Electron-Ion Collider at JLab: Conceptual Design, and Accelerator R&D

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for

JLab Electron-Ion Collider Accelerator Design Team

DIS 2013 -- XXI International Workshop on Deep Inelastic Scatterings and Related Subjects, Marseille, France, April 22-28, 2013

Outline

- Introduction
- Machine Design Baseline
- Anticipated Performance
- Accelerator R&D Highlights
- Summary

Introduction

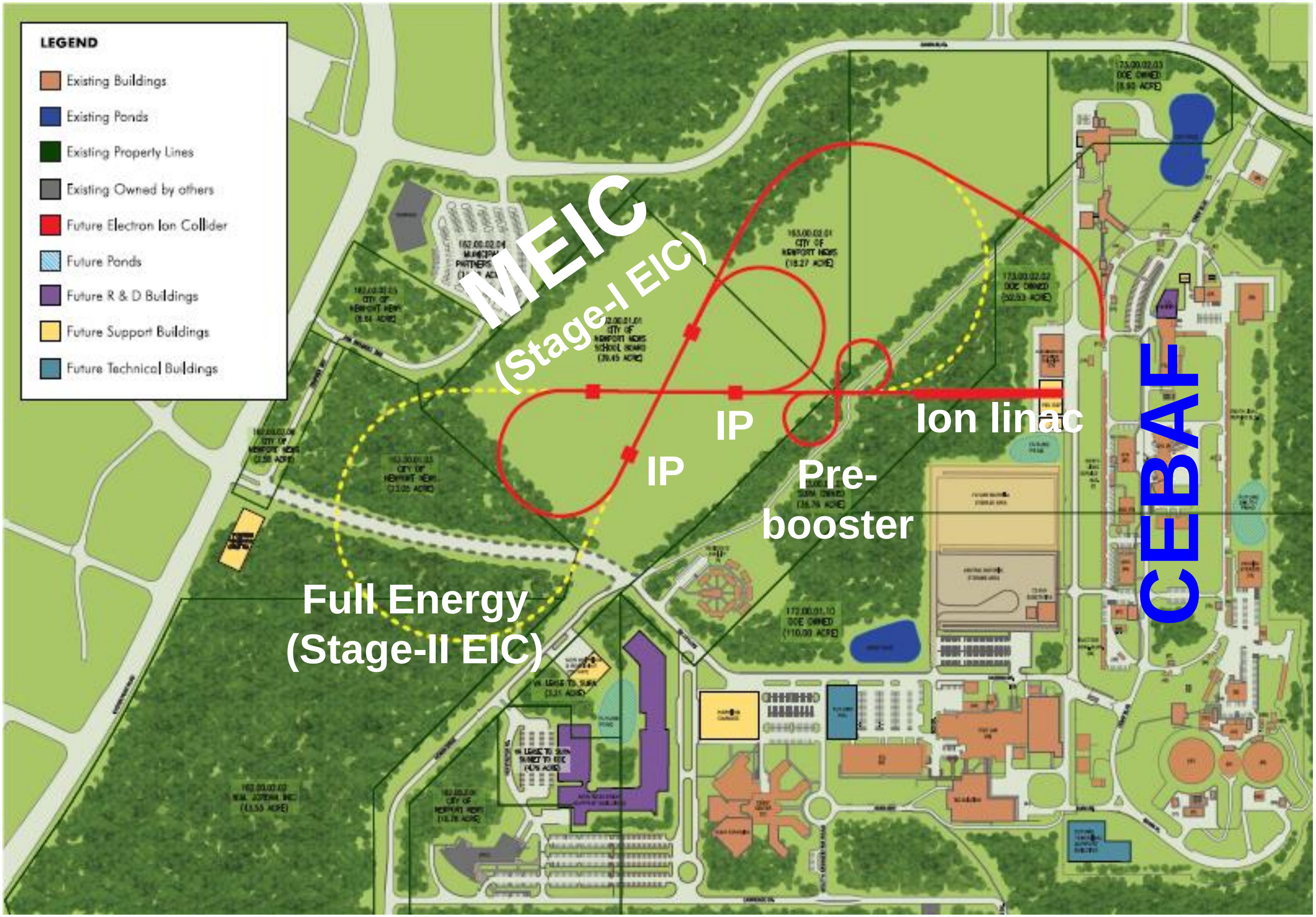
- A *Medium* energy *Electron-Ion Collider* (MEIC) at JLab will open new frontiers in nuclear science.
- The timing of MEIC construction can be tailored to match available DOE-ONP funding while the 12 GeV physics program continues.
- MEIC parameters are chosen to optimize science, technology development, 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 Goals

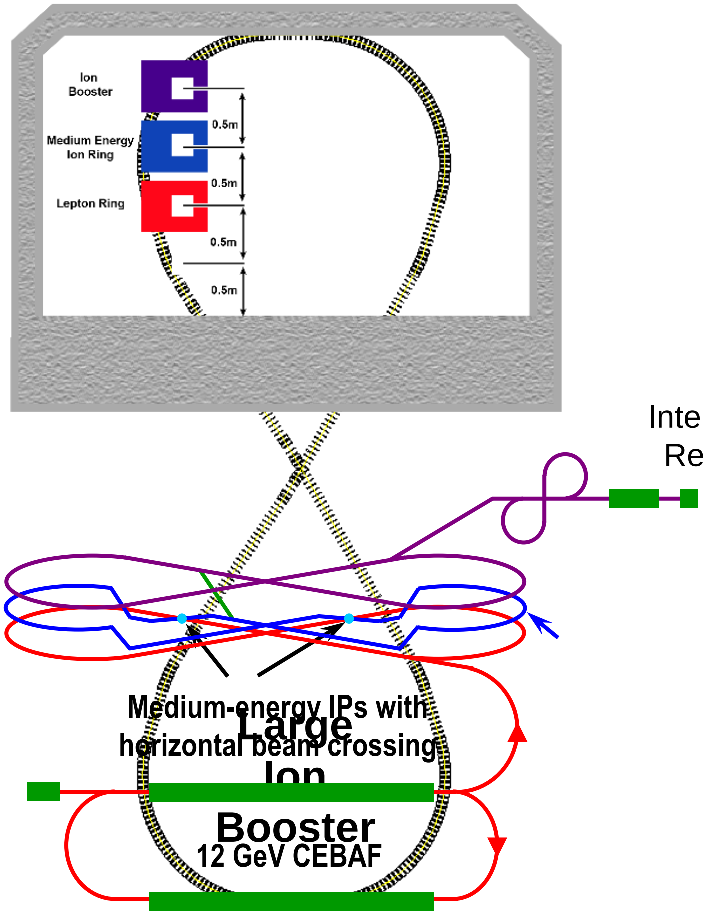
Base EIC Requirements per INT Report & White Paper

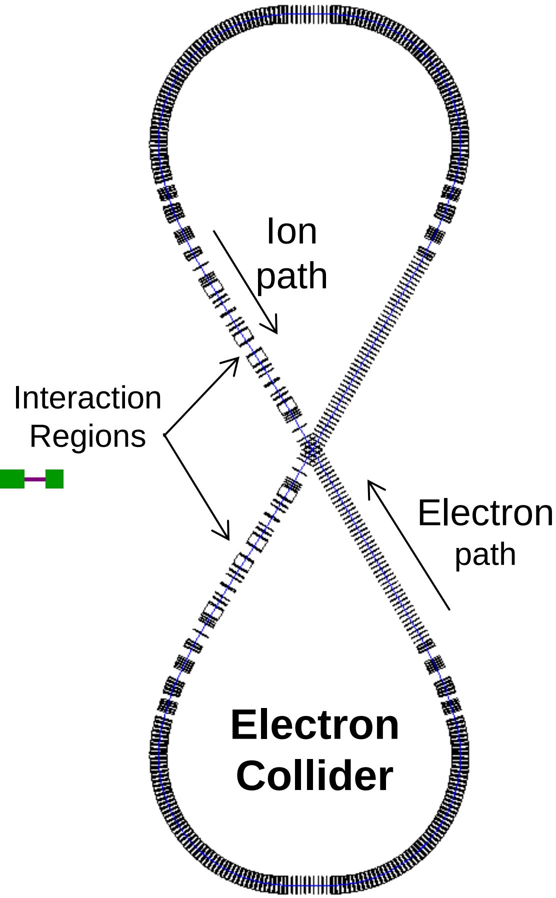
- **Energy** (*bridging the gap of 12 GeV CEBAF & HERA/LHeC*)
  - Full coverage of *s* from a few 100 to a few 1000 GeV^2
  - Electrons 3-12 GeV, protons 20-100 GeV, ions 12-40 GeV/u
- **Ion species**
  - Polarized light ions: p, d, ^{3}He, and possibly Li, and polarized heavier ions
  - Un-polarized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

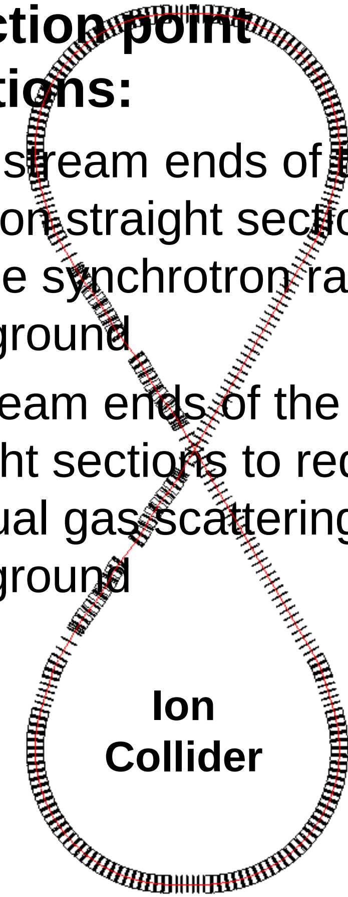
MEIC/EIC Layout



MEIC Layout







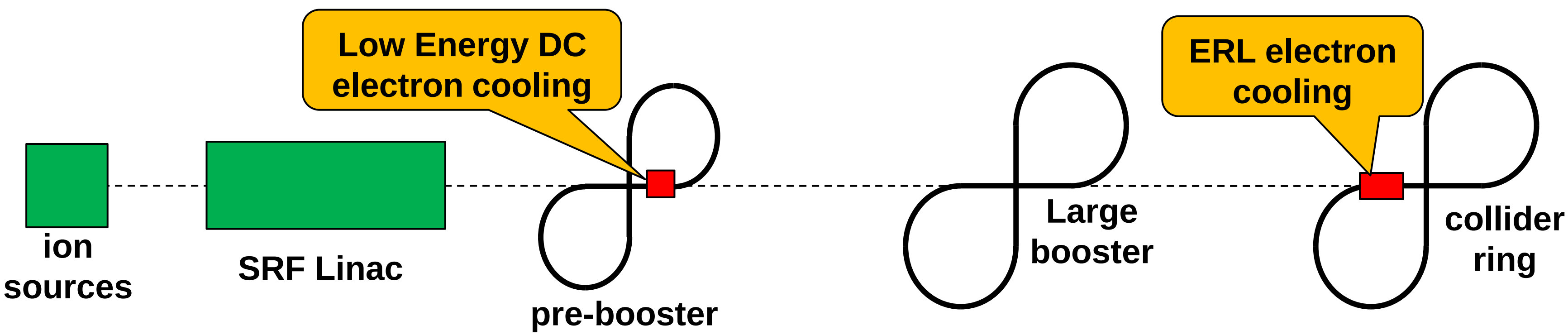
Interaction point locations:

- 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 of nearly identical rings (max. deviation: 4 m; ring circumferences: 1350 m)
- Ion beams execute vertical excursion to the plane of the electron orbit for a horizontal crossing
- Horizontal crab crossing (50 mrad) at Ips; Figure-8 crossing angle: 60 deg.

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



Components	Max. energy (GeV/u)	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

MEIC Design Point Parameters

Detector type		Full acceptance		high luminosity & Large Acceptance	
		Proton	Electron	Proton	Electron
Beam energy	GeV	60	5	60	5
Collision frequency	MHz	750	750	750	750
Particles per bunch	10^{10}	0.416	2.5	0.416	2.5
Beam Current	A	0.5	3	0.5	3
Polarization	%	> 70	~ 80	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1	~ 3	7.1
RMS bunch length	mm	10	7.5	10	7.5
emittance, normalized	µm rad	0.35/0.07	54/11	0.35/0.07	54/11
Horizontal and vertical β*	cm	10 and 2	10 and 2	4 and 0.8	4 and 0.8
Vertical beam-beam tune shift		0.014	0.03	0.014	0.03
Laslett tune shift		0.06	Very small	0.06	Very small
Distance from IP to 1st FF quad	m	7	3.5	4.5	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6		14.2	

MEIC Design Report

JSA Science Council 08//29/12)

- ✓ **"… was impressed by the outstanding quality of the present MEIC design"**
- ✓ **"The report is an excellent integrated discussion of all aspects of the MEIC concept."**

Overall MEIC design features:

- **High luminosity over broad range**
- **Highly polarized beams (including D)**
- **Full acceptance & high luminosity**
- **Minimized technical risk and R&D**

Design concept is stable


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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[14] Science and Technique Laboratory Zaryad, Novosibirsk, R...
[15] University of Wisconsin-Madison, Madison, W... USA

...: Y. Zhang and J. Bisognano

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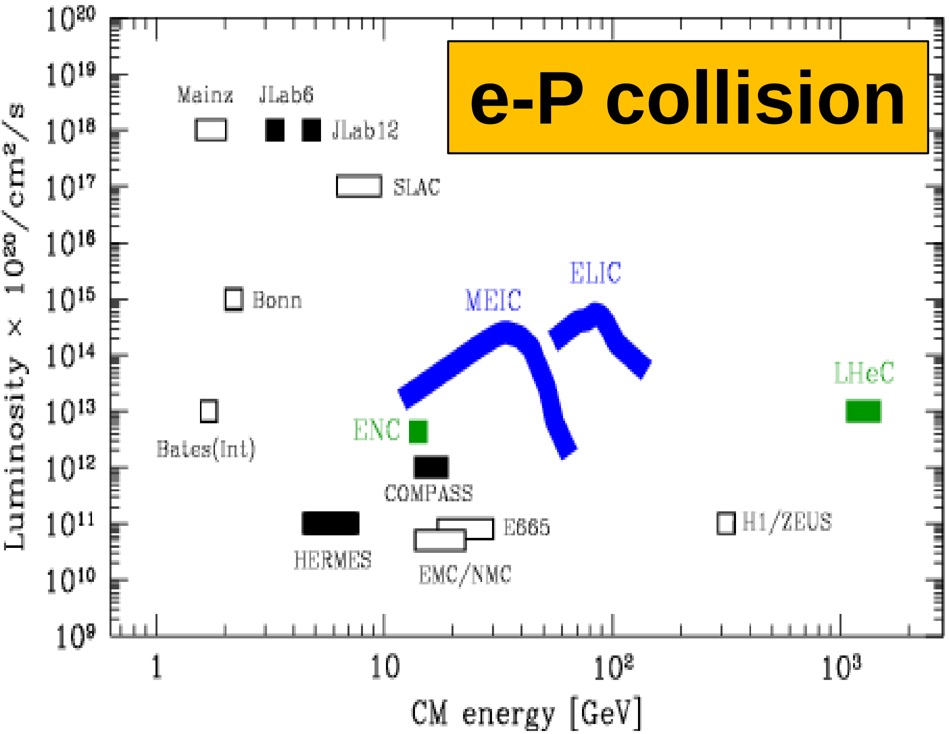
arXiv:1209.0757

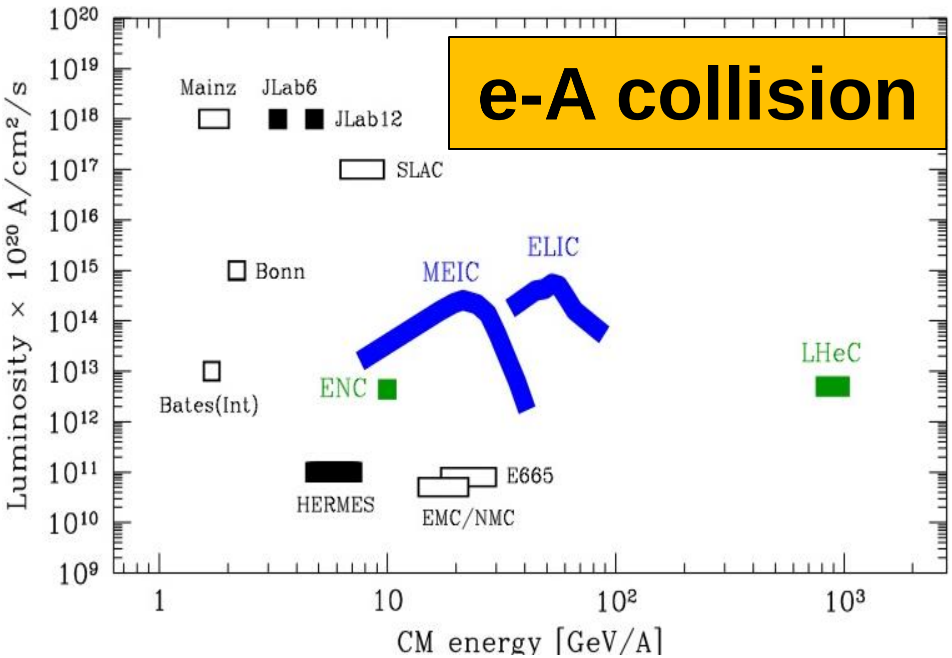
EPJA article by JLab theory on MEIC science case (arXiv:1110.1031; EPJ A48 (2012) 92)

Performance: High Luminosity



- High luminosity over a broad energy range
- MEIC peak luminosity above 10^{34} $cm^{-2}s^{-1}$

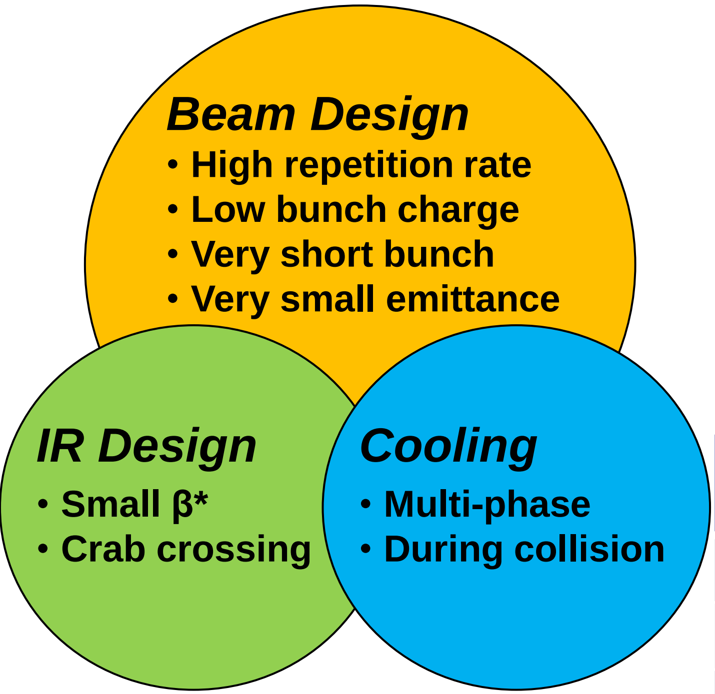
(*A full/high detector acceptance can be achieved simultaneously*)



A. Accardi

MEIC High Luminosity Concept

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



KEK-B has reached >2x10^{34} /cm^2/s

JLab is poised to replicate same success in an 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
Repetition rate	MHz	**509**	**748.5**
Energy (e^-/e^+ or p/e^-)	GeV	8/3.5	60/5
Particles/bunch (e^-/e^+ or p/e^-)	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
Horiz. & vert. β*	cm	56/0.56	10/2~4/0.8
Luminosity/IP, 10^{33}	/cm^{2}s	20	5.6 ~ 14

Performance: High Ion Polarization

We are quite confident MEIC could deliver *superior* ion polarization!

Primary technology innovation: Figure-8 ring

➔All ion rings (two boosters, a collider) have a figure-8 shape

➔ Most simple (in principle)

- Spin precession in the left & right parts of the ring are exactly cancelled
- Special insertions invented to provide energy independent spin tune off 0 at constant orbit
- Ensures an ***easy means*** of spin preservation and manipulation
- Avoids energy-dependent spin sensitivity for ion all species

➔ Polarized deuterons

- **The only practical way to accommodate medium energy polarized deuterons which allows for "clean" neutron measurements**

➔ No-pain operation

Offers ***firm no-pain long term operation runs*** for all polarized beams at all energies,

- Intrinsic spin resonances stay away
- High order intrinsic effects are diminished with *cooled emittance*

Performance: High Electron Polarization

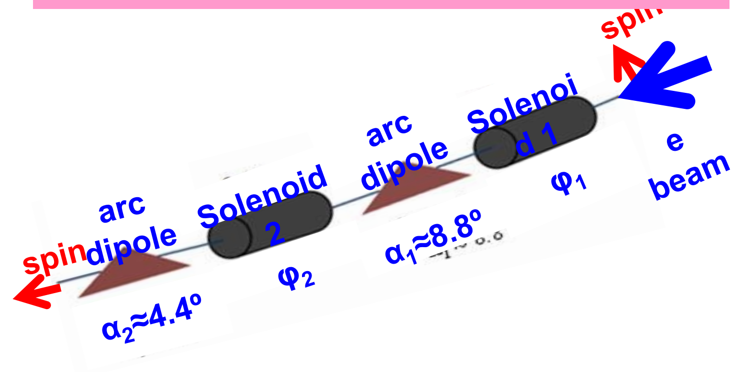
- **MEIC Physics program demands**
  - High polarization (>70%) and long life-time (>10 min.)
  - Longitudinal direction at IPs and spin flip
- **MEIC electron polarization design**
  - **CEBAF polarized electron source (superior, >85%) as a full energy injector**
  - Beam in the ring can be frequently replaced
  - Inject e-beam with vertical spin in arcs
  - Using ***universal spin rotators*** for longitudinal spin at IP
  - Employing ***spin matching*** to minimizing depolarization

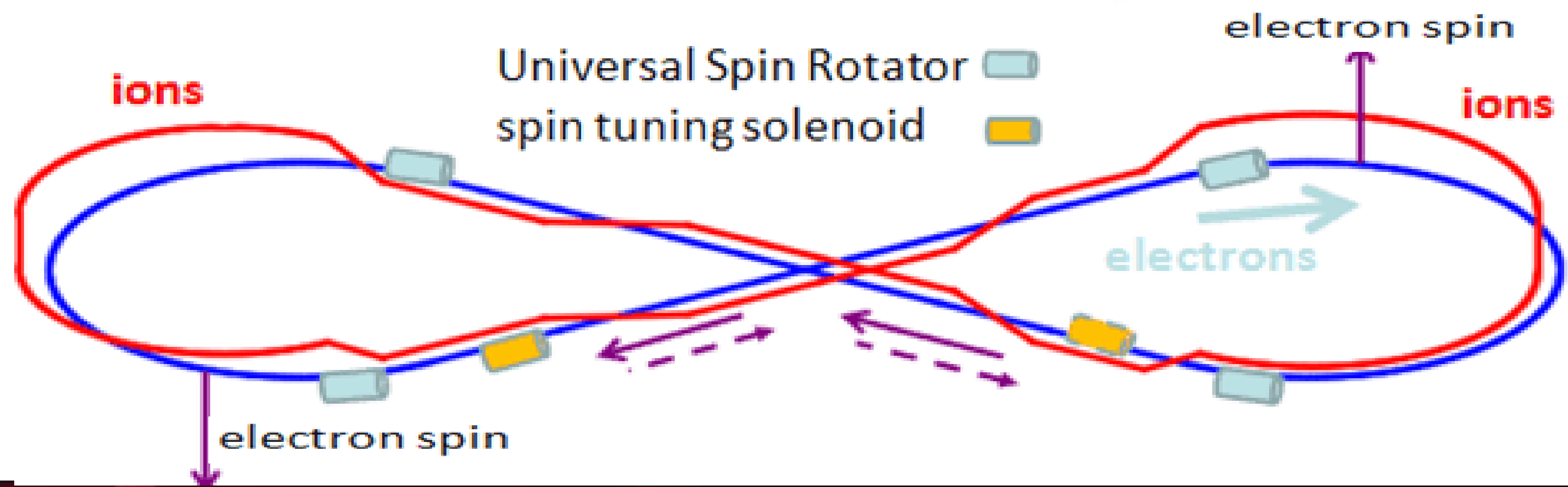
Universal Spin Rotator

rotating spin from vertical to longitudinal direction

➔ ***energy independent***

➔ ***orbit (geometry) independent***





Performance: Low Energy Electron-Ion Collisions

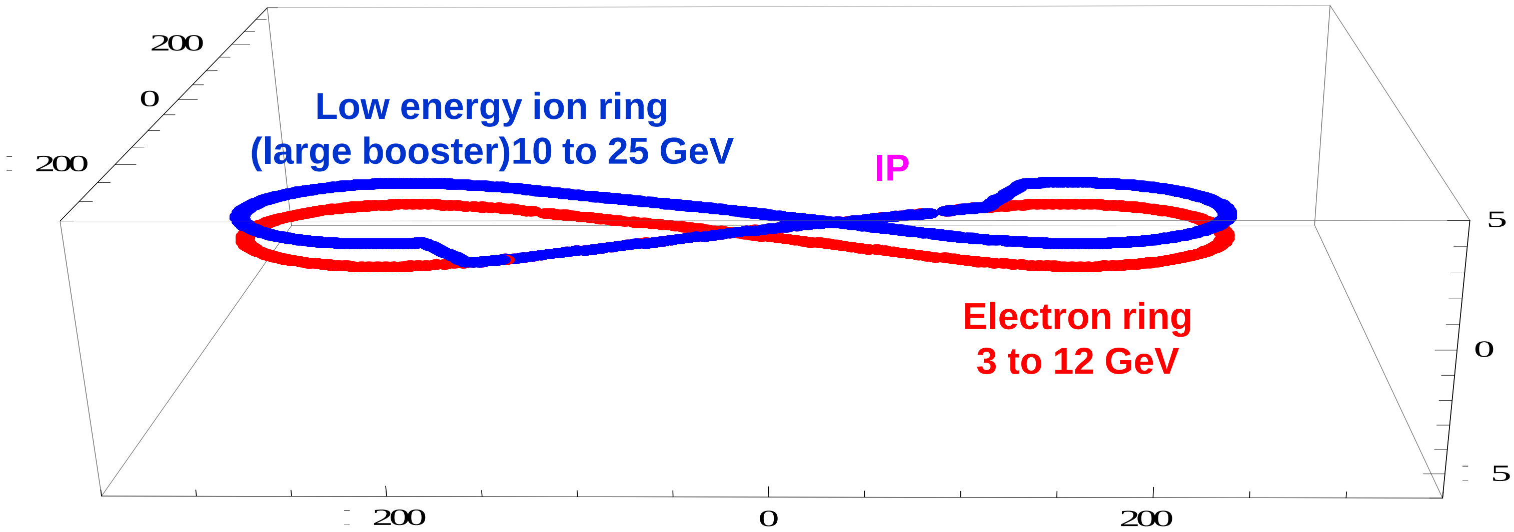
Implementation of low energy electron-ion collisions

➔ Converting large ion booster to a collider ring

➔ Peak luminosity can reach 10^{33} cm^{-2}s^{-1}

➔ Could be a 3rd IP as an additional capability or the 1st phase of EIC@JLab

- Design flexibility, detector ***interchangeable***
- No SC ring for large booster ➔ easier to start
- Low technology R&D challenges, reduce risk



Performance: Polarized Positrons

MEIC/LEIC can collide polarized positrons with ions, achieving high luminosity similarly to electron-ion collisions

➔ Only be possible with a ring-ring collider (a lepton storage ring)

- Use CEBAF beam to generate unpolarized positrons
  (Development of an optimum scheme in process)
- Accelerate in CEBAF, inject and stack in the lepton storage ring
- Arrange and wait for possibly fastest self-polarization (Sokolov-Ternov effect)
  (at 10-12 GeV, and/or by using special wigglers)
- Ramp energy down to the target value for experiment
- Use spin-resonance SC cavities for *spin flip* (***frequent*** flip for the ***whole*** beam or ***one-time*** flip for ***half*** beam***)***

MEIC Accelerator R&D Toward CD1

- **Electron cooling**
  - **Electron cooling of medium energy ion beam (by simulations)**
  - **ERL circulator cooler design optimization, technology development**
  - **Cooling with bunched electron beams**
  - **ERL-circulator cooler demo (using JLab FEL facility)**
- Interaction region
  - Optimization of detector integration
  - **Sufficient dynamic aperture with low beta insertions**
- Beam Synchronization
  - A scheme has been developed; SRF cavity frequency tunability study is in progress
- 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 priority

Jefferson Lab

Cooling: No. 1 R&D Priority

- 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)

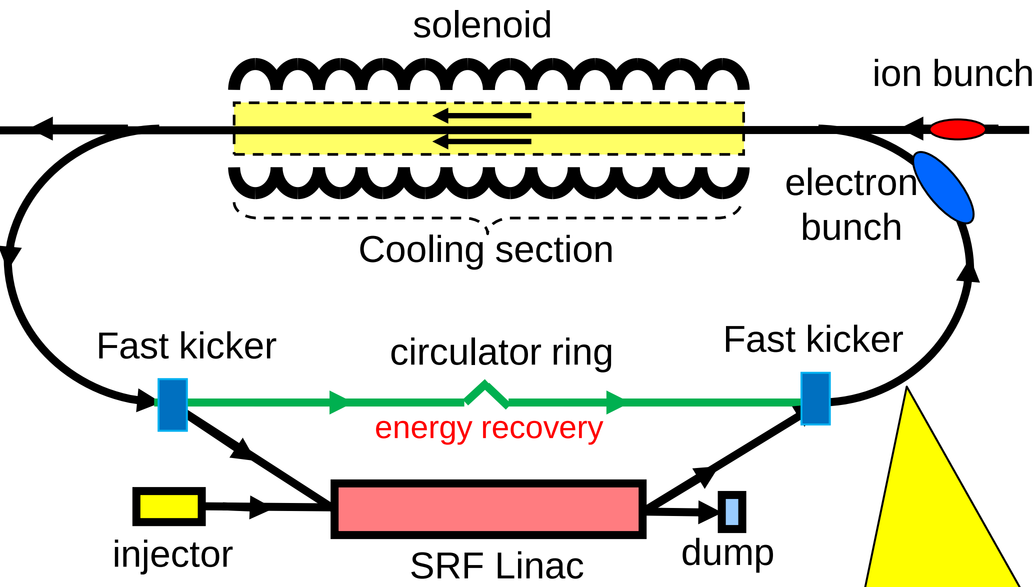
Energy (proton / electron)	GeV/MeV	20 / 10.9	100 / 54
Current & Particles/bunch, p/e	A / 10^{10}	0.5/1.5 and 0.417/1.25	
Ion bunch length	cm	coasting	→ 1
Electron bunch length	cm	2	
Proton emittance, horiz. /vert.	μm		0.35/0.07
Cooling time	min	10	~ 0.4

Medium energy	**Bunched e-beam**
ERL	**Circulator ring**

→ Cooling of medium energy (up to 100 GeV) hadrons w/ a bunched electron beam (state-of-art: 8 GeV p-bar at Fermilab, DC)

→ Generating 3 A, 55 MeV cooling electron beam

Design Concept: ERL Circulator Cooler



e-bunches circulates 10+ turns
➔ reduction of current from an ERL by a same factor

Design Choices

- Energy Recovery Linac (ERL)
- Compact circulator ring

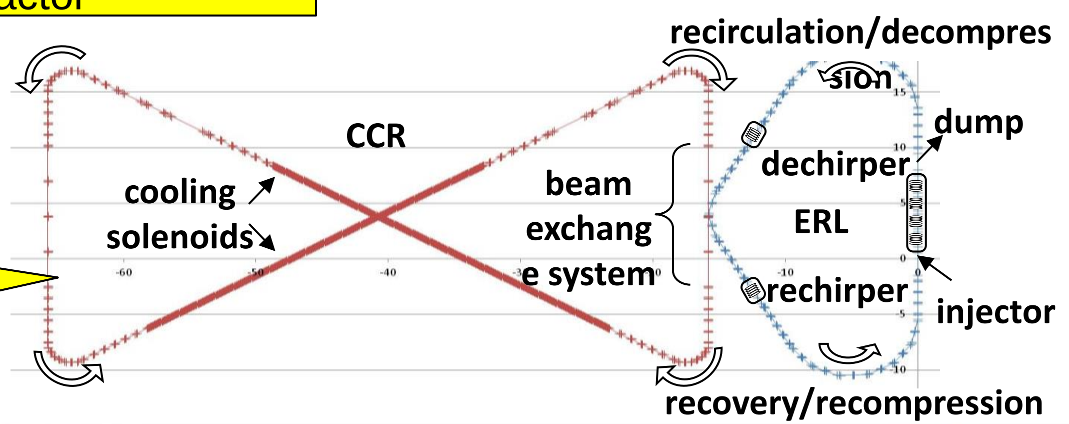
to meet design challenges

- 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



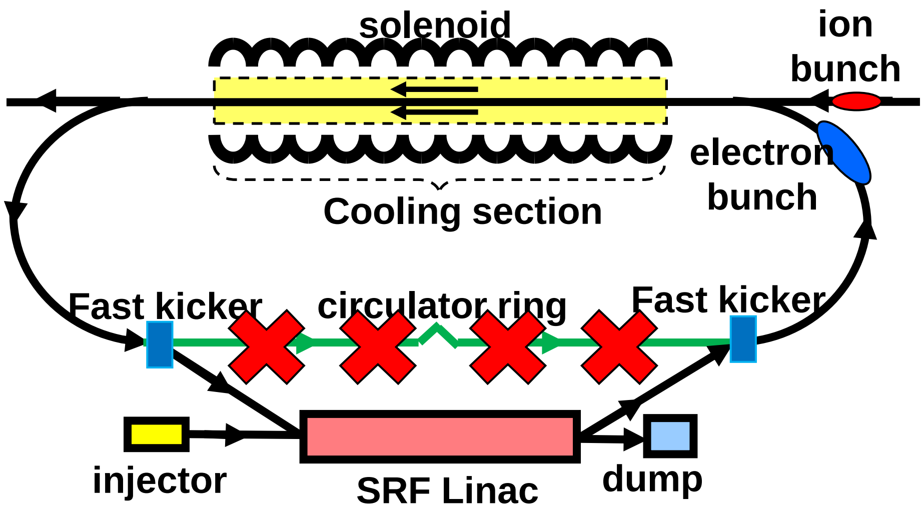
Design Concept Optimization

		Ion energy (GeV/u)	Ready-to-build	Ultimate	Old scheme
Pre-booster	DC electron cooling to assist accumulation of positive ions	0.1	✓	✓	✓
	DC electron cooling for emittance reduction	3	✓	✓	
Collider ring	ERL electron cooling at injection energy for emittance reduction	20			✓
	ERL electron cooling at top energy for emittance reduction	Up to 100		✓	✓
	ERL electron cooling during collision to suppress IBS induced emittance growth	Up to 100	"Weak" ✓	✓	✓
	Stochastic cooling of heavy ions during collision to suppress IBS induced emittance growth	Up to 100	✓		
Luminosity	**10^{33} 1/cm^2/s**		**1 ~ 3**	**5.6 ~ 14**	

- The "ready-to-build" version utilizes only (loosely speaking) the existing and proven accelerator technologies.
- "Weak" ERL cooling means using much lower electron current

Existing Cooling Technologies

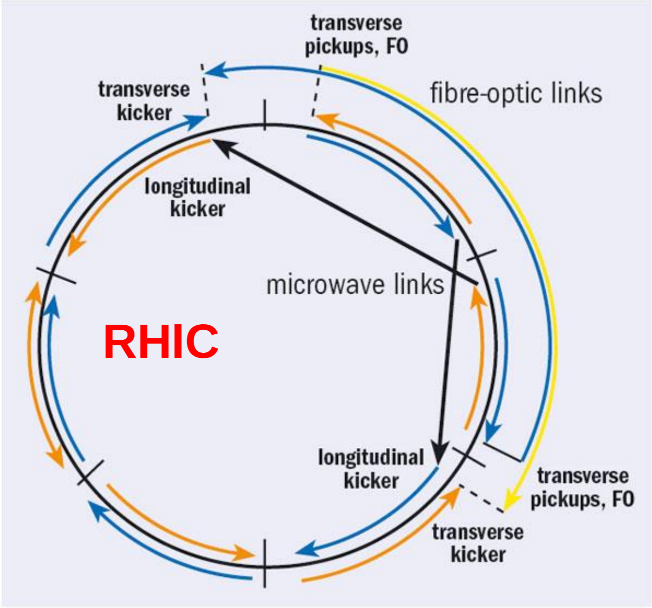
"Weak" ERL Cooler



- No circulating ring (no fast kicker)
- Electron current: ~100 mA (state-of-art)
- Needs ERL (e-beam power: 5.5 MW)

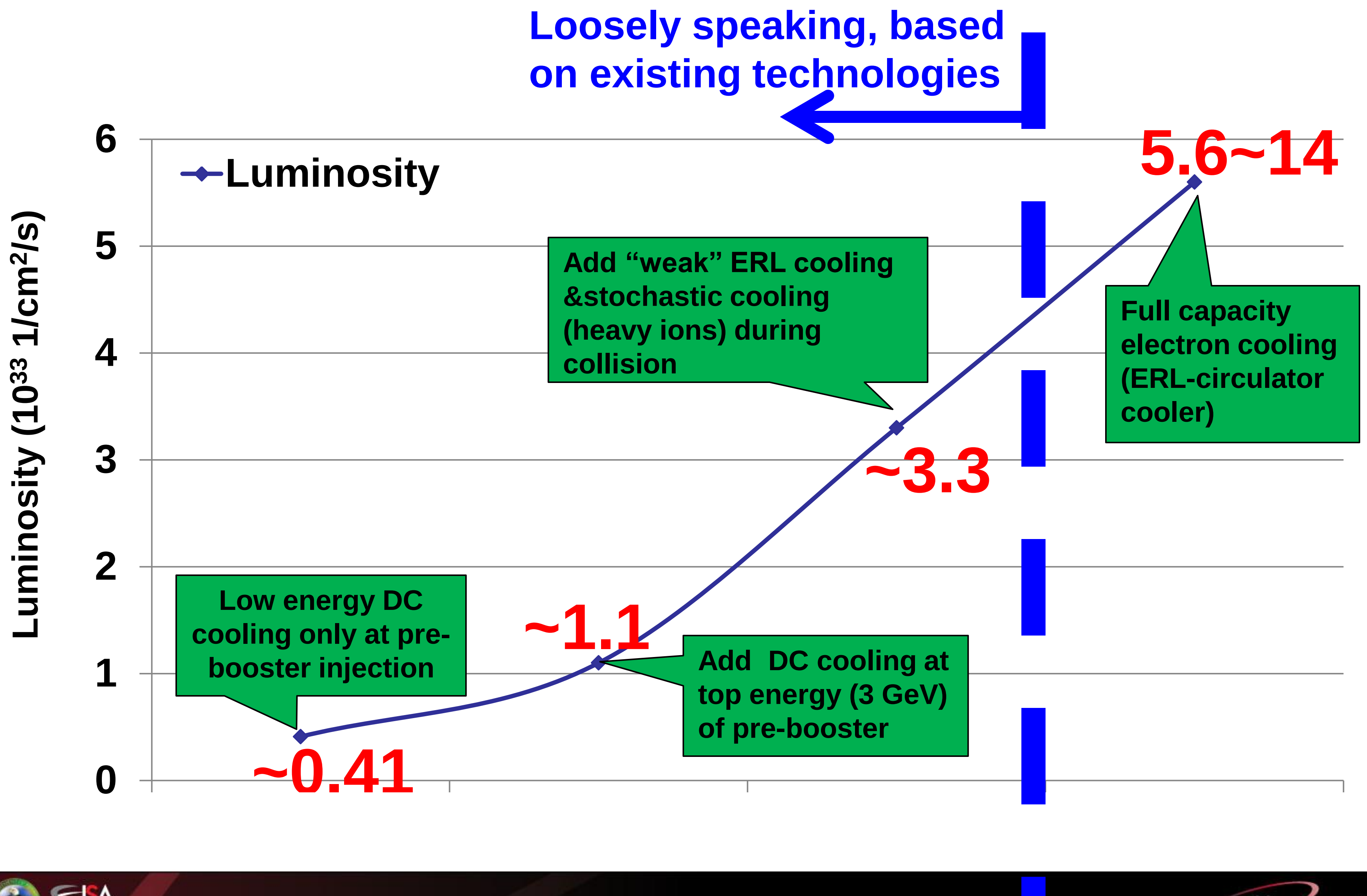
Medium energy	Bunched e-beam
ERL	Circulator ring

Bunched Stochastic Cooling



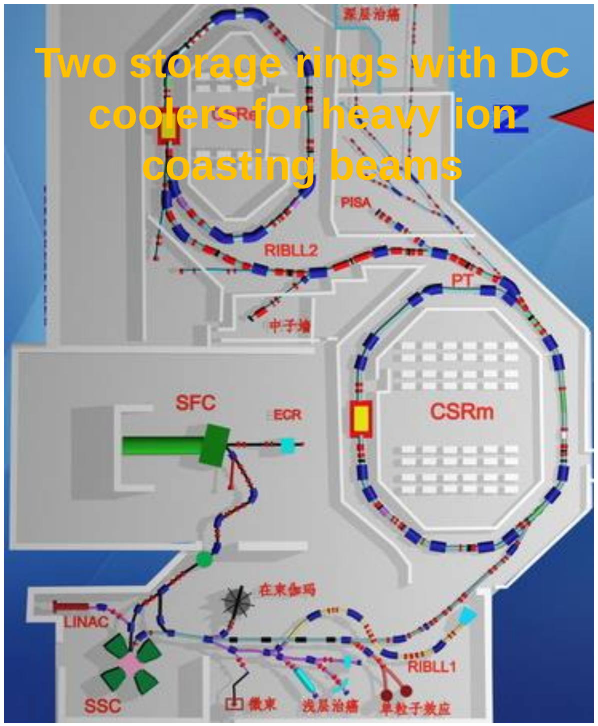
- Only for ***heavy ions***
- Bandwidth: 4~9 GHz
- Lead ions: 5.1x10^7 per bunch
- Cooling time: ~ 14 min

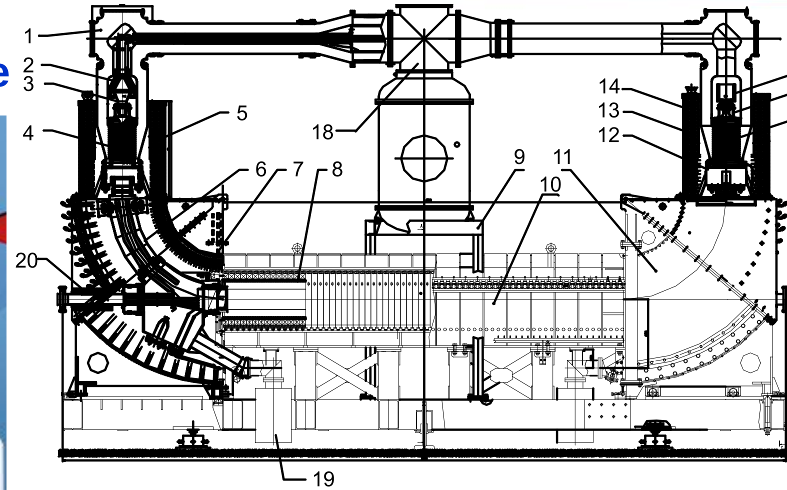
MEIC Phased Cooling Scheme



Cooling Experiments at IMP

Institute of Modern Physics, Chinese Academy of Science





Medium energy	**Bunched e-beam**
ERL	**Circulator ring**

Purpose: testing cooling with a bunched electron beam (*Andrew Hutton*)

➔ Modulated the DC beam into a bunched beam with a high repetition rate by applying a pulsed voltage to the bias-electrode of the electron gun (*Hongwei Chao, IMP*)

➔ Replacing the existing thermionic gun by a JLab photo-cathode gun (Matt *Poelker, JLab*)

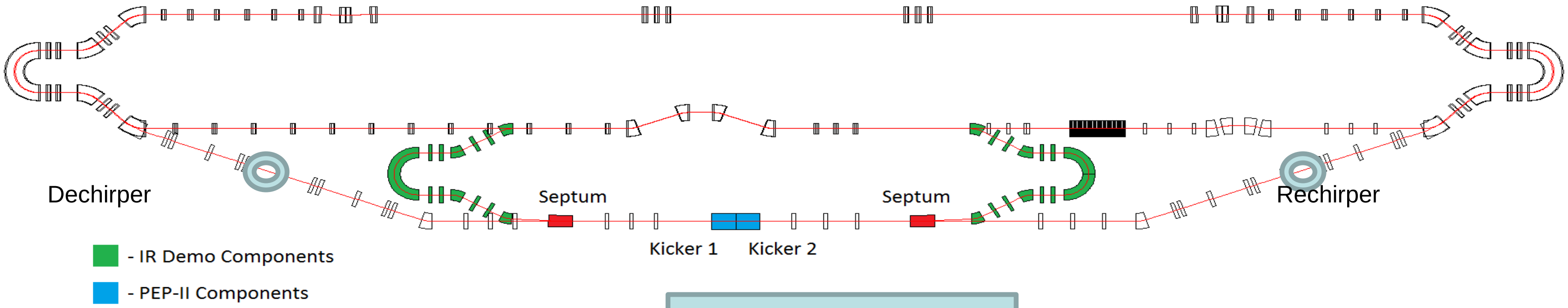
Low cost, non-invasive experiment, as early as 08/2013

Supporting the "Ready-to-Build" design concept

Phase II: adding an RF cavity for bunching the ion beams)

testing a bunched electron beam to cool a bunched ion beam

ERL-Circulator Cooler Proof-of-Concept Experiment at JLab FEL-ERL



Cooler Test Facility @ JLab FEL ERL

Purpose

- ***Demonstrate the design concept***
- Develop/test key accelerator technologies (faster beam kickers, etc.)
- Study dynamics of the cooling electron bunches in a circulator ring

Medium energy	Bunched e-beam
ERL	Circulator ring

Phase 1 scope

- Using the existing ERL without new upgrade except two 180° beam lines (available at JLab)
- Supporting MEIC to deliver the high luminosity (5.6~14 x 10^{33} 1/cm^2/s), ***not needed*** for the "ready-to-build" version
- To be completed (*hopefully*) before 2016

Summary

- The MEIC design has been completed and a comprehensive design report has been released.
- Low energy electron-ion collisions can be realized either as an add-on or as a first stage, expanding the science reach
- We anticipate superior performance of MEIC, particularly in luminosity, lepton and light ion polarization, detection acceptance, etc.
- The focus of the MEIC team has shifted to design optimization (low cost and less technical uncertainty) and critical accelerator R&D.
- Cooling is considered the most critical R&D
  - Optimizing the cooling scheme by using more existing (DC) technology
  - "Ready-to-Build" enables luminosity above 10^{33} $cm^{-2}s^{-1}$, meets the EIC white paper requirement;
  - R&D will bring an order of magnitude booster
  - Two low-cost experiments will demonstrate the design concept

Acknowledgement

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