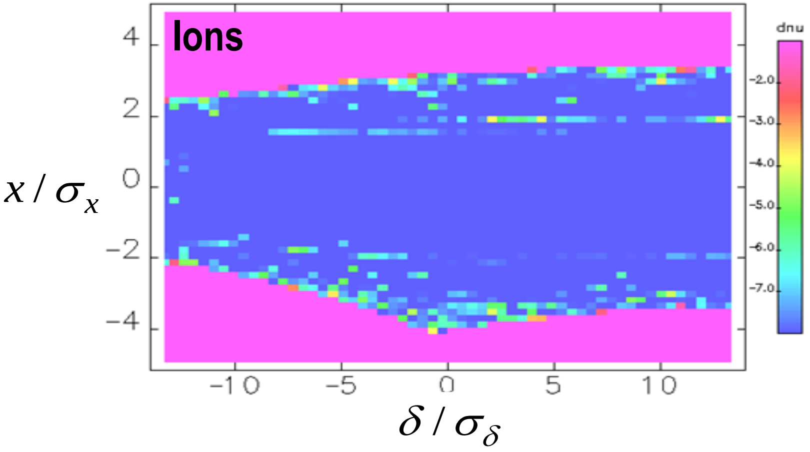


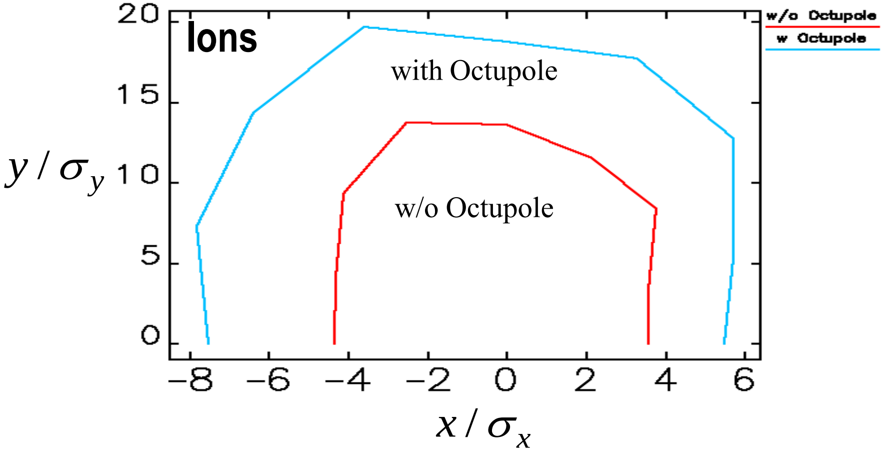
# Momentum Acceptance & Dynamic Aperture

- Compensation of chromaticity with 2 sextupole families only using symmetry
- Nonlinear dynamic studies (aperture optimization and error impact) under way



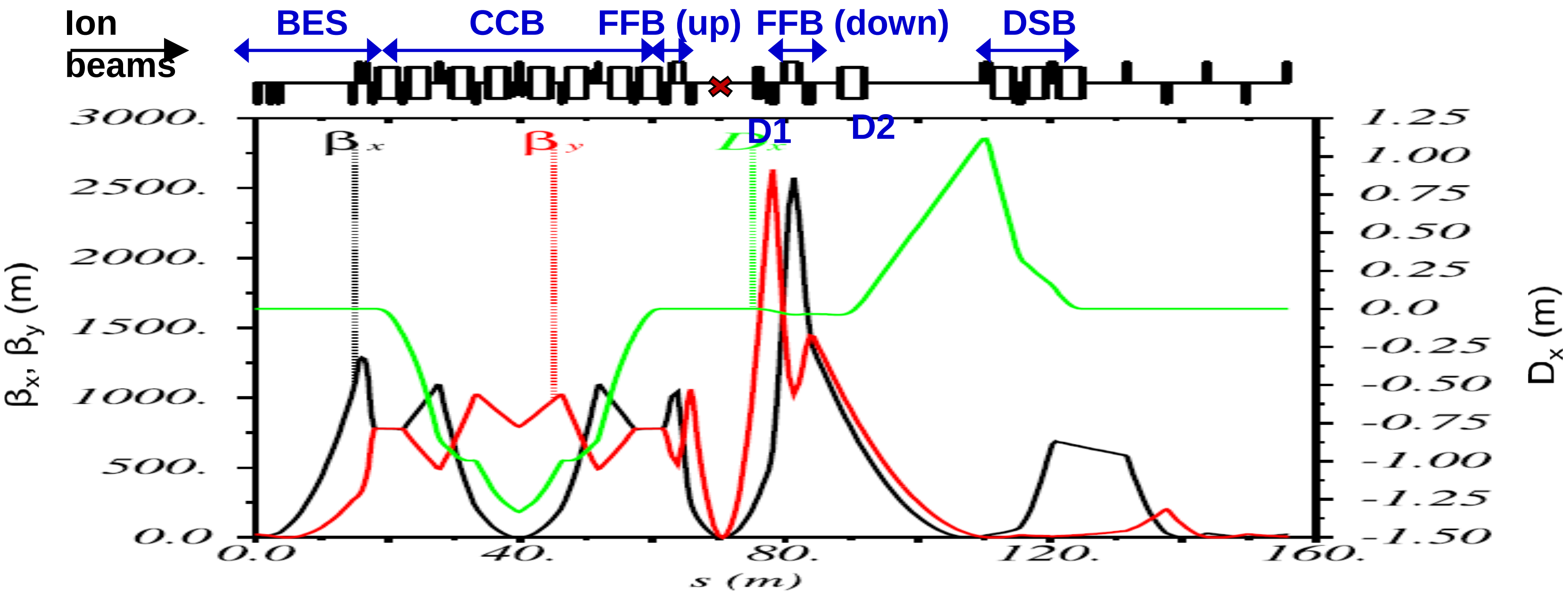




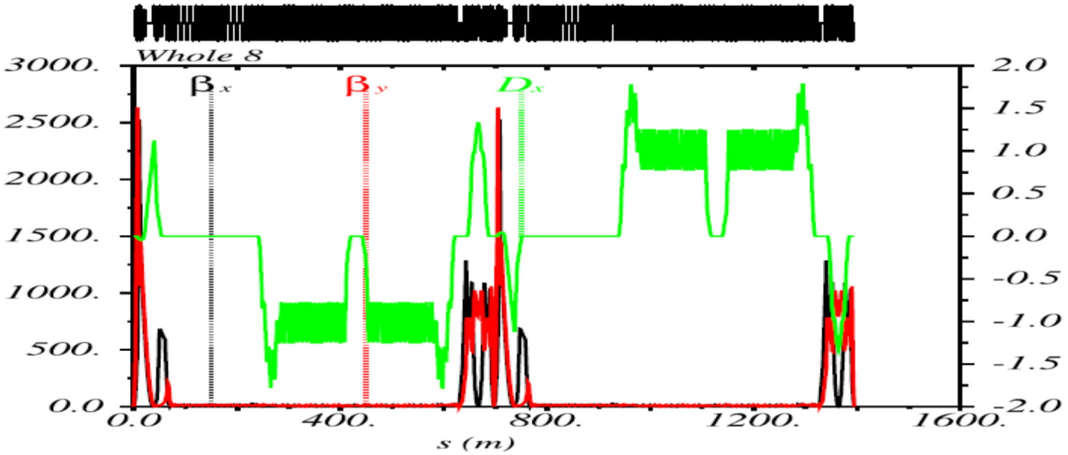


**F. Lin's talk at the 2nd Detector/IR Mini-workshop**
**F, Lin, *et al*, IPAC2012 paper**

# Ion Interaction Region Optics Optimized for Both Detector and Chromaticity Compensation

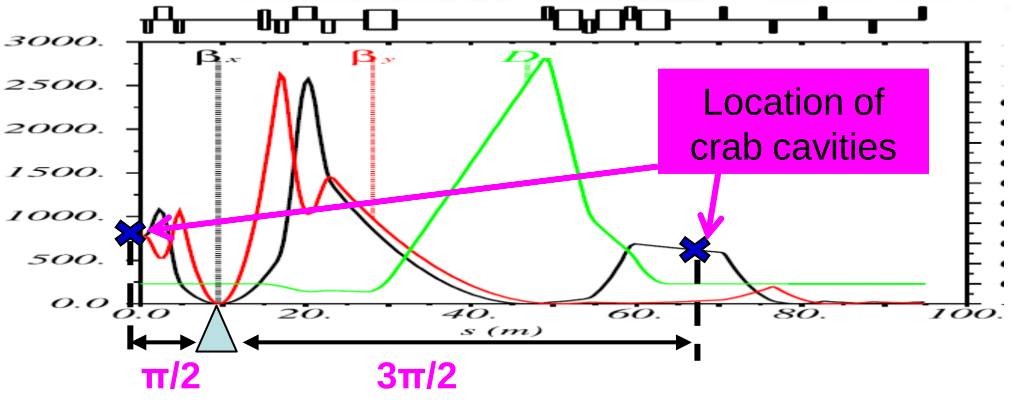


- BES: Beam Extension Section
- FFB: Final Focusing Block
- D1,D2: Spectrometer Dipoles
- DSB: Dispersion Suppression Block
- Two sextupole families are inserted symmetrically in the CCB for the chromaticity compensation

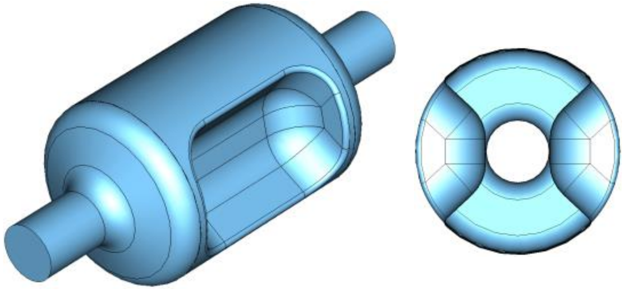


# Crab Crossing Scheme

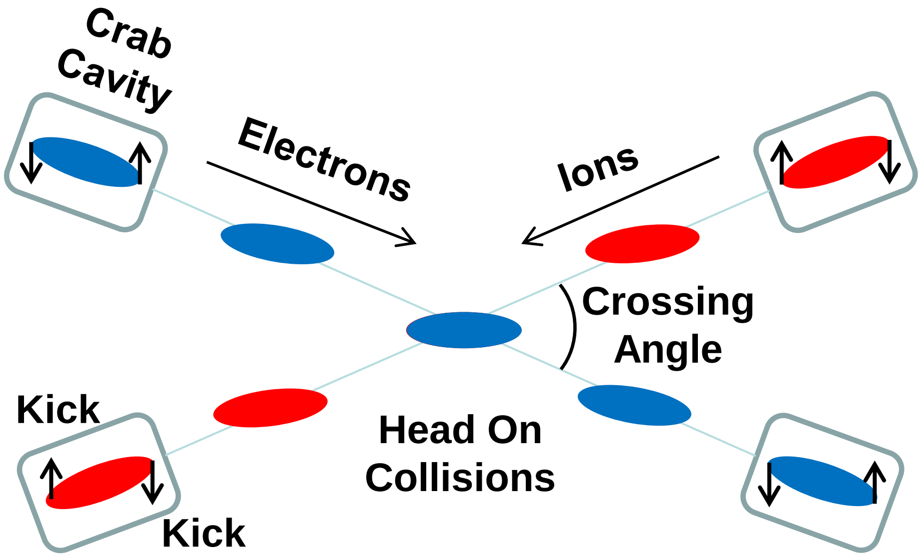
- Required for supporting high bunch repetition rate (small bunch spacing)
- Local crab scheme
- Two cavities are placed at (n+1)π/2 phase advance relative to IP.
- Large $\beta_x$ at location of crab cavities for minimizing the required kicking voltage.



Location of crab cavities



**SRF crab cavity@ ODU**



Crab Cavity

Electrons

Ions

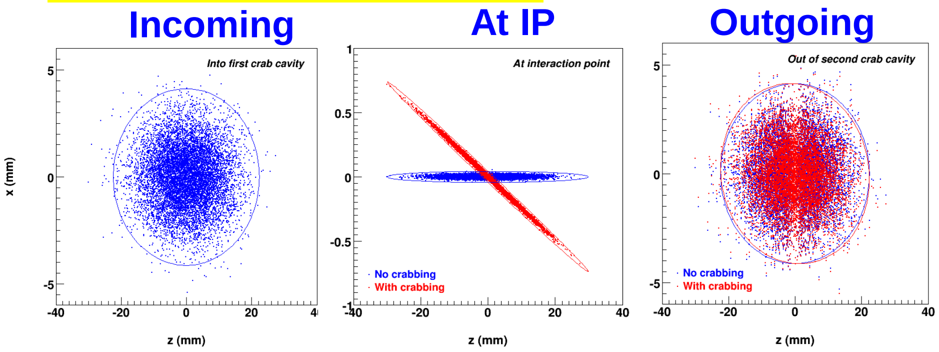
Crossing Angle

Kick

Head On Collisions

Kick

**Tracking Simulations**



# Beam Synchronization at IP & Collision Pattern

## Path length difference in collider rings

- Electrons travel at the speed of light, protons/ions are slower
- Slower proton/ ion bunches will not meet the electron bunch again at the IP after one revolution
- Synchronization must be achieved at *every IP* in the collider ring *simultaneously*

## Present conceptual solution

- **Varying number of bunches** (harmonic number) in the ion collider ring would synchronize beams at IPs for a set of ion energies (harmonic energies)
- To cover the energies between the harmonic values
  - **varying electron orbit** up to half bunch spacing
  - **varying RF frequency** (less than 0.01%)

## Collision pattern at IP

- Each time it returns to the IP, an Ion bunch will collide with a different electron bunch

  (*Specifically, If n is the difference of ion and electron harmonic numbers, then an ion bunch will always collide the n-th bunch in the electron bunch train*)
- An ion bunch will collider all or a subset (eg. all even numbers) electron bunches

| **Bunches in ion ring** | **Energy (GeV/u)** | |
|---|---|---|
| | Proton | Lead |
| 3370 | 100 | |
| 3371 | 35.9 | 35.9 |
| 3372 | 26.3 | 26.3 |
| 3373 | 21.7 | 21.7 |
| 3374 | | 18.9 |
| 3375 | | 17.0 |

- **Number of bunch in the electron ring is always 3370**
- **Assuming electron and ion have a same circumference (1350 m) at 100 GeV proton energy**

**MEIC design report section 5.9**

# Suppressing Synchrotron Radiation at IR

**MEIC Design optimized for suppressing synchrotron radiation at IR**

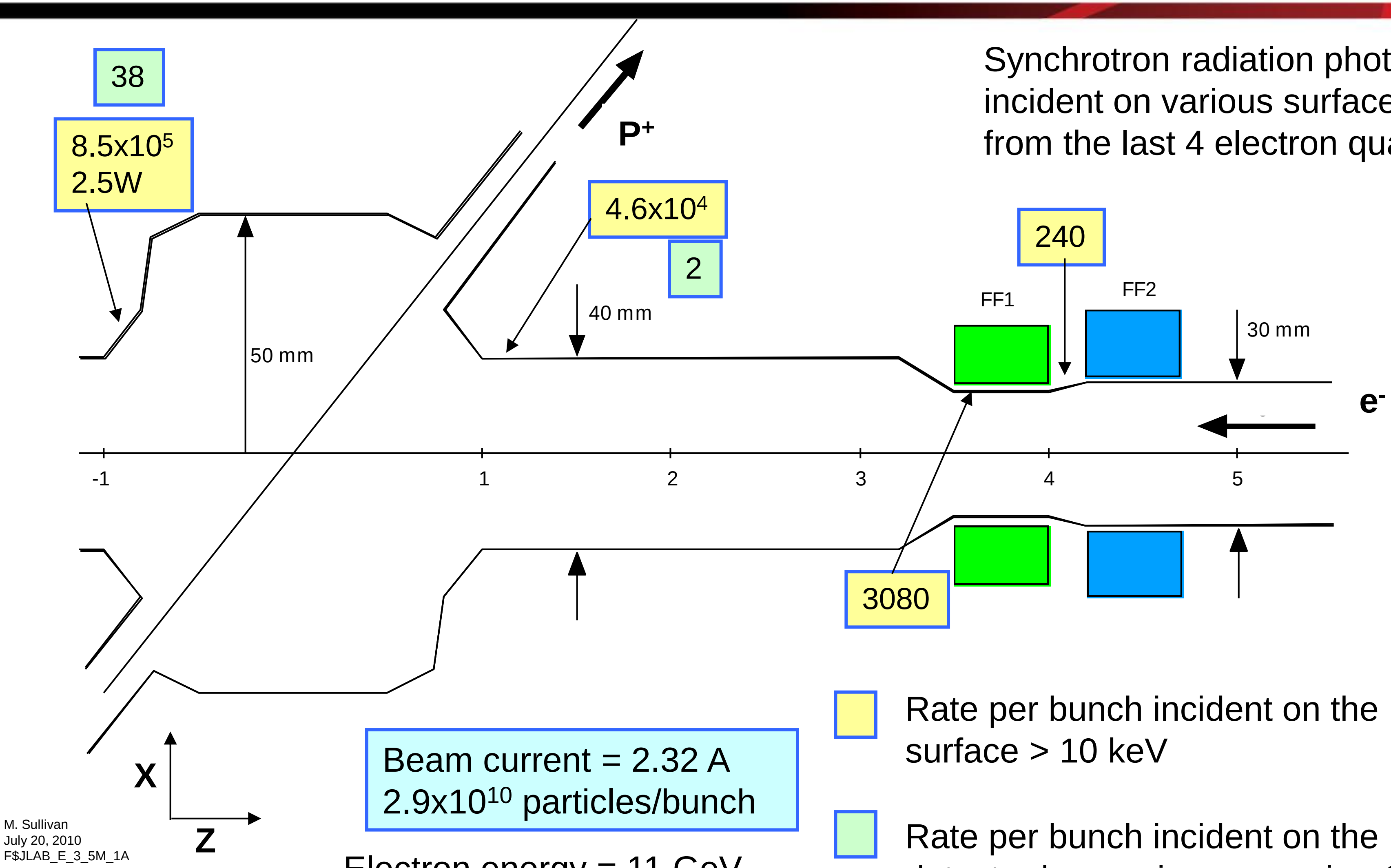
- Flat electron ring ➔ ions travels to the plane of the electron ring for horizontal crab crossing at collision points
- Detector solenoid is along the electron beamline
- Gentle bending of electrons at end of each arcs
- Minimizing bending of electrons in long straights of figure-8
- Keep bending angles of dipoles in chromaticity compensation blocks small
- (Place IP close to the end of arc where ion beam comes from)

**More synchrotron radiation issues**

- A high forward detector design requires carefully tracing synchrotron radiation fans from bend magnets to see
  - where the power goes
  - how this interacts with the beam pipe design in front of the detector
- Local forward and back scattering rates from nearby beam pipe surface

# Initial SR background calculations

Synchrotron radiation photons incident on various surfaces from the last 4 electron quads



M. Sullivan
July 20, 2010
F$JLAB_E_3_5M_1A

Beam current = 2.32 A
$2.9\times10^{10}$ particles/bunch

Electron energy = 11 GeV
$\varepsilon_x/\varepsilon_y$ = 1.0/0.2 nm-rad

🟨 Rate per bunch incident on the surface > 10 keV

🟩 Rate per bunch incident on the detector beam pipe, assuming 1% reflection coefficient and 4.4% solid angle acceptance

**M. Sullivan's talk at the 2nd Detector/IR Mini-workshop**

# 6. Outlook and Summary

# Accelerator pre-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
  - (Long time scale) 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

Bold font
indicates
high priority

# LEIC as An Intermediate Technology Stage

**LEIC minimizes technology challenges, and provides a test bed for MEIC**

- **Electron cooling**
  - Requires lower electron energies (13.6 MeV vs. 4.3 MeV Fermilab cooler) and a lower (~0.5 A) current electron cooling beam
- **Ion linac/pre-booster**
  - An accumulation of a lower current ion beam in the pre-booster
- **Beam synchronization**
  - Variation of number of bunches in the LEIC ion collider ring provides a large set of synchronization energies for experiments
  - Variation of the warm LEIC ion ring path-length for covering other energies is technically feasible, RF frequency variation can be avoided
- **Crab cavity**
  - The integrated kicking voltage is reduced by a factor of 4, now about 3 times of KEK-B
- **Chromaticity**
  - Only one IR, the chromaticity is reduced by half.
- **IR magnets**
  - The maximum fields are reduced by a factor of 4, no longer a problem and also less cost.
- **Ion polarization**
  - Magnetic field of some spin rotators are reduced by a factor of 4.

# US EIC Collaborations

## Electron-Ion Collider Collaboration

- More than 100 physicists from over 20 laboratories & universities worldwide
- Working to realize an EIC in the US
- Four working groups (eP physics, eA physics, detector, electron beam polarimetry)
- Organizes one to two workshops or collaboration meetings each year

## EIC International Advisory Committee

- Appointed by directors of BNL and JLab
- Consists of 14 nuclear & accelerator physicists
- Three advisory committee meetings (2/2009, 11/2009 and 4/2011)

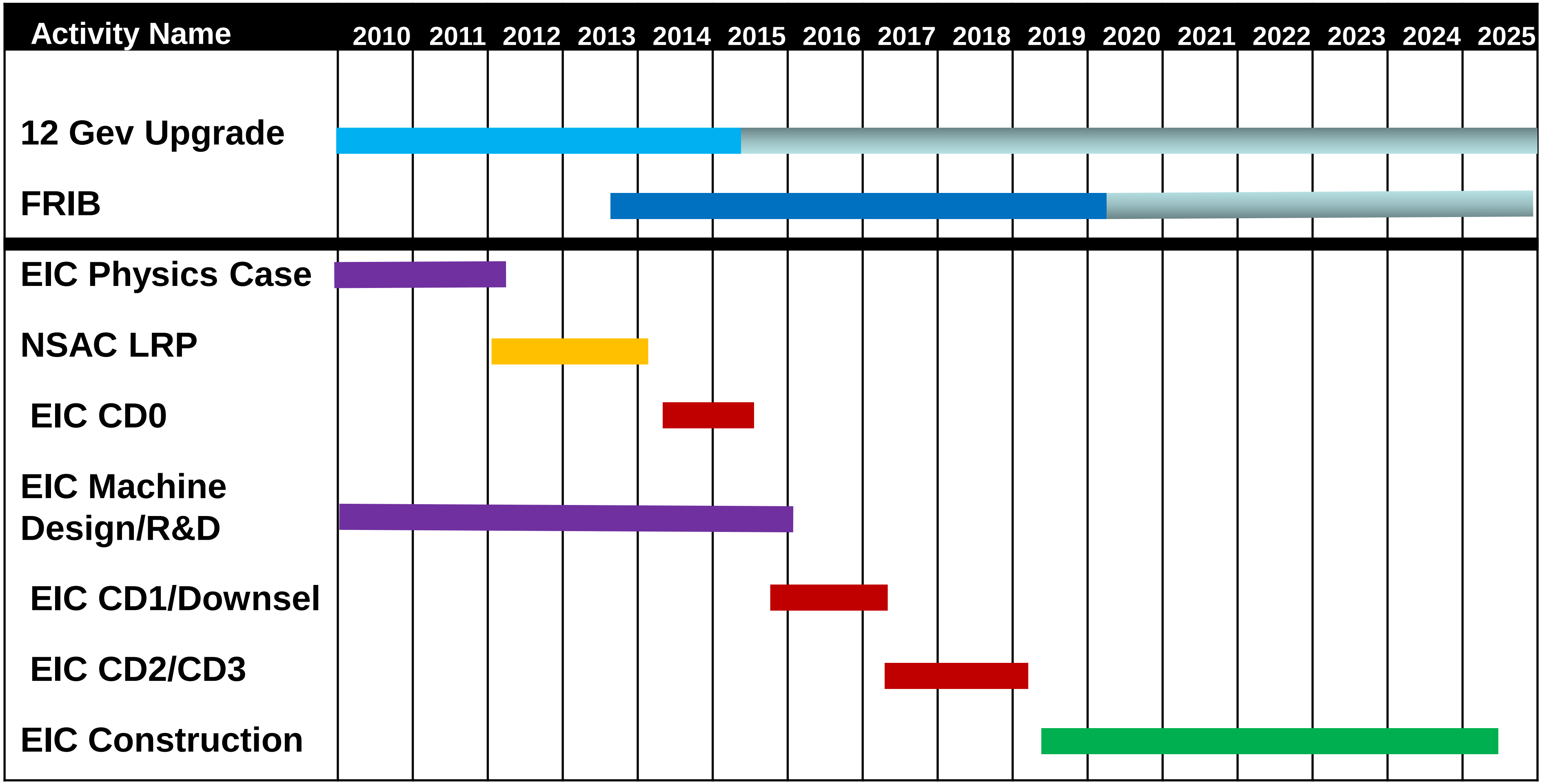
## Highlights on Recent EIC Activities

- Five JLab CEBAF User Workshops on EIC (2010), reports produced
- Ten-week EIC Science Program at INT (Sept. to Nov. 2010), report produced
- BNL sponsored generic detector R&D program (in progress)

## LHeC

- US participation in accelerator, detector and physics development as well as in steering and oversight.

# US EIC Realization Imagined

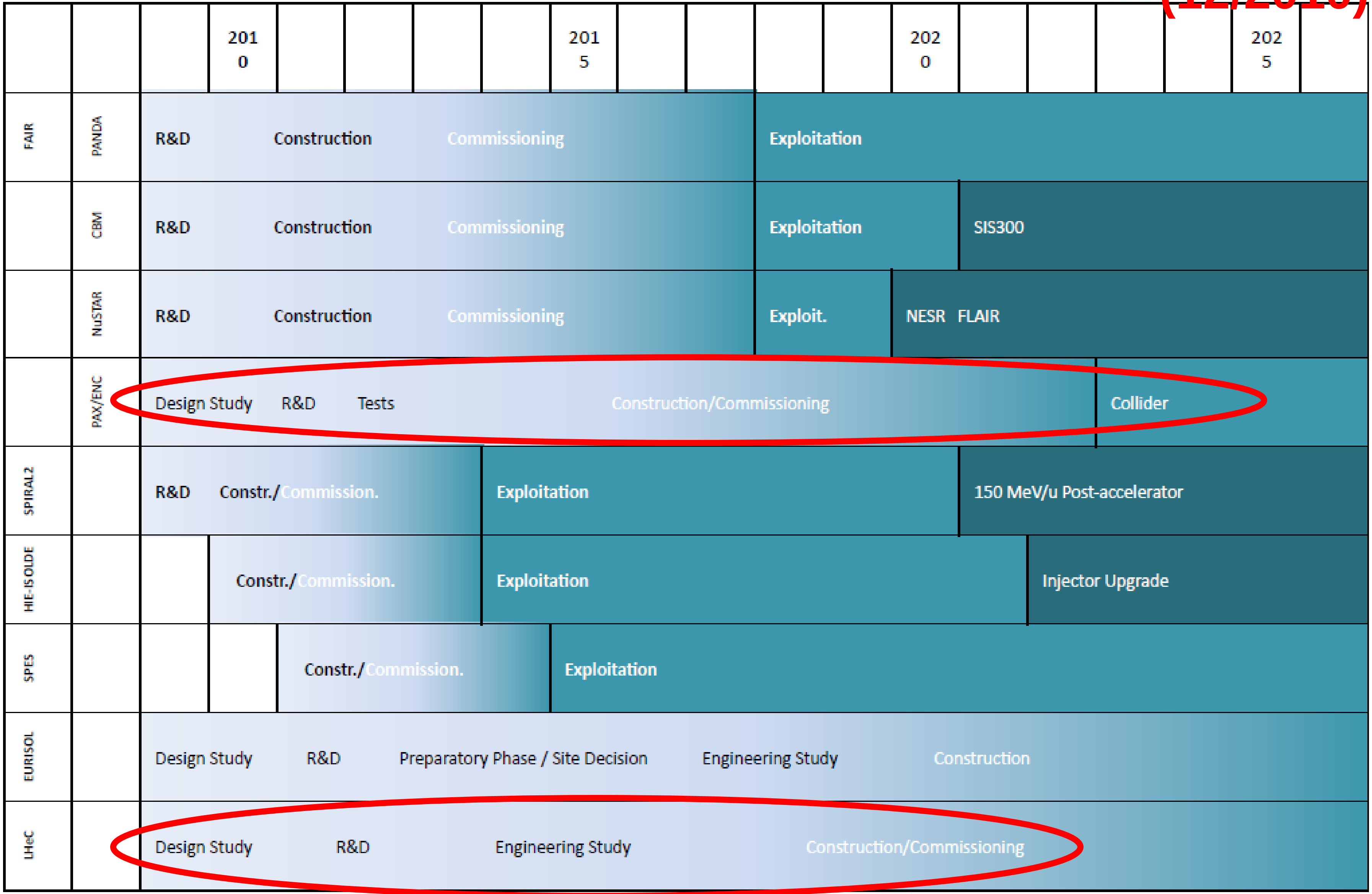


**Note: 12 GeV LRP recommendation in 2002 – CD3 in 2008**

(Mont@INT)

# NuPECC Roadmap: New Large-Scale Facilities

(12/2010)



| | | | 2010 | | | | | 2015 | | | | | 2020 | | | | | 2025 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FAIR | PANDA | R&D | Construction | | | Commissioning | | | | | Exploitation | | | | | | | | |
| | CBM | R&D | Construction | | | Commissioning | | | | | Exploitation | | | SIS300 | | | | | |
| | NuSTAR | R&D | Construction | | | Commissioning | | | | | Exploit. | | NESR FLAIR | | | | | | |
| | PAX/ENC | Design Study | | R&D | Tests | | | Construction/Commissioning | | | | | | | | Collider | | | |
| SPIRAL2 | | R&D | Constr./Commission. | | | | Exploitation | | | | | | | 150 MeV/u Post-accelerator | | | | | |
| HIE-ISOLDE | | | Constr./Commission. | | | | Exploitation | | | | | | | | Injector Upgrade | | | | |
| SPES | | | | Constr./Commission. | | | | Exploitation | | | | | | | | | | | |
| EURISOL | | Design Study | | R&D | Preparatory Phase / Site Decision | | | | | Engineering Study | | | Construction | | | | | | |
| LHeC | | Design Study | | R&D | | | Engineering Study | | | | Construction/Commissioning | | | | | | | | |

G. Rosner, NuPECC Chair, Madrid 5/10

# Summary

- The 1st design of MEIC is completed and a comprehensive design report has been released
- The MEIC interaction region has been designed to support a full-acceptance detector and also optimized for achieving good chromaticity compensation
- The focus of the MEIC team is now shifted to design optimization (low cost and less technical uncertainty) and critical accelerator R&D.
- Electron cooling is the most critical R&D and will be addressed both in simulation studies and proof-of-principle experiment (cooler)
- We seek international collaborations for EIC.

# Announcement

## EIC14

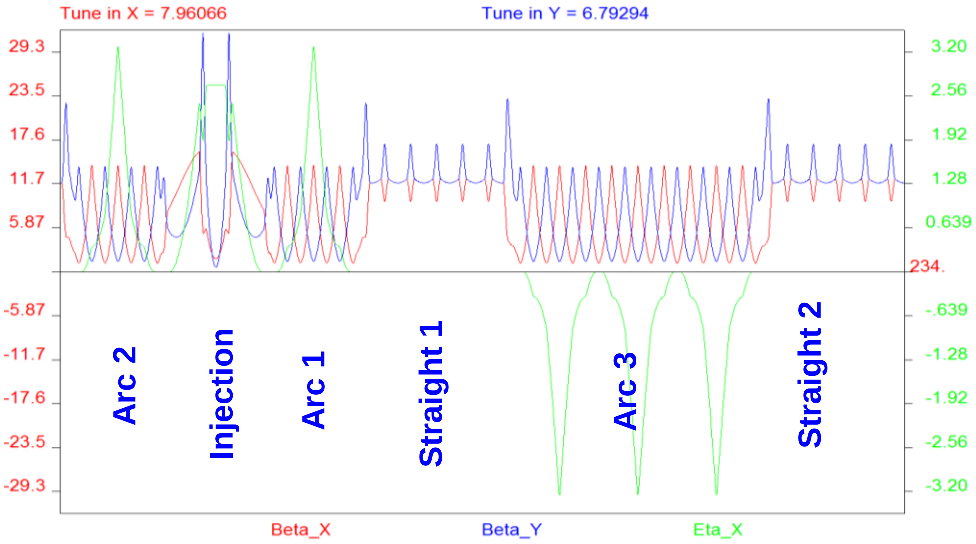
## The International Workshop for Accelerator science and Technology for Electron-ion Collider

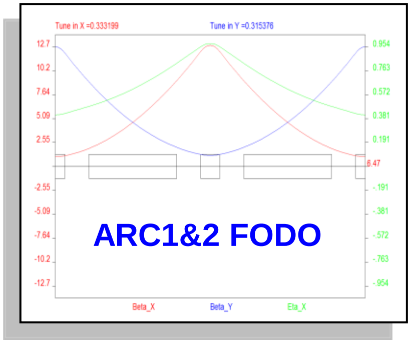
**March 17 – 21, 2014**

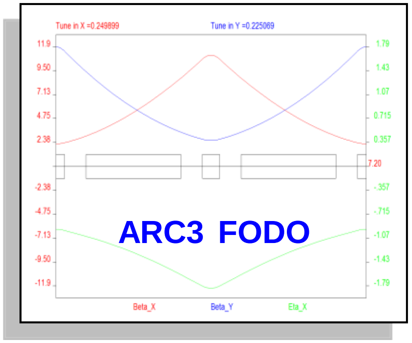
**Newport News, Virginia, USA**

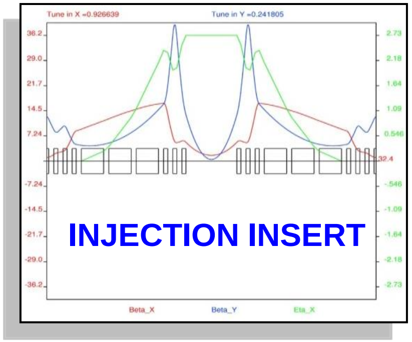
**WELCOME TO VIRGINIA!**

# Pre-booster Magnetic Lattices







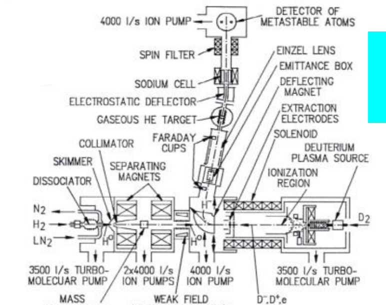


| | | |
|---|---|---|
| Circumference and crossing angle | m/deg | 234 / 75 |
| # of dispersive FODO cells (Type I & 2) | | 6 / 9 |
| # of triplet cells & matching cells | | 10 / 4 |
| Minimum drift length between magnets | cm | 50 |
| Drift in the injection & between triplets | m | 5 |
| Beta maximum in X and Y | m | 16 / 32 |
| Maximum beam size | cm | 2.3 |
| Maximum vertical beam size in dipoles | cm | 0.5 |
| Maximum dispersion | m | 3.36 |
| Normalized dispersion at injection | $m^{1/2}$ | 2.53 |
| Tune in x and y | | 7.96 / 6.79 |
| γ of particle and transition gamma | | 4.22 & 5 |
| Momentum compaction | | 0.04 |

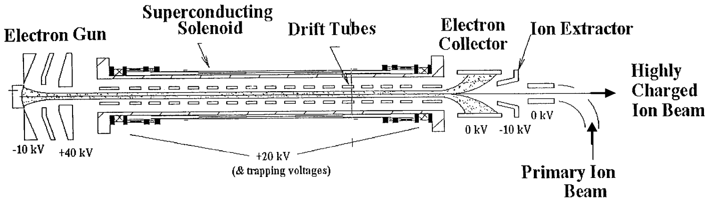
| | | | | |
|---|---|---|---|---|
| Quad | 95 | Length | cm | 40 |
| | | Half Aperture | cm | 5 |
| | | Max. pole tip field | T | 1.53 |
| | | Min. pole tip field | T | 0.15 |
| Dipole | 36 | Length | cm | 219 |
| | | Radius | cm | 9 |
| | | Vertical aperture | cm | 3 |
| | | Strength | T | 1.41 |
| | | Bending angle | deg | 14 |

# Ion Sources Prototype & Parameters

**Polarized light Ions**

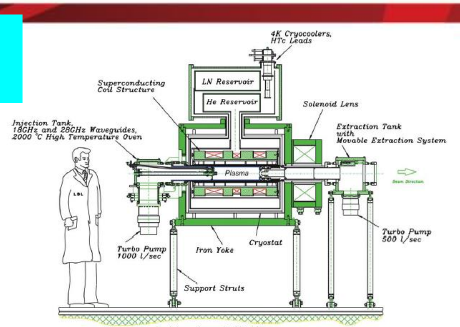


**Universal Atomic Beam Polarized Ion Sources (ABPIS)**



**Electron-Cyclotron Resonance Ion Source (ECR)**

**Non-Polarized Ions**



Electron-Cyclotron Resonance Ion Source (ECR)

| Ions | Source Type | Pulse Width (μs) | Rep. Rate (Hz) | Pulsed current (mA) | Ions/pulse ($10^{10}$) | Polarization ($P_z$) | Emittance (90%) (π·mm·mrad) | Note |
|---|---|---|---|---|---|---|---|---|
| $H^-/D^-$ | ABPIS | 500 | 5 | 4 (10) | 1000 | >90% (95) | 1.0 / 1.8 (1.2) | |
| $H^-/D^-$ | ABPIS | 500 | 5 | 150 / 60 | 40000/15000 | 0 | 1.8 | |
| $^3He^{++}$ | ABPIS-RX | 500 | 5 | 1 | 200 | 70% | 1 | |
| $^3He^{++}$ | EBIS | 10 to 40 | 5 | 1 | 5 (1) | 70% | 1 | BNL |
| $^6Li^{+++}$ | ABPIS | 500 | 5 | 0.1 | 20 | 70% | 1 | |
| $Pb^{30+}$ | EBIS | 10 | 5 | 1.3 (1.6) | 0.3 (0.5) | 0 | 1 | BNL |
| $Au^{32+}$ | EBIS | 10 to 40 | 5 | 1.4 (1.7) | 0.27 (0.34) | 0 | 1 | BNL |
| $Pb^{30+}$ | ECR | 500 | 5 | 0.5 | 0.5 (1) | 0 | 1 | |
| $Au^{32+}$ | ECR | 500 | 5 | 10.5 | 0.4 (0.6) | 0 | 1 | |

- Numbers in **red** are “realistic extrapolation for future”; numbers in **blue** are “performance requirements of BNL EBIS

- MEIC ion sources rely on existing and matured technologies
- Design parameters are within the state-of-art

**V. Dudnikov**

# Polarized Ion Beams in Figure-8 Ring

## Design Requirements

- High (>70%) polarization of stored electron beam
- Preservation of polarization during acceleration (in boosters and collider ring)
- ***Longitudinal and transverse*** polarization at interaction points
- ***Polarized deuteron***

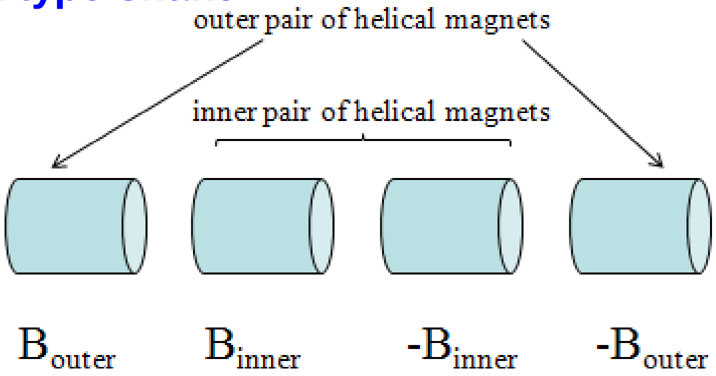
## Design Choices

* Polarized ion sources     * Figure-8 ring     * Siberian snakes

## Polarization schemes we have worked out

- Proton: longitudinal, transverse and combined polarizations at IPs
- Deuteron: longitudinal and transverse polarization at IPs

**BNL type snake**



Snake parameters for longitudinal scheme

| E (GeV) | 20 | 40 | 60 | 100 | 150 |
|---|---|---|---|---|---|
| $B_{outer}$ (T) | -2.13 | -2.16 | -2.173 | -2.177 | -2.184 |
| $B_{inner}$ (T) | 2.83 | 2.86 | 2.88 | 2.89 | 2.894 |

Snake parameters for transverse scheme

| E (GeV) | 20 | 40 | 60 | 100 | 150 |
|---|---|---|---|---|---|
| $B_{outer}$ (T) | -1.225 | -1.241 | -1.247 | -1.251 | -1.253 |
| $B_{inner}$ (T) | 3.943 | 3.994 | 4.012 | 4.026 | 4.033 |

# Perspectives of MEIC Cooling R&D

## Electron cooling

- High energy (up to 100 GeV *p* / 55 MeV *e*) ← an order of magnitude above the state-of-art
- Bunched cooling electron beam from an SRF linac
- Multi-stage
- Cooling while collisions

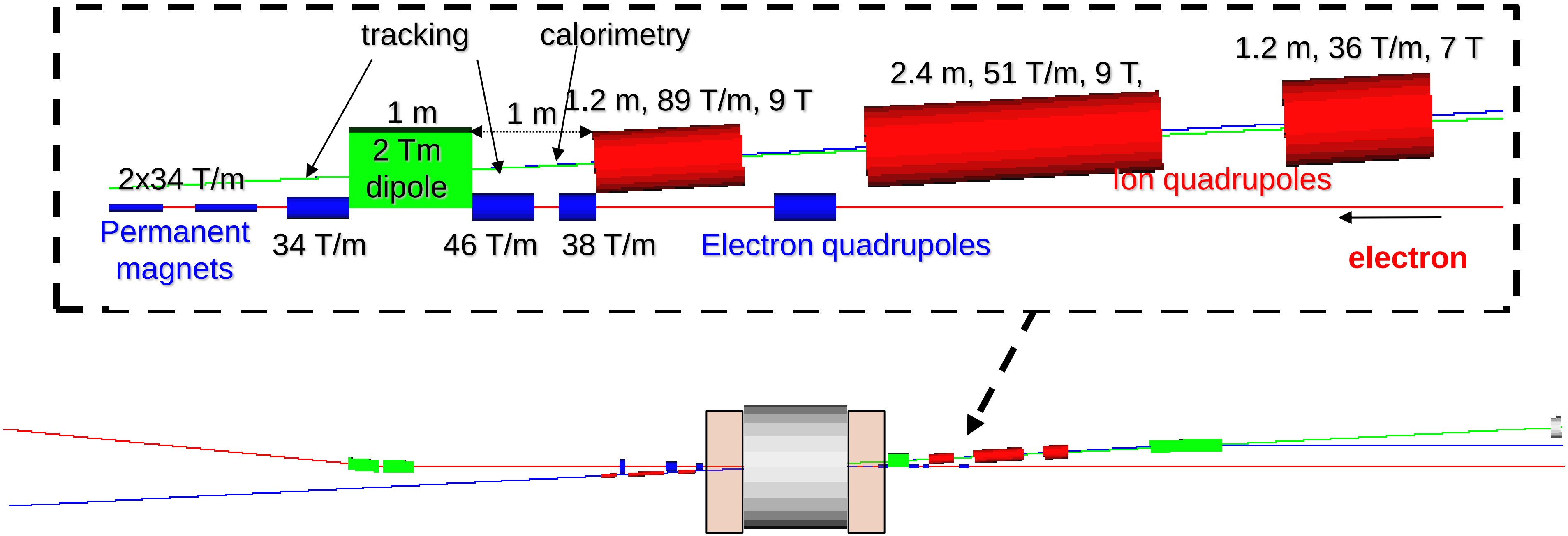
| | |
|---|---|
| **Medium energy** | **Bunched e-beam** |
| **ERL** | **Circulator ring** |

## Electron cooler

- A magnetized photo-cathode electron gun with long life-time
- High bunch charge (2 nC) ← a significant challenge in injector/ERL
- High Average current and high repetition rate
- High current ERL
- ***Ultra fast kicker with high repetition rate and short rise/full time***
- Transporting a magnetized beam
- Collective beam effects (Coherent synchrotron radiation, longitudinal space charge)
- Intra and inter beam heating
- Coupling of multiple beams (colliding beams and cooling beam)

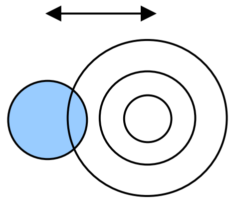
***Cooling is the No.1 priority of MEIC accelerator R&D!***

# (Small Angle) Hadron Detection Prior to Ion FFQs



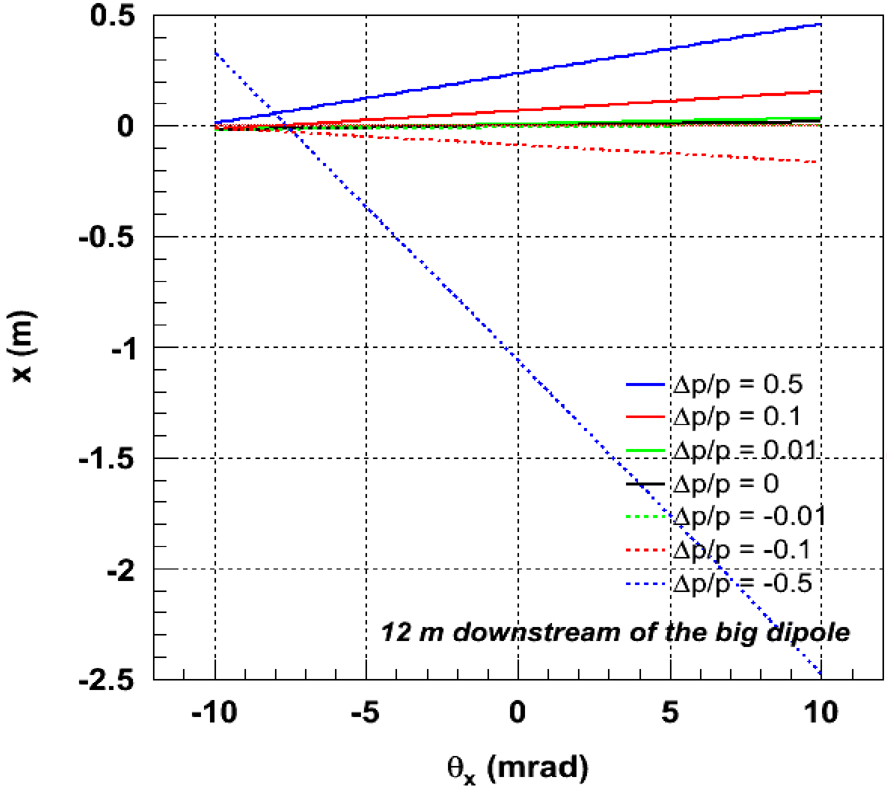
- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Large-acceptance dipole further improves resolution in the few-degree range

Crossing angle



# Forward Ion Momentum & Angle Resolution at Focal Point

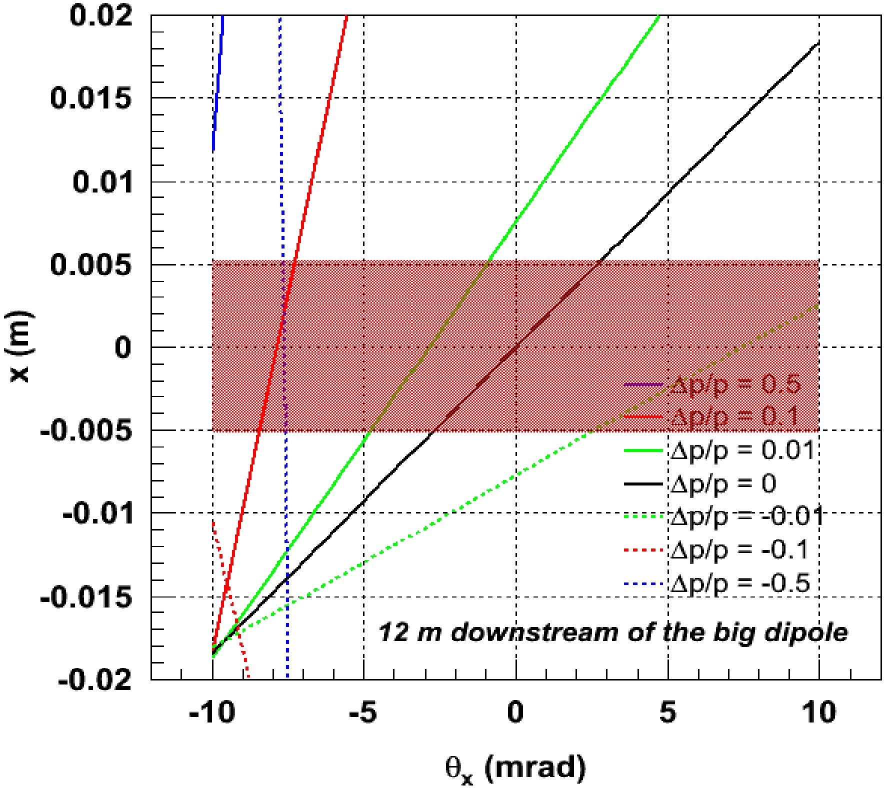
- Protons with different $\Delta p/p$ launched with $\theta_x$ spread around nominal trajectory



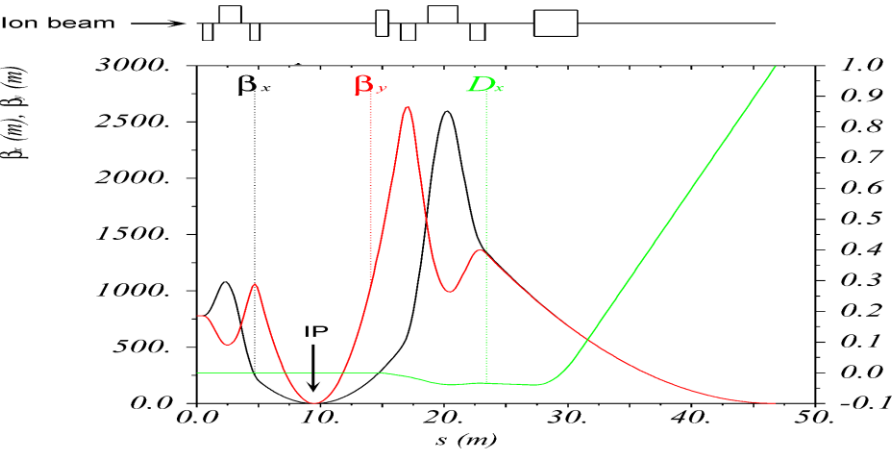
**electron beam** ↓

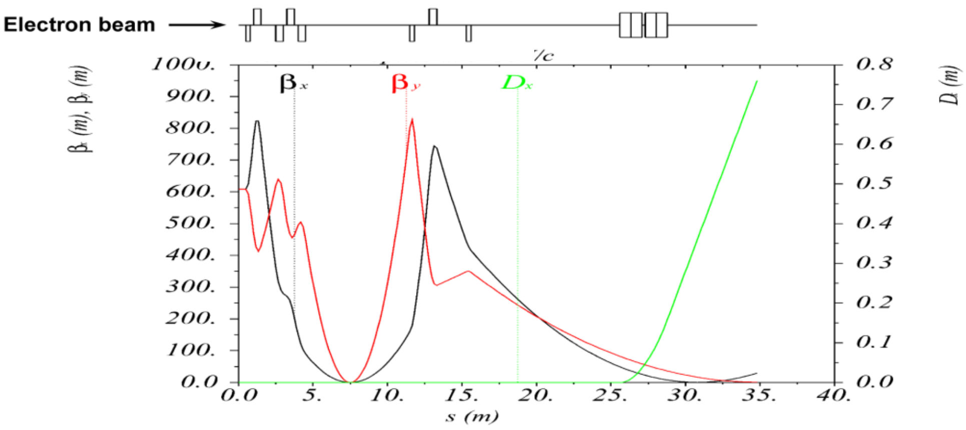
**← electron beam**

**$|\theta_x| > 3$ mrad @ $\Delta p/p = 0$**



# IR Optics Optimized for Detector Integration





- Upstream FFB is much closer to the IP
  - ➔ lower betatron functions
  - ➔ smaller contribution to the chromaticity
- Downstream FFB has larger apertures and distance from the IP
  - ➔ maximizing acceptance to the forward-scattered hadrons
- Focusing in the downstream allows to place the detectors close to the beam center. Combining with ~1 m dispersion, it can detect particles with small momentum offset Δp/p

- Similar optics to ion beam
- two permanent magnetic quadrupoles are used in the upstream FFB and vey close to the IP to maximize the ion detector acceptance by reducing the solid angle blocked by the final focusing quadrupoles.
- Changing of their focusing strengths with energy can be compensated by adjusting the upstream electric quadruples.