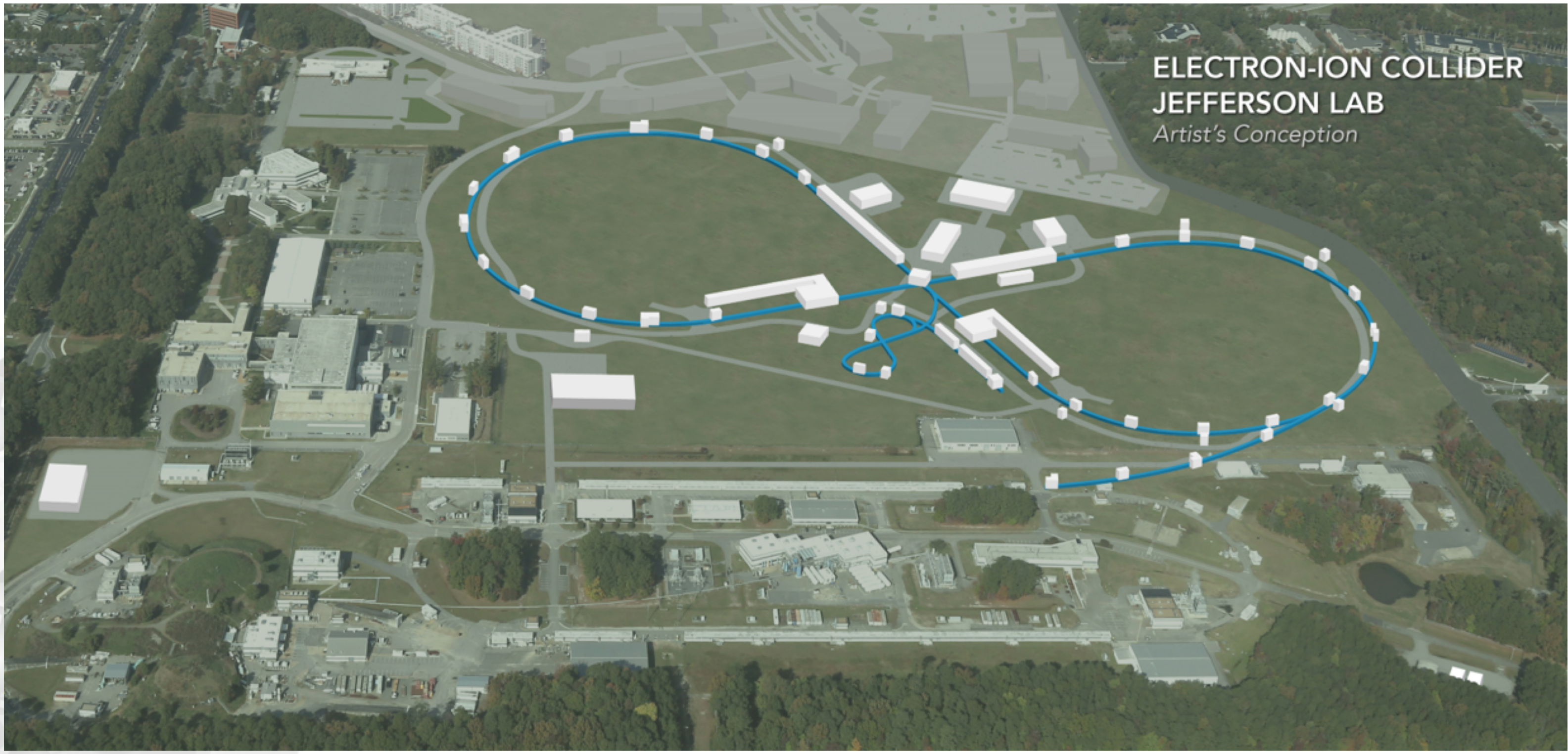
Jefferson Lab's EIC Design

Fanglei Lin (JLab)
on behalf of JLEIC Collaboration



23rd International Spin Symposium (SPIN2018), Ferrara, Italy, September 10-14, 2018

JLEIC Collaboration

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

D.P. Barber - **DESY**, Germany

Y. Cai, Y.M. Nosochkov, M. Sullivan - **SLAC**, CA

S. Manikonda, B. Mustapha, U. Wienands - **Argonne National Laboratory**, IL

P.N. Ostroumov, R.C. York - **Michigan State University**, MI

S. Abeyratne, B. Erdelyi - **Northern Illinois University**, IL

J. Delayen, H. Huang, C. Hyde, K. Park, S. De Silva, S. Sosa, B. Terzic - **Old Dominion University**, VA

P. Nadel-Turonski, **SUNY**, NY

Z. Zhao - **Duke University**, NC

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

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

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

V. Dudnikov, R.P. Johnson - **Muons, Inc.**, IL

I. Pogorelov, G. Bell, J. Cary - **Tech-X Corp.**, CO

D. Bruhwiler - **Radiasoft**, CO

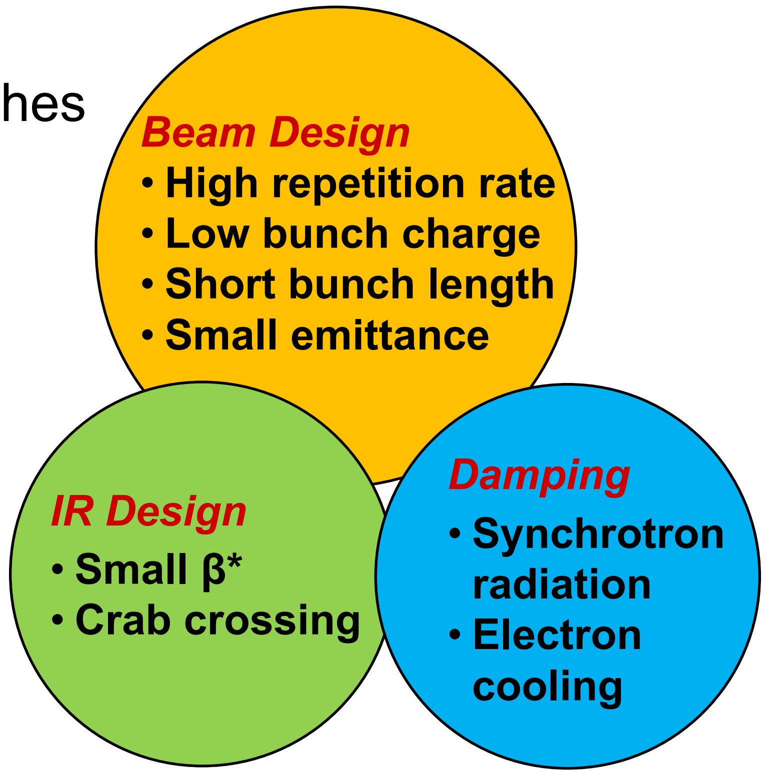
Outline

- Overall layout of JLEIC
- Electron complex
  - CEBAF as a full-energy injector
  - Electron collider ring
  - Electron polarization
- Ion complex
  - Ion injector complex: ion sources, linac, and booster
  - Ion collider ring
  - Ion polarization
  - Electron cooling
- Detector region
  - Layout
  - Crab crossing
- Conclusions

Key Design Concepts

- **High luminosity**: **high collision rate** of short modest-charge low-emittance bunches
  - **Small beam size**
    - Small β* ⇒ Short bunch length ⇒ Low bunch charge, high repetition rate
    - Small emittance ⇒ Cooling
  - Similar to lepton colliders such as KEK-B with L > 2×10^{34} cm^{-2}s^{-1}

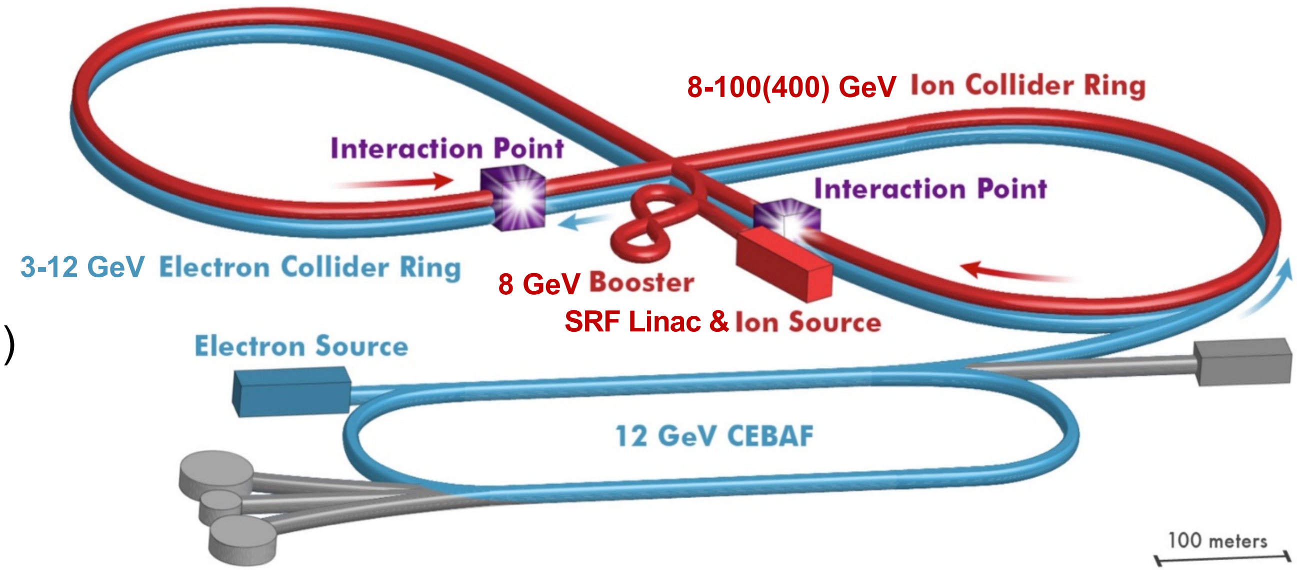
$$L = f\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim f\frac{n_1 n_2}{\varepsilon\beta_y^*}$$

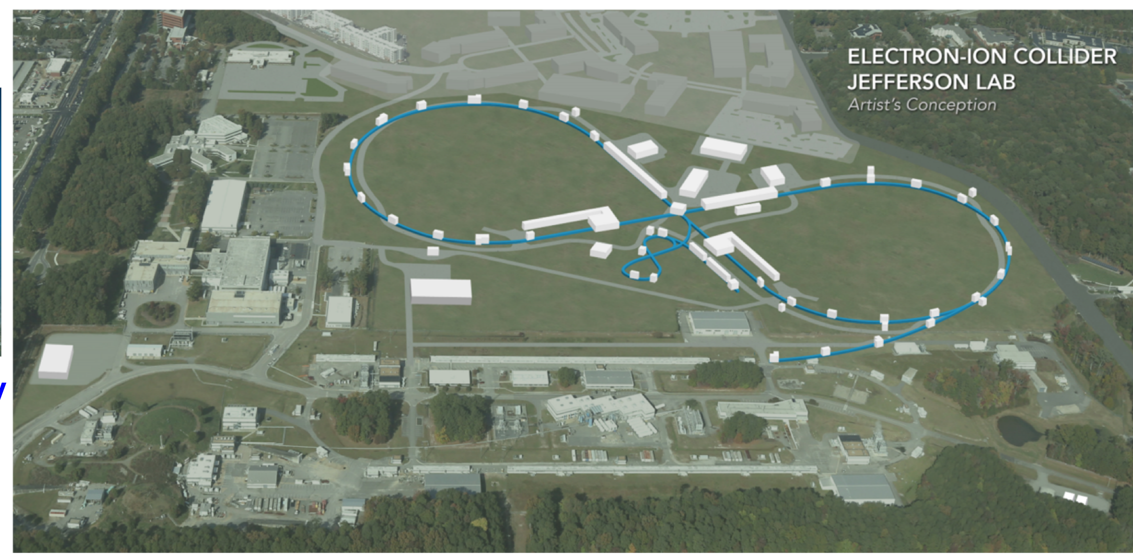


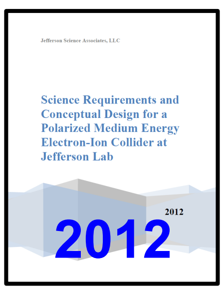
- **High polarization**: **figure-8** ring design
  - Net spin precession zero
  - Spin easily controlled by small magnetic fields for any particle species
- **Full acceptance primary detector** including **far-forward acceptance**

JLEIC Layout

- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac (280 MeV for protons)
  - Booster
  - Ion collider ring
- Up to two detectors at minimum background locations

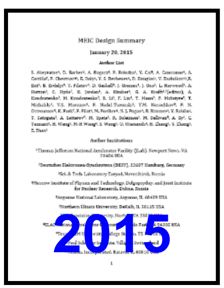





Jefferson Science Associates, LLC

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

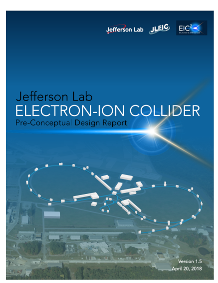
2012


MEIC Design Summary

January 20, 2015

Author List

2015



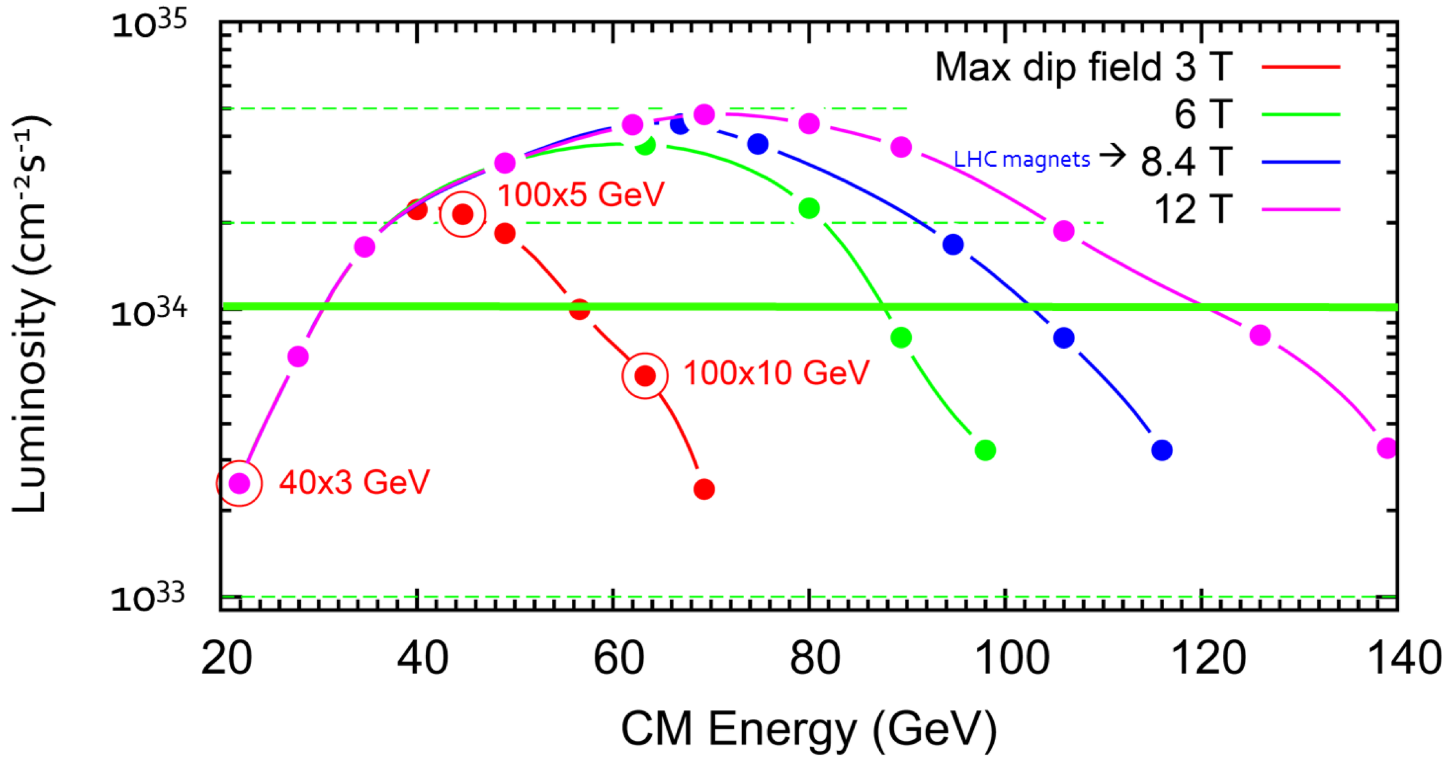
arXiv:1209.0757
arXiv:1504.07961

Completed by October 2018

JLEIC Parameters (3T option)

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. emittance, hor / ver	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**	5.1/1.0	10.5/2.1	4/0.8
Ver. beam-beam parameter		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}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**5.9**	

JLEIC Energy Reach and Luminosity

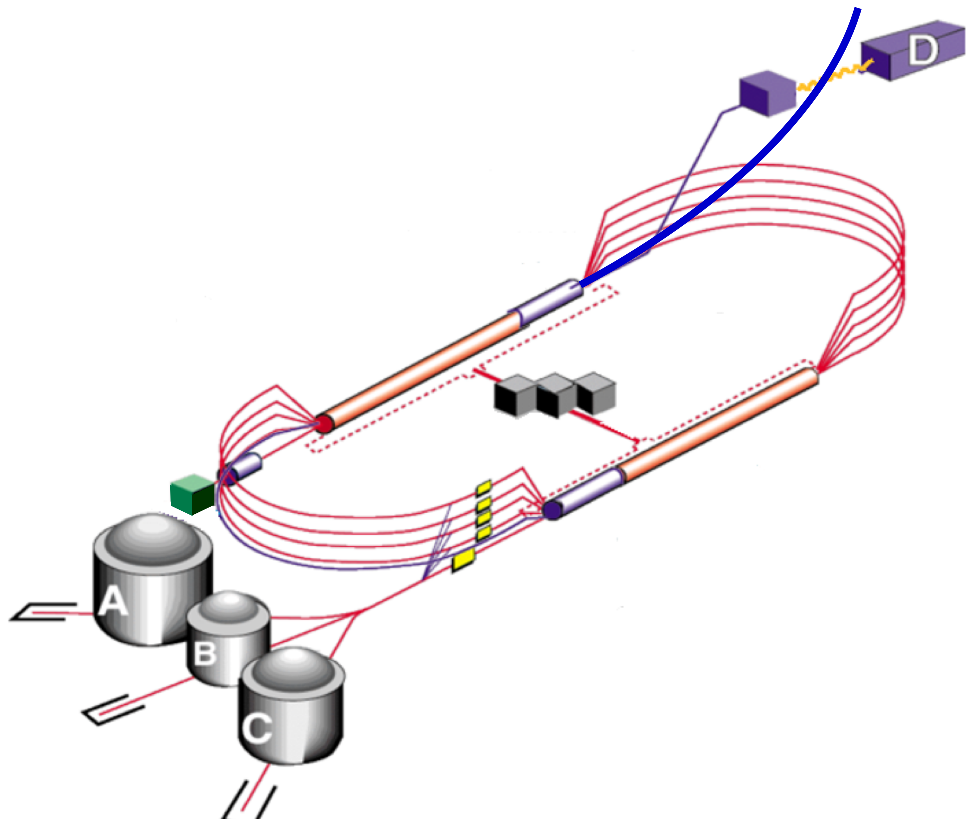


CM Energy (in each scenario)	Main luminosity limitation
low	space charge
medium	beam-beam
high	synchrotron radiation

12 GeV CEBAF as Injector

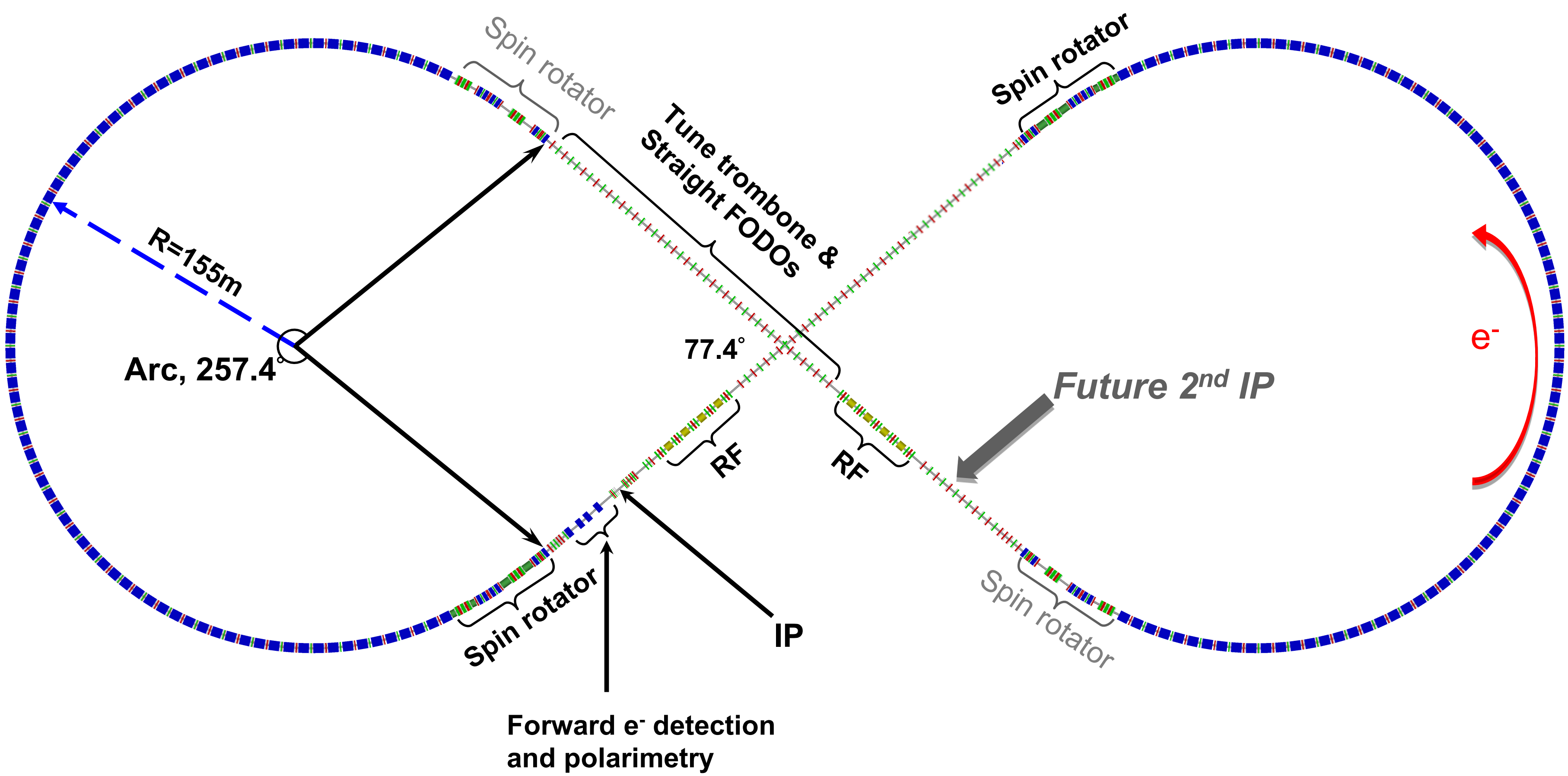
- Extensive fixed-target science program
  - Fixed-target program compatible with concurrent JLEIC operations
- JLEIC injector
  - Fast fill of collider ring
  - Full energy
  - ~85% polarization
  - Enables top-off
- New operation mode but no hardware modifications

Up to 12 GeV to JLEIC



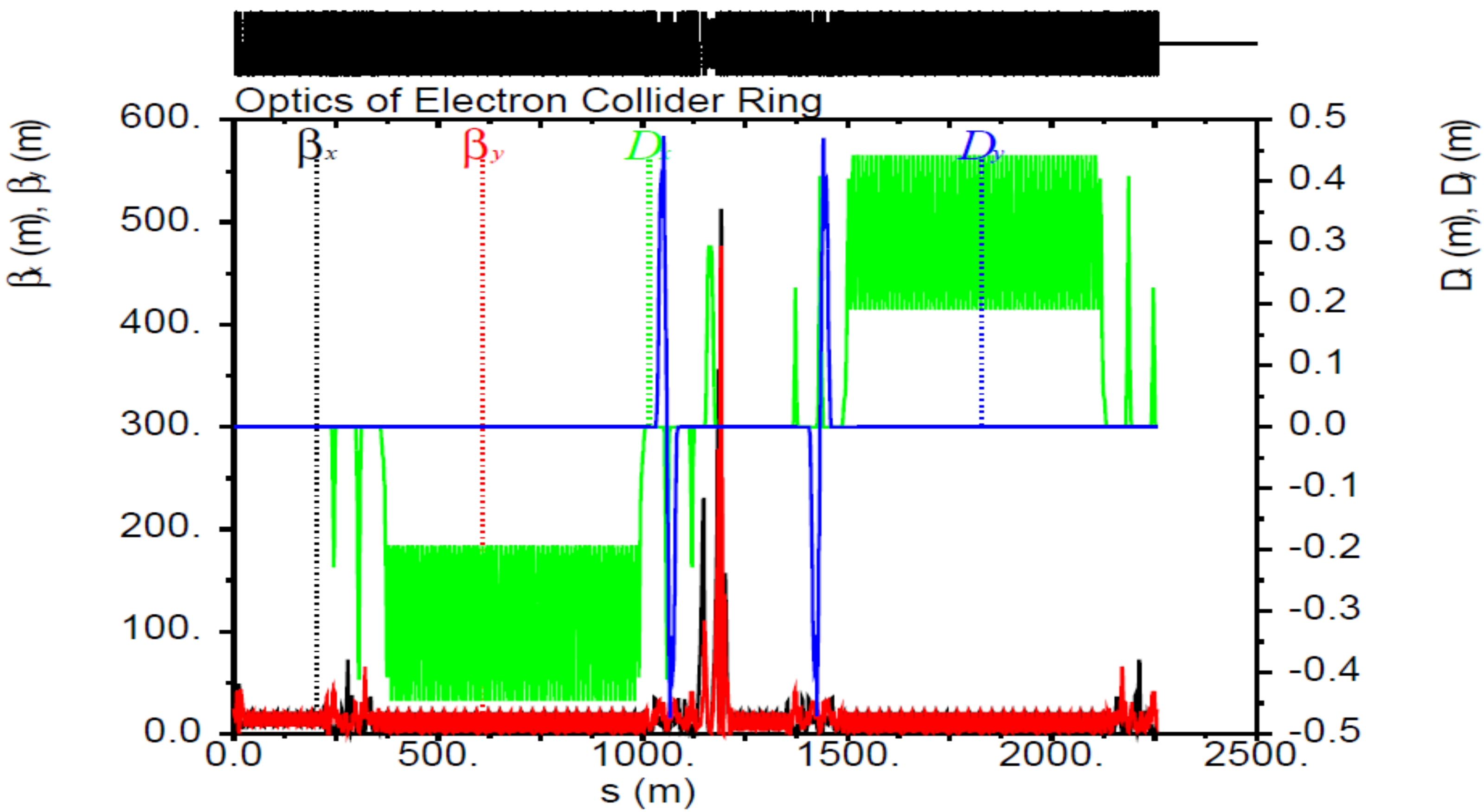
Electron Collider Ring Layout

- Possible cost reduction by reusing PEP-II RF and vacuum pipe



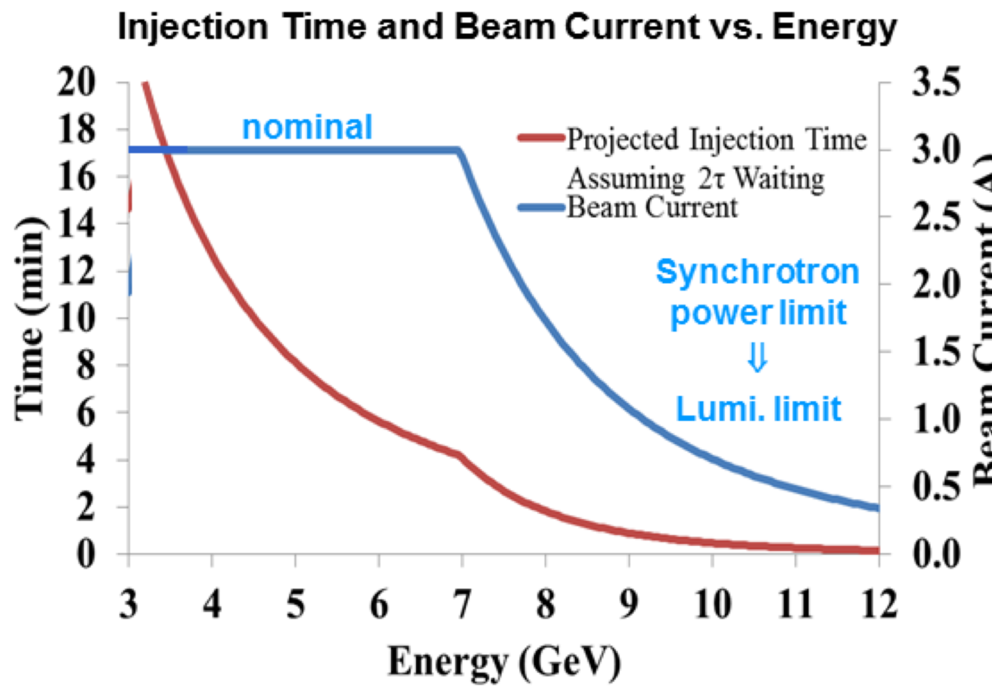
Electron Collider Ring Optics

- Global chromaticity compensation scheme



Electron Beam

- Electron beam
  - **3 A** at up to 7 GeV
  - Normalized emittance **58 µm** @ 5 GeV
  - Synchrotron power density < **10 kW/m**
  - Total power up to **10 MW**



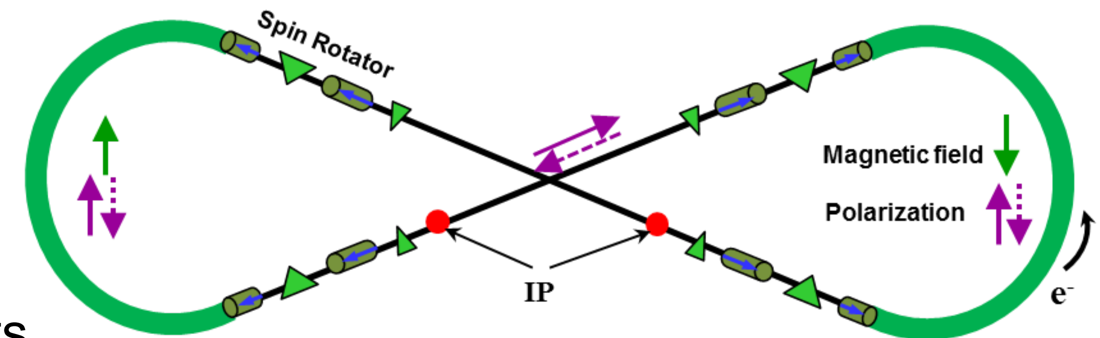
Beam energy	GeV	3	5	6.9	9	10	12
Beam current	A	3	3	3	1	0.69	0.33
Total SR power	MW	0.4	2.7	9.6	9.3	9.8	9.7
Energy loss per turn	MeV	0.12	0.88	3.2	9.3	14.2	29.4
Energy spread	10^{-4}	2.8	4.6	6.4	8.4	9.3	11.1
Transverse damping time	ms	389	84	32	14	11	6
Longitudinal damping time	ms	194	42	16	7	5	3
Normalized Emittance	um	13	58	152	337	462	799

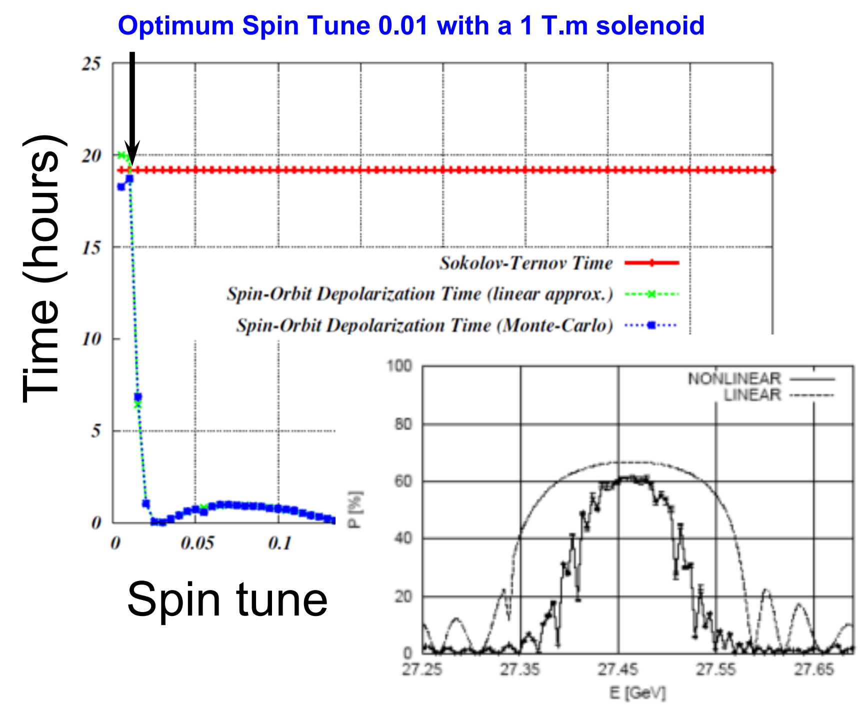
Electron Polarization

- Two highly polarized bunch trains maintained by top-off
- Universal spin rotator
  - Sequence of solenoid and dipole sections
  - Makes the spin longitudinal in the straights
  - Basic spin match

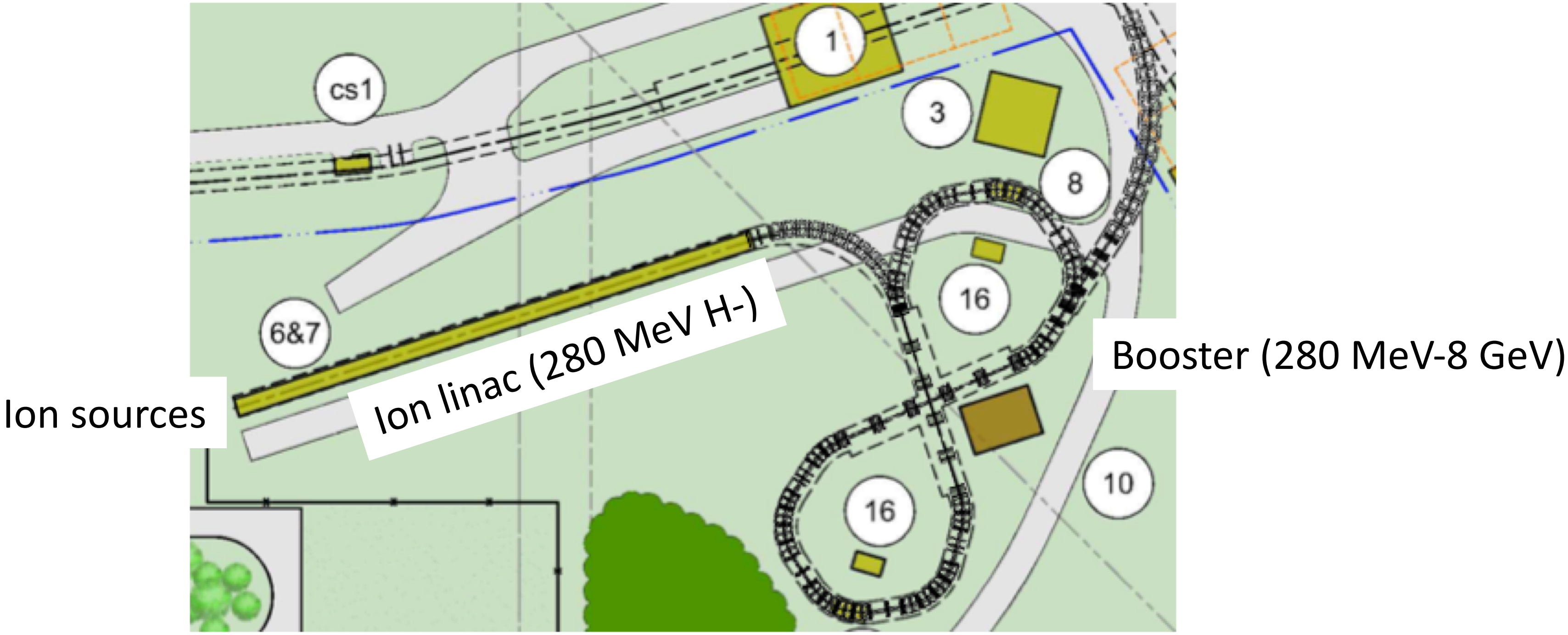
Energy (GeV)	3	5	7	9	12
Lifetime (hours)	116	9	1.7	0.5	0.1

  - Lifetimes are the same for both states
- Advantage of figure-8 geometry: minimum depolarization demonstrated by spin tracking





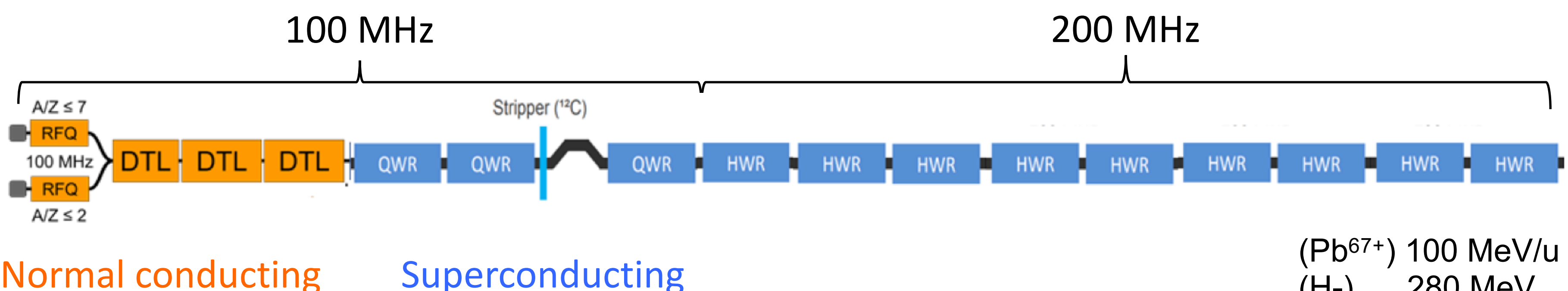
Ion Injector Complex Overview



- Ion injector complex relies on demonstrated technologies for sources and injectors
  - Atomic Beam Polarized Ion Source (ABPIS) for polarized or unpolarized light ions, Electron Beam Ion Source (EBIS) and/or Electron Cyclotron Resonance (ECR) ion source for unpolarized heavy ions
  - Design for an SRF linac based on ANL design
  - 8 GeV Booster with no transition energy crossing
  - Injection/extraction lines to/from Booster are designed

JLEIC Injector Linac Design

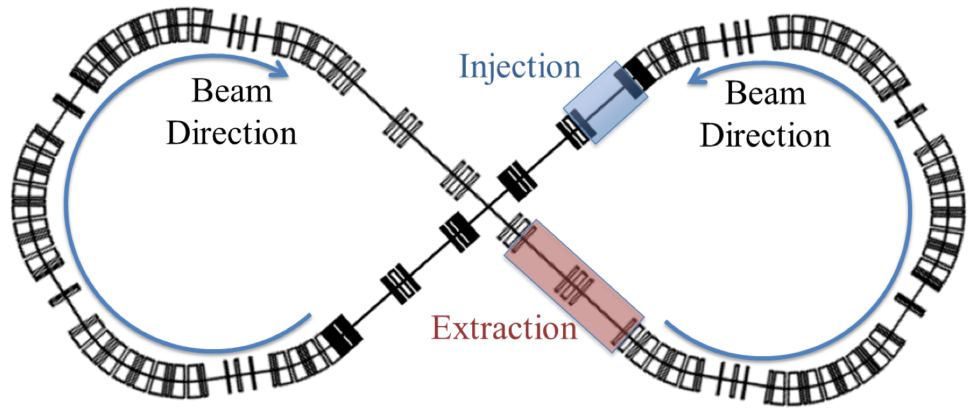
- Two RFQs: One for light ions (A/q ~ 2) and one for heavy ions (A/q ~ 7)
  - Different emittances and voltage requirements for polarized light ions and heavy ions
- Separate LEBTs and MEBTs for light and heavy ions
- RT Structure: IH-DTL with FODO Focusing Lattice
- Stripper section for heavy-ions followed by an SRF section
- Pulsed Linac: up to 10 Hz repetition rate and ~ 0.5 ms pulse length

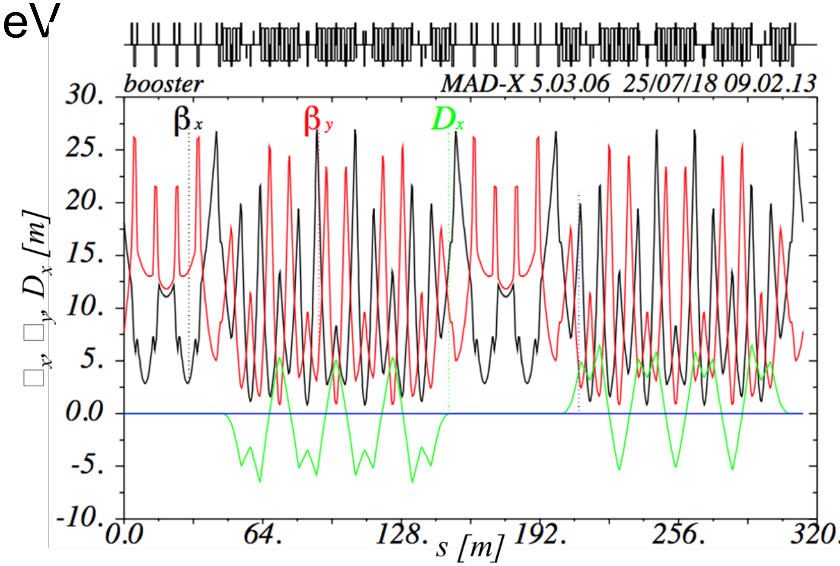


(Pb^{67+}) 100 MeV/u
(H-). 280 MeV

Booster

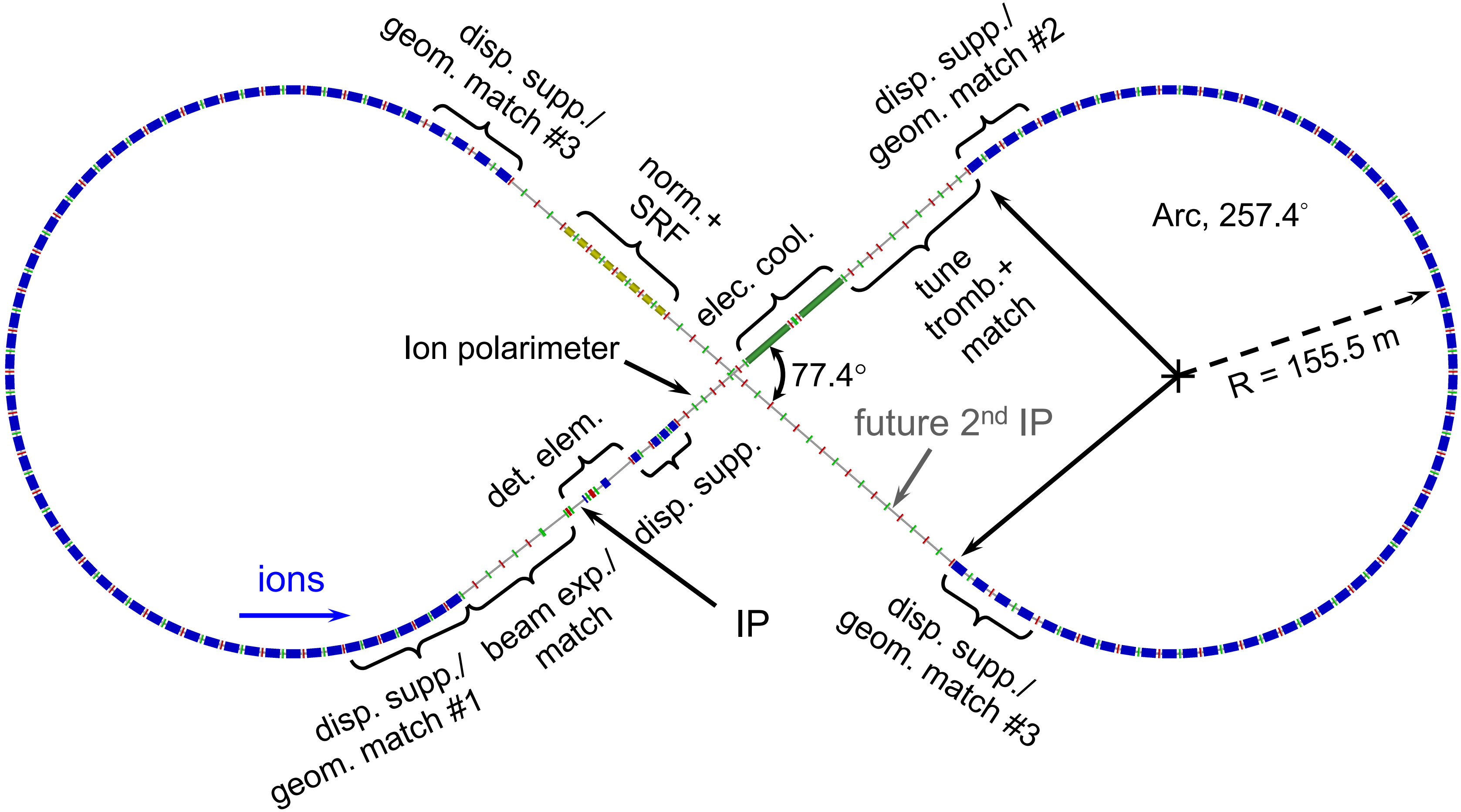
- 8 GeV/c Booster serves for
  - Accumulation of ions injected from Linac Cooling
  - Acceleration of ions
  - Extraction and transfer of ions to the collider ring
  - Electron cooling for heavy ions
- Injection
  - H^- single pulse charge stripping at 280 MeV (pulse length is 0.5 ms long or 305 turns)
  - Phase-space painting
- Design
  - Circumference of 313 m
  - No transition energy crossing, $\gamma_t = 18.64$
  - Figure-8 shape for preserving ion polarization





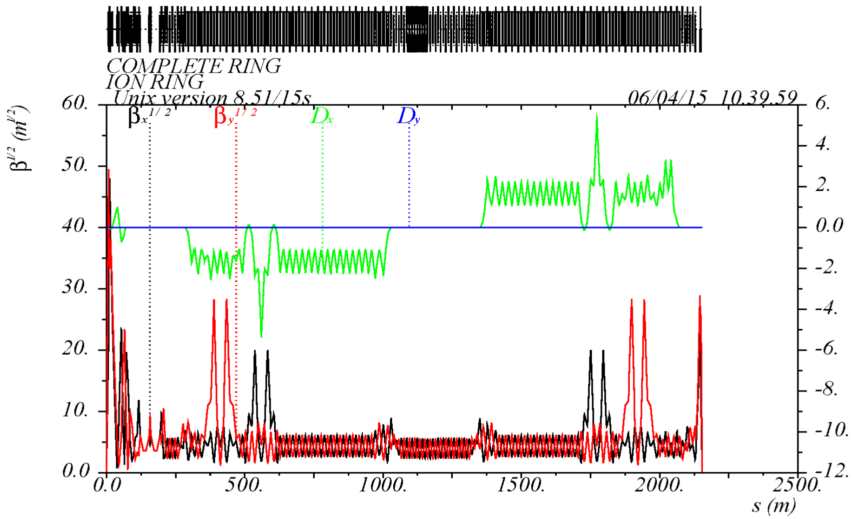
Ion Collider Ring Layout

- Protons: 100 GeV/u (63 GeV/u in COM with 10 GeV e)
  Lead: 40 GeV/u (40 GeV/u in COM with 10 GeV e)
- 3 T $\cos\theta$ conventional superconducting magnets

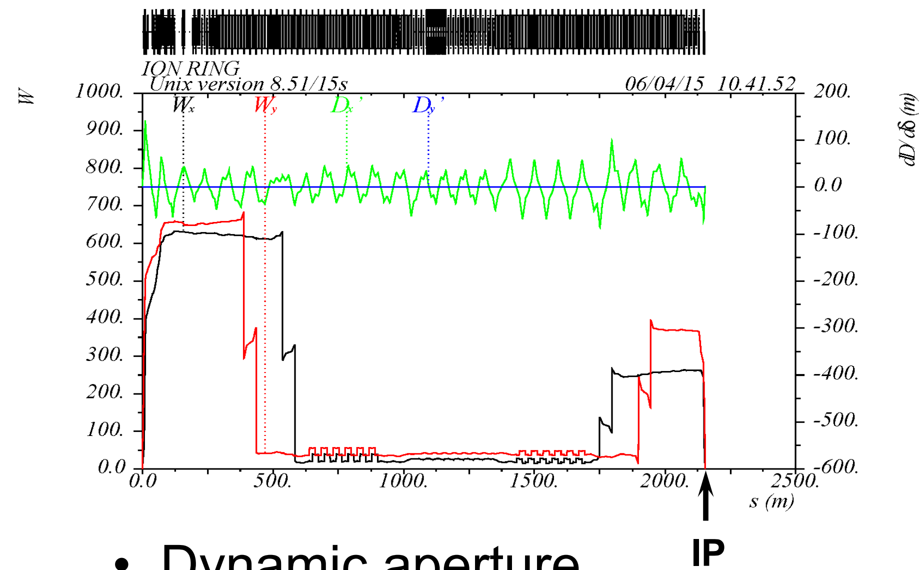


Ion Beam Dynamics

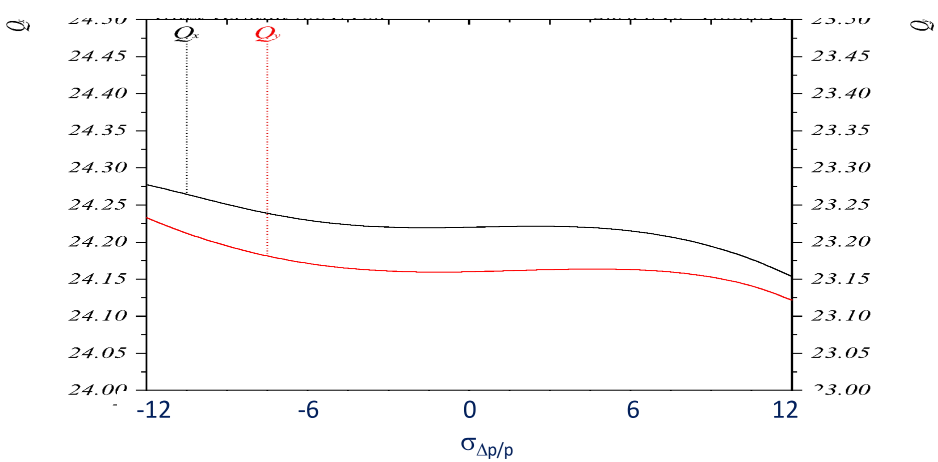
- Linear optics



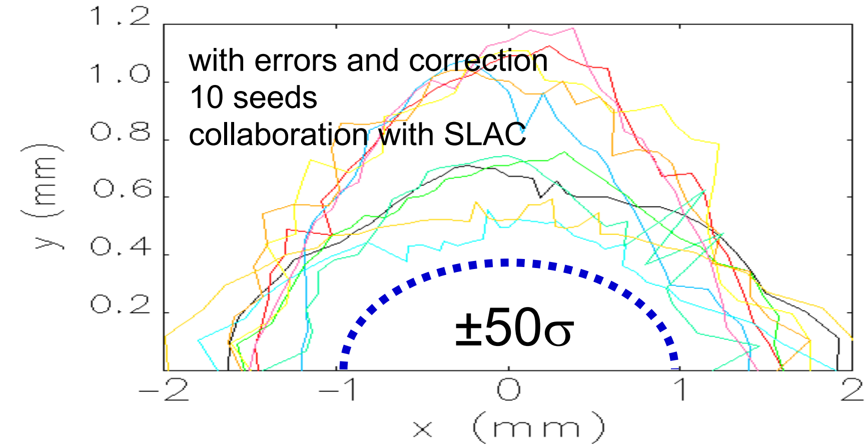
- Chromaticity compensation



- Momentum acceptance

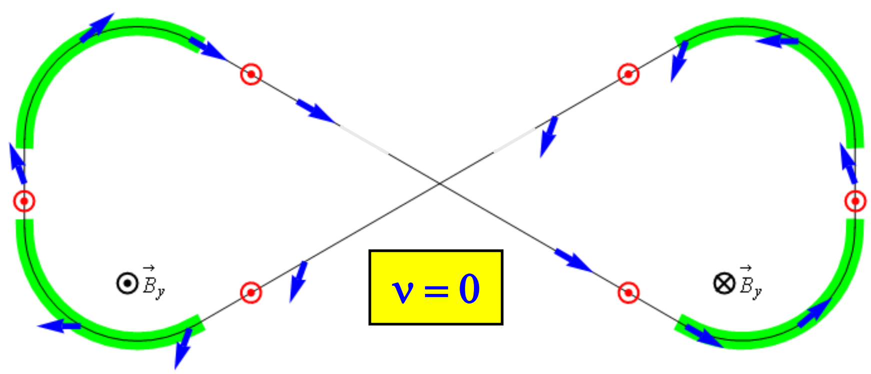


- Dynamic aperture



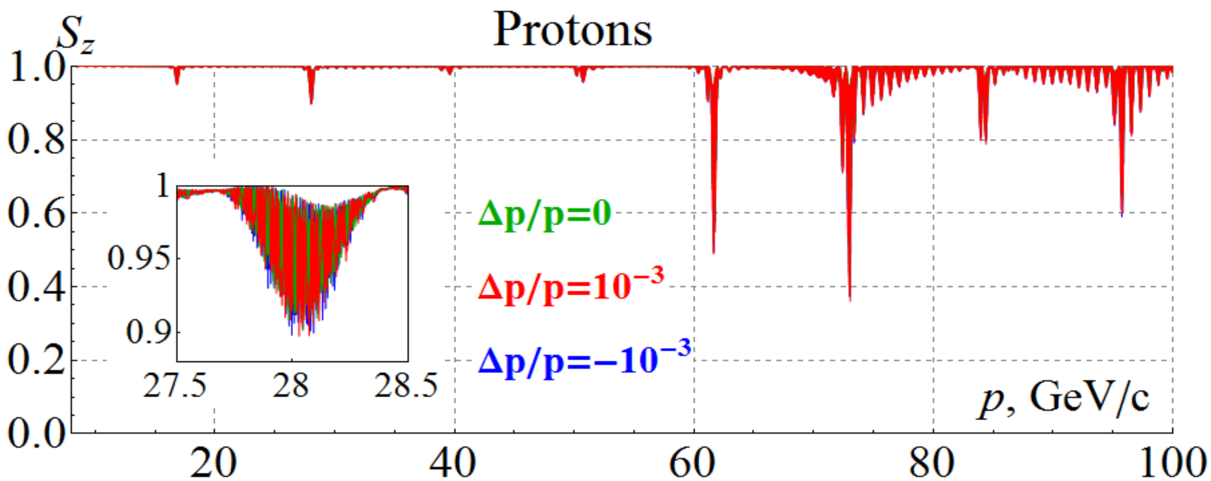
Ion Polarization

- Figure-8 concept: Spin precession in one arc is exactly cancelled in the other
- Spin stabilization by small fields: ~3 Tm vs. < 400 Tm for deuterons at 100 GeV
  - Criterion: induced spin rotation >> spin rotation due to orbit errors
- 3D spin rotator: combination of small rotations about different axes provides any polarization orientation at any point in the collider ring
- No effect on the orbit
- Polarized deuterons
- Frequent adiabatic spin flips



Start-to-End Proton Acceleration in Ion Collider Ring

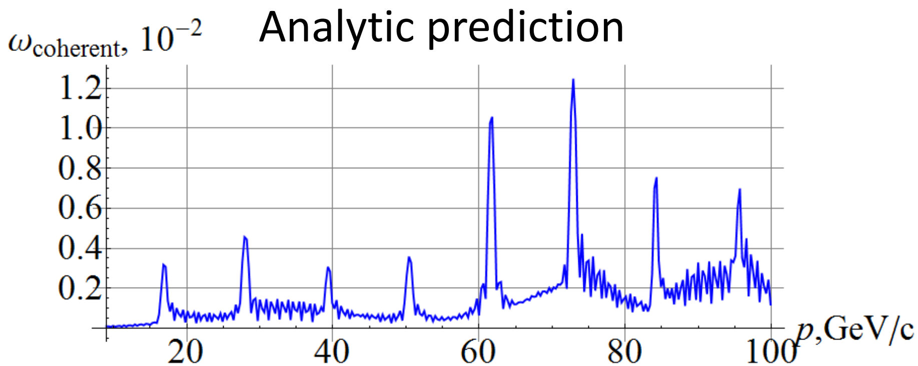
- Three protons with $\varepsilon^N_{x,y} = 1\,\mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms CO excursion, $\nu_{sp} = 0.01$ (1.2 Tm solenoid)



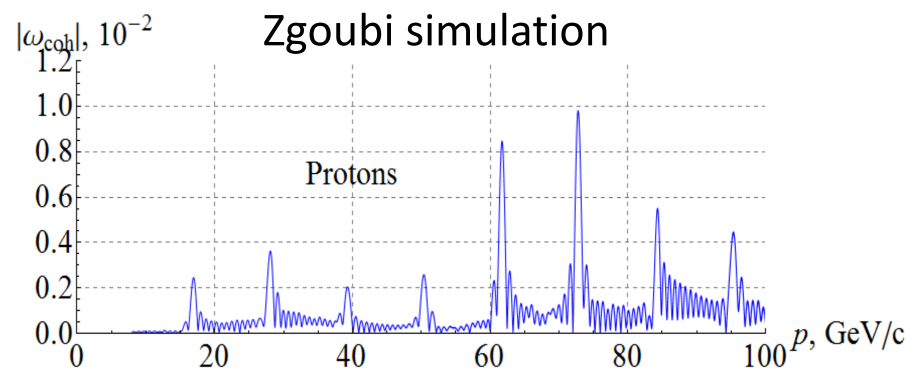
Zgoubi simulation

- Coherent resonance strength component

Analytic prediction

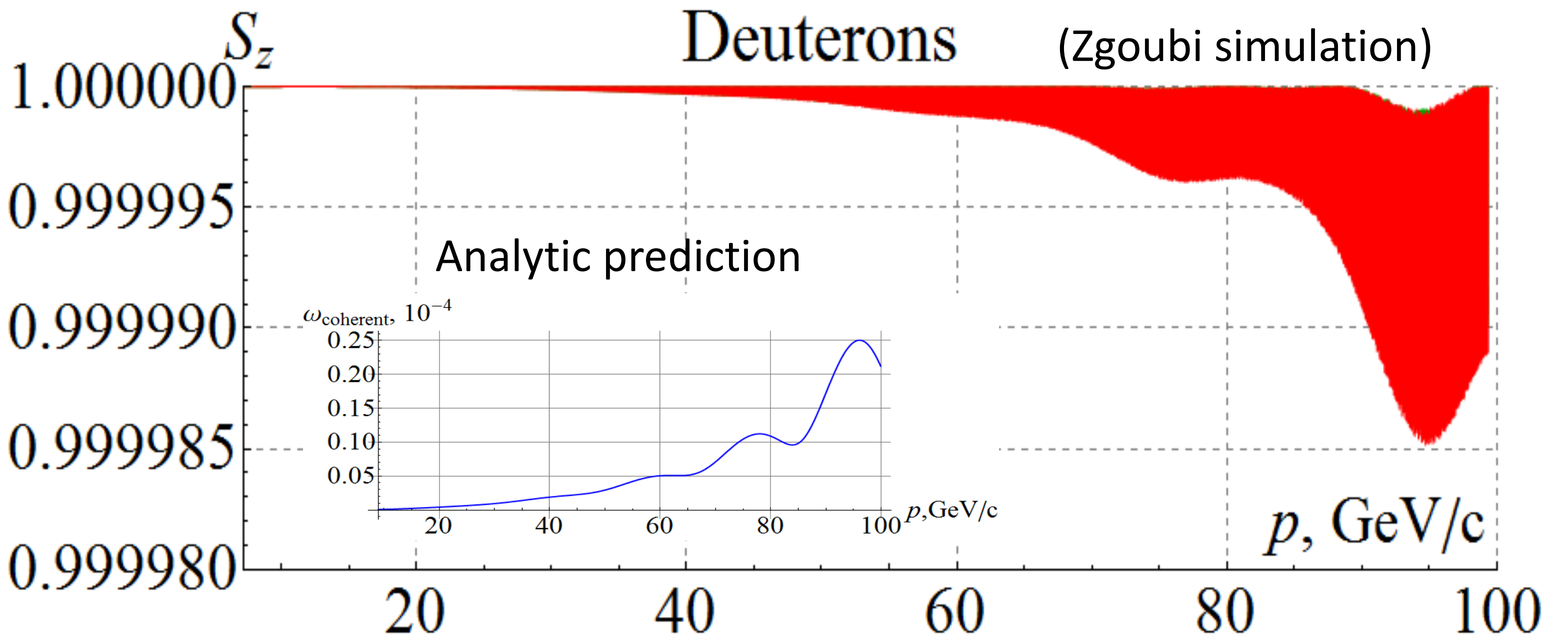


Zgoubi simulation



Start-to-End Deuteron Acceleration in Ion Collider Ring

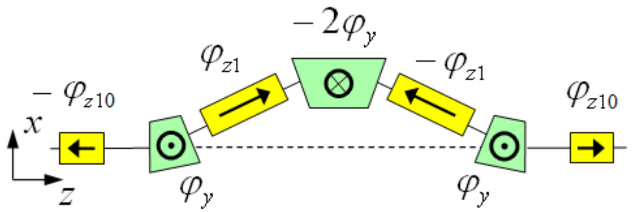
- Three deuterons with $\varepsilon_{x,y}^{N} = 0.5\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 3 \cdot 10^{-3}$



- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

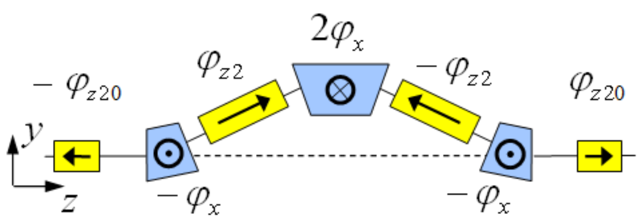
3D Spin Rotator in Ion Collider Ring

- Provides control of the radial, vertical, and longitudinal spin components
- Module for control of the radial component (fixed radial orbit bump)

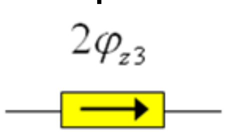


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

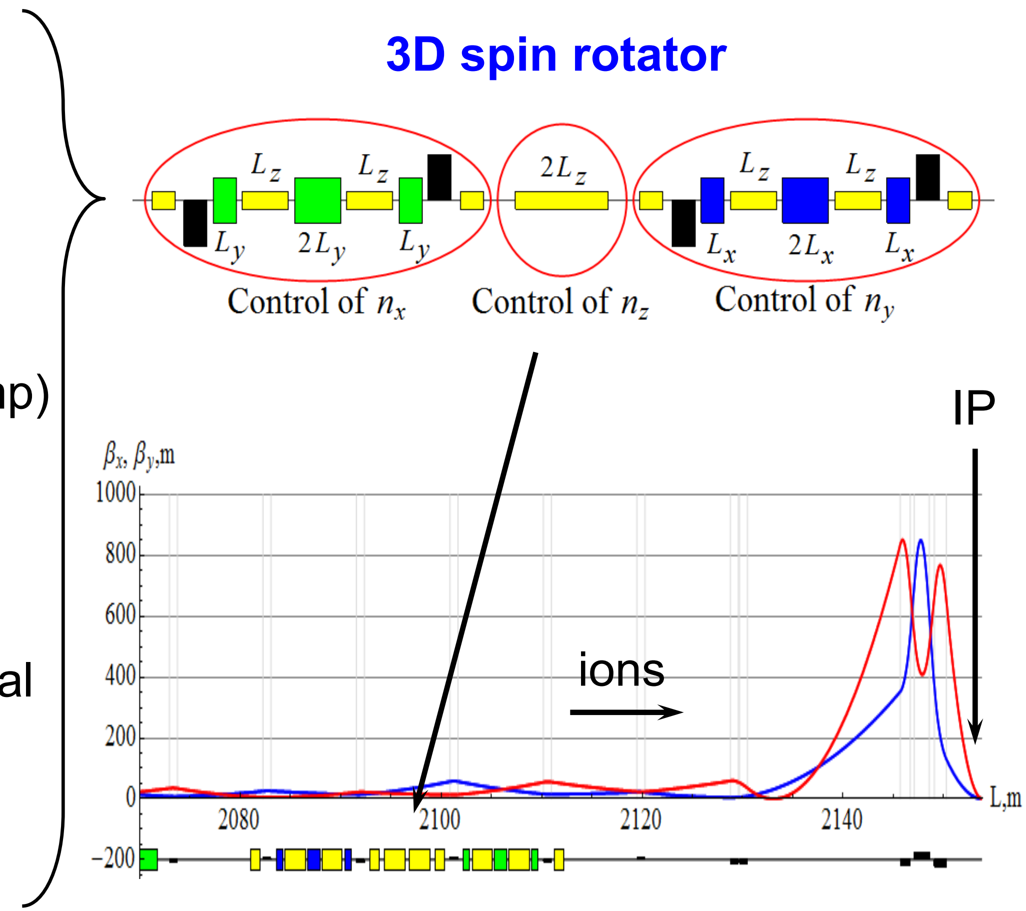
- Module for control of the vertical component (fixed vertical orbit bump)



- Module for control of the longitudinal component



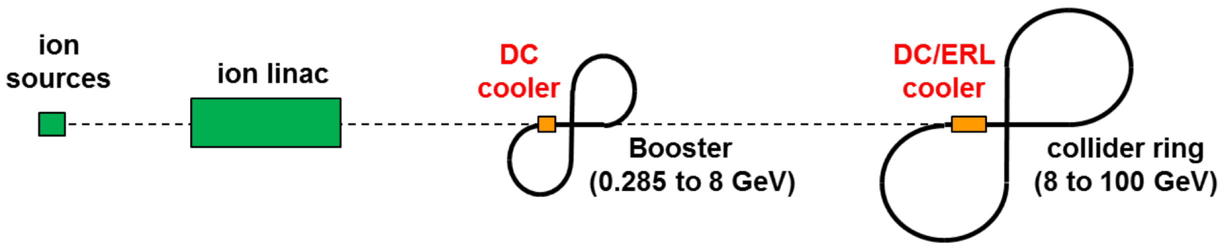
$L_x = L_y = 0.6$ m, $L_{zi} = 2$ m, $L_{zi0} = 1$ m, $\alpha_{orb} = 0.31^\circ$



JLEIC

Multi-Step Cooling Scheme

- Cooling of JLEIC proton/ion beams for
  - Achieving small emittance (~10x reduction)
  - Reaching short bunch length ~1 cm (with SRF)
  - Suppressing IBS induced emittance degradation



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	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion	Electron	
booster ring	Accumulation of positive ions		0.1 (injection)	0.054	DC
collider ring	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	DC
	Maintain emitt. during collision	Up to 100	Up to 40	Up to 54.5	ERL

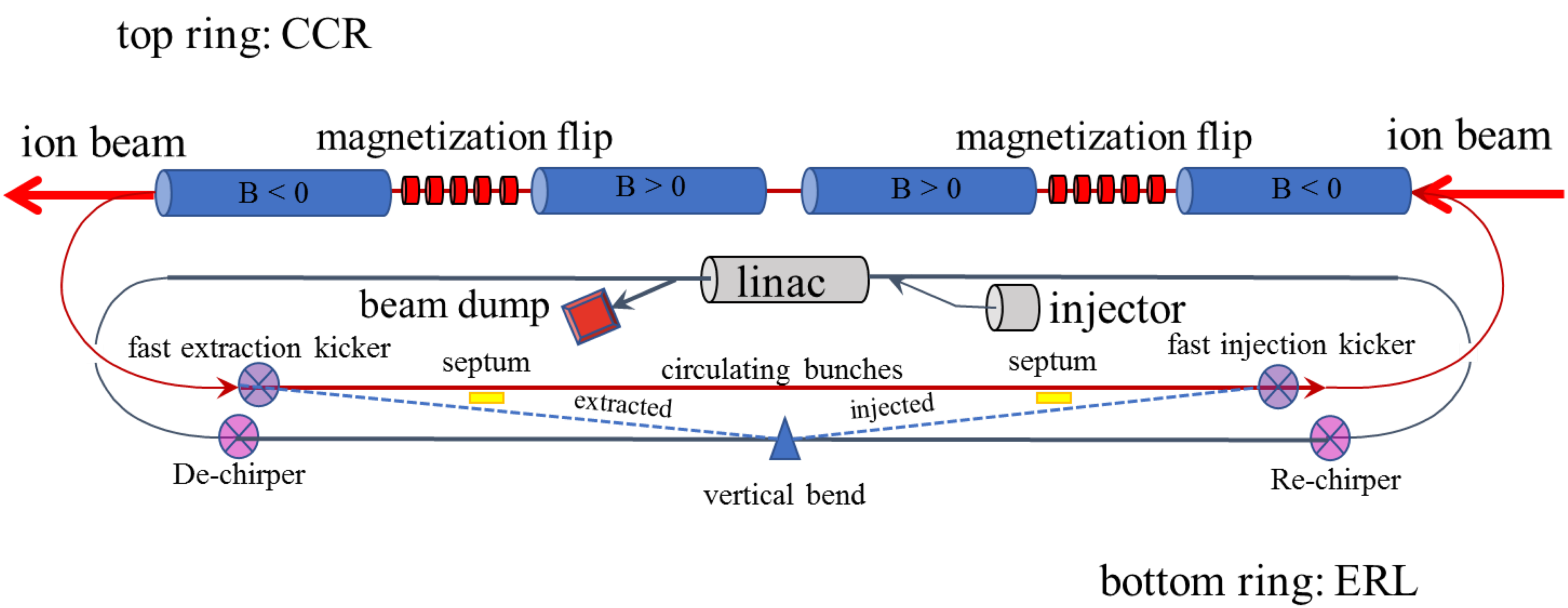
Can't reduce emittance due to space charge limit

Pre-cooling both protons and lead ions

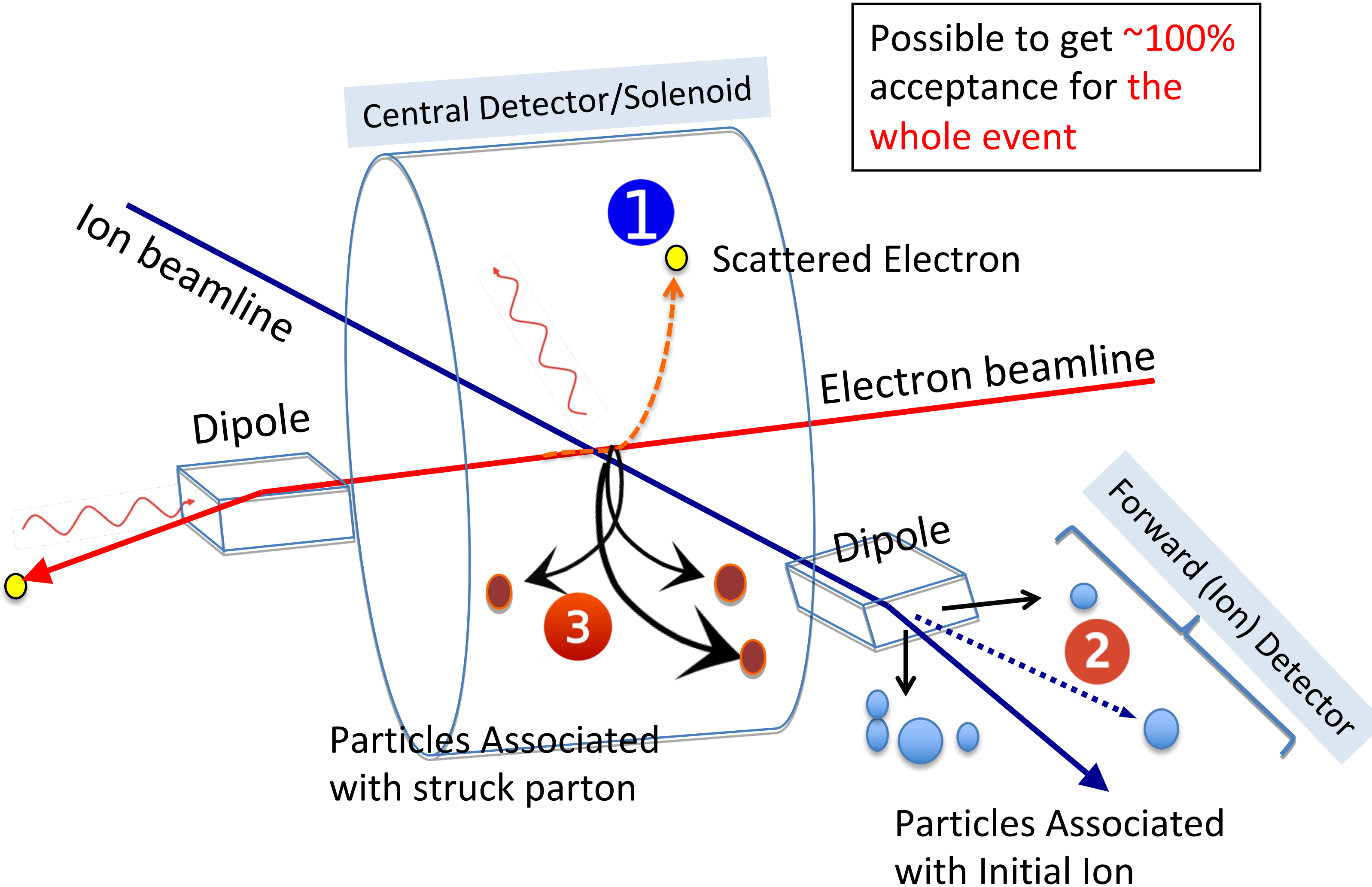
ERL cooler can't reach energy below 20 MeV

Cooling Ring Fed by ERL

- Same-cell energy recovery in 952.6 MHz SRF cavities
- Uses harmonic kicker to inject and extract from CCR (divide by 11)
- Assumes high charge, low rep-rate injector (w/ subharmonic acceleration and bunching)
- Use magnetization flips to compensate ion spin effects

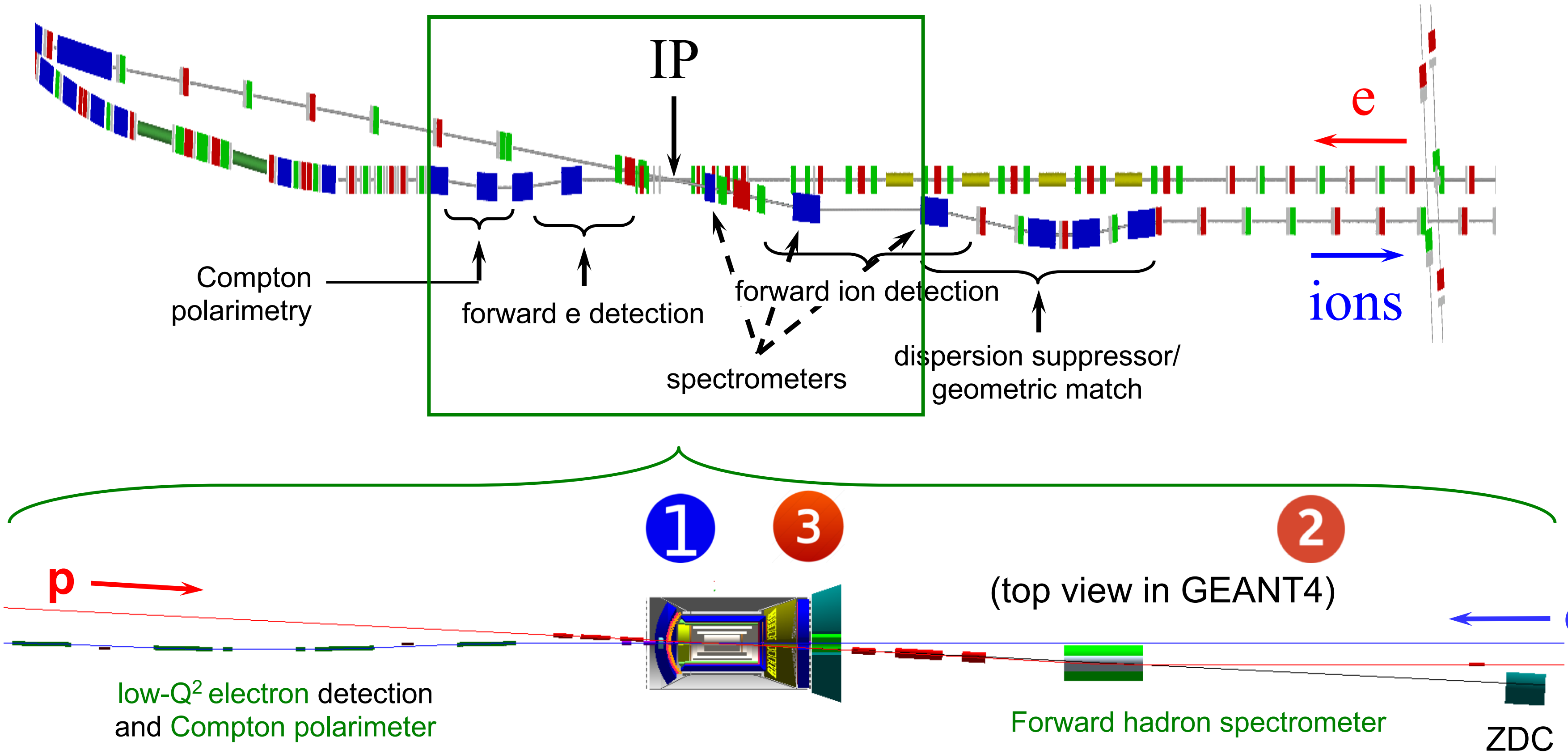


Interaction Region Concept



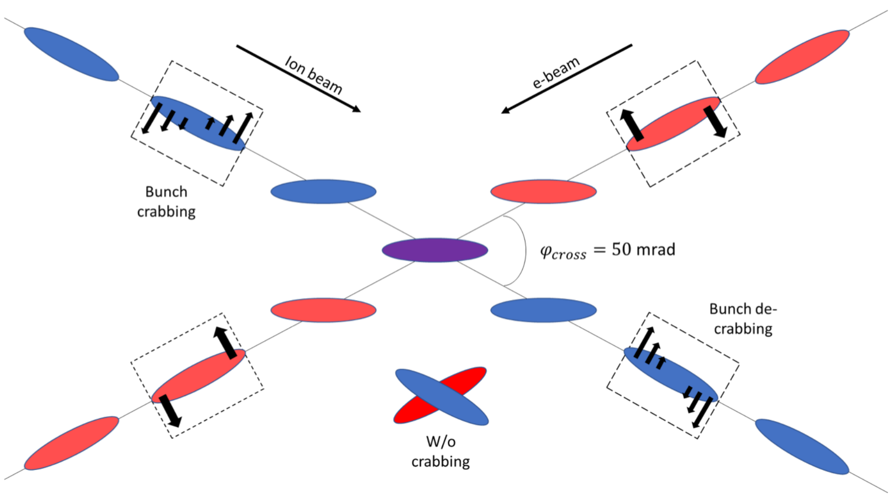
Detector Region

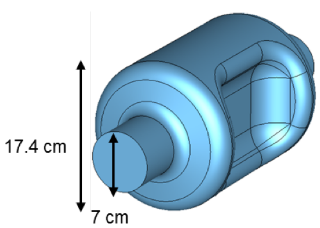
- Integrated detector region design developed satisfying requirements of detection, beam dynamics and geometric match
- GEANT4 detector model developed, simulations in progress



Crab Crossing

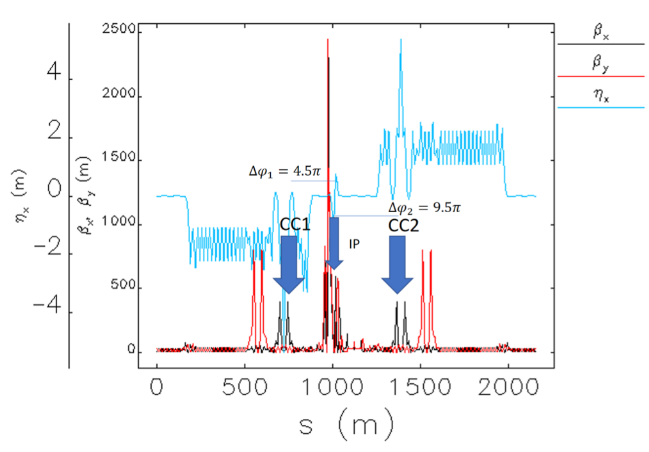
- Electron and ion beams have to cross at an angle in an EIC
  - Create space for independent electron and ion IR magnets
  - Avoid parasitic collisions of shortly-spaces bunches
  - Improves detections
  - Improves detector background
- Without compensation, geometric luminosity loss is about a factor of 12 and there is potential for dynamic instabilities
- Crabbing restores effective head-on collisions
- Local compensation scheme
  - Set of crab cavities upstream and downstream of IP
- Deflective crabbing
  - Demonstrated at KEK-B
  - Being tested with ions at LHC
  - Prototype developed at ODU





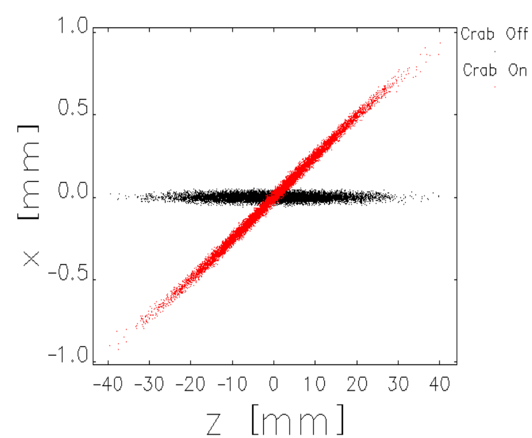
Crab Crossing Scheme of JLEIC

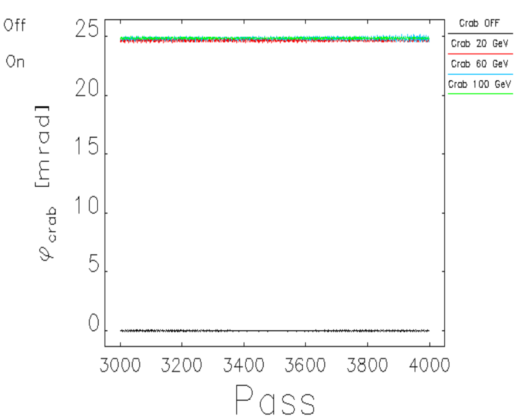
- Locations of horizontal chromatic sextupoles are also adequate for crab cavities:
  - Right phase advance
  - High β_x values
- Found that sextupoles between crab cavities may lead to emittance increase, avoid them
- Dispersion at the crab cavities satisfies the beam stability criterion



Parameter	Unit	Proton
Energy	GeV	100
Frequency	MHz	952.6
Crossing angle	mrad	50
β^*	cm	10
β_x @ crab cavity location	m	363
Crab voltage	MV	20.8

Beam parameters	
# of particles	500
ε_{nx}	0.35 μm
$\Delta p/p$	$3 \cdot 10^{-4}$
σ_s	1 cm
Gaussian distribution 3σ	





Conclusion

- JLEIC conceptual design is nearly complete
- Key features:
  - High luminosity
  - High polarization
  - Full-acceptance detection
- Current work
  - Key R&D
  - Completion of consistent design
  - Performance and cost optimization
  - Evaluation of engineering challenges
  - Completion of a pre-CDR

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