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

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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

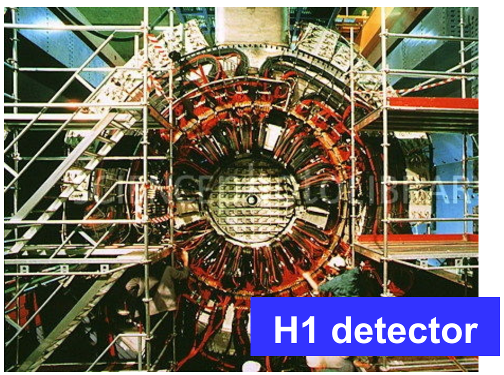
Introduction

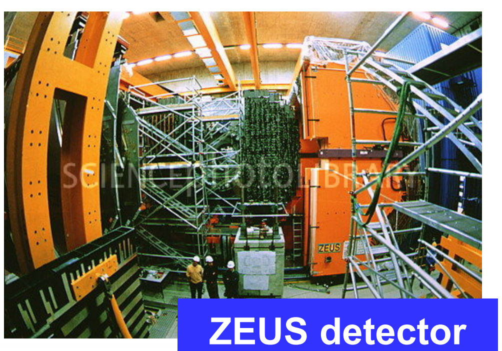
- Electron-Ion collider (EIC) utilizes deep-inelastic scatterings to probe structures of nucleus
- *HERA*, the only e-p collider ever built and operated, ended its science program in 2007. Over the past 15 years, 7 next generation EICs were envisioned worldwide for high energy and nuclear physics.
- 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} /cm^2/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.

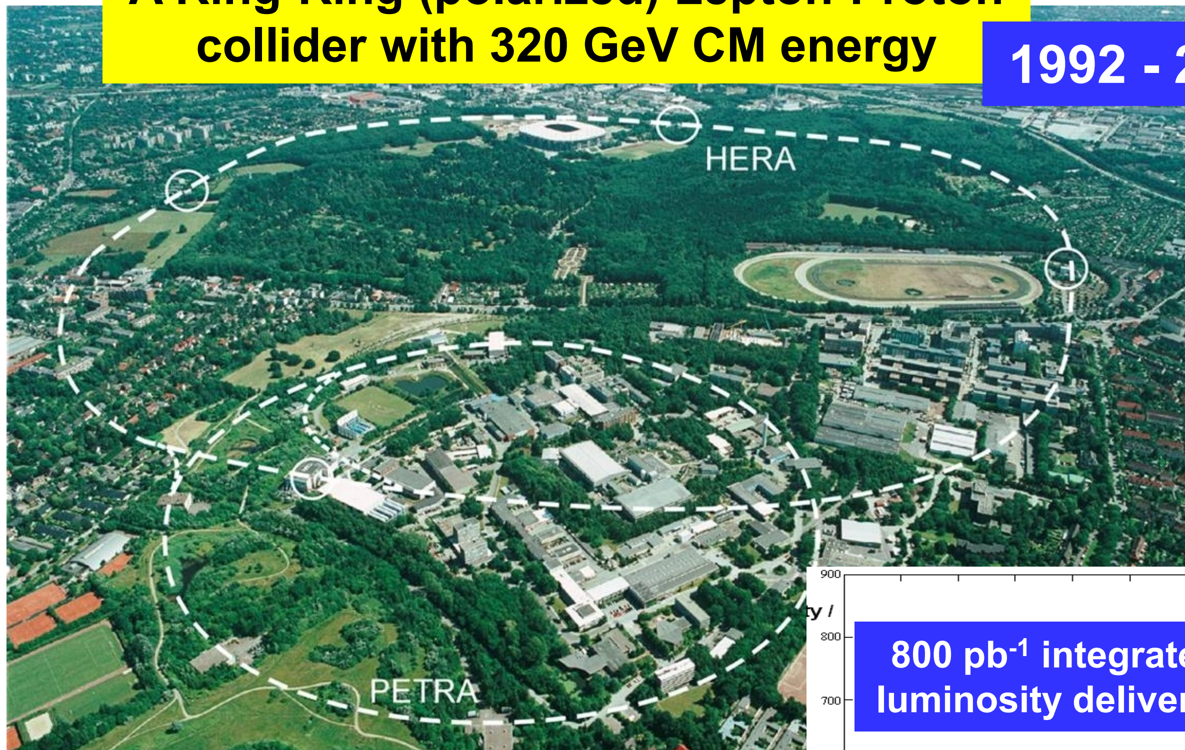
HERA@DESY: The World 1st *ep* Collider

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

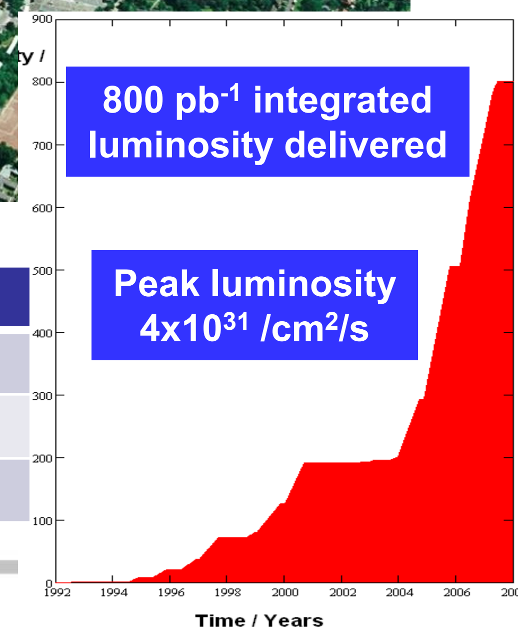
1992 - 2007



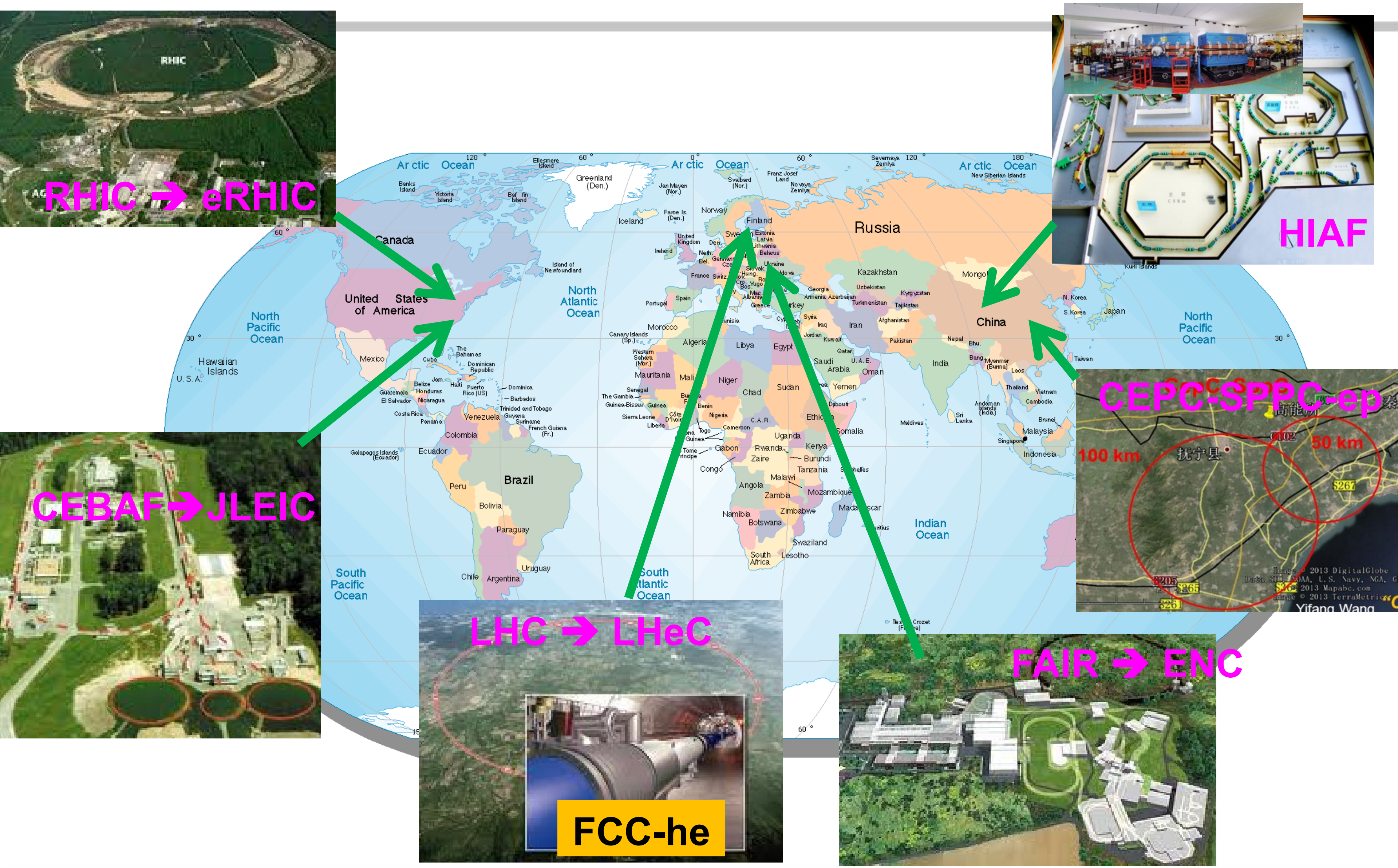




		Lepton	proton
Energy	GeV	27.5	920
e-polarization	%	30 to 50	--
Final lumi.	$cm^{-2}s^{-1}$	$(1.5 \text{ to } 4)\times10^{31}$	

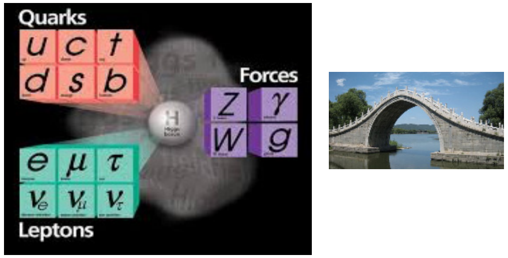


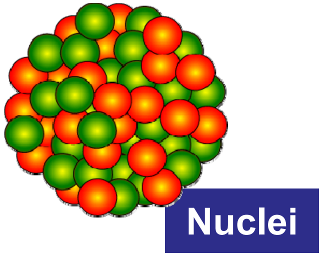
A New World of Electron-Ion Colliders



A New EIC for The Next QCD Frontier

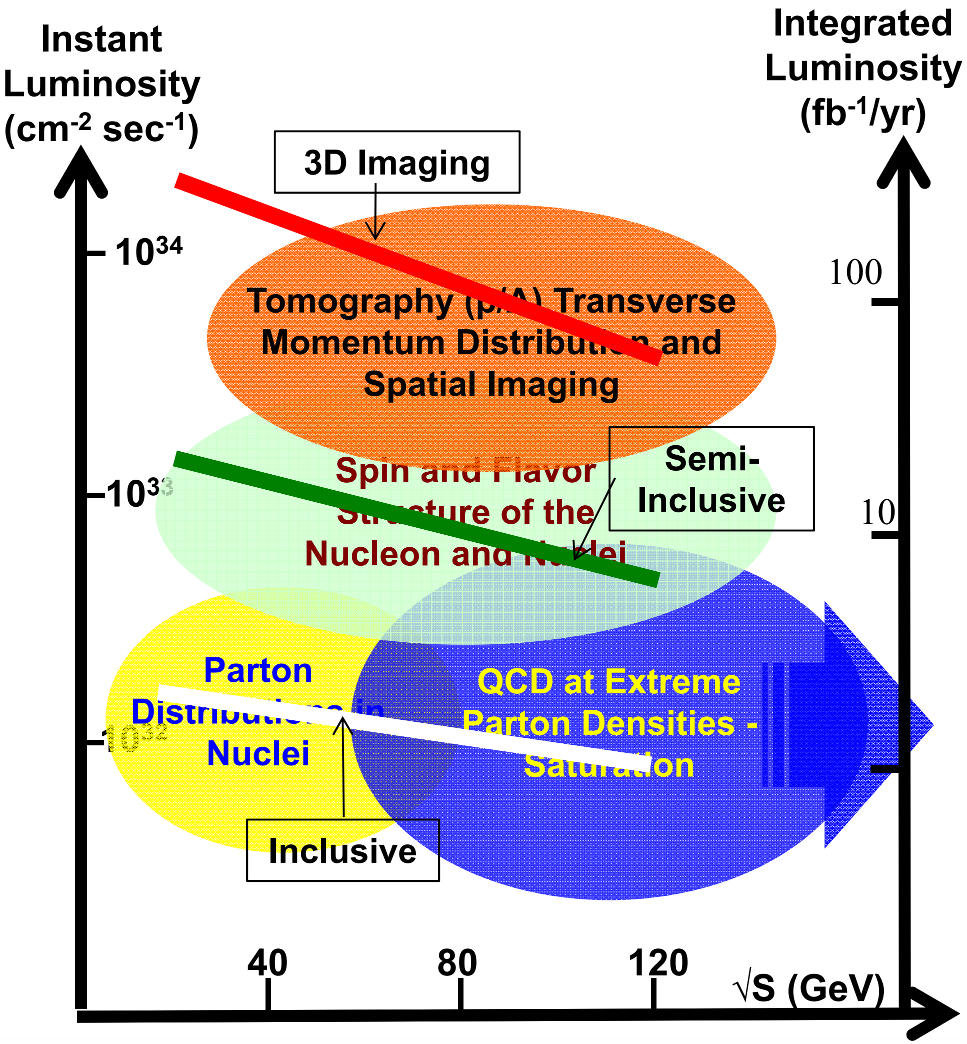
A Gluon Microscopy for Understanding the Glue that Binds Us All





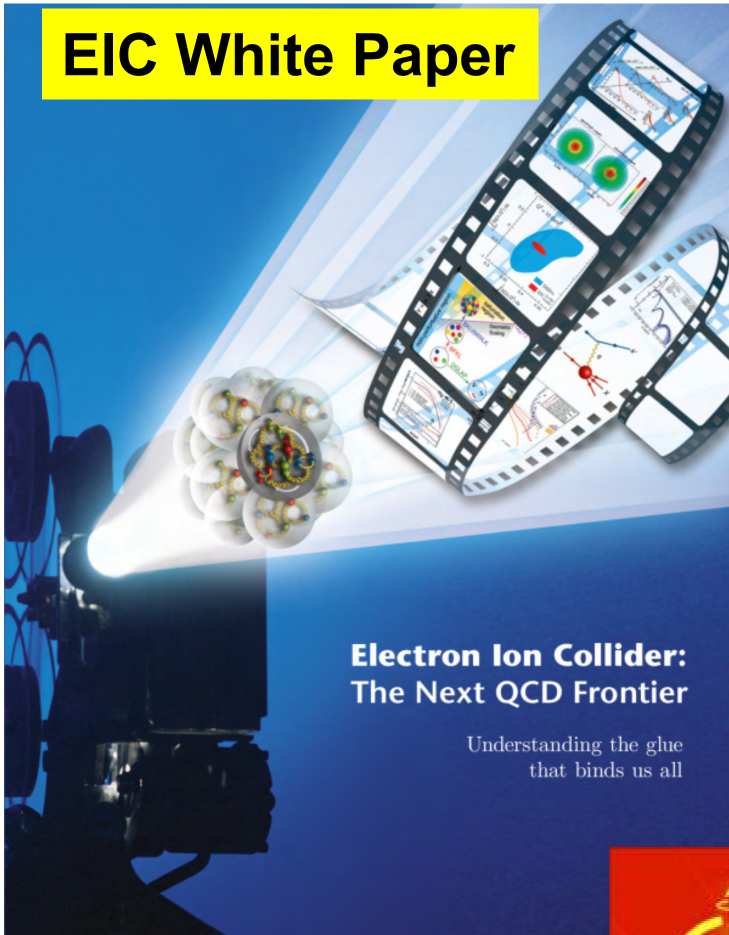
An EIC, with a versatile range of
beam species, ***kinematics***, ***polarizations***, ***high luminosity***
is required

- 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



arXiv:1212.1701.v3

Will Be World's *first* !

Polarized electron-proton/light ion collider

Electron-Nucleus collider

e-p collisions

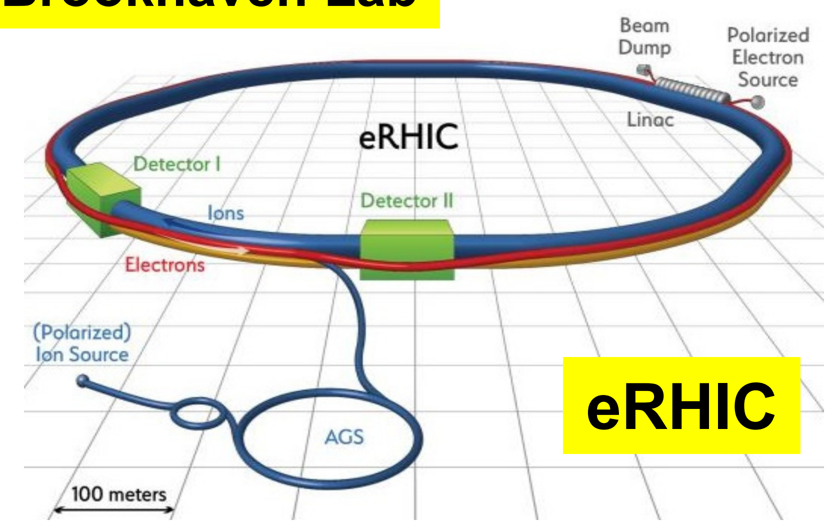
- ✓ More than one interaction point
- ✓ Polarized beams: e, p (>70%)
- ✓ Variable CM: 20-~100 (~140) GeV
- ✓ Electron beam: 3-10(20) GeV
- ✓ Proton beam: up to 250 GeV
- ✓ Luminosity ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$
  100-1000 times HERA

e-A collisions

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

Two Labs Looking for Hosting the US EIC

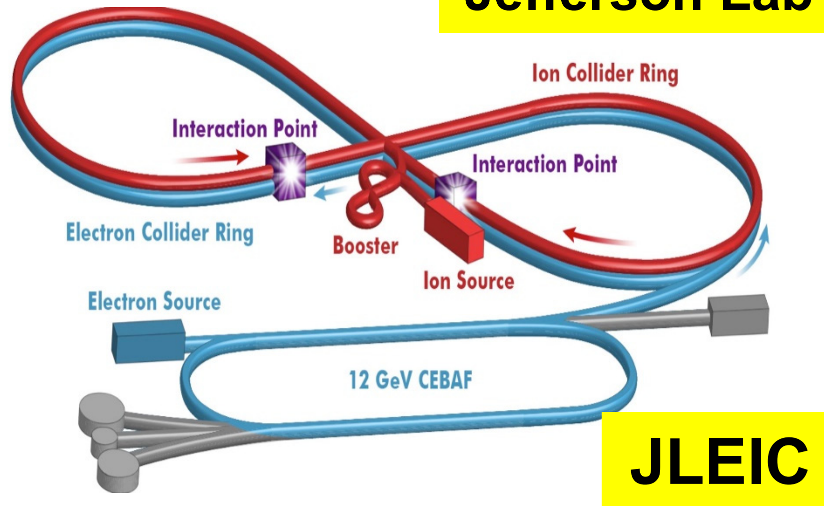
Brookhaven Lab



Needs an electron beam

- **Based on RHIC and its injector complex**
  - polarized proton and ^{3}He, 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



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 ^{3}He
  - Other all stripped ions, up to lead
  - Up to 100 GeV/u ion energy

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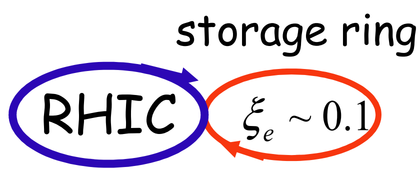
eRHIC Linac(ERL)-Ring Design

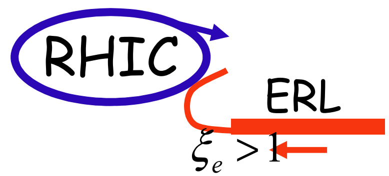
- Ring-ring

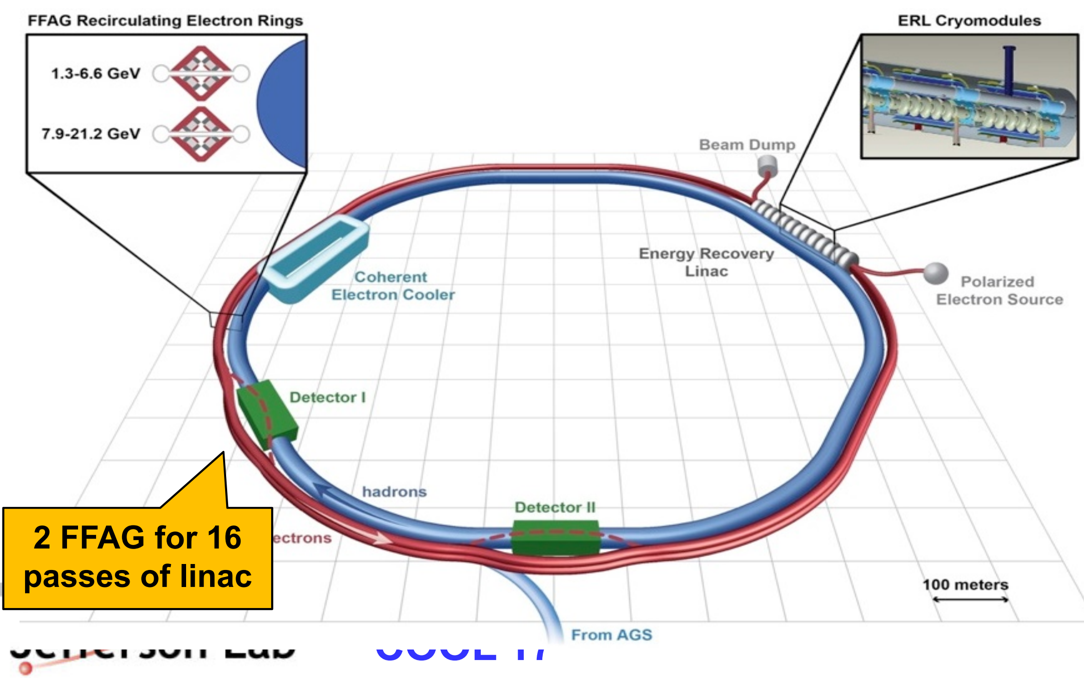
$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e}\right)(\xi_h\xi_e)(\sigma'_h\sigma'_e)f$$



- Linac-ring **L × 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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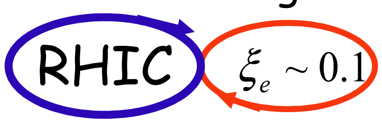

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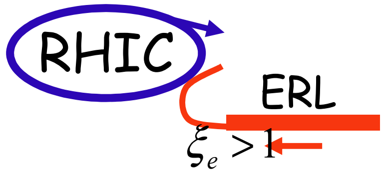

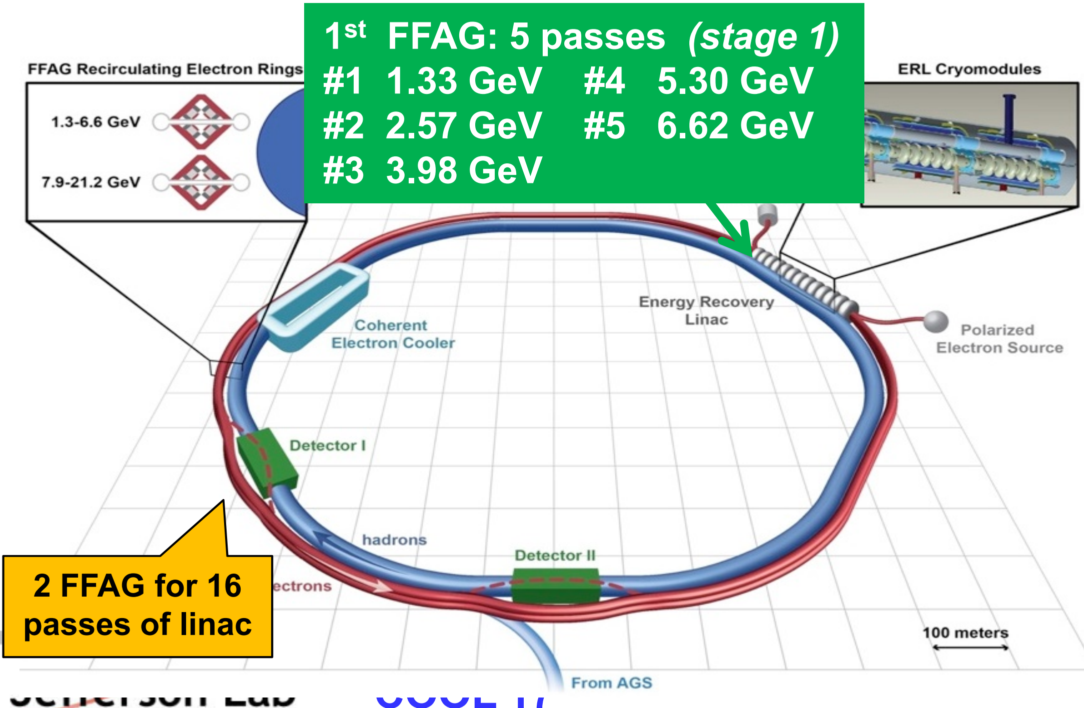

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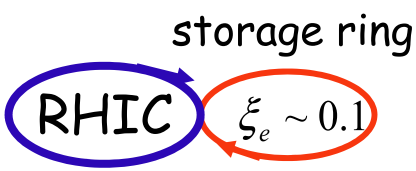

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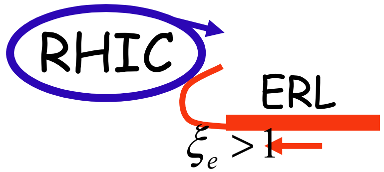

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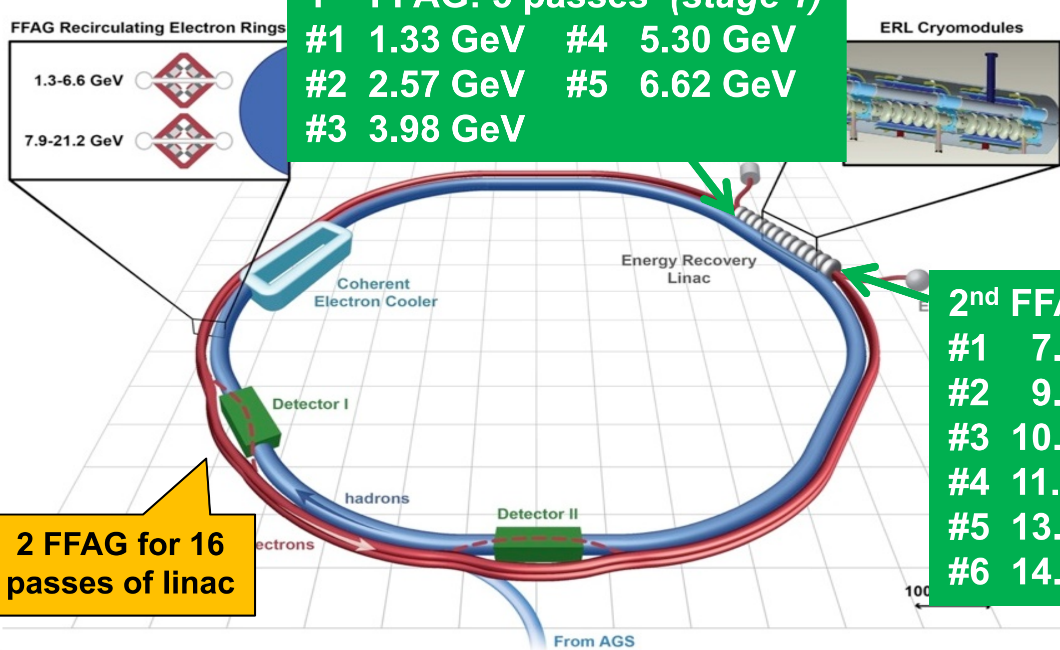


1st FFAG: 5 passes (*stage 1*)

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

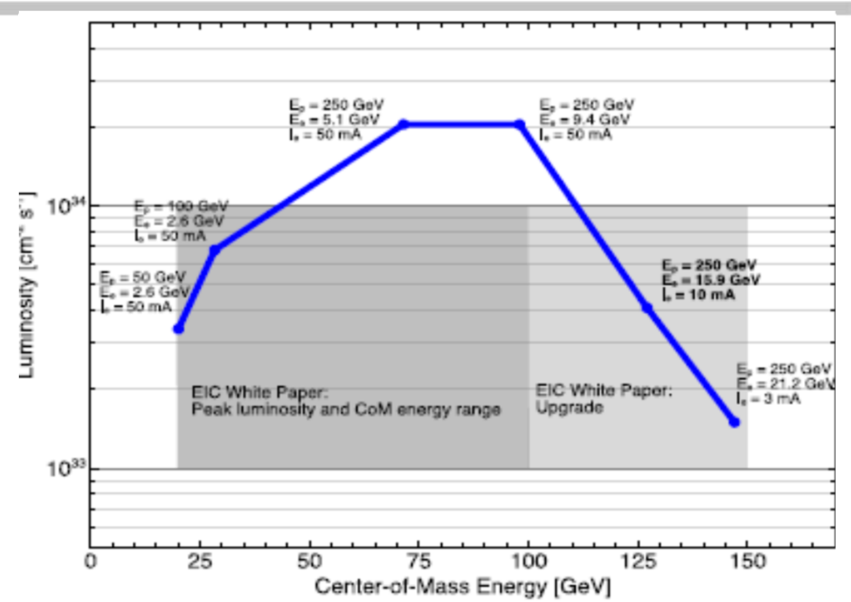
2nd FFAG: 11 passes (*stage 2*)

#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		

2 FFAG for 16 passes of linac

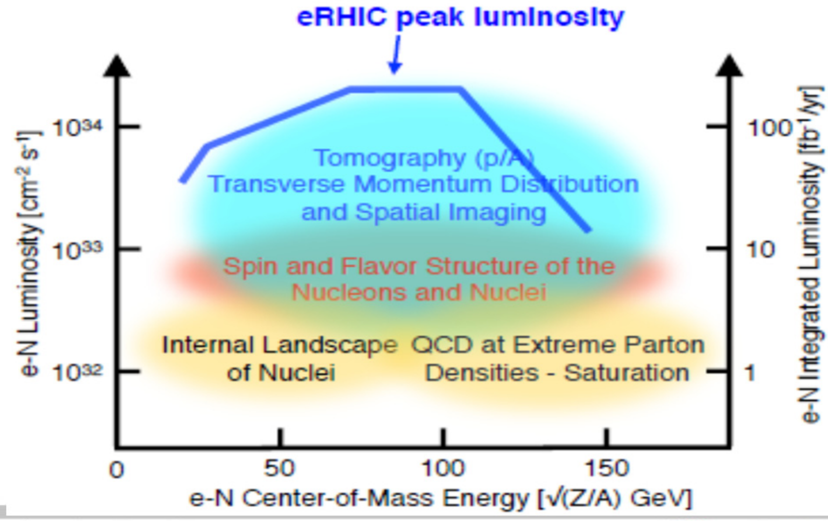
eRHIC Linac(ERL)-Ring Design

	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[um]	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 [um]	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} $cm^{-2}s^{-1}$]	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*
- *β*=5 cm*
- *HOM damped SRF cavities*



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beta*, h/v [cm]	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [um]	15.3/15.3		8.4/8.4	
IP rms ang. .sprea				
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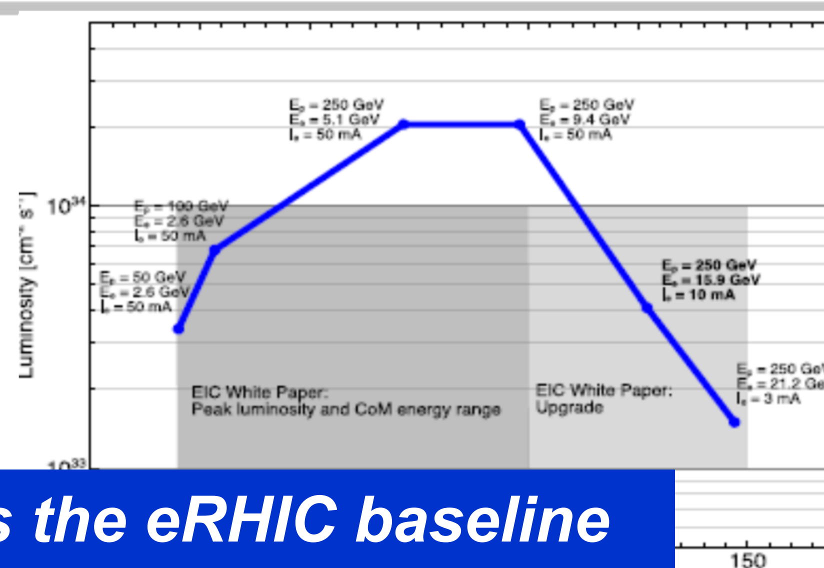

This design approach was the eRHIC baseline until very recent, replaced by a ring-ring design

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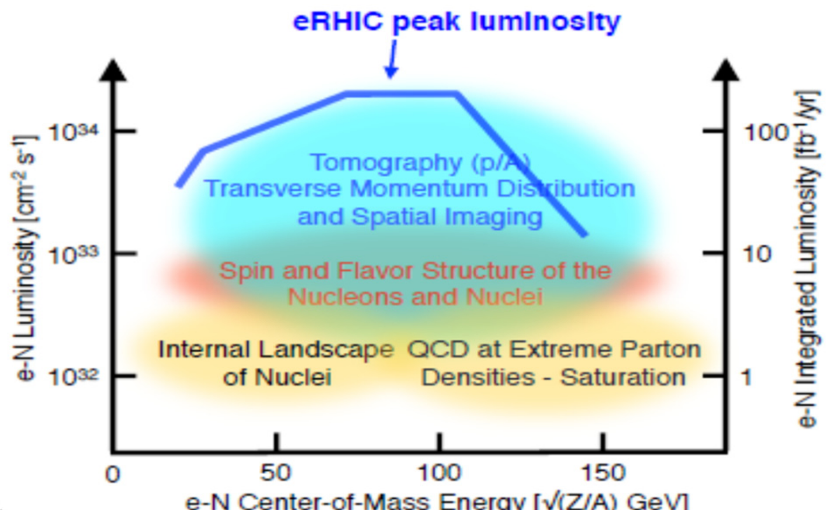
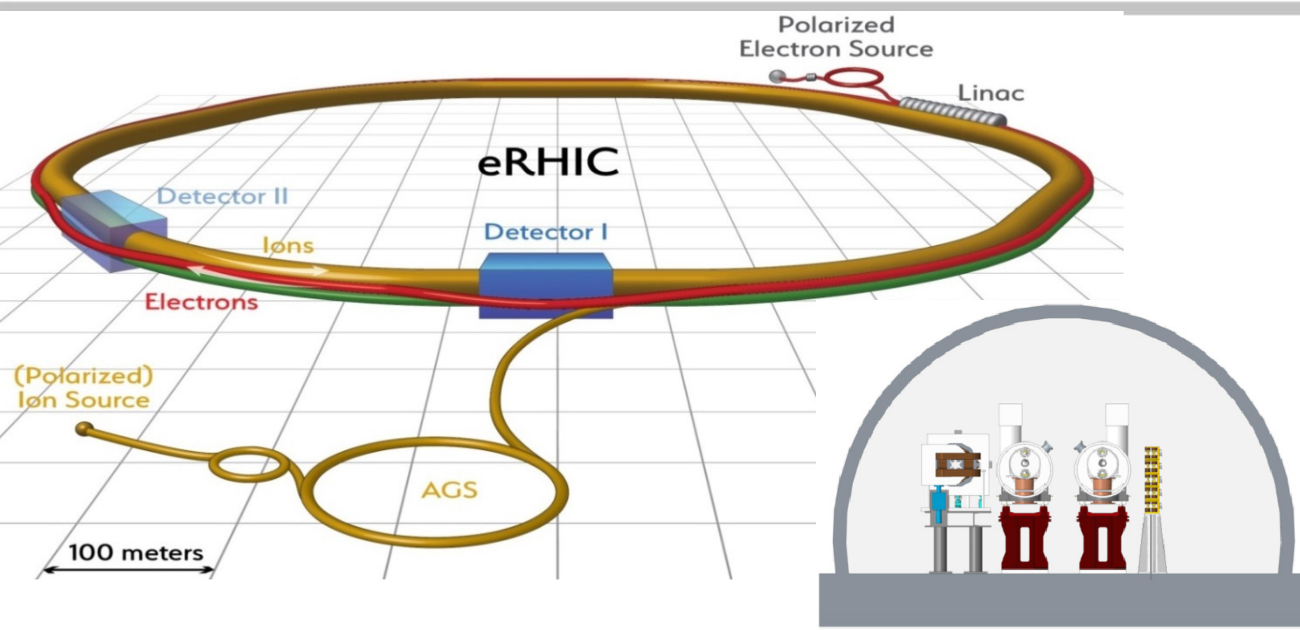


eRHIC Present Baseline: Ring-Ring



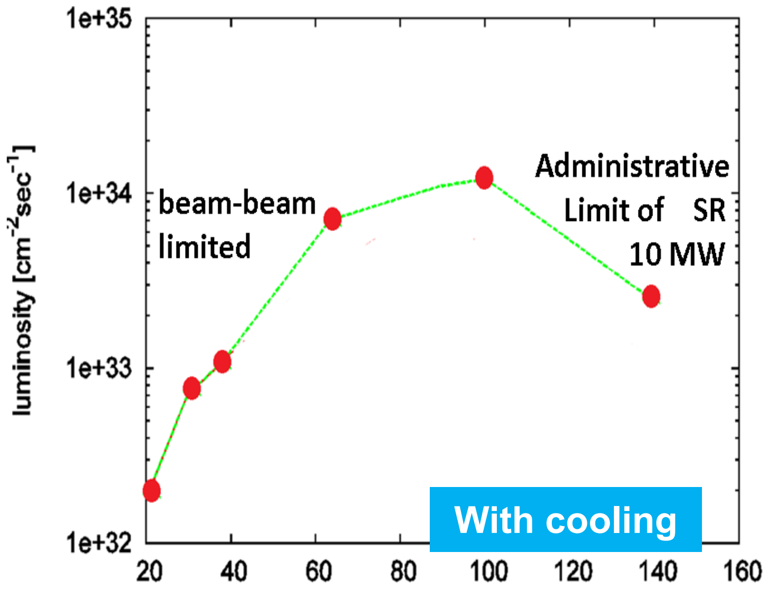
		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

- 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 1.1×10^{34} /cm^2/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
$\sigma_x'^*$	mrad	0.137	0.2	0.13	0.39
$\sigma_y'^*$	mrad	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	$10^{34}cm^{-2}s^{-1}$	0.29		1.21	



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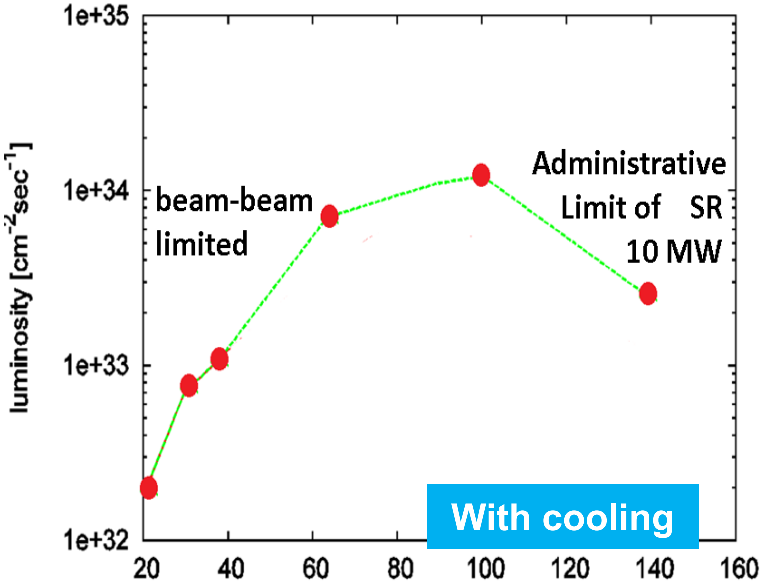

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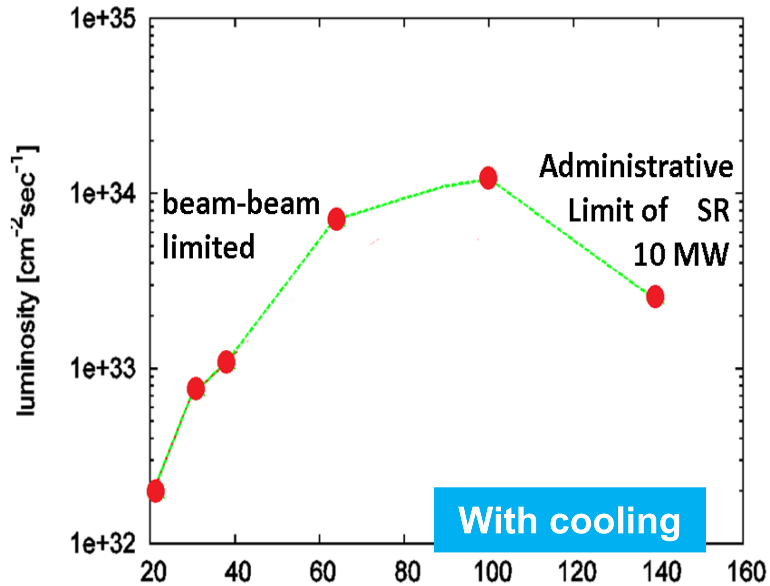

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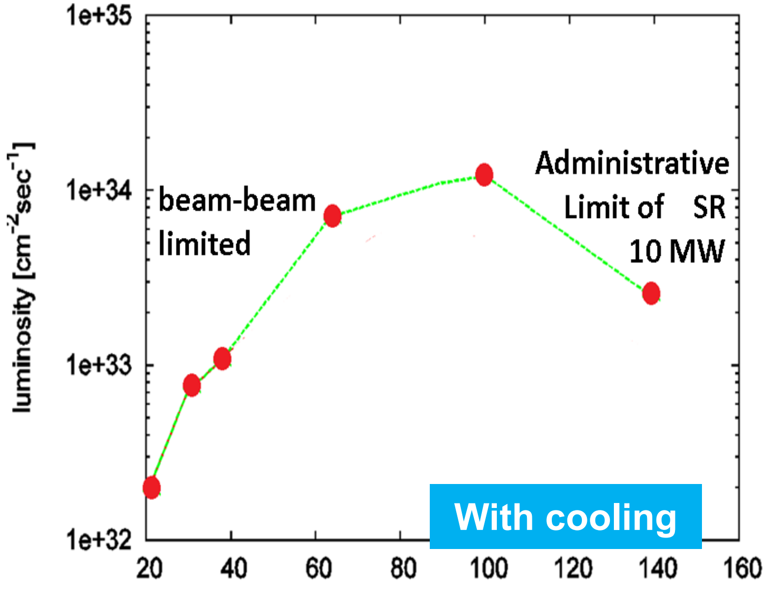

Main Parameters for Maximum Luminosity

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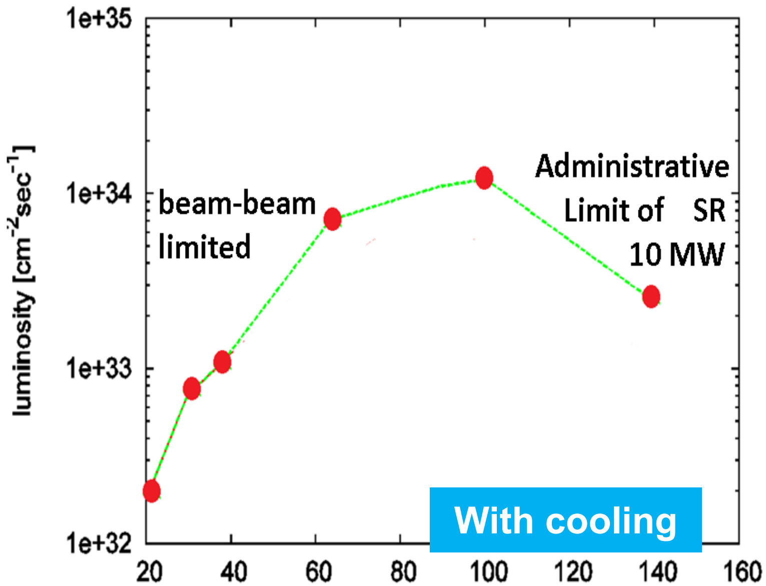
Parameter	**Units**	**Protons**	**Electrons**	**Protons**	**Electrons**
Center of Mass Energy	GeV	100		100	
Beam Energy	GeV	275	10	275	10
Particles/bunch	10^{10}	11.6	31	5.6	15.1
Beam Current	mA	456	1253	920	2480
Number of Bunches		330		1320	
Hor. Emittance	nm	17.6	24.4	8.3	24.4
Vertical Emittance	nm	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
$\sigma_x'^*$	mrad	0.137	0.2	0.13	0.39
$\sigma_y'^*$	mrad	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	$10^{34}cm^{-2}s^{-1}$	0.29		1.21	

High bunch frequency



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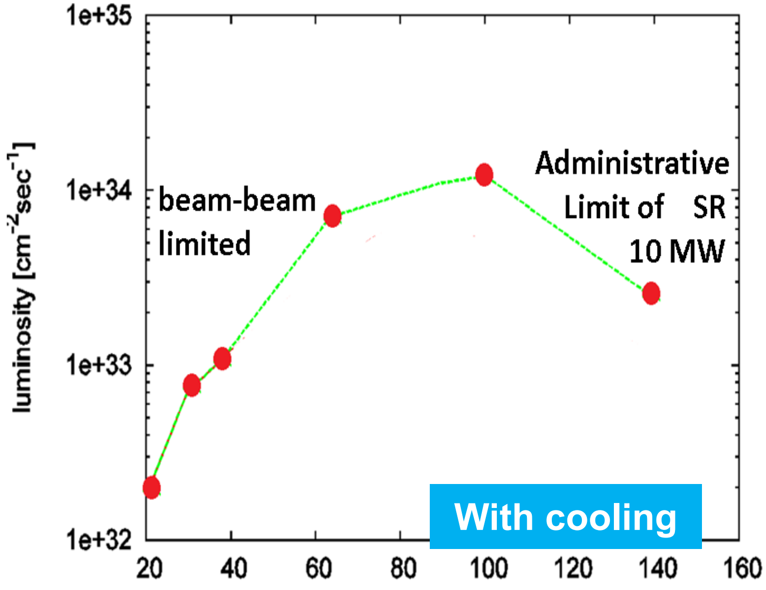


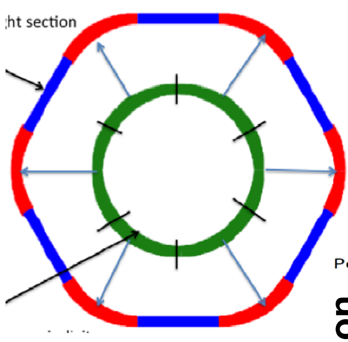
Cooling could boost luminosity by 4 times

eRHIC Full Energy Electron Injector

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

Booster design approach

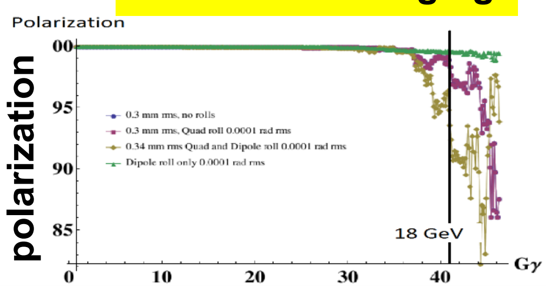
- Under study: rapid cycling synchrotron (RCS) (Cost effective)
- Main challenge: preserving electron polarization during acceleration
- Idea: RCS with highly symmetric arcs connected by lattice with unity transport



Spin Transparent Straight

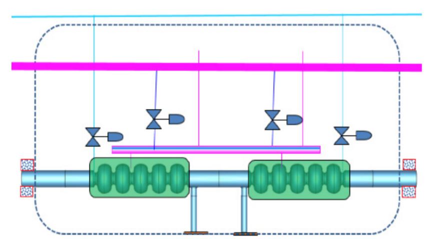
P=48 super-periodicity

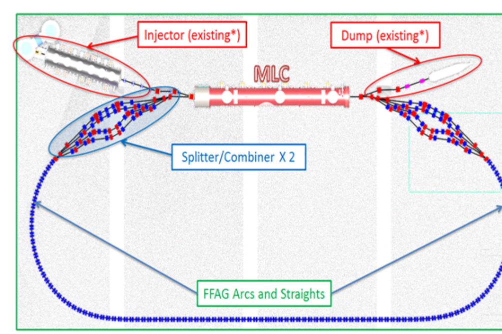
First simulation results encouraging

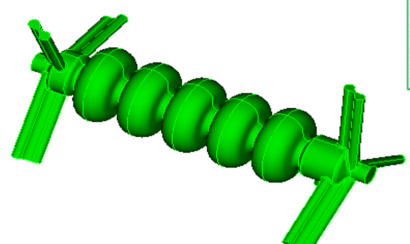


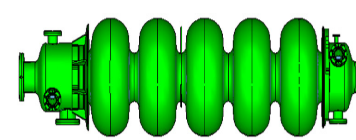
SRF linac design approach (fall back)

- 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)



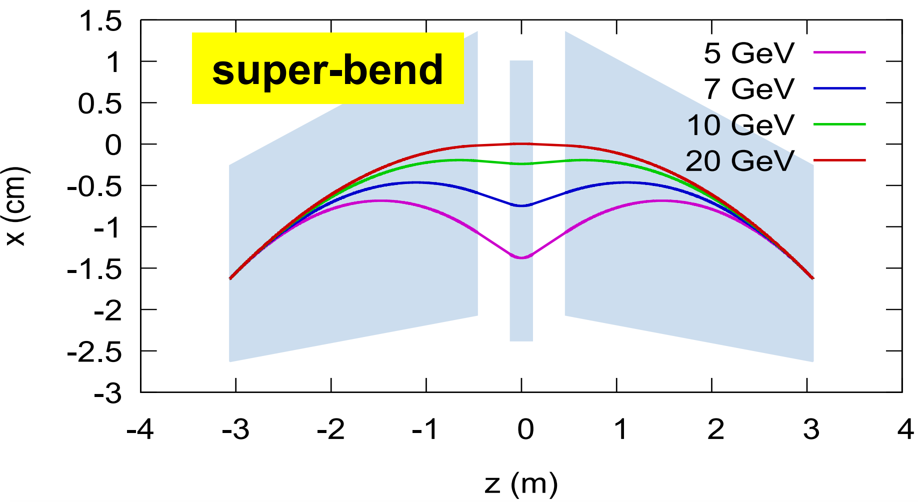


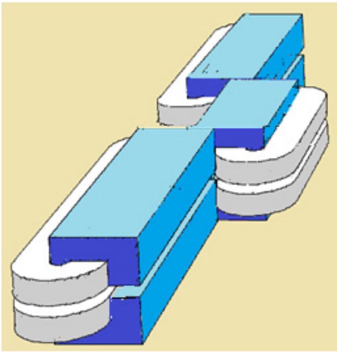




New Electron Storage Ring for eRHIC

- 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} cm^{-2} s^{-1}**)
- Total synchrotron radiation power limited to **10 MW** (30 single cell 560 MHz SC cavities
- Peak radiation linear density < **6 kW/m** ➔ 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**, **^{3}He**, and possibly **Li**
- Un-polarized light to heavy ions up to A above 200 (Au, Pb)

Support 2 detectors

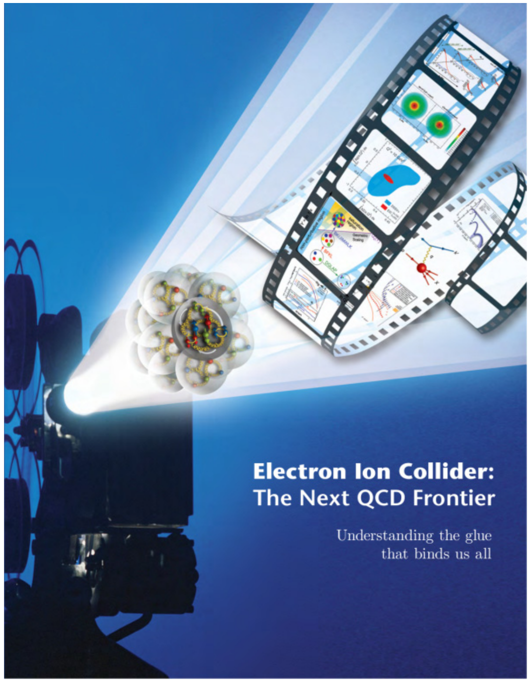
- **Full acceptance** capability is critical for the primary detector

Luminosity

- **10^{33} to 10^{34}** /cm^{2}s 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

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- Electrons **3-10** GeV, protons up to **100** GeV, ions up to **40** GeV/u

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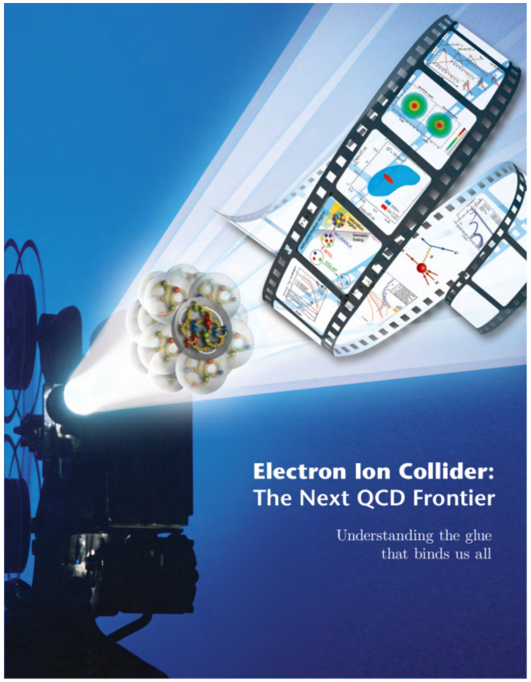

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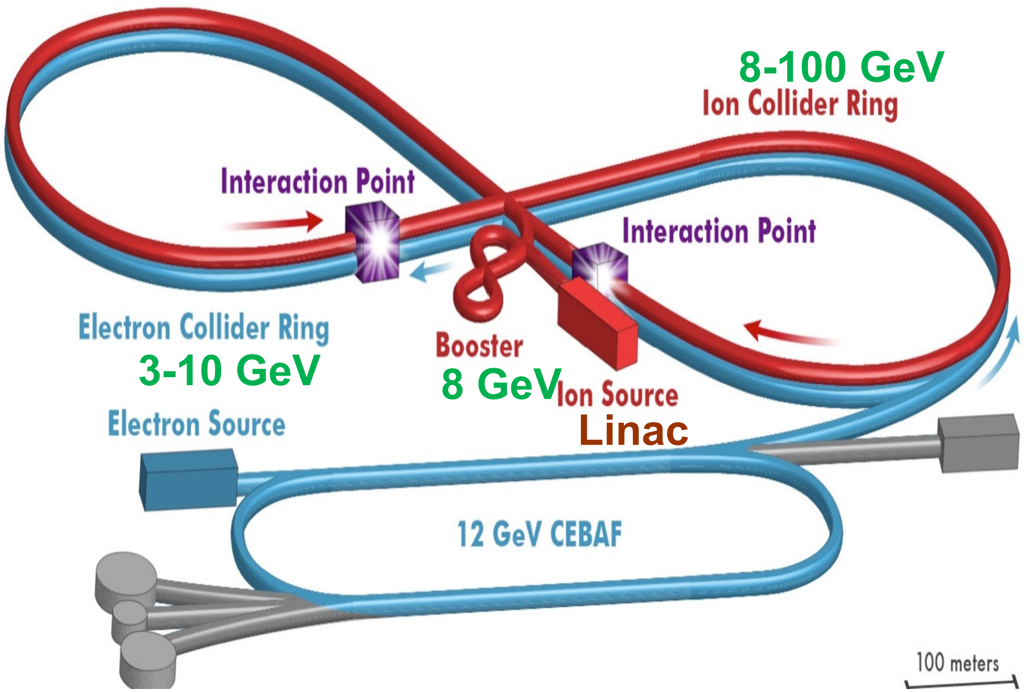
JLEIC Layout and On JLab Site Map



- **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

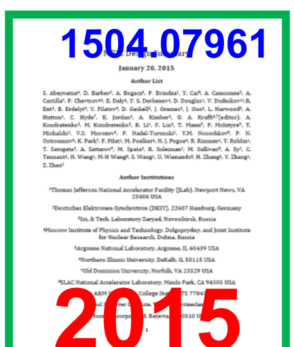
Design Report

1209.0757

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

2012

1504.07961



January 20, 2015

Author List

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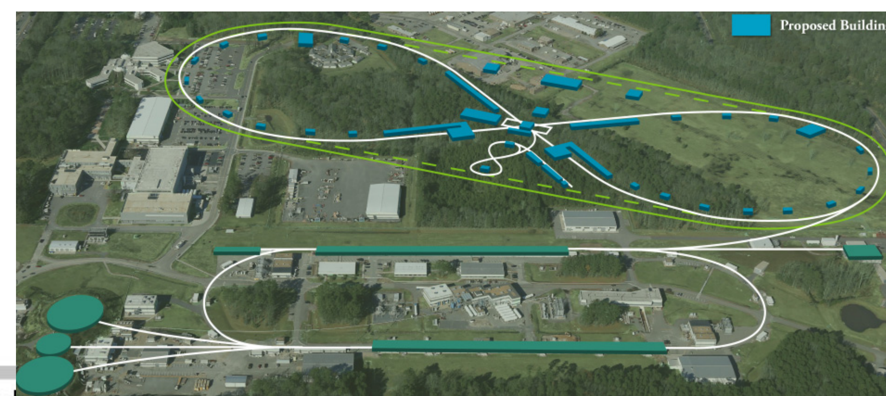
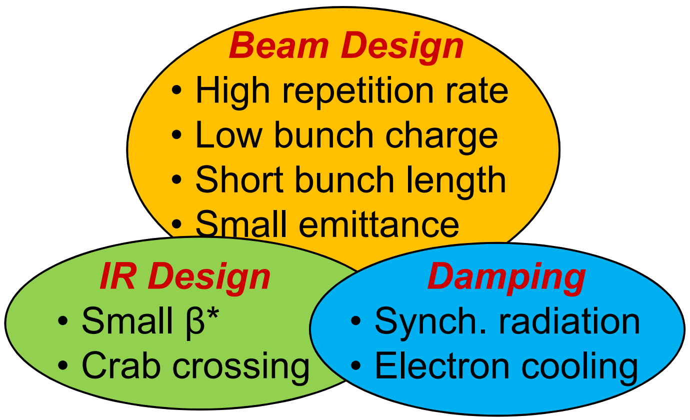


Strategy for Achieving High Performance

High Luminosity

- Based on ***high bunch repetition rate CW colliding beams***

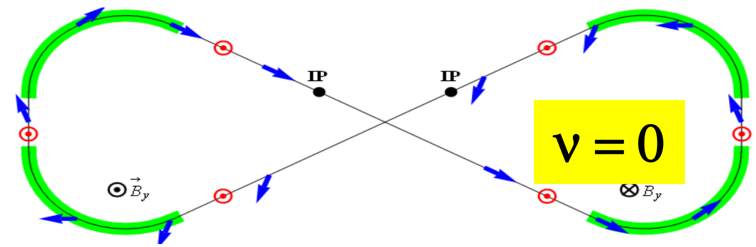
$$L = f\frac{n_1 n_2}{4\pi\sigma^*_x\sigma^*_y} \sim f\frac{n_1 n_2}{\varepsilon\beta^*_y}$$



- A standard approach for lepton colliders (KEK-B reached > **2×10^{34}** /cm²/s)
- JLEIC based on CEBAF, its beam has a bunch rep-rape ***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

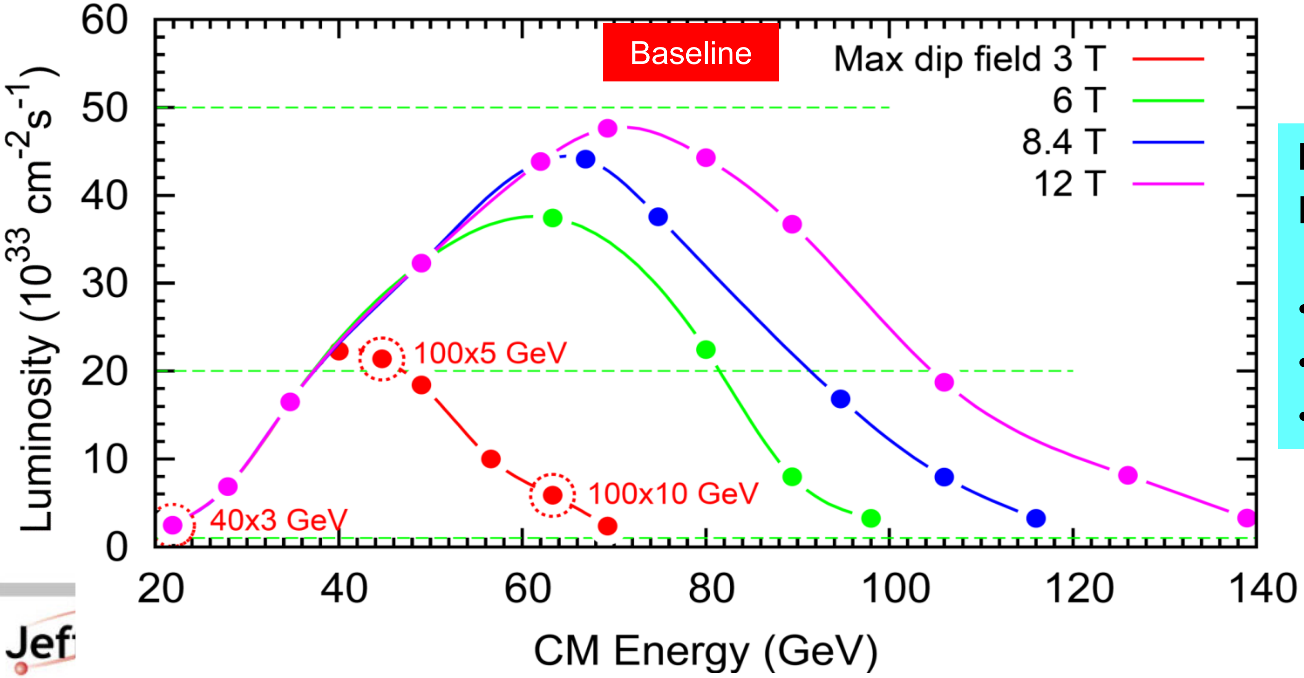
All rings are in a figure-8 shape
➔ critical advantages for both beams



- 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)	
		p	*e*	*p*	*e*	*p*	*e*
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}	$cm^{-2}s^{-1}$	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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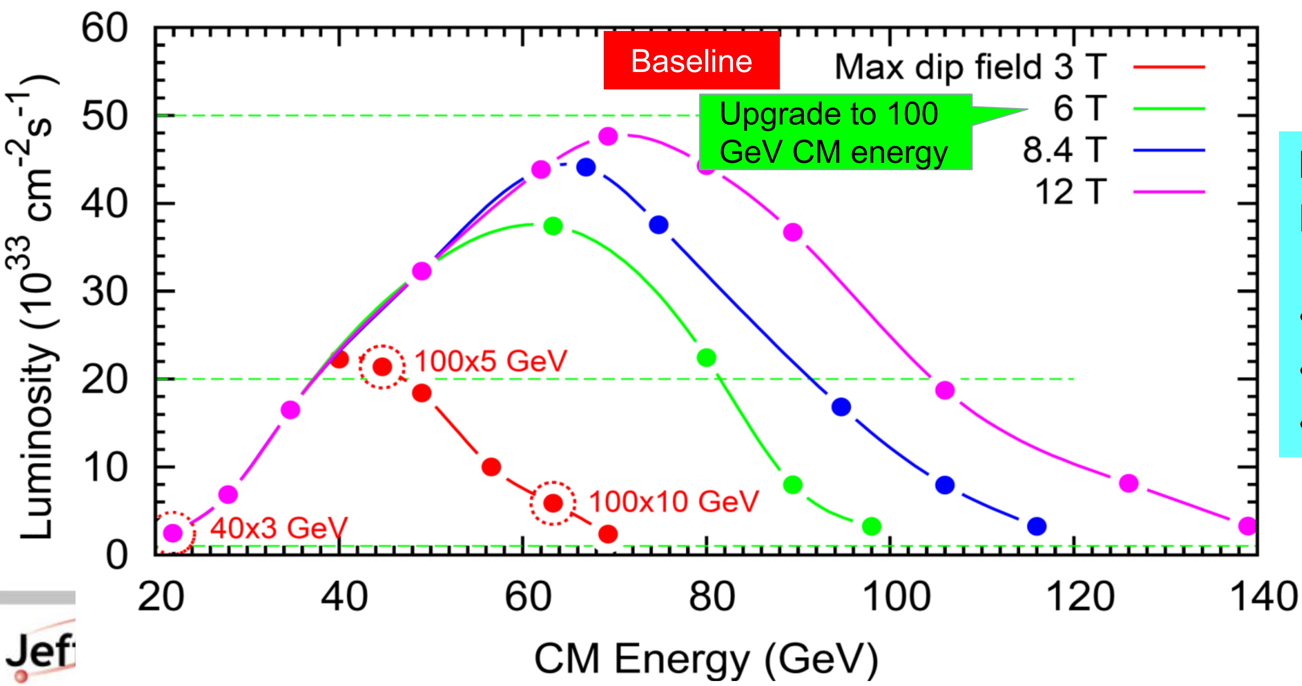

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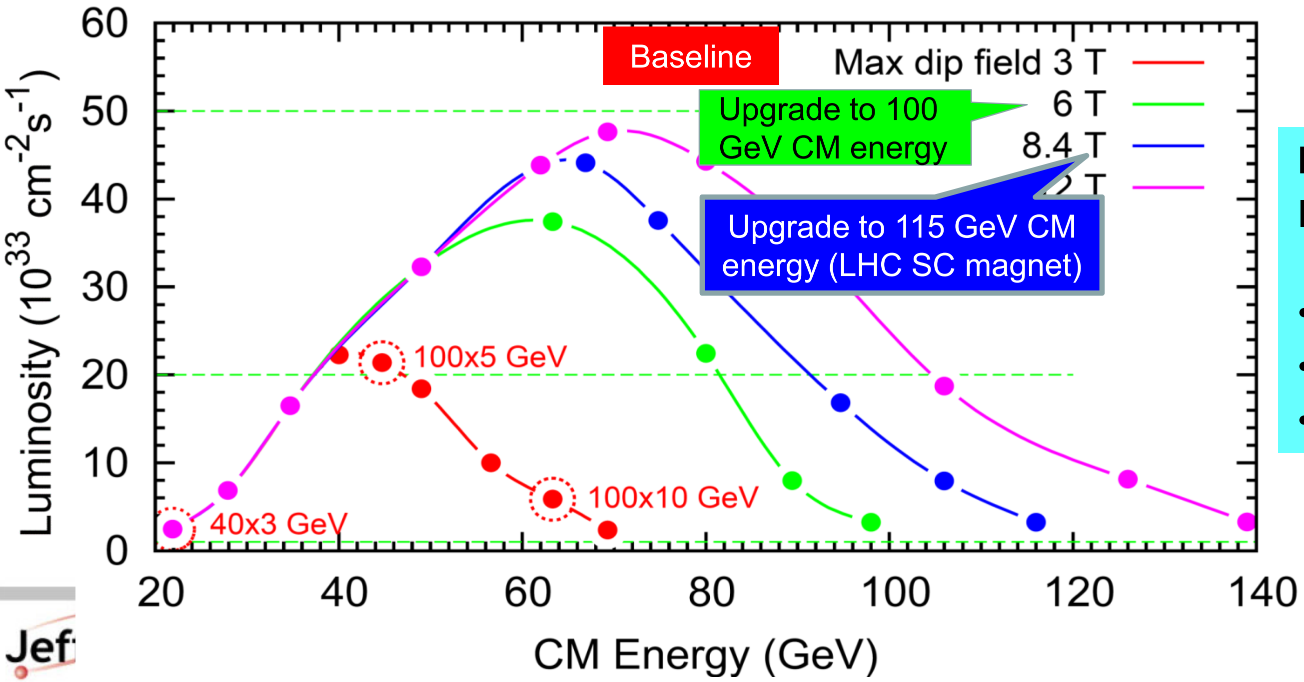

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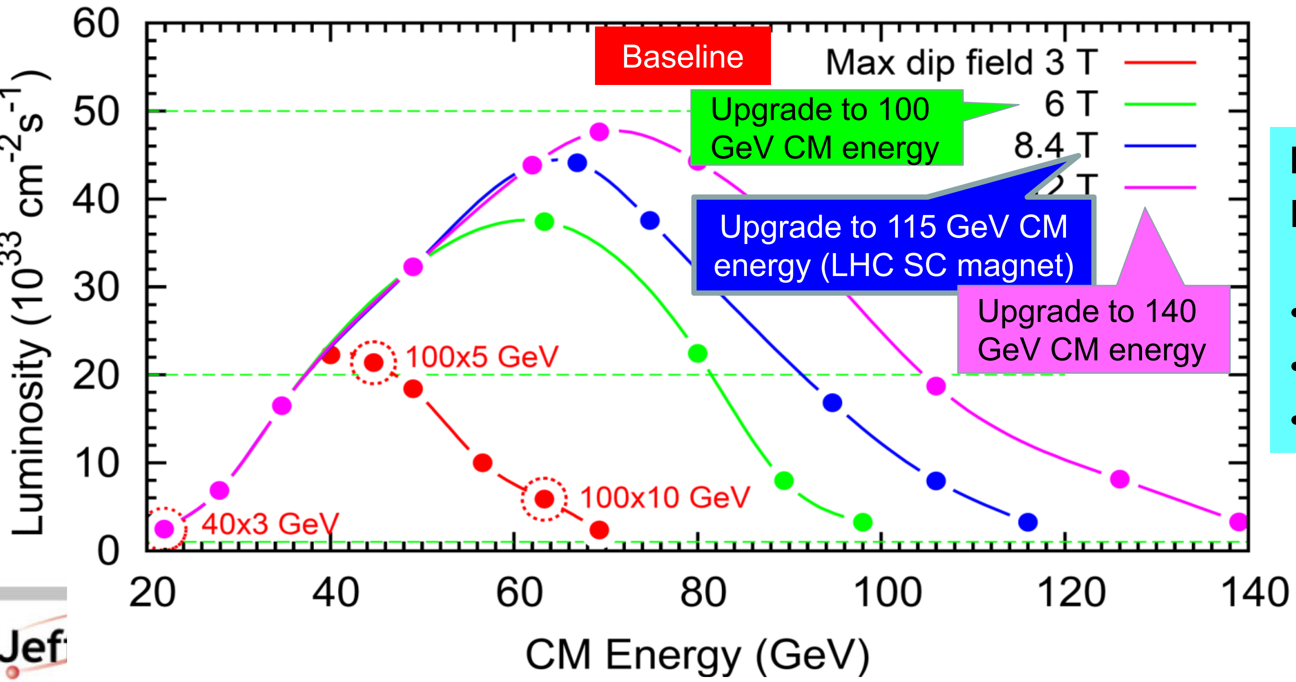

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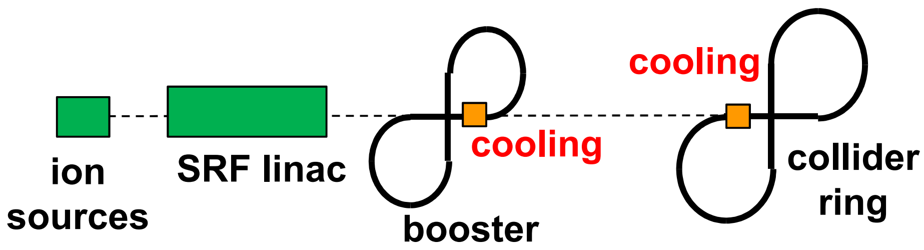
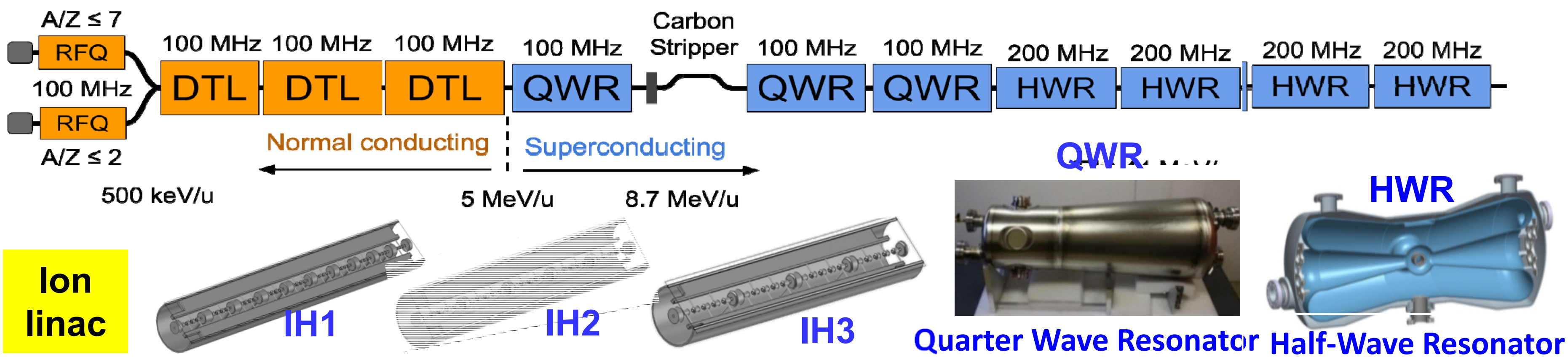
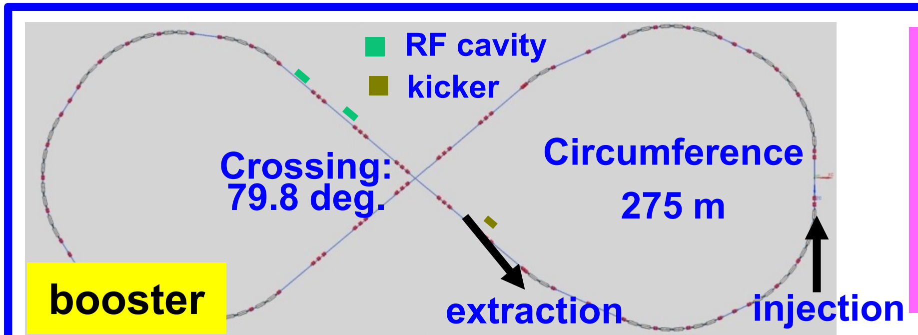
A New Ion Complex for JLEIC



- 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



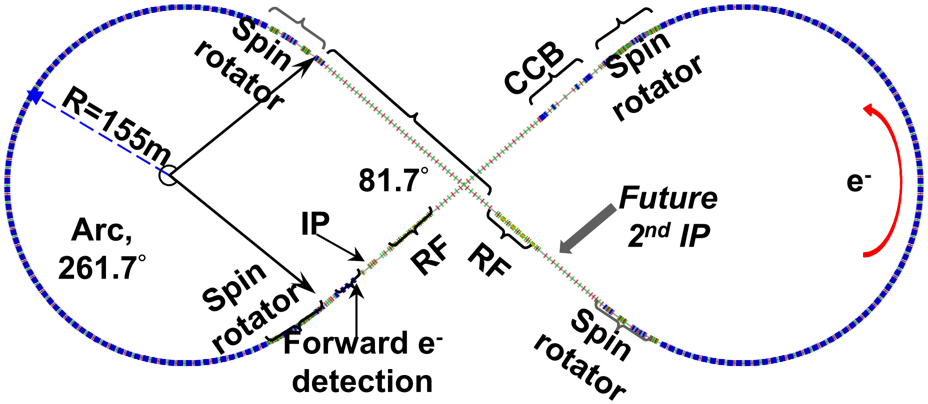
	Length (m)	Max. energy (GeV)
SRF linac		0.2
booster	~275	8
collider ring	~2250	100



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

JLEIC Collider Rings

Electron ring w/ major machine components

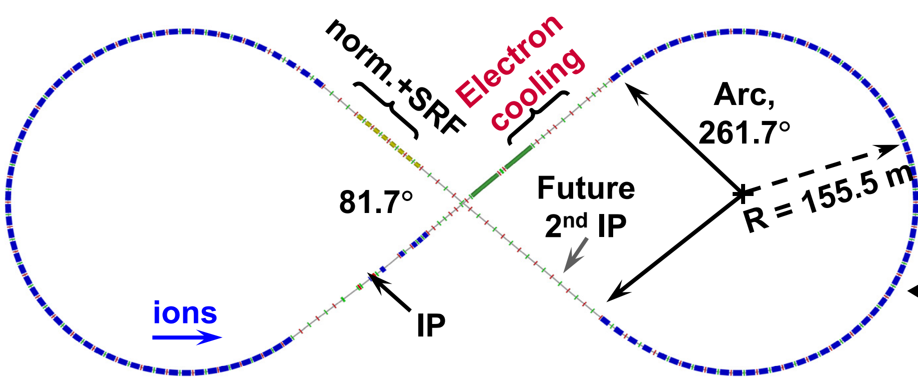


- Two rings w/ same footprint, ***stack vertically***
- Having a ***horizontal crab crossing*** at IPs
- Supports two IPs and fit to the JLab site
- Beamline/optics design completed (including low-β insertion, chromatic compensation, etc.)
- ***Ion magnet field*** determines CM energy range

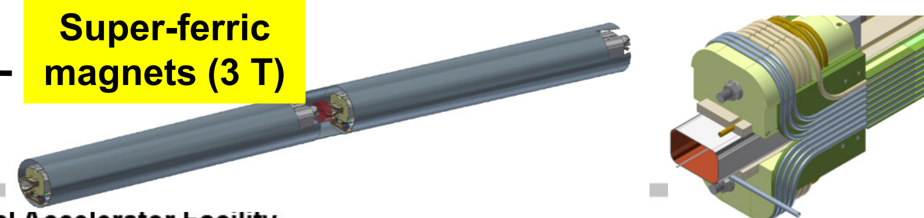
		p	e
Circumference	m	2154	
Crossing angle	deg	81.7	
Lattice		FODO	FODO
Dipole & quad	m	8 & 0.8	5.4 & 0.45
Cell length	m	22.8	15.2
Max. dipole field	T	3	~1.5
SR power density	kW/m		10
Transition γ_{tr}		12.5	21.6

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

Ion ring w/ major machine components



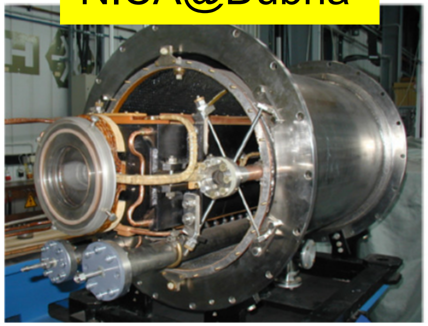
Super-ferric magnets (3 T)



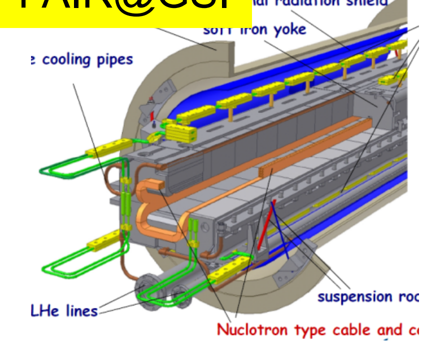
Super-Ferric Magnets for Ion Rings

- 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

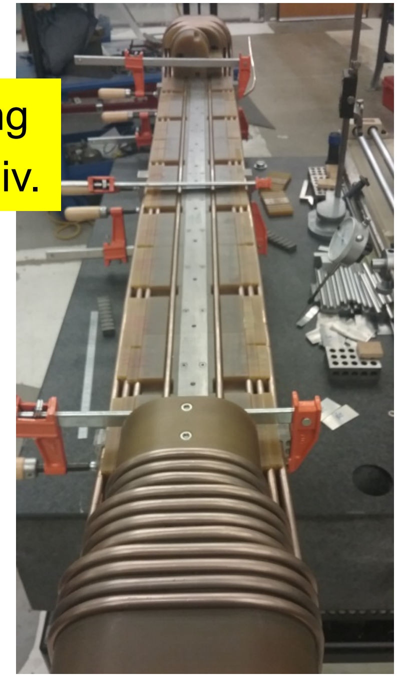
NICA@Dubna

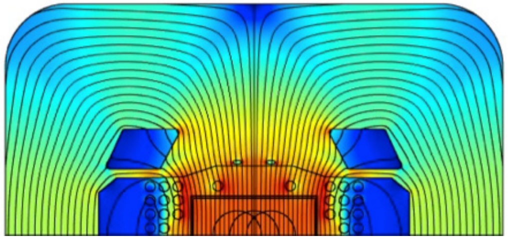


FAIR@GSI

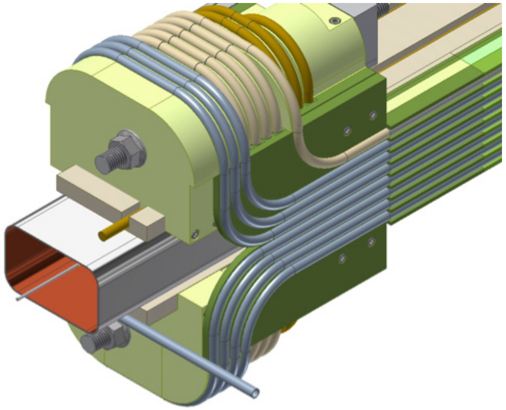


Prototype winding @Texas A&M Univ.





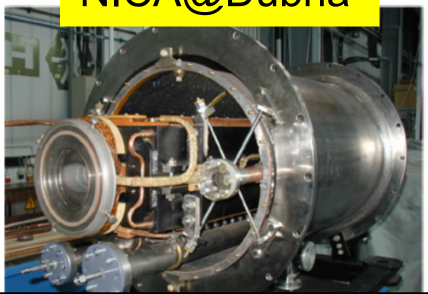
Cable-in-conduit



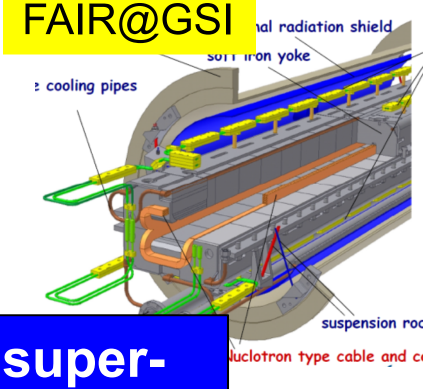
Super-Ferric Magnets for Ion Rings

- 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/c
  - Up to 3 T
  - Fast ramp (1 T/s) for booster ring magnets
  - Cable-in-conduit conductor

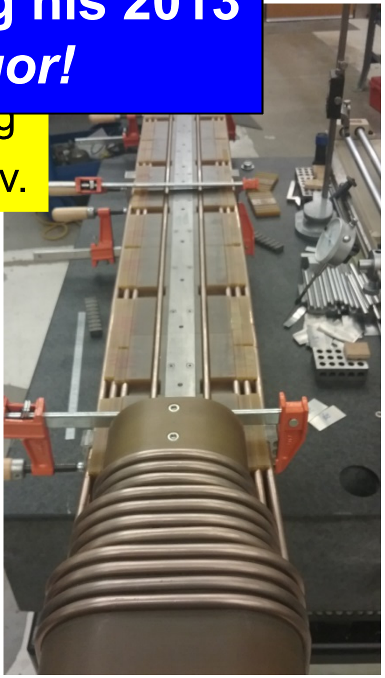
NICA@Dubna



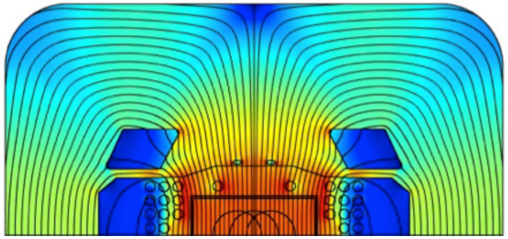
FAIR@GSI



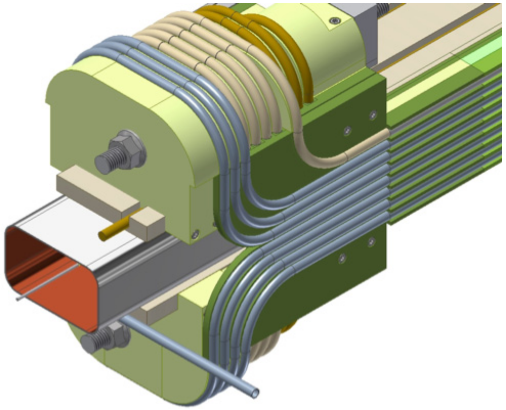
Prof. I. Meshkov first suggested super-ferric magnets for JLEIC during his 2013 visit to JLab. ***Thank you, Igor!***



Prototype winding @Texas A&M Univ.



Cable-in-conduit



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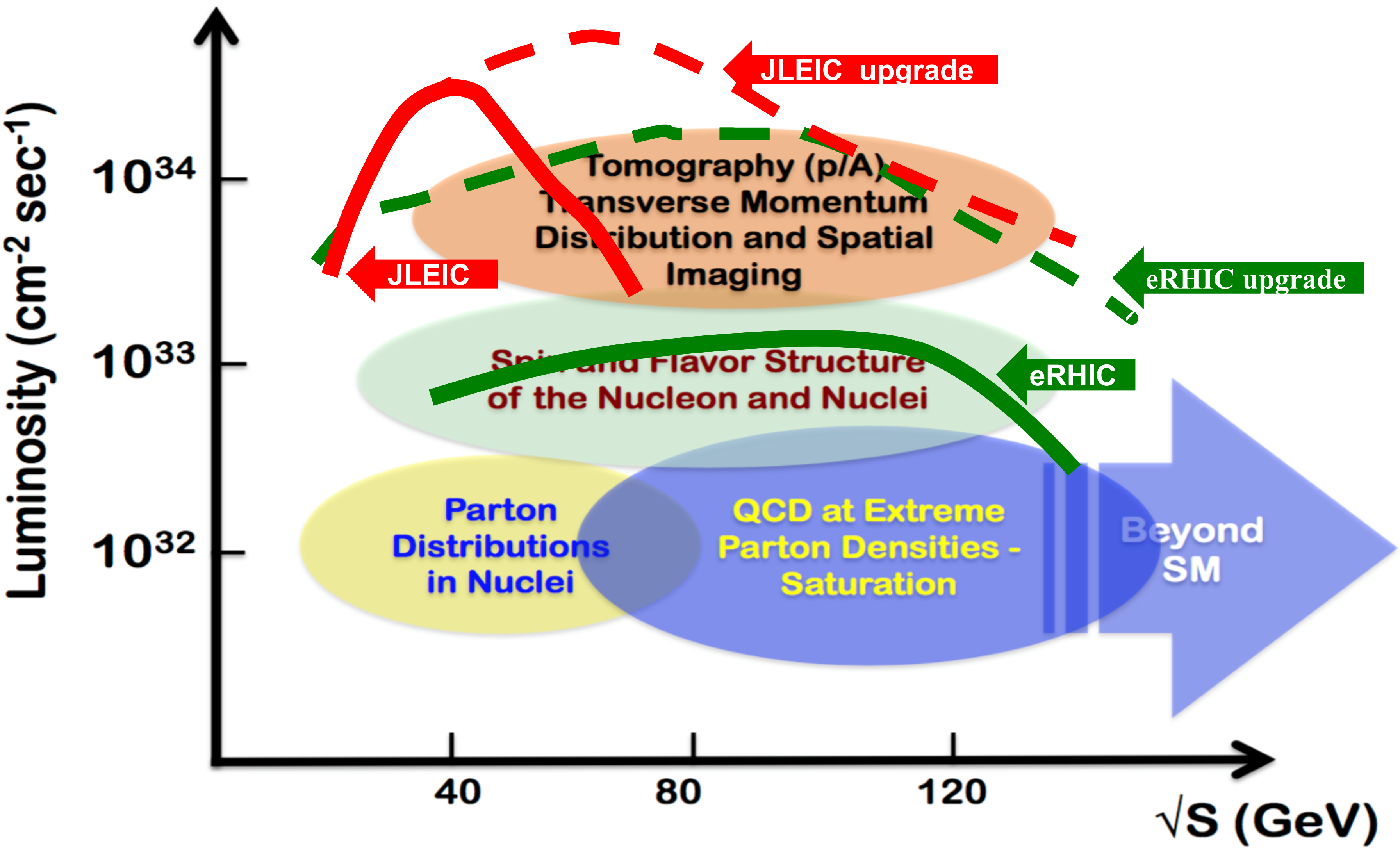
US EIC Luminosity vs. CM Energy



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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Released
Oct. 15, 2015

NSAC LRP 2015

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

vever *Not*
r in US

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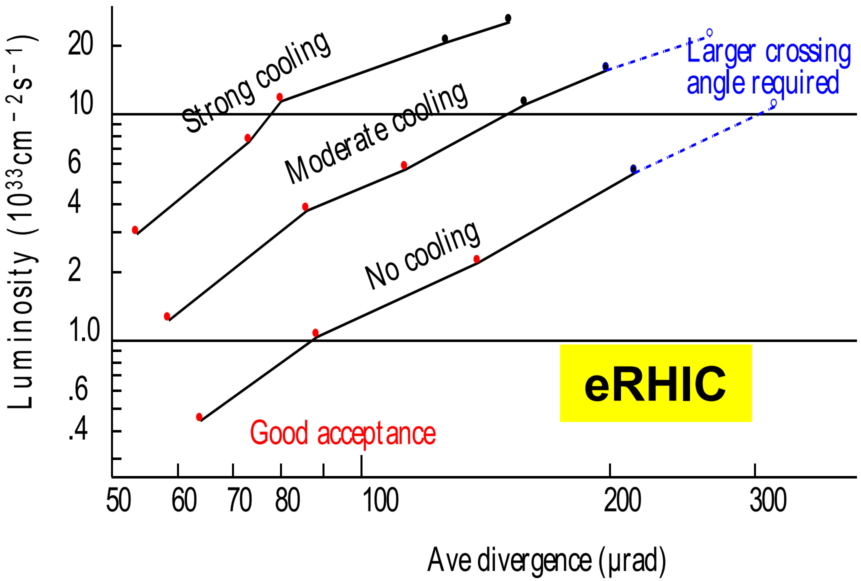
ever *Not*
r in US

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} /cm^2 s (~100x higher than the final HERA luminosity). Some EIC measurements needs even higher luminosities, at or above ~10^{34} /cm^{2}s
- To reach >10^{34}/cm^{2}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 ➔ small beam size ➔ high intensity ➔ strong IBS ➔ 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/cm^{2}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)

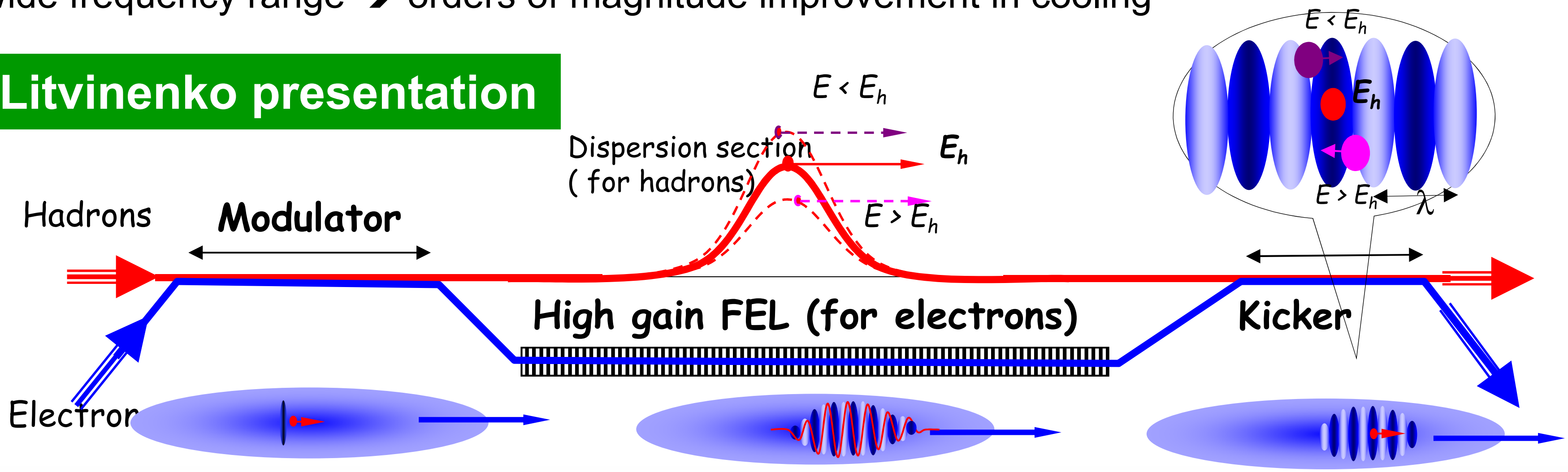
- Demands very small emittance (~0.27 mm mrad at 250 GeV) in both horiz. & vert. dimensions
- Coherent-electron-Cooling was chosen for this task (reducing and maintaining emittance)

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 ➔ much wide frequency range ➔ orders of magnitude improvement in cooling

V. Litvinenko presentation



CeC Proof-of-Principle Experiment

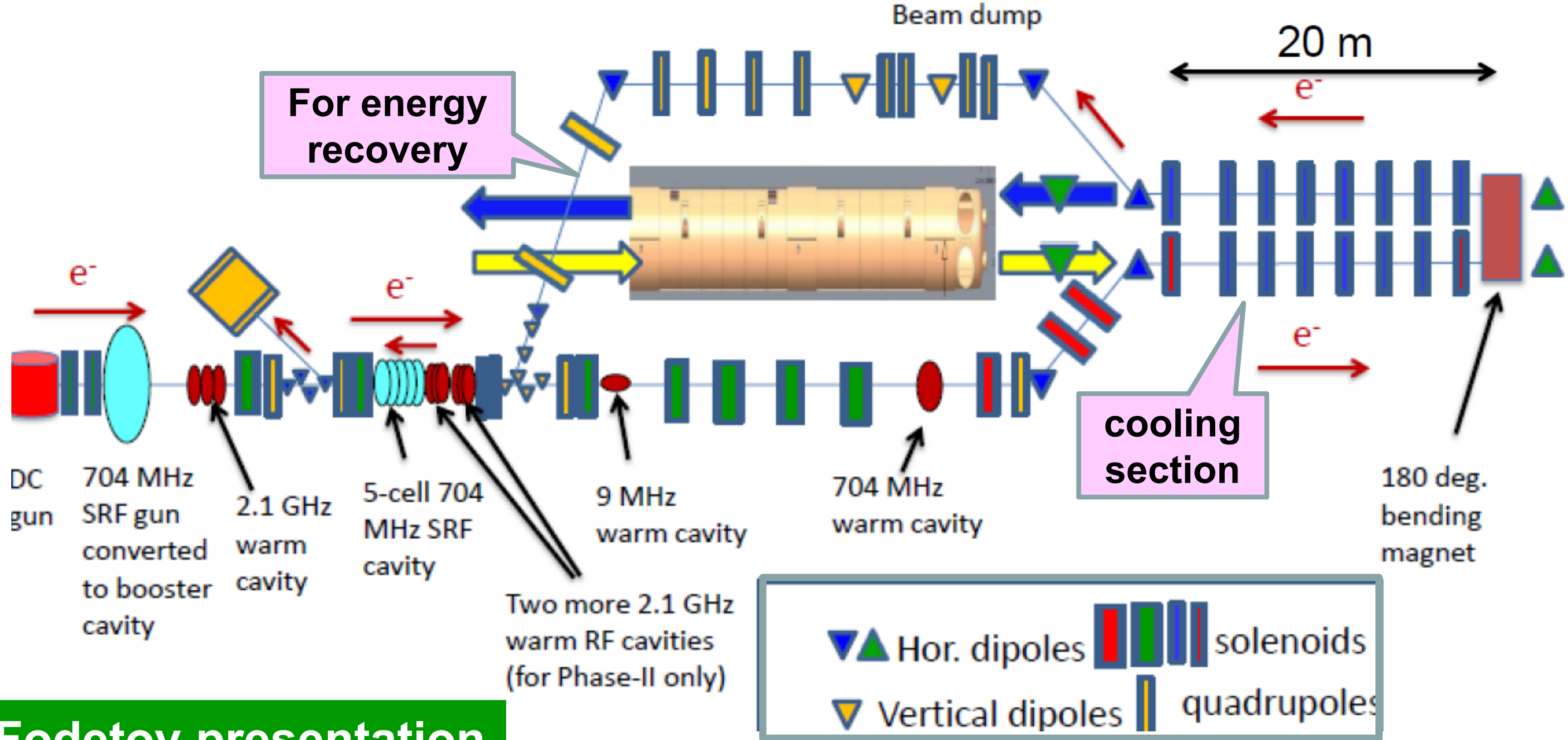
- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- All equipment and infrastructure had been installed into RHIC's IP2, including 20 MeV SRF linac, helical wigglers for FEL amplifier and beam transported to low energy dump
- 1st beam from SRF gun (3 nC/bunch, 1.7 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 μA
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)

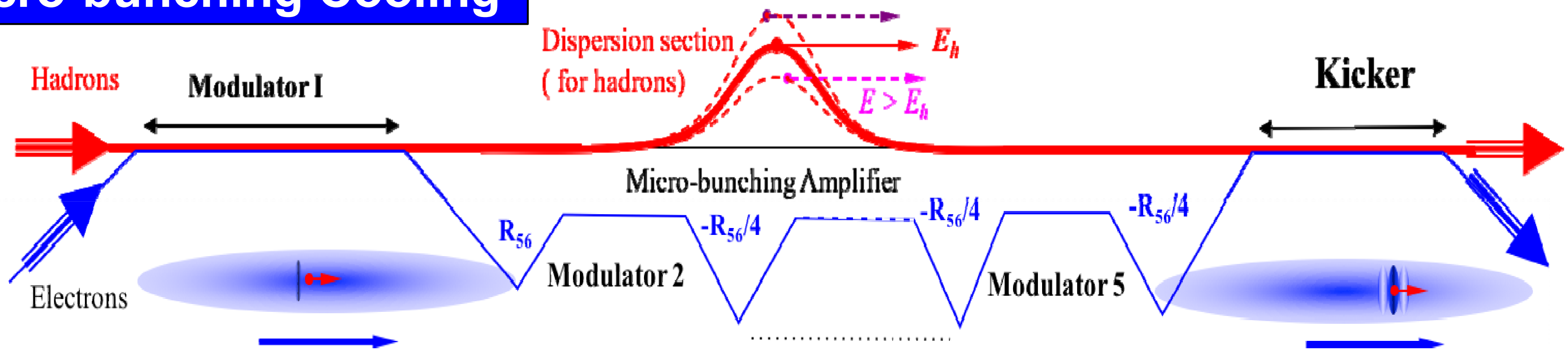


A. Fodetov presentation

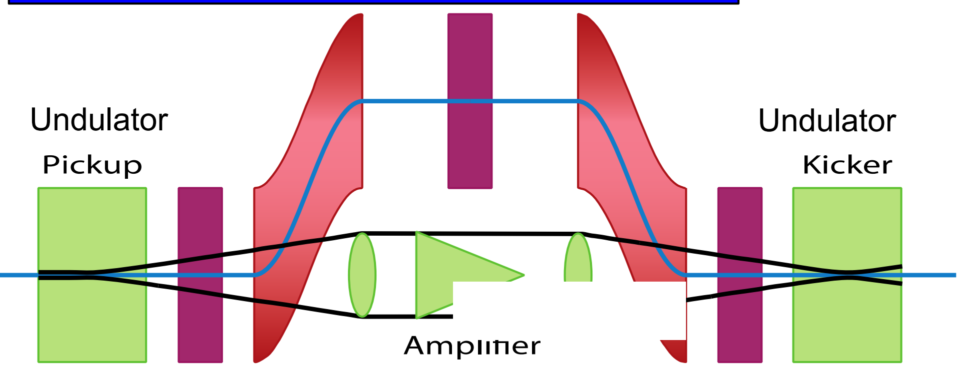
Other Concepts Under Consideration for eRHIC

Micro-bunching Cooling

D. Ratner, PRL, 2013



Optical Stochastic Cooling



Ion radiates light in undulator

The radiation is amplified by optical amplifier (Ti:Sapphire, OPAs, 0.6-18 mm)

Ion interacts with amplified radiation, receiving cooling kick

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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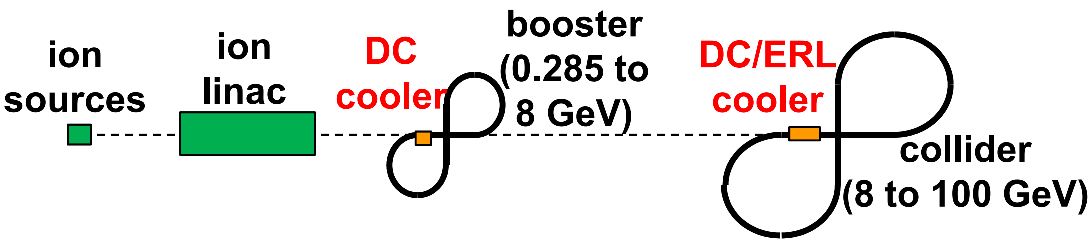
Multi-Step Cooling for JLEIC High Luminosity

- **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)



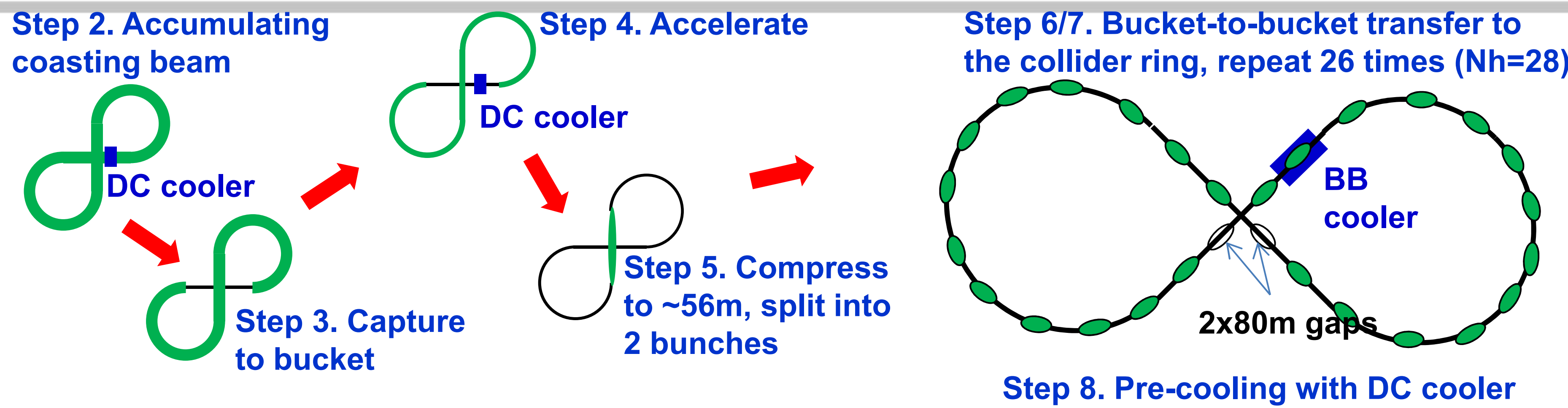
Ring	Functions	Proton kinetic E (GeV)	Lead ion kinetic E (GeV/u)	Electron kinetic E (MeV)	Cooler type
booster ring	Accumulation of positive ions		0.1 (injection)	**0.054**	DC
collider ring	Maintain emitt. during stacking		2 (injection)	**1.1**	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9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

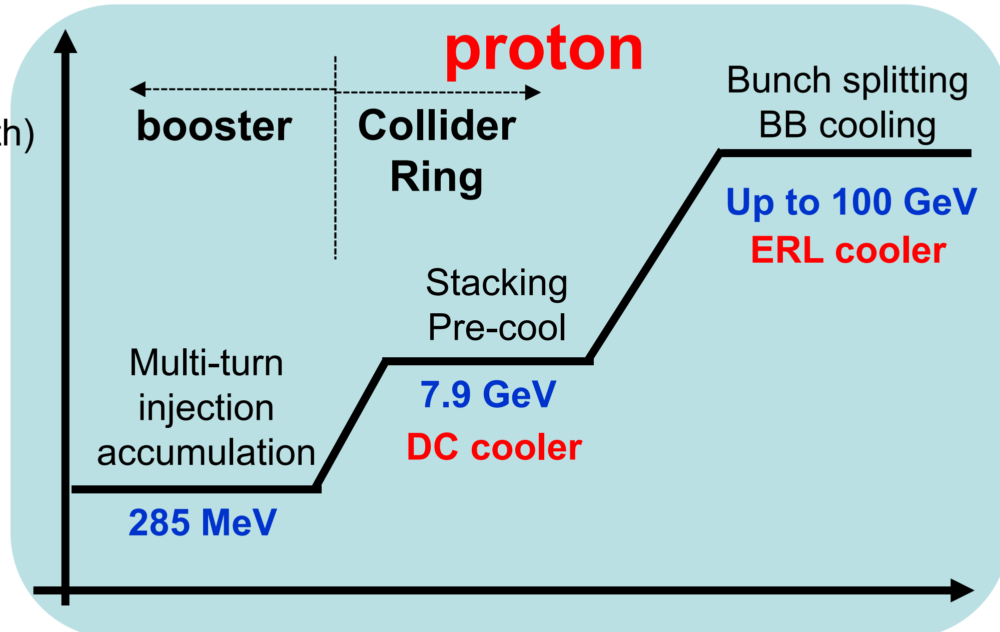
ERL cooler can't reach energy below 20 MeV

Ion Beam Formation Cycles



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 # Nh=3584
10. Start high energy cooling to preserve emittance
11. Start collision program



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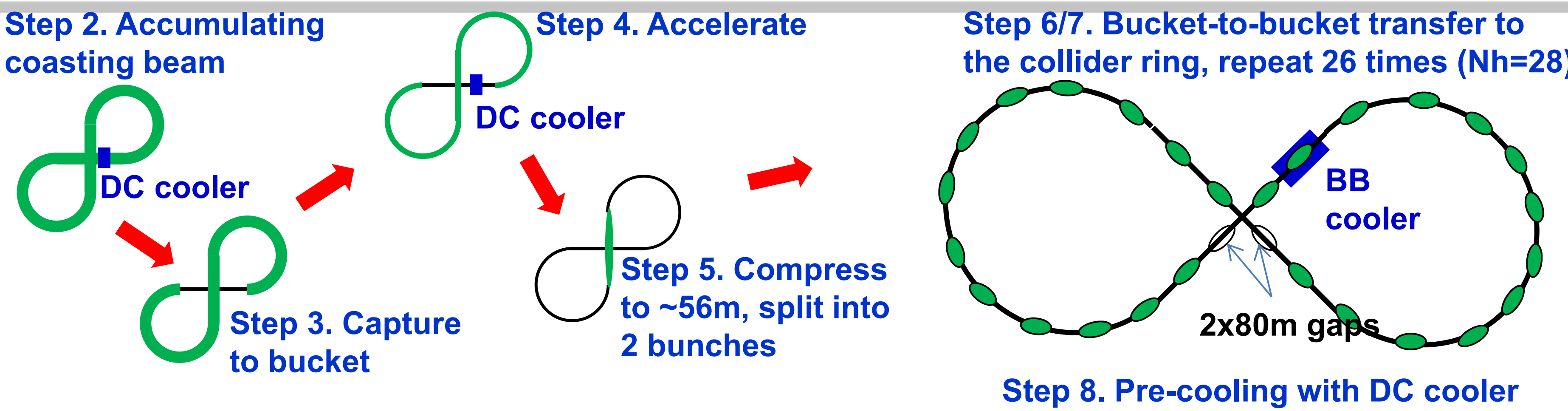

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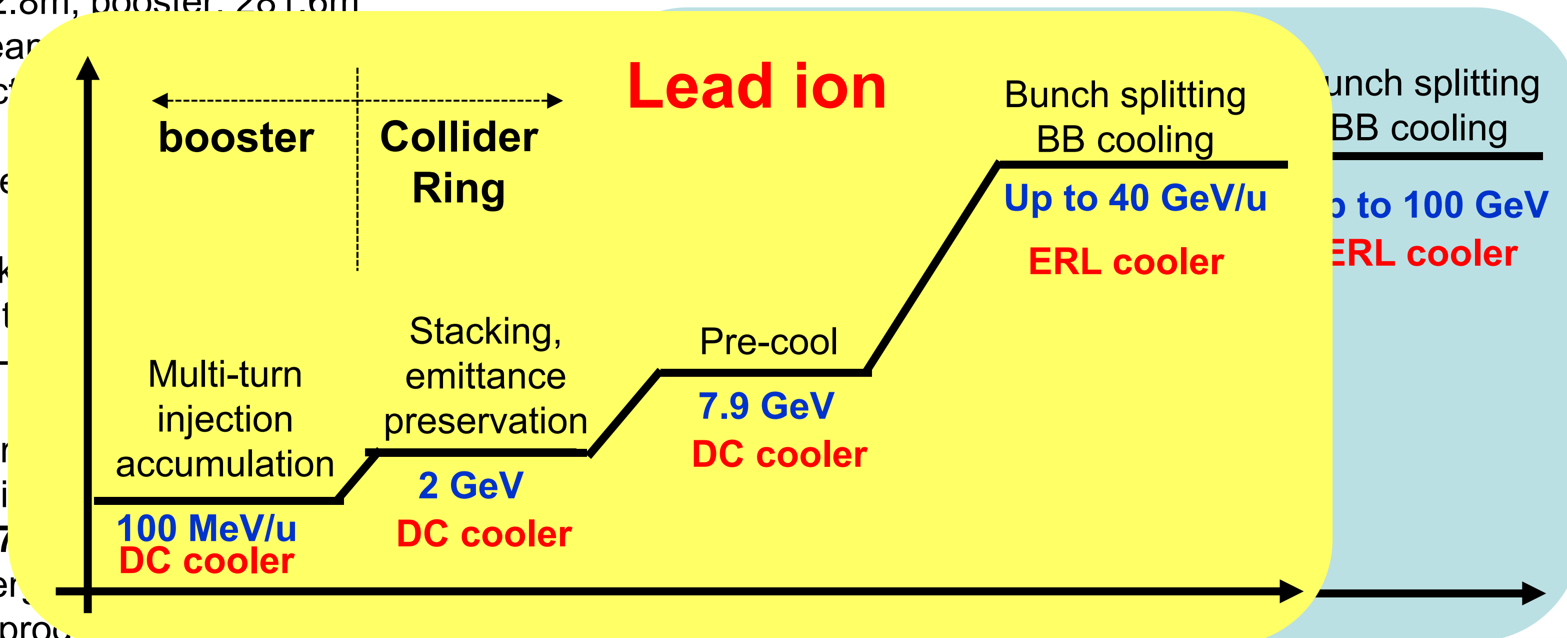
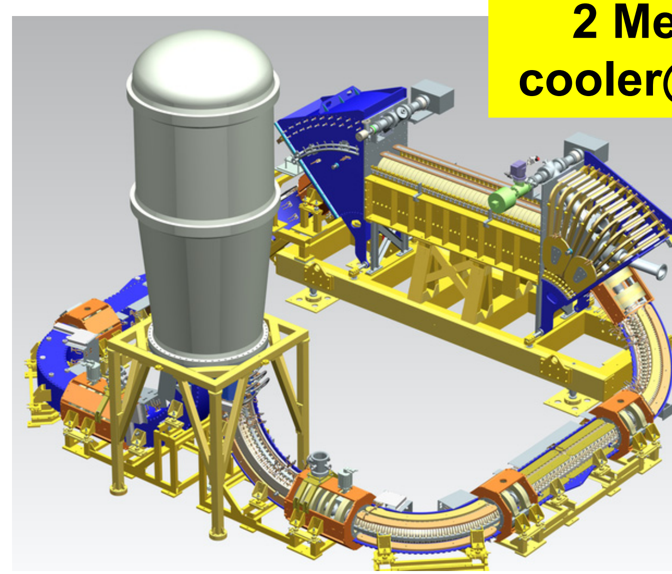
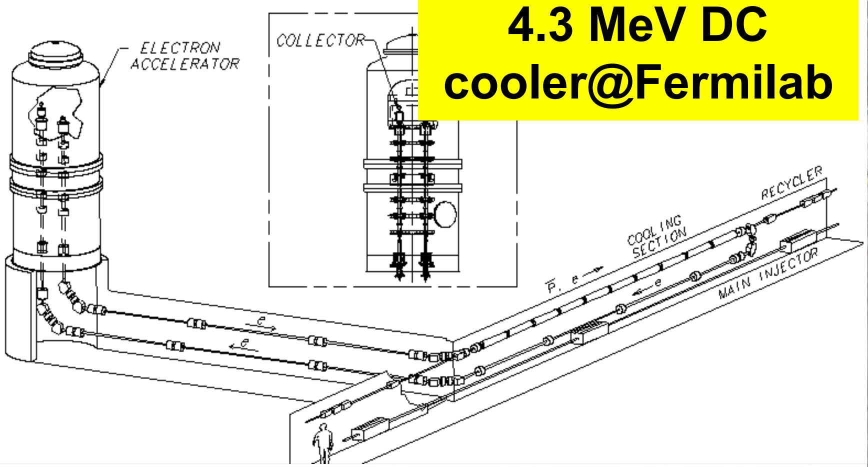


DC Cooler: Within State-of-Art

Low energy DC cooler@IMP, China



2 MeV DC cooler@Jülich



4.3 MeV DC cooler@Fermilab

JLEIC Bunched Beam Electron Cooler

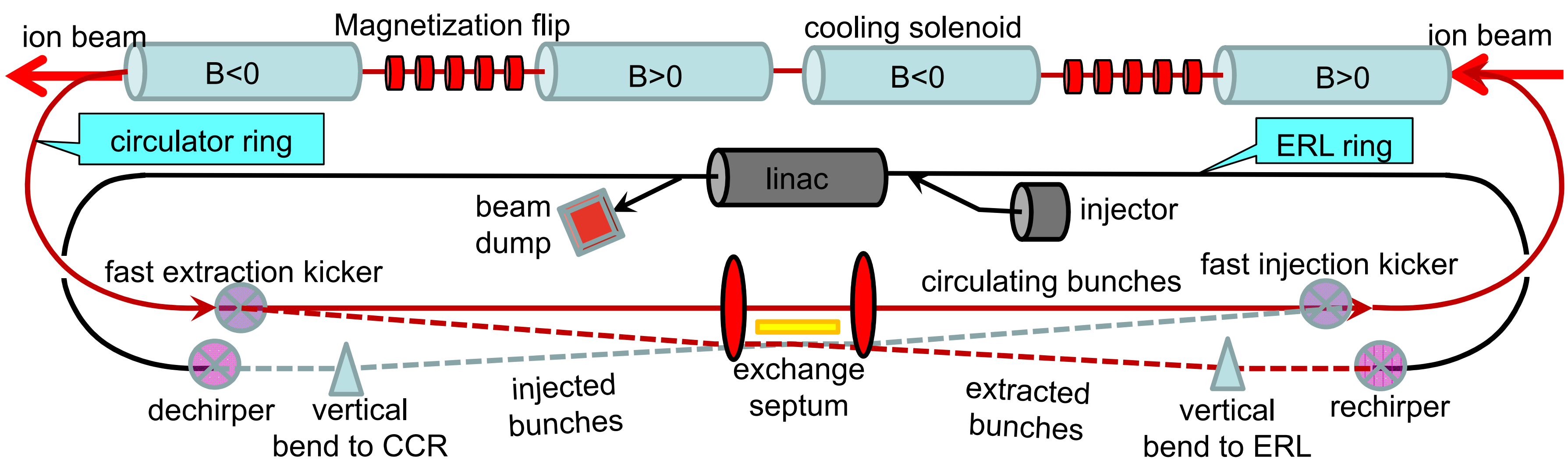
Requirements of cooling beam

- 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



S. Benson presentation

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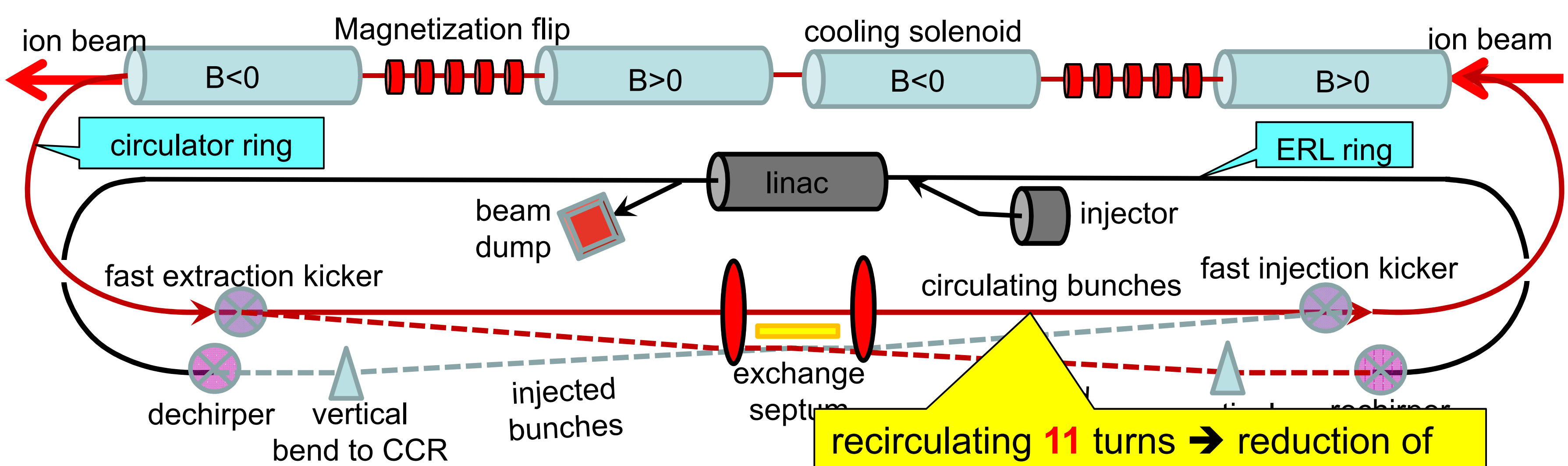
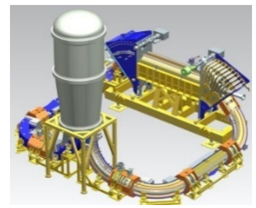


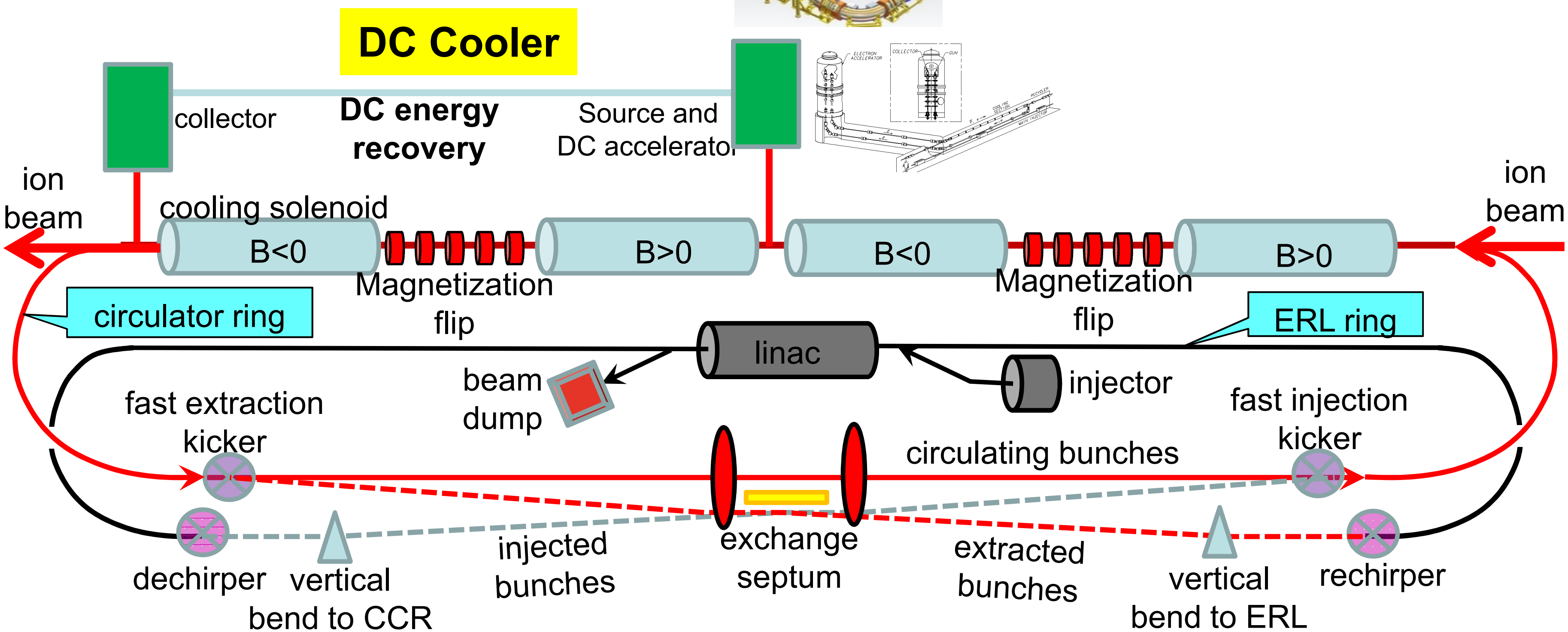
recirculating 11 turns ➔ reduction of current from the ERL by a same factor

S. Benson presentation

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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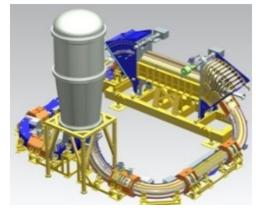

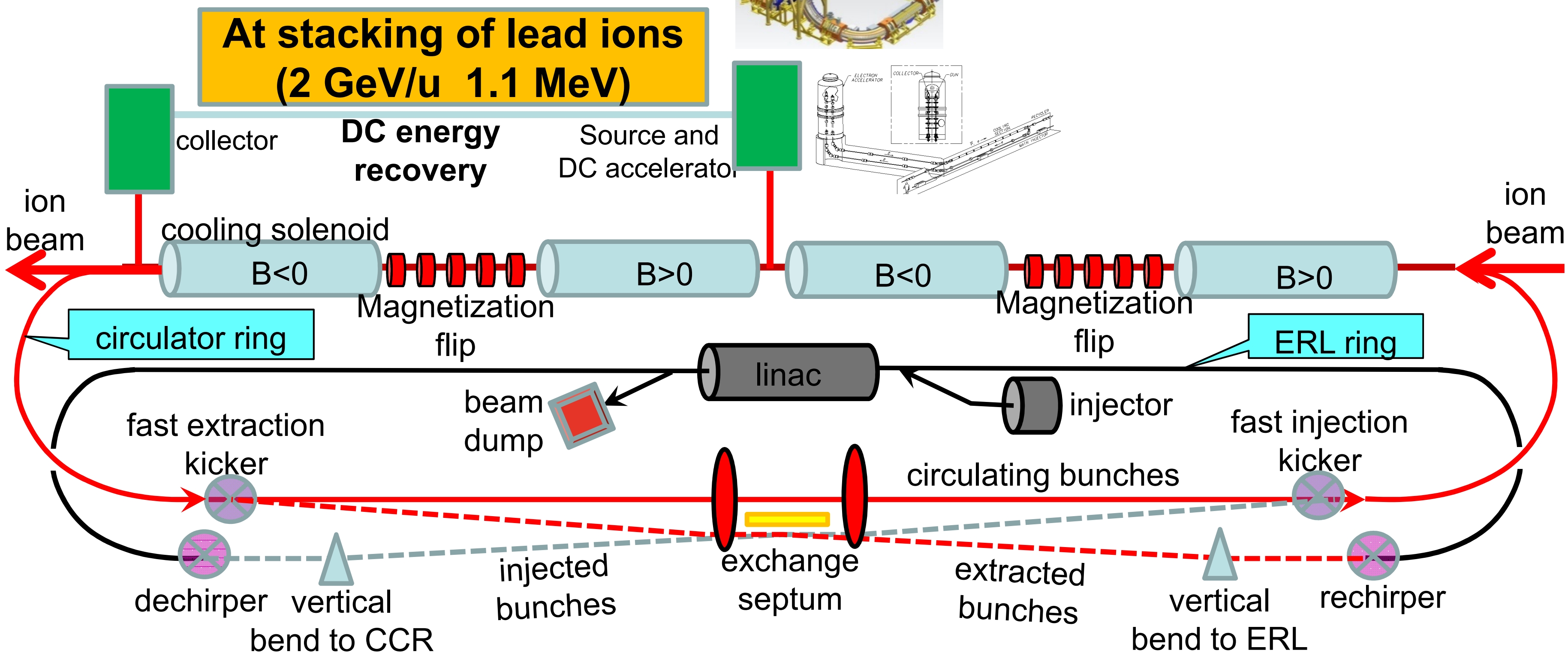

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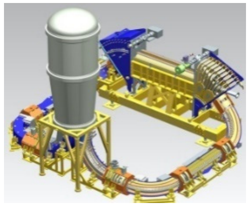

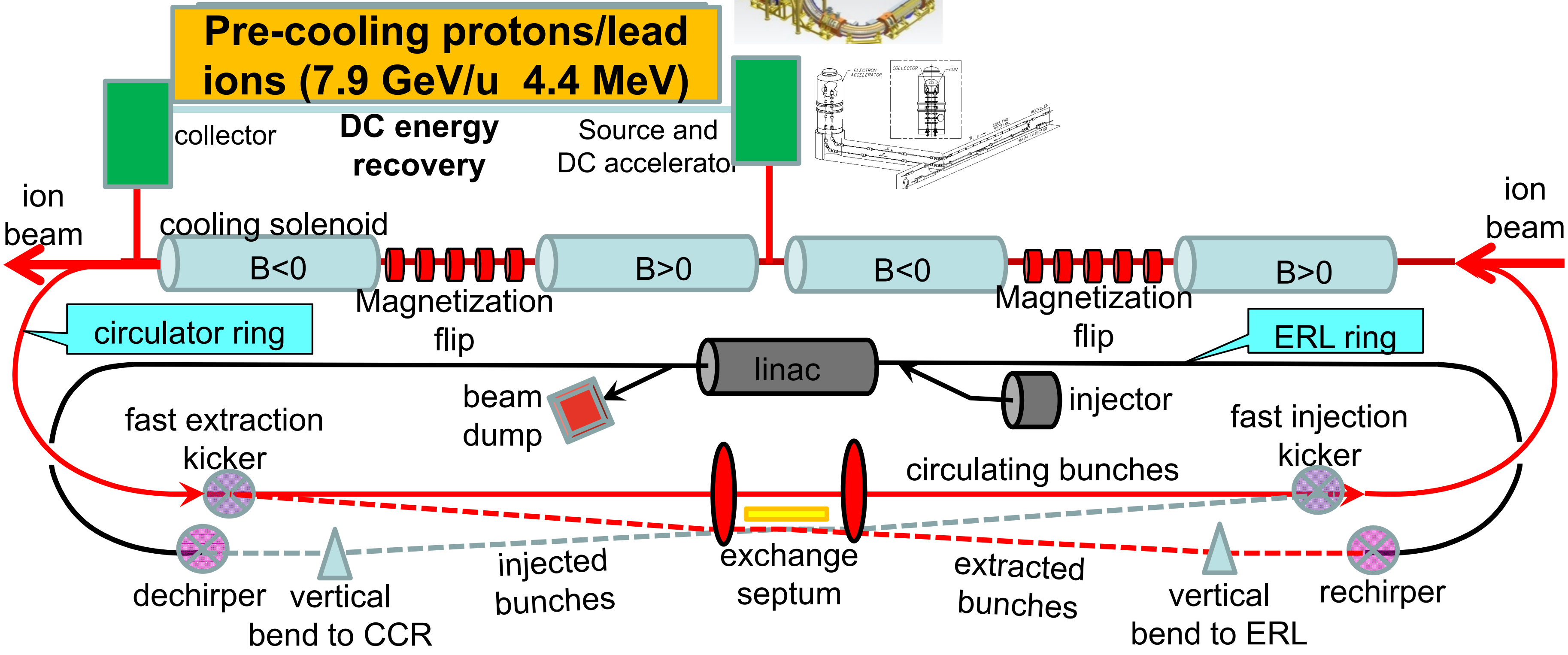

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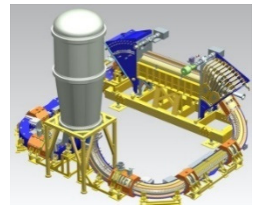

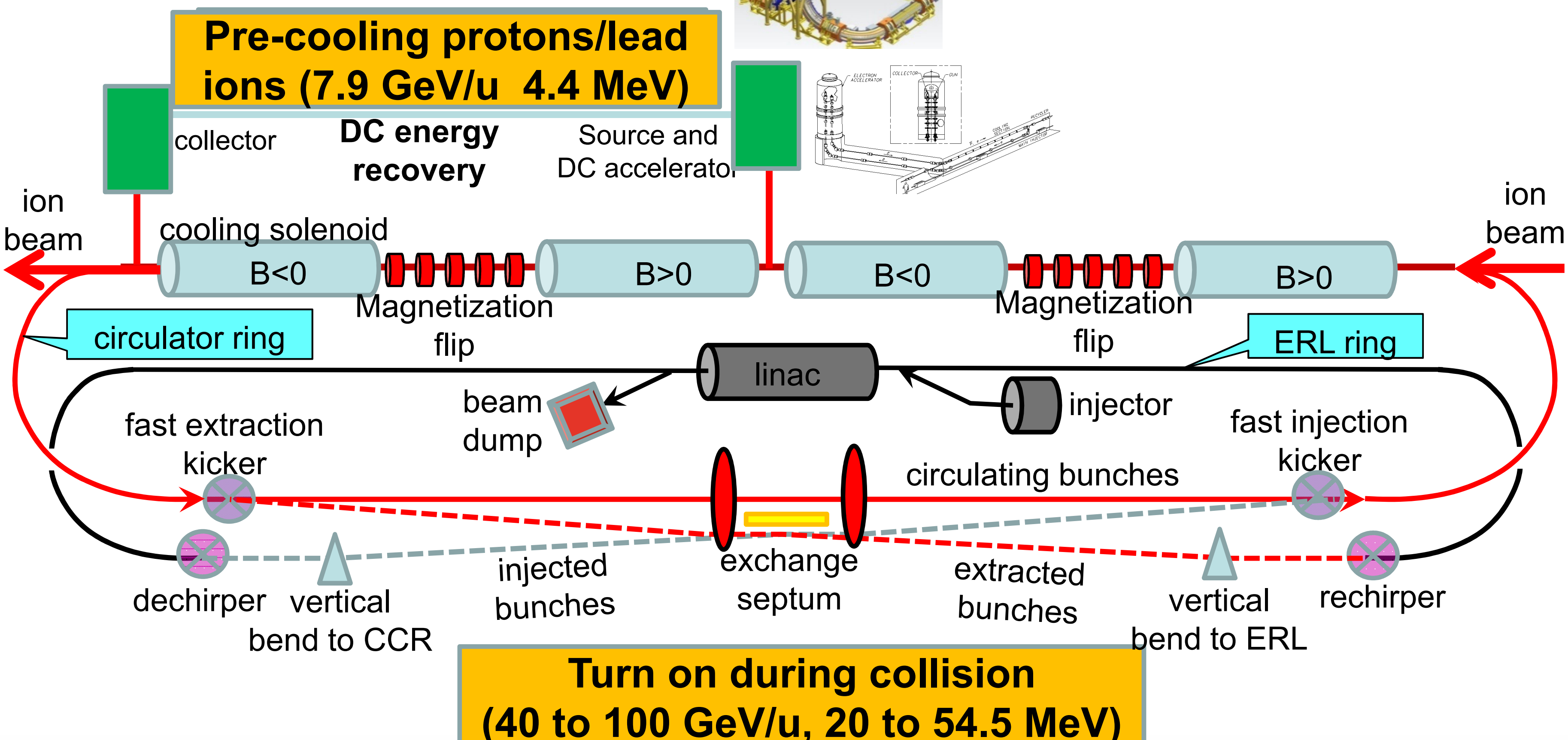

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JSPEC: New Cooling Simulation Code

Goals

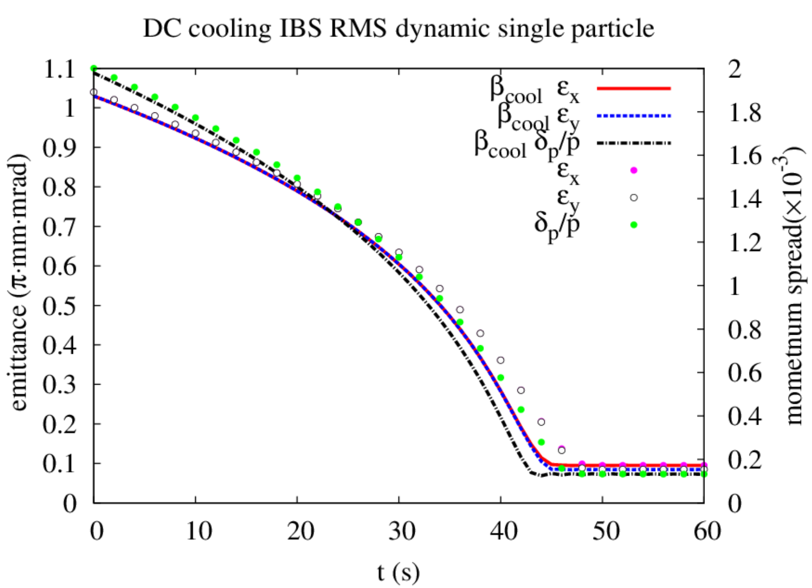
- Fulfill the specific needs for JLEIC electron cooling scheme
- Applicable to different cooling flavors: DC and bunched beam
- Flexibility, higher efficiency (adaptive to the multi-core platform)

Supported by JLab LDRD (two years)

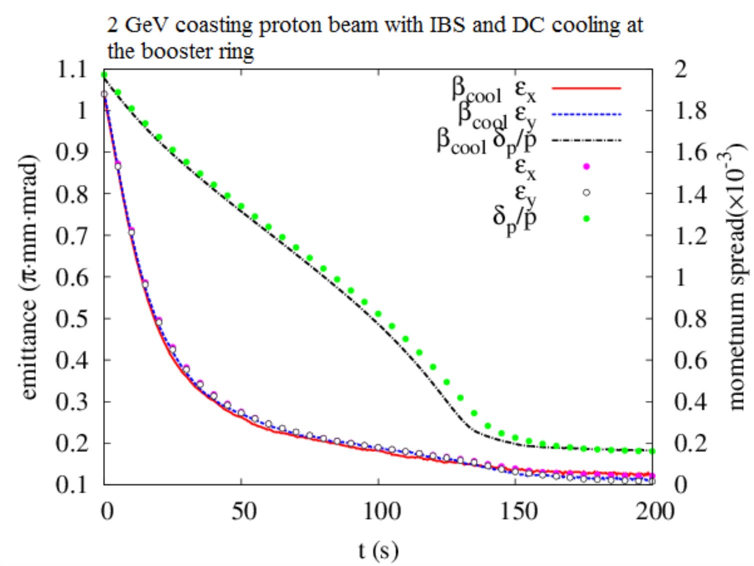
Formulas and models implemented

- 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



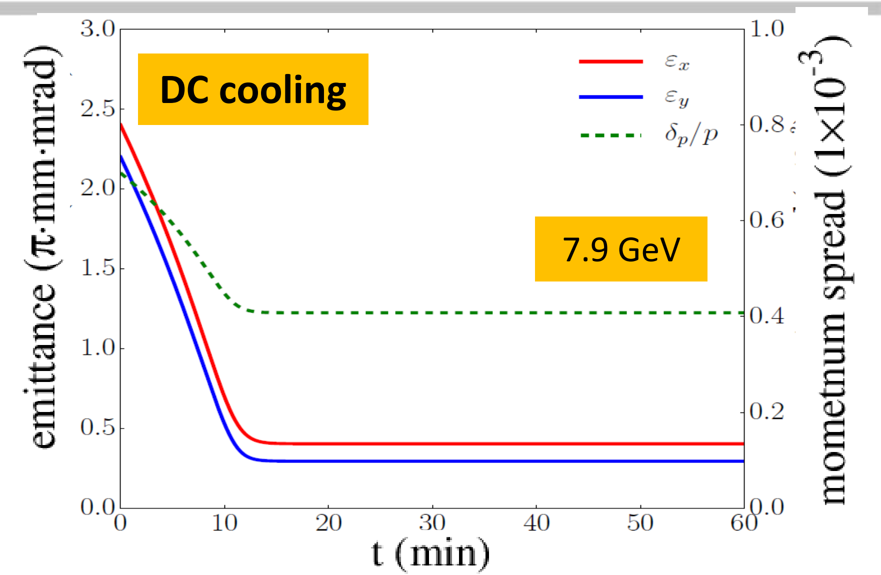
Benchmark with BETACOOL

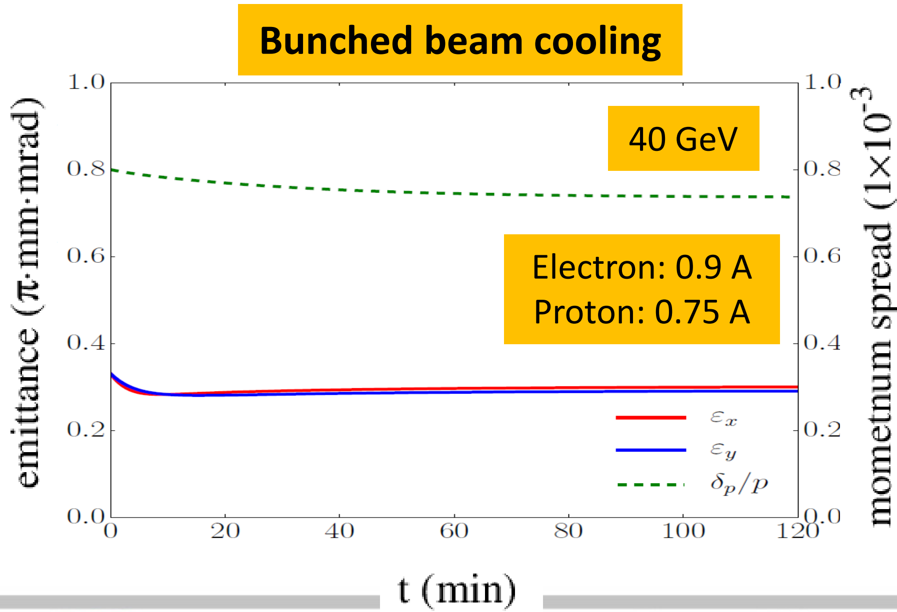


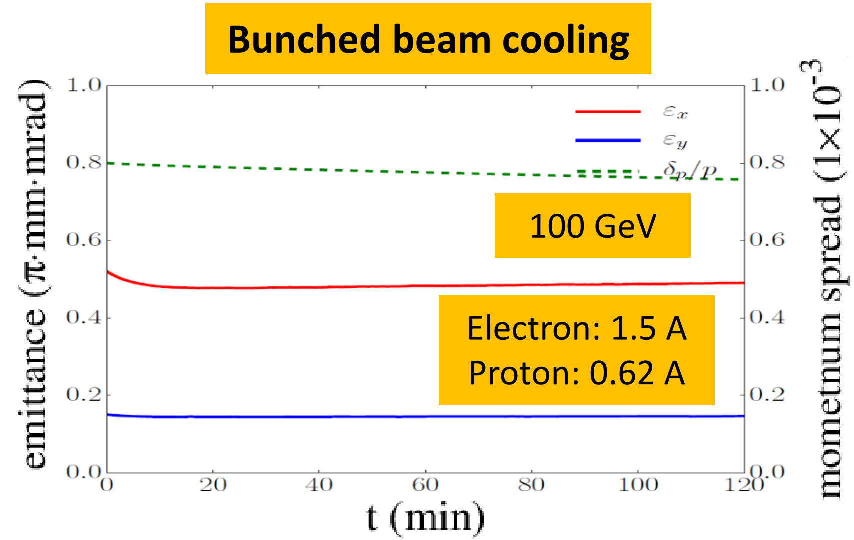
Electron Cooling Simulations

- **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 $\boldsymbol{H_c}$ is the perturbation:

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

$$H_0(\vec{p}_{ion},y_e,\vec{p}_e)=\frac{1}{2m_{ion}}\left(p_{ion,x}^2+p_{ion,y}^2+p_{ion,z}^2\right)+\frac{1}{2m_e}\left[\left(p_{e,x}+eB_0y_e\right)^2+p_{e,y}^2+p_{e,z}^2\right]$$

$$H_C(\vec{x}_{ion},\vec{x}_e)=\frac{-Ze^2}{4\pi\varepsilon_0}\Big/\sqrt{(x_{ion}-x_e)^2+(y_{ion}-y_e)^2+(z_{ion}-z_e)^2}$$

$$\vec{B}=B_0\,\hat{z} \qquad \vec{A}=-B_0y\,\hat{x}$$

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

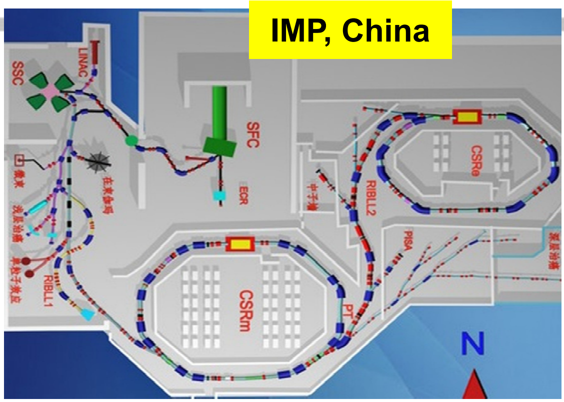
Plan

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.

$$H(\vec{x}_{ion},\vec{p}_{ion},\vec{x}_e,\vec{p}_e)=H_0(\vec{p}_{ion},y_e,\vec{p}_e)+H_C(\vec{x}_{ion},\vec{x}_e)$$
$$+\;H_{space-charge}(\vec{x}_{ion},\vec{x}_e)+H_{solenoid-field-errors}(\vec{x}_{ion},\vec{x}_e,?)$$

Courtesy D. Bruhilwer (Radiasoft)

Bunched Beam Cooling Experiment at IMP

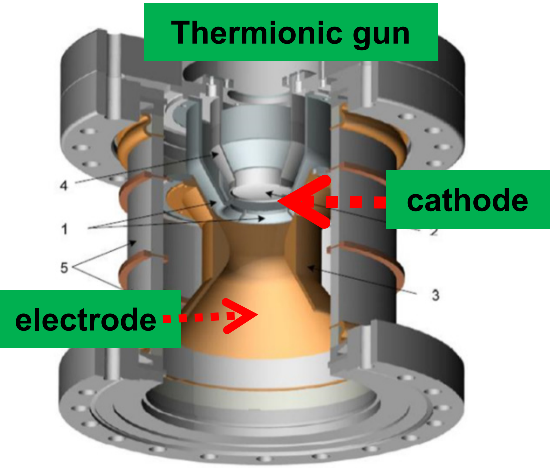


- All electron cooling to date achieved using a DC electron beam
- Cooling by a bunched e-beam is one critical R&D item for JLEIC
- ***Proof-of-Principle Experiment:*** utilizing an existing DC cooler, modulating grid voltage of a thermionic gun to generate a pulsed electron beam (as short as ~100 ns)

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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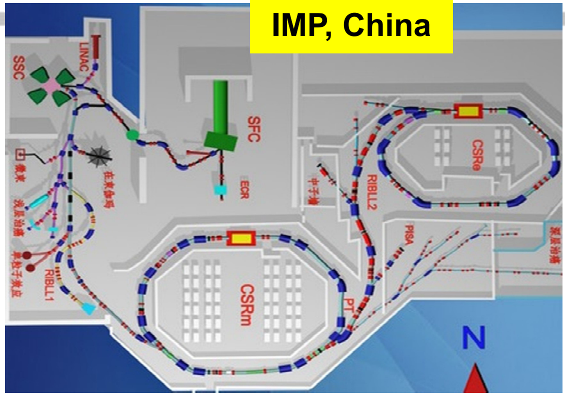

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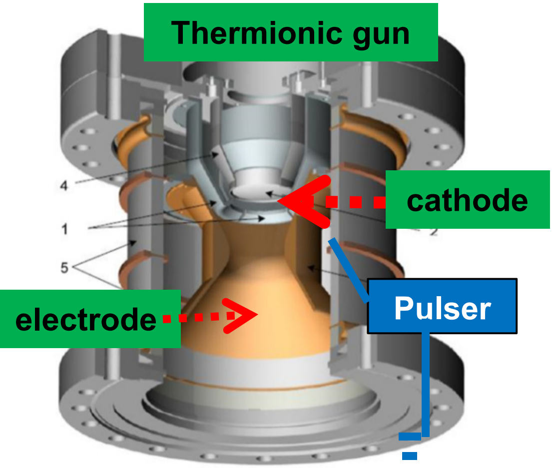

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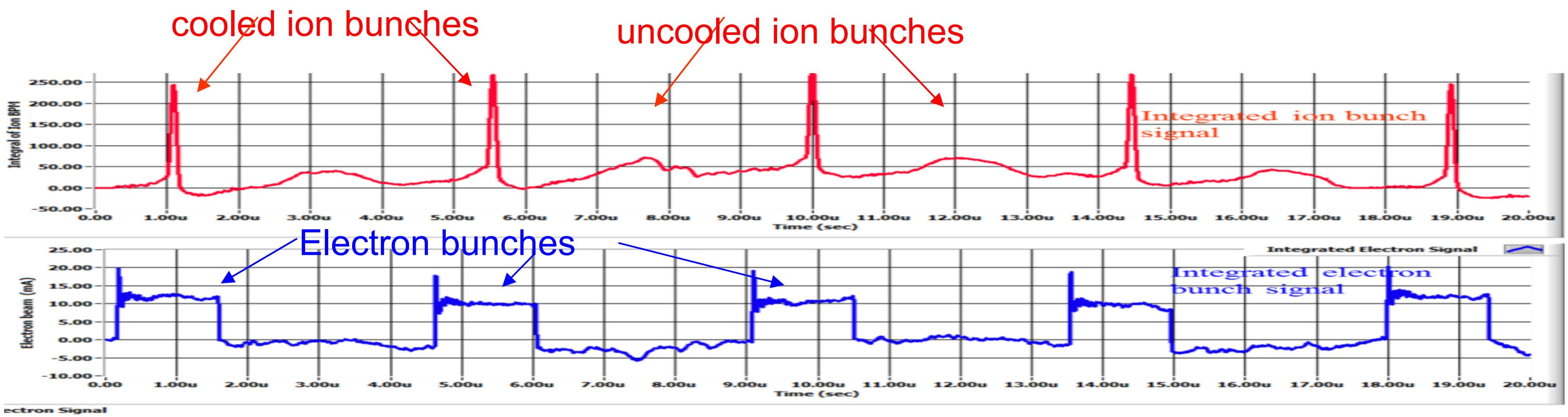
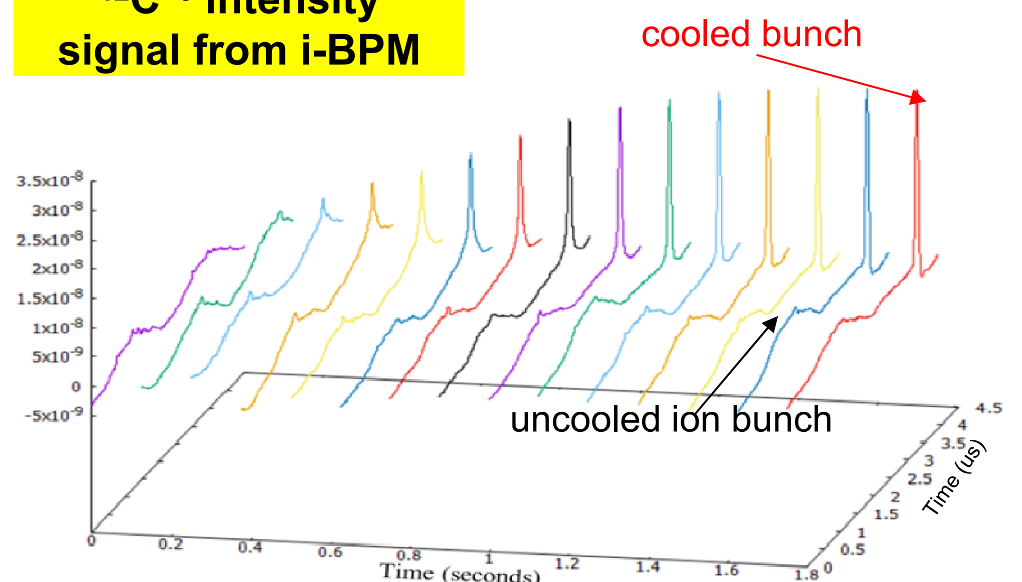
First Results of Bunched Beam Cooling

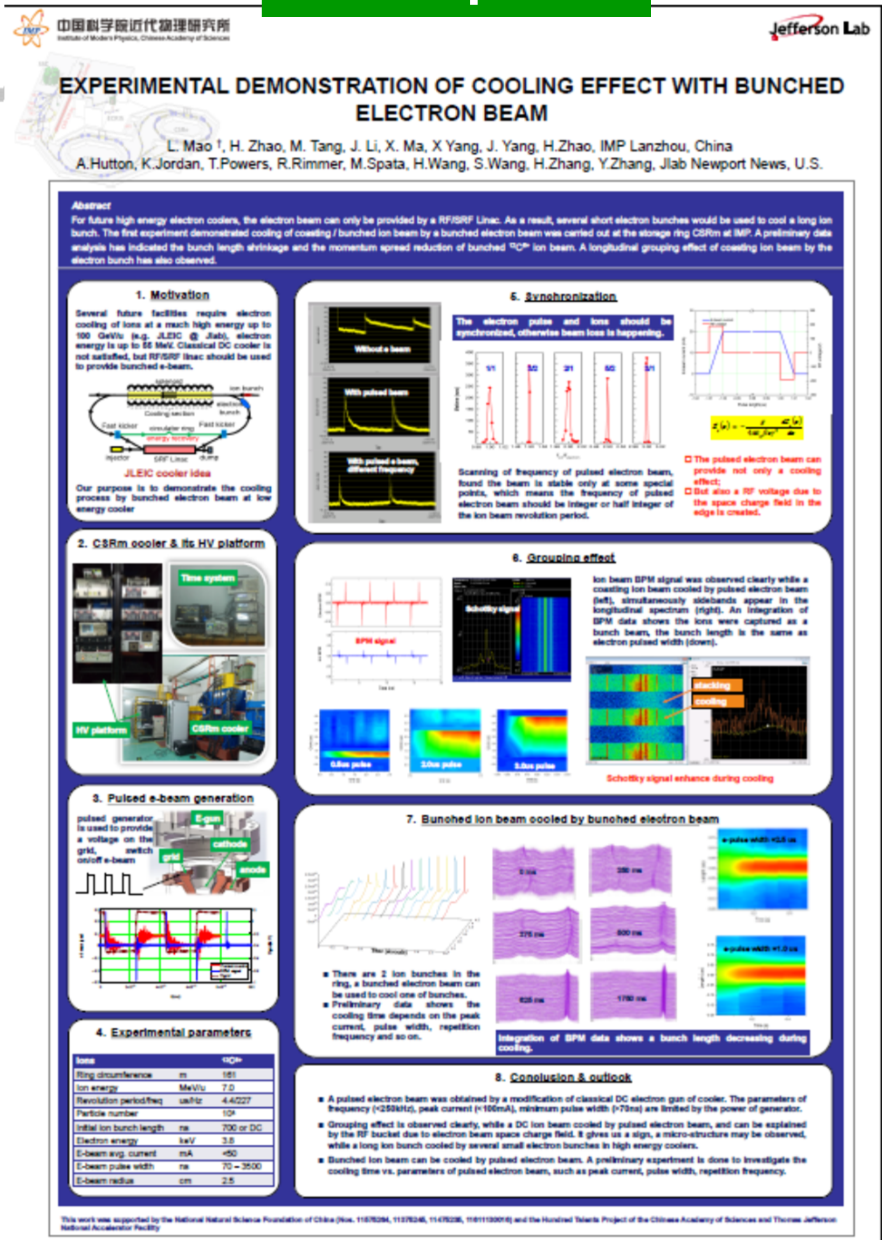


$^{12}C^{+6}$ intensity signal from i-BPM

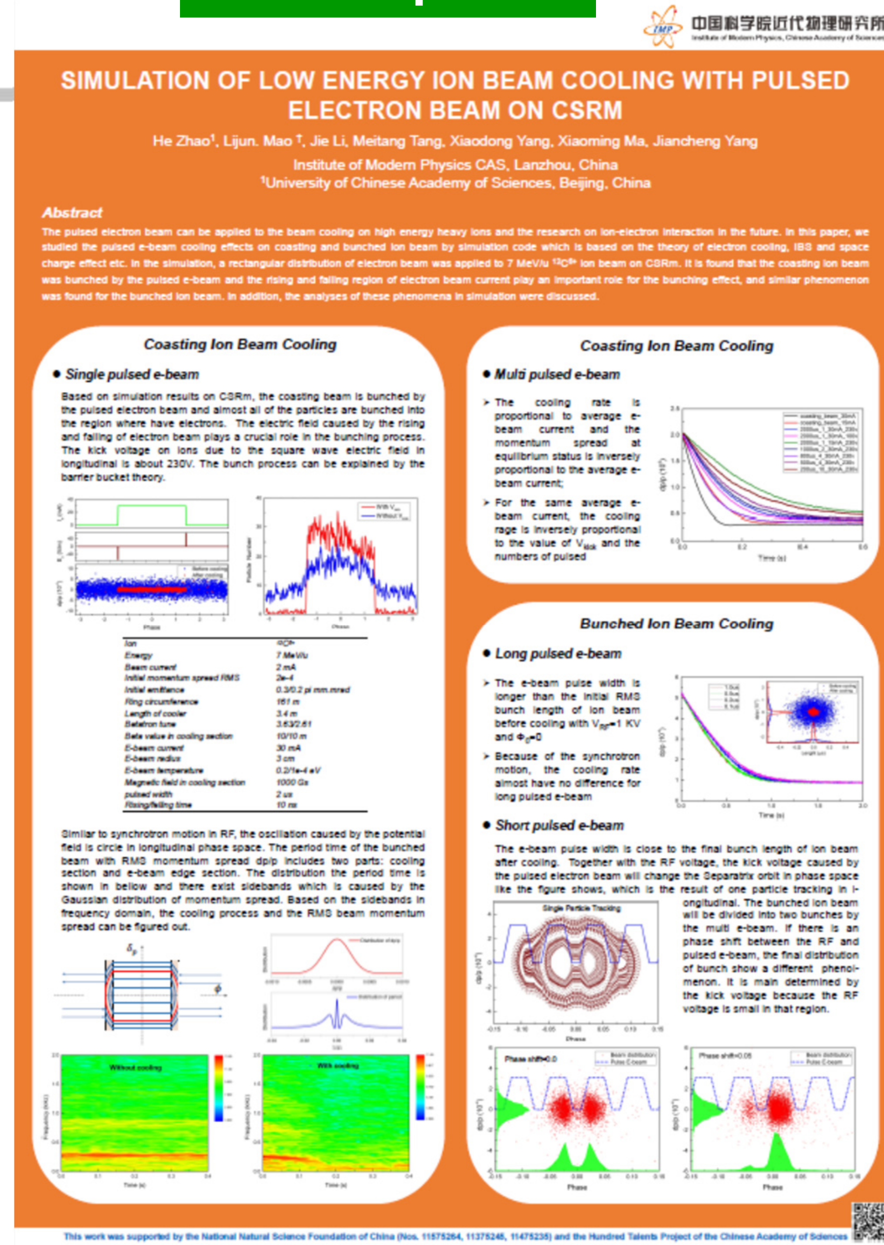


Ions		$^{12}C^{6+}$
Ring circumference	m	161
Ion energy	MeV/u	7.0
Revolution period/freq	us/Hz	4.4/227
Particle number		10^8
Initial ion bunch length	ns	700 or DC
Electron energy	keV	3.8
E-beam avg. current	mA	<50
E-beam pulse width	ns	70 – 3500
E-beam radius	cm	2.5

L. Mao poster



H. Zhao poster



Electron Cooling Theory

Full translation of Ya. Derbenve's D.Sci. Thesis **arxiv.org/abs/1703.09735**

THEORY OF ELECTRON COOLING

Yaroslav Derbenev*

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Translation supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

Table of Contents

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 $10^{34}/cm^2/s$)
- 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.

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

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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

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

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