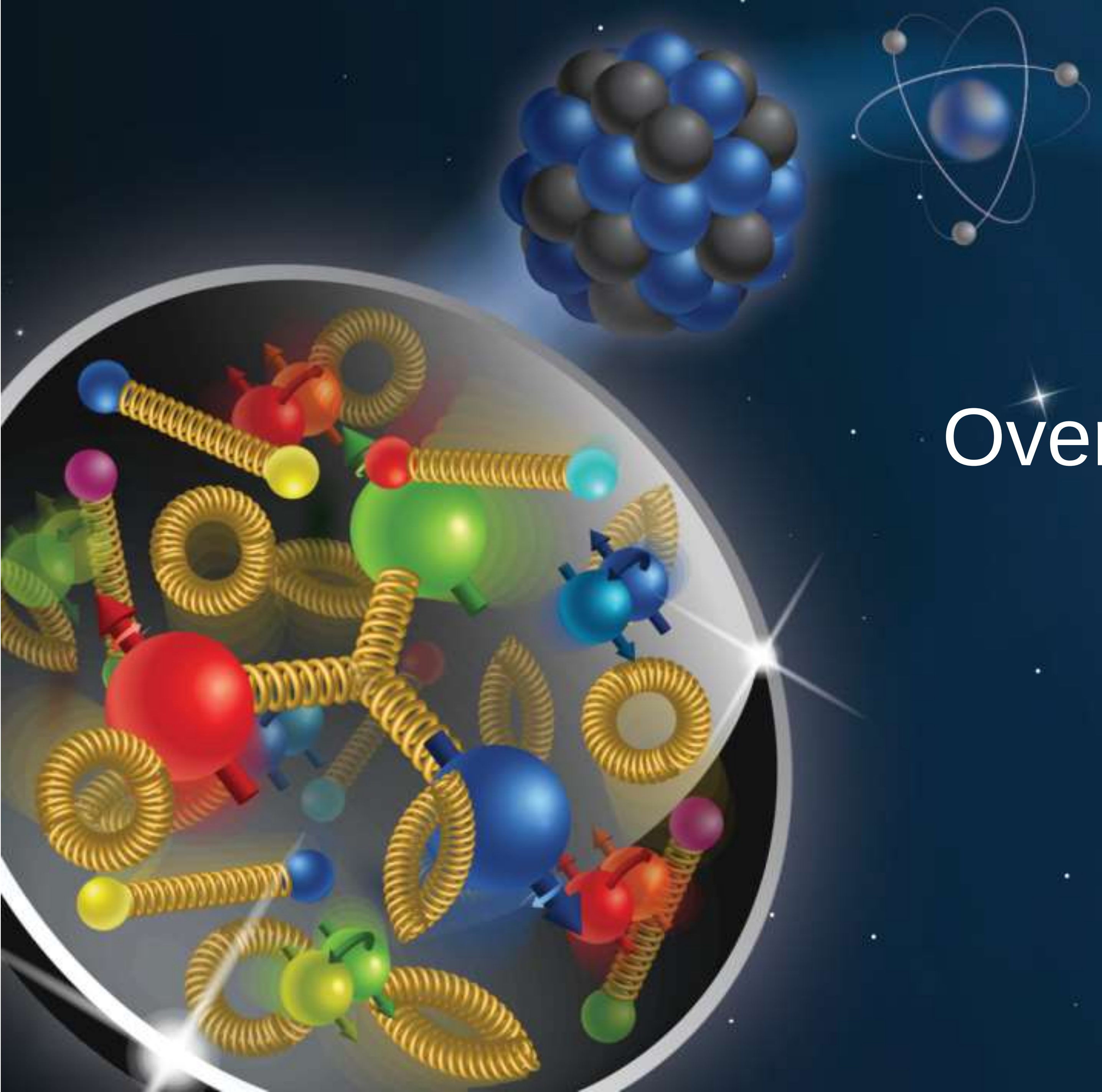


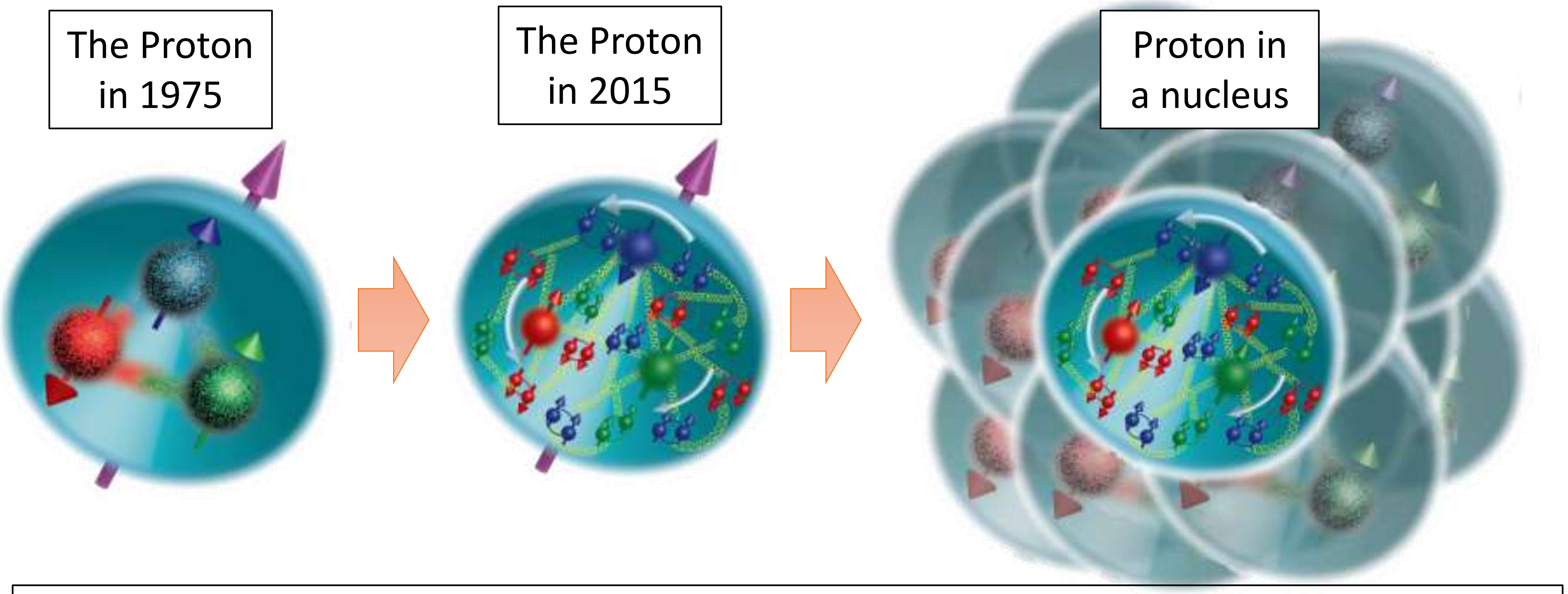
Overview of the Electron-Ion Collider (EIC)

Christoph Montag, BNL
FRIB ADS-APES Seminar
April 22, 2022

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY Office of Science

Modern view of the nucleus



Fundamental questions:

- How does the proton get its mass?
- How does the proton get its spin?
- How do protons and neutrons form nuclei?

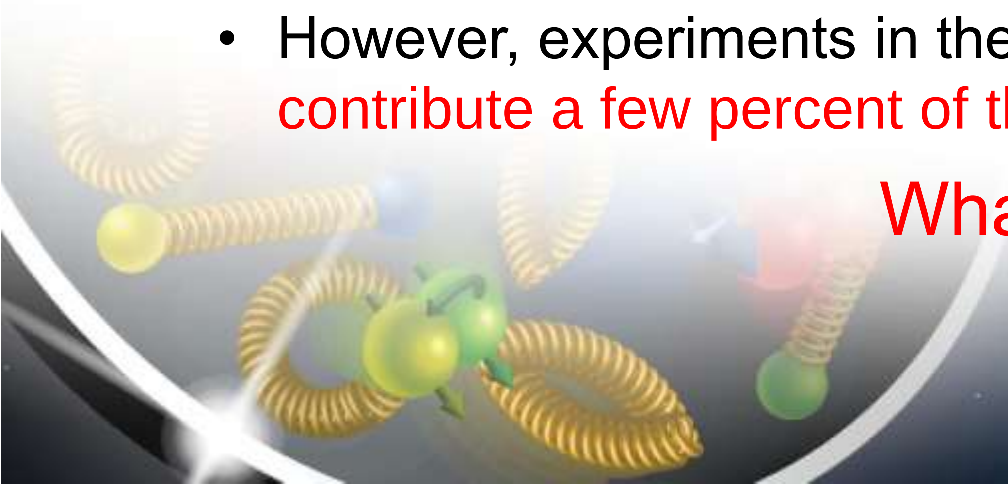
The Mass of the Proton

- Proton is composed of three “valence” quarks (two “up”, one “down” quark)
- Each of these three quarks has a mass of ~4.5 MeV/c
- But the proton has a mass of 938 MeV/c – almost two orders of magnitude more!

The Spin of the Proton

- Proton is composed of three “valence quarks”
- Each quark carries spin ½
- Proton carries spin ½ - two quarks with spin “up” and one with spin “down” would yield a net “up” spin of ½
- However, experiments in the 1980’s revealed that the three valence quarks only contribute a few percent of the proton spin!

What’s going on???

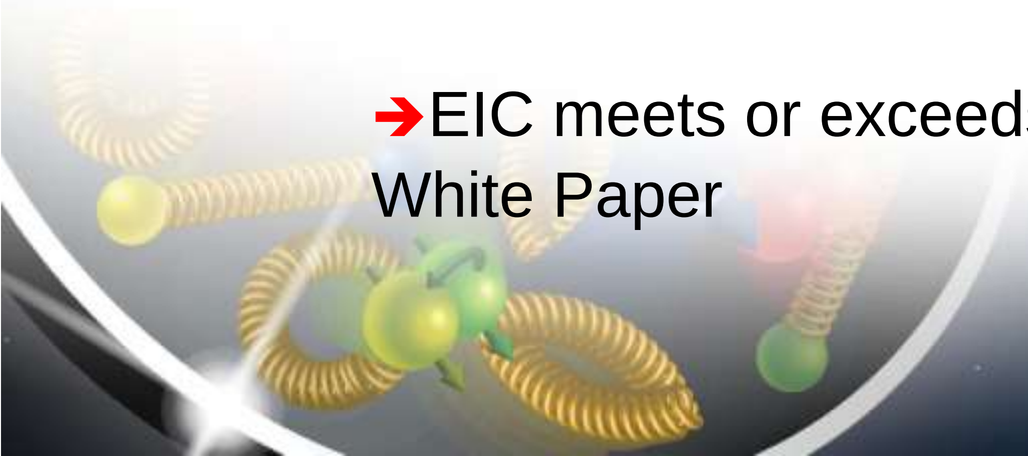


Let’s build a super-microscope – the EIC – and find out!

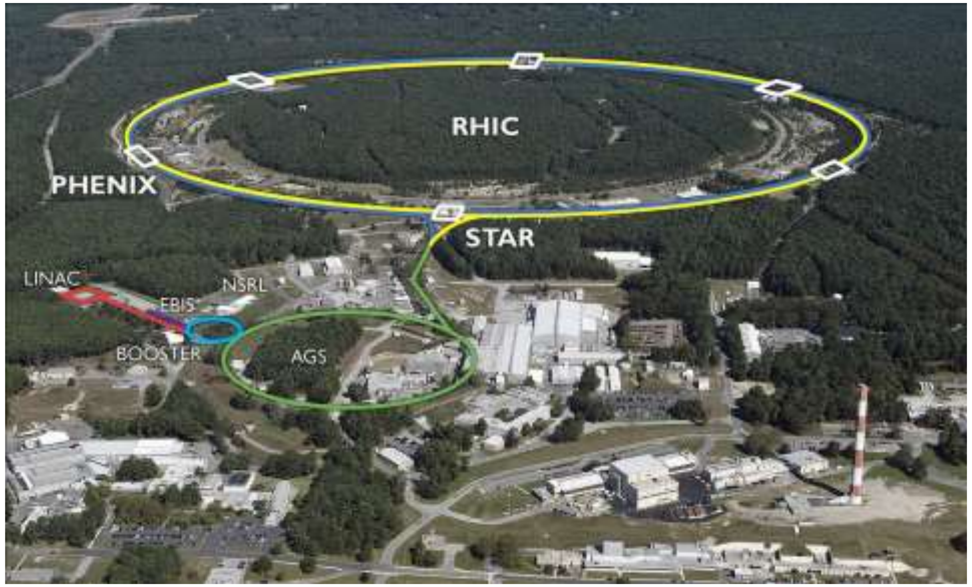
Requirements for an Electron-Ion Collider are defined in the White Paper:

- 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,…)

➔EIC meets or exceeds the requirements formulated in the White Paper



Relativistic Heavy Ion Collider (RHIC)

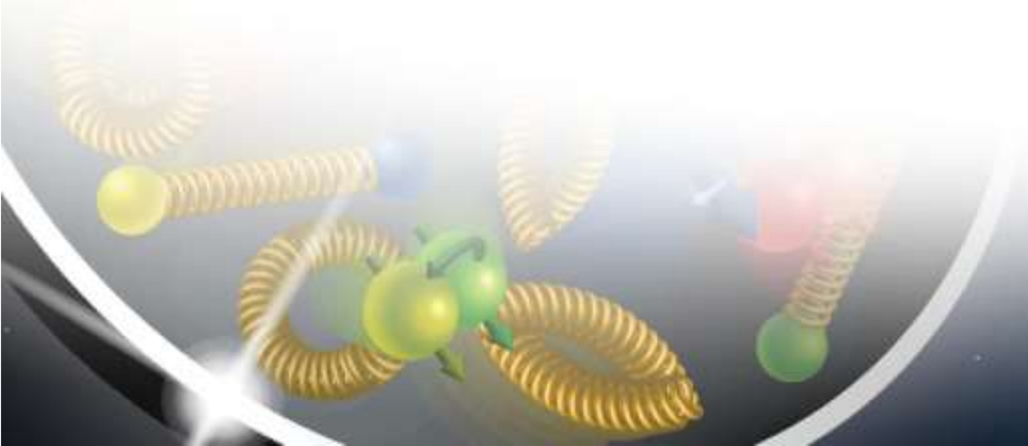


- Two superconducting storage rings
- 3.8km circumference
- Energy up to 255GeV protons, or 100GeV/n gold
- 110 bunches/beam
- Ion species from protons to uranium
- 60% proton polarization – world's only polarized proton collider
- Exceeded design luminosity by factor 44 - unprecedented
- 6 interaction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

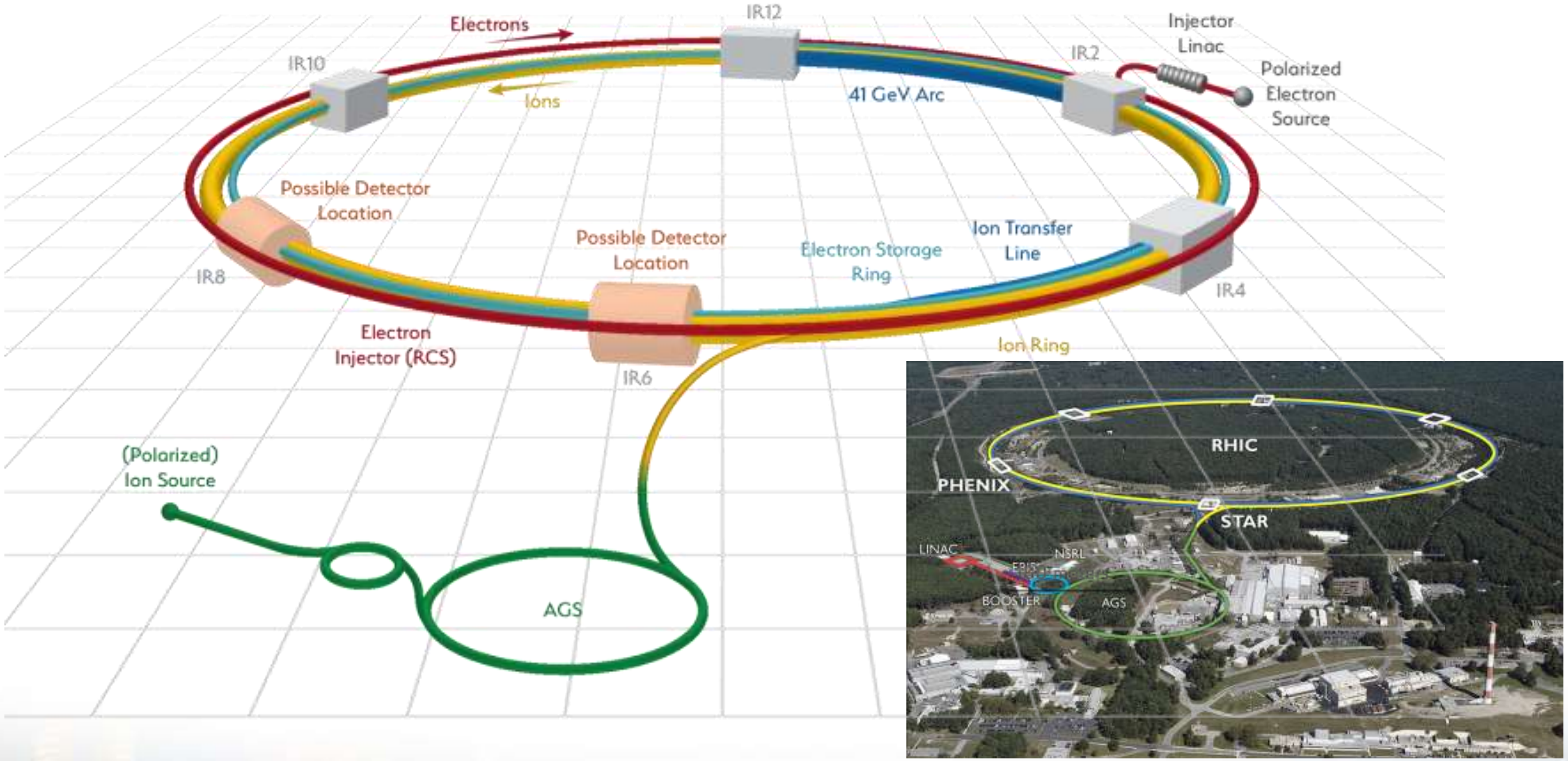
EIC is based on existing RHIC facility

EIC Design Concept

- EIC is based on the RHIC complex: Hadron Storage Ring (HSR), injectors, ion sources, infrastructure; needs only relatively few modifications and upgrades
- Todays RHIC beam parameters are close to what is required for EIC (except number of bunches, 3 times higher beam current, and vertical emittance)
- Add a 5 to18 GeV electron storage ring & its injector complex to the RHIC facility ➔ E_{cm} = 29-141 GeV
- Design and built a suitable interaction region
- EIC design aims to meet the goals formulated in the EIC WHITE PAPER, in particular the high luminosity of $L = 10^{34} cm^{-2}s^{-1}$ and high polarization



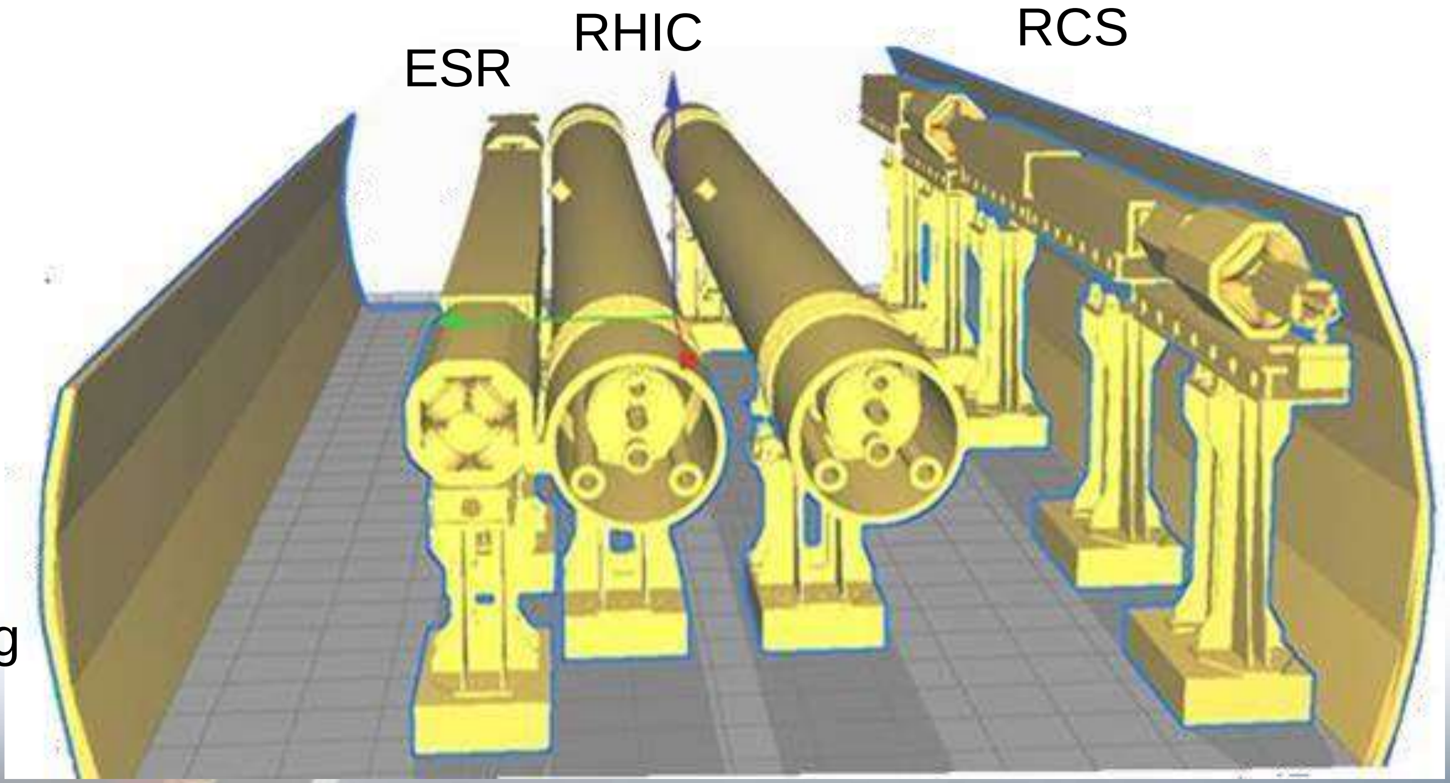
Facility layout



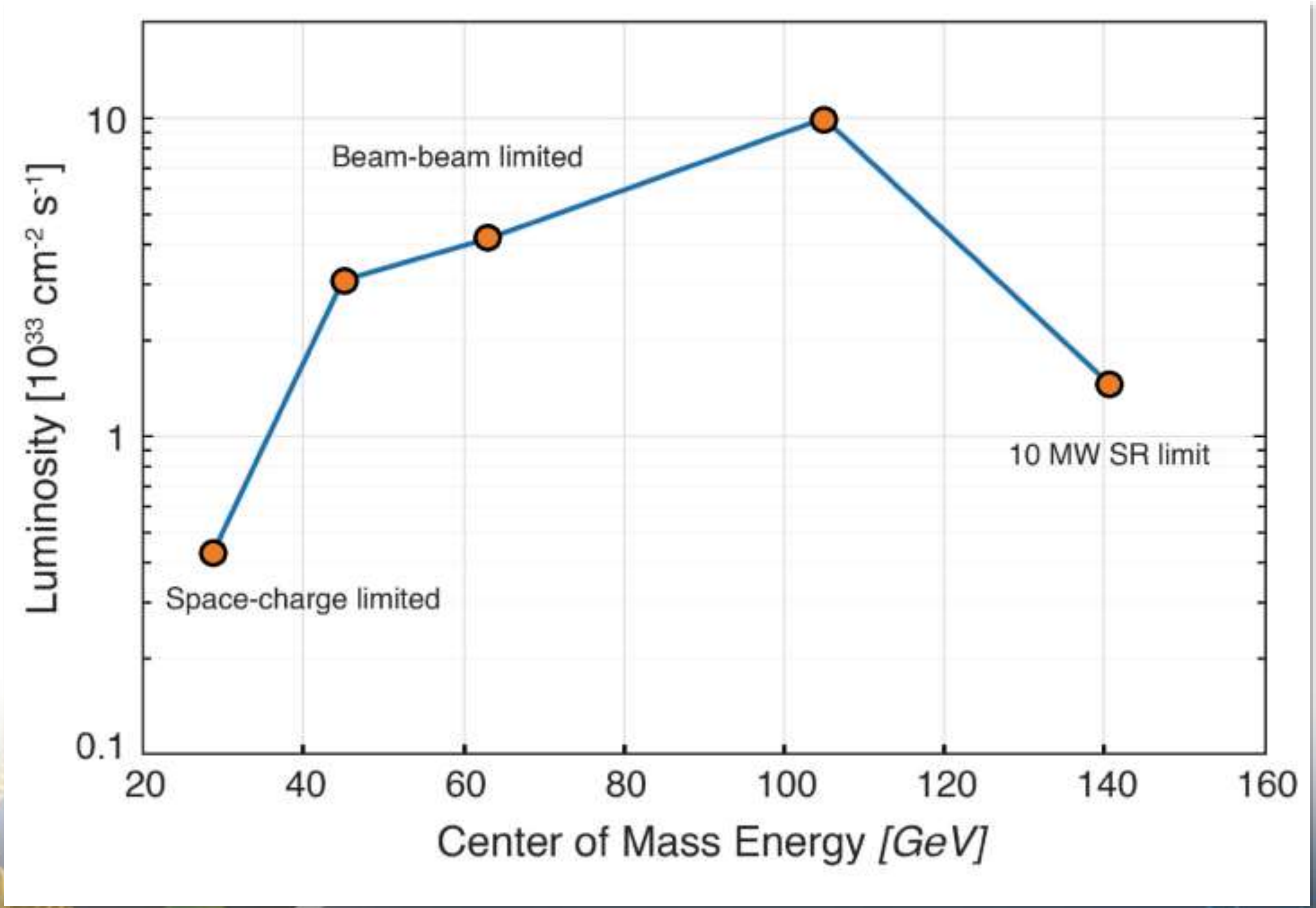
Electron complex to be installed in existing RHIC tunnel – cost effective

Tunnel Cross Section

All accelerators fit into the existing tunnel

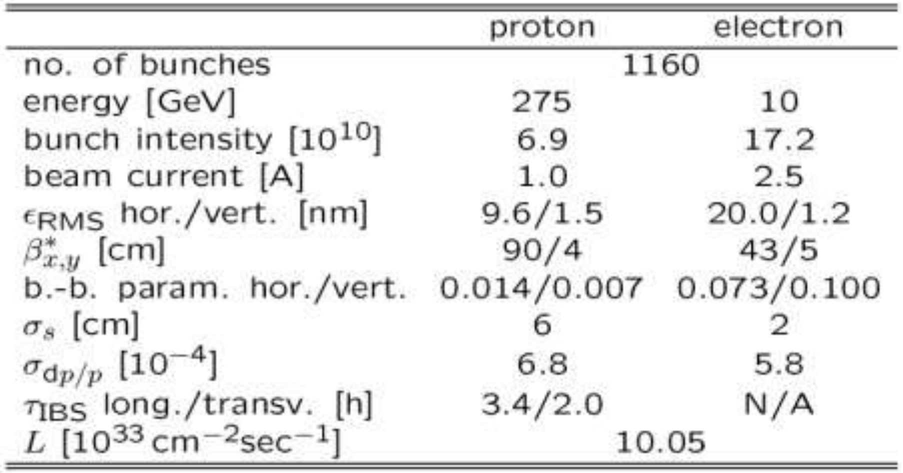


Luminosity versus Center-of-Mass Energy



Electron-Ion Collider

Parameters for Highest Luminosity



	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
b.-b. param. hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	2
$\sigma_{\text{dp}/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [$10^{33}\,\text{cm}^{-2}\text{sec}^{-1}$]	10.05	

- Hadron beam parameters similar to present RHIC, but smaller vertical emittance and many more bunches
- 2 hour IBS growth time requires strong hadron cooling
- Electron beam parameters resemble a B-Factory

Parameters optimized for high luminosity at high energy

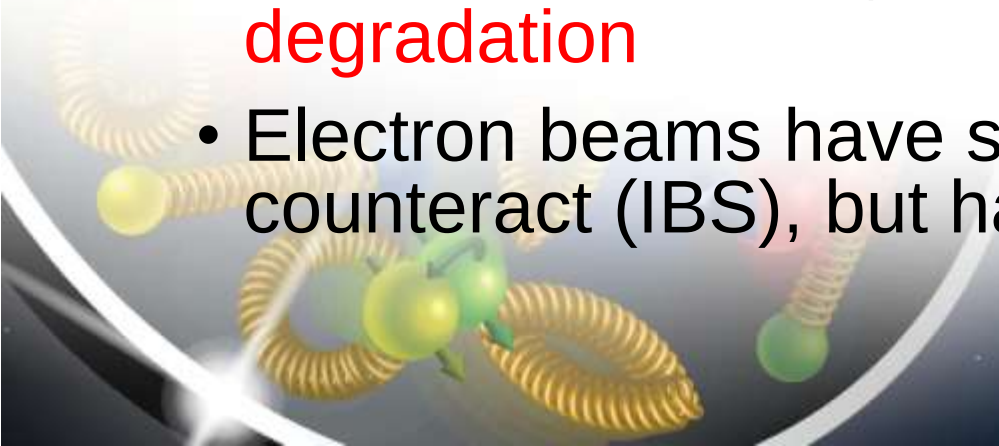
Alternative optimizations are possible, for example for high luminosity at low energy

Hadron Storage Ring Modifications

- EIC Hadron Storage Ring (HSR) to be composed of existing arcs of the two RHIC rings
- Insert sleeves coated with copper and amorphous carbon into superconducting magnet beam pipes to improve conductivity and reduce secondary electron yield (-> electron cloud)
- Add strong hadron cooling to counteract intra-beam scattering

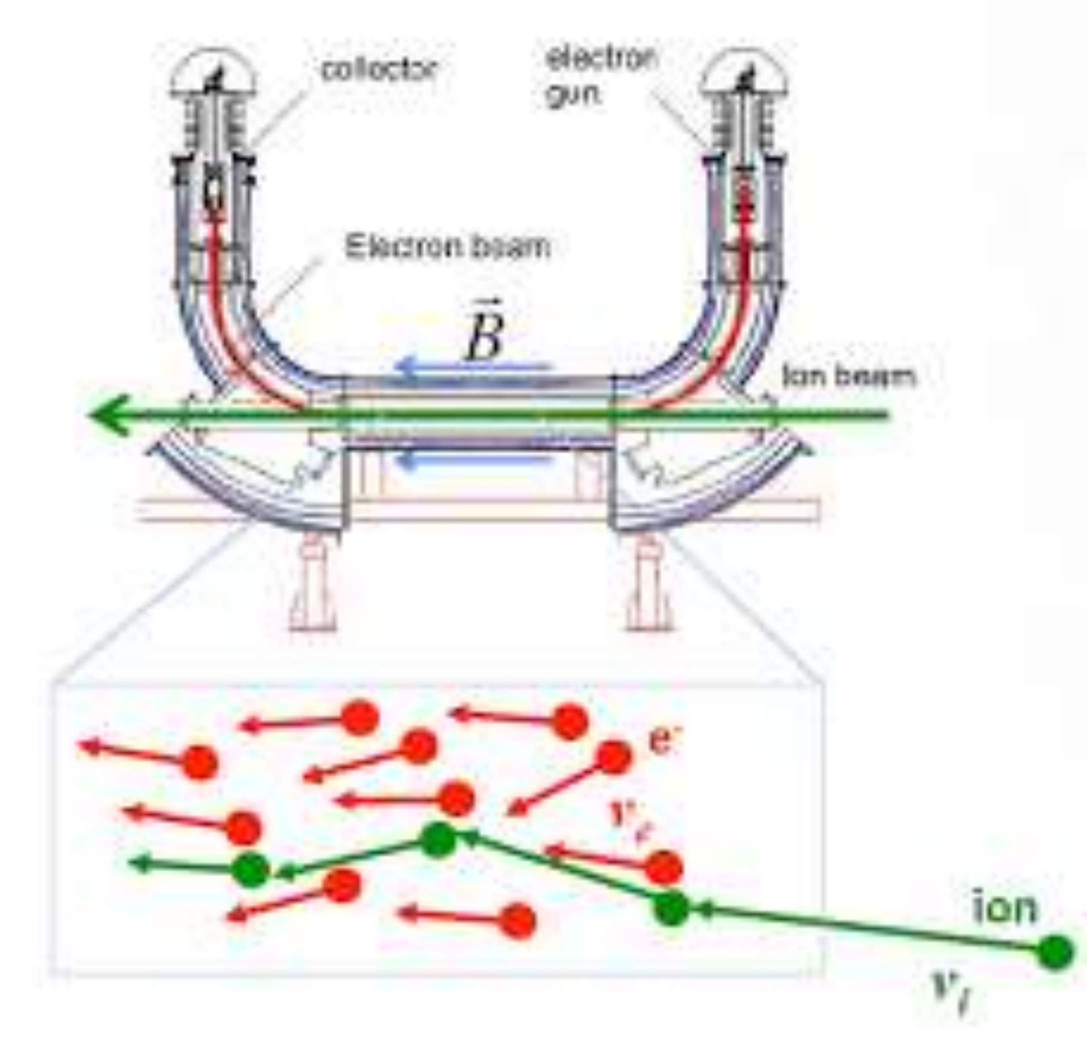
Intra-beam Scattering (IBS)

- Individual particles in the beam are focused by the magnets
- As a result, individual particles are constantly moving within the bunch
- As particles pass each other, they scatter off each other
- This multiple scattering results in emittance growth – the denser the bunch, the faster the growth
- If not counteracted, emittance growth results in luminosity degradation
- Electron beams have synchrotron radiation damping to counteract (IBS), but hadron beams need cooling



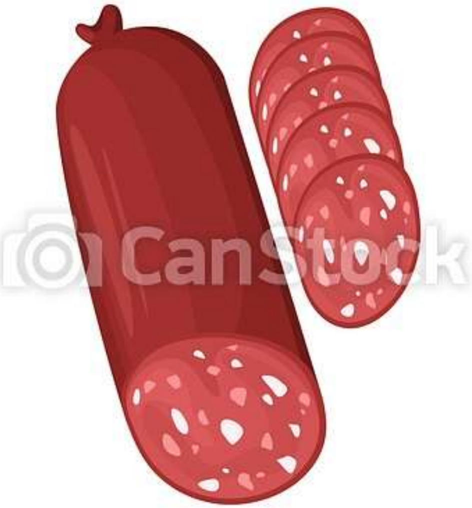
Hadron Beam Cooling

- Conventional electron cooling
  - Energy exchange between stored hadrons and an intense, “cold” (= low emittance) electron beam
  - Transverse cooling times scale as γ^5 - very challenging (but not impossible) above a few GeV



Hadron Beam Cooling

- Stochastic cooling
  - Measure the 3D offsets of small subsets of the particles in a bunch, and correct them a short distance downstream
  - Synchrotron motion in the rest of the ring leads to mixing of particles, such that each time these subsets consist of different particles with non-zero net offsets
  - Cooling time proportional to (system bandwidth)/(number of particles per bunch). Few GHz bandwidth leads to ~30 minutes cooling time for 10^9 particles. Suitable for heavy ions in EIC, but not for protons due to factor 100 higher bunch population



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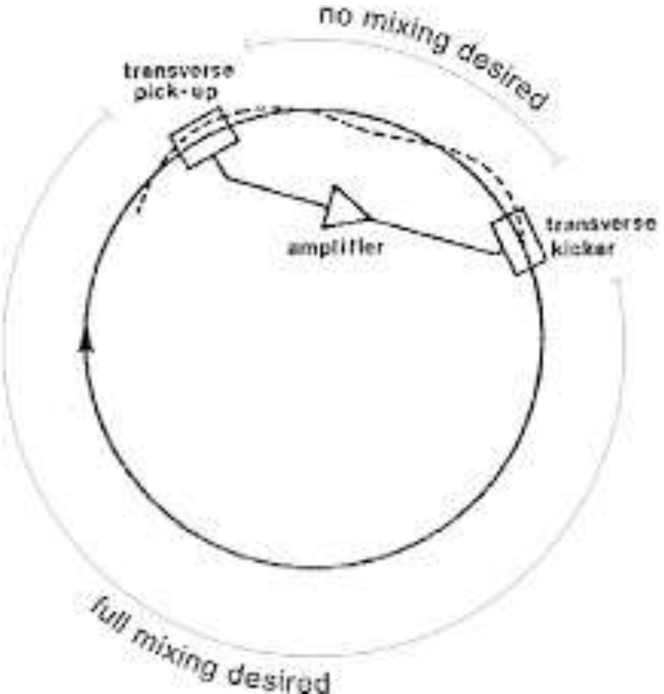
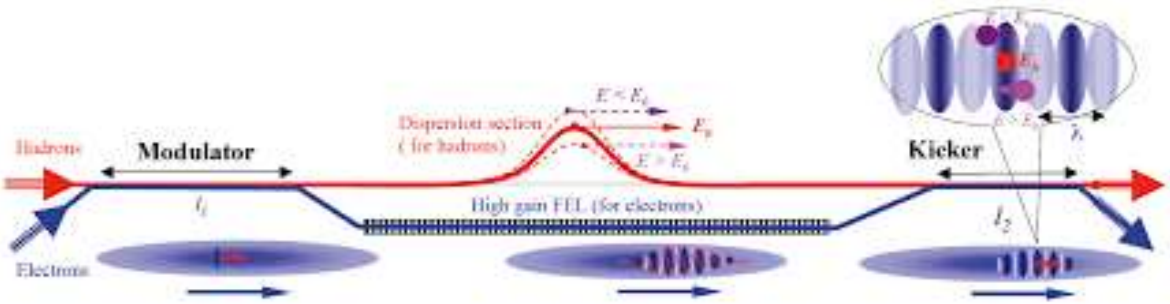


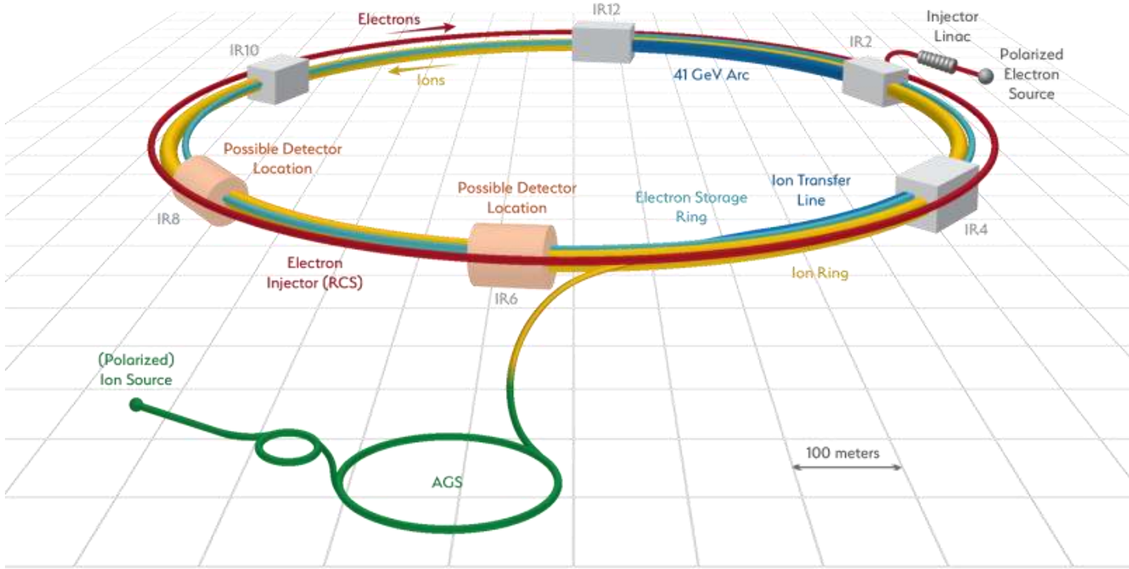
Hadron Beam Cooling



- Coherent electron cooling
  - Essentially, an ultra-high bandwidth stochastic cooling system
  - Instead of conventional pick-up, amplifier and kicker, and electron beam serves as pick-up and kicker
  - Hadron beam distribution is imprinted on electron beam
  - This imprinted signal is amplified, for example in a free-electron laser (FEL)
  - Electron beam is then merged again with the hadron beam (with the correct phase) to serve as a kicker and “correct” the hadron beam distribution
  - Bandwidth: tens of THz

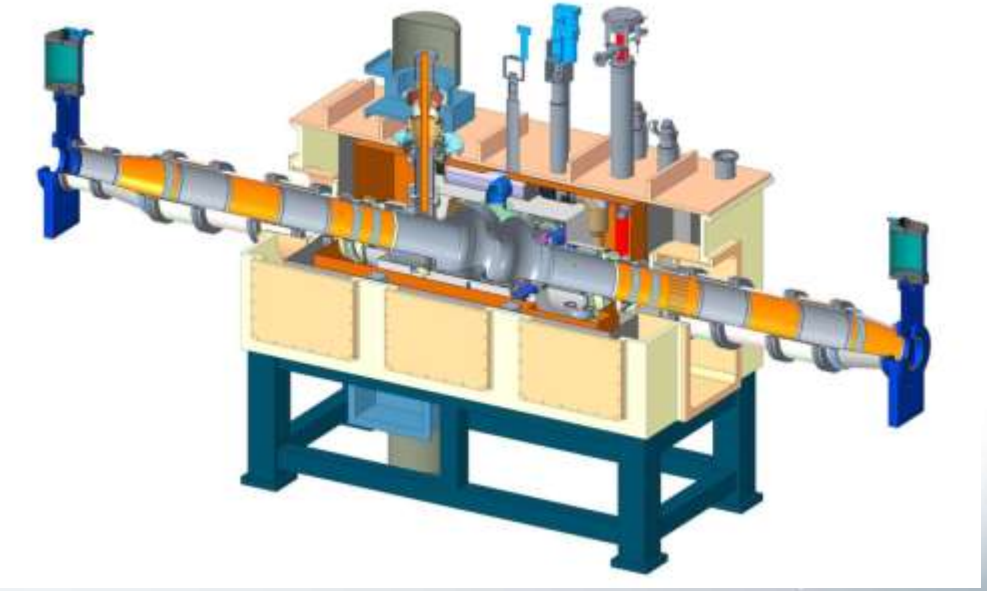
Collision Synchronization

- HSR needs to operate over a wide energy range
- Changing the beam energy in the HSR causes a significant velocity change
- To keep the two beams in collision, they have to be synchronized so bunches arrive at the detector(s) at the same time
- Synchronization accomplished by path length change
- Between 100 and 275 GeV, this can be done by a small radial shift – there is enough room in the beampipe
- For lower energies, use an inner instead of an outer arc as a shortcut. 90 cm path length difference corresponds to 41 GeV beam energy



Electron Storage Ring

- Electron Storage Ring (ESR) consists of six FODO-cell arcs, and six straight sections (IRs)
- Straight sections are used for:
  - Detectors (IR6 and IR8)
  - RF cavities (IR10)
  - Injection and cross-over with HSR (IR12)
  - Instrumentation (IR2)
  - Cross-over with HSR (IR4)



Emittance Control in the ESR

- EIC needs constant 24 nm emittance from 5 to 18 GeV, but equilibrium emittance in an electron storage ring depends on beam energy:

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

- Synchrotron radiation integrals:

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} \mathrm{d}s, \qquad I_2 = \oint \frac{1}{\rho^2} \mathrm{d}s$$

- “curly H” function depends on Twiss parameters:

$$\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta {D'}^2$$

- Changing the beam optics changes the emittance

- Remember:

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

- For a single FODO cell,

$$I_{5,\mathrm{FODO}} = \frac{\phi^5 (1 - \frac{3}{4}\sin^2\frac{\mu}{2} + \frac{1}{60}\sin^4\frac{\mu}{2})}{4L_p \sin^2\frac{\mu}{2} \sin\mu}$$

- Betatron phase advance μ per FODO cell is the “knob” to adjust the emittance
- 60 degrees at 10 GeV and 90 degrees at 18 GeV both yield ~24 nm
- How about 5 GeV?

Emittance at 5 GeV

- Again,

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

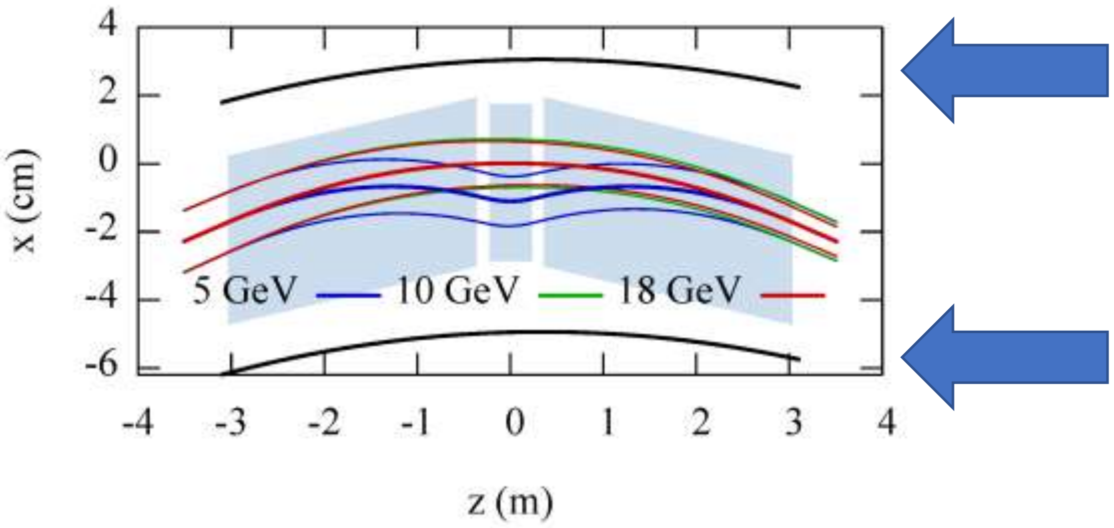
with

$$I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} \mathrm{d}s, \qquad I_2 = \oint \frac{1}{\rho^2} \mathrm{d}s$$

- Changing the bending radius changes the emittance – but how do we do that?

Super-Bends

- Arc dipoles to be split into 3 segments:



Vacuum chamber aperture

- Above 10 GeV, all segments powered uniformly
- At 5 GeV, short center dipole provides a reverse bend to reach desired 24 nm emittance
- In addition, the reverse bend also increases the radiation damping decrement, allowing for larger beam-beam parameter (see later slides)

Emittance Fine-Tuning

- FODO cell phase advances of 60 degrees at 5 and 10 GeV, and 90 degrees at 18 GeV result in almost the right emittance
- For good dynamic aperture, each sextupole needs a (nearby) partner 180 degrees away, such that nonlinear effects cancel
- This limits the choice of phase advances to values such as 45, 60, 72, or 90 degrees
- Deviating from those phase advances would give the right emittance, but would be detrimental for dynamic aperture

What else can be used to fine-tune the emittance?

Damping Partition Numbers

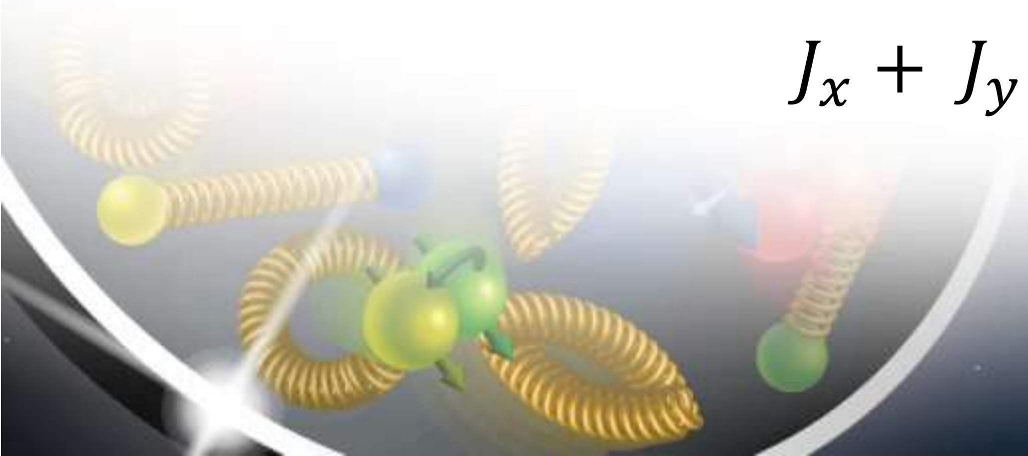
- Once more,

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2}$$

with damping partition number J_x horizontal

- Sum of horizontal, vertical and longitudinal damping partition number is constant,

$$J_x + J_y + J_z = 4$$



Manipulating Damping Partition Numbers

- Rewrite damping partition numbers as

$$J_x = 1 - D$$

$$J_y = 1$$

$$J_z = 2 + D$$

with

$$\mathcal{D} = \frac{\oint [\left[\frac{D}{\rho}\left(2k_{\mathrm{quad}} + \frac{1}{\rho^2}\right)\right] \mathrm{d}s}{\oint \frac{\mathrm{d}s}{\rho^2}}$$

Radial Shift

- In any lattice with separated-function magnets only (dipoles, quadrupoles, …), either

$$1/\rho = 0 \text{ (in quadrupoles)}$$

or

$$k_{quad} = 0 \text{ (in dipoles)}$$

so

$$D = 0$$

However, a radial shift makes every quadrupole a combined-function magnet where $1/\rho \neq 0$ and $k_{quad} \neq 0$

- As a result,

$$D \neq 0$$

$$J_x \neq 1$$

and the resulting equilibrium emittance is modified

EIC Electron Polarization

- Physics program requires bunches with spin “up” and spin “down” (in the arcs) to be stored simultaneously
- Sokolov-Ternov self-polarization would produce only polarization anti-parallel to the main dipole field
- Only way to achieve required spin patterns is by injecting bunches with desired spin orientation at full collision energy
- Sokolov-Ternov will over time re-orient all spins to be anti-parallel to main dipole field
- Spin diffusion reduces equilibrium polarization
- Need frequent bunch replacement to overcome Sokolov-Ternov and spin diffusion

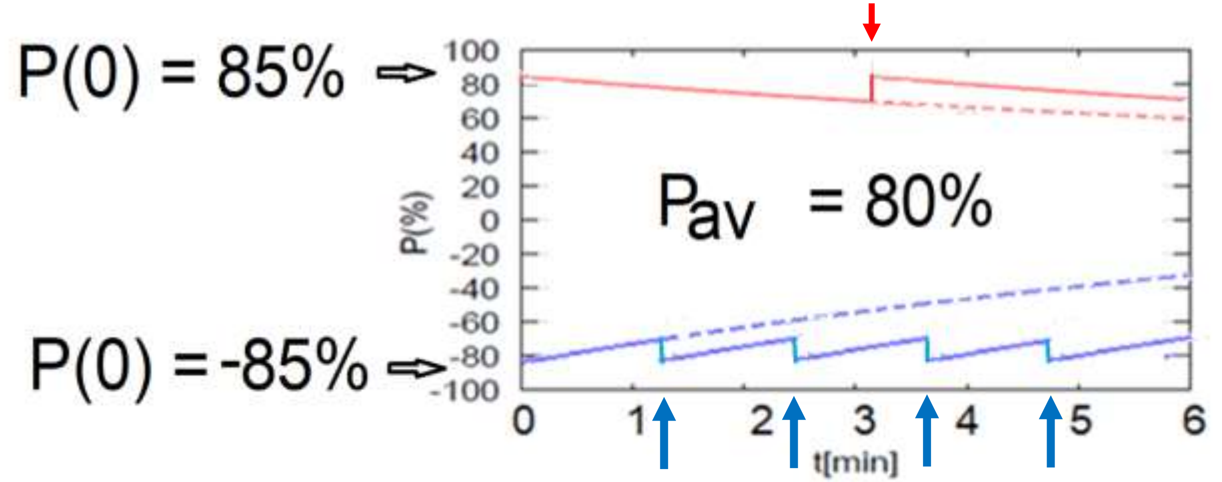
High Average Electron Polarization

- Frequent injection of bunches with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50%
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 2Hz

B P ↓↓ Refilled every 1.2 minutes

B P ↓↑ Refilled every 3.2 minutes

Re-injection



P_∞= 30% (conservative)

Re-injections

Rapid Cycling Synchrotron as Injector for ESR

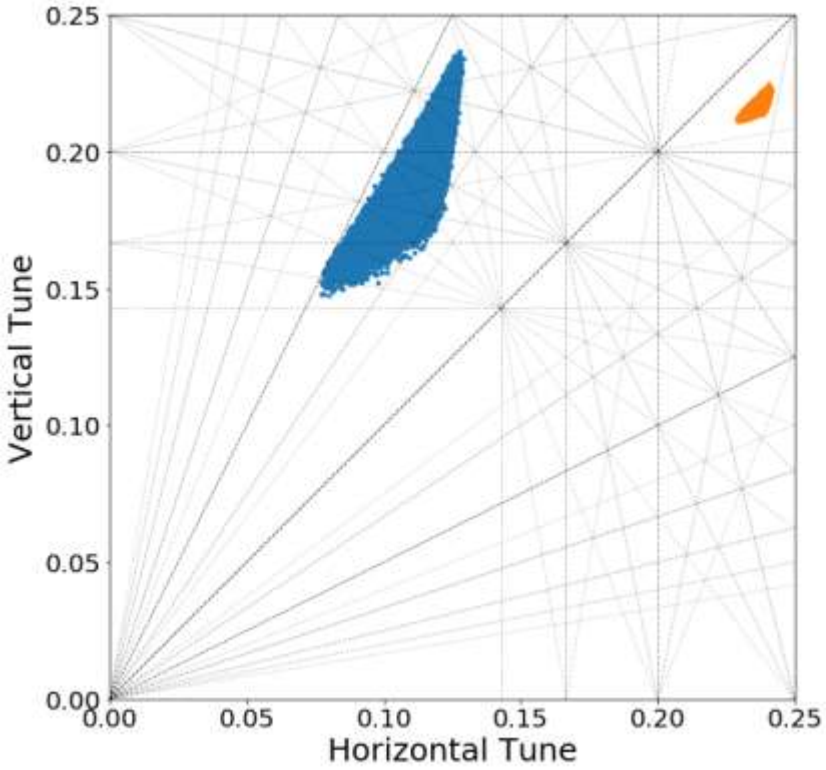
- Both the strong intrinsic and imperfection resonances that cause depolarization occur at spin tunes:
  - **GϒＹ** = nP +/- Qy
  - **Gϒ** = nP +/- [Qy] (integer part of tune)
- To preserve polarization, these resonances need to be avoided
- To accelerate from 400 MeV to 18 GeV requires the spin tune 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 **Gϒ**2 = 96 – 50 = 46
- Spin tracking shows 98 percent polarization transmission with realistic magnet misalignments

Beam-beam Interaction

- Beam-beam force is highly non-linear:

$$F_z(x,y) = \frac{Ne^2 z}{2\pi\epsilon_0}\frac{z}{r^2}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right], \qquad r^2 = x^2+y^2, \qquad z = x, y$$

- Particles in the core experience stronger focusing than particles in the transverse tails
- Amplitude-dependent focusing results in betatron tune spread
- Resulting tune footprints need to be placed in-between strong resonance lines

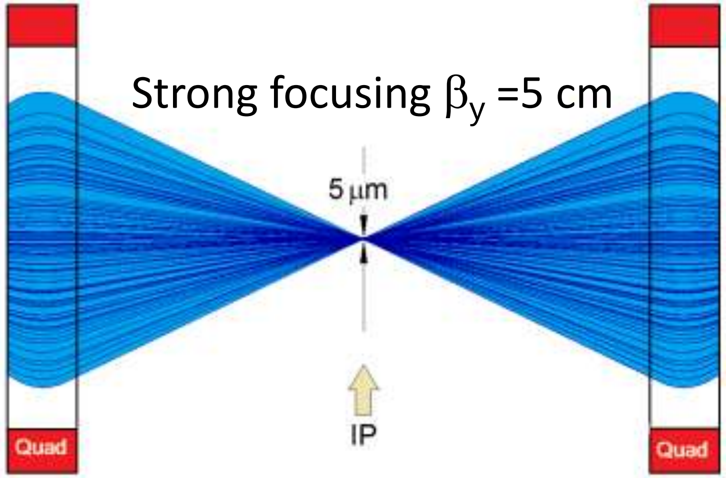


- Synchrotron radiation damping allows for larger tune spread for electrons than for hadrons

Luminosity and Focusing

- Luminosity ~ 1/(spot size)
- A smaller spot size at the IP means more luminosity

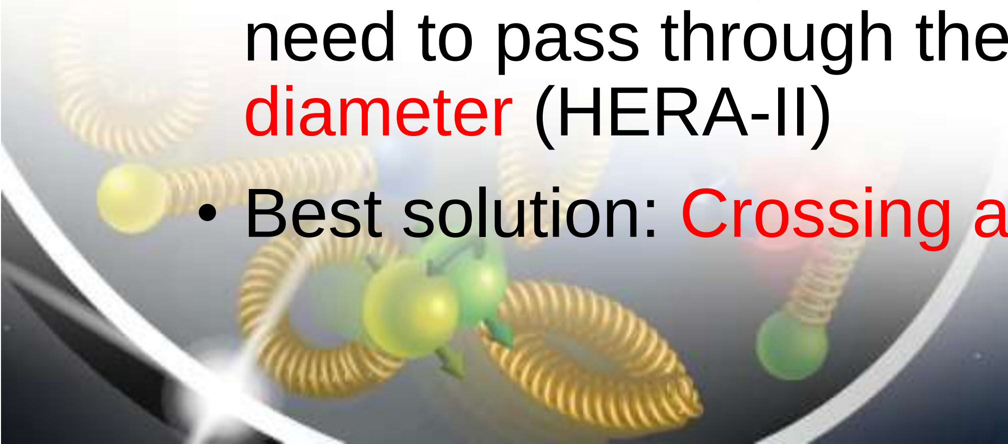
- At the IP, (beam size)X(beam divergence)= const. in each plane (emittance)
- For a given beam (= fixed emittance), a smaller IP beam size means larger divergence
- A larger beam divergence leads to a larger beam size at the nearest focusing magnets – (size at magnet)=(divergence)X(distance)
- Magnets need to have larger aperture while gradient (= focusing strength) remains the same – peak field at magnet poles is technically limited


Strong focusing β_y =5 cm

Focusing elements for both beams need to be as close as possible to the IP

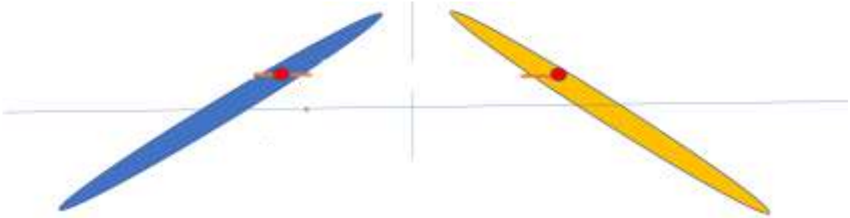
Crossing angle collisions

- Beam energies of electrons and hadrons are vastly different in EIC
- Focusing elements for electrons would have only little effect on hadrons, while hadron magnets would overfocus electrons
- Beams need to be separated into their respective focusing systems as close as possible to the IP
- A separator dipole would have to deflect the (“weaker”) electrons and would therefore generate a wide synchrotron radiation fan that would need to pass through the detector – requires large beam pipe diameter (HERA-II)
- Best solution: Crossing angle collisions!



Crossing Angle and Luminosity

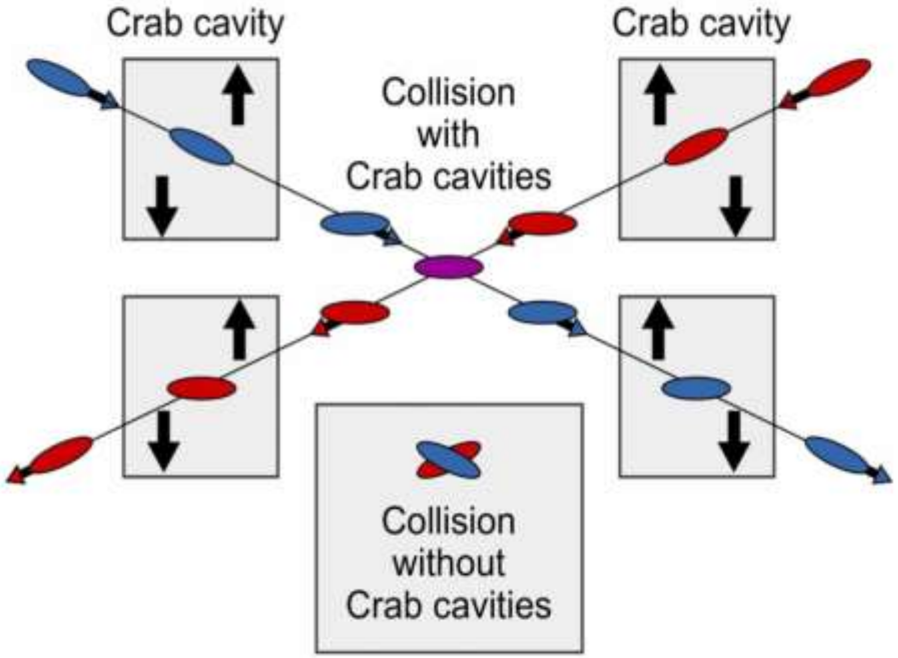
- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



- Long (~+/-6 cm), skinny (100 um) bunches colliding at an angle have very little overlap
- With 25 mrad crossing angle, each particle can only interact with a +/-4 mm thick slice of the +/-6 cm long oncoming bunch

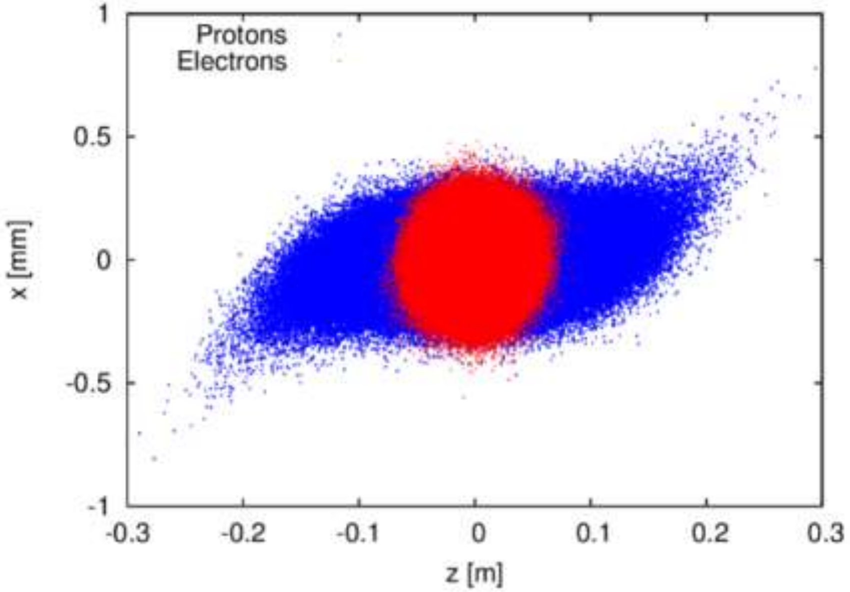
Crab Crossing to the Rescue

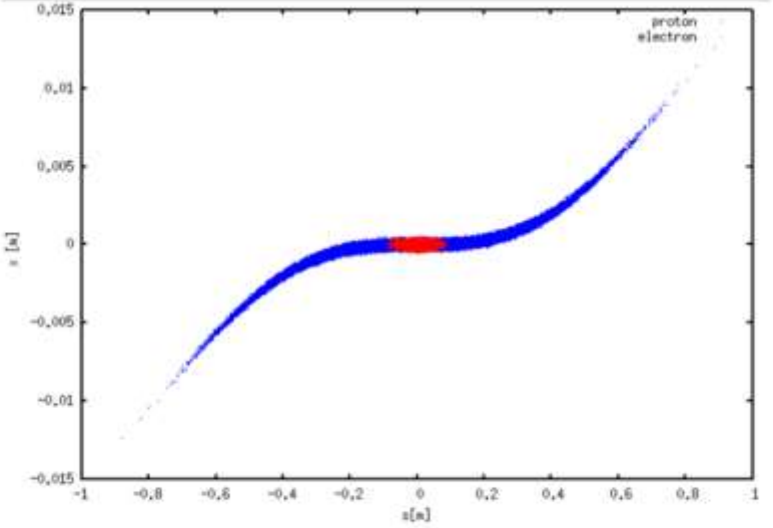
- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction



Nobody’s perfect

- Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
- Long hadron bunches are “S”-shaped during collision
- Distorted shape results in transverse offset between electron bunch and head and tail of proton bunch – reduced luminosity and severe beam dynamics effects
- Longer bunches, skinnier bunches, or increased crossing angle all make this worse
- Higher harmonic crab cavities can “straighten out” the kick and therefore the bunch, but at a cost – space and money
- EIC already plans on 197 MHz crab cavities, plus 394 MHz harmonics
- 197 MHz as low as technically feasible (niobium sheets for cavity production, cavity size in tunnel)



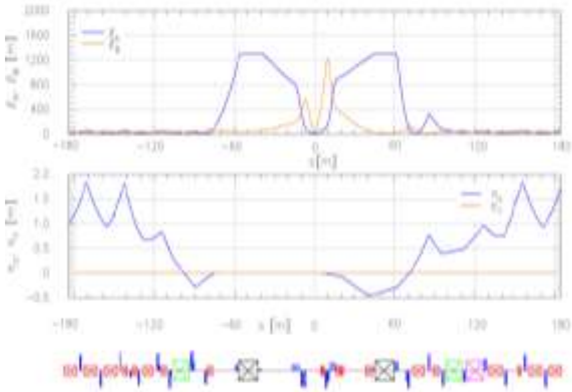


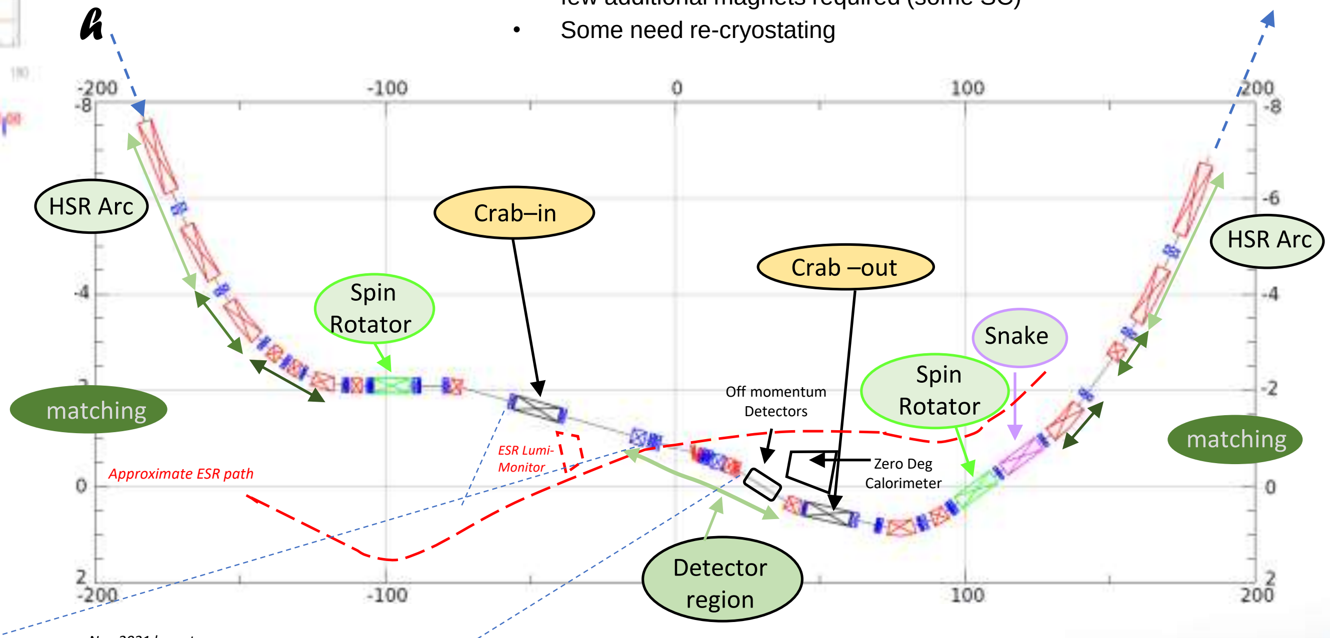
Spin Rotators

- Both electrons and protons will have longitudinal polarization at the IP
- Hadron spin rotators will be taken from present RHIC (helical dipoles)
- Electron spin rotators are based on solenoid magnets with subsequent dipole – large chunk of beamline with fixed geometry, challenging to fit into existing tunnel

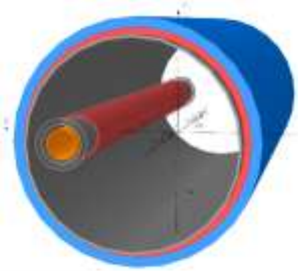
HSR layout in IR6

- Forward and rear hadron lattice matched into RHIC
    - Snake at correct angle
    - Beta = 1300m at crab cavities
        - Hor. phase advance 90º
    - Matching Magnets
        - Mostly repurposed RHIC magnets
        - few additional magnets required (some SC)
        - Some need re-cryostating



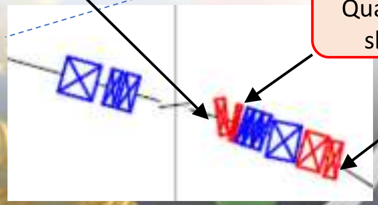


Nov 2021 layout



B0pF spectrometer

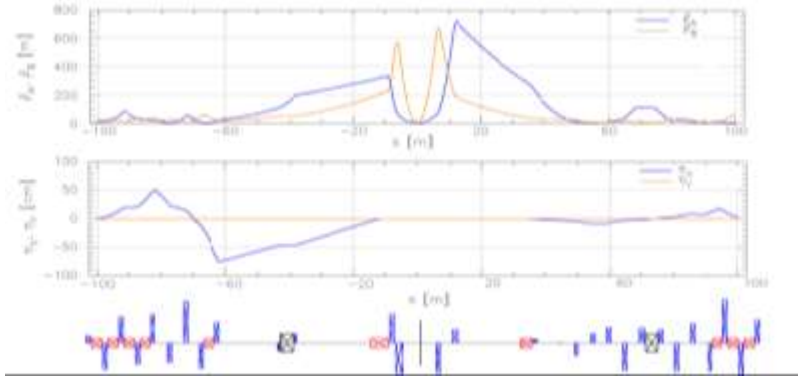
3 Dipoles and 3 Quadrupoles in one shared cryostat

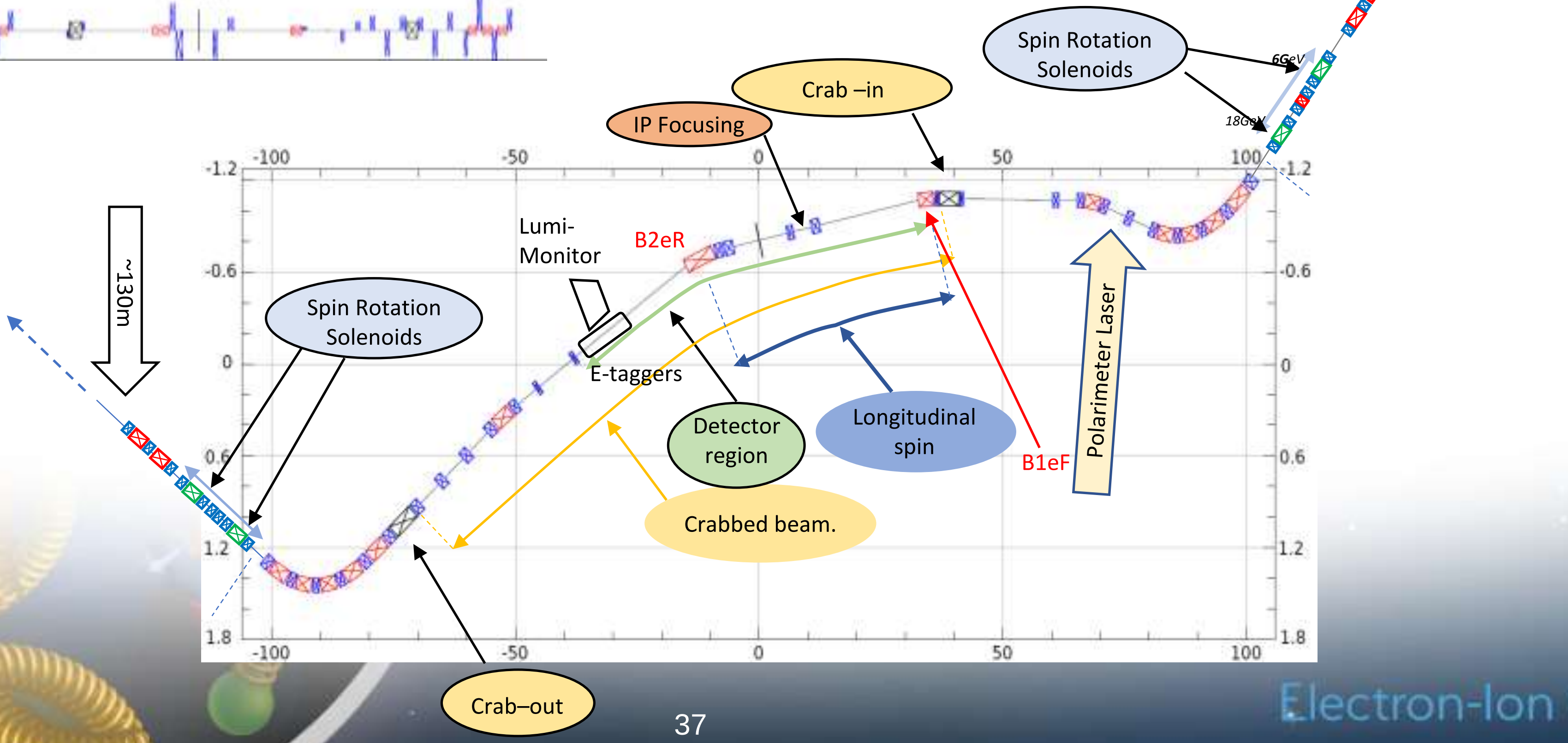


ESR layout in IR6

Design to:

- Provide room for detector components
- Mitigate synchrotron radiation issues
- Provide longitudinal spin (new spin rotators)
- Match into the arcs
- Provide conditions for crabbing
- Allow 3 rings and beam elements





Spin Rotation Solenoids

Crab –in

IP Focusing

Lumi-Monitor

B2eR

E-taggers

Detector region

Longitudinal spin

B1eF

Polarimeter Laser

Crabbed beam.

Spin Rotation Solenoids

Crab–out

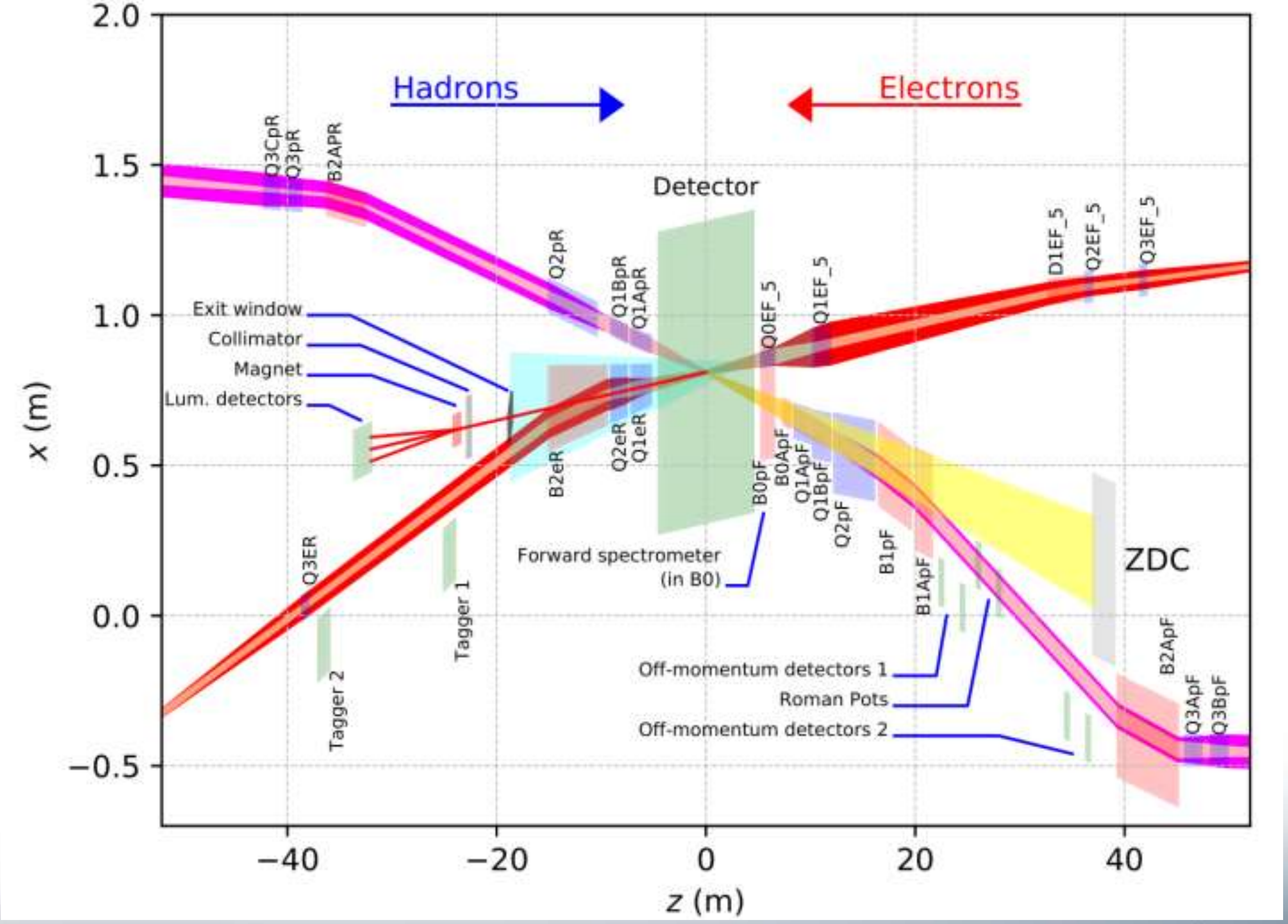
EIC IR Layout

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

- The EIC will be the next large nuclear physics facility, starting operations ~2031
- It fulfills all the requirements listed in the White Paper, facilitating a rich physics program
- These requirements make it a very challenging machine – high beam currents, polarization, novel hadron cooling technique, large energy range, …
- A great opportunity to work on the forefront of accelerator science and technology!