Quest for Superior Ion Beams for Electron-Ion Collider

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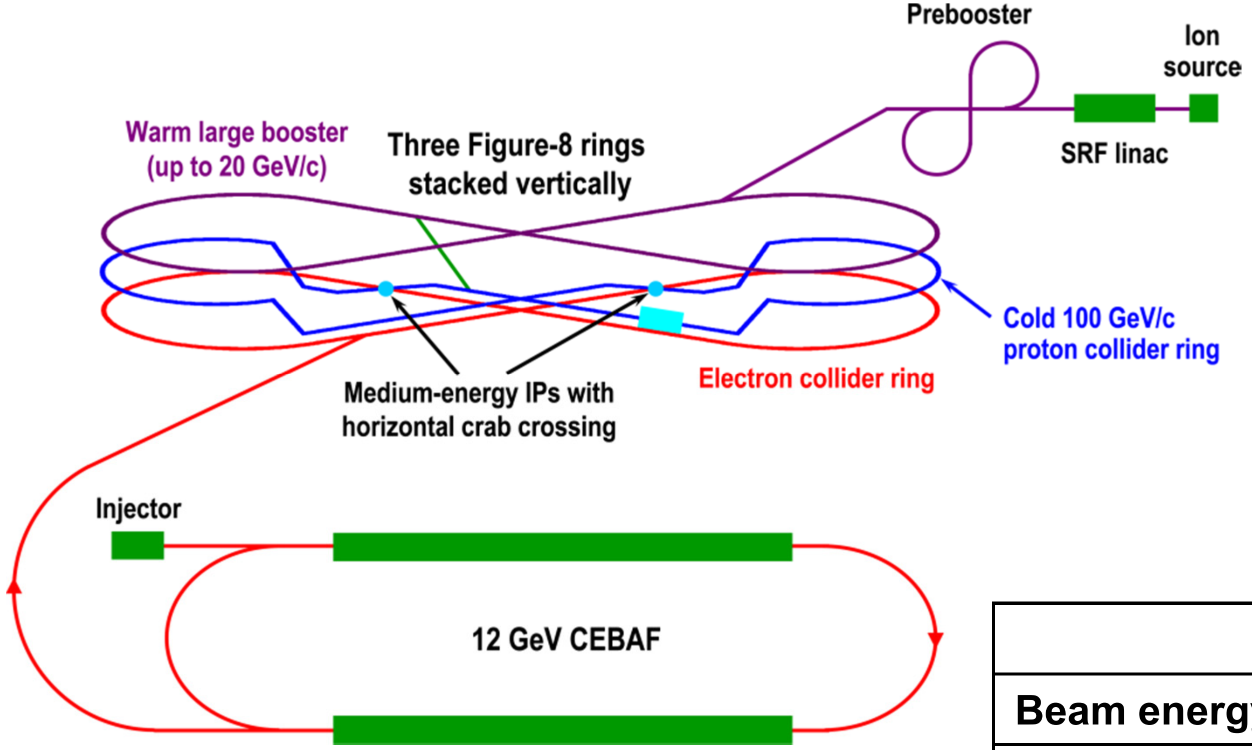
Outline

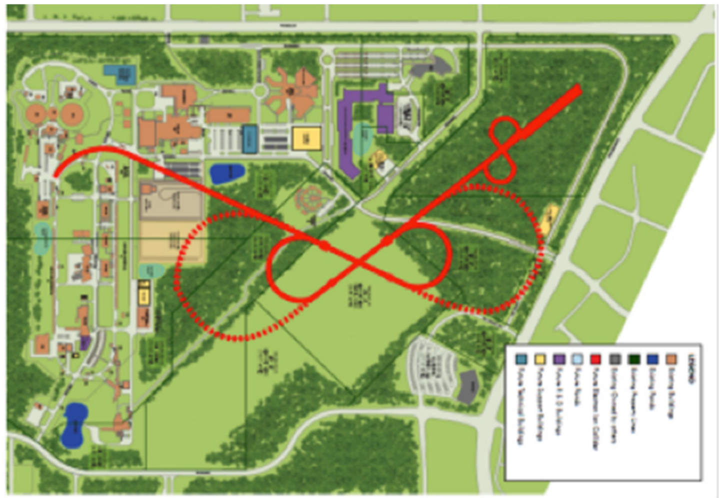
- Introduction
- MEIC and Its Luminosity Concept
- Formation of MEIC Colliding Ion Beams
- ERL Circulator Cooler and P-o-P Experiment
- Summary

Introduction

- JLab is a US DOE funded nuclear physics national lab, and operates a recirculating SRF linac, CEBAF (in upgrade to 12 GeV), for a fixed target program with over 1200 users worldwide
- Development of science case and conceptual design of an electron-ion collider (MEIC) at JLab since year 2000
- The future science program drives MEIC design
  - Polarized light ions (H, D, ^{3}He), non-polarized ions up to lead, and variable energies
  - High luminosity (>10^{33} $cm^{-2}s^{-1}$) per detector over multiple interaction points
  - High polarization (>80%) for electrons and (>70%) for light ions
- MEIC machine design is based on
  - CEBAF as a full-energy electron injector
  - A new ion complex and collider rings optimized for high luminosity/polarization
- MEIC adopts a “new” luminosity concept; superior ion beams must be generated for supporting the design concept
  - High bunch repetition rate, very low intensity however high brightness
  - Ion complex design addresses the main machine challenges
  - Electron cooling is the essential component of the design

MEIC Conceptual Design

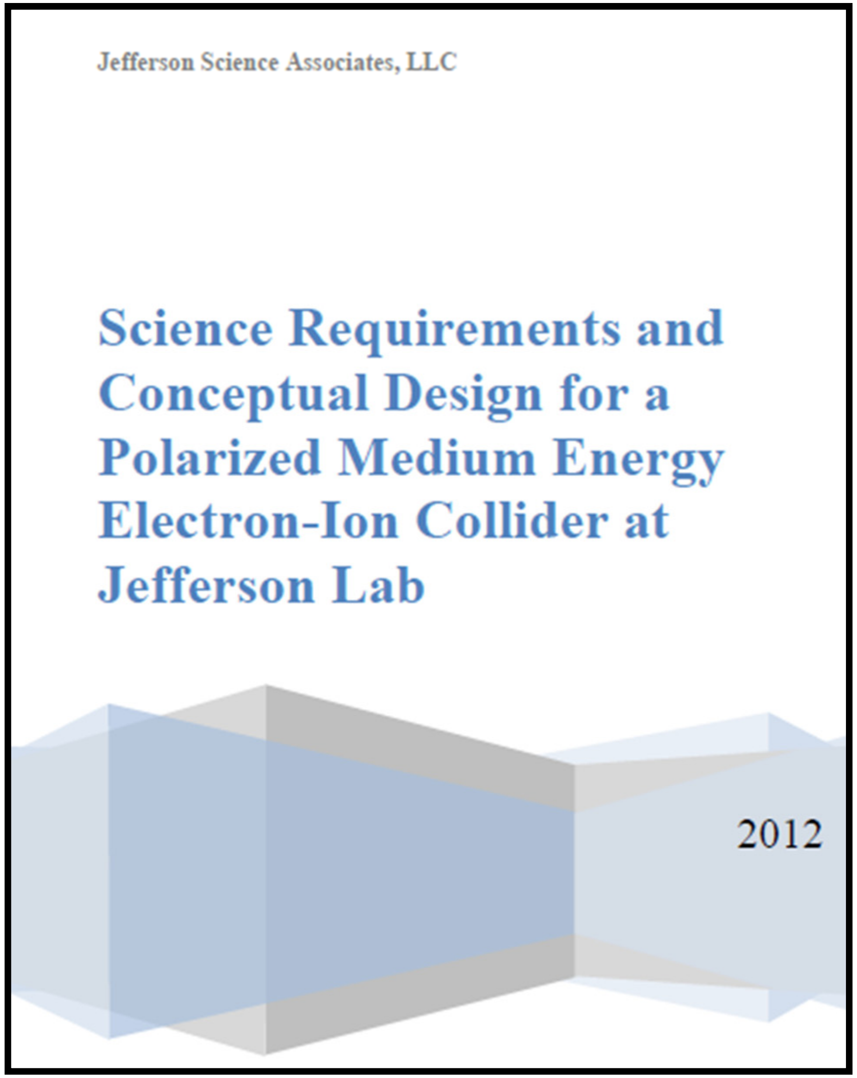




- A ring-ring collider with multiple IPs
- Collisions of 3-11 GeV electron and 20-100 GeV/u protons and ions
- CEBAF as a full energy injector (12 GeV upgrade by 2015)
- JLab nuclear physics program beyond 2025

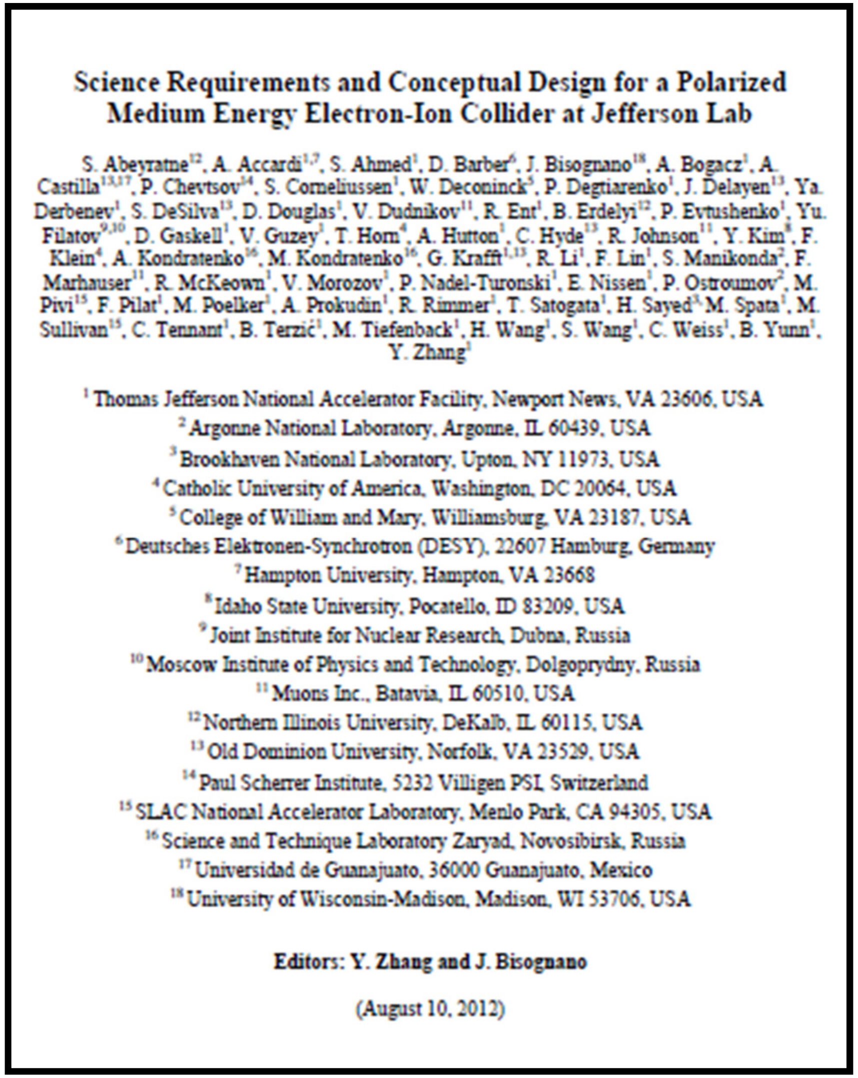
		p	e
Beam energy	**GeV**	**60**	**5**
Collision frequency	**MHz**	**750**	
Current/particles per bunch	**A /10^{10}**	**0.5/0.4**	**3/2.5**
Bunch length (RMS)	**cm**	**10**	**7.5**
Normalized emitt. (x/y)	**µm rad**	**.35/.07**	**54/11**
Horizontal & vertical β*	**cm**	**10 and 2**	
Vert. beam-beam tune shift		**0.014**	**0.03**
Distance from IP to 1st FFQ	**m**	**7 (4.5)**	**3.5**
Luminosity per IP, 10^{33}	**$cm^{-2}s^{-1}$**	**5.6 (14.2)**	

Design Report Available at http://arxiv.org/abs/1209.0757


Jefferson Science Associates, LLC

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

2012


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

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Editors: Y. Zhang and J. Bisognano

(August 10, 2012)

- **Over 160 pages, by over 50 co-authors from 18 US & international institutions**
- **First public release Aug. 10, 2012**

MEIC Key Design Features

High Luminosity (based on *high bunch repetition rate colliding beams*)

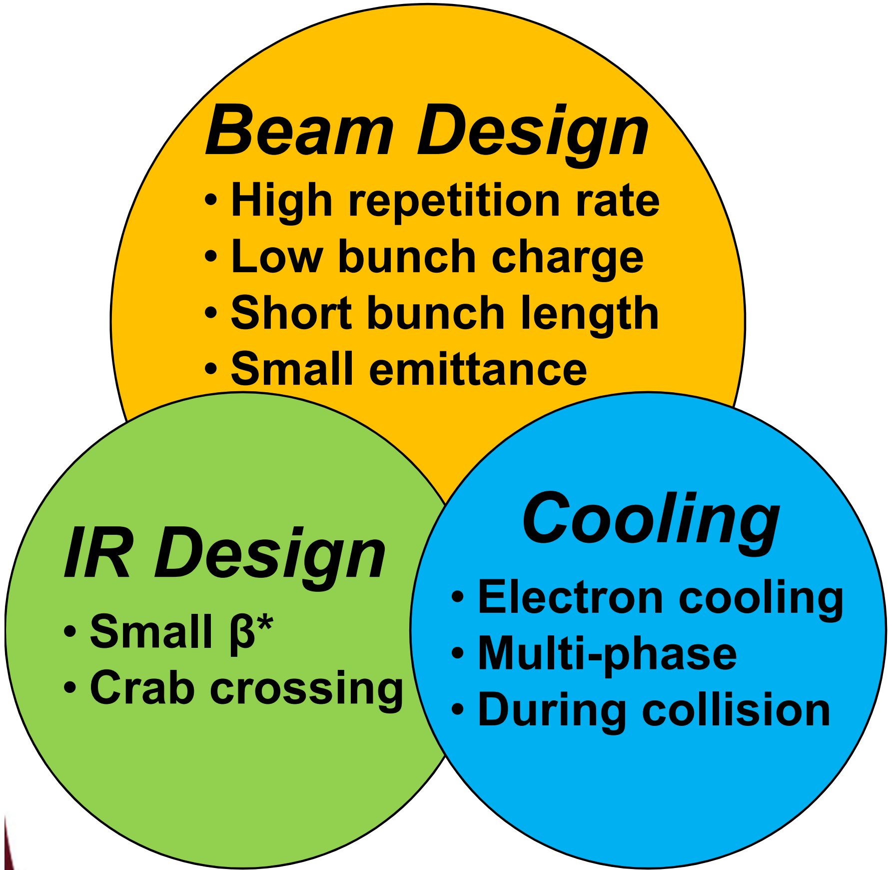
- MEIC luminosity up to 1.4×10^{34} /cm^2/s
- A proved concept: KEK-B @ 2×10^{34} /cm^2/s
- MEIC will replicate the same success in colliders with hadron beams
  - The electron beam from CEBAF possesses a high bunch repetition rate
  - Ion beams from a new ion complex can match the electron beam

High Polarization (*All ion rings have a figure-8 shape*)

- Spin precessions in the left & right half ring are exactly cancelled
- Net spin precession (spin tune) is zero, thus energy independent
- Ensures spin preservation and ease of spin manipulation
- Avoids energy-dependent spin sensitivity for ion all species
- ***The only practical way to accelerate and store medium energy polarized deuterons for collisions***

Design of MEIC Colliding Ion Beams

MEIC high luminosity is based on *high bunch repetition rate CW colliding beams*



		KEK-B	MEIC
Repetition rate	MHz	**509**	**748.5**
Particles/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
Hori. & vert. β*	cm	56 / 0.56	10/2 to 4/0.8
Lumi./IP, 10^{34}	$cm^{-2}s^{-1}$	2	0.56 ~ 1.4

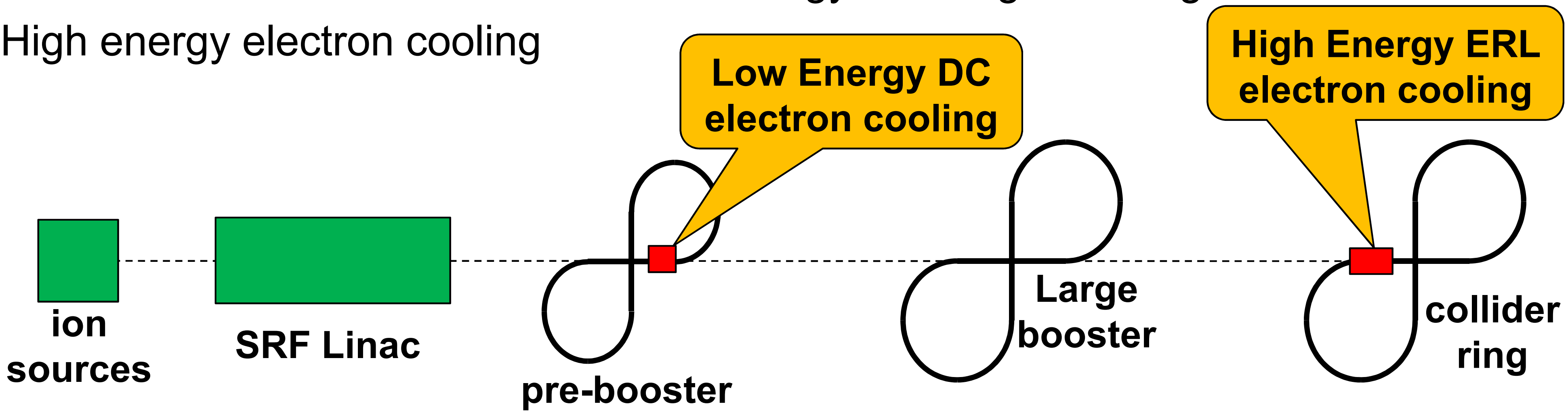
~50 times smaller than conventional hadron colliding beams

Design features

- High bunch repetition rate → low bunch charge intensity
- Ultra short bunch length → high longitudinal brightness
- Very small transverse emittance → high transverse brightness

Formation of Ion Beams in a Green Field 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



	Max. energy (GeV/c)	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)	Bunched/ERL	Coasting/rebunching

* Numbers in parentheses represent energies per nucleon for heavy ions

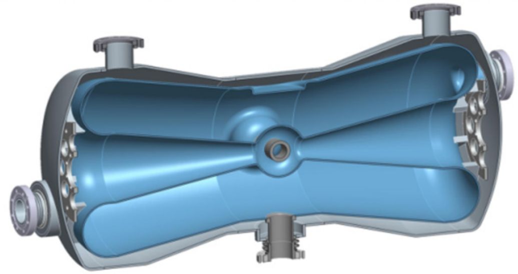
Forming Polarized Proton Beam w/ ABPIS

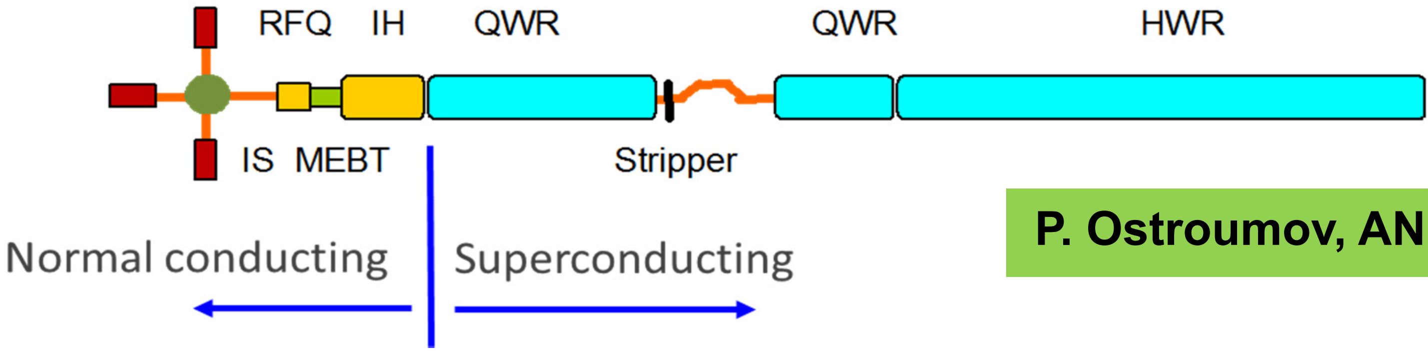
		Source	Linac	Pre-booster		booster	Collider
		ABPIS	At exit	At Injection	After boost	After boost	After boost
Charge status		-1	-1	+1	+1	+1	+1
		H^-	H^-	H^+	H^+	H^+	H^+
Kinetic energy	GeV/u	~0	0.0013	0.285	3	20	100
γ				1.3	4.2	22.3	106.4
β				0.64	0.97	1	1
Velocity boost					1.51	1.03	1
Pulse current	mA	2	2	2			
Pulse length	ms	0.5	0.5	0.22			
Charge per pulse	μC	1	1	0.44			
ions per pulse	10^{12}	3.05	3.05	2.75			
Number of pulses				1			
efficiency				0.9			
Total stored ions	10^{12}			2.52	2.52	2.52x5	2.52x5
Stored current	A			0.33	0.5	0.5	0.5
Reason of current change					Velocity change		

Forming Fully Stripped Lead Ion Beam w/ EBIS

		Source	Linac	Pre-booster		Larger booster		Collider
		EBIS	After stripper	At Injection	After boost	Stripping before injection	After boost	After boost
Charge status		30	67	67	67	82	82	82
		$^{208}Pb^{30+}$	$^{208}Pb^{67+}$	$^{208}Pb^{67+}$	$^{208}Pb^{67+}$	$^{208}Pb^{82+}$	$^{208}Pb^{82+}$	$^{208}Pb^{82+}$
Kinetic Energy	GeV/u	~0	0.013	0.1	0.67	0.67	7.9	40
γ				1.11	1.71	1.71	9.4	42.6
β				0.43	0.81	0.81	0.99	1
Velocity boost					1.88		1.1	
Pulse current	mA	1 to 4	0.28					
Pulse length	ms	.01~.04	0.04					
Charge per pulse	μC	0.056 @ 1.4mA	0.011					
ions per pulse	10^{10}	1.17	0.104					
# of pulses				62				
efficiency			0.2	0.7		0.75		
Total stored ions	10^{10}			4.5	4.5	3.375x5	3.375x5	3.375x5
Stored current	A			0.26	0.5	0.447	0.54	0.54
Reason of current change			stripping	Multi-pulse injection	Velocity change	stripping	Velocity change	

MEIC SRF Ion Linac





P. Ostroumov, ANL

- Pulsed linac, peak power 680 kW
- Consists of quarter wave and half wave resonators
- Originally developed at ANL as a heavy-ion driver accelerator for ***Rare Isotope Beam Facility***
- Adopted for MEIC ion linac for
  - Satisfying MEIC ion linac requirement
  - Covering similar energies, variety of ion species
  - Excellent and matured design
- All sub-systems are either ***commercially available*** or based on ***well-developed technologies***

Ion species		p to Pb
reference design		$^{208}Pb^{+82}$
Kinetic energy	MeV/u	280 & 100
Max. pulse current		
Light ions (A/q≤3)	mA	2
Heavy ions (A/q>3)	mA	0.5
Pulse repetition rate	Hz	up to 10
Pulse length		
Light ions (A/q≤3)	ms	0.5
Heavy ions (A/q>3)	ms	0.25
Max. pulsed power	kW	680
Fundamental freq.	MHz	115
Total length	m	121

	Q ion source	Energy at the stripper MeV/u	Q after the stripper	Total energy MeV/u
Proton	1	55	1	285
Dueteron	1	32.8	1	169
^{40}Ar	12	22.4	18	150
^{132}Xe	26	16.5	48	120

Space Charge Dominated Ion Beam in the Pre-booster

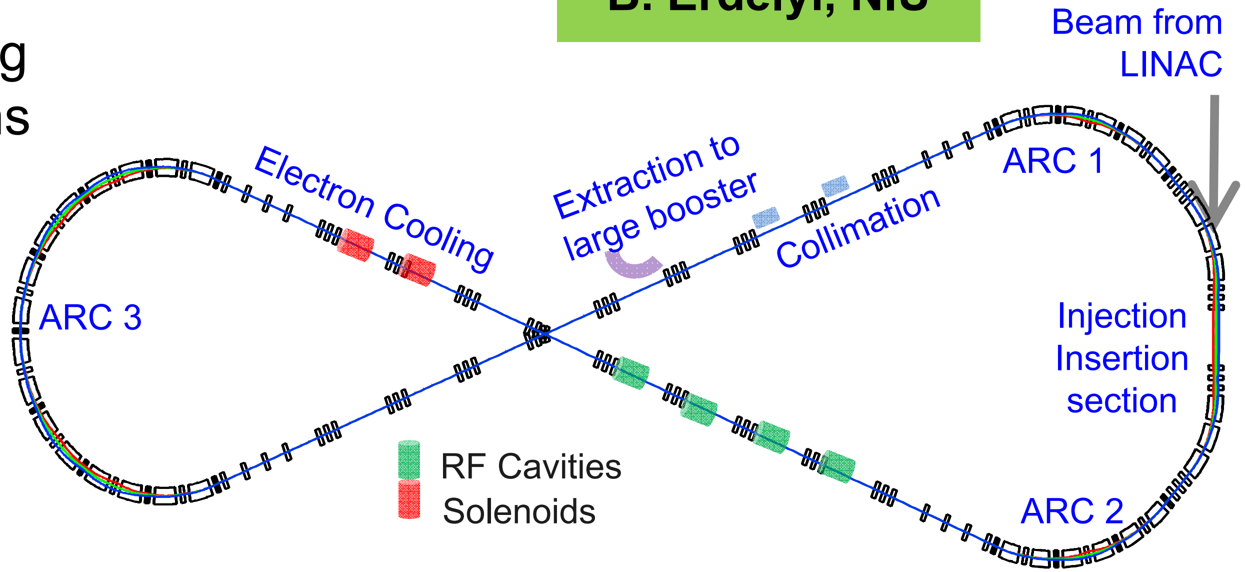
Conceptual Design

- Low energy DC electron cooling for accumulation of positive ions

Simulation studies

- Tracking & dynamic aperture
- Analysis of chromaticity, amplitude-dependent tune shifts, resonance strengths
- Working point optimization.

B. Erdelyi, NIU



Conceptual developments

- ***Circular optics*** to realize the ***matched electron cooling*** for diminishing the space charge impact
- ***Painting*** technique for stripping injection of polarized light ion beams
- ***Barrier-bucket*** RF technique for stacking and acceleration as an alternative to the cavity-based RF system

Electron Cooling in MEIC

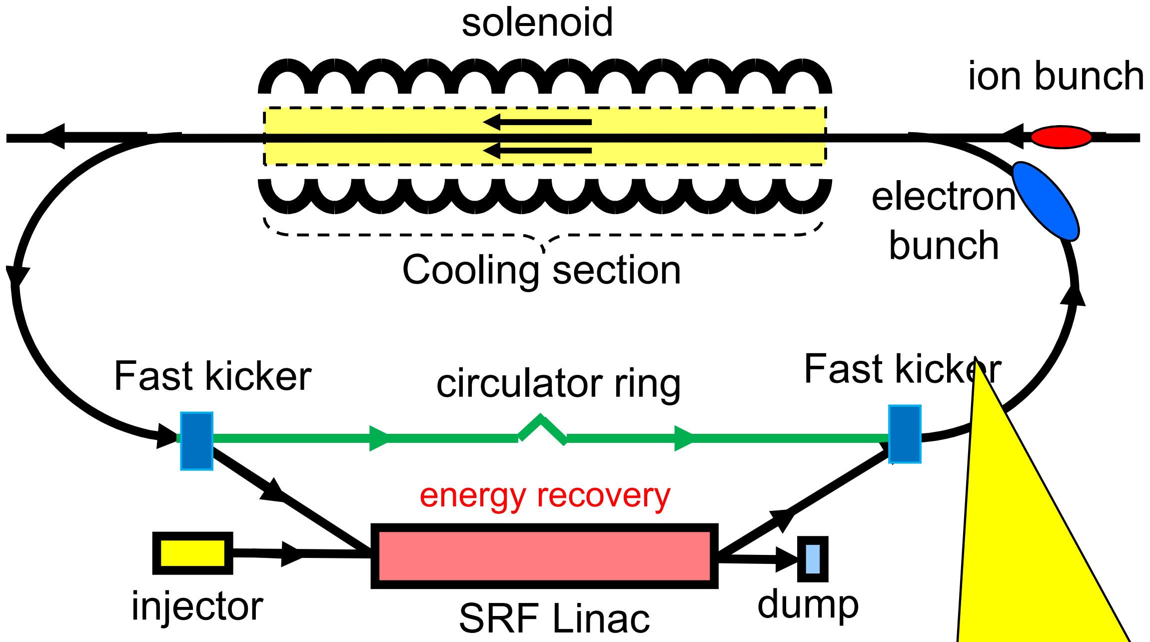
- Essential to achieve high luminosity for MEIC
- Based on traditional electron cooling
- ***Multi-phase cooling*** **scheme**

  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
Cooling length/circumference	m	60 / 1350	
Current and Particles/bunch	A and 10^{10}	0.5 / 1.5 and 0.417 / 1.25	
Bunch frequency	MHz	~ 1 / 748.5	748.5
Energy spread	10^{-4}	10 / 3	5 / 3
Ion bunch length	cm	coasted	coasted → 1
Electron bunch length	cm	2	
Proton emittance, horiz. /vert.	µm	4	4 → 0.35/0.07
Cooling time	min	10	~ 0.4

ERL Circulator Cooler for MEIC Collider Ring



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

Design Choices

- Energy Recovery Linac (ERL)
- Compact circulator ring

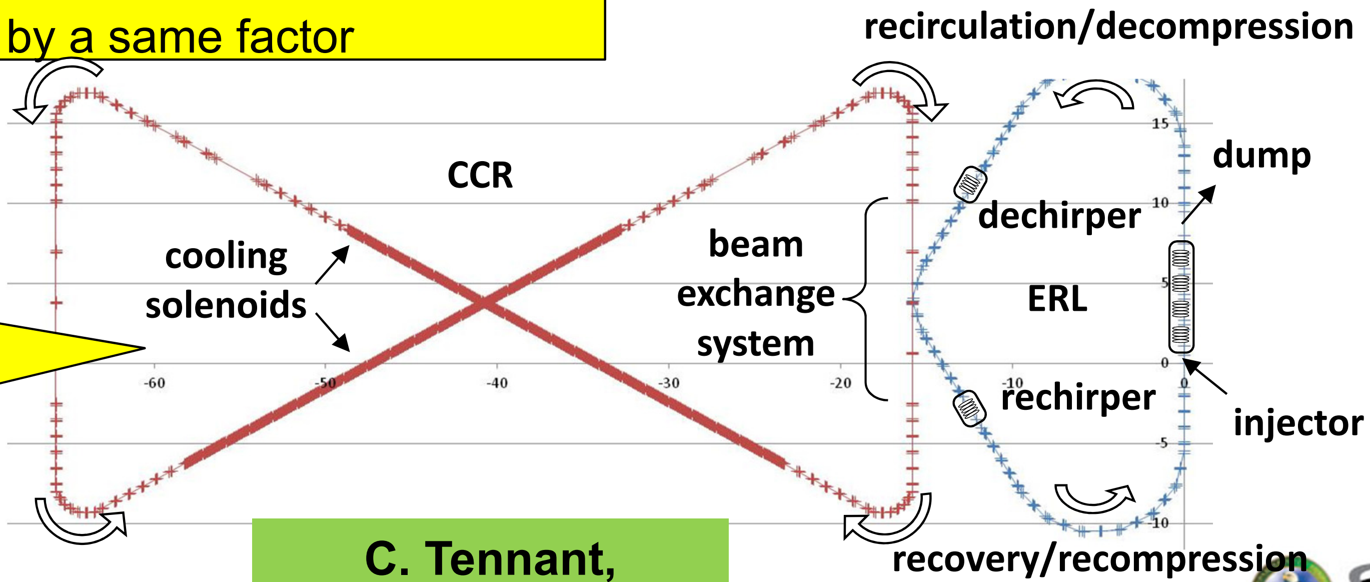
to meet design challenges

- 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



**C. Tennant,
D. Douglas, JLab**

ERL Circulator Cooler: A Test Facility a nd Proof-of-Principle Experiment

A Test Facility based on JLab ERL-FEL

- It is an ERL, providing similar energy range
- Reuses the existing hardware, reducing the cost

		FEL ERL	ERL-CR
Energy	MeV	80-210	10-54
Bunch charge	nC	0.135	2
Turns in CR			10-100
Bunch frequency	MHz	75	75-7.5
Gun current	mA	10	150–15
Trans. emit., norm.	μm	10	1-3
Long. emittance	keV-ps	25-75	150
Energy spread	%	0.4	0.01
RMS bunch length	ps	2	100

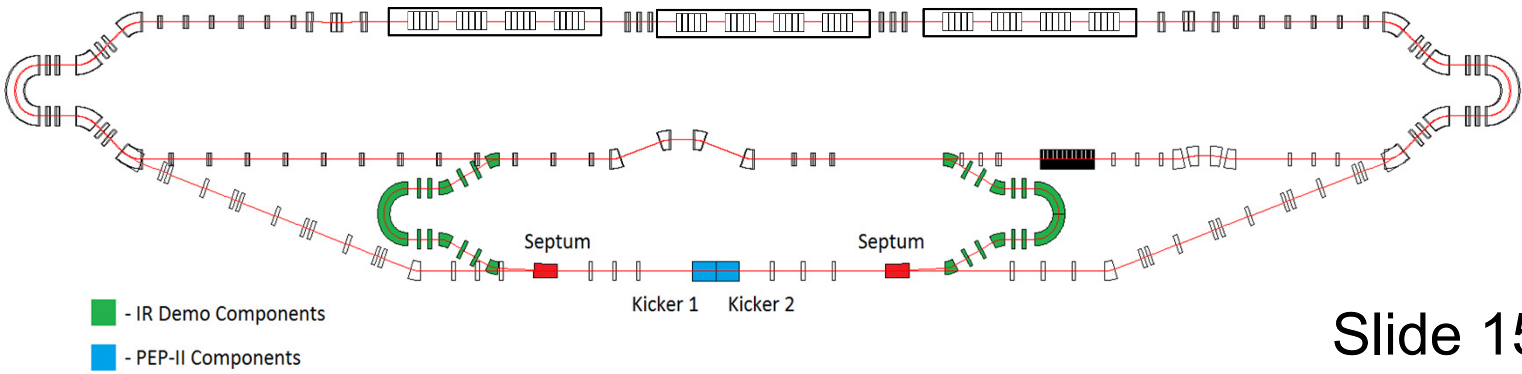
Proof-of-Principle experiment

- Demonstrate bunch exchange between ERL and circulator ring
- Demonstrate bunch decompression/compression
- Test bed for collective beam effect studies
- Develop supporting technologies

Status (expected completion 2015)

- Circulator ring optics design completed
- Initial tracking shows CSR could be a problem
- RF source specifications under development

E. Nessin, JLab



Summary

- The conceptual design of MEIC was completed. The design report is available on arXiv web site.
- Ion beams with ultra high bunch repetition rate, low intensity but high brightness must be produced and stored to support the high luminosity of the collider. Such beams have never been produced before.
- The design concept of a new ion complex has been developed to specifically address these challenging issues, including suppressing space charge and intra-beam scatterings.
- A test facility based on JLab ERL FEL was proposed for a proof-of-principle experiment for the ERL-circulator electron cooler design concept. Expect to complete this experiment in three years.
- Design optimization (cost reduction/staging option) and other R&D are also in progress