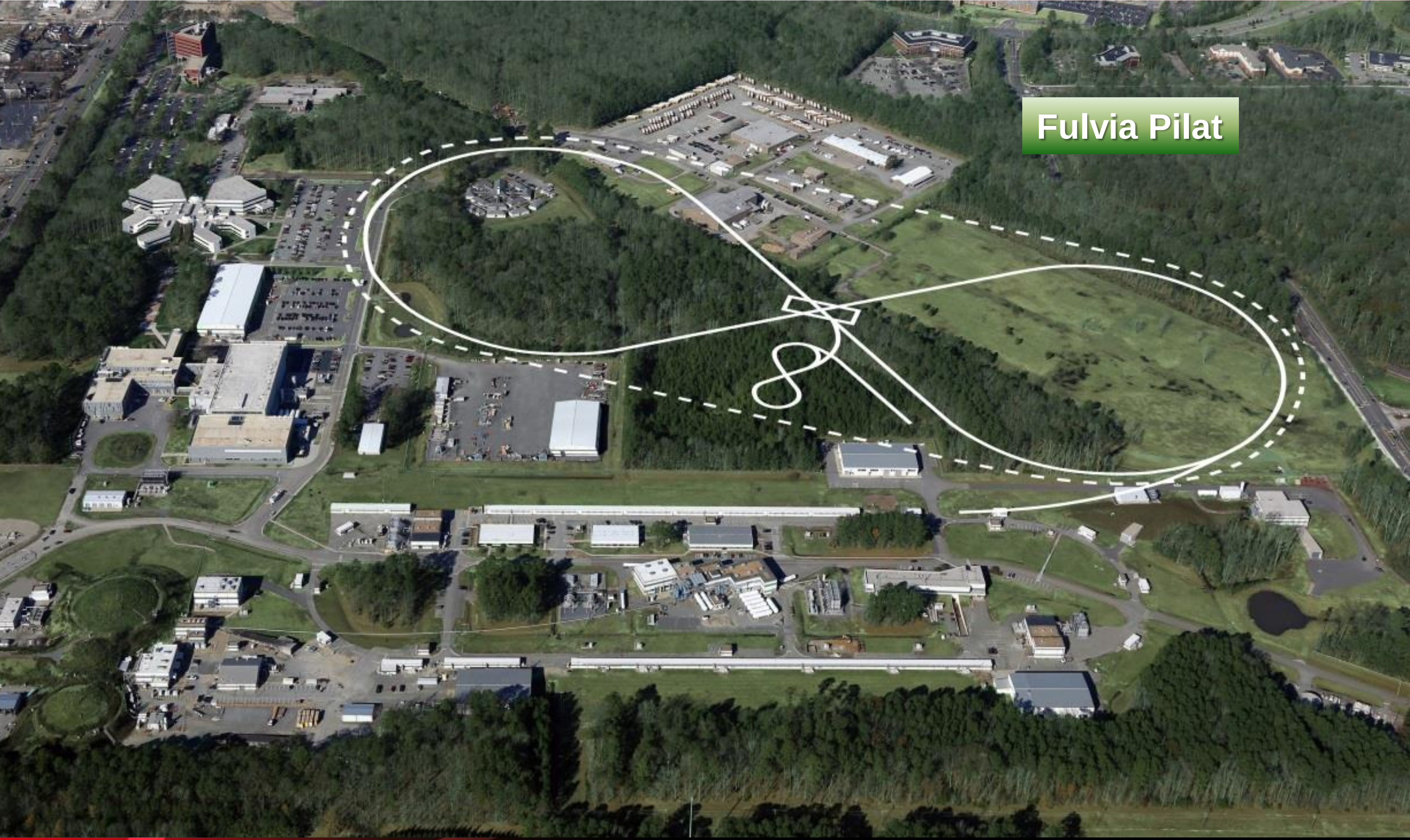
MEIC Design Update



Fulvia Pilat

POETIC 2015
September 7 2015

Outline

MEIC baseline

- Design strategy for high luminosity and polarization
- 2.1km figure-8 ring-ring collider, e-ring based on **PEP-II** design and components and **CEBAF** as full energy injector, new ion complex based on **super-ferric** magnets
- Focus: minimization of technical risk
- Design and cost estimate successfully reviewed in January 2015

Present focus

- Design optimization for cost reduction and further minimization of technical risk
- Development and execution of pre-project R&D program

Future plans

MEIC Design Goals

Energy

Full coverage of √**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)

Space for at least 2 detectors

Full acceptance is critical for the primary detector

Luminosity

10^{33} to 10^{34}cm^{-2}s^{-1} per IP in a *broad* CM energy range

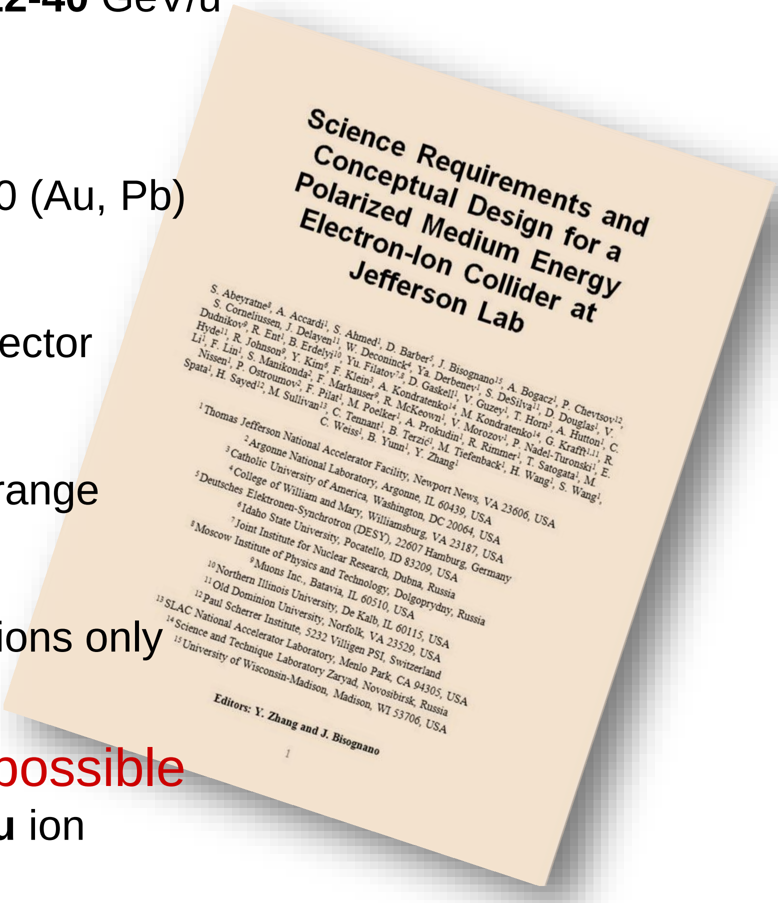
Polarization

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



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

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

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Editors: Y. Zhang and J. Bisognano

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Design goals consistent with the White Paper requirements

Design Strategy: High Luminosity and polarization

- 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

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

Beam Design

- **High repetition rate**
- **Low bunch charge**
- **Short bunch length**
- **Small emittance**

IR Design

- **Small β***
- **Crab crossing**

Damping

- **Synchrotron radiation**
- **Electron cooling**

All rings are figure-8 → critical advantages for both ion and electron beam polarization

- 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

MEIC Baseline

Baseline for the cost estimate

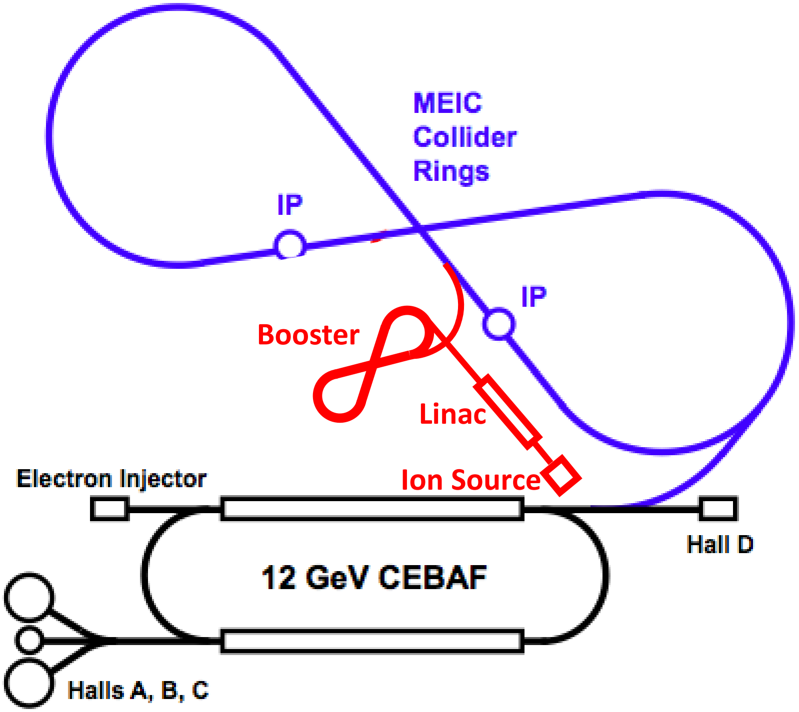
- Collider ring circumference: ~2100 m
- Electron collider ring and lines : PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider and booster ring: super-ferric magnets
- SRF ion linac
- Electron cooling: DC cooler and single-pass ERL, bunched-beam e-cooler

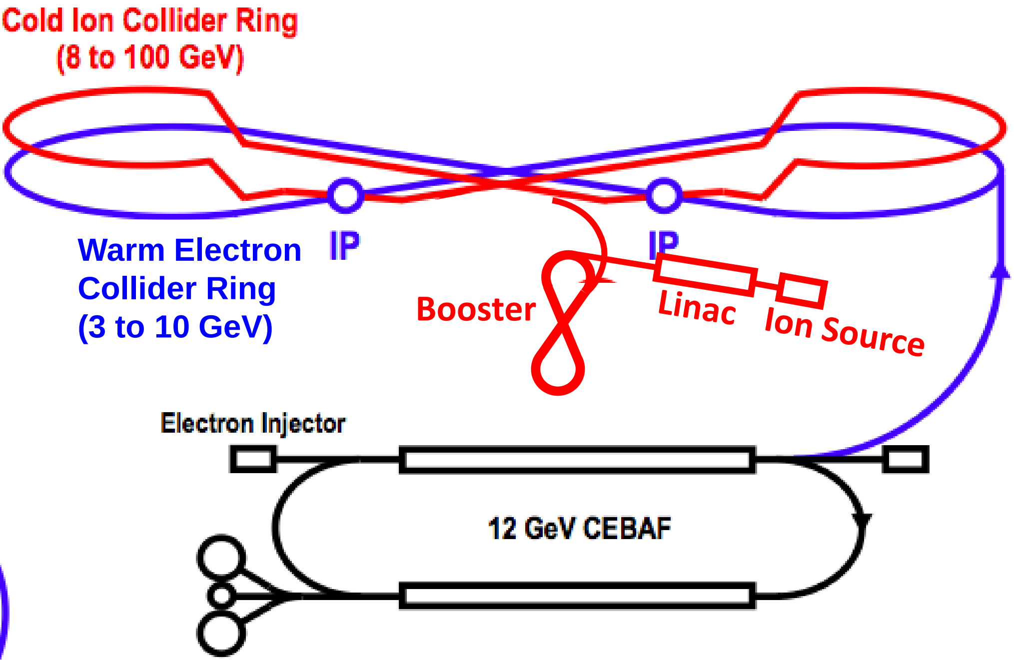
Energy range

- Electron: 3 to 10 GeV
- Proton: 20 to 100 GeV
- Lead ions: up to 40 GeV

Design point	p energy (GeV)	e- energy (GeV)	Main luminosity driver
low	30	4	space charge
medium	100	5	beam beam
high	100	10	synchrotron radiation

Baseline Layout





CEBAF is a full energy injector.
Only minor gun modification is needed

Campus Layout

~2.1 km circumference

E-ring from PEP-II

Ion-ring with super-ferric magnets

Tunnel consistent with a 250+ GeV upgrade

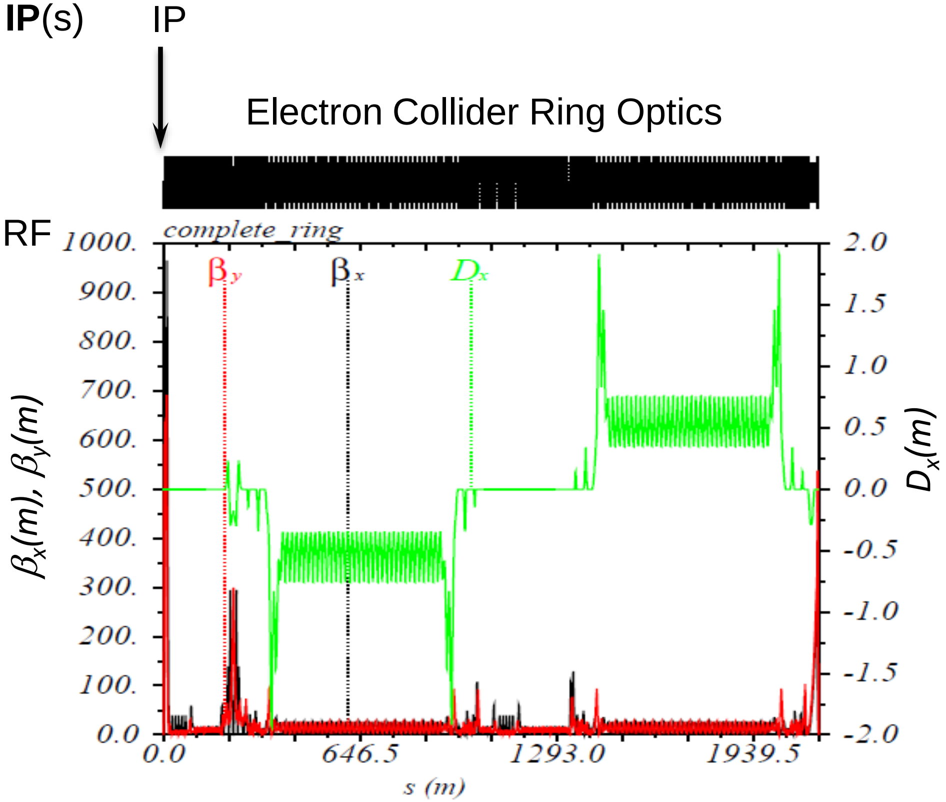
MEIC Electron Complex

- CEBAF provides up to 12 GeV, high repetition rate and high polarization (>85%) electron beams, no further upgrade needed beyond the 12 GeV CEBAF upgrade.

- Electron collider ring design
  - circumference of 2154.28 m = 2 x 754.84 m arcs + 2 x 322.3 m straights
  - Meets design requirements
  - Provides **longitudinal electron polarization at IP**(s)
  - incorporates **forward electron detection**
  - accommodates **up to two detectors**
  - includes non-linear beam dynamics
  - reuses PEP-II magnets, vacuum chambers and RF

- Beam characteristics
  - **3A** beam current at 6.95 GeV
  - Normalized emittance **1093** µm @ 10 GeV
  - Synchrotron radiation power density **10kW/m**
  - total power **10 MW** @ 10 GeV

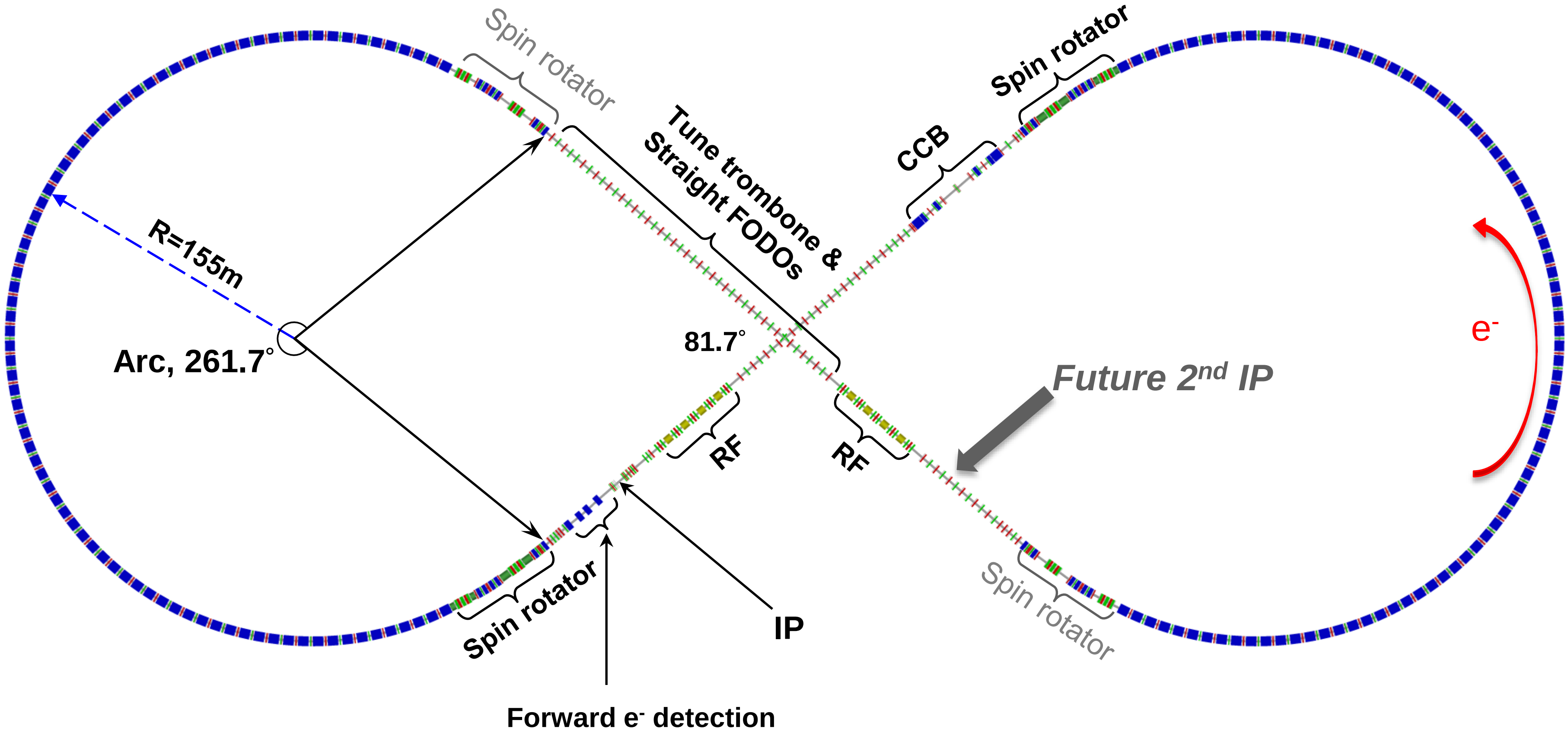
- CEBAF and the electron collider provide the required electron beams for the EIC.


Electron Collider Ring Optics

Electron Collider Ring Layout

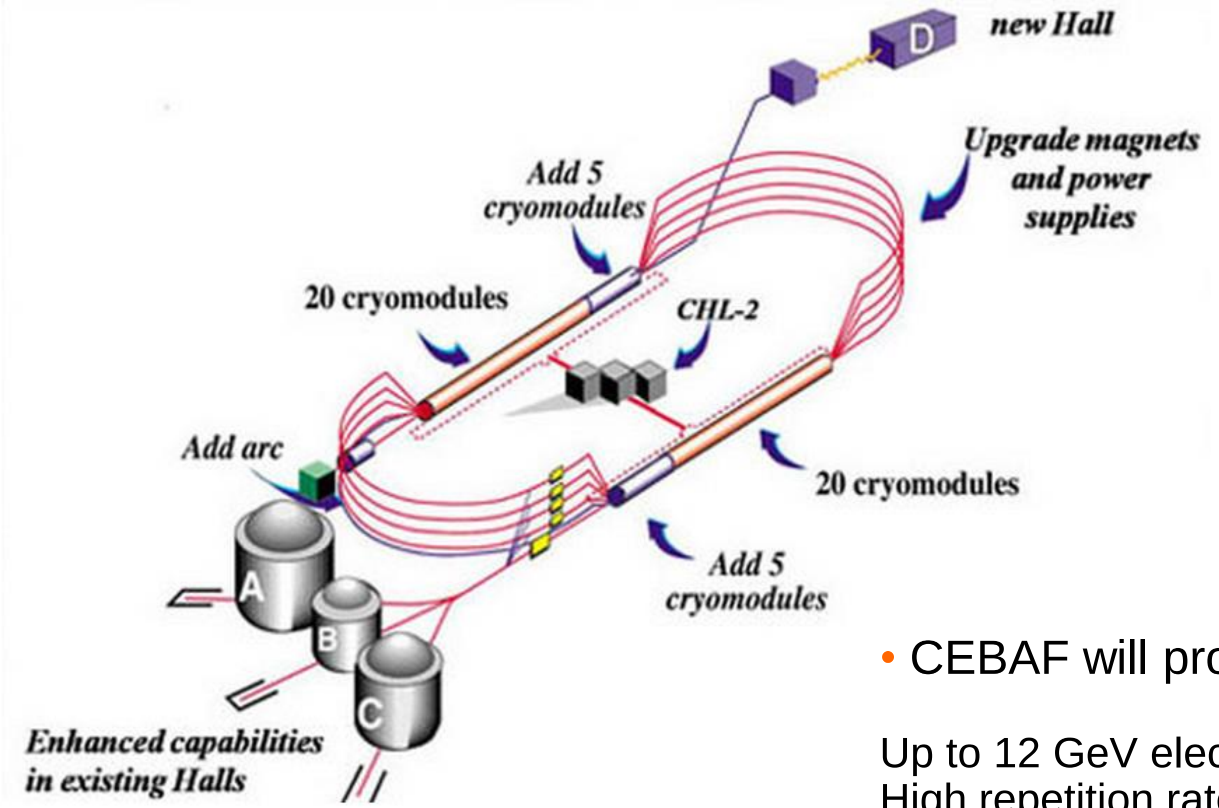
- Circumference of 2154.28 m = 2 x 754.84 m arcs + 2 x 322.3 m straights Figure-8, crossing angle **81.7°**

Electron collider ring w/ major machine components



CEBAF - Full Energy Injector

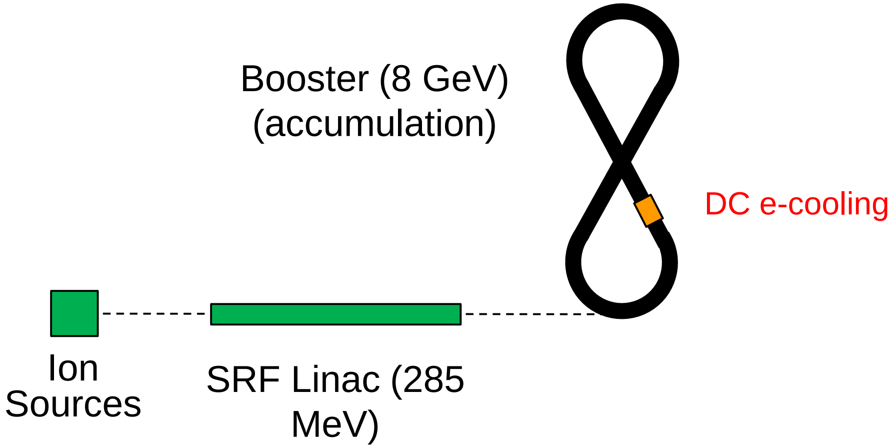
- CEBAF fixed target program
  - 5-pass recirculating SRF linac
  - Exciting science program beyond 2025
  - **Can be operated concurrently with the MEIC**



- CEBAF will provide for MEIC

Up to 12 GeV electron beam
High repetition rate (up to 1497 MHz)
High polarization (>85%)
Good beam quality up to the mA level

Ion Injector Complex



Booster (8 GeV)
(accumulation)

DC e-cooling

Ion
Sources

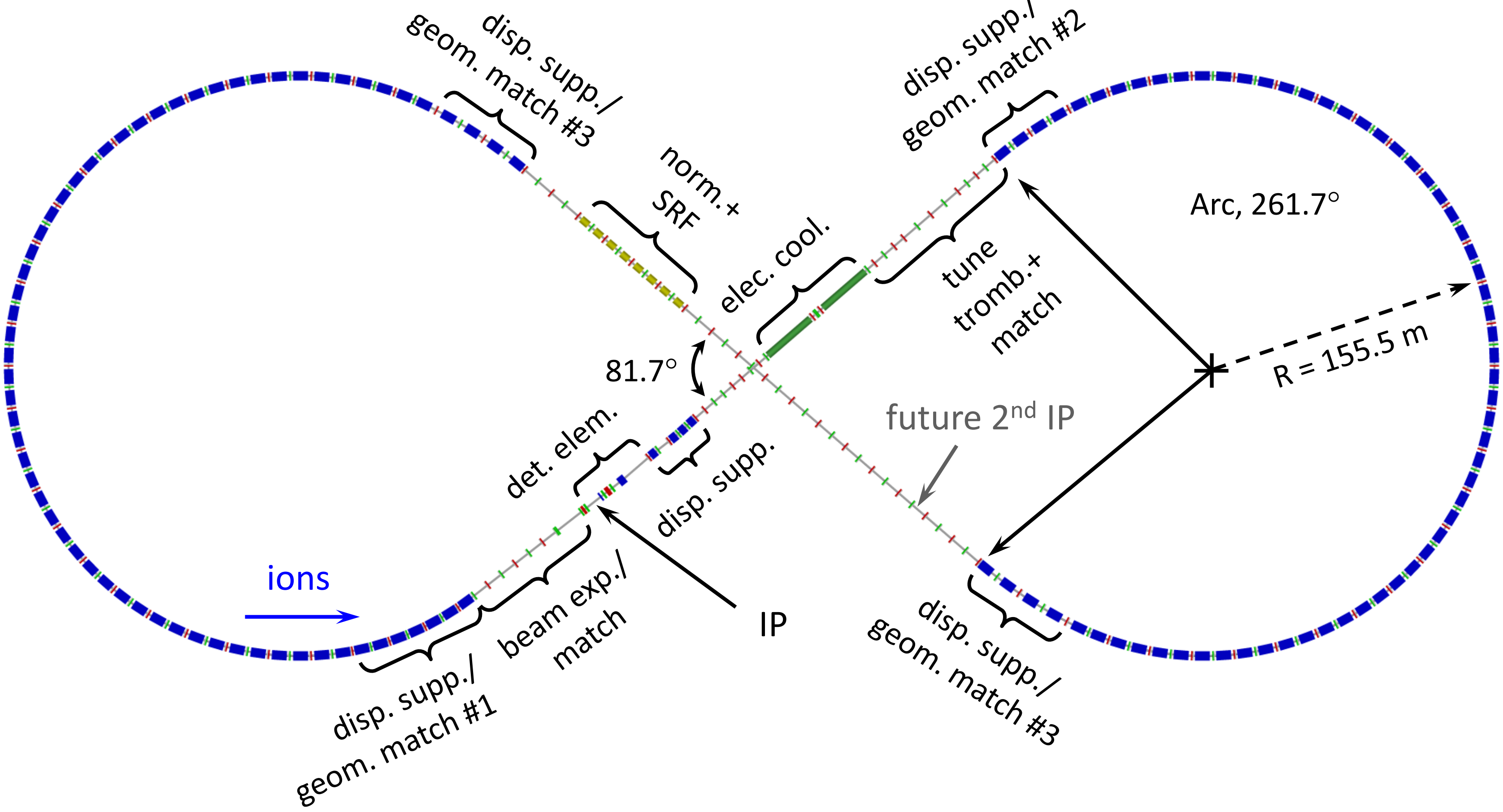
SRF Linac (285
MeV)

Status of the ion injector complex:

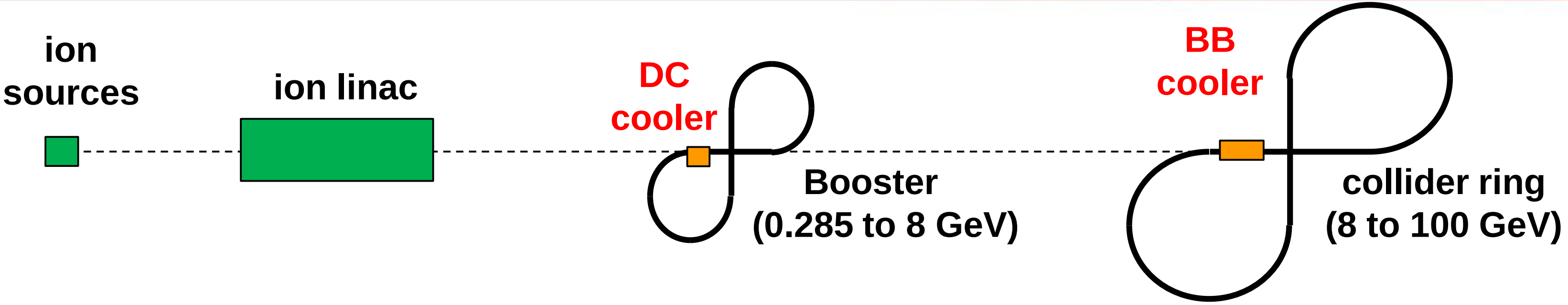
- Relies on **demonstrated technology** for injectors and sources
- **SRF linac**
- **8 GeV Booster** to avoid transition for all ion species and based on super-ferric magnet technology
- Injection/extraction lines to/from Booster are designed

Ion Collider Ring

- Figure-8 ring with a circumference of 2153.9 m
- Two 261.7° arcs connected by two straights crossing at 81.7°



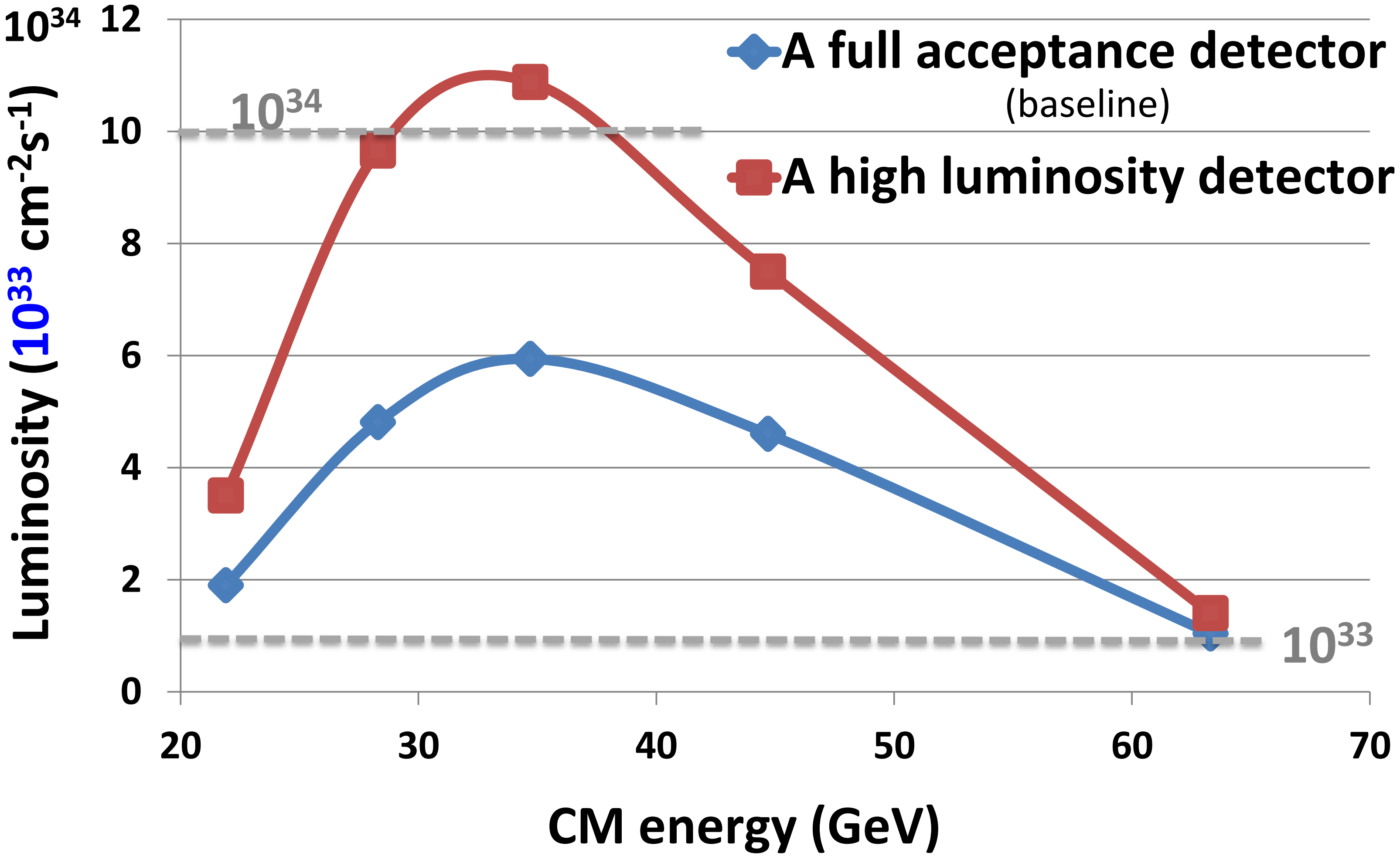
MEIC Multi-Step Cooling Scheme



Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	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

- DC cooling for emittance reduction
- BBC cooling for emittance preservation

e-p Luminosity

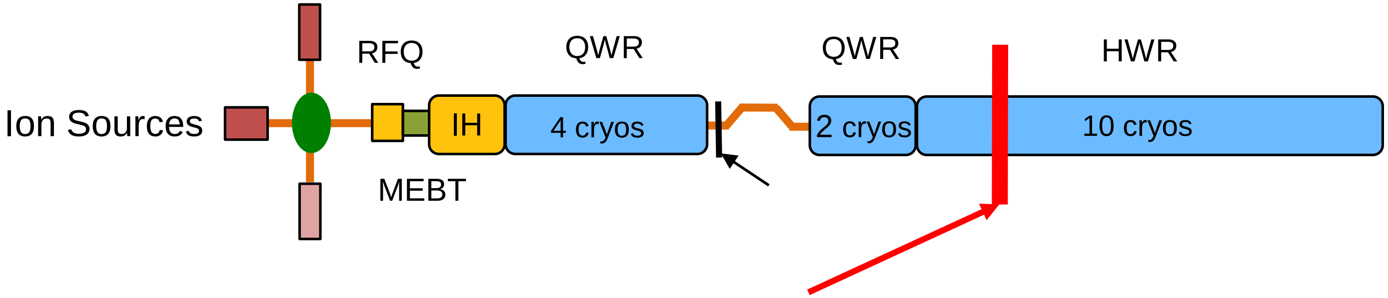


The baseline performance requires a **ERL bunched beam cooler** but no circulator cooler

Design optimization

- Study of lower energy SRF linac, stripping scheme (Collaboration ANL)
- DC cooler design (Collaboration Budker institute)
- Polarization design and spin tracking
- ERL cooler design
- Reduction of e- emittance in e- ring
- Complete scheme of proton and ion beam formation
- Beam synchronization

SRF Linac

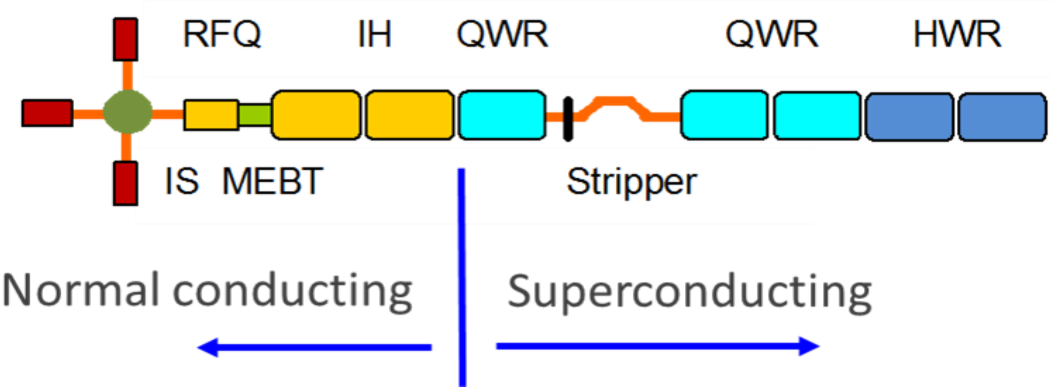


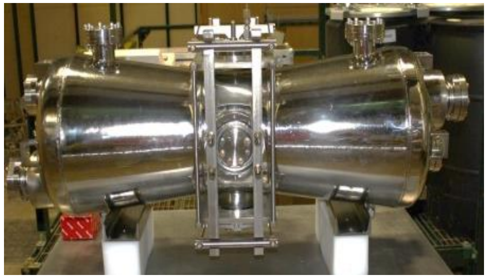
Evaluating to limit the linac energy to ~120 MeV as a cost mitigation option

- 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

New pulsed SRF ion linac design





Parameter	**Units**	**Value**
Ion species		H^+ to Pb
Fundamental frequency	MHz	100
Kinetic energy of protons & lead ions	MeV/u	130&42
Maximum pulse current		
Light ions ($A/q\leq3$)	mA	2
Heavy ions ($A/q>3$)	mA	0.5
Pulse repetition rate	Hz	up to 10
Pulse length		
Light ions ($A/q\leq3$)	ms	0.5
Heavy ions ($A/q>3$)	ms	0.25
Maximum pulsed beam power	kW	260
# of QWR cryomodules		3
# of HWR cryomodules		2
Total length	m	~55

- QWR and HWR cavity design based on existing design for the ANL Atlas upgrade
- Energy reduction from 285 to 100 MeV → potential cost reduction by a factor 2-3
- Preliminary evaluation of impacts of lower injection energy to booster is positive, more evaluation in progress

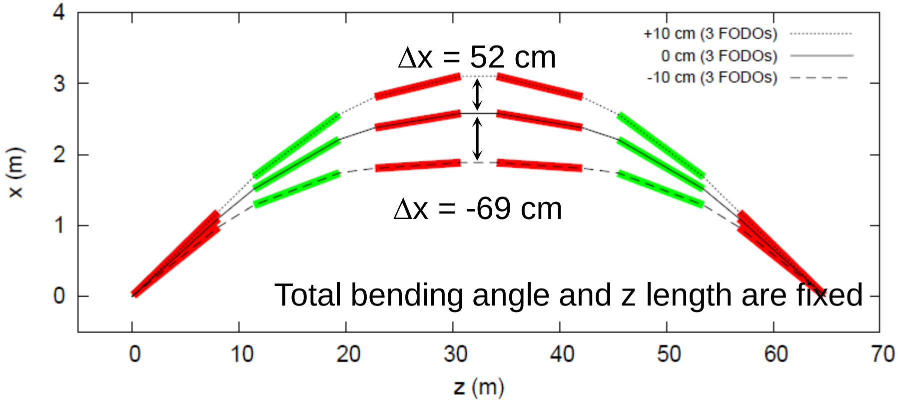
Beam synchronization

Issue → synchronize energy dependent ion velocity with electrons

- Conventional schemes involve magnet movement
  - Moving magnets in the **ion** collider ring
    - Moving whole arcs or a small number of magnets in chicane(s)
    - With or without harmonic jump
  - Moving magnets in the **electron** collider ring & adjusting RF in both rings
    - Moving (almost) whole arcs or a small number of magnets in chicane(s)
    - With or without harmonic jump
  - Some combination of the two schemes

Report on MEIC synchronization is to be published in September 2015

Example of a chicane design for the ion ring



All simpler and more practical conventional schemes require harmonic jump

→ **asymmetric collision pattern** a.k.a. "gear changing"

Non conventional schemes (scanning synchronization) do not require orbit change but move slightly the interaction point

Gear changing: the good and the bad….

The bad

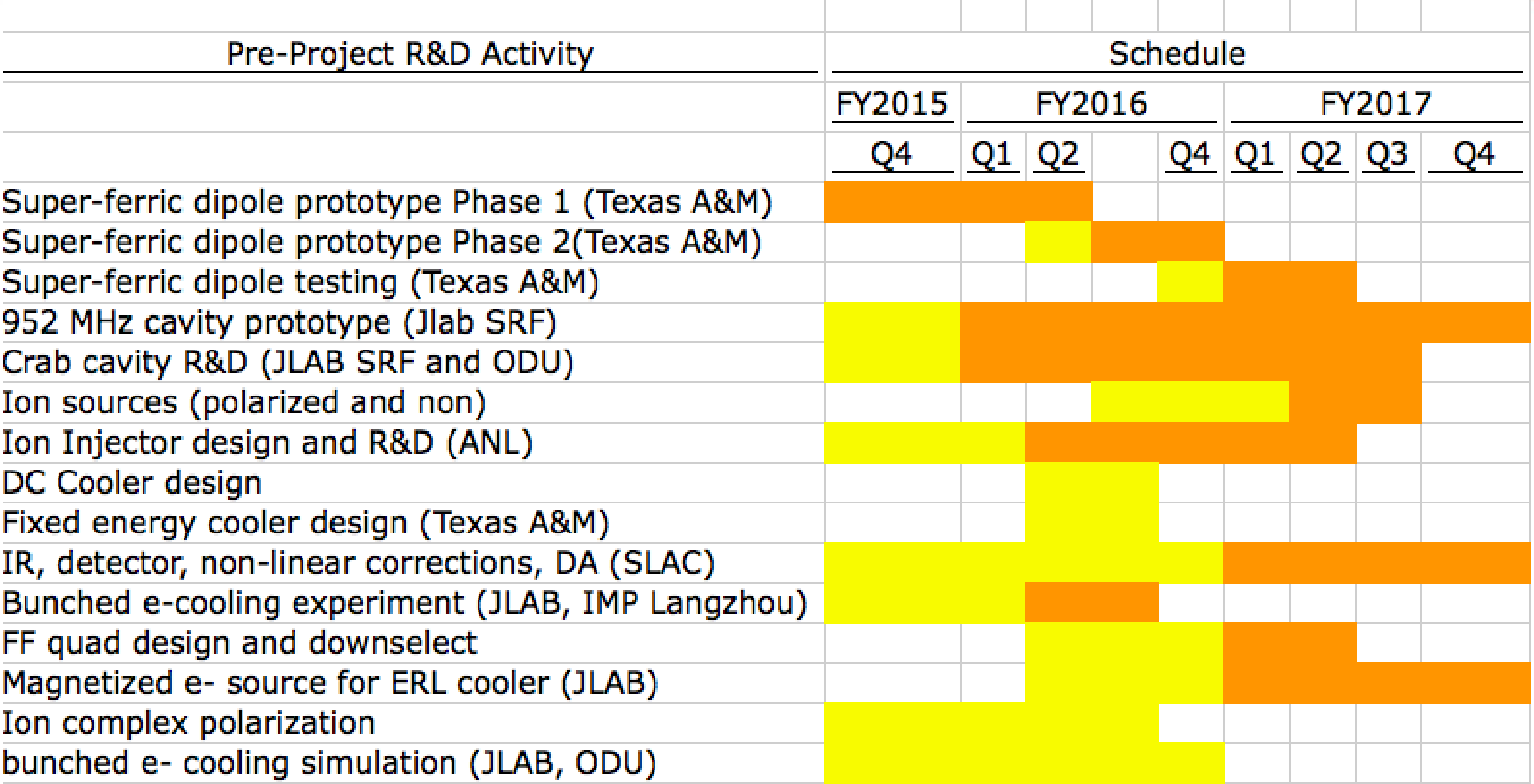
Leads to potential orbit and beam size instabilities (MEIC possible mitigating Factors: strong focusing, Landau damping may dump instabilities)

The good

- Highly desirable to have each bunch from a ring collide with all other bunches of the other ring for physics measurements
- No need to track FOM for each bunch pair as a function of time, each bunch train can be treated as a long macro-bunch thus decoupling the experimental uncertainties from the microstructure of the accelerator
- Especially important for polarization measurement in a high repetition accelerator where bunch by bunch measurements are difficult/impossible

JLAB in collaboration with Old Dominion University is developing a new code **GHOST** (GPU-accelerate High-Order Symplectic Tracking) to tackle beam-beam and gear-changing effects (development time ~ 2 years)

MEIC R&D Program



Pre-Project R&D Activity	Schedule								
	FY2015	FY2016				FY2017			
	Q4	Q1	Q2		Q4	Q1	Q2	Q3	Q4
Super-ferric dipole prototype Phase 1 (Texas A&M)	🟧	🟧	🟧						
Super-ferric dipole prototype Phase 2(Texas A&M)			🟨	🟧	🟧				
Super-ferric dipole testing (Texas A&M)					🟨	🟧	🟧		
952 MHz cavity prototype (Jlab SRF)	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Crab cavity R&D (JLAB SRF and ODU)	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
Ion sources (polarized and non)				🟨	🟨	🟨	🟧	🟧	
Ion Injector design and R&D (ANL)	🟨	🟨	🟧	🟧	🟧	🟧	🟧		
DC Cooler design			🟨	🟨					
Fixed energy cooler design (Texas A&M)			🟨	🟨					
IR, detector, non-linear corrections, DA (SLAC)	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧
Bunched e-cooling experiment (JLAB, IMP Langzhou)	🟨	🟨	🟧	🟧					
FF quad design and downselect			🟨	🟨	🟨	🟧	🟧		
Magnetized e- source for ERL cooler (JLAB)			🟨	🟨	🟨	🟧	🟧	🟧	🟧
Ion complex polarization	🟨	🟨	🟨	🟨					
bunched e- cooling simulation (JLAB, ODU)	🟨	🟨	🟨	🟨	🟨				

Pre-project R&D necessary to support a pre-conceptual Design Report (CD0)

Total pre-project R&D budget ~5 M$ (EIC NP R&D funds, LDRD, ops redirect, SBIR, VA Commonwealth funds

MEIC super-ferric dipole

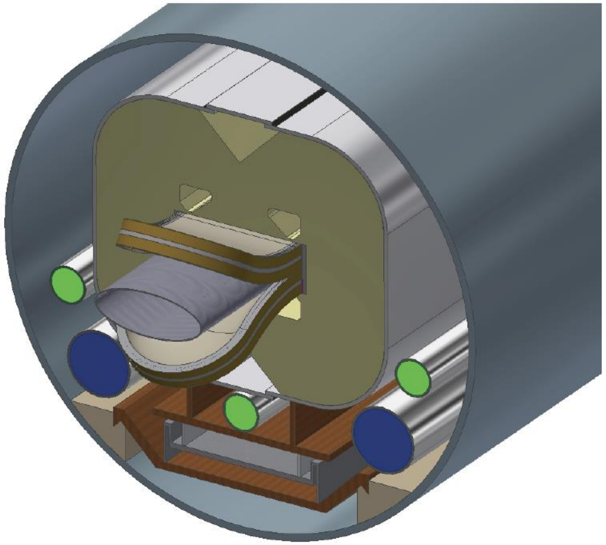


Figure 3. Isometric view of the end region of the v1a ICR dipole in its cryosta

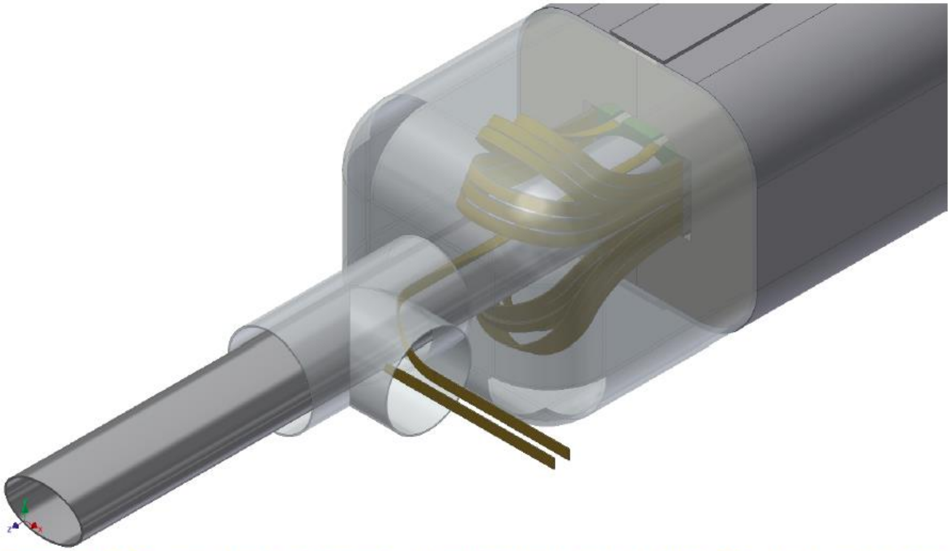


Figure 4. ICR arc dipole structure, showing lead-end cabling, He shell, and beam tube.

- 2 X 4m long dipole
- NbTi cable
- 3 T
- Correction sextupole
- Common cryostat

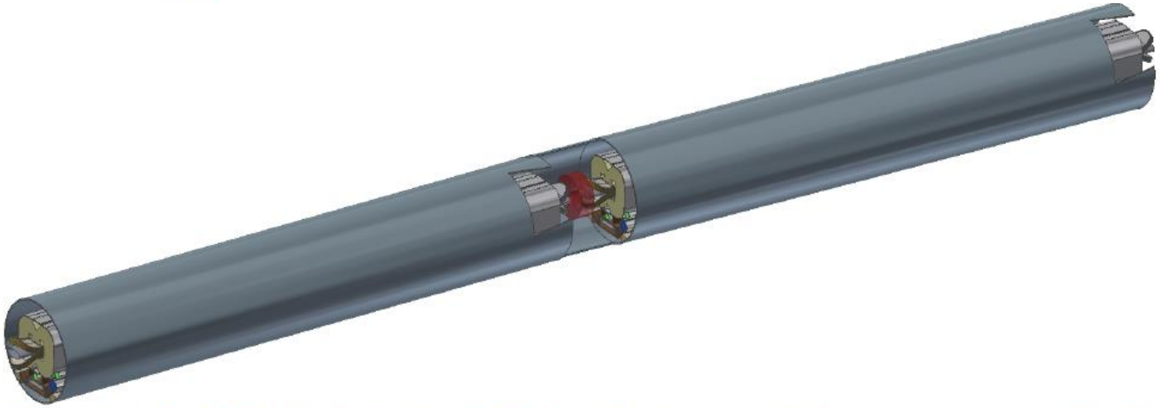
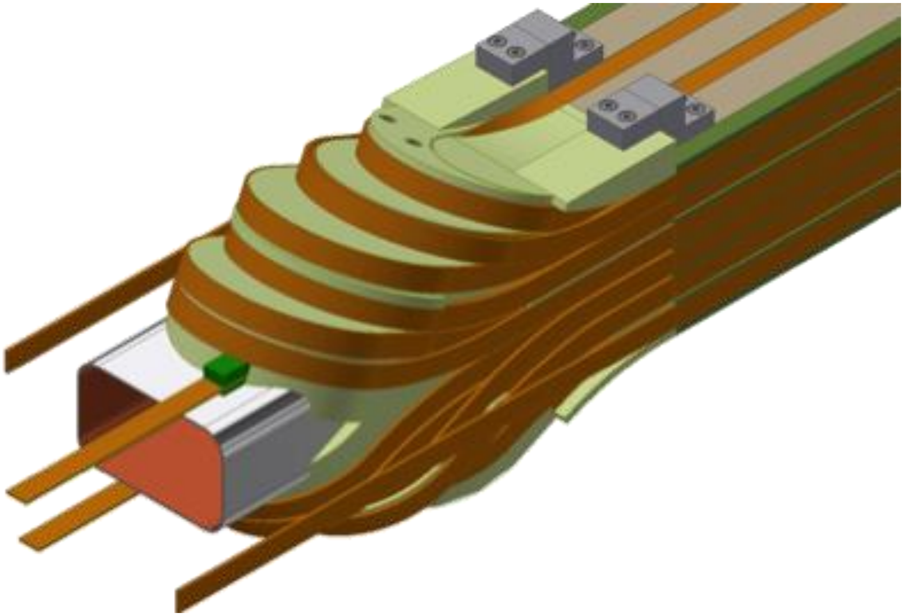


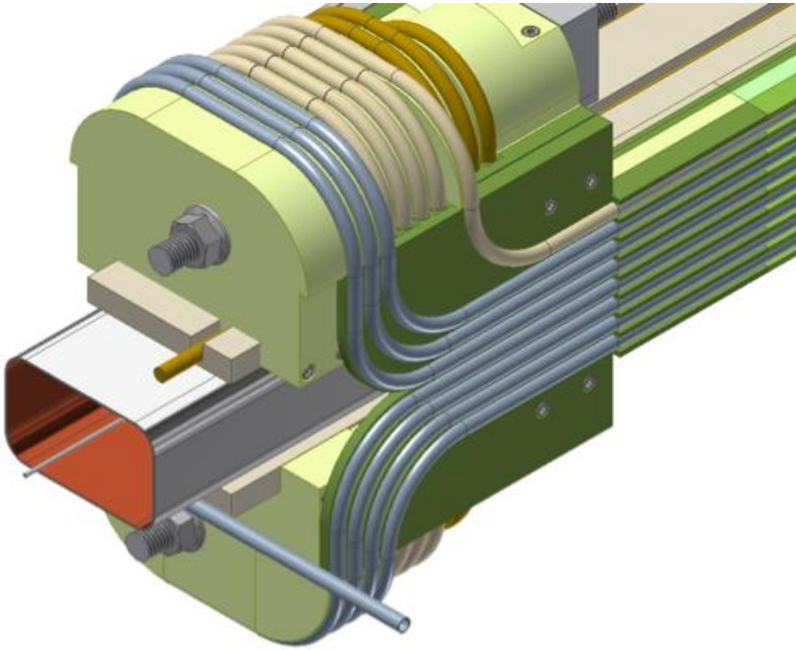
Figure 6. v1b MEIC dual dipole: 2 3.85 m dipoles assembled on a common rail with correction sextupole (red) at center.

Cabling techniques

NbTi Rutherford cable

NbTi Cable-in-Conduit





Pros: Uses mature cable technology (LHC).

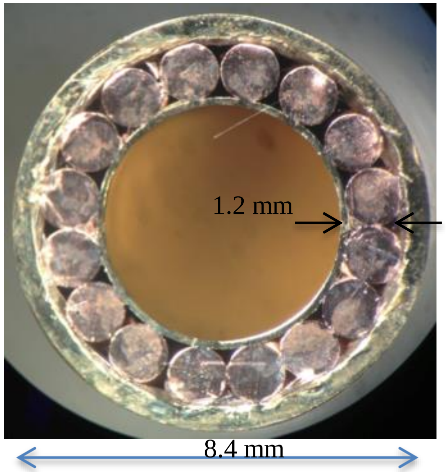
Semi-rigid cable makes simpler end winding.
Semi-rigid round cable can be precisely located.
Cryogenics contained within cable.

Cons: Ends tricky to support axial forces.
Entire cold mass is a He vessel.

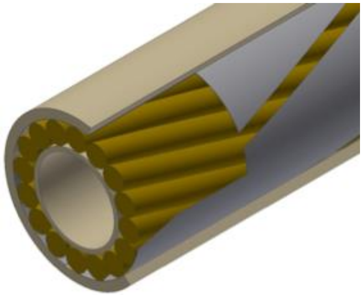
Cable requires development and validation.

Fabricating CIC conductor for MEIC

cabling wires onto perforated spring tube



cross-section of fabricated cable



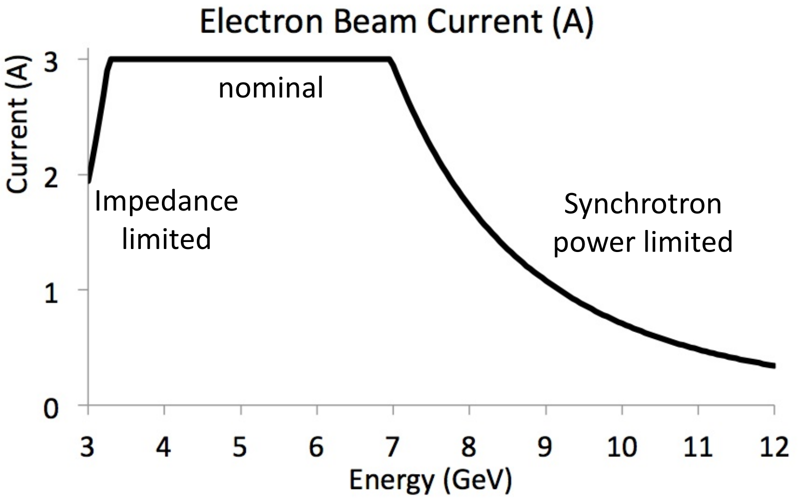
cutaway showing foil over-wrap

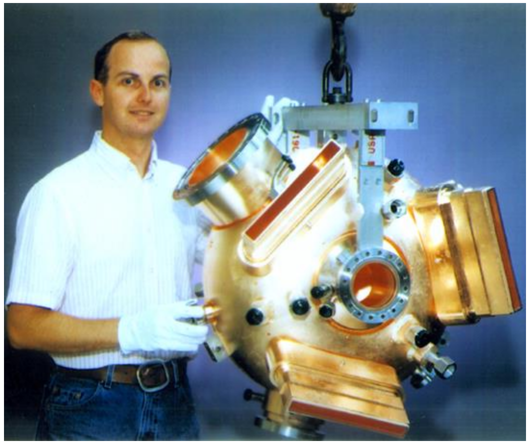
drawing sheath onto the cable

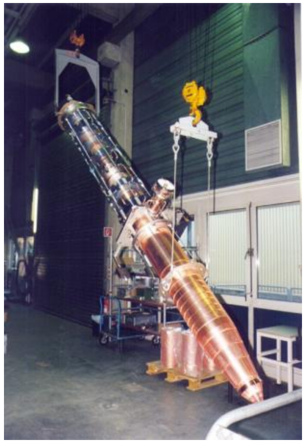
cable bent 180° on 2” radius.

e-ring RF design

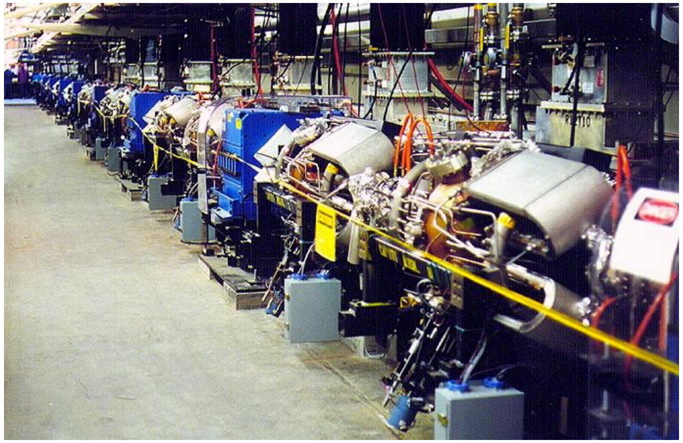
- Re-use proven PEP-II RF stations
- 476 MHz HOM damped 1-cell cavities
  - 34 cavities available
- 1.2 MW klystrons, 13 available
  - Including power supplies etc.
- Current limited by synch. rad. power at high energy, impedance at low energy




PEP-II RF cavity

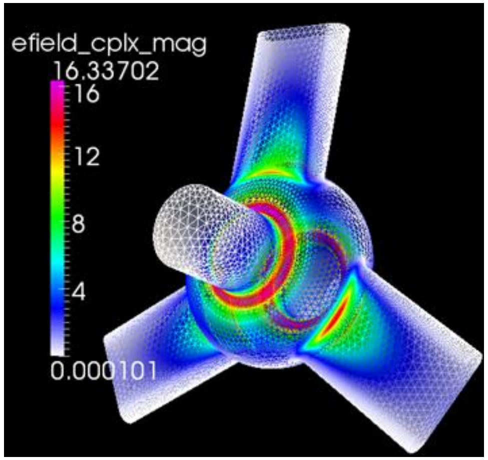

1.2 MW Klystron


2 MVA HVPS

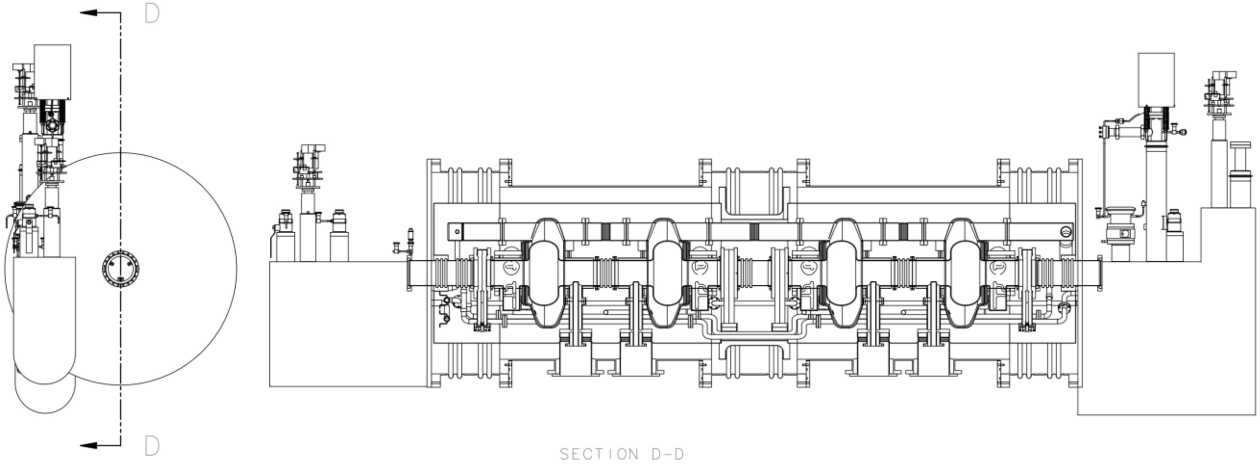

PEP-II Cavities in the SLAC tunnel

ion-ring RF design

- **952.6 MHz** HOM damped 1-cell cavities, modular JLab type cryomodule
  - High frequency/high voltage for short bunch (re-bucket at energy)
  - Double repetition rate for future luminosity upgrade



New HOM damped cavity concept



952.6 MHz single cell 4-seater CM
(~4.3m flange to flange)

Crab cavity

Design by ODU (A. Castilla Ph.D project)

- **952.6 MHz** “RF dipole” like LHC
- Modest RF system (no beam loading)
- Must have good HOM damping
- Count for 1 IP in baseline
- Assume cryostat cost/cavity same as ion storage ring

Parameter	Units	Electron	Proton
Beam energy E_b	GeV	10	100
Bunch frequency n_b	MHz	952.0	
Crossing angle φ_c	mrad	50	
Betatron function at the IP β_x^*	cm	10	
Betatron fn. at the crab cavity β_x^c	m	200	750
Integrated kicking voltage V_T	**MV**	**1.76**	**14.48**
Number of cavities (per side of IP)	--	2	6
Total number of cavities (per specie)	--	4	12

Conclusions and Outlook

The MEIC **baseline** based on a ring-ring design is mature and can deliver luminosity from a few **10^{33}** to a few **10^{34}** and polarization over **70%** in the √**s** 15-65 GeV range with **low technical risks.**

We are planning and executing the pre-project R&D (total cost ~5 M$)

We continue to optimize the present design for cost and performance.

The design can be upgraded in energy and luminosity

We are planning to produce a pre-conceptual design in ~2 years

Backup Slides

Performance MEIC baseline

Achieved with a single pass ERL cooler

For a full acceptance detector

CM energy	GeV	21.9 **(low)**		44.7 **(medium)**		63.3 **(high)**	
		p	*e*	*p*	*E*	*p*	*e*
Beam energy	GeV	30	4	100	5	100	10
Collision frequency	MHz	476		476		159	
Particles per bunch	10^{10}	0.66	3.9	0.66	3.9	2.0	2.8
Beam current	A	0.5	3	0.5	3	0.5	0.72
Polarization	%	>70%	>70%	>70%	>70%	>70%	>70%
Bunch length, RMS	cm	2.5	1.2	1	1.2	2.5	1.2
Norm. emitt., vert./horz.	μm	0.5/0.5	74/74	1/0.5	144/72	1.2/0.6	1152/576
Horizontal and vertical β^*	cm	3	5	2/4	2.6/1.3	5/2.5	2.4/1.2
Vert. beam-beam param.		0.01	0.02	0.006	0.014	0.002	0.013
Laslett tune-shift		0.054	small	0.01	small	0.01	small
Detector space, up/down	m	7/3.6	3.2 / 3	7/3.6	3.2 / 3	7/3.6	3.2 / 3 (3)
Hour-glass (HG) reduction		0.89		0.88		0.73	
Lumi./IP, w/HG, 10^{33}	$cm^{-2}s^{1}$	**1.9**		**4.6**		**1.0**	

For a high(er) luminosity detector

Horizontal and vertical β^*	cm	1.2	2	1.6 / 0.8	1.6 / 0.8	2 /1	1.6 / 0.8
Vert. beam-beam param.		0.01	0.02	0.004	0.021	0.001	0.021
Detector space, up/down	m	±4.5	3	±4.5	3	±4.5	3
Hour-glass (HG) reduction		0.67		0.74		0.58	
Lumi./IP, w/HG, 10^{33}	$cm^{-2}s^{1}$	**3.5**		**7.5**		**1.4**	

e-ion luminosity

For a full acceptance detector

		Electron	**Proton**	**Deuteron**	**Helium**	**Carbon**	**Calcium**	**Lead**
		e	P	d	$^{3}He^{++}$	$^{12}C^{6+}$	$^{40}Ca^{20+}$	$^{208}Pb^{82+}$
Beam energy	GeV	5	100	50	66.7	50	50	39.4
Particles/bunch	10^{10}	3.9	0.66	0.66	0.33	0.11	0.033	0.008
Beam current	A	3	0.5	0.5	0.5	0.5	0.5	0.5
Polarization		>70%	>70%	> 70%	> 70%	-	-	-
Bunch length, RMS	cm	1.2	1	1	1	1	1	1
Norm. emit., horz./vert.	µm	144/72	1/0.5	0.5/0.25	0.7/0.35	0.5/0.25	0.5/0.25	0.5/0.25
β^*, hori. & vert.	cm	2.6/1.3	4/2	4/2	4/2	4/2	4/2	5/2.5
Vert. beam-beam parameter		0.014	0.006	0.006	0.006	0.006	0.006	0.005
Laslett tune-shift			0.01	0.041	0.022	0.041	0.041	0.041
Detector space	m	3.2 / 3	7 / 3.6					
Hour-glass (HG) reduction factor			0.89	0.89	0.89	0.89	0.89	0.89
Lumi/IP/***nuclei***, w/ HG correction	$10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		4.6	4.6	2.2	0.77	0.23	0.04
Lumi/IP/**nucleon**, w/HG correction,	$10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		4.6	9.2	6.6	9.2	9.2	7.8

For a high(er) luminosity detector

β^*, hori. & vert.	cm	1.6/0.8	1.6/0.8	1.6/0.8	1.6/0.8	1.6/0.8	1.6/0.8	1.6/0.8
Vert. beam-beam parameter		0.02	0.004	0.004	0.004	0.004	0.004	0.004
Detector space	m	3	4.5					
Hour-glass (HG) reduction factor			0.74	0.74	0.74	0.74	0.74	0.74
Lumi/IP/***nuclei***, w/ HG correction	$10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		7.5	9.3	3.7	1.37	0.38	0.08
Lumi/IP/**nucleon**, w/HG correction,	$10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		7.5	15.1	11.1	15.1	15.1	17.3