Conceptual Design of A Medium Energy Polarized Electron-Ion Collider at JLab

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for

Jefferson Lab EIC Study Group

Physics with Secondary Hadron Beams in the 21st Century

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Electron-Ion Collider (EIC) at JLab

- Over the decade, JLab has been developing a conceptual design of an EIC as its future science program beyond 12 GeV CEBAF upgrade
- The future science program, as NSAC LRP articulates, drives the EIC design, focusing on:
  - High luminosity (above 10^{33} $cm^{-2}s^{-1}$) per detector over multiple detectors
  - High polarization (>80%) for electrons and (>70%) for light ions
- Presently, we focus on a ***M***edium-energy ***E***lectron-***I***on ***C***ollider (MEIC) as an immediate goal, as the best compromise between science, technology and project cost
- We maintained a well defined path for future upgrade to higher energies and high luminosity
- The JLab EIC machine design is based on
  - CEBAF as full-energy electron injector
  - A new ion complex and collider rings optimized for polarization

MEIC Design

- **Energy**
  - Full coverage in *s* from a few hundred to a few thousand

    Bridging the gap of 12 GeV CEBAF and HERA/LHeC
  - Electron 3 to 11 GeV, proton 20 to 100 GeV, ion 12 to 40 GeV/u
  - Design point: **60 GeV proton on 5 GeV electron**

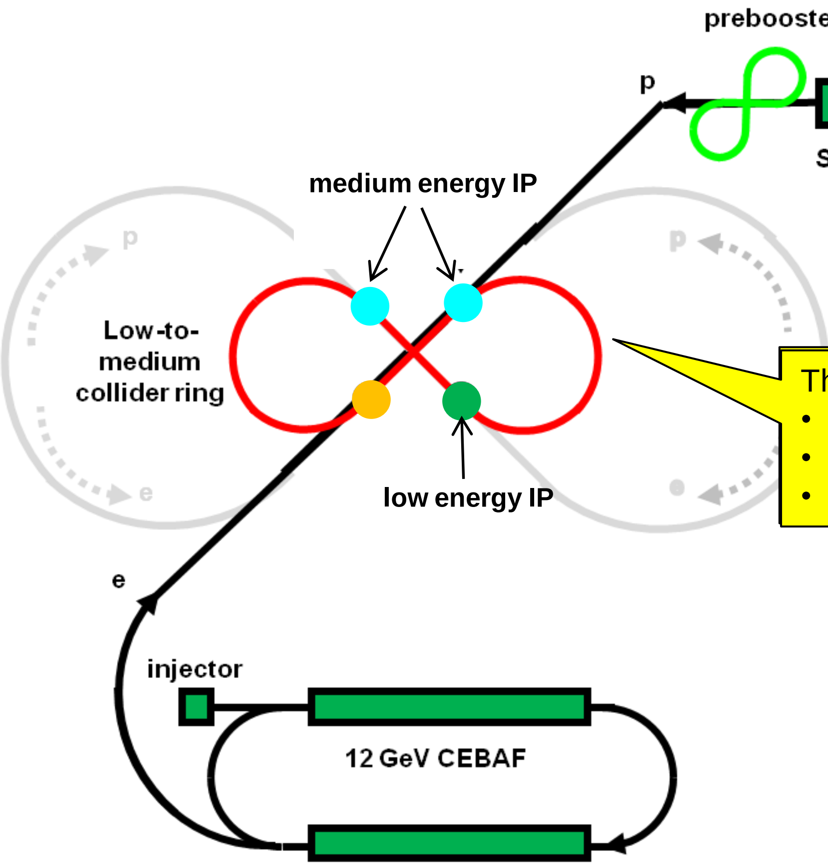
- **Ion species**
  - Polarized light ion: p, d, ^{3}He and possibly Li
  - Un-polarized ions up to A=200 or so (Au, Pb)

- **Detectors**
  - Up to three interaction points, two for medium energy (20 to 100 GeV)
  - One ***full-acceptance*** detector (primary), ***7 m*** between IP & 1st final focusing quad, our initial priority with a more challenging design
  - One ***high luminosity*** detector (secondary), ***4.5 m*** between IP and 1st final focusing quad

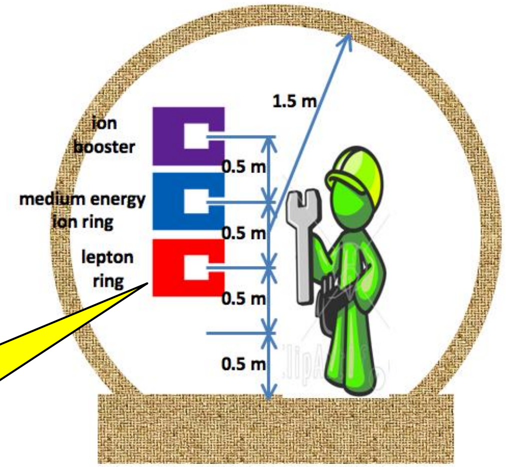
MEIC Design (cont.)

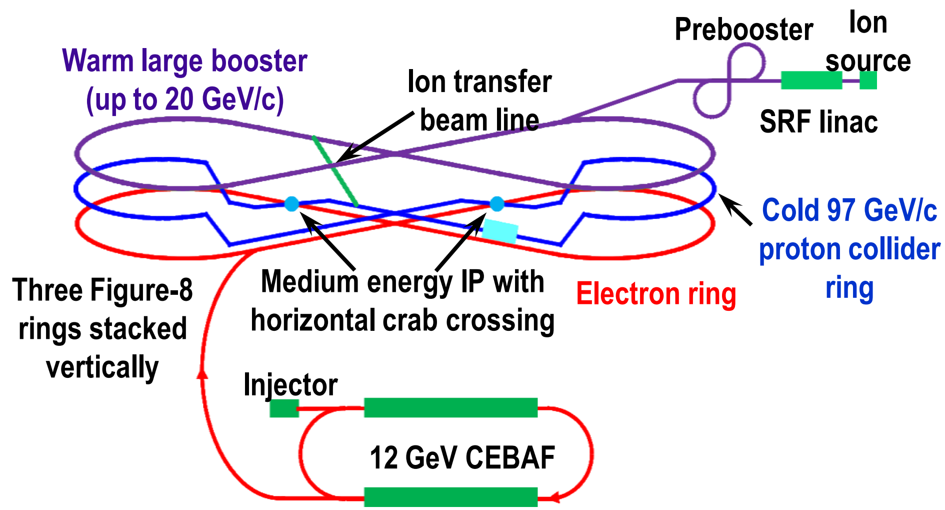
- **Luminosity**
  - About 10^{34} cm^{-2} s^{-1} (e-nucleon) optimized at s=2000 GeV^2
  - Greater than 10^{33} cm^{-2} s^{-1} for s=500-2500 GeV^2
- **Polarization**
  - Longitudinal at the IP for both beams
  - Transverse at IP for ions only
  - All polarizations >70% desirable
  - Spin-flip of both beams (at least 0.1 Hz) being developed
- **Upgradeable to higher energies and luminosity**
  - 20 GeV electron, 250 GeV proton and 100 GeV/u ion,
  - facility fits the JLab site
- **Positron beam highly *desirable***
  - Positron-ion collisions with similar luminosity

MEIC Layout

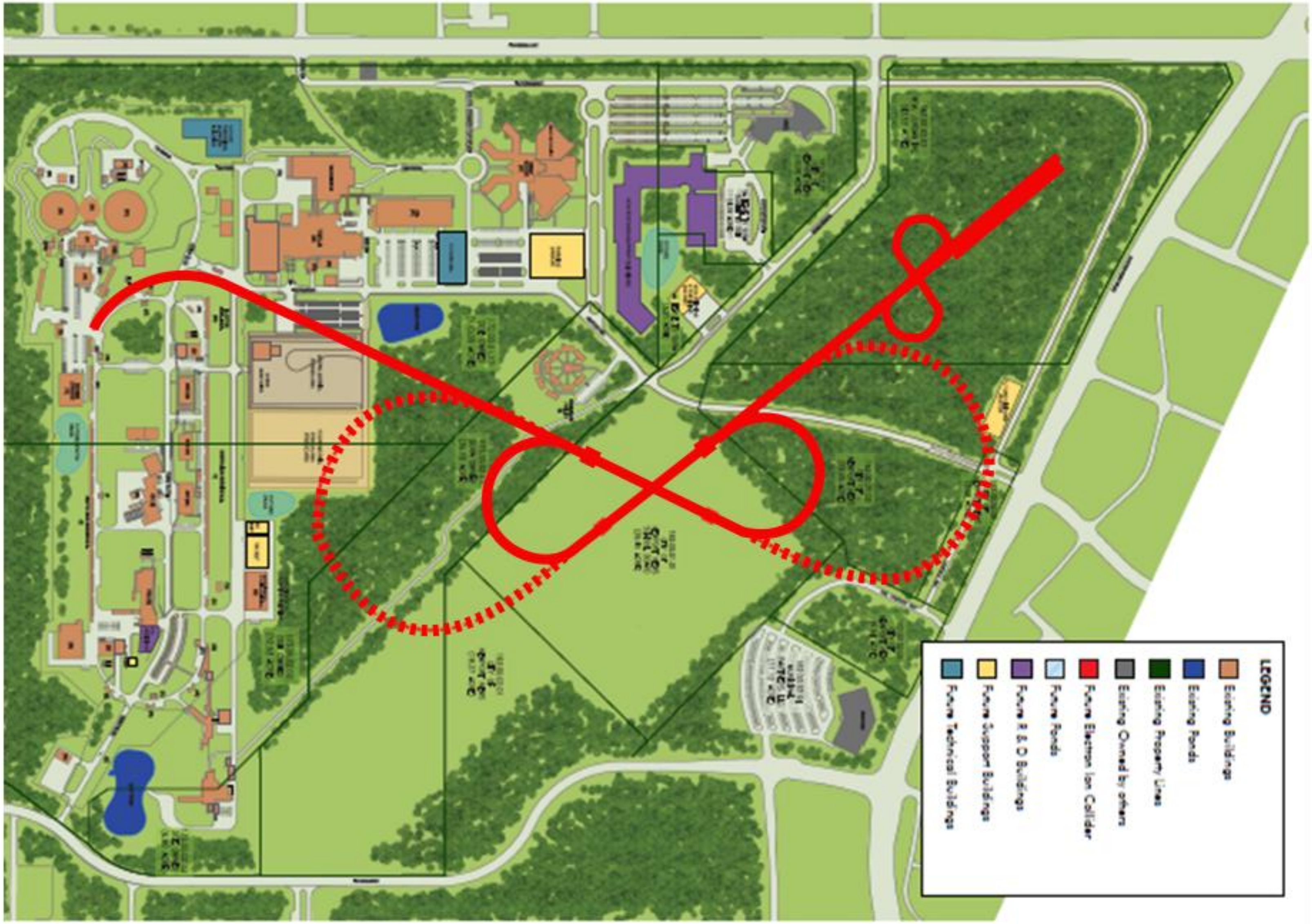


Three compact rings:
- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)





MEIC and Upgrade on JLab Site Map



Luminosity Concept: High Bunch Repetition Rate

Luminosity of KEKB and PEP II follow from

- Very small β* (~6 mm)
- Very short bunch length (σ_z~ β*)
- Very small bunch charge (5.3 nC)
- High bunch repetition rate (509 MHz)

➔ **KEK-B already over 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 (so can match e-beam)**
- **Electron cooling to allow short ion bunches**

		KEK B	MEIC
Repetition rate	MHz	509	750
Particles per bunch	10^{10}	3.3 / 1.4	**0.42 / 2.5**
Beam current	A	1.2 / 1.8	0.5 / 3
Bunch length	cm	0.6	**1** / 0.75
Horizontal & vertical β*	cm	56/0.56	**10 / 2**
Luminosity per IP, 10^{33}	cm^{-2}s^{-1}	20	5.6 ~ 14

Parameters for *Full Acceptance* Interaction Point

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

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

The Current Design Status

The electron complex

- **CEBAF as a full energy injector**
  - Already exist! Possible top-off mode
- **Electron collider ring**
  - Linear optics design: ***done!***

The ion Complex

- **Ion sources**
  - Identified ABPIS for polarized H^-/D^-, light ions
  - Identified ECR/EBIS for heavy ions
- **Linac**
  - Technical design: ***done!***
  - Design of component (RFQ, cavity, etc): ***done!***
- **Pre-booster**
  - Linear optics design: ***done!***
  - Injection, accumulation, acceleration: ***done!***
  - Conventional DC electron cooling **exist!**
- **Large booster**
  - Ring optics design: ***done!***
- **Ion collider ring**
  - **Llinear optics design: *done!***

Interaction region

- **Electron IR**
  - Optics design & chromatic correction: ***done!***
  - Tracking & dynamic aperture: ***in progress***
- **Ion IR**
  - Optics design & chromatic correction: ***done!***
  - Tracking & dynamic aperture: ***in progress!***
- **Crab cavity: *Has a design!***
- **SR and detector background: *checked!***

• Beam polarization

- **Electron polarization design: *done!***
- **Proton/deuteron polarization design: *done!***
- **Spin matching & tracking: *in progress!***

• Electron cooling in collider ring

- **Staged electron cooling concept: *done!***
- **ERL-circulator e-cooler concept: *done!***
- **Fast kicker development: *has a concept***

• Beam synchronization: *done!*

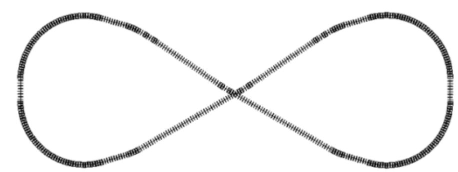
MEIC Design Details

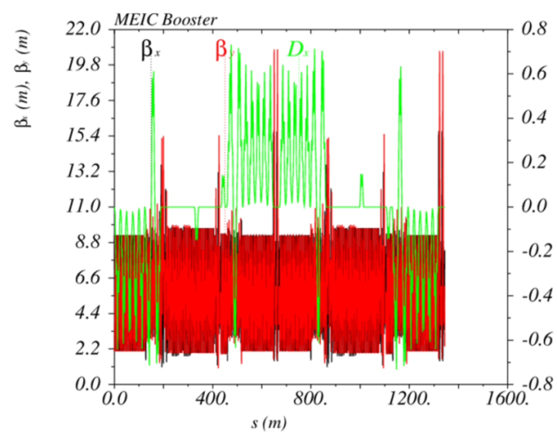
Our present design is *mature*, having addressed -- in various degrees of detail -- the following important aspects of MEIC:

- Forming the high-intensity ion beam: SRF linac, pre and large booster
- Electron and ion ring optics
- Detector design
- IR design and optics
- Chromaticity compensation
- Crab crossing
- Synchrotron rad. background
- Ion polarization
- Electron polarization
- Electron cooling
- Beam synchronization
- Beam-beam simulations

Large Booster

- Takes ions from 3 GeV to 20 GeV proton equivalent energy.
- Designed to fit in the tunnel along with the collider rings.



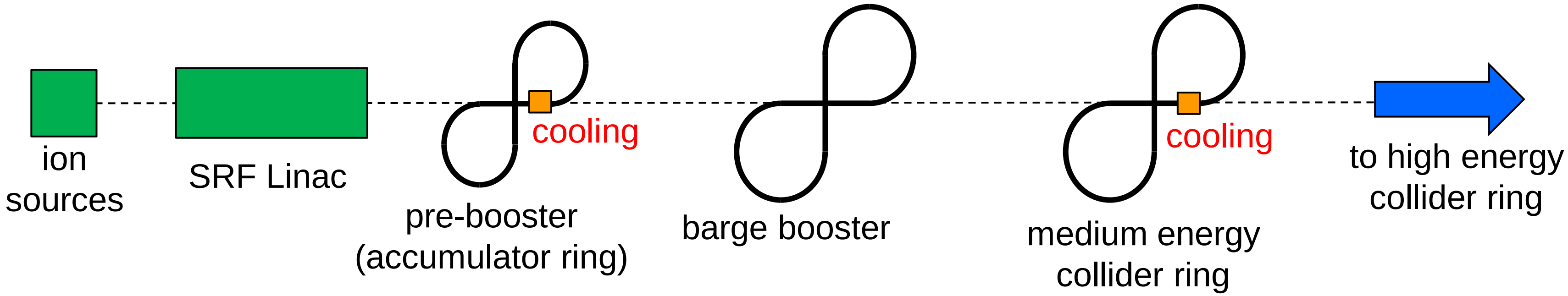


- Uses warm magnets and RF.
- γ_{tr}=25.03 to avoid transition crossings.
- Quadrupole based dispersion suppression.
- Tuneable to any working point.

A New Ion Complex

MEIC ion complex design goal

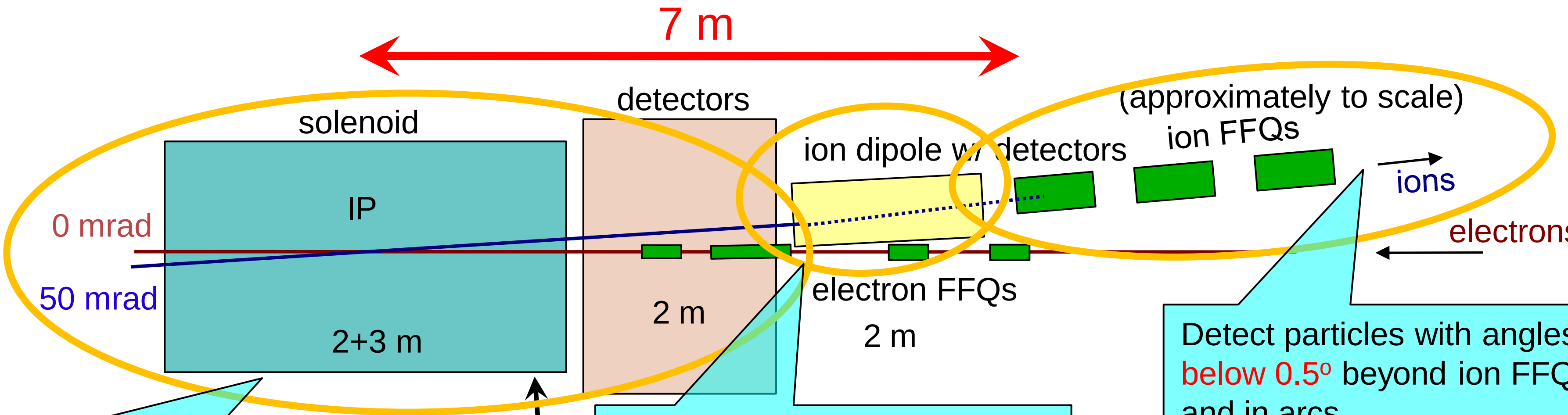
- Be able to generate/accumulate and accelerate ion beams for collisions
- Covering all required varieties of ion species
- Matching the time, spatial and phase space structure of the electron beam (bunch length, transverse emittance and repetition



	Length (m)	Max. energy (GeV/c)	e-Cooling	Process
SRF linac		0.2 (0.08)		
Pre-booster	~300	3 (1.2)	DC	accumulating
booster	~1350	20 (8 to 15)		
collider ring	~1350	96 (40)	Staged/ERL	

* Numbers in parentheses represent energies per nucleon for heavy ions

MEIC "Full-Acceptance" Detector



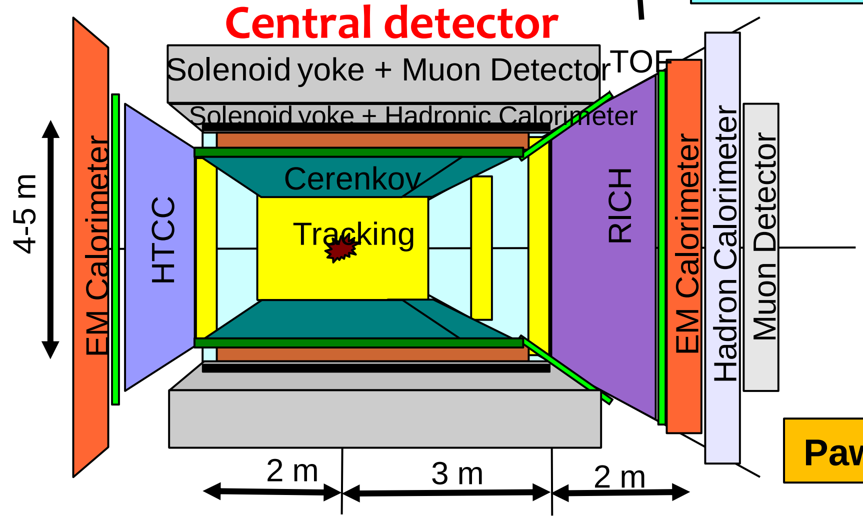
Detect particles with angles below 0.5º beyond ion FFQs and in arcs.

Central detector, more detection space in ion direction as particles have higher momenta

Detect particles with angles down to 0.5º before ion FFQs. Need up to 2 Tm dipole in addition to central solenoid.

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

Central detector

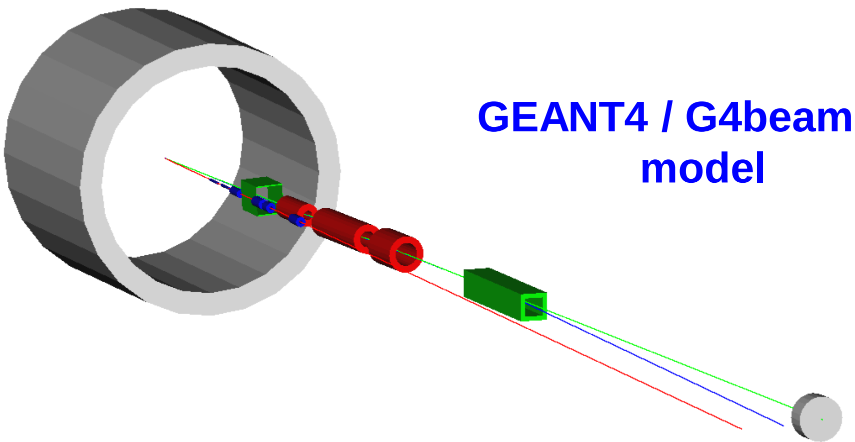


Distance IP – electron FFQs = 3.5 m
Distance IP – ion FFQs = 7.0 m
(Driven by push to 0.5° detection before ion FFQs)

Pawel Nadel-Turonski & Rolf Ent

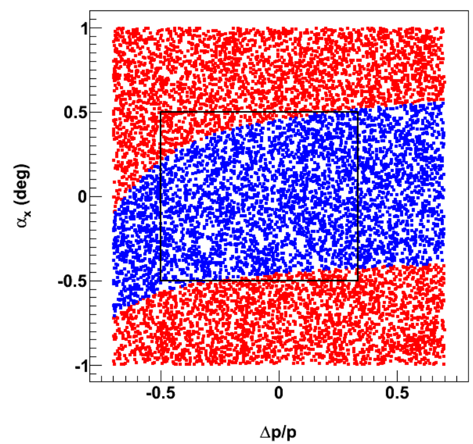
Detector Integration

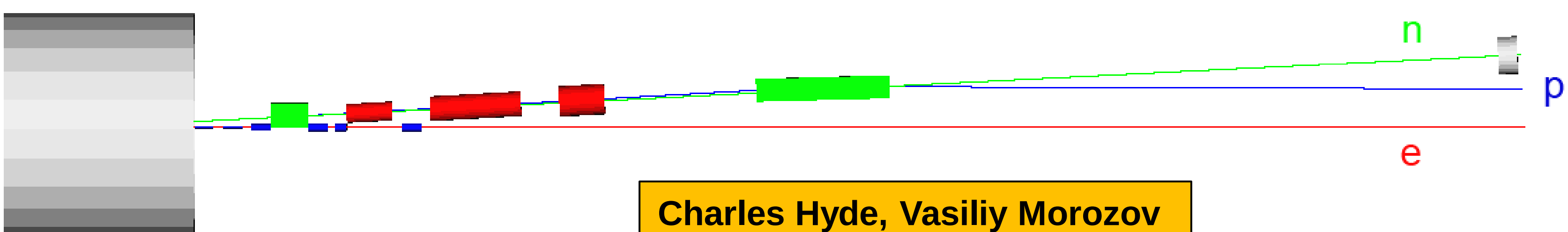
- Large 50 mrad crossing angle: improved detection, fast beam separation
- Forward small-angle hadrons pass through large-aperture final focusing quads before detection
- Final Focusing Block/spectrometer dipole combo optimized for acceptance and detector resolution



GEANT4 / G4beamline model

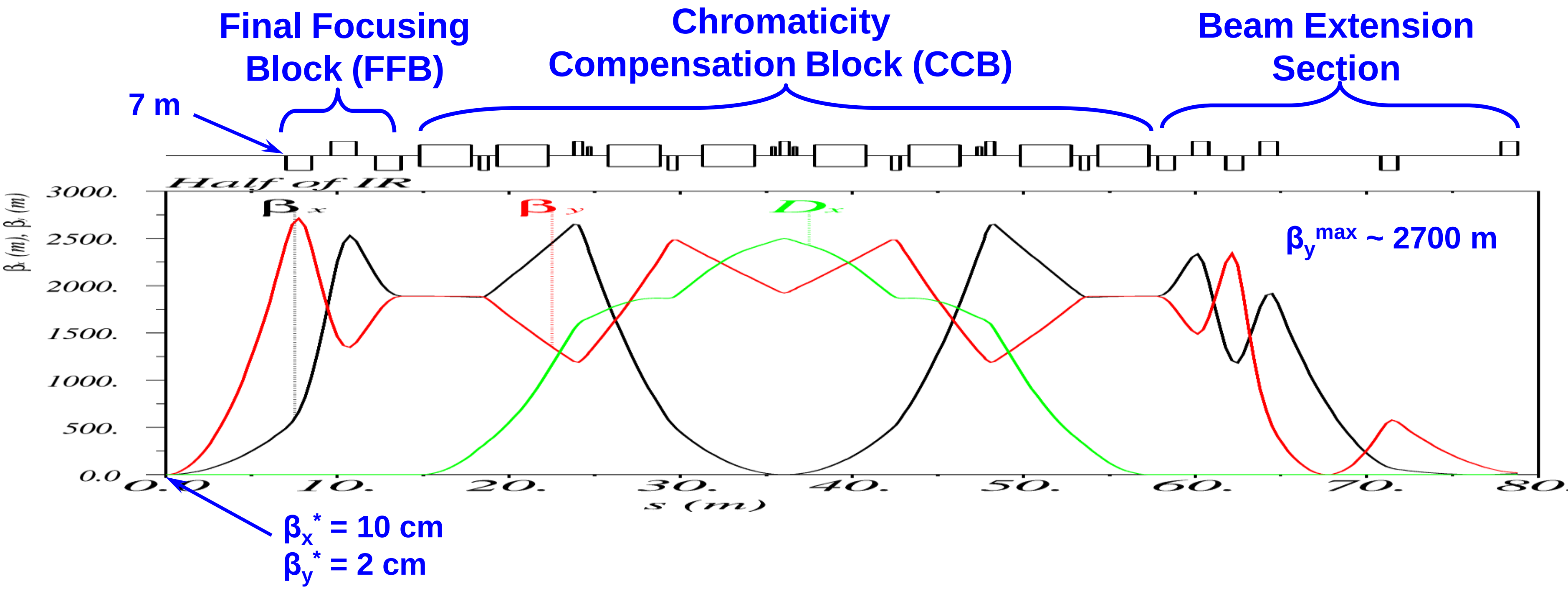
Forward Acceptance (B < 6 T)



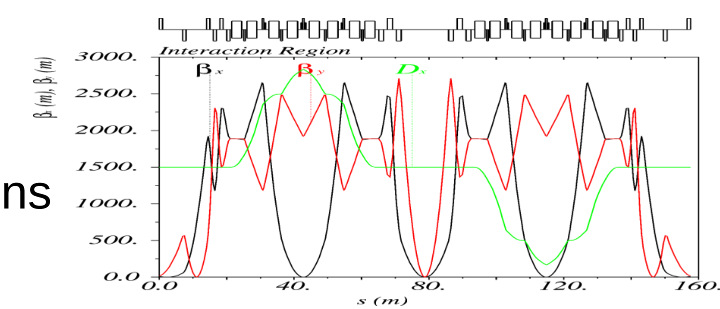


Charles Hyde, Vasiliy Morozov and Pawel Nadel-Turonski

Interaction Region: Ions



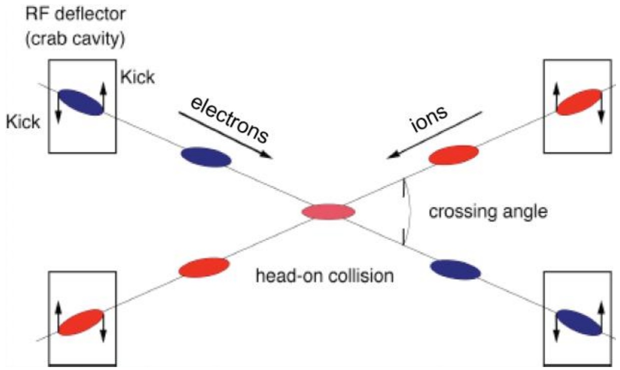
Whole Interaction Region: 158 m

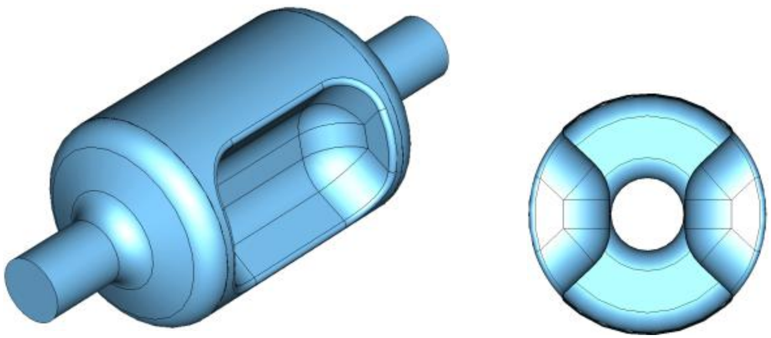


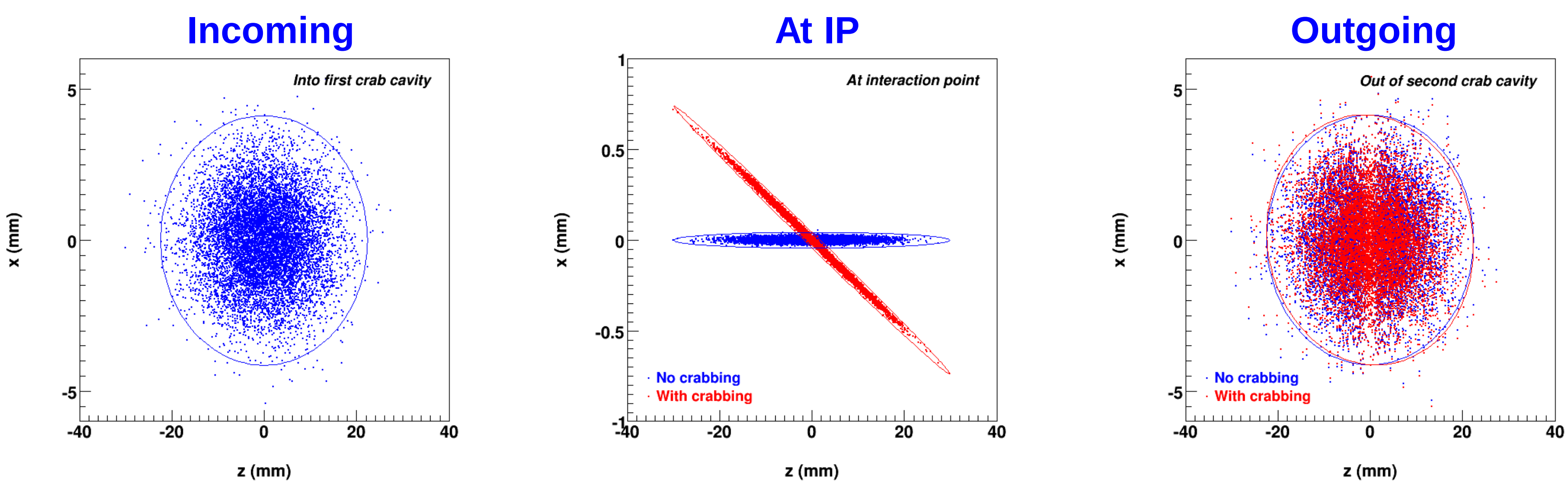
- Distance from the IP to the first FF quad = **7 m**
- Maximum quad pole tip field at 100 GeV/c = 6T
  - Allows ±0.5° forward detection
  - Evaluating detailed detector integrationand positions of collimators
- Symmetric CCB design for efficient chromatic correction

Crab Crossing

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

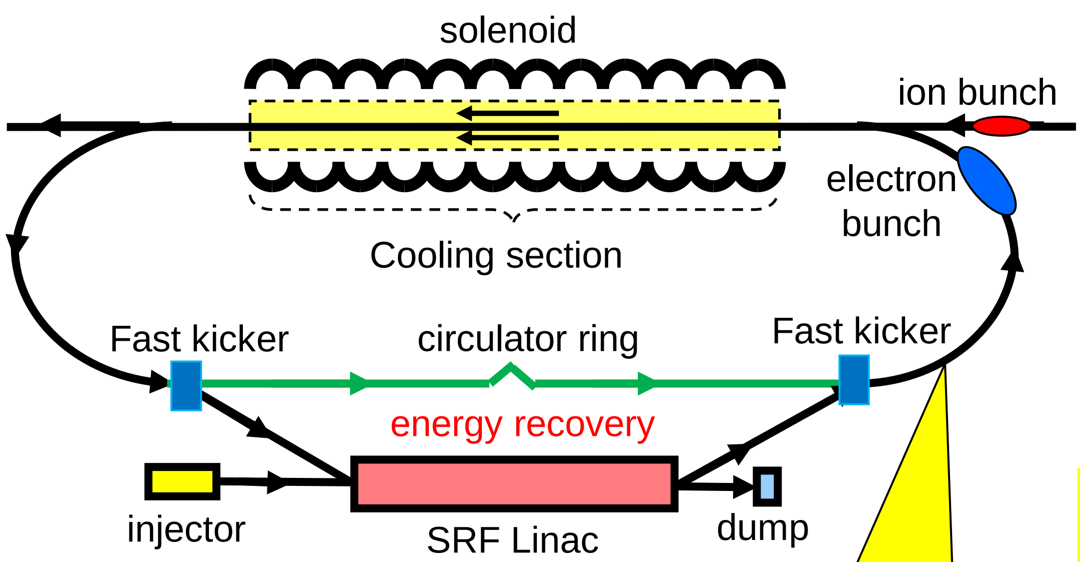






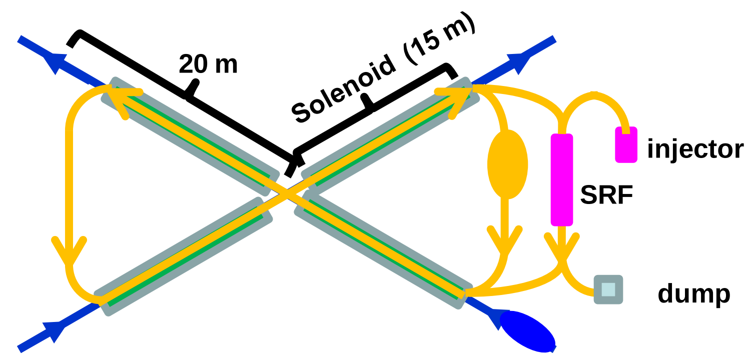
Electron Cooler

- Conventional electron cooling
- Staged electron cooling scheme
- ERL based to relax power and cathode requirements



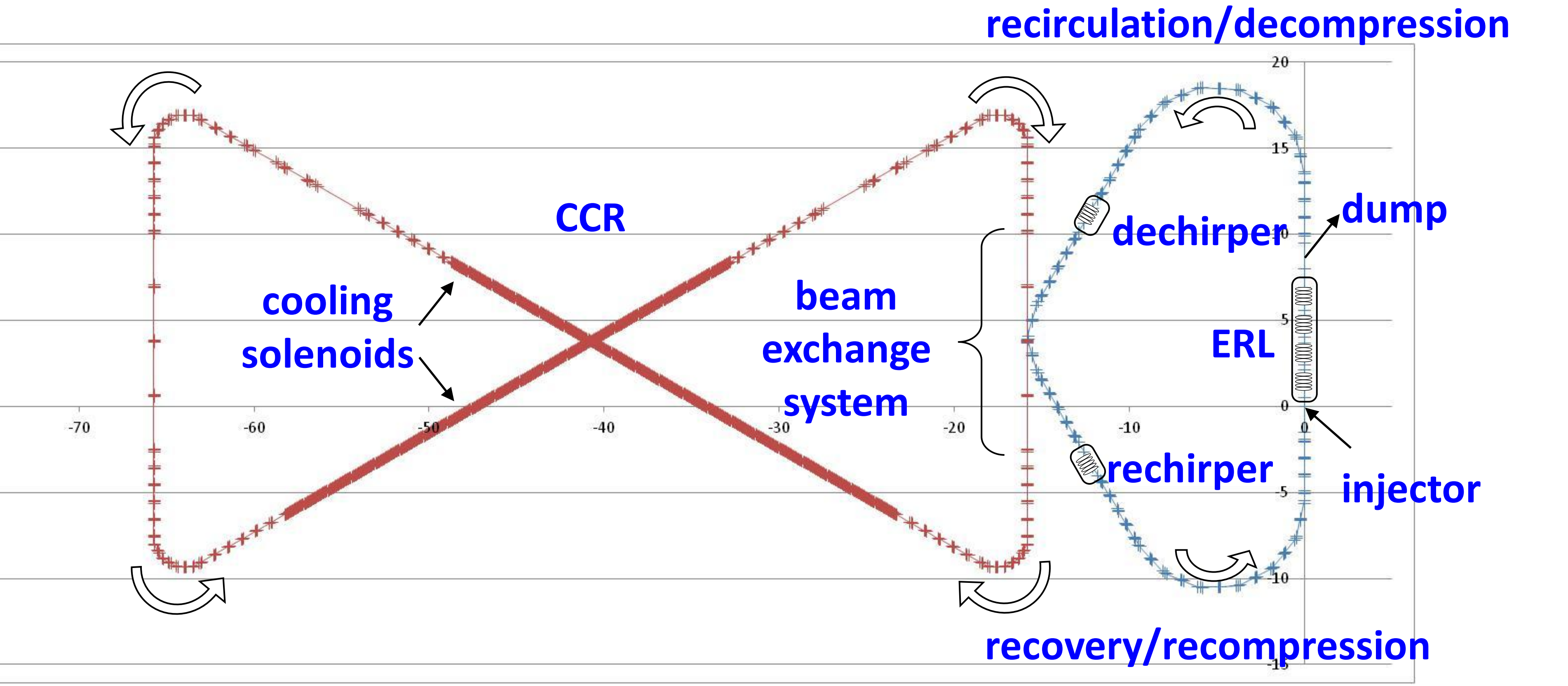
Electron bunches circulates 100+ times, leads to a factor of 100+ reduction of current from a photo-injector/ERL

Cooling at Figure-8 crossing

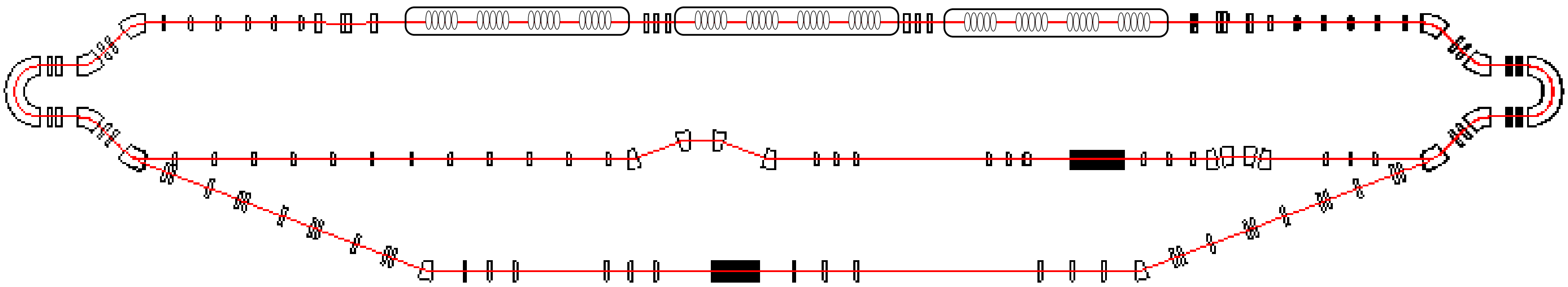


Eliminating a long return path could
- **cut cooling time by half, or**
- **reduce the cooling electron current by half, or**
- **reduce the number of revolutions by half**

The First Design of MEIC ERL Circulator Cooler



Cooling Test Facility



Test Recovered Energy Circulator System

Jefferson Lab Free Electron Laser Facility

1) Determine lifetime of a bunch in the circulator ring.
2) Examine feasability of magnetized electron gun.
3) Test fast kickers, currently under development.
4) Beam dynamics of an ERL with recirculation.

Summary

- Close and frequent collaboration with our nuclear physics colleagues regarding the machine, interaction region and detector requirements have taken place. This has led to agreed-upon baseline parameters:
  - Energy range: 3 to 11 GeV electrons, 20 to 100 GeV protons
  - Luminosity around 10^{34} cm^{-2} s^{-1} (e-nucleon) per interaction point
  - Longitudinally polarized (~80%) electrons, longitudinally or transversely polarized (>70%) protons and deuterons

- Ring layouts for MEIC have been developed, which include two interaction regions, one full acceptance, one high luminosity.

- Chromatic compensation for the baseline parameters has been achieved in the design. Significant progress has been made with determining and optimizing the dynamic aperture.

- Designs for staged Electron cooling have been developed and will be tested using the Jefferson Lab FEL.

JLab EIC Study Group

A. Accardi, S. Ahmed, A. Bogacz, P. Chevtsov, Ya. Derbenev, D. Douglas, R. Ent, V. Guzey, T. Horn, A. Hutton, C. Hyde, G. Krafft, R. Li, F. Lin, F. Marhauser, R. McKeown ,V. Morozov, P. Nadel-Turonski, E. Nissen, F. Pilat, A. Prokudin, R. Rimmer, T. Satogata, M. Spata, C. Tennat, B. Terzić, H. Wang, C. Weiss, B. Yunn, Y. Zhang --- Thomas Jefferson National Accelerator Facility

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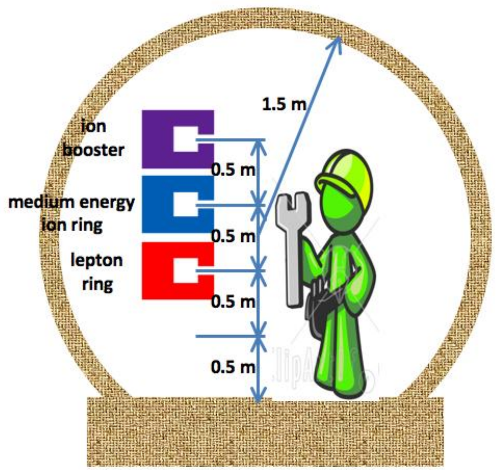
S. Abeyratne, B. Erdelyi, -- Northern Illinois University

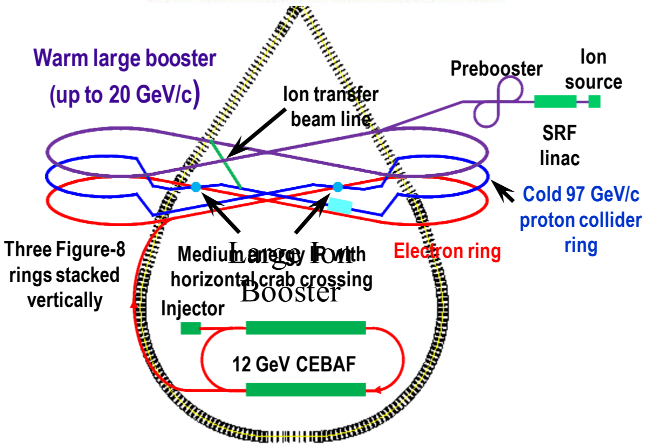
V. Dudnikov, R. Johnson, -- Muons, Inc

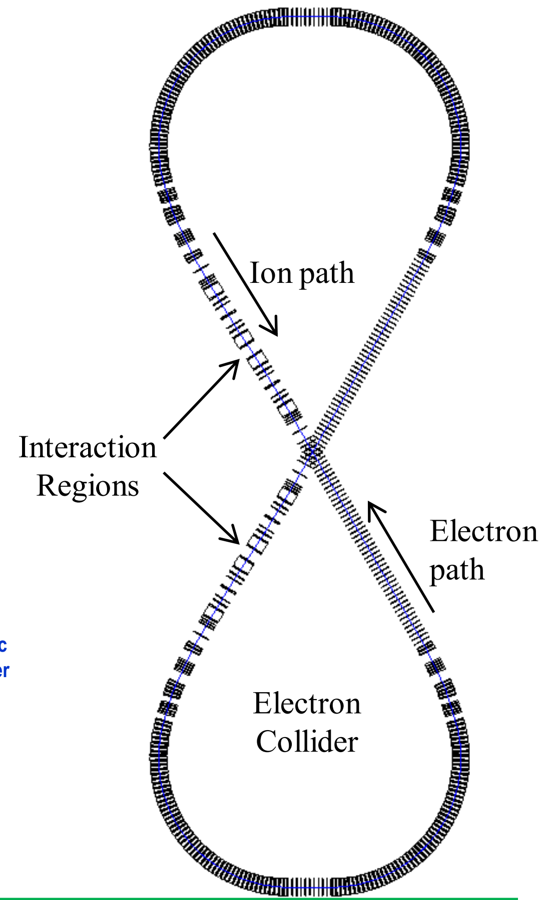
A. Kondratenko, -- STL "Zaryad", Novosibirsk, Russian Federation

Y. Kim -- Idaho State University

MEIC Layout

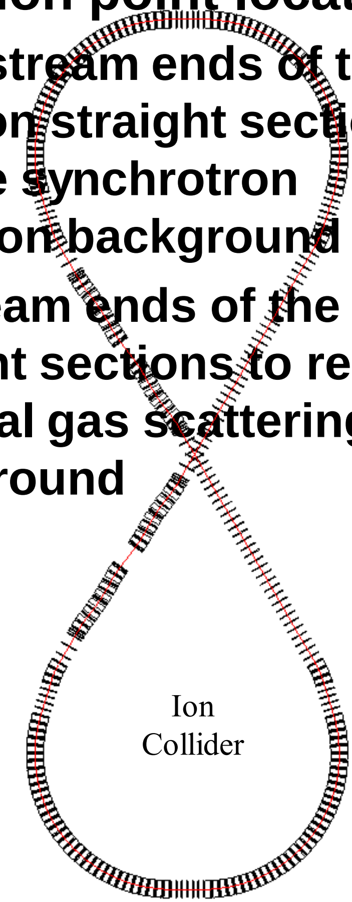






Interaction point locations:

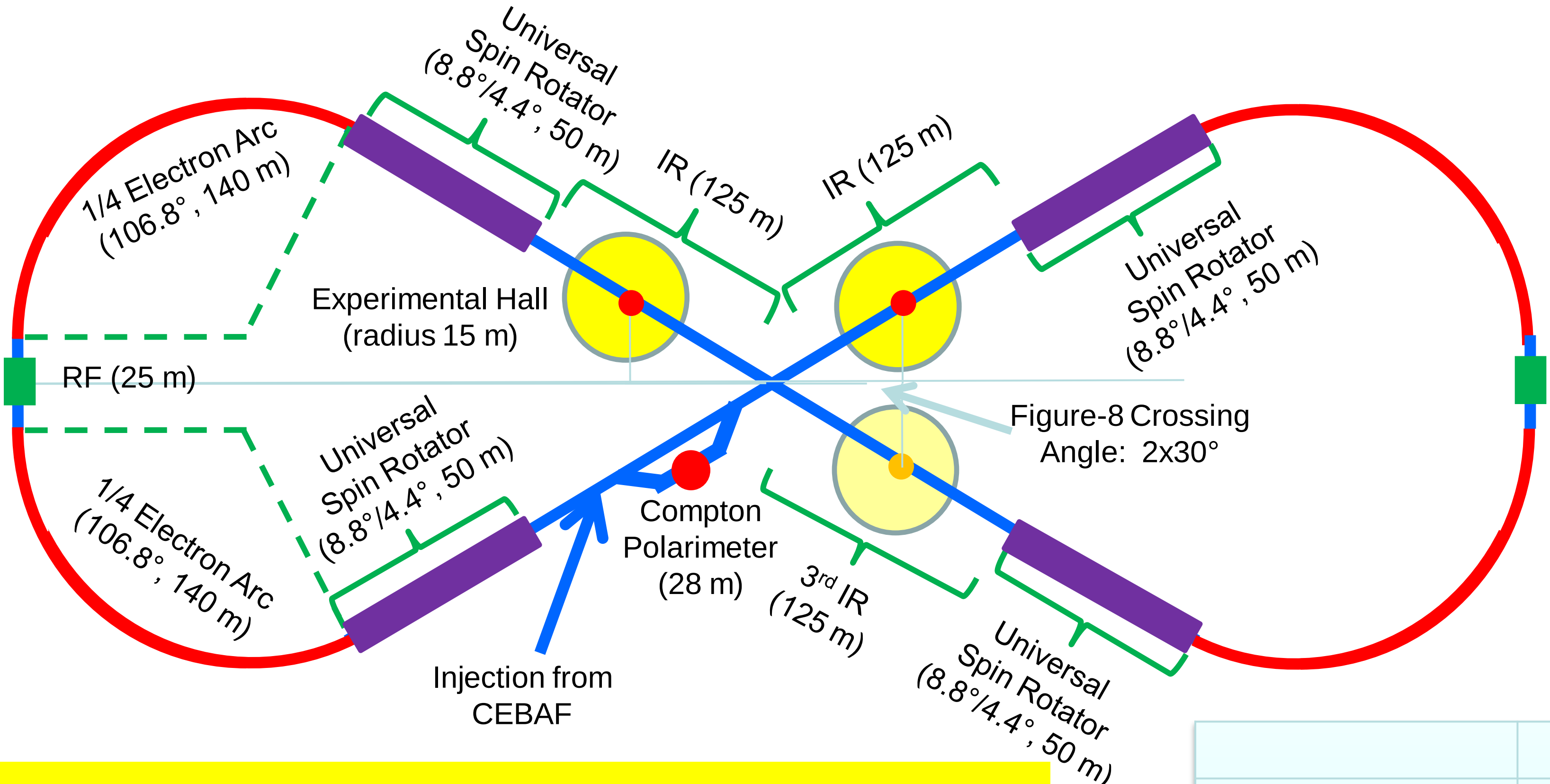
- Downstream ends of the electron straight sections to reduce synchrotron radiation background
- Upstream ends of the ion straight sections to reduce residual gas scattering background



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

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

MEIC Electron Ring Footprint



Ring design is a balance between

- Synchrotron radiation ➔ prefers a large ring (arc) length
- Ion space charge ➔ prefers a small ring circumference

Multiple IPs require long straight sections

Straights also hold required service components
(cooling, injection and ejection, etc.)

	m
Quarter arc	140
Universal spin rotator	50
IR insertion	125
Figure-8 straight	140 x 2
RF short straight	25
Circumference	~ 1300