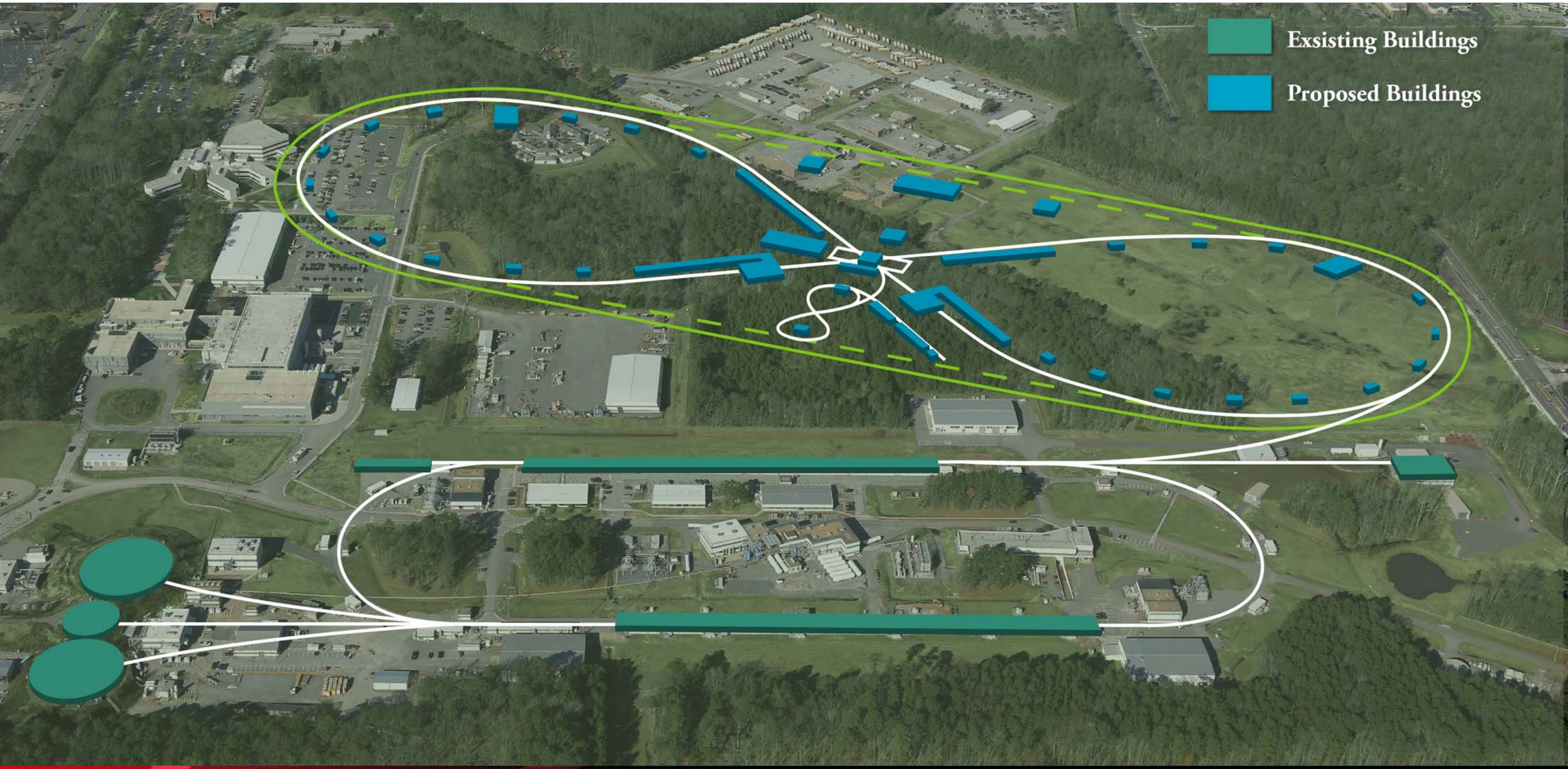
Overview of Jefferson Lab EIC Design and R&D

Vasiliy Morozov for JLEIC Collaboration



NAPAC'16, Chicago, IL, October 10, 2016

JLEIC Collaboration

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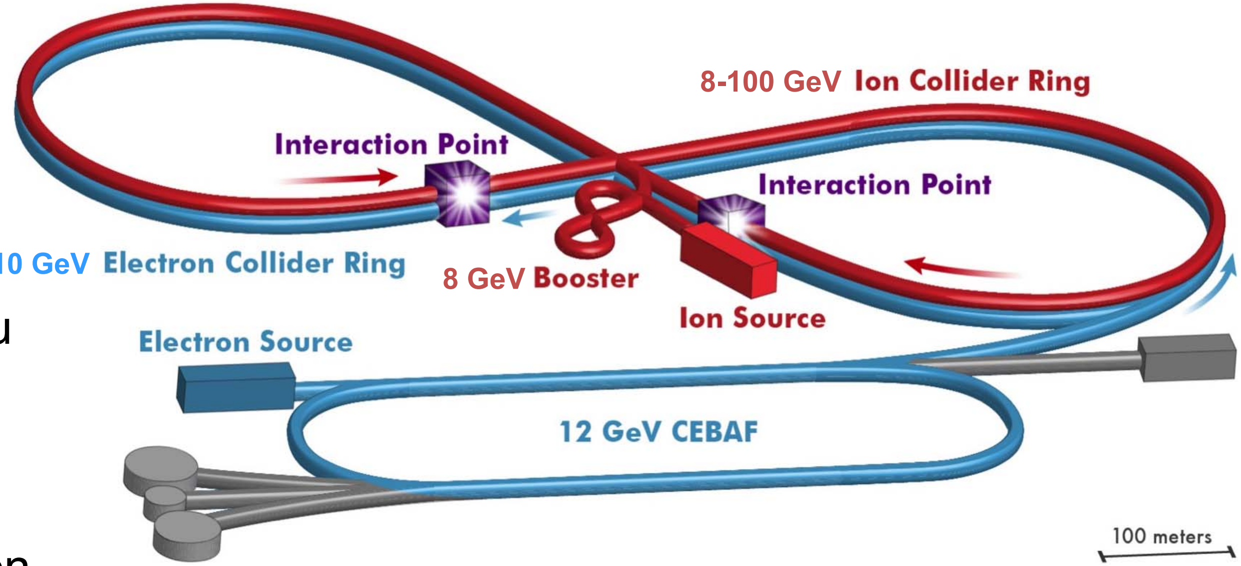
Outline

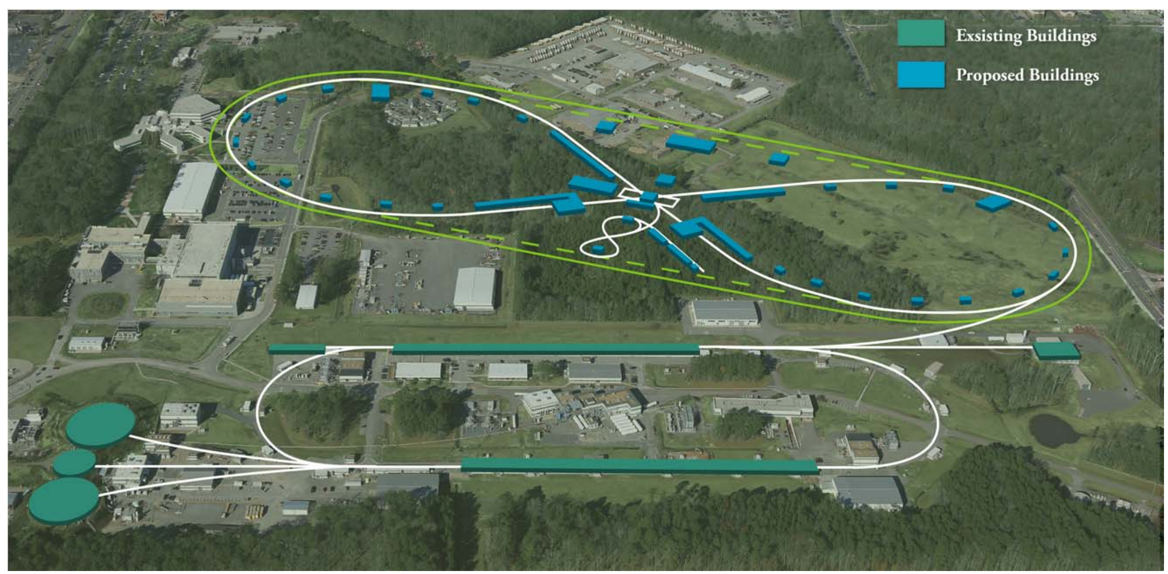
- Introduction
  – JLab's approach to the design
  – JLEIC design overview
- Electron complex
  – CEBAF as a full-energy injector
  – Electron collider ring
  – Electron polarization
- Ion complex
  – Ion injector complex
  – Ion collider ring
  – Electron cooling
  – Ion polarization
- Detector region
- R&D status and plans
- Conclusions

JLEIC Layout

- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac (285 MeV/u for protons)
  - Booster
  - Ion collider ring
- Optimum detector location for minimizing background



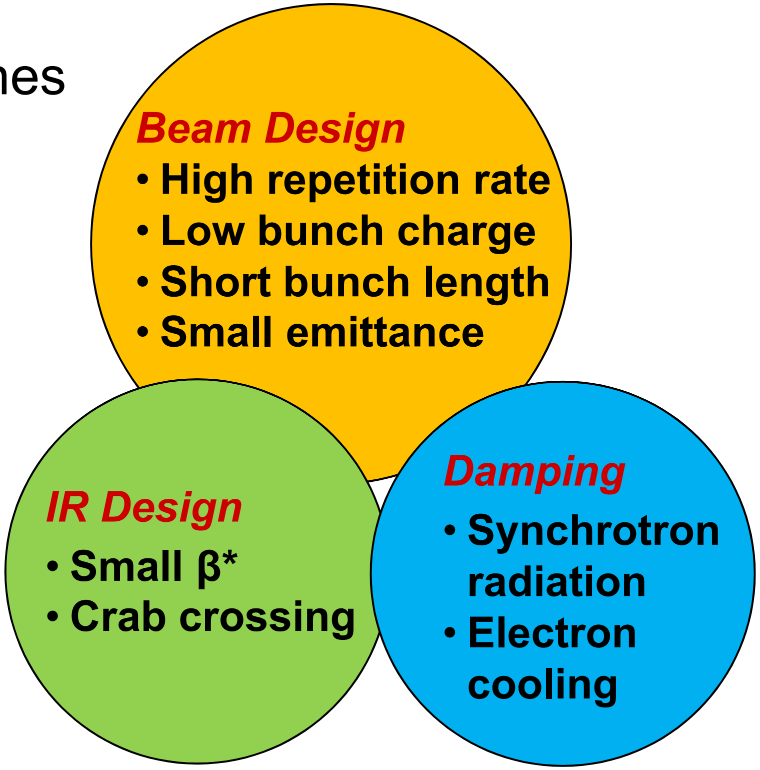
arXiv:1504.07961



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} $cm^{-2}s^{-1}$

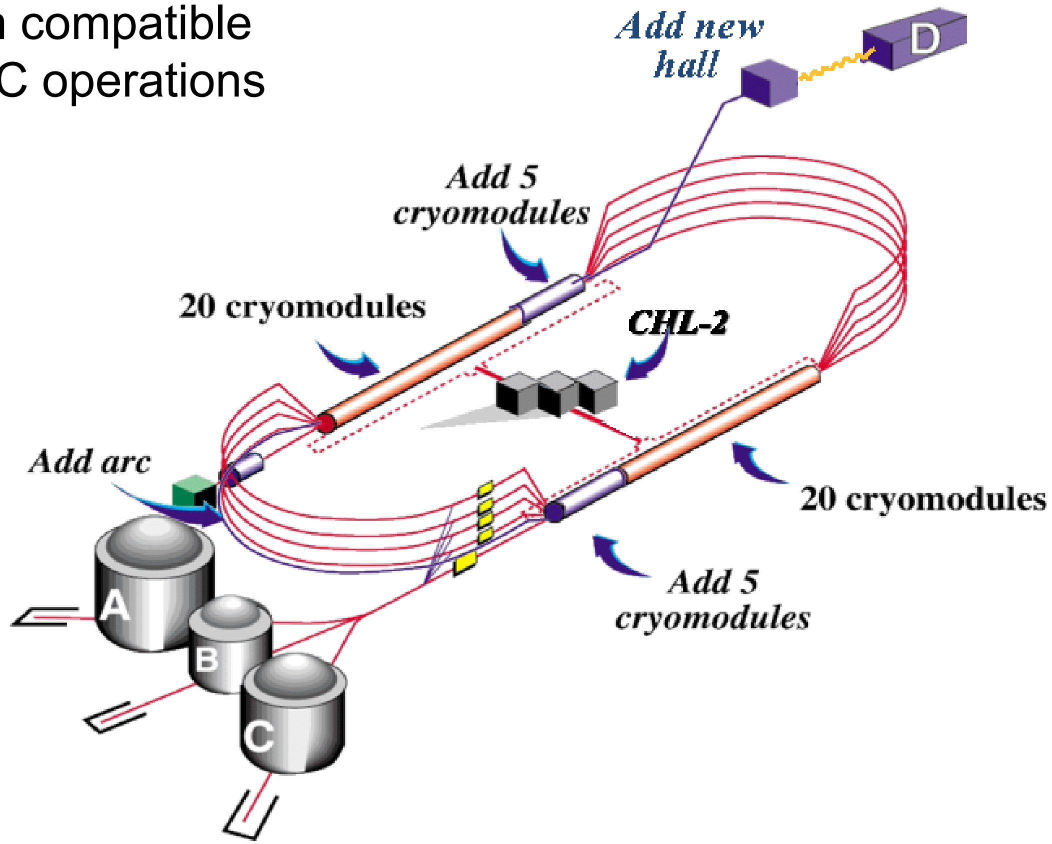
$$L = f\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*} \sim f\frac{n_1 n_2}{\varepsilon\beta_y^*}$$



- **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**

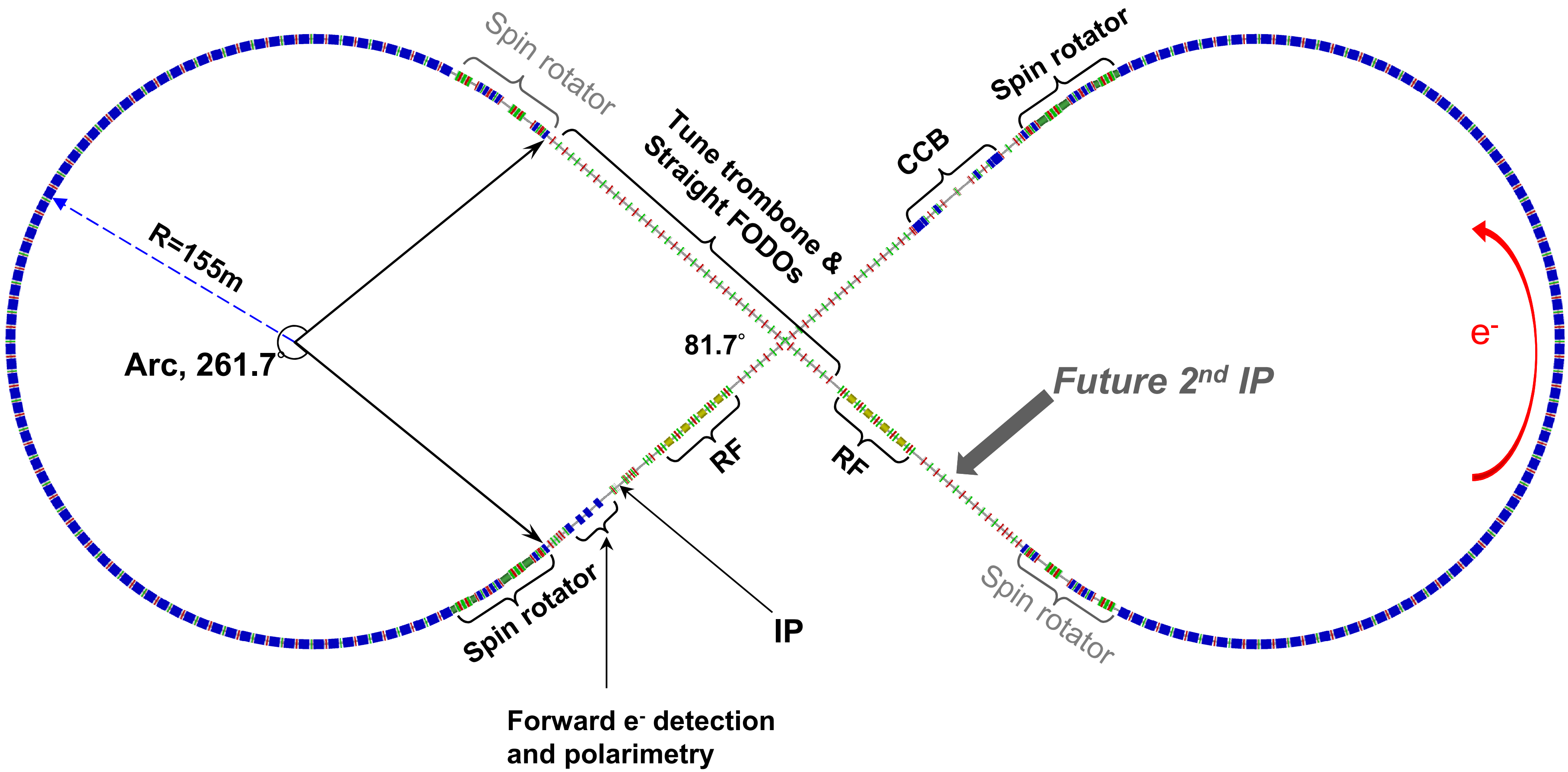
CEBAF… more than full-energy injector!

- Commissioned in Spring 2014
- Operated at 12 GeV in Fall 2015
- First Physics Run in Spring 2016
- Exciting science fixed target program
  - Fixed-target program compatible with concurrent JLEIC operations



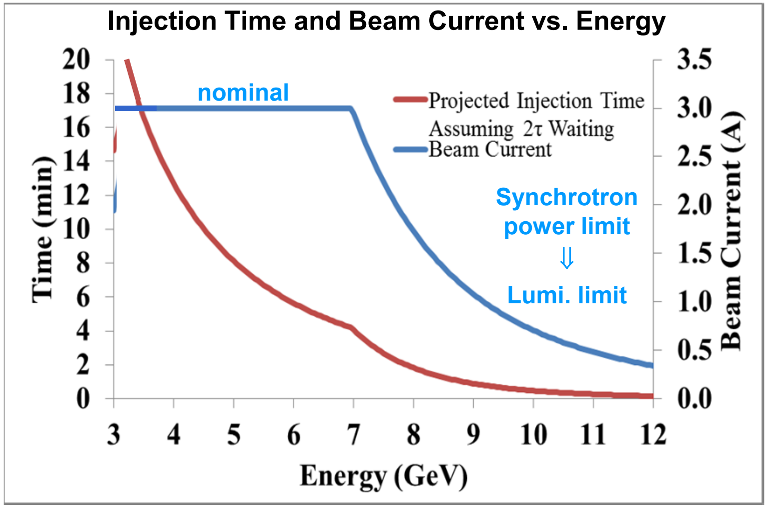
Electron Collider Ring Layout

- Circumference of 2154.28 m
- Possible cost reduction by reusing PEP-II vacuum pipe, RF and magnets



Electron Beam Dynamics

- Electron injection from CEBAF
  - Existing CEBAF source gun
  - Two polarization states injection
  - f_{ring} / f_{cebaf} = 476.3MHz / 1497MHz = 7 / 22
- Electron beam
  - **3A** at up to 7 GeV
  - Normalized emittance **96 μm** @ 5 GeV
  - Synchrotron power density < **10kW/m**
  - Total power **10 MW** @ 10 GeV



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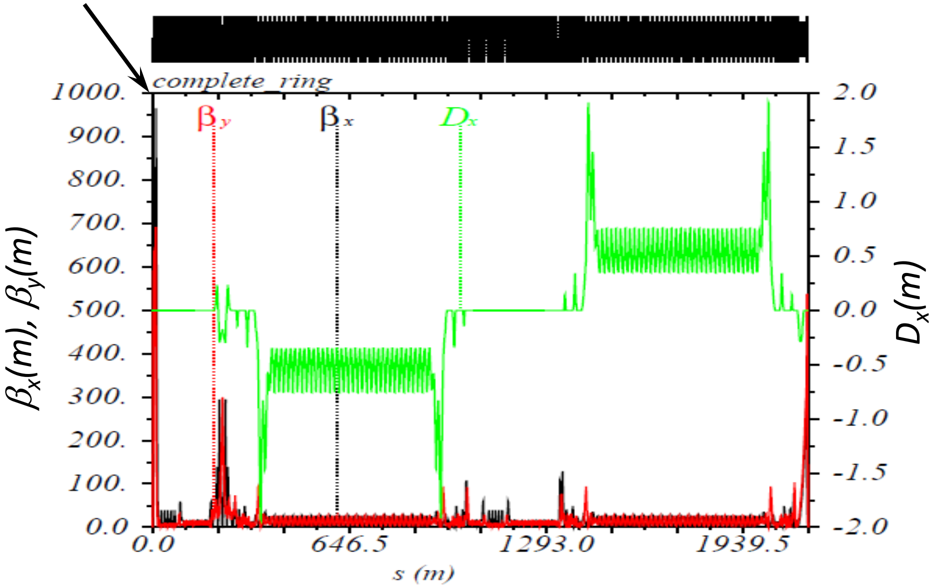
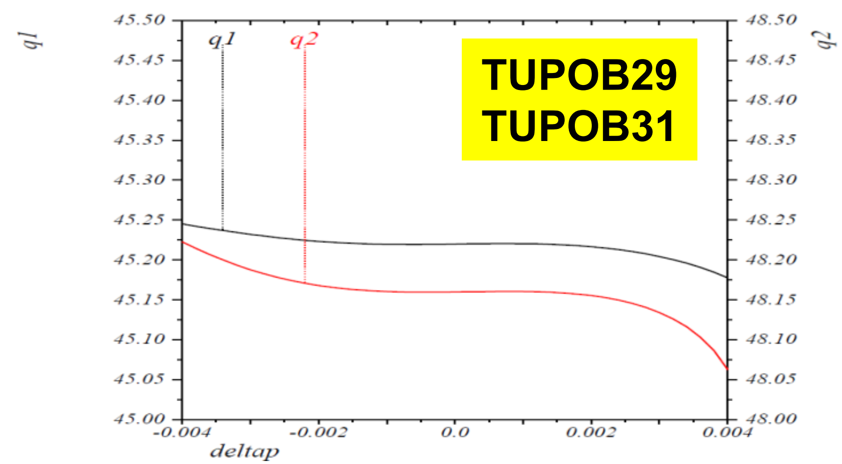
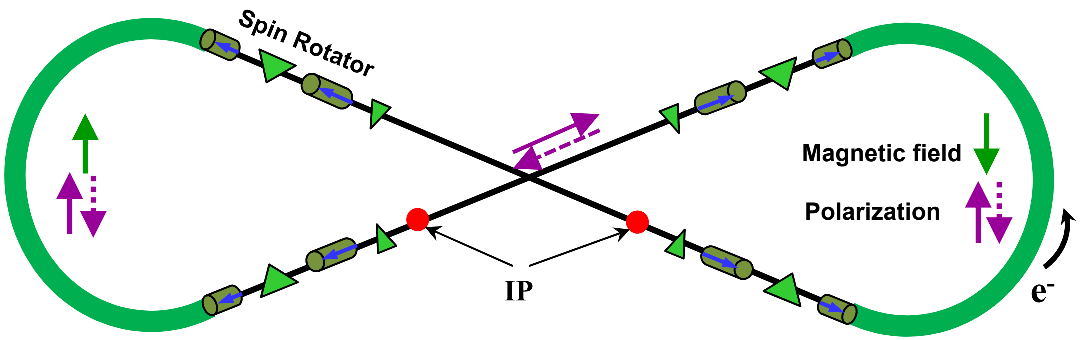


- Emittance and non-linear dynamics optimization in progress



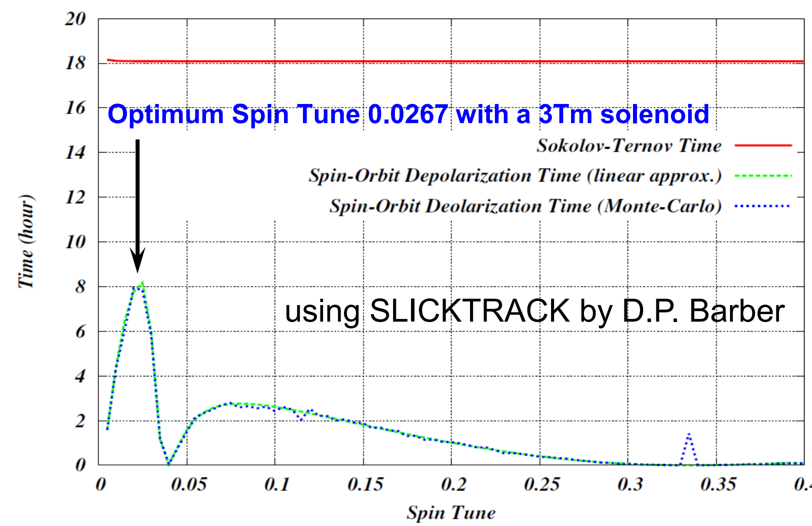
Electron Polarization

- Two vertically polarized bunch trains injected from CEBAF in an arc
- Universal spin rotator
  - Sequence of solenoid and dipole sections
  - Makes the spin longitudinal in the straights
  - First order spin matched



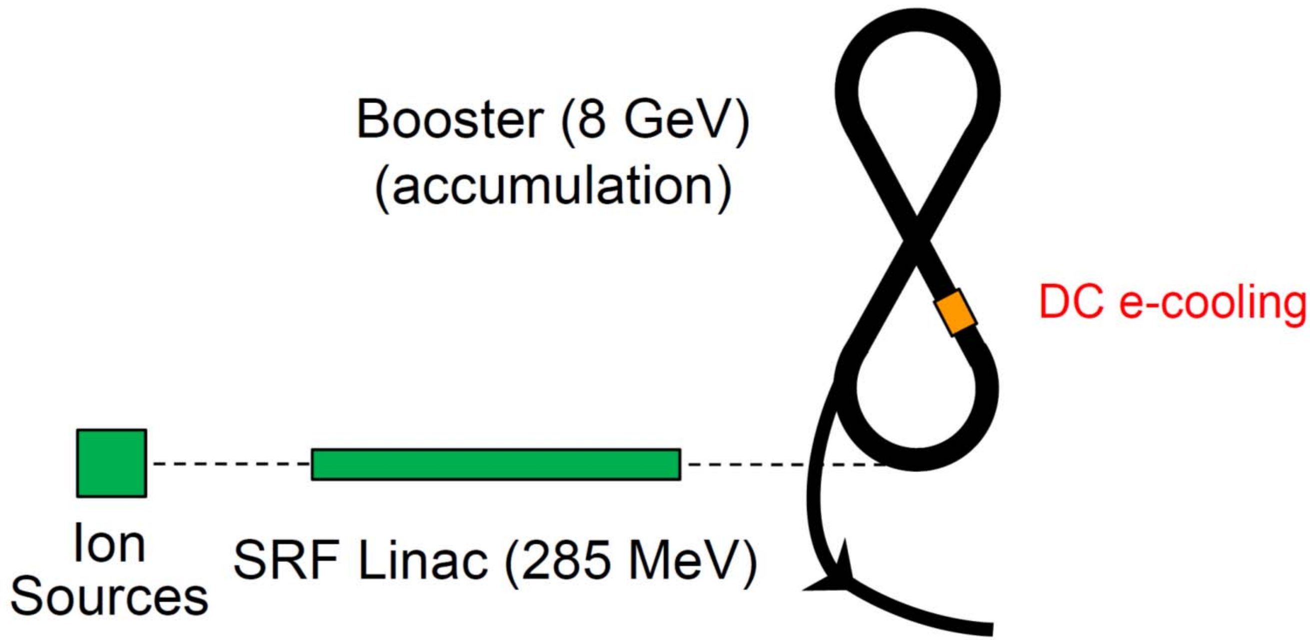
Energy (GeV)	3	5	7	9	10
Estimated Pol. Lifetime (hours)	66	5.2	2.2	1.3	0.8

  - Spin dynamics symmetric for oppositely polarized states



- Feature of figure-8: no synchrotron side-band spin resonances in contrast to racetrack

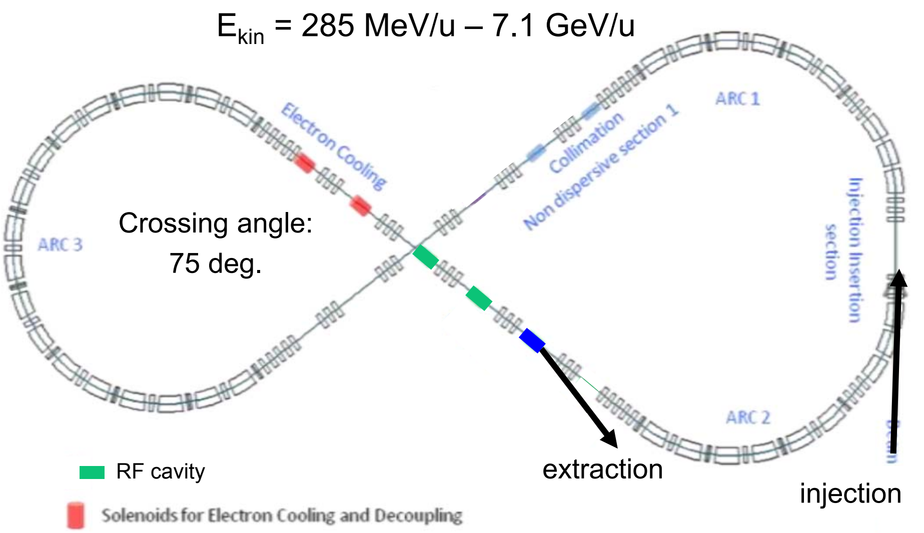
Ion Injector Complex Overview

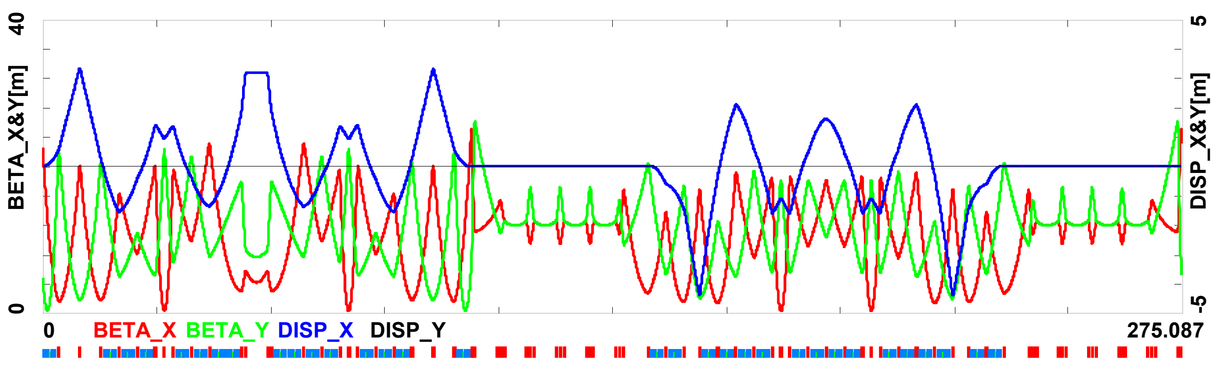


- Ion injector complex relies on demonstrated technologies for sources and injectors
  - Atomic Beam Polarized Ion Source (ABPIS) for polarized or unpolarized light ions, Electron Beam Ion Source (EBIS) and/or Electron Cyclotron Resonance (ECR) ion source for unpolarized heavy ions
  - Design for an SRF linac based on ANL design
  - 8 GeV Booster with imaginary transition energy
  - Injection/extraction lines to/from Booster are designed

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
- Injection
  - H^- single pulse charge stripping at 285 MeV/u (0.22 – 0.25 ms long pulses ~180 turns)
  - Phase-space painting combined with electron cooling for heavy ions
- Design
  - Circumference of 275 m
  - No transition energy crossing
  - Figure-8 shape for preserving ion polarization





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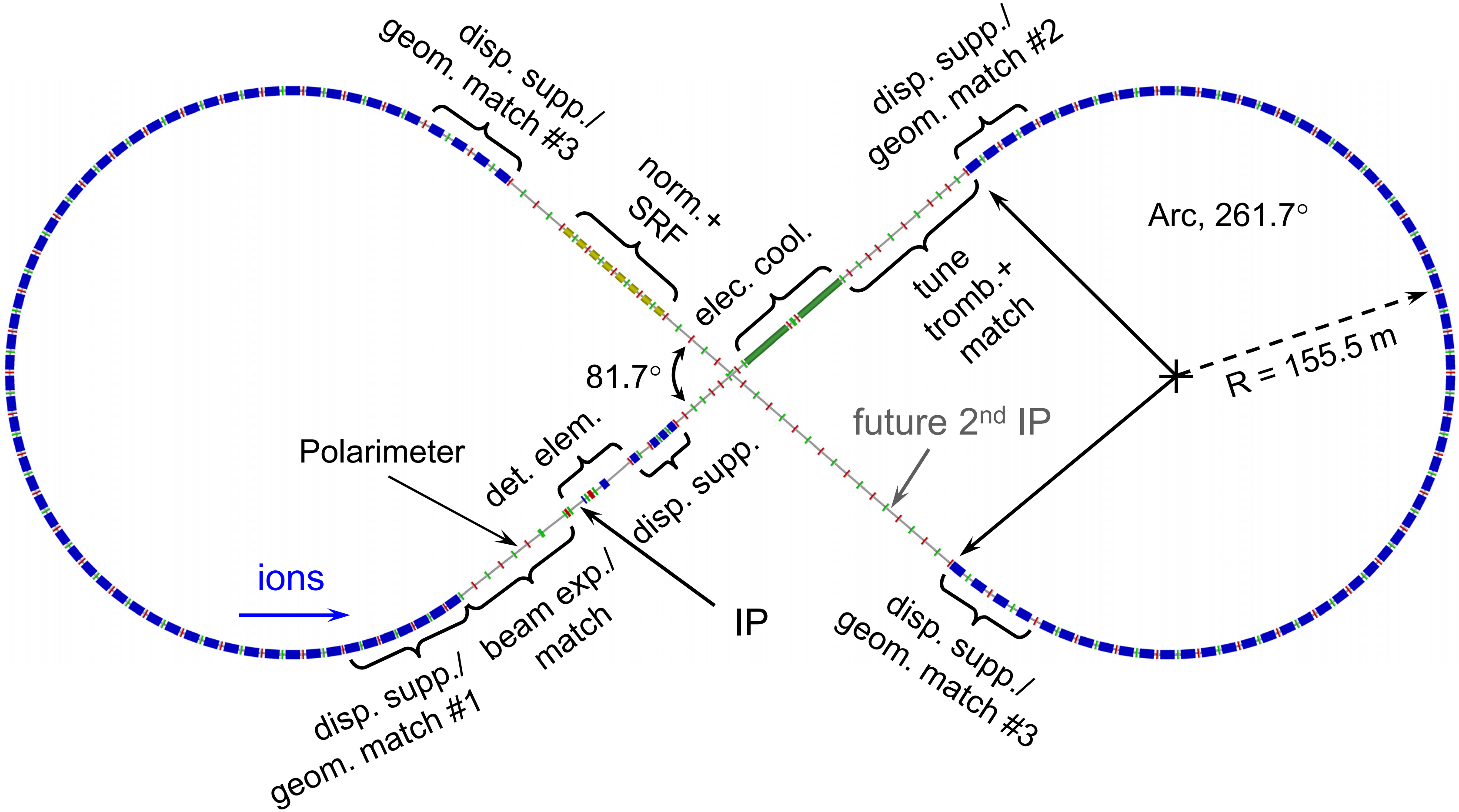
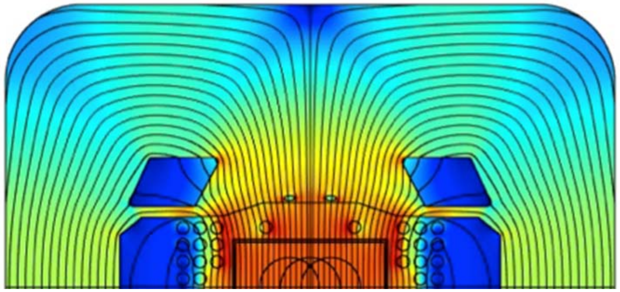
Ion Collider Ring Layout

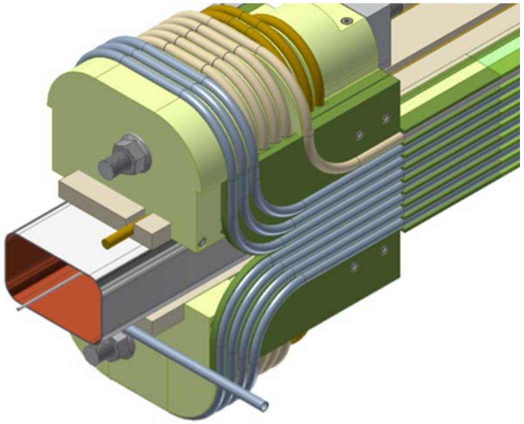
- Circumference of 2153.9 m
- Protons: 100 GeV/u (63 GeV/u in COM with 10 GeV e)
  Lead: 40 GeV/u (40 GeV/u in COM with 10 GeV e)
- Super-ferric magnets (cosθ under consideration as risk mitigation)



Super-Ferric Magnets

- 3 T
- Cost effective
- Fast ramp rate [1 T/s]
- Cable-in-conduit conductor





- Prototype winding

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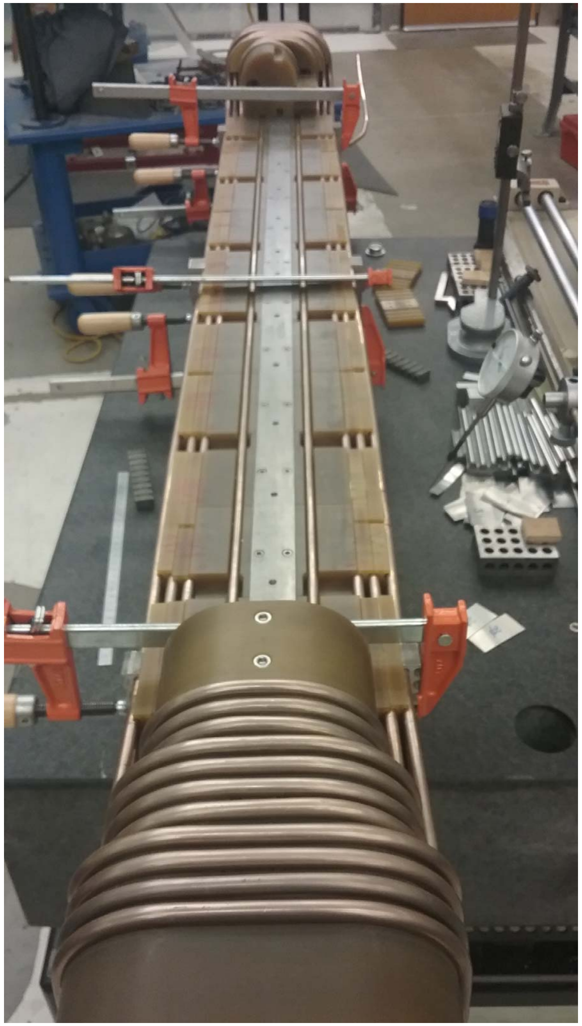
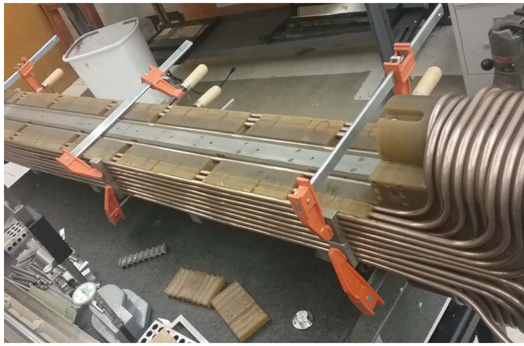
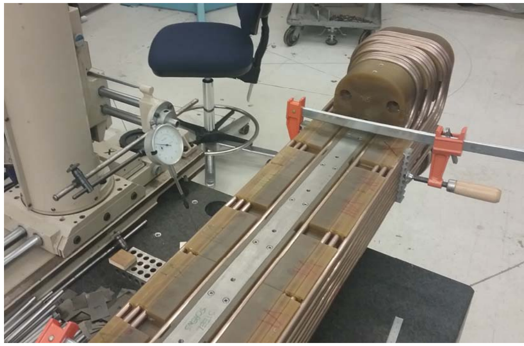


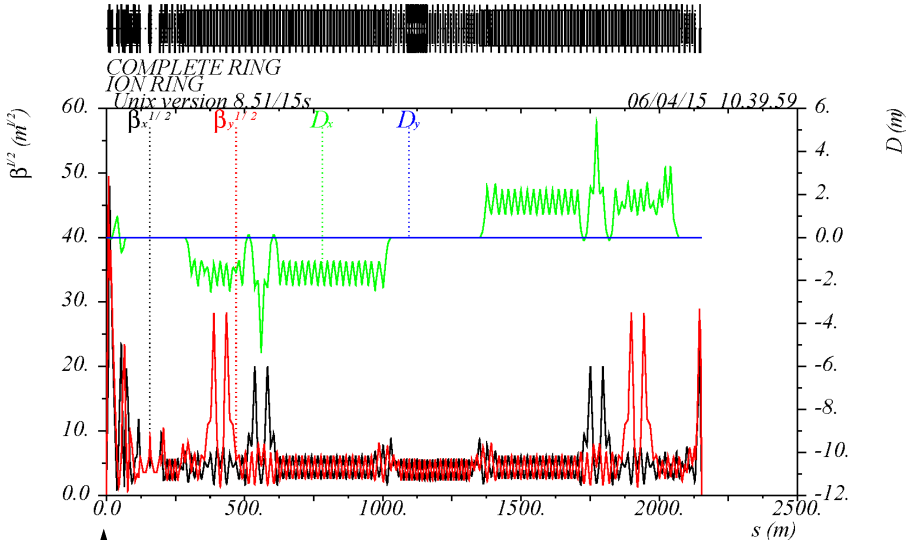


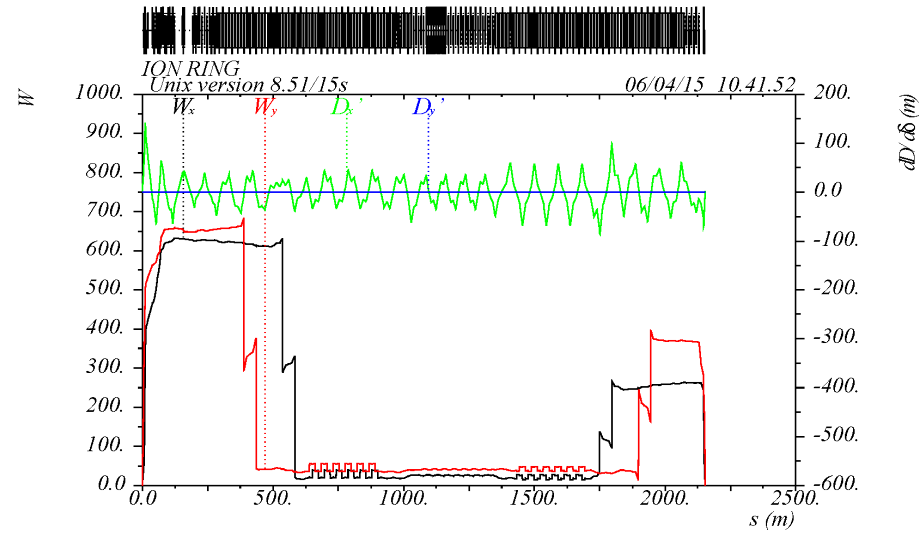


Nonlinear Dynamics

- Nonlinear dynamics optimized: “–*I* ” sextupoles pairs in the arcs

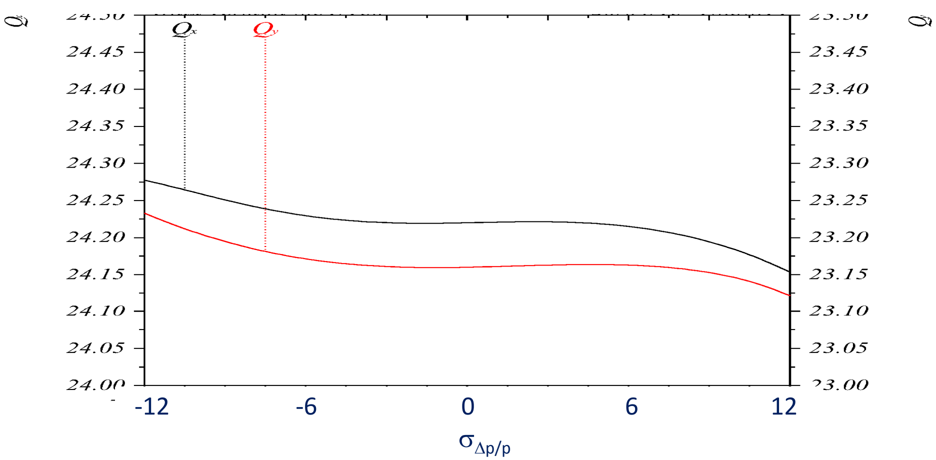
MOA4CO03



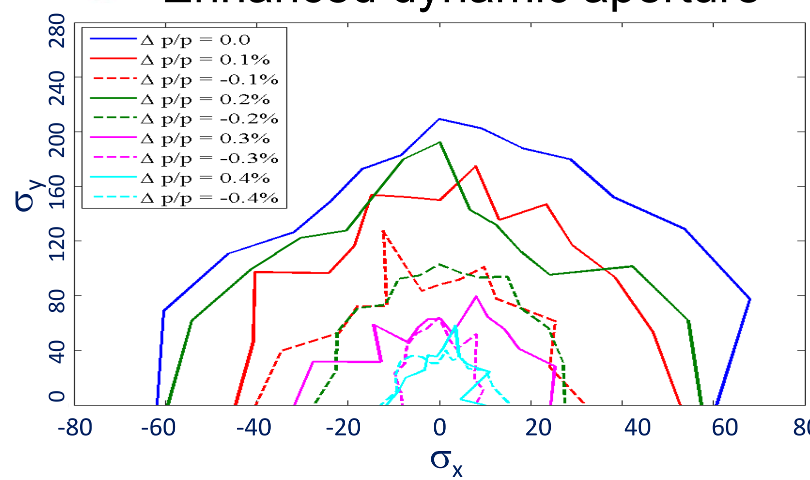


↑
IP

- Momentum acceptance

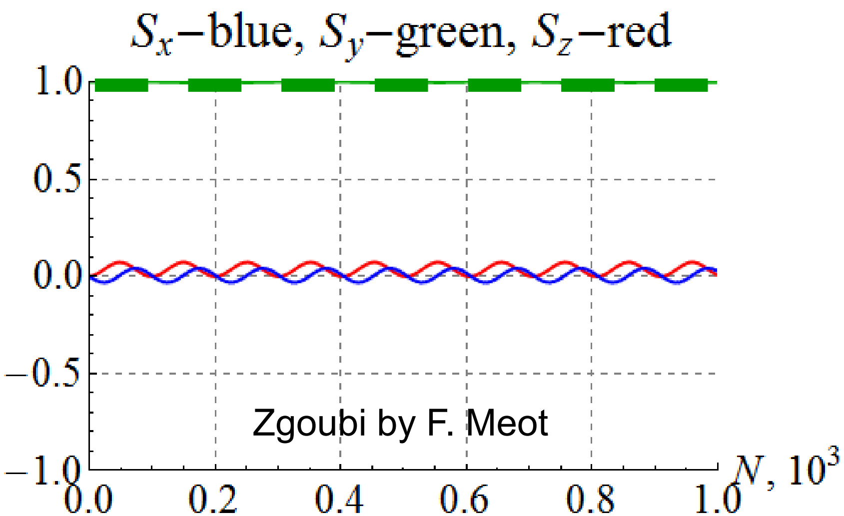


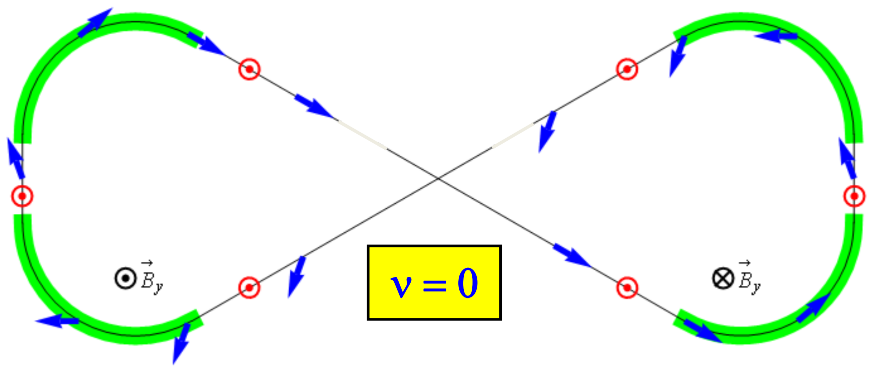
- Enhanced dynamic aperture

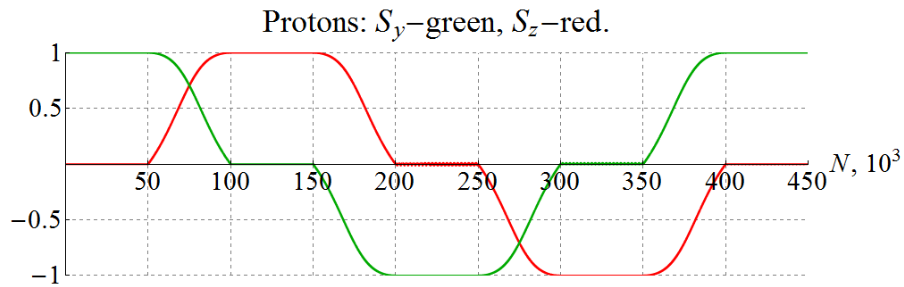


Ion Polarization

- 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
- Simulations in progress



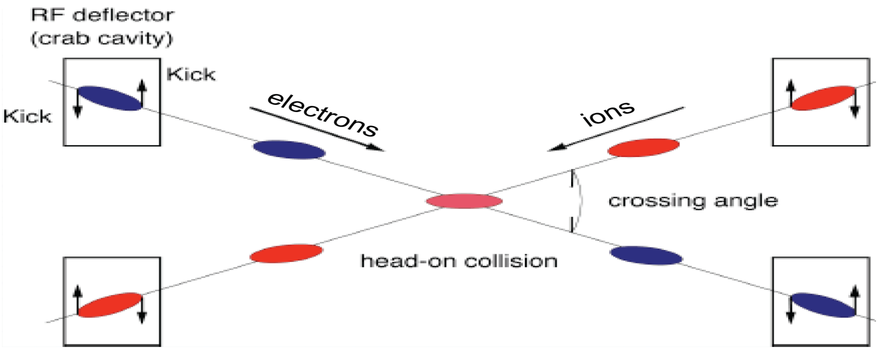


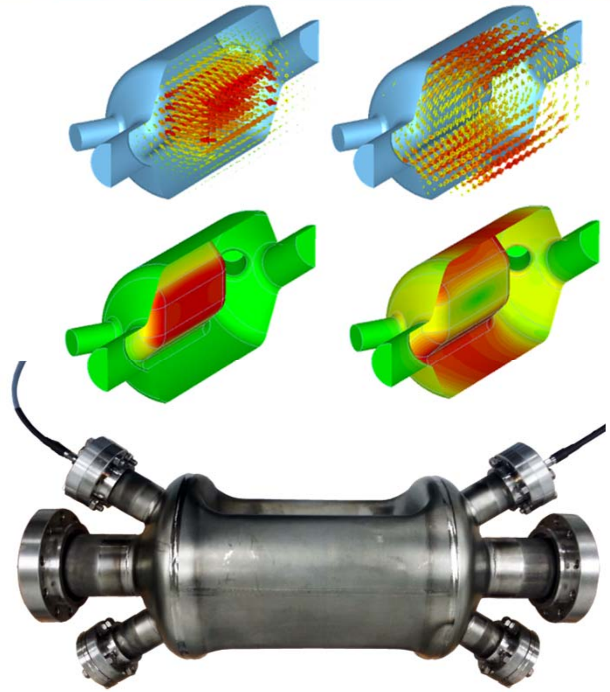


TUPOB30

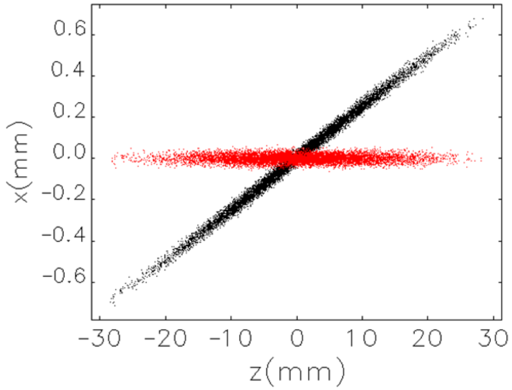
Crab Crossing ⇒ 10x Luminosity Gain

- Effective head-on bunch collisions restored with 50 mrad crossing angle
- Local crab scheme

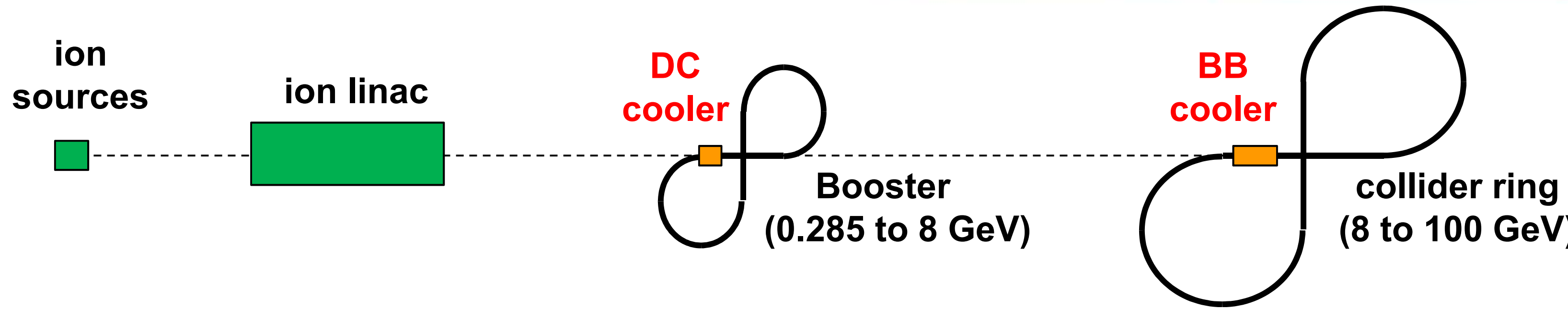




- Two cavities are placed at $(n+1)\pi/2$ phase advance relative to IP
- Optimal β_x at locations of crab cavities for minimizing the required kicking voltage
- Deflective crabbing using transverse electric field of SRF cavities (as at KEK-B)
- Prototype fabricated and characterized at ODU
- Crab dynamics simulations in progress



Multi-Step Cooling Scheme



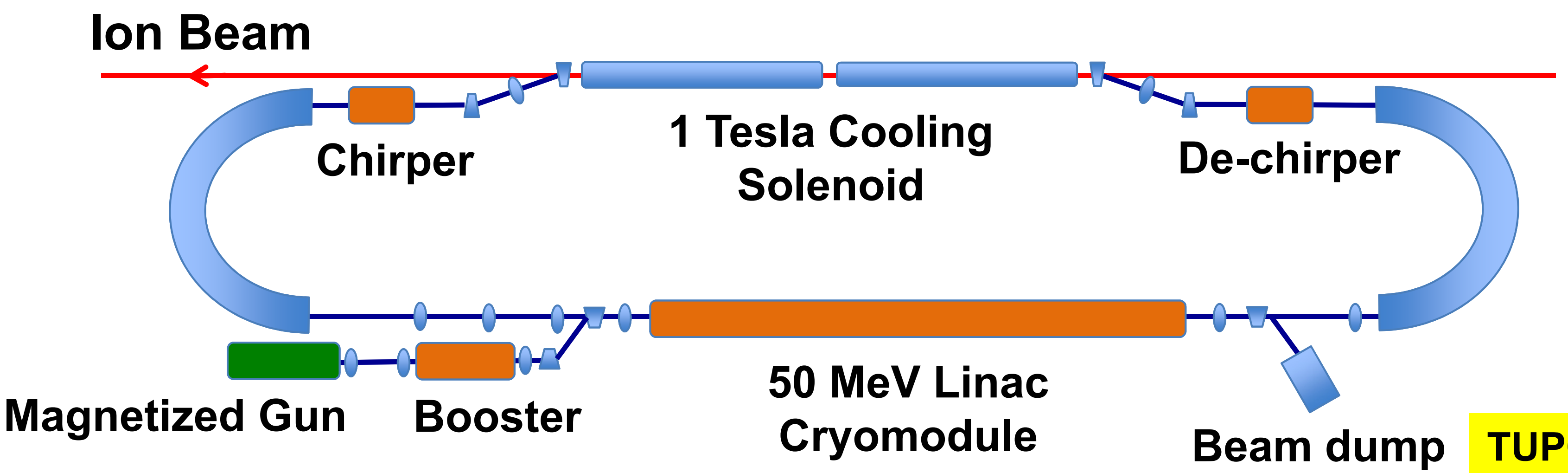
Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	MeV
Booster ring	DC	Injection/accumulation of positive ions	0.11 ~ 0.19 (injection)	0.062 ~ 0.1
		Emittance reduction	2	1.1
Collider ring	Bunched Beam Cooling **(BBC)**	Maintain emittance during stacking	7.9 (injection)	4.3
		Maintain emittance	Up to 100	Up to 55

- DC cooling for emittance reduction
- BBC for emittance preservation against intra-beam scattering

ERL Cooler

- Bunched electron cooling
- Magnetized cooling beam for higher efficiency
- Concept experimentally tested at IMP, China
- Progress on magnetized gun development
- Demonstration of magnetized beam transport in simulations
- Space charge and CSR shown not to be issues
- 952 MHz cavity development started

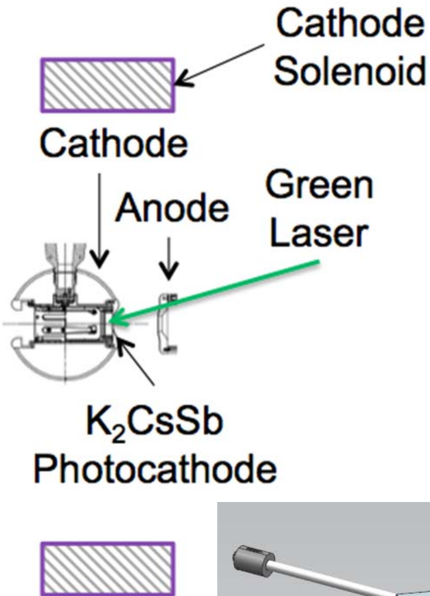
PARAMETERS	
energy	20–55 MeV
charge	420 pC
linac frequency	952.6 MHz
bunch length	2 cm
gun voltage	400 kV
solenoid field	1 T
solenoid length	2 x 30m



TUPOB36

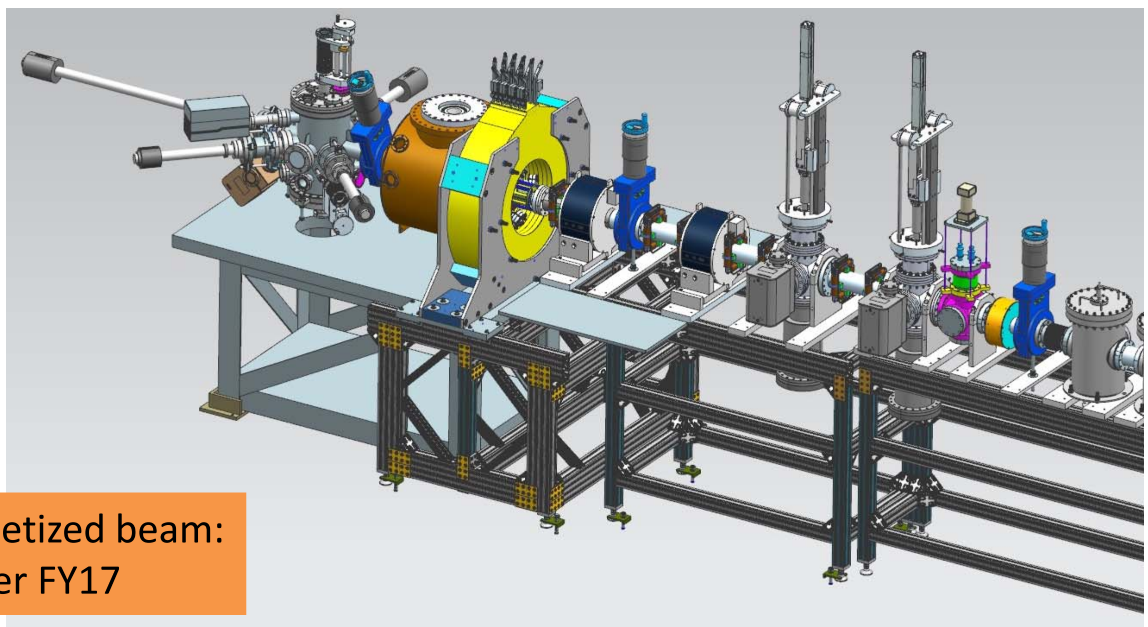
Source for Magnetized Cooling

Proposal awarded JLAB 2016 LDRD

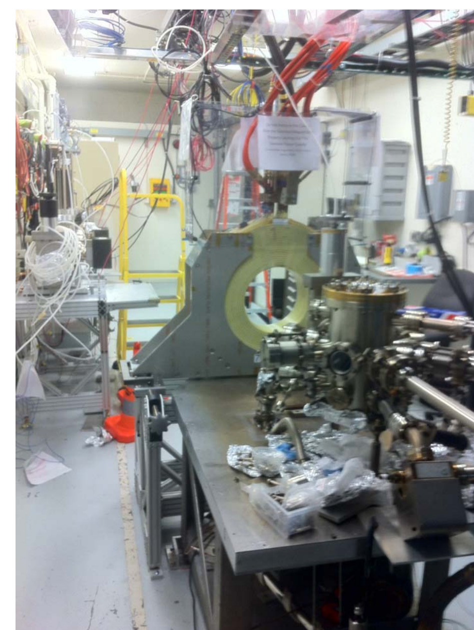


Bunch length	60 ps (2 cm)
Repetition rate	476.3 MHz
Bunch charge	420 pC
Peak current	7.0 A
Average current	200 mA
Transverse normalized emittance	10s microns
Cathode spot radius – Flat-top (a_0)	1.56 mm
Solenoid field at cathode (B_z)	2 kG

Test: 32mA
limited only by PS

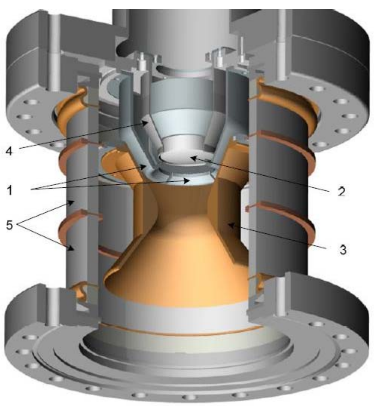


First magnetized beam: first quarter FY17

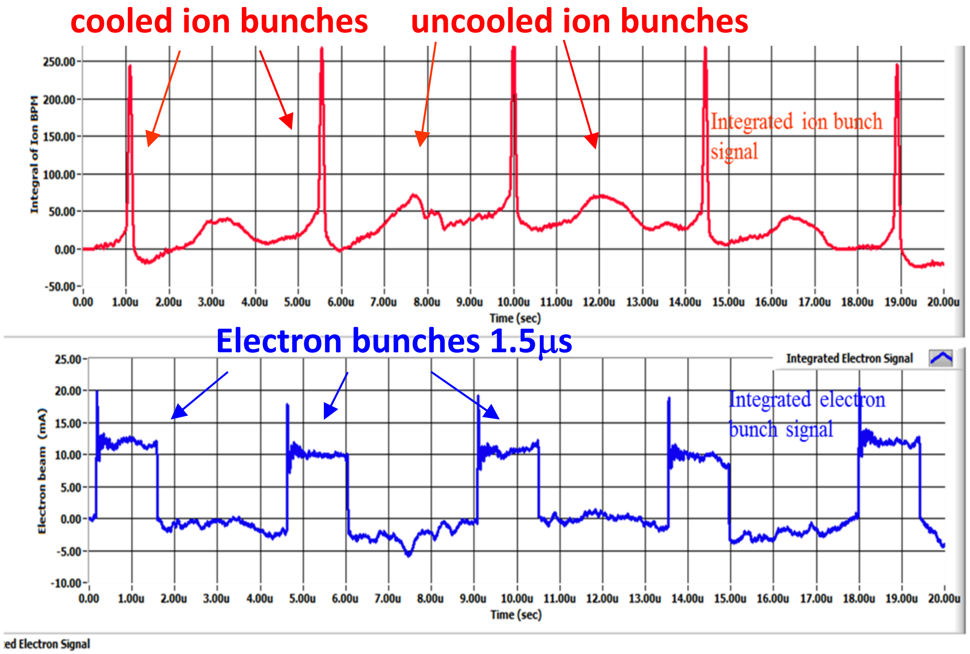


Bunched Beam Experiment

- Collaboration between JLab and Institute of Modern Physics (IMP), China
- Cooling electron bunches produced by pulsing the source of conventional DC electron cooler
- First experiment on May 17-22, 2016 using 7 MeV/u $^{12}C^{6+}$ beam stored in the CSRm ring
- Cooling of ion beam observed: first successful step towards experimental demonstration of bunched beam cooling
- Data analysis in progress

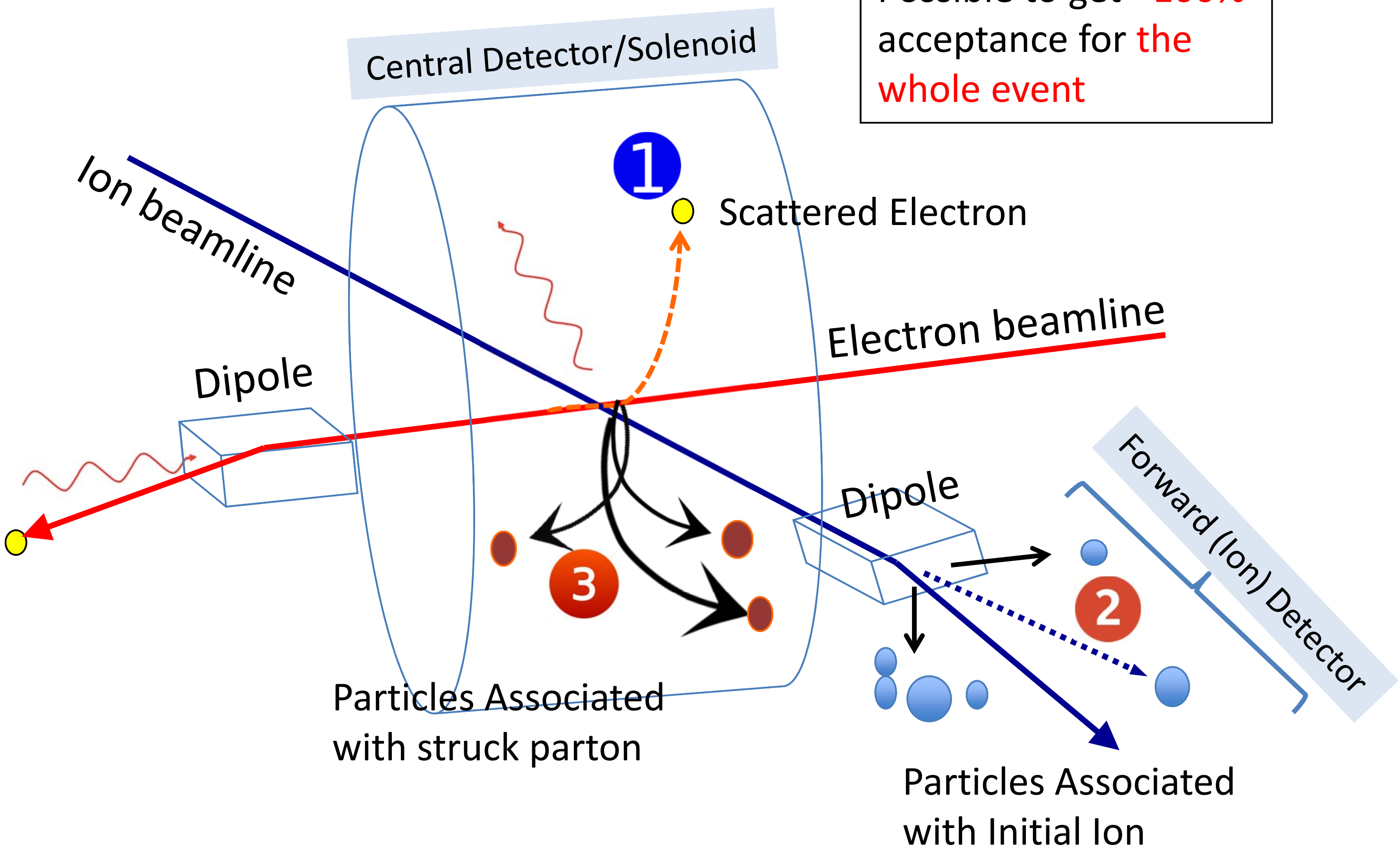


Experimental data from BPMs



Interaction Region Concept

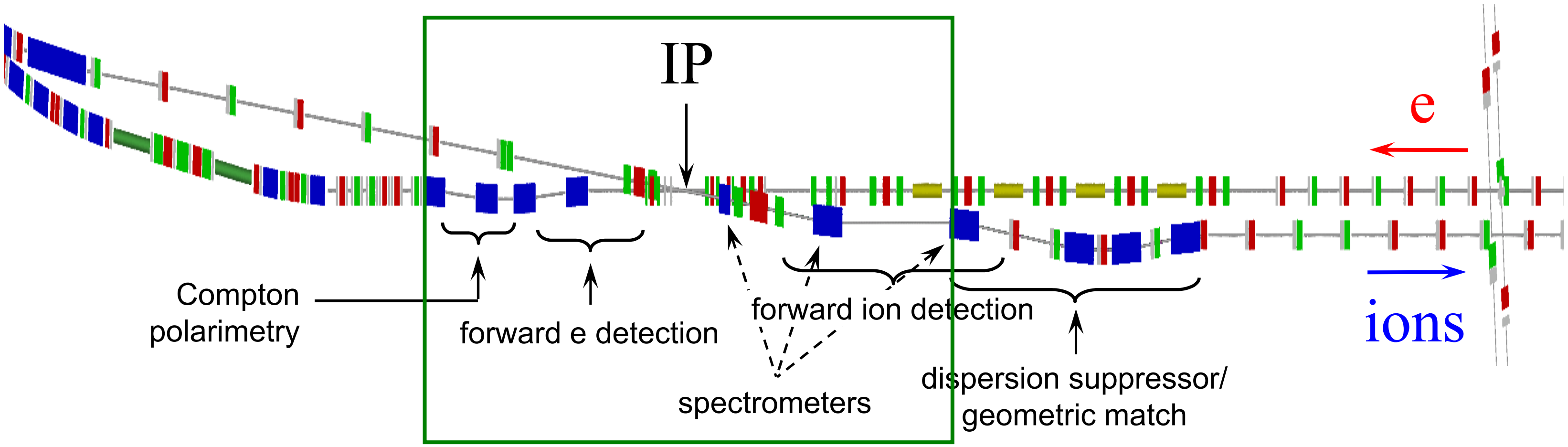
Possible to get ~100% acceptance for the whole event

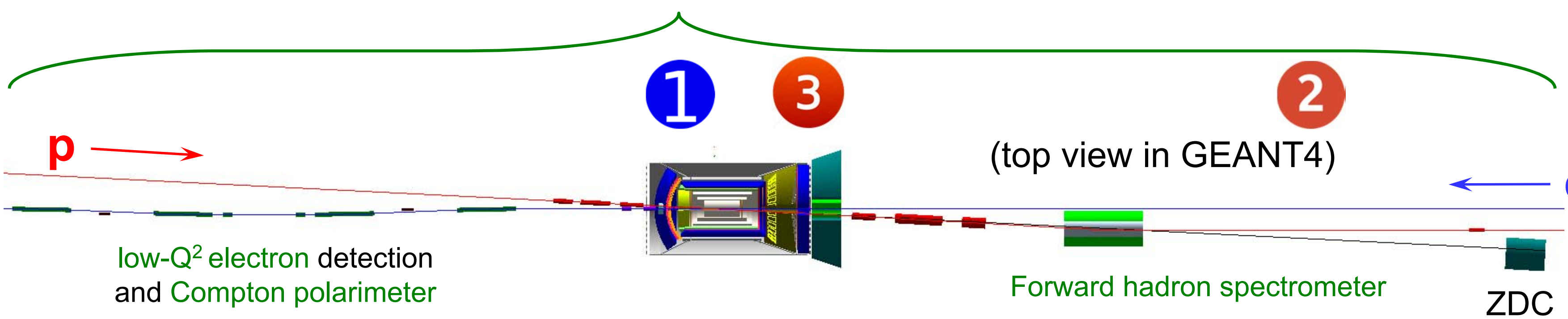


Courtesy of R. Yoshida

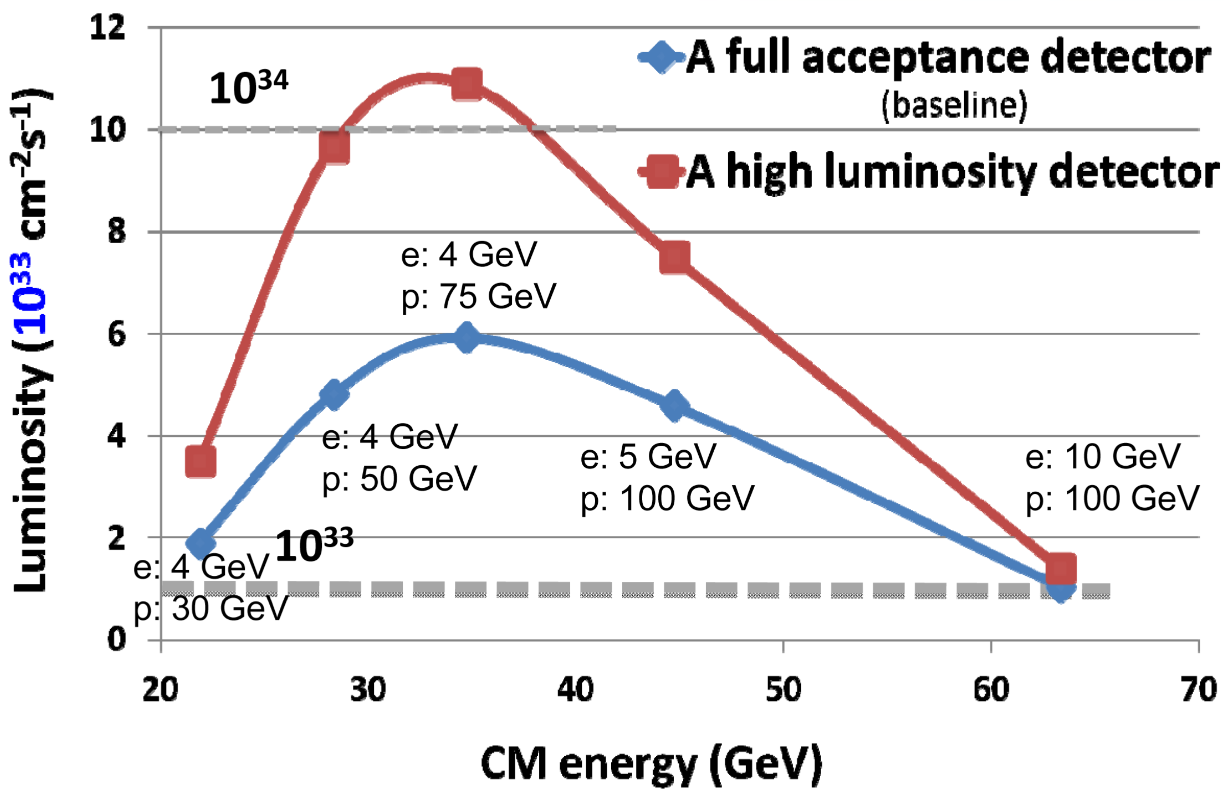
Detector Region

- Integrated detector region design developed satisfying the requirements of
  – Detection – Beam dynamics – Geometric match
- GEANT4 detector model developed, simulations in progress





e-p Collision Luminosity



Design point (CM)	p energy (GeV)	e^- energy (GeV)	Main luminosity limitation
low	30	4	space charge
medium	100	5	equilibrium emittances
high	100	10	synchrotron radiation

Work in Progress

Performance optimization:

- Upgrade to multi-turn electron cooling (recirculate cooling beam a few times) due to recent progress on
  - ERL cooler design
  - Fast kicker development
- Development of low emittance lattice of electron collider ring
- Collision parameter optimization

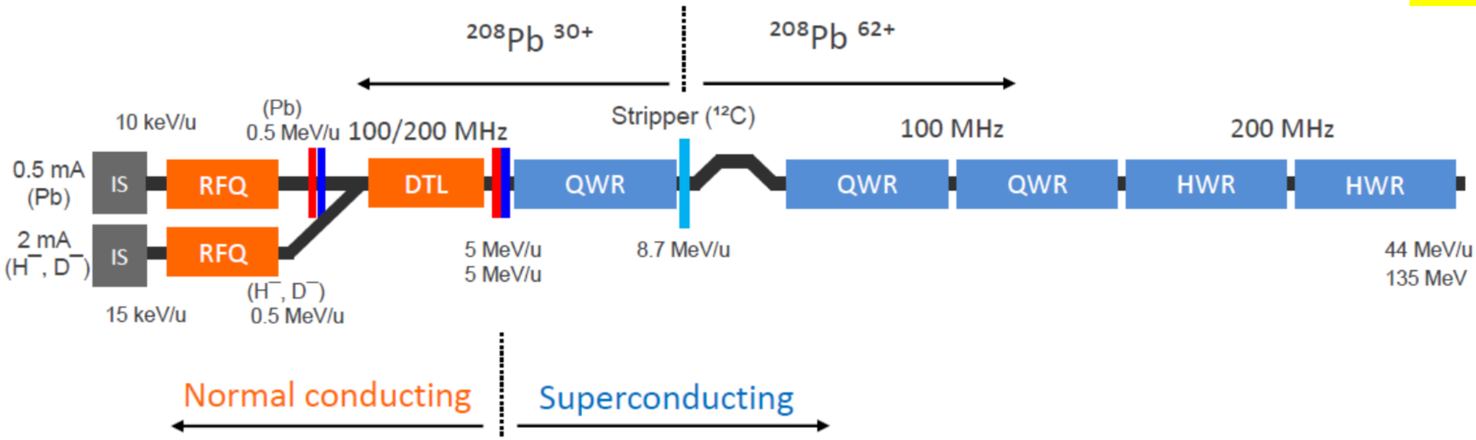
Cost optimization:

- Evaluation of SRF linac energy reduction to 140 MeV/u

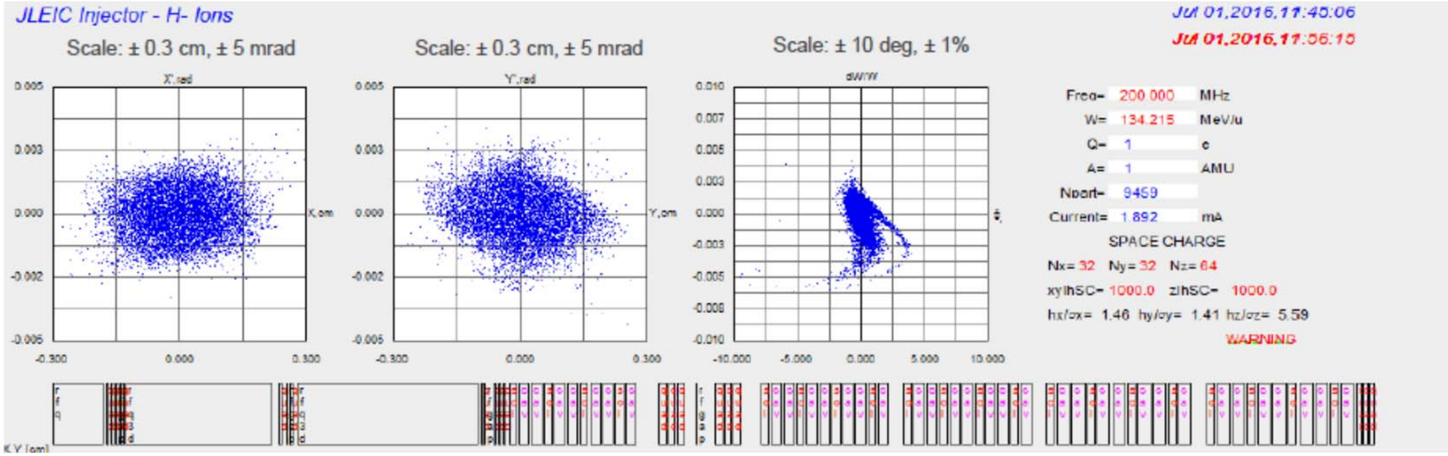
Lower-Energy Linac

- Has been designed and optimized

MOB4CO04



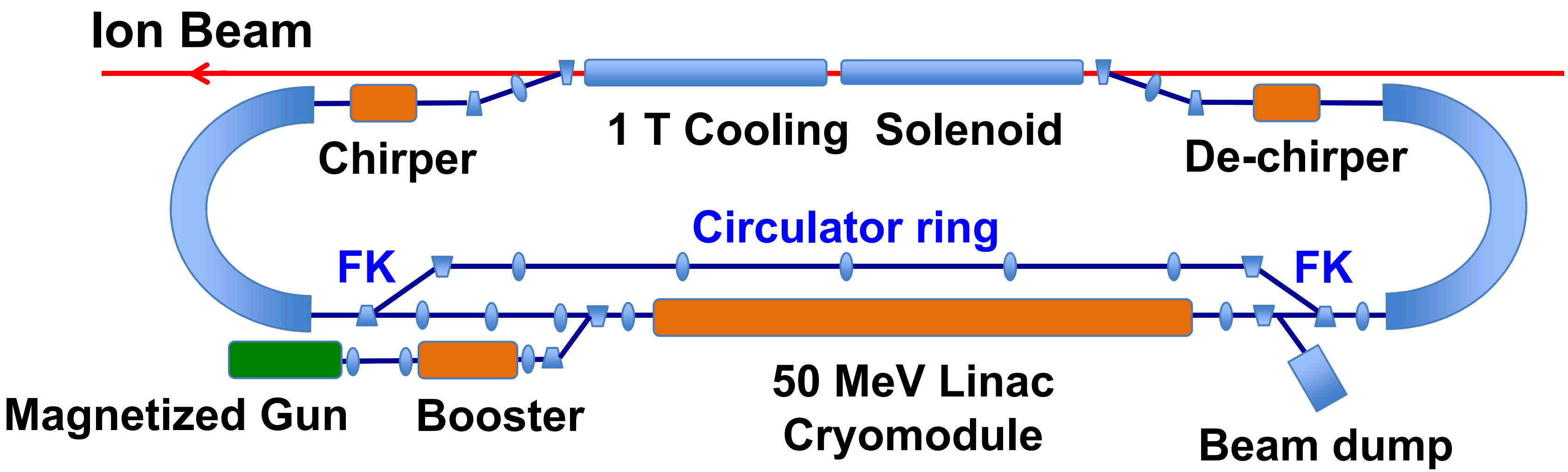
- End-to-end simulation completed



- Low-energy Booster studies in progress

Multi-Turn Cooling

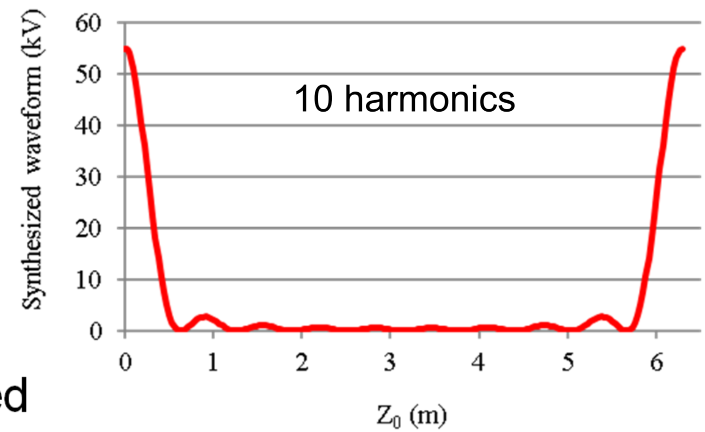
- Electrons circulate 10 to 30 turns in **circulator ring**,
- Beam current and bunch repetition frequency reduced by a factor of 10 to 30
- **Fast kickers (FK)** needed with rise and fall-off times of a fraction of a ns

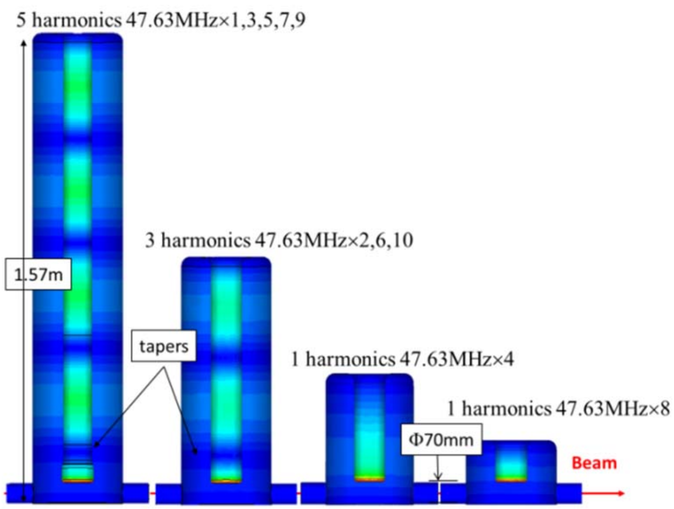


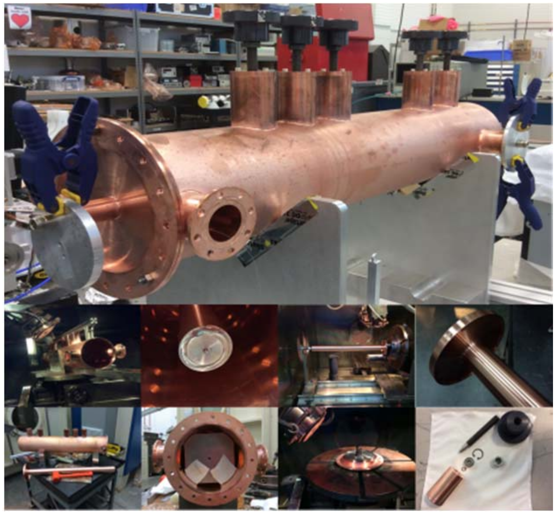
Fast Kicker

THA2CO04

- Enables cooling upgrade: performance improved / requirements relaxed by circulating cooling beam a few times
- Main challenge: kicking 952 MHz electron bunches in and out of circulator ring
- Harmonic kicker:
  combination of N of RF harmonics
  kicks every N's bunch
- Harmonic cavity kicker
  - High power efficiency
  - 10 harmonics → 4 cavities
- 5 harmonic prototype built and being tested







Possible 4x Luminosity Increase

		Present design		Updated design	
		p	e	p	e
Beam energy	GeV	100	5	100	5
Collision frequency	MHz	476		476	
Particles per bunch	10^{10}	0.66	3.9	0.98	3.7
Beam current	A	0.5	3	**0.75**	2.82
Polarization		>70%	>70%	>70%	>70%
Bunch length, rms	cm	1	1.2	1.2	1.2
Norm. emittance, x/y	μm	1/0.5	144/72	**0.5/0.1**	**70/14**
x/y β*	cm	4/2	2.6/1.3	**6/1.2**	**4/0.8**
Vert. beam-beam param.		0.006	0.014	0.015	0.053
Laslett tune shift		0.01	Small	0.048	Small
Detector space, up/down **(full-acceptance detector)**	m	3.6/7	2.4/1.6	3.6/7	2.4/1.6
Hourglass (HG) reduction		0.88		0.80	
Lumi./IP, w/HG, 10^{33}	**$cm^{-2}s^{-1}$**	**4.6**		**19.5**	

Conclusion

- JLEIC design is driven by and optimized for physics requirements
- The overall risk is low
- Key features:
  - High luminosity
  - High polarization
  - Full-acceptance detection
- Minimal R&D necessary
  - Electron cooling
  - Magnet design
- Next steps - optimizations
  - Performance
  - Cost

JLEIC-Related Presentations

Talks:

MOPLIO04	Nuclear Physics at the Electron Ion Collider Plenary (Speaker: R. Ent)
MOA4CO03	Complete Beam Dynamics of the JLEIC Ion Collider Ring Including Imperfections, Corrections, and Detector Solenoid Effects (Speaker: G. Wei)
MOB4CO04	Design of the Room-Temperature Front-End for a Multi-Ion Linac Injector (Speaker: A. Plastun)
THA2CO04	Bench Measurement of a Multifrequency Cavity of the Ultra-fast RF Kicker for ERL Circular Cooler Ring of JLEIC (Speaker: Y. Huang)

Posters:

MOPOB54	Superferric arc dipoles for the Ion Ring and Booster of JLEIC (Presenter: J. Breitschopf)
TUPOB04	A More Compact Design for the JLEIC Ion Pre-Booster Ring (Presenter: B. Mustapha)
TUPOB05	An Alternative Approach for the JLEIC Ion Accelerator Complex (Presenter: B. Mustapha)
TUPOB29	Simulations of Nonlinear Beam Dynamics in the JLEIC Electron Collider Ring (Presenter: V. Morozov)
TUPOB30	Spin Flipping System in the JLEIC Collider Ring (Presenter: V. Morozov)
TUPOB31	Compensation of Chromaticity in the JLEIC Electron Collider Ring (Presenter: V. Morozov)
TUPOB36	Simulation Study on JLEIC High Energy Bunched Electron Cooling (Presenter: H. Zhang)