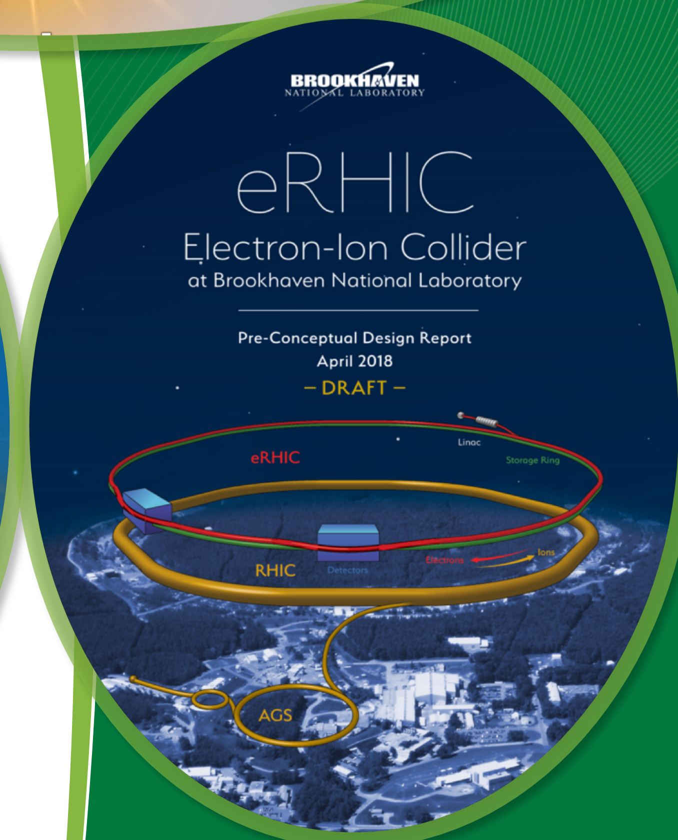
Ideas and concepts for future electron-ion colliders



Fulvia Pilat

Oak Ridge National Laboratory

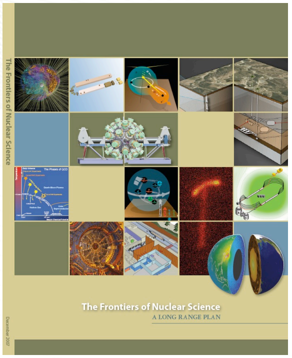
IPAC'18

Vancouver, April 29 - May 4, 2018

Outline

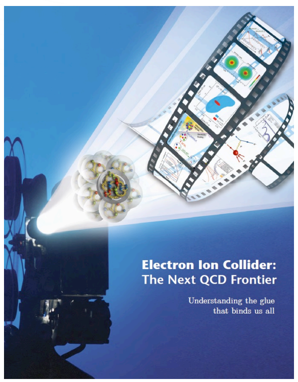
- Introduction to the Electron-Ion Collider (EIC) concept
- Accelerator design requirements and challenges
- EIC designs evolution
- JLab Electron-Ion Collider (JLEIC) design
- Electron Relativistic Heavy Ion Collider (eRHIC) design
- EIC accelerator R&D
- Program outlook (from program to project….)

EIC history

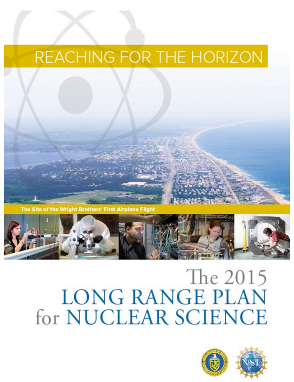


NSAC 2007 Long-Range Plan:

"An **EIC** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next quantum Chromodynamics (QCD) frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."



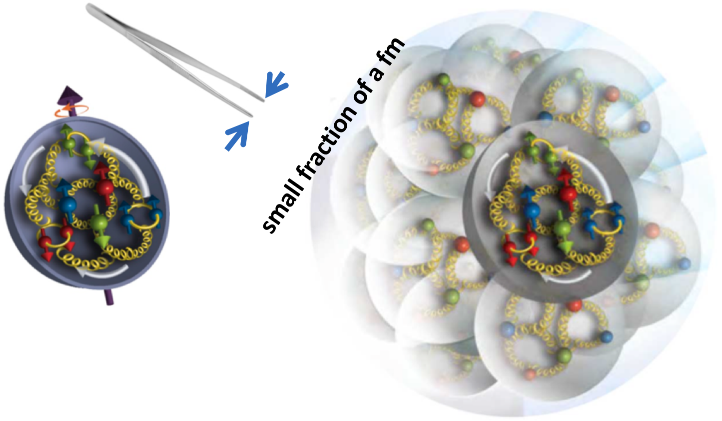
2013 EIC White Paper
(Writing committee convened by JLab/BNL)



RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

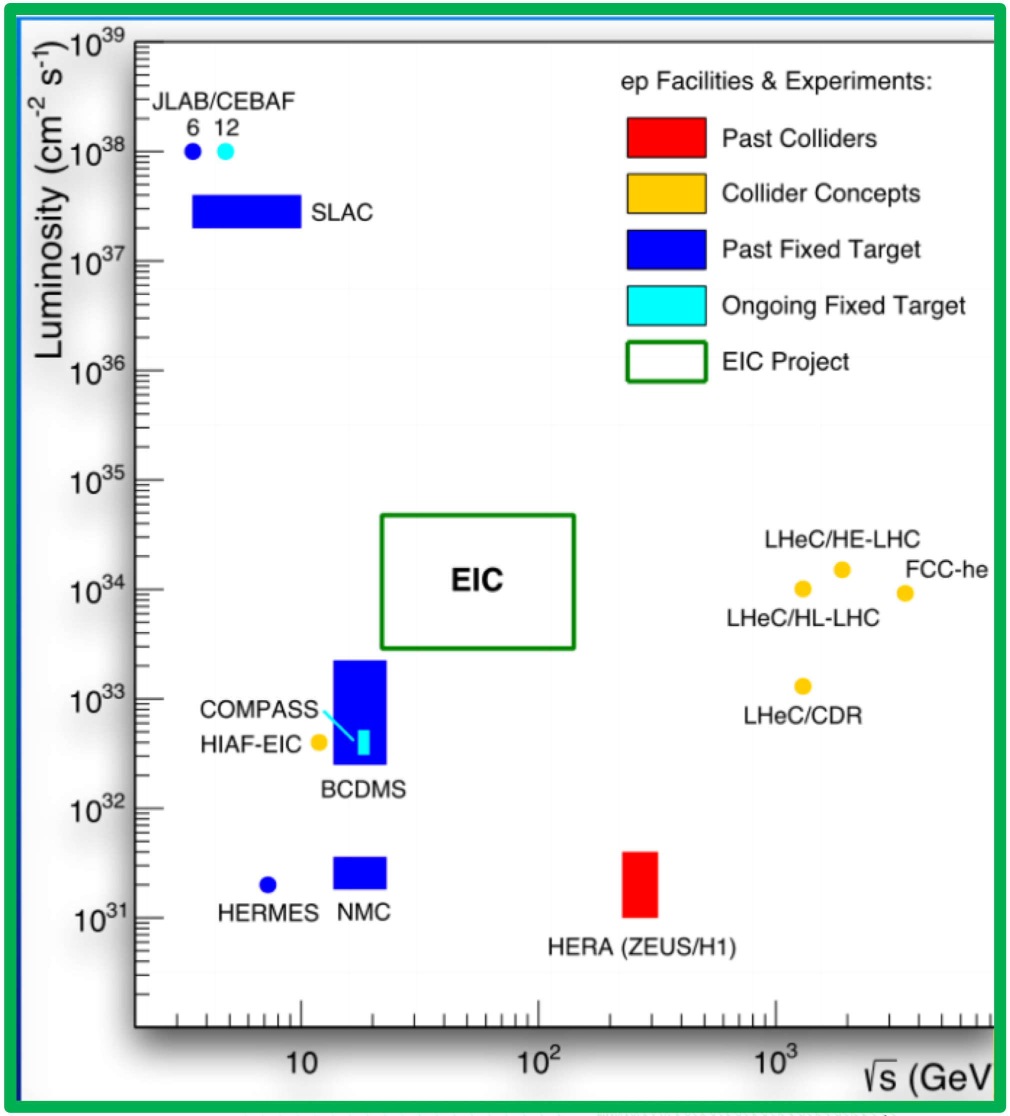
The physics case



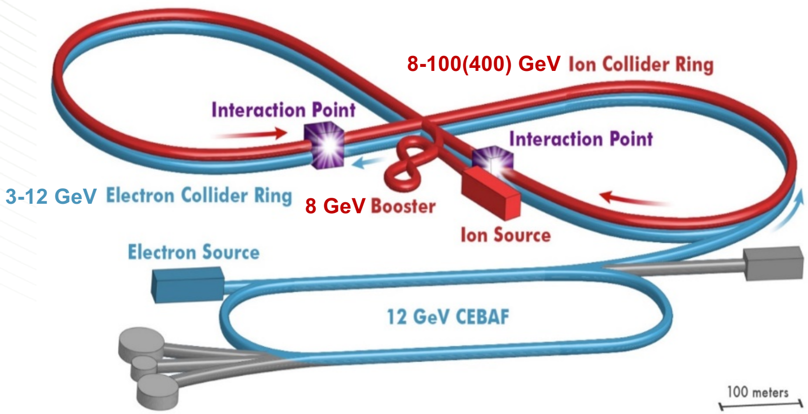
- Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and compose nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei.
- The EIC will, for the first time, **precisely image gluons in nucleons and nuclei**. It will definitively reveal the **origin of the nucleon spin** and will explore a new QCD frontier of **ultra-dense gluon fields**, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

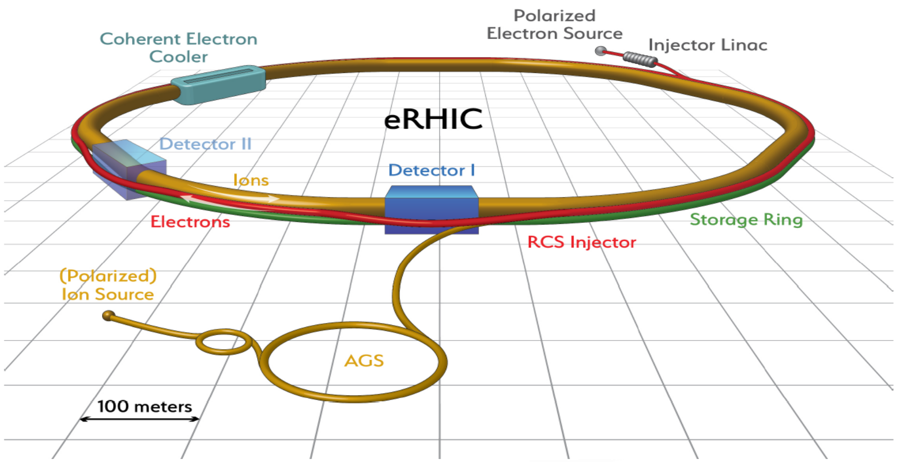
EIC design requirements and challenges
(as identified in the Long Range Plan)

- High collision luminosity ~$10^{33\text{-}34}$ cm^{-2} sec^{-1} **50x HERA**
- Polarized (~**70%**) electrons, protons and light nuclei **first ever fully polarized collider**
- Ion beams from deuterons to the heaviest nuclei **many species**
- Variable center of mass energies ~**20-100 GeV**, upgradable to ~140 GeV **wide range of collision energies and energy ratios**
- More than 1 interaction region first ever e-p and e-A collisions with **~100% reconstruction of nuclei in final state**



EIC accelerator designs





- CEBAF full-energy electron injector
- New e-ring
- New ion complex

- RHIC ion complex
- New electron complex

  Option 1*: ring-ring

  Option 2: ERL linac - ring

***ring-ring option selected in 2017**

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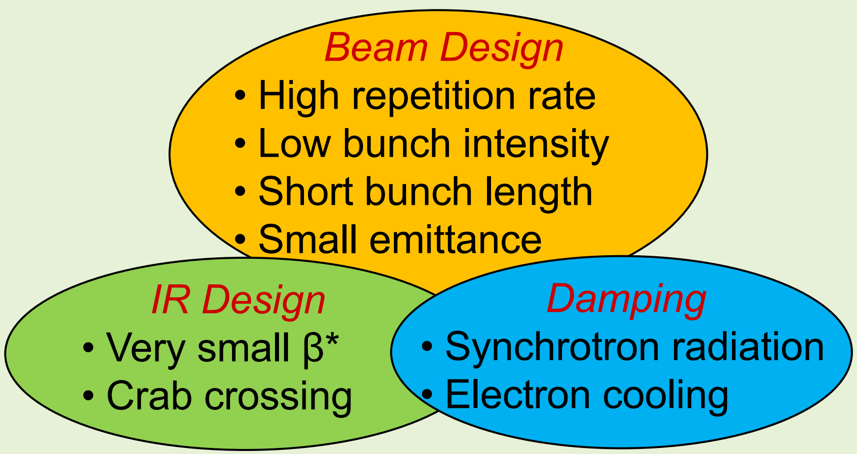
JLEIC: Design fundamentals

High Luminosity

- Based on high bunch-repetition-rate and small bunch-charge of colliding beams

$$L = f \frac{n_1 \, n_2}{4\pi \, \sigma_x^\star \, \sigma_y^\star} \sim f \frac{n_1 \, n_2}{\epsilon \, \beta_y^\star}$$

- KEK-B reached > 2x10^{34} /cm^2/s



- CEBAF provides **1.5 GHz** bunch repetition rate as electron injector
- New ion complex is also designed to deliver high bunch repetition rate

High Polarization: Figure-8

All rings are in a figure-8 shape

critical advantages for both beams

- **Spin precession** in the left & right arcs of the ring are exactly cancelled
- Net spin precession (**spin tune**) is **zero**, thus energy independent
- Spin can be controlled & stabilized by **small solenoids** or other compact spin rotators
- **Deuteron polarization** can also be maintained (unique feature of Figure-8)

Detectors

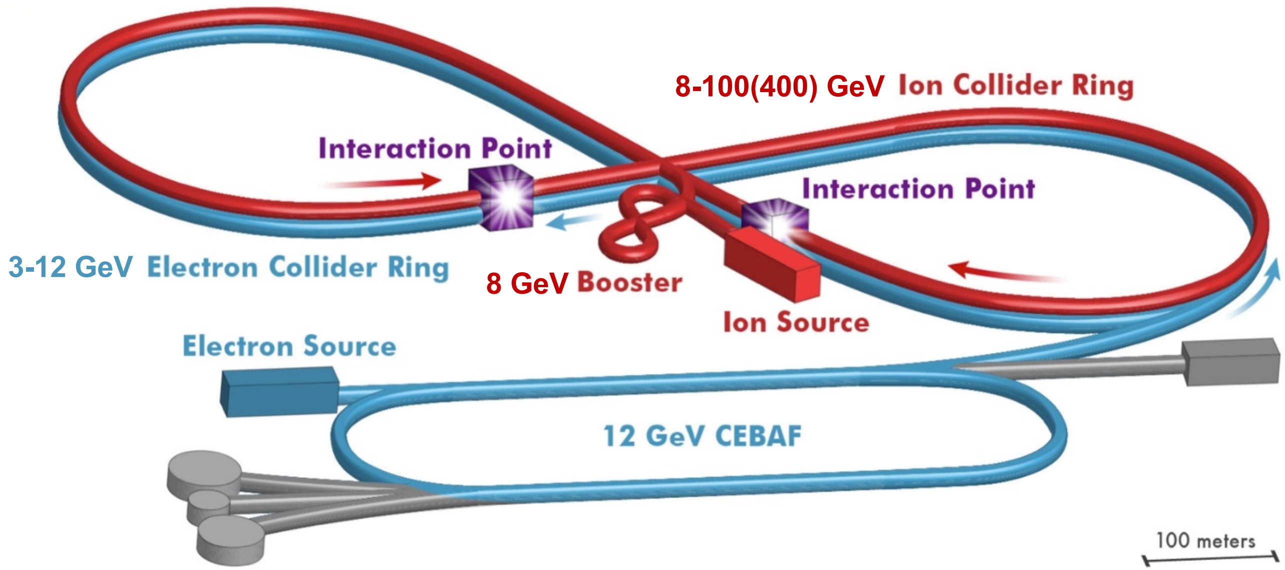
Interaction region is design to support

- Full acceptance detection (including forward tagging)
- Low background

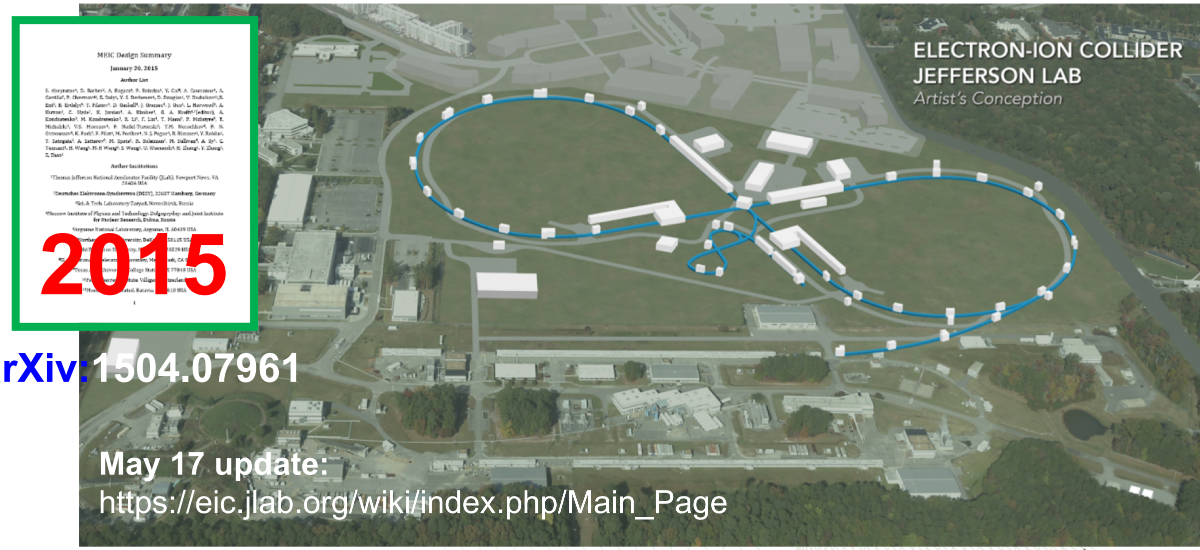
JLEIC: baseline design

energy range:
e-: **3-10** GeV
p : **20-100** GeV
√s: up to **65 GeV**

Range to to √s=**100 GeV** and √s=**140 GeV** possible



- **Electron complex**
  - CEBAF
  - Electron collider ring
- **Ion complex**
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring
- Fully integrated IR and **detector**
- DC and bunched beam **coolers**



arXiv:1504.07961

May 17 update:
https://eic.jlab.org/wiki/index.php/Main_Page

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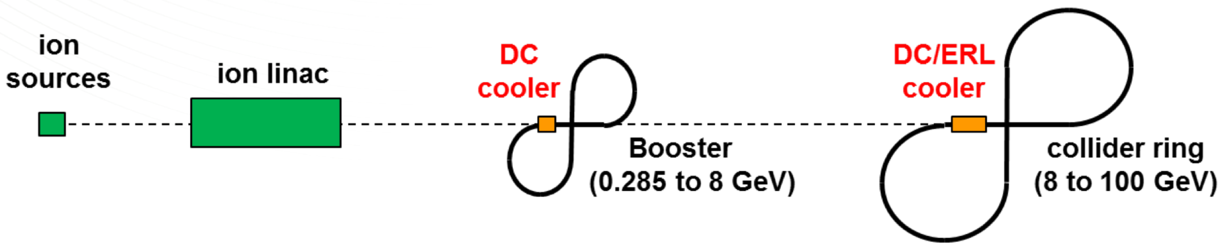
JLEIC: multi-step cooling scheme

- Cooling of JLEIC proton/ion beams for
  - **Emittance** reduction (~factor 10)
  - Short **bunch length** (~1 cm)
  - Counteract **IBS** emittance growth



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

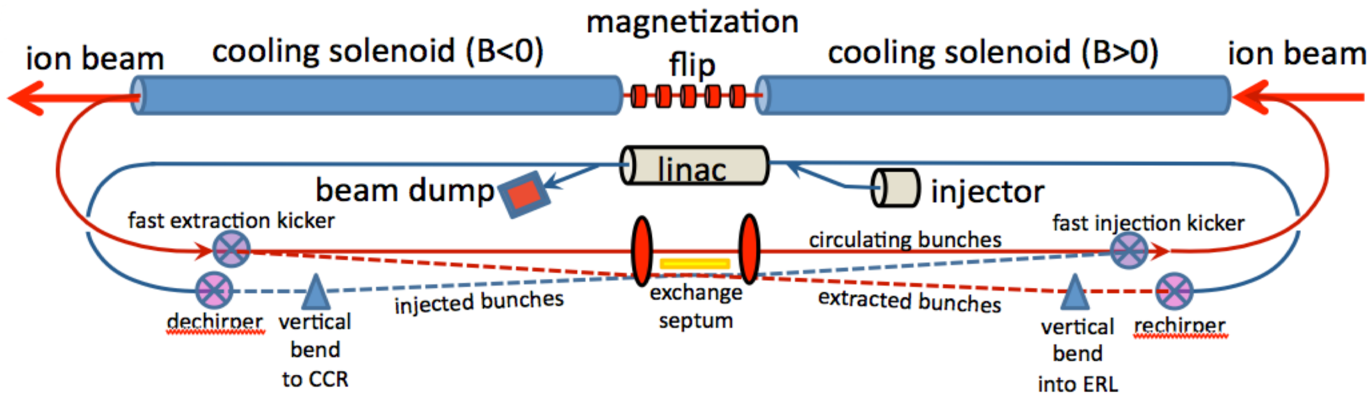
Pre-cooling both protons and lead ions

ERL cooler can't reach energy below 20 MeV

JLEIC: strong magnetized cooling

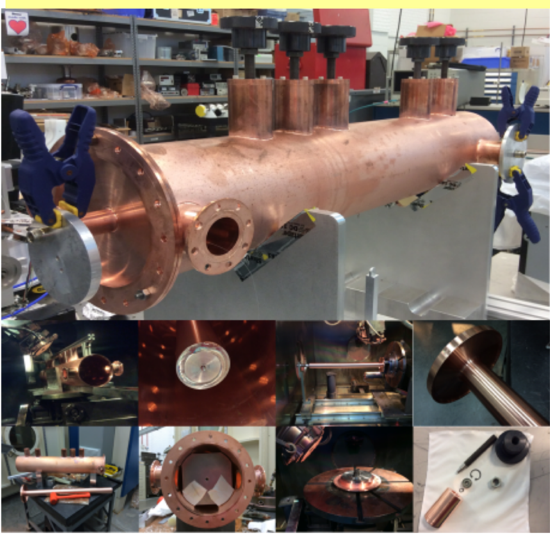
ERL cooler + Multi-turn circulator ring

top ring: CCR

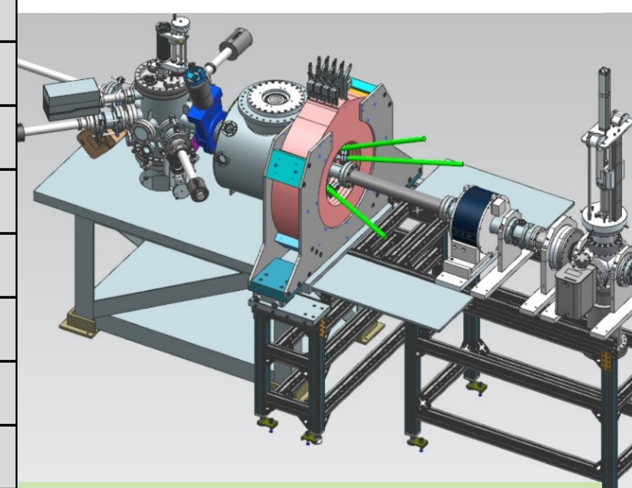


bottom ring: ERL

Enabling technologies :
Fast kickers risetime <1 nsec

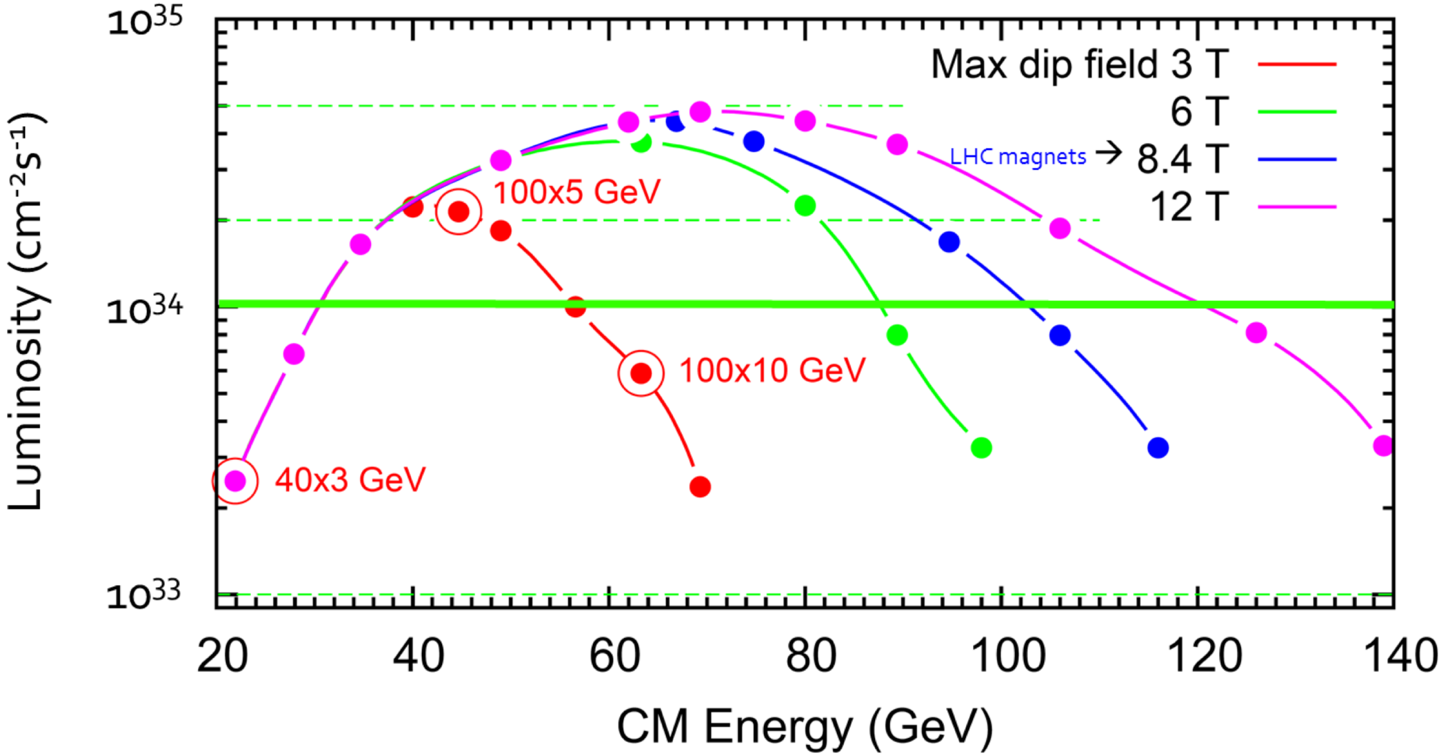


Electron energy	MeV	up to 55
Bunch charge	nC	3.2
Turns in circulator ring	turn	~20
Current in CCR/ERL	A	1.5/0.075
Bunch repetition	MHz	476
Cooling section length	m	60
RMS Bunch length	cm	3
Energy spread	10^{-4}	3
Cooling solenoid field	T	1
Cooling section length	m	2x30



Magnetized source ~75mA

JLEIC: luminosity and energy range



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

JLEIC parameters (3T magnets)

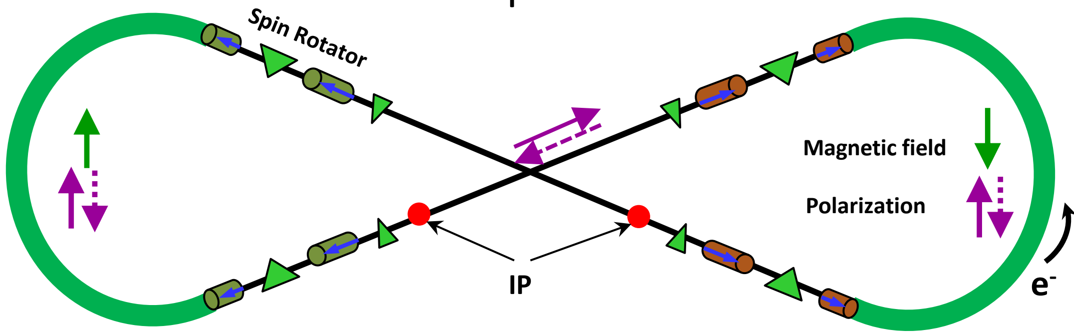
CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	**80%**	**80%**	**80%**	**80%**	**80%**	**75%**
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**	

A fall back position without strong cooling and more conservative beam parameters results in a luminosity **$L = \sim 0.3 \cdot 10^{34} cm^{-2}s^{-1}$**

JLEIC high polarization: figure-8

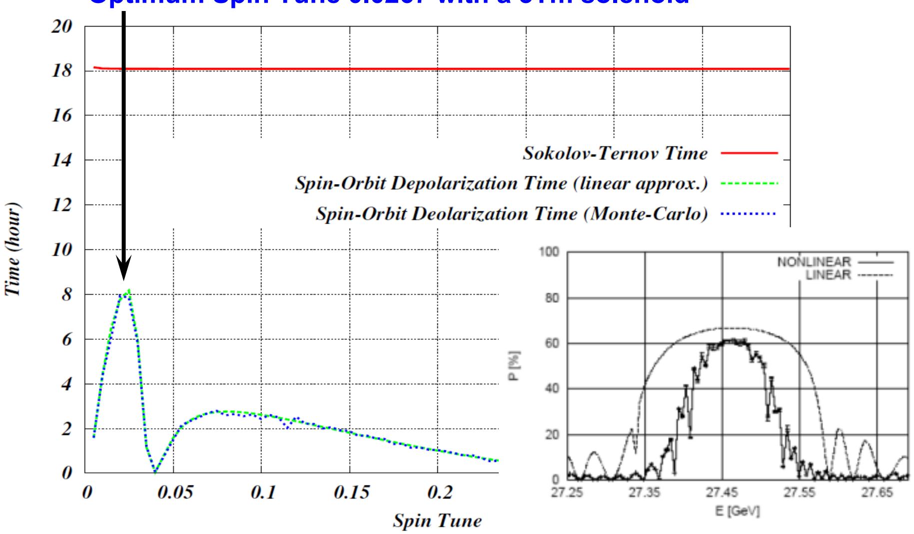
- Spin stabilization by small fields: ~3 Tm vs. ~ 400 Tm for **deuterons** at 100 GeV. polarized deuterons simple
- Universal spin rotator
  - Sequence of solenoid and dipole sections
  - Makes the spin longitudinal in the straights
- Figure 8: Minimum depolarization demonstrated by spin tracking

Electron polarization

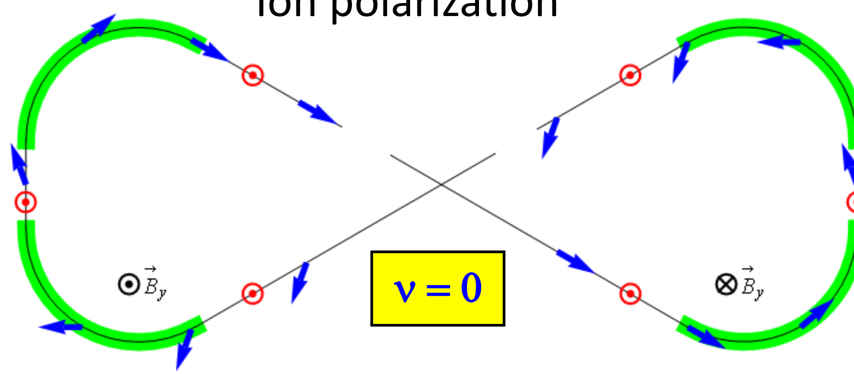


E- energy (GeV)	3	5	7	9	10
Estimated Pol. Lifetime (hours)	66	5.2	2.2	0.9	0.3

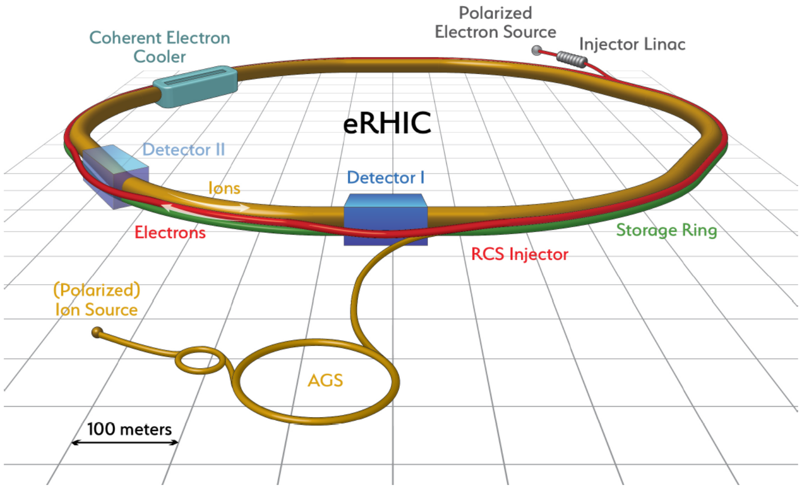
Optimum Spin Tune 0.0267 with a 3Tm solenoid



Ion polarization



eRHIC: design fundamentals



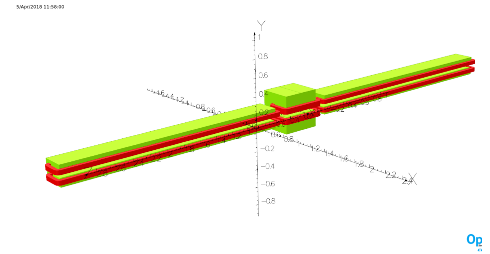
- eRHIC design goal: **L= 10^{34}cm^{-2}s^{-1}**
- eRHIC is based on the RHIC complex:
- eRHIC **beam parameters** close to present RHIC (except number of bunches ~factor 10 higher and 40% higher beam current)
- A (5-18) GeV electron storage ring & injectors are added to the RHIC complex with 41 - 275 GeV protons ➔ **E_{cm} = (29-141) GeV**
- **Assumption that each beam will have parameters (in particular beam-beam tune shift) as demonstrated in collisions between equal species** (HERA Concept): $\xi_e \leq$ **0.1** (B-factories); $\xi_p \leq$ **0.012** (RHIC)
- The requirement to store electron beams with a variable spin pattern requires an on-energy, **spin transparent injector**.
- The total **synchrotron radiation power** of the electron beam is assumed to be limited to **10 MW**. This is a design choice.

eRHIC storage ring

Composed of six FODO arcs with 60º /cell for 5-10 GeV

90º /cell for 18 GeV

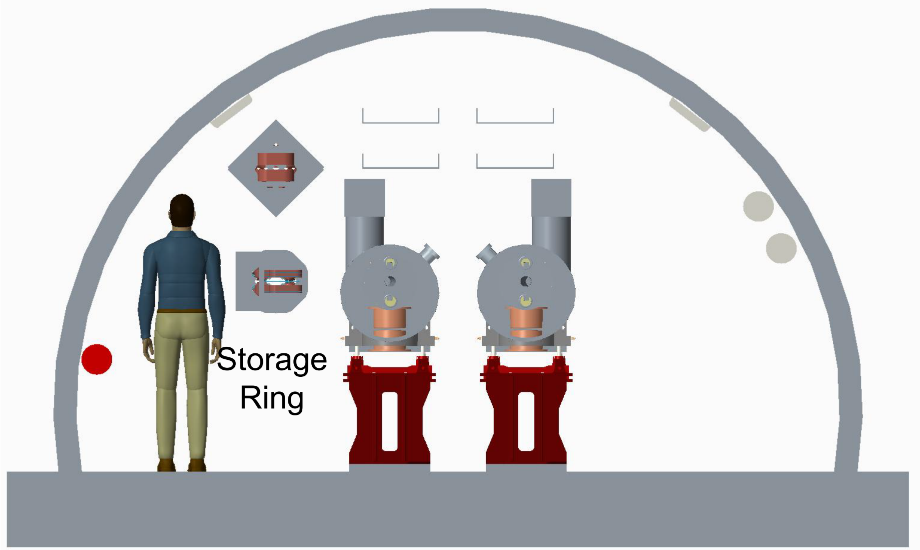
Super-bends for 5-10 GeV for emittance control

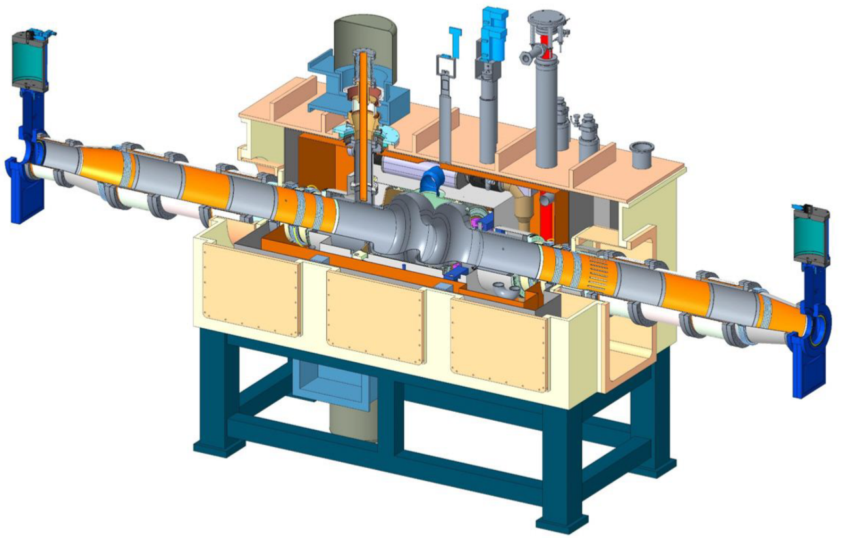


6 Straight sections with simple layout

Radiate some **10 MW** for maximum luminosity parameters at 10GeV

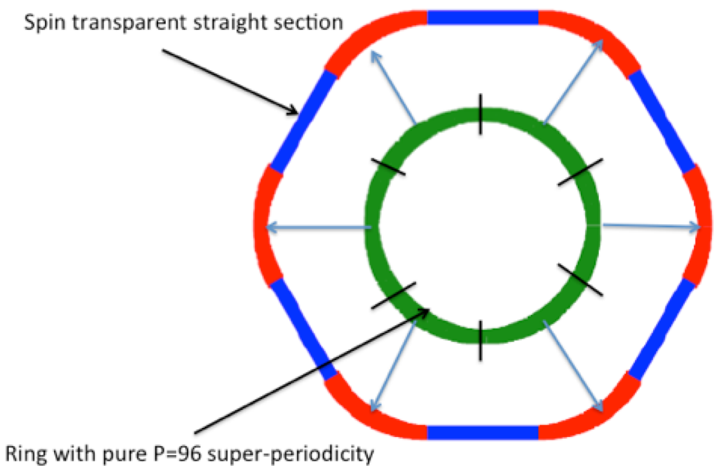
➔ 11 superconducting 2-cell 500 MHz RF cavities



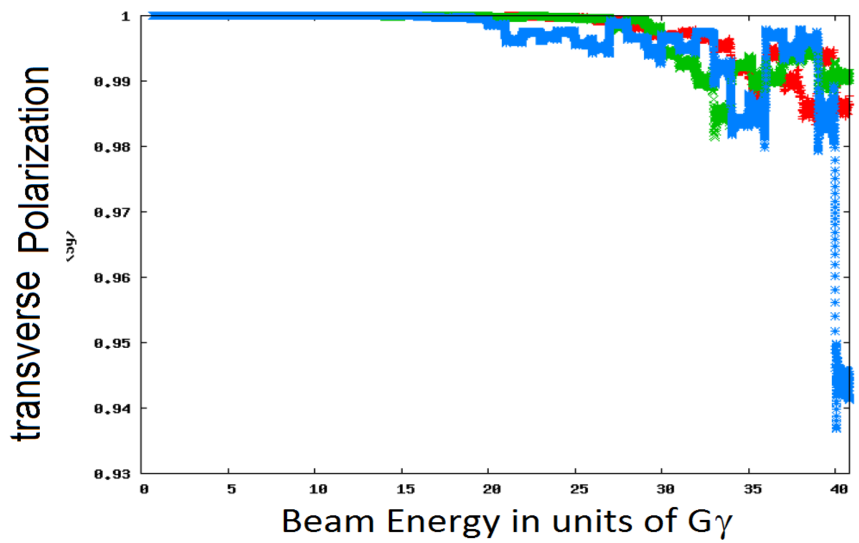


eRHIC electron injector: rapid cycling synchrotron

High Quasi-symmetry
➔ Good spin transparency properties



Blue: **200 ms** ramp sufficiently fast to cross resonances



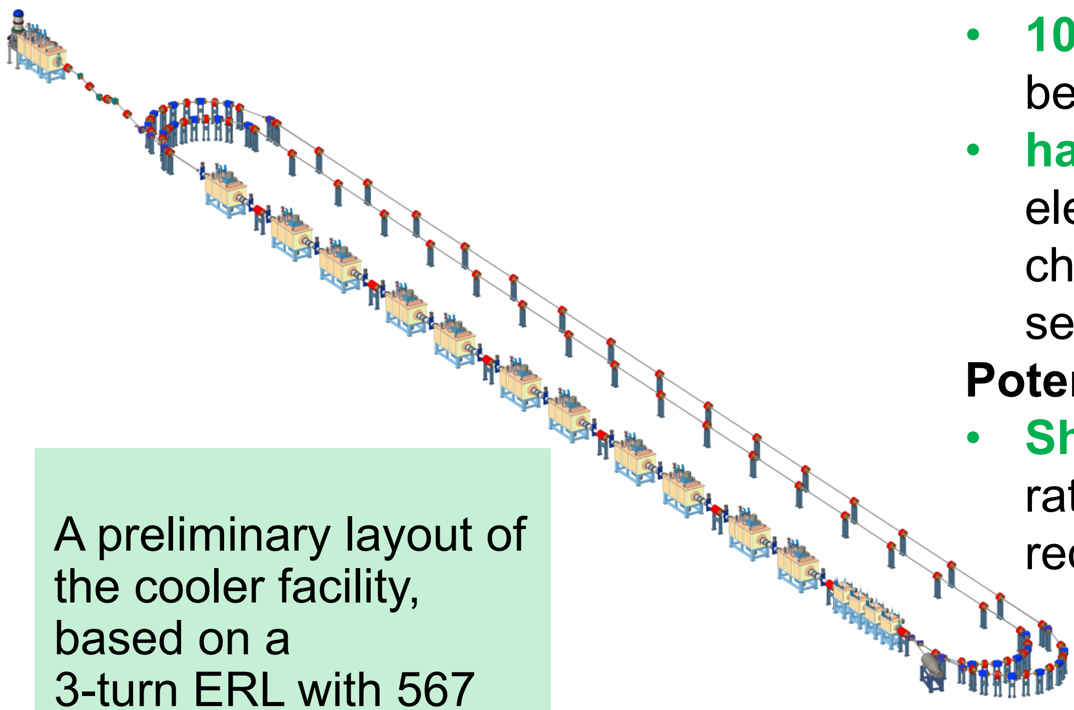
- 5-18 GeV spin polarized electrons are required for injection into the storage ring.
- spin-transparent **rapid cycling synchrotron** in the RHIC tunnel
- **High lattice quasi-symmetry** (achieved by straight sections designed as unity transformations) suppress systematic depolarizing resonance during the ramp
- **Tight control of orbit and stray fields**: challenging but feasible

eRHIC: strong hadron cooling

The most promising approach up to cool 275 GeV protons is **micro-bunched electron beam cooling** with 2 plasma amplification stages.

Achievable **cooling rates** with **100 mA** electron current and flat beams are of the order of **1 hour**

Vigorous R&D program needed:



A preliminary layout of the cooler facility, based on a 3-turn ERL with 567 MHz cavities

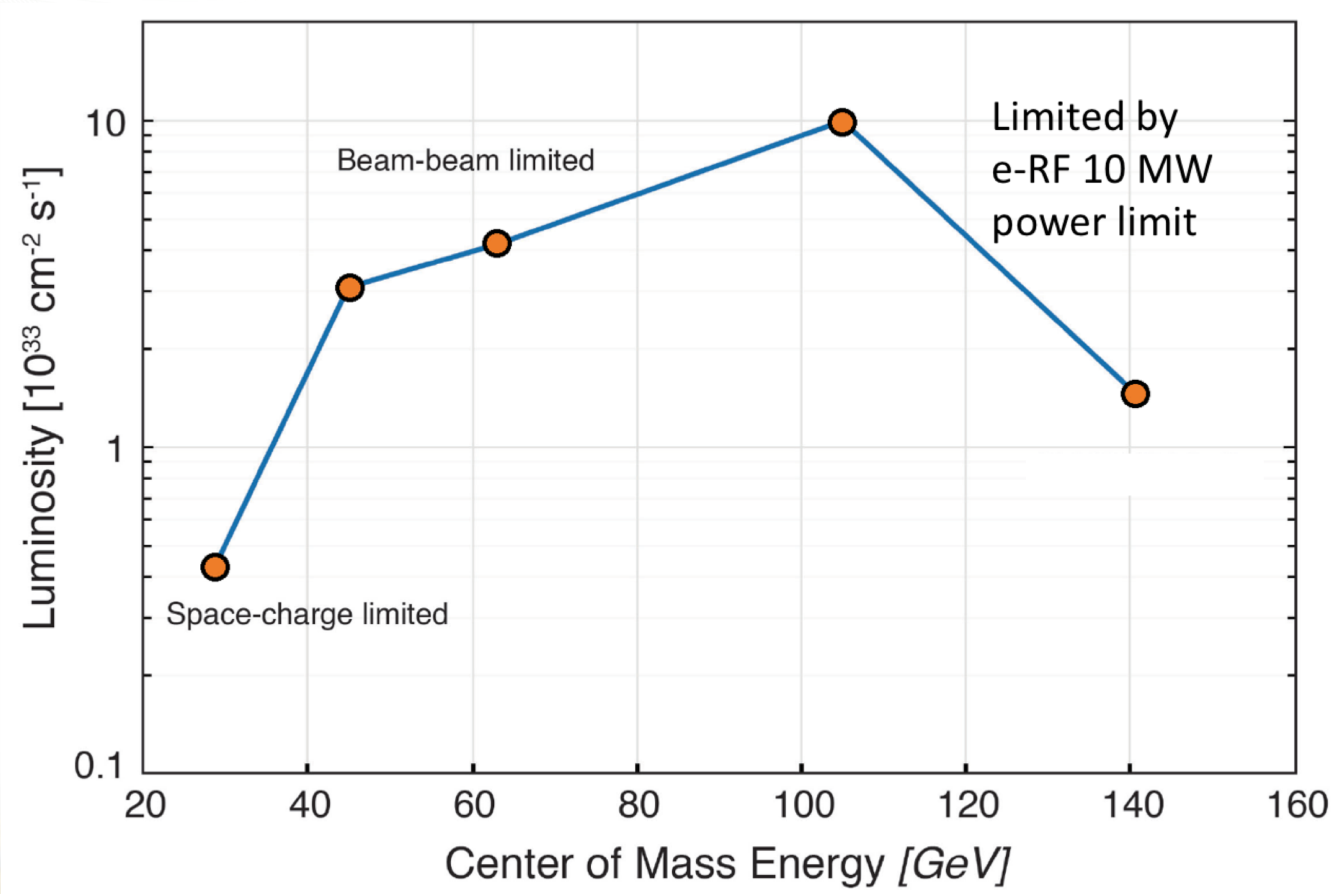
Challenges:

- **100 mA CW electron source** is beyond state of the art
- **hadron chicane** to compensate for electron delay in the micro-bunching chicanes is a considerable effort (need several blue ring s.c. RHIC magnets)

Potential:

- **Short bunches** might boost the cooling rate, reduce the electron current and reduce number of amplifications.

eRHIC: luminosity versus cm energy



A fall back position without strong cooling and more conservative beam parameters results in a luminosity **L= $0.44 \cdot 10^{34} cm^{-2}s^{-1}$**

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eRHIC: maximum luminosity parameters

- High beam currents
- Many bunches
- Large beam-beam tune-shift (B-factories, RHIC)
- Flat beams
- Need strong hadron cooling
- Short hadron bunches
- 22 mrad crossing angle with crab cavities

➔ Large Luminosity

Parameter	hadron	electron
Center of Mass Energy [GeV]	104.9	
Energy [GeV]	275	10
Number of Bunches	1320	
Particles per bunch [10^{10}]	6.0	15.1
Beam Current [A]	1.0	2.5
Horizontal Emittance [nm]	9.2	20.0
Vertical Emittance [nm]	1.3	1.0
Hor. beta function at IP β_x^* [cm]	90	42
Vert. beta-function at IPβ_y^* [cm]	4.0	5.0
horizontal/vertical fractional betatron tunes	0.08/0.06	0.3/0.31
Horizontal Divergence $d\sigma_x^*/ds$ [mrad]	0.101	0.219
Vertical Divergence $d\sigma_y^*/ds$ [mrad]	0.179	0.143
Horizontal Beam-Beam Parameter ξ_x	0.013	0.064
Vertical Beam-Beam Parameter ξ_y	0.007	0.01
IBS Growth Time longitudinal/horizontal [hours]	2.19/2.06	-
Synchrotron Radiation Power [MW]	-	9.18
Bunch Length [cm]	5	1.9
Hourglass and crab reduction factor	0.87	
Luminosity [10^{34} cm^{-2}sec^{-1}]	1.05	

eRHIC polarization

Hadron polarization in RHIC

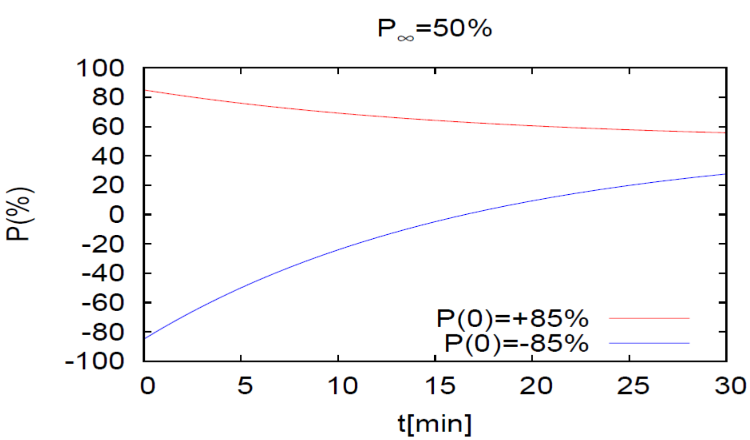
- **RHIC operational experience**: polarization levels **~50-60%**
- Use **additional Siberian snakes** to reach **~70 % levels**
- Detector solenoid: influence not yet checked, important for p

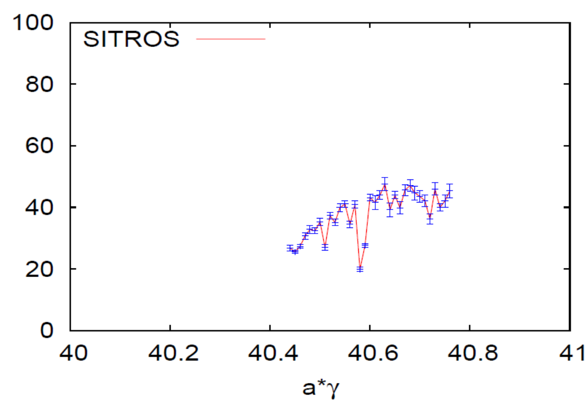
Polarization in electron ring

Need to store bunches with **85%** initial polarization with spin parallel ↑ ↑ and spin antiparallel ↑↓ to guide field in the arc.

➔ Need to replace bunches with parallel spin ↑ ↑ with a rate of up to 1/(5 minutes) because of Sokolov-Ternov Depolarization (defines the injection chain)

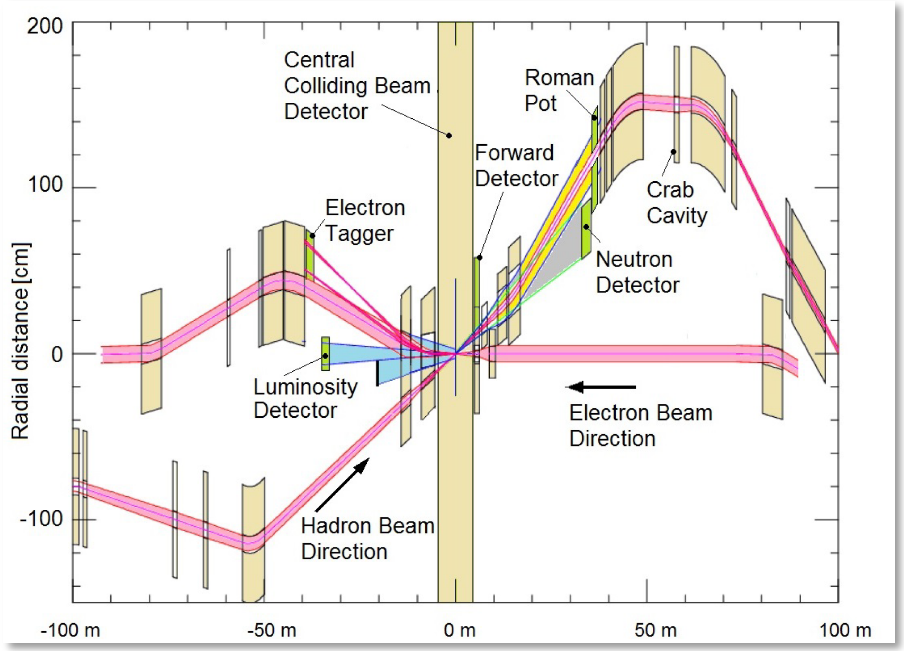
- Polarization with beam-beam not yet done (HERA polarization suffered only indirectly from BB: non-colliding bunches pushed to unfavorable tunes by fixing the tunes for colliding ones)





Polarization with realistic machine errors

eRHIC: IR layout



IR design requirements:

- Small β* for high luminosity
- Low β* quadrupole aperture
- Consider Chromaticity limitations
- Large Detector acceptance
  - ➔ Quadrupole aperture, limited beam divergence
- Accommodate dipole spectrometer
- No accelerator magnets +/-4.5 m
- Crossing angle, crab crossing, crab cavities
- Avoid Synchrotron radiation, no electron bends on the forward side
  absorb SR far from IP
- Accommodate spin rotators, spin matching
- Space for luminosity monitor, neutron detector

➔**Very constrained systems**, requires novel types of magnets in the IR

EIC R&D timeline

- **Pre-project R&D** ongoing since 10+ years
- Program execution up to 2017: NP EIC R&D FOA (~2M$ level), operating funds, state funds, laboratory LDRD, SBIR
- EIC R&D thoroughly reviewed and at the **NP EIC Community Review Panel** (a.k.a. "Jones Panel") in November 2017
- Final Review Panel Report and R&D Priorities released in March 2017
- **FY 2018 Research and Development for Next Generation Nuclear Physics Accelerator Facilities (FOA)** (~7M$ level) issued in December 2017, full proposals due in January 2018
- Review and Selection Committee met in February 2018
- Award selections finalized.

EIC R&D topics

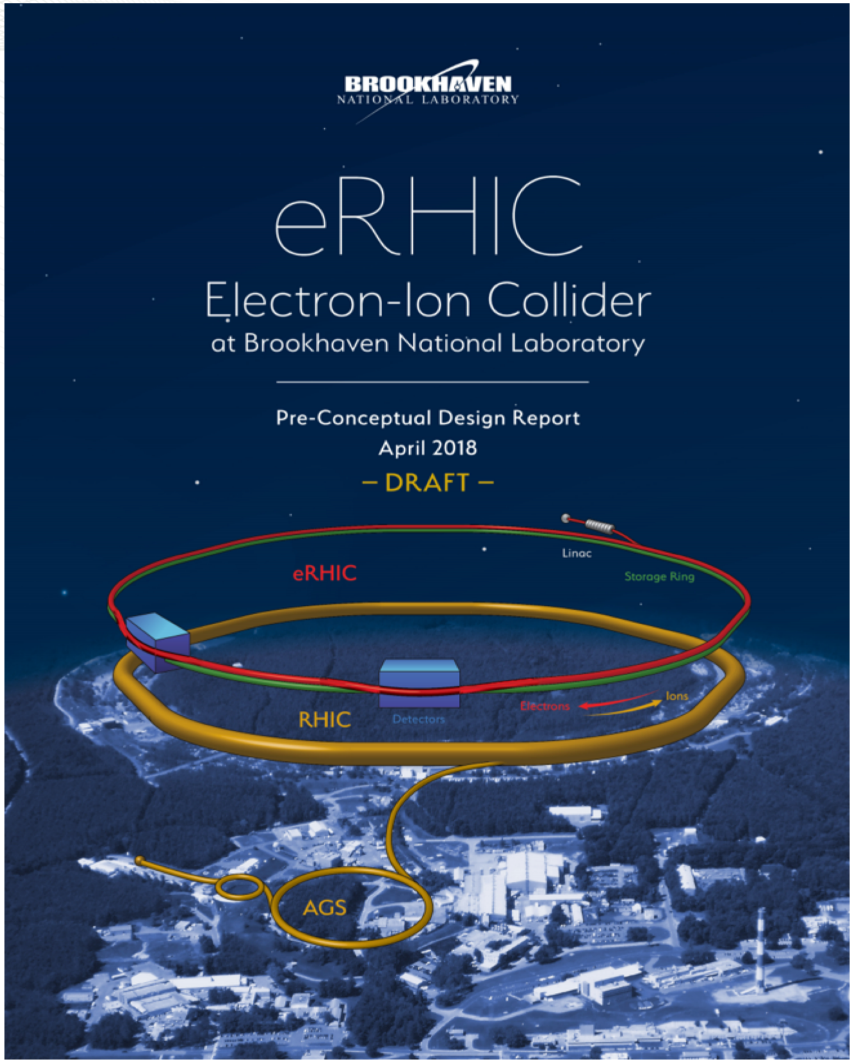
- *"Priority will be given to potential initiatives identified by the community as compelling, such as in the **NSAC LRP** for Nuclear Science. Relative to a potential electron-ion collider, **community sponsored review panels** and workshops have identified a number of areas where focused R&D and prototyping could advance technical feasibility and pre-conceptual design; priority will be given to these areas of study … Thus, the relevance of proposed electron-ion collider efforts to the R&D **priorities** established in that [Jones panel] report should be **clearly articulated** in the application."*

Highest priority to EIC R&D topics common to all designs:

- **Strong cooling**
- **IR systems: magnets and crab cavities**
- **Polarization**
- **Beam dynamics and modeling**

Collaborative proposals were encouraged and received funding priority – Excellent response from accelerator based National Labs

Pre-CDRs

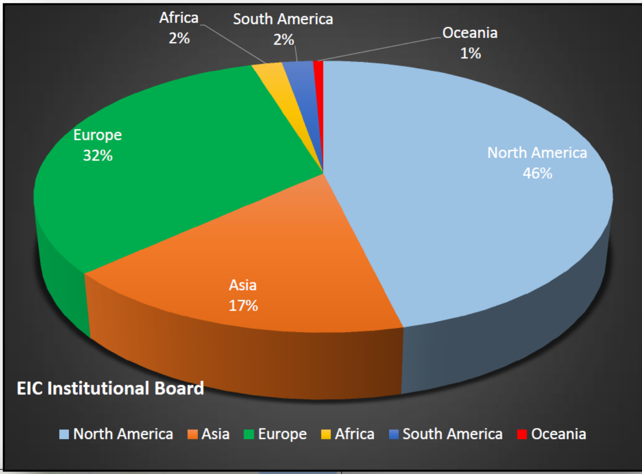


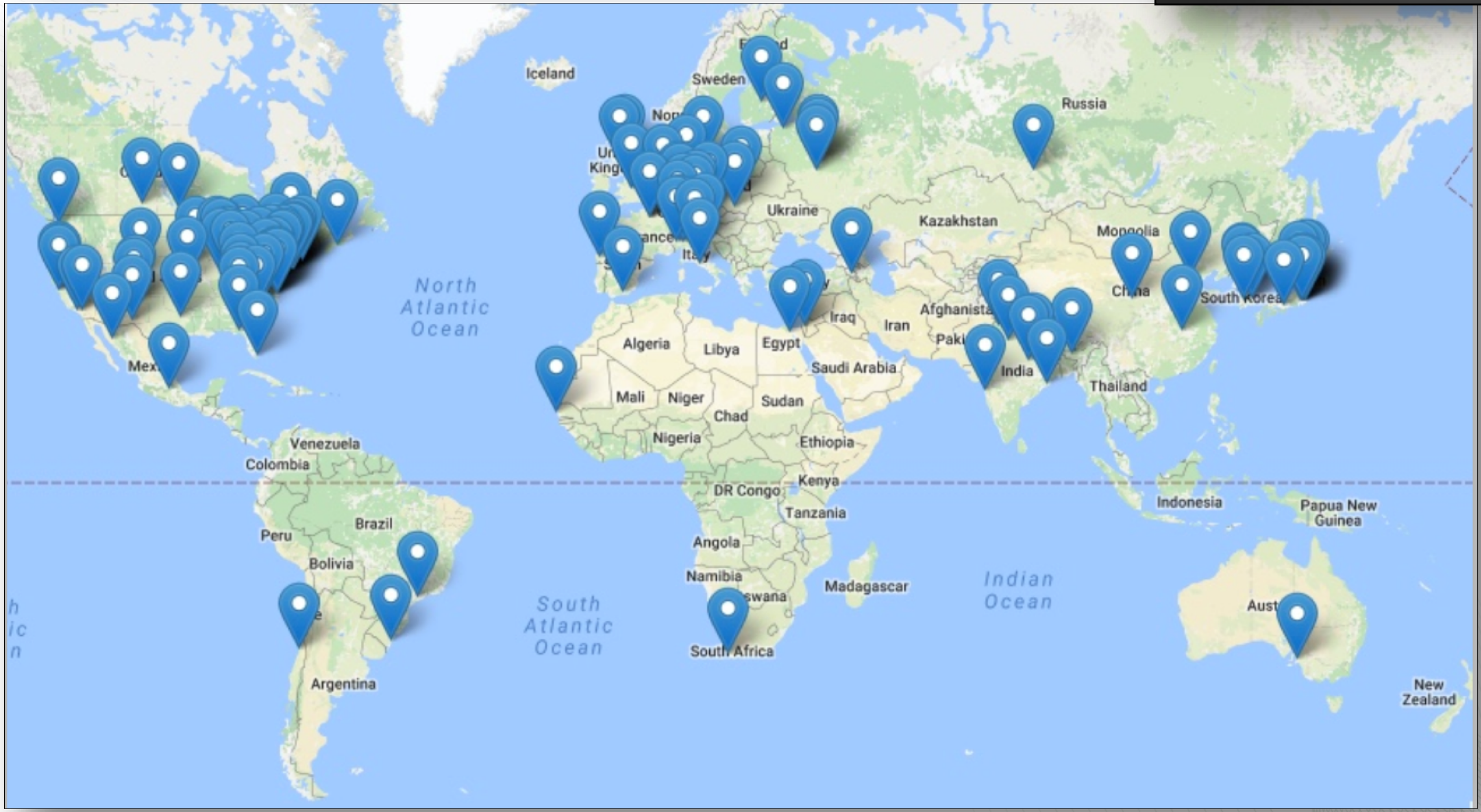
BROOKHAVEN
NATIONAL LABORATORY
eRHIC
Electron-Ion Collider
at Brookhaven National Laboratory
Pre-Conceptual Design Report
April 2018
– DRAFT –
Linac
eRHIC
Storage Ring
RHIC
Detectors
Electrons
Ions
AGS

Jefferson Lab
JLEIC
EIC2
Jefferson Lab
ELECTRON-ION COLLIDER
Pre-Conceptual Design Report
Version 1.5
April 20, 2018

USERS Group

Formed 2016, currently 732 members
169 institutions, 29 countries





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Outlook: from program to project

ONGOING:

- **National Academy of Sciences Study**: 2017-18 – report written, under review, expect release in next few months
- **R&D program** (accelerator and detectors)
- **Pre-CDRs**
- **Community building:** users group, national and international collaboration

POSSIBLE OUTLOOK:

- EIC hopes to receive **CD-0** at the end of 2018
- **Site selection** in 2019-20
- **CD-1** in 2021-22
- **CD-2** in 2023-24
- **CD-3** in 2025
- Commissioning in 2029
- **CD4** in 2030

Conclusions

- The recognition in the U.S. of the EIC as the highest priority for new construction in nuclear physics has set firm foundations to build this challenging accelerator
- Two alternative designs exist at BNL and JLAB that capitalize on the existing RHIC and CEBAF facilities
- In order to achieve the challenging beam requirements, the designs use strong cooling for high luminosity, novel concepts for polarization and a high level of integration between accelerator and detectors in the IR
- A strong collaborative R&D program is in place to validate the most challenging design elements
- The EIC program and the nuclear physics community are engaging the national and international scientific communities toward the realization of this challenging and exciting project

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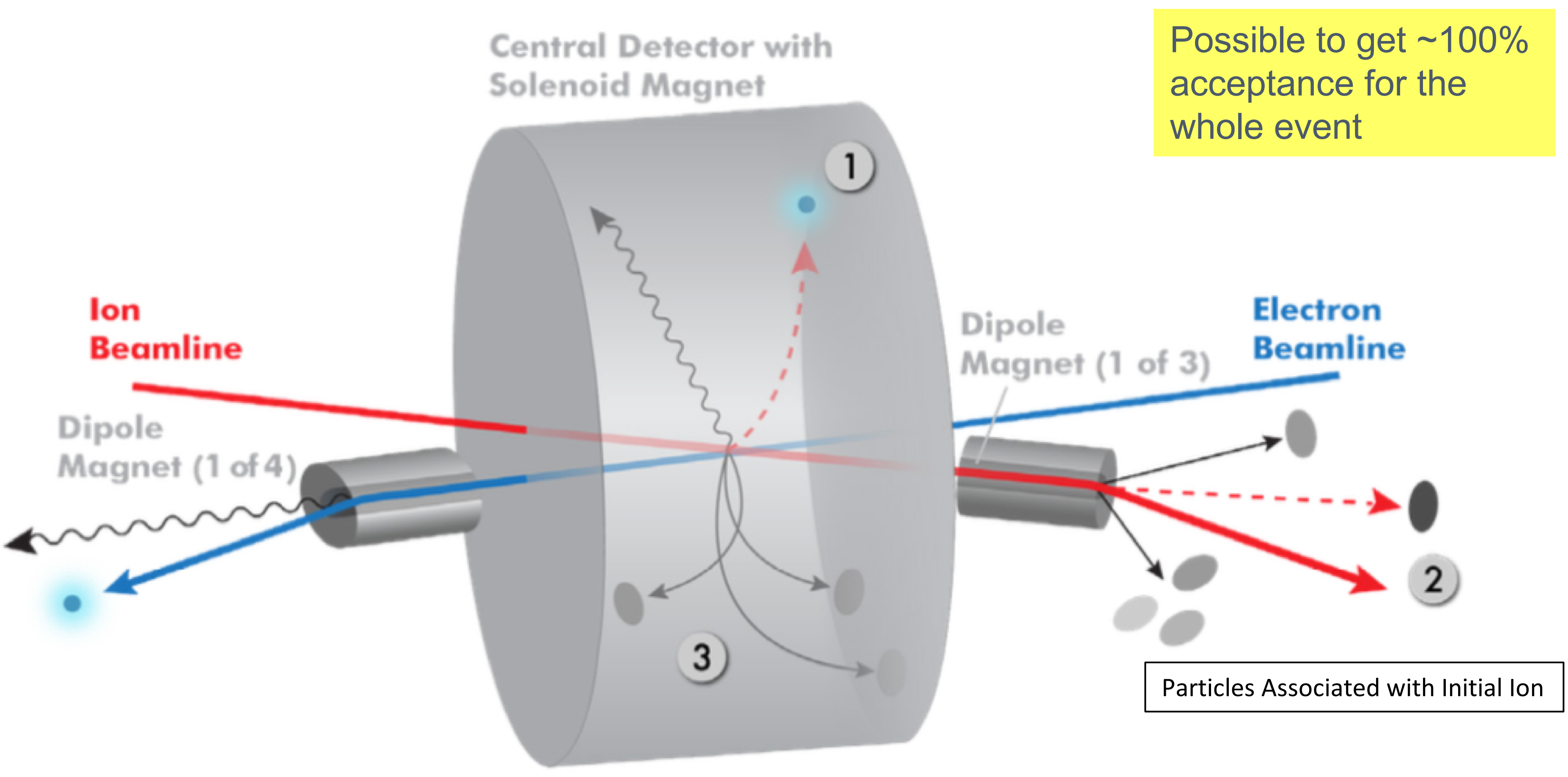
JLEIC IR: total acceptance detector

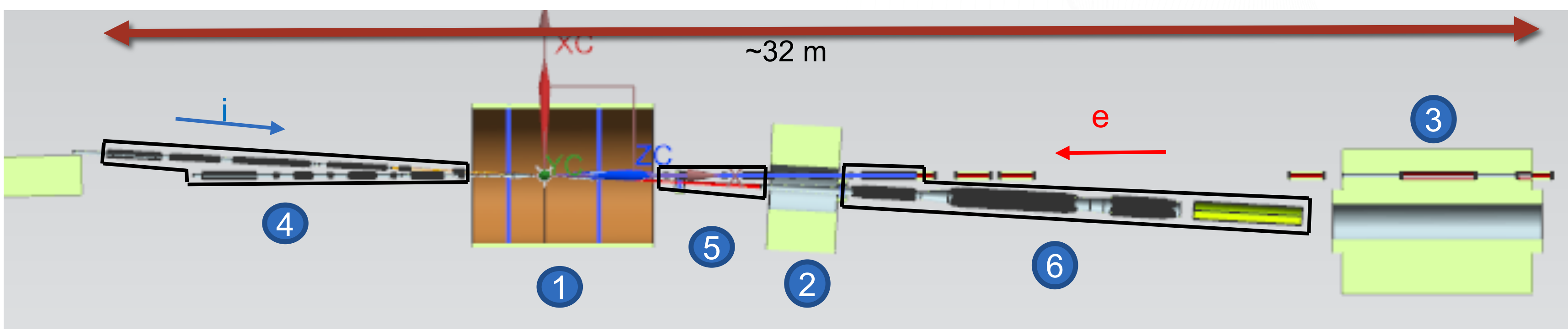


Possible to get ~100% acceptance for the whole event

Large crossing angle (50 mr) combined with **large aperture final focus magnets**, and forward dipoles are keys to this design.

JLEIC: IR region

- The design thus far has been considered six distinct areas
  1. Detector Solenoid (4 m)
  2. SB1 dipole (1.5 m)
  3. SB2 dipole (~4.6 m)
  4. Ion entrant side cryostat (~8.7 m)
  5. Electron entrant cryostat between the SB1 and Detector Solenoid (~2.6 m)
  6. Ion down beam cryostat between the two dipoles (~11.1 m)



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