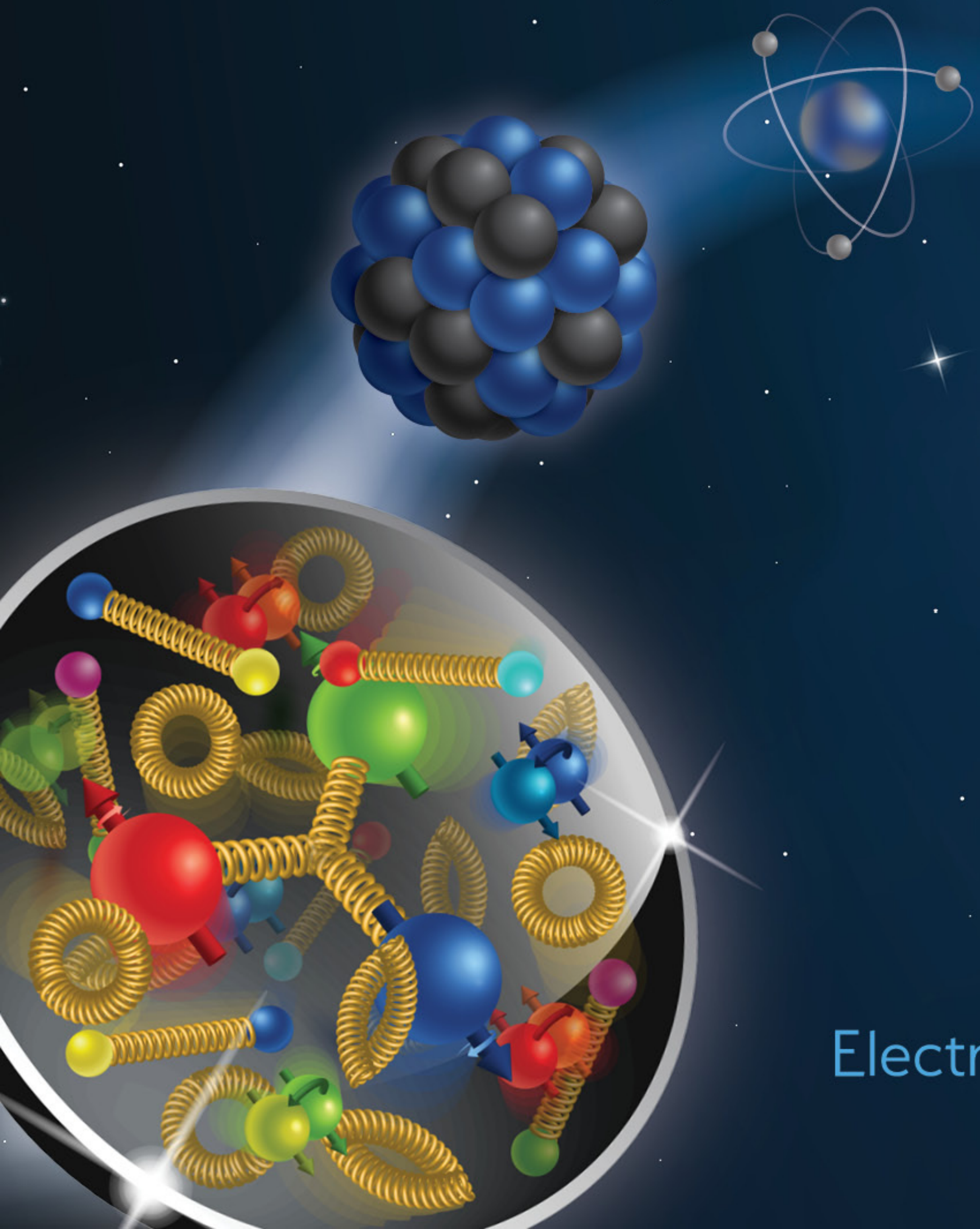

eRHIC Design Overview

Christoph Montag, BNL
IPAC’19
May 19-24, 2019

Electron Ion Collider – eRHIC

eRHIC Team

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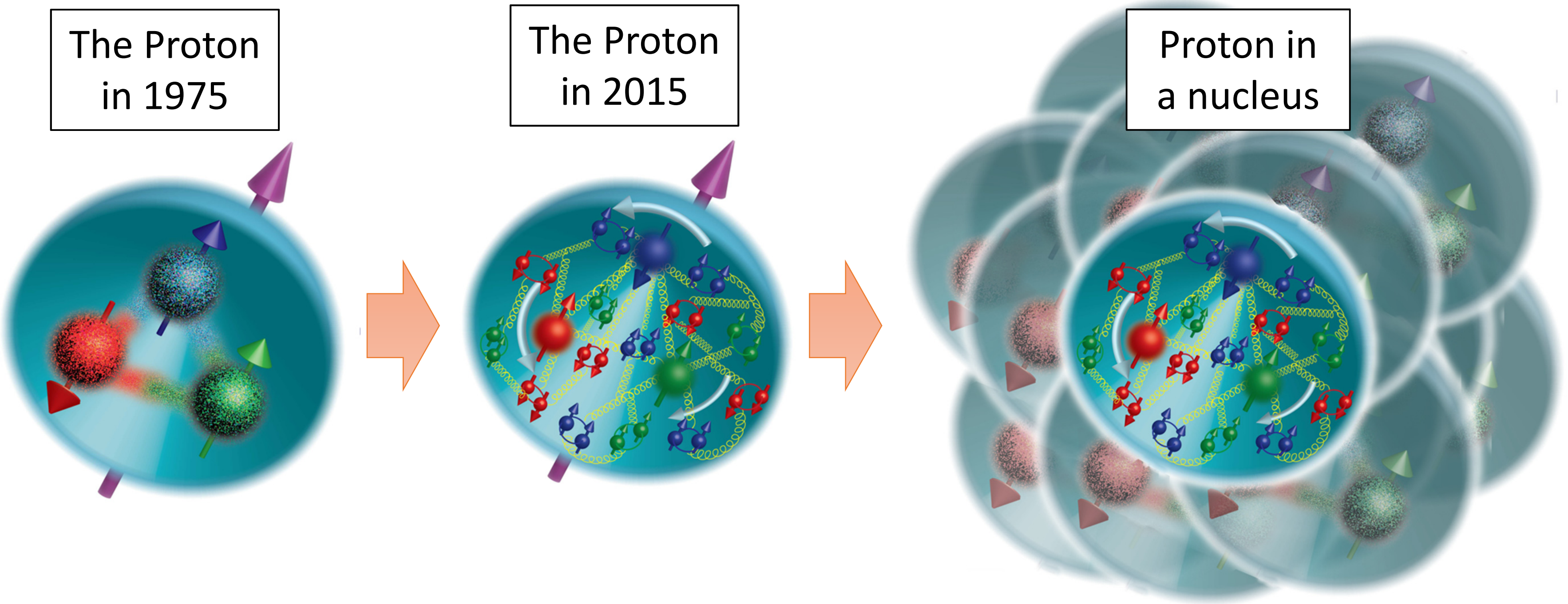
Modern view of the nucleus



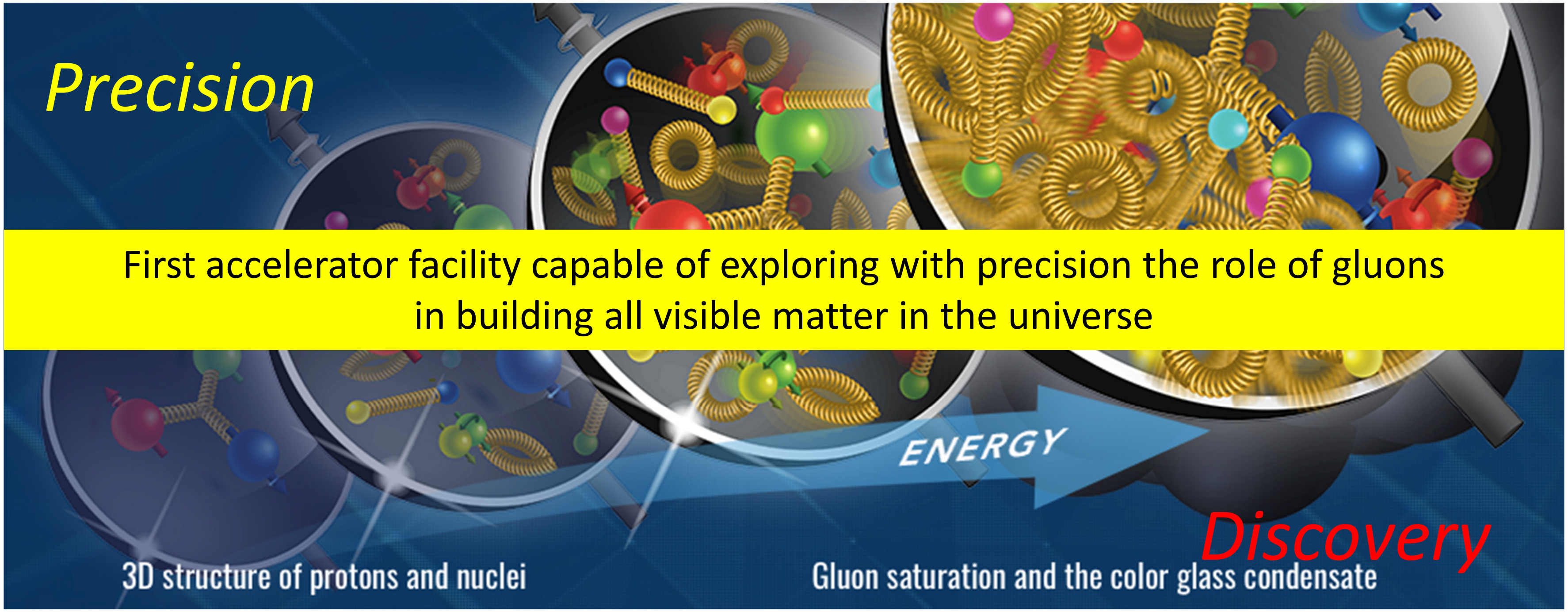
The Proton
in 1975

The Proton
in 2015

Proton in
a nucleus

The goal of the EIC is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms themselves, which lies at the heart of modern technologies.

EIC: Compelling Science Case



First accelerator facility capable of exploring with precision the role of gluons in building all visible matter in the universe

NAS Study of the Science Case for a U.S. based EIC

In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics.

Requirements for the EIC

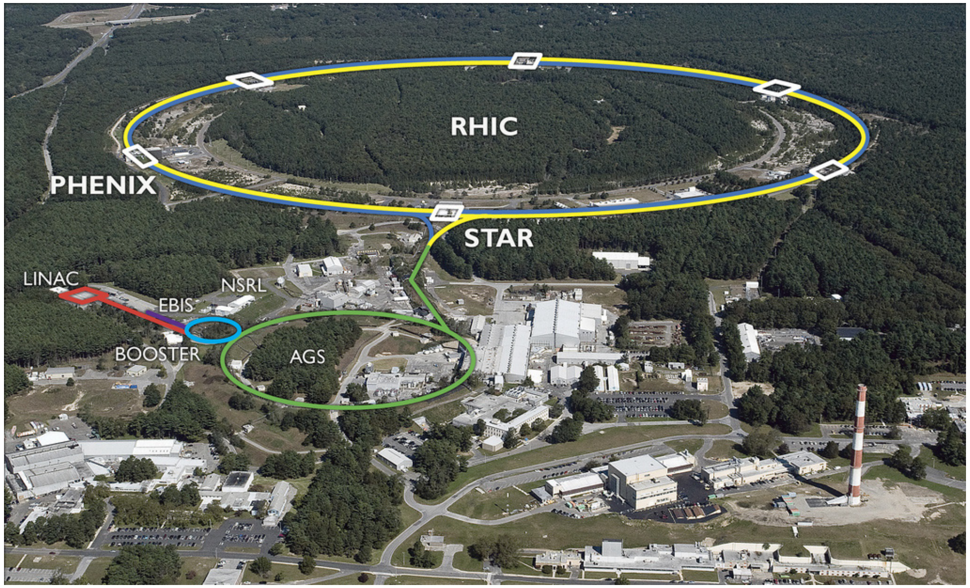
Requirements for an Electron-Ion Collider are defined in the White Paper:

- High luminosity: L = 10^{33} to 10^{34} $cm^{-2}sec^{-1}$ - factor 100 to 1000 beyond HERA
- Large range of center-of-mass energies E_{cm}= 29 to 140 GeV
- Polarized beams with flexible spin patterns
- Favorable condition for detector acceptance such as p_T =200 MeV
- Large range of hadron species: protons ….Uranium
- Collisions of electrons with polarized protons and light ions (↑^{3}He, ↑d,…)

➔

eRHIC meets or exceeds the requirements formulated in the White Paper on EIC

RHIC

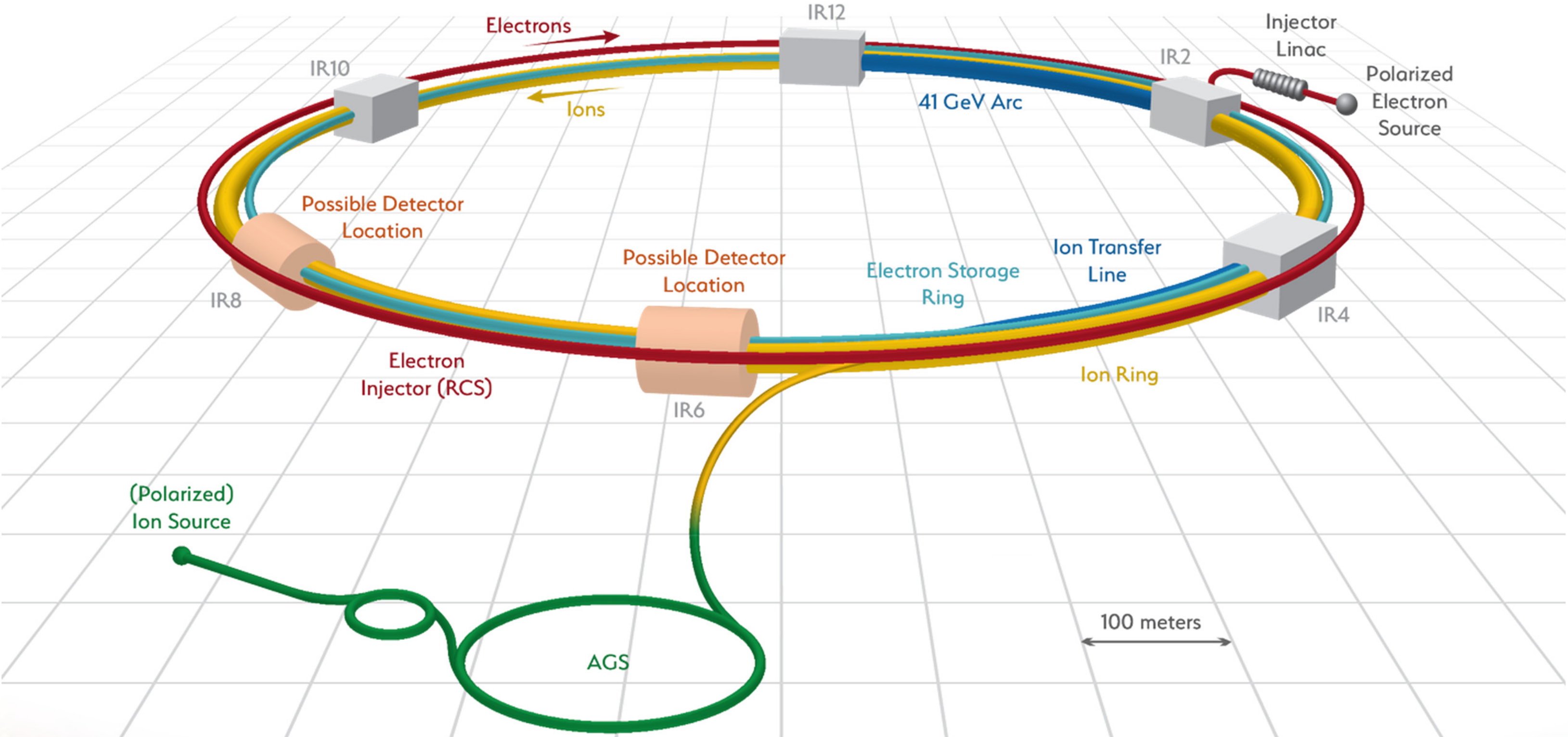


- Two superconducting storage rings
- 3.8km circumference
- Energy up to 255GeV protons, or 100GeV/n gold
- 110 bunches/beam
- Ion species from protons to uranium
- 60% proton polarization – world’s only polarized proton collider
- Exceeded design luminosity by factor 44 - unprecedented
- 6 interaction regions, 2 detectors
- In operation since 2001

Design Concept

- eRHIC is based on the RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure; needs only relatively few modifications and upgrades
- Todays RHIC beam parameters are close to what is required for eRHIC (except number of bunches, 3 times higher beam current, and vertical emittance)
- A 5 to18 GeV electron storage ring & its injectors are added to the RHIC complex ➔ E_{cm} = 29-141 GeV
- Design aims to meet the goals formulated in the EIC WHITE PAPER, in particular the high luminosity of $L = 10^{34}cm^{-2}s^{-1}$.
- Design is optimized under the assumption that each beam will have the parameters (in particular beam-beam tune shift) as demonstrated in collisions between equal species (HERA Concept).
- 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, not a technical limitation.

Facility layout



Electron complex to be installed in existing RHIC tunnel – cost effective

MOPRB093

Electron Storage Ring

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

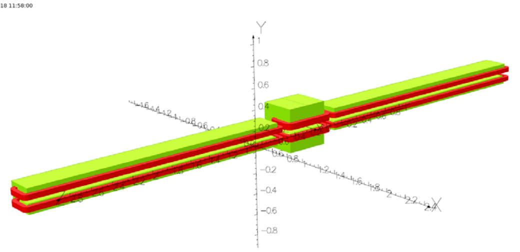
90º /cell for 18 GeV

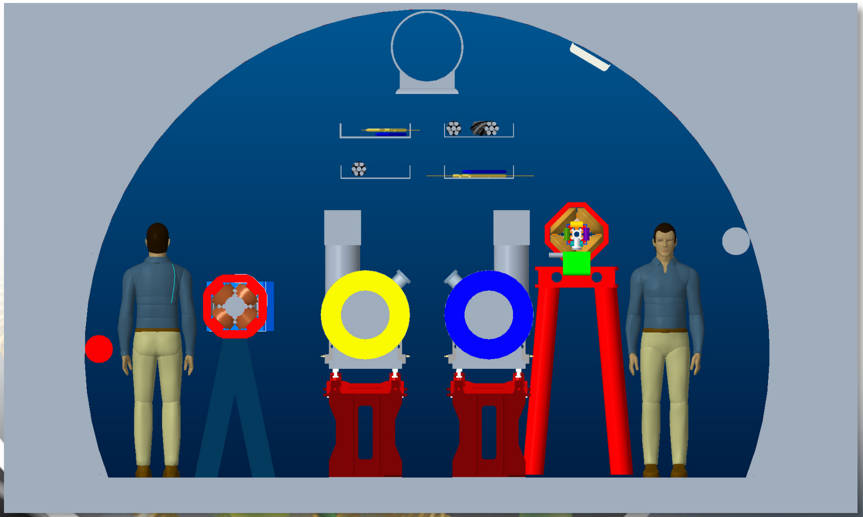
Super-bends for 5 to 10 GeV for emittance control

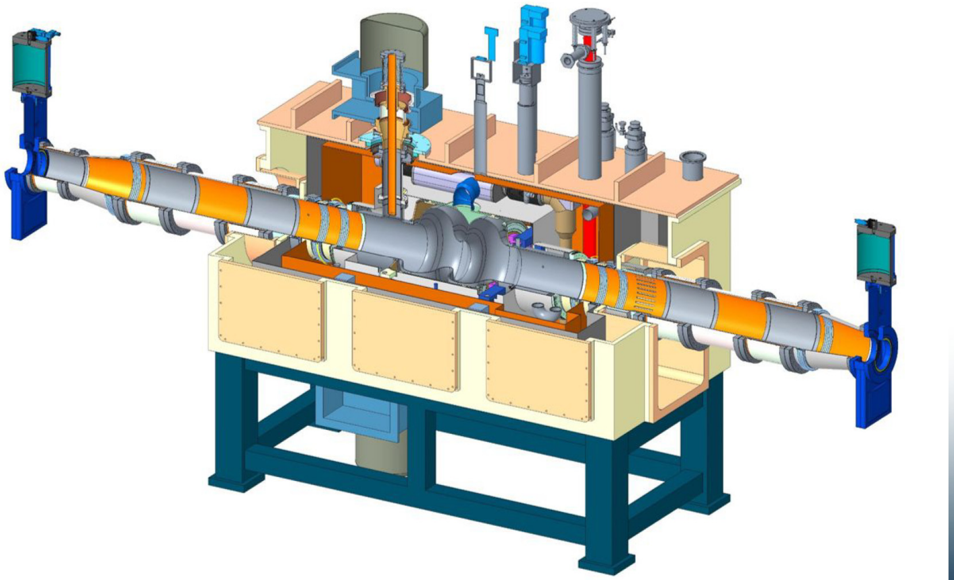
5 straight sections with simple layout, plus IR straight

Radiate approx. 10 MW for maximum luminosity parameters at 10GeV

➔ 14 superconducting 2-cell 591 MHz RF cavities







Hadron Storage Ring Modifications

WEPMP052
THPTS080
THPTS081

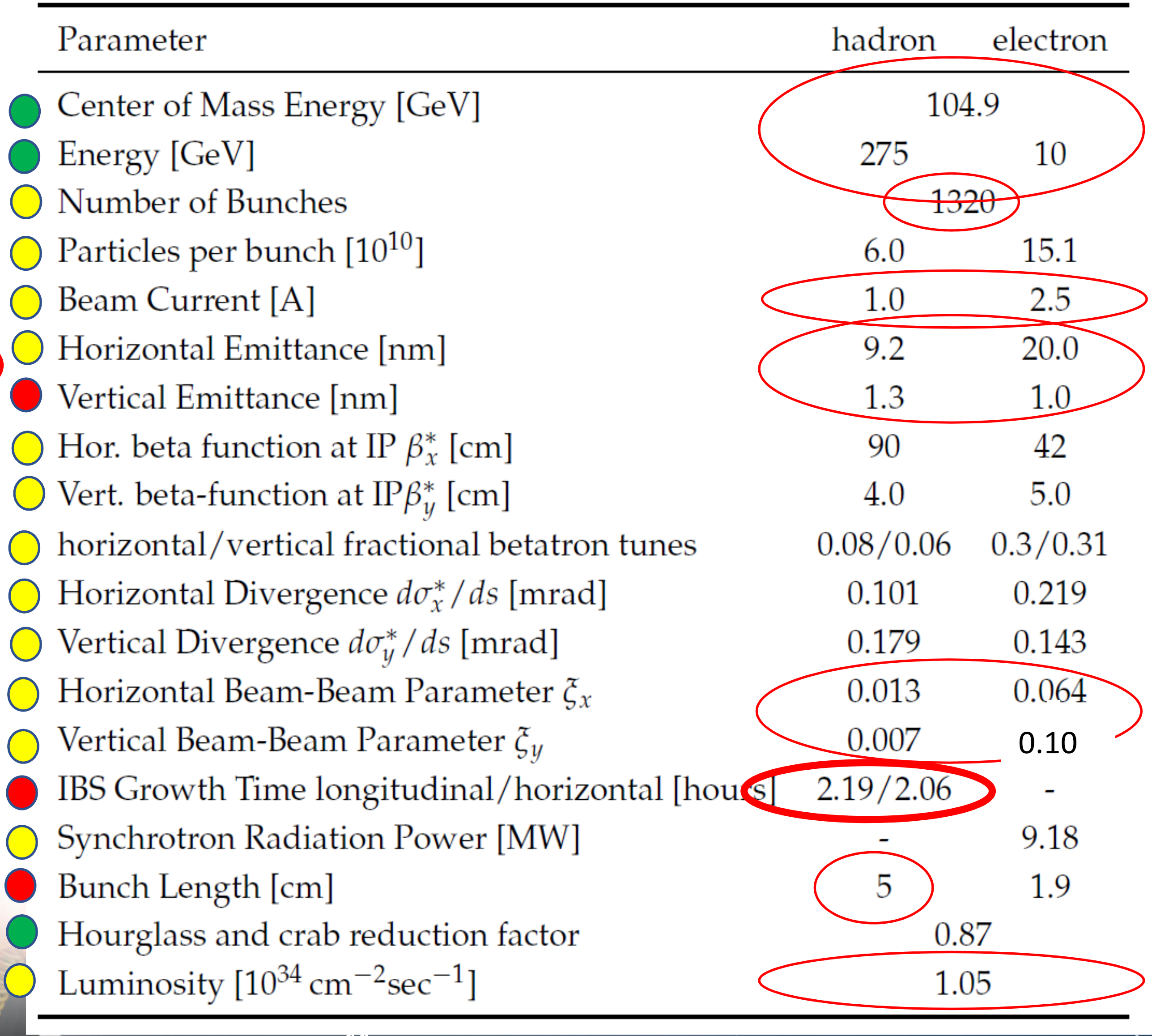
- YELLOW RHIC ring will serve as eRHIC hadron ring
- In-situ beam pipe coating with copper and amorphous carbon to improve conductivity and reduce SEY
- BLUE arc from IR6 to IR4 as transfer line extension to new injection area
- Remove energy-limiting DX separator dipoles
- BLUE inner arc between IRs 12 and 2 for circumference matching during 41 GeV low-energy operation
- (Energy range from 100 to 275 GeV can be covered by radial shift)

Maximum Luminosity Parameters

MOPRB072

- High beam currents
- Many bunches
- Large beam-beam tune-shift
- Flat beams
- **Need strong hadron cooling**
- Short hadron bunches
- 22 mrad crossing angle with crab cavities

➔ Large Luminosity



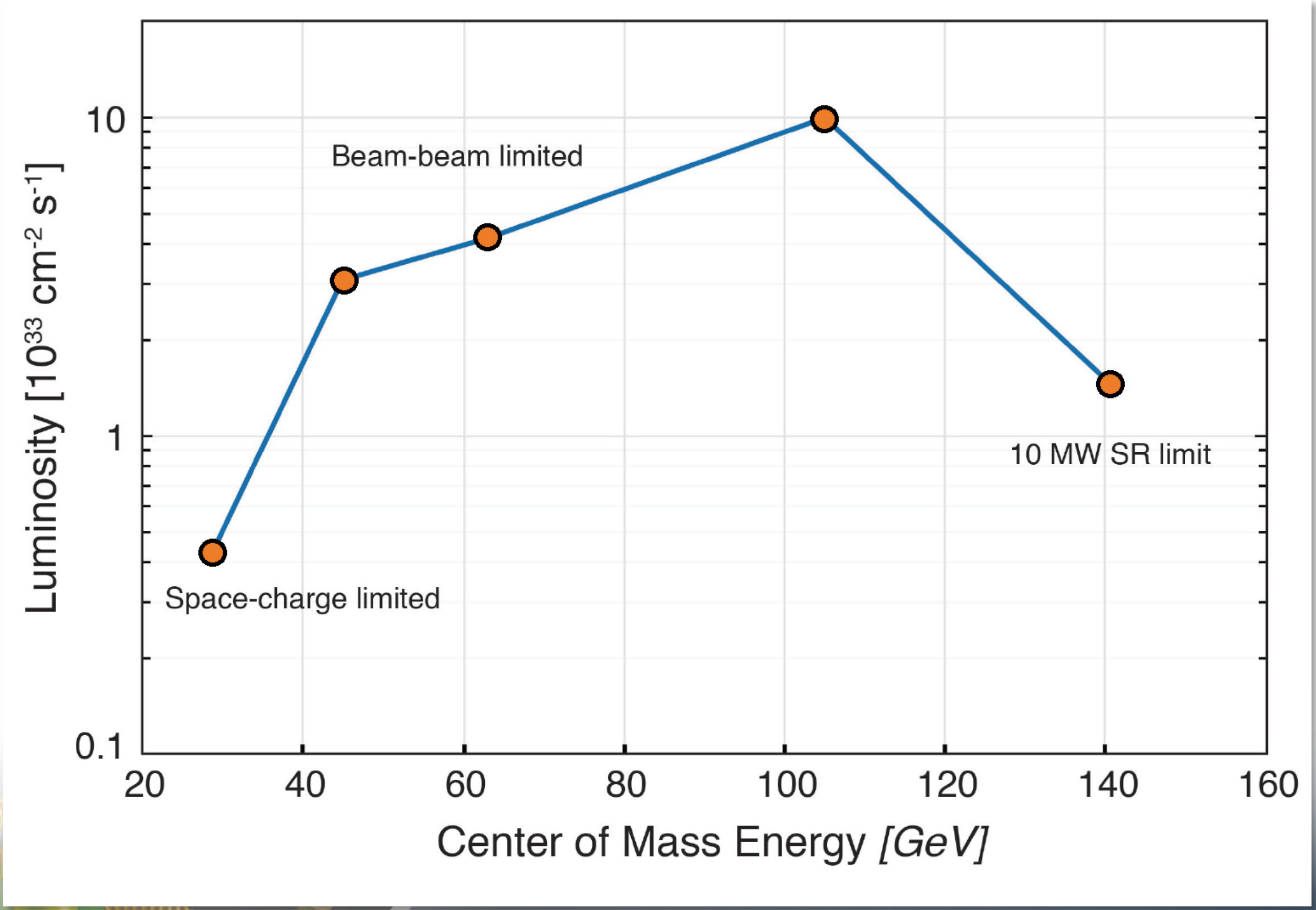
	Parameter	hadron	electron
🟢	Center of Mass Energy [GeV]	104.9	
🟢	Energy [GeV]	275	10
🟡	Number of Bunches	1320	
🟡	Particles per bunch [10^{10}]	6.0	15.1
🟡	Beam Current [A]	1.0	2.5
🟡	Horizontal Emittance [nm]	9.2	20.0
🔴	Vertical Emittance [nm]	1.3	1.0
🟡	Hor. beta function at IP β_x^* [cm]	90	42
🟡	Vert. 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	0.10
🔴	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	

🟢 No problem

🟡 Challenge

🔴 Difficult/R&D required

Luminosity versus Center-of-Mass Energy



Strong Hadron Cooling

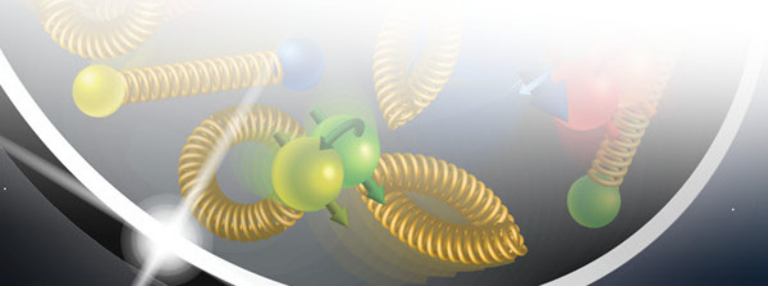
MOPRB085
MOPRB109

2 hour IBS emittance growth time requires strong hadron cooling

Several methods of strong hadron cooling have been studied:

- Bunched Beam Electron Cooling using an electron storage ring with wigglers
- Coherent electron cooling with FEL amplifier or micro-bunching amplifier – essentially a stochastic cooling concept using an electron beam as pick-up and kicker

➔ Both methods yield ~1h cooling time in simulations



Alternative Scheme Using Injection-Energy Hadron Cooling Only

- Use existing BLUE ring as full-energy injector (requires polarity reversal of quench protection diodes)
- Cool proton bunches at (or slightly above) 25 GeV injection energy in the BLUE ring – much easier due to strong energy dependence of cooling force
- Ramp BLUE ring and replace entire fill every ~ 15 minutes (<< IBS growth time of 2h). Average luminosity is >90 percent of peak luminosity

Mitigation of Strong Hadron Cooling Risk
(without using BLUE ring as injector, no cooling whatsoever)

Solution with L = $0.44 \cdot 10^{34} cm^{-2} s^{-1}$ and IBS growth rates of 9 h – same as present RHIC
IBS growth times determine luminosity lifetime and therefore useful store length

Moderate Luminosity Parameters for 10 GeV electrons on 275 GeV hadrons.

Parameter	hadron	electron
Center of Mass Energy [GeV]	105	
Energy [GeV]	275	10
Number of Bunches	660	
Particles per bunch [10^{11}]	1.05	3.
Beam Current [A]	0.87	2.48
Horizontal Emittance [nm]	13.9	20
Vertical Emittance [nm]	8.5	4.9
horizontal β_x^* at IP [cm]	90	63
Vertical β_y^* at IP [cm]	5.9	10.4
Horizontal Divergence $d\sigma/ds_x^*$ [mrad]	0.124	0.0.179
Vertical Divergence $d\sigma/ds_y^*$ [mrad]	0.380	0.216
Horizontal Beam-Beam Parameter ξ_x	0.015	0.1
Vertical Beam-Beam Parameter ξ_y	0.005	0.083
IBS Growth Time long/hor [hours]	10.1/9.2	-
Synchrotron Radiation Power [MW]	-	9.1
Bunch Length [cm]	7	1.9
Luminosity [10^{33} cm^{-2}sec^{-1}]	4.4	

Beam-Beam Physics

MOPRB081
MOPRB082
MOPRB090
MOPRB091

- Operate electron ring just above integer resonance to benefit from dynamic focusing and to stay away from half-integer spin resonance

Concerns:

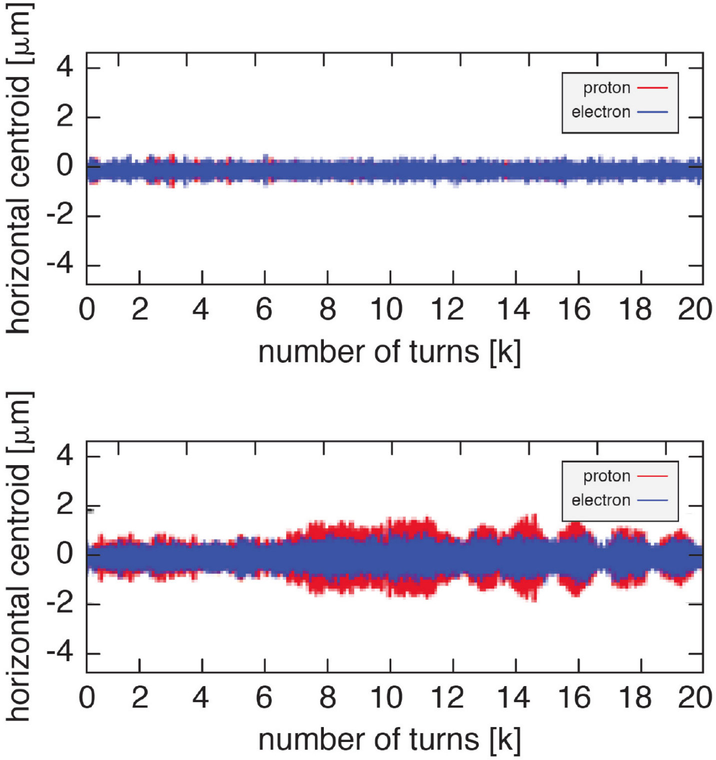
- Slow hadron emittance growth, examined using long term weak-strong simulations

➔ No evidence in head-on collisions; optimum choice of crab cavity frequency on-going

- Coherent beam-beam instability, examined by strong-strong simulations using several codes

➔ Threshold found at twice the design intensities

- No strong dependence of beam-beam parameter on radiation damping decrement found



Electron Storage Ring Polarization

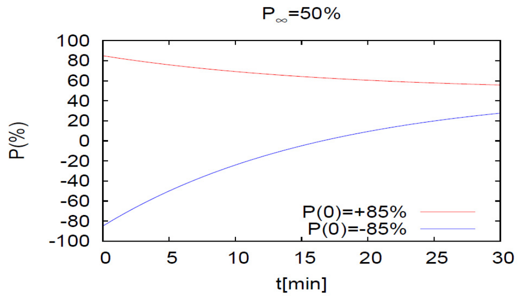
Need to store bunches with 85% initial polarization and spins parallel ↑ ↑ and spins antiparallel ↑↓ to guide field in the arc.

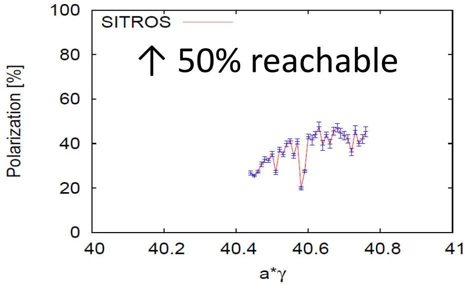
➔Need to replace bunches with parallel spin ↑ ↑ with a rate of up to 1/(5 minutes) because of Sokolov-Ternov depolarization (defines the injection chain – Rapid Cycling Synchrotron)

- Equilibrium polarization P_∞ = 50% in eRHIC sufficient

  to maintain polarization with <P> = 63% (spin ↑↓➔ 80%)
- Higher vertical tune better due to easier orbit control

  (beam-beam feasibility to be checked))
- Spin matching between rotators essential





↑ 50% reachable

Polarization with realistic machine errors

Conclusion:

- Polarization ok so far,
- More improvements expected by longitudinal spin matching, harmonic bumps, BBA, etc

Rapid Cycling Synchrotron with Spin Resonance Free Lattice as Full Energy Polarized Injector

- Both the strong intrinsic and imperfection resonances occur at spin tunes:
  - **$G\Upsilon$** = nP +/- Qy
  - **$G\Upsilon$** = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\Upsilon < 41$.**
- If we use a periodicity of P=96 and a tune Qy with an integer value of 50 then our first two intrinsic resonances will occur outside of the range of our spin tunes
  - **$G\Upsilon$**$1 = 50+\nu_y$ (ν_y is the fractional part of the tune)
  - **$G\Upsilon$**$2 = 96 – (50+\nu_y) = 46-\nu_y$
  - Also our imperfection resonances will follow suit with the first major one occurring at **$G\Upsilon$**2 = 96 – 50 = 46
- Spin tracking shows 98 percent polarization transmission with realistic magnet misalignments

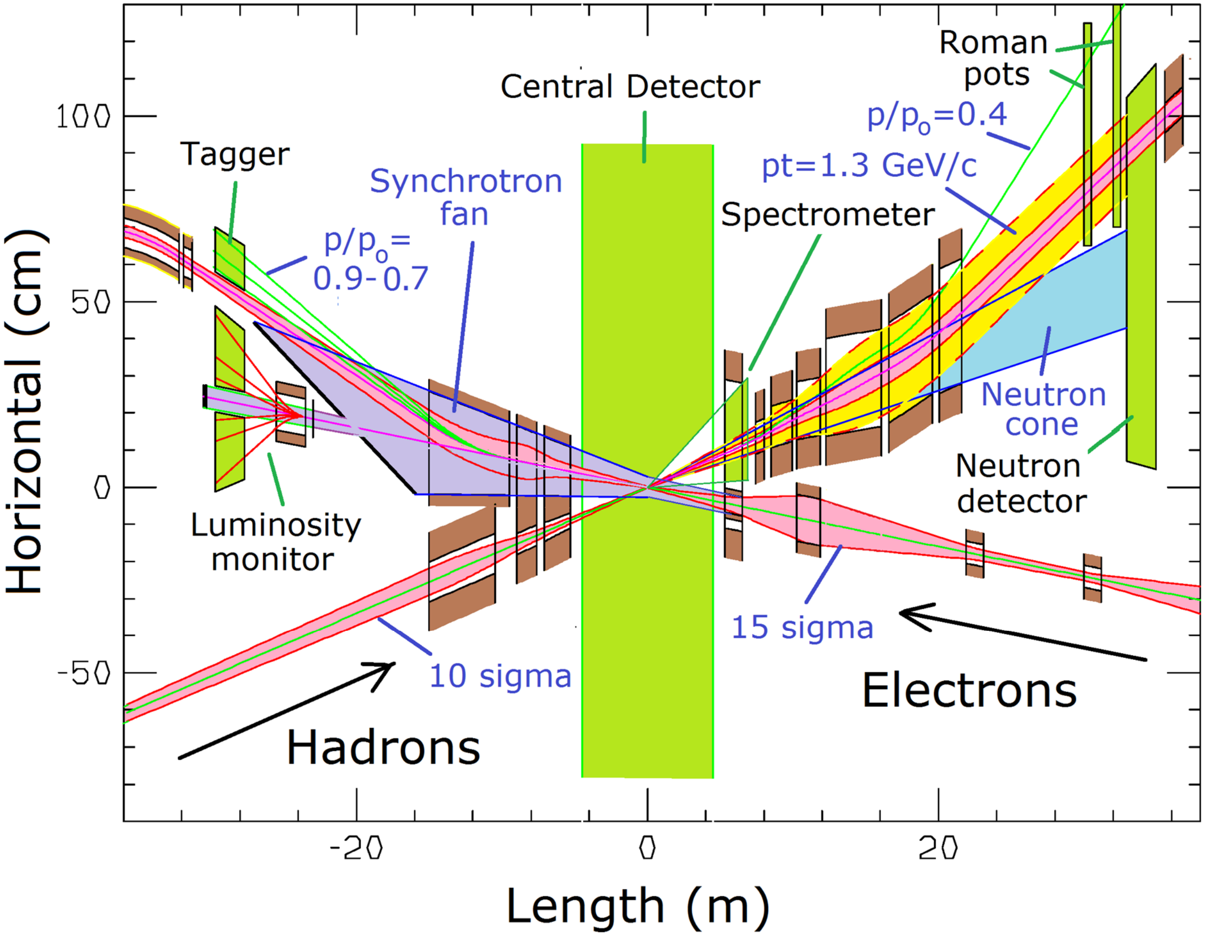
IR Layout

MOPRB100

High luminosity:
- Small b* for high luminosity
- Limited IR chromaticity contributions
- Large final focus quadrupole aperture

Physics requirements:
- Large detector acceptance
- Forward spectrometer
- No machine elements within +/- 4.5m from the IP
- Space for luminosity detector, neutron detector, “Roman Pots”

Multi-stage separation:
- Electrons from protons
- Protons from neutrons
- Electrons from Bethe-Heitler photons (luminosity monitor)



Summary

- eRHIC design reaches a peak luminosity of

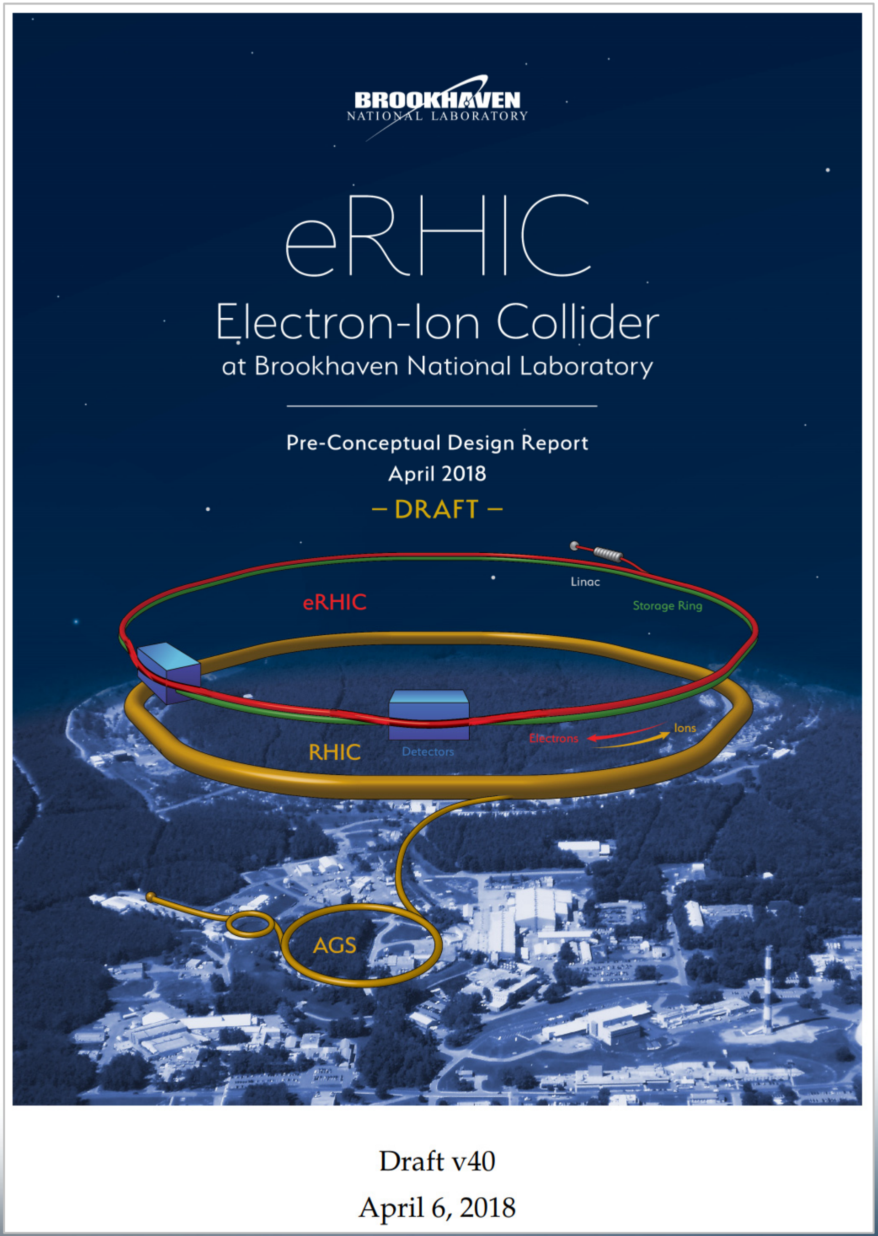
$$L= 1.05\cdot 10^{34} cm^{-2}s^{-1}$$

- However, this can only be achieved with strong hadron cooling, which is beyond state of the art (highest energy electron cooling so far was achieved in 8 GeV FNAL Recycler Ring, with DC beam), and is a topic of ongoing R&D.
- An alternative scheme using a full-energy injector exists that still needs electron cooling at 25 GeV – much easier but still beyond what has been achieved
- The corresponding design risk is mitigated by R&D, exploring variants for hadron cooling and by a fall-back solution with a respectable luminosity of

$$L= 0.44\cdot 10^{34} cm^{-2}s^{-1}$$

- eRHIC design has progressed very well and a tremendous amount of design work was accomplished.
- There are still critical beam dynamic issues which require more effort. They could have an impact on achievable luminosity but do not constitute a risk of missing the EIC White Paper Requirement

- Pre-Conceptual Design Report delivered to DOE on August 20, 2018 – soon to be published
- ~800 pages, with many subsystems already beyond pre-conceptual stage
- Active R&D program on strong hadron cooling
- Full-energy hadron injection scheme to be worked out in more detail



BROOKHAVEN
NATIONAL LABORATORY

eRHIC

Electron-Ion Collider
at Brookhaven National Laboratory

Pre-Conceptual Design Report
April 2018
– DRAFT –

Draft v40
April 6, 2018