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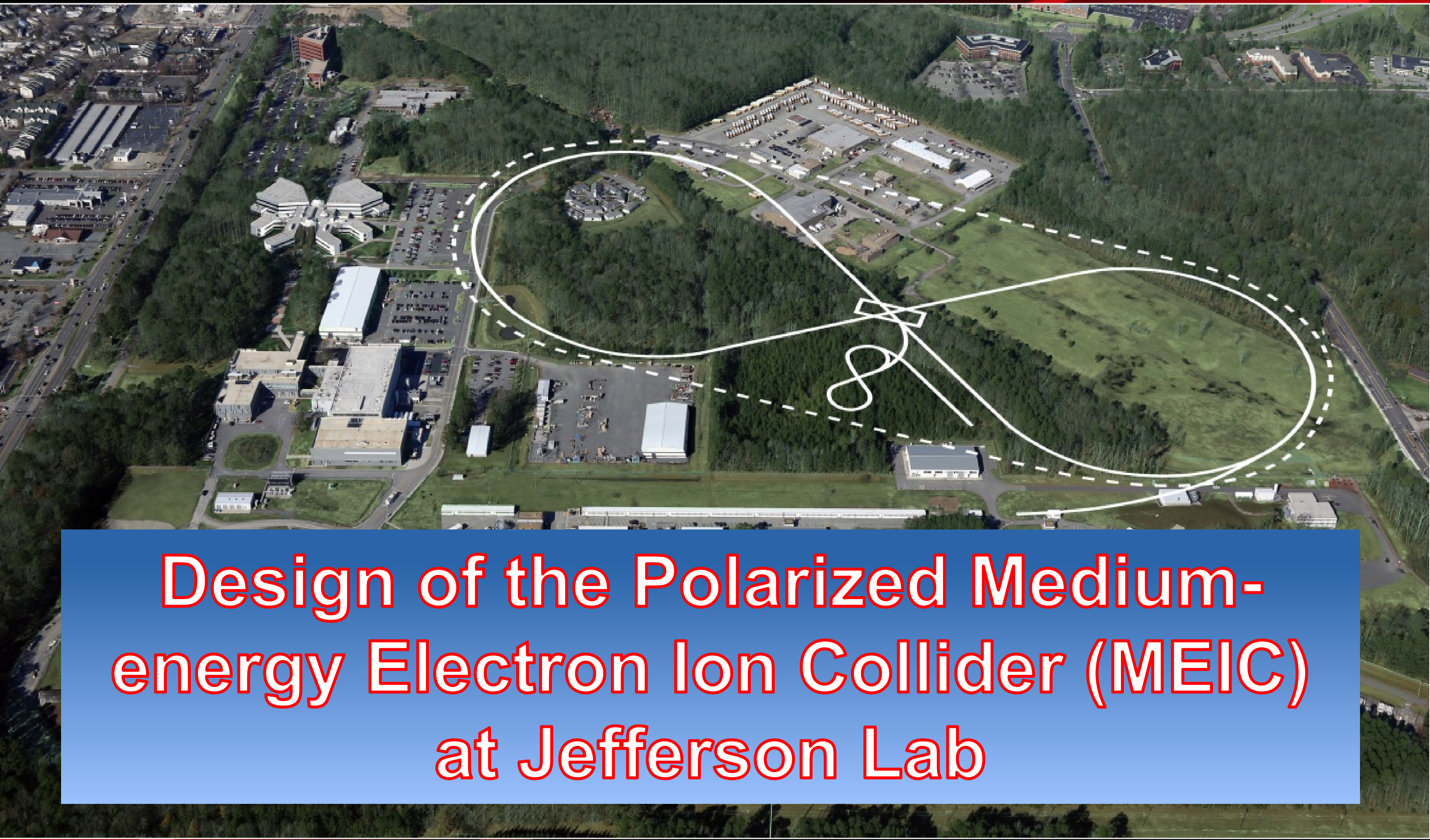

Design of the Polarized Medium-energy Electron Ion Collider (MEIC) at Jefferson Lab

Fanglei Lin for MEIC Study Group

IPAC'15, Richmond, May 3-8 2015

Jefferson Lab
Thomas Jefferson National Accelerator Facility

MEIC Study Group

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Outline

- **EIC Science highlights and design strategies for the MEIC at JLAB**

- **MEIC baseline design**
  - Machine complex
  - Detector integration
  - Chromaticity compensation
  - Crab crossing
  - Electron cooling
  - Polarization
  - Machine performance
  - Overview of R&D

- **Summary and Outlook**

Electron Ion Collider

NSAC 2007 Long-Range Plan:

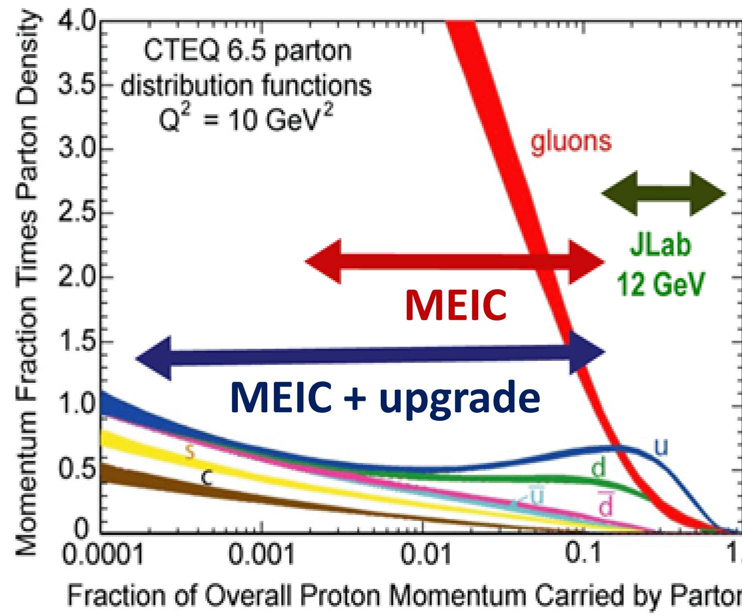
"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

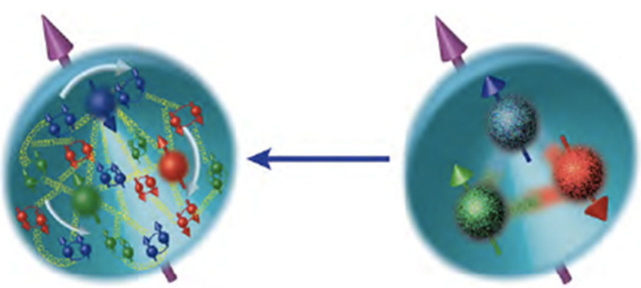
EIC Community White Paper arXiv:1212.1701

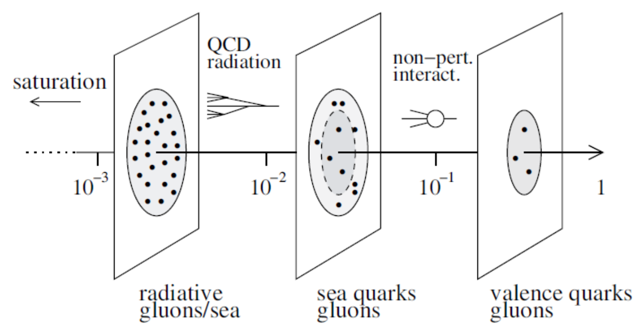
- Highly polarized (~ 70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~ 20 – ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10^{33-34} $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region

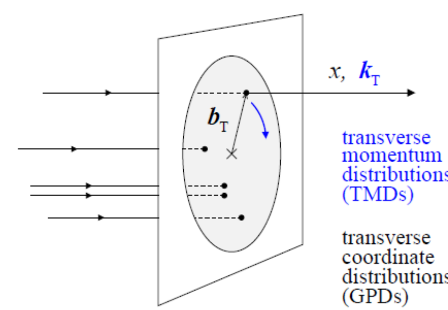
EIC Physics Highlights

- An EIC will study the sea quark and gluon-dominated matter
  - 3D structure of nucleons
    - How do gluons and quarks bind into 3D hadrons?
  - Role of orbital motion and gluon dynamics in the proton spin
    - Why do quarks contribute only ~30%?
  - Gluons in nuclei (splitting/recombining)
    - Does the gluon density saturate at small x?
- Need luminosity, polarization and good acceptance to detect spectator & fragments









MEIC Design Goals

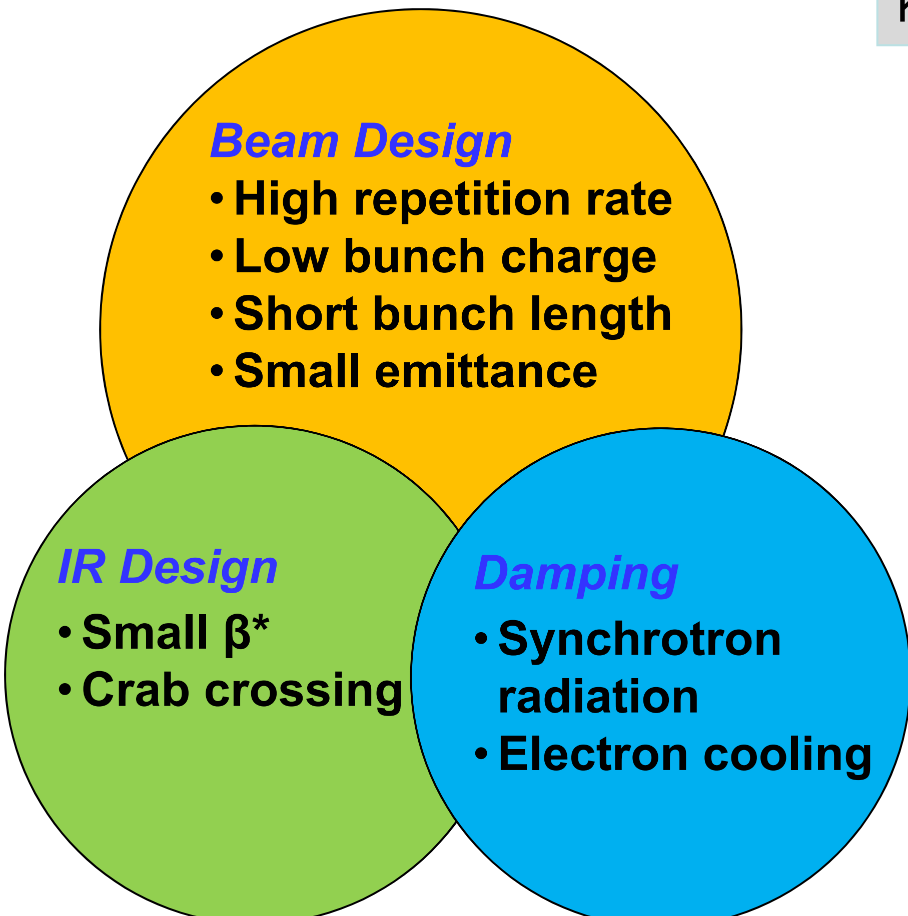
- **Energy**
  - Full coverage of center-of-mass energy $\sqrt{s}$ from **15** to **65** GeV
  - Electrons **3 -10** GeV, protons **20 -100** GeV, ions **12** - **40** GeV/u
- **Ion species**
  - Polarized light ions: **p**, **d**, ^{3}**He**, and possibly **Li**
  - Un-polarized light to heavy ions up to A above 200 (Au, Pb)
- **2 detectors**
  - **Full acceptance** is critical for the primary detector
- **Luminosity**
  - $\mathbf{10^{33}}$ to $\mathbf{10^{34}}$ $cm^{-2}s^{-1}$ **per IP** in a *broad* CM energy range
- **Polarization**
  - At IP: both longitudinal and transverse for ion beam, longitudinal for electron beam
  - **All polarizations >70%**
- **Upgrade to higher energies and luminosity possible**
  - 20 GeV electron, 250 GeV proton, and 100 GeV/u ion

Design goals are consistent with the Nuclear physics requirements.

Design Strategy for High Luminosity

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

KEK-B already reached above 2×10^{34} /cm^2/s

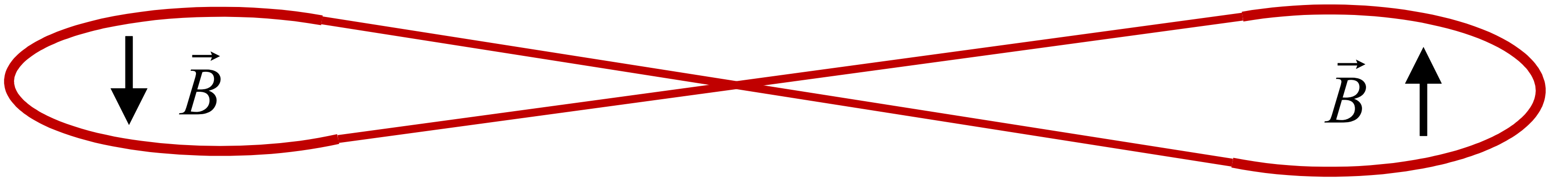


$$L = f \frac{n_1 n_2}{4\pi\sigma^*_x \sigma^*_y} \sim f \frac{n_1 n_2}{\varepsilon \beta^*_y}$$

"Traditional" hadrons colliders
- Small number of bunches
- Small collision frequency f
- Large bunch charge n_1 and n_2
- Long bunch length
- Large beta-star

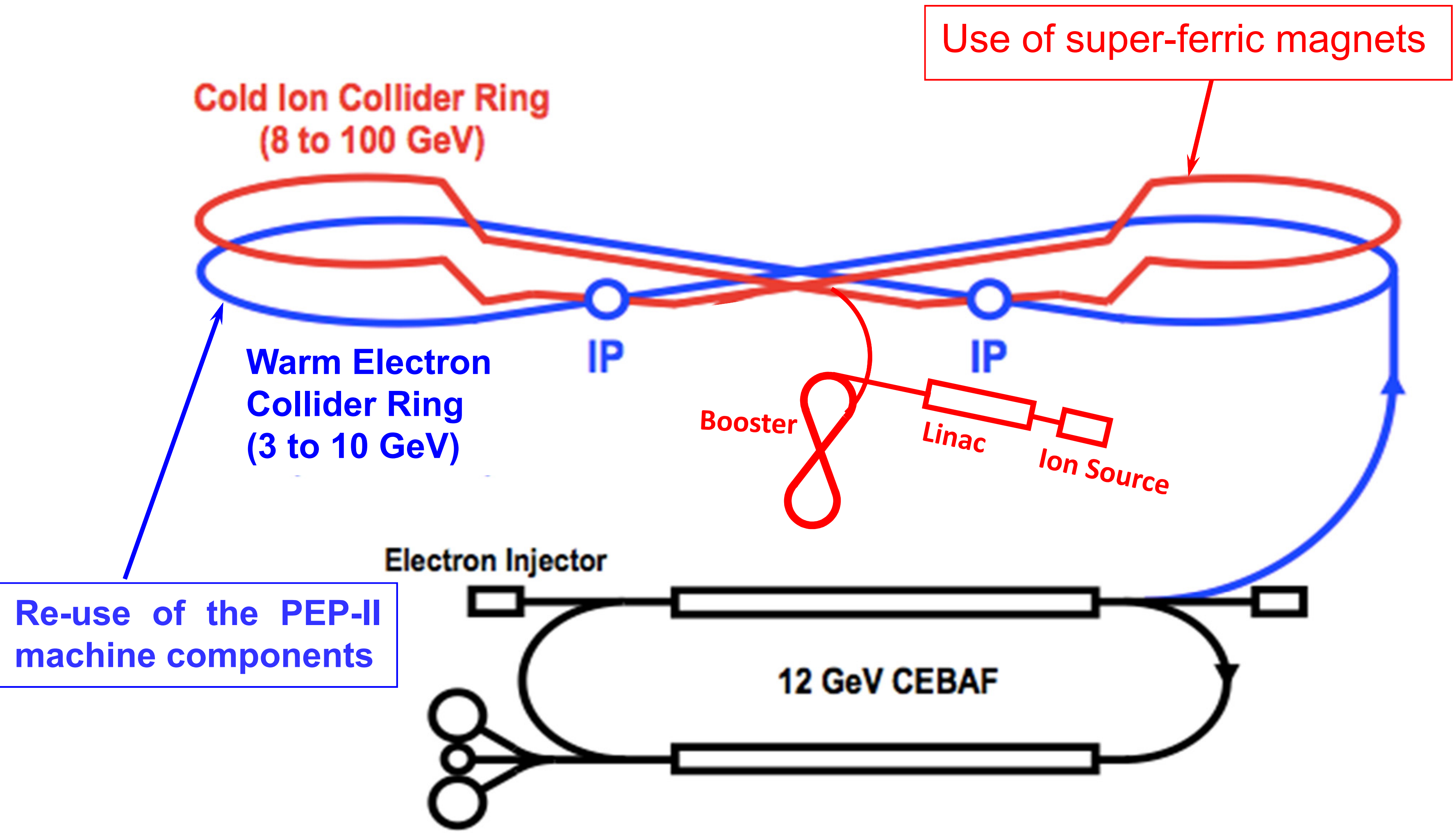
Design Strategy for High Polarization

- The MEIC design concept for high luminosity is based on the **unique figure-8 shape ring structure**
  - Spin precession in one arc is exactly cancelled in the other
  - Zero spin tune independent of energy
  - Spin control and stabilization with small solenoids or other compact spin rotators

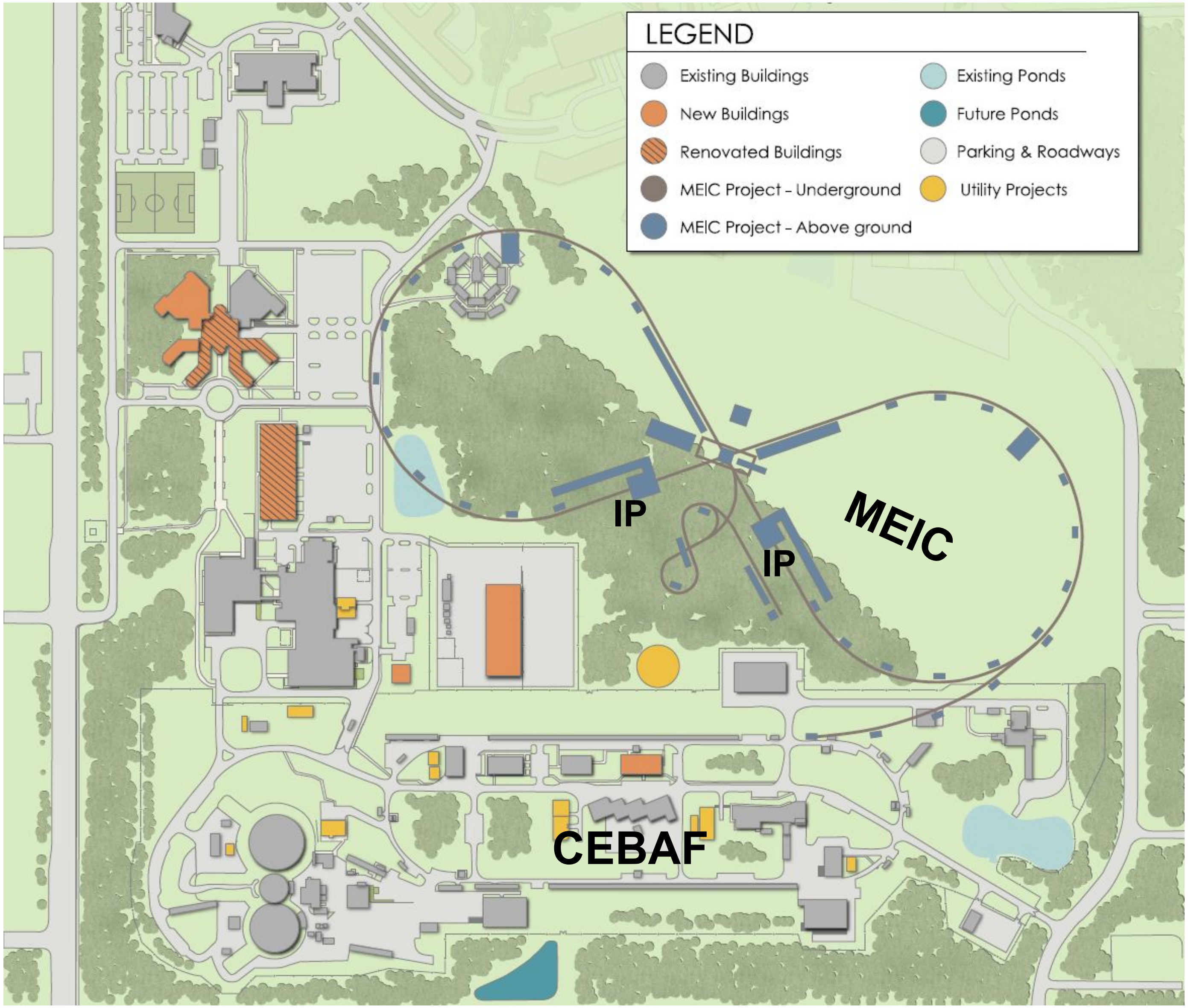


- Advantage 1: Efficient preservation of ion polarization during acceleration
  - Energy-independent spin tune
- Advantage 2: Ease of spin manipulation
  - Any desired polarization orientation at the IP
  - Spin flip
- Advantage 3: A simple way to accommodate polarized deuterons
  - Particles with small anomalous magnetic moment
- Advantage 4: Strong reduction of electron depolarization due to the energy independent spin tune

MEIC Layout


Use of super-ferric magnets
Cold Ion Collider Ring
(8 to 100 GeV)
Warm Electron
Collider Ring
(3 to 10 GeV)
IP
IP
Booster
Linac
Ion Source
Electron Injector
12 GeV CEBAF
Re-use of the PEP-II
machine components

JLAB Campus Layout

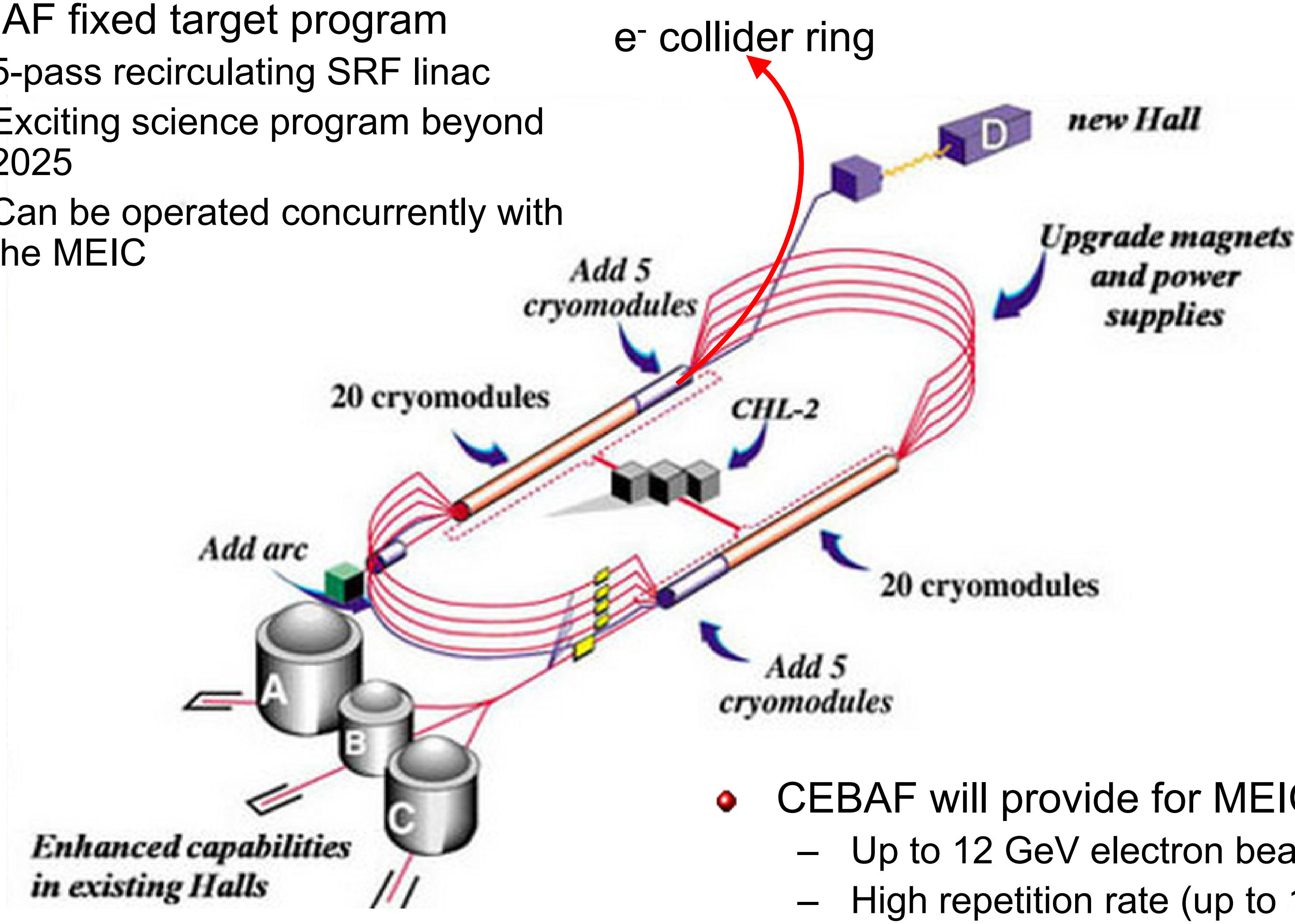


~2.2 km circumference

Tunnel consistent with a 250+ GeV upgrade

CEBAF - Full Energy Injector

- CEBAF fixed target program
  - 5-pass recirculating SRF linac
  - Exciting science program beyond 2025
  - Can be operated concurrently with the MEIC

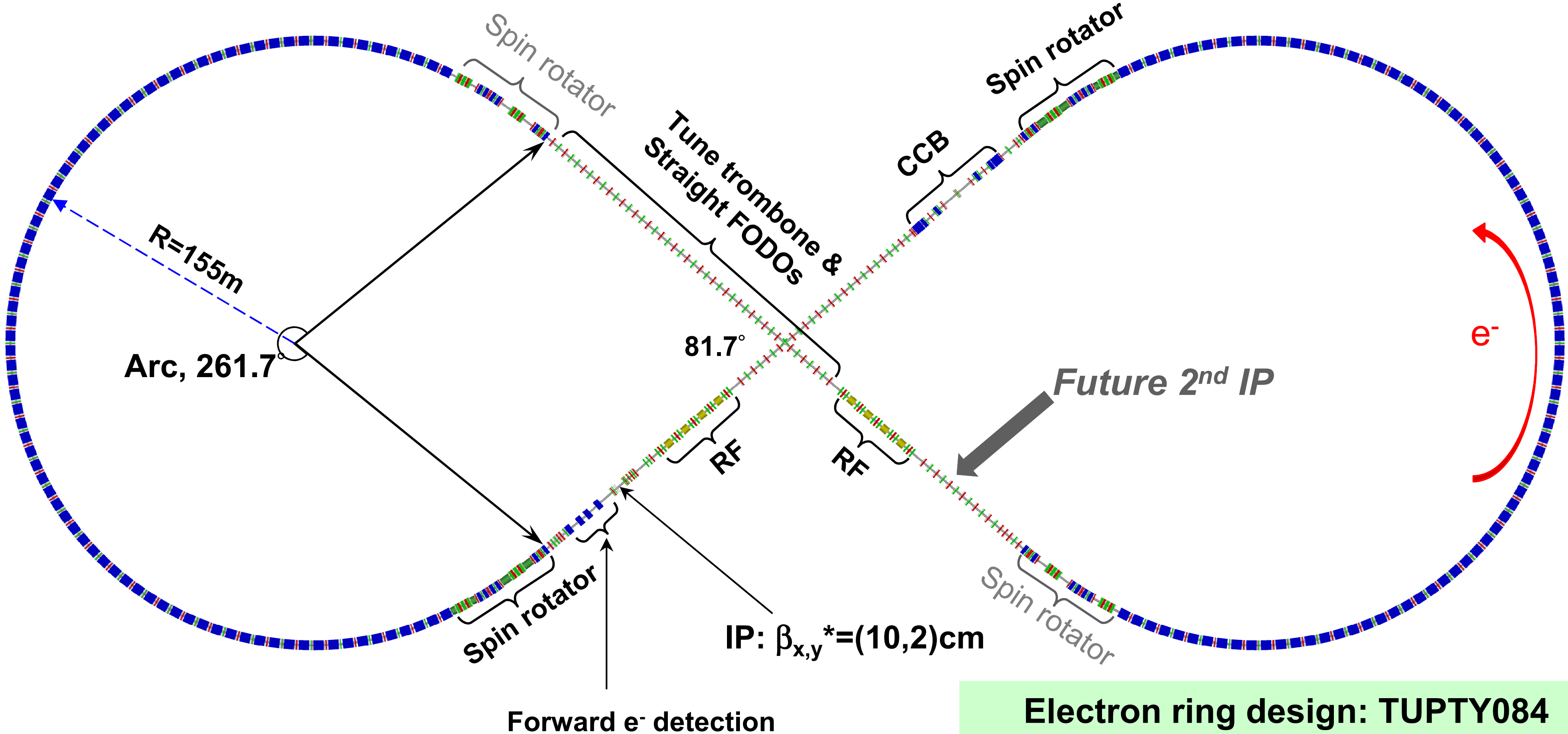


- CEBAF will provide for MEIC
  - Up to 12 GeV electron beam
  - High repetition rate (up to 1497 MHz)
  - High polarization (>85%)
  - Good beam quality

Injection scheme: TUPTY083

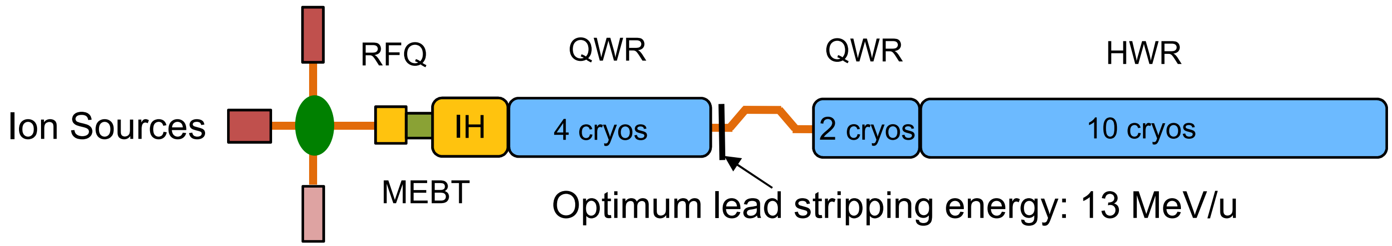
Electron Collider Ring

- Electron collider ring design
  - Circumference of **2154.28** m = 2 x **754.84** m arcs + 2 x **322.3** m straights
  - **Reuses PEP-II** magnets, vacuum chambers and RF
- Beam characteristics
  - **3A** beam current up to 6.95 GeV
  - Synchrotron radiation power density **10kW/m**
  - Total power **10 MW**



Electron ring design: TUPTY084

Ion Sources and Linac

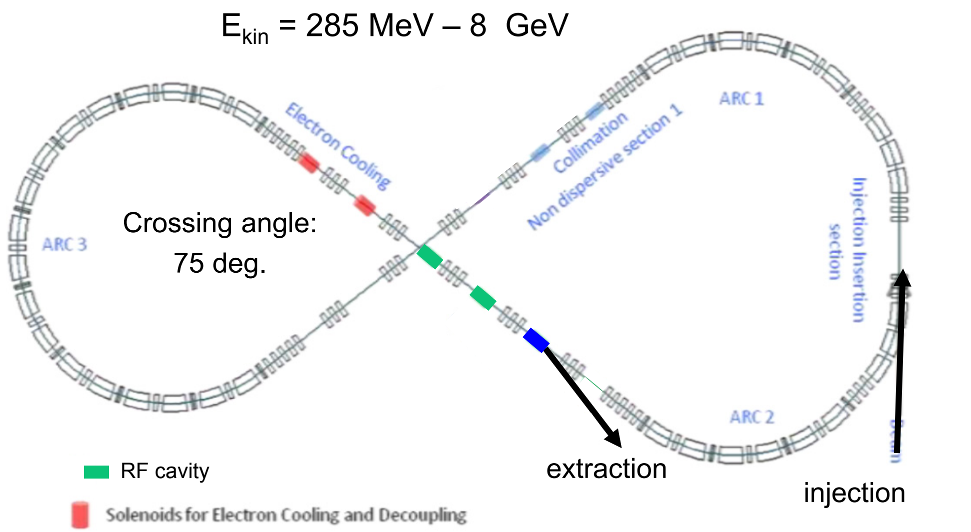


- ABPIS for polarized or un-polarized light ions, EBIS and/or ECR for un-polarized heavy ions
- Linac design based on the ANL linac design. Pulsed linac capably of accelerating multiple charge ion species (H^- to $Pb^{67}+$)
  - Warm Linac sections (115 MHz)
    - RFQ (3 m)
    - MEBT (3 m)
    - IH structure (9 m)
  - Cold Linac sections
    - QWR + QWR (24 + 12 m) 115 MHz
    - Stripper, chicane (10 m) 115 MHz
    - HWR section (60 m) 230 MHz

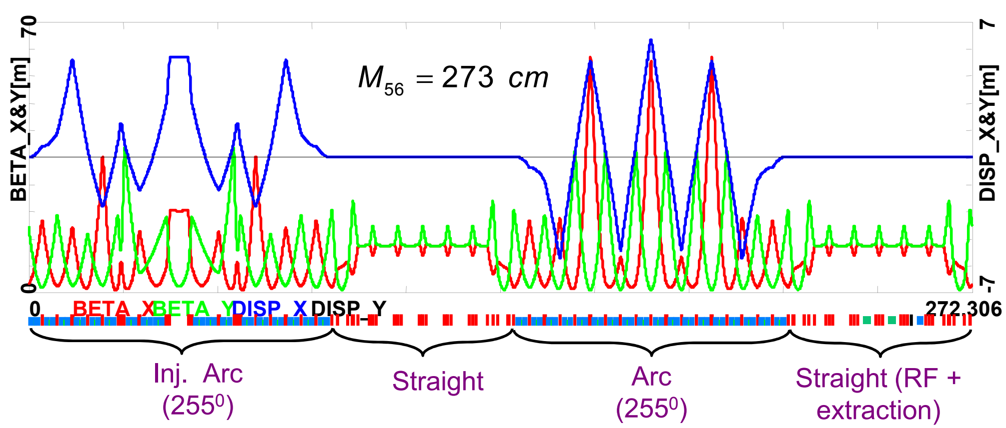
Ion species: p to Pb	
Ion species for the reference design	^{208}Pb
Kinetic energy (p, Pb)	285 MeV 100 MeV/u
Maximum pulse current: Light ions (A/Q<3) Heavy ions (A/Q>3)	2 mA 0.5 mA
Pulse repetition rate	up to 10 Hz
Pulse length: Light ions (A/Q<3) Heavy ions (A/Q>3)	0.50 ms 0.25 ms
Maximum beam pulsed power	680 kW
Fundamental frequency	115 MHz
Total length	121 m

Booster

- Purpose of Booster
  - Accumulation of ions injected from Linac
  - Cooling
  - Acceleration of ions
  - Extraction and transfer of ions to the collider ring

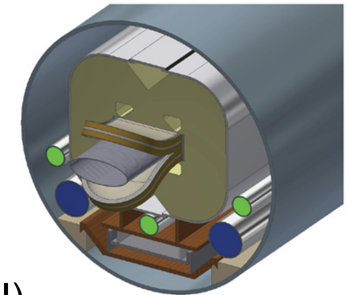


- 8 GeV Booster design
  - Based on super-ferric magnet technology
  - Circumference of 273 m
  - Achromatic arcs' design with partly negative horizontal dispersion to minimize momentum compaction to avoid transition crossing
  - Figure-8 shape for preserving ion polarization

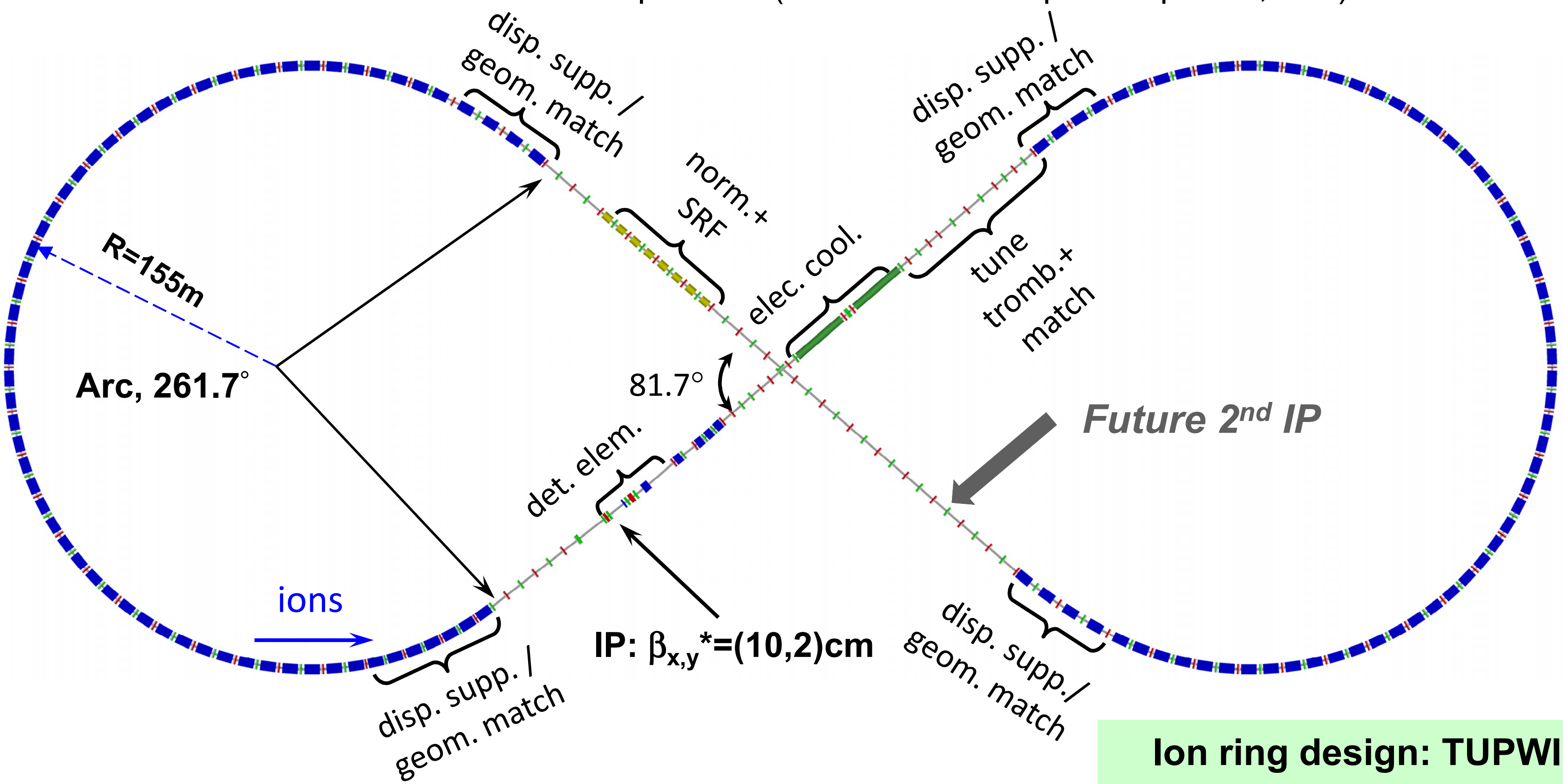


Ion Collider Ring Layout

- Ion collider ring design
  - match the geometry of PEP-II-component-based electron ring
  - Use Super-ferric magnets
    - **~3 T** maximum field for maximum proton momentum of **100 GeV/c**, **4.5 k** operating temperature
    - Cost effective construction and operation (factor of ~2 cheaper to operate, GSI)



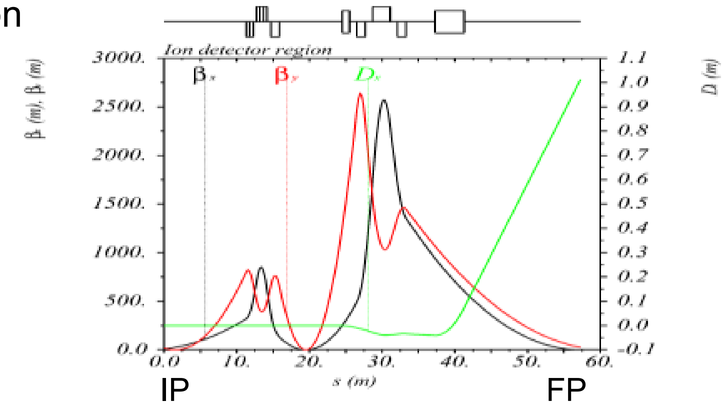
igure 3. Isometric view of the end region of the v1a ICR dipole in its cryostat.

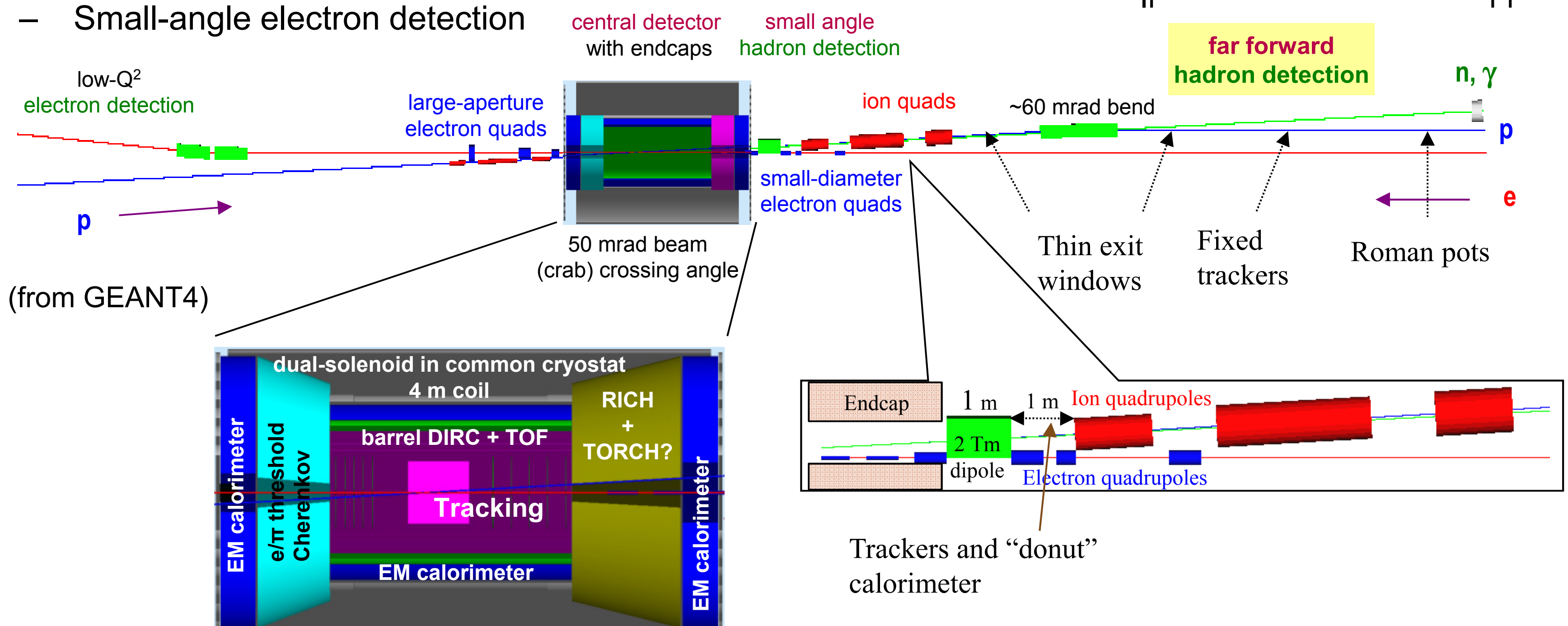


Ion ring design: TUPWI031

Full-Acceptance Detector

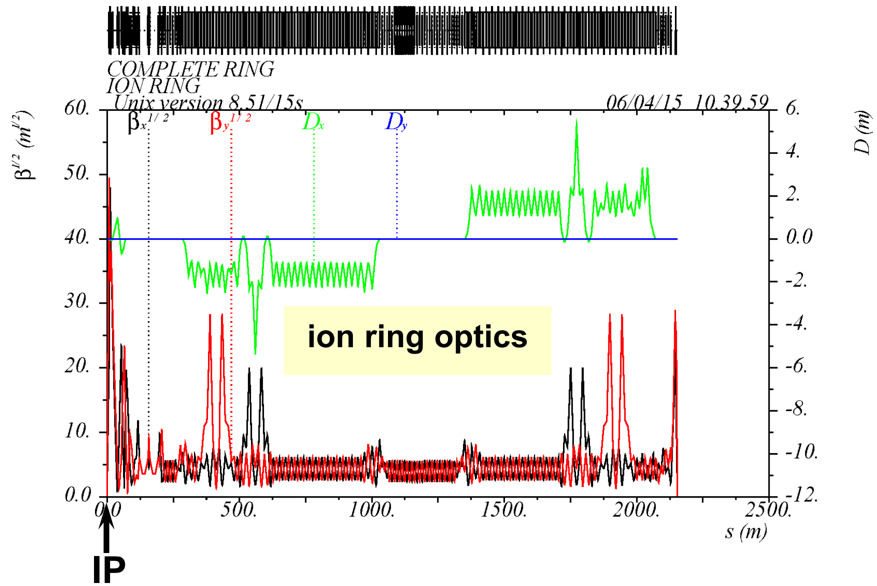
- 50 mrad crossing angle
  - No parasitic collision, fast beam separation, improved detection
- Forward hadron detection in three stages
  - Endcap
  - Small dipole covering angles up to a few degrees
  - Far forward, up to one degree, for particles passing through accelerator quads
- Low-Q^2 tagger
  - Small-angle electron detection



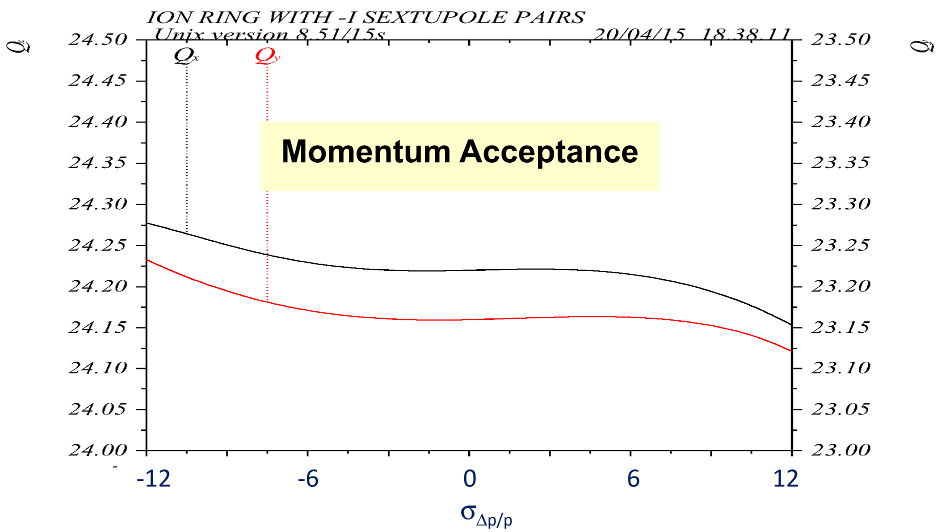


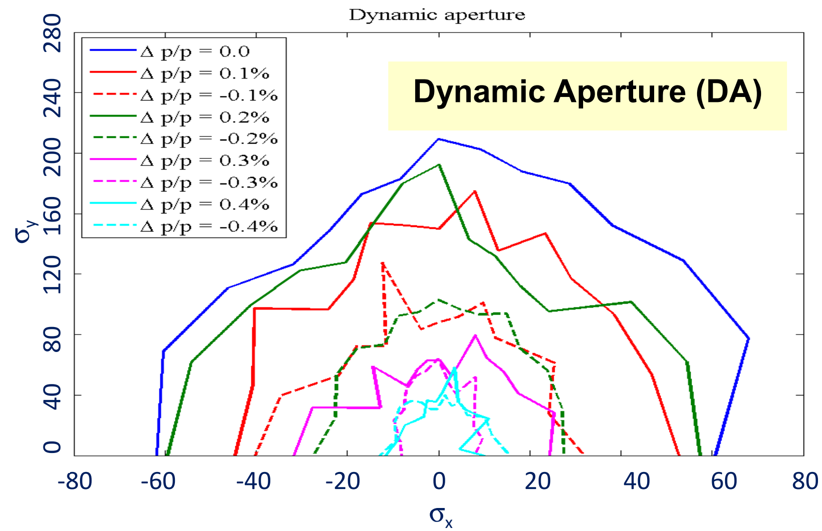
Chromaticity Compensation

- Distributed sextupole compensation
  - "-*I*" approach with two sextupole families to build up chromatic β wave in the arcs to cancel FFB's chromatic kick
  - Another two sextupole families with π/2 phase advance to compensate the residual linear chromaticities



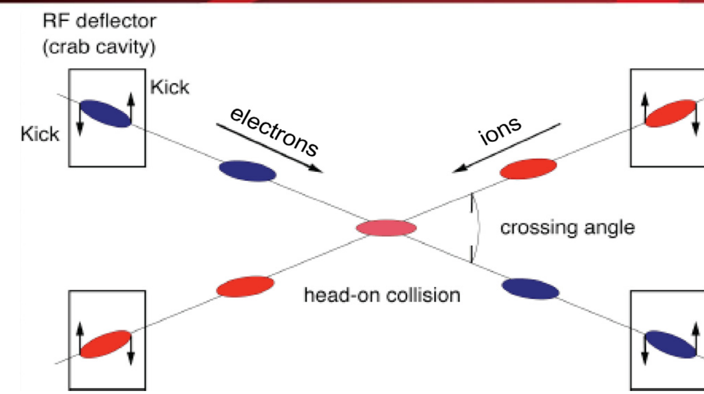
Nonlinear Beam Dynamics: TUPWI032

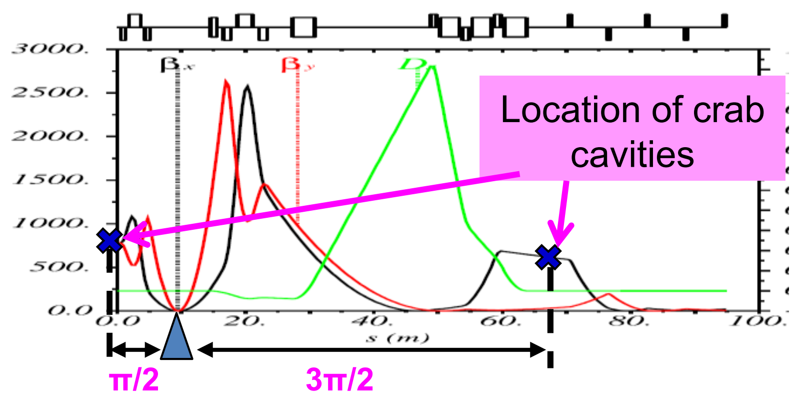


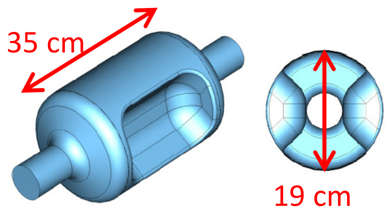


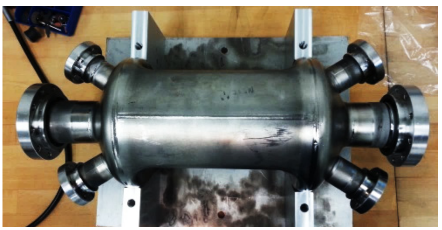
Crab Crossing

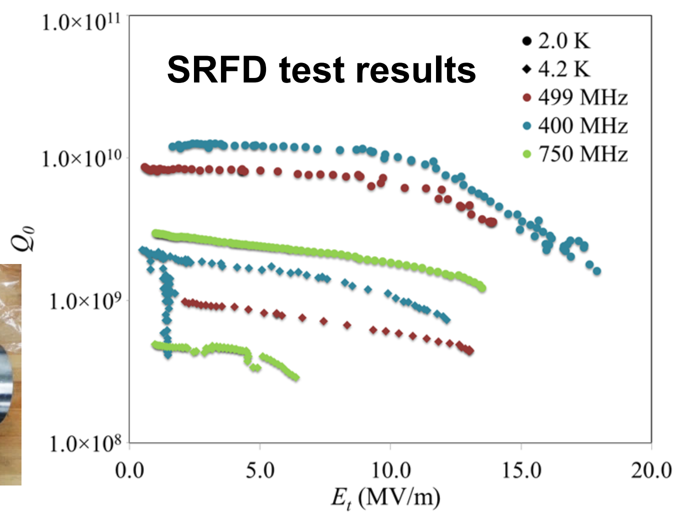
- Large crossing angle required to avoid parasitic collisions
- Local crab scheme to restore effective head-on bunch collisions
- Cavities are placed at (n+1)π/2 phase advance relative to IP with large β_x
- Deflective SRF crab cavities have been tested with promising results

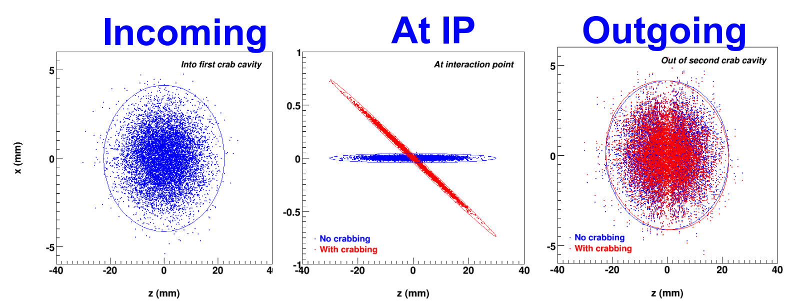










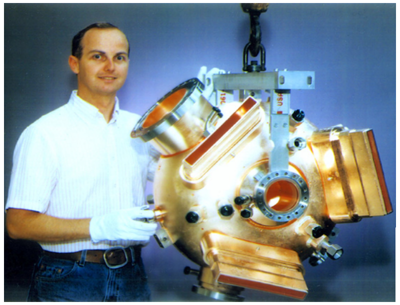


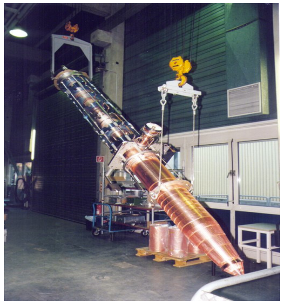
Crab Cavities : TUPWI039, WEPWI034

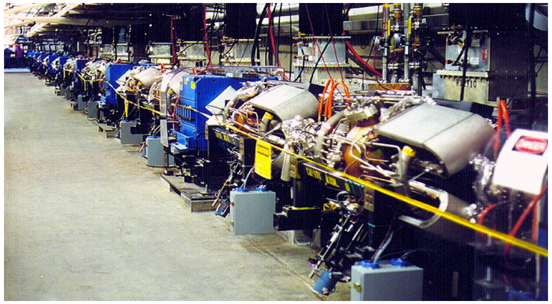
RF Cavities

- Electron collider ring --- reuse PEP-II RF stations
  - 476 MHz HOM damped 1-cell cavities, 34 cavities available
  - 1.2 MW klystrons including power supplies etc., 13 available

RF System: TUPWI034, WEPWI024

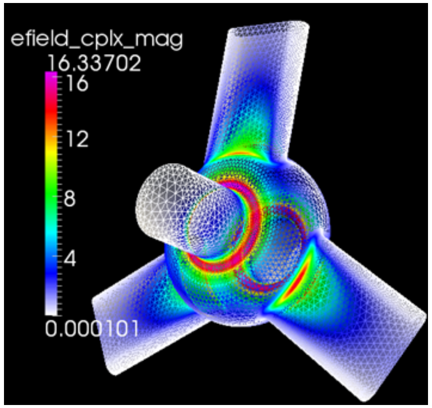


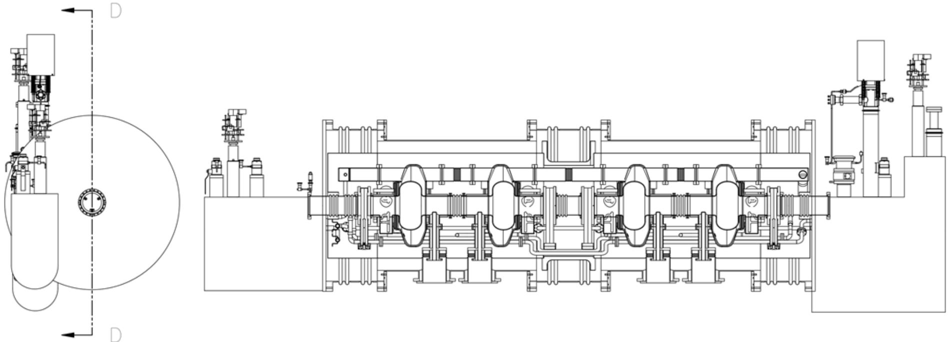




- Ion collider ring --- design 952.6 MHz HOM damped 1-cell cavities
  - High frequency/high voltage for short bunch (re-bucket at energy)
  - Double the repetition rate for the future luminosity upgrade

New HOM damped cavity concept



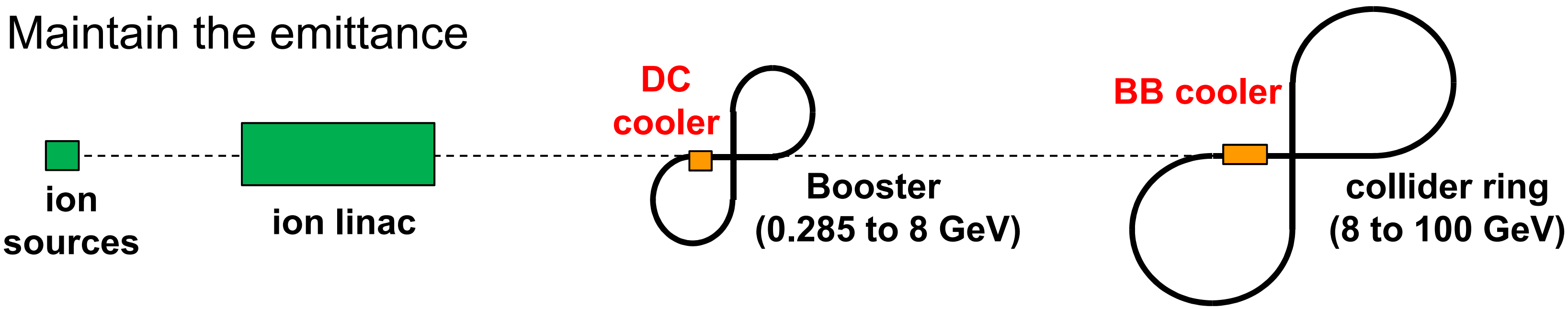


952.6 MHz single cell 4-seater CM

Multi-Step Electron Cooling Scheme

- Cooling of ion beams in the MEIC is critical in delivering high luminosity over a broad CM energy range
  - Help accumulation of positive ions
  - Reduce the emittance
  - Maintain the emittance

$$\tau_{cool} \sim \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$$



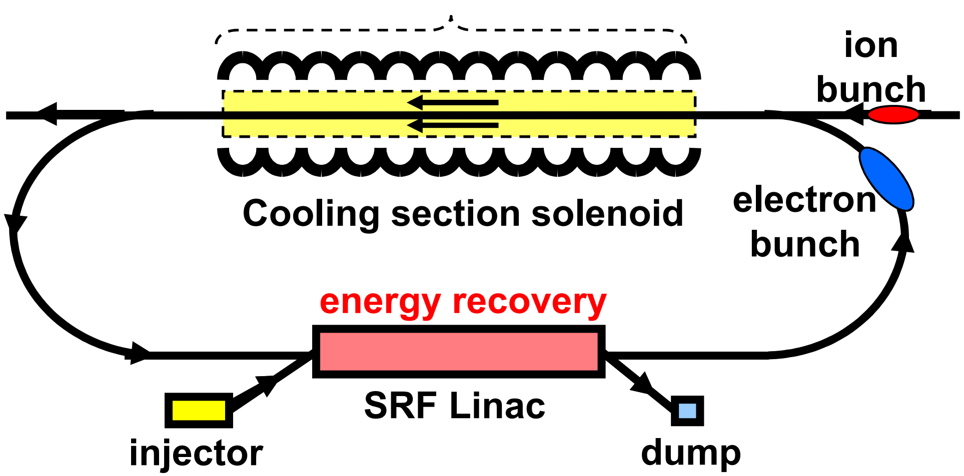
Ring	Cooler	Function	Ion energy (GeV/u)	Electron energy (MeV)
Booster ring	DC	Injection/accumulation of positive ions	0.11 ~ 0.19 (injection)	0.062 ~ 0.1
		Emittance reduction	2	1.1
Collider ring	Bunched Beam Cooling (BBC)	Maintain emittance during stacking	7.9 (injection)	4.3
		Maintain emittance	Up to 100	Up to 55

Bunched Beam Electron Cooler

- Baseline cooling requirements
  - Emittance 0.5 to 1 mm-mrad -> reduce IBS effect
  - Magnetized beam, up to 55 MeV energy, 200 mA current
  - Linac for acceleration
  - Must utilize energy-recovery-linac (beam power is 11 MW)

- Solution : cooling by a bunched electron beam

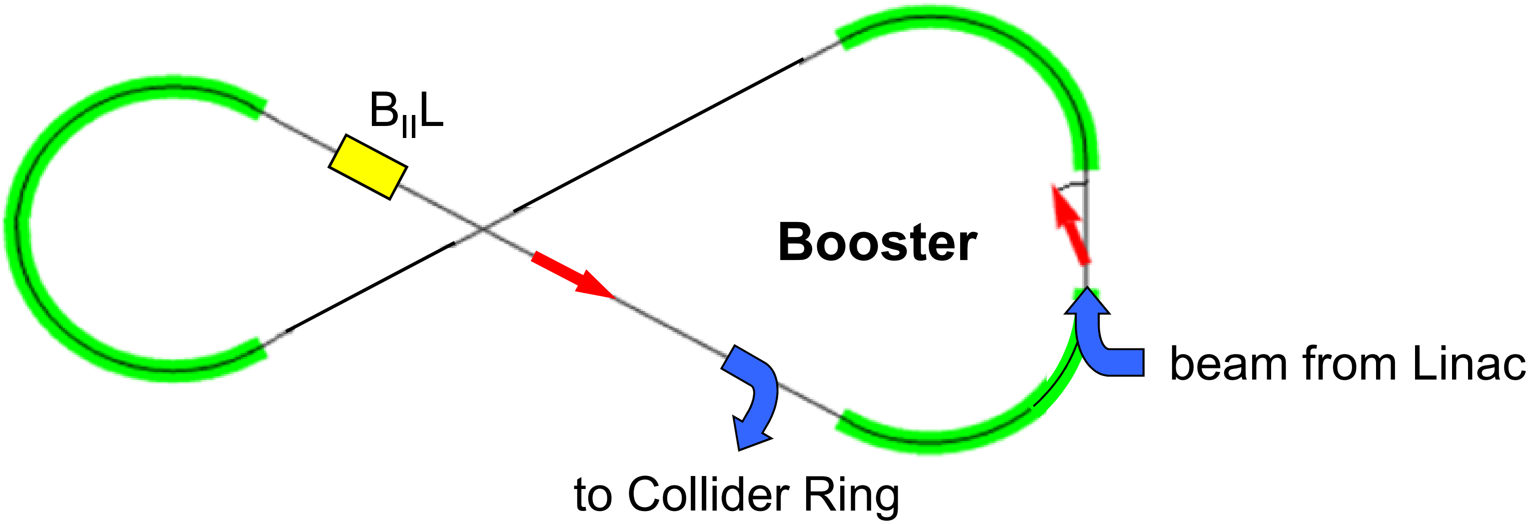
Electron Cooling: MOPMN011, TUPWI037, TUPMA034, TUPMA035, TUPWI038, TUPWI040, WEPMN025



Electron energy	MeV	up to 55
Current and bunch charge	A / nC	0.2 / 0.42
Bunch repetition	MHz	476
Cooling section length	m	60
RMS Bunch length	cm	3
Electron energy spread	10^{-4}	3
Cooling section solenoid field	T	2
Beam radius in solenoid/cathode	mm	~1 / 3
Solenoid field at cathode	KG	2

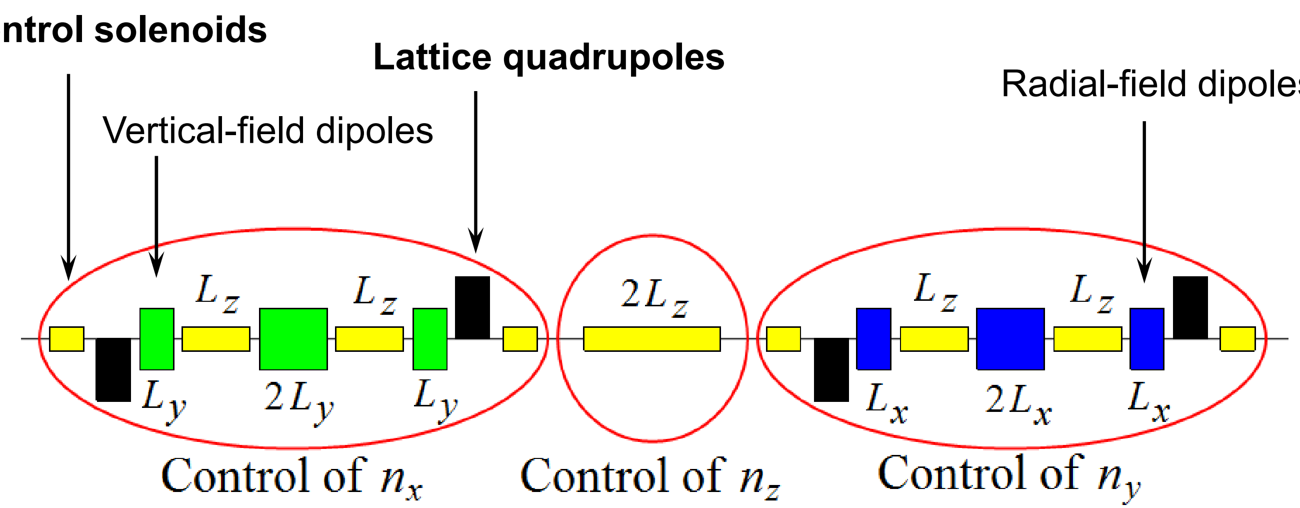
Ion Polarization in Booster

- No special care is needed for ion polarization before the booster
  - highly polarized ion source + no polarization loss in the linac
- Polarization in Booster stabilized and preserved by a single weak solenoid
  - 0.7 Tm at 9 GeV/c
  - $\nu_d / \nu_p = 0.003 / 0.01$
- Longitudinal polarization in the straight with the solenoid
- Comparison: Conventional 9 GeV accelerators require $B_{||}L$ of ~30 Tm for protons and ~110 Tm for deuterons

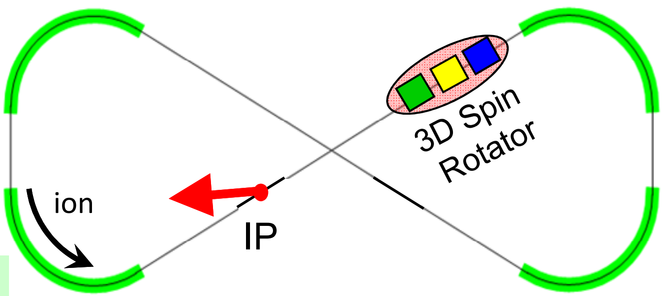


Ion Polarization in Collider Ring

- "3D spin rotator" rotates the spin about any chosen direction in 3D and sets the stable polarization orientation $\vec{S} = (n_x, n_y, n_z)$
  - Maximum $B_\perp$ of 3 T and $B_{//}$ of 3.6 T => $\nu_d / \nu_p = 0.00025 / 0.01$



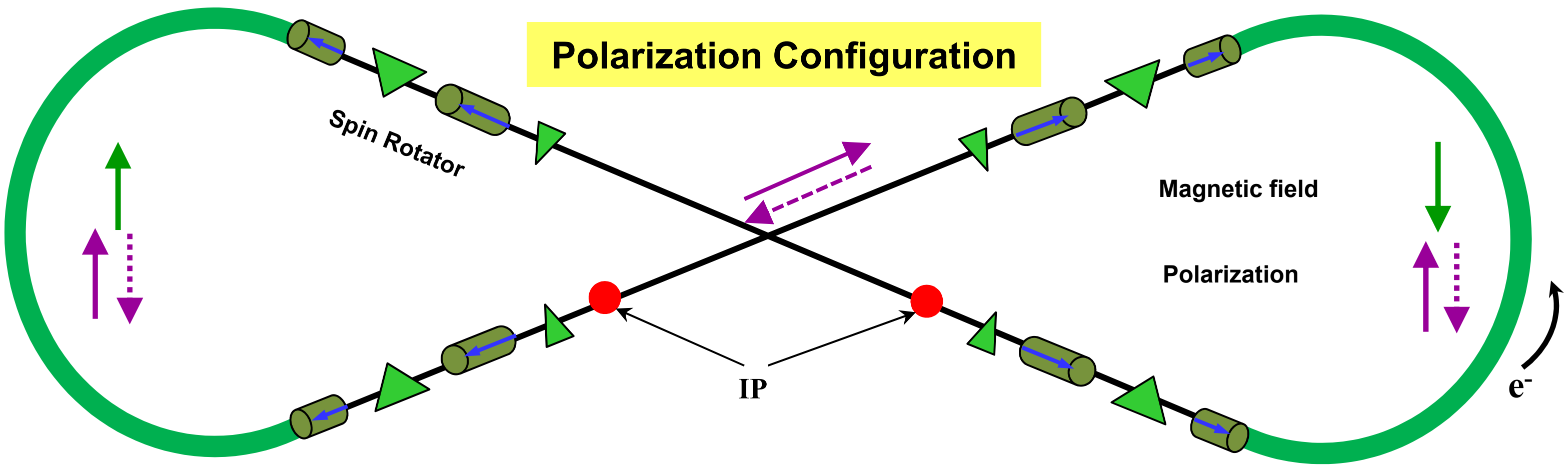
- Placement of 3D spin rotator in the collider ring
- Another 3D spin rotator suppresses the zero-integer spin resonance

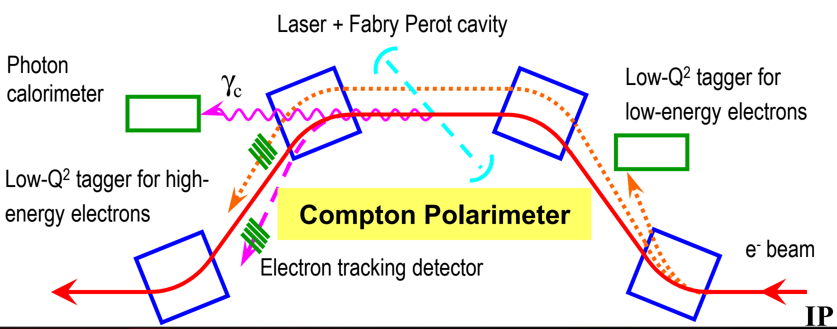


Ion polarization: TUPWI029, TUPWI030

Electron Polarization

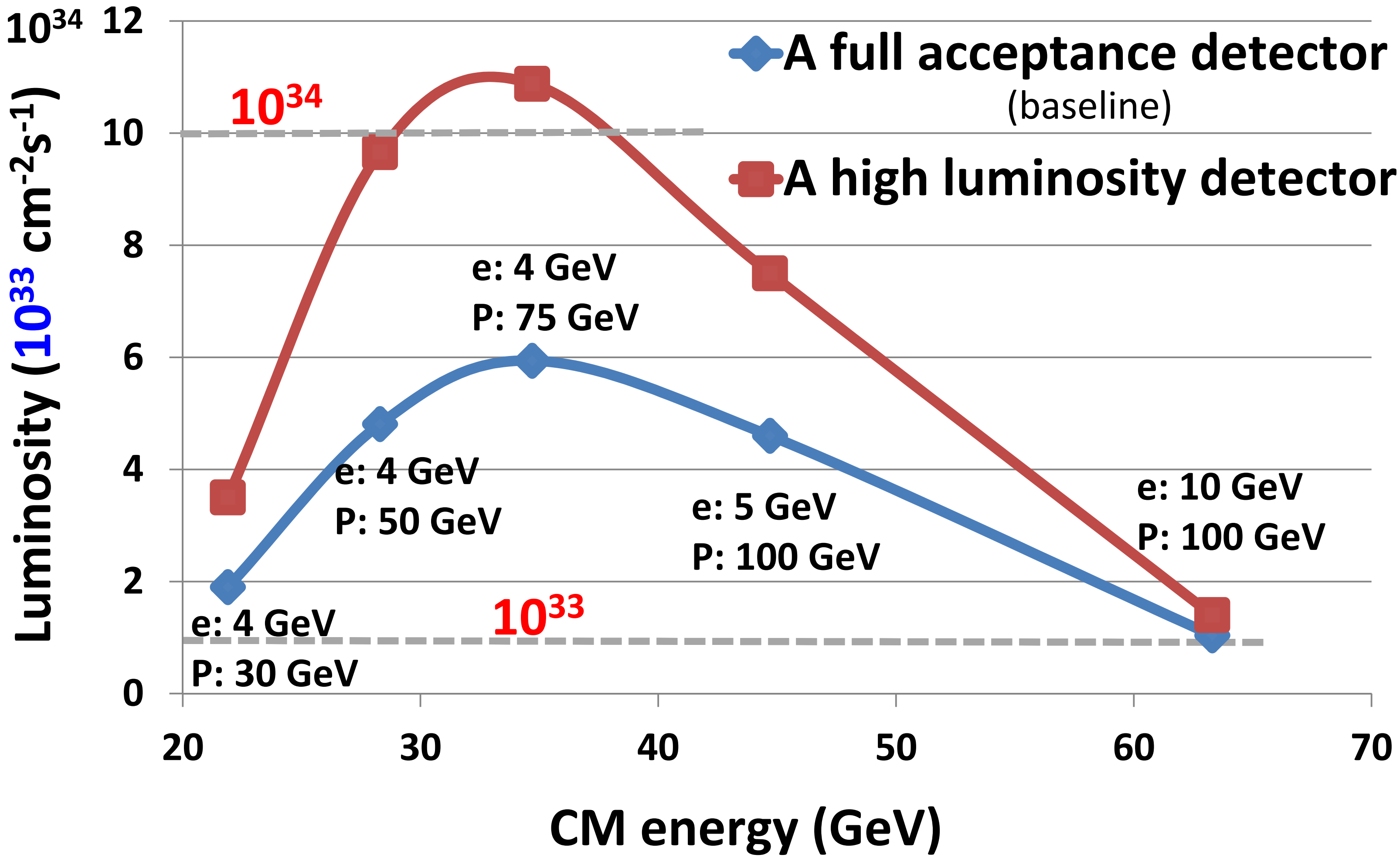
- Electron polarization design:
  - Vertically polarized (>85%) electron beam from CEBAF
  - Vertical polarization in the arcs and longitudinal at collision points
  - Spin rotator for the polarization rotation
  - Compton polarimeter provides non-invasive measurements of polarization
  - Average electron polarization reaches above 70%





Energy (GeV)	3	5	7	9	10
Estimated Pol. Lifetime (hours)	66	5.2	2.2	1.3	0.8

e-p Collision Luminosity



Overview of R&D

- Prototypes
  - Development and testing of 1.2m 3T SF magnets for MEIC ion ring and booster Collaboration with Texas A&M , FY15-16
  - Crab cavity development (collaboration with ODU, leveraging R&D for LHC / LARP crab)
  - 952 MHz Cavity development, FY15-17
- Design optimization/Modeling
  - Optimization of conceptual design of MEIC ion linac

    Collaboration with ANL and/or FRIB, FY 15-17
  - Optimization of Integration of detector and interaction region design, detector background, non-linear beam dynamics, PEP-II components

    Collaboration with SLAC, FY 12-17
  - Feasibility study of an experimental demonstration of cooling of ions using a bunched electron beam

    Collaboration with Institute of Modern Physics, China
  - Studies and simulations on preservation and manipulation of ion polarization in a figure-8 storage ring

    Collaboration with A. Kondratenko, FY 13-15
  - Algorithm and code development for electron cooling simulation, FY 15-16

Summary and Outlook

- The baseline design of MEIC based on a ring-ring concept
  - delivers luminosities from **10^{33}** up to **10^{34}** $cm^{-2}s^{-1}$ in a broad CM energy range,
  - provides beam polarizations over **70%**,
  - has **low** technical risks.
- MEIC baseline design meets the nuclear physics community requirements.
- We continue the work for R&D items.
- We continue to optimize the present design for cost and performance.
- The MEIC design can be upgraded in energy and luminosity.

MEIC Posters

- MOPMN011 Studies of Beam Cooling for MEIC
- TUPWI029 Baseline Scheme for Polarization Preservation and Control in the MEIC Ion Complex
- TUPWI030 Numerical Calculation of the Ion Polarization in MEIC
- TUPWI031 Status of the MEIC Ion Collider Ring Design
- TUPWI032 Progress on Optimization of the Nonlinear Beam Dynamics in the MEIC Collider Rings
- TUPWI034 Capture, Acceleration and Bunching RF Systems for the MEIC Booster and Storage Rings
- TUPWI037 Electron Cooling Study for MEIC
- TUPMA034 Control of Coherent Synchrotron Radiation Effects During Recirculation with Bunch Compression
- TUPMA035 Control of Coherent Synchrotron Radiation Effects During Recirculation
- TUPWI038 A Multi-Gun Injector for the MEIC Bunched Beam Electron Cooling Facility
- TUPWI039 Modeling Crabbing Dynamics in an Electron-Ion Collider
- TUPWI040 Electron Cooling Simulation for MEIC
- TUPTY083 Concepts for Using CEBAF as a Full-energy Injector for the MEIC Electron Ring
- TUPTY084 Update on the MEIC Electron Collider Ring Design
- WEPWI024 RF System Requirements for a Medium-Energy Electron-Ion Collider (MEIC) at Jlab
- WEPWI034 Multipole Budget of Crab Cavities for an Electron-Ion Collider
- WEPMN025 Harmonic Resonant Kicker Design for the MEIC Electron Circular Cooler Ring

Thank You for Your Attention !