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

Overarching Goal: Explore Hadron Structure

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

R. Ent (2011)

JLab Nuclear Science: 12 GeV CEBAF

CEBAF fixed target program

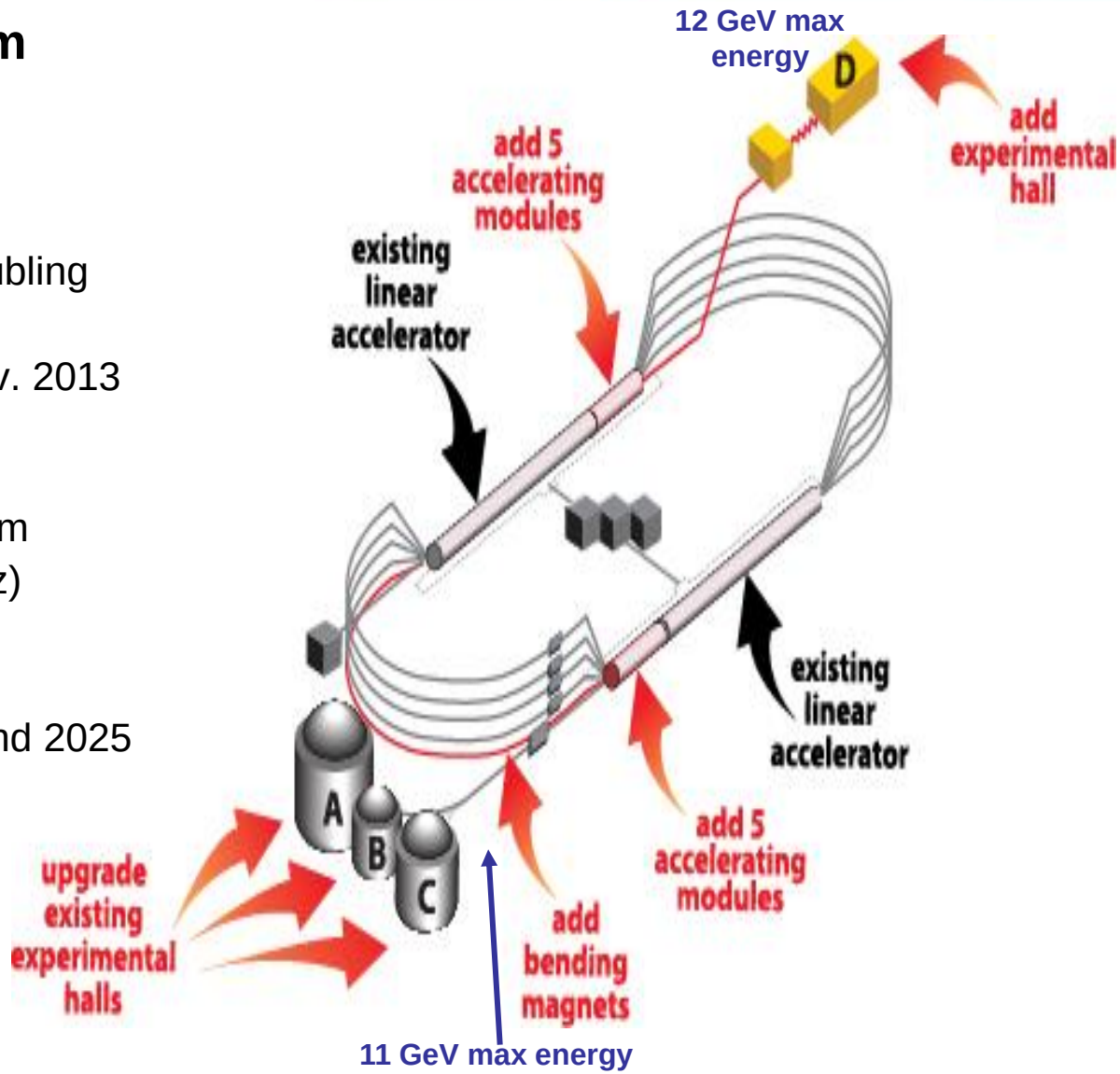
- 5-pass recirculating SRF linac

12 GeV CEBAF Upgrade

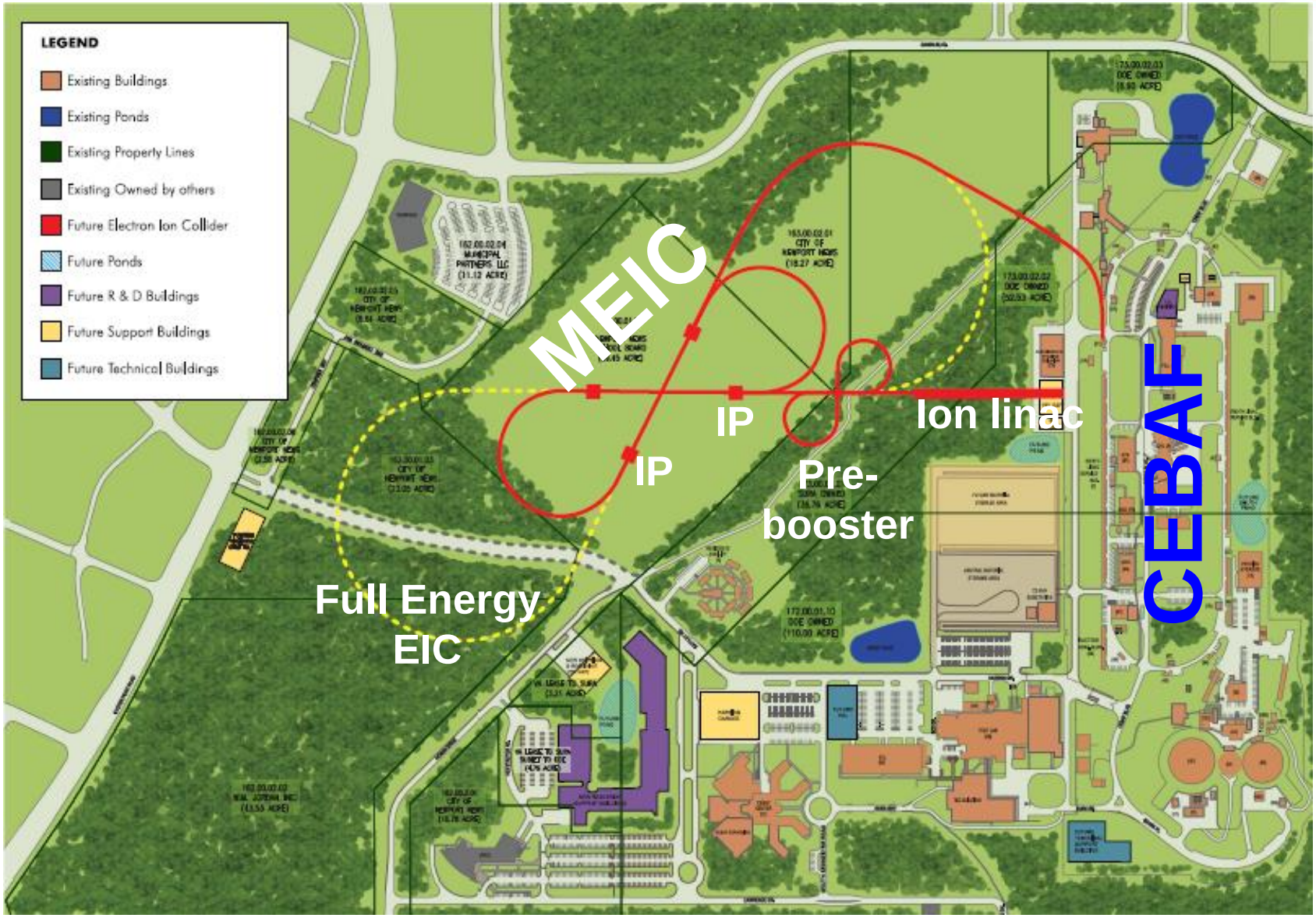
- A $340M project for energy doubling
- Construction near completion
- Commissioning will start on Nov. 2013

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: MEIC



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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Executive Summary

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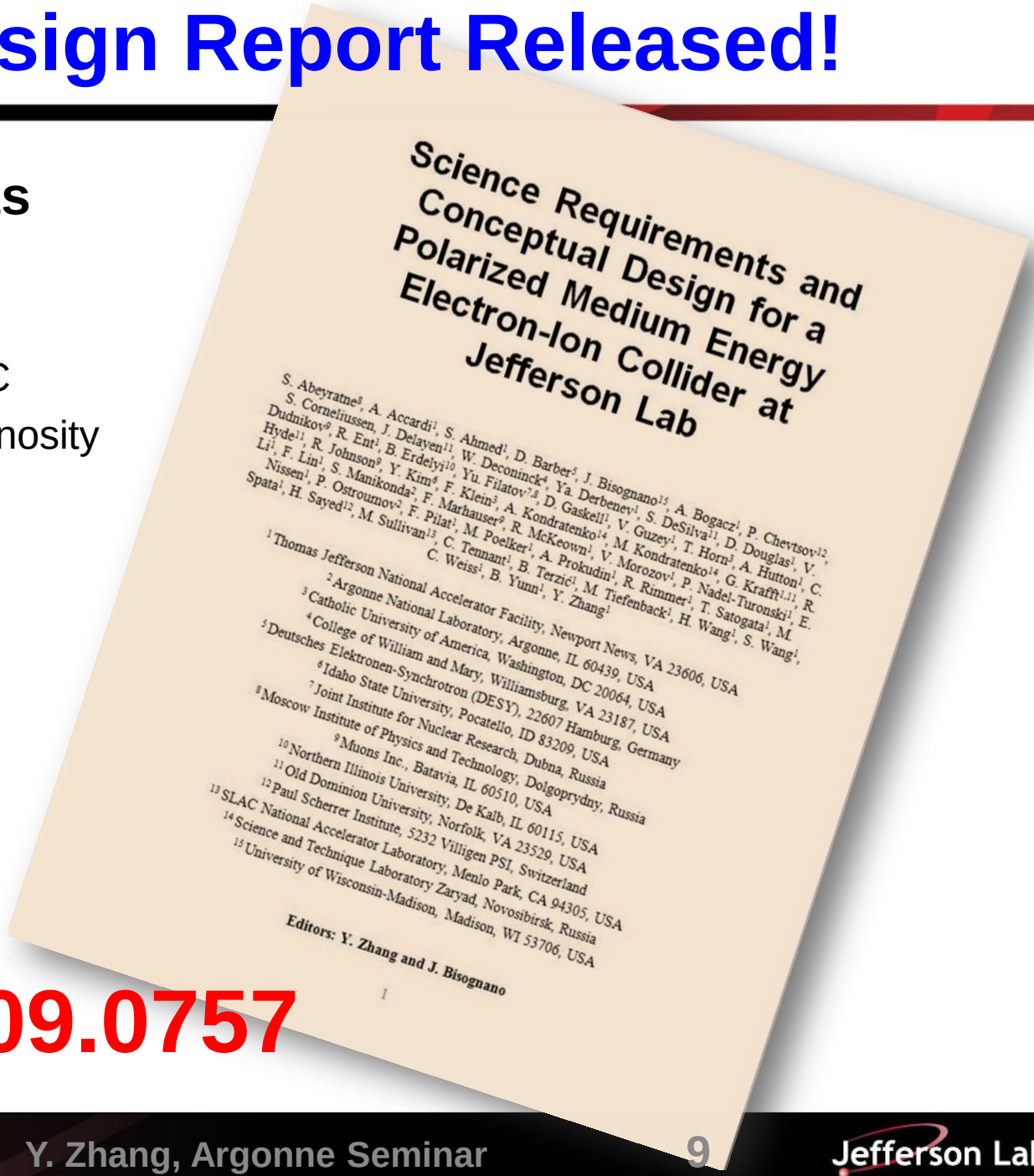

Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

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Editors: Y. Zhang and J. Bisognano

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arXiv:1209.0757

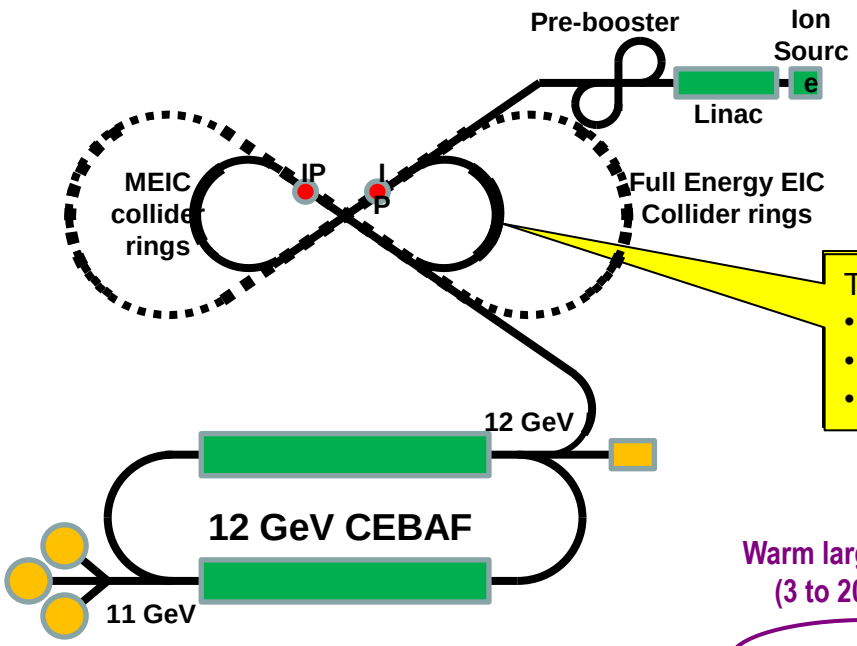
2. MEIC Baseline Design

MEIC Design Goals

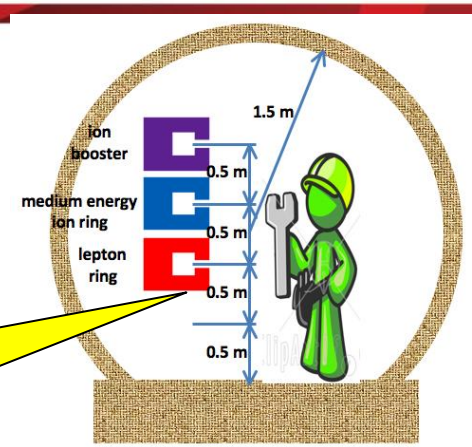
- **Energy**

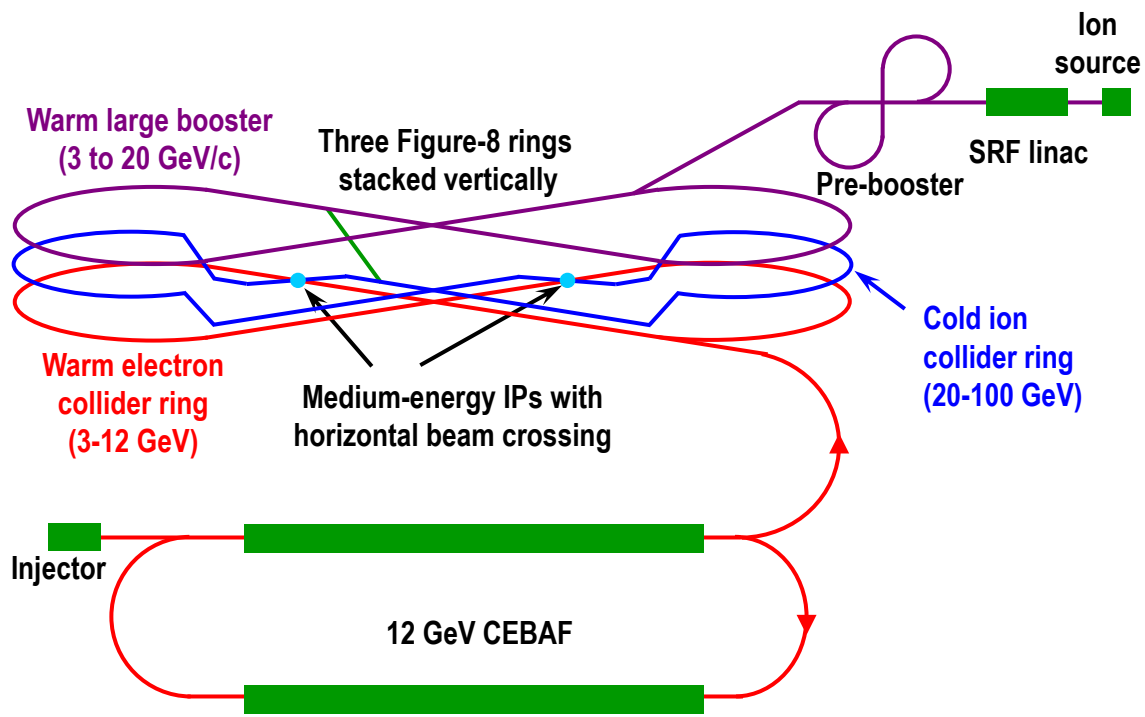
  (*bridging the gap of 12 GeV CEBAF & HERA/LHeC*)
  - Full coverage of *s* from a few 100 to a few 1000 GeV^2
  - Electrons 3-12 GeV, protons 20-100 GeV, ions 12-40 GeV/u
- **Ion species**
  - Polarized light ions: p, d, ^{3}He, and possibly Li, and polarized heavier ions
  - Un-polarized light to heavy 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)





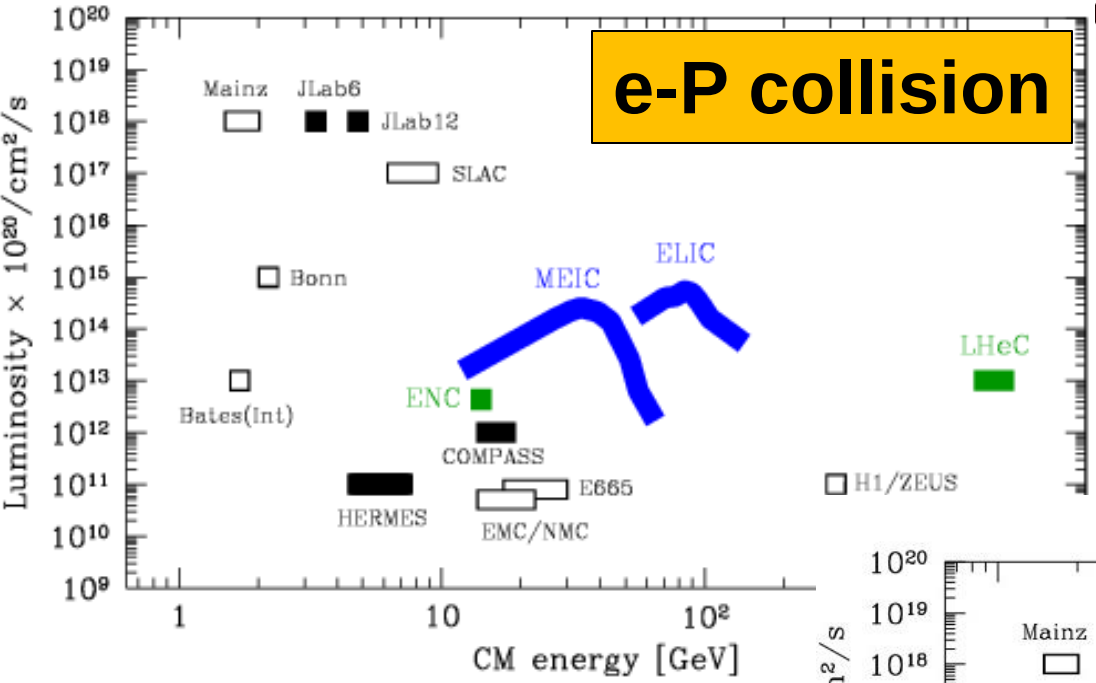
Parameters for *Full Acceptance* Interaction Point

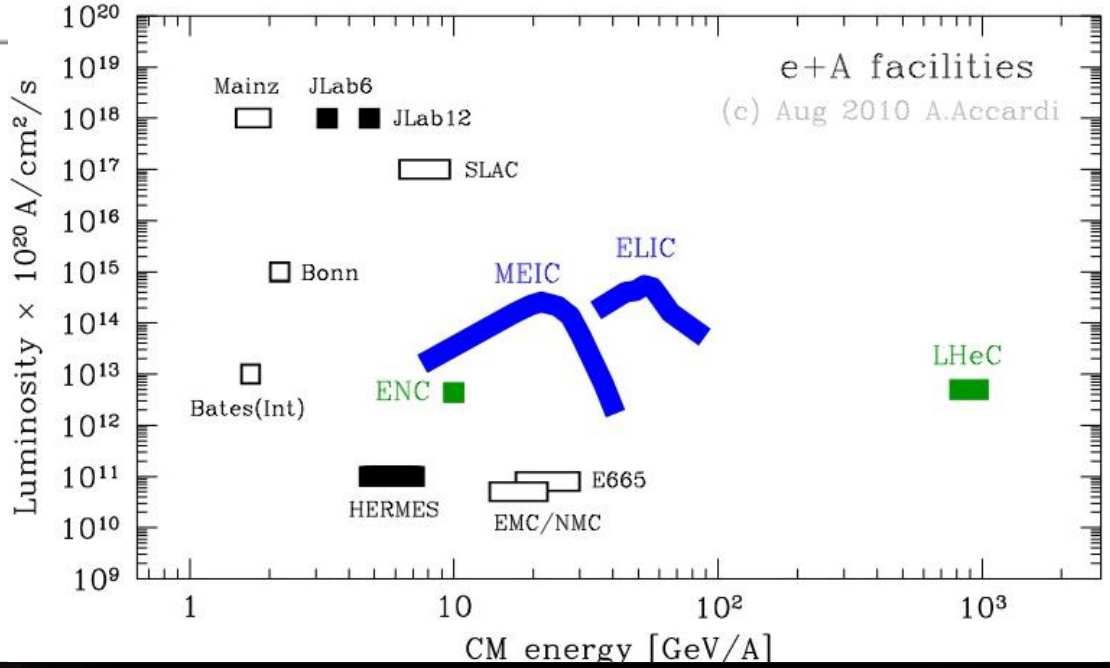
		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	MHz	750	750
Particles per bunch	10^{10}	0.416	2.5
Beam Current	A	0.5	3
Polarization	%	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1
RMS bunch length	cm	1	0.75
Horizontal emittance, normalized	μm rad	0.35	54
Vertical emittance, normalized	μm rad	0.07	11
Horizontal 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
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 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
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	14.2	

MEIC/ELIC Luminosity Plot

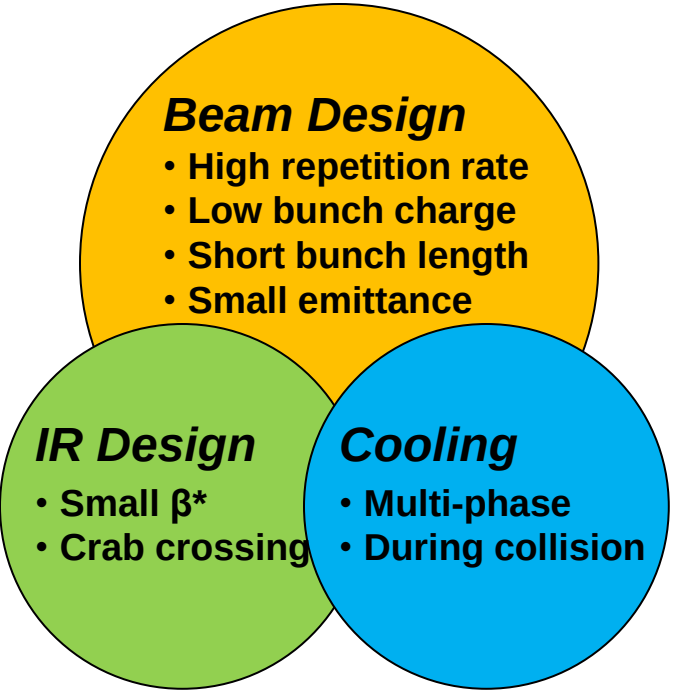




A. Accardi

MEIC Design Feature: High Luminosity

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



KEK-B already reached above $2x10^{34}$ /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 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

- Delivering desired polarization at multiple collision points

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

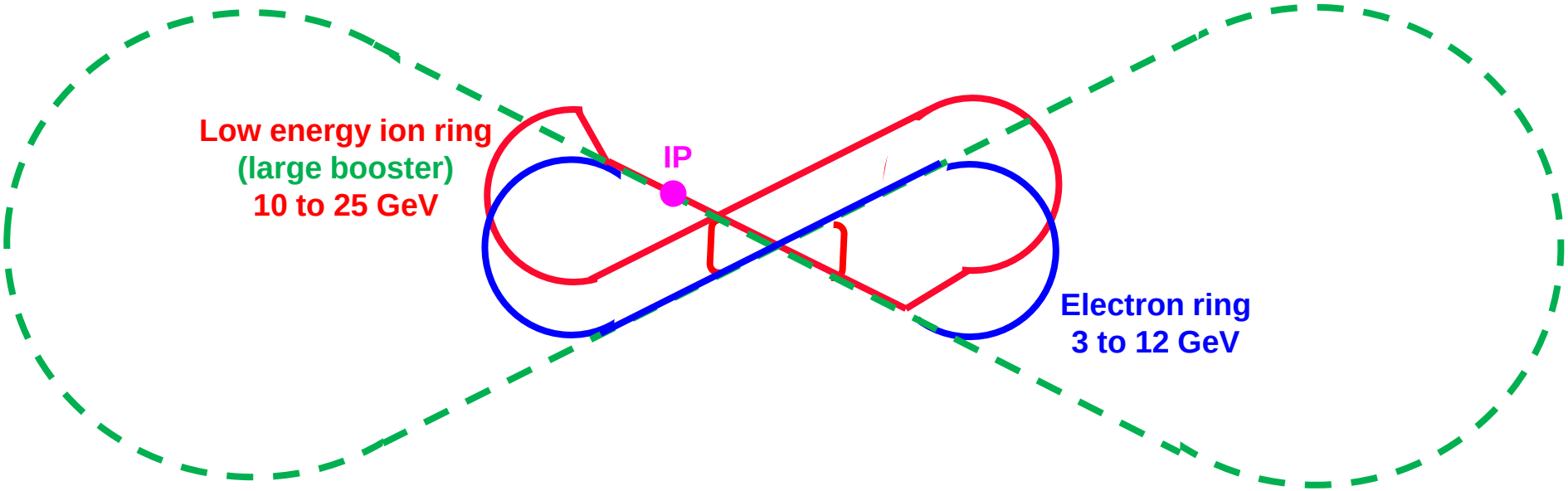
(The electron ring has a similar shape since it shares a tunnel with the ion ring)

LEIC: Low Energy Electron-Ion 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

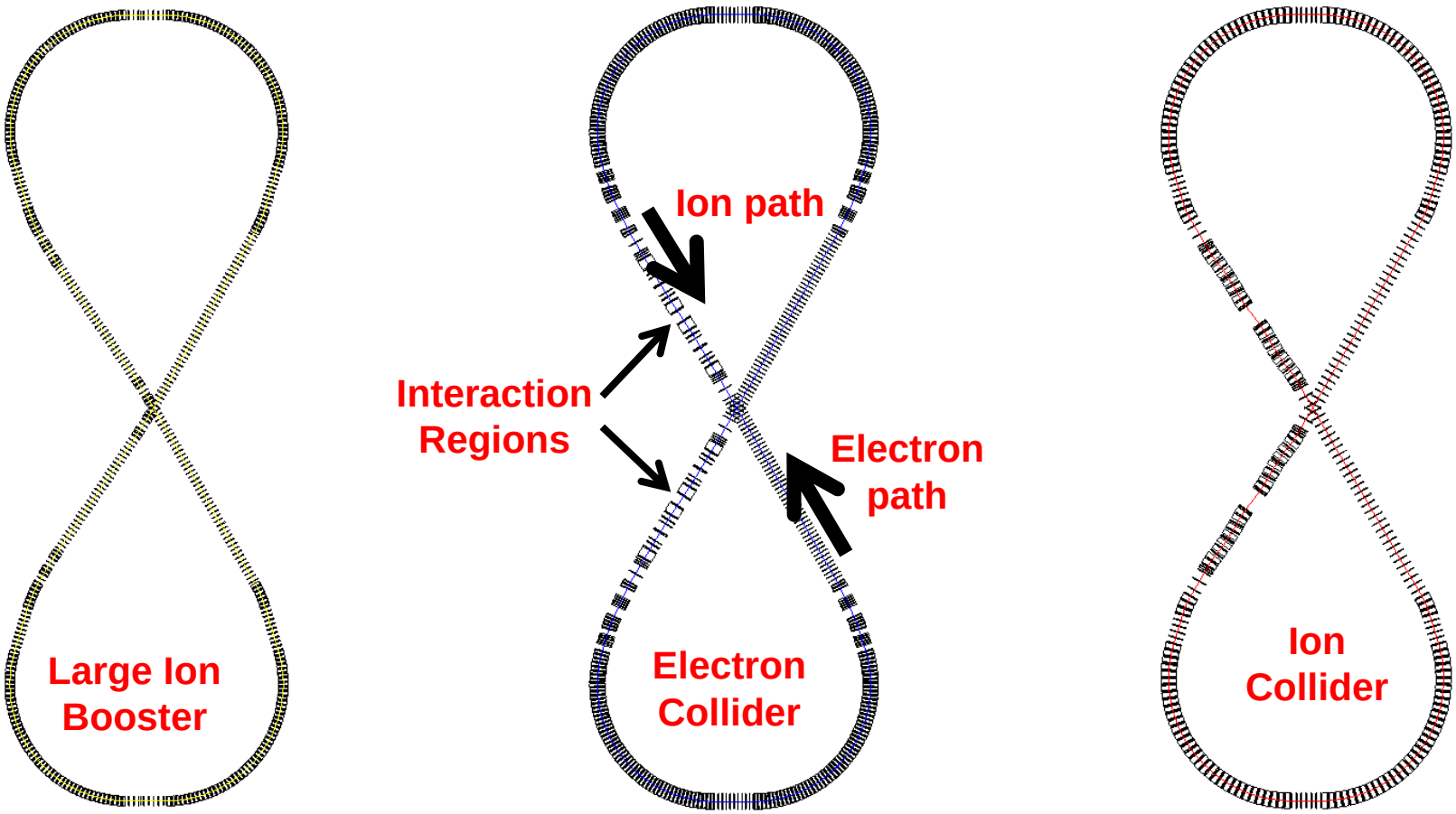
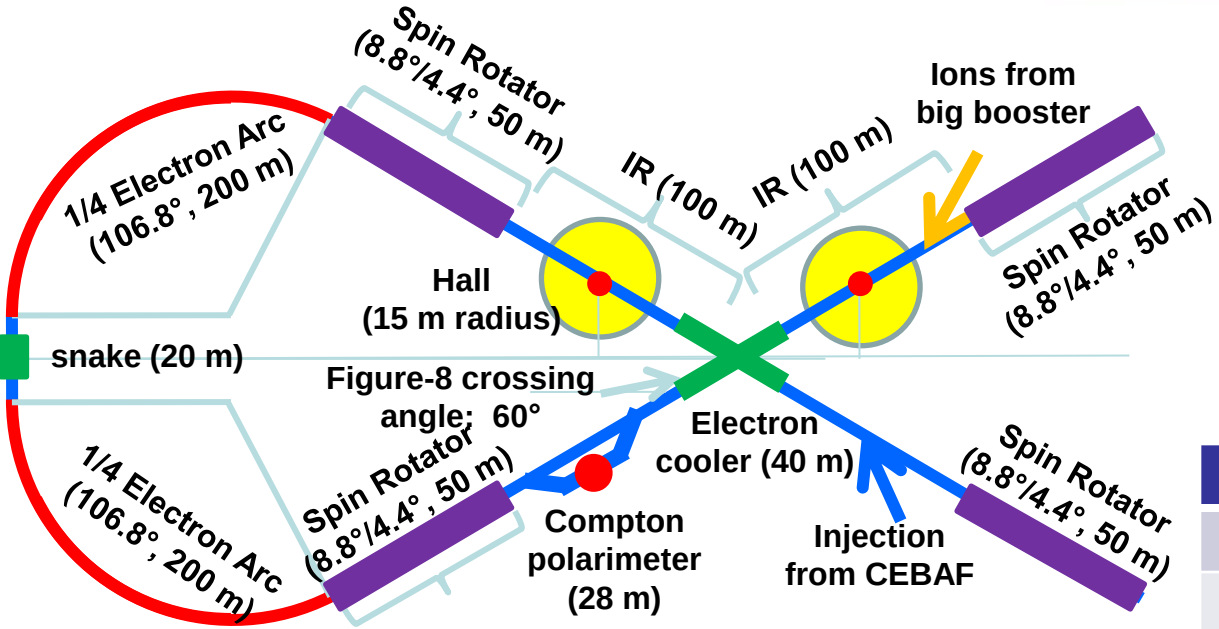
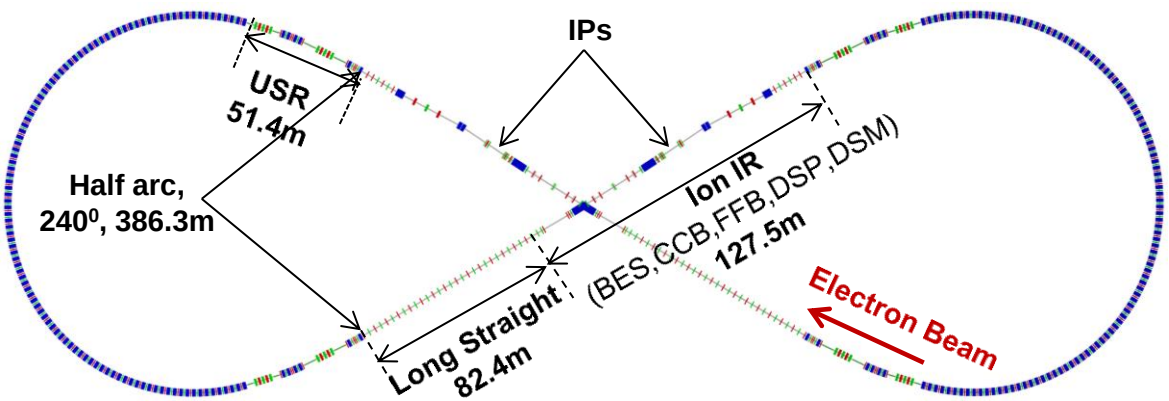


Figure-8 Electron Collider Ring



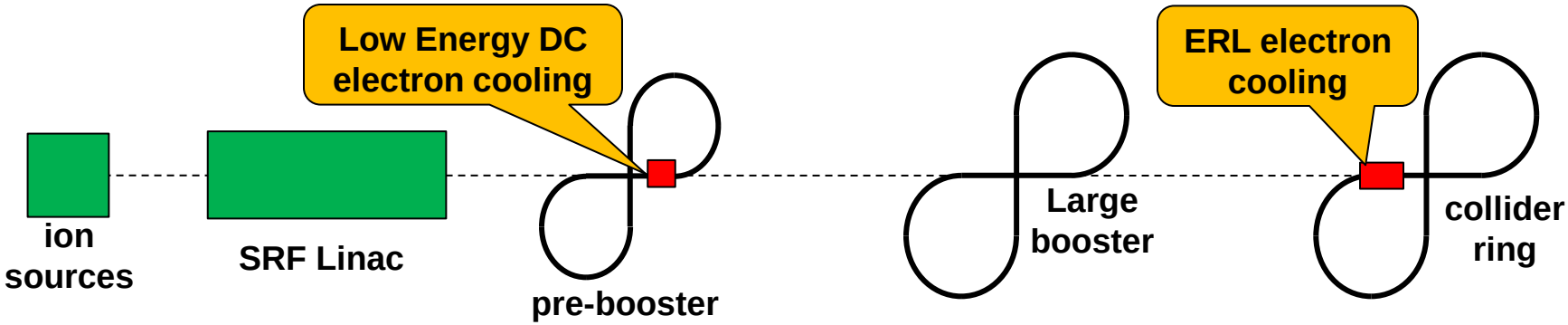
- Normal conduct magnets
- FODO lattice (60º phase/cell)
- Utilizing dispersion suppressor (varying quad strength)
- High transition energy



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 Ion Complex

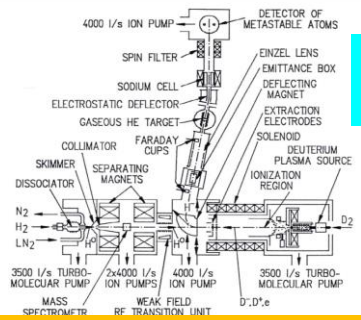
- Goals: covering all required ion species & energies, matching phase-space structures
- Challenges: beam formation ← *space charge effect at low energy*
  maintaining beam phase density ← *intra-beam scatterings*
- Low energy DC electron cooling for assisting accumulation of heavy ions
- SRF linac and 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 refer

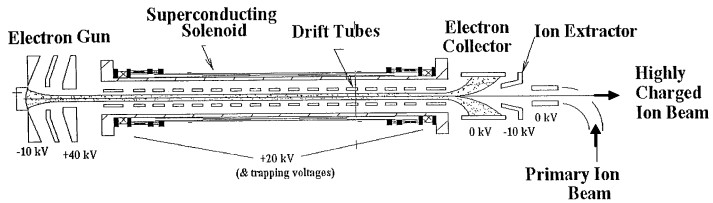
Ion Sources Prototype & Parameters



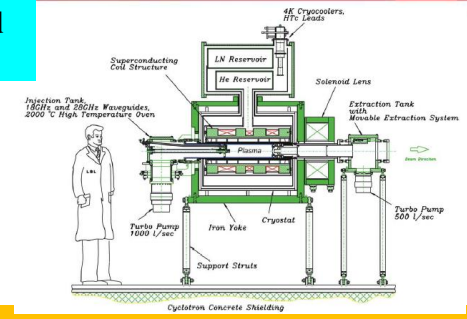
Polarized light Ions

Universal Atomic Beam Polarized Ion Sources (ABPIS)

Non-Polarized Ions



Electron-Cyclotron Resonance Ion Source (ECR)



Electron-Cyclotron Resonance Ion Source (ECR)

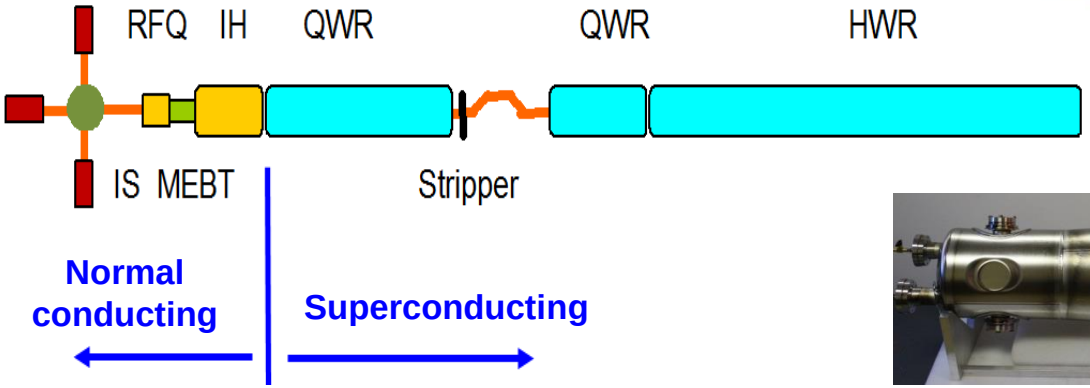
Ions	Source Type	Pulse Width (μs)	Rep. Rate (Hz)	Pulsed current (mA)	Ions/pulse (10^{10})	Polarization (P_z)	Emittance (90%) (π·mm·mrad)	Note
H^-/D^-	ABPIS	500	5	4 (10)	1000	>90% (95)	1.0 / 1.8 (1.2)	
H^-/D^-	ABPIS	500	5	150 / 60	40000/15000	0	1.8	
$^3He^{++}$	ABPIS-RX	500	5	1	200	70%	1	
$^3He^{++}$	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	

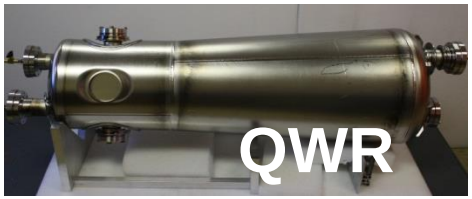
- Numbers in **red** are "realistic extrapolation for future"; numbers in **blue** are "performance requirements of BNL EBIS

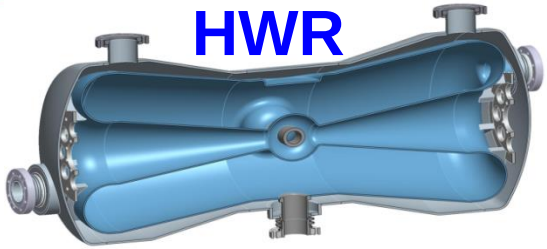
- MEIC ion sources rely on existing and matured technologies
- Design parameters are within the state-of-art

V. Dudnikov

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***

Parameters	Unit	Value
Species		p to lead
Reference Design		^{208}Pb
Kinetic energy	MeV/u	100
Max. pulse current Light ions (A/q≤3) Heavy ions (A/q≥3)	 mA mA	 2 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

P. Ostroumov, ANL

Ion Pre-booster

Purpose of pre-booster

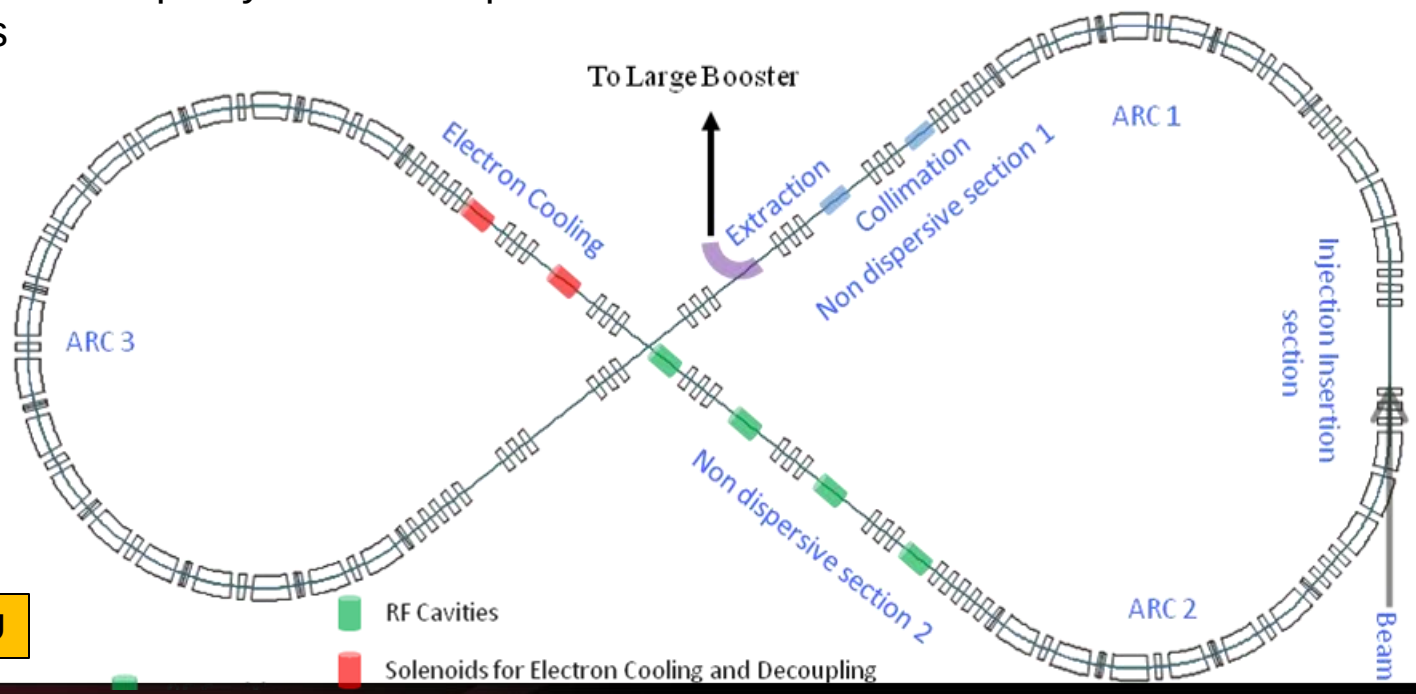
- Accumulating ions injected from linac
- Accelerating ions
- Extracting/sending ions to the large booster

Design Concepts

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

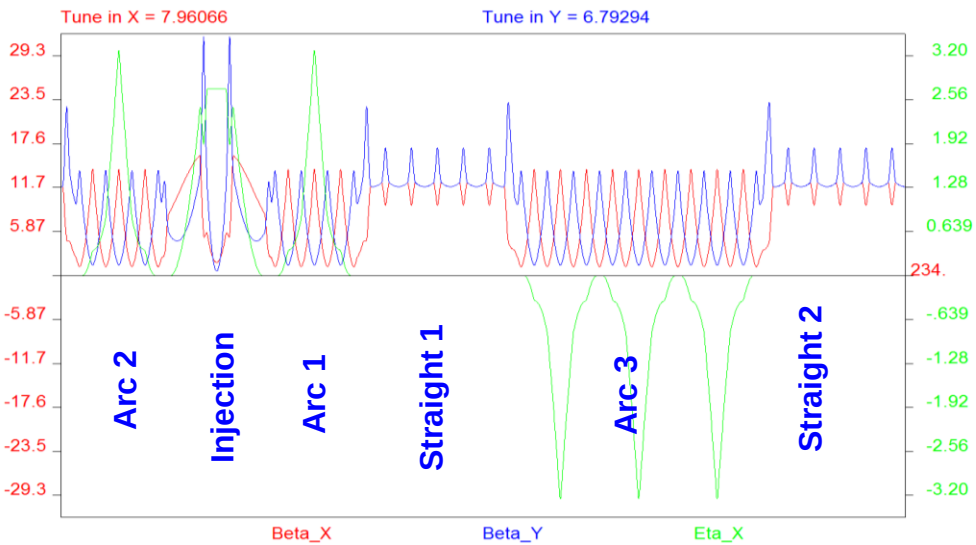
Design constraints

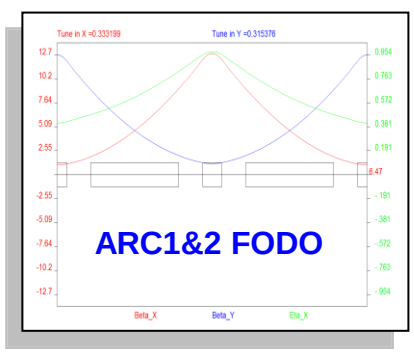
- Maximum bending field: 1.5 T
- Maximum quad field gradient: 20 T/m
- Momentum compaction smaller than 1/25
- Maximum beta functions less than 35 m
- Maximum full beam size less than 2.5 cm,
- 5m dispersion-free sections for RF, cooling, collimation and extraction.

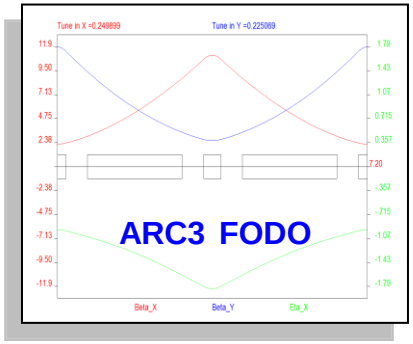


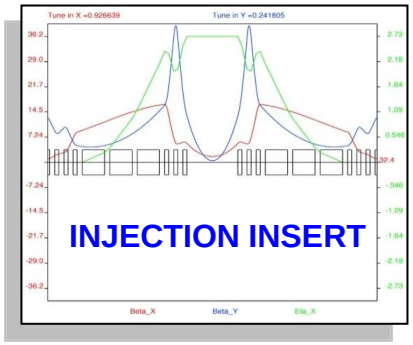
B. Erdelyi, NIU

Pre-booster Magnetic Lattices







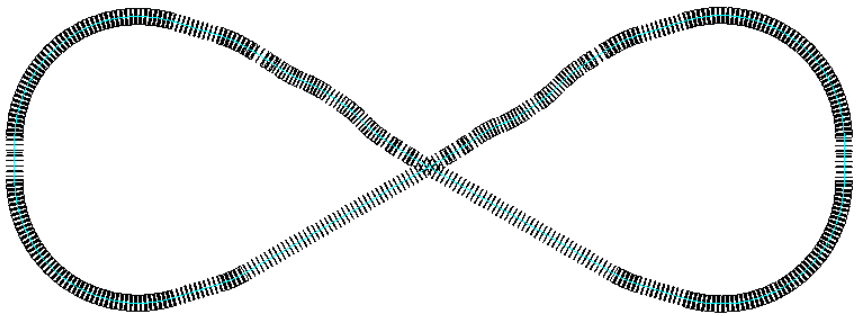


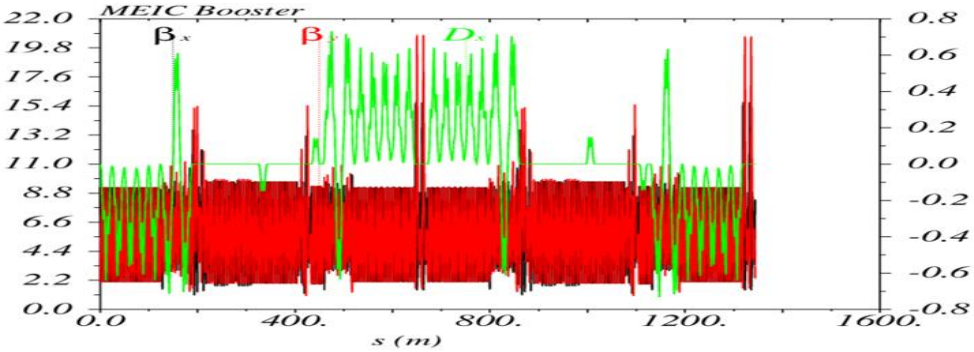
Circumference and crossing angle	m/deg	234 / 75
# of dispersive FODO cells (Type I & 2)		6 / 9
# of triplet cells & matching cells		10 / 4
Minimum drift length between magnets	cm	50
Drift in the injection & between triplets	m	5
Beta maximum in X and Y	m	16 / 32
Maximum beam size	cm	2.3
Maximum vertical 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

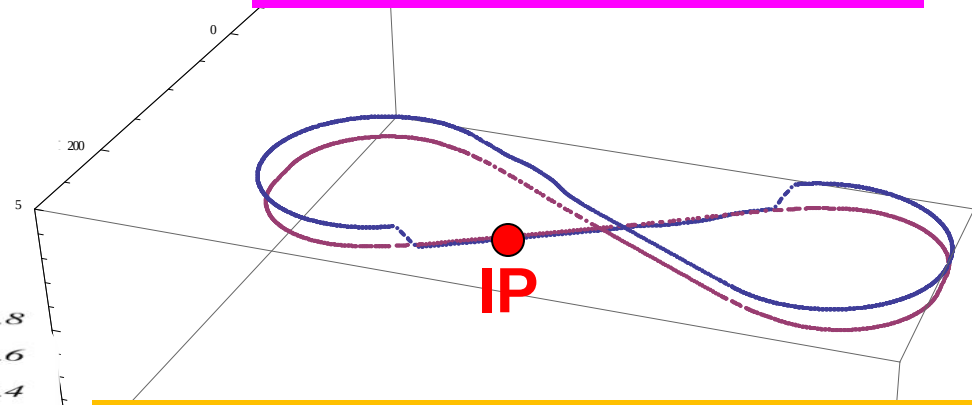
MEIC Ion Large Booster/LEIC Collider Ring

- 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 γ_t=25.03)
- Quadrupole based dispersion suppression.
- Tuneable to any working point.



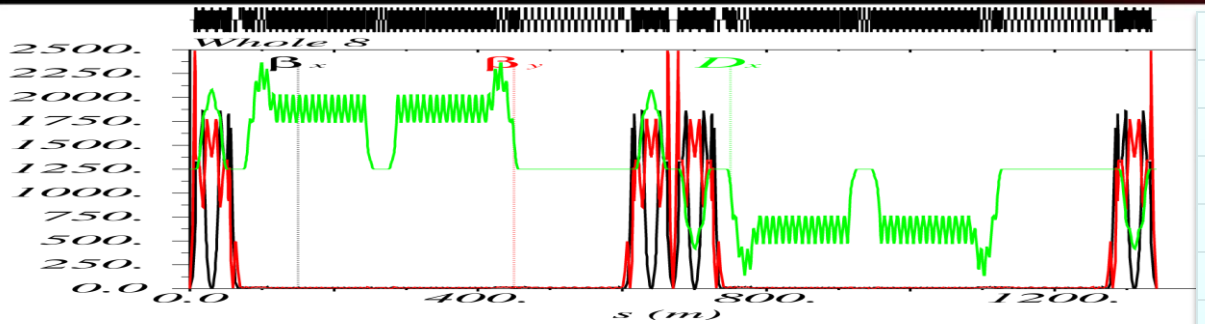


Large booster converted to a low energy collider ring



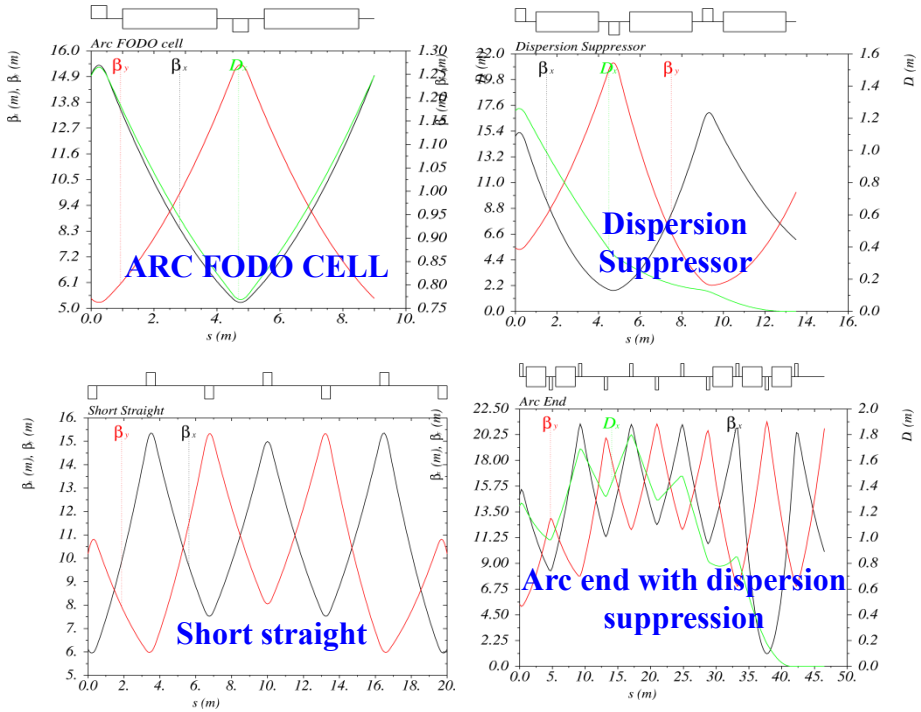
- Vertical chicane to bring low energy ions to the plane of the electron ring
- Add electron cooling and SRF
- Share detector with MEIC

MEIC Ion Collider Ring



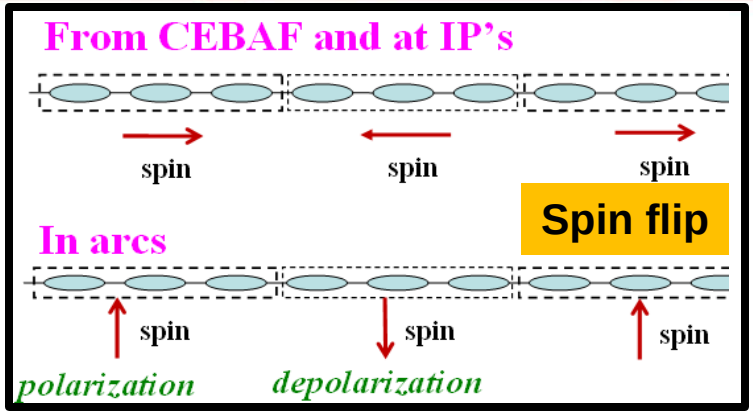
Dipole		144
Length	m	3
Bending radius	M	53.1
Bending Angle	deg	3.236
Field @ 60 GeV	T	3.768
Quad		298
Length	M	0.5
Strength @ 60 GeV	T/m	92 / 89

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 (ν_x, ν_y)		25.501 /25.527
Momentum compaction	10^{-3}	5.12
Transition gamma		13.97
Dispersion suppression		Adjusting quad strength

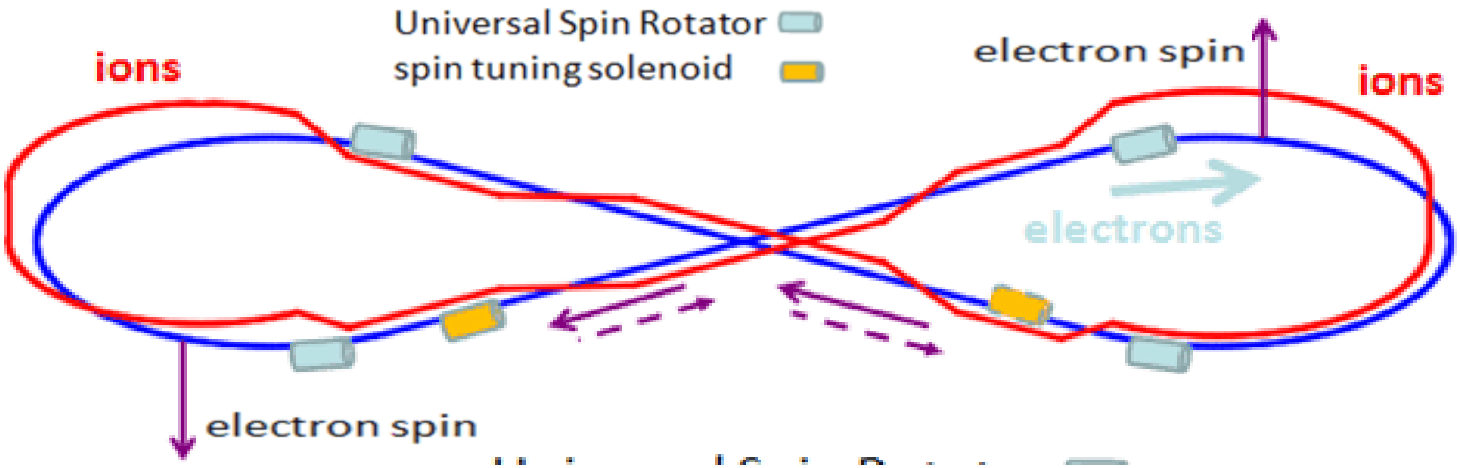


Polarized Beam in the Electron Ring

- **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

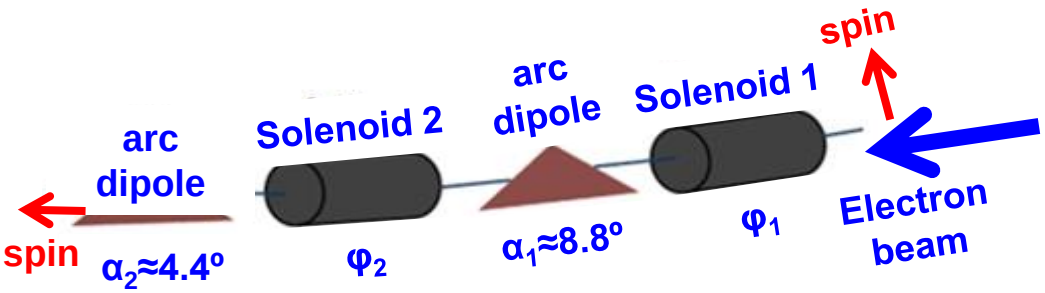


- **MEIC electron polarization design**
  - CEBAF polarized electron source (>85%)
  - Utilizing Sokolov-Ternov effect for preserving polarization (vertical, anti-parallel to B-field in arc)
  - Using universal spin rotators for aligning spin in longitudinal direction at the interaction points
  - Employing spin matching to suppressing depolarization



Universal Spin Rotator

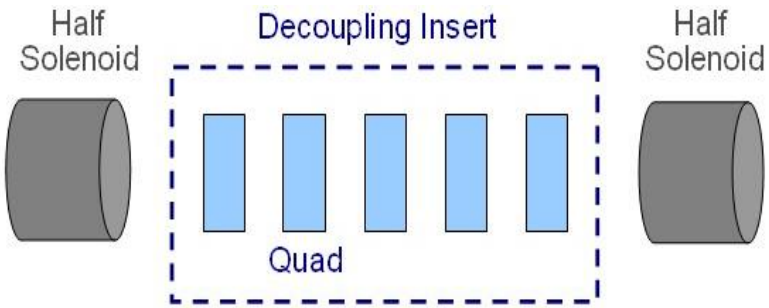
- Rotating spin from vertical to longitudinal
- Consists of 2 solenoids & 2 (fixed angle) arc dipoles
- ***Universal***
  - ➔ ***energy independent***
    works for all energies (3 to 12 GeV)
  - ➔ ***orbit independent***
    does not affect orbital geometry

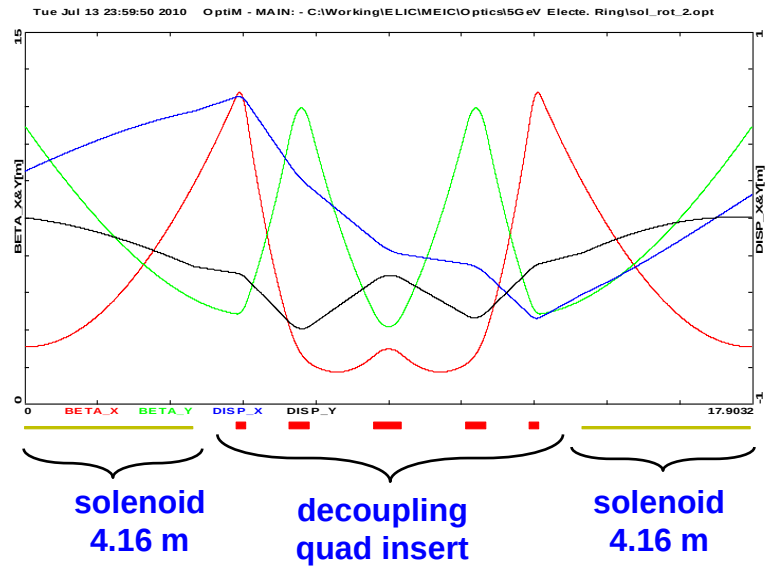


E (GeV)	φ_1	BL_1 (Tm)	α_1	φ_2	BL_2 (Tm)	α_2
3	$\pi/2$	15.7	$\pi/3$	0	0	$\pi/6$
6	0.62	12.3	$2\pi/3$	1.91	38.2	$\pi/3$
9	$\pi/6$	15.7	π	$2\pi/3$	62.8	$\pi/2$
12	0.62	24.6	$4\pi/3$	1.91	76.4	$2\pi/3$

Compensation of solenoid x-y coupling

V. Livinenko & A. Zholents, 1980





Sayed, Bogacz

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***

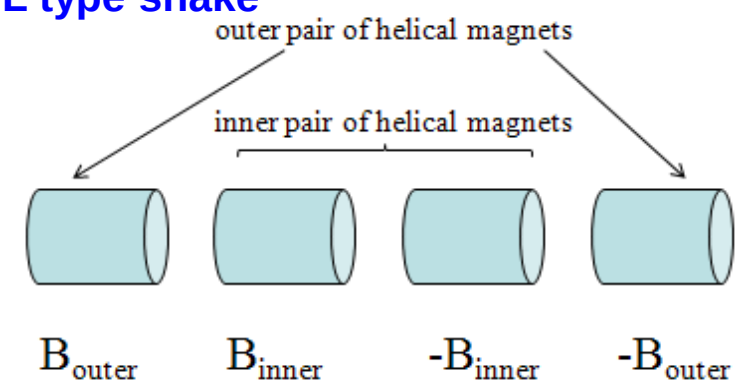
Design Choices

* 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

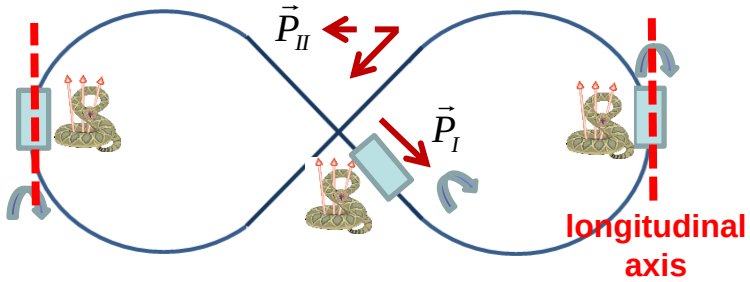
E (GeV)	20	40	60	100	150
B_{outer} (T)	-2.13	-2.16	-2.173	-2.177	-2.184
B_{inner} (T)	2.83	2.86	2.88	2.89	2.894

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

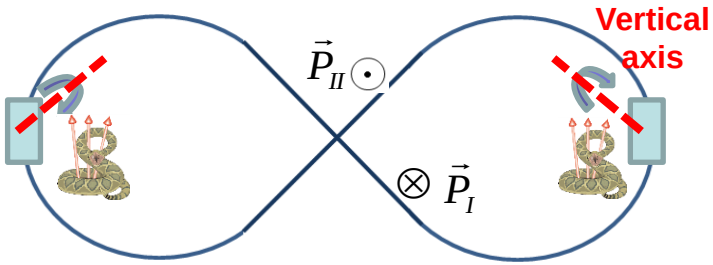
Proton/He-3 Polarization at IPs

Case 1: Longitudinal Proton Polarization at IP's



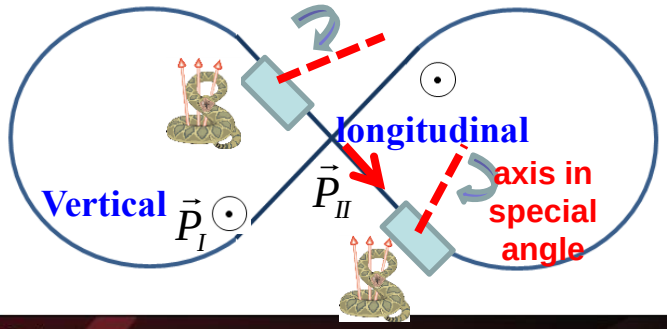
- Three Siberian snakes, all longitudinal-axis
- Third snake in straight is for spin tune
- Spin tune: 1/2

Case 2: Transverse proton polarization at IP's



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

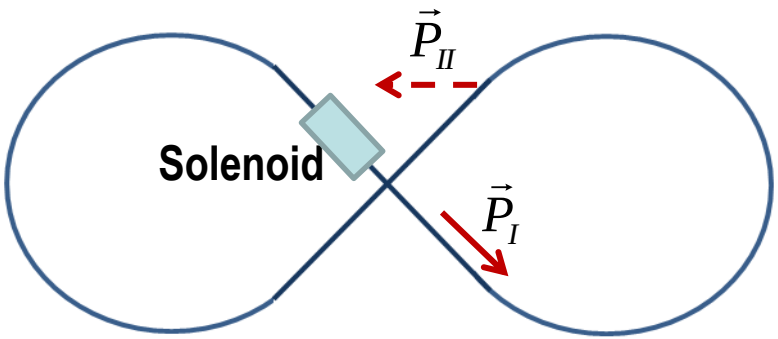
Case 3: Longitudinal & transverse proton polarization on two straights



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

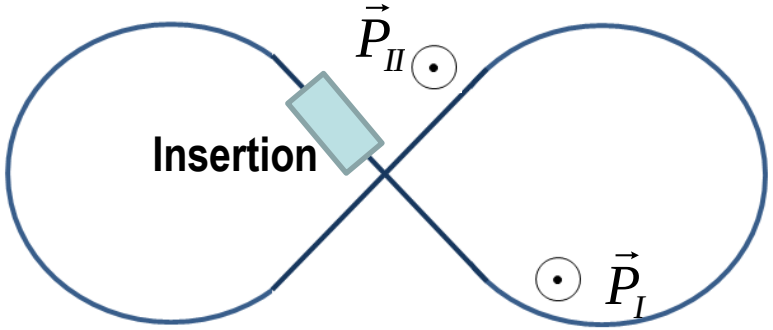
Deuteron Polarizations at IPs

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

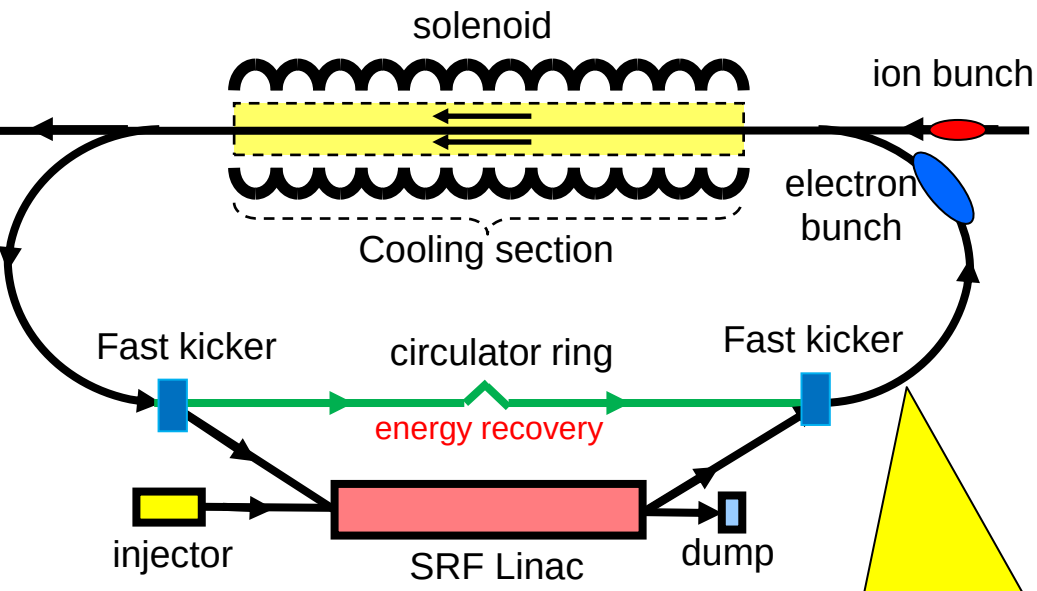
- Essential to achieve high luminosity for MEIC
- Based on traditional electron cooling
- ***Multi-phase cooling* scheme**

Pre-booster: *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

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

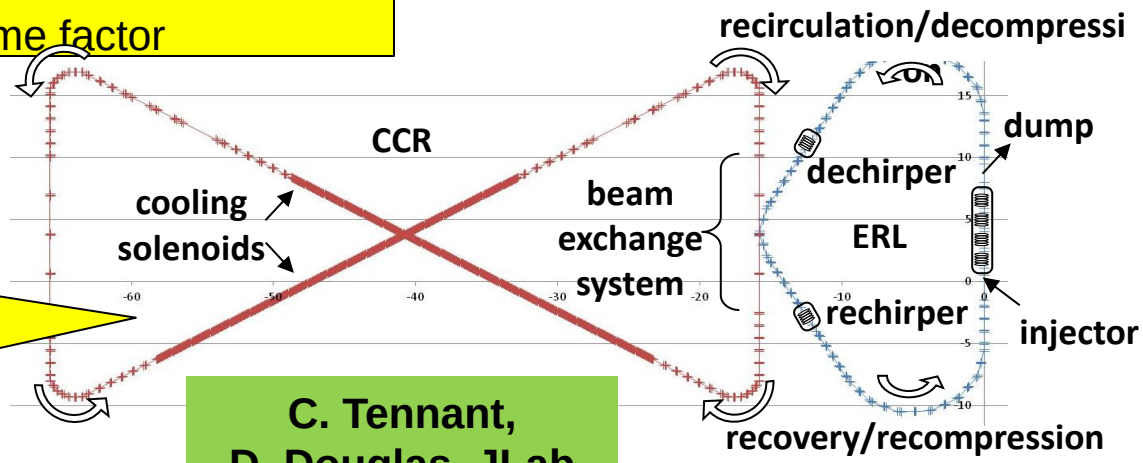
to meet design challenges

- 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

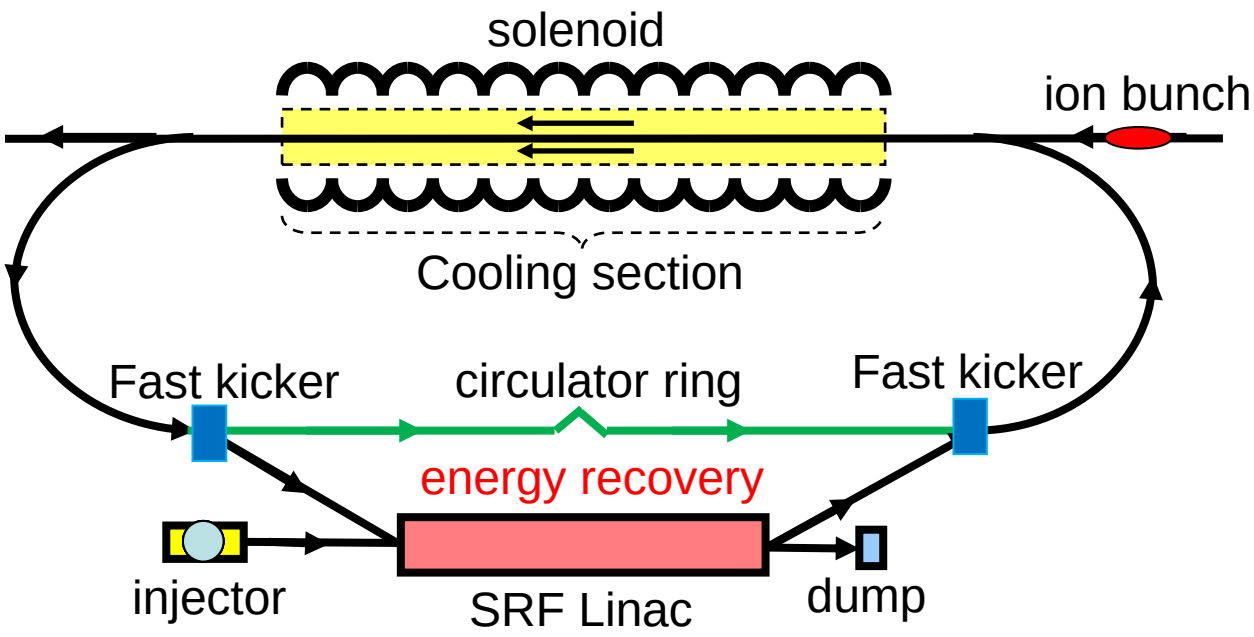
Optimization:
Put it at center of the Figure-8 ring, for eliminating the long return path doubles the cooling rate



C. Tennant, D. Douglas, JLab

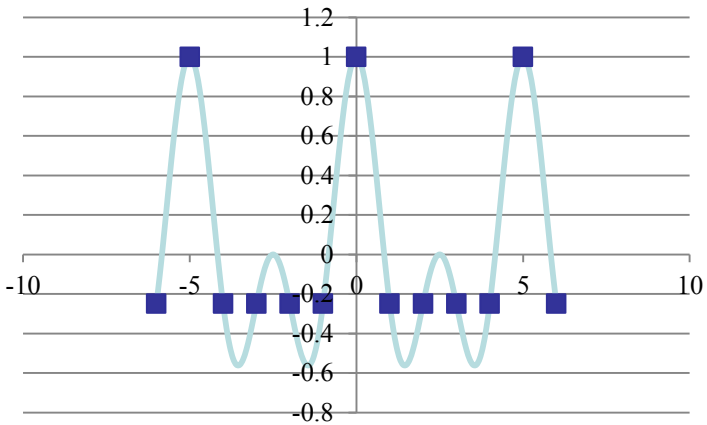
Fast Bunch Replacement in a Circulator Cooler

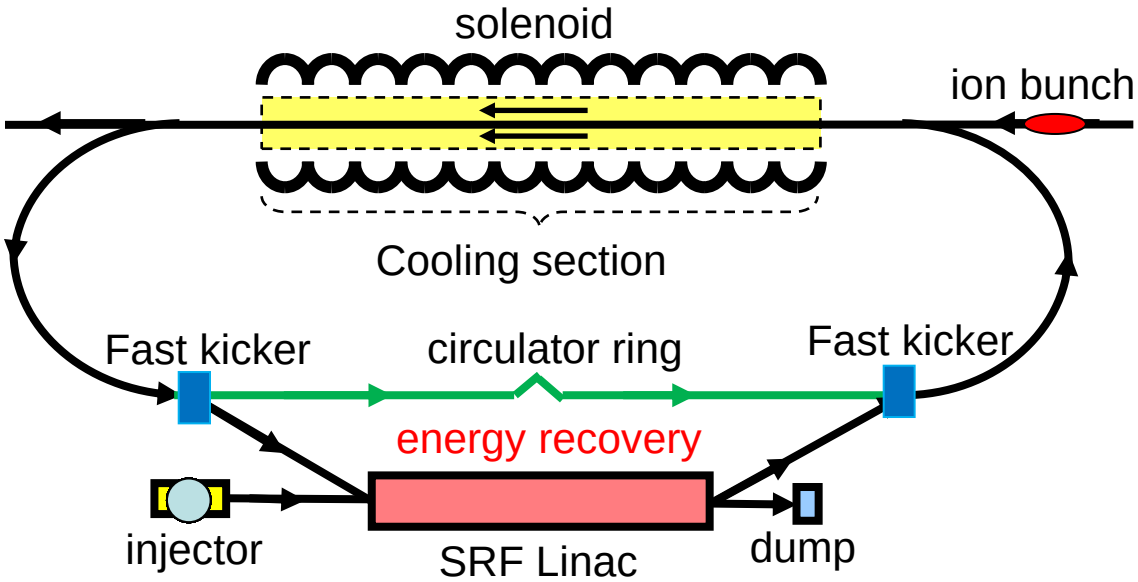
- Needs faster kicker technology
- Enabling large number turns in the circulator ring



A Circulator Cooler with RF Resonant

- 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 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

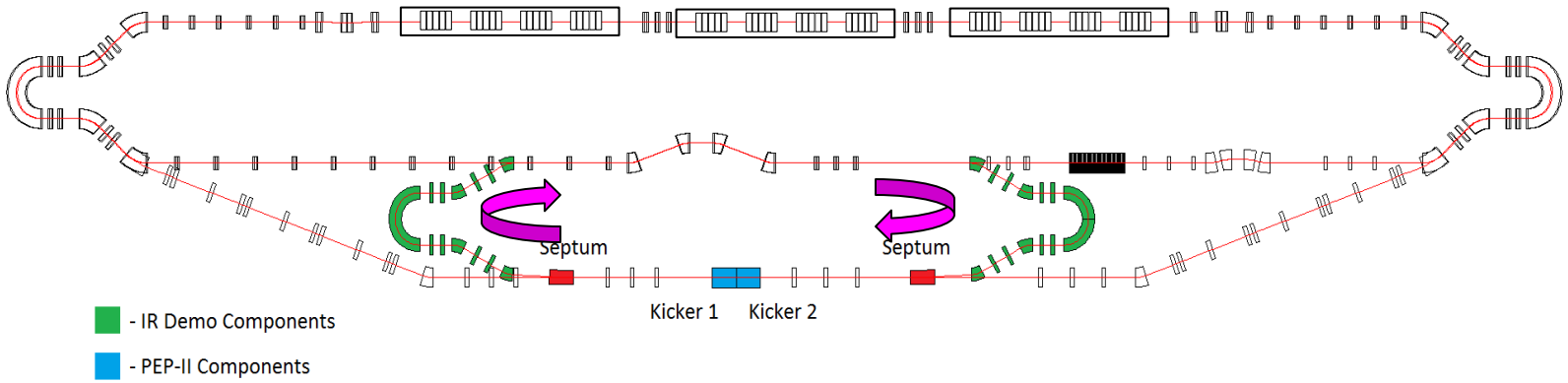
		FEL ERL	ERL-CR
Energy	MeV	80-210	10-54
Bunch charge	nC	0.135	2
Turns in CR			10-100
Bunch frequency	MHz	75	75-7.5
Gun current	mA	10	150–15
Trans. emit., norm.	μm	10	1-3
Long. emittance	keV-ps	25-75	150
Energy spread	%	0.4	0.01
RMS bunch length	ps	2	100

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

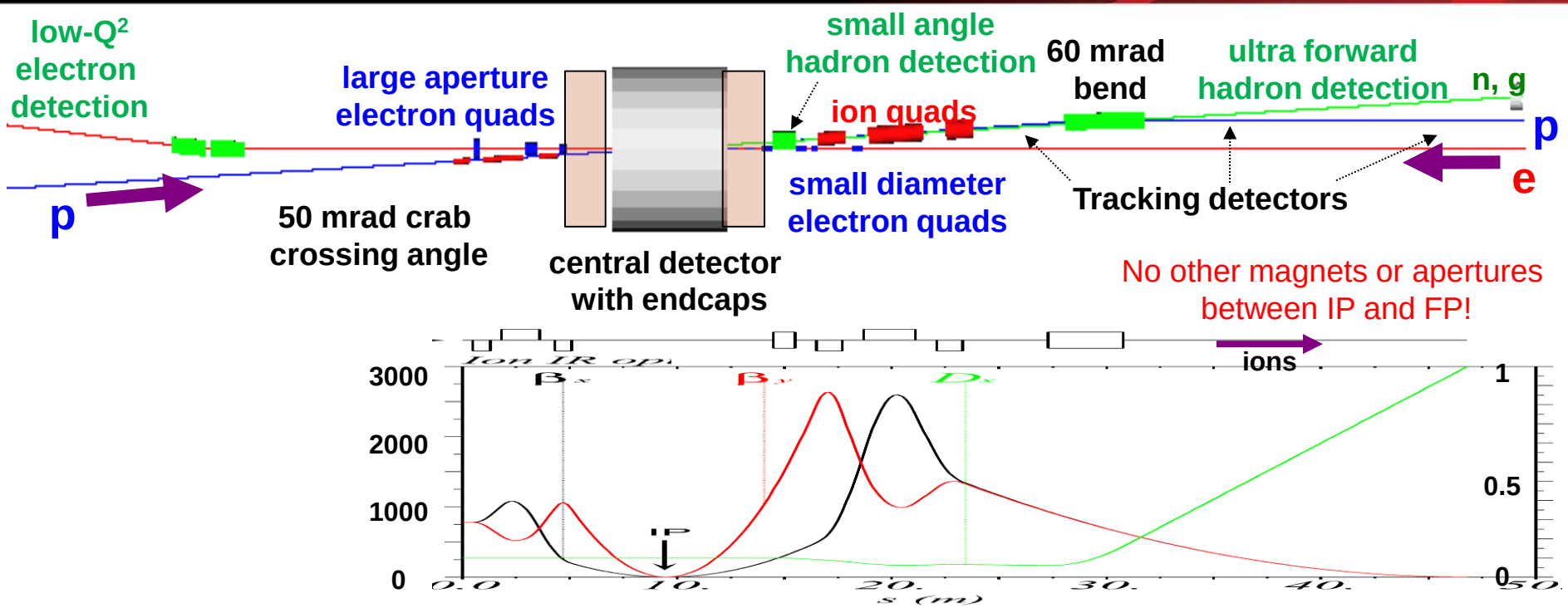
JLab MEIC Detector-IR Workshops

- **MEIC Detector & Interaction Region Design Mini-Workshop** (Oct. 31, 2011)
  http://casa.jlab.org/meic/workshops/detector_2011/detector_ir_workshop_2011.shtml

- **The 2nd MEIC Detector & Interaction Region Design Mini-Workshop** (Nov. 2, 2012)
  http://casa.jlab.org/meic/workshops/detector2012/detector_ir_workshop2012.shtml

1:00 PM -- 1:15 PM	Opening Remark and Workshop Charge	Rolf Ent
1:15 PM -- 1:40 PM	MEIC Detector Design	Pawel Nadel-Turonski
1:40 PM -- 2:05 PM	MEIC Interaction Region Design & Detector Integration	Vasiliy Morozov
2:05 PM -- 2:30 PM	MEIC Optics and Nonlinear Beam Dynamics	Fanglei Lin
2:30 PM -- 2:55 PM	Synchrotron Radiation and Detector Backgrounds	Michael Sullivan
2:55 PM -- 3:15 PM	Coffee Break	
3:15 PM -- 3.45 PM	Discussion Session I: MEIC Primary Detector	
3:45 PM -- 4:15 PM	Discussion Session II: MEIC Secondary Detector	
4:15 PM -- 4:25 PM	LEIC Luminosity	Yuhong Zhang
4:25 PM -- 4:55 PM	Discussion Session III: LEIC	
4:55 PM -- 5:00 PM	Workshop Summary	Andrew Hutton

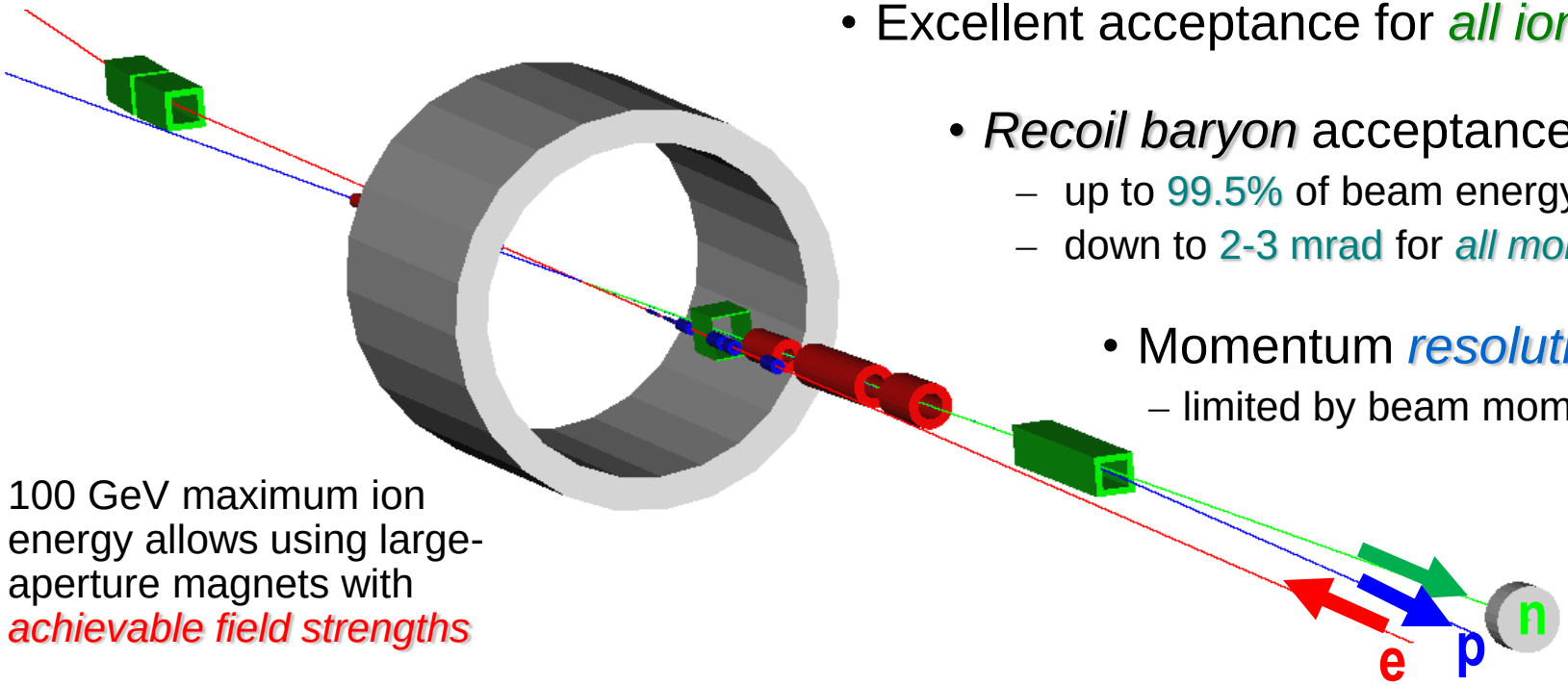
Interaction Region w/ Integration of Detector



- ***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

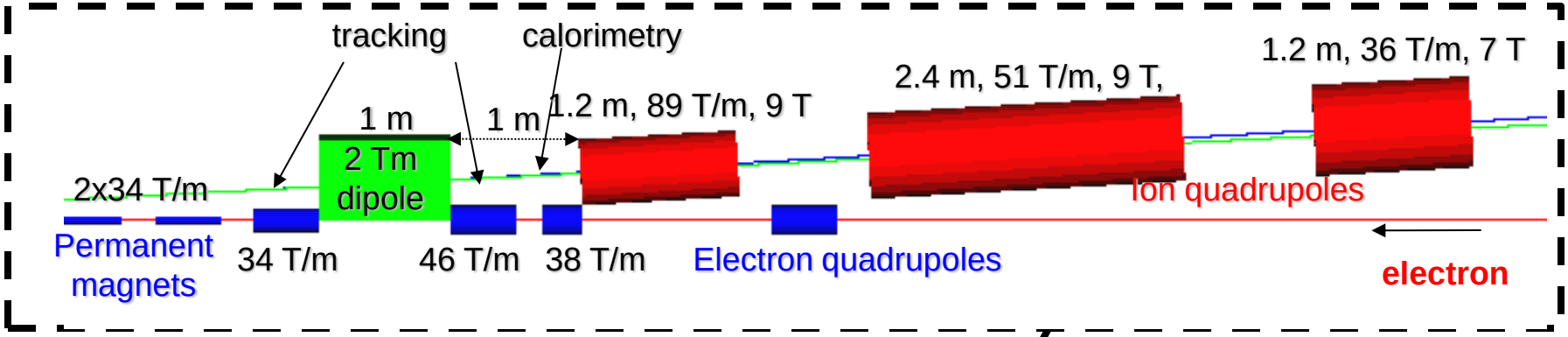
A 3D View of Detector & Small-angle Ion Detection

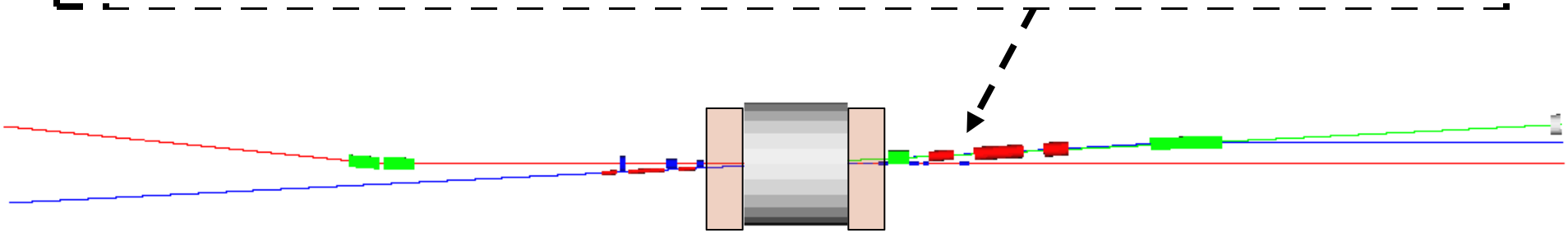
- *Neutron* detection in a 25 mrad cone *down to zero degrees*
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to 2-3 mrad for *all momenta*
- Momentum *resolution* $< 3\times10^{-4}$
  - limited by beam momentum spread



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

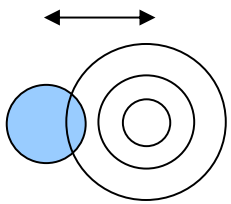
(Small Angle) Hadron Detection Prior to Ion FFQs



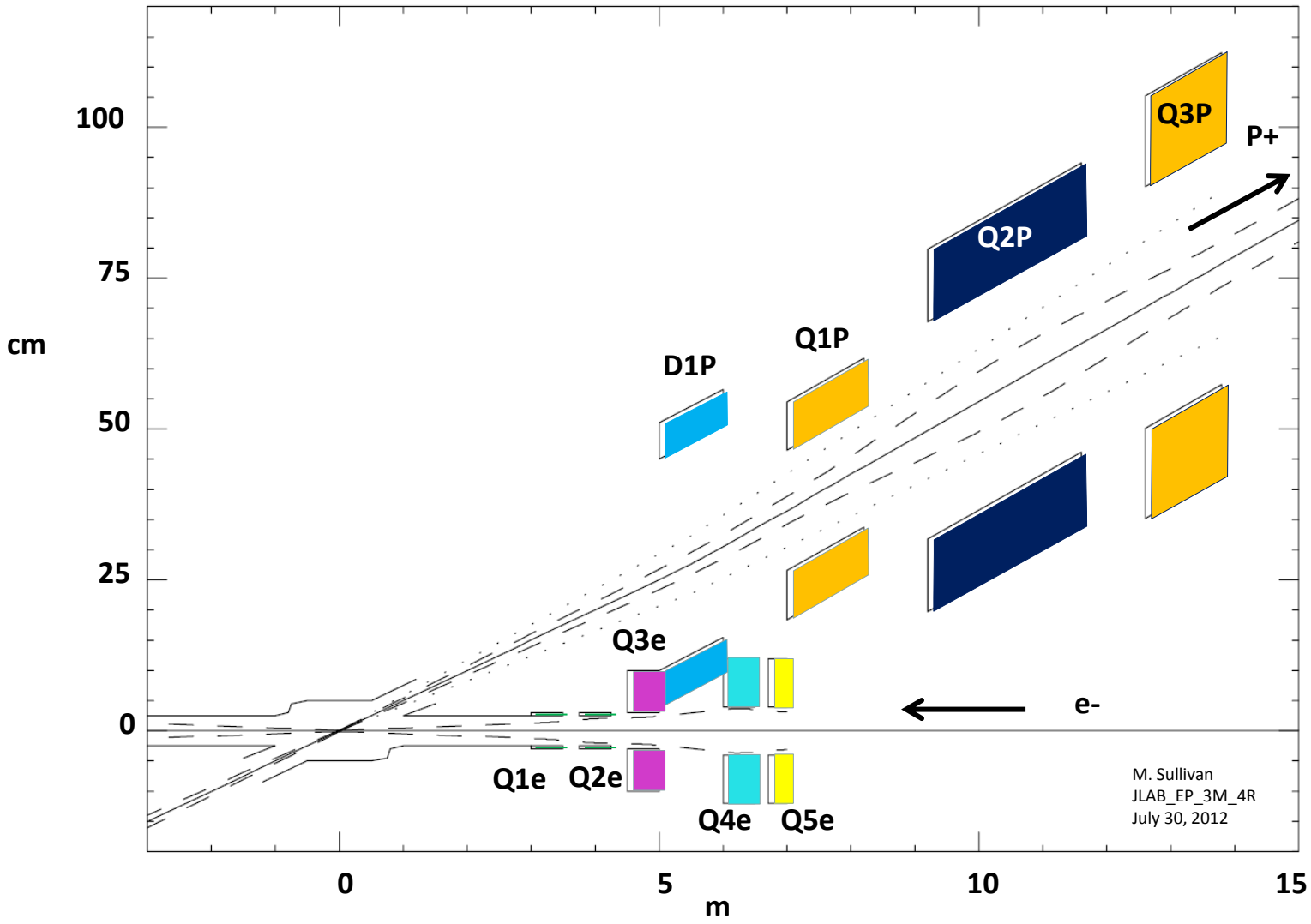


- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Large-acceptance dipole further improves resolution in the few-degree range

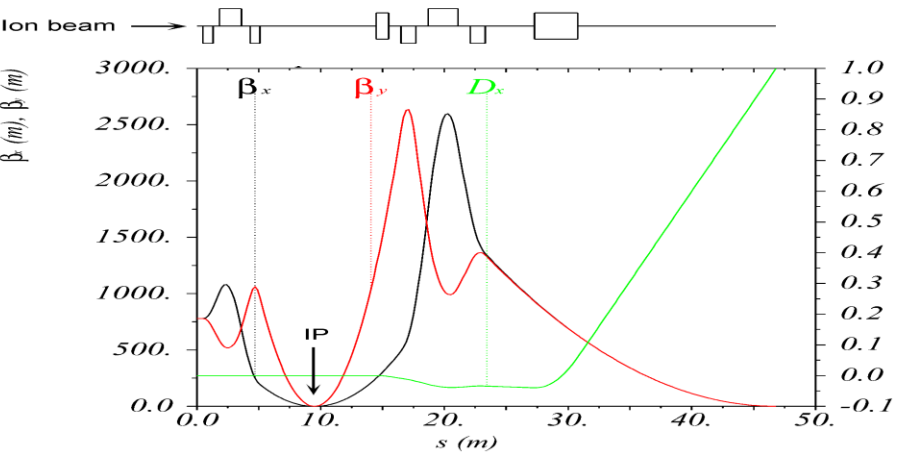
Crossing angle

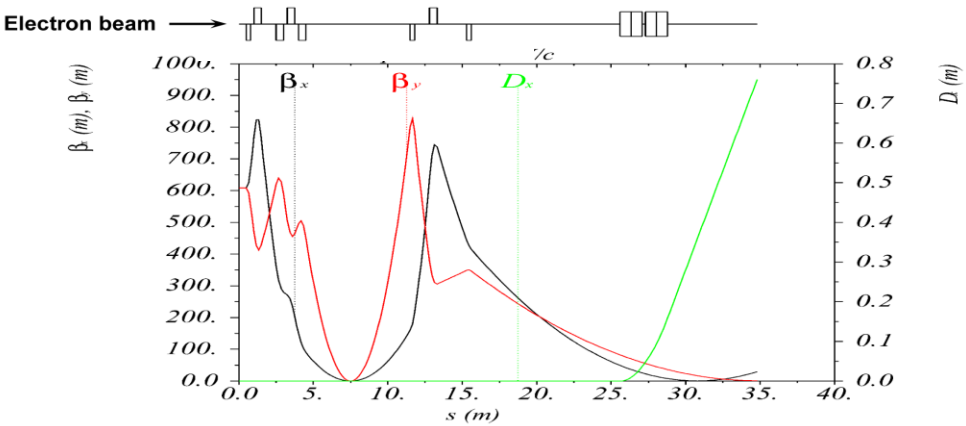


Another View of MEIC Interaction Region



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

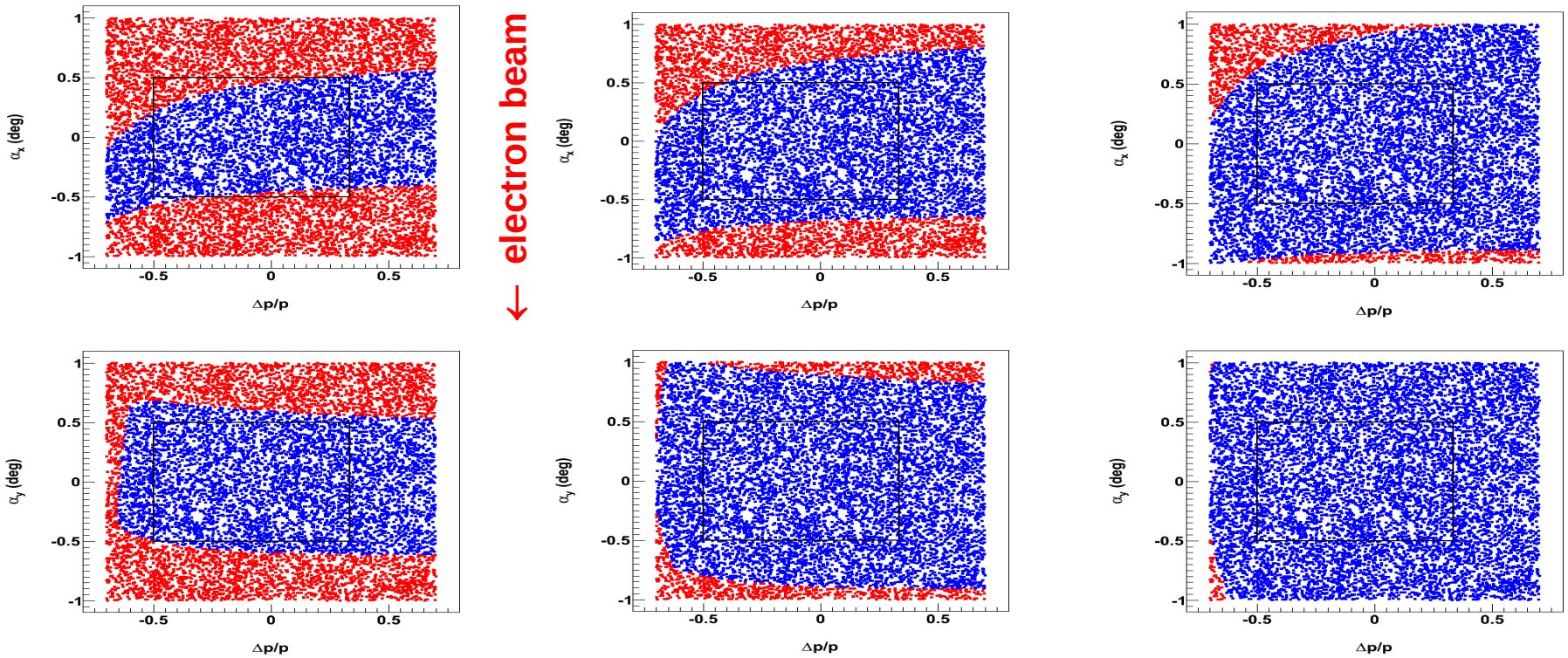
- Similar optics to ion beam
- two permanent magnetic quadrupoles are used in the upstream FFB and vey close to the IP to maximize the ion detector acceptance by reducing the solid angle blocked by the final focusing quadrupoles.
- Changing of their focusing strengths with energy can be compensated by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

Proton Acceptance at Downstream Ion FFB

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

G4Beamline/GEANT4 Model

6 T max | **9 T max** | **12 T max**

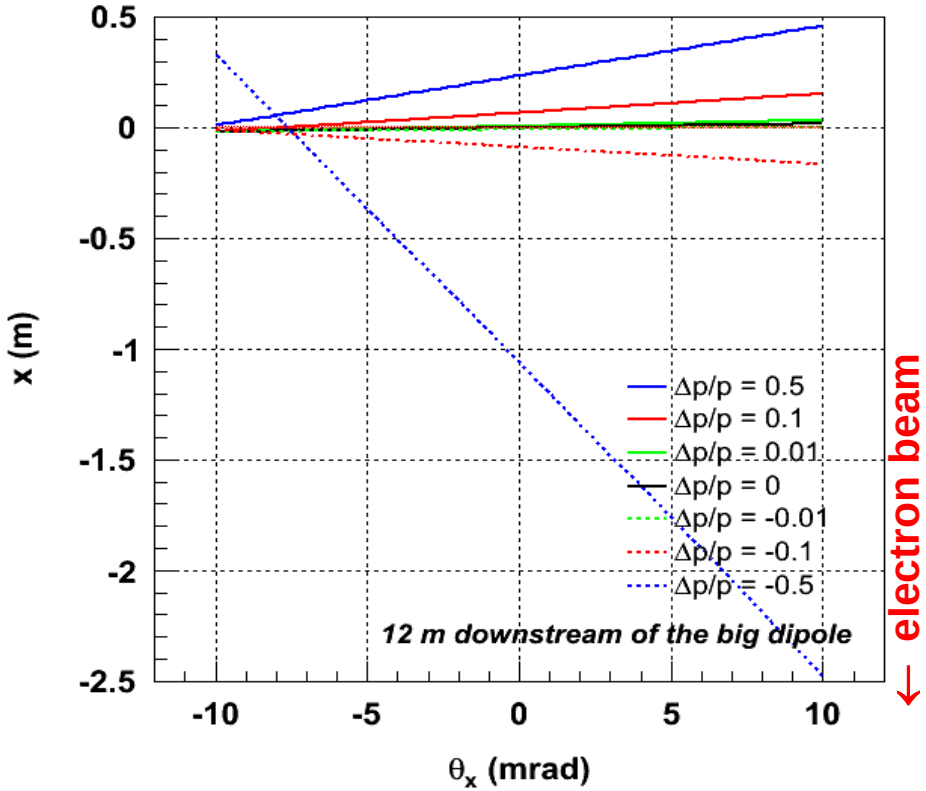


Red: Detection between the 2 Tm upstream dipole and ion quadrupoles
Blue: Detection after the 20 Tm downstream dipole

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

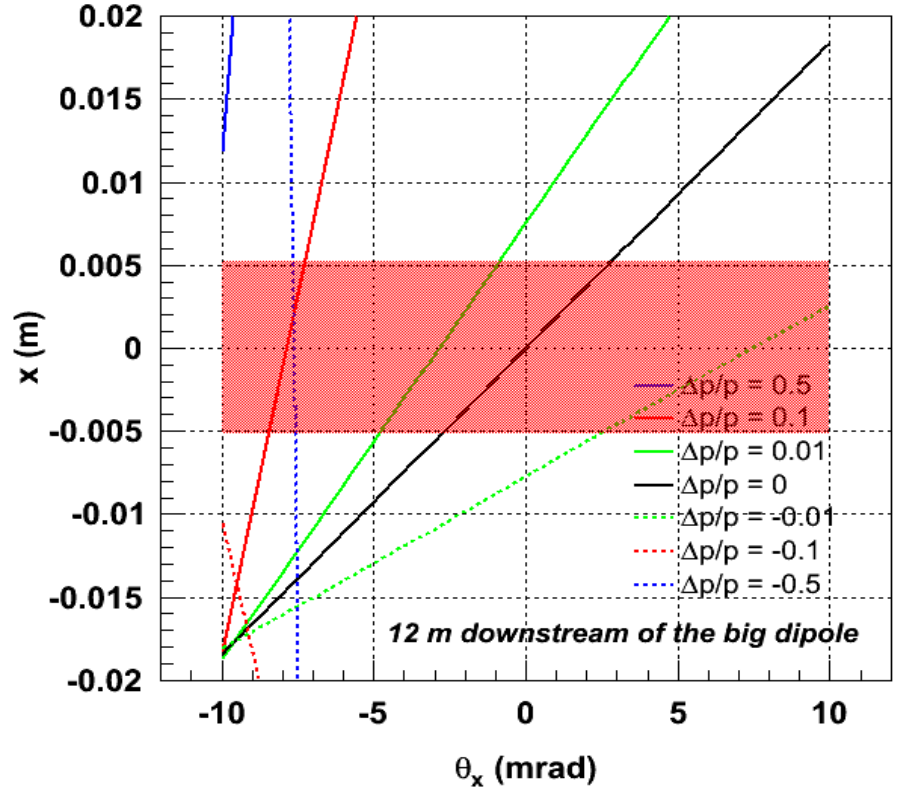
Forward Ion Momentum & Angle Resolution at Focal Point

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



← electron beam

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



Nonlinear Beam Dynamics

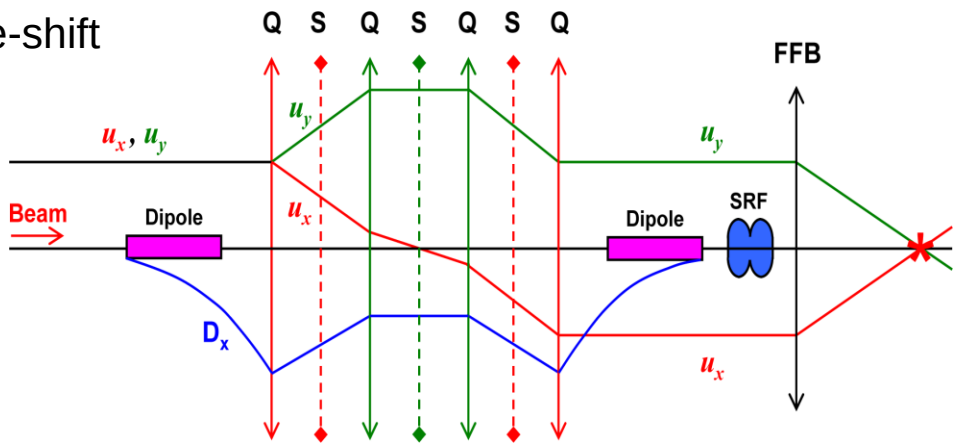
Chromaticity is an issue in MEIC design, particularly due to the low-β insertions

- Chromatic turn spread
- Chromatic beta-smear at IP

	Ion ring (ξ_x/ξ_y)	Electron ring (ξ_x/ξ_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

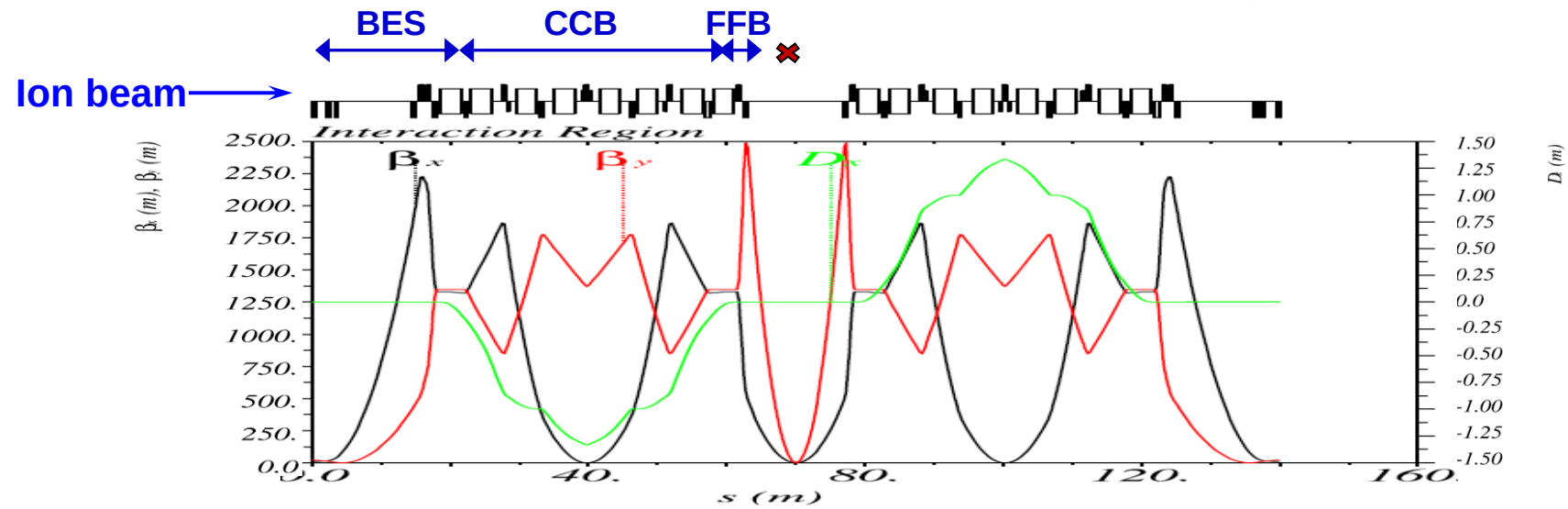
MEIC chromaticity compensation scheme

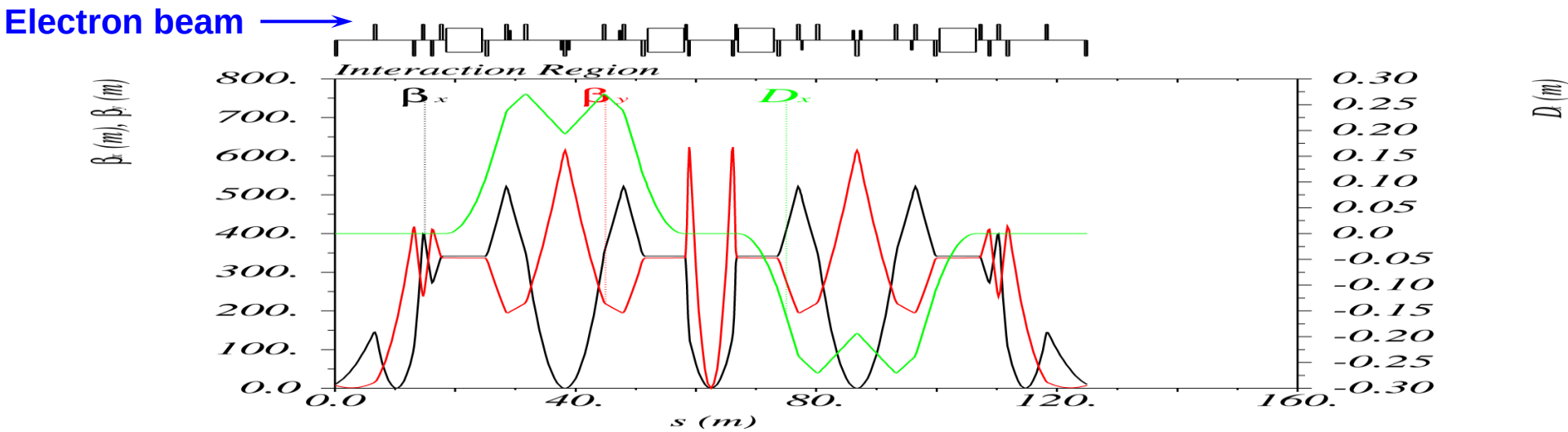
- Local compensation scheme: dedicated chromaticity compensation blocks (CCB) near an IP
- Using families of sextupoles and octupoles
- simultaneous compensation of chromatic tune-shift and beam smear at IP
- Symmetric CCB (with respect to its center)
  - u_x is anti-symmetric, u_y is symmetric
  - D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



MEIC design report Section 7.4

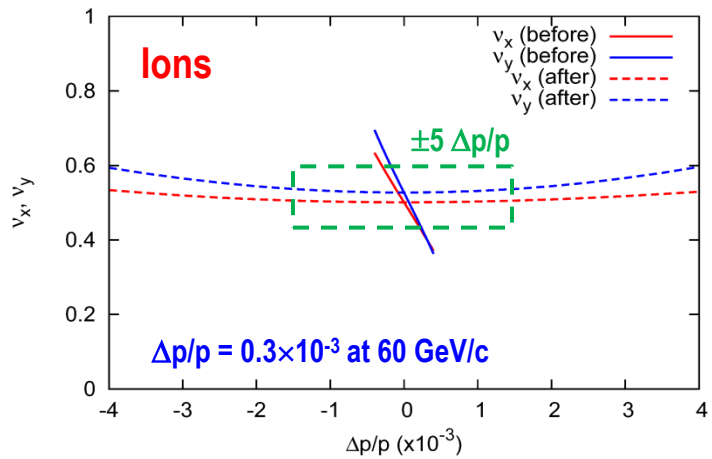
IR Optics Optimized for Chromaticity Compensation

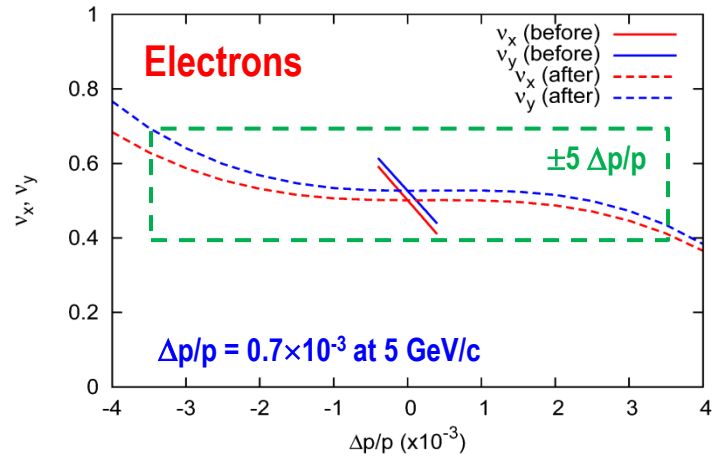


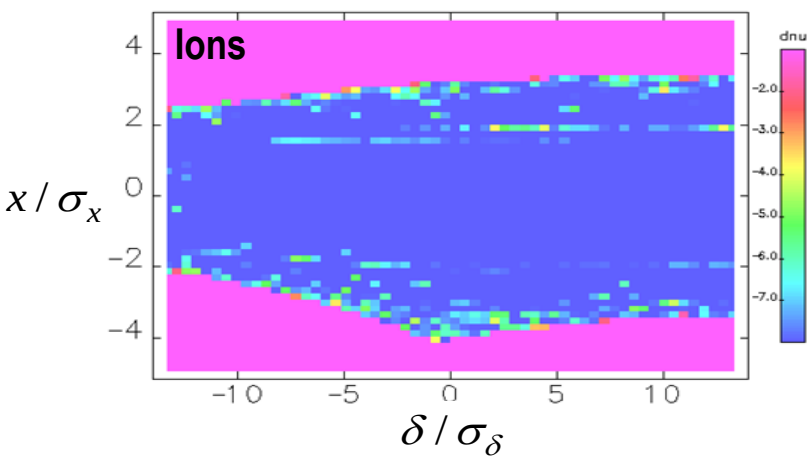


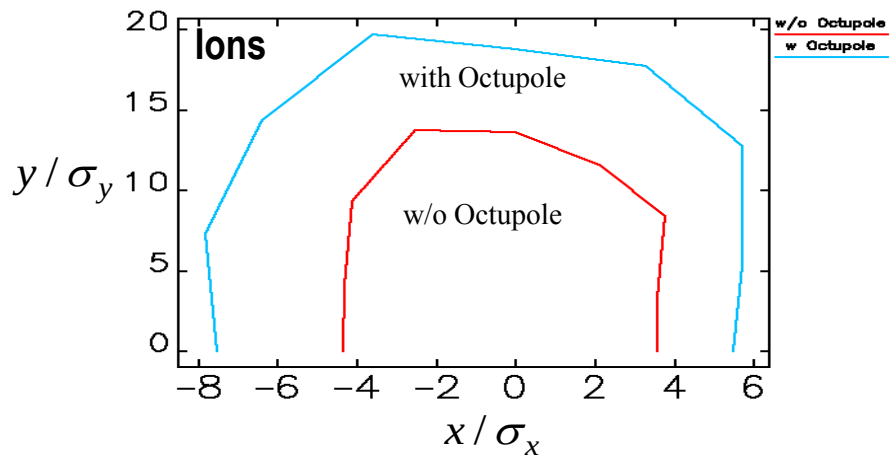
Momentum Acceptance & Dynamic Aperture

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



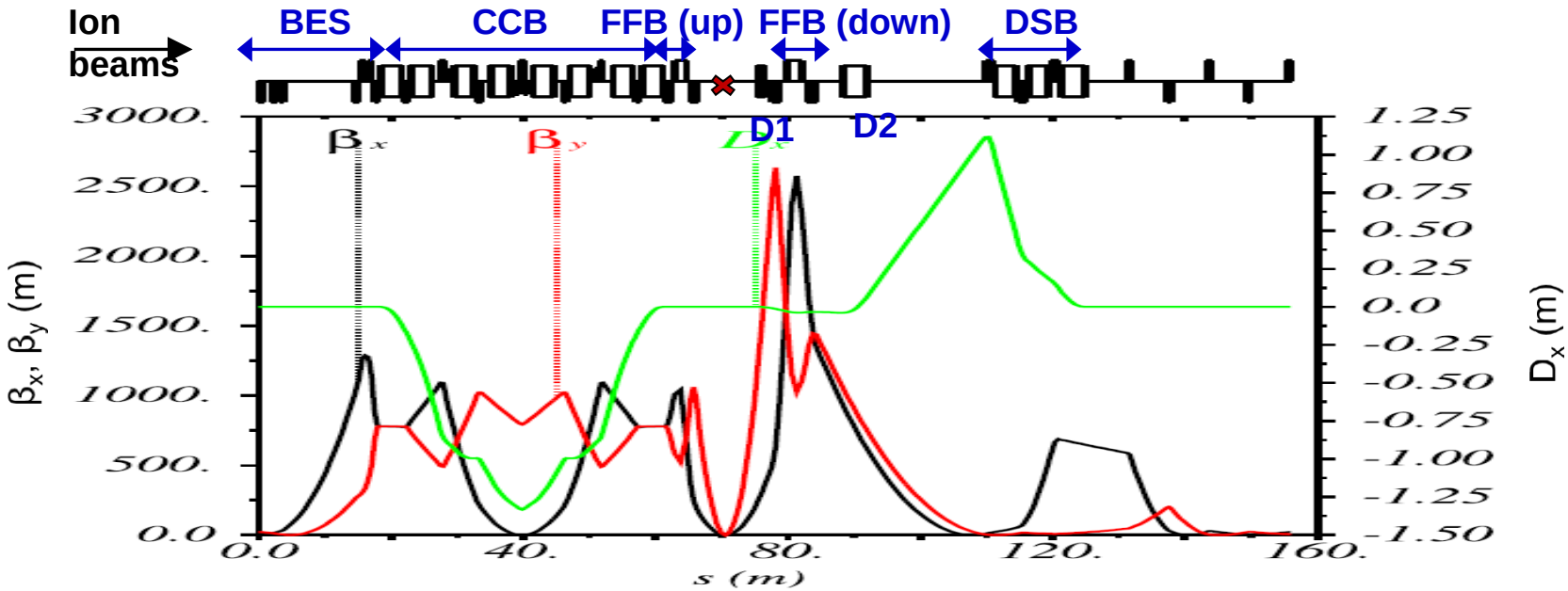




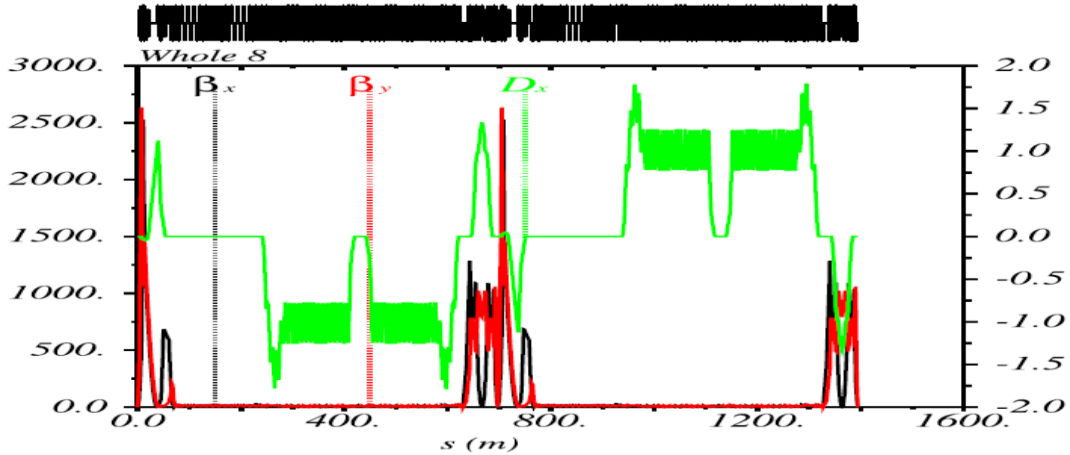


F. Lin's talk at the 2nd Detector/IR Mini-workshop
F, Lin, *et al*, IPAC2012 paper

Ion Interaction Region Optics Optimized for Both Detector and Chromaticity Compensation

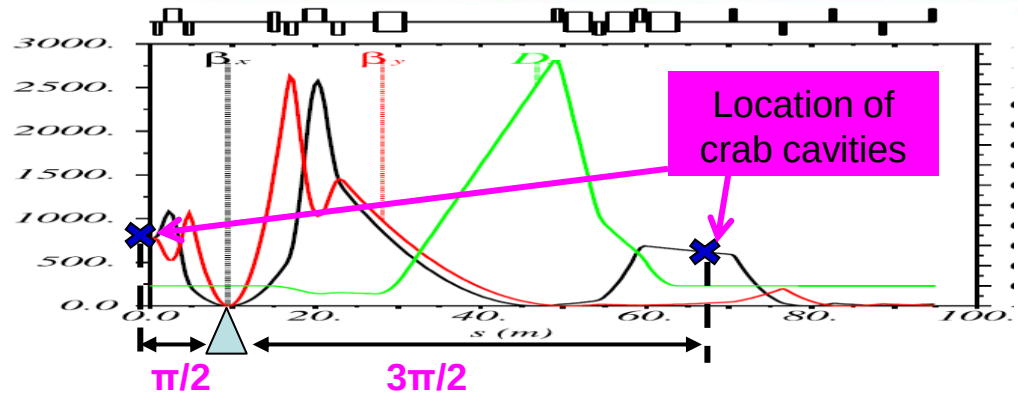


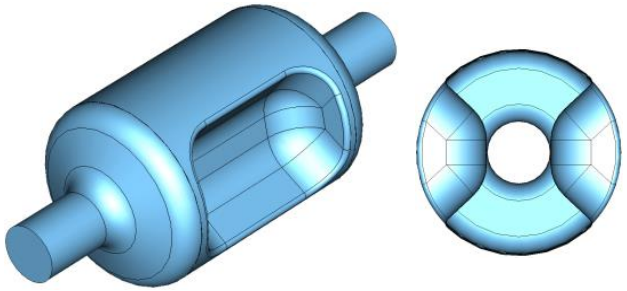
- BES: Beam Extension Section
- FFB: Final Focusing Block
- D1,D2: Spectrometer Dipoles
- DSB: Dispersion Suppression Block
- Two sextupole families are inserted symmetrically in the CCB for the chromaticity compensation



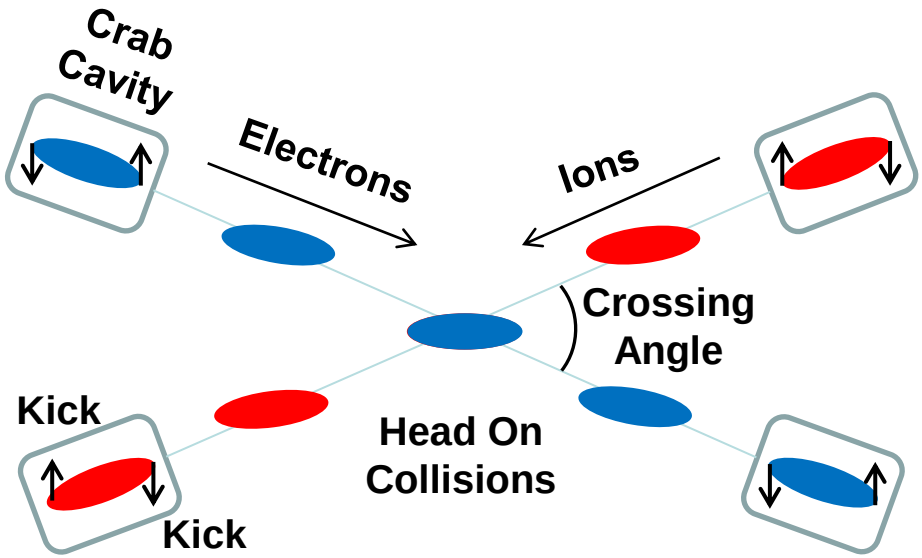
Crab Crossing Scheme

- 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 β_x at location of crab cavities for minimizing the required kicking voltage.

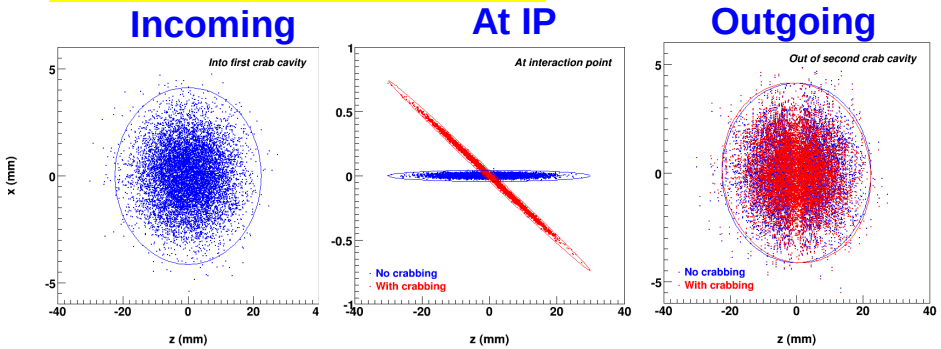




SRF crab cavity@ ODU



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%)

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**

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

MEIC design report section 5.9

Suppressing Synchrotron Radiation at IR

MEIC Design optimized for suppressing synchrotron radiation at IR

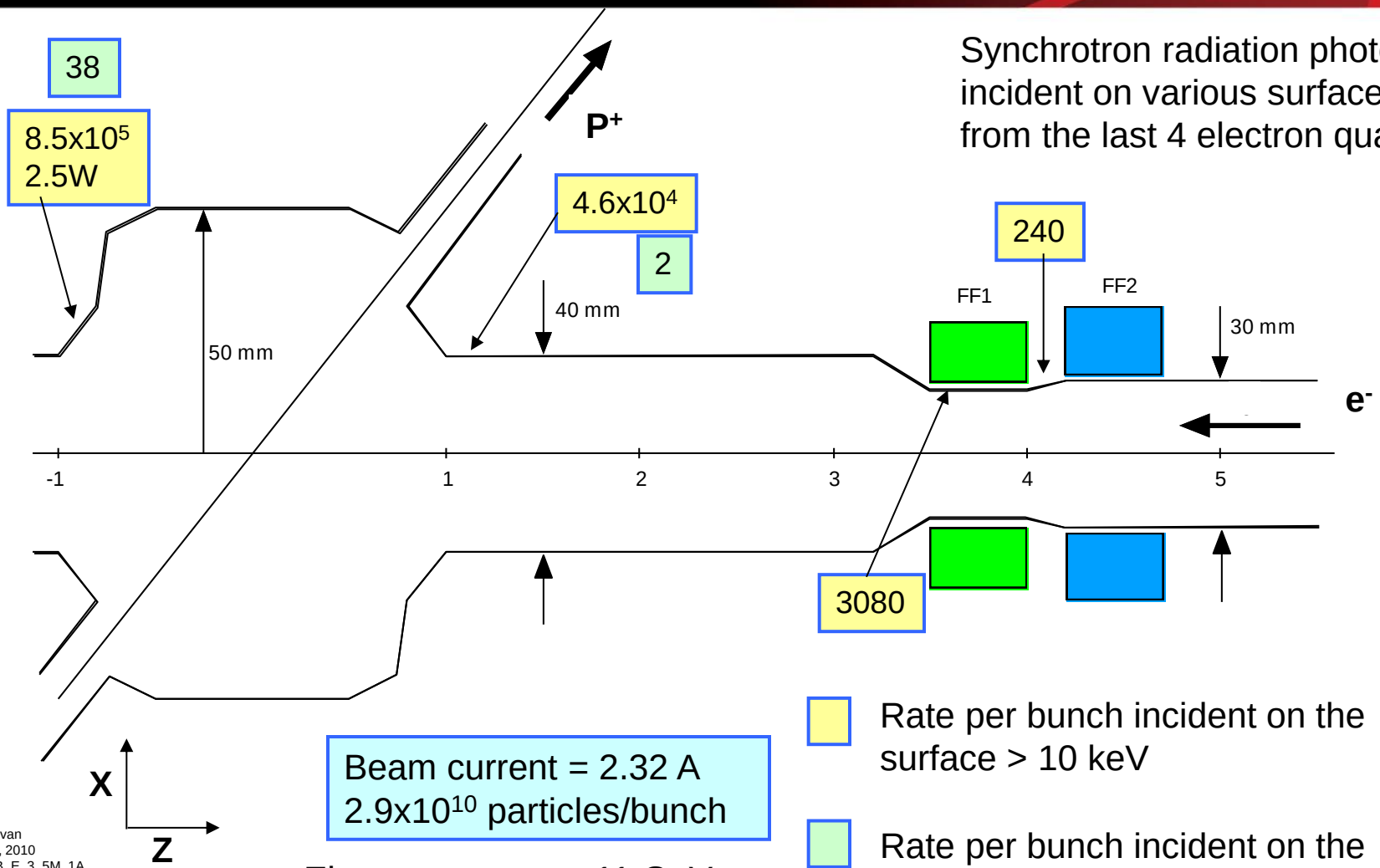
- Flat electron ring ➔ ions travels to the plane of the electron ring for horizontal crab crossing at collision points
- Detector solenoid is along the electron beamline
- Gentle bending of electrons at end of each arcs
- Minimizing bending of electrons in long straights of figure-8
- Keep bending angles 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
2.9×10^{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)

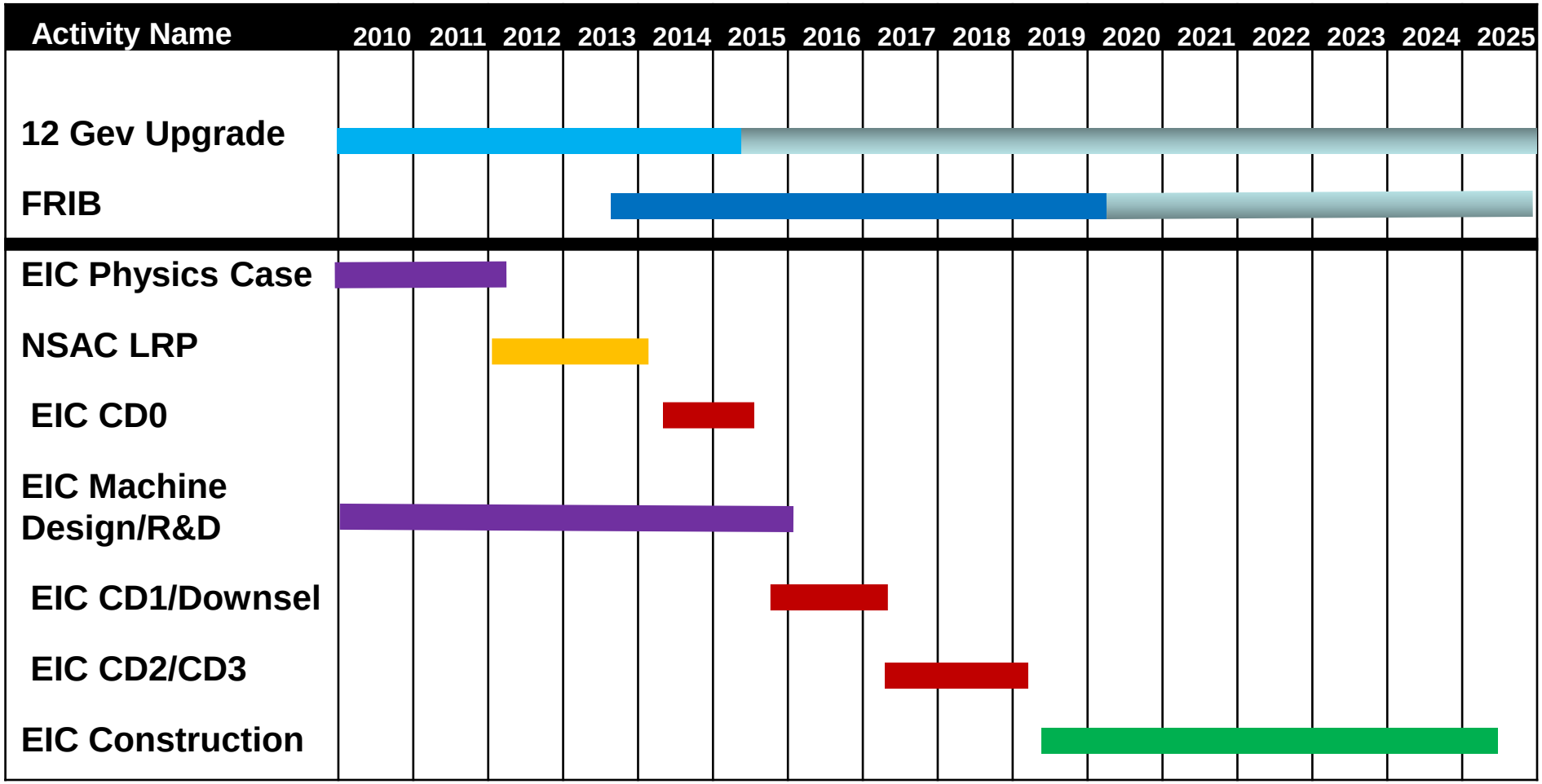
Highlights on Recent EIC Activities

- 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

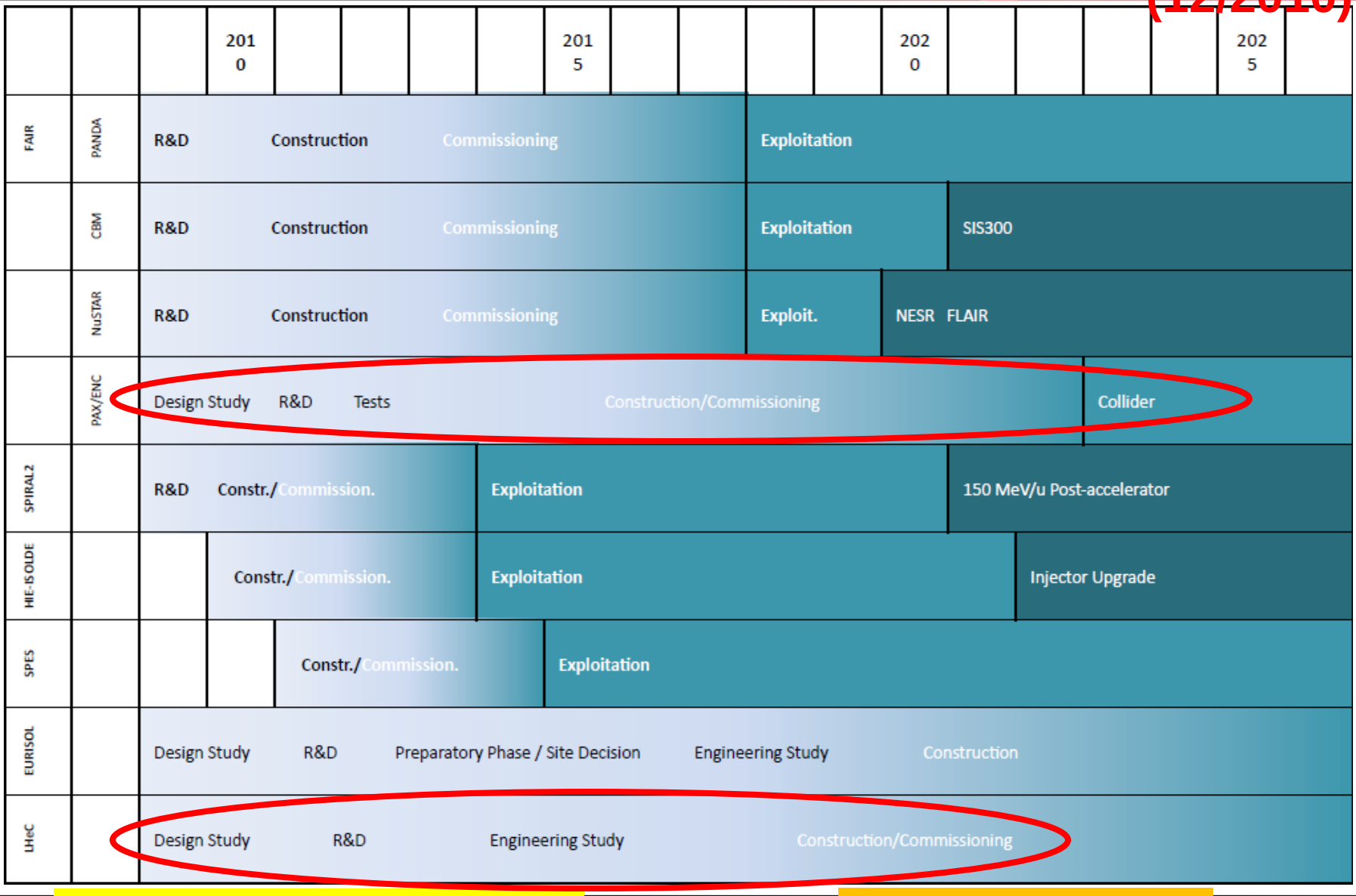


Note: 12 GeV LRP recommendation in 2002 – CD3 in 2008

(Mont@INT)

NuPECC Roadmap: New Large-Scale Facilities

(12/2010)



G. Rosner, NuPECC Chair, Madrid 5/10

K. Aulenbacher @ SPIN 2010

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 MEIC design is optimized for suppressing synchrotron radiation in the interaction regions and at the detectors.
- The focus of the MEIC team is not 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 are also engaged in design studies for also a low energy EIC.
- We seek international collaborations for EIC.

Acknowledgement

- **JLab MEIC team**
  Ya. Derbenev, R. Li, F. Lin, V. Morozov, E. Nissen, B. Yunn, H. Zhang
- **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.)
- **Electron cooling**
  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.)
- **Polarization** A. Kondratenko (NTL Zaryad, Novosibirsk), D. Barber (DESY)
- **Beam-beam simulation** J. Qiang (LBL)
- **Feedback** Y. Kim (Idaho State Univ.)

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!