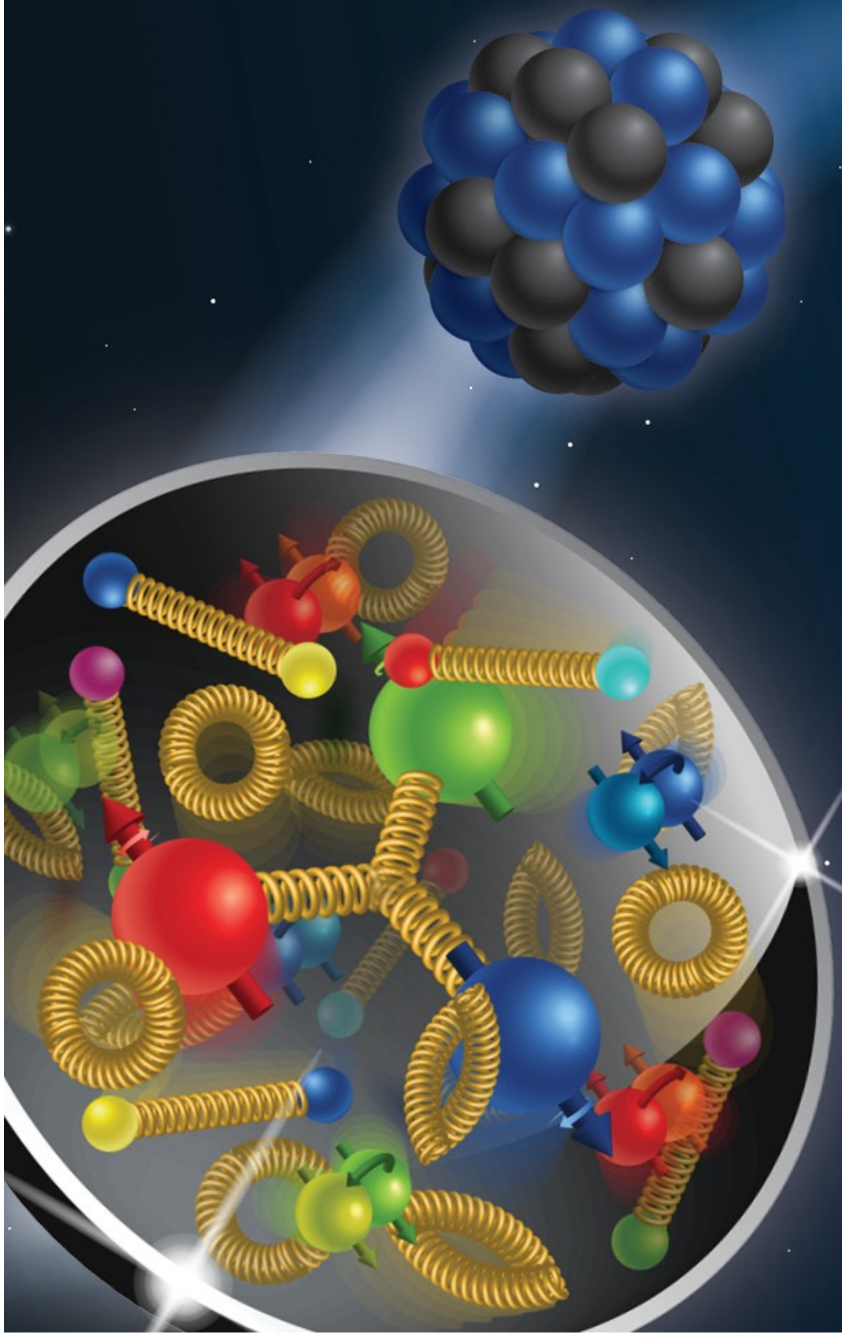


Hadron Storage Ring of Electron-Ion Collider

ASET seminar, April 12, 2024

Vadim Ptitsyn
Hadron Ring Manager
EIC Project
Brookhaven National Laboratory

Electron-Ion Collider

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

Outline

- From RHIC to EIC
- EIC Main Components
- Beam Screens and BPMs
- Hadron Cooling
- Polarized beams
- Injection System Upgrade
- Concluding Notes

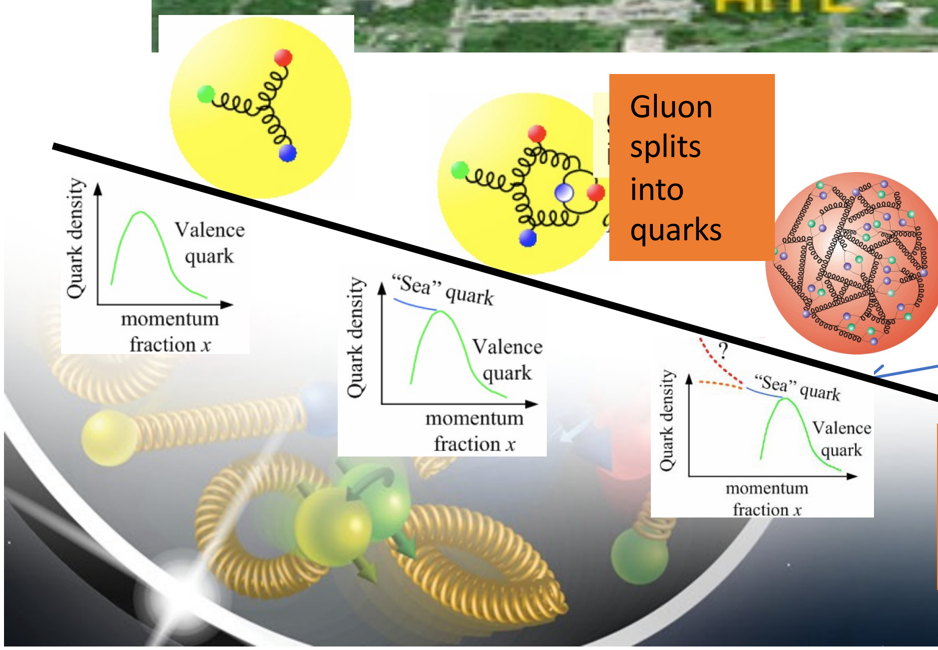
From RHIC to EIC

Relativistic Heavy Ion Collider at BNL

- Operates for more than 20 years
- Only collider in the US right now
- Heavy ions up to Au ions
- Polarized protons
- Two detectors
- Last operation year: 2025

From RHIC to EIC

Modified RHIC Hadron Ring + Electron accelerator = EIC



Gluon splits into quarks

Quark splits into gluon splits into quarks …

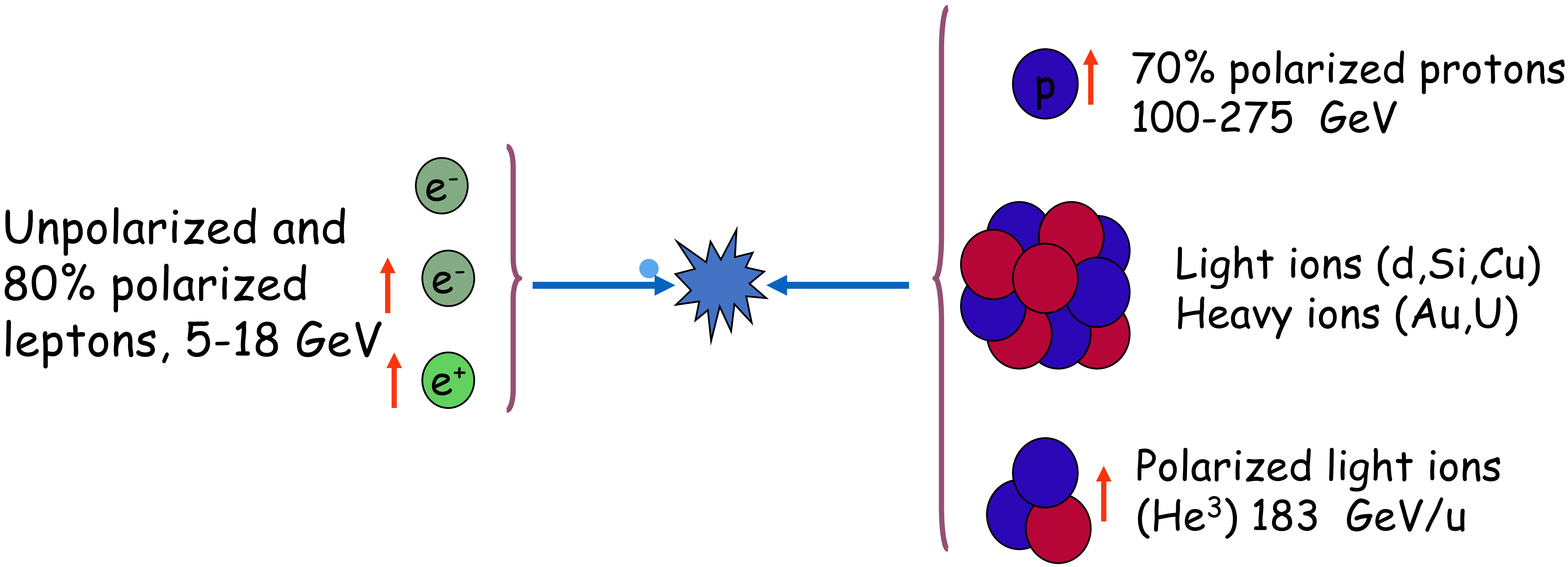
Increasing resolution

High precision femtoscope for the nucleons and nuclei:

✓resolving nucleon spin puzzle
✓3-D tomography of nucleons
✓ non-linear QCD regime of high gluon densities (saturation)

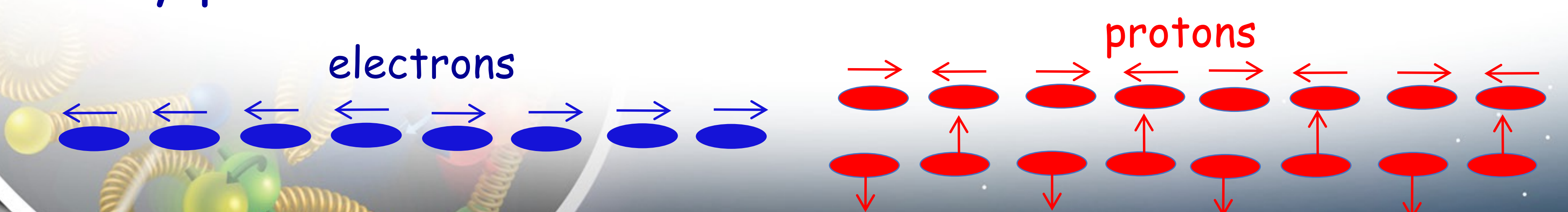
Electron-Ion Collider

Electron-Ion Collider: QCD Facility at BNL



Center of mass energy range: 30-140 GeV

Any polarization direction in electron-hadrons collisions



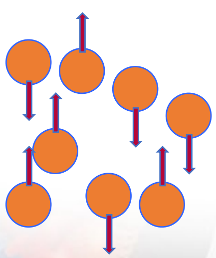
Particle Spin and Polarized Beams

- On microscopic level the spin is the analog of the angular momentum
  The spin is an intrinsic property of the elementary particles.

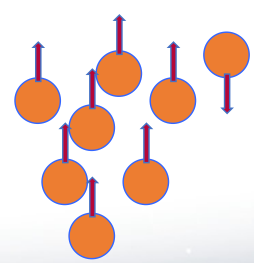
- The beam polarization can be defined as statistical average value of particle spins.
  The beam polarization is a vector. It has value and direction.
  Longitudinal direction (along particle velocity) is often required by experiments.

- For protons, highly polarized beam I produced by a source. Then the polarization must be preserved during acceleration process.

Unpolarized beam



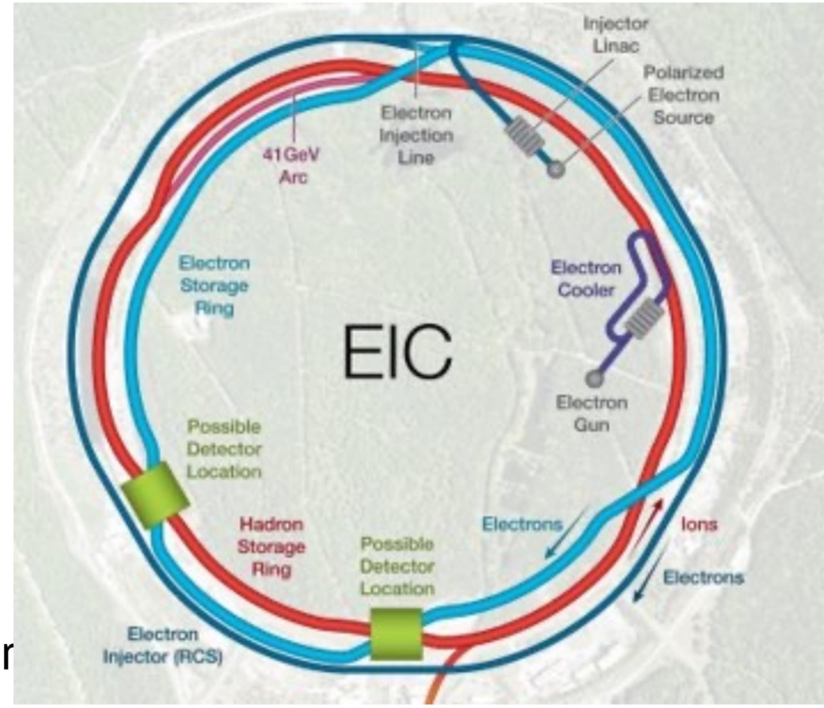
Polarized beam

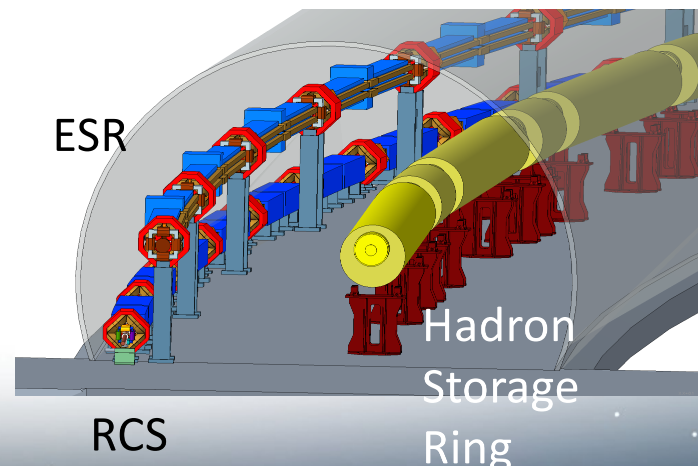


EIC Main Components

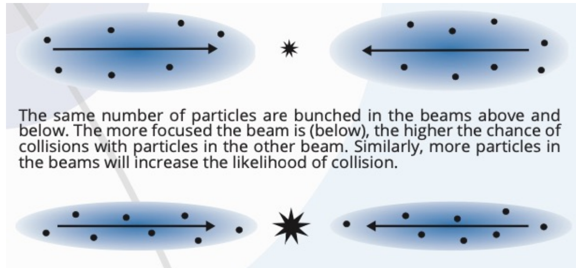
EIC Major Components

- Design based on **existing RHIC Complex in BNL**
- **Hadron Storage Ring (HSR) 40-275 GeV**
  - Superconducting magnets (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong hadron cooling
- **Electron Storage Ring (ESR) 5 – 18 GeV**
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C. RF cavities
  - Need to inject polarized bunches
- **Electron Rapid Cycling Synchrotron (RCS) 0.4- 18GeV**
  - 1 Hz
  - Spin transparent due to high periodicity





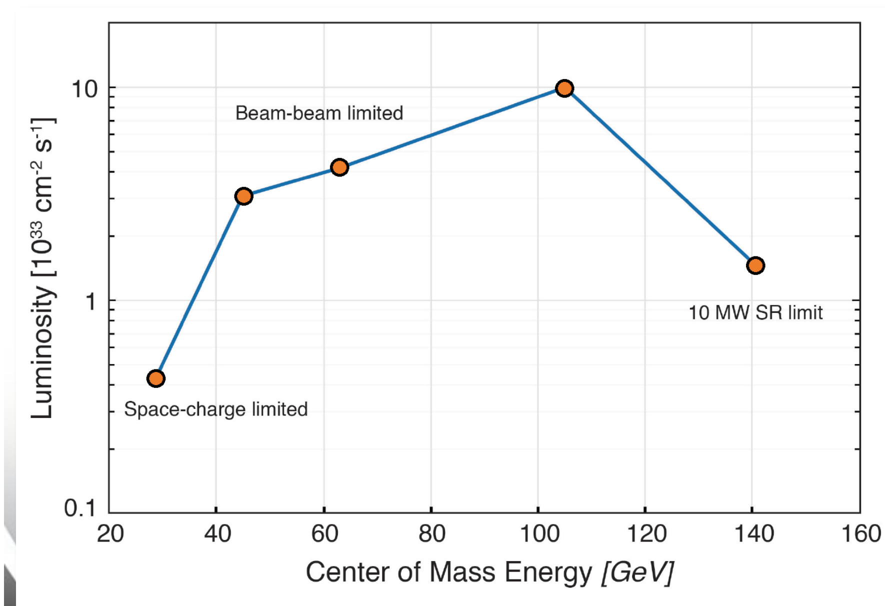
EIC Luminosity



Optimization yields $10^{34} cm^{-2} sec^{-1}$ luminosity at 105 CME GeV (275 GeV p x 10 GeV e)

$$L = f_b \frac{\pi \gamma_e \gamma_h}{r_{0e} r_{0h}} \cdot (\xi_h \sigma_h') \cdot (\xi_e \sigma_e') \frac{(1+K)^2}{K} \cdot H,$$

$K = \sigma_y/\sigma_x$, H-hourglass and crab-crossing factor



High luminosity ingredients:

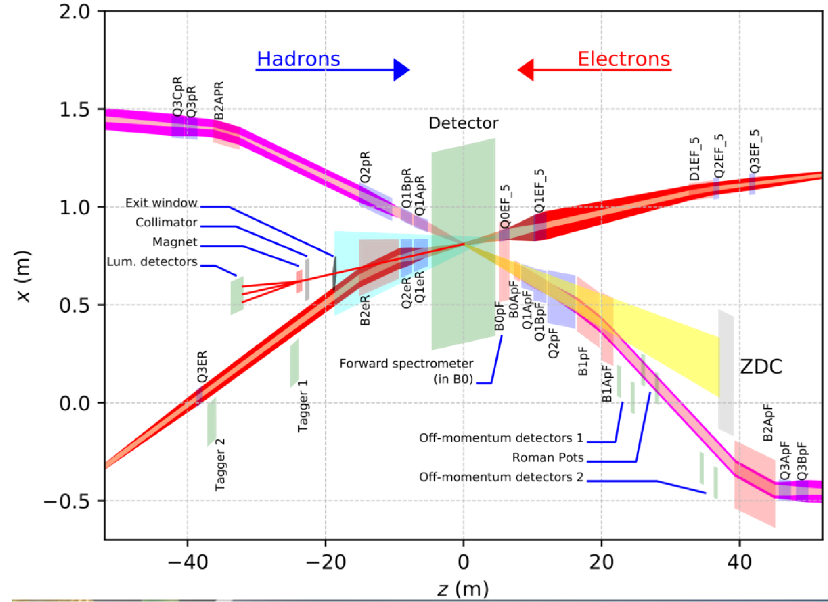
-high beam-beam parameters

-flat beams at the IP

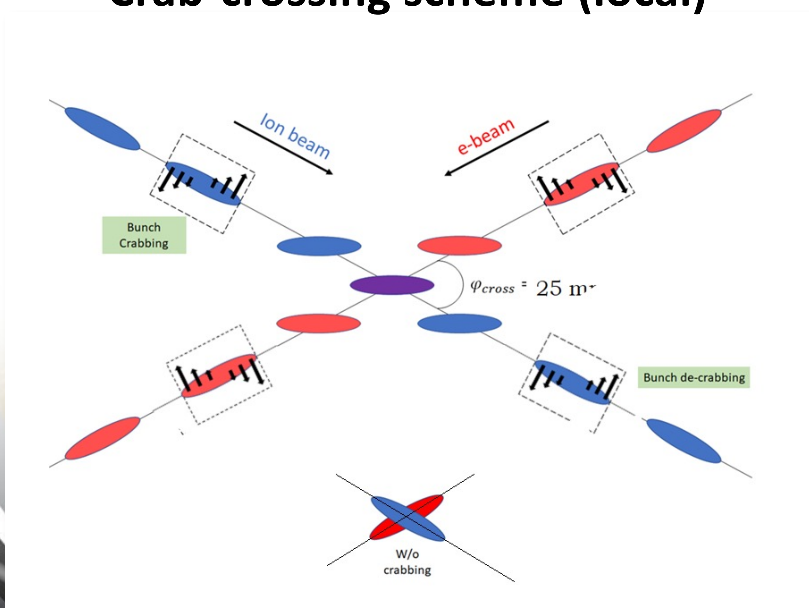
-high number of bunches
(at fixed optimized single bunch collision parameters)

Interaction Region

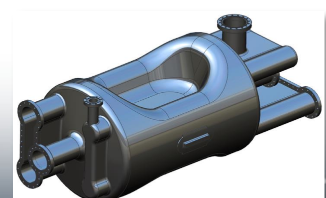
- 25 mrad crossing angle
- Compact superconducting final focus magnets
- Spin rotators: strong solenoids for e, helical magnets for
- Large acceptance for forward scattered hadrons



Crab-crossing scheme (local)



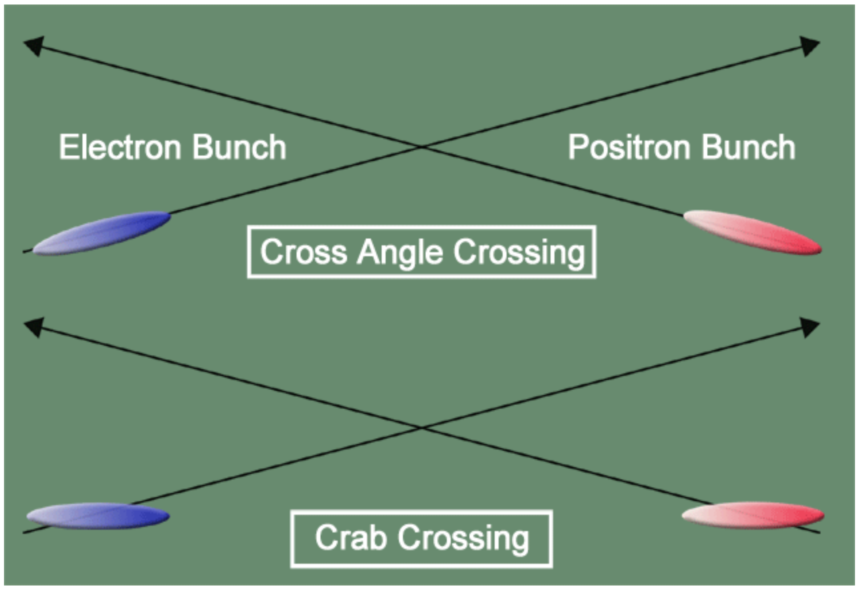
Crab cavities ➔quasi head on collisions
For hadrons:
Second harmonic cavity to minimize synchro-betatron resonances.
Not fully local. 175° phase advance between cavities on left and right sides of the IP.

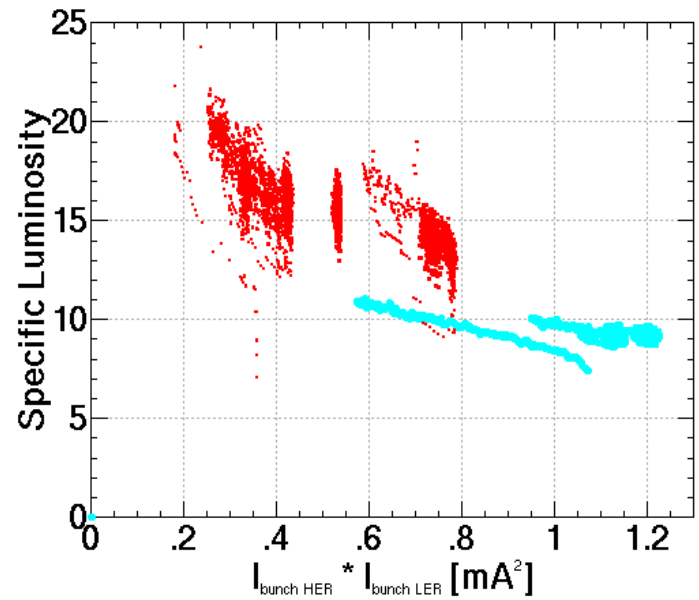


197 MHz crab-cavity

Crab-crossing

Used at KEK B-factory





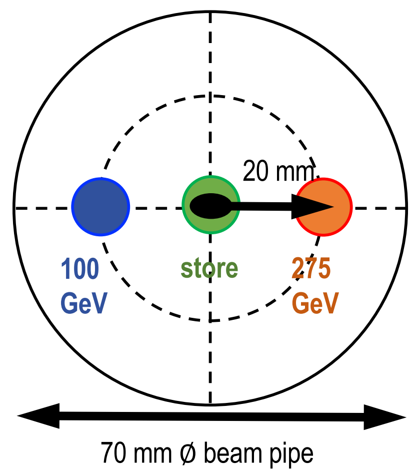
Crab-crossing was implemented in the electron-positron collider: KEKB (Japan).
It has never been used for hadron beams.

Hadron Ring Modificadtions: Beam Screens and BPMs

EIC Hadron Beam Parameters are Advanced Compared with RHIC

Parameter	Proton	
	EIC design	RHIC demonstrated
Energy [GeV/nucleon]	275	255
Particle per bunch [10^{10}]	20	22.5
Number of bunches	290,1160	111
Beam Current [A]	1	0.34
RMS nor. Emit. h/v [μm]	3.3/0.3	3.1/3.1
BB parameter, h/v [10^{-3}]	12/12	-18/-18*
RMS bunch length [cm]	6	55
Polarization [%]	70	60

Large radial orbit offsets (up to 20mm) in arc magnets are used for purpose of synchronization of hadron and electron revolution frequencies.



Tripled beam current, shorter bunch length, shorter bunch distance, small vertical emittance call for upgrades of vacuum system and beam instrumentation.

Unacceptable resistive-wall heating of RHIC vacuum chamber for EIC beams

- Beam-induced currents on resistive walls of vacuum chamber dissipate heat.
- Presently, vacuum chamber of 4.55 K *RHIC Superconducting magnets* is a round, stainless steel 316LN beam pipe.

- Resistive-wall heating:

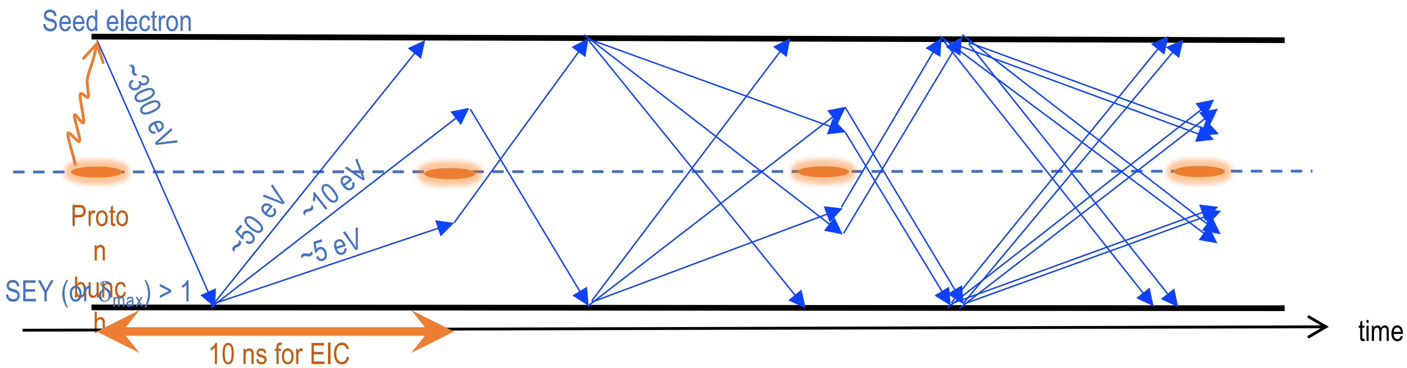
	Species	E (GeV/u)	M	N (10^9 ppb)	I_{ave} (A)	σ_z (m)	P' (W/m)*
RHIC	p↑	255	111	197	0.27	0.6	0.05
EIC	p↑	275	290	198	0.72	0.06	😱 4.03

- If heat is not reduced or extracted, the superconducting magnets will **quench**

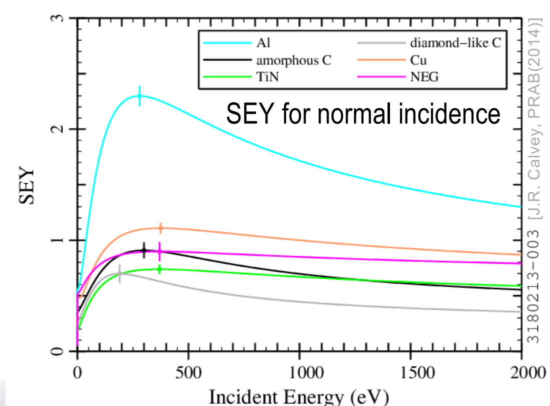
- ***UPGRADE*** **⟹ use better electrical conductor** (Cu at 10 K→ P' ~ 0.35 W/m)

Unacceptable secondary electron yield (SEY) of the RHIC vacuum chamber for EIC beams

- Electron cloud buildup refers to a cascade multiplication of the electrons present in the vacuum chamber of a particle accelerator as result of the electrons acquiring energy from the passing beam and featuring the appropriate energy to extract electrons from the surface of the chamber.



- Electron clouds deteriorate vacuum and beam quality, heat up the chamber and, in some cases, lead to beam loss.
- The number of emitted secondary electrons per primary electron is the Secondary Electron Yield (SEY) and is material dependent (surface topography and electronic properties of material).



Unacceptable secondary electron yield (SEY) of the RHIC vacuum chamber for EIC beams

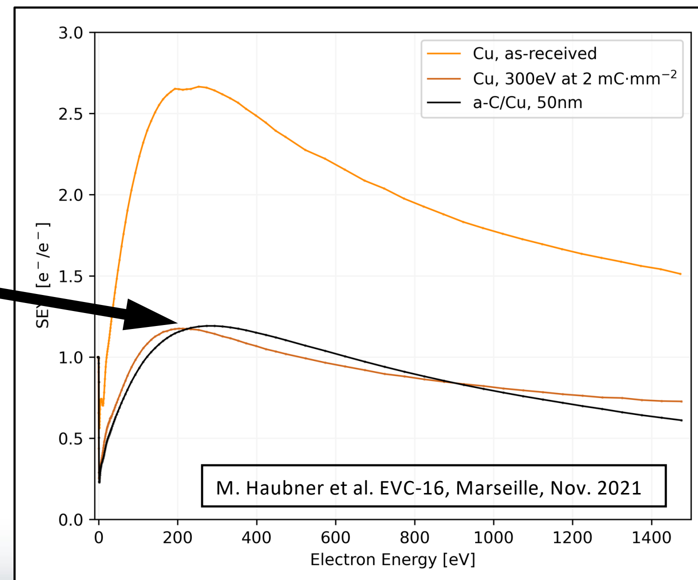
The high-intensity EIC beams, with short bunch spacing, lead to **e-cloud buildup**.

	RHIC	LHC	EIC HSR
Bunch charge (x10^{11} ppb)	1.35	1.15	0.69
Bunch spacing (ns)	108	50 -- 25	10.15

SEY of scrubbed stainless steel is about 1.35.

To mitigate risks of electron cloud buildup:

UPGRADE **⟹ use low SEY surface** (a-C)

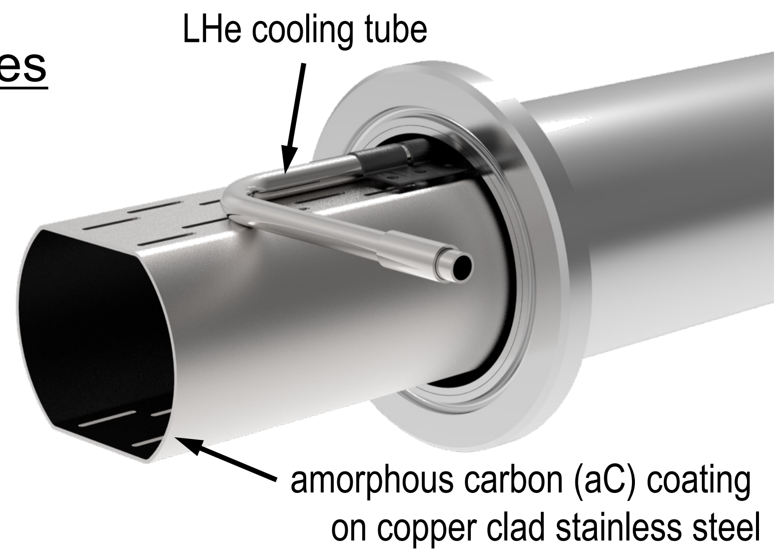


The Upgrade in a Nutshell

<u>Install beam screens inside existing SC magnet bores</u>

- Copper cladded stainless steel
- High RRR reduces resistive wall heating
- Temperature control by active cooling
- aC coating reduces the SEY of the surface

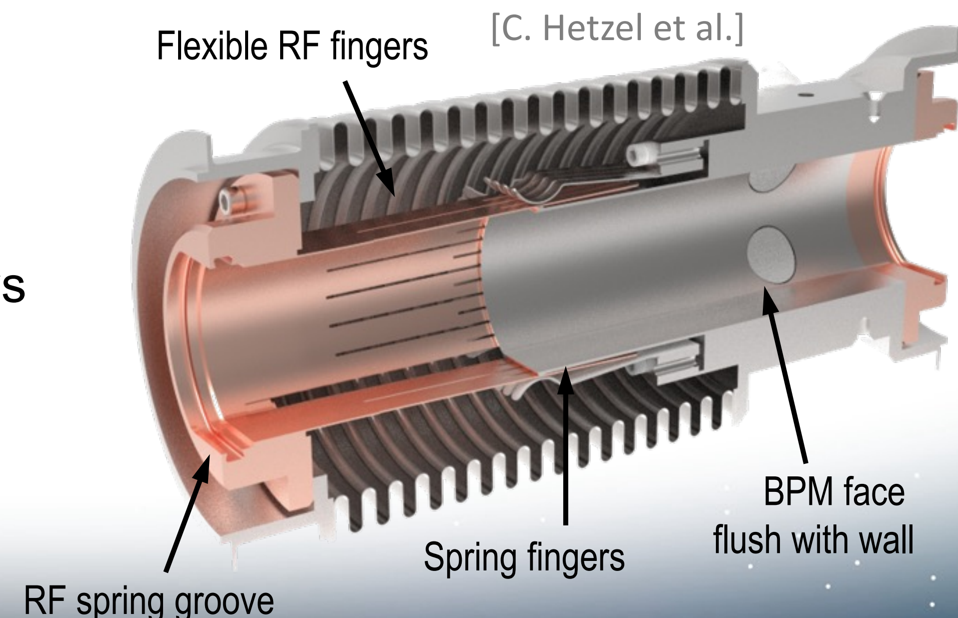
(Inspired on solutions for LHC and HL-LHC.)



[C. Hetzel et al.]

<u>Redesigned interconnect</u>

- Impedance-driven requirement
- Replace bellows by RF shielded bellows
- Shield existing stripline BPMs
- Integration of new BPMs and screens

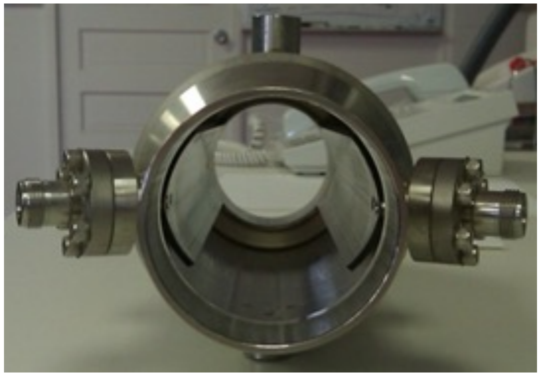


Hadron Beam Position Monitors

- RHIC stripline BPMs cannot be used at EIC peak current values and large orbit radial shifts, because of BPM cable heating issues.
- Corner arrangement of the buttons reduces button heating by radially shifted beam
- Design verification prototypes are being built

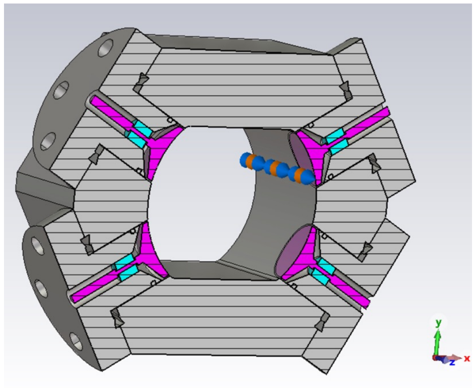
UPGRADE **⟹ new BPMs**

RHIC BPM



Existing stripline BPM (shown above) will be shielded and button BPMs (shown below) will be installed adjacent

EIC HSR BPM



Hadron Cooling

HSR emittances

For achieving high luminosity the small vertical emittance is required

Injected beam with equal emittance → **Pre-cooling** → Injection energy. Design emittances. $\varepsilon_y / \varepsilon_x \sim 0.09$ → **Acceleration Ramp** → Beginning of the store. Design emittances. $\varepsilon_y / \varepsilon_x \sim 0.09$ → **Store** →

Pre-cooling: Low energy cooling based on incoherent electron cooling.

14 MeV ERL-based electron accelerator, ~100mA.
~1-1.5h cooling time.

Forming emittances!
Classical electron cooling

Acceleration Ramp: Coupling control on acceleration ramp. Decoupling feedback.

Store: Counteracting emittance diffusion processes. Strong Hadron Cooling (CeC Microbunched cooling)

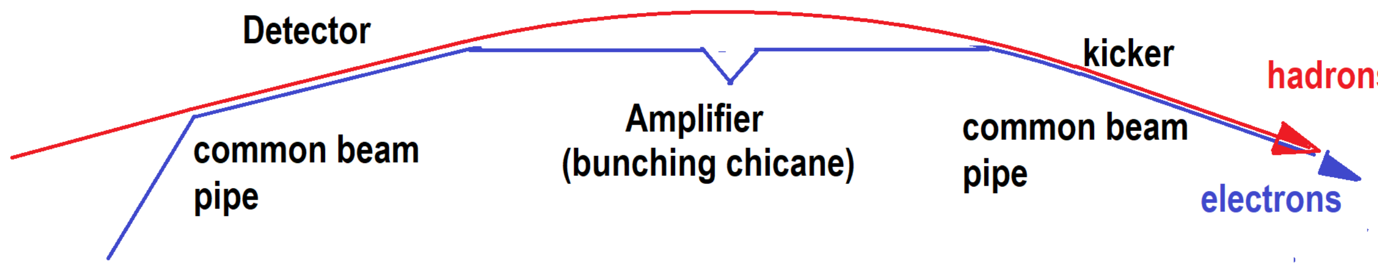
150 MeV ERL-based electron accelerator, ~100mA

Maintaining emittances!
Coherent electron cooling

Classical Electron Cooling

- Mechanism:
  - Co-moving hadron and electron beam
  - In moving beam frame:
    heat exchange between hadron gas and colder electron gas by means of binary particle collisions
  - Effectively reduces the hadron beam velocity spread (both longitudinal and transverse)
- Implemented in many low energy ion accelerator rings
- It was used in RHIC to cool 4.6 GeV/u gold ions
- The classical electron cooling will be applied in the EIC to form beam emittances at the injection energy of 24 GeV.

Coherent Electron Cooling



$$\gamma_h = \gamma_e$$

(Electrons and hadrons have exactly the same speed)

Novel technique! Not used so far in any accelerator.

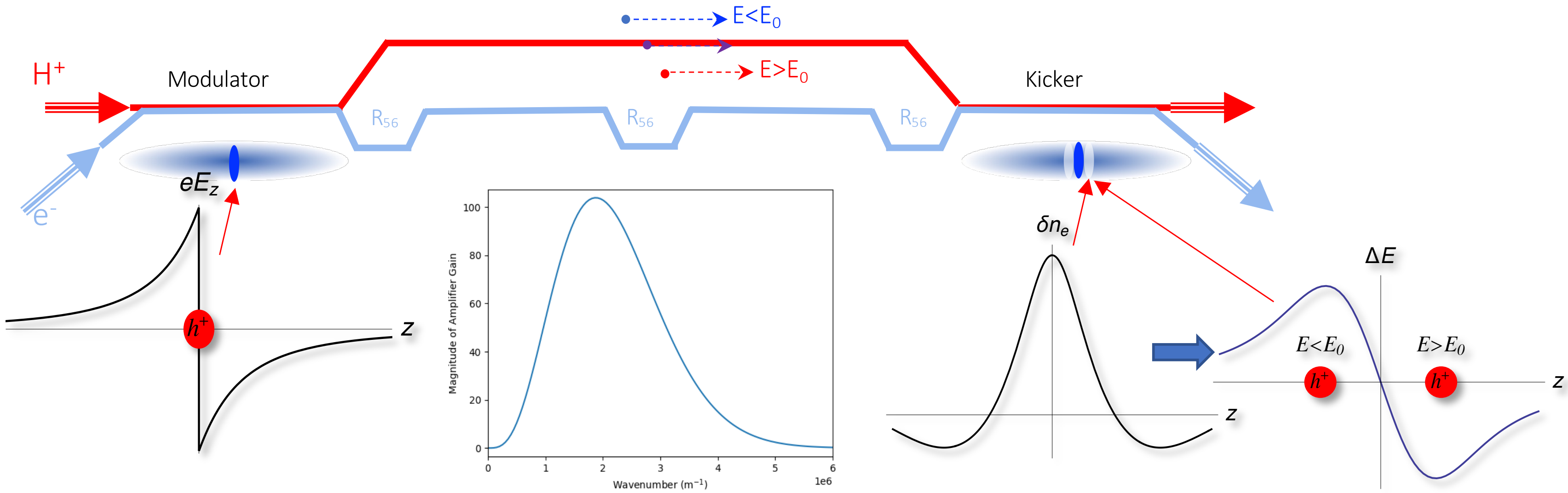
Imprinting: density fluctuation in hadron beam causes **energy modulation** of e-beam

Amplification: e-beam energy modulations are converted **to density fluctuation** by chicane

Hadron chicane: **Controls hadron travel time** with respect to electron path. Transfer to **correlated energy modulation**.

Kicker: longitudinal electric field of electrons **reduces the hadron beam correlated energy spread.**

CeC using micro-bunched amplificadtion



High cooling rates (~1-2h)

- Density modulated electron beam subject to **plasma oscillations** while drifting
- (drift quarter of electron beam plasma wavelength)
- ➔**More energy modulation ➔ another chicane ➔ more micro-bunching**
- EIC Strong hadron cooler: 2 such plasma amplification stages

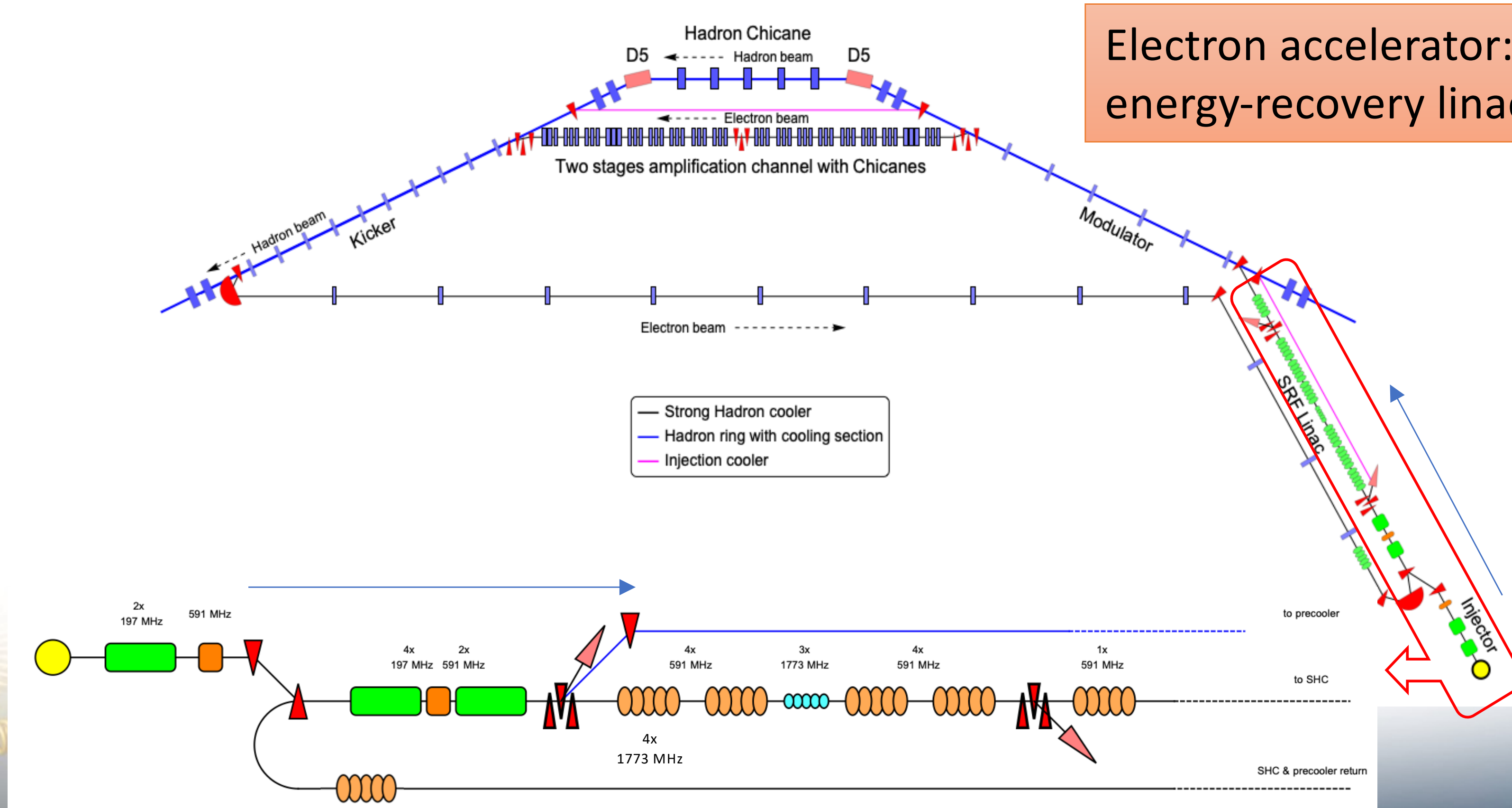
❖ Extensive theoretical and simulation studies continues to resolve challenges (precise e-p synchronization in kicker, cooling diagnostics, …)

❖ CeC Proof-of-Principle experiment in RHIC

EIC Hadron Cooling Facility at IR2

Strong Hadron Cooler and Low Energy Cooler are integrated into one cooling facility with many shared hardware elements, including the electron source, pre-injector, some RF cavities, cooling sections and the return loop.

Electron accelerator: 100 mA energy-recovery linac

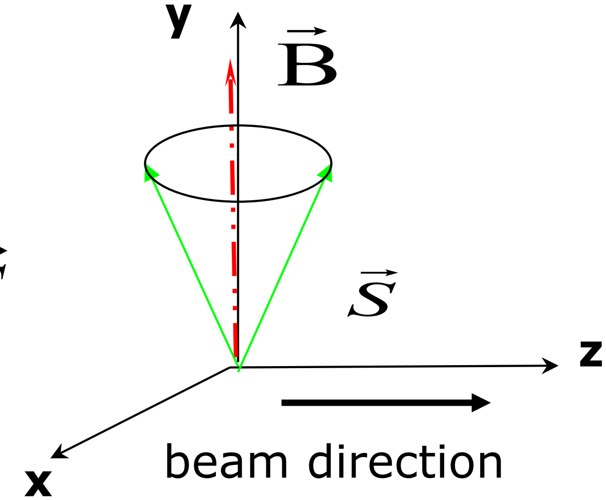


Polarized beams

Spin motion in a circular accelerator

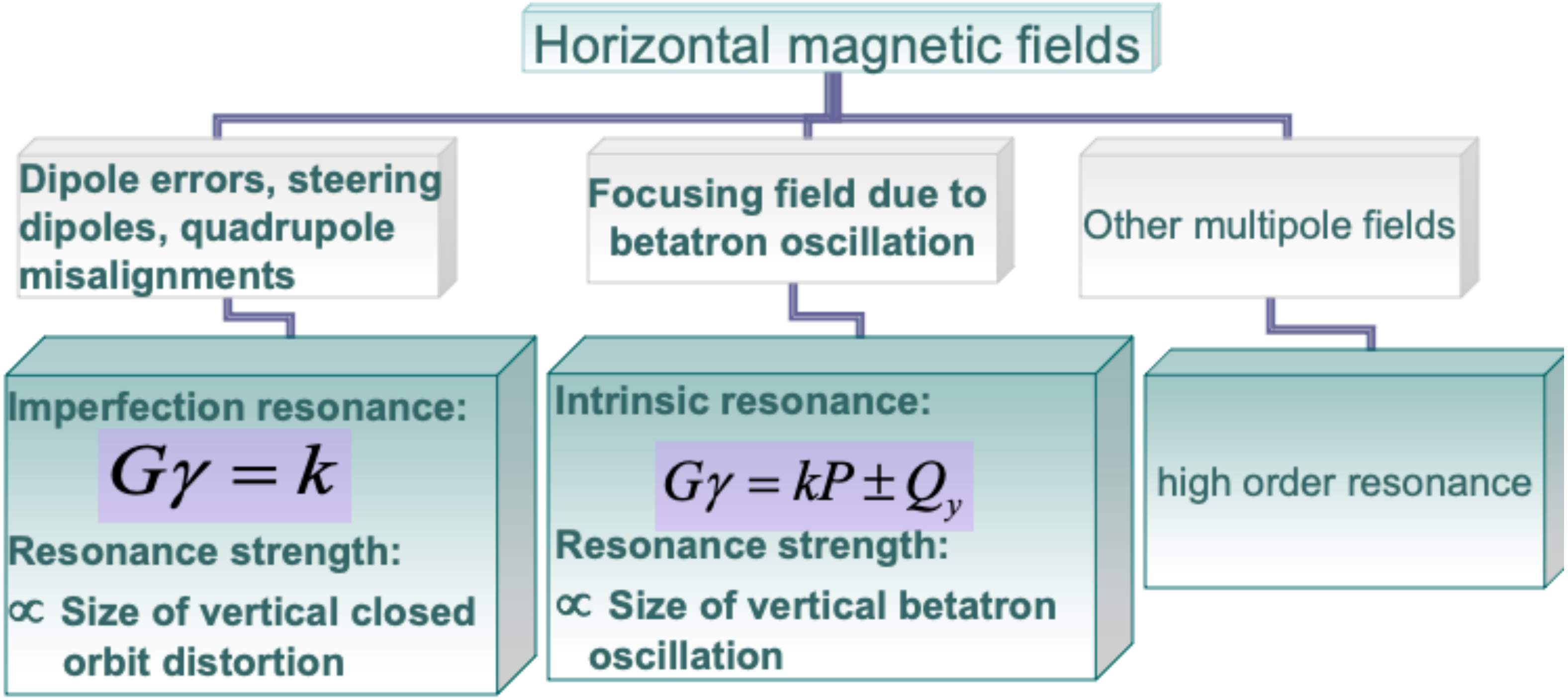
- Thomas BMT equation

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m}[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{//}] \times \vec{S}$$



- In a perfect accelerator, spin vector precesses around its guiding field, i.e. vertical
- Spin tune *Qs*: number of precessions in one orbital revolution. In general, $Q_s = G\gamma$
- Kicks on the spin vector from horizontal field leads the spin vector away from its stable direction, i.e. vertical
  - Depolarization resonance when the spin vector gets kicked at a frequency close to the frequency it precesses

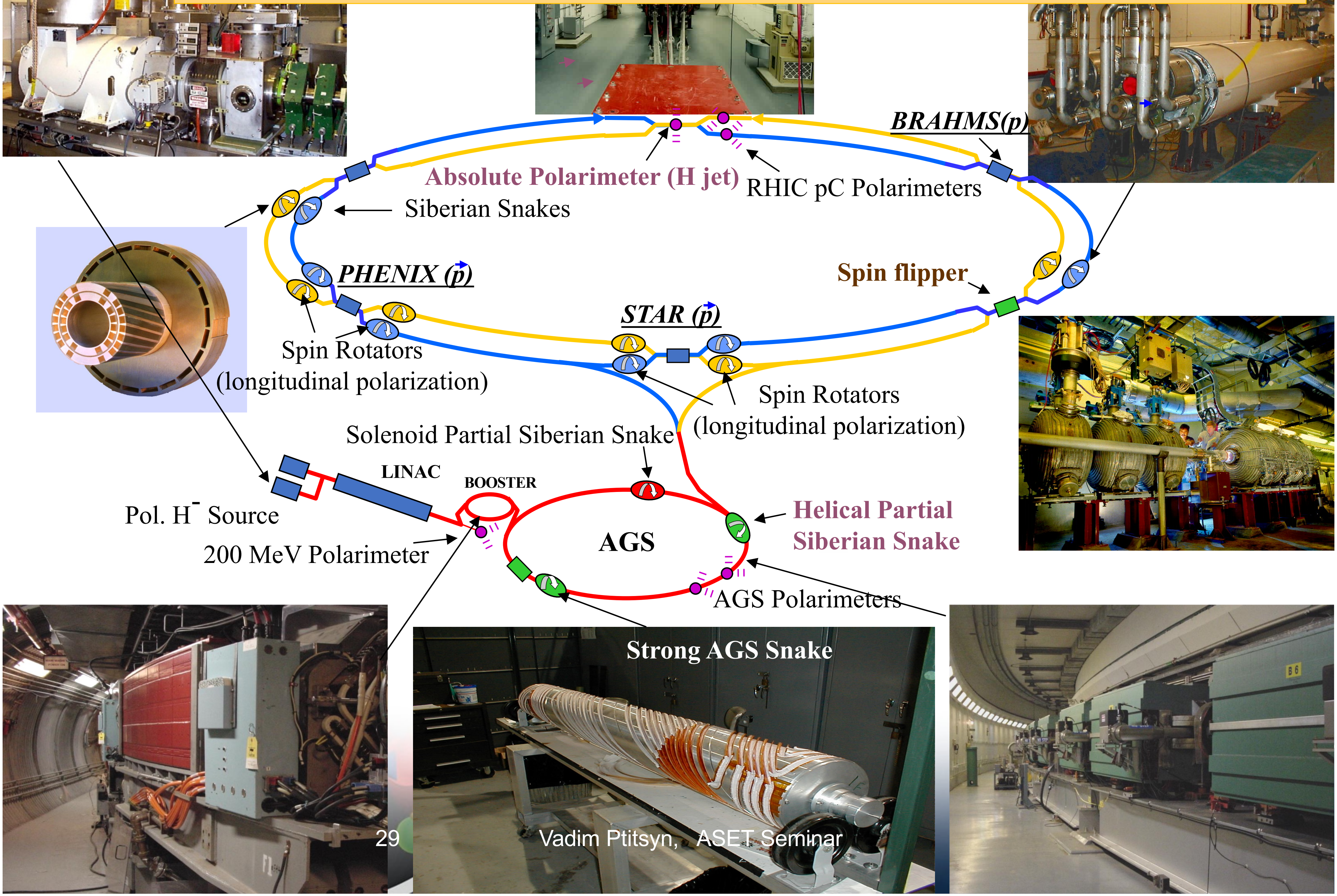
Depolarizing spin resonances



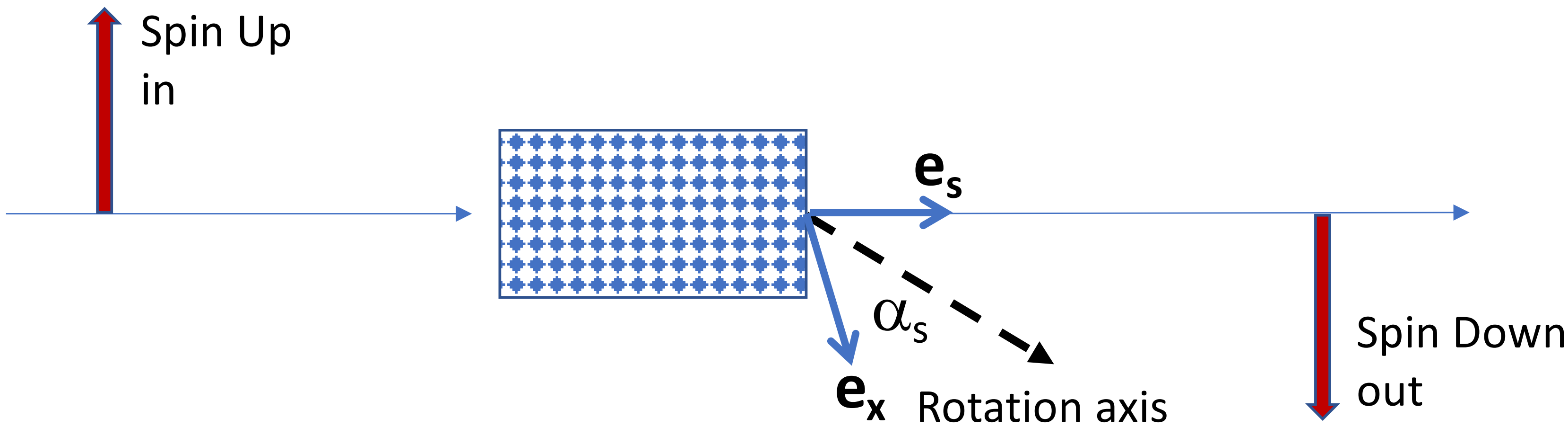
Each imperfection spin resonance is spaced by 523 MeV (for protons)

During acceleration process many resonance may need to be crossed since γ increases.

Polarized proton acceleration complex at BNL



Siberian Snake

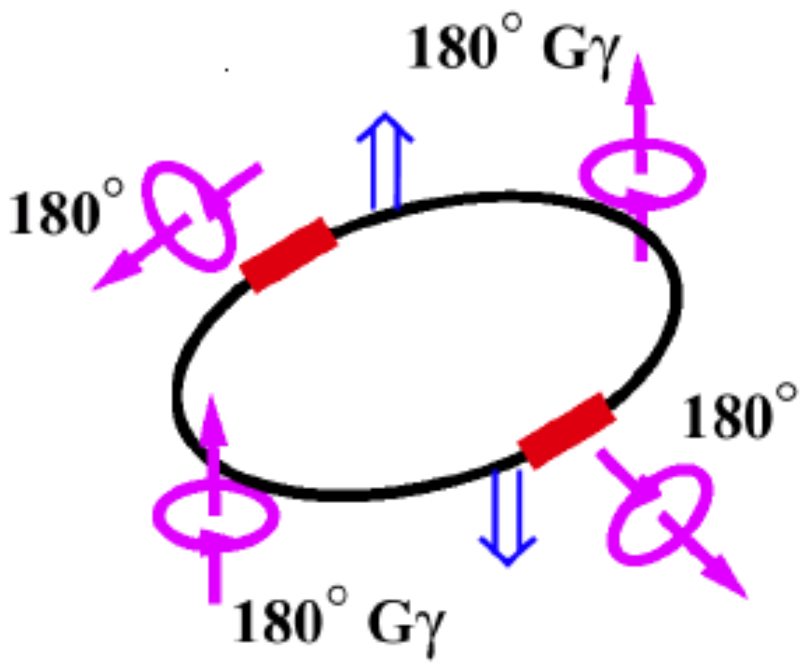


Siberian Snake (or **Full Snake**):
spin rotating device which rotates particle spin by 180 degree around a rotation axis, called **Snake axis (**which is usually in horizontal plane).

Snake axis angle α_s characterizes the orientation of the Snake axis in the horizontal plane.

RHIC uses a pair of Siberian Snakes to preserve polarization during acceleration

- **RHIC:**
  - Energy: 23.8 GeV ~ 250 GeV (maximum store energy)
  - A total of 146 imperfection resonances and about 10 strong intrinsic resonances from injection to 250 GeV.
    - ***Two full Siberian snakes***



Makes spin tune independent on the beam energy!

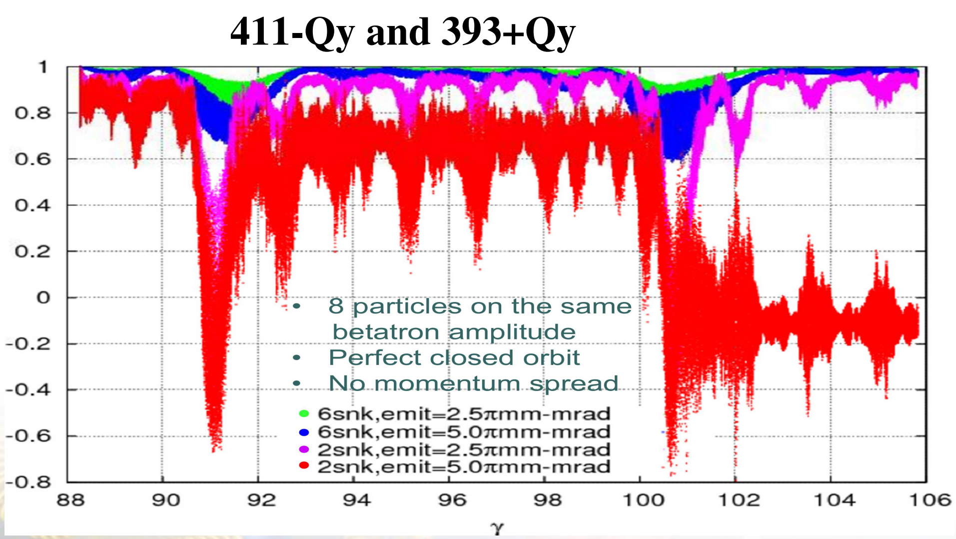
$$Q_s = \frac{1}{\pi}\left|\varphi_1 - \varphi_2\right| \Rightarrow Q_s = \frac{1}{2}$$

Preserving Hadron Polarization in HSR

- Main challenge: preserving polarization of helions ($^3He^{+2}$ ions) during acceleration process.
- Spin of helions is stronger coupled with magnetic fields than spin of protons because of large factor G.

	p	$^3He^{+2}$
m, GeV	*0.938*	*2.808*
G	*1.79*	*-4.18*
E/u, GeV	*24-275*	*16-183*
$\lvert G\gamma \rvert$	*46.5-525.5*	*72.6-819.4*

Crossing strongest spin resonance with 2 and 6 Snakes with helions

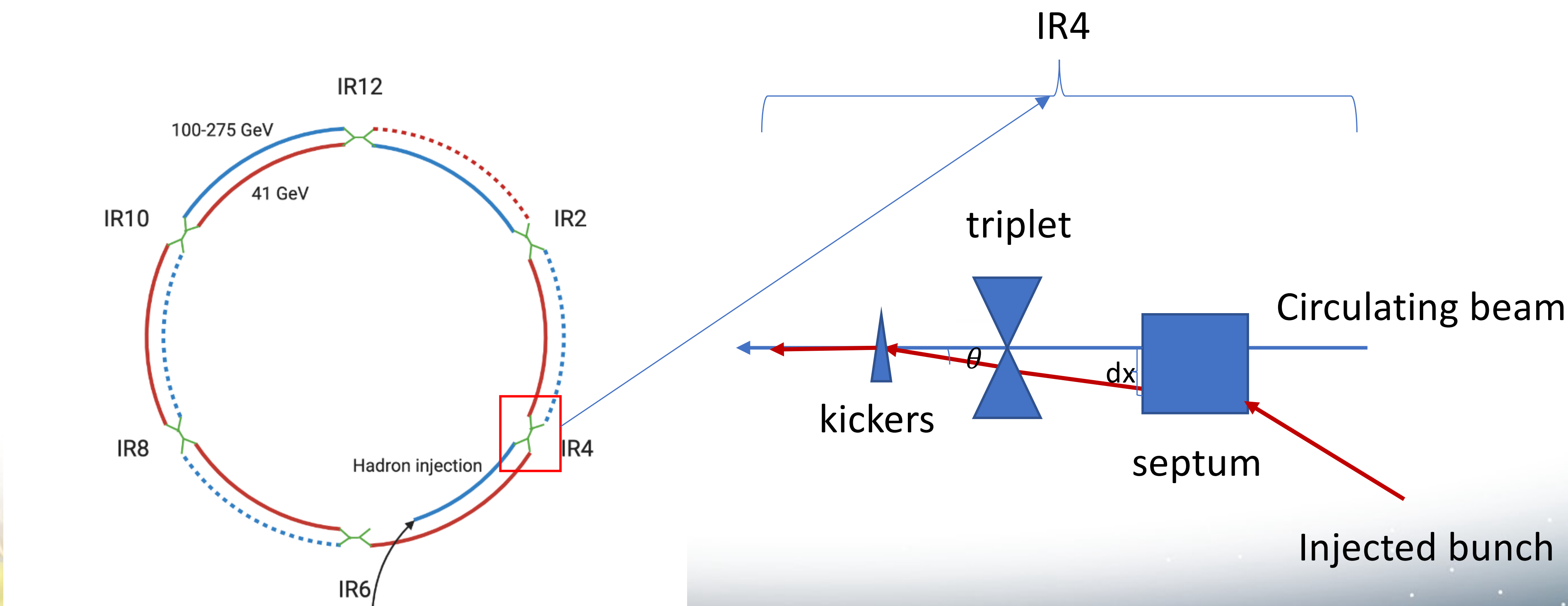


UPGRADE $\Longrightarrow$ **increase the number of Siberian Snakes from 2 to 6**

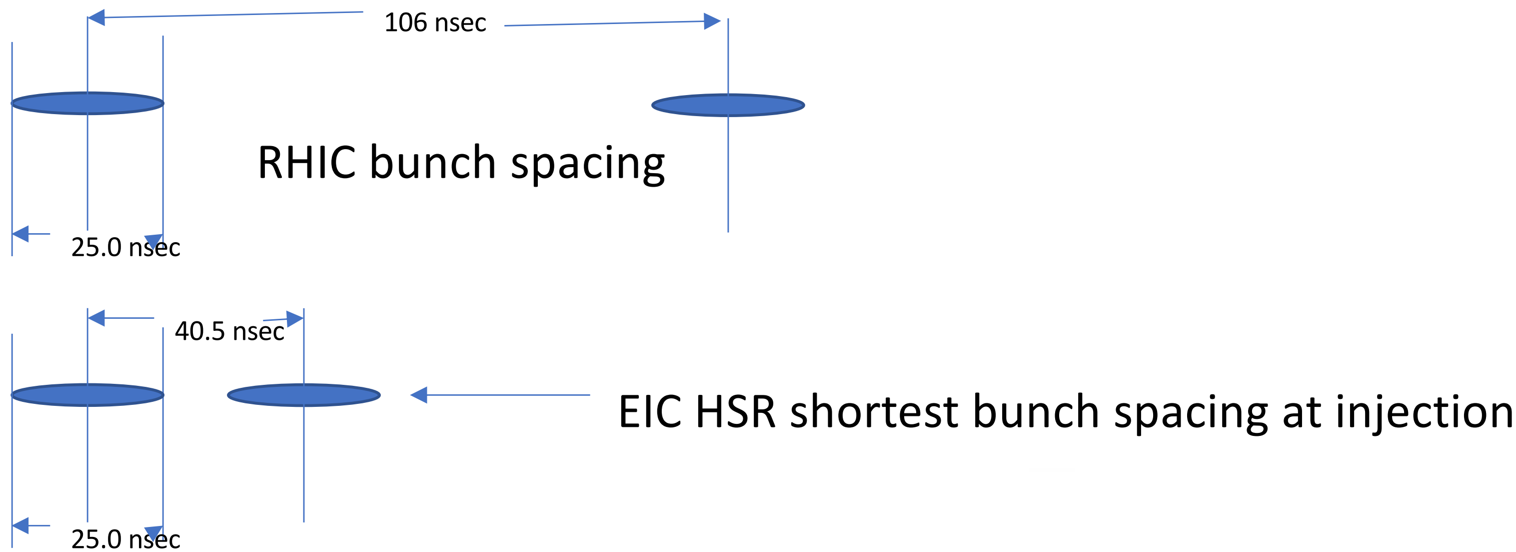
Injection System Upgrade

Schematic of HSR injection

Proton beam injection is done at the energy of 24 GeV.
About once every second a new bunch arrives for the injector chain This bunch has to be placed inside the Hadron Storage Ring precisely on the circulating beam orbit.



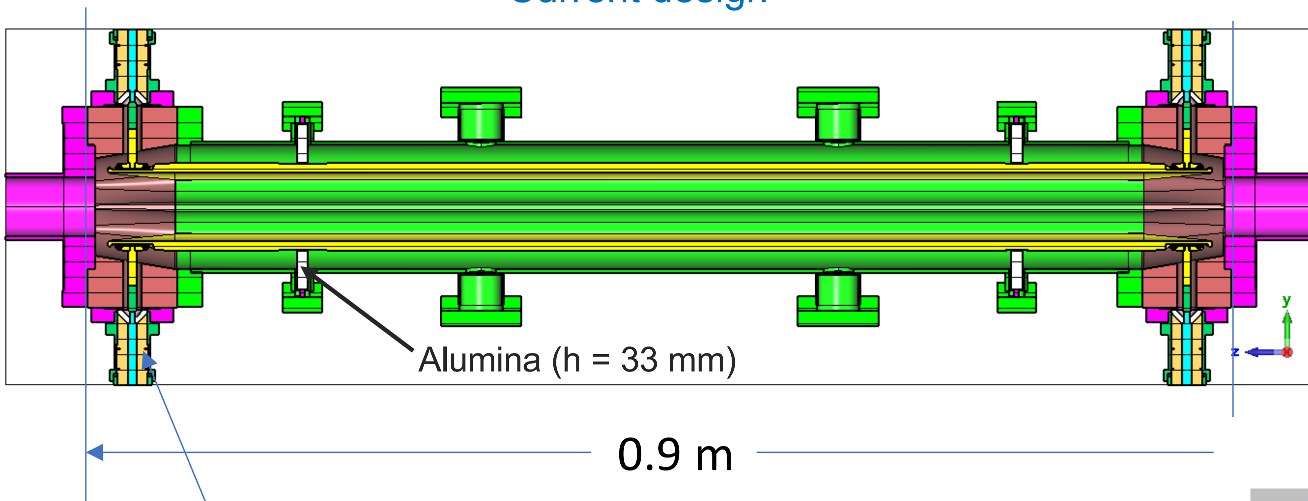
Bunch distance in RHIC and HSR



UPGRADE **⟹ new injector kickers with shorter rise time (~7ns)**

The Strip Line Kicker Z≈50 Ω

Current design

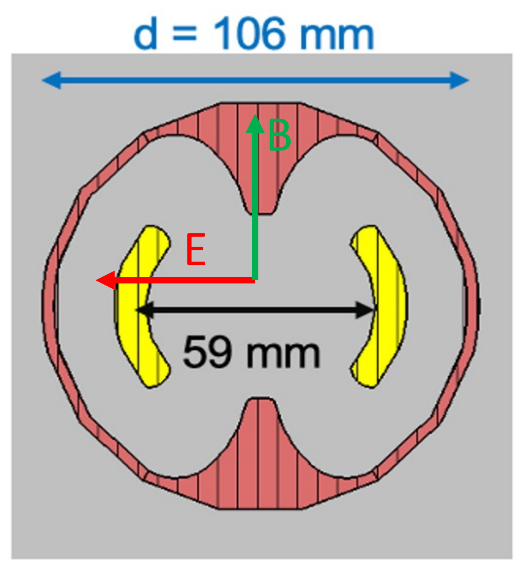


FID feedthrough

V =20-25 kV

More voltage -> less number of kickers needed

Prototype kicker is being built and will be tested later this year.



TEM

Concluding Notes

- The Electron-Ion Collider project is advancing steadily to meet its ambitious goals, with a present focus on engineering design and beginning of construction.
- We start this month construction of some components requiring longer time for construction/procurement (so-called Long Lead Procurements). This includes HSR Button BPMs , HSR BPM cryo-cables and the copper-clad material for HSR beam screens.
- Advanced hadron beam parameters call for significant modifications and upgrades of RHIC rings to convert them into EIC Hadron Storage Ring.
- One of the primary accelerator physics challenges highlighted is the design of Strong Hadron Cooling capable of cooling a 275 GeV proton beam.

Thank you for your attention!