

Overview of US Electron-Ion Collider Project and Its Cooling Programs

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Thomas Jefferson National Accelerator Facility

***COOL'17* - International Workshop on
Beam Cooling and Related Topics**

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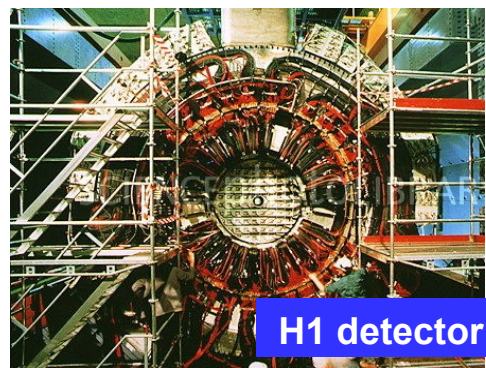
Outline

- Introduction
- BNL eRHIC Design
- JLab JLEIC Design
- eRHIC Beam Cooling
- JLEIC Beam Cooling
- Additional topics: Experiment, Simulation and Advanced Concepts
- Summary

Introduction

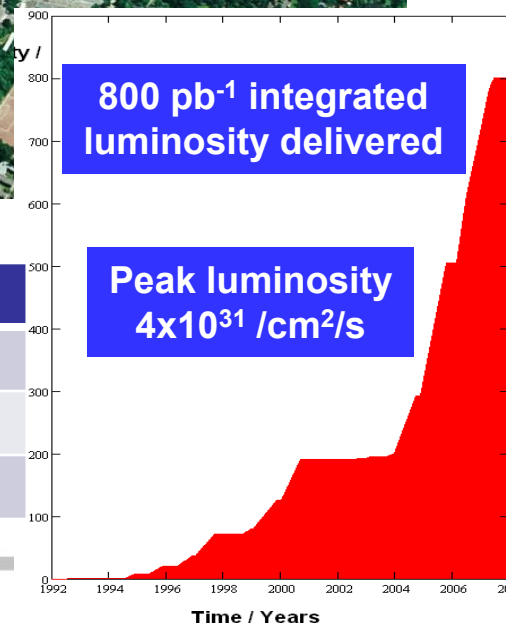
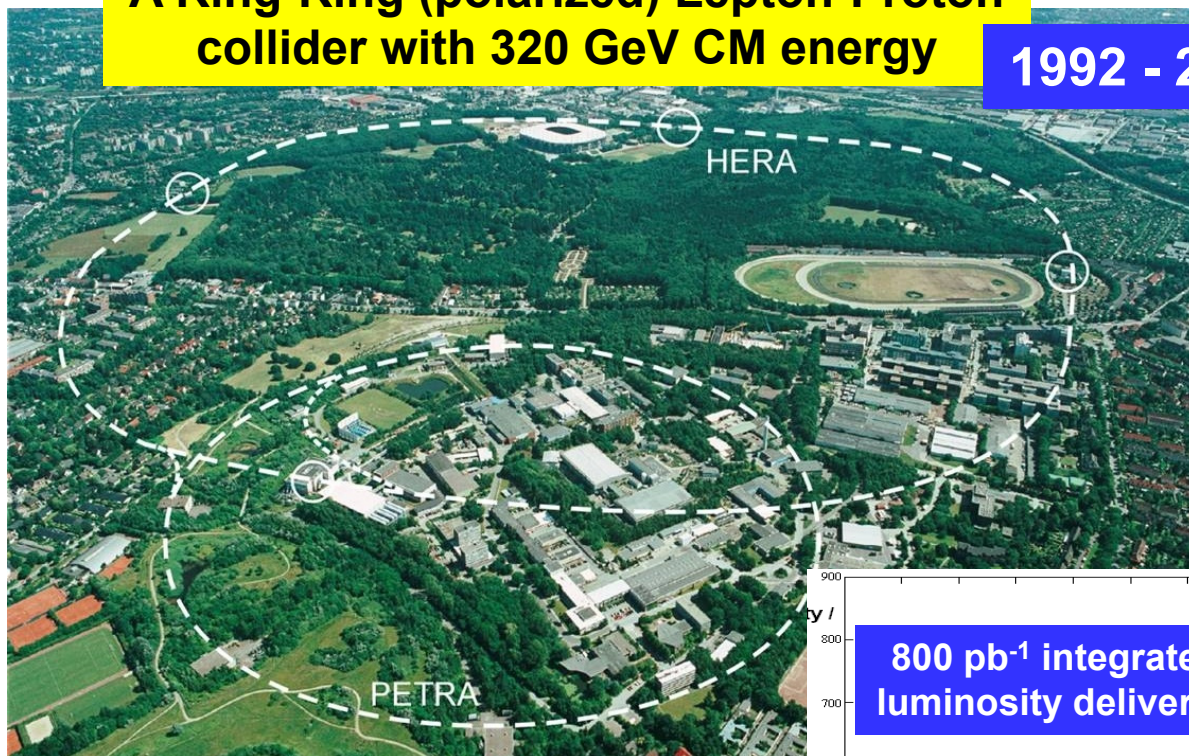
- Electron-Ion collider (EIC) utilizes deep-inelastic scatterings to probe structures of nucleus
- *HERA*, the only e-p collider ever built and operated, ended its science program in 2007. Over the past 15 years, 7 next generation EICs were envisioned worldwide for high energy and nuclear physics.
- In US, two electron-ion colliders, eRHIC and JLEIC, have been proposed in BNL and JLab respectively. The US EIC designs were guided by the science program (EIC White Paper)
- The US NSAC Long Range Plan (2015) recommended EIC as the next major facility in US for QCD frontier. If approved by DOE, construction will likely be completed around 2025
- Cooling of proton/ion beams is essential for eRHIC and JLEIC to reach luminosity above 10^{34} /cm²/s. It enables emittance reduction up to an order of magnitude in all dimensions
- eRHIC adopts novel Coherent-electron-Cooling (CeC) concept. JLEIC has chosen magnetized electron cooling for the baseline, utilizing a multi-stage cooling scheme
- Both CeC and high energy magnetized EC are under active development
 - BNL plans to conduct a proof-of-principle test of CeC at RHIC next year;
 - JLab focuses on a technical design and technology development for a high energy bunched beam electron cooler based on ERL and circulator ring.

HERA@DESY: The World 1st ep Collider



A Ring-Ring (polarized) Lepton-Proton collider with 320 GeV CM energy

1992 - 2007



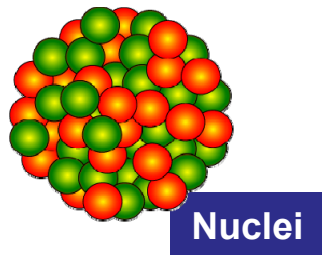
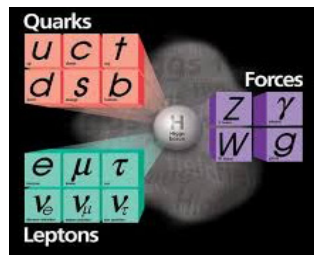
		Lepton	proton
Energy	GeV	27.5	920
e-polarization	%	30 to 50	--
Final lumi.	cm ⁻² s ⁻¹	(1.5 to 4)x10 ³¹	

A New World of Electron-Ion Colliders



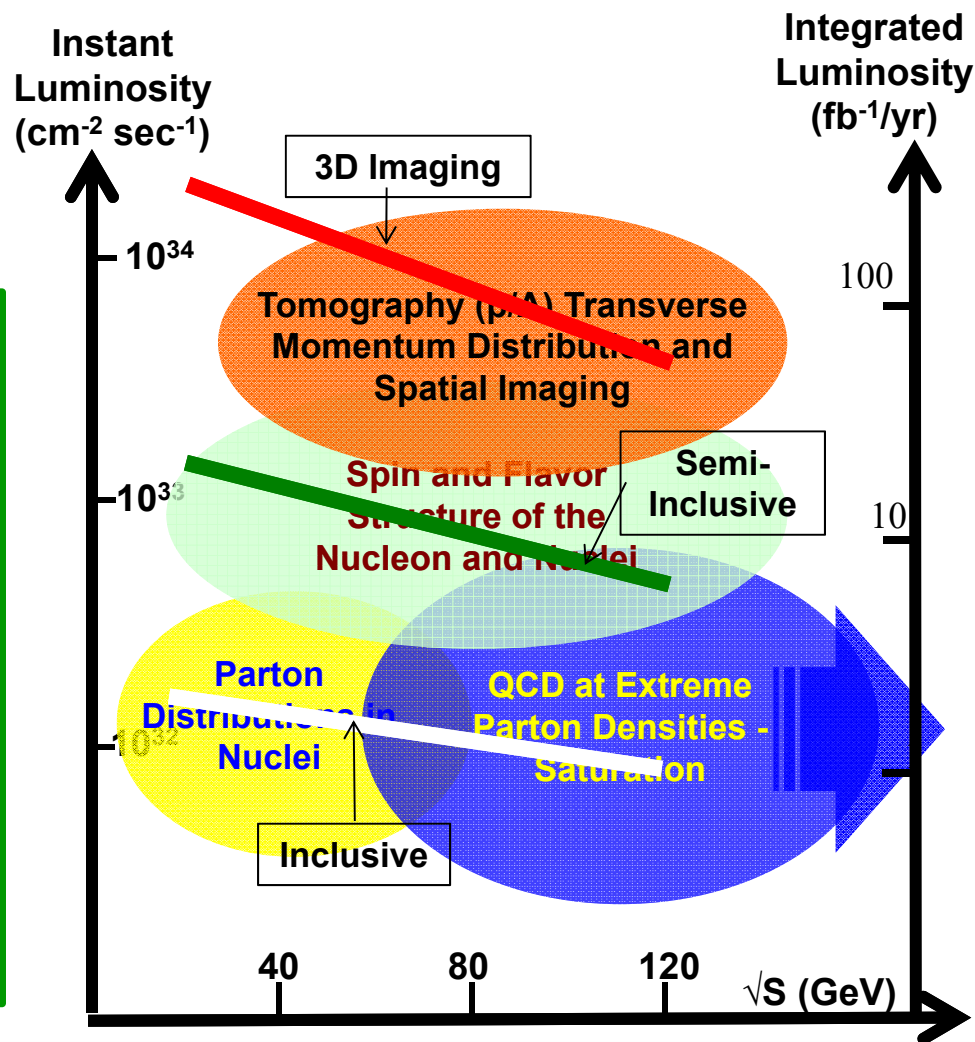
A New EIC for The Next QCD Frontier

A Gluon Microscopy for Understanding the Glue that Binds Us All



An EIC, with a versatile range of **beam species, kinematics, polarizations, high luminosity** is required

- To precisely image the sea quarks and gluons in nucleons and nuclei,
- To explore the new QCD frontier of strong color fields in nuclei
- To resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD



EIC Machine Requirements from White Paper

EIC White Paper

Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

arXiv:1212.1701.v3

Will Be World's *first* !

Polarized electron-proton/light ion collider
Electron-Nucleus collider

e-p collisions

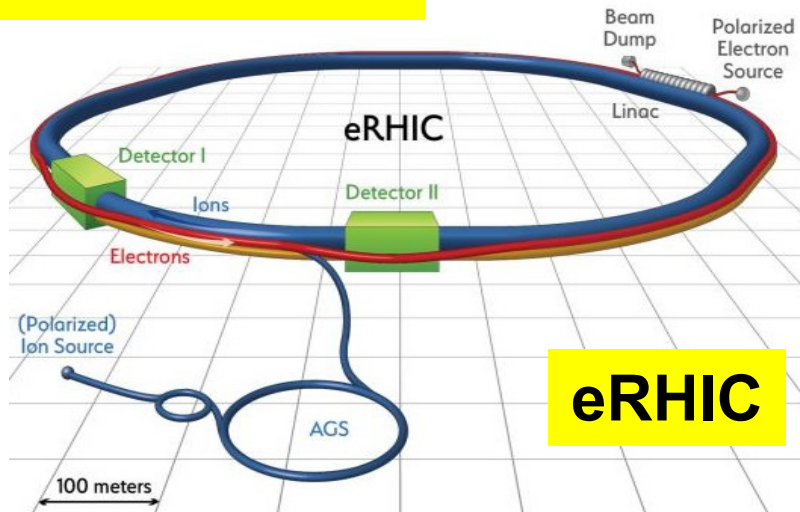
- ✓ More than one interaction point
- ✓ Polarized beams: e, p (>70%)
- ✓ Variable CM: 20-~100 (~140) GeV
- ✓ Electron beam: 3-10(20) GeV
- ✓ Proton beam: up to 250 GeV
- ✓ Luminosity $\sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
100-1000 times HERA

e-A collisions

- ✓ Wide range in nuclei
(deuteron to heaviest uranium or lead)
- ✓ Polarized beams: e, d/ ^3He (>70%)
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

Two Labs Looking for Hosting the US EIC

Brookhaven Lab

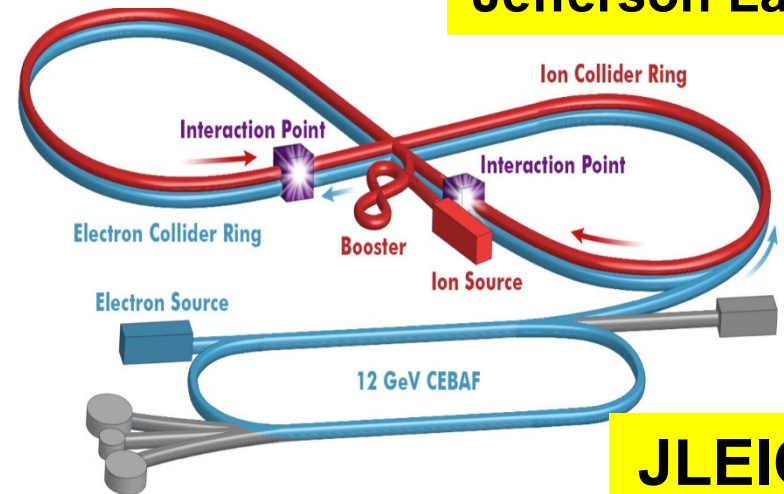


eRHIC

Needs an electron beam

- Based on RHIC and its injector complex
 - polarized proton and ^3He , up to 250 GeV/u
 - other all-stripped ions, up to gold 100 GeV/u
- Add a polarized electron beam up to 18 GeV
 - A recirculating ERL (*linac-ring* design)
 - A storage ring (*ring-ring* design) (*present baseline*)

Jefferson Lab



JLEIC

Needs a proton/ion beam

- Based on CEBAF recirculated SRF linac
 - polarized electron beam up to 12 GeV,
- Add ion injector and two storage rings (*ring-ring* design)
 - Polarized proton, deuteron and ^3He
 - Other all stripped ions, up to lead
 - Up to 100 GeV/u ion energy

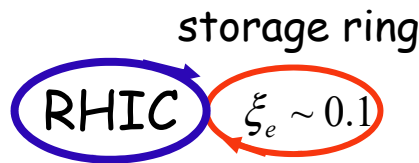
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eRHIC Linac(ERL)-Ring Design

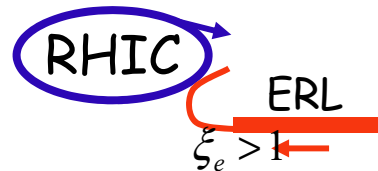
- Ring-ring

$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e} \right) (\xi_h \xi_e) (\sigma'_h \sigma'_e) f$$

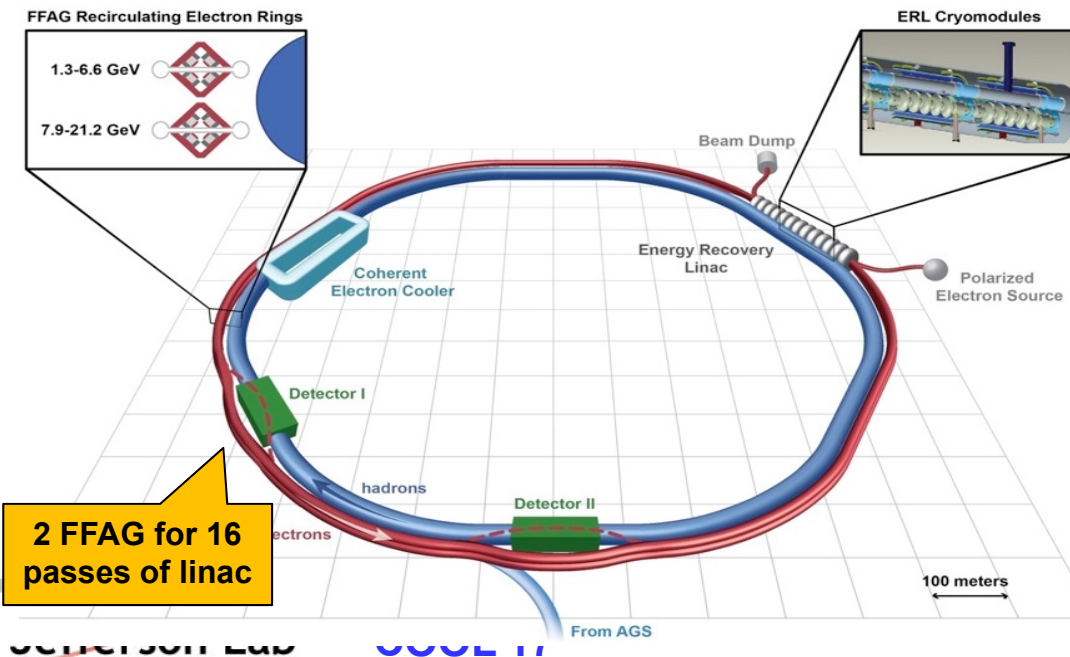


- Linac-ring $L \times 50(?)$

$$L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta_h^* r_h}$$



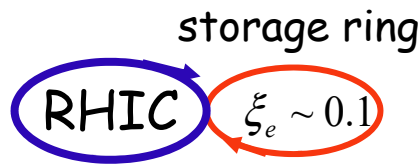
- In a linac-ring collider, a lepton beam can tolerate much higher beam-beam perturbations since the beam is not stored/reused
- It could (*theoretically*) achieved a much higher luminosity than a ring-ring collider of **same collision frequency** and other beam parameters
- ERL is a practical way to accelerate high current beam with a low RF power
- Design had gone several round of revisions. The latest one is **Non-Scaling Fixed-Field Alternating Gradient** (NS-FFAG)



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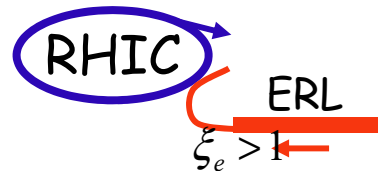
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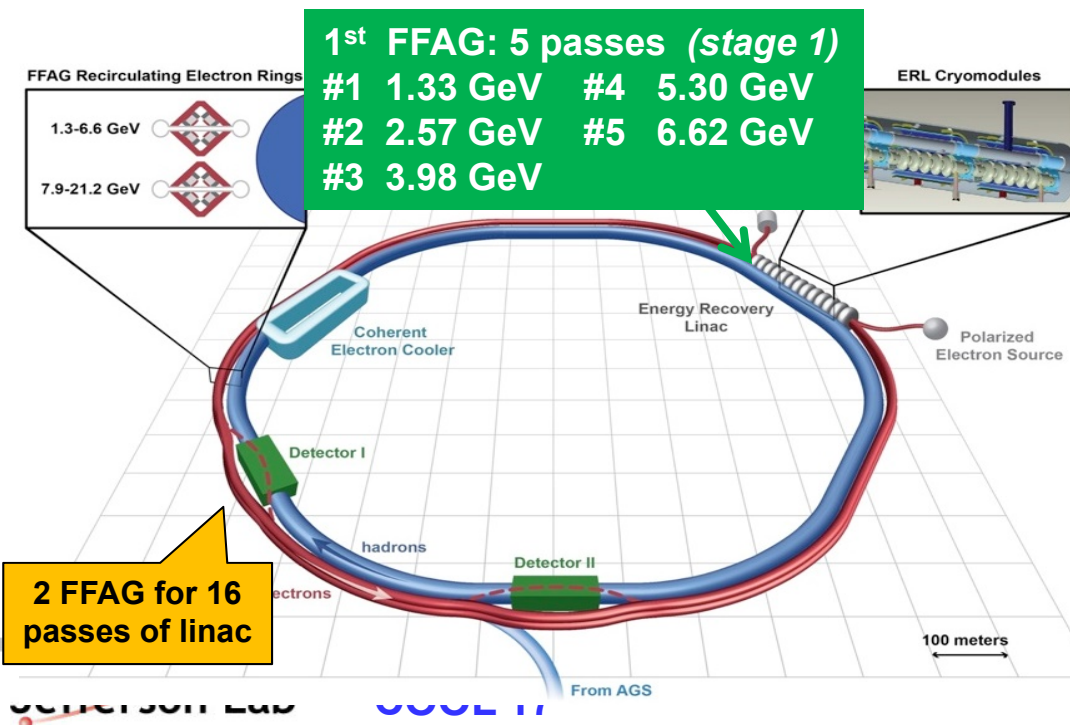


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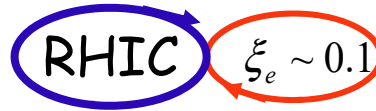


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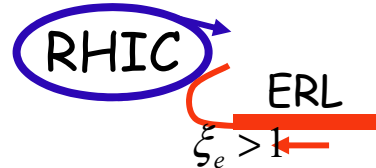
storage ring



- In a linac-ring collider, a lepton beam can tolerate much higher beam-beam perturbations since the beam is not stored/reused

- Linac-ring $L \times 50(?)$

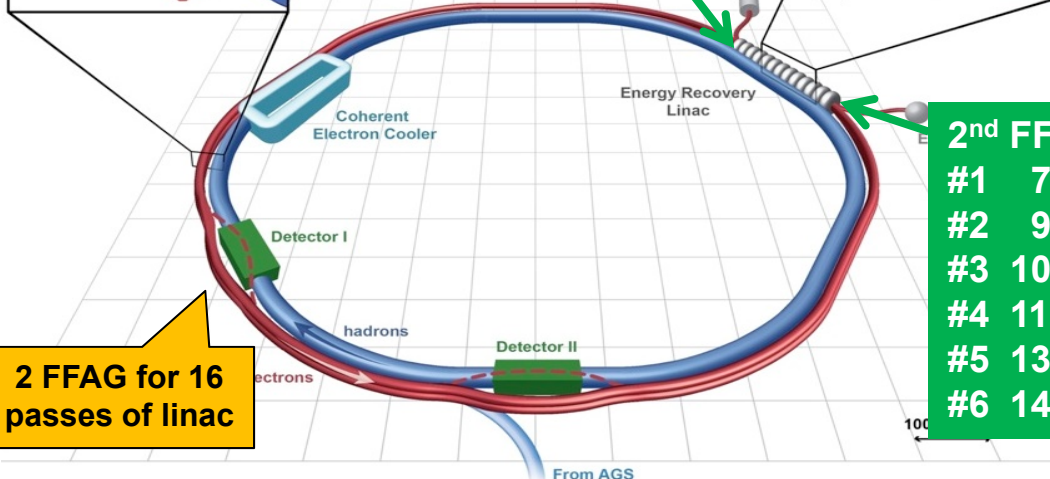
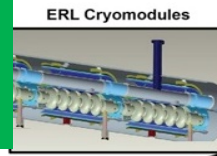
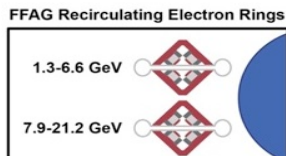
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1st FFAG: 5 passes (stage 1)

#1 1.33 GeV	#4 5.30 GeV
#2 2.57 GeV	#5 6.62 GeV
#3 3.98 GeV	



2nd FFAG: 11 passes (stage 2)

#1 7.94 GeV	#7 15.88 GeV
#2 9.27 GeV	#8 17.20 GeV
#3 10.59 GeV	#9 18.52 GeV
#4 11.91 GeV	#10 19.84 GeV
#5 13.23 GeV	#11 21.16 GeV
#6 14.55 GeV	

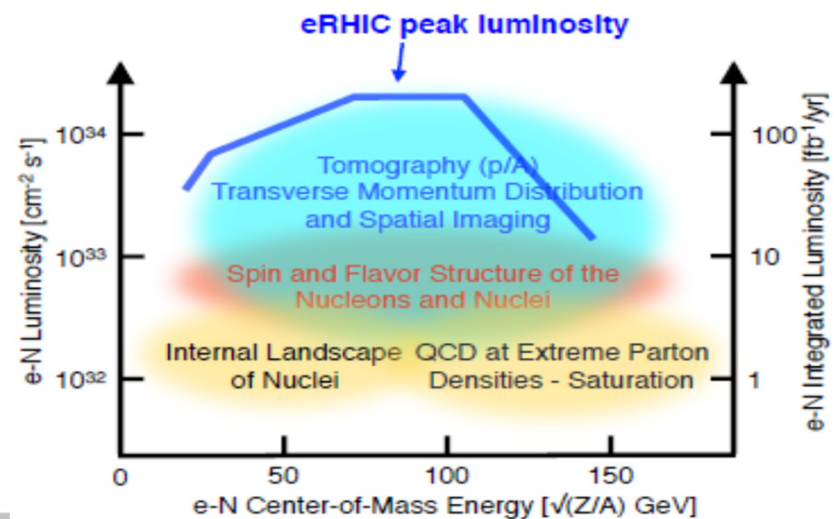
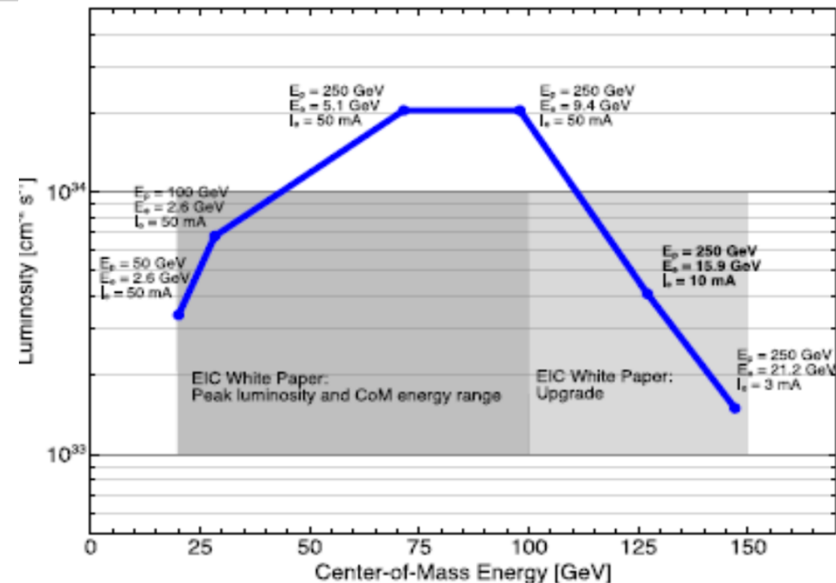
erator Facility

eRHIC Linac(ERL)-Ring Design

	LR Nominal design		LR Ultimate design	
	e	p	e	p
Energy [GeV]	10	250	8.3	250
CM energy [GeV]	100		91	
Bunch frequency [MHz]	9.4		9.4	
Bunch intensity [10^{10}]	1.7	20	3.3	30
Beam current [mA]	26	277	50	415
rms norm.emittance h/v[μm]	36.7/36.7	0.5/0.5	16.5/16.5	0.27/0.27
rms emittance h/v [nm]	1.9/1.9	1.9/1.9	1.0/1.0	1.0/1.0
beta*, h/v [cm]	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [μm]	15.3/15.3		8.4/8.4	
IP rms ang. spread h/v [urad]	120/120	120/120	120/120	120/120
max beam-beam parameter	1.2	0.004	4.1	0.015
e-beam disruption parameter	20		36	
max space charge parameter	1.4e-4	0.006	8.6e-4	0.058
rms bunch length [cm]	0.3	16.5	0.3	5
Polarization [%]	80	70	80	70
Peak luminosity [$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$]	1.0		14.4	

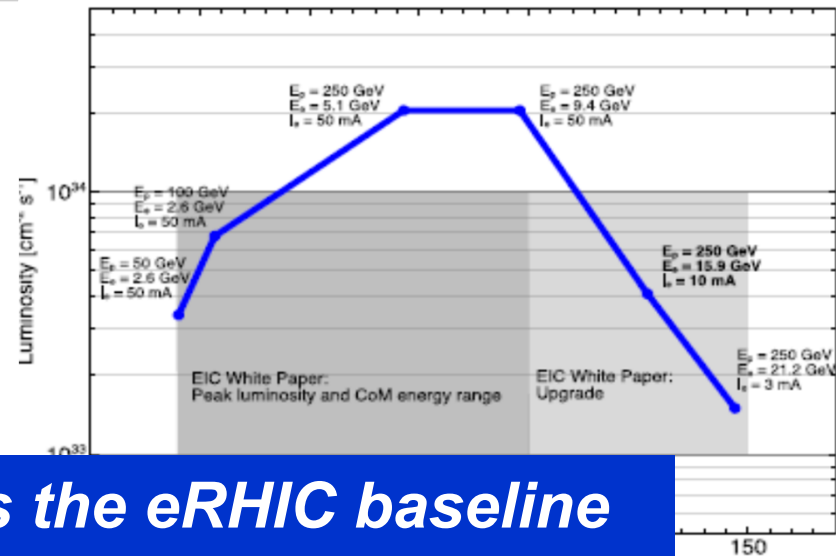
**Required
R&D**

Polarized electron gun
Coherent Electron Cooling
Multi-pass SRF ERL with FFAG arcs -
Crab cavities
Polarized ^3He production
Linac-ring beam-beam affects
 $\beta^=5 \text{ cm}$*
HOM damped SRF cavities



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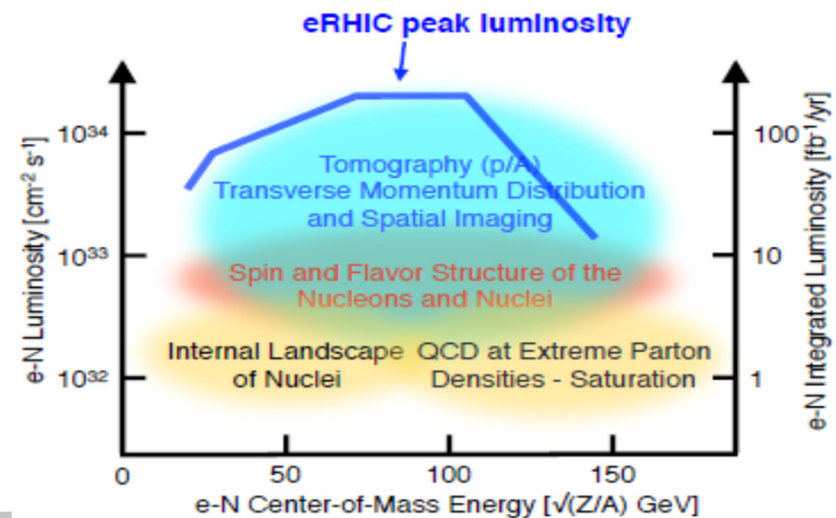
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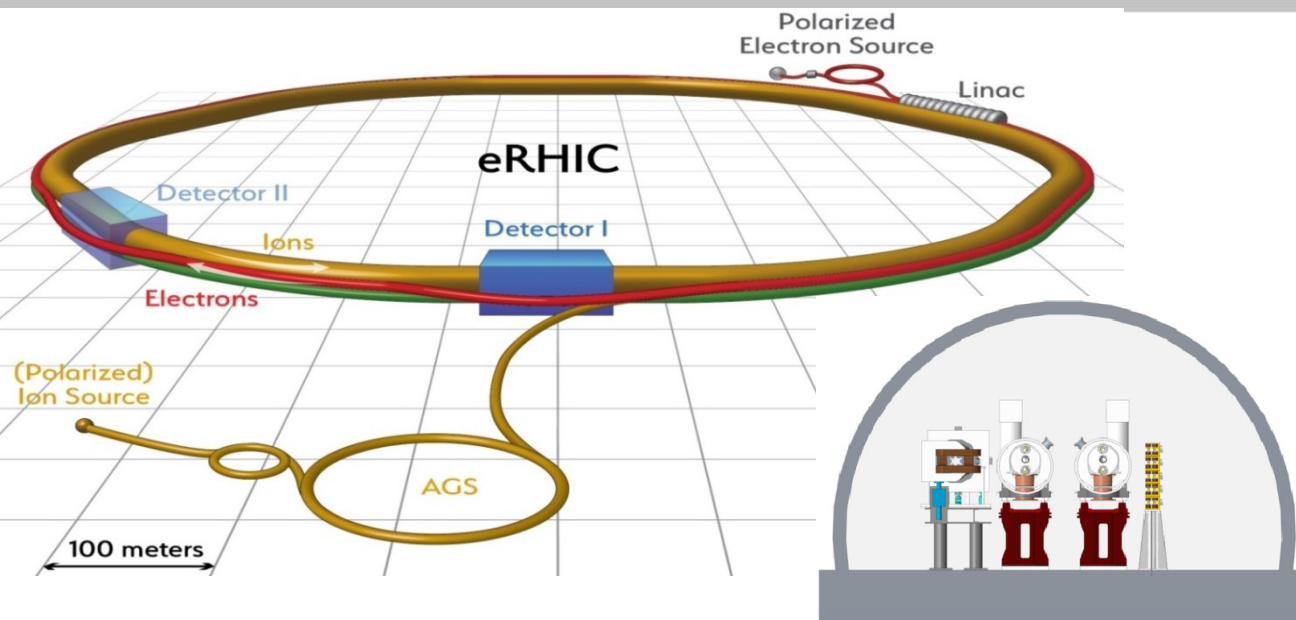
This design approach was the eRHIC baseline until very recent, replaced by a ring-ring design

Required R&D

Polarized electron gun
Coherent Electron Cooling
Multi-pass SRF ERL with FFAG arcs -
Crab cavities
Polarized ^3He production
Linac-ring beam-beam effects
 $\beta^=5 \text{ cm}$*
HOM damped SRF cavities



eRHIC Present Baseline: Ring-Ring



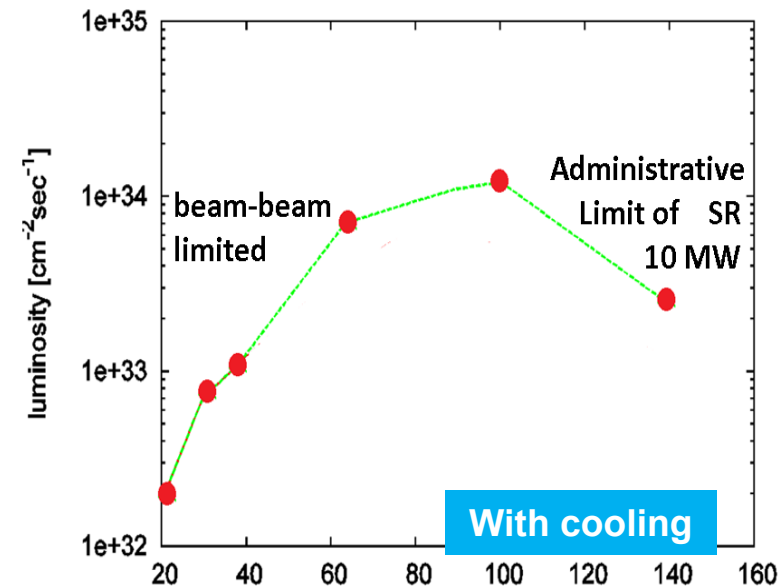
		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

- Based on existing RHIC with up to 275 GeV polarized protons and up to 100 GeV/u gold ions
- Additional electron storage ring with (5 – 18) GeV in the RHIC tunnel
 - Up to 2.7 A current – 1320 bunches per ring similar to B-Factories
 - 10 MW maximum RF power (*administrative limit*)
- Need strong cooling of the hadron beam emittances
- Proton bunch intensities moderate: $0.75 \cdot 10^{11}$, achieved in RHIC
- On-energy polarized electron injector (up to 18 GeV)

**Designed for maximum
peak luminosity
 $1.1 \times 10^{34} \text{ /cm}^2/\text{s}$**

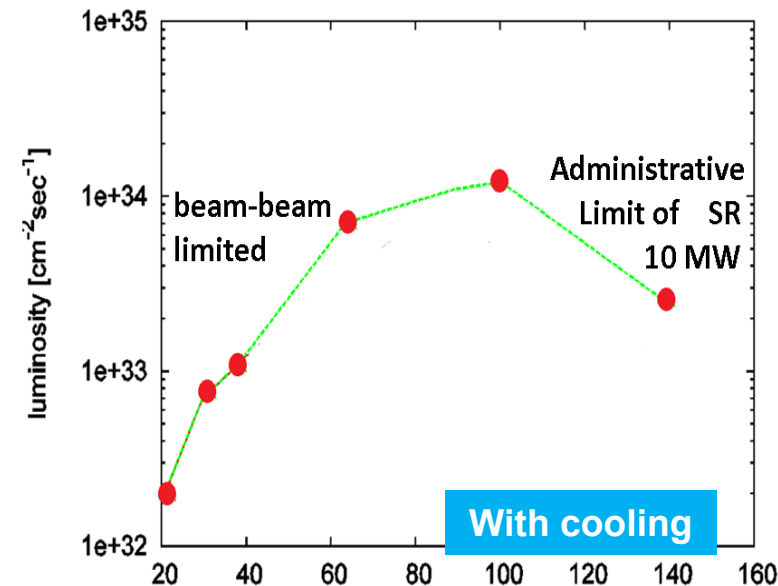
Main Parameters for Maximum Luminosity

		No Hadron Cooling		Strong Hadron Cooling	
Parameter	Units	Protons	Electrons	Protons	Electrons
Center of Mass Energy	GeV	100		100	
Beam Energy	GeV	275	10	275	10
Particles/bunch	10^{10}	11.6	31	5.6	15.1
Beam Current	mA	456	1253	920	2480
Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	6.76	3.5	3.1	1.7
β_x^*	cm	94	62	47	16
β_y^*	cm	4.2	7.3	2.1	3.7
σ_x^{1*}	mm	0.137	0.2	0.13	0.39
σ_y^{1*}	mm	0.401	0.22	0.38	0.21
Beam-Beam ξ_x		0.014	0.084	0.012	0.047
Beam-Beam ξ_y		0.0048	0.075	0.0043	0.084
τ_{IBS} long/hor	hours	10/8	-	4.4/2.0	-
Synchr. Rad Power	MW	-	6.5	-	10
Bunch Length	cm	7	0.3	3.5	0.3
Luminosity	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.29		1.21	



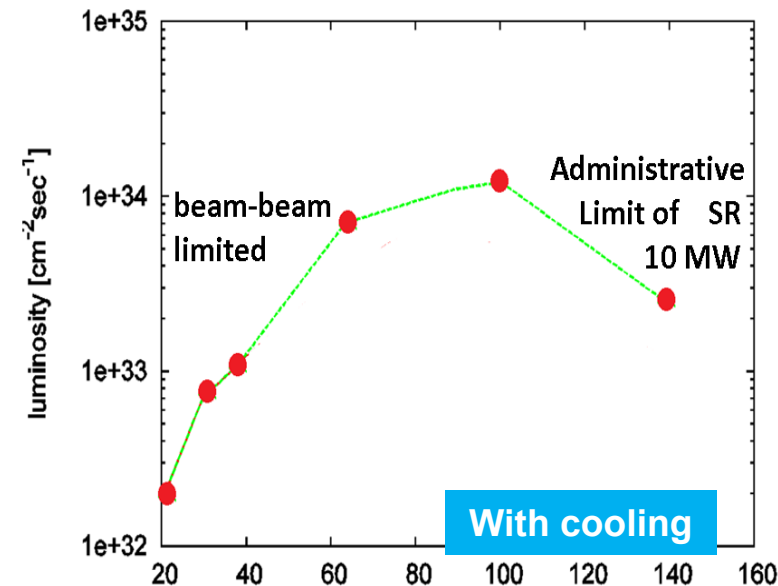
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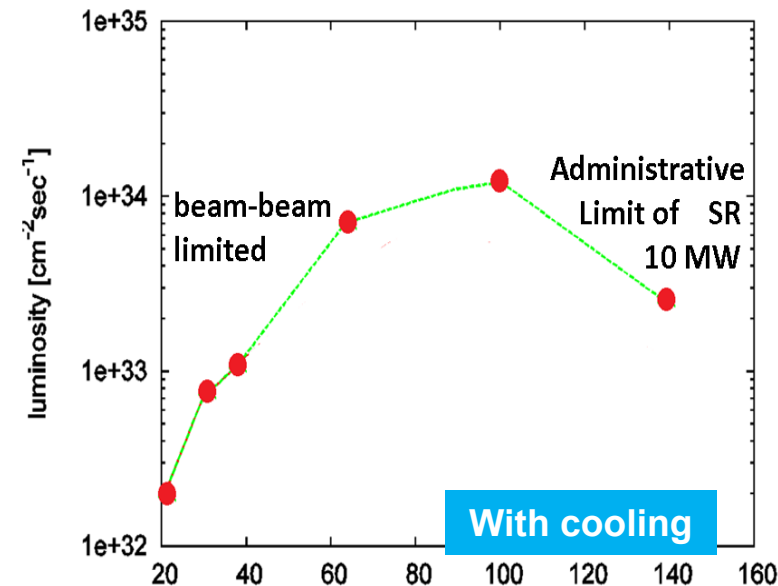
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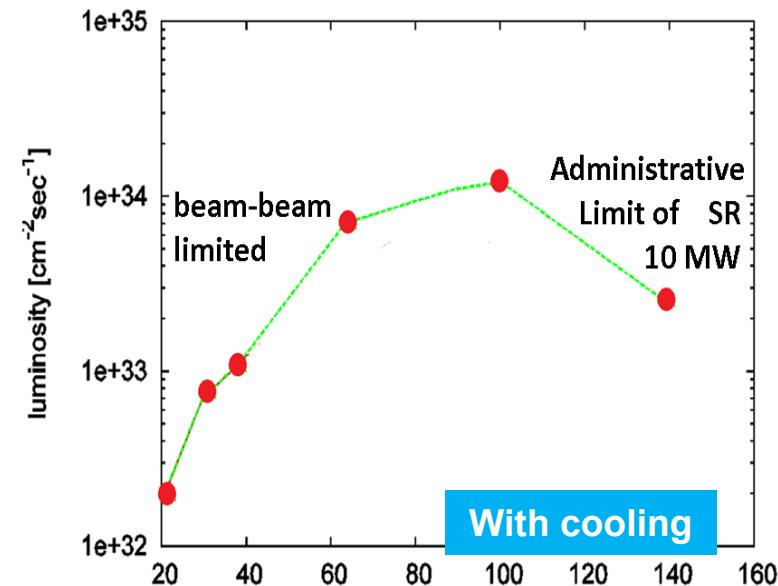
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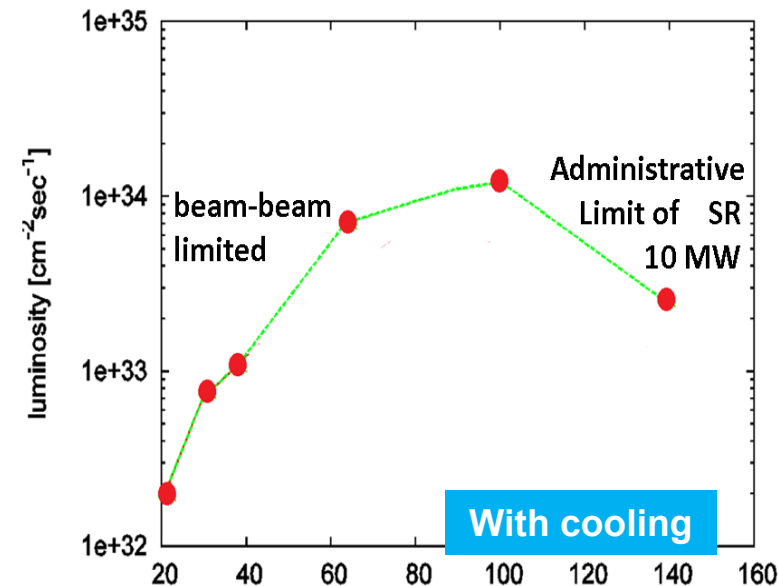
High bunch frequency



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Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	6.76	3.5	3.1	1.7
β_x^*	cm	94	62	47	16
β_y^*	cm	4.2	7.3	2.1	3.7
σ_x^{1*}	mmrad	0.137	0.2	0.13	0.39
σ_y^{1*}	mmrad	0.401	0.22	0.38	0.21
Beam-Beam ξ_x		0.014	0.084	0.012	0.047
Beam-Beam ξ_y		0.0048	0.075	0.0043	0.084
τ_{IBS} long/hor	hours	10/8	-	4.4/2.0	-
Synchr. Rad Power	MW	-	6.5	-	10
Bunch Length	cm	7	0.3	3.5	0.3
Luminosity	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.29		1.21	

High bunch frequency



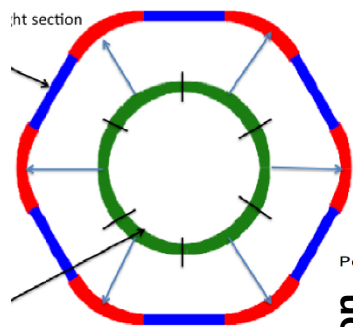
Cooling could boost luminosity by 4 times

eRHIC Full Energy Electron Injector

eRHIC needs a 18 GeV injector for full energy injection into the storage ring

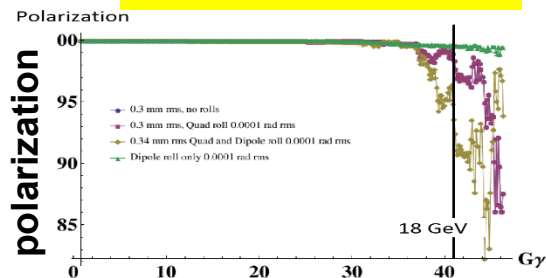
Booster design approach

- Under study: rapid cycling synchrotron (RCS) (Cost effective)
- Main challenge: preserving electron polarization during acceleration
- Idea: RCS with highly symmetric arcs connected by lattice with unity transport



Spin
Transparent
Straight

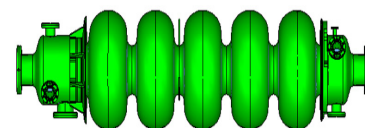
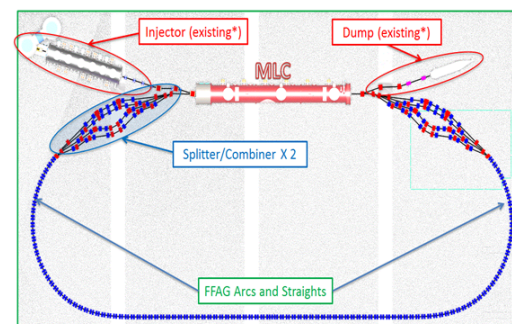
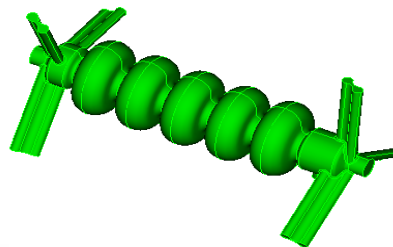
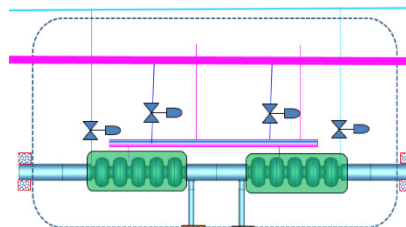
First simulation
results encouraging



P=48 super-periodicity

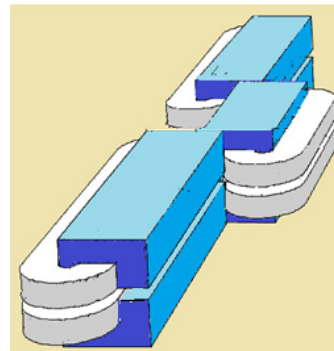
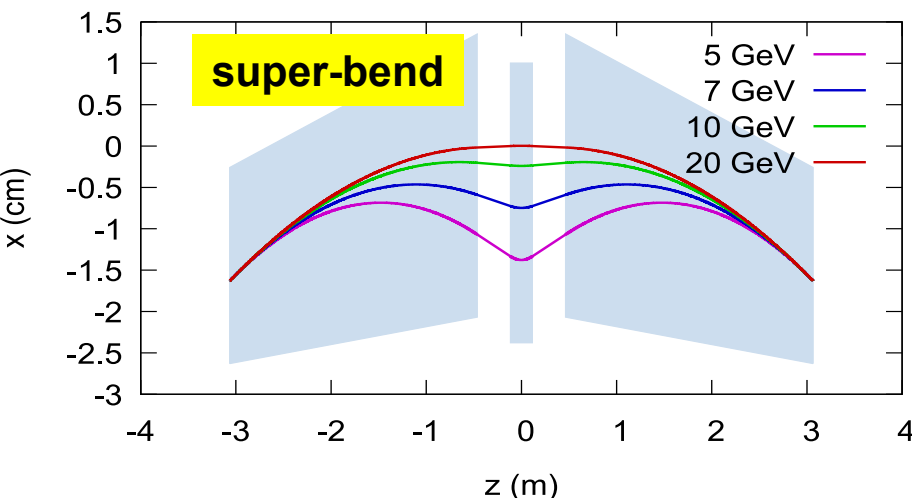
SRF linac design approach (fall back)

- 3 GeV SRF linac, acc. gradient: 25 MV/m
rep Rate 1 Hz, single bunch 50 nC
- Six passes of the linac reaching 18 GeV
- Space challenge: fit 5 recirculation beam line inside the tunnel together with 2 collider rings
- High cost: need 120 m of active structure at ~\$(1-1.5)M/m, plus \$250M for 5 return loops. (mitigation: FFAG return paths)



New Electron Storage Ring for eRHIC

- Average beam current up to **2.7 A**: not unprecedented (KEK-B, Super-B),
- Has **330** bunches, high bunch charge (**>10x** of KEK-B), beam heating more challenging (**1320** bunches/high rep rate bring luminosity above **$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$**)
- Total synchrotron radiation power limited to **10 MW** (30 single cell 560 MHz SC cavities)
- Peak radiation linear density **< 6 kW/m** $\rightarrow$ less than KEK-B, ok with Cu beam pipe
- Strong electron Beam-Beam effects require strong radiation damping
- Coupled Bunch instability: need active damper
- Resistive Wall Instability ok, fast Ion instability growth time manageable



- Achieving 11 GeV damping times at 5 GeV to match KEKB damping decrement
- Helps polarization

Outline

- Introduction
- BNL eRHIC Design
- JLab JLEIC Design
- Outlook of US EIC Project
- eRHIC Beam Cooling
- JLEIC Beam Cooling
- Additional topics: Experiment, Simulations and Advanced Concepts
- Summary

JLEIC Achieved Design Goals

Energy

- Full coverage of CM energy from **15** to **65** GeV
- Electrons **3-10** GeV, protons up to **100** GeV, ions up to **40** GeV/u

Ion species

- Polarized light ions: **p**, **d**, **³He**, and possibly **Li**
- Un-polarized light to heavy ions up to **A** above 200 (Au, Pb)

Support 2 detectors

- **Full acceptance** capability is critical for the primary detector

Luminosity

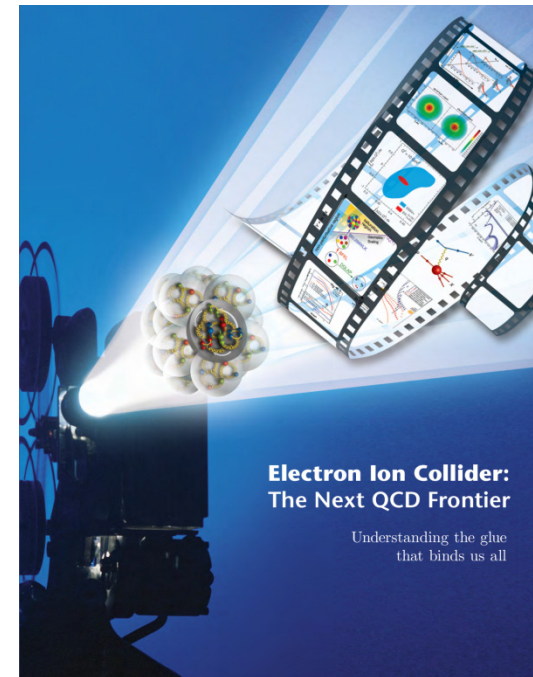
- **10^{33} to 10^{34}** /cm²s per IP in a *broad* CM energy range,
- Highest luminosity at CM energy around 45 GeV

Polarization

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

Upgradable to higher CM energy/luminosity possible

- **14 GeV** electron, **400 GeV** proton, and **160 GeV/u** ion → **~150 GeV** CM



JLEIC Achieved Design Goals

Design goals consistent with the EIC White Paper requirements

Energy

- Full coverage of CM energy from **15** to **65** GeV
- Electrons **3-10** GeV, protons up to **100** GeV, ions up to **40** GeV/u

Ion species

- Polarized light ions: **p**, **d**, **³He**, and possibly **Li**
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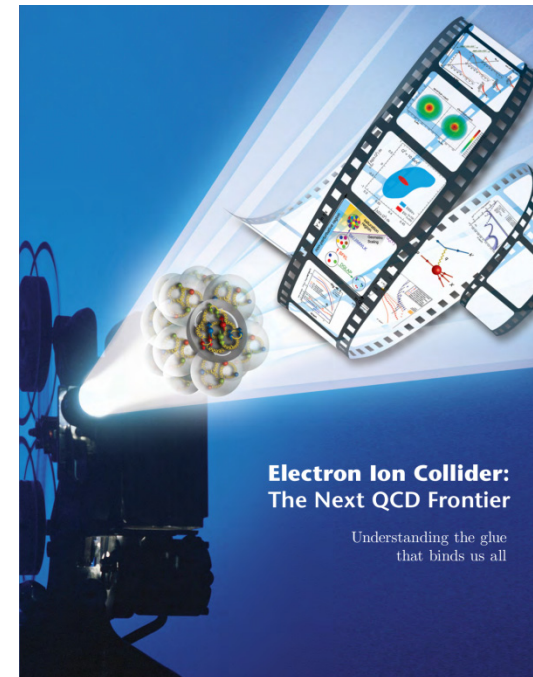
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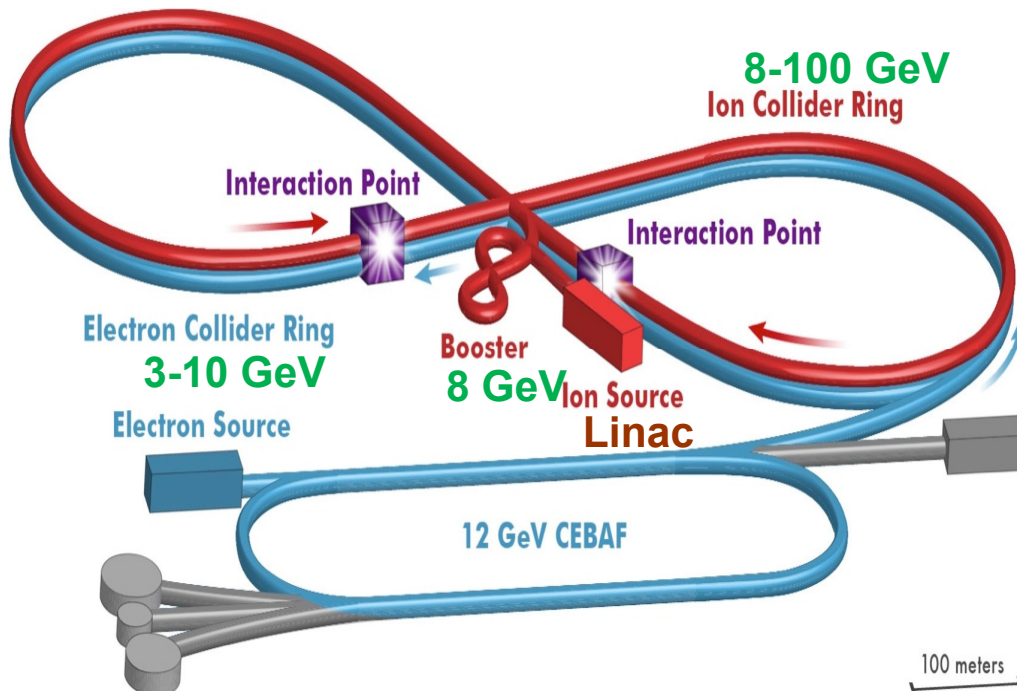
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Upgradable to higher CM energy/luminosity possible

- **14 GeV** electron, **400 GeV** proton, and **160 GeV/u** ion → **~150 GeV** CM



JLEIC Layout and On JLab Site Map



• Electron complex

- CEBAF as a full energy injector
- Collider ring

• Ion complex

- Ion source/Linac
- Booster (8 GeV)
- Collider ring

• IP/detectors

- Two, full acceptance
- Hori. crab crossing

• Polarization

- Figure-8 shape

Design
Report

1209.0757

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

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2012

1504.07961

January 28, 2015

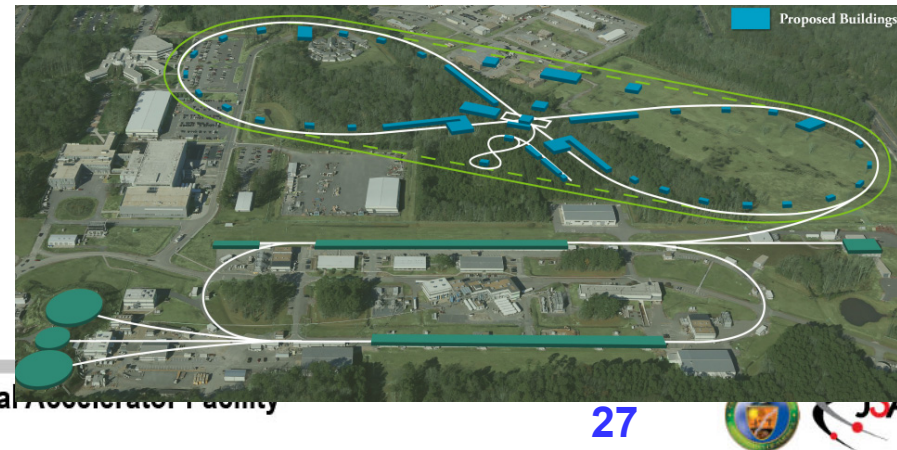
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2015



Strategy for Achieving High Performance

High Luminosity

- Based on high bunch repetition rate CW colliding beams

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

Beam Design

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

IR Design

- Small β^*
- Crab crossing

Damping

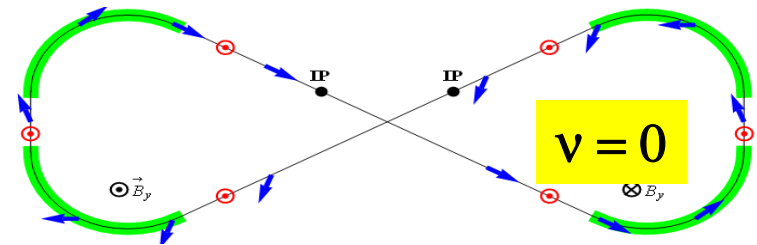
- Synch. radiation
- Electron cooling

- A standard approach for lepton colliders (KEK-B reached $> 2 \times 10^{34}$ /cm²/s)
- JLEIC based on CEBAF, its beam has a bunch rep-rate already up to 1.5 GHz
- JLEIC **Green field** ion complex can be designed to deliver high bunch rep rate

High Polarization w/ Figure-8

All rings are in a figure-8 shape

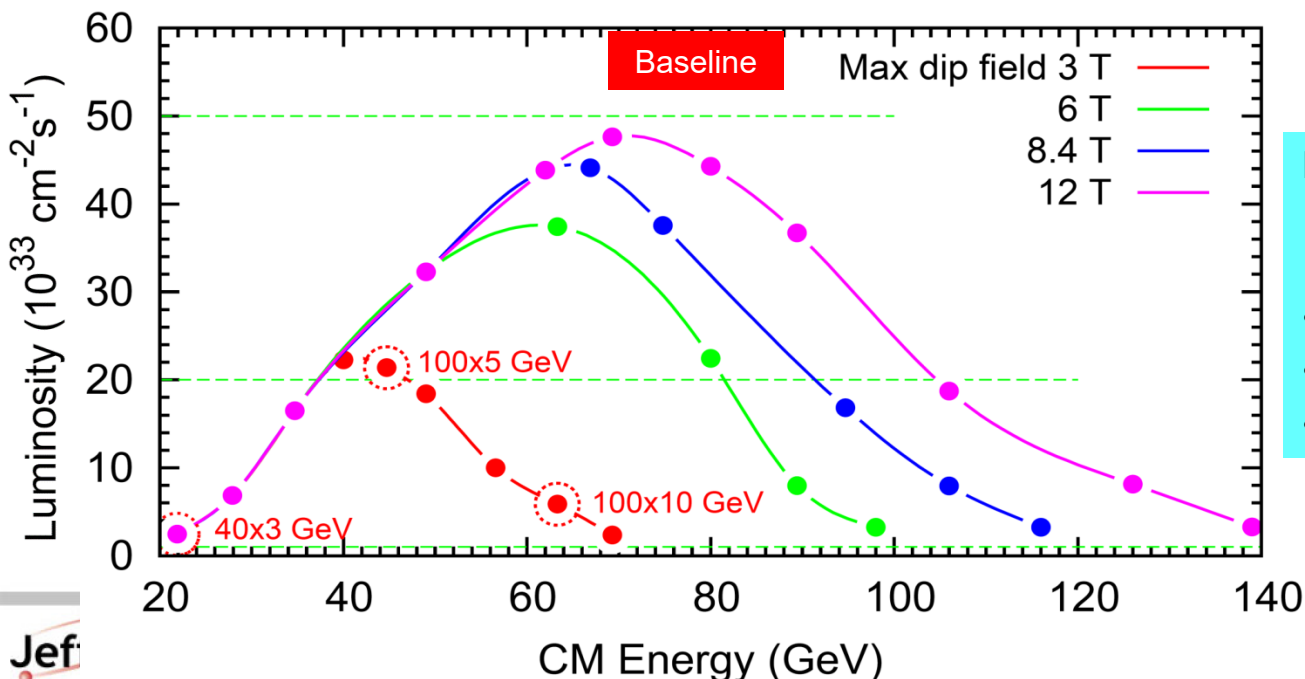
➔ critical advantages for both beams



- Spin precessions in the left & right parts of the ring are exactly cancelled
- Net spin precession (*spin tune*) is zero, thus energy independent
- Spin can be controlled/stabilized by small solenoids or other compact spin rotators
- Only practical way for accelerating/storing polarized deuteron beam
- An opportunity for a **Green Field** design

JLEIC Baseline Parameters

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β^*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Luminosity/IP, w/HG, 10^{33}	$\text{cm}^{-2}\text{s}^{-1}$	2.5		21.4		5.9	

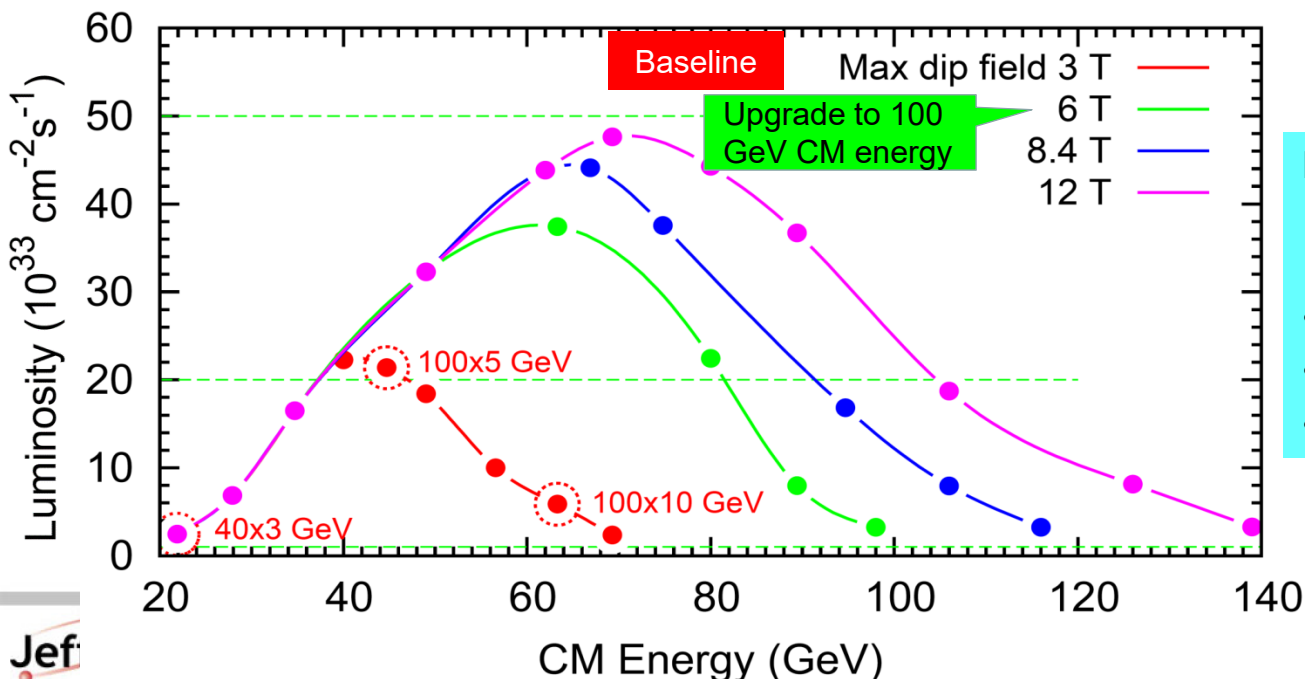


Future energy upgrade options

Ion ring SC magnets max field	Proton energy up to
• 6 T (super-ferric):	~200 GeV
• 8.3 T (LHC):	~280 GeV
• 12 T (TBD):	~400 GeV

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Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β^*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
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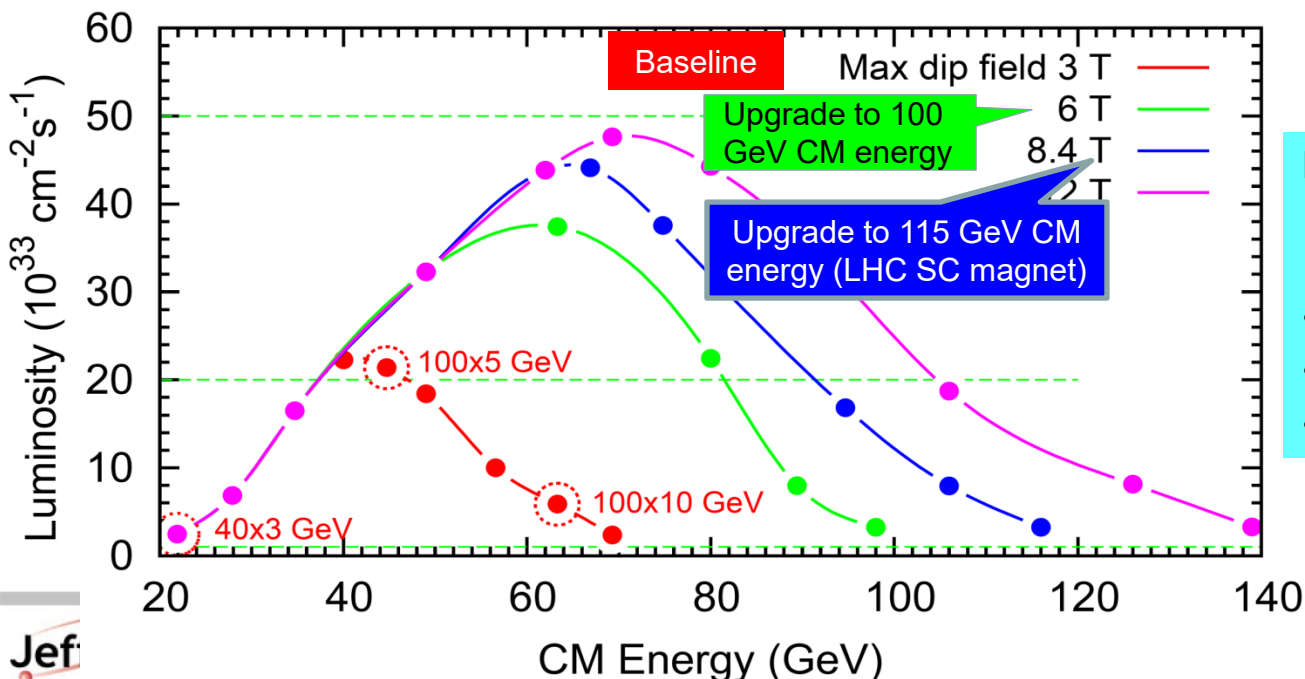


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Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β^*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Luminosity/IP, w/HG, 10^{33}	$\text{cm}^{-2}\text{s}^{-1}$	2.5		21.4		5.9	



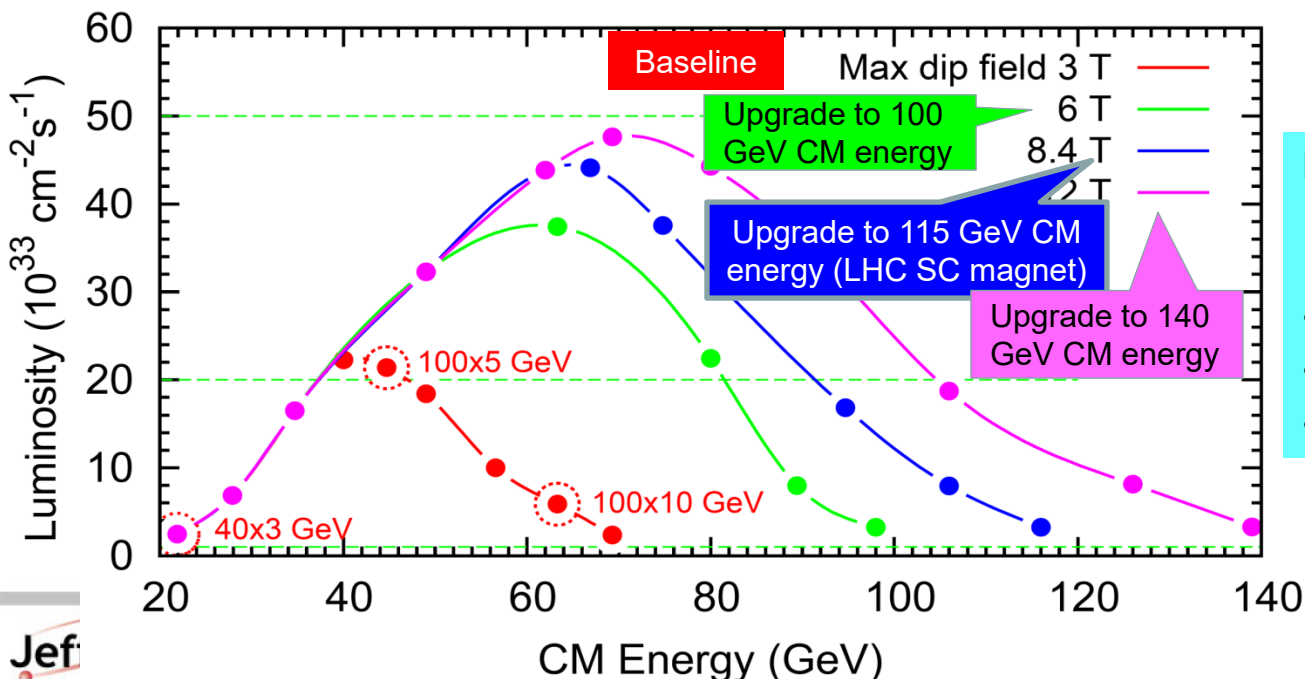
Future energy upgrade options

Ion ring SC magnets Proton energy
max field up to

- 6 T (super-ferroc): ~200 GeV
- 8.3 T (LHC): ~280 GeV
- 12 T (TBD): ~400 GeV

JLEIC Baseline Parameters

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>	<i>p</i>	<i>e</i>
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
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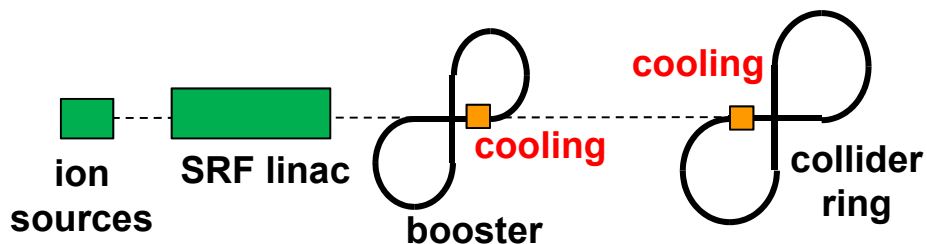


Future energy upgrade options

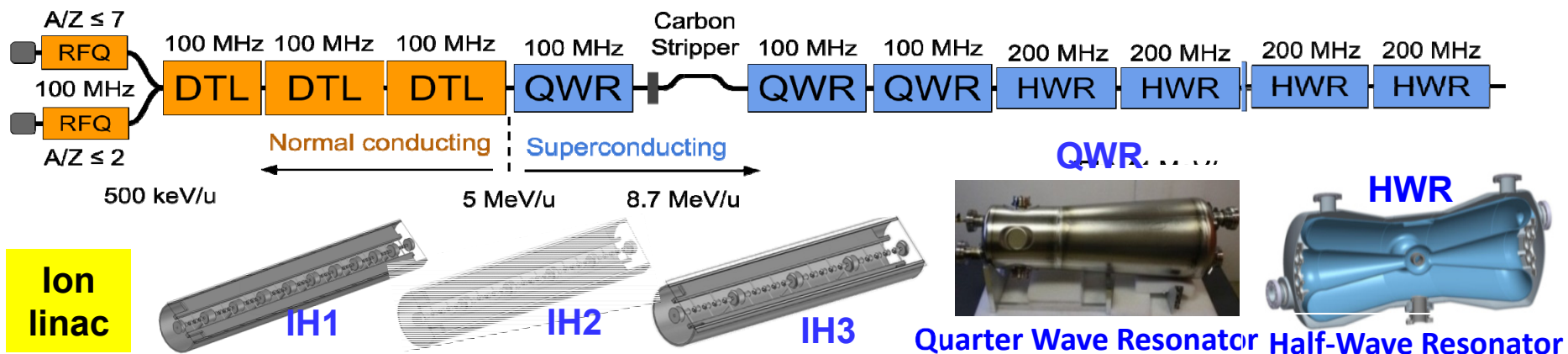
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max field up to

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- 8.3 T (LHC): ~280 GeV
- 12 T (TBD): ~400 GeV

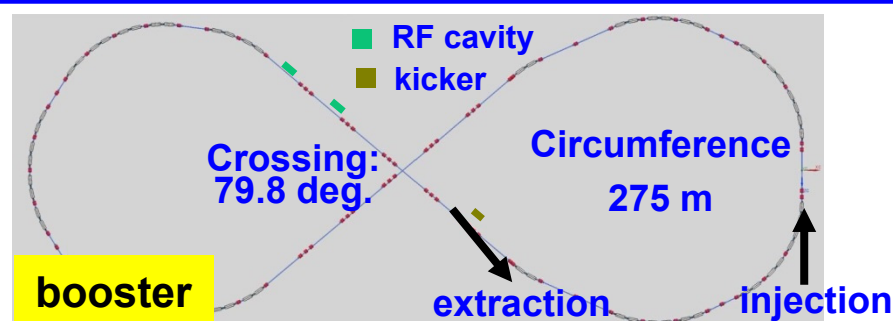
A New Ion Complex for JLEIC



- Generate, accumulate & accelerate ions
- Covering all required ion species
- Delivering required time/phase space structure for matching with electron beam
- High polarization for protons/light ions



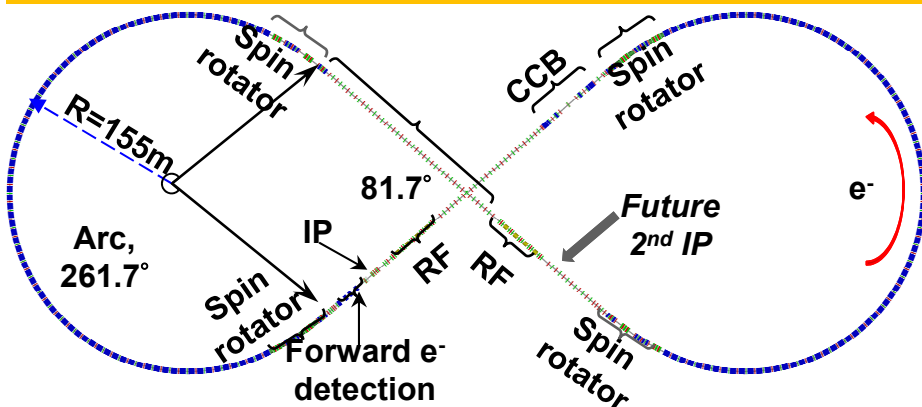
	Length (m)	Max. energy (GeV)
SRF linac		0.2
booster	~275	8
collider ring	~2250	100



- Figure-8 shape for preserving ion polarization
- No transition energy crossing

JLEIC Collider Rings

Electron ring w/ major machine components

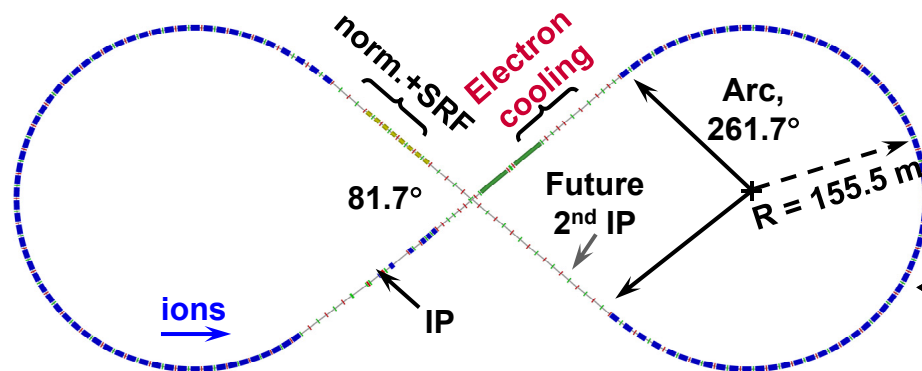


- Two rings w/ same footprint, **stack vertically**
- Having a **horizontal crab crossing** at IPs
- Supports two IPs and fit to the JLab site
- Beamline/optics design completed (including low- β insertion, chromatic compensation, etc.)
- **Ion magnet field** determines CM energy range

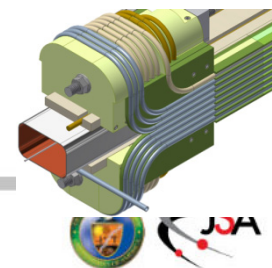
		p	e
Circumference	m	2154	
Crossing angle	deg	81.7	
Lattice		FODO	FODO
Dipole & quad	m	8 & 0.8	5.4 & 0.45
Cell length	m	22.8	15.2
Max. dipole field	T	3	~1.5
SR power density	kW/m	10	
Transition γ_{tr}		12.5	21.6

- 12GeV CEBAF as a full energy (polarized) injector
- Capability of top-off injection or continuous injection

Ion ring w/ major machine components



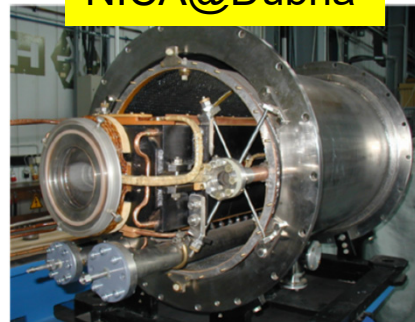
Super-ferric magnets (3 T)



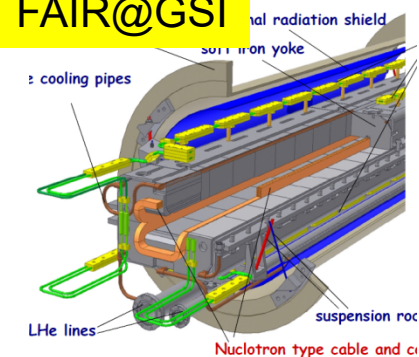
Super-Ferric Magnets for Ion Rings

- Technology developed long ago (~SSC era)
- Adopted for FAIR SIS100 ring & NICA (1.8 T)
- Advantages
 - Higher fields (than warm magnets)
 - Fast ramp rate
 - Cost efficient
- JLEIC adopted it for booster/collider ring
 - Up to 3 T
 - Fast ramp (1 T/s) for booster ring magnets
 - Cable-in-conduit conductor

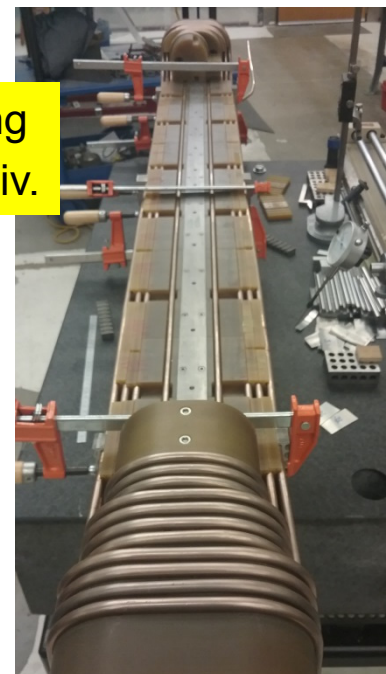
NICA@Dubna



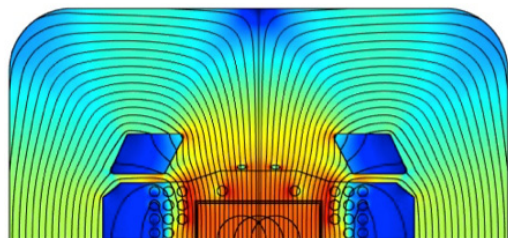
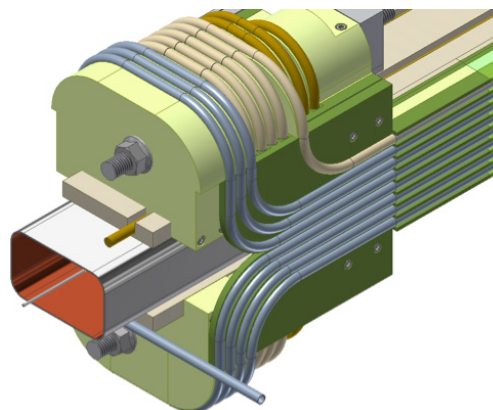
FAIR@GSI



Prototype winding
@Texas A&M Univ.



Cable-in-conduit

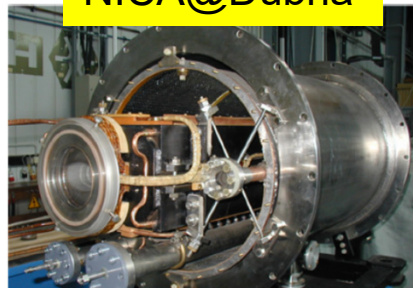


Super-Ferric Magnets for Ion Rings

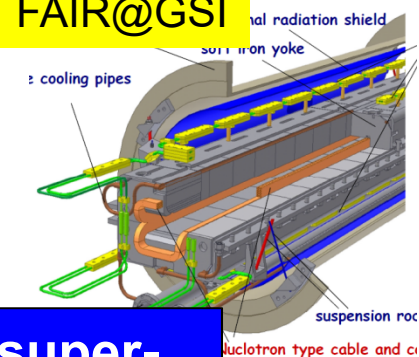
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 - Cost efficient
- JLEIC adopted it for booster/cooling rings
 - Up to 3 T
 - Fast ramp (1 T/s) for booster ring magnets
 - Cable-in-conduit conductor

Prof. I. Meshkov first suggested super-ferric magnets for JLEIC during his 2013 visit to JLab. Thank you, Igor!

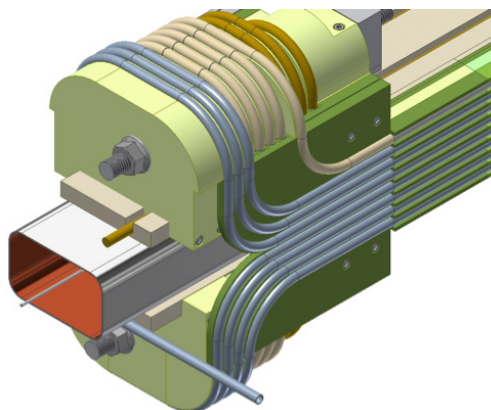
NICA@Dubna



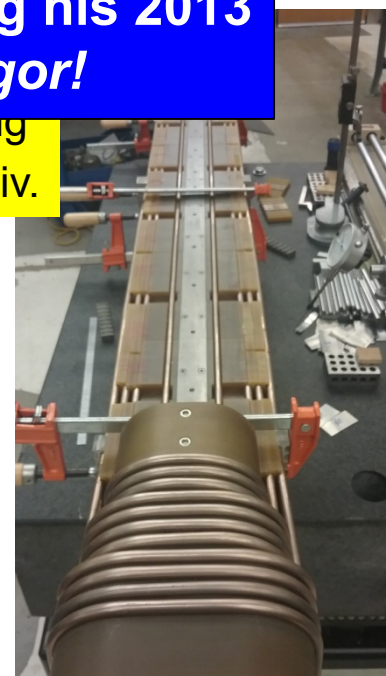
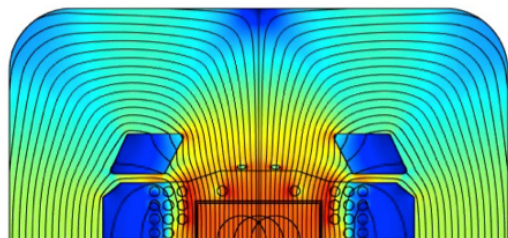
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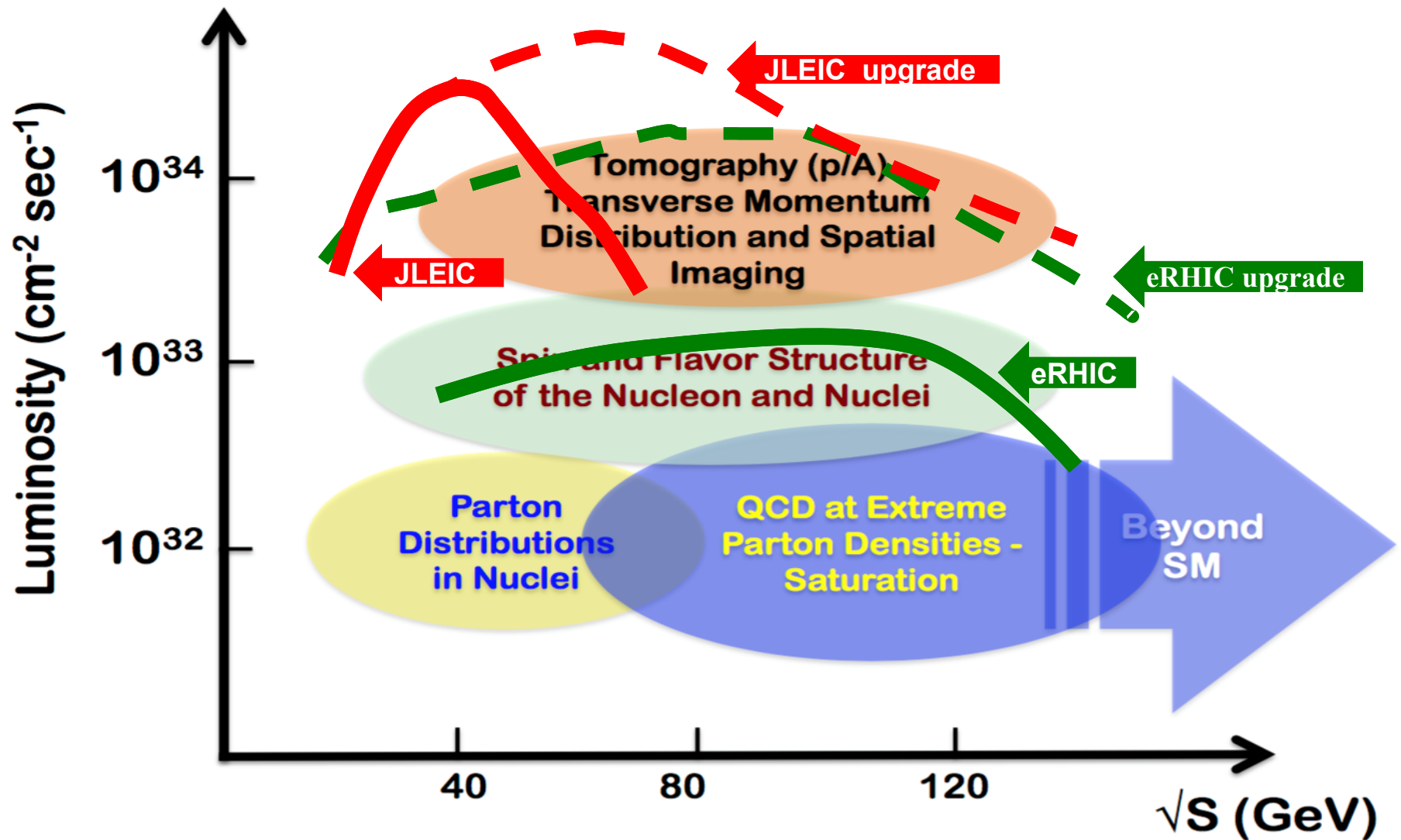
Cable-in-conduit



Outline

- Introduction
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US EIC Luminosity vs. CM Energy



US NSAC Long Range Plan (LRP)

- **NSAC** (Nuclear Science Advisory Committee) is commissioned by the US Department of Energy (DOE) and the National Science Foundation (NSF).
(Presently 19 members, all leading nuclear and accelerator scientists)
- NSAC provides advices on assessment and prioritization of the national program for basic nuclear science research.
- Every 6 to 8 years, NSAC produces a Long Range Plan (**LRP**), with 3 to 5 **recommendations**, basically it is a roadmap for large nuclear science facilities in US for the next 10 years
- *LRP 1979, 1983, 1989, 1996, 2002, 2007, 2015*

To be selected as one recommendation in *LRP 2015* is a **Necessary** however **Not Sufficient** Step toward the Final Construction of An Electron-Ion Collider in US

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NSAC LRP 2015

- We recommend a high-energy high-luminosity polarized Electron-Ion Collider for new facility construction following the completion of FRIB

never ~~Not~~
in US

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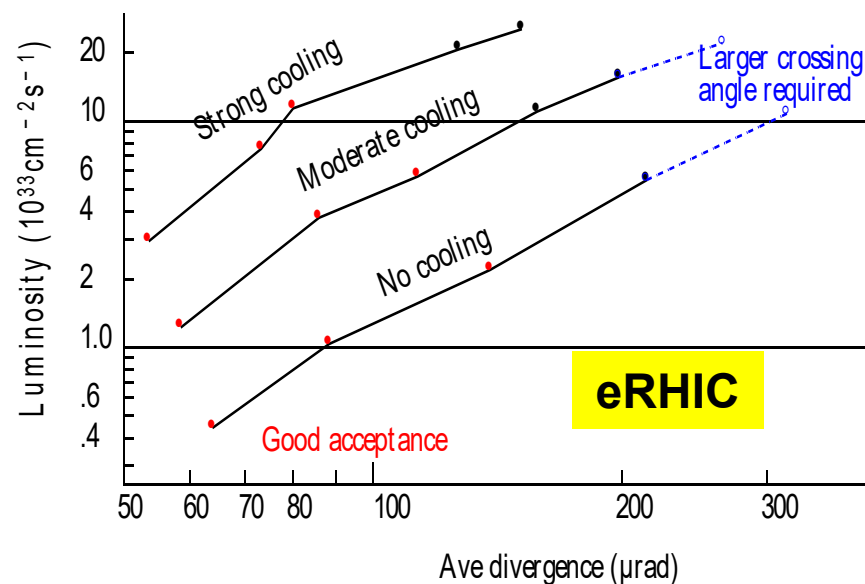
Last Step of the process for approval of EIC:
National Academy of Science Review (*in progress*)

EIC Cooling Requirement and Impact on Luminosity Performance

- EIC science demands luminosity above $10^{33} / \text{cm}^2 \text{ s}$ ($\sim 100\times$ higher than the final HERA luminosity). Some EIC measurements needs even higher luminosities, at or above $\sim 10^{34} / \text{cm}^2 \text{ s}$
- To reach $>10^{34}/\text{cm}^2 \text{ s}$, the ion emittance must achieve a reduction up to ***an order of magnitude***
- Role of cooling: reduction of emittance, maintaining emittance (suppressing IBS)
- It is equally challenging to maintain small emittance at medium energy (30 GeV to 275 GeV):
small emittance $\rightarrow$ small beam size $\rightarrow$ high intensity $\rightarrow$ strong IBS $\rightarrow$ fast emittance growth

design parameters

		eRHIC		JLEIC	
Strong cooling		No	Yes	No	Yes
emittance, norm.	μm	5.2/2	2.4/0.9 (0.27, L-R)	~ 3	0.3
Energy spread	10^{-3}			~ 3	~ 0.5
Bunch length	cm	7	3.5	3	~ 1
Lumi, 10^{33}	$1/\text{cm}^2 \text{ s}$	~ 3	12	~ 3	20



Similarly, JLEIC luminosity has a factor of ~ 5 difference without & with strong cooling

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eRHIC Strong Beam Cooling

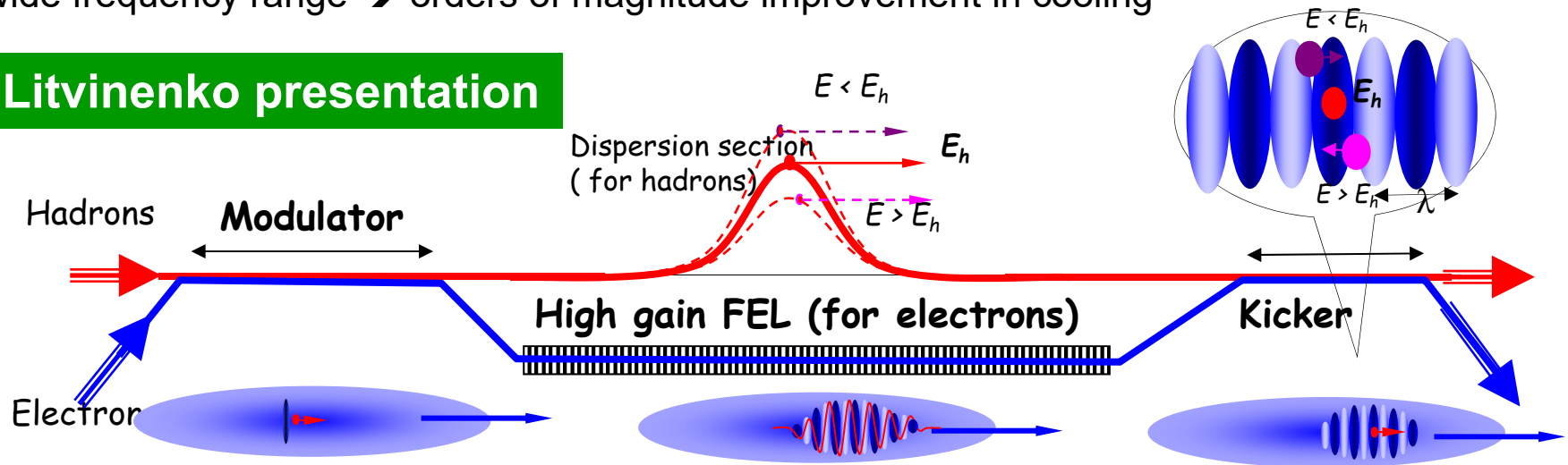
eRHIC linac-ring design (the previous version of its baseline)

- Demands very small emittance (~ 0.27 mm mrad at 250 GeV) in both horiz. & vert. dimensions
- Coherent-electron-Cooling was chosen for this task (reducing and maintaining emittance)

eRHIC linacring-ring design (the present baseline)

- The requirement of emittance reduction (2.4 and 0.9 mm mrad at 275 GeV) is less demanding but is still challenging
- Present baseline is still Coherent-electron-Cooling (may be an option of upgrade)
- But will consider alternative schemes as well
- **CeC** is a novel concept proposed by Ya. Derbenev, further developed by V. Litvinenko/Derbenev
- Fundamentally a **stochastic cooling**, however, using high-gain FEL for amplification $\rightarrow$ much wide frequency range $\rightarrow$ orders of magnitude improvement in cooling

V. Litvinenko presentation



CeC Proof-of-Principle Experiment

- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- All equipment and infrastructure had been installed into RHIC's IP2, including 20 MeV SRF linac, helical wigglers for FEL amplifier and beam transported to low energy dump
- 1st beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- P-o-P demo with 40 GeV/n Au scheduled during RHIC Run 16&17. Cooling studies planned for 18
- Improvements after first commissioning in 2016 implemented, recommissioning in progress

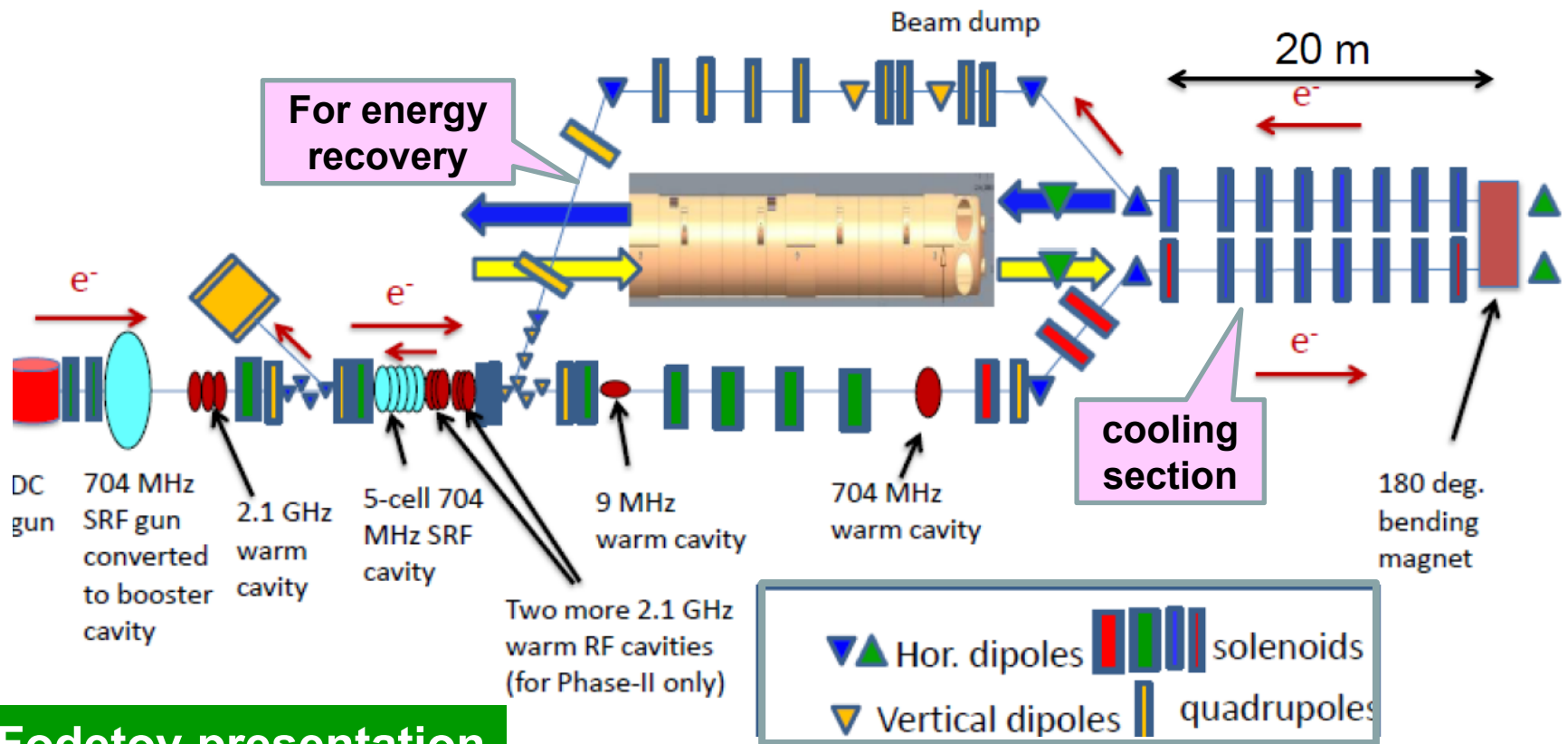
Parameter	Value	Status
Species in RHIC	Au ⁺⁷⁹ ions, 40 GeV/u	✓
Relativistic factor	42.96	✓
Particles/bucket	10 ⁸ - 10 ⁹	✓
Electron energy	21.95 MeV	10 MeV
Charge per e-bunch	0.5-5 nC	✓ (> 3.5 nC)
Rep-rate	78.17 kHz	5 kHz*
e-beam current	0.39 mA	Few μ A
Electron beam power	8.6 kW	< 10 W



I. Pinayev presentation

Alternate Approaches Under Consideration for eRHIC

- Electron cooling is a fall back option for ring-ring eRHIC
- Magnetized electron cooling at 250 GeV is also challenging
- Non-magnetized e-cooler is under construction for low energy RHIC operation (LEReC)

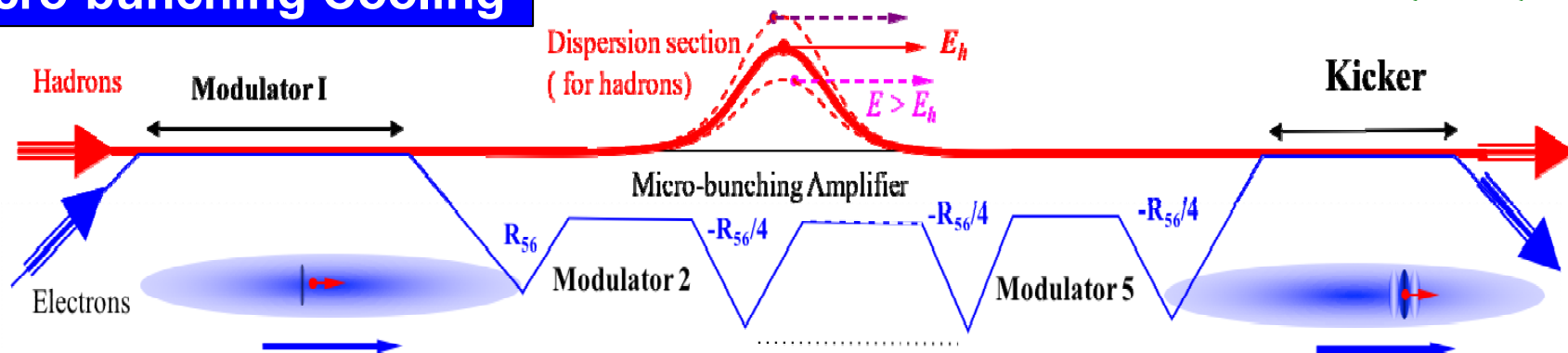


A. Fodetov presentation

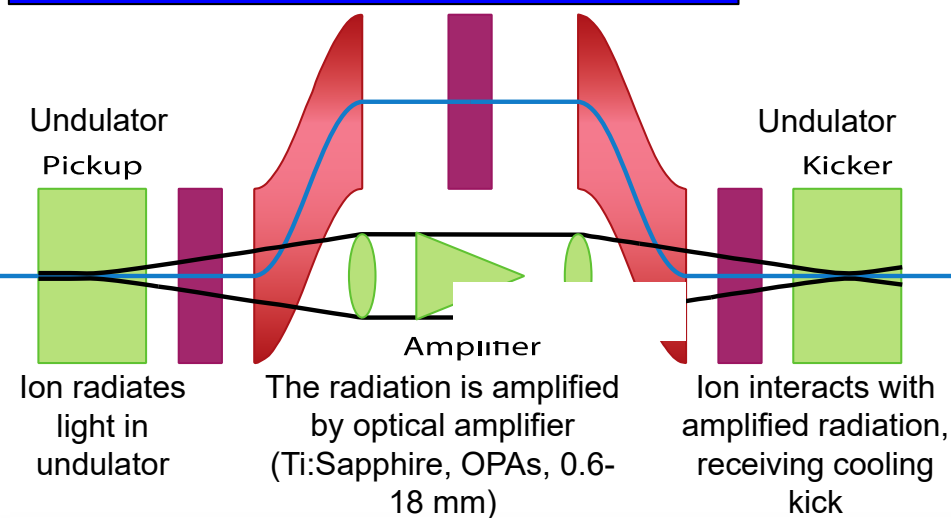
Other Concepts Under Consideration for eRHIC

Micro-bunching Cooling

D. Ratner, PRL, 2013



Optical Stochastic Cooling



eRHIC Cooling R&D Plan

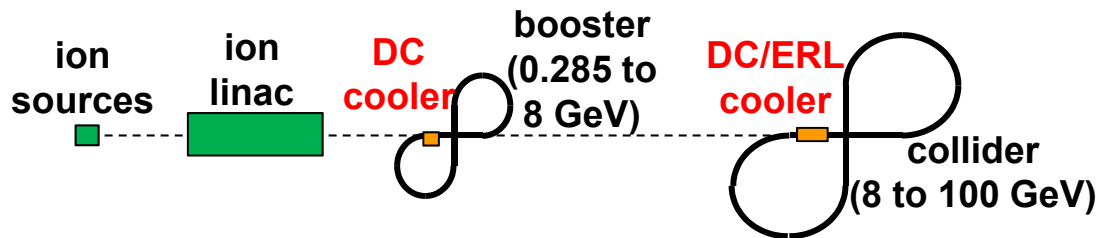
- CeC PoP experiment in BNL. Potential upgrade for micro-bunching cooling studies.
- R&D for Amp-scale current electron cooler on the basis of recirculator in JLab
- Proposed optical stochastic cooling experiment in FNAL (on IOTA facility)
- Multi-pass high-current ERL developments (CBETA facility in Cornell, ...)

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Multi-Step Cooling for JLEIC High Luminosity

- **Cooling of JLEIC proton/ion beams**
 - Achieving very small emittance (**~10x reduction**) & very short bunch length **~1 cm** (with SRF)
 - Suppressing IBS induced emittance degradation
 - high cooling efficiency at low energy & small emittance



Pre-cool when energy is low

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

Cool when emittance is small
(after pre-cool at low energy)

Ring	Functions	Proton kinetic E (GeV)	Lead ion kinetic E (GeV/u)	Electron kinetic E (MeV)	Cooler type
booster ring	Accumulation of positive ions		0.1 (injection)	0.054	DC
collider ring	Maintain emitt. during stacking		2 (injection)	1.1	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	DC
	Maintain emitt. during collision	Up to 100	Up to 40	Up to 54.5	ERL

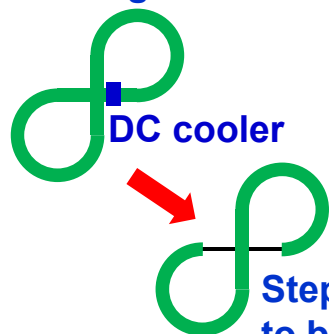
Can't reduce emittance due to space charge limit

Pre-cooling both protons and lead ions

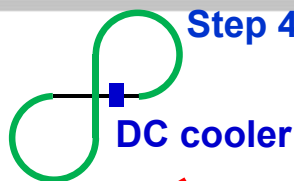
ERL cooler can't reach energy below 20 MeV

Ion Beam Formation Cycles

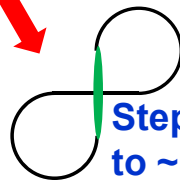
Step 2. Accumulating
coasting beam



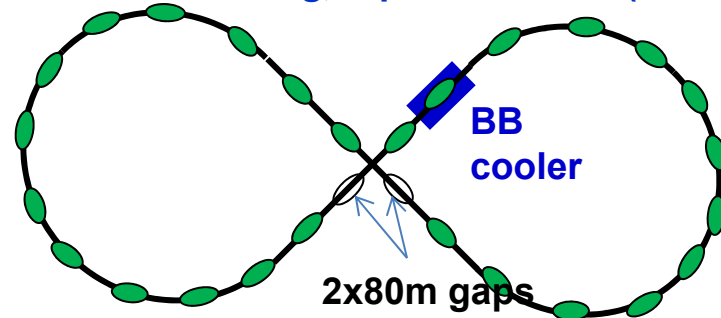
Step 4. Accelerate



Step 5. Compress
to ~56m, split into
2 bunches



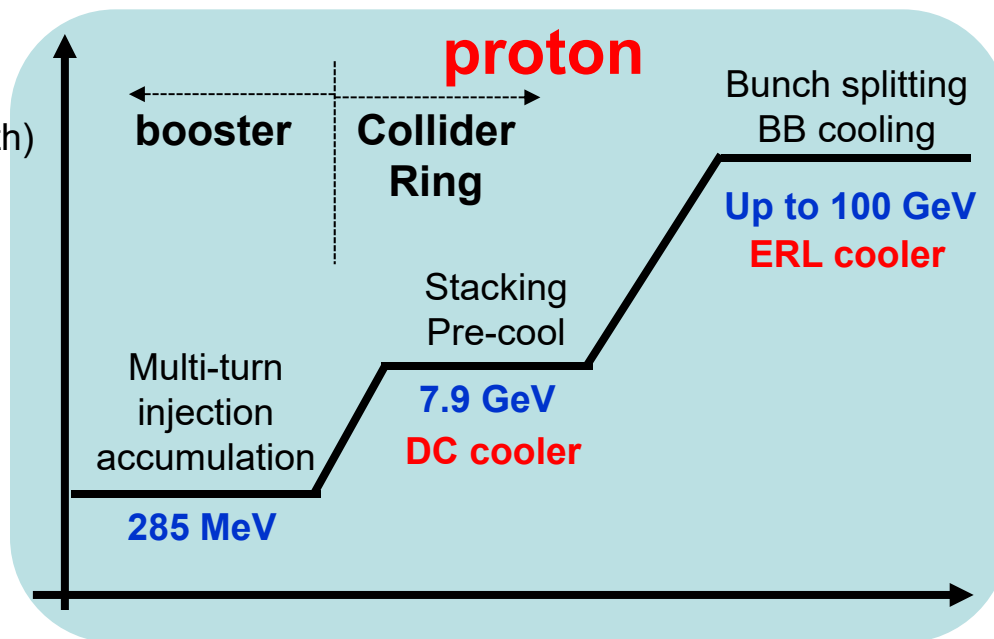
Step 6/7. Bucket-to-bucket transfer to
the collider ring, repeat 26 times ($N_h=28$)



Step 8. Pre-cooling with DC cooler

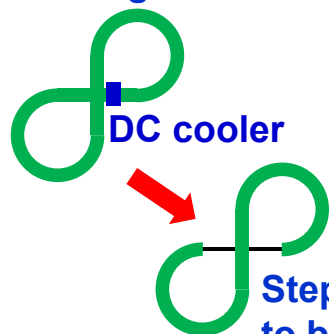
Collider ring: 2252.8m, booster: 281.6m

1. (Eject used beam, cycle the ring magnets)
2. Multi-turn injection of polarized proton to booster
3. Capture beam into a bucket (~200 m bunch length)
4. Ramp to ~8 GeV
5. Compress the bunch length to 56 m
6. Bucket-to-bucket transfer the long bunch into collider ring with DC cooling
7. Repeat step 2-6 for **26** times, each cycle ~20 s, total ~10 min
8. DC cooling to reduce emittance to design values
9. Ramp to collision energy, perform binary bunch splitting up to **7** times to harmonic # $N_h=3584$
10. Start high energy cooling to preserve emittance
11. Start collision program



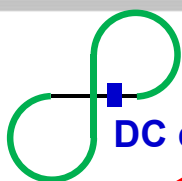
Ion Beam Formation Cycles

Step 2. Accumulating coasting beam

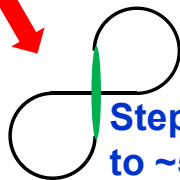


Step 3. Capture to bucket

Step 4. Accelerate

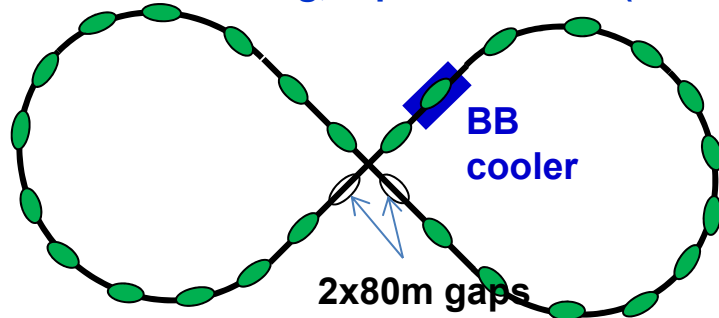


DC cooler



Step 5. Compress to ~56m, split into 2 bunches

Step 6/7. Bucket-to-bucket transfer to the collider ring, repeat 26 times ($N_h=28$)

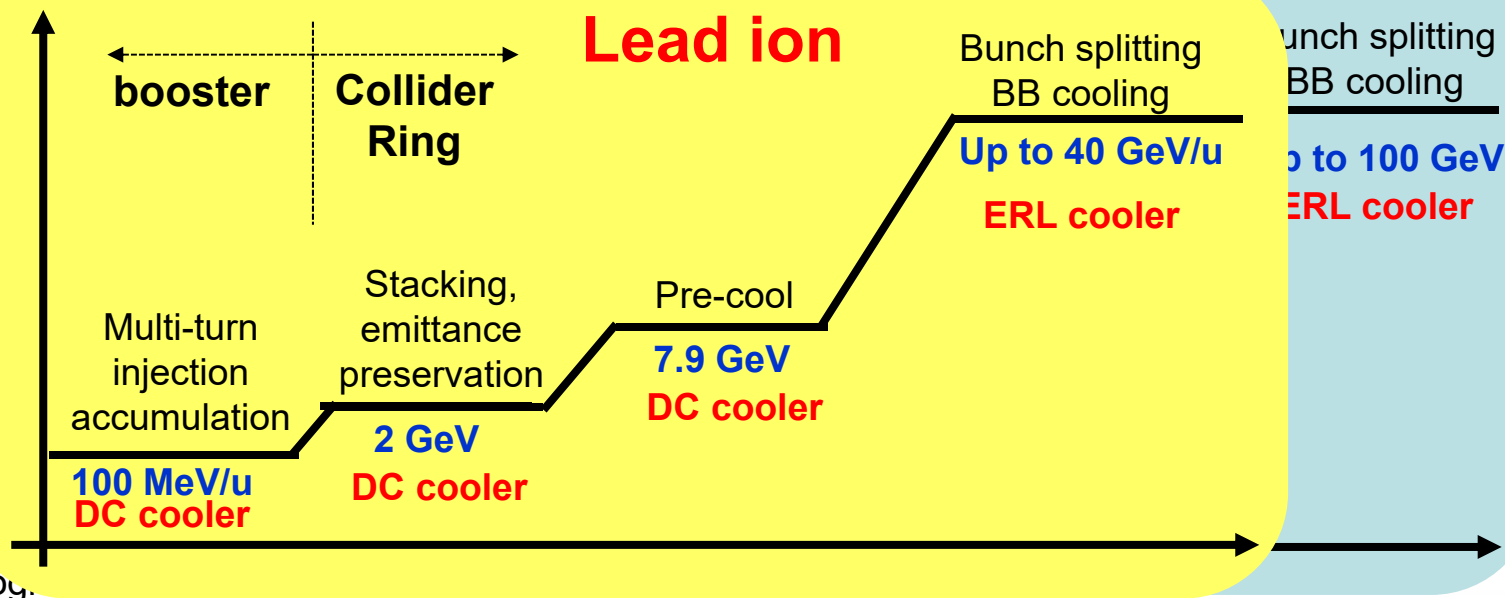


2x80m gaps

Step 8. Pre-cooling with DC cooler

Collider ring: 2252.8m, booster: 281.6m

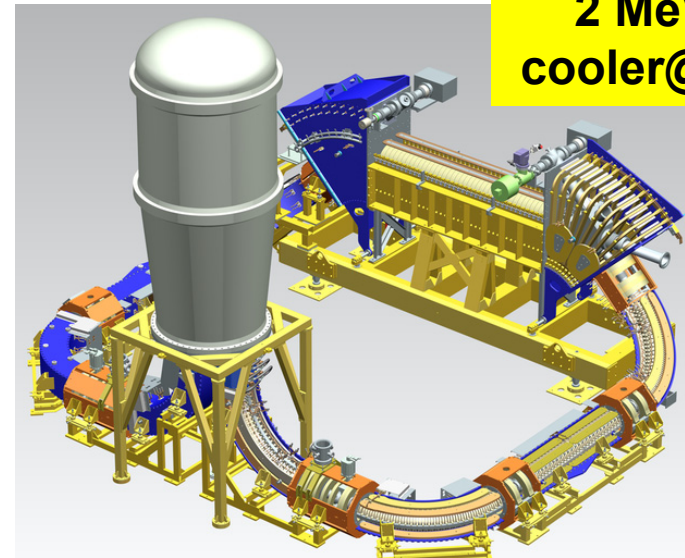
1. (Eject used beam)
2. Multi-turn injection
3. Capture beam
4. Ramp to ~ 8 GeV
5. Compress the beam
6. Bucket-to-bucket transfer to the collider ring with 100% efficiency
7. Repeat step 2-6 for each bunch train total ~ 10 min
8. DC cooling to ~ 100 mK
9. Ramp to collision energy and start beam splitting up to 70% for each beam
10. Start high energy physics
11. Start collision program



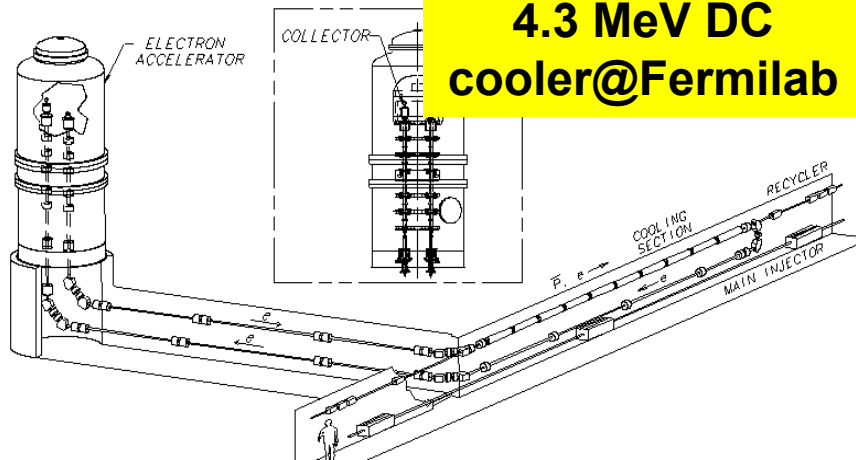
DC Cooler: Within State-of-Art



Low energy DC cooler@IMP, China



2 MeV DC cooler@Jülich



4.3 MeV DC cooler@Fermilab



JLEIC Bunched Beam Electron Cooler

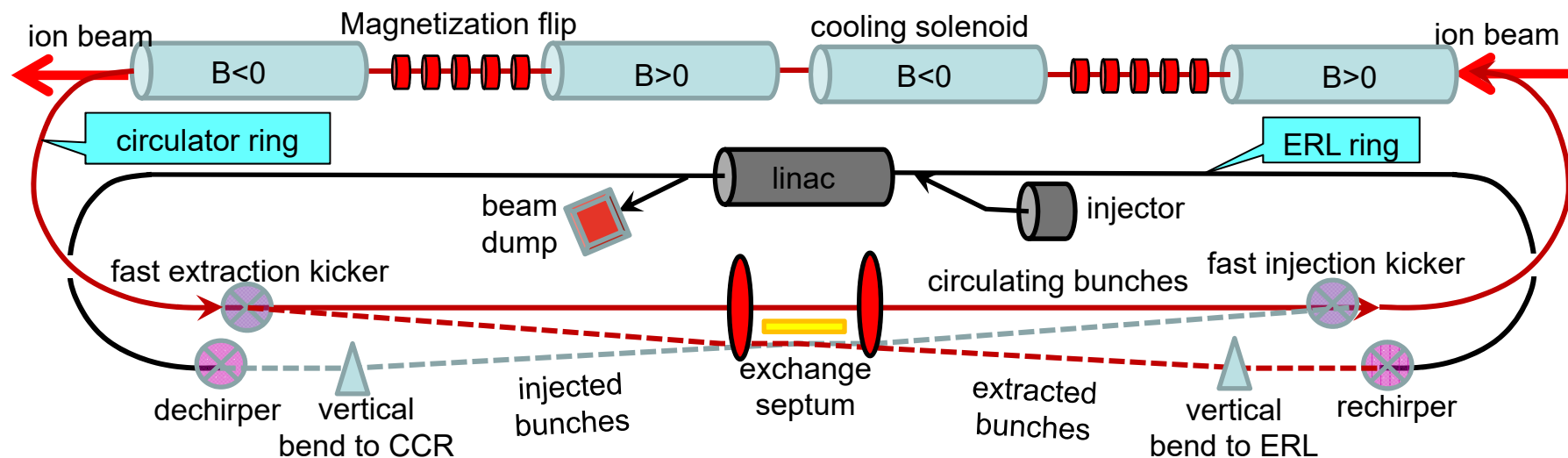
Requirements of cooling beam

- Beam: 1.5 A CW at 476 MHz rep rate
- Energy: up to 55 MeV
- Beam power: 81 MW

Technical approaches

- **Magnetized cooling** (*magnetized gun*)
- SRF linac (*bunched beam*)
- Energy recovery (*power management*)
- Circulator ring (*current management*)

Electron energy	MeV	20 to 55
Bunch charge	nC	3.2
Turns in circulator ring	turn	~11
Current in CCR/ERL	A	1.5/0.14
Bunch rep rate in CCR/ERL	MHz	476 / 43.3
Cooling section length	m	4x15
RMS Bunch length	cm	3
Energy spread	10^{-4}	3
Cooling solenoid field	T	1



JLEIC Bunched Beam Electron Cooler

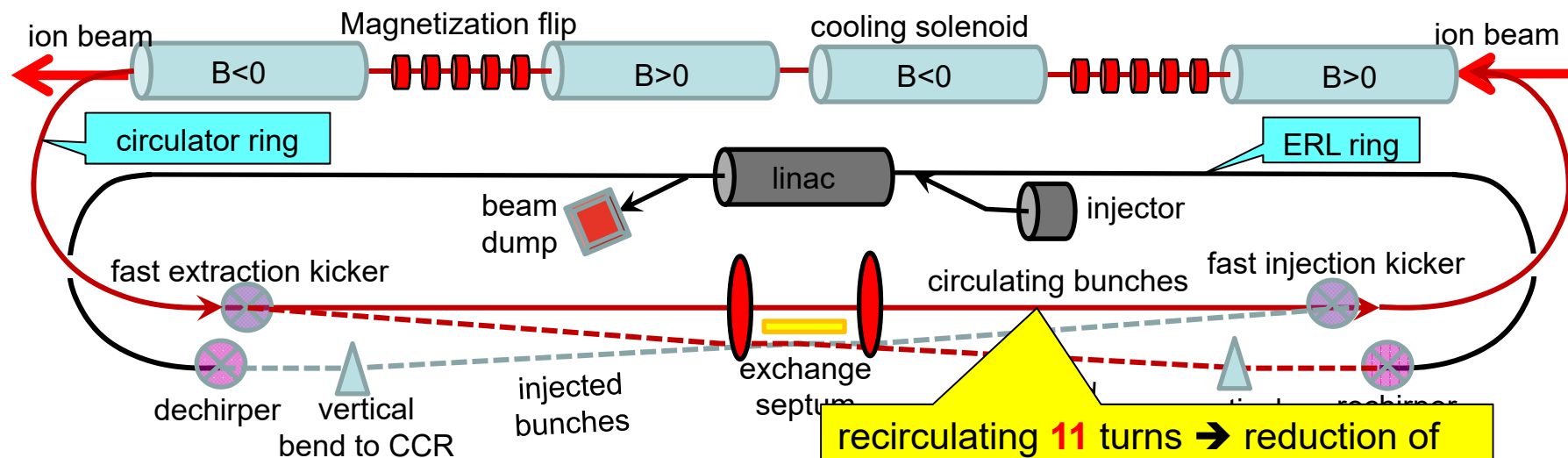
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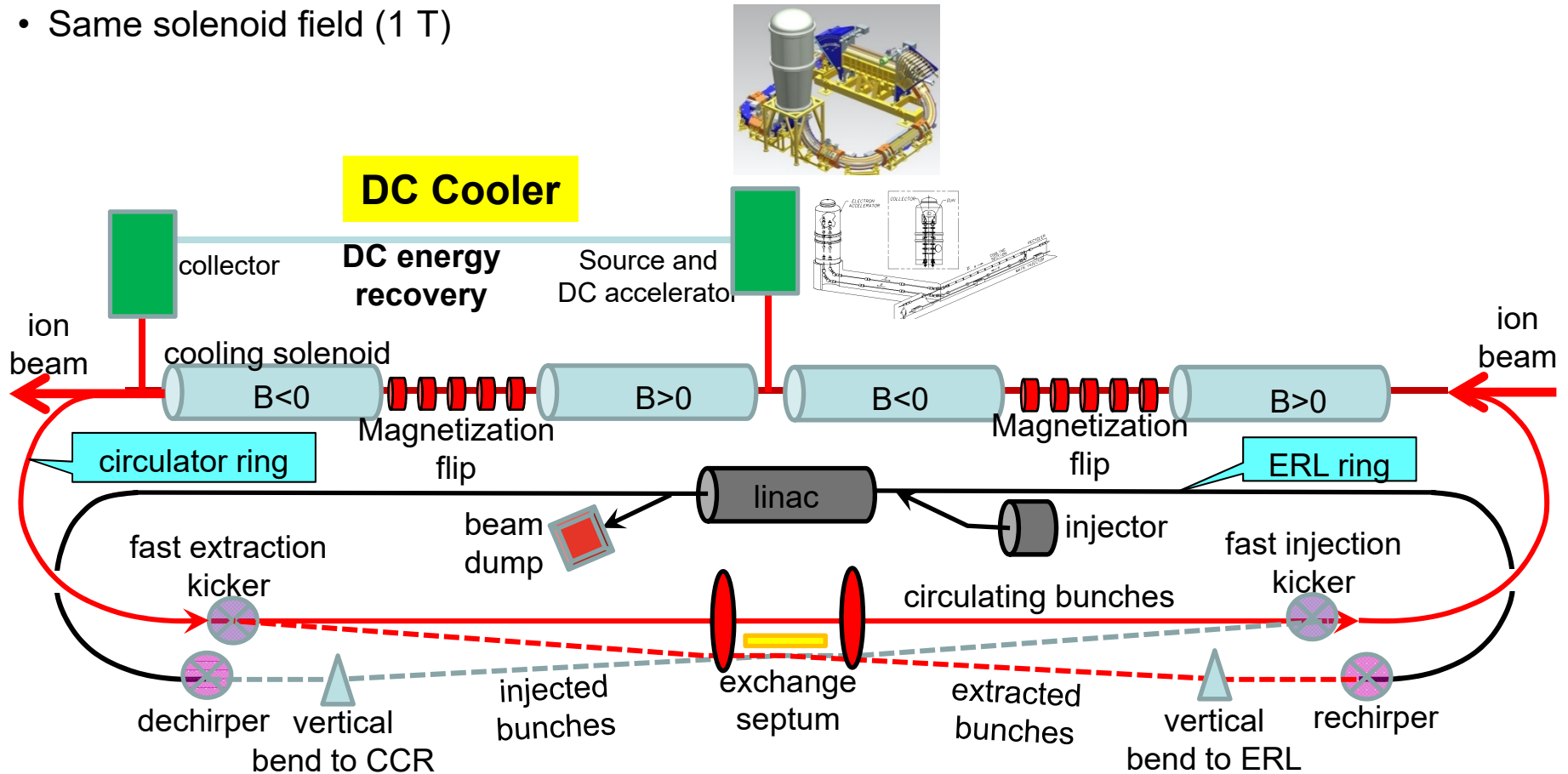
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Cooling solenoid field	T	1



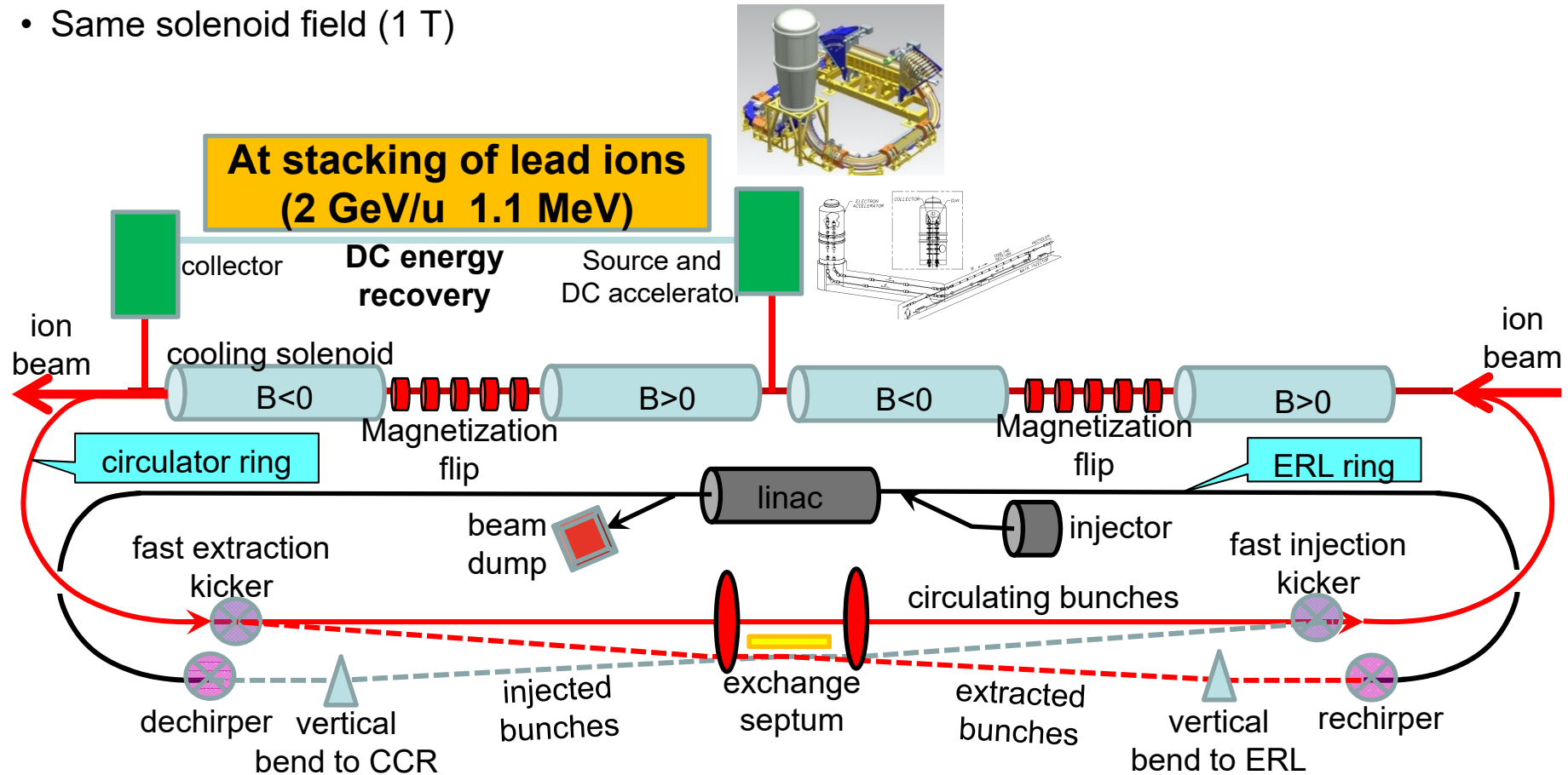
ERL/DC Hybrid Electron Cooler

- ERL cooler and DC cooler share a solenoid (*no show-stopper found*)
- Lower cost, saving beam line space
- Same solenoid field (1 T)



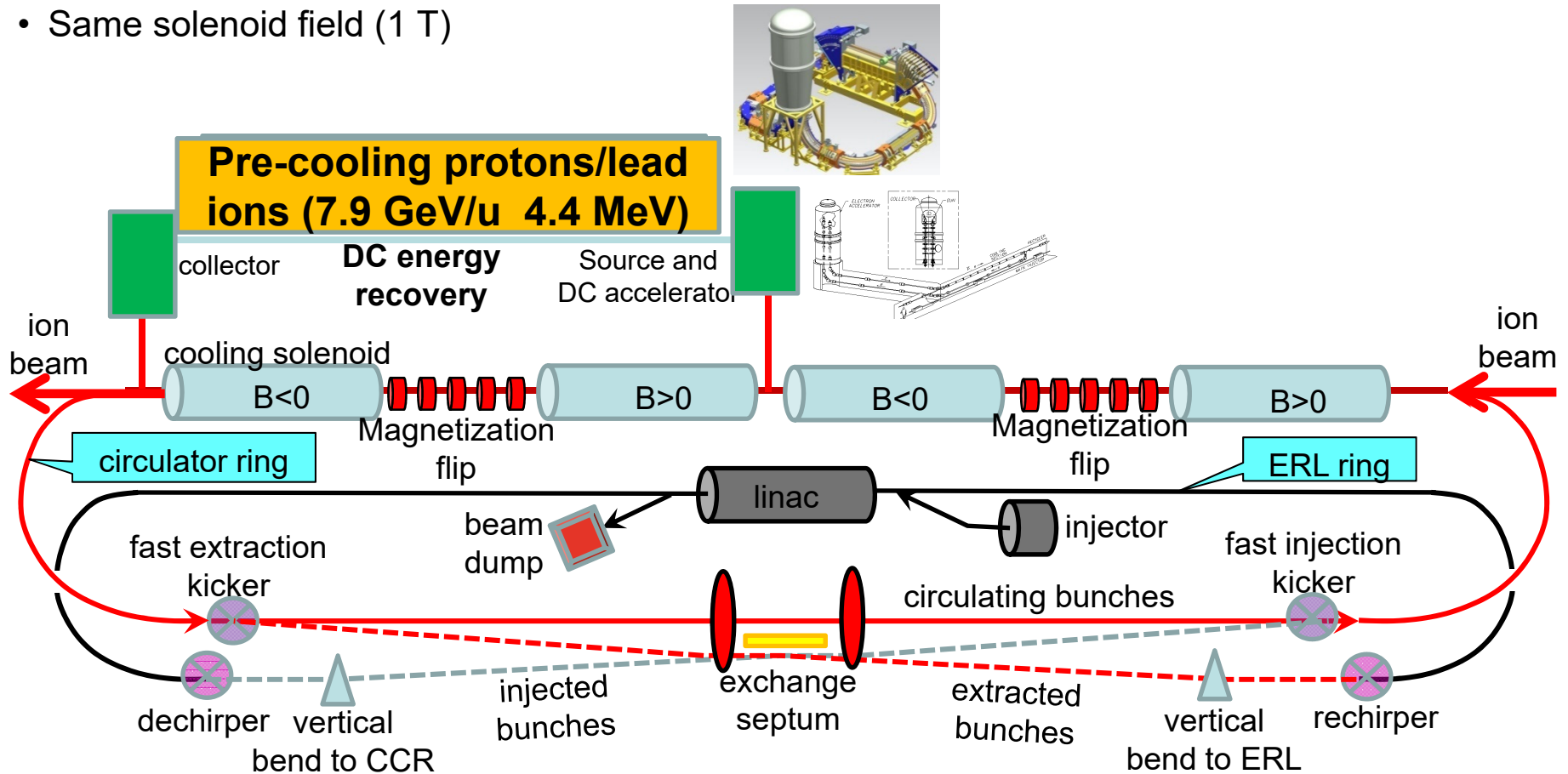
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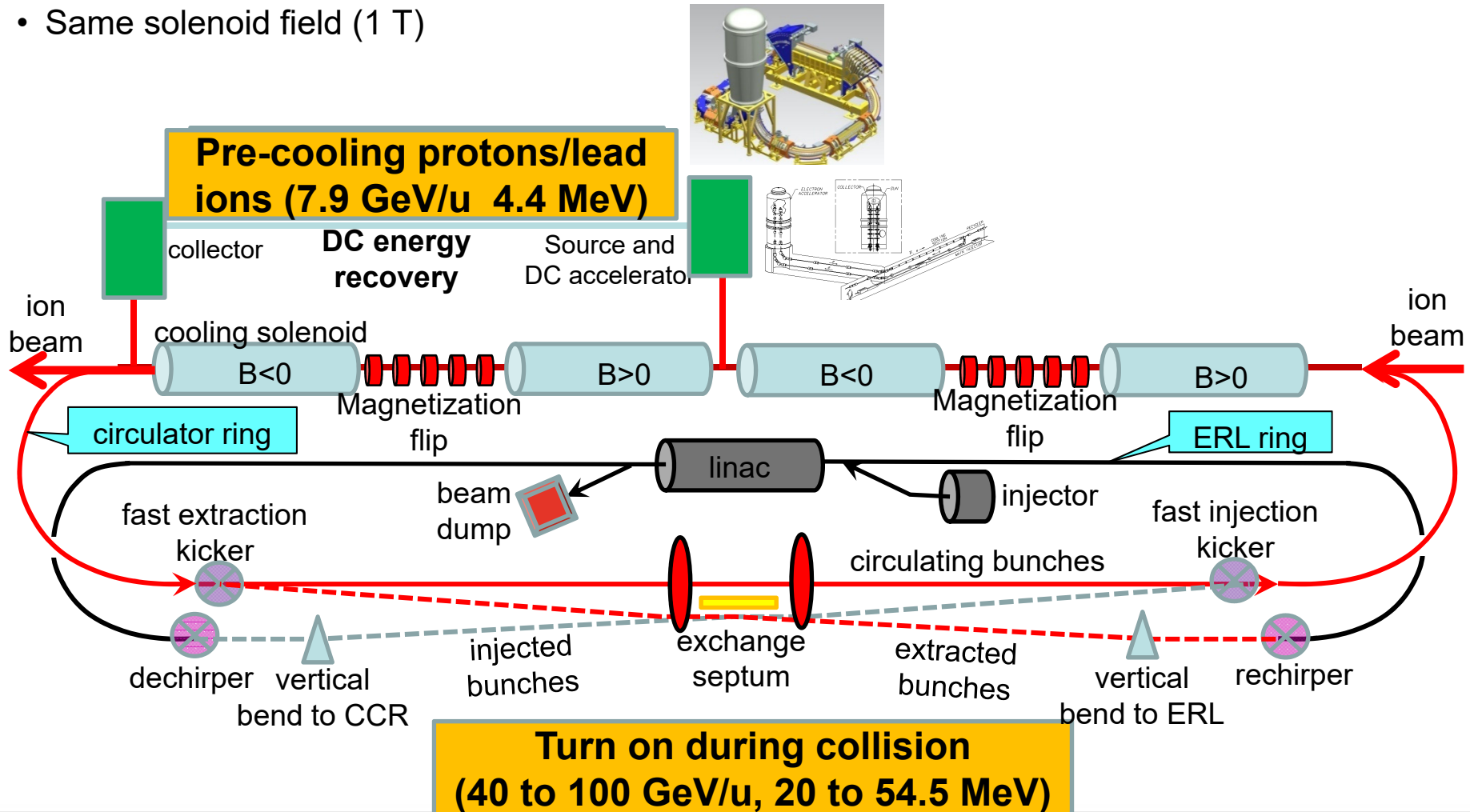
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Outline

- Introduction
- BNL eRHIC Design
- JLab JLEIC Design
- Outlook of US EIC Project
- eRHIC Beam Cooling
- JLEIC Beam Cooling
- Additional topics: Experiment, Simulations and Advanced Concepts
- Summary

JSPEC: New Cooling Simulation Code

Goals

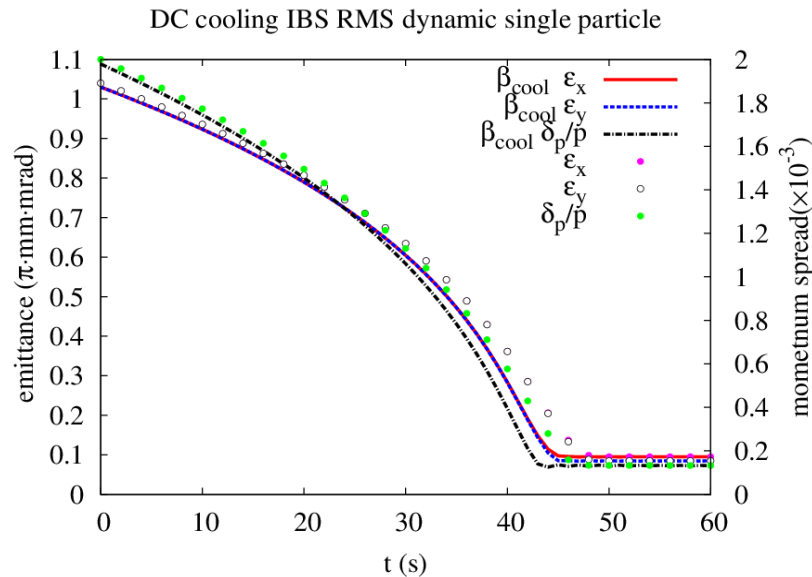
- Fulfill the specific needs for JLEIC electron cooling scheme
- Applicable to different cooling flavors: DC and bunched beam
- Flexibility, higher efficiency (adaptive to the multi-core platform)

**Supported by JLab
LDRD (two years)**

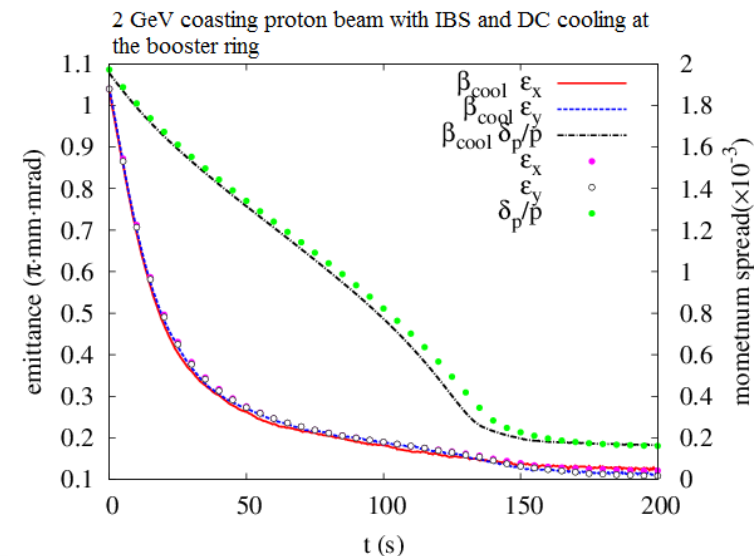
Formulas and models implemented

- IBS: Martini model (no vertical dispersion lattice)
- Friction force: Parkhomchuk formula (magnetized cooling)
- Cooling rate: single particle model, Monte Carlo model
- Cooling dynamics: Four-step procedure

Source codes/tutorial online:
<https://github.com/zhanghe9704/electroncooling>



**Benchmark
with
BETACOOOL**



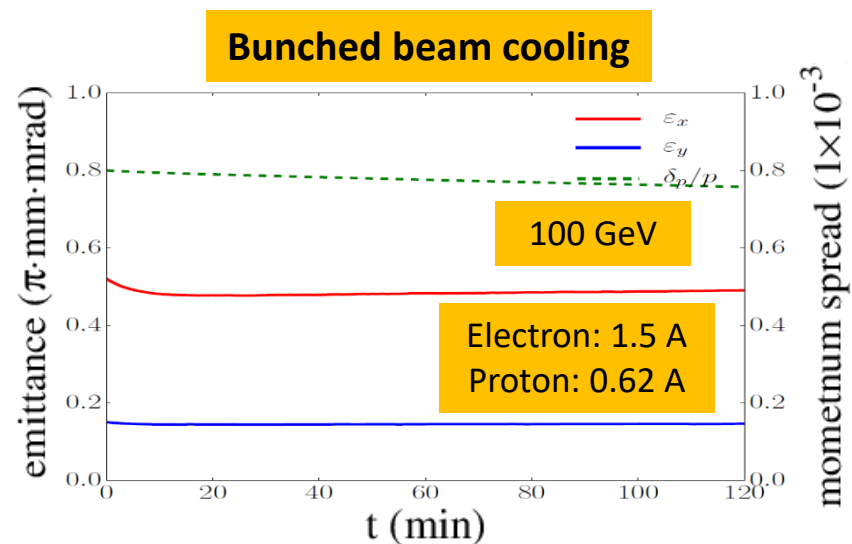
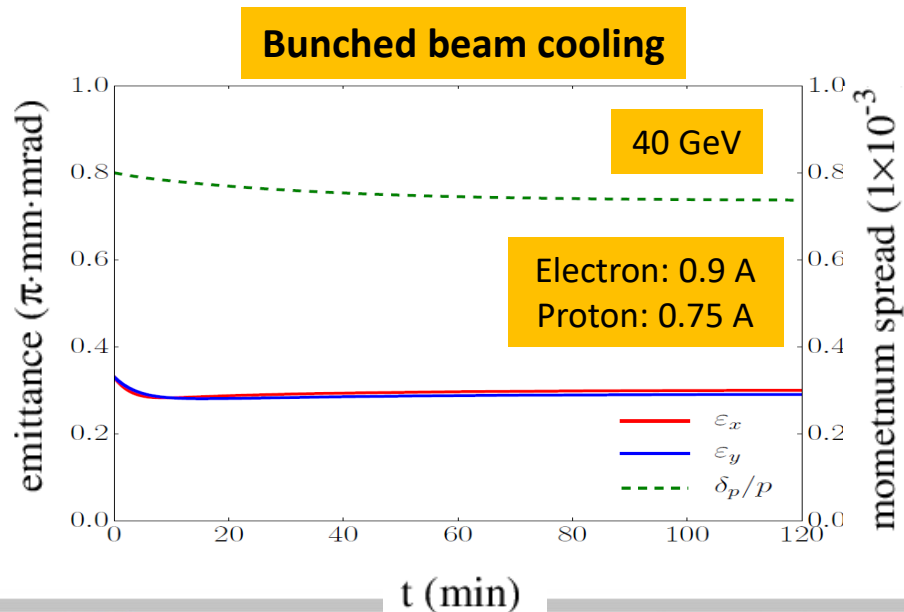
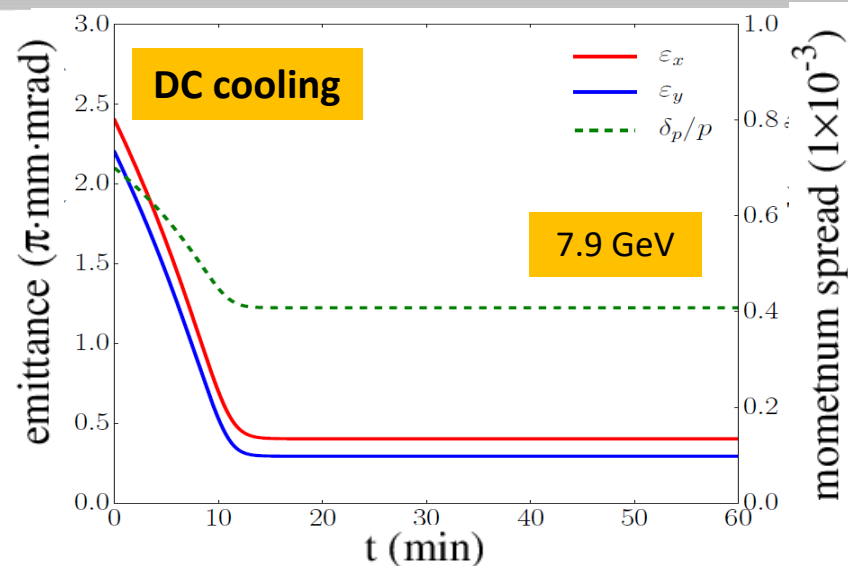
Electron Cooling Simulations

• DC cooling:

Proton: kinetic energy 7.9 GeV, current 0.75 A
 DC electron beam current: 3 A
 Cooler length: 30 m, B field: 1 T

• Bunched beam cooling:

Proton: kinetic energy 30 to 100 GeV, current 0.75 A
 Bunch repetition rate: 476 MHz
 Beam current: 0.9 to 1.5 A, bunch charge: 2 to 3.2 nC
 Cooler length: 2x30 m, B field: 1 T



New Approach to the Semi-Analytic Calculation of Magnetized Friction is Under Development

D. Bruhwiler and S. Webb, “New algorithm for dynamical friction of ions in a magnetized electron beam,” in *AIP Conf. Proc.* **1812**, 050006 (2017); <http://aip.scitation.org/doi/abs/10.1063/1.4975867>

Base: The momentum exchange between a drifting ion and a magnetized electron is calculated approximately using Hamiltonian formalism, the Coulomb interaction H_C is the perturbation:

$$H(\vec{x}_{ion}, \vec{p}_{ion}, \vec{x}_e, \vec{p}_e) = H_0(\vec{p}_{ion}, y_e, \vec{p}_e) + H_C(\vec{x}_{ion}, \vec{x}_e)$$

$$H_0(\vec{p}_{ion}, y_e, \vec{p}_e) = \frac{1}{2m_{ion}}(p_{ion,x}^2 + p_{ion,y}^2 + p_{ion,z}^2) + \frac{1}{2m_e}[(p_{e,x} + eB_0 y_e)^2 + p_{e,y}^2 + p_{e,z}^2]$$

$$H_C(\vec{x}_{ion}, \vec{x}_e) = \frac{-Ze^2}{4\pi\epsilon_0} \frac{1}{\sqrt{(x_{ion} - x_e)^2 + (y_{ion} - y_e)^2 + (z_{ion} - z_e)^2}}$$

$$\vec{B} = B_0 \hat{z} \quad \vec{A} = -B_0 y \hat{x}$$

$$p_{e,x} = m_e(v_{e,x} - \Omega_L y_e)$$

Plan

- 1. Near term:** Numerically integrate over Gaussian electron distributions, for a variety of ion initial conditions. Compare the results with Derbenev & Skrinsky, Parkhomchuk (JLEIC parameters)
- 2. Mid-term:** Apply directly to simulated electron distributions. Monte-Carlo integration over Dp_{ion} yields friction force for arbitrary distributions.
- 3. Longer-term:** Generalize the calculation to include the effects of space charge forces and magnetic field errors, which reduce the friction force.

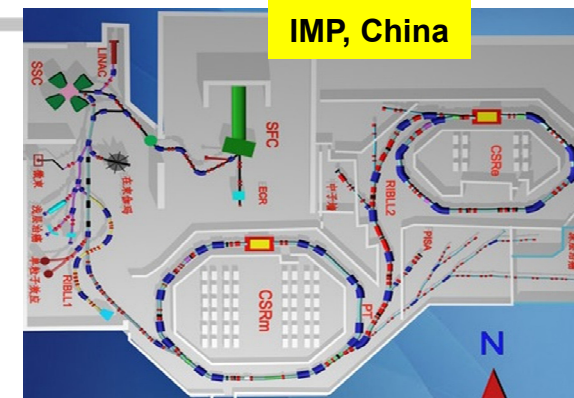
$$H(\vec{x}_{ion}, \vec{p}_{ion}, \vec{x}_e, \vec{p}_e) = H_0(\vec{p}_{ion}, y_e, \vec{p}_e) + H_C(\vec{x}_{ion}, \vec{x}_e)$$

$$+ H_{space - charge}(\vec{x}_{ion}, \vec{x}_e) + H_{solenoid - field - errors}(\vec{x}_{ion}, \vec{x}_e, ?)$$



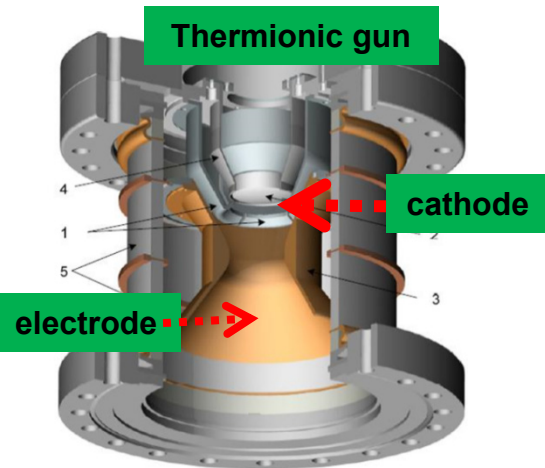
Bunched Beam Cooling Experiment at IMP

- All electron cooling to date achieved using a DC electron beam
- Cooling by a bunched e-beam is one critical R&D item for JLEIC
- **Proof-of-Principle Experiment:** utilizing an existing DC cooler, modulating grid voltage of a thermionic gun to generate a pulsed electron beam (as short as ~100 ns)



A collaboration of Jlab and IMP (China)

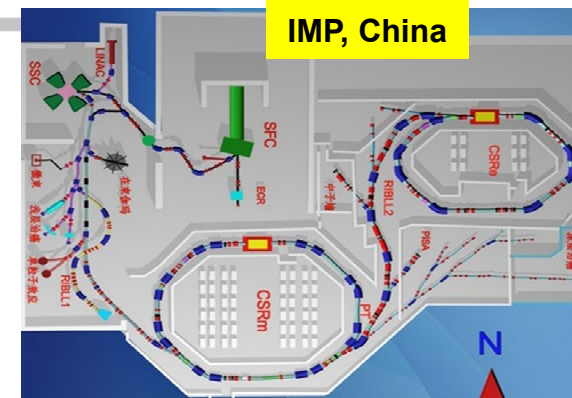
IMP: L. Mao (PI), H. Zhao, M. Tang, J. Li, X. Ma, X Yang, J. Yang, H. Zhao
Jlab: Y. Zhang (co-PI), A. Hutton, K. Jordan, T. Powers, R. Rimmer, M. Spata, H. Wang, S. Wang, H. Zhang



- May 2016, 1st experiment: bunched beam cooling was observed
- Nov. 2016, machine development (improving beam diagnostics)
- April 2017, 3rd experiment: more measurements (under analysis)

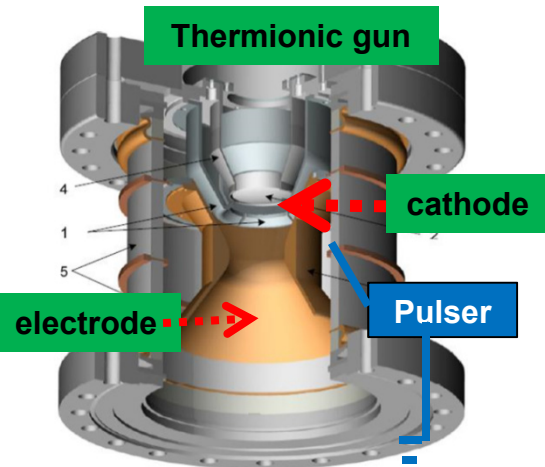
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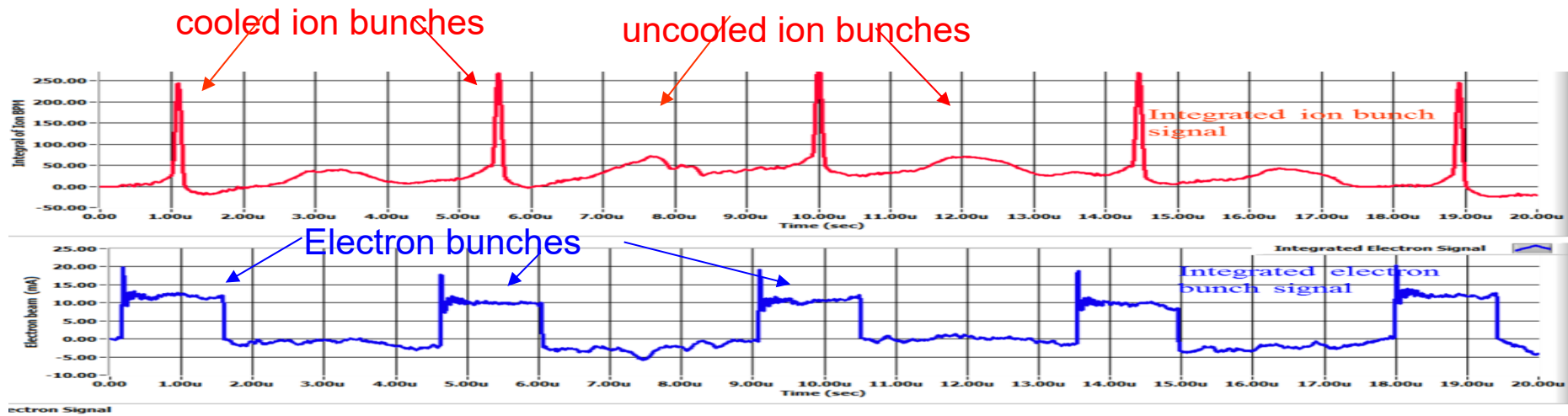
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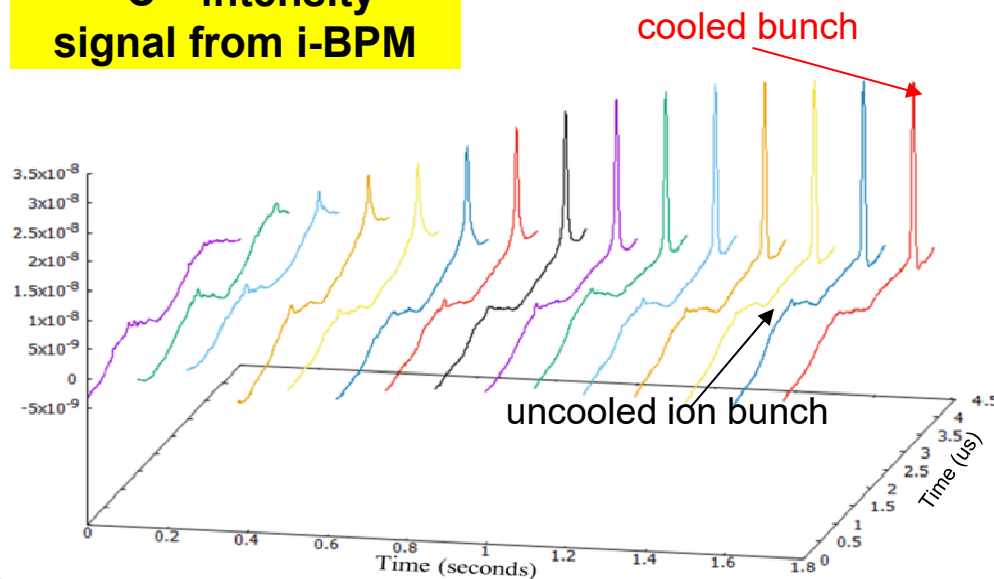


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First Results of Bunched Beam Cooling



**$^{12}\text{C}^{6+}$ intensity
signal from i-BPM**



Ions		$^{12}\text{C}^{6+}$
Ring circumference	m	161
Ion energy	MeV/u	7.0
Revolution period/freq	us/Hz	4.4/227
Particle number		10^8
Initial ion bunch length	ns	700 or DC
Electron energy	keV	3.8
E-beam avg. current	mA	<50
E-beam pulse width	ns	70 – 3500
E-beam radius	cm	2.5

EXPERIMENTAL DEMONSTRATION OF COOLING EFFECT WITH BUNCHED ELECTRON BEAM

L. Mao¹, H. Zhao, M. Tang, J. Li, X. Ma, X. Yang, J. Yang, H. Zhao, IMP Lanzhou, China
A. Hutton, K. Jordan, T. Powers, R. Rimmer, M. Spata, H. Wang, S. Wang, H. Zhang, Y. Zhang, JLab Newport News, U.S.

Abstract

For future high energy electron colliders, the electron beam can only be provided by a RF/DSRF Linac. As a result, several short electron bunches would be used to cool a long ion bunch. The first experiment demonstrated cooling of coasting/bunched ion beam by a bunched electron beam was carried out at the storage ring CSR at IMP. A preliminary data analysis has indicated the bunch length shrinkage and the momentum spread reduction of bunched ¹⁰⁰MeV ion beam. A longitudinal grouping effect of coasting ion beam by the electron bunch has also been observed.

1. Motivation

Several future facilities require electron cooling of ions at a much high energy up to 100 GeV/c (e.g. JLEIC @ JLab), electron energy is up to 60 MeV. Classical DC cooler is not sufficient, but RF/DSRF linac should be used to provide bunched e-beam.

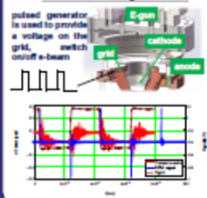
JLEIC cooler idea

Our purpose is to demonstrate the cooling process by bunched electron beam at low energy cooler

2. CSR cooler & its HV platform



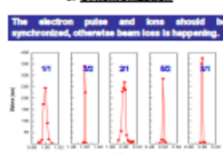
3. Pulsed e-beam generation



4. Experimental parameters

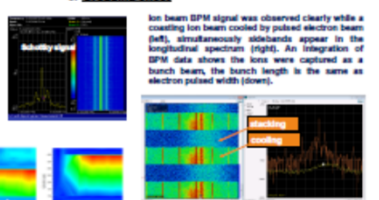
Item	Value
Ring circumference	181 m
Ion energy	100 MeV/c
Revolutions per turn	4.4227
Particle number	10 ⁹
Initial ion bunch length	~700 ps DC
Electron energy	10 MeV
E-beam current	~50 mA
E-beam pulse width	70 ~ 300 ns
E-beam radius	0.5 mm

5. Synchronization



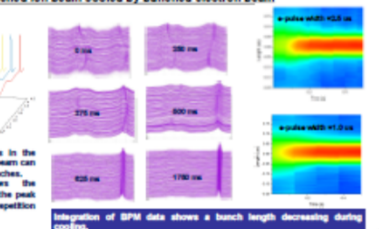
The electron pulse and ion should be synchronized, otherwise beam loss is happening.

6. Grouping effect



Ion beam BPM signal was observed clearly while a coasting ion beam cooled by pulsed electron beam (left), simultaneously sidebands appear in the longitudinal spectrum (right). An integration of BPM data shows the ions were captured as a bunch beam, the bunch length is the same as electron pulse width (down).

7. Bunched ion beam cooled by bunched electron beam



Integration of BPM data shows a bunch length decreasing during cooling.

8. Conclusion & outlook

- A pulsed electron beam was obtained by a modification of classical DC electron gun of cooler. The parameters of frequency (~250 kHz), peak current (~100 mA), minimum pulse width (~70 ns) are limited by the power of generator.
- Grouping effect is observed clearly, while a DC ion beam cooled by pulsed electron beam, and can be explained by the RF bucket due to electron beam space charge field. It gives us a sign, a micro-structure may be observed, while a long ion bunch cooled by several small electron bunches in high energy colliders.
- Bunched ion beam can be cooled by pulsed electron beam. A preliminary experiment is done to investigate the cooling time vs. parameters of pulsed electron beam, such as peak current, pulse width, repetition frequency.

SIMULATION OF LOW ENERGY ION BEAM COOLING WITH PULSED ELECTRON BEAM ON CSR

He Zhao¹, Lijun. Mao¹, Jie Li, Meitang Tang, Xiaodong Yang, Xiaoming Ma, Jiancheng Yang
Institute of Modern Physics CAS, Lanzhou, China
¹University of Chinese Academy of Sciences, Beijing, China

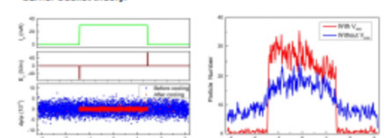
Abstract

The pulsed electron beam can be applied to the beam cooling on high energy heavy ions and the research on ion-electron interaction in the future. In this paper, we studied the pulsed e-beam cooling effects on coasting and bunched ion beam by simulation code which is based on the theory of electron cooling, IBS and space charge effect etc. In the simulation, a rectangular distribution of electron beam was applied to 7 MeV/u ¹⁰⁰MeV ion beam on CSR. It is found that the coasting ion beam was bunched by the pulsed e-beam and the rising and falling region of electron beam current play an important role for the bunching effect, and similar phenomenon was found for the bunched ion beam. In addition, the analyses of these phenomena in simulation were discussed.

Coasting Ion Beam Cooling

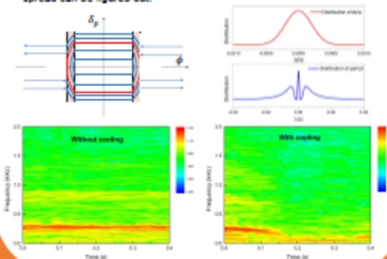
• Single pulsed e-beam

Based on simulation results on CSR, the coasting beam is bunched by the pulsed electron beam and almost all of the particles are bunched into the region where have electrons. The electric field caused by the rising and falling of electron beam plays a crucial role in the bunching process. The kick voltage on ions due to the square wave electric field in longitudinal is about 230V. The bunch process can be explained by the barrier bucket theory.



Ion Energy	7 MeV/u
Beam current	2 mA
Initial momentum spread RMS	3e-4
Initial emittance	0.302 μm mrad
Ring circumference	181 m
Length of cooler	3.4 m
Rotation time	3.632 μs
Rate value in cooling section	10000 m
E-beam current	30 mA
E-beam radius	3 cm
E-beam temperature	0.201 eV
Magnetic field in cooling section	1000 G
pulse width	2 μs
Rising/falling time	10 ns

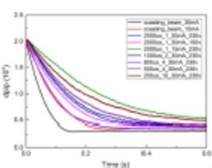
Similar to synchrotron motion in RF, the oscillation caused by the potential field is circle in longitudinal phase space. The period time of the bunched beam with RMS momentum spread diplo includes two parts: cooling section and e-beam edge section. The distribution the period time is shown in below and there exist sidebands which is caused by the Gaussian distribution of momentum spread. Based on the sidebands in frequency domain, the cooling process and the RMS beam momentum spread can be figured out.



Coasting Ion Beam Cooling

• Multi pulsed e-beam

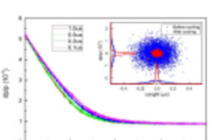
- The cooling rate is proportional to average e-beam current and the momentum spread at equilibrium status is inversely proportional to the average e-beam current.
- For the same average e-beam current, the cooling rate is inversely proportional to the value of V_{kick} and the numbers of pulsed.



Bunched Ion Beam Cooling

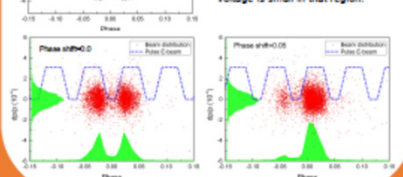
• Long pulsed e-beam

- The e-beam pulse width is longer than the initial RMS bunch length of ion beam before cooling with $V_{kick}=1$ KV and $\Phi_{e0}=0$.
- Because of the synchrotron motion, the cooling rate almost have no difference for long pulsed e-beam.



• Short pulsed e-beam

The e-beam pulse width is close to the final bunch length of ion beam after cooling. Together with the RF voltage, the kick voltage caused by the pulsed electron beam will change the separatrix orbit in phase space like the figure shows, which is the result of one particle tracking in longitudinal. The bunched ion beam will be divided into two bunches by the multi e-beam, if there is an phase shift between the RF and pulsed e-beam, the final distribution of bunch show a different phenomenon. It is main determined by the kick voltage because the RF voltage is small in that region.



Electron Cooling Theory

Full translation of Ya. Derbenev's D.Sci. Thesis

arxiv.org/abs/1703.09735

THEORY OF ELECTRON COOLING

Yaroslav Derbenev*

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

**Translated from Russian by V.S. Morozov, Jefferson Lab, VA 23606, USA
Translation supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.*

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Introduction

- I. General Properties of Electron Cooling
- II. Interaction of Heavy Particles With Magnetized Electron Beam
- III. Effects of Non-Uniformity and Non-Stationary When Cooling By Magnetized Beam
- IV. Collective Stability of Cooled Beam
- V. Intrabeam Scattering

Summary

- NSAC Long Range Plan (2015) recommends an EIC as a future US accelerator facility for the OCD frontier, science cases were fully developed and very strong
- Two electron-ion colliders, eRHIC and JLEIC, have been proposed in BNL and JLab respectively for future nuclear physics research
- Both eRHIC and JLEIC accelerator designs aim for high performance, orders of magnitude better than HERA, to meet science needs
- Cooling is essential for both eRHIC and JLEIC to reach ultra high luminosity (above $10^{34}/\text{cm}^2/\text{s}$)
- There are clear and promising cooling concepts for eRHIC and JLEIC, and much progress has been made in technical designs and technology R&D
- However, there are still lots of work need to be done.

The banner features a dark blue background with a large, glowing blue and black nucleus in the center. To the left is a stylized atomic model with a blue nucleus and grey electrons on white orbits. To the right is a cross-section of an accelerator with yellow coils and blue particles. The text 'EIC Accelerator Collaboration Meeting 2017' is in white, bold font.

EIC Accelerator Collaboration Meeting 2017

Hosted at Brookhaven National Laboratory
October 10-12, 2017

<https://www.bnl.gov/eiccm2017/>

Acknowledgement

To prepare this presentations, I borrowed slides for eRHIC from several BNL colleagues including Christoph Monteg, Vadim Ptitsyn and Ferdinand Willeke. I want to thank these colleagues

I want to thank IMP colleagues for collaboration of the bunched beam electron cooling experiment

We also want to thank the Jefferson Lab EIC team and many collaborators.

*S. Benson, A. Bogacz, P. Brindza, A. Camsonne, E. Daly, Ya. Derbenev, M. Diefenthaler, D. Douglas, R. Ent, Y. Furletova, D. Gaskell, R. Geng, J. Grames, J. Guo, F. Hanna, L. Harwood, T. Hiatt, H. Huang, A. Hutton, K. Jordan, A. Kimber, G. Krafft, R. Li, F. Lin, F. Marhauser, R. McKeown, T. Michalski, V. Morozov, E. Nissen, H. Park, F. Pilat, M. Poelker, T. Powers, R. Rimmer, Y. Roblin, T. Satogata, M. Spata, R. Suleiman, A. Sy, C. Tennant, H. Wang, S. Wang, G. Wei, C. Weiss, R. Yoshida, H. Zhang, Y. Zhang – **Jefferson Lab**, VA*

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*P. Ostroumov, A. Plastun, R. York - **Michigan State University**, MI*

*S. Abeyratne, B. Erdelyi - **Northern Illinois Univ.**, IL, Z. Zhao - **Duke Univ.**, NC*

*J. Delayen, C. Hyde, S. De Silva, S. Sosa, B. Terzic - **Old Dominion Univ.**, VA*

*J. Gerity, T. Mann, P. McIntyre, N. Pogue, A. Sattarov - **Texas A&M Univ.**, TX*

*P. Nadel-Turonski, **Stony Brook Univ.**, NY, V. Dudnikov, R. Johnson - **Muons, Inc.**, IL*

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