MEIC Project at Jefferson Lab

Fanglei Lin

Center for Advanced Studies of Accelerators, Jefferson Lab

29th Annual Hampton University Graduate Studies Program

HUGS 2014, Jefferson Lab, June 2-20, 2014

Jefferson Lab

Thomas Jefferson National Accelerator Facility

MEIC Study Group

S. Abeyratne[12], A. Accardi[1,7], S. Ahmed[1], D. Barber[6], J. Bisognano[18], A. Bogacz[1], A. Castilla[13,17], P. Chevtsov[14], S. Corneliussen[1], W. Deconinck[5], P. Degtiarenko[1], J. Delayen[13], Ya. Derbenev[1], S. DeSilva[13], D. Douglas[1], V. Dudnikov[11], R. Ent[1], B. Erdelyi[12], P. Evtushenko[1], Yu. Filatov[9,10], D. Gaskell[1], R. Geng[1], J. Grames[1], V. Guzey[1], T. Horn[4], A. Hutton[1], C. Hyde[13], R. Johnson[11], Y. Kim[8], F. Klein[4], A. Kondratenko[16], M. Kondratenko[16], G. Krafft[1,13], R. Li[1], F. Lin[1], S. Manikonda[2], F. Marhauser[11], R. McKeown[1], V. Morozov[1], P. Nadel-Turonski[1], E. Nissen[1], P. Ostroumov[2], M. Pivi[15], F. Pilat[1], M. Poelker[1], A. Prokudin[1], R. Rimmer[1], T. Satogata[1], H. Sayed[3,] M. Spata[1], M. Sullivan[15], C. Tennant[1], B. Terzić[1], M. Tiefenback[1], H. Wang[1], S. Wang[1], C. Weiss[1], B. Yunn[1], Y. Zhang[1]

[1] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[2] Argonne National Laboratory, Argonne, IL 60439, USA
[3] Brookhaven National Laboratory, Upton, NY 11973, USA
[4] Catholic University of America, Washington, DC 20064, USA
[5] College of William and Mary, Williamsburg, VA 23187, USA
[6] Deutsches Elektronen-Synchrotron (DESY), 22607 Hamburg, Germany
[7] Hampton University, Hampton, VA 23668
[8] Idaho State University, Pocatello, ID 83209, USA
[9] Joint Institute for Nuclear Research, Dubna, Russia
[10] Moscow Institute of Physics and Technology, Dolgoprydny, Russia
[11] Muons Inc., Batavia, IL 60510, USA
[12] Northern Illinois University, DeKalb, IL 60115, USA
[13] Old Dominion University, Norfolk, VA 23529, USA
[14] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[15] SLAC National Accelerator Laboratory, Menlo Park, CA 94305, USA
[16] Science and Technique Laboratory Zaryad, Novosibirsk, Russia
[17] Universidad de Guanajuato, 36000 Guanajuato, Mexico
[18] University of Wisconsin-Madison, Madison, WI 53706, USA

Introduction

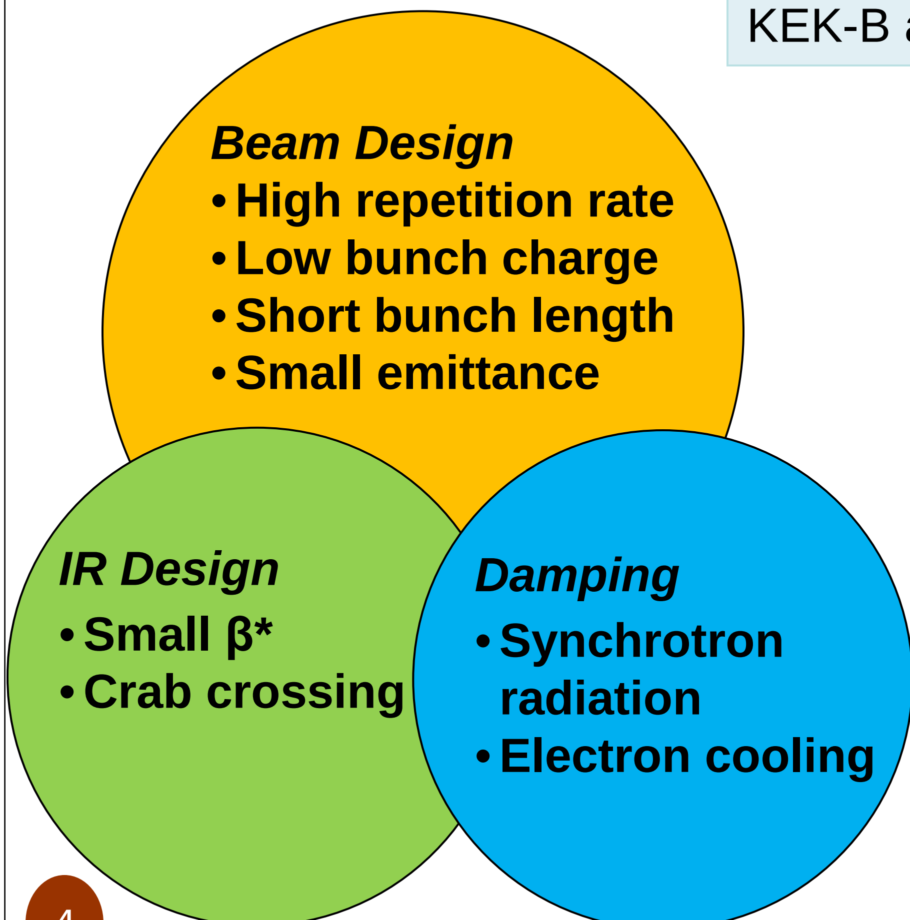
- JLab's fixed target program after the 12 GeV CEBAF upgrade will be world-leading for at least a decade
- A *Medium* energy *Electron-Ion Collider* (MEIC) at JLab will open new frontiers in nuclear science.
- MEIC parameters are chosen to optimize science, technology development, and project cost.
- We maintain a well-defined path for future upgrade to higher energies and luminosities.
- A design report was released on August, 2012, providing a base for performance evaluation, cost estimation, and technical risk assessment.
- We are working for a complete Conceptual Design Report in 2-3 years.

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 2x10^{34} /cm^2/s

$$L = f\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim f\frac{n_1 n_2}{\varepsilon_y^*}\xi$$



"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

Linac-Ring colliders
- Large beam-beam parameter for the electron beam
- Need to maintain high polarized electron current
- High energy/current ERL

Design Strategy for High Polarization

- All rings have a figure-8 shape with critical advantages for both ion and electron beam
  - Spin precessions in the left & right parts of the ring are exactly cancelled
  - Net spin precession (***spin tune***) is zero, thus energy independent
  - Spin is easily controlled and stabilized by small solenoids or other compact spin rotators
- Advantage 1: Ion spin preservation during acceleration
  - Ensures spin preservation
  - Avoids energy-dependent spin sensitivity for all species of ions
  - Allows 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*
- Advantage 4: Strong reduction of quantum depolarization thanks to the energy independent spin tune
  - Helps to preserve polarization of the electron beam continuously injected from CEBAF

MEIC Design Parameters

❖ Energy

- Full coverage of center of mass energy from 15 to 65 GeV
- Electrons 3-12 GeV, protons 25-100 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)

❖ At least 2 detectors

- Full acceptance is critical for the primary detector

❖ Luminosity

- Maximum luminosity >$\mathbf{10^{34}}$ optimized to be around $\sqrt{s}$=45 GeV
- Above 10^{33} $cm^{-2}s^{-1}$ per IP in a *broad* CM energy range

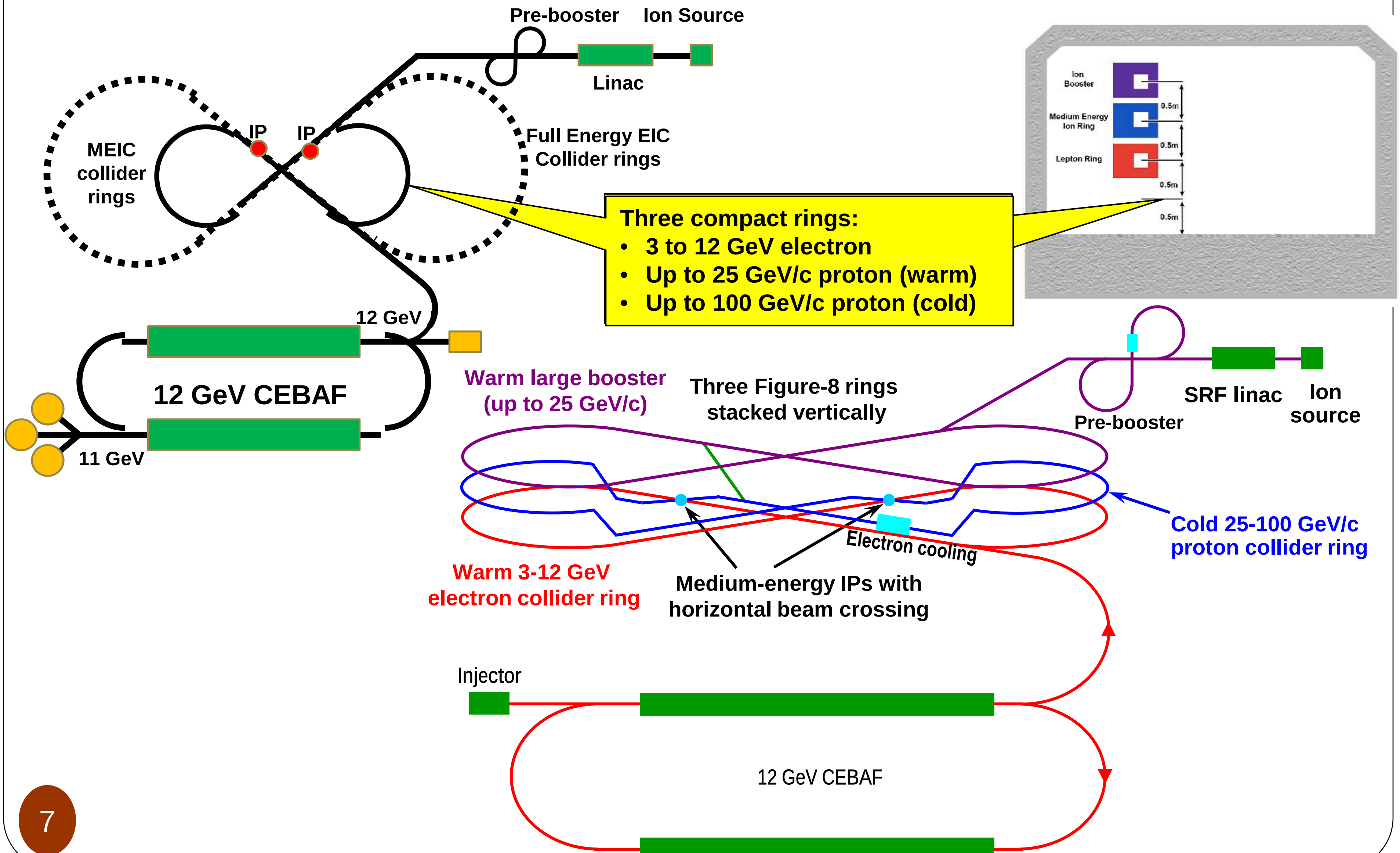
❖ Polarization

- At IP: longitudinal for both beams, transverse for ions only
- All polarizations >70%

❖ Upgrade to higher energies and luminosity possible

- 20 GeV electron, 250 GeV proton, and 100 GeV/u ion

MEIC Layout

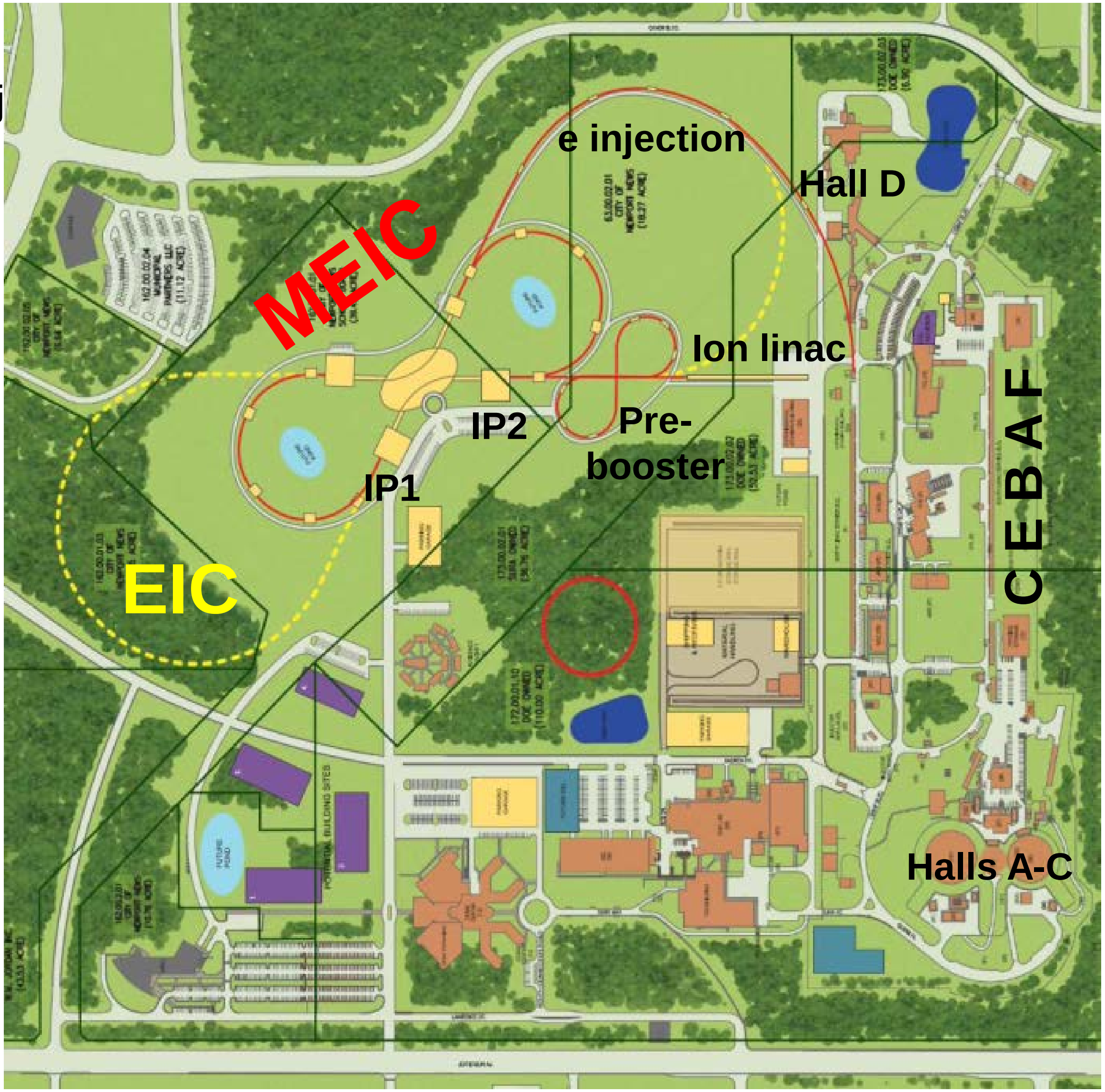

Pre-booster
Ion Source
Linac
MEIC collider rings
IP
IP
Full Energy EIC Collider rings
Ion Booster
Medium Energy Ion Ring
Lepton Ring
0.5m
0.5m
0.5m
0.5m
Three compact rings:
• 3 to 12 GeV electron
• Up to 25 GeV/c proton (warm)
• Up to 100 GeV/c proton (cold)
12 GeV
12 GeV CEBAF
11 GeV
Warm large booster (up to 25 GeV/c)
Three Figure-8 rings stacked vertically
Pre-booster
SRF linac
Ion source
Cold 25-100 GeV/c proton collider ring
Electron cooling
Warm 3-12 GeV electron collider ring
Medium-energy IPs with horizontal beam crossing
Injector
12 GeV CEBAF

EIC at JLab

❖ Stage I MEIC
- CEBAF as full-energy e^-/e^+ inj
- 3-12 GeV e^-/e^+
- 25-100 GeV protons
- 12-40 GeV/u ions

❖ Stage II EIC
- up to 20 GeV e^-/e^+
- up to 250 GeV protons
- up to 100 GeV/u ions

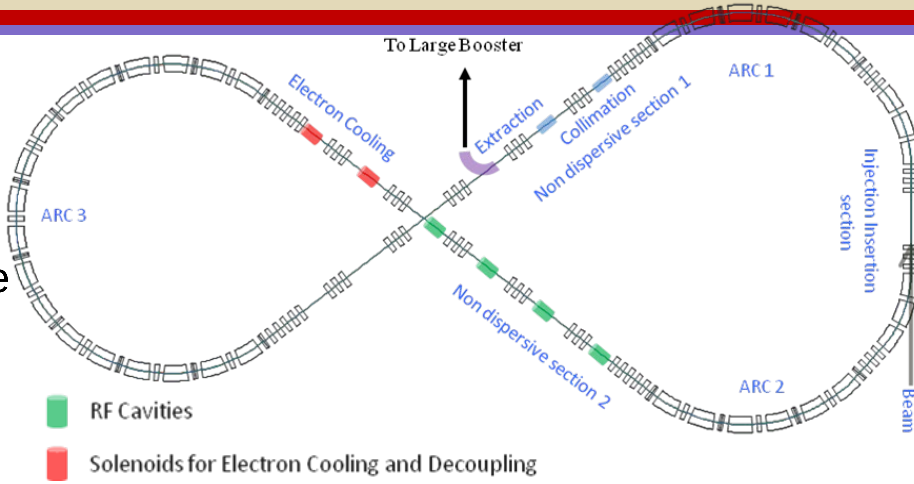
❖ Two independent but complementary detectors



Ion Pre-booster

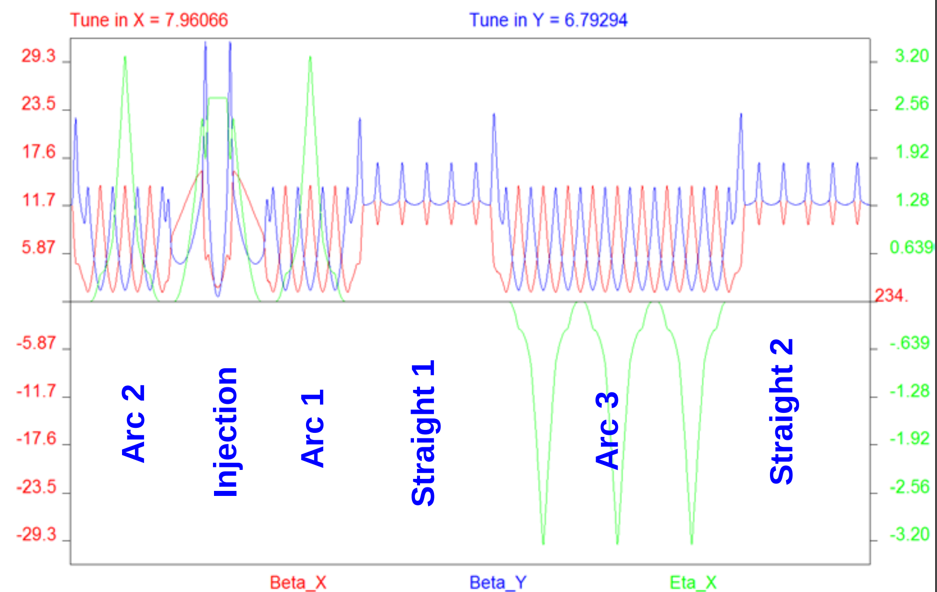
❖ Purpose of pre-booster

- Accumulation of ions injected from linac
- Acceleration of ions
- Extraction and transfer of ions to the large booster



❖ Design concepts

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



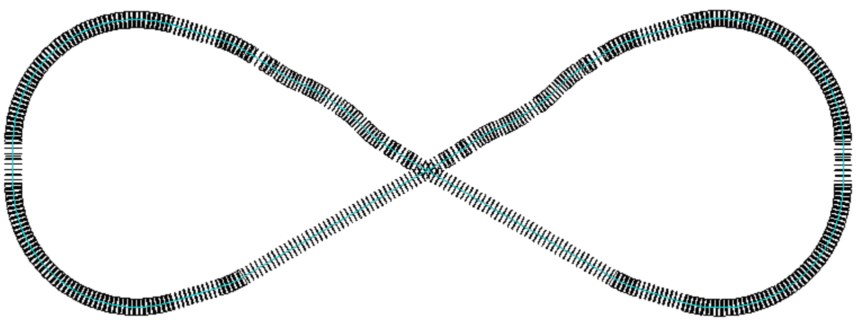
❖ Design considerations

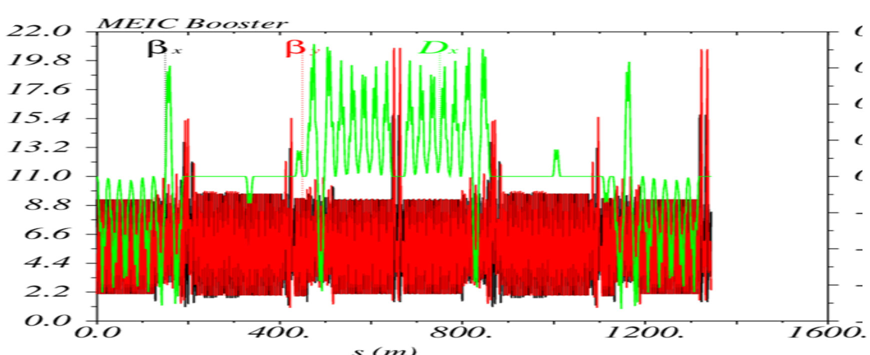
- Maximum bending field: **1.5 T**
- Maximum quad field gradient: **20 T/m**
- Momentum compaction smaller than 1/25
- Maximum beta functions less than 35 m
- Maximum full beam size less than 2.5 cm
- 5m dispersion-free drifts between triplets for RF, cooling, collimation and extraction

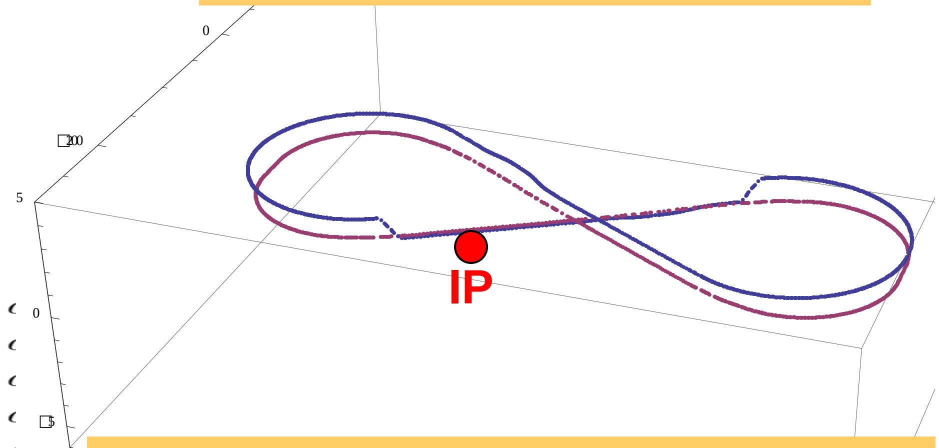
Ion Large Booster

- Accelerates protons from **3 to 25 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=26.65)
- Quadrupole based dispersion suppression
- Tunable to any working point

Possible to convert the large booster to a low energy collider ring

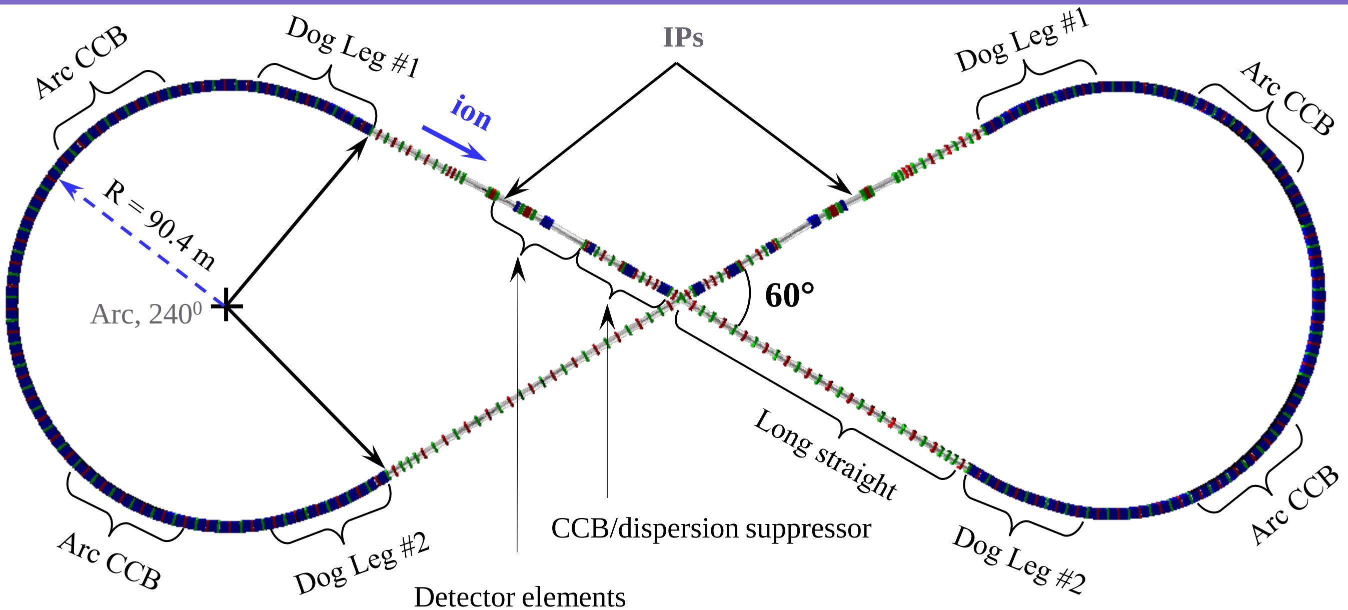


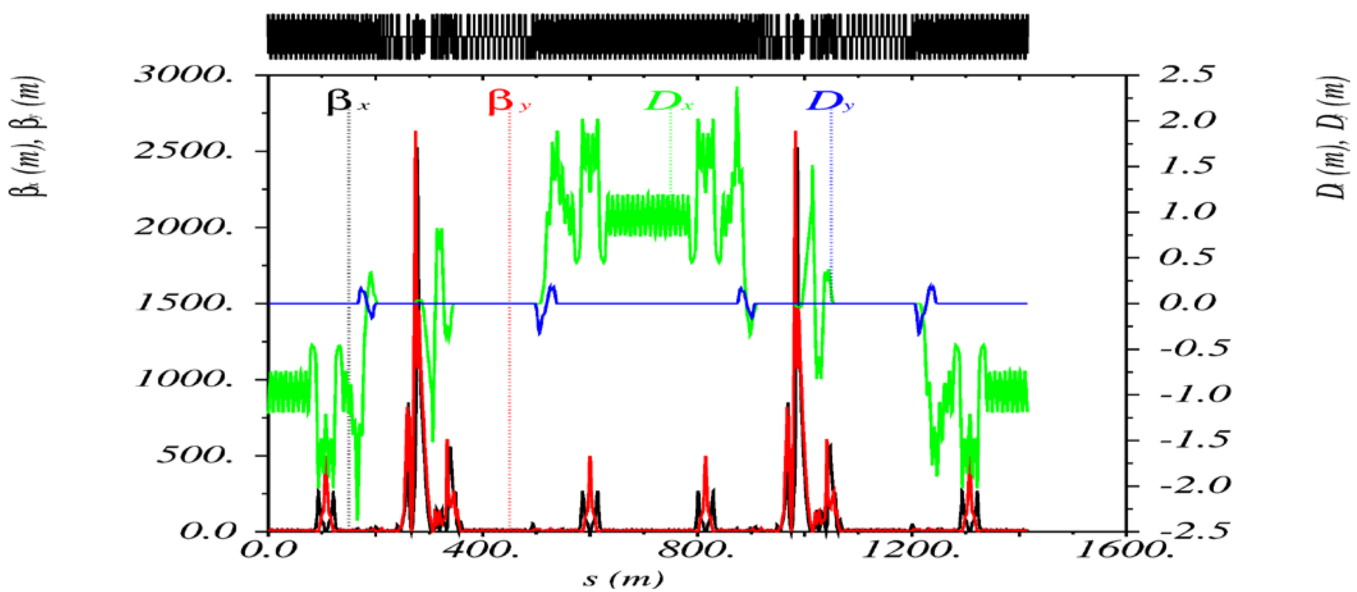




- Vertical chicane to bring low energy ions to the plane of the electron ring
- Add electron cooling and SRF
- Share detector with MEIC

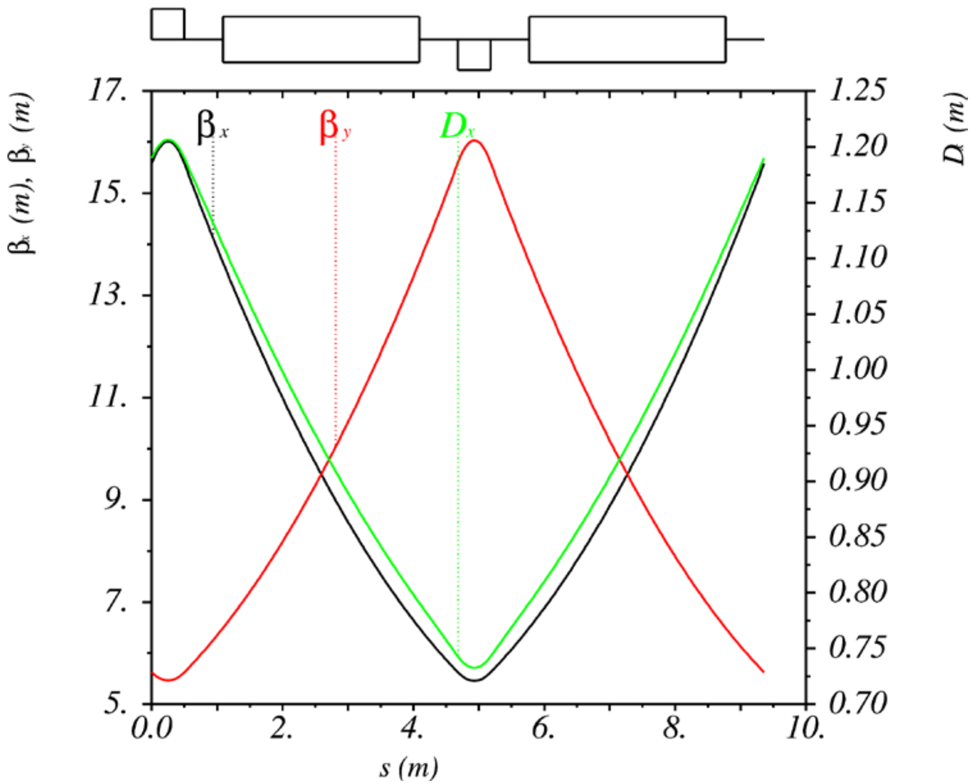
MEIC Ion Collider Ring





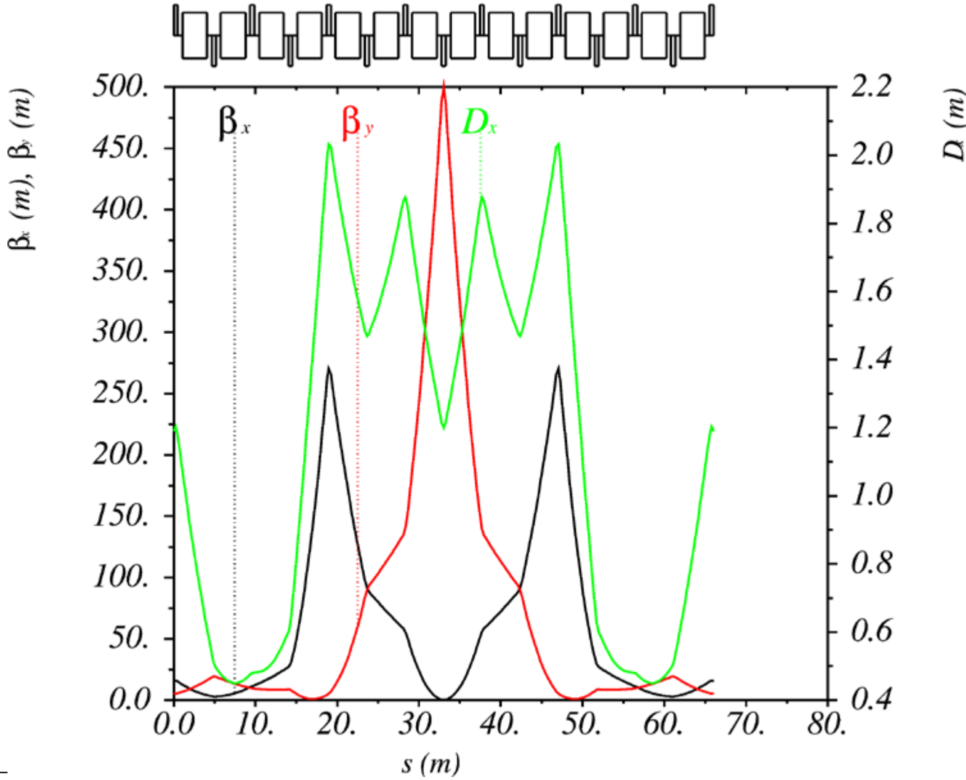
Ion Arc FODO Cell

- Arc basic building block
  - Dipole field ~5.8T at 100 GeV/c
  - Quad gradient ~150 T/m with 60° phase advance at 100 GeV/c



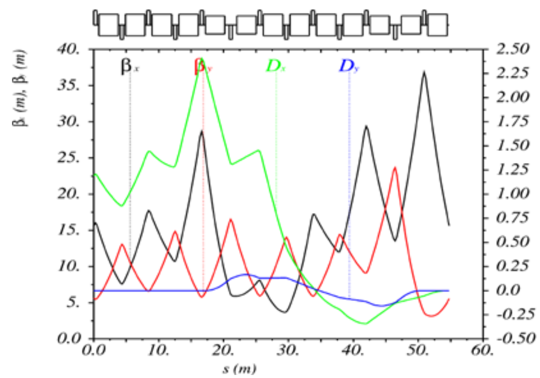
Ion Chromaticity Compensation Block

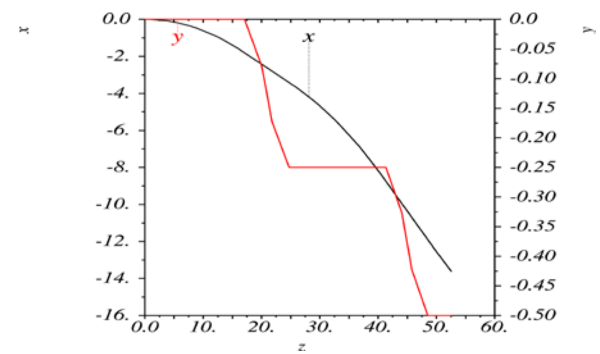
- CCB
  - Based on and matched to regular FODO lattice
  - Provides necessary orbital and magnetic symmetries
  - Placed in arc to save space in straights
  - Adjustable max β function values for non-linear dynamics optimization
  - Chromatic contribution ~-8 in both planes



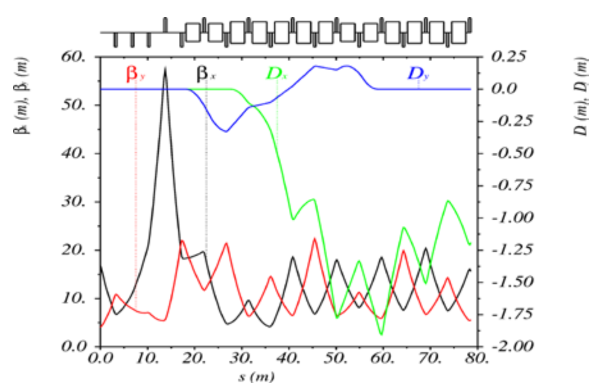
Ion Vertical Doglegs

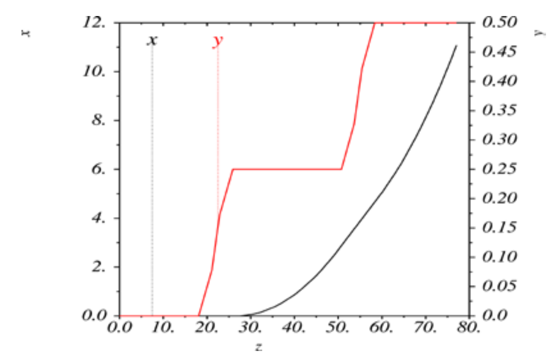
- Bring ion beam to electron ring plane at arc ends
  - Combined with horizontal bend to save space
  - Suppressed/compensated horizontal/vertical dispersions
- Dogleg upstream of IP: shaped to provide 50mrad crossing angle





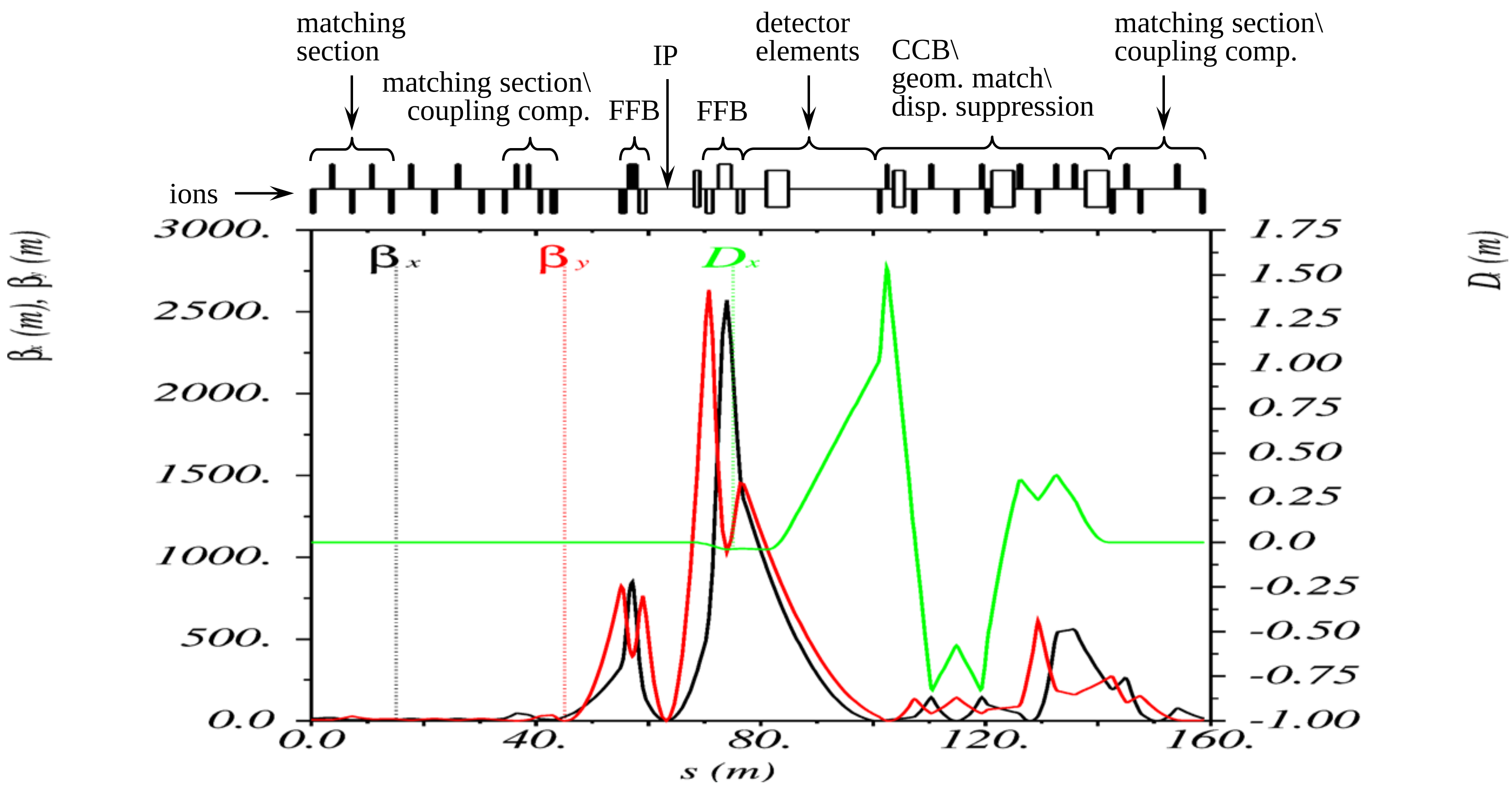
- Dogleg downstream of IP: shaped to provide 2m separation from electron beam





Ion Interaction Region

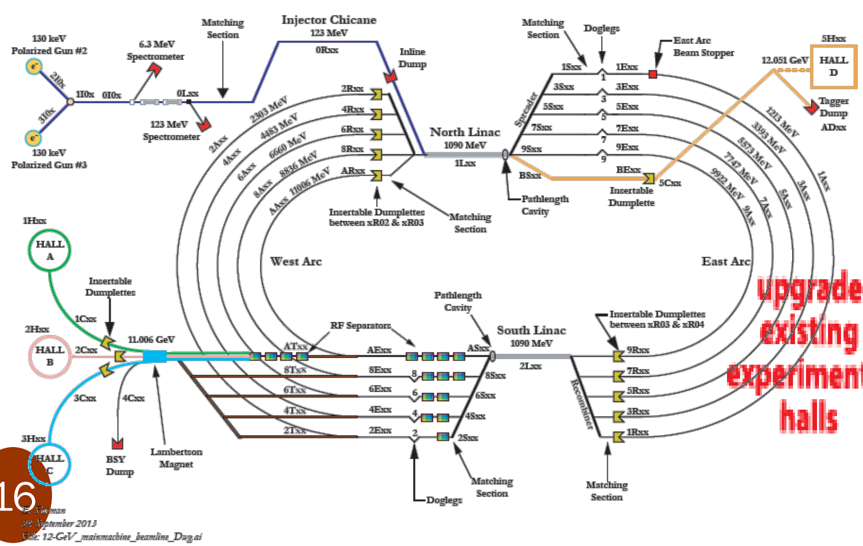
- IR design features
  - Based on triplet final focusing blocks (FFB)
  - Asymmetric design to satisfy detector requirements and reduce chromaticity
  - Spectrometer dipoles before and after downstream FFB, second focus downstream of IP
  - No dispersion at IP, downstream dispersion suppression designed to function as CCB

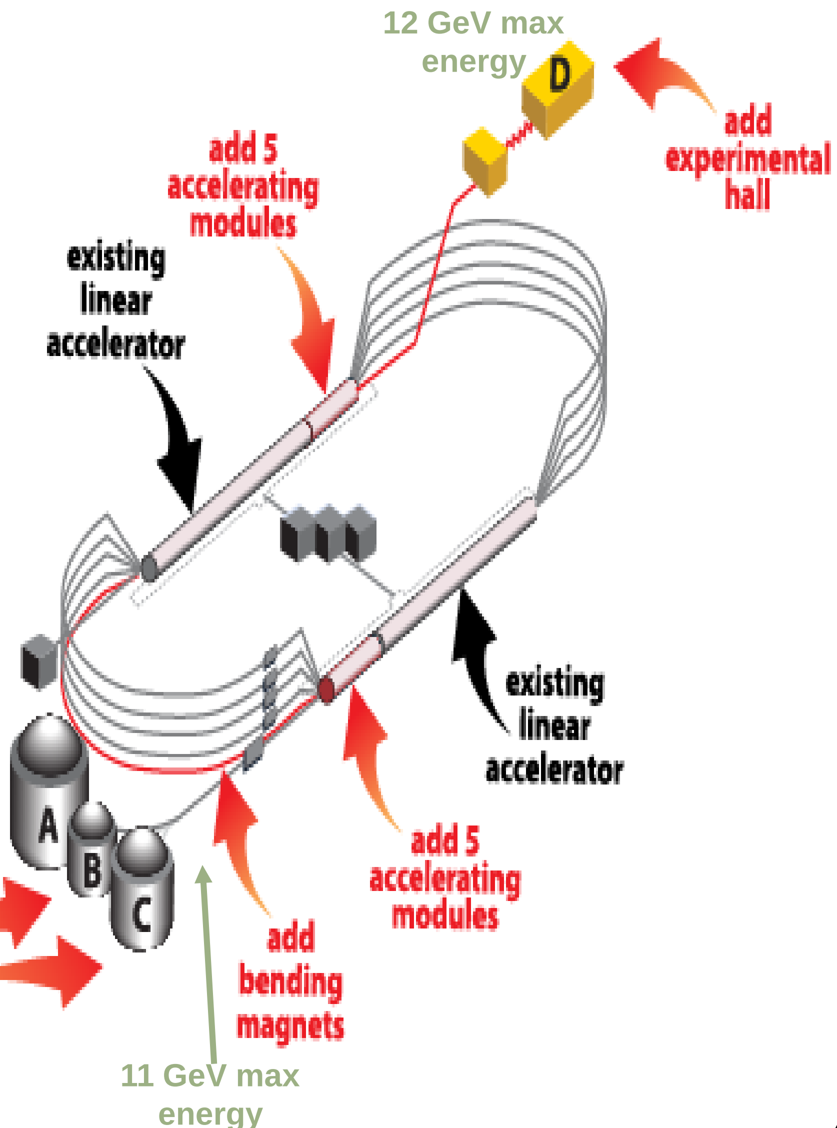


12 GeV CEBAF

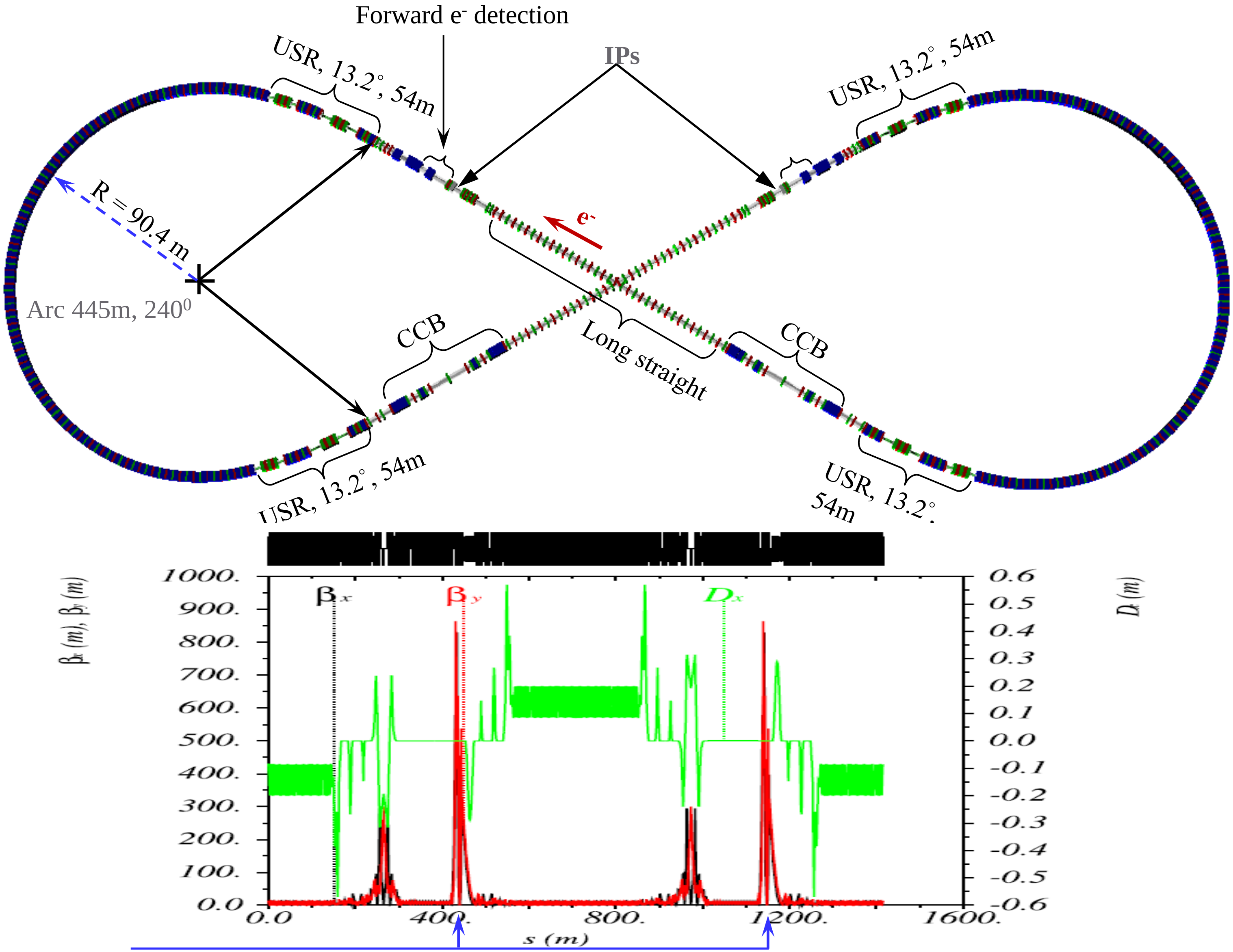
- CEBAF fixed target program
  - 5-pass recirculating SRF linac
- CEBAF will provide
  - Up to 12 GeV CW electron beam
  - High repetition rate (3)
  - High polarization (>85%)
  - Good beam quality up to mA level
  - Exciting science program beyond 2025

JEFFERSON LAB 12 GeV BEAMLINE



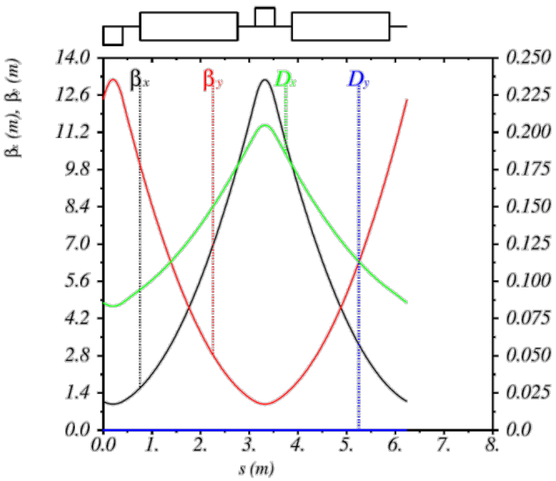


Electron Collider Ring Layout

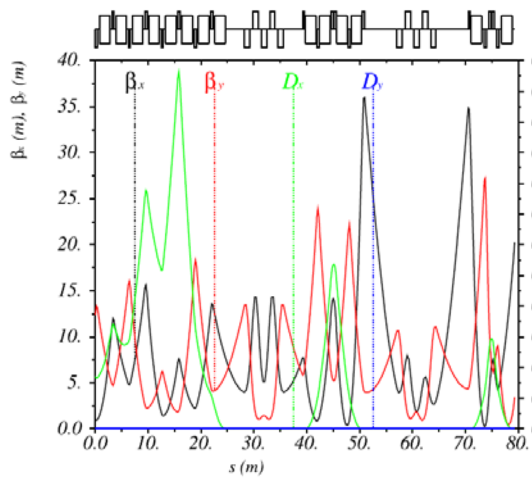


Electron Collider Ring Optics

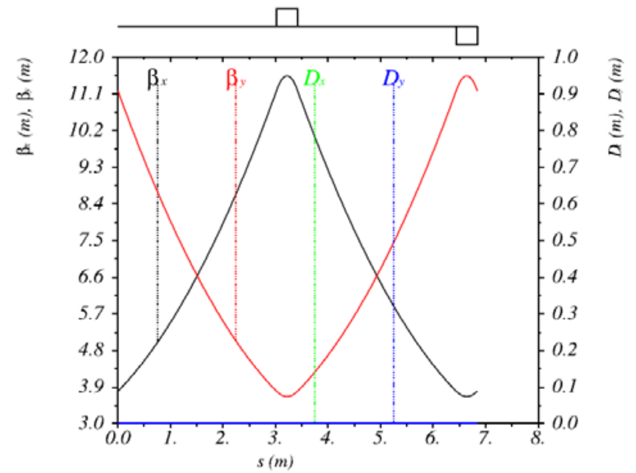
Arc FODO cell



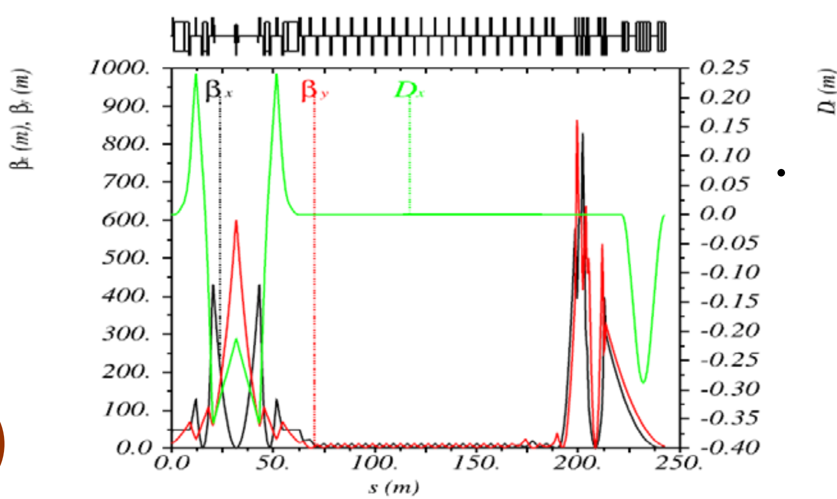
Matching + USR



LS FODO cell



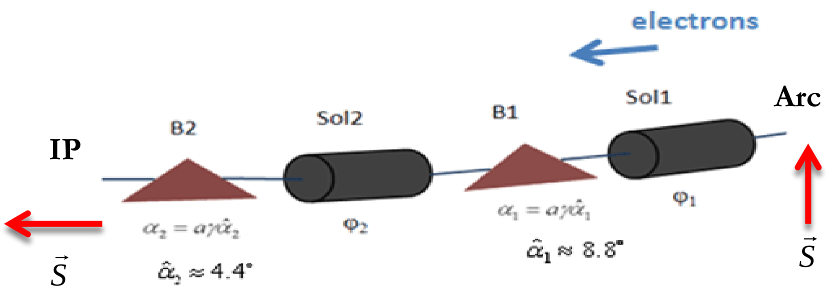
CCB + LS + IR



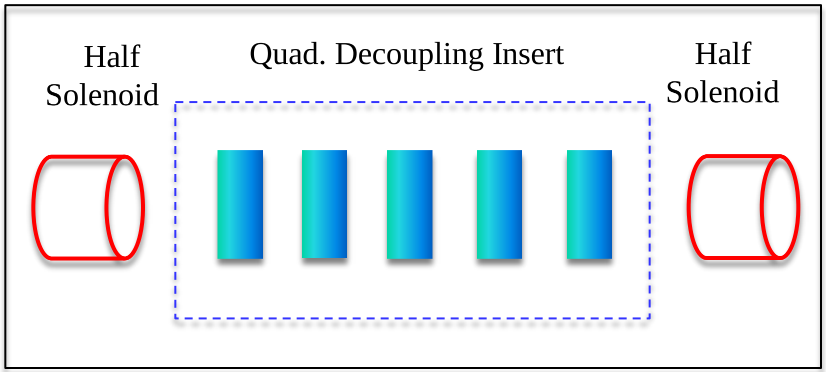
- Chromaticity needs to be compensated
  - locally using sextupole families in the CCBs for the IR and
  - globally using sextupole families in the Arcs

Universal Spin Rotator (USR)

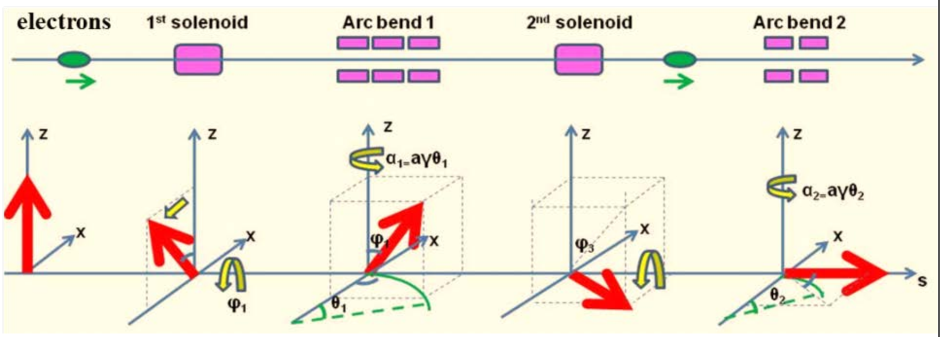
❖ Schematic drawing of USR

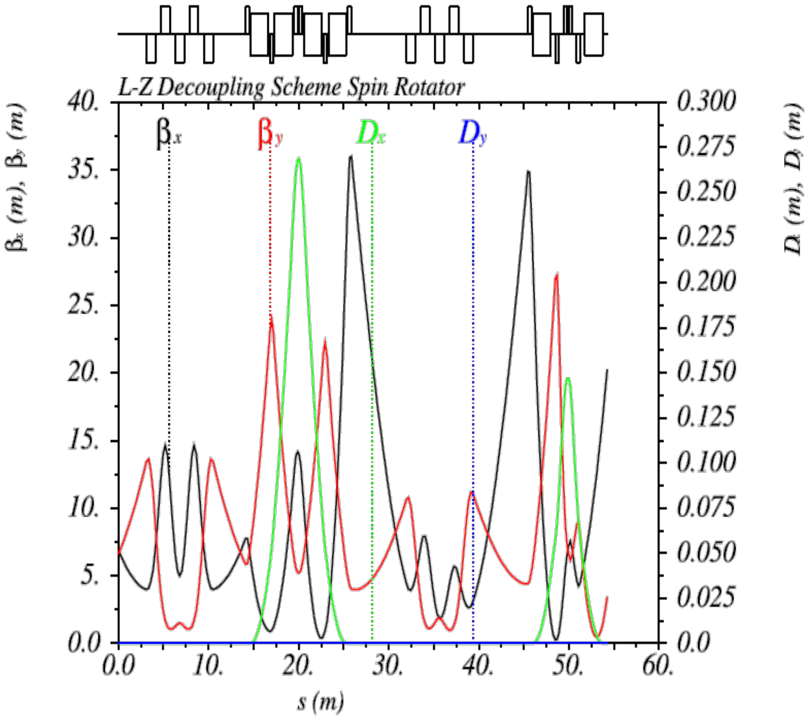


P. Chevtsov et al., Jlab-TN-10-026



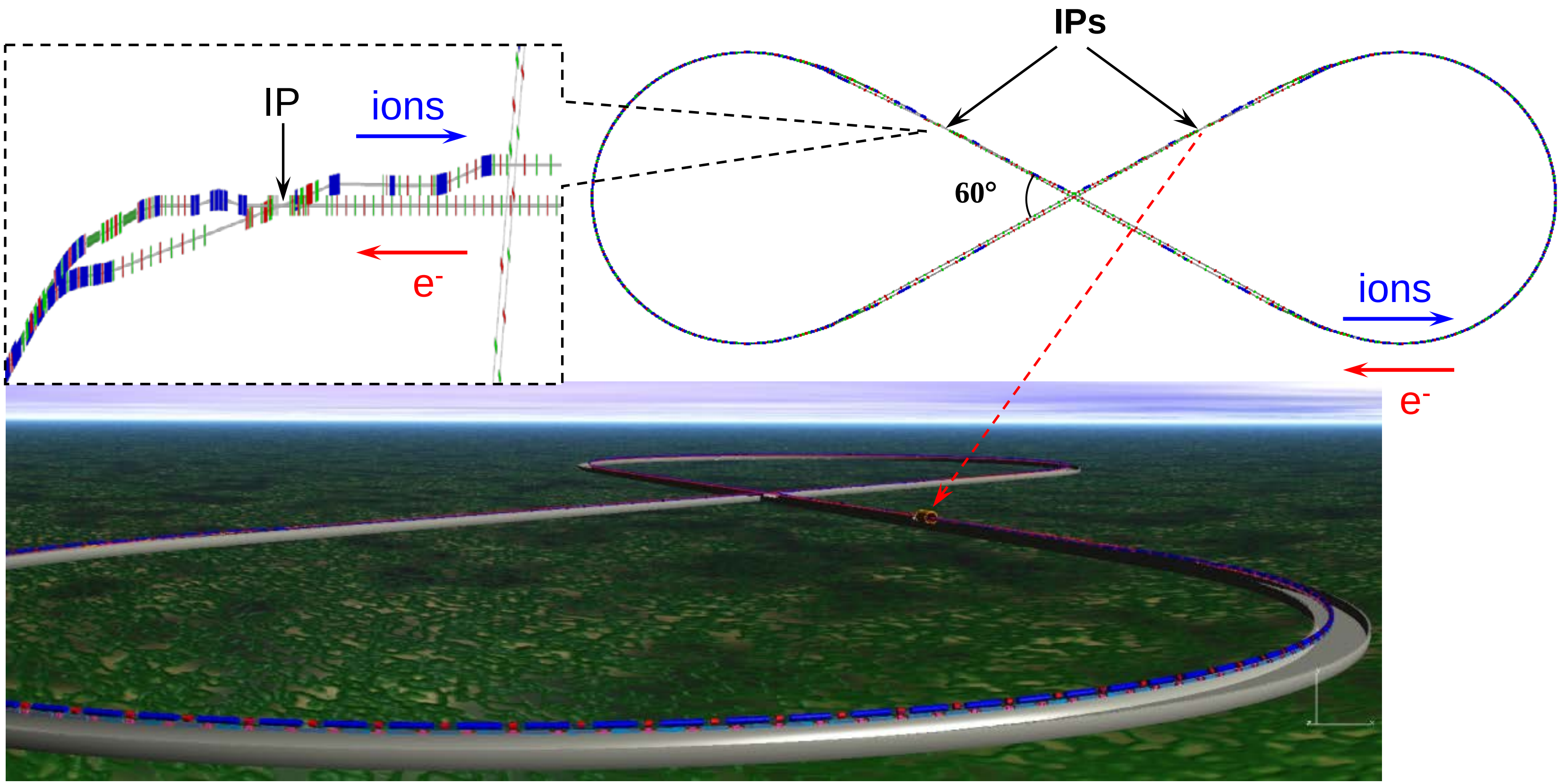
❖ Illustration of spin rotation by USR





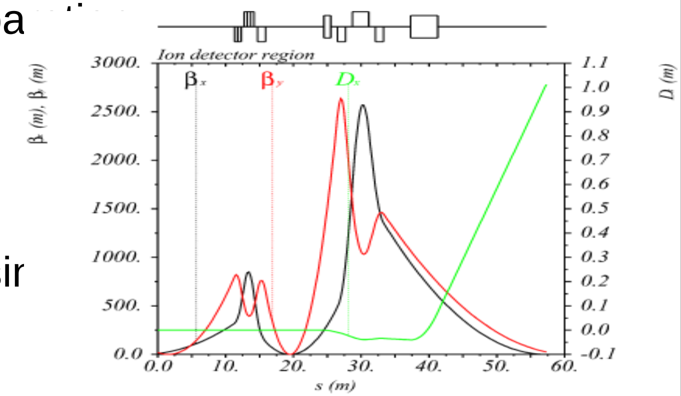
Collider Ring and IR Layout

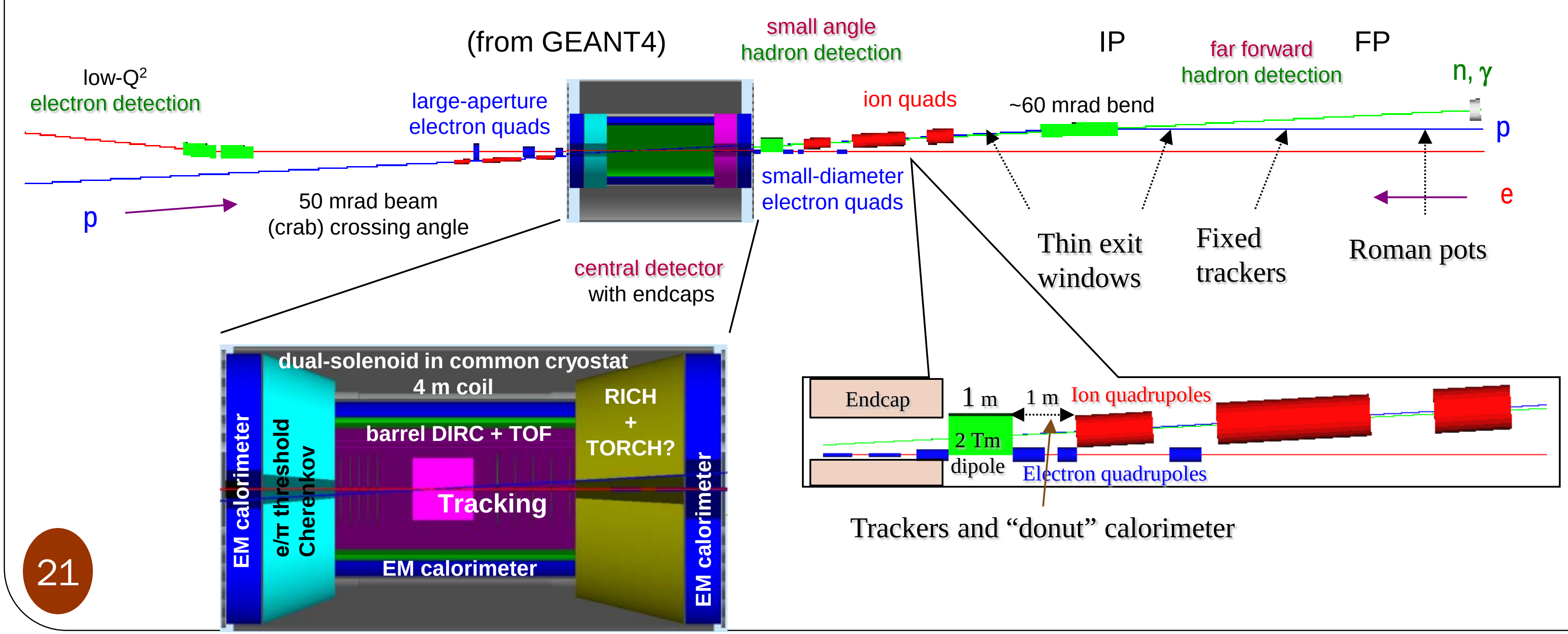
- Lattice design satisfying
  - **Detector** requirements: full acceptance and high resolution
  - **Beam dynamics** requirements: consistent with non-linear dynamics requirements
  - **Geometric** constraints: matched collider ring footprints and decouple the ring geometry from IR layout



Full Acceptance Detection System

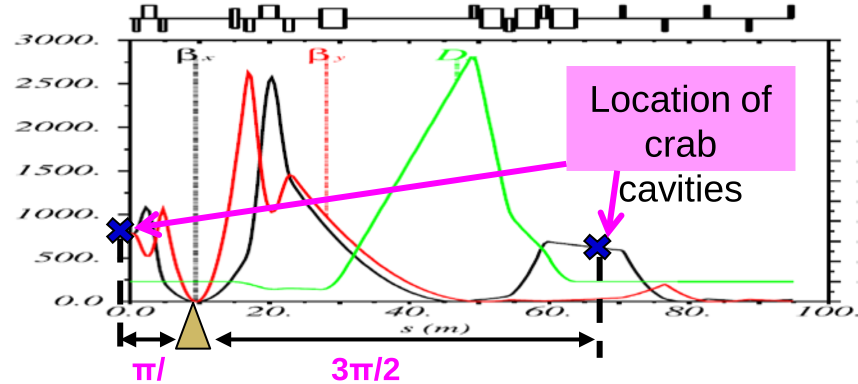
- 50 mrad crossing angle
  - Improved detection, no parasitic collision, fast beam sepa
- Forward
  - Endcap with 50 mrad crossing angle
  - Small dipole covering angles up to a few degrees
  - Far forward covering up to one degree for particles passir
- Low-Q^2 tagger: small-angle electron detection

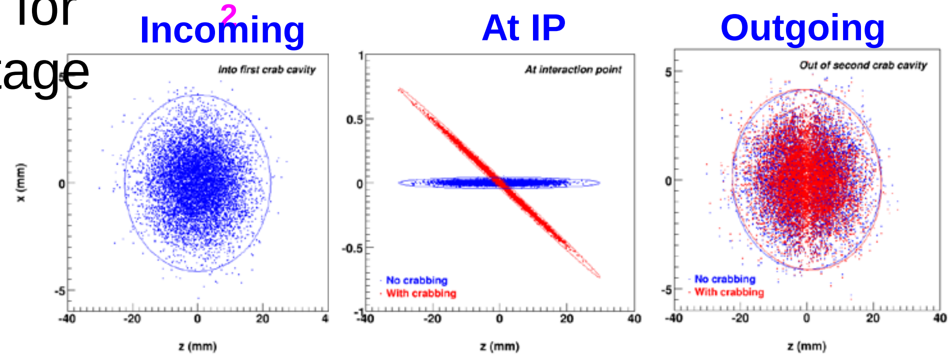


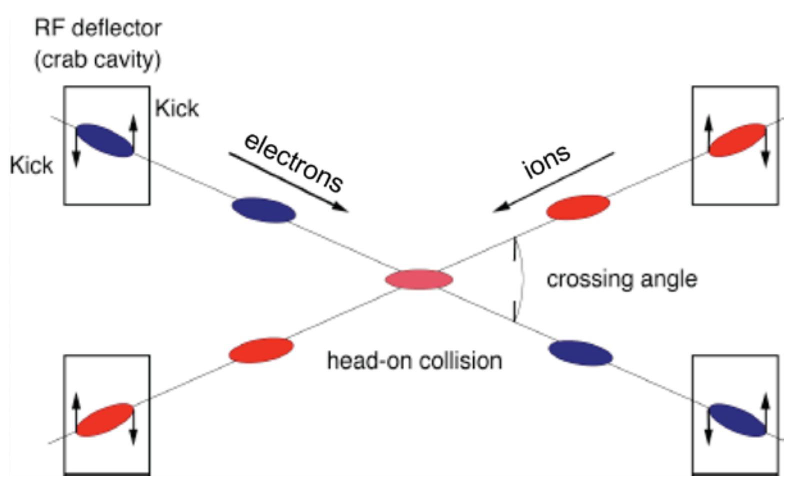


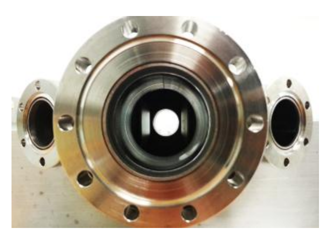
Crab Crossing

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







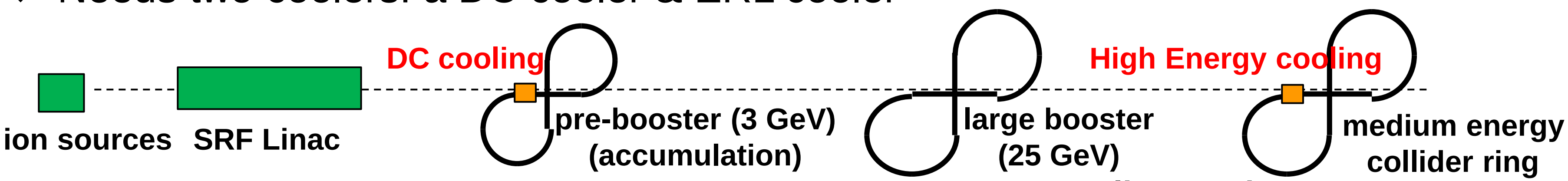


Electron Cooling for Ion Beams

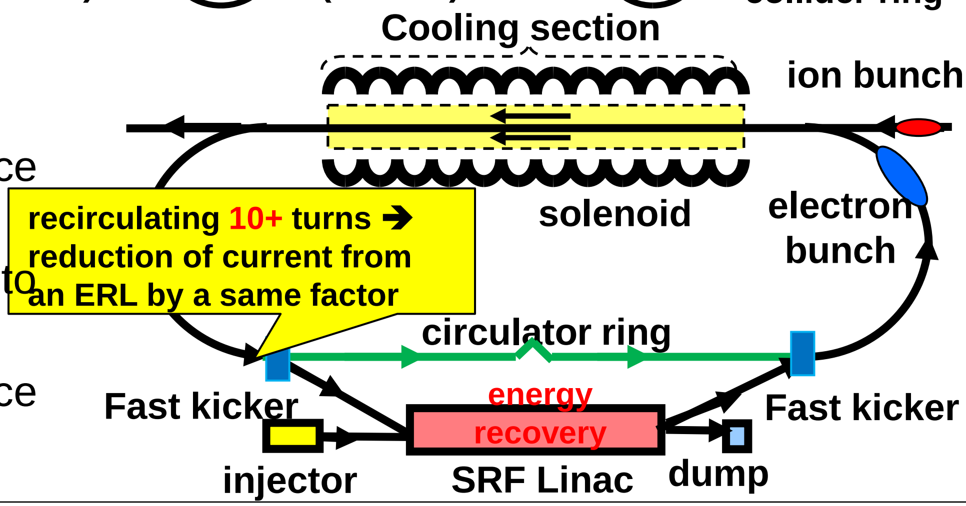
- Cooling of protons/ions: => small emittance and short bunch (w strong SRF)
  => enabling ultra strong final focusing and crab crossing
  => suppressing IBS, expanding high luminosity lifetime
- MEIC adopts traditional electron cooling
- Multi-phased scheme takes advantages of high cooling efficiency at low energy and small 6D emittance

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

- Needs two coolers: a DC cooler & ERL cooler



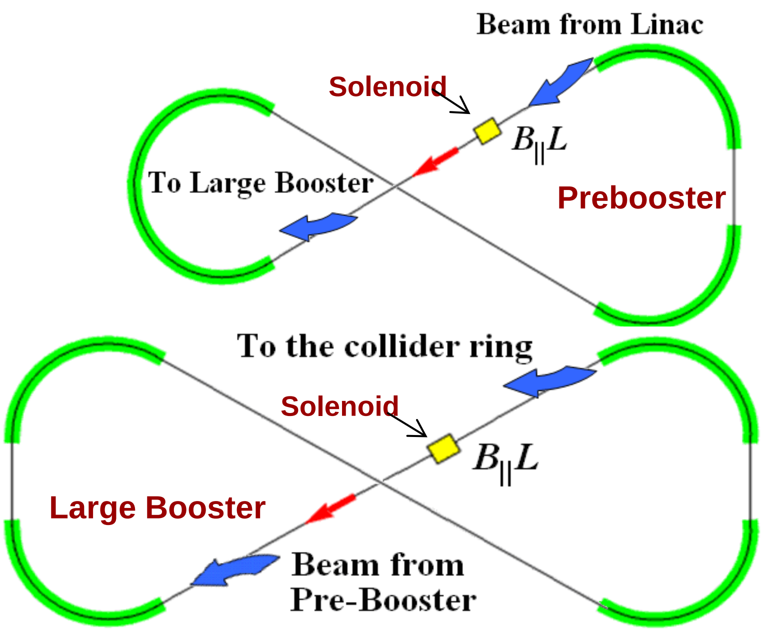
- Cooler design solution
  - Magnetized beam to mitigate space charge and CSR
  - Energy recovery linac (ERL) to minimize power requirements
  - Circulator cooler ring (CCR) to reduce source and ERL requirements



Ion Polarization

- Figure-8 structure as
  - No preferred periodic spin direction, energy-independent zero spin tune => polarization can be controlled by small magnetic fields
  - Avoids energy-dependent spin sensitivity for all species of ions
  - Works for all ion species including **deuterons** with small anomalous magnetic moment
- Acceleration and spin matching
  - Polarization is stabilized by weak (< 3 Tm) solenoids in all ion rings
  - Injection and extraction from straight with solenoid

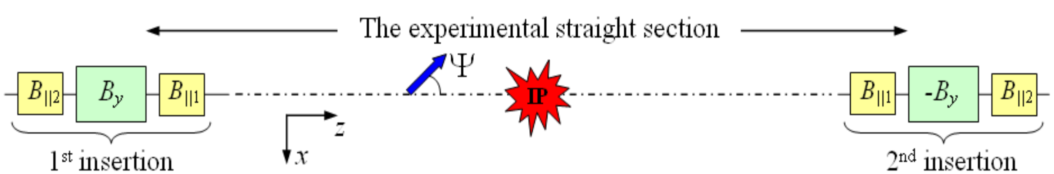
	$P_{inj/ext}$ (GeV/c)	$(BL)_{inj/ext}$ (T.M)	L (cm)	ν_{deut}/ν_{prot}
Pre-booster (1 solenoid)	0.785 / 3.83	0.06 / 0.28	60	0.003 / 0.01
Large booster (1 solenoid)	3.83 / 20	0.28 / 1.5	120	0.003 / 0.01



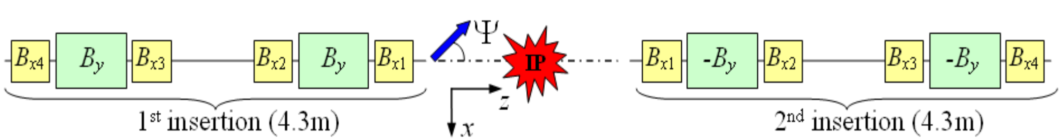
Ion Polarization (cont'd)

- Polarization control in the collider ring
  - Beam is injected longitudinally polarized, accelerated and then the desired spin orientation is adjusted
  - Weak solenoid for deuterons (< 1.5 Tm each)
  - Weak radial-field dipoles for protons (< 0.25 Tm each)
  - Small or no orbit excursions, easy magnet field ramp

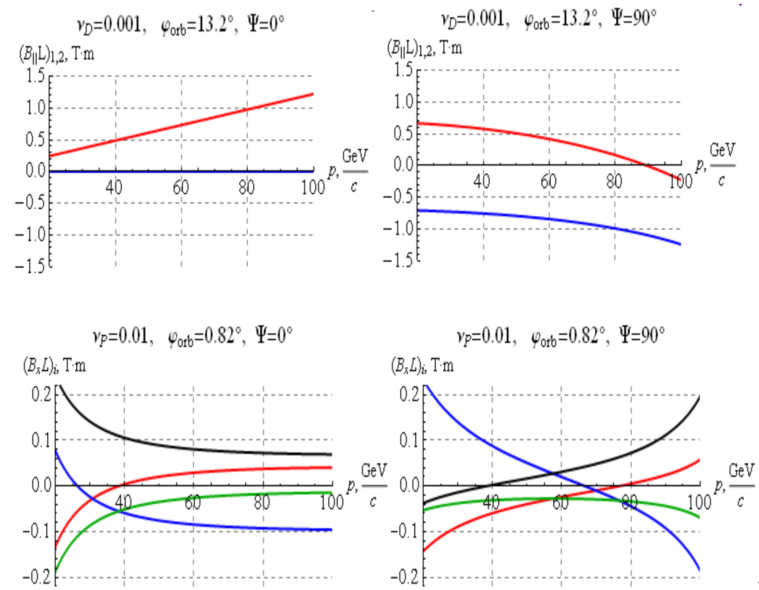
- Deuteron polarization control



- Proton polarization control

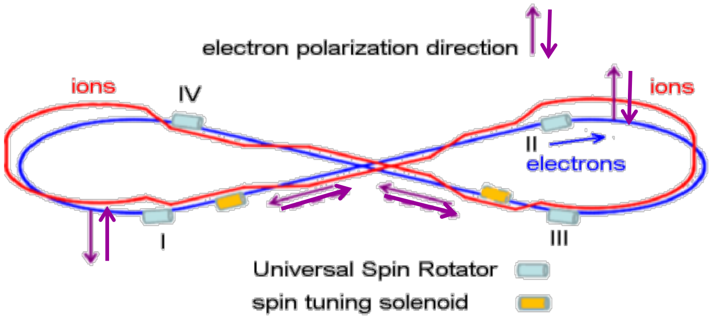


longitudinal polarization **radial polarization**

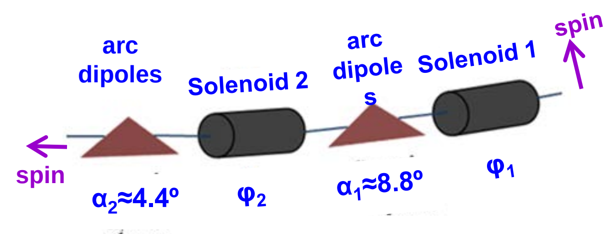


Electron Polarization

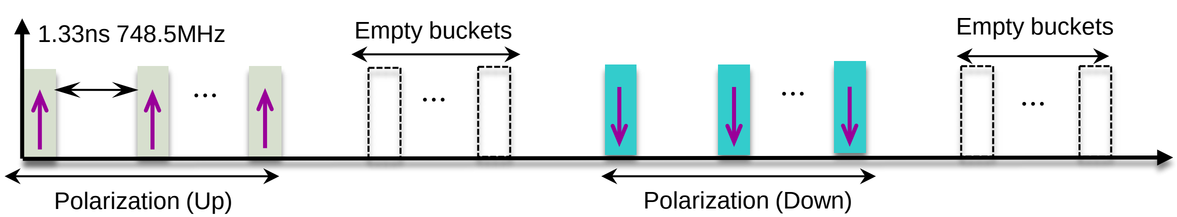
- Highly polarized electron beams are injected from CEBAF
- Polarization is designed to be vertical in the arc to avoid spin diffusion and longitudinal at collision points using spin rotators



Universal Spin Rotator (USR)



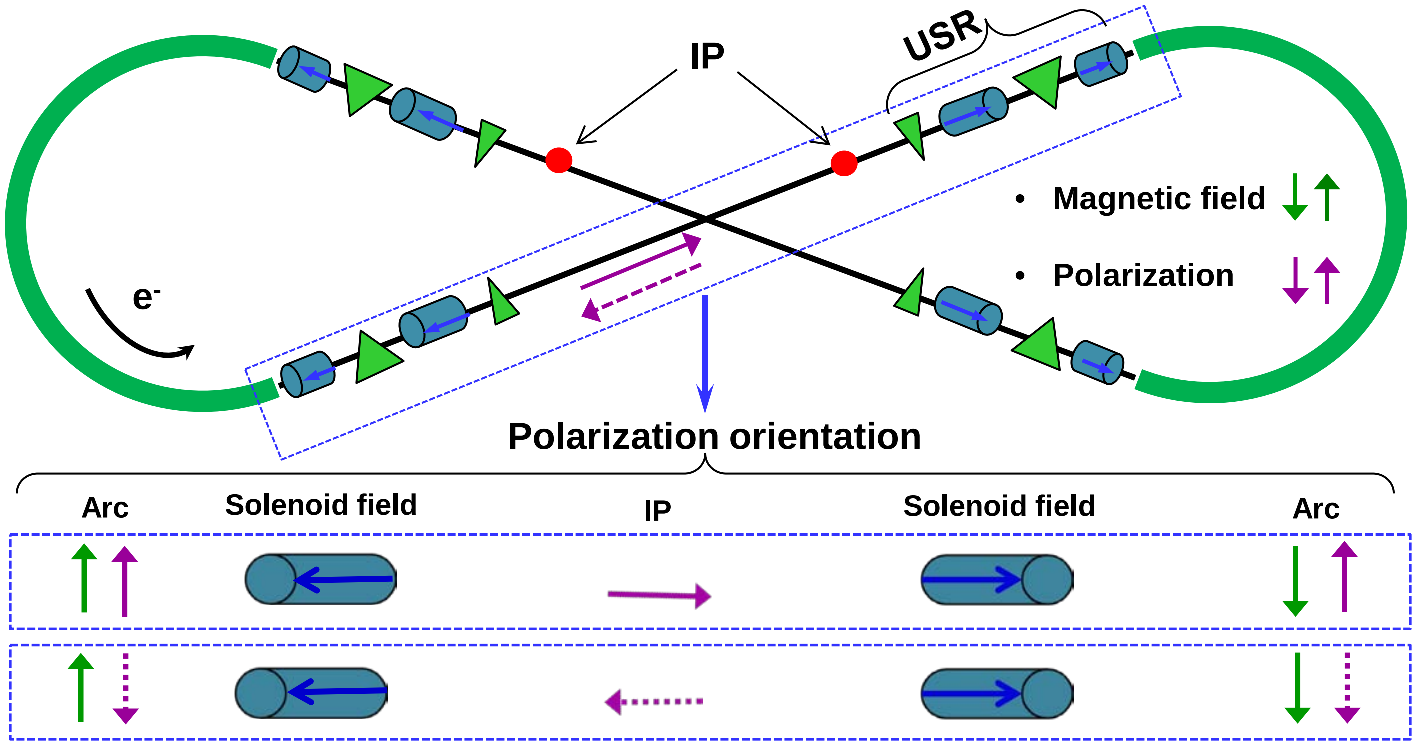
- New developed universal spin rotator rotates polarization from 3 to 12GeV
- Desired spin flipping can be implemented by changing the source polarization
- Compton polarimeters are considered to measure the electron polarization
  - Two long opposite polarized bunch trains simplify the compton polarimetry



Bunch train & polarization pattern in collide ring

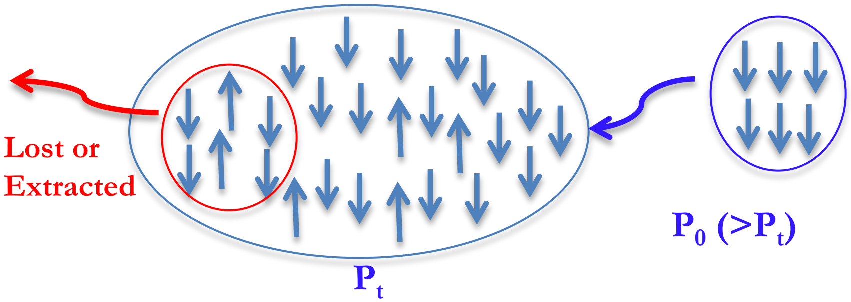
Electron Polarization Configuration

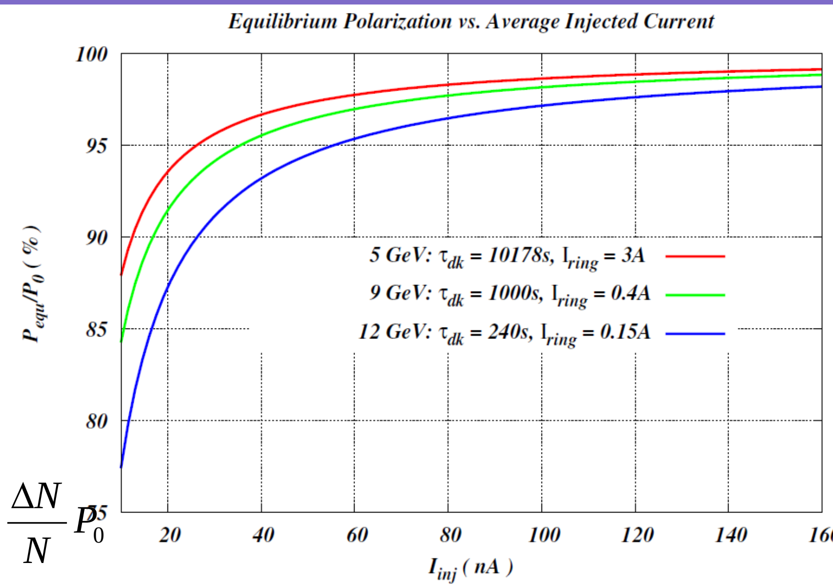
- Polarization configuration
  - Unchanged polarization (for any polarization direction) in two arcs
  - 1st order spin perturbation for the off-momentum particles vanishes due to zero net integral of solenoid fields in the long straight section
  - Figure-8 removes spin tune energy dependence => significant reduction of quantum depolarization



Continuous Injection Technique

- Continuous injection to preserve electron polarization





- Polarization at t+Δt $P_{t+\Delta t} = (1 - \frac{\Delta N}{N})(P_t + \frac{\Delta P_t}{\Delta t}\Delta t) + \frac{\Delta N}{N} P_0$

- Equilibrium polarization $P_{equ} = P_0 (1 + \frac{T_{rev} I_{ring}}{\tau_{dk} I_{inj}})^{-1}$

- Note that:
  - Continuous injection mainly considered at higher energies
  - A relatively low averaged beam current of tens-of-nA level needed
  - Constant beam current maintained