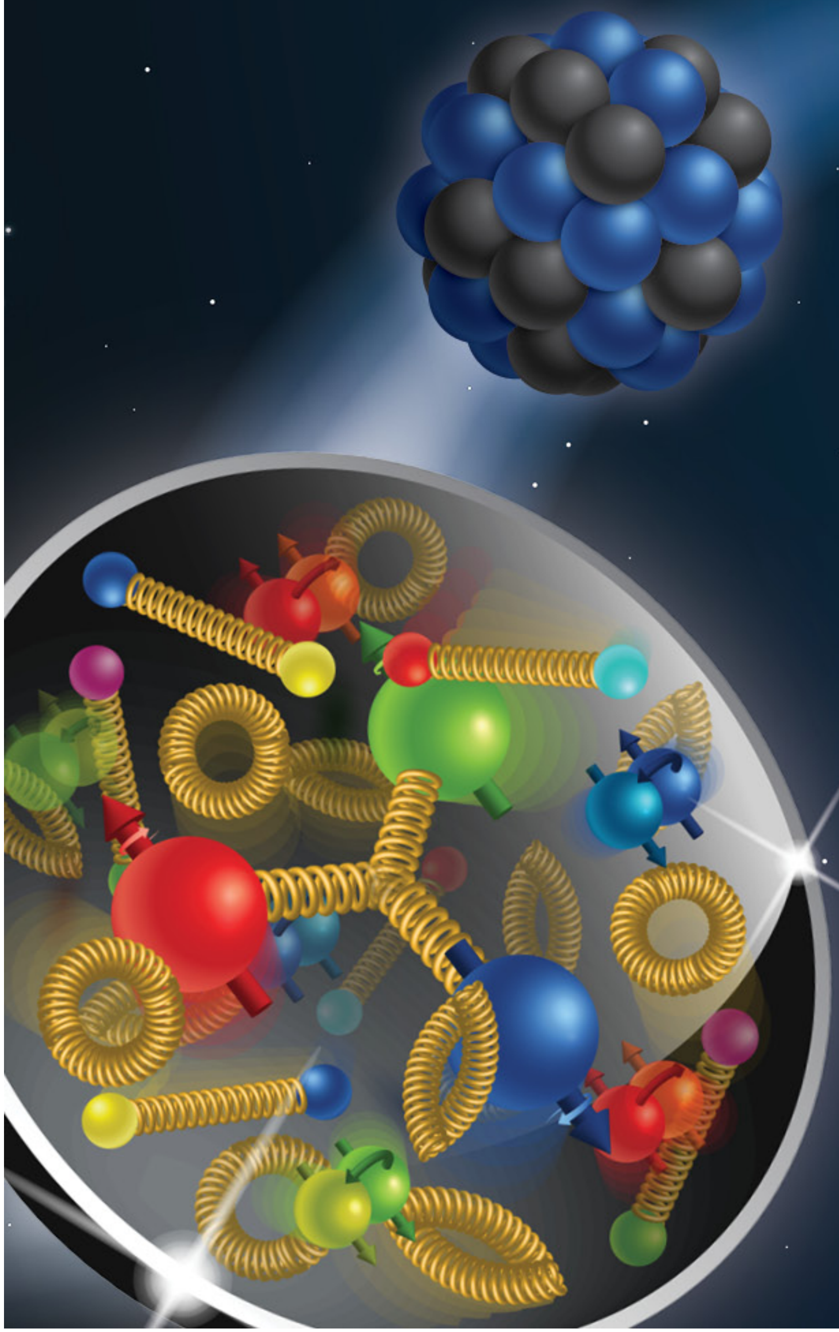


EIC Accelerator Overview

Vadim Ptitsyn, BNL

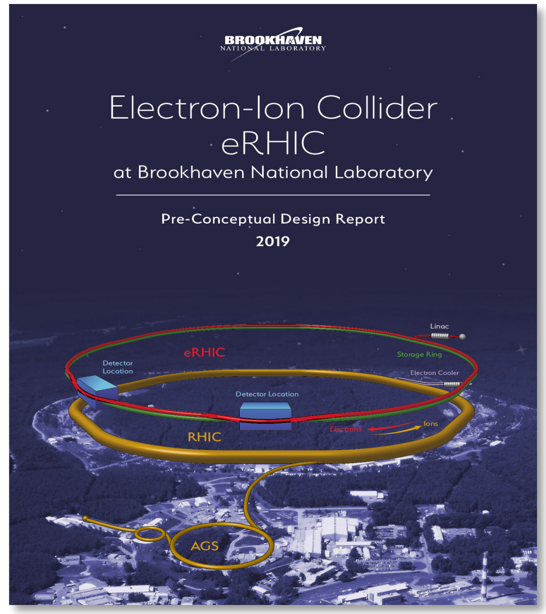
Workshop on Physics and Detector Requirements at Zero-Degree of Colliders, Stony Brook 2019

Electron Ion Collider

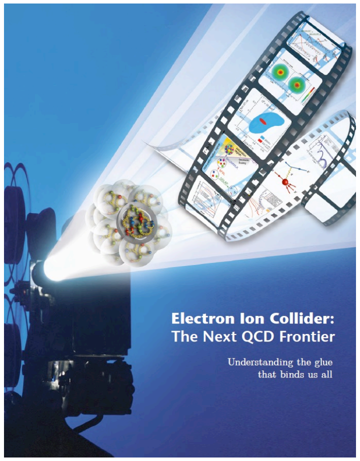
U.S. DEPARTMENT OF ENERGY | Office of Science

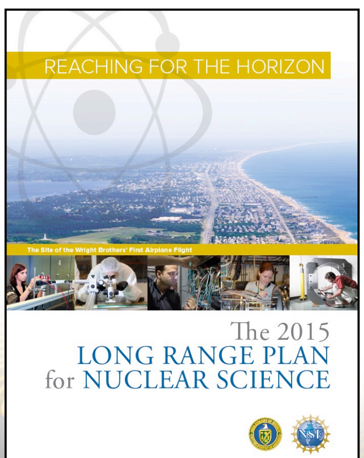
Outline

- Requirements
- Design concepts
- Luminosity
- Polarization
- Hadron Cooling
- Beam Dynamics Consideration
- R&D
- Summary



Requirements on EIC Performance



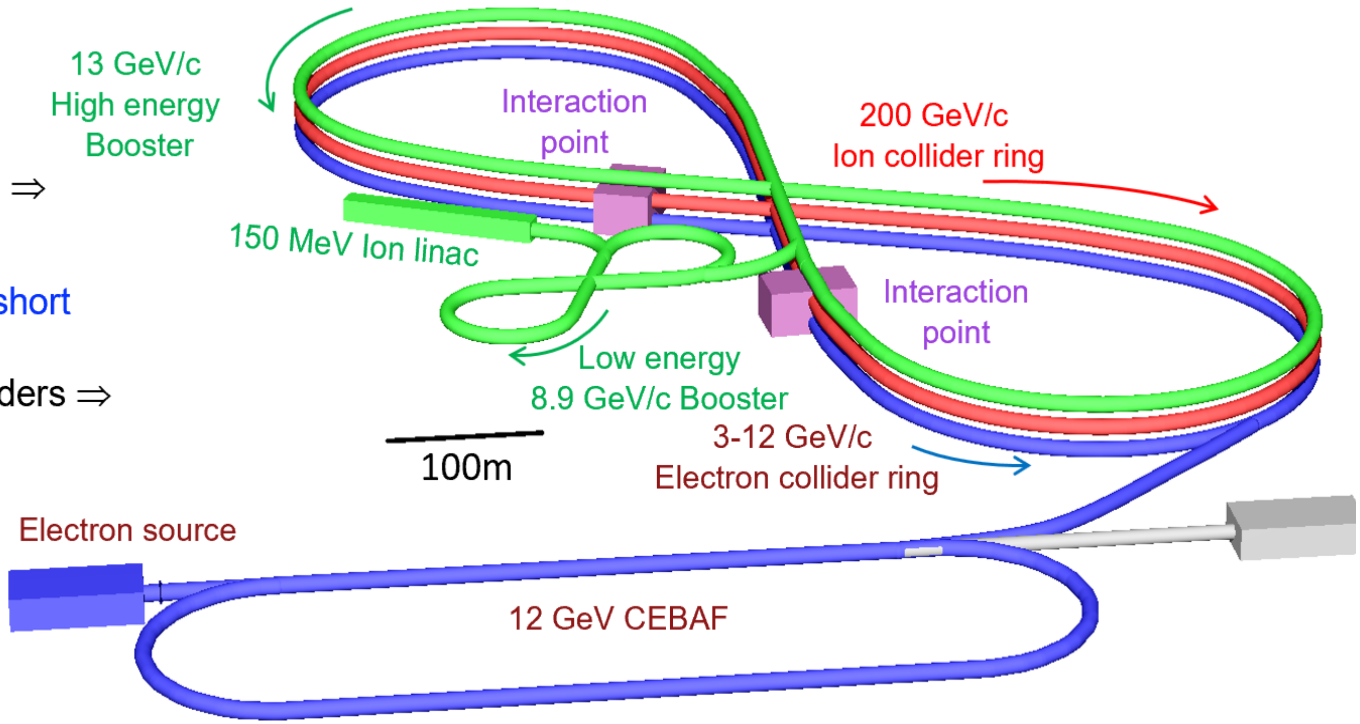


The EIC is designed to meet the requirements set forth in the Community White Paper and re-emphasized in 2015 NSAC Long Range Plan and the NAS report:

- Highly polarized (~70%) electron and nucleon beams
- Ion beams from deuterons to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 - ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10^{33} – 10^{34} $cm^{-2}s^{-1}$
- Possibilities of having more than one interaction region

JLEIC Layout

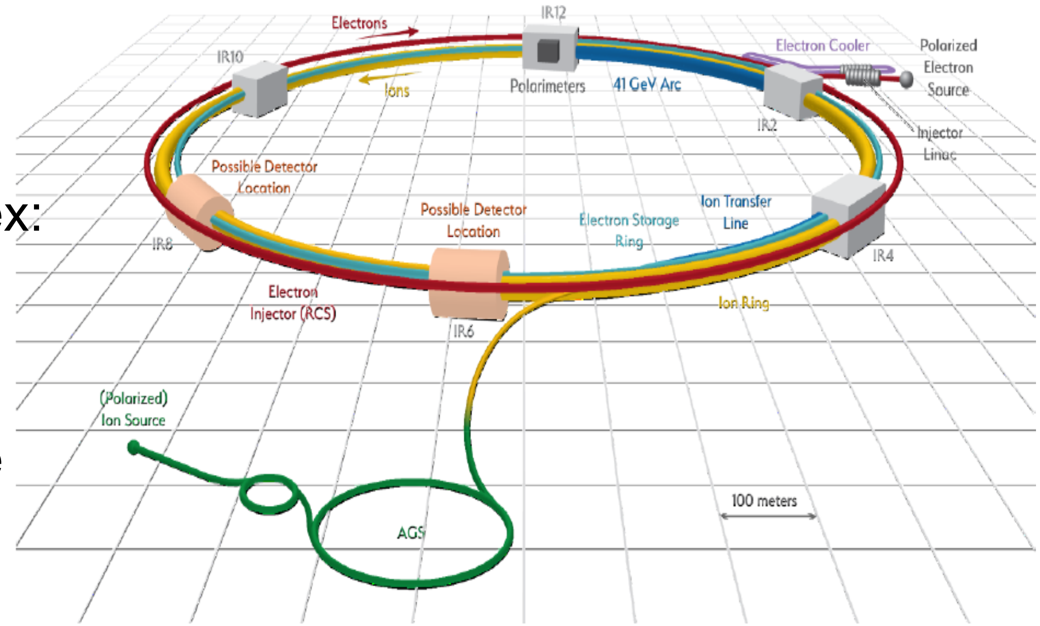
- Full-energy top-up injection of highly polarized electrons from CEBAF ⇒
  High electron current and polarization
- Full-size high-energy booster ⇒
  Quick replacement of colliding ion beam ⇒
  High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches similarly to record-luminosity lepton colliders ⇒
  High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒
  Small ion emittance ⇒
  High luminosity



- Figure-8 ring design ⇒
  High electron and ion polarizations, polarization manipulation and spin flip
- Integrated full acceptance detector with far-forward detection sections being parts of both machine and detector
- Upgradable to 140 GeV CM by replacing the ion collider bending dipoles only with 12 T magnets

Courtesy: V Morozov, A Seryi

eRHIC Layout



- **Hadrons up to 275 GeV**

  eRHIC is using the existing RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure,
- Need only few modifications for eRHIC
- Todays RHIC beam parameters are close to what is required for eRHIC

- **Electrons up to 18 GeV**

- Electron storage ring with up to 18GeV ➔ E_{cm} = 20 GeV -141 GeV installed in RHIC tunnel. Beam current are limited by the choice of installed RF power 10 MW.
- Electron beams with a variable spin pattern accelerated in the on-energy, spin transparent injector: Rapid Cycling Synchrotron with 1-2 Hz cycle frequency in the RHIC tunnel
- Polarized electron source and 400 MeV s-band injector linac in existing tunnel
- Design meets the high luminosity goal of **$L = 10^{34} cm^{-2} s^{-1}$**

Key EIC Machine Parameters

as required by the NSAC LRP & NAS

Parameter	Unit	JLEIC	eRHIC
Center of Mass Energies	[GeV]	20-100 a)	20-140
Ion Species		p to U	p to U
Number of Interaction Regions		2	2
Hadron Beam Polarization		85%	80%
Electron Beam Polarization		80%-85%	80%
Maximum Luminosity	$[10^{34} cm^{-2} s^{-1}]$	1.55	1.3

a) upgradable to 140 GeV

Similar Approach is Used to Reach High Luminosity

As both designs, JLEIC and eRHIC are storage ring designs, the same ingredients are required for large luminosity

- **Many bunches** ➔ large total beam currents

  ➔ crossing angle collision geometry

- **Small beam size** at collision point achieved by

  * **small emittance**

  ➔ Small hadron emittance requires strong hadron cooling (or frequent injection)

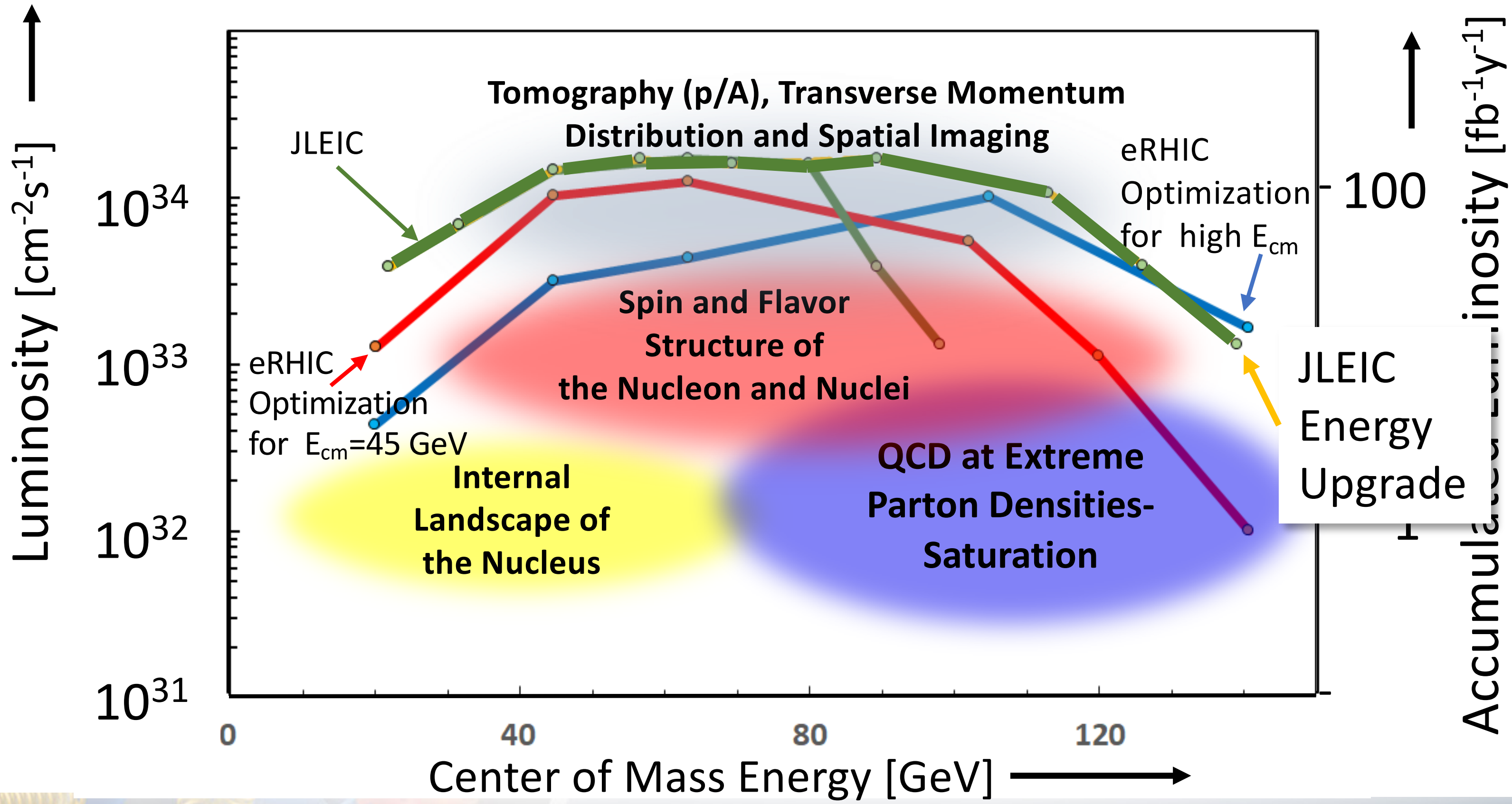
  * **and strong focusing at IR** (small β)

  ➔ required short bunches ➔ need strong cooling

Beam-Beam Limit: Transverse beam density at collision point limited by the detrimental effect of the corresponding nonlinear lens

EIC Luminosity

IR Designs can be adjusted to obtain peak luminosity at different center of mass energies. The curves below show luminosity vs E_{cm} with IRs optimized for high or low center of mass energy.



Strong Hadron Cooling and High Luminosity

The strong hadron cooling (at the EIC storage energy) is desirable if not necessary to avoid rapid decay of the luminosity caused by emittance blow-up due to intrabeam scattering

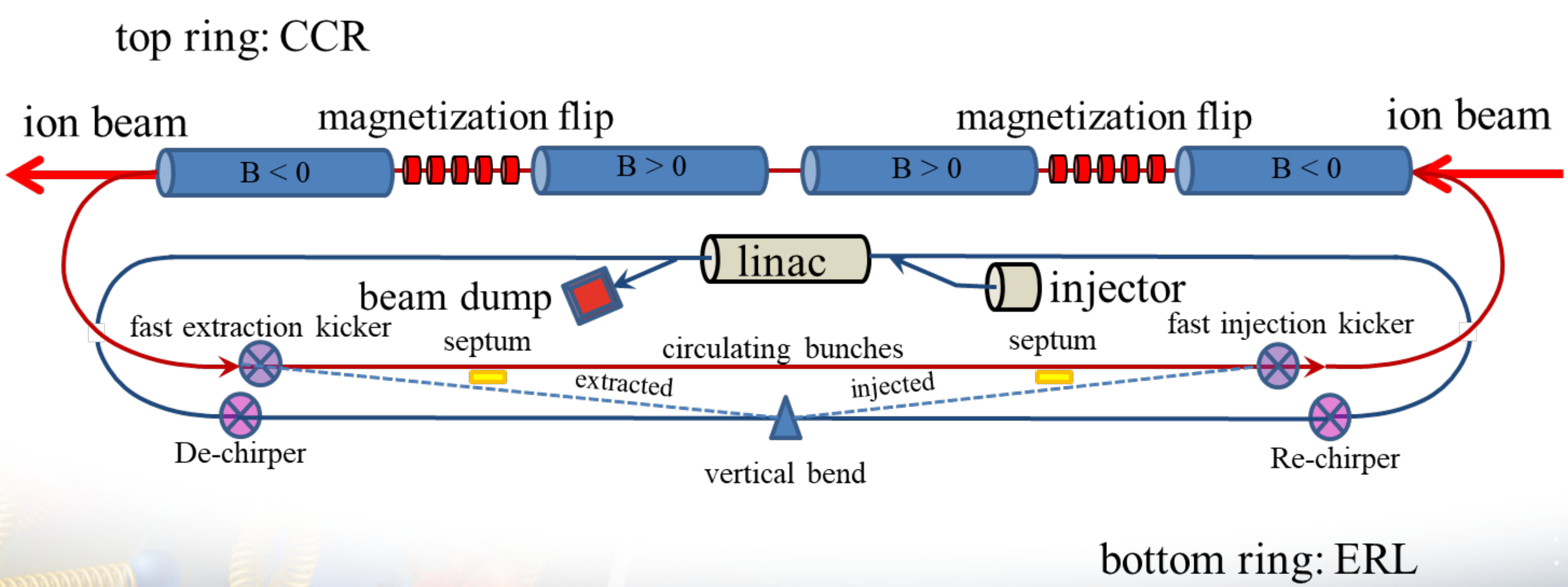
The two proposals operate at different ranges of hadron energy and the cooling systems are optimized accordingly.

- **JLEIC:**
  - Incoherent electron cooling in Boosters to reduce beam emittances
  - At store energies 30-150 GeV: multi-turn magnetized bunched electron beam cooling ring fed by an energy recovery linac to balance IBS growth time between 5 and 40 minutes.
  - As alternative to store energy cooling it can use short fills with rapid turn arounds for achieving high average luminosity quoted as $1\cdot10^{34}$ cm^{-2}s^{1}.

- **eRHIC:**
  - At store energies (41-275 GeV): micro-bunched electron cooling to balance IBS growth rates between 25min to 2h for highest luminosity.
  - As alternative to the strong cooling:
    an on-energy for frequent injections available which results in an average luminosity which is still 90% of the peak luminosity.

Strong Hadron Cooling Scheme for JLEIC

- Magnetized electron beam for higher cooling efficiency
- Cooling electron beam is energy-recovered to minimize power consumption
- 11-turn circulator ring with 1 amp of beam current relaxes electron source requirements
- Fast harmonic kicker to kick electrons in and out of the circulator ring
- Pre-cooling a low energy is essential to achieve the anticipated performance

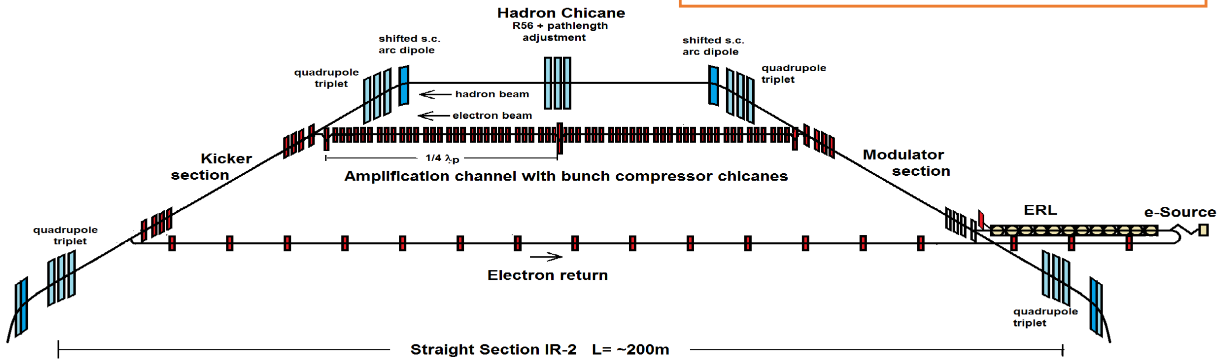


Courtesy: V Morozov, A Seryi

eRHIC Hadron Cooling and On-Energy Injection Alternative

Goal: τ_{cool} < 1h at 275 GeV

- Strong hadron cooling at store energy presents the convenience of the long experimental stores, maximizing average luminosity, maintaining constant beam sizes
- Different methods of strong hadron cooling are being explored conceptually, by simulations and experimentally



Coherent Electron Cooling with μ-bunching amplification (SLAC/BNL)

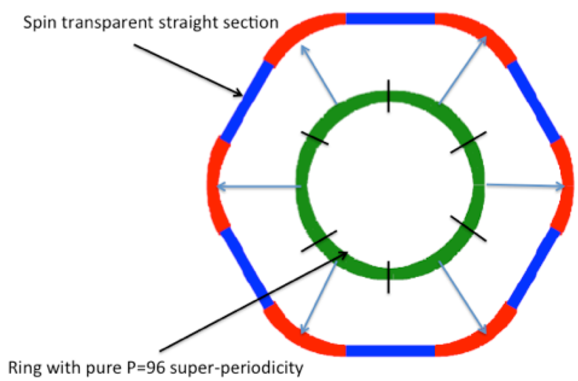
- Alternative to the hadron cooling at the store energy is on-energy hadron injector scheme.
- The scheme fully employs both of the existing RHIC rings:
  - Yellow RHIC ring is used as the eRHIC hadron Storage ring
  - Blue RHIC ring is used as the eRHIC hadron Accelerator ring
- The stored hadron beam will be replaced with 1-1.5h our intervals, with average luminosity >90% of the peak one.
- The peak luminosity of 10^{34} cm^{-2} s^{-1} in this scheme can be achieved by the cooling at low energies: in AGS (several GeV) and/or at the eRHIC hadron injection energy (25 GeV).

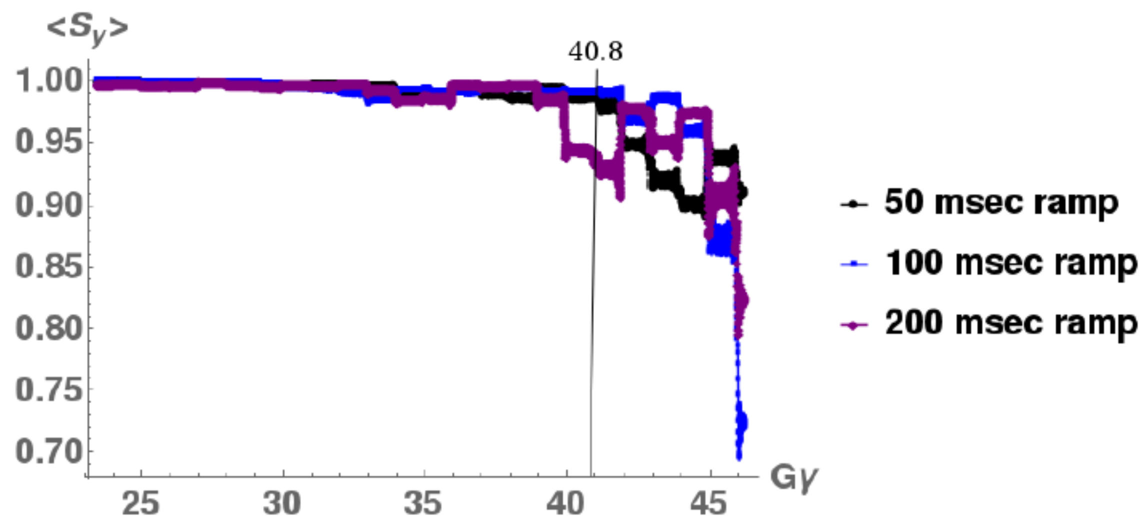
eRHIC Rapid Cycling Synchrotron Polarization

Spin transparent optical design: High periodicity arcs and unity transformation in the straights suppresses all systematic depolarizing resonances up to $G\gamma$ =45

➔ resonance free acceleration up >18 GeV

➔ no loss of polarization on the entire ramp up to 18 GeV (100 ms ramp time)



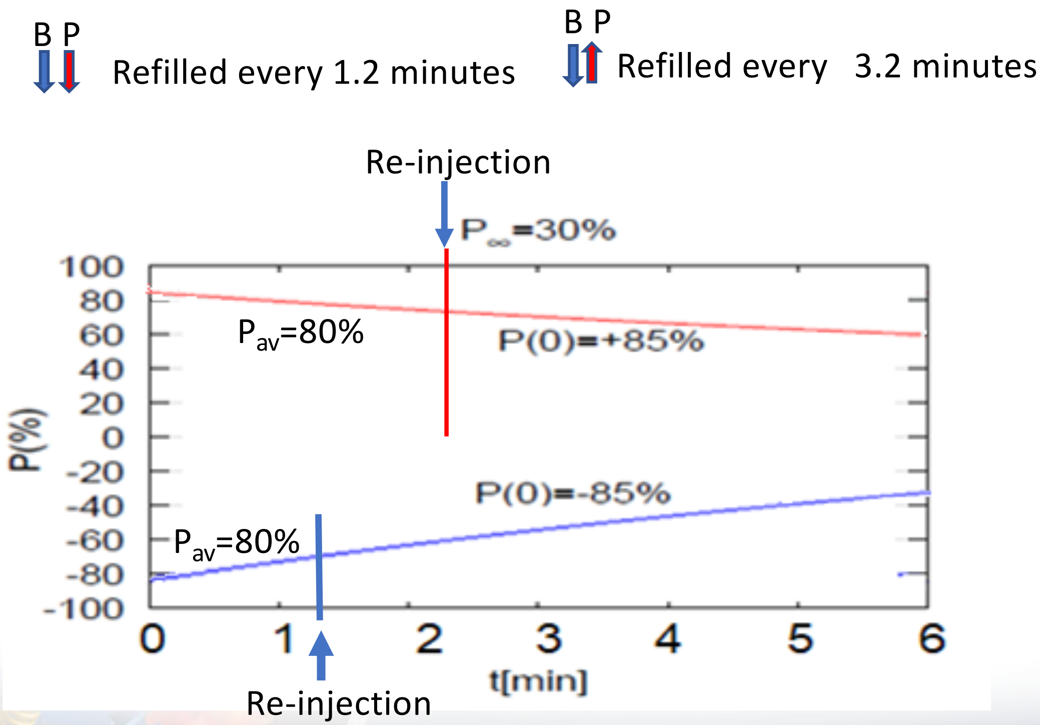


Need well aligned quadrupoles and rms orbit ≤ 0.5 mm and good reproducibility

➔ Well within the present state of the art of orbit control and achieved today by NSLS-II Booster synchrotron

Polarization in the electron storage ring

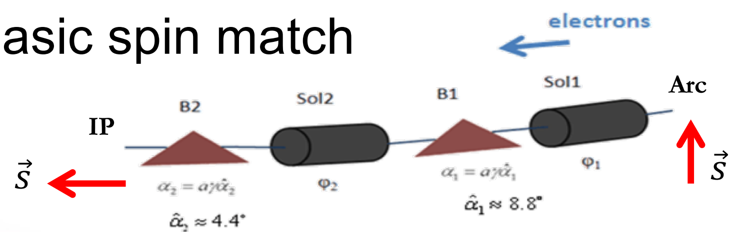
- Solenoid based Spin rotators ➔ longitudinal spin in collisions (arcs: vertical polarization)
- High initial polarization of 85% will decay towards equilibrium polarization $\mathbf{P}_\infty$ due to Sokolov-Ternov effect and stochastic depolarization
- P_∞ of 40-50% achievable (HERA experience and eRHIC simulations)
- Time evolution of high polarization of bunches injected into the eSR at 18 GeV (worst case) RCS cycling rate = 2Hz ➔ on average, every bunch refilled in 2.2 min

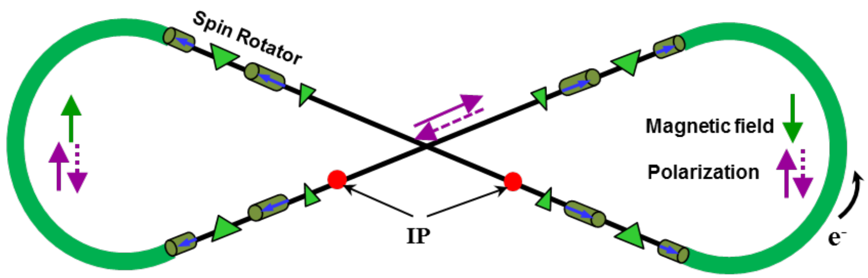


Note: Calculation with P_∞=30% is conservative as P_∞= 50% was shown feasible

JLEIC High Electron Polarization

- Two highly polarized bunch trains maintained by top-off
- Universal spin rotator
  - Minimizes spin diffusion by switching polarization between vertical in arcs and longitudinal in straights
  - Sequence of solenoid and dipole sections
  - Geometry independent of energy
  - Two polarization states with equal lifetimes
  - Basic spin match





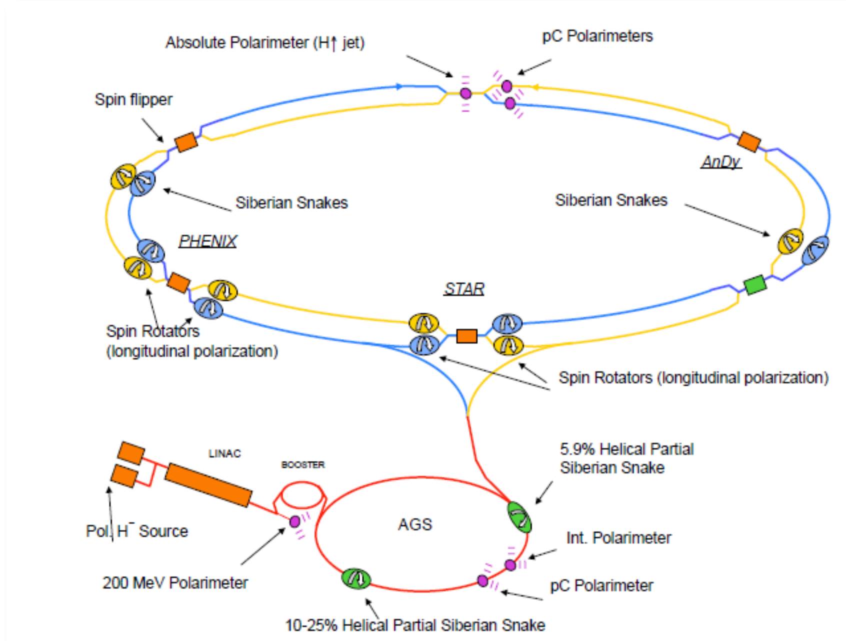
Energy (GeV)	3	5	7	9	10
Lifetime (hours)	66	8	2.2	0.9	0.3

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

Courtesy: V Morozov, A Seryi

eRHIC Hadron Polarization

eRHIC will fully benefit from present RHIC polarization and near future upgrades



Measured RHIC Results:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

Planned near term improvements:

AGS: Stronger snake, skew quadrupoles, increased injection energy

➔expect 80% at extraction of AGS

RHIC: Add 2 snakes to 4 existing no polarization loss

➔ expect 80% in Polarization in RHIC and eRHIC

Expected results obtained from simulations which are benchmarked by RHIC operations

^{3}He in eRHIC with six snakes

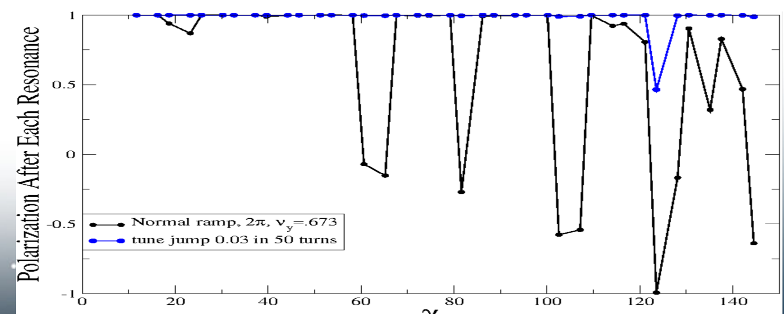
Achieved 85% polarization in 3He ion source

Polarization preserved with 6 snakes for up to twice the design emittance

Deuterons in eRHIC:

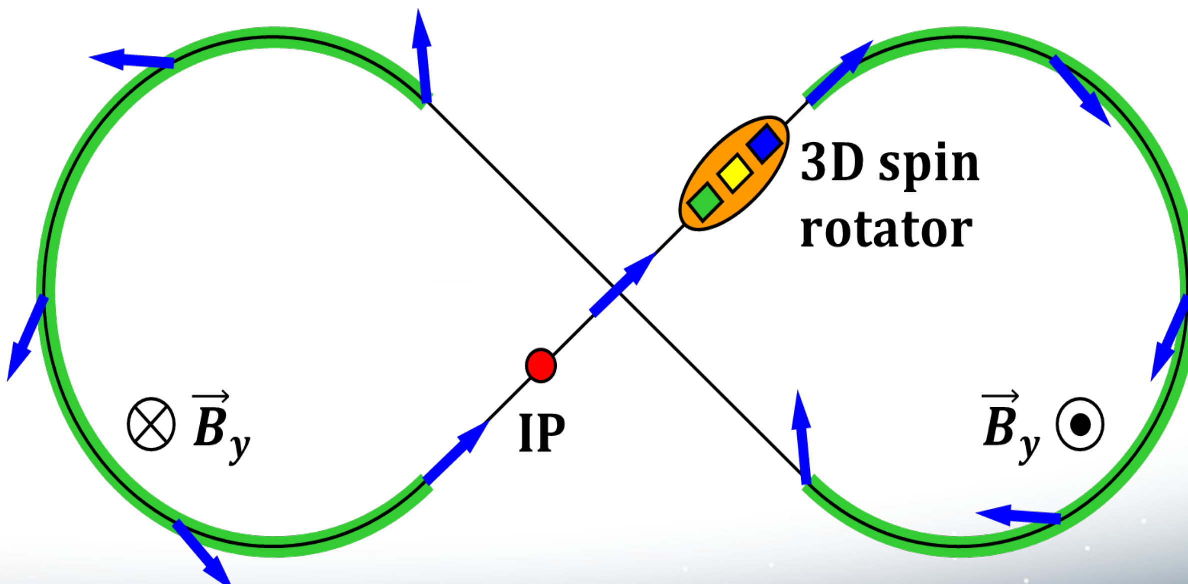
Requires tune jumps and partial Snake (detector solenoid) in eRHIC hadron ring.

No polarization **loss** expected in the eRHIC hadron ring



Ion Polarization in JLEIC

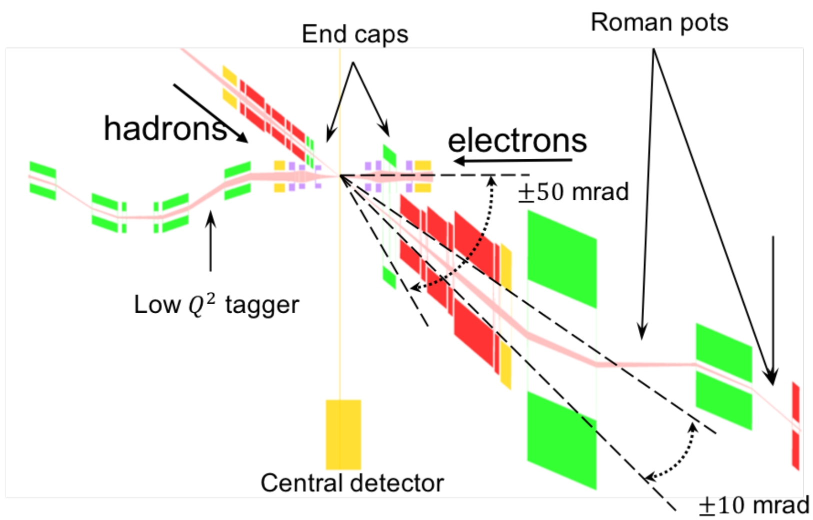
- Figure-8 concept: Spin precession in one arc is exactly cancelled in the other
- Spin stabilization by small fields: ~3 Tm vs. < 400 Tm for deuterons at 100 GeV
  - Criterion: induced spin rotation >> spin rotation due to orbit errors
- 3D spin rotator: combination of small rotations about different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



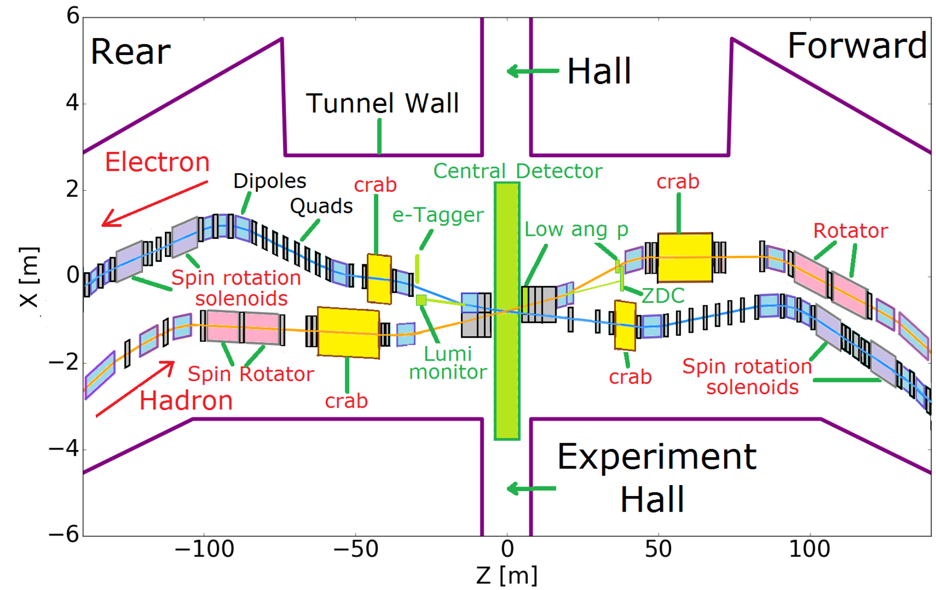
Courtesy: V Morozov, A Seryi

EIC Interaction Regions

JLEIC



eRHIC



Covered in dedicated talks at this Workshop.

Both designs have similar challenges:

- Magnet design
- Integrating forward detector elements
- Managing synchrotron radiation
- Managing dynamic aperture
- Vacuum chamber for high current operation

EIC High Luminosity with a Crossing Angle

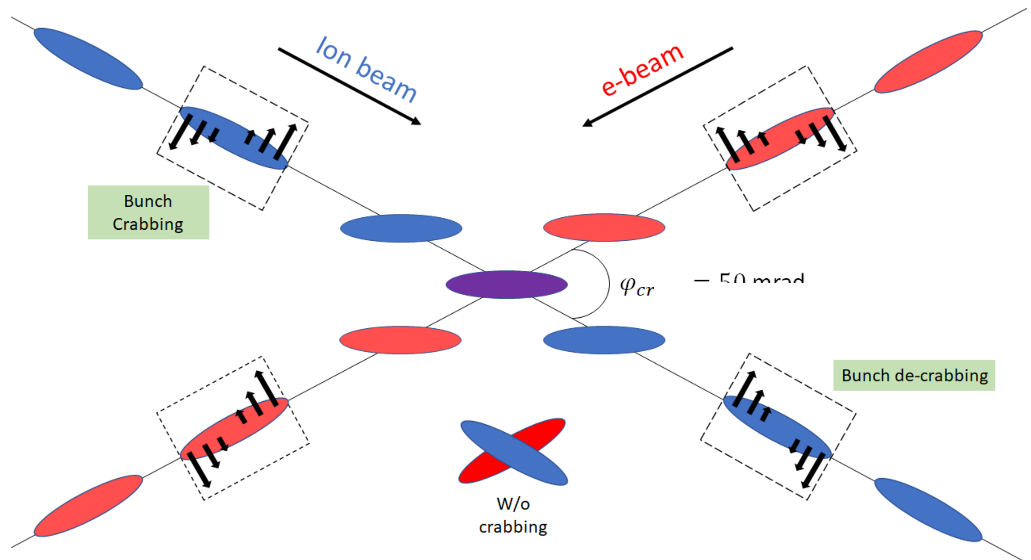
crossing angle is necessary to avoid parasitic collisions due to short bunch spacing, make space for machine elements, improve detection and reduce detector background, θ_c = 50 mrad (JLEIC), 25mrad (eRHIC)

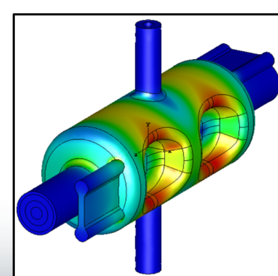
However, crossing angle causes
- Low luminosity
- Beam dynamics issues

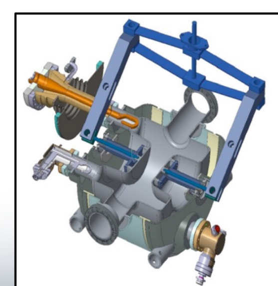
→ Crab Crossing

Effective head-on collision restored and most severe beam dynamic issue resolved

Both JLAB and BNL developed prototypes which have been tested with beam in the Cern-SpS







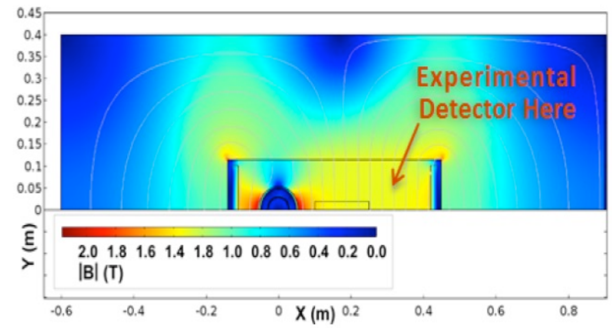
EIC Beam Dynamics Challenges

- Proton Beam Stability (emittance growth, halo forming) in presence of strong, crab-enhanced beam-beam effects, strong chromatics
- Electron cloud in the hadron vacuum, suppression of secondary emission yield
- Fast Ion instability for the electron beam
- Multi-bunch stability and feedback: Feedback noise and hadron emittance growth
- Impedance optimization in the IR
- Dynamic aperture with extreme beta in the IR

On-Going EIC R&D Effort

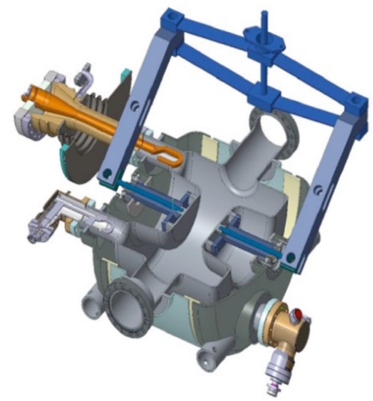
Component Development

- Crab Cavity design development and prototyping
- IR magnet development and prototyping
- HOM damping for RF structure development
- Variable coupling high power forward power couplers development
- Effective in situ Cu coating of the beam pipe (BNL hadron only)
- High average current electron gun development
- Polarized ^{3}He source
- Bunch by bunch polarimetry



Instrumented accelerator magnet

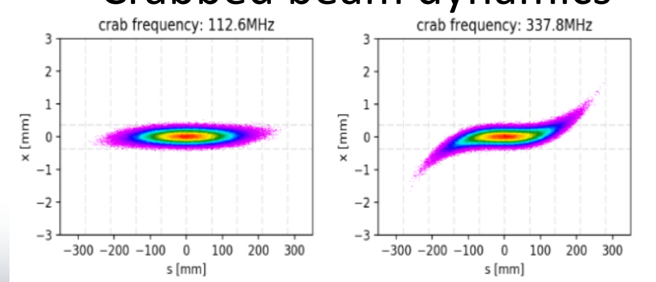
Crab cavity



Accelerator Physics R&D

- Strong hadron cooling CeC, cooling development (simulation and experimental)
- Strong hadron cooling bunches electron beam cooling (simulation and experimental)
- ERL development for strong hadron cooling
- Test of suppression of intrinsic depolarizing resonances
- Experimental verification of figure-8 configuration
- Study of residual crab cavity effect on beam emittance

Crabbed beam dynamics



Path Forward

- A Mission Need Statement for an EIC has been approved by DOE
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC has been accomplished (May-July)
- DOE has organized a Panel to assess options for siting and consideration of “best value” between the two proposed concepts
- Both proposals submitted required documentation. Oral presentations from both proposals to the Panel on October 8.

Summary

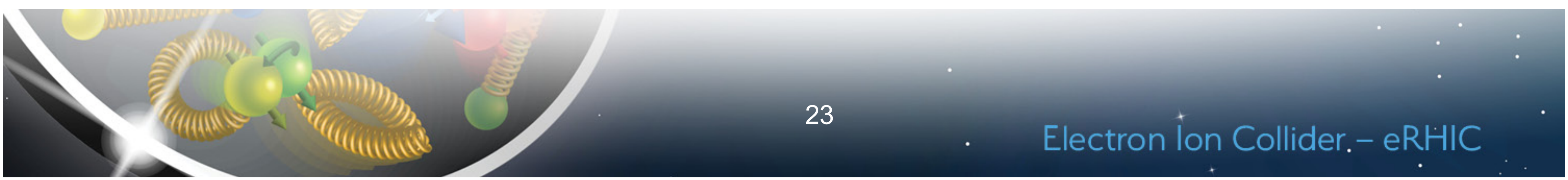
- Both EIC designs made significant progress which led to the pCDRs for both JELIC and eRHIC
- Both designs rely on very similar approach to achieve high luminosity
- The two designs rely for the most part on established accelerator technology
- Crab cavity, IR magnets, and ERL are close to state of the art

  strong hadron cooling is beyond, but is well mitigated
- The EIC design teams in Jlab and BNL continue to work on optimization and analyzing the performance of both design concepts and is looking forward for collaborative efforts for making the EIC a reality

EIC parameters

Courtesy of A.Seryi

design	eRHIC		JLEIC		eRHIC-opt.		JLEIC-upgrade	
parameter	proton	electron	proton	electron	proton	electron	proton	electron
center-of-mass energy [GeV]	104.9		44.7		63.3		105.8	
energy [GeV]	275	10	100	5	100	10	400	7
number of bunches	1160		3456		2320		864	
particles per bunch [10^{10}]	6.9	17.2	1.06	4.72	3.4	8.6	4.2	19.3
beam current [A]	1.0	2.5	0.75	3.35	1.0	2.5	0.75	3.4
beam polarization [%]	80	80	85	85	80	80	85	85
total crossing angle [mrad]	25		50		50		50	
ion forward acceptances [mrad]	±20/±4.5		±50/±10		±35/±8		±50/±5.6	
h./v. norm. emittance [μm]	2.8/0.45	391/24	0.65/0.13	83/16.6	1.5/0.15	391/24	3/0.5	228/45.6
bunch length [cm]	6	2	2.5	1	4	2	3.5	1
β_x^* / β_y^* [cm]	90 / 4.0	43 / 5.0	8 / 1.3	5.72 / 0.93	18 / 2	13 / 2.4	40 / 2.25	16.9 / 0.8
hor./vert. beam-beam param.	.014/.007	.073/.1	.015/.0135	.049/.044	.012/.013	.036/.062	.014/.008	.076/.037
peak lumi. [$10^{34}cm^{-2}s^{-1}$]	1.01		1.46		1.24		1.78	
average lumi. [$10^{34}cm^{-2}s^{-1}$]	0.93*		1.4		0.95*		1.47*	



EIC parameters

Courtesy of A.Seryi

design parameter	eRHIC proton	eRHIC electron	JLEIC proton	JLEIC electron	eRHIC-opt. proton	eRHIC-opt. electron	JLEIC-upgrade proton	JLEIC-upgrade electron
center-of-mass energy [GeV]	104.9		44.7		63.3		105.8	
energy [GeV]	275	10	100	5	100	10	400	7
number of bunches	1160		3456		2320		864	
particles per bunch [10^{10}]	6.9	17.2	1.06	4.72	3.4	8.6	4.2	19.3
beam current [A]	1.0	2.5	0.75	3.35	1.0	2.5	0.75	3.4
beam polarization [%]	80	80	85	85	80	80	85	85
total crossing angle [mrad]	25		50		50		50	
ion forward acceptances [mrad]	±20/±4.5		±50/±10		±35/±8		±50/±5.6	
h./v. norm. emittance [μm]	2.8/0.45	391/24	0.65/0.13	83/16.6	1.5/0.15	391/24	3/0.5	228/45.6
bunch length [cm]	6	2	2.5	1	4	2	3.5	1
β_x^* / β_y^* [cm]	90 / 4.0	43 / 5.0	8 / 1.3	5.72 / 0.93	18 / 2	13 / 2.4	40 / 2.25	16.9 / 0.8
hor./vert. beam-beam param.	.014/.007	.073/.1	.015/.0135	.049/.044	.012/.013	.036/.062	.014/.008	.076/.037
peak lumi. [10^{34}cm^{-2}s^{-1}]	1.01		1.46		1.24		1.78	
average lumi. [10^{34}cm^{-2}s^{-1}]	0.93*		1.4		0.95*		1.47*	

L_{ave} numbers with * are without strong cooling