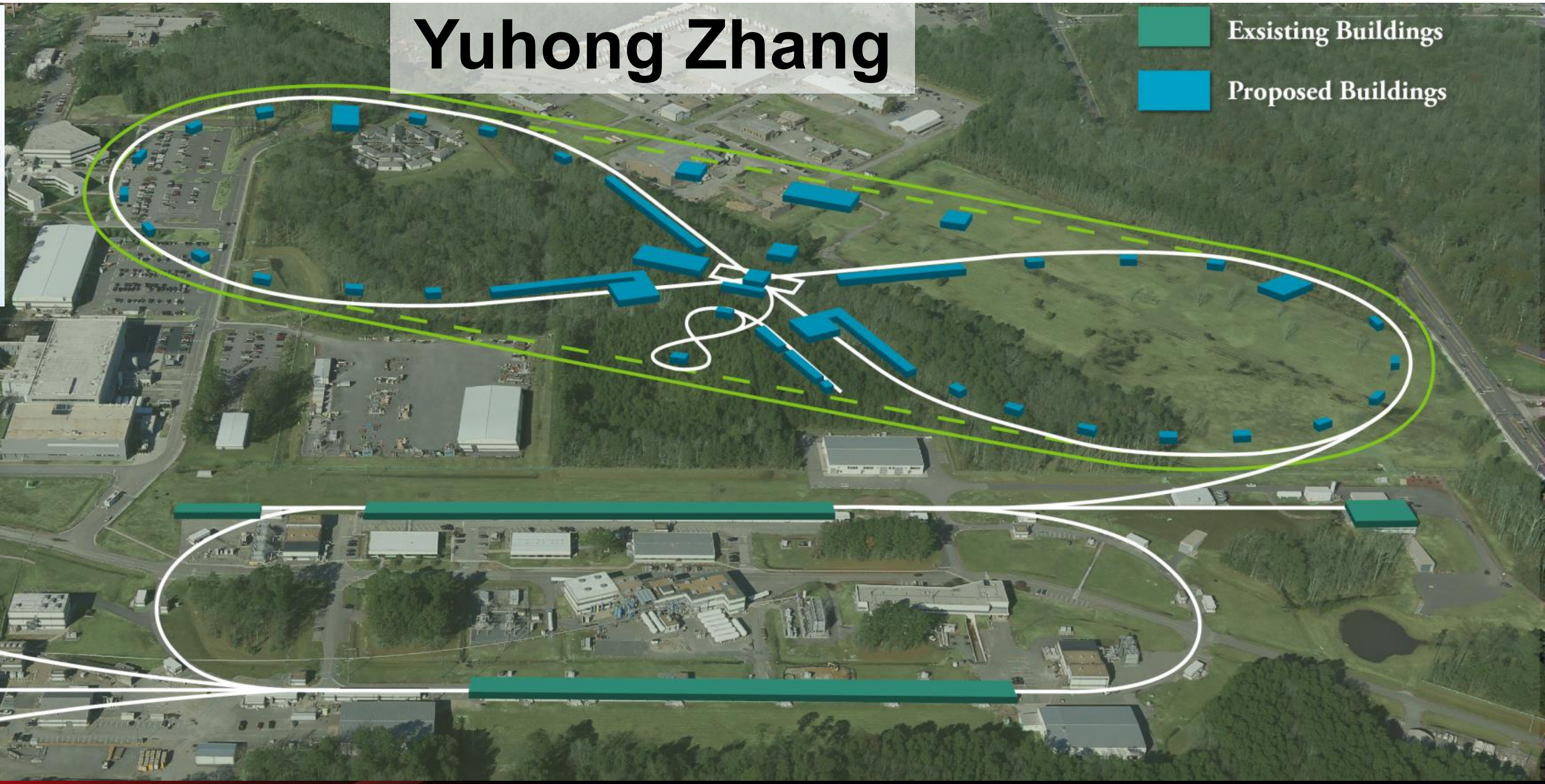
JLEIC Ultimate Luminosity Performance with Strong Electron Cooling

Yuhong Zhang



IPAC2017, Copenhagen, Denmark
May 14-19, 2017

Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

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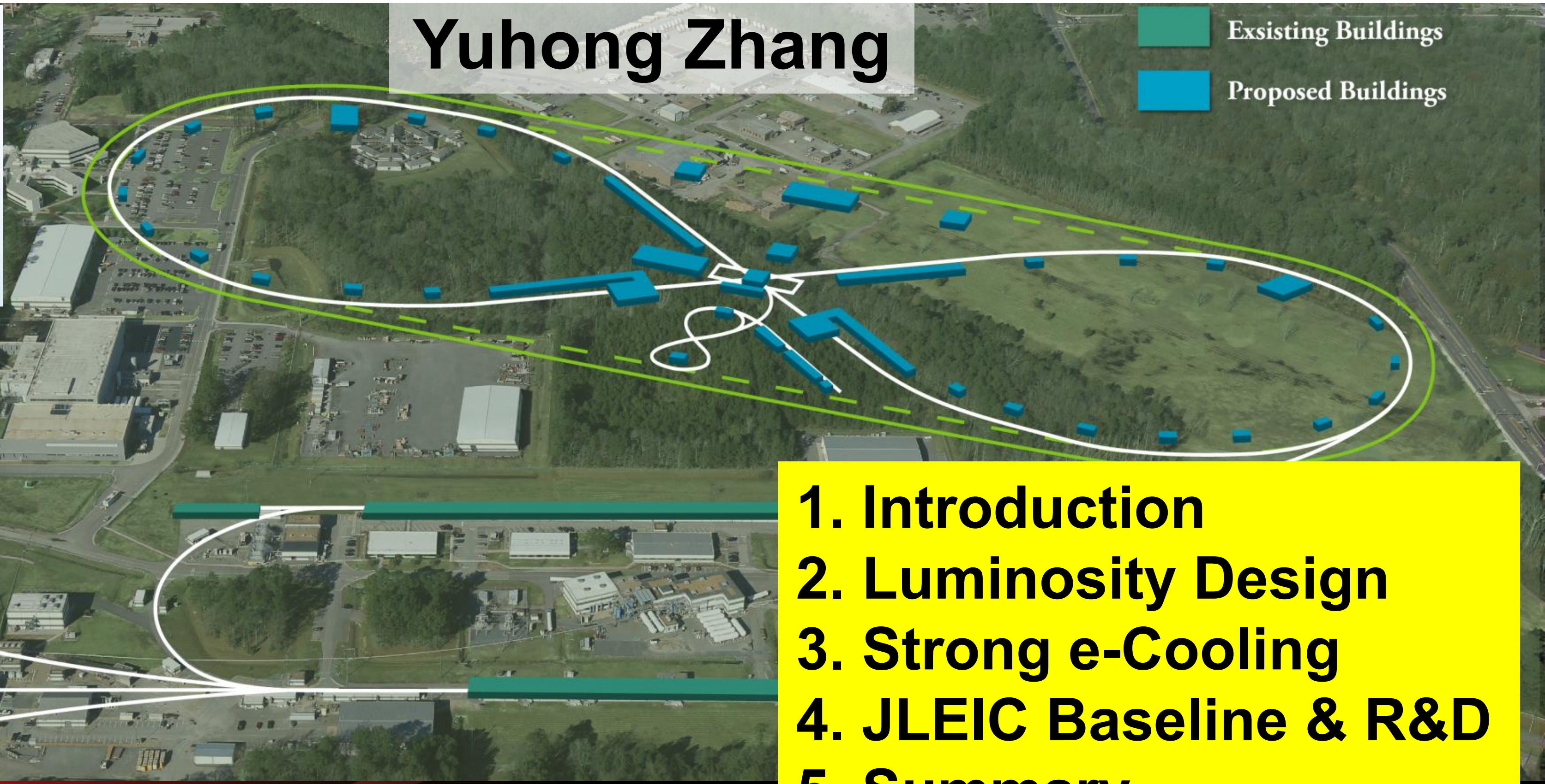

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2. Luminosity Design
3. Strong e-Cooling
4. JLEIC Baseline & R&D
5. Summary

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JLEIC Collaboration

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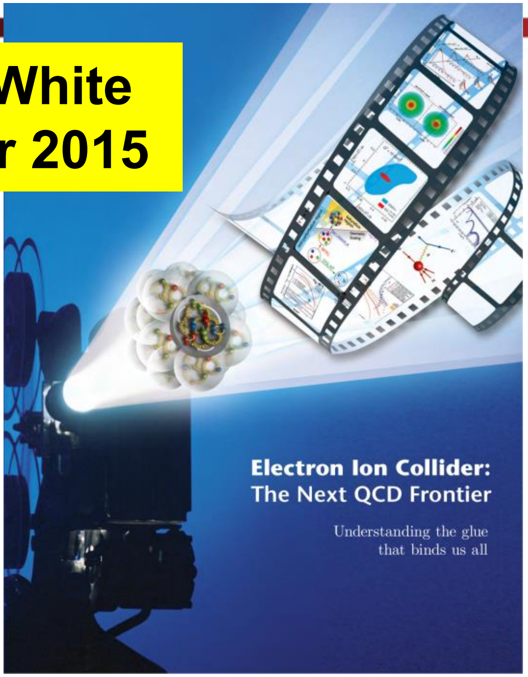
I have borrowed slides/materials from these colleagues for preparing my presentation. I want to thank them.

Introduction: JLEIC In the QCD Frontier

- The international nuclear science community has long envisioned a high luminosity polarized electron-ion collider for the future QCD frontier
- ***JLEIC*** is a **J**efferson **L**ab proposed **E**lectron-**I**on **C**ollider for responding to this science need
- BNL has proposed ***eRHIC*** for the same science
- JLEIC is designed for delivering high performance including high luminosity, high polarization and full detector acceptance
- The JLEIC design concept has been stable over the last 10 years
- The implementation has been continuously updated and optimized to enhance performance, mitigate technical risk and reduce costs

EIC White Paper 2015



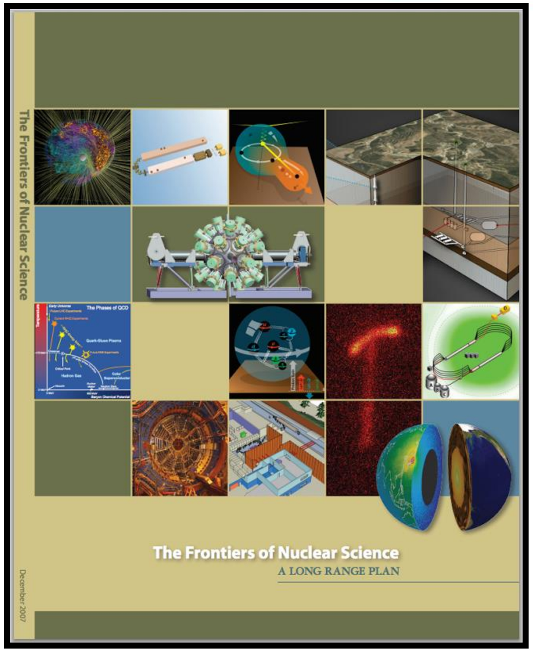
EIC Science in Media

May 2015 issue

EIC in US NSAC Long Range Plan

- Nuclear Science Advisory Committee (**NSAC**) is commissioned by US Department of Energy and National Science Foundation
- NSAC provides advice 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,*** ➔ a roadmap for nuclear science facilities for the next 10 years
- *LRP 1979, 1983, 1989, 1996, 2002, 20*

Just completed !
Science has begun



NSAC LRP 2007

- **Completion of the 12 GeV CEBAF Upgrade at Jefferson Lab.**
- **Construction of the Facility for Rare isotope Beams, FRIB**

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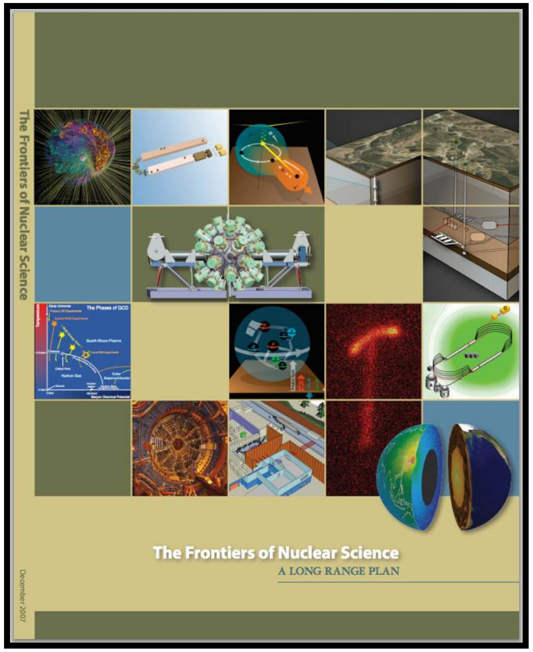

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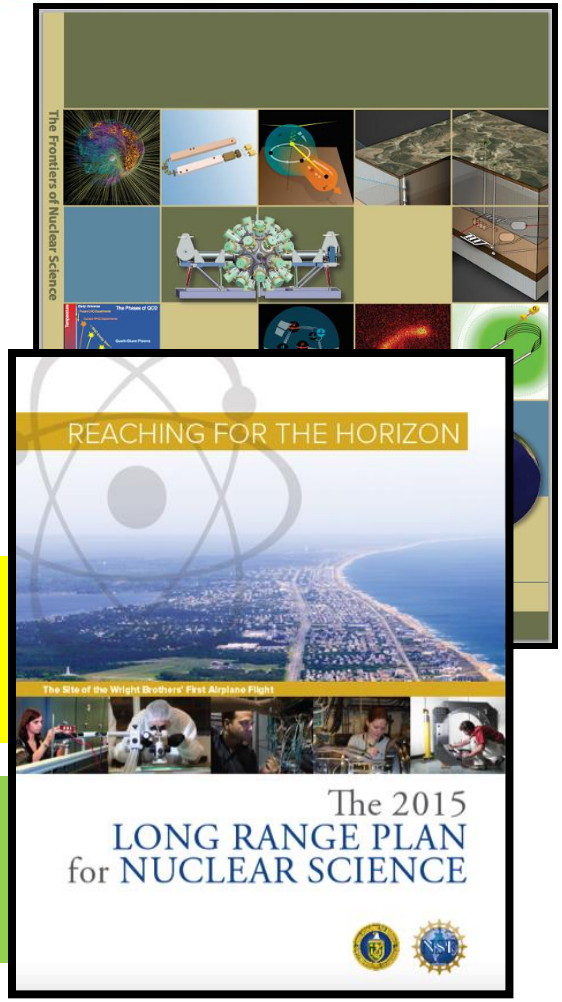
NSAC LRP 2007

- **Completion of the 12 GeV CEBAF Upgrade at Jefferson Lab.**
- **Construction of the Facility for Rare isotope Beams, FRIB**

Under construction

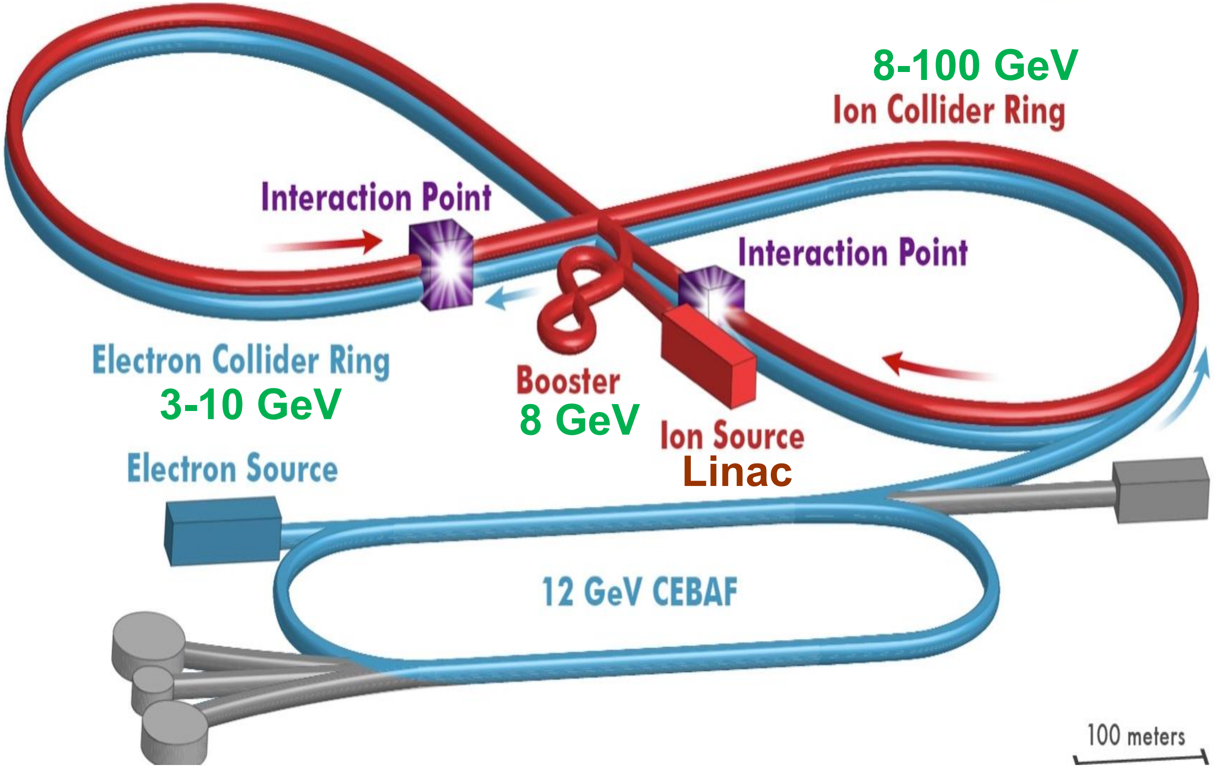
NSAC LRP 2015

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



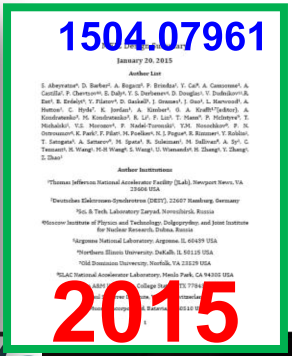
- Last milestone of the long process for approval of an EIC in US: **National Academy of Science Review** (presently *in progress, report expected at the end of 2017)*
  (http://sites.nationalacademies.org/BPA/BPA_177106)

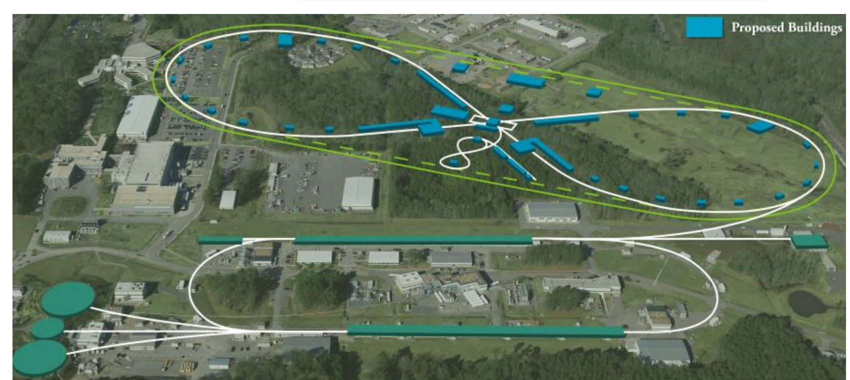
JLEIC Layout and On JLab Site Map



- **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





JLEIC High Luminosity Design Concept

- *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 traditional 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	-	0.9
HERA	8.2	7.3	16	18
JLEIC	**476**	**1**	**1**	**1.2**
KEK-B	158 - 458	6.4 – 2.1	~0.6	0.59

Beam Design
- **High repetition rate**
- **Low bunch intensity**
- **Short bunch length**
- **Small emittance**

IR Design
- **Very small β***
- **Crab crossing**

(~~crab waist~~)

Damping
- **Synch. radiation**
- ***Electron cooling***
- ***Stochastic cooling***

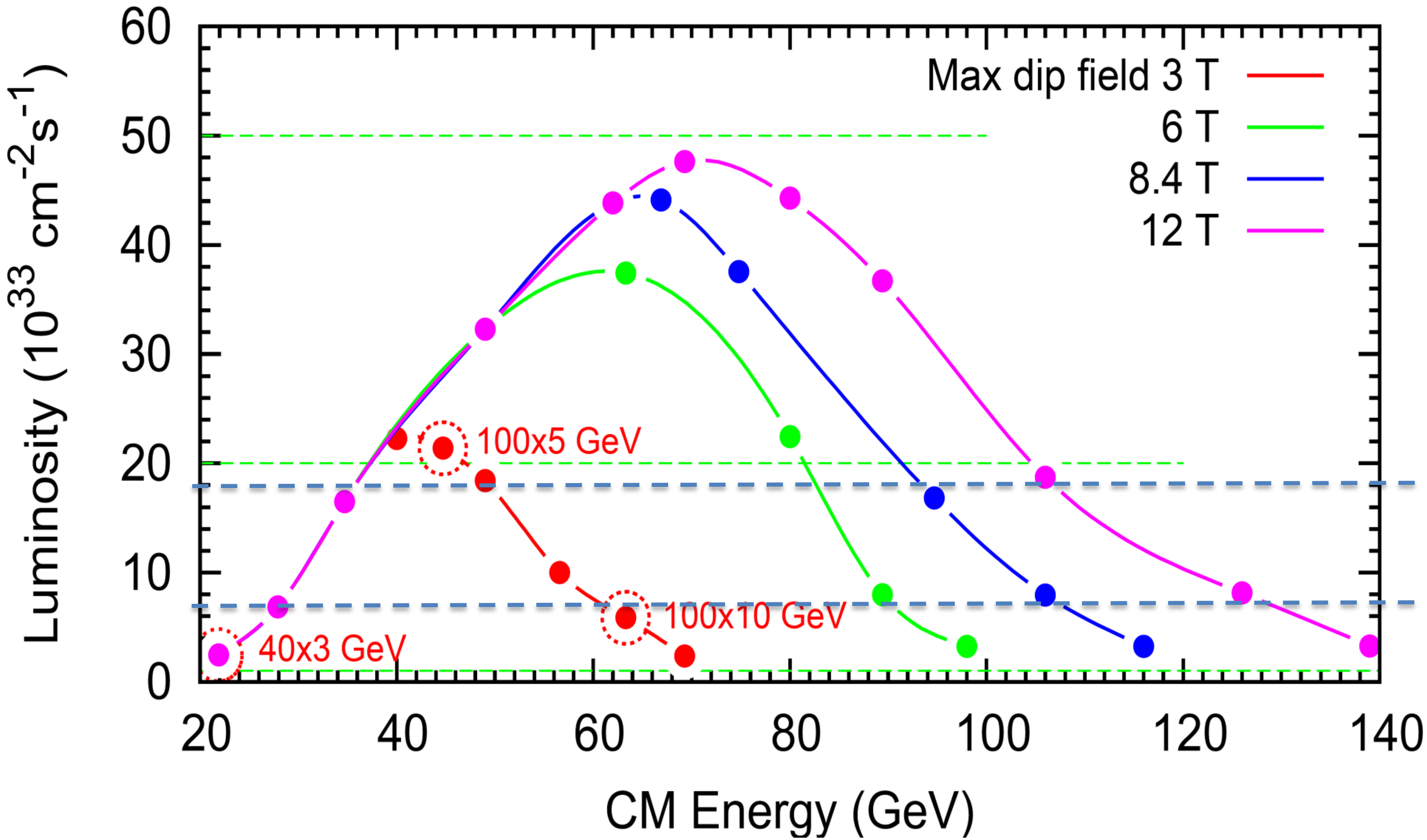
Role of cooling of ion beams
- Damping is critical for beam formation and emittance preservation
- Electron has a natural damping -SR
- No SR for protons/ions in this medium energy range
- JLEIC relies on *electron cooling* for providing a damping mechanism

JLEIC Baseline *e-p* Parameters

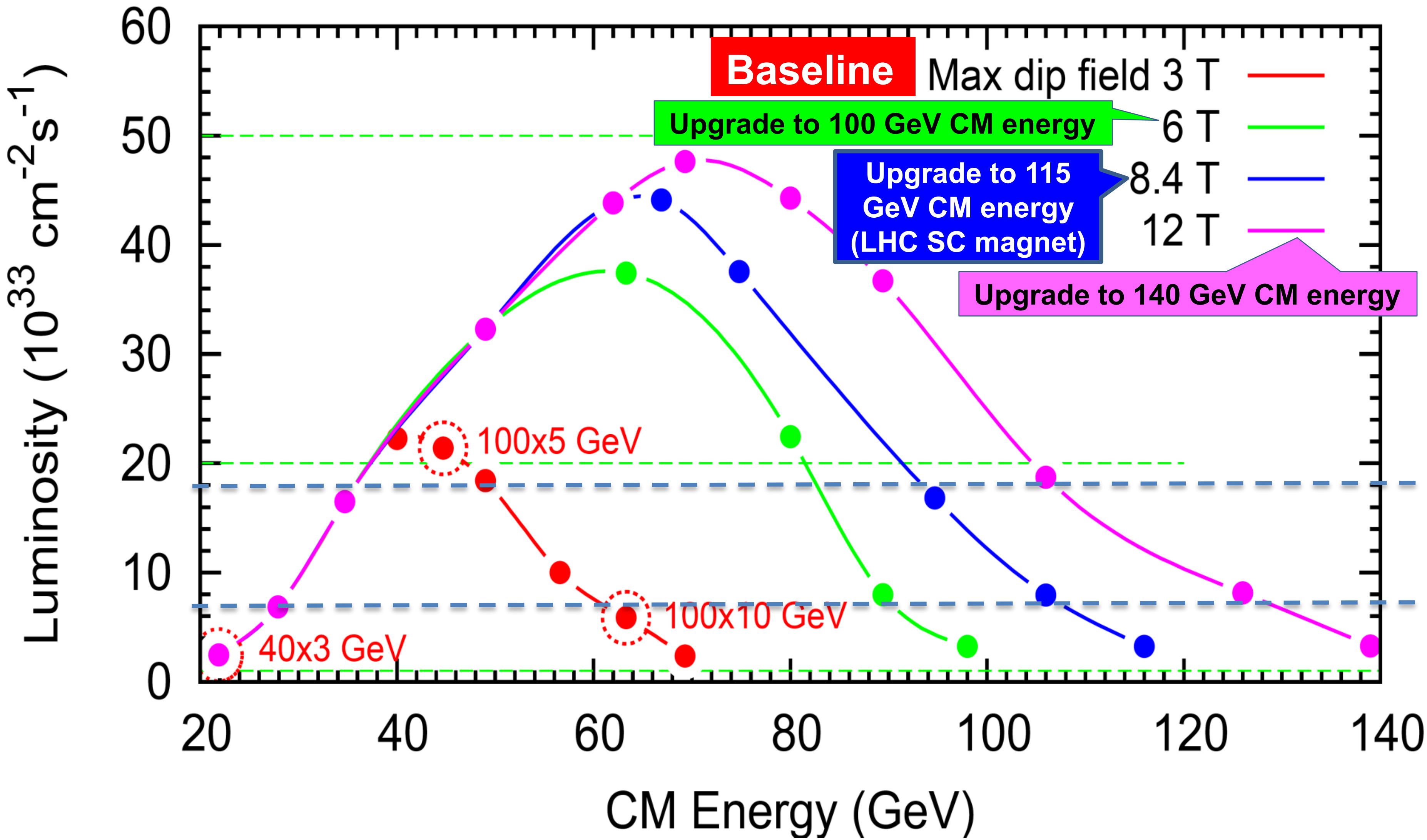
CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	**476**		**476**		**476/4=119**	
Particles per bunch	10^{10}	**0.98**	3.7	**0.98**	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	**3**	1	**1**	1	**2.2**	1
Norm. emitt., horiz./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 param.		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**	

Similar high performance can be achieved for electron-ion (*e-A*) collisions

JLEIC *e-p* Luminosity & Upgrade Potential



JLEIC *e-p* Luminosity & Upgrade Potential



Multi-Step Cooling for High Luminosity

- **Cooling of JLEIC proton/ion beam**
  - Achieving very small emittance (**a factor of 10 reduction**)
  - Achieving very short bunch length **~1 cm** (with strong 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)

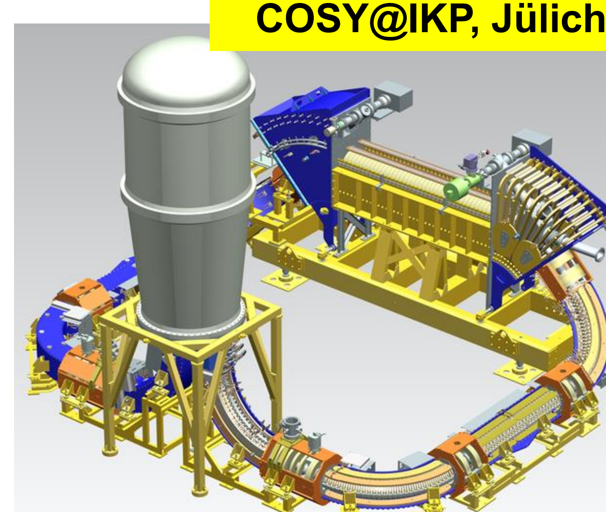
- **JLEIC: conventional electron cooling**

  Well established technology (in the low energy DC regime)

- **Multi-step scheme**
  - high cooling efficiency at low energy and small emittance

Ring	Cooler	Functions	Ion energy (GeV)	Electron energy (MeV)
Booster	DC	Accumulation of positive ions	0.11~0.19 (injection)	0.062~0.1
		Pre-cooling for emittance reduction	~2	1.1
Collider	ERL	Maintain emittance during stacking	7.9 (injection)	4.3
		Maintain emittance during collision	Up to 100	Up to 55

2 MeV DC Cooler for COSY@IKP, Jülich



High Energy Magnetized Electron Cooler Based on ERL and Circulator Ring

Design/simulations show 1 to 2 A electron current required for achieving/maintaining very small emittance for ultimate luminosity

Electron energy	MeV	up to 55
Bunch charge	nC	3.2
Turns in circulator	turn	~20
Curr. in CCR/ERL	A	1.5/0.075
Bunch repetition	MHz	476
Cooling section	m	60
Cooling solenoid	T	1

Cooler requirements beyond *state-of-art*

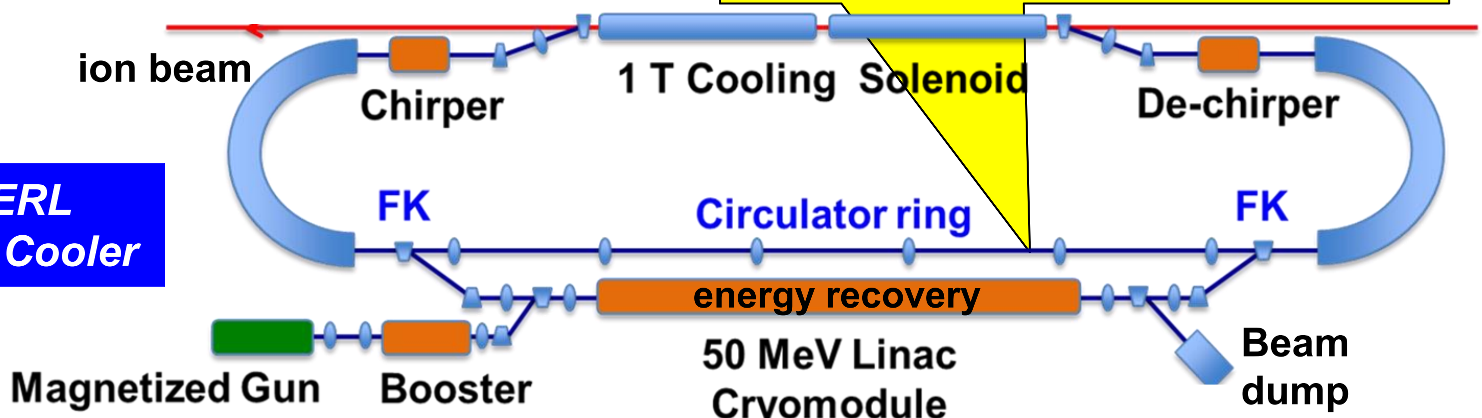
- Current: 1 to 2 A / 3.2 nC (***strong cooling/baseline***)
  ~0.2 A / 0.4 nC (week cooling)
- Energy: up to 55 MeV (*must use a **RF/SRF linac***)
- Beam power: ~81 MW (*too big to dump, **must ER***)

Technical approaches

- High current/intensity magnetized electron beam
- SRF linac for acceleration with energy recovery
- Circulator ring

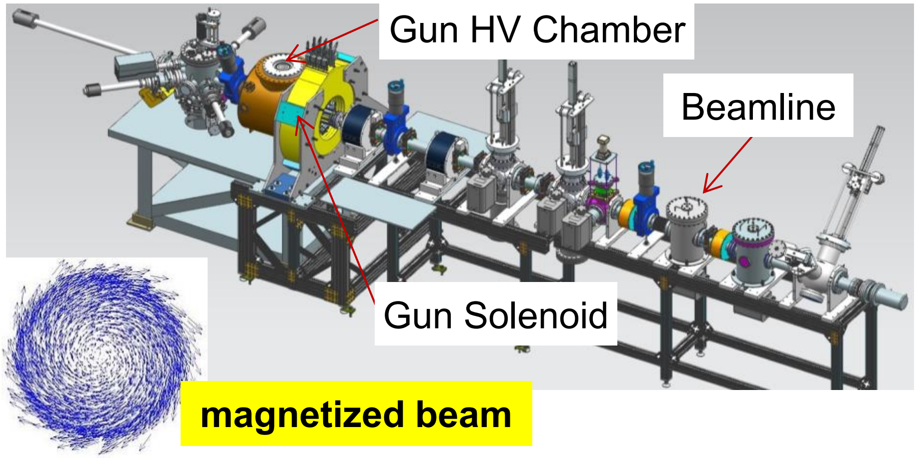
Strong cooling (Amp-class current)
➔ recirculating ~20 turns
➔ Boosting the linac cooling beam current by a same factor

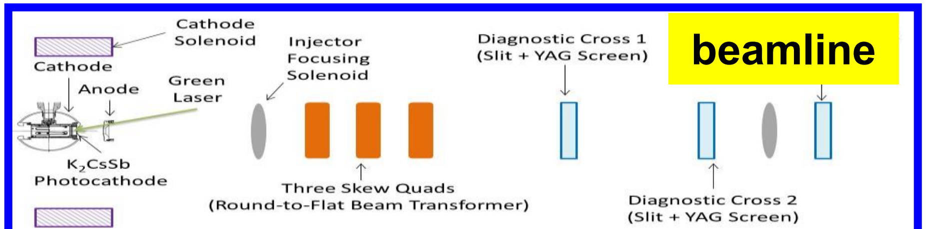
JLEIC ERL Circulator Cooler

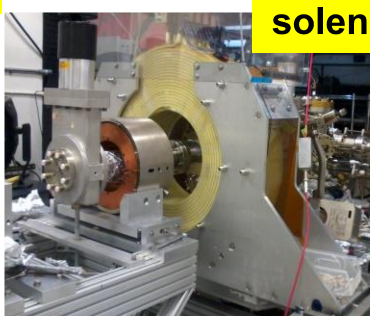


ERL-Circulator Cooler R&D

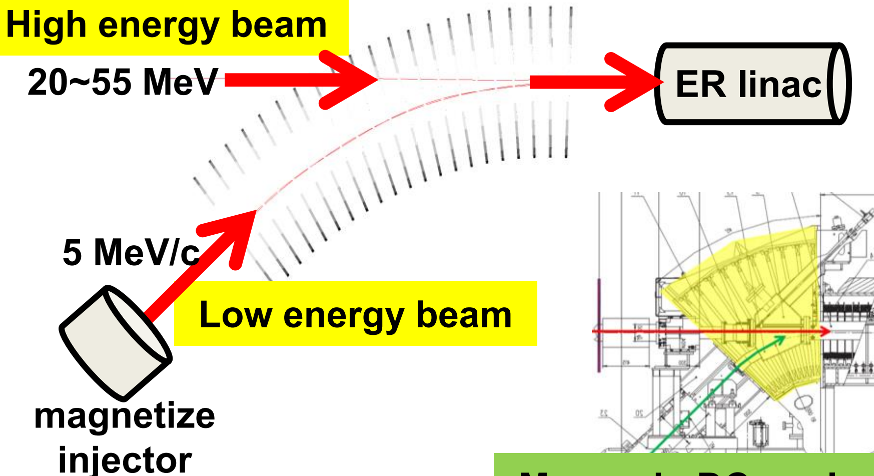
Magnetized source development



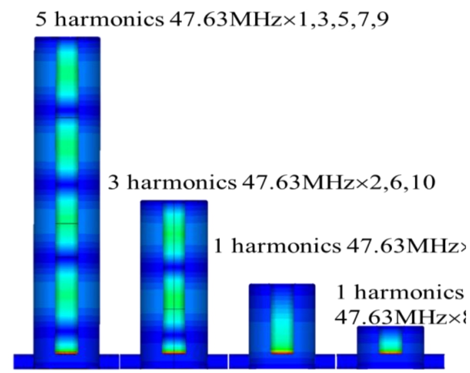




Toroidal merger for ERL



Harmonic RF Fast kicker



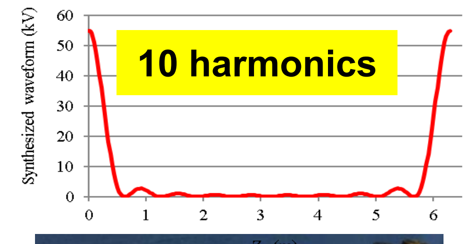


Figure-8 Ring® for High Polarization

- Electrons & protons/light ions are injected polarized from sources
- Rings are designed to preserve the polarization

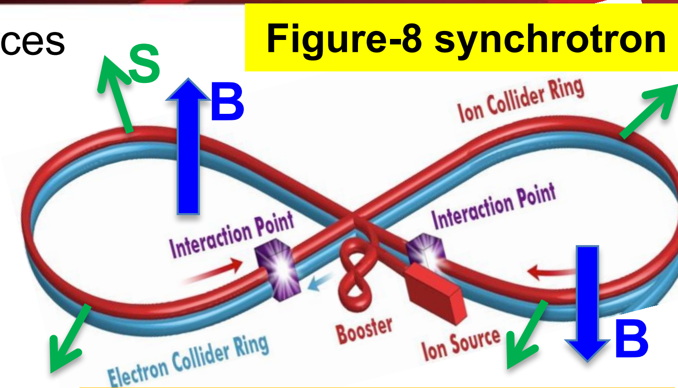
- JLEIC adopted a figure-8 topology for ion rings
  ← *enabled by a* ***green field*** *collider ring design*
- A brilliant invention of ***Dr. Yaroslav Derbenev***

- 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

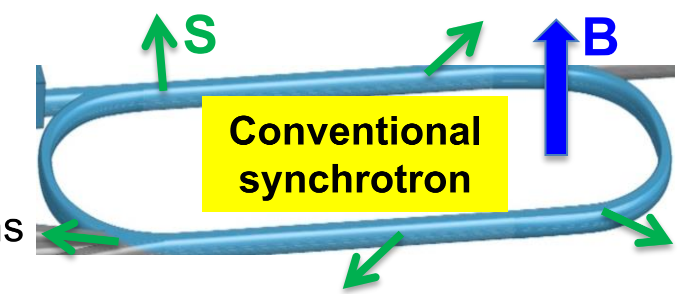
- Spin can be controlled and stabilized by compact spin rotators (e.g., moving spin tune away from 0)
- No need of Siberian Snakes

- The ***only practical way*** to accelerate/store polarized deuterons in medium energy range (gyromagnetic ratio *g-2* too small)

- The electron ring follows the figure-8 foot-print of the ion ring
- Figure-8 helps the electron polarization under spin flip



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



- Spin precession/spin tune is energy dependent
- Cross many spin resonances during acceleration
- Siberian Snake may help, but still difficult

JLEIC Achieved Design Goals

Design goals consistent with the EIC White Paper requirements

Energy

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

Ion species

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

Support 2 detectors

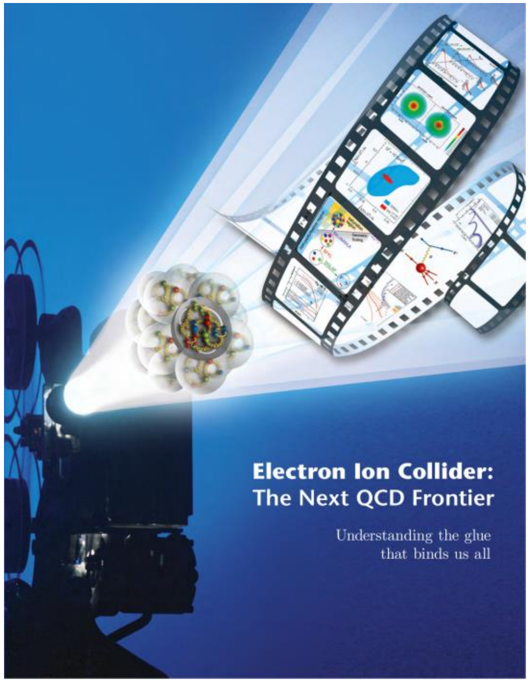
- **Full acceptance capability** is critical for the primary detector

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

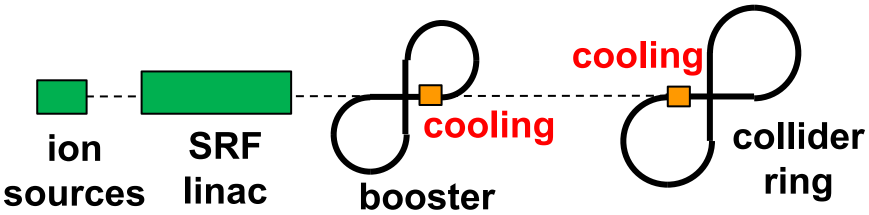
- At IP: longitudinal for both beams, transverse for ions only
- All polarizations >70%



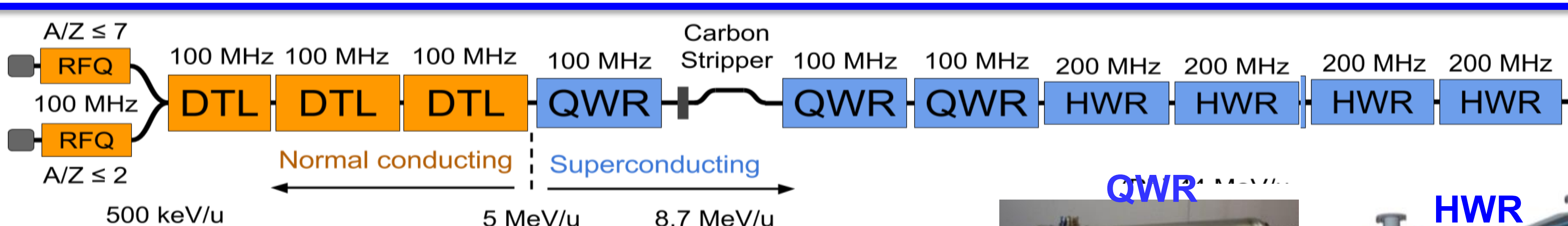
Upgradable to higher CM energy/luminosity possible

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

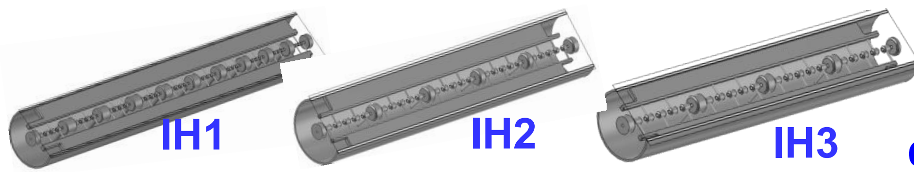
A New Ion Complex for JLEIC



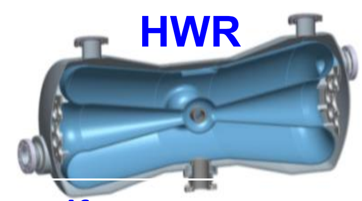
- Generate, accumulate & accelerate ion beams
- Covering all required ion species
- Delivering required time/phase space structure for matching with electron beam
- High polarization for protons/light ions



Ion linac

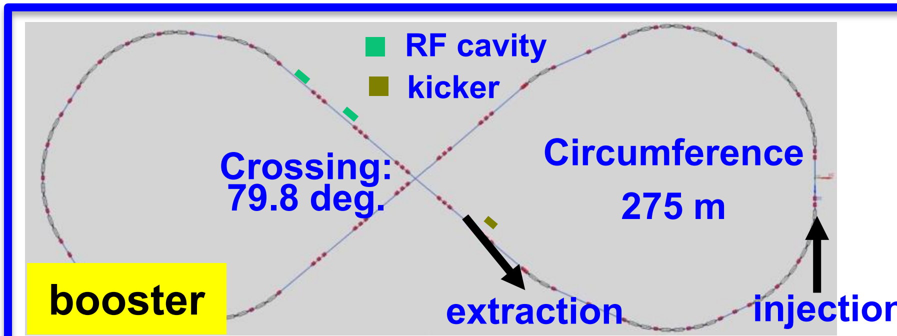


Quarter Wave Resonator



Half-Wave Resonator

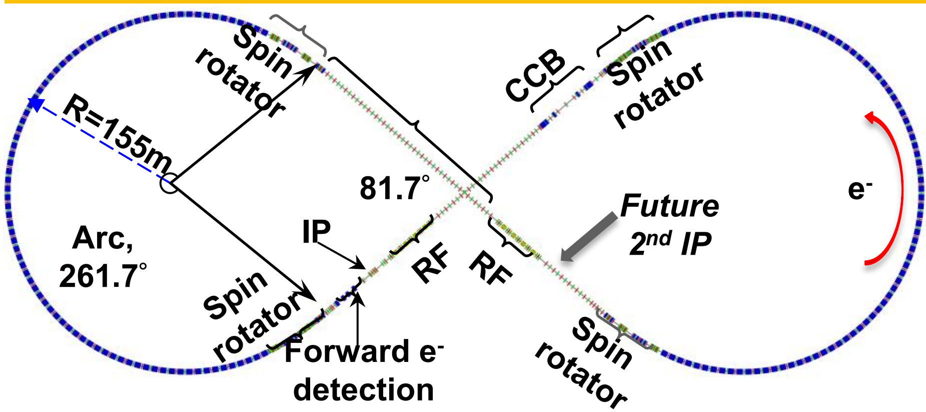
	Length (m)	Max. energy (GeV)
SRF linac		0.2
booster	~75	8
collider ring	~2250	100



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

JLEIC Collider Rings

Electron ring w/ major machine components

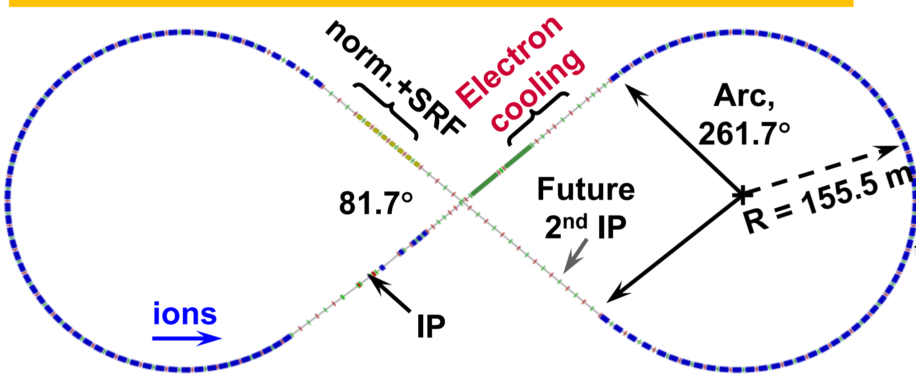


- Two rings have same footprint, **stack *vertically***
- Having a ***horizontal crab crossing*** at IPs
- Supports two IPs and fit to the JLab site
- Beamline/optics design completed (including low-β insertion, chromatic compensation, etc.)
- ***Ion magnet fields*** determines CM energy range

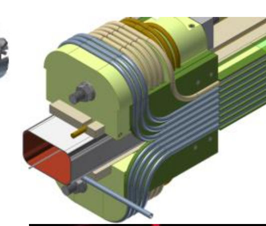
		p	e
Circumference	m	2154	
Crossing angle	deg	81.7	
Lattice		FODO	FODO
Dipole & quad	m	8 & 0.8	5.4 & 0.45
Cell length	m	22.8	15.2
Max. dipole field	T	3	~1.5
SR power density	kW/m		10
Transition γ_{tr}		12.5	21.6

- 12GeV CEBAF as a full energy (polarized) injector
- Capability of top-off injection or continuous injection
- Reuse PEP-II equipment's (RF, vacuum chamber, and possibly magnets)

Ion ring w/ major machine components



Super-ferric magnets (3 T)

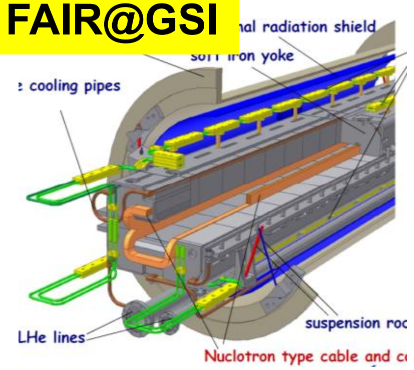


Super-Ferric Magnets for Ion Rings

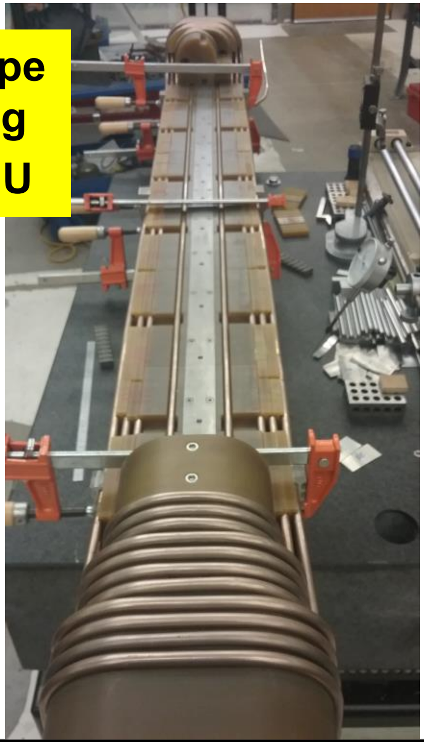
- Technology developed long ago (~SSC era)
- Adopted for FAIR SIS100 ring & NICA (1.8 T)
- Advantages
  - Higher fields (than warm magnets)
  - Fast ramp rate
  - Cost efficient
- JLEIC adopted it for booster/collider ring
  - Up to 3 T
  - Fast ramp (1 T/s) for booster ring magnets
  - Cable-in-conduit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

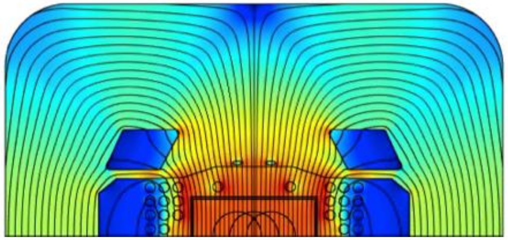
NICA@Dubna

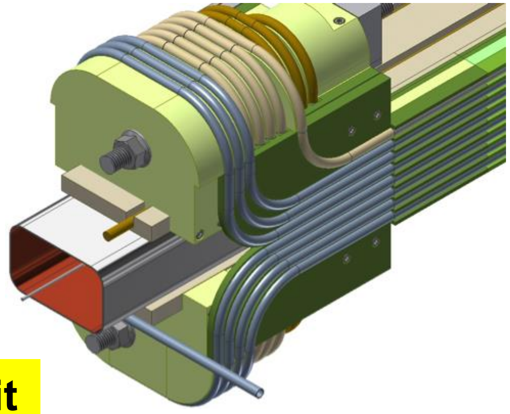
FAIR@GSI



Prototype winding @ TAMU



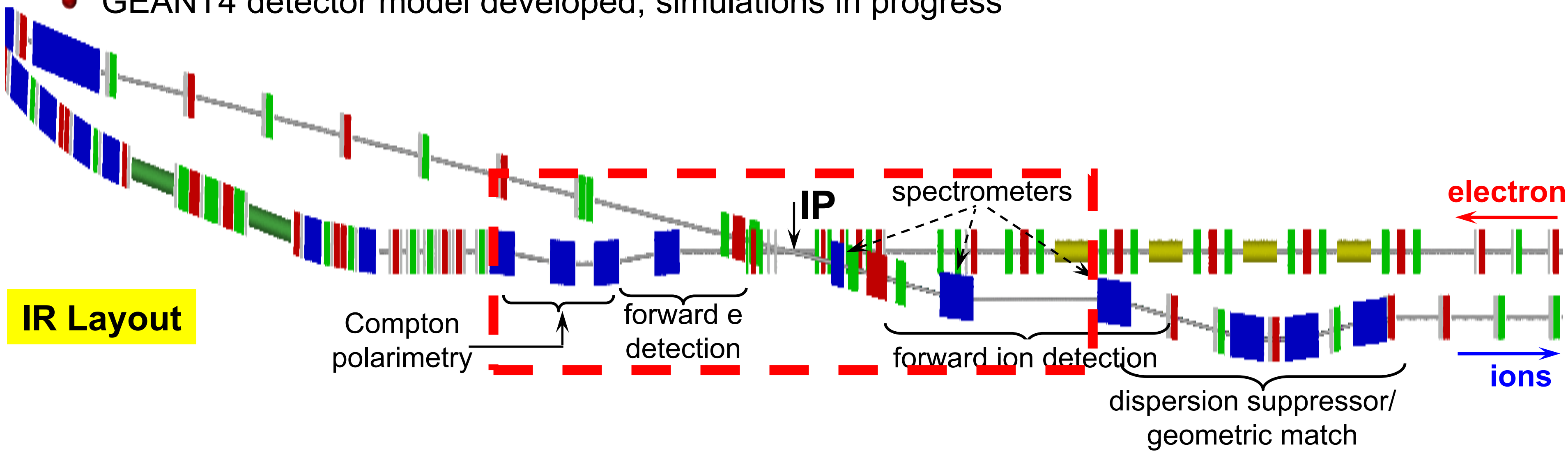




Cable-in-conduit

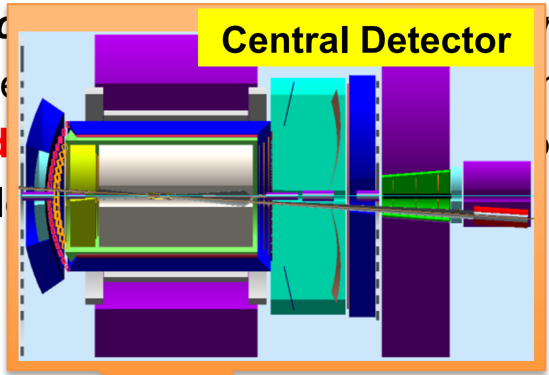
JLEIC Detector & Interaction Region (IR)

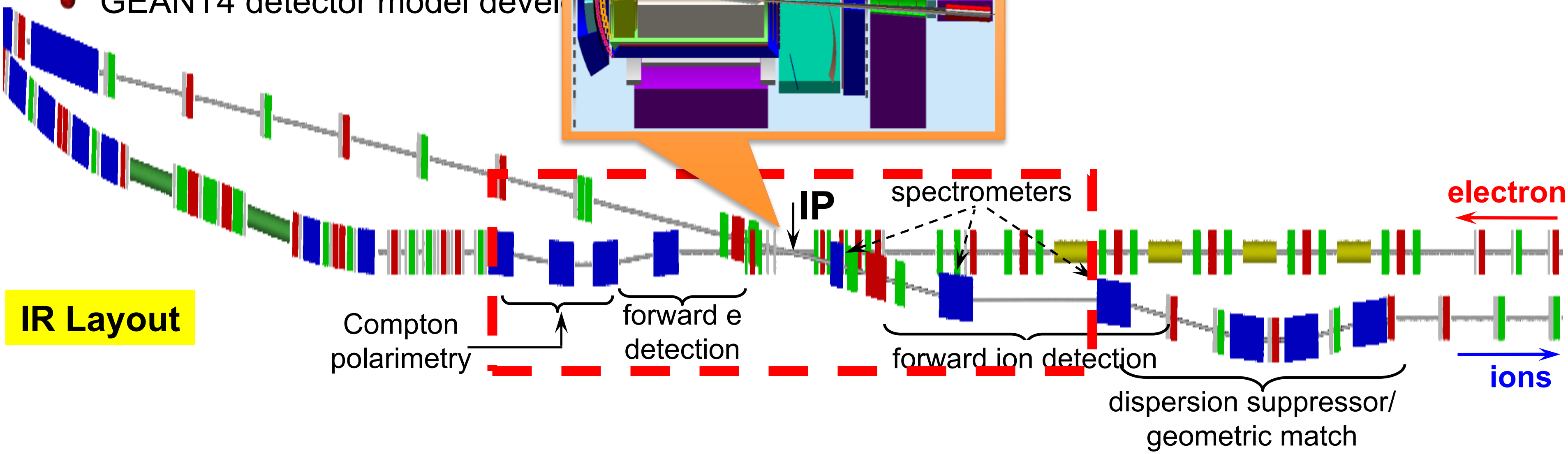
- IR designed to support ***full-acceptance*** detection ← *unprecedented requirement*
- Satisfy geometric match (elements) and **beam dynamics** (chromatic compensation)
- Crab crossing: large (**50 mrad**), **avoiding parasitic collisions**, **optimizing particle detections**
- GEANT4 detector model developed, simulations in progress



JLEIC Detector & Interaction Region (IR)

- IR designed to support ***full-acc*** *recedented requirement*
- Satisfy geometric match (eleme hromatic compensation)
- Crab crossing: large (**50 mrad** **ns, optimizing particle detections**
- GEANT4 detector model devel





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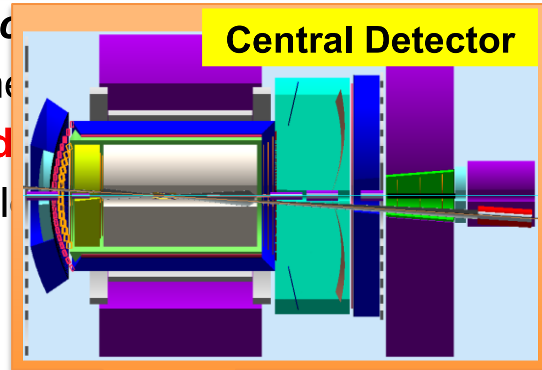
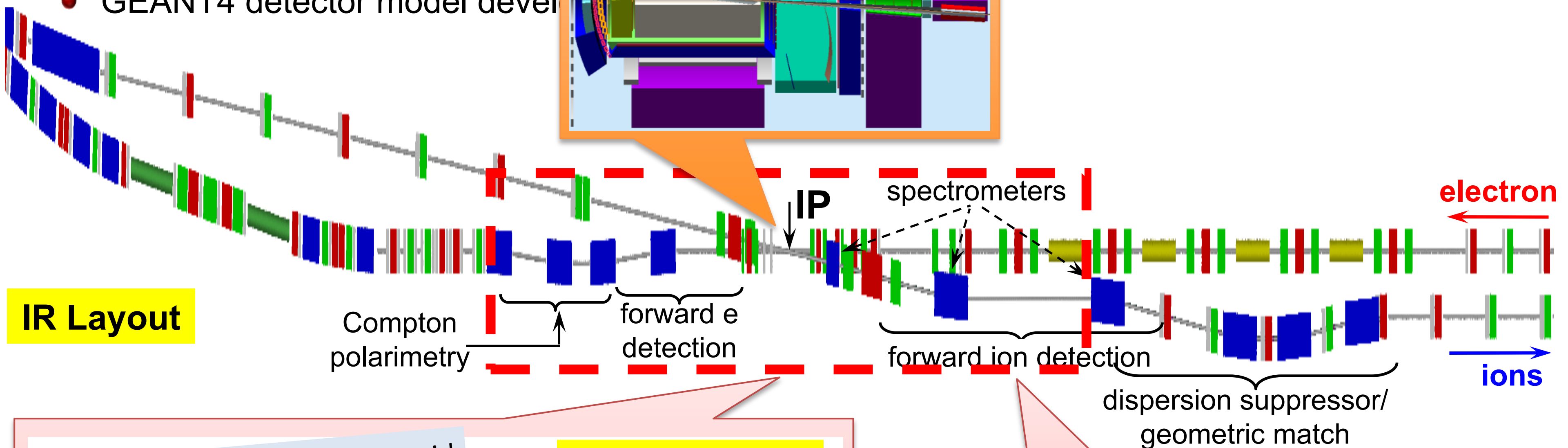
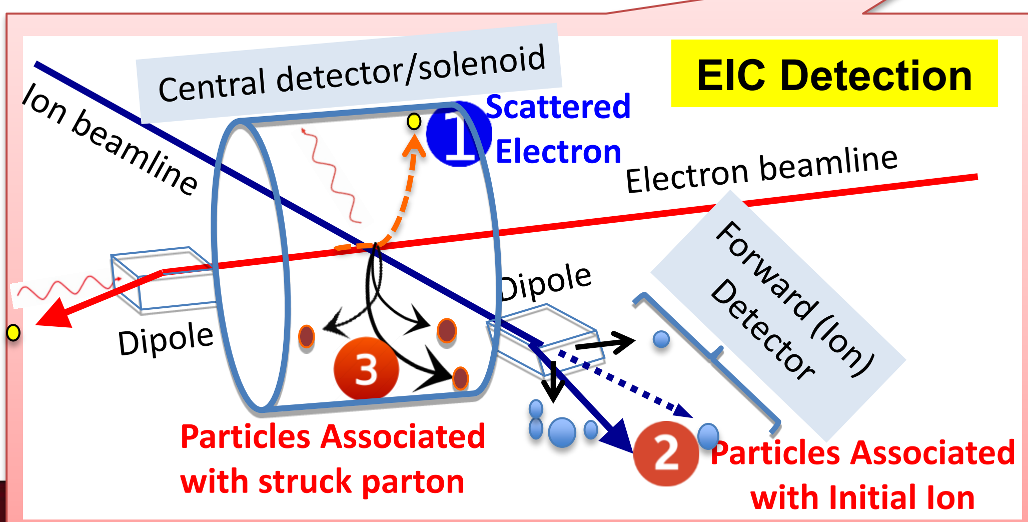
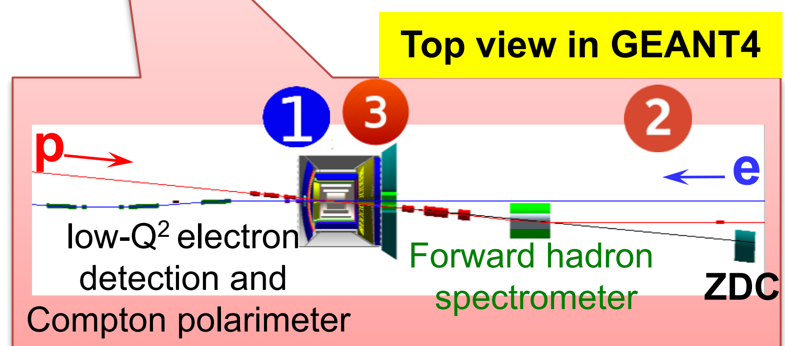


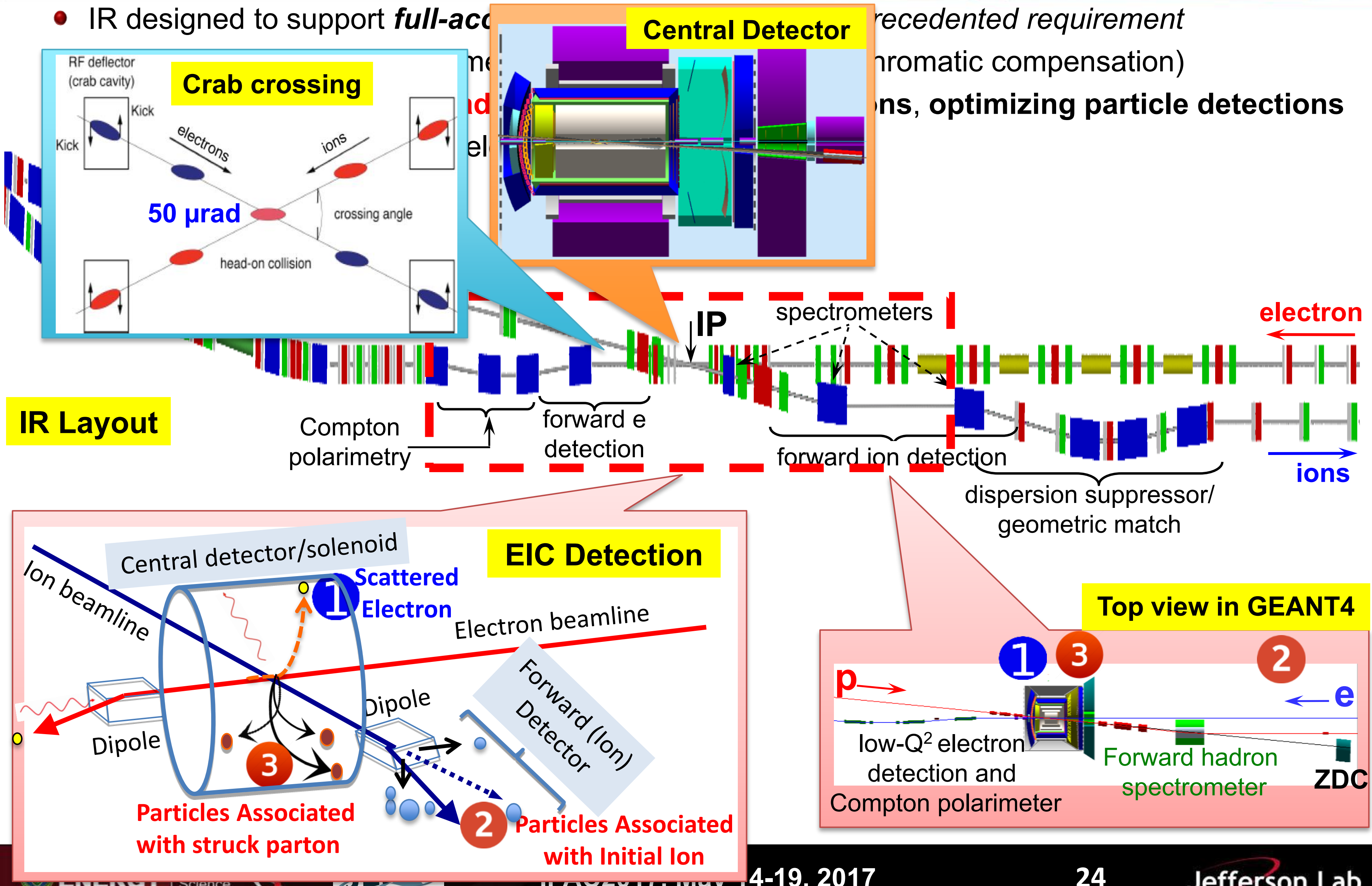






JLEIC Detector & Interaction Region (IR)

- IR designed to support ***full-acc*** ... *recedented requirement*
- me ... hromatic compensation)
- **d ... ns, optimizing particle detections**
- el



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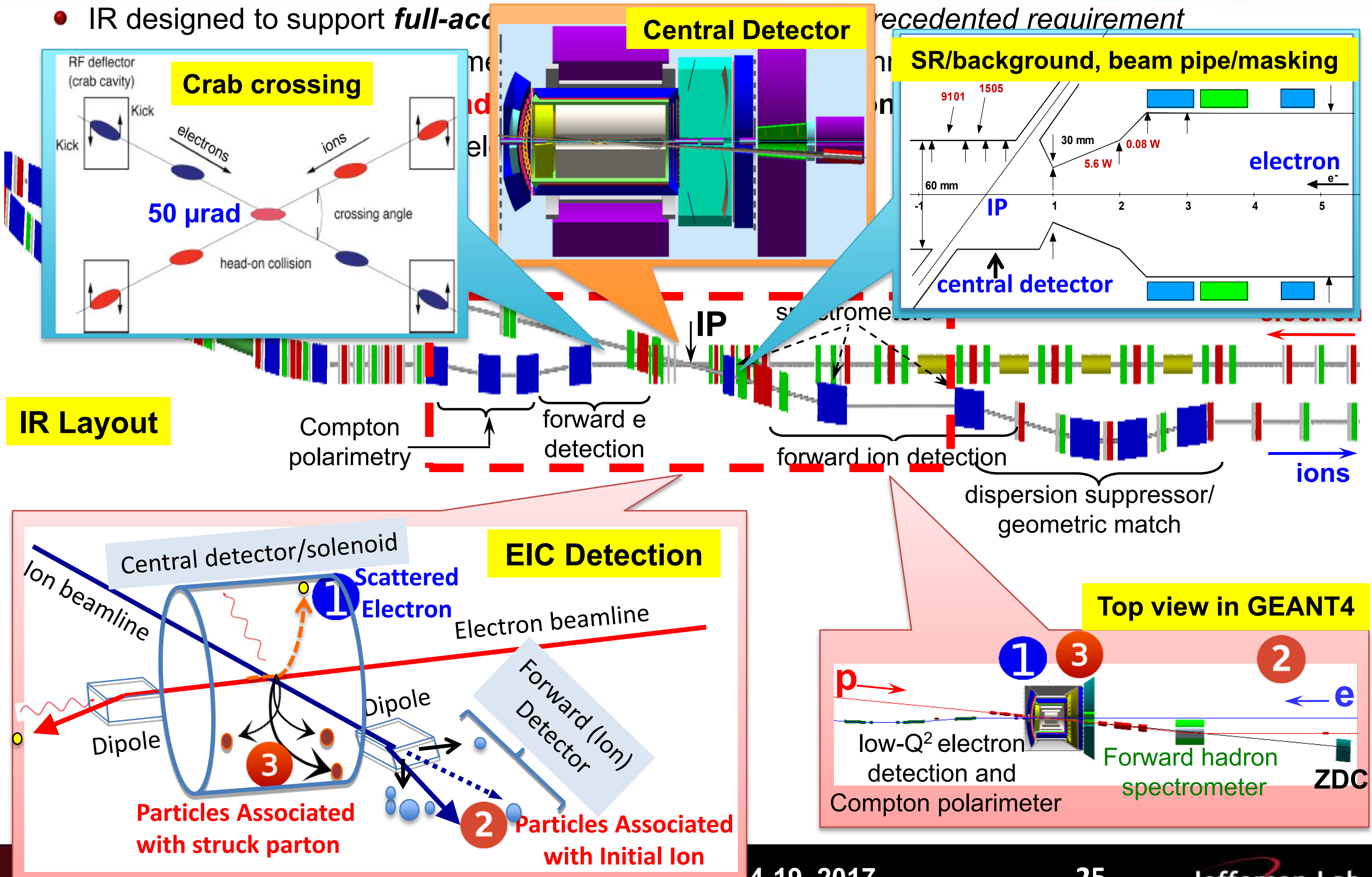

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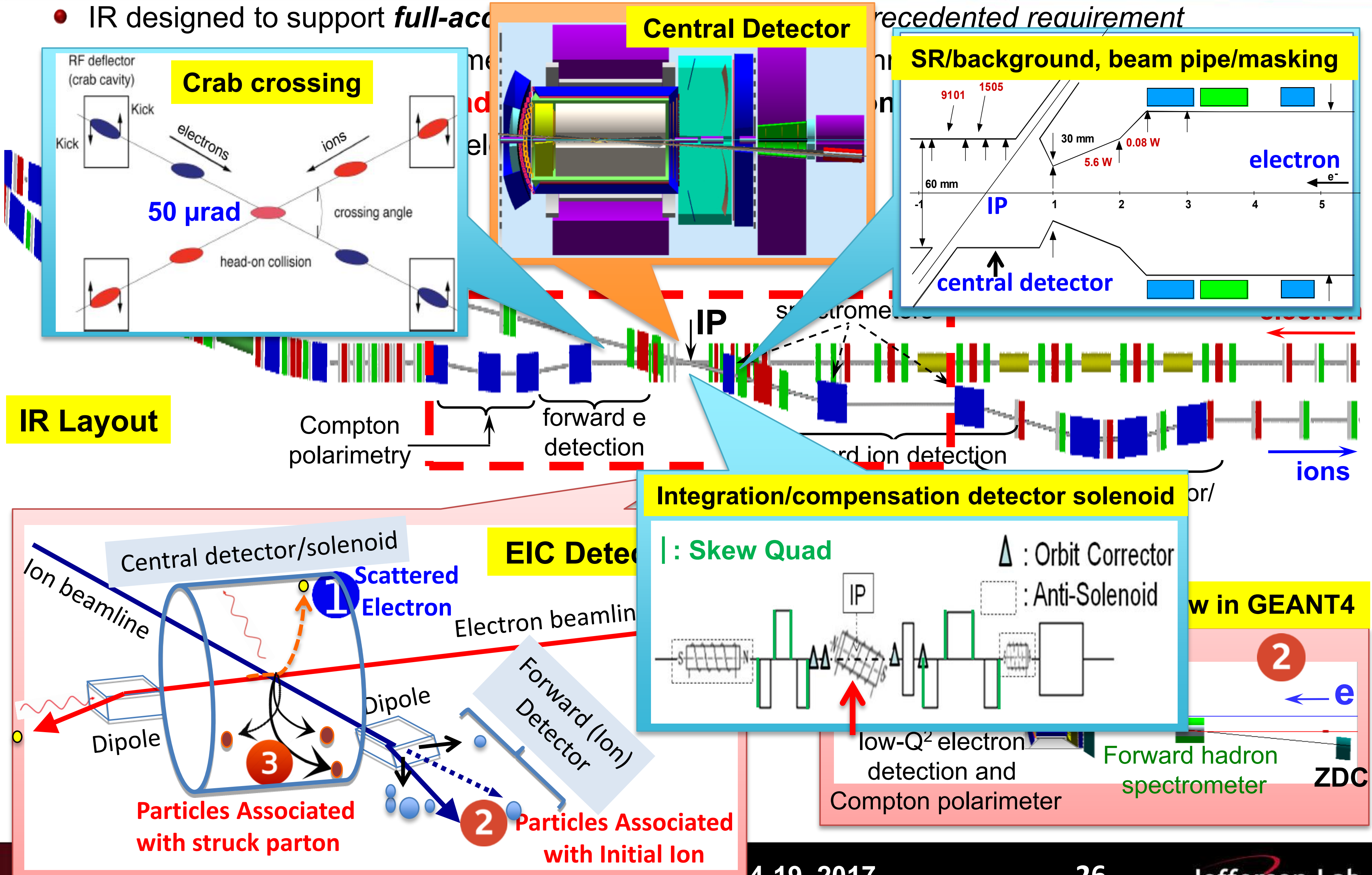
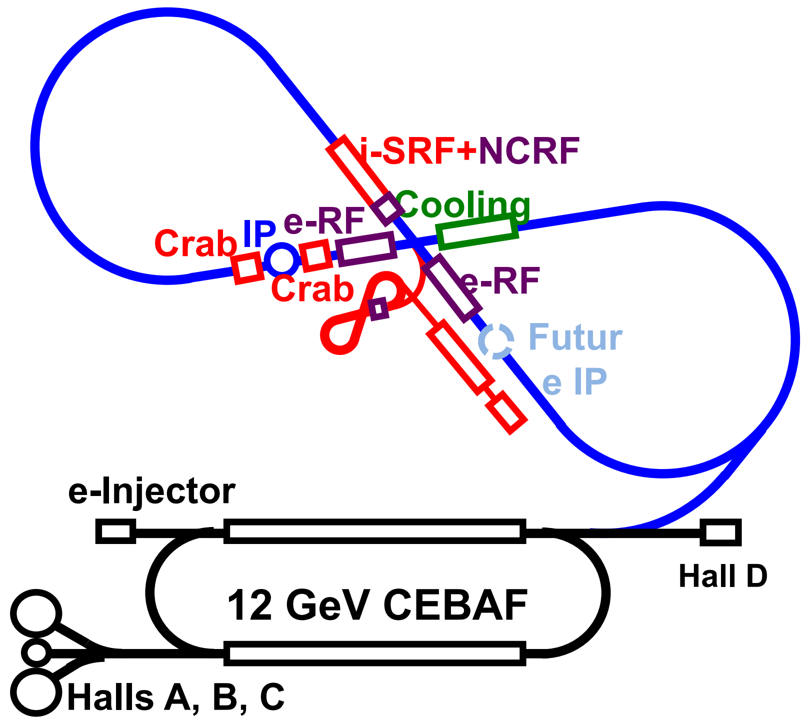


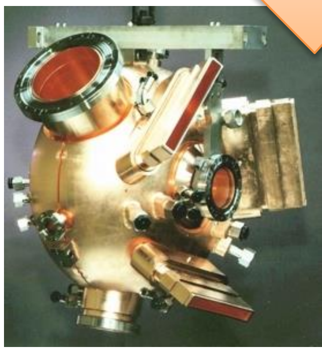
Development of RF cavities for JLEIC



Cavities at various stages of development: conceptual and technical design, simulation, proto-typing and testing

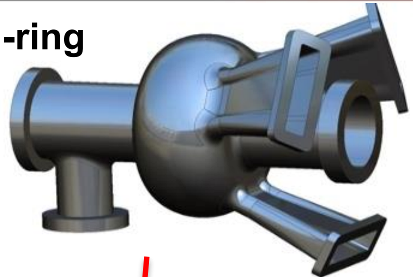
Development of RF cavities for JLEIC

JLEIC electron ring will reuse PEP-II RF systems

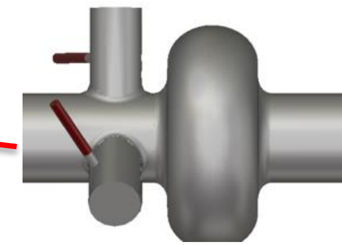


476.3 MHz e-ring (NCRF PEP-II)

952.6 MHz i-ring (SCRF)

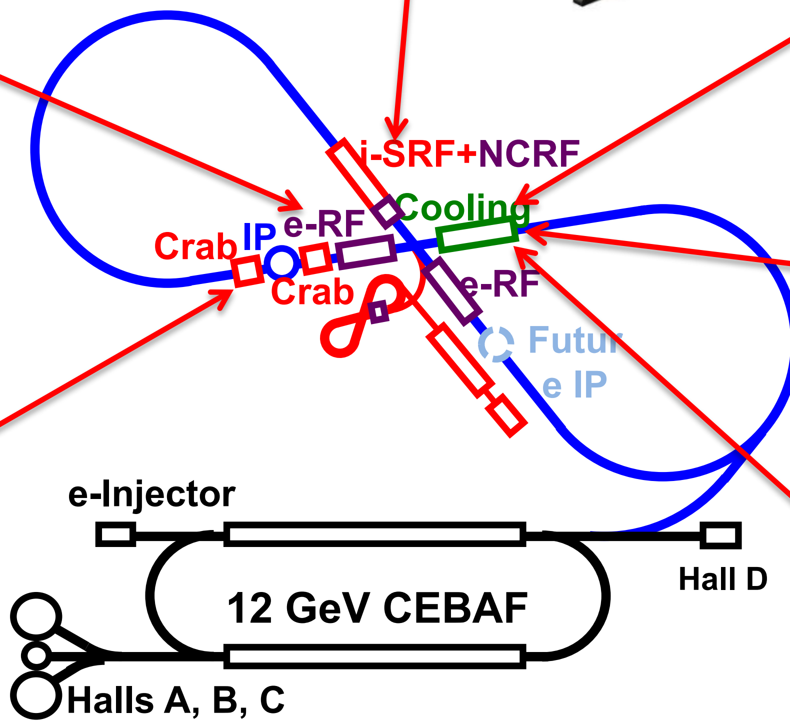


952.6 MHz cooler ERL (SCRF)



952.6 MHz booster for cooler ERL (SCRF)

952.6 MHz crab (SCRF)

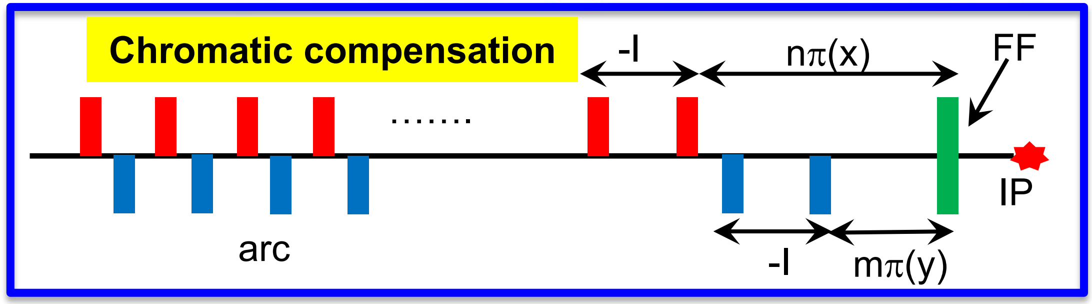


Harmonic RF Fast kicker for cooler ring

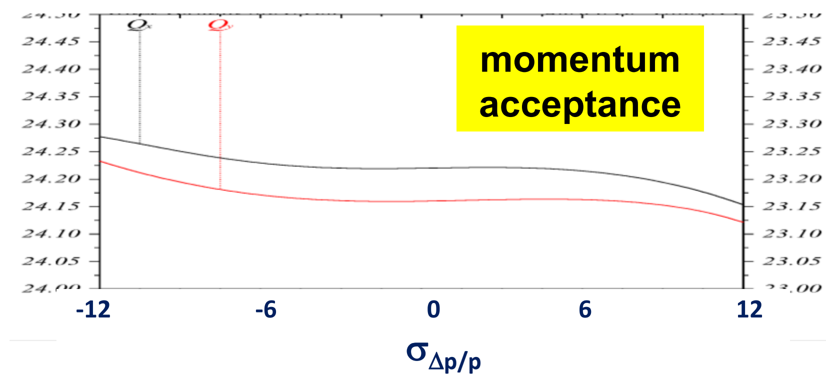
Cavities at various stages of development: conceptual and technical design, simulation, proto-typing and testing

Nonlinear Beam Dynamics

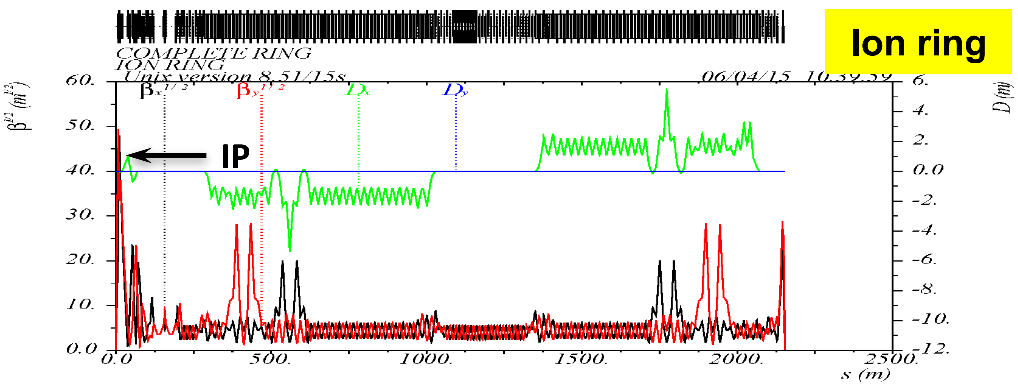
- Chromaticity issues
  - Beam smear at IP
  - Large tune footprint
  - Limiting dynamic aperture

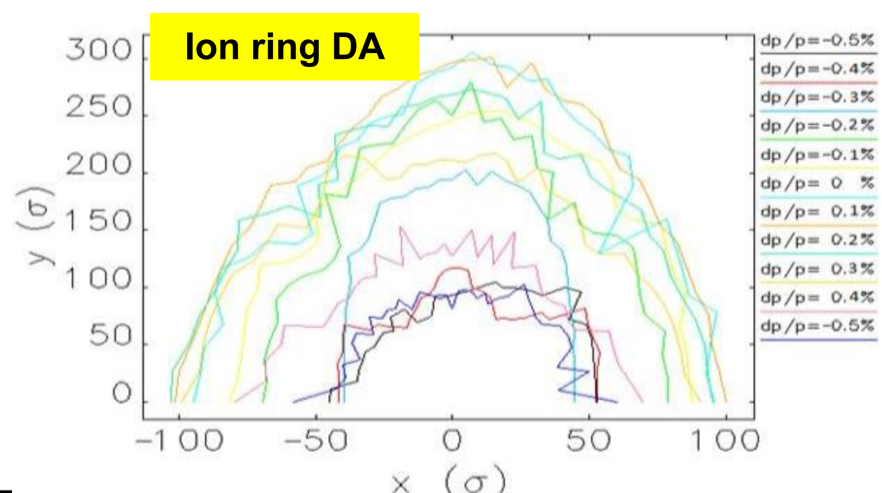


- High contributions from
  - low-β insertion with a large detector space
  - Strong focusing lattice for low emittance in e-ring



- Compensation: "–*I*" sext pairs in arcs





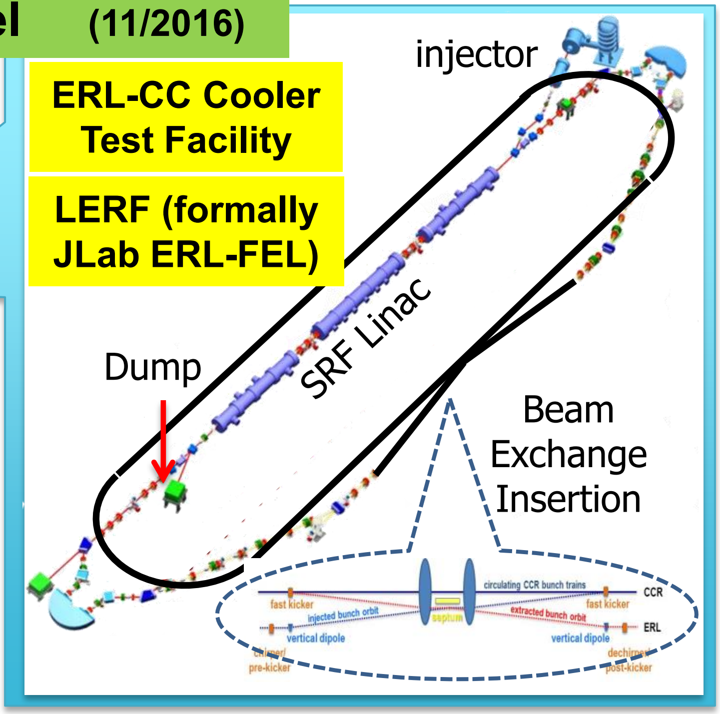
- Ion collider ring: dynamic aperture $15\sigma_x$ x $20\sigma_y$ @100 GeV (with magnet multipole errors)
- Electron collider ring: work in progress

JLEIC *Prioritized* Pre-Project R&D Topics

Prioritization was endorsed by a DOE EIC R&D Community Review Panel (11/2016)

High priority

- Strong hadron cooling
- High current single-pass ERL for hadron cooling
- A high current magnetized electron injector
- Magnet design/prototyping for high acceptance IP
- An ERL-CC test facility using existing infrastructure (LERF) with magnetized beam & fast kicker
- Crab cavity operation in a hadron ring
- Complete and test of a full scale super-ferric magnet
- Gear change synchronization & impact on beam dynamics
- High power fast kicker for (2ns bunch spacing) feedback



High-medium priority

- Electron cooling simulations
- Fast kicker prototype for multi turn cooler
- Spin tracking in ion and electron rings
- Fast kicker proto-type/test for circulator cooler
- IR design and detector integration
- Super-ferric 3T fast ramping short dipole
- SRF cavity systems including crab cavity
- Polarized ion sources (D^-, $^3He^{++}$)
- Operating CEBAF in the JLEIC injection mode

Medium priority

- Nonlinear beam dynamics in collider rings
- Space charge in ion complex, beam formation
- Instability and feedback systems
- Ion & electron ring background & vacuum
- Bunched beam cooling experiment
- Fast kicker test with beam

JLEIC Working Groups and Collaborations

Ion injector complex	(Todd Satogata)	WEPIK035 WEPVA040 WEPIK081
Ion linac	(Brahim Mustapha, **ANL**)	
Ion and electron polarization	(Fanglei Lin, Vasiliy Morozov) (Kondratenko group, **Zaryad, Russia**)	WEPIK038 WEPIK114
Electron cooler design	(Steve Benson)	MOPIK116 WEPIK040 WEPIK042
Cooler magnetized electron source	(Riad Suleiman)	
Simulations / Instability	(Yves Roblin / Rui Li)	WEPIK080 WEPIK082 WEPIK086
IR / non-linear studies	(Vasiliy Morozov, Yuri Nosochkov, **SLAC**)	WEPIK041 WEPIK115
Crab crossing / Crab cavity	(Vasiliy Morozov / Jean Delayen, **ODU**)	WEPIK043 WEPIK044
MDI / detector / Backgrounds	(Mike Sullivan, **SLAC** / Rik Yoshida)	WEPIK084
SRF / Fast kicker	(Bob Rimmer)	MOPVA136 WEPIK037
Engineering	(Tim Michalski)	
Super-ferric magnets	(Peter McIntyre, **Texas A&M**)	

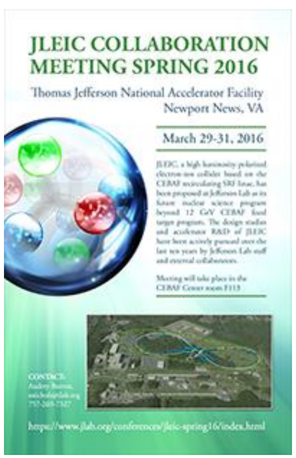
Posters in this IPAC

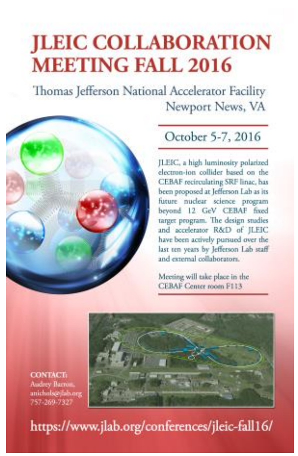
Names for leaders/coordinators of working groups or collaborations

More working group/collaborations will be formed

Summary

- JLEIC design is driven by and optimized for EIC physics requirements
- JLEIC delivers high luminosity over a broad CM energy range, up to above 2×10^{34} /cm^2/s, using a design concept based on high bunch repetition colliding beams and strong electron cooling
- JLEIC delivers high polarization based on a revolutionary concept of figure-8 ring
- JLEIC IR design supports full acceptance detectors critical to its science program
- JLEIC design is stable and mature, the technical risk and required R&D are modest
- The JLEIC team/collaboration is presently engaged in pre-project accelerator R&D, aiming for delivering a comprehensive pre-CDR in 2 years





- **Five *biannual* JLEIC collaboration meetings**
- **Next one: Oct. 2017**
- **We welcome our US and international colleagues**

JLEIC-Related Posters at IPAC2017

MOPIK116	Toroidal Merger Simulations for an ERL Bunched Beam Electron Cooler Ring	(Presenter: A. Sy)
MOPVA134	HOM Analysis of 952.6MHz Multi-Cell RF-Dipole Crabbing Cavity for JLEIC	(Presenter: S. Sliva)
WEPIK035	Adapting the JLEIC Electron Ring for Ion Acceleration	(Presenter: B. Mustapha)
WEPIK037	SRF Systems for the Jefferson Lab *EIC*	(Presenter: F. Marhauser)
WEPIK038	Acceleration of Polarized Protons & Deuterons in Ion Collider Ring of JLEIC	(Presenter: V. Morozov)
WEPIK040	Beam Reconditioning	(Presenter: Y. Zhang)
WEPIK041	Update on the JLEIC Electron Collider Ring Design	(Presenter: Y. Nosochkov)
WEPIK042	JLEIC Luminosity Performance Optimization w/ Cooling During Collision	(Presenter: Y. Zhang)
WEPIK043	Modeling Local Crabbing Dynamics in the JLEIC Ion Collider Ring	(Presenter: S. Sosa)
WEPIK044	Impact of Crab Cavitiy Multipoles on JLEIC Ion Ring Dynamic Aperture	(Presenter: S. Sosa)
WEPIK113	Entrance and Exit CSR Impedance for Non-ultrarelativistic Beams	(Presenter: R. Li)
WEPIK114	Study of electron polarization dynamics in the JLEIC at JLab	(Presenter: F. Lin)
WEPVA040	Design of Imaginary Transition Gamma Booster Synchrotron for JLEIC	(Presenter: A Bogacz)
THPAB080	Estimations of Coherent Instabilities for JLEIC	(Presenter: R. Li)
THPAB081	The Effects of Space-Charge on the Dynamics of the Ion Booster in JLEIC	(Presenter: E. Nissen)
THPAB082	The Beam-Beam Effect and Its Consequences for the Modeling of JLEIC	(Presenter: E. Nissen)
THPAB084	Integration of the Full-Acceptance Detector Into the JLEIC	(Presenter: G. Wei)
THPAB086	Long-Term Simulations of Beam-Beam Dynamics on GPUs	(Presenter: B. Terzic)

EIC User Group: *A Growing International Community*

EIC User Group (http://www.eicug.org)
Currently **673 members** from **149 institutions** from **28 countries**.

Physicists around the world are thinking about and are defining **the EIC research program**.

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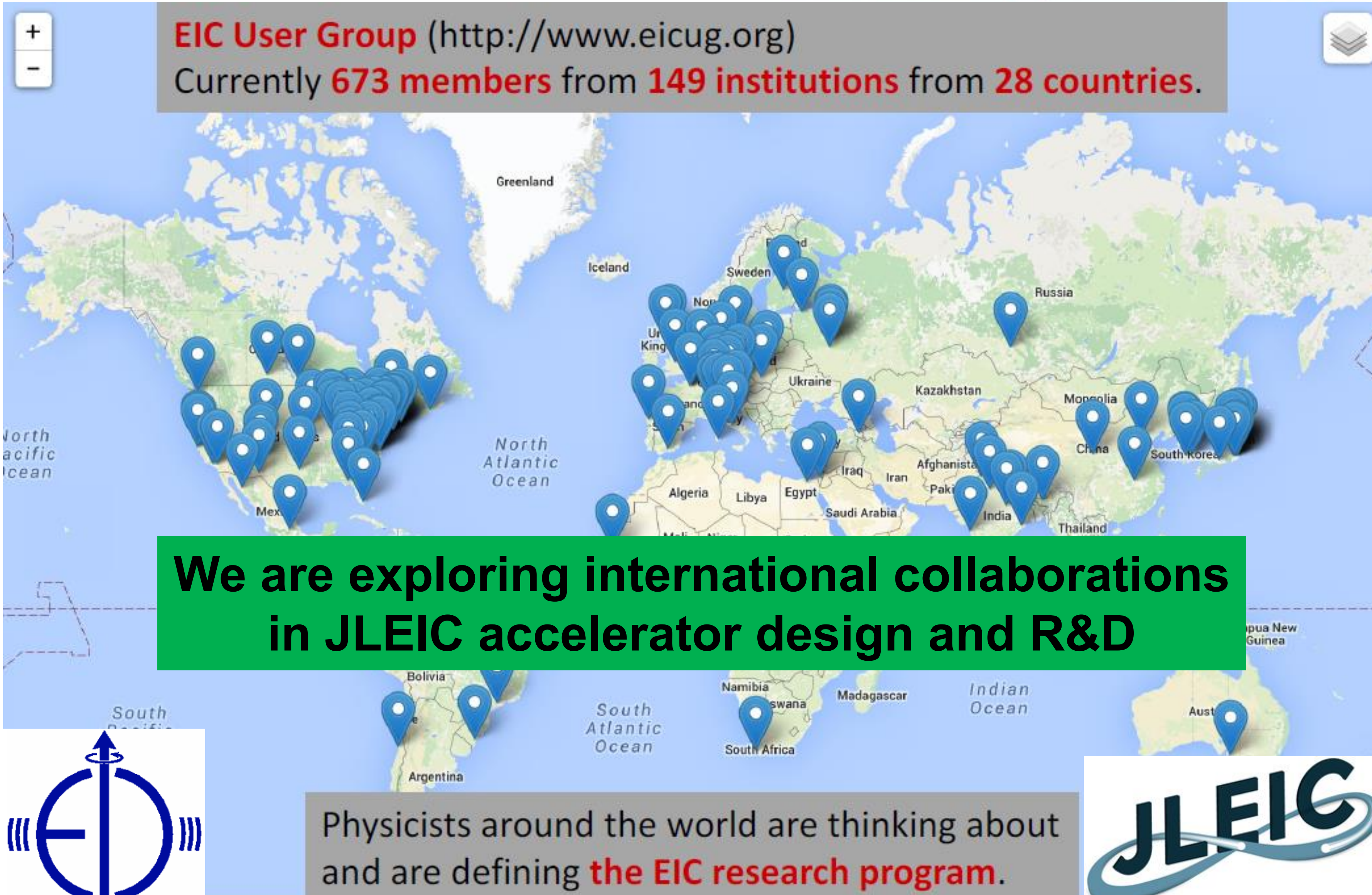

We are exploring international collaborations in JLEIC accelerator design and R&D

Physicists around the world are thinking about and are defining **the EIC research program**.