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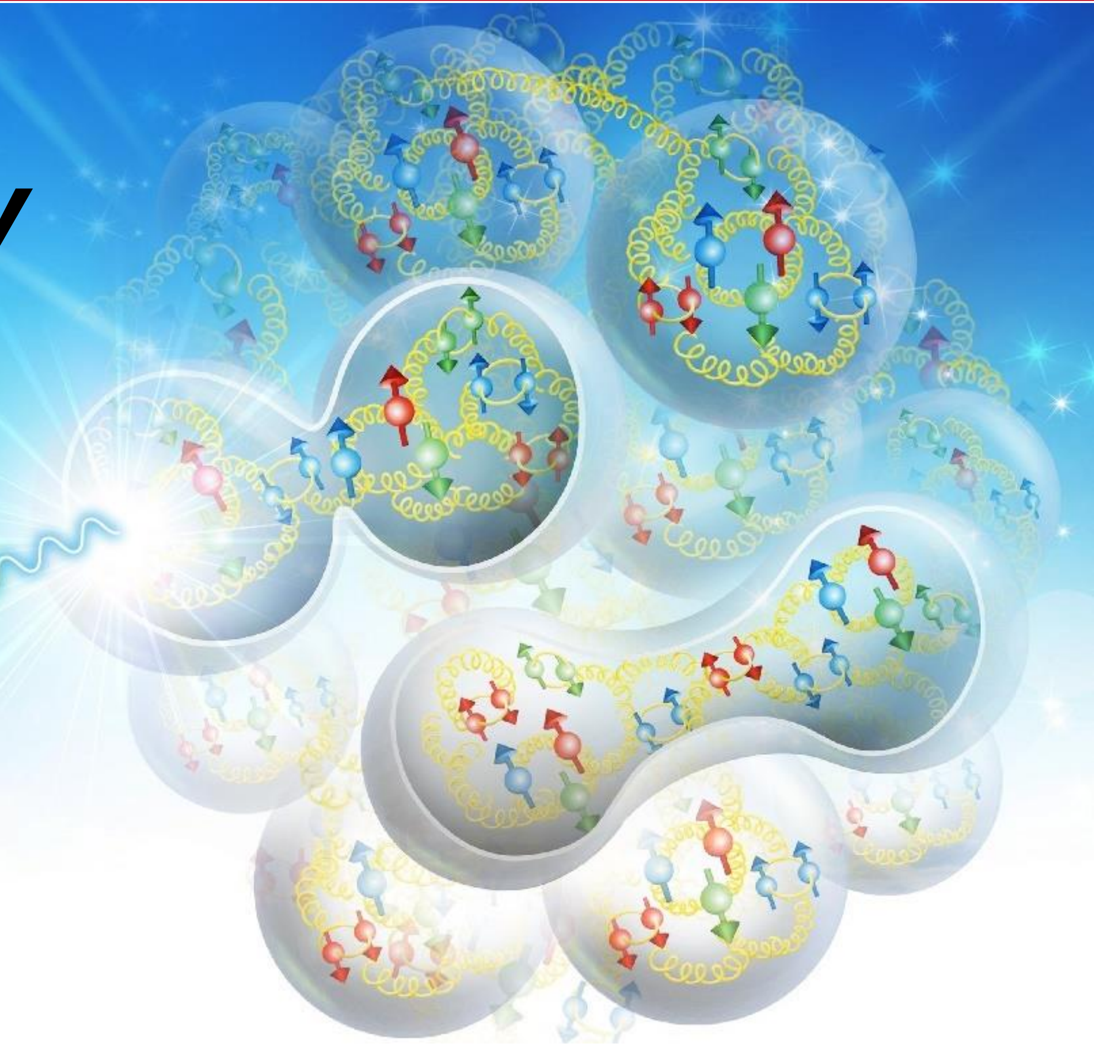
Thomas Jefferson National Accelerator Facility

JLEIC: A High Luminosity Polarized Electron-Ion Collider at Jefferson Lab



Jefferson Lab

2019 DPF Northeastern

2019 Meeting of Division of Particles & Fields of APS
July 29 – August 2, 2019

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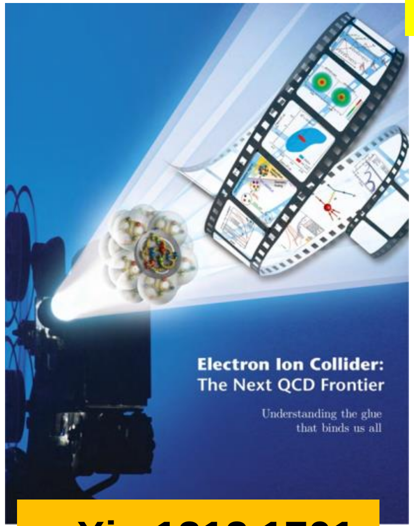
JSA

EIC for QCD Frontier: From White Paper to NAS Assessment

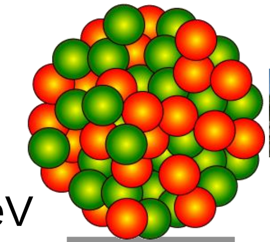
A Gluon Microscopy for Understanding the Glue that Binds Us All



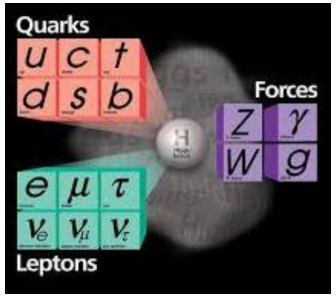
arXiv:1212.1701

EIC Community White Paper 2012

- Highly polarized (~70%) electron and light beams
- Ion beams from deuteron to the heaviest stable nuclei (U or Pb)
- Variable CM energies from ~20 – ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~$10^{33\text{-}34}$ $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region



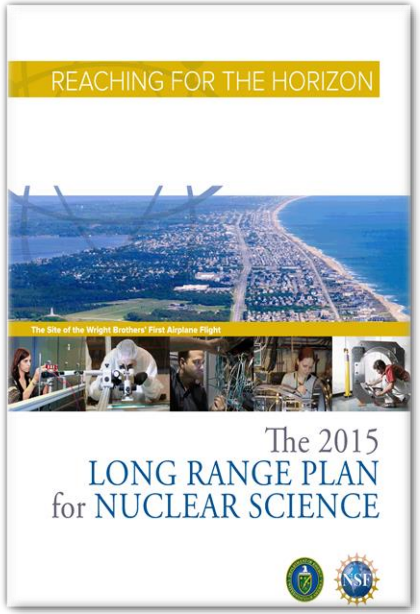
Nuclei

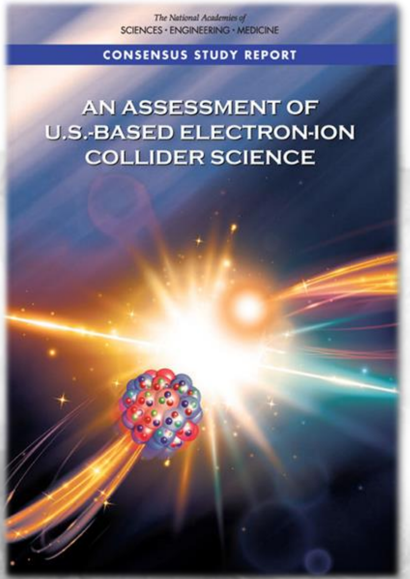


NSCA Long Range Plan 2015

- Nuclear Science Advisory Committee (NSCA) is commissioned by DOE and NSF
- Every 5 to 7 years, it produces a Long Range Plan, with ***3 to 5 recommendations,*** ➔ a roadmap for nuclear science facilities for the next 10 years (*LRP 1979, 1983, 1989, 1996, 2002, 2007, 2015)*

NSAC LRP 2015 A **high-energy high-luminosity polarized Electron-Ion Collider** for new facility construction following the completion of FRIB





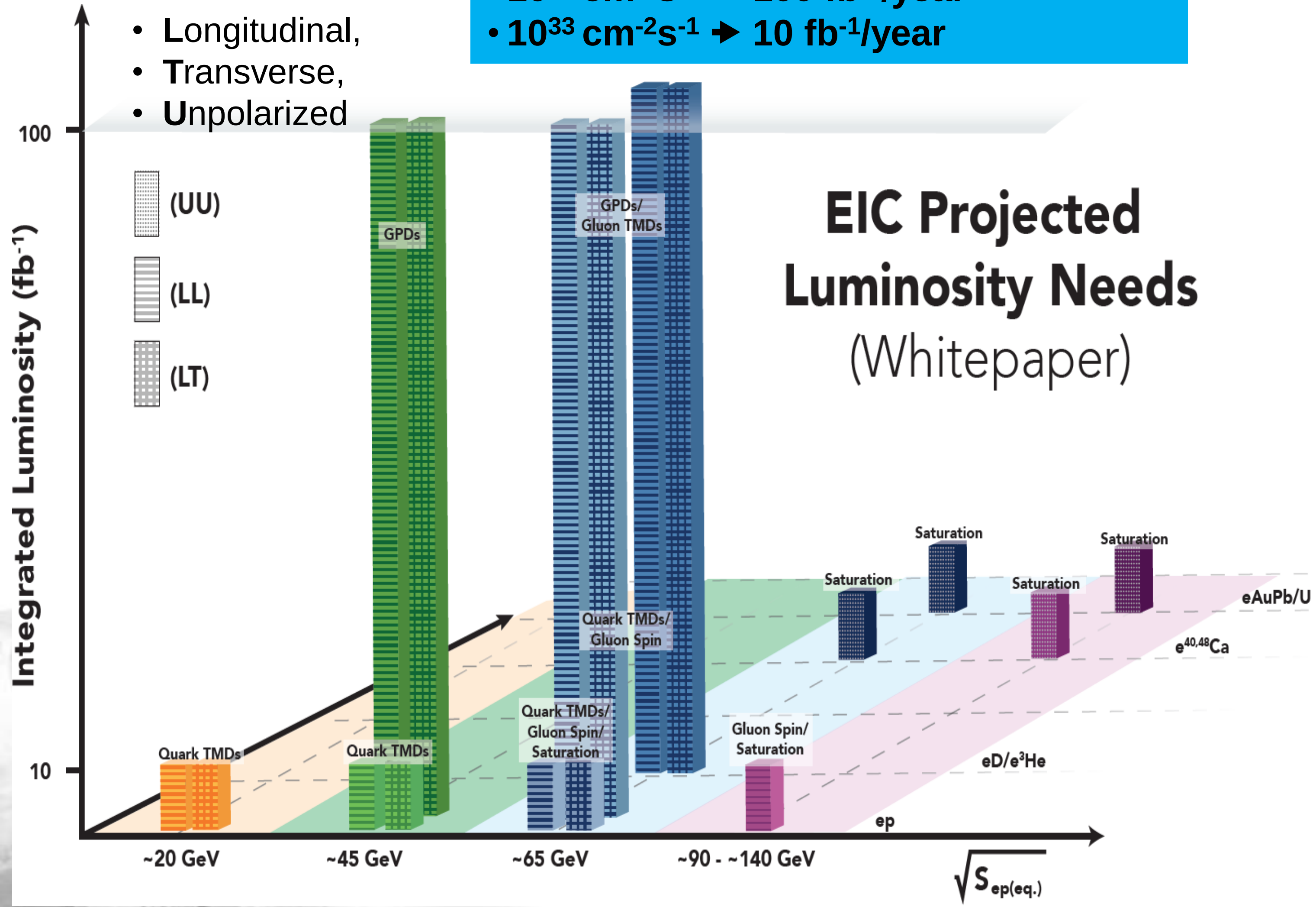
NAS Assessment of EIC 2018

*"In summary, the committee finds **a compelling scientific case** for such a facility. The science questions that an EIC will answer are **central to completing** an understanding of atoms as well as being **integral to the agenda** of nuclear physics today. In addition, the development of an EIC would **advance accelerator science and technology** in nuclear science; it would as well **benefit other fields** of accelerator based science and society, from medicine through materials science to elementary particle physics."*

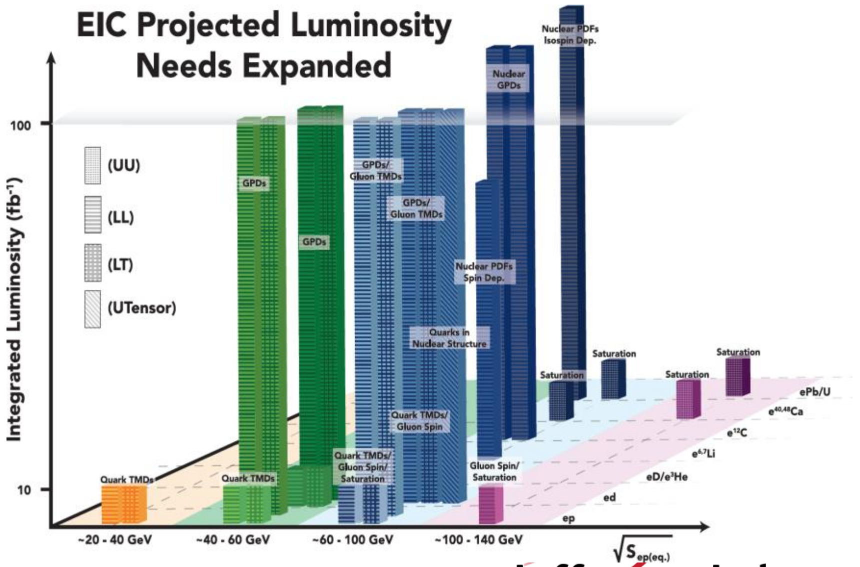
EIC Integrated Luminosity Requirements

White paper: ~710 fb^{-1} required
- **10^{34} cm^{-2}s^{-1} → 100 fb^{-1}/year**
- **10^{33} cm^{-2}s^{-1} → 10 fb^{-1}/year**

HERA: 0.8 fb^{-1} integrated luminosity delivered

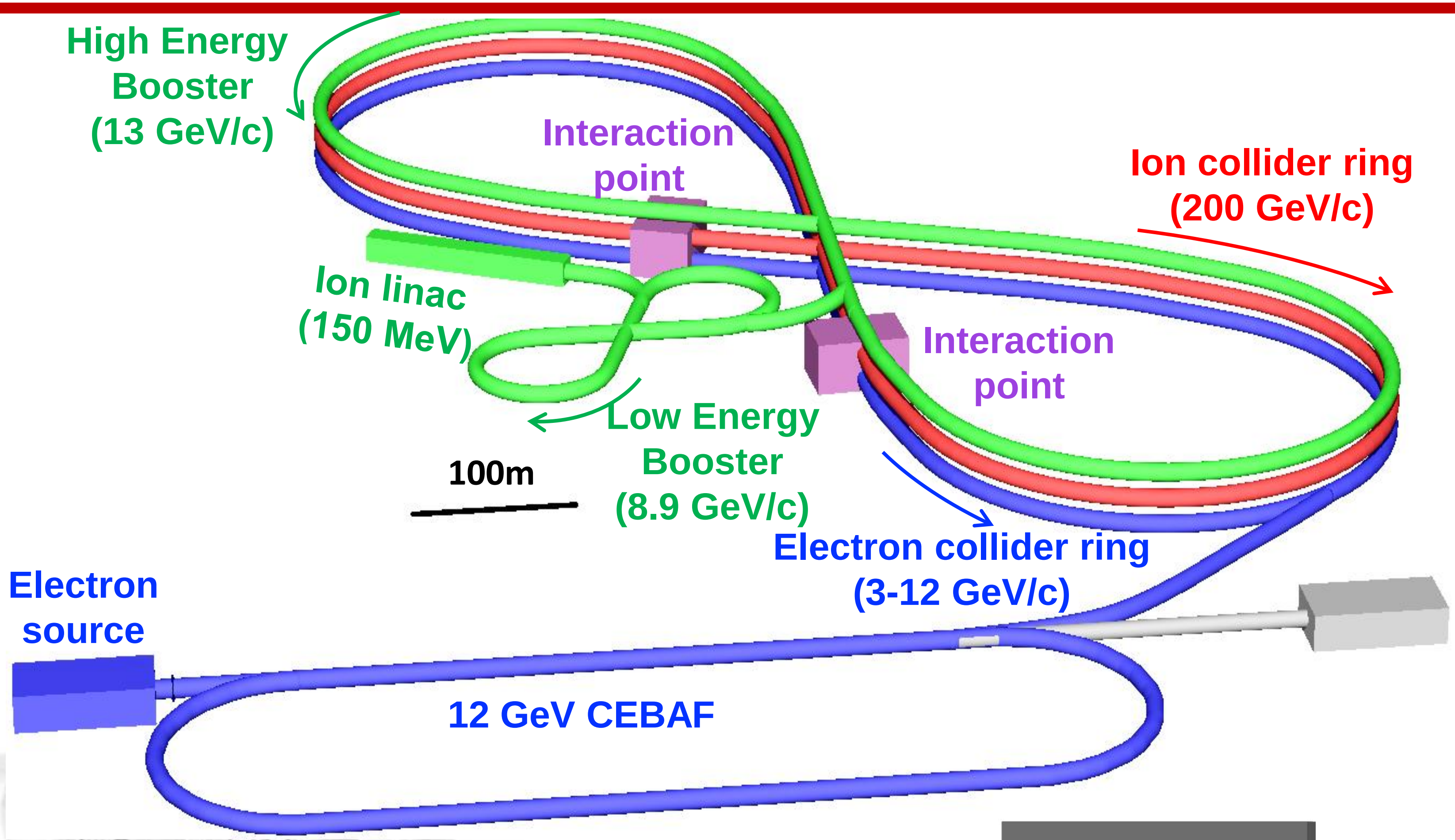


Envisioned extended EIC program, requiring ~1400 fb^{-1}

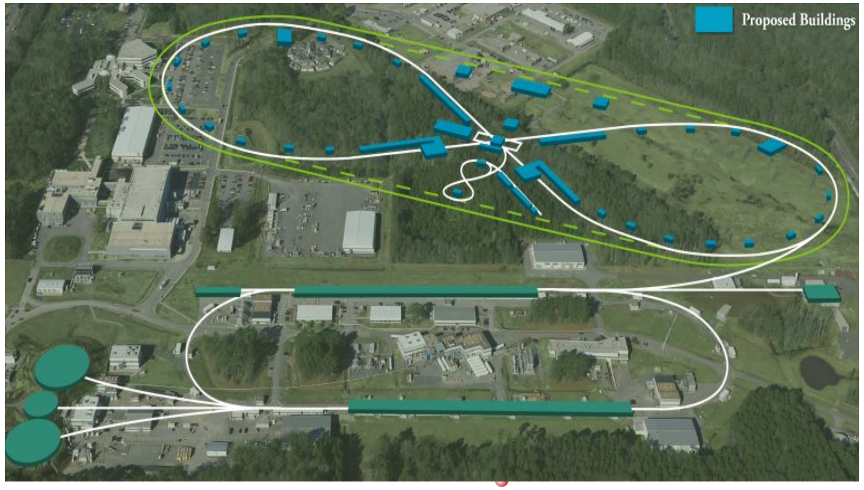


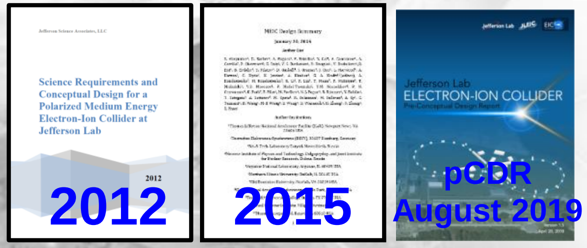
95% of program is at CM energies below 100 GeV

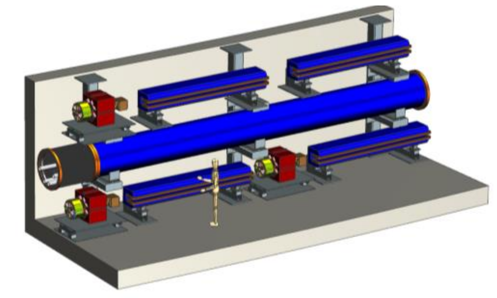
JLEIC Layout

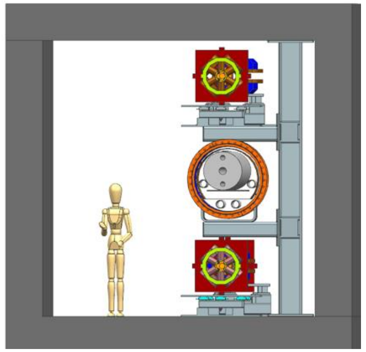


- **Electron complex**
  - CEBAF as a full energy injector
  - Electron collider ring: 3-12 GeV/c
- **Ion complex**
  - Ion source
  - SRF linac: 150 MeV for protons
  - Low Energy Booster: 8.9 GeV/c
  - High Energy Booster: 13 GeV/c
  - Ion collider ring: 200 GeV/c
- **Up to two detectors** at minimum background locations
- **Upgradable to 140 GeV CM**





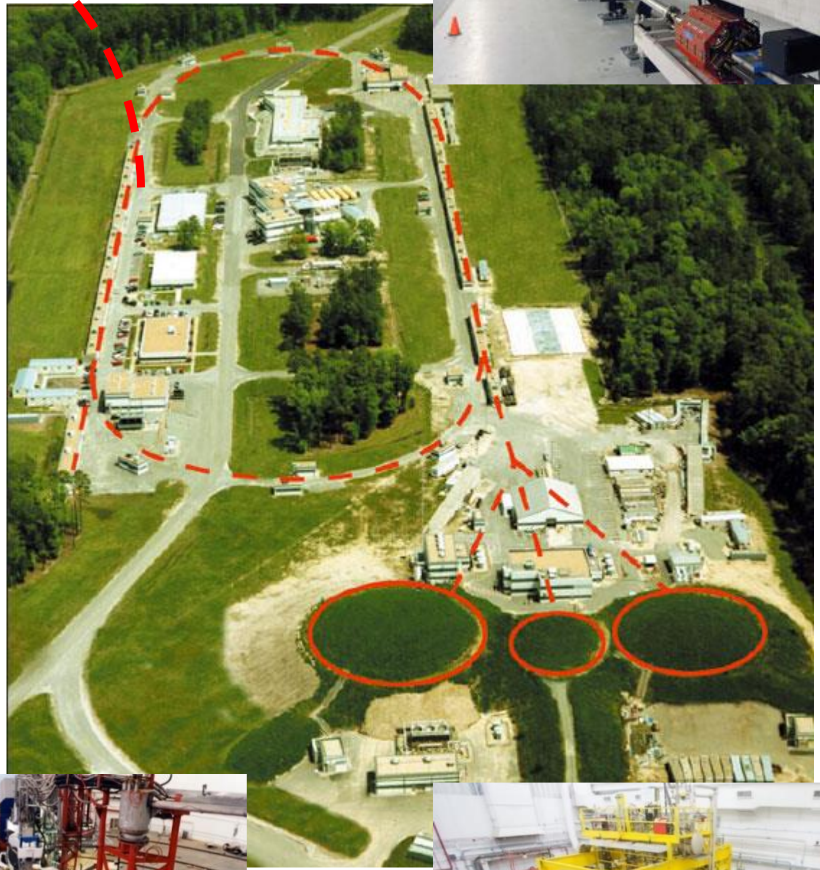


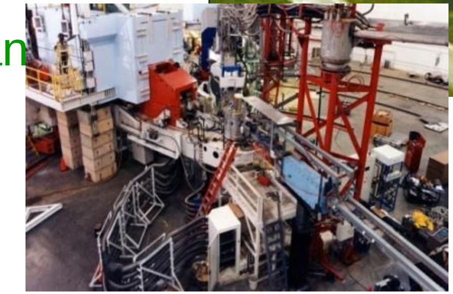


Why Jefferson Lab is the ideal site for EIC

- Large established ***user community*** in the field
- ***CEBAF***, the world highest energy CW SRF linac
  - As a full energy injector (without requiring any upgrade)
  - Maintains highly-polarized high-current beam in the electron collider ring using demonstrated top-up injection technique
- ***New collider complex***
  - Modern design and technology
  - No constraints imposed by existing infrastructure
  - Design driven by experimental requirements
    - Novel high luminosity concept
    - Luminosity optimized around CM energy range of physics interest
    - Novel figure-8 design for high polarization of any particles including deuterons
    - Deeply integrated detector and machine design for full acceptan
  - Balance of good performance and low technical risk

Up to 12 GeV @1.5 GHz





JLEIC High Luminosity Concept: Many Small Short Bunches

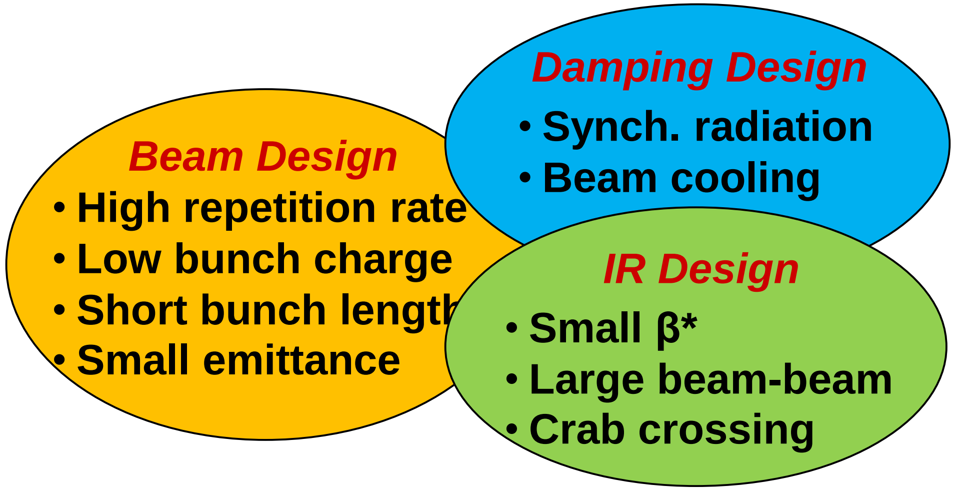
- *Conventional* approach for hadron colliders
  - Few colliding bunches ➔ low bunch frequency
  - High bunch intensity ➔ long bunch & large β^*
- JLEIC takes a new approach:
  high bunch repetition rate + short bunch colliding beams

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

- A standard approach for lepton colliders
  (KEK-B reached **> 2x10^{34} /cm^2/s)**
- JLEIC advantages
  - Based on CEBAF, its beam ***already*** up to 1.5 GHz
  - ***New green field*** ion complex can be designed to deliver high bunch repetition rate

	Bunch freq. (MHz)	Bunch intensity (10^{10})	Bunch length (cm)	β^*_y (cm)
RHIC	9.4	20	-	~90
HERA	8.2	7.3	16	18
JLEIC	476	1	1	1.2
KEKB	158 - 458	6.4 – 2.1	~0.6	0.59

***Strategy*: Design a *lepton-hadron* collider like a *lepton-lepton* collider**

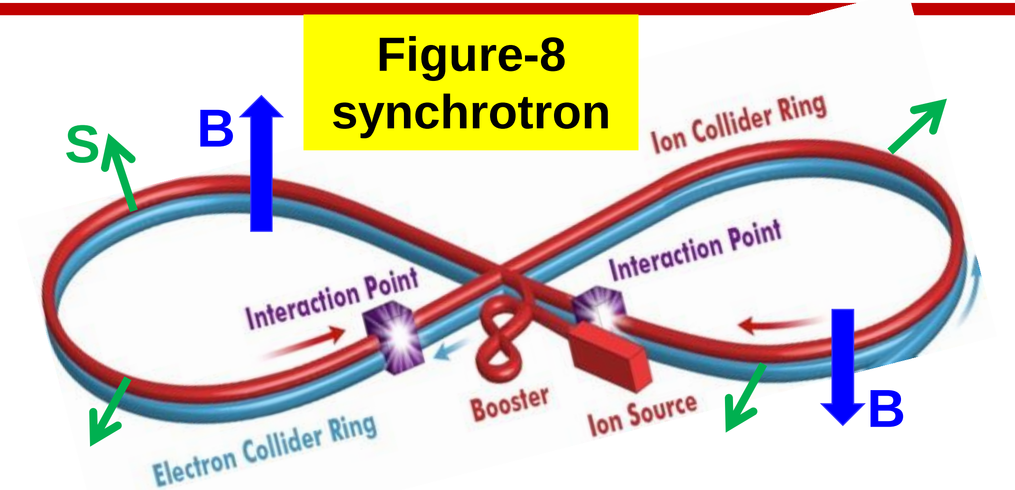


Role of cooling of ion beams

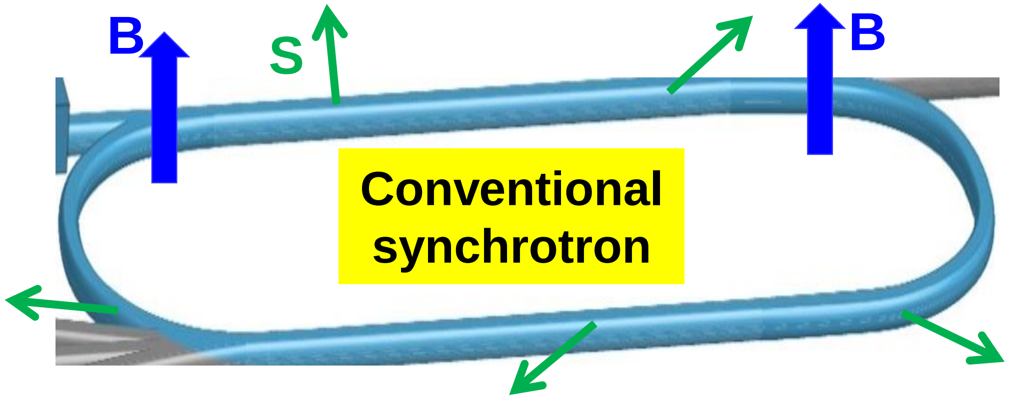
- Critical for formation, emittance reduction/preservation
- Electron has SR --- natural damping
- No SR for protons/ions in JLEIC medium energy range
- JLEIC relies on *electron cooling* for providing a damping mechanism

JLEIC High Polarization Concept: Figure-8 Shape Ring

- Electrons, protons & light ions are injected polarized from sources
- JLEIC adopted a figure-8 topology for ion rings
  ➔ A brilliant invention of ***Dr. Yaroslav Derbenev***
  ➔ *Enabled by a **green field** collider ring design*
- Spin precessions in the left & right parts of a figure-8 ring are ***exactly cancelled*** ➔ net spin precession is ***zero***
  ➔ spin tune is ***zero***
- Does not cross spin resonance during energy ramp
- Spin can be controlled and stabilized by compact spin rotators (e.g., rotating spin, and moving spin tune away from 0)
- No need of Siberian Snakes
- The ***only practical way*** to accelerate/store **polarized deuterons** in medium energy range (gyromagnetic ratio *g-2* too small)
- The electron ring follows the ion ring figure-8 foot-print
- Figure-8 helps the electron polarization under spin flip



Spin precessions in left & right are cancelled
➔ Spin turn is zero (energy independent)



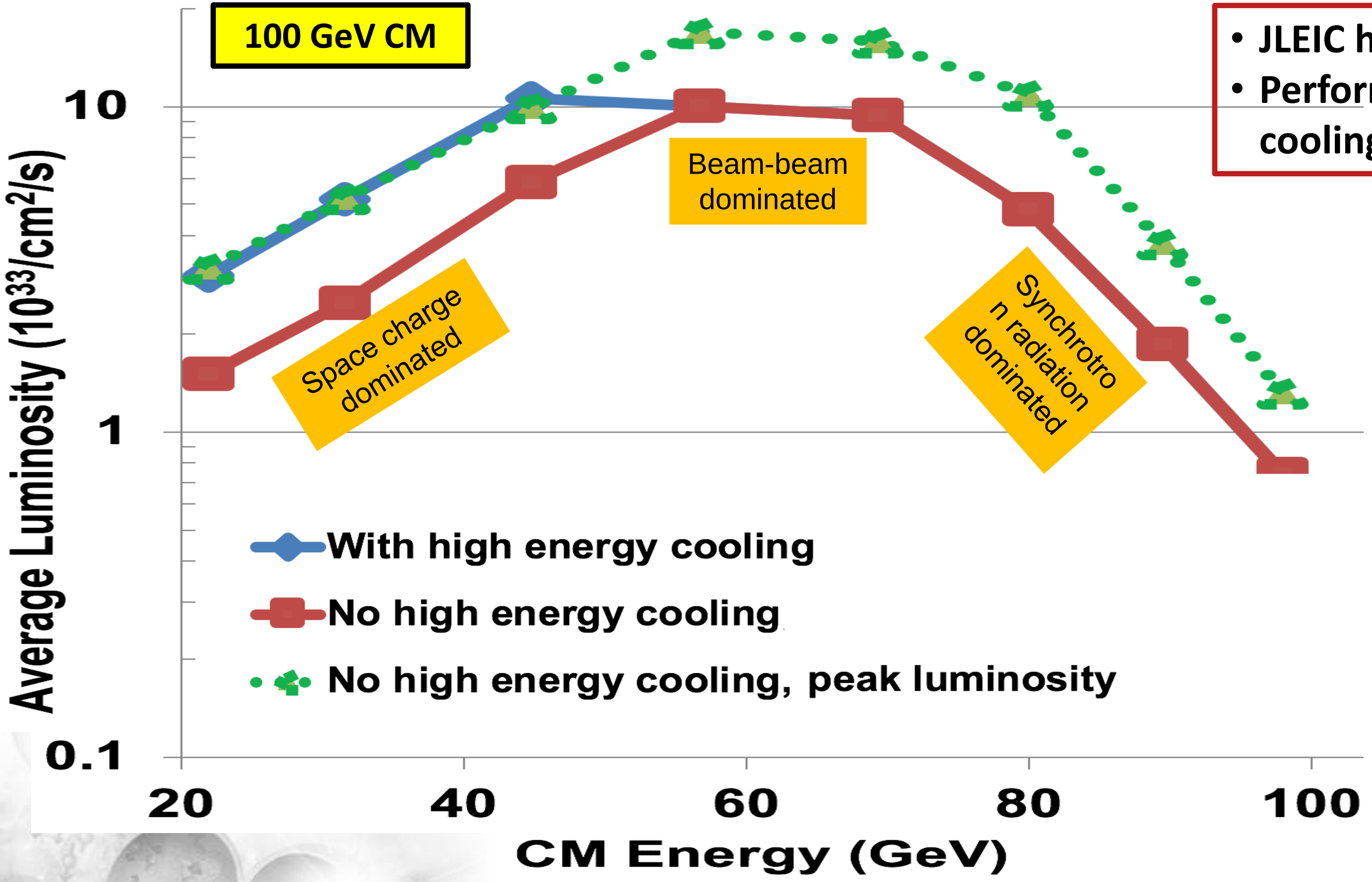
- Energy dependent spin precession
- Cross spin resonances during acceleration
- Siberian Snake may help but still difficult

JLEIC Parameters and Luminosity

CM energy	GeV	21.9		44.7		63.3		89.4		98	
		p	e	p	e	p	e	p	e	p	E
Beam energy	GeV	40	3	100	5	200	5	200	10	200	12
Collision freq	MHz	476		476		476/4=119		476/4=119		476/4=119	
Particles/bunch	10^{10}	0.59	3.9	0.98	4.7	3	8.9	3.93	4.2	3.93	2.05
Beam current	A	0.45	3	0.75	3.6	0.57	1.7	0.75	0.8	0.75	0.39
Polarization	%	85	>85	85	>80	85	>80	85	~80	85	~80
Bunch length	cm	2.5	1	2.5	1	3.2	1	3.2	1	3.2	1
Norm. emitt, x	µm	0.5	18	0.65	83	1.26	83	1.5	664	1.5	1145
Norm. emitt, y	µm	0.2	3.6	0.13	16.6	0.5	16.6	0.5	133	0.5	229
Horizontal β*	cm	8	30	8	5.72	21	14.5	19.2	4	27.5	4
Vertical β*	cm	1.3	9.8	1.3	0.93	1.6	2.2	2.3	0.8	3.3	0.8
Beam-beam, x		0.015	0.12	0.015	0.045	0.015	0.136	0.006	0.022	0.003	0.013
Beam-beam, x		0.01	0.15	0.0135	0.041	0.0065	0.120	0.003	0.022	0.002	0.013
Laslett tune-shift		0.055	small	0.018	small	0.0039	Small	0.0051	Small	0.0052	Small
Hour-glass (HG)		0.85		0.73		0.84		0.66		0.67	
Peak lumi., w/HG	$10^{33}/cm^2s$	3.2		14.6		9.84		3.8		1.31	
Average lumi.*	$10^{33}/cm^2s$	2.3		10.5		8.2		1.9		0.74	

* Average luminosity was calculated assuming a one or two hour proton beam store without or with high energy bunched beam electron cooling plus 5 min beam formation time (mainly due to detector overhead), and a 75% duty factor of machine operation.

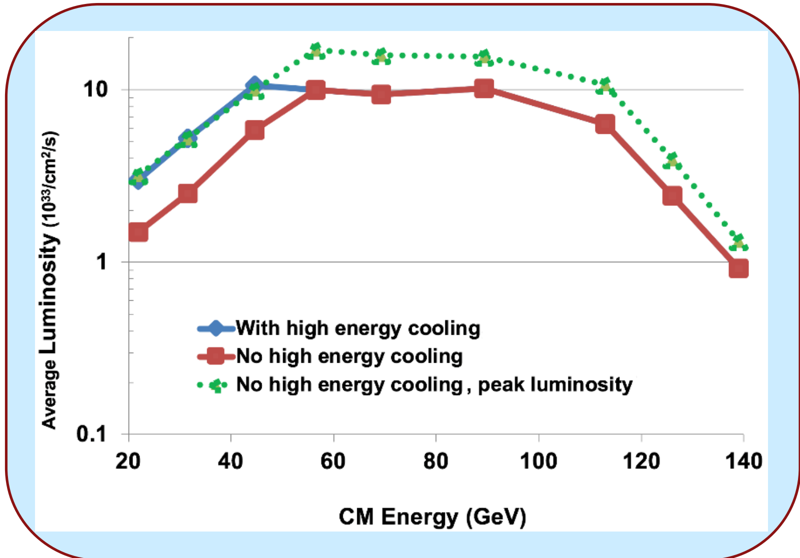
JLEIC Luminosity Performance



- JLEIC has robust luminosity performance
- Performance options mitigate high energy cooling risk

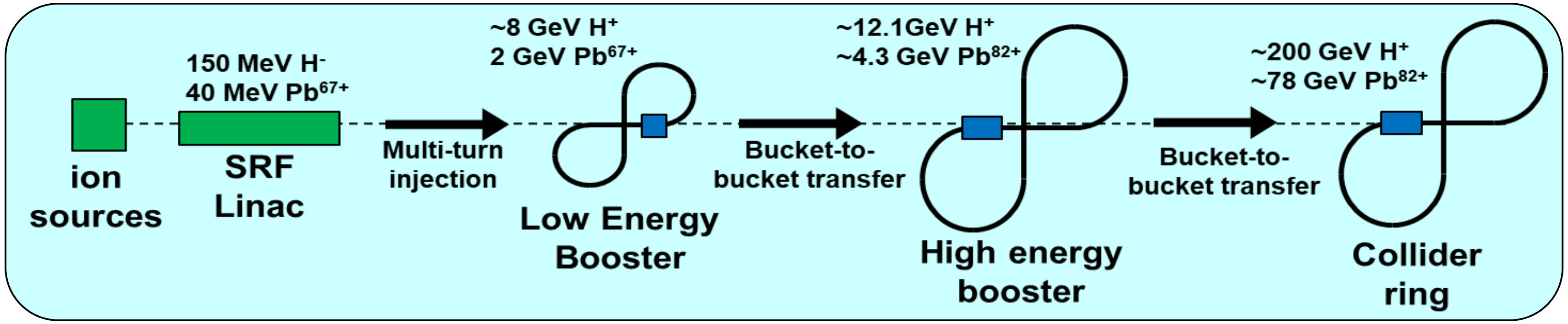
CM energy	Main luminosity limitation
low	Ion space charge
medium	Beam-beam
high	Electron synchrotron radiation

Upgrade to 140 GeV CM

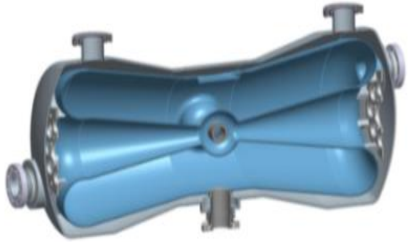


Average luminosity was calculated assuming a 1 or 2 hour proton beam store, without or with high energy beam electron cooling respectively, plus 5 min beam formation time (mainly due to detector overhead), and a 75% duty factor of machine operation.

JLEIC Ion Injector: Warm/SRF Linac

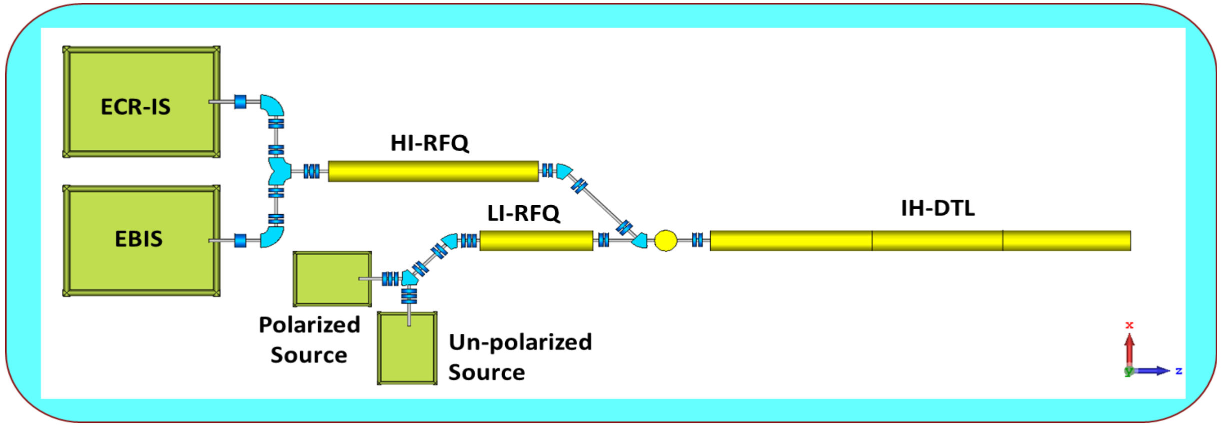


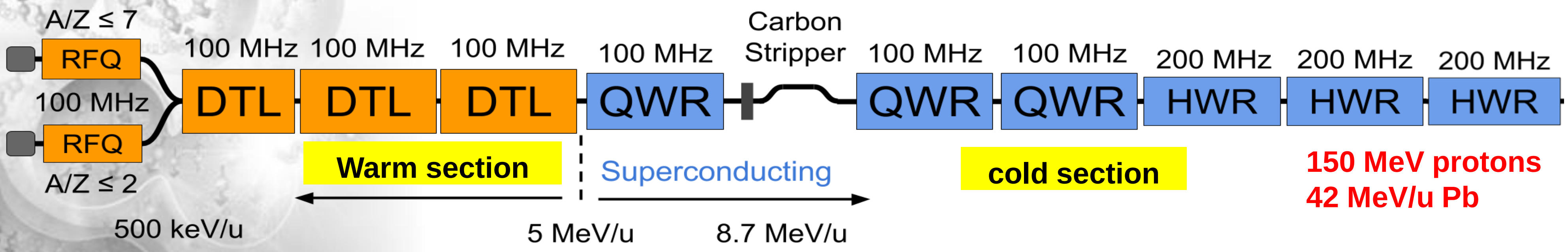
Quarter Wave Resonator (QWR)



Half-Wave Resonator (HWR)

- Two RFQs: light ions (A/q~2) and heavy ions (A/q~7)
  - Different emittances and voltage requirements
- Separate LEBTs and MEBTs for light and heavy ions
- RT Structure: IH-DTL with FODO focusing lattice
  - significantly better beam dynamics
- SRF section made of 3 QWR and 9 HWR modules
- Stripper section for heavy-ions after 2nd QWR module
- Pulsed Linac: up to 10 Hz rep rate, ~ 0.5 ms pulse length





150 MeV protons
42 MeV/u Pb

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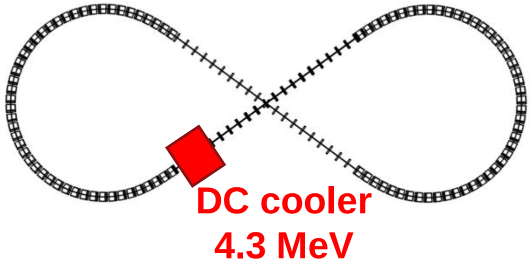
Low and High Energy Boosters, Ion Beam Formation

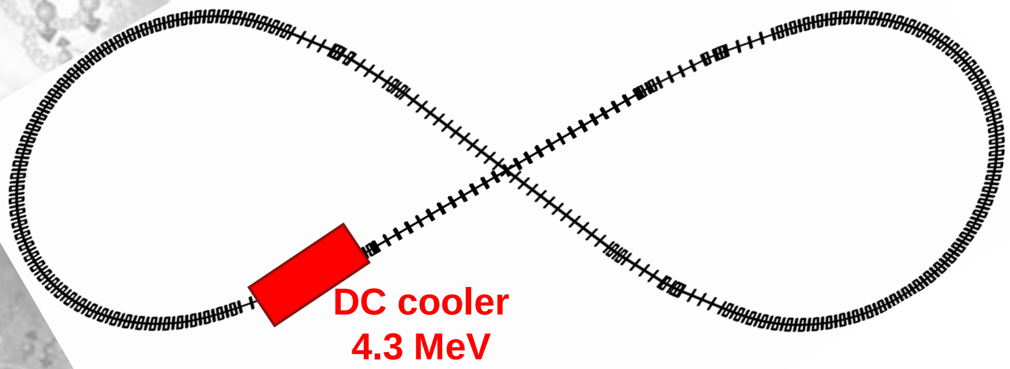
Low Energy Booster

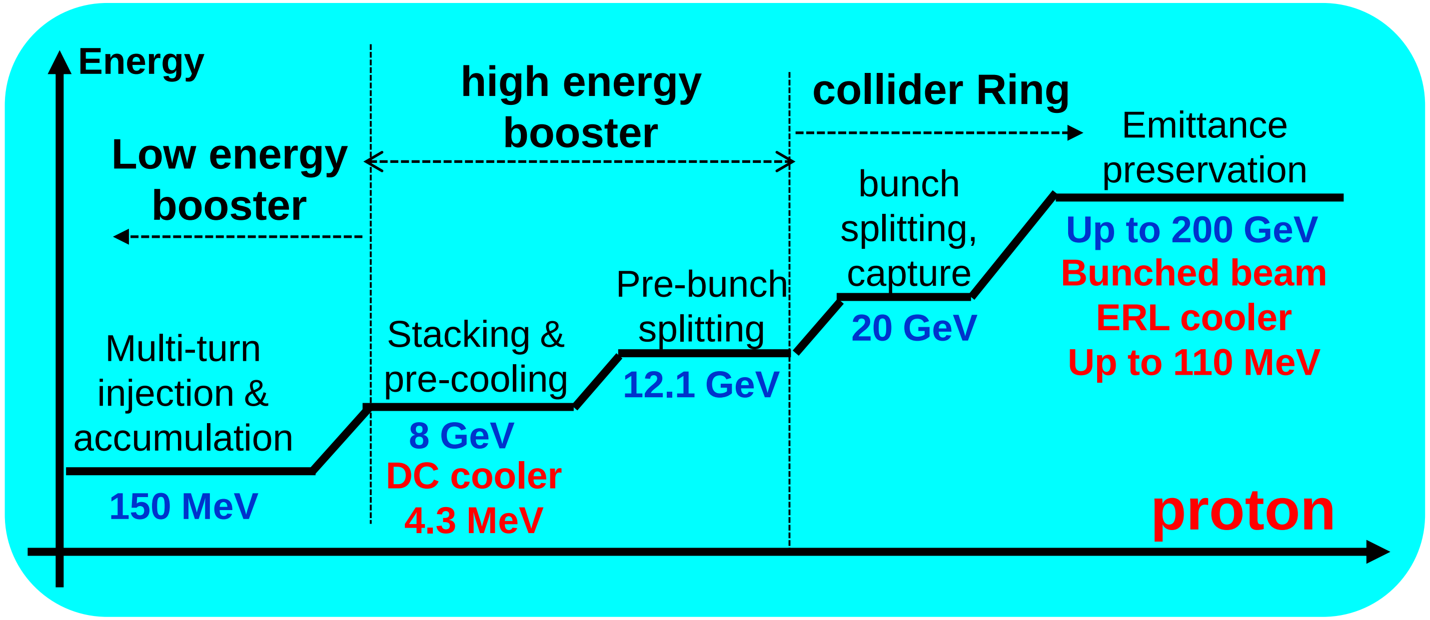
- Takes 150 MeV protons from the ion linac
- Proton extraction energy: 8 GeV
- Ring circumference is 604.13 m,
- Use warm magnets and FODO lattice
- γ_t=10.6 to avoid transition crossing

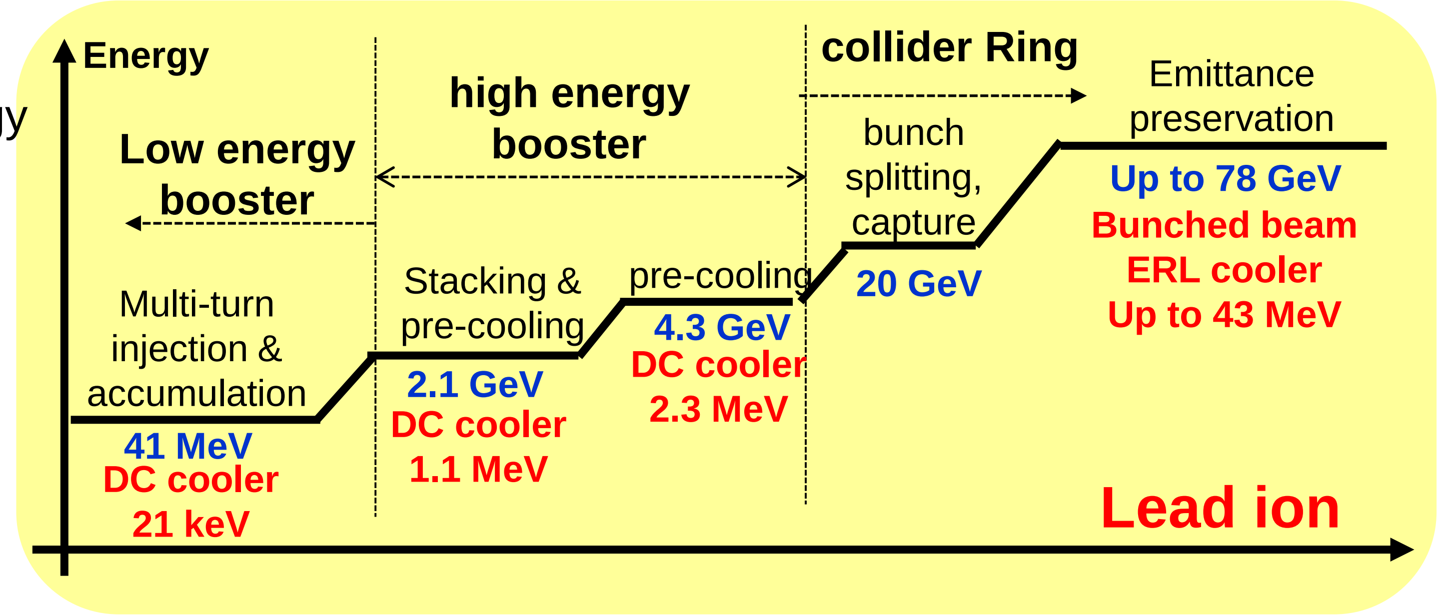


High Energy Booster

- In the tunnel along with the two collider rings.
- Accelerates protons from 8 to 12.1 GeV kinetic energy
- Ring circumference is 2336 m
- Uses a FODO lattice with a γ_t of 15.6

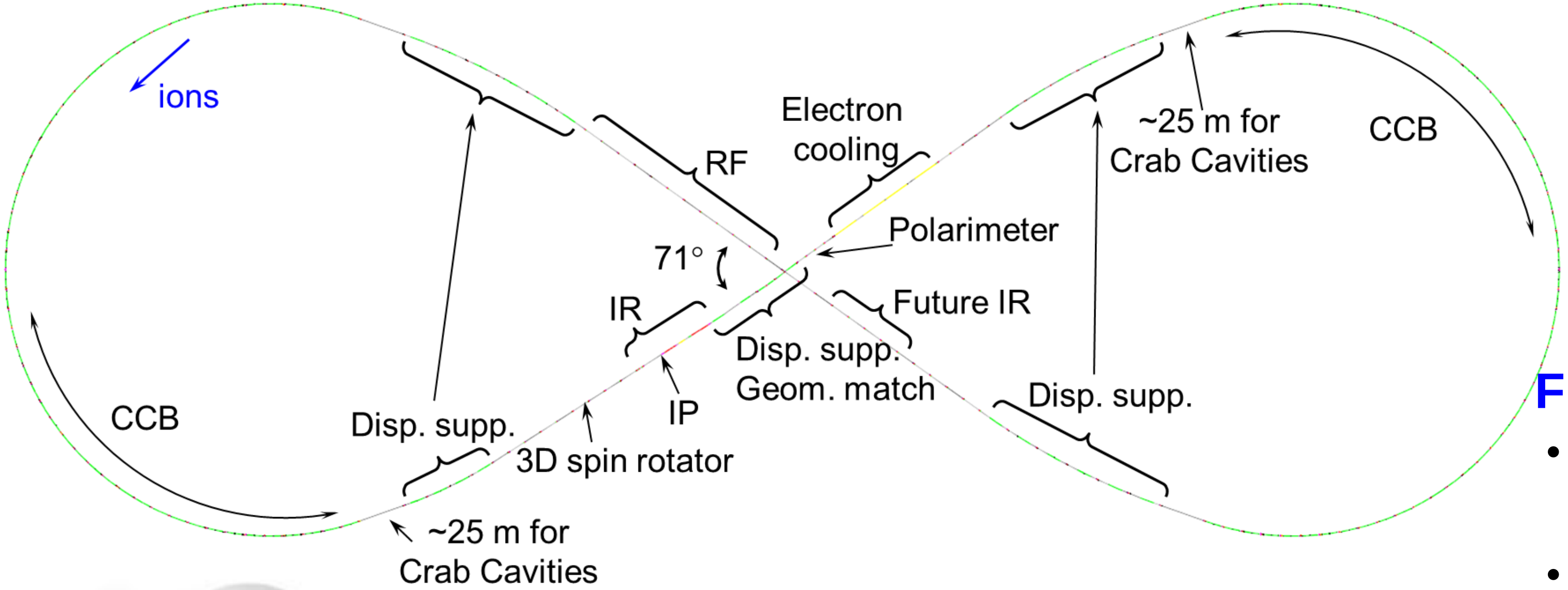






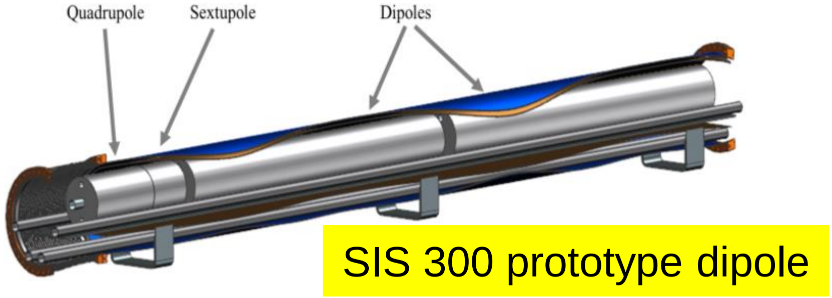
Ion Collider Ring and Ion Beam Polarization

- Circumference of 2336 m optimized for synchronization
- 200 GeV/c protons, 6 T $\cos\theta$ dipoles and $\cos 2\theta$ quadrupoles

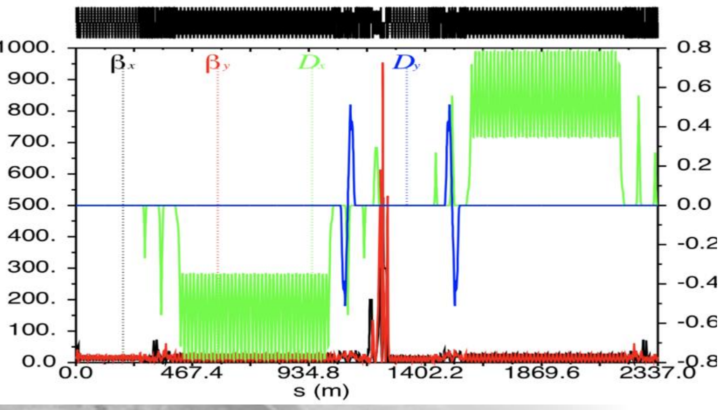


Arc SC magnets: 6 T

- Based on the SIS 300 prototype dipole design



SIS 300 prototype dipole



3D spin rotator

- Combination of small rotations about different axes
- Provides any polarization orientation at any point in the collider ring

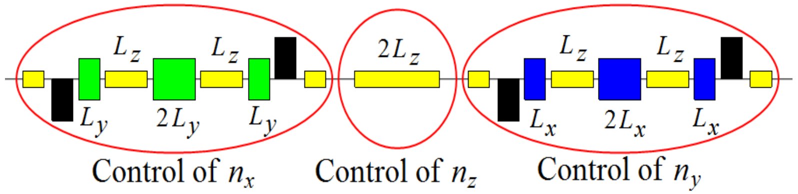
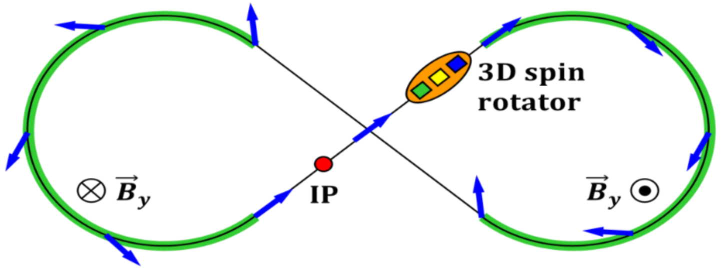


Figure-8 based polarization design

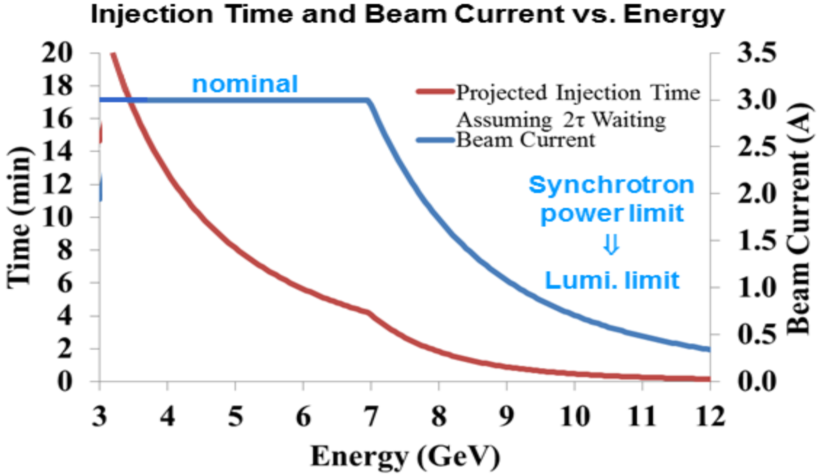
- Figure-8: spin precession in one arc is exactly cancelled in the other arc
- Polarized deuterons
- Spin stabilization by small fields: ~3 Tm vs. < 400 Tm for deuterons at 100 GeV
- Frequent adiabatic spin flips



Electron Collider Ring and Electron Polarization

- Full energy injection from CEBAF
  - New operation mode but no hardware modifications
  - Fixed-target program compatible with concurrent JLEIC operations
- SR power density up to **10 kW/m,** total up to **10 MW**

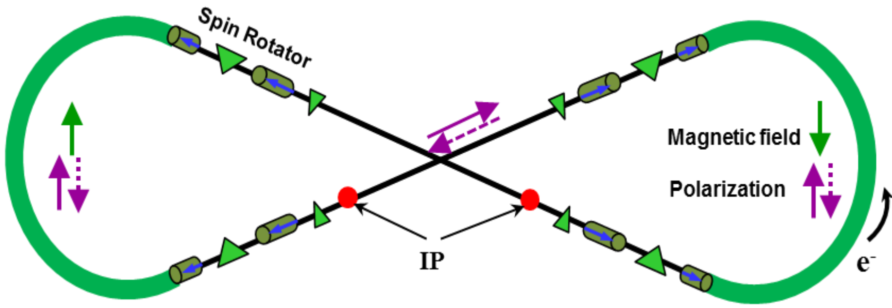
Parameter	Units					
Energy	GeV	3	5	7	10	12
Beam current	A	3	3.5	3	0.8	0.39
Total SR power	MW	0.30	2.28	8.76	9.73	9.84
Energy loss per turn	MeV	0.10	0.76	2.92	12.17	25.23
Energy spread	10^{-4}	2.5	4.1	5.8	8.2	9.9
Transverse damping time	ms	474	102	37	13	7
Longitudinal damping time	ms	237	51	19	6	4
Normalized horizontal emittance	um	18	85	234	683	1180
Normalized vertical emittance	um	1.3	6.0	16.6	48.3	83.5
Bunch length	cm	1	1	1	1	1.32



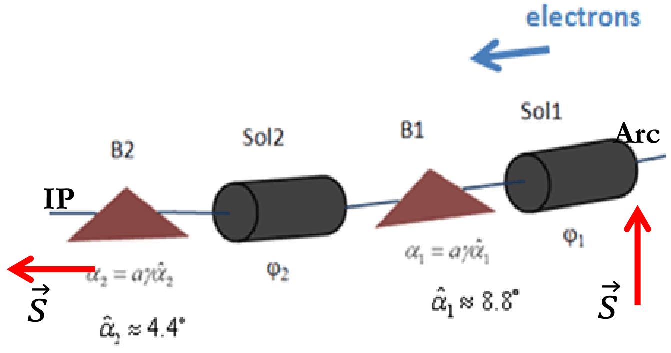
Electron polarization design

- Electron polarization from CEBAF polarized source >85%
- Spin-flip: 2 polarized bunch trains maintained by top-off injection
- Figure-8 helps maintaining polarization
- Minimizes spin diffusion by switching polarization orientation between vertical in arcs and longitudinal in straights

Energy (GeV)	3	5	7	10
Lifetime (hours)	66	8	2.2	0.3



Universal spin rotator: geometry, optics independent of energy



E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3

Multi-Phase Electron Cooling

Conventional electron cooling

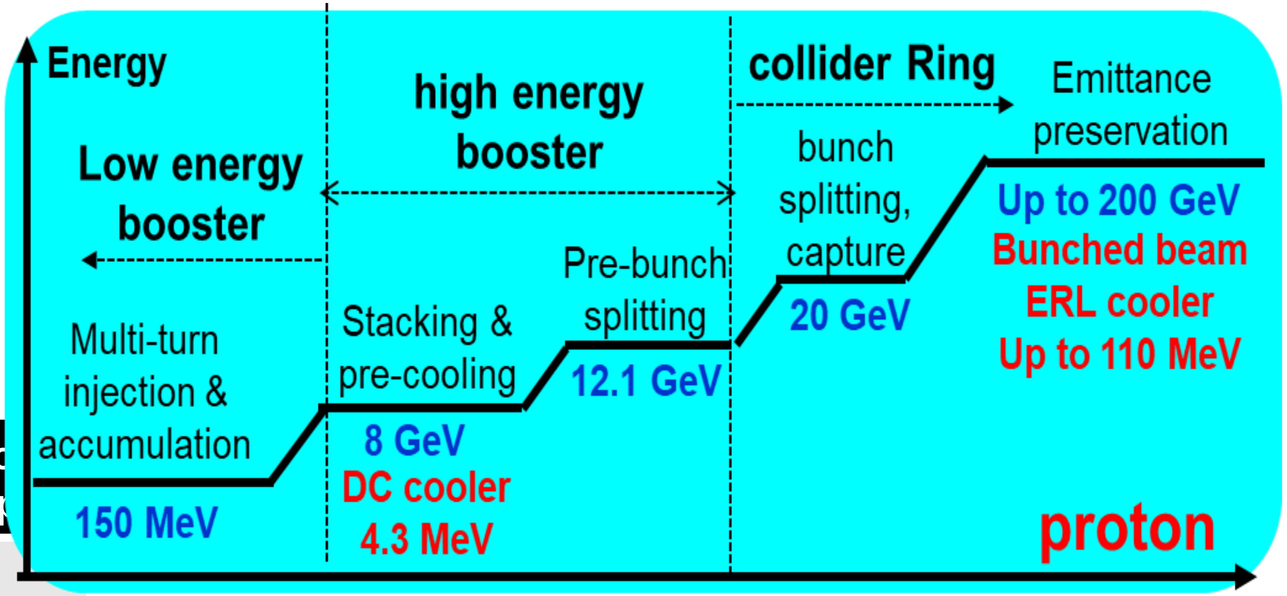
- Proved technology but in a new parameter regime
- Achieving very small emittance (up to **~10 times** reduction) and very short bunch (**~2 cm**) with SRF
- Assisting injection/accumulation of heavy ions
- Suppressing IBS induced emittance growth during beam store
- High cooling efficiency at low energy & small emittance

Pre-cool when energy is low

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

Cool at reduced emittance (after pre-cool)

Up to two orders of magnitude reduction of total cooling time



Multi-phase cooling scheme

- High cooling efficiency at low energy and/or low emittance
- Pre-cooling at low energy critical for 2 order of magnitude reduction of cooling time

Ring	Functions	Kinetic energy (GeV / MeV)			Coo typ
		Proton	Lead ion	Electron	
Low Energy Booster	Accumulation of positive ions		0.1 (injection)	0.054	DC
High Energy booster	Maintain emitt. during stacking	7.9 (injection)	2 (injection)	4.3 (proton) 1.1 (lead)	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	
collider ring	Maintain emitt. during collision	Up to 150	Up to 78	Up to 81.8	ERL

COSY cooler
2 MV magnetized

IMP cooler

Fermilab cooler
4 MV non-magnetized

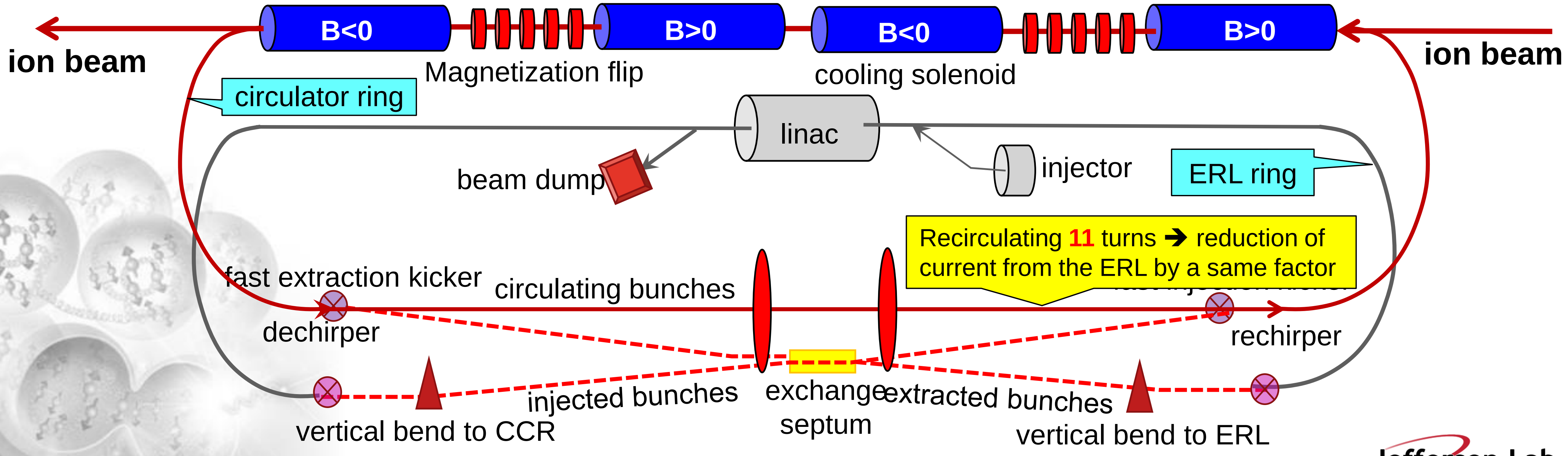
High Energy ERL-Circulator-Ring Cooler

Cooler requirements beyond *state-of-art*

- Current: 1.5 A / 3.2 nC (*strong cooling/baseline*)
- Energy: up to 82.5 MeV (*must use a RF/SRF linac*)
- Beam power: up to 124 MW (*too big to dump, must ER*)

Technical approaches

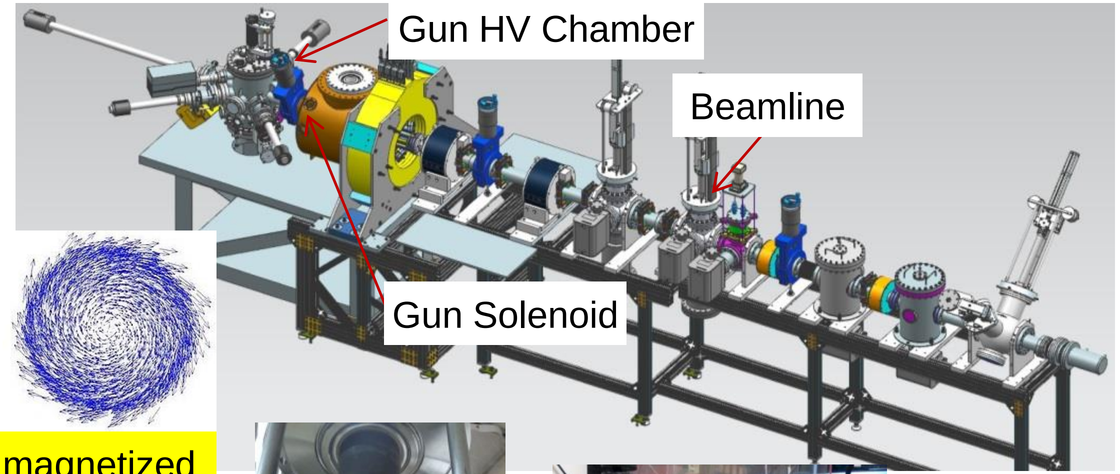
- Magnetized cooling (*magnetized gun*)
- SRF linac (*bunched beam*)
- Energy recovery (*power management*)
- Circulator ring (*current management*)
- Uses harmonic kicker to inject and extract from CCR
- Assumes high charge, low rep-rate injector



Jefferson Lab

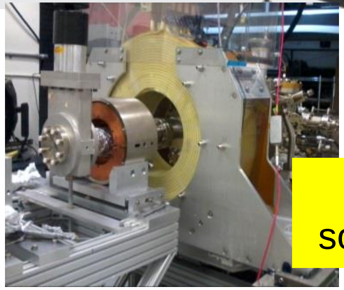
ERL-Circulator-Ring Cooler Technology Development

Magnetized source development



magnetized beam

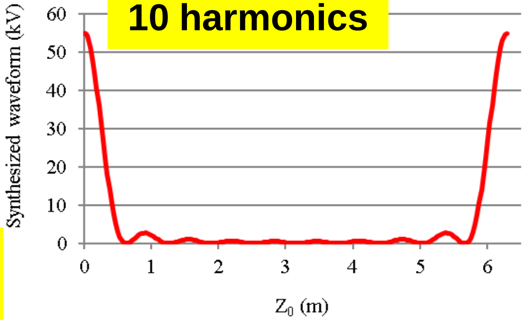
Gun HV chamber



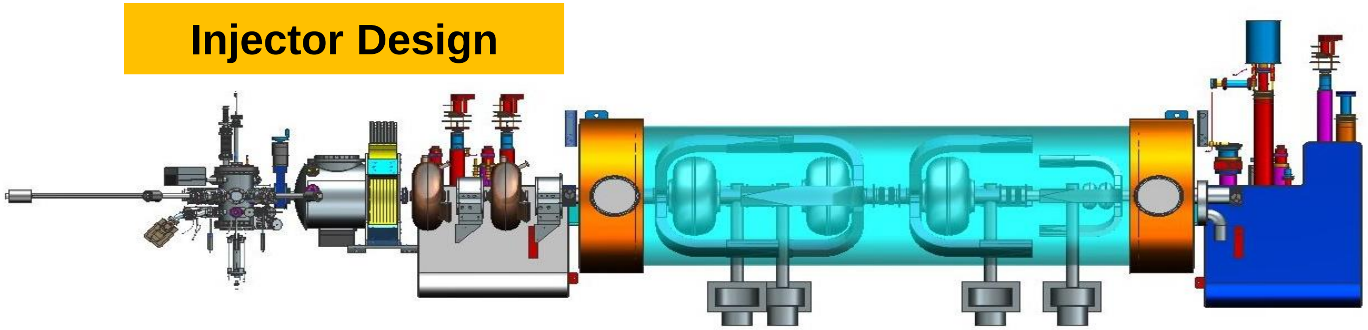
Gun solenoid

Harmonic RF Fast kicker

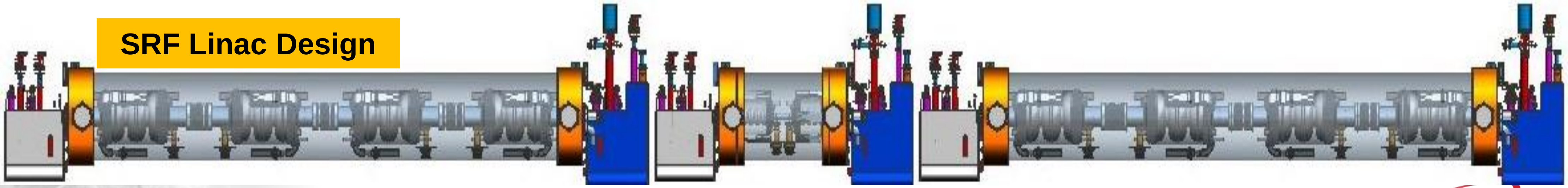
5 harmonic prototype



Injector Design

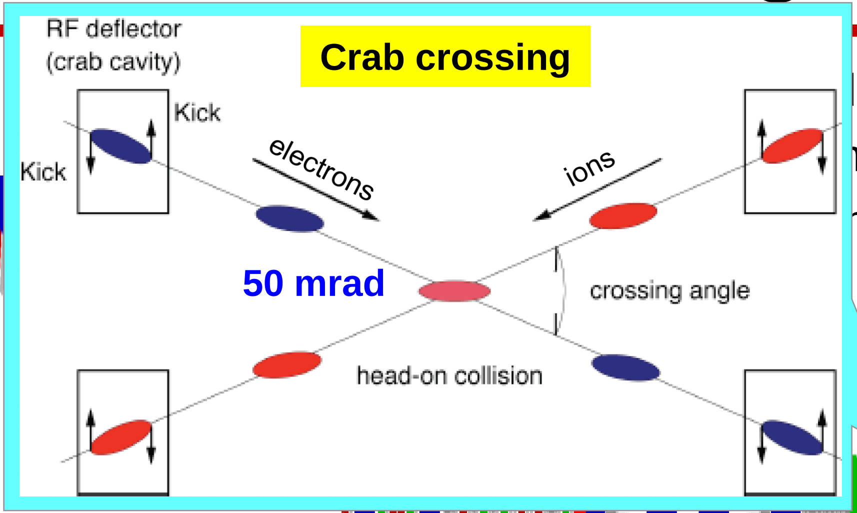


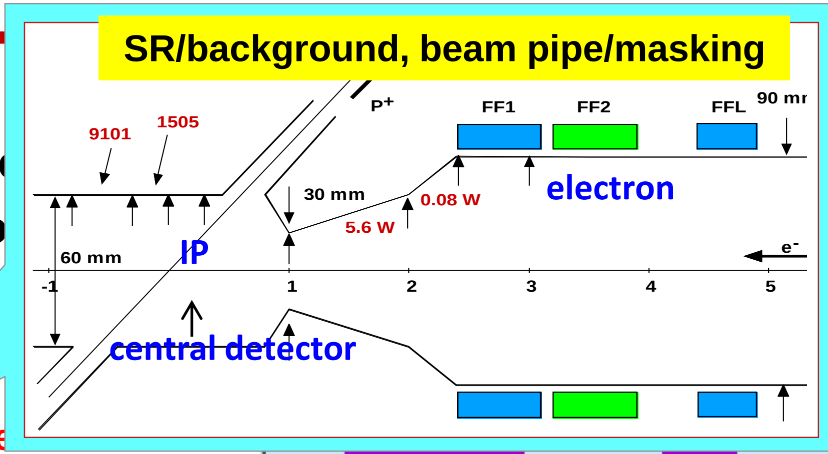
SRF Linac Design

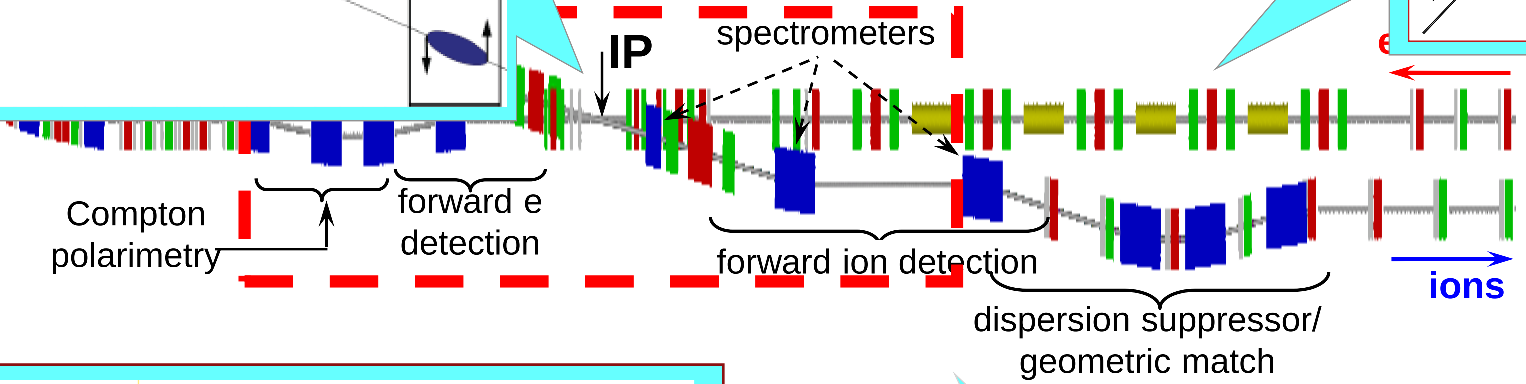


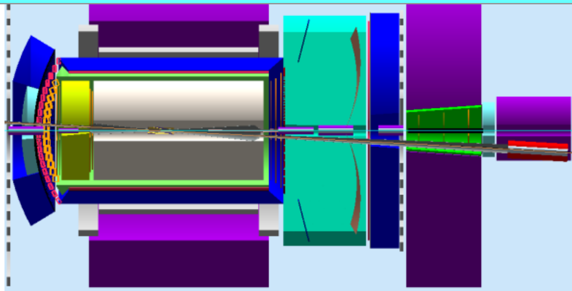
Interaction Region and Machine-Detector Interface

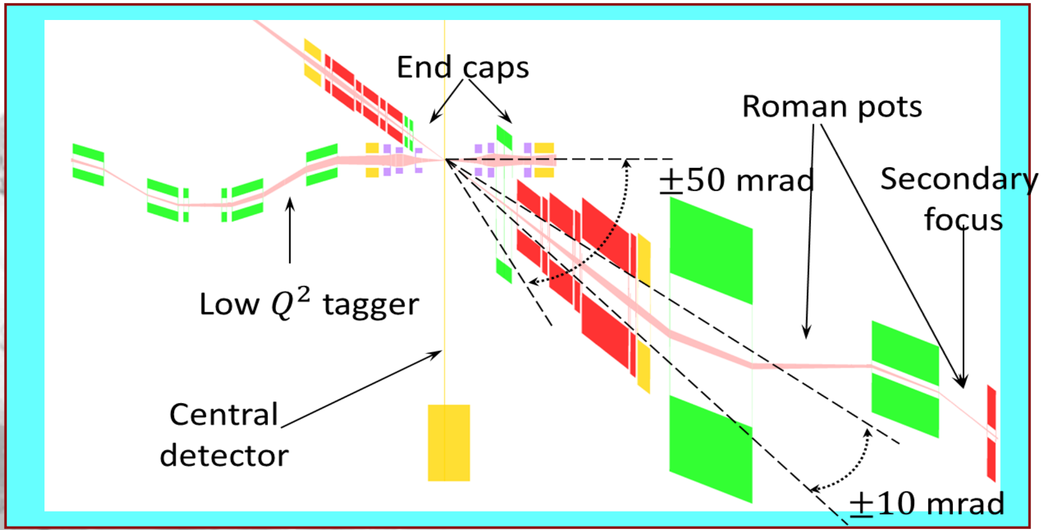
- to support ***full-acceptance*** detection ←
- metric match (elements) and **beam dynamic**
- ng: large (**50 mrad**), **avoiding parasitic co**

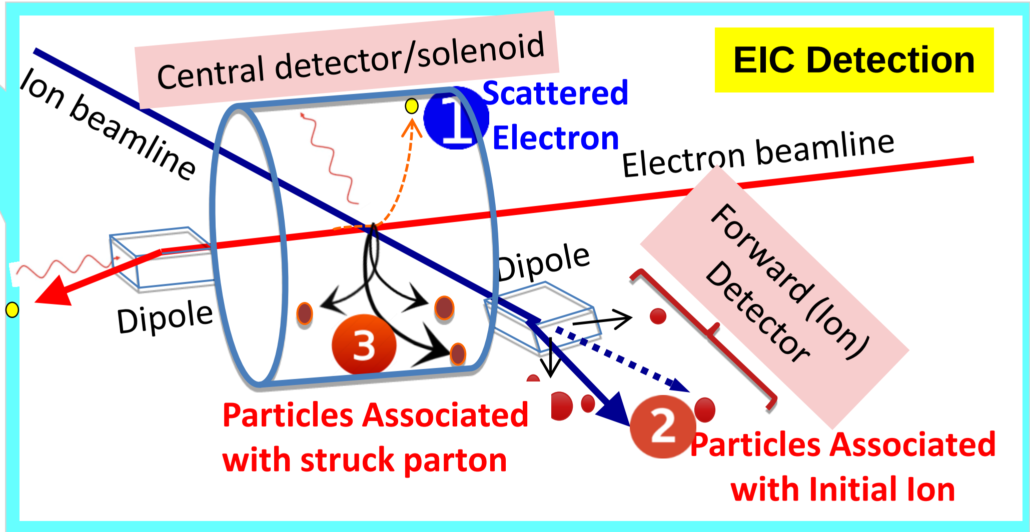






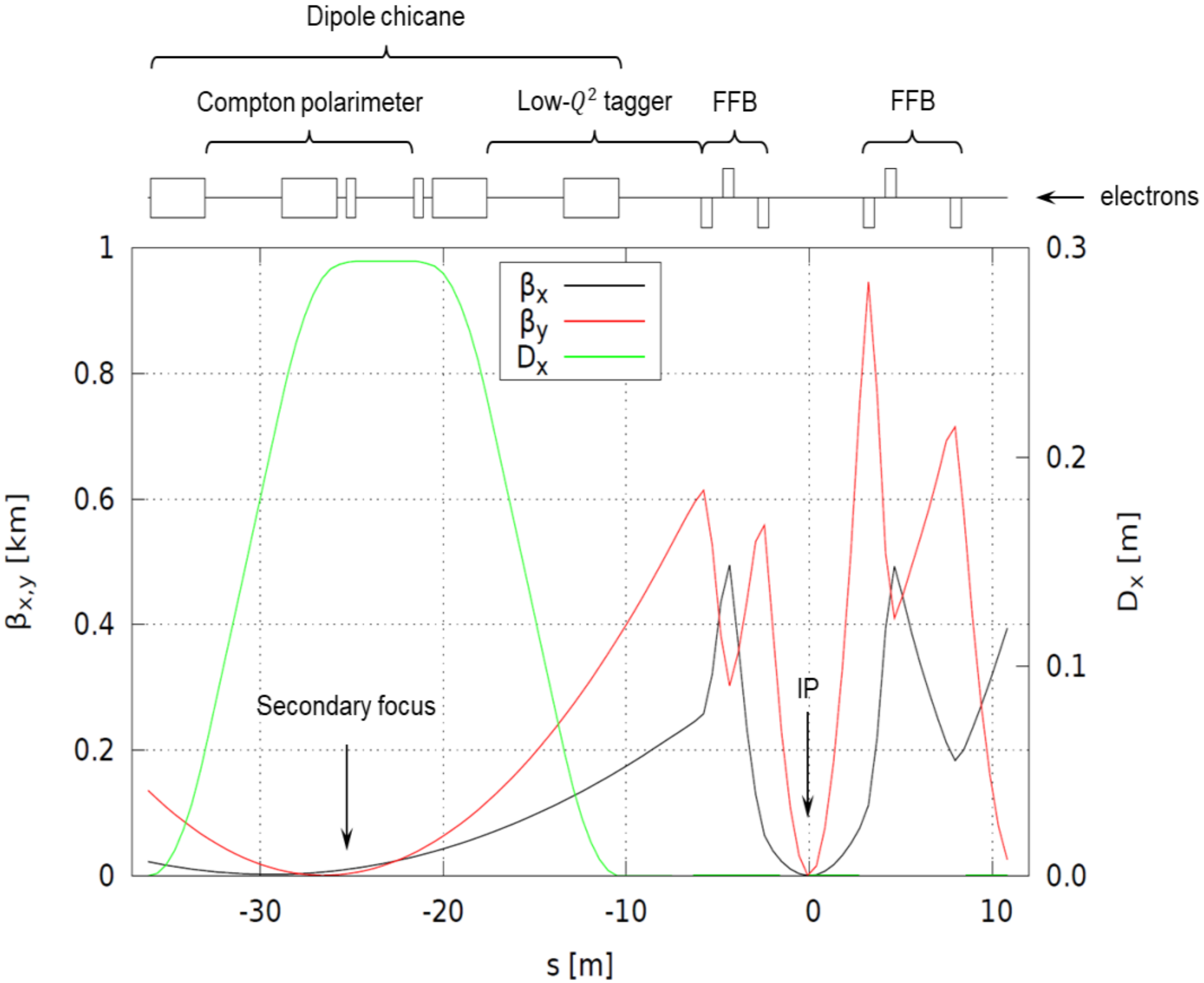




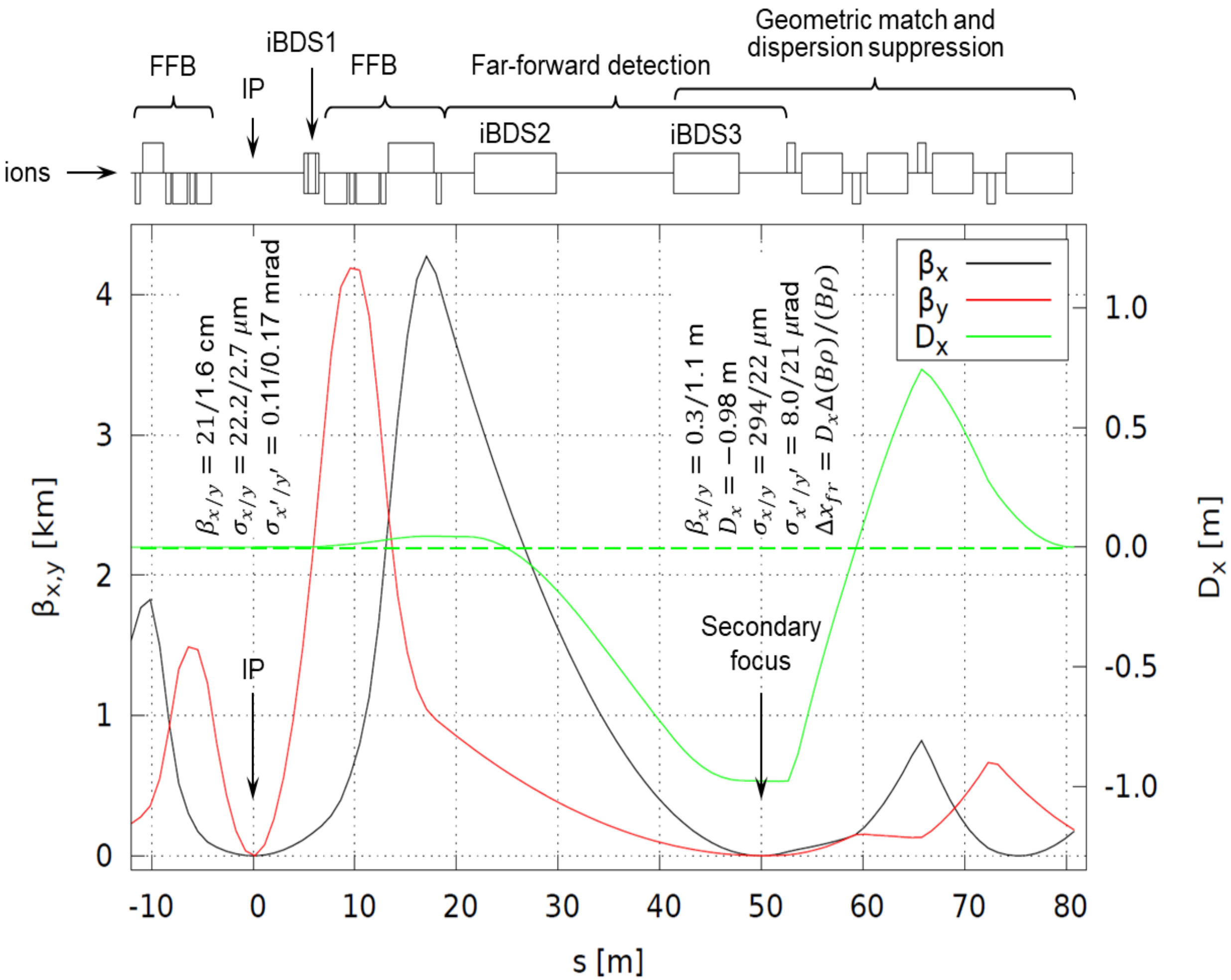


Interaction Region Optics in Electron & Ion Collider Ring

Electron IR



Ion IR



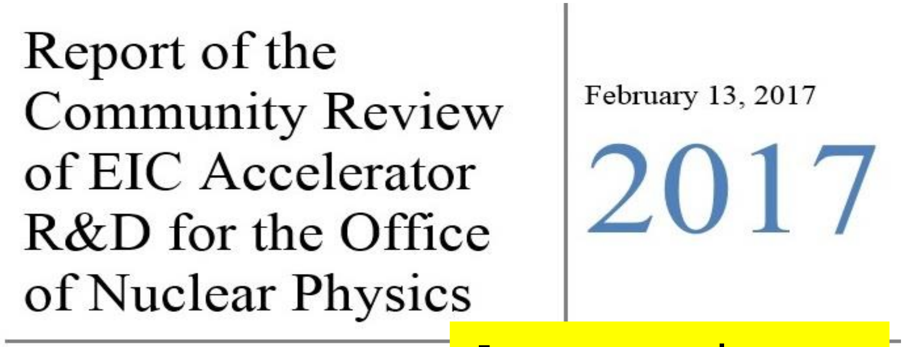
- Downstream chicane for low-Q^2 tagging and polarimetry

- Conventional NbTi technology
- Secondary focus with high dispersion

Jefferson Lab

EIC R&D at Jefferson Lab with Collaborations

- High-Priority EIC R&D topics defined by a community review panel (Jones panel)
- Accelerator R&D funded by NP – FY17, *completed*
  - Crab system design and experimental test
  - Electron cooler design
  - IR magnet design
  - Simulation software development
- Accelerator R&D fund by FY18-19
  - Crab cavity operation in a hadron ring (BNL, JLab, ODU)
  - Strong hadron cooling
    - Development of innovative high-energy magnetized electron cooling for an EIC (BNL, FNAL, JLab, ODU)
    - Strong hadron cooling with micro-bunched electron beams (ANL, BNL, JLab, SLAC)
  - Magnet design
    - High Gradient Actively Shielded Quadrupole (BNL, JLab, LBNL)
    - Validation of EIC IR magnet parameters and requirements using existing magnet results (JLAB, LBNL, SLAC)
  - Benchmarking of EIC simulations
    - Development & test of simulation tools for EIC beam-beam interaction (BNL, JLab, LBNL MSU)
    - Experimental verification of spin transparency mode in an EIC (BNL, JLab)
  - Electron complex
    - High Bandwidth Beam Feedback Systems for a High Luminosity EIC (ANL, JLab)


Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

Jones panel report

Jefferson Lab

Demonstration of Cooling of Ions by a Bunched e-Beam

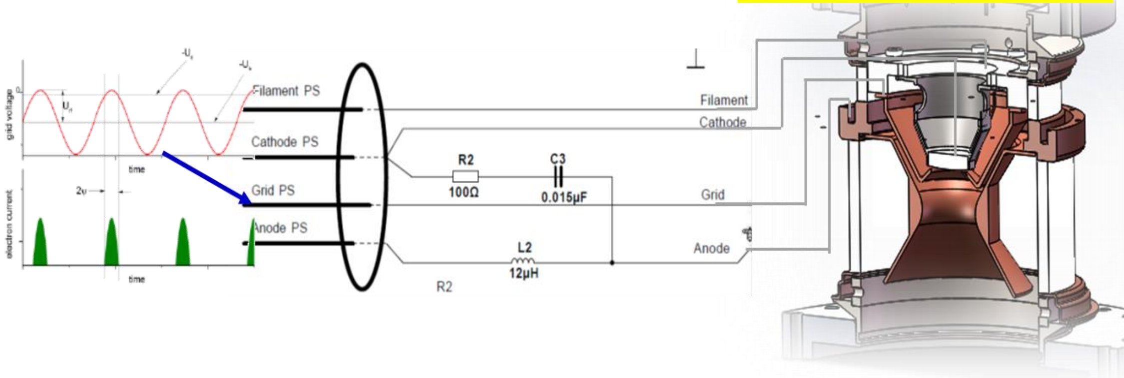
JLab-IMP Collaboration

- Using a DC cooler to demonstrate cooling by a bunched electron beam
- Pulsed electron beam from a thermionic gun by switching on/off the grid electrode
- 1st Experiments performed on 4/2016, follow-up experiment on 4/2017, 12/2018

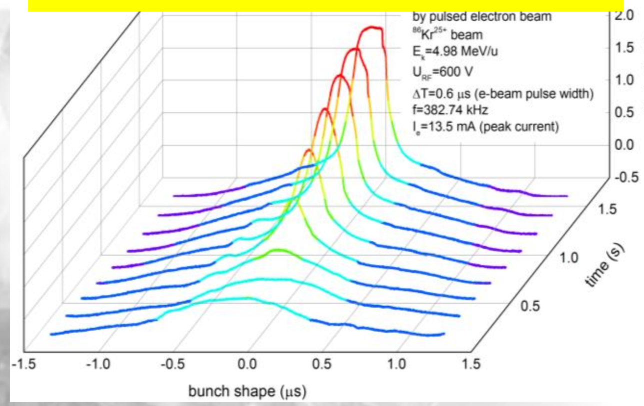
A DC electron cooler at Institute of Modern Physics, China

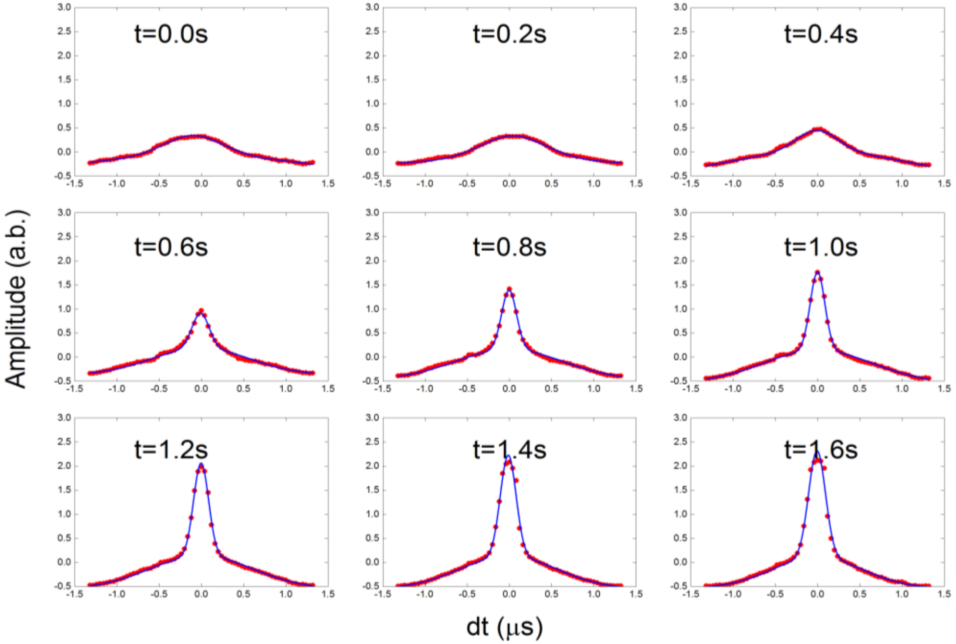
Energy (i/e)	5 MeV/u & 2.7 KeV
Ion bunches	2
RF voltage	600 V
Stored ions	~10^8
Anode voltage	400 V, 600 V, 800 V
Pulse width	300 ns to 1200 ns

thermionic gun

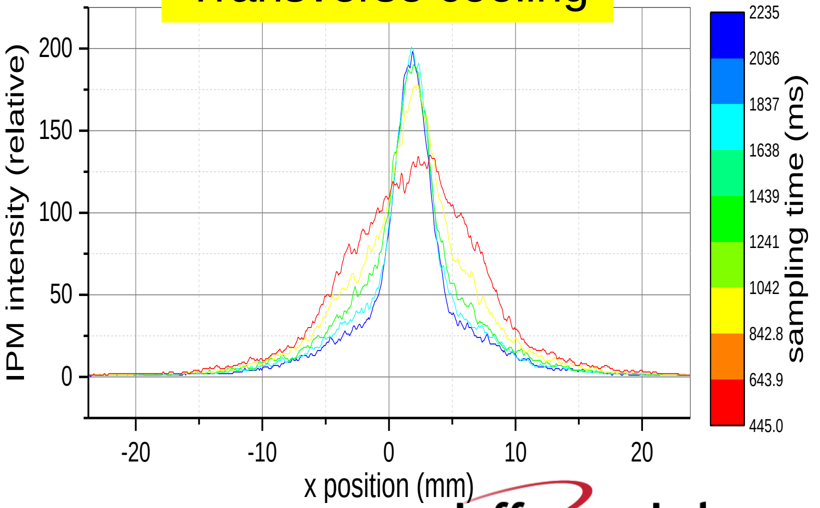


Longitudinal cooling (reduction of bunch length)





Transverse cooling



Jefferson Lab

Summary

- JLEIC ***meets or exceeds*** the EIC requirements (High luminosity, high polarization, full-acceptance detection)
- JLEIC takes advantage of modern SRF electron linac and a green-field ion complex
- Pre-CDR is completed and will be released soon
- Present focus: design optimization for robustness & cost efficiency, accelerator R&D

EIC White Paper Requirements (2013), page 9	NSAC Long Range Plan Requirements (2015), page 39	NAS Report Requirements (2018), pages 53/54	JLEIC Design (2019)	
Variable CM energies from ~20-~100 GeV, upgradable to ~140 GeV.	Variable CM energies ~20-100 GeV, upgradable to ~140 GeV	Extensive CM energy range from ~20-~100 GeV, upgradable to ~140 GeV.	Center-of-mass energy 19 to 98 GeV upgradable to 140 GeV.	✓
Ion beams from deuteron to the heaviest nuclei (uranium or lead).	Ion beams from deuteron to the heaviest stable nuclei.	Ion beams from deuterons to the heaviest stable ions.	Protons, deuterons, ^{3}He (all polarizable) and up to Pb/U.	✓
High collision luminosity ~$10^{33\text{-}34}$ $cm^{-2}s^{-1}$	High collision luminosity ~$10^{33\text{-}34}$ $cm^{-2}s^{-1}$	Luminosity 100 to 1000 times HERA. (equivalent to 10^{33} to 10^{34} $cm^{-2}s^{-1}$ average luminosity)	Average luminosity 10^{33} to >10^{34} $cm^{-2}s^{-1}$ over center-of-mass energy range 19 to >90 GeV.	✓
Highly polarized (~70%) electron and nucleon beams	Polarized (~70%) electrons, protons, and light nuclei.	Spin Polarized (~70% at a minimum) electron and proton/light-ion beams.	85% polarization for electrons and proton/light-ion beams.	✓
Possibilities of more than one interaction region.	Possibly have more than one interaction region.	One or more interaction regions.	Two interaction regions.	✓

JLEIC Collaboration

For Accelerator and Detector

S. Benson, A. Bogacz, P. Brindza, M. Bruker, A. Camsonne, P. Degtyarenko, E. Daly, Ya. Derbenev, M. Diefenthaler, K. Deitrick, D. Douglas, R. Ent, R. Fair, Y. Furletova, R. Gamage, D. Gaskell, R. Geng, P. Ghoshal, J. Grames, K. Jorden, J. Guo, F. Hanna, L. Harwood, T. Hiatt, H. Huang, A. Hutton, K. Jordan, A. Kimber, D. Kashy, G. Krafft, R. Lessiter, R. Li, F. Lin, M. Mamum, F. Marhauser, R. McKeown, T. Michalski, V. Morozov, E. Nissen, G. Park, H. Park, M. Poelker, T. Powers, R. Rajput-Ghoshal, R. Rimmer, Y. Roblin, T. Satogata, A. Seryi, M. Spata, R. Suleiman, A. Sy, C. Tennant, H. Wang, S. Wang, C. Weiss, M. Wiseman, W. Wittmer, R. Yoshida, H. Zhang, S. Zhang, Y. Zhang – **JLab**

Y. Nosochkov, G. Stupakov, M. Sullivan, C. Tsai, M. Wang - **SLAC** *J. Qiang, G. Sabbi* – **LBNL** *D. Barber* – **DESY**

M. Blaskiewicz, H. Huang, Y. Luo, Q. Wu, F. Willeke – **BNL** *Z. Conway, B. Mustapha, U. Wienands, A. Zholents* – **ANL**

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J. Delayen, C. Hyde, S. De Silva, S. Sosa, B. Terzic - **Old Dominion Univ.** *P. Nadel-Turonski*, - **Stony Brook Univ.**,

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

V. Dudnikov, R. Johnson - **Muons, Inc.**, *D. Abell, D. Bruhwiler, I. Pogorelov* - **Radiasoft**, *G. Bell, J. Cary* - **Tech-X Corp.**,

A. Kondratenko, M. Kondratenko - **Sci. & Tech. Laboratory Zaryad**, Russia

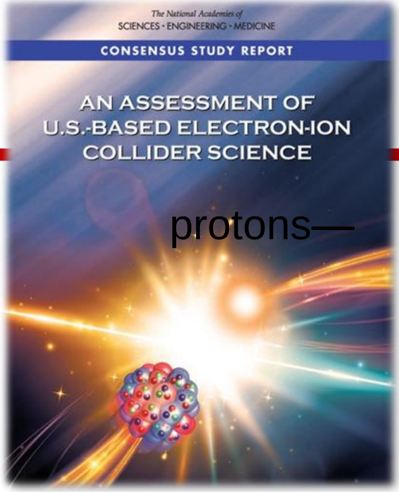
Yu. Filatov - **Moscow Institute of Physics and Technology**, Russia

Y. Huang, X. Ma, L. Mao, Y. Yuan, H. Zhao, H.W. Zhao – **IMP**, China

Gone but not forgotten

S. Ahmed, K. Beard, A. Castilla, Y. Chao, P. Chevtsov, L. Merminga, F. Pilat, H. Sayed, G. Wei, B. Yunn,

EIC Science Assessments by US NAS



Finding 1: (Science) An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Finding 2: (Accelerator) These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Finding 3: An EIC would be a unique facility in the world, and would maintain U.S. leadership in nuclear physics.

Finding 4: An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.

Finding 5: Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Finding 6: The current accelerator R&D program supported by the Department of Energy is crucial to addressing outstanding design challenges.

Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and further, to glean the fundamental insights into QCD that an EIC can reveal.

Finding 8: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high luminosity polarized Electron Ion Collider (EIC) as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Finding 9: The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.