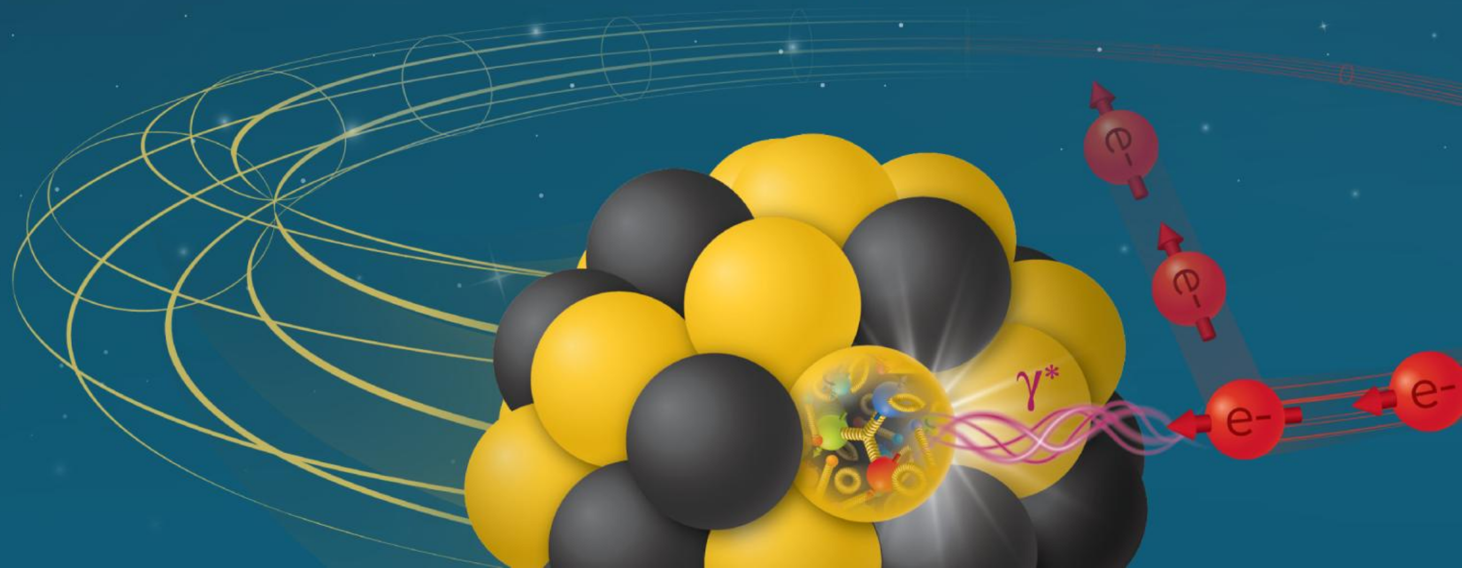
Accelerator Technology for the EIC

Christoph Montag, BNL

June 3, 2026

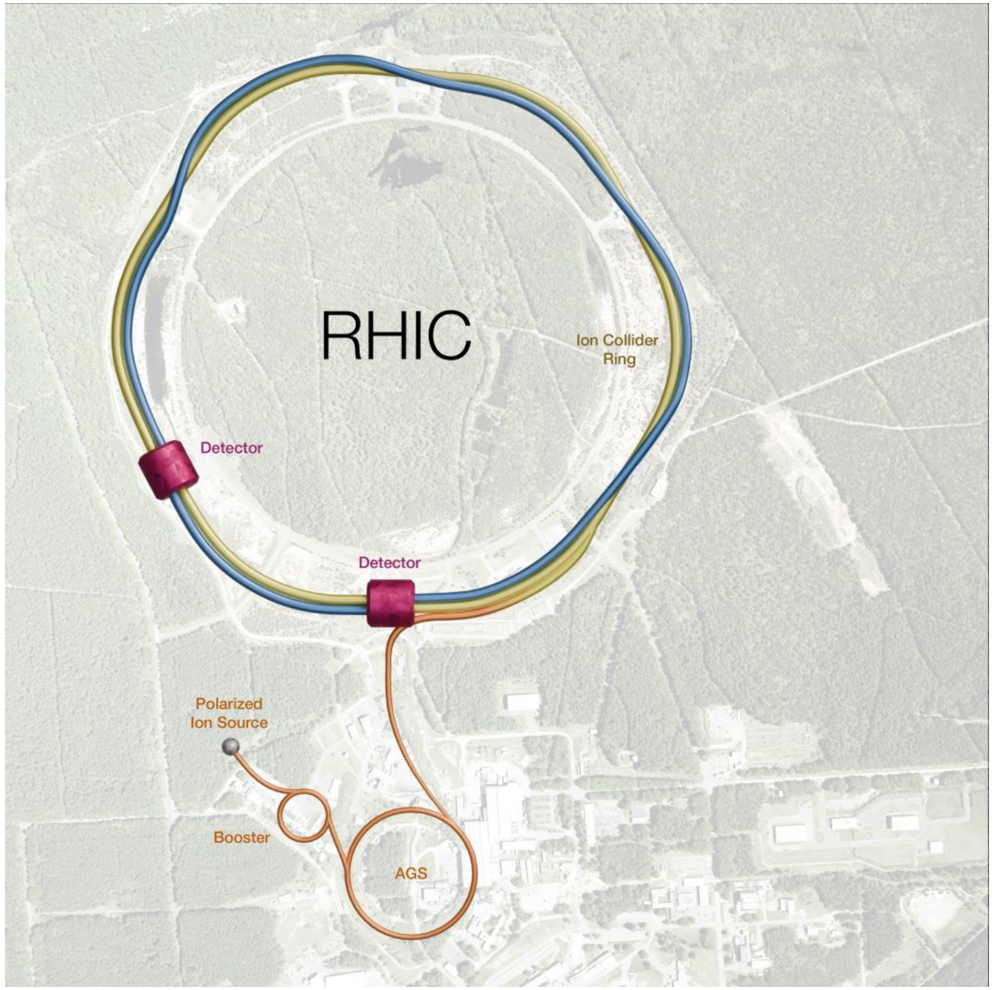


Electron-Ion Collider

From RHIC to EIC

RHIC:

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



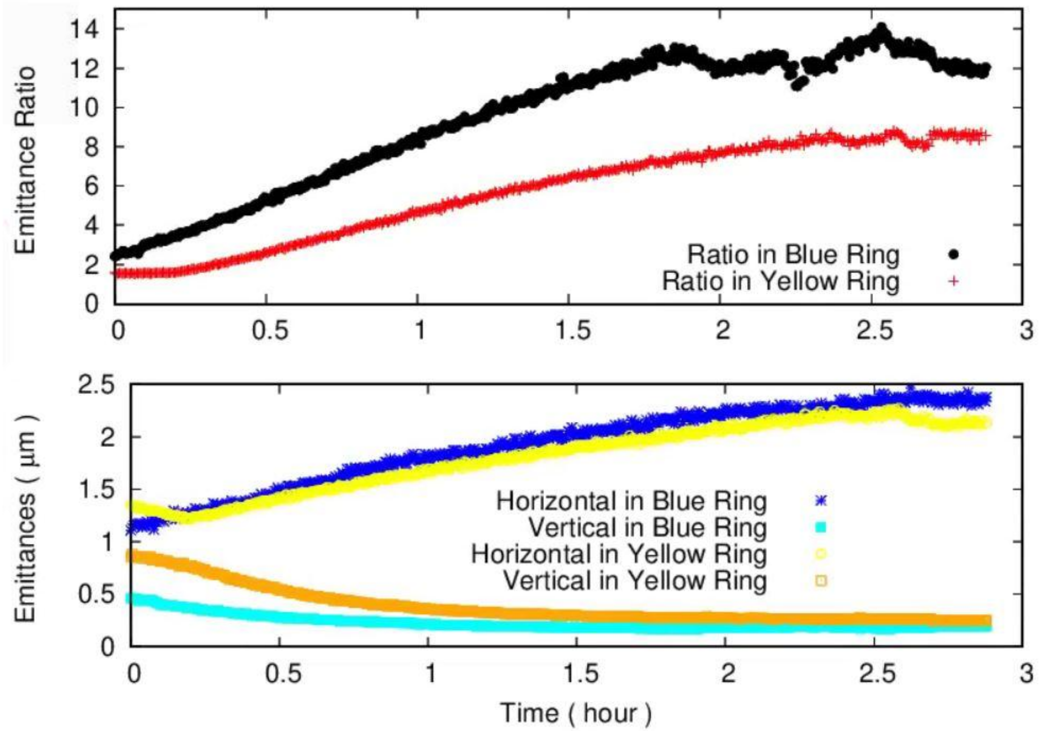
EIC Design Concept

- 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

EIC Design and Performance Parameters

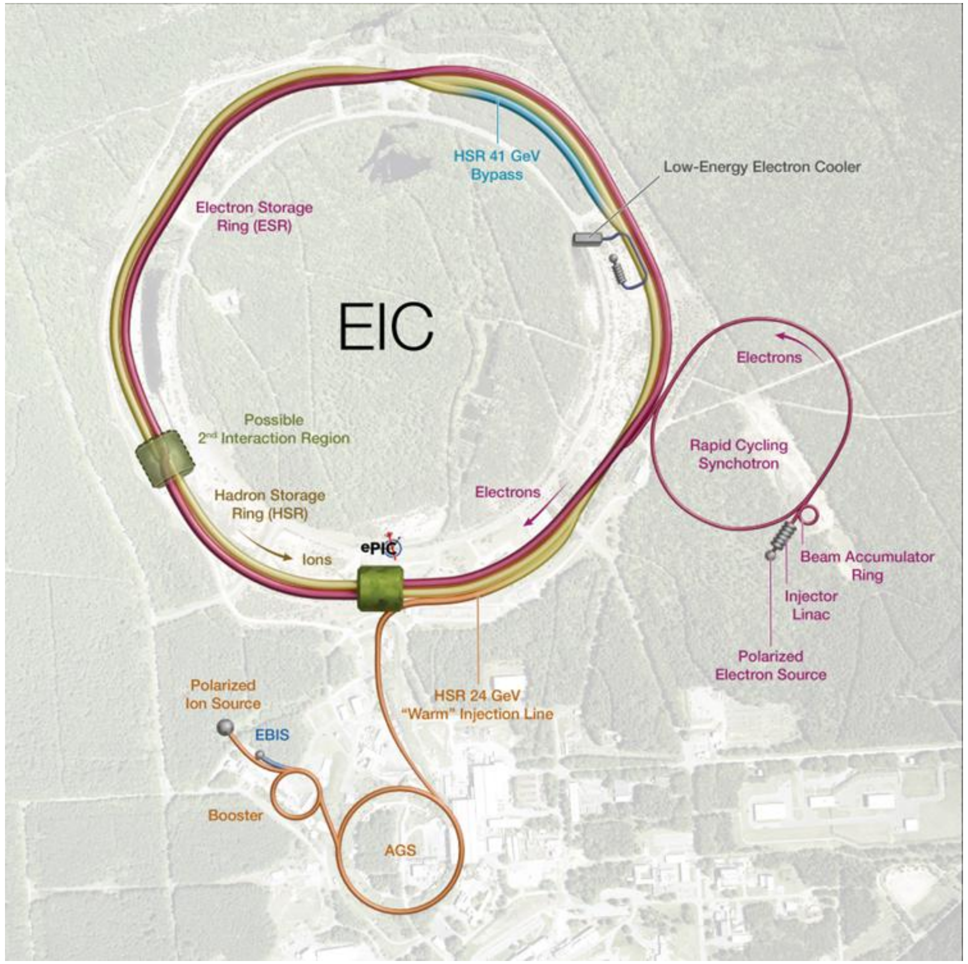
- Choice of EIC beam performance parameters informed by parameters achieved at other facilities: RHIC, HERA, KEK-B
- Parameters backed up by comprehensive & systematic simulation studies: Beam-beam, dynamic aperture, instabilities & collective effects, sensitivities to imperfections
- Some of the EIC parameters and assumptions tested experimentally in RHIC: generation of and collisions with flat hadron beams, or extreme off-center/off energy operations to operate at different energies with the same revolution frequency

Feasibility of EIC Design Parameters: Generation of & collisions with flat hadron beam demonstrated in RHIC, emittance ratio $\frac{\varepsilon_y}{\varepsilon_x} = 0.09$

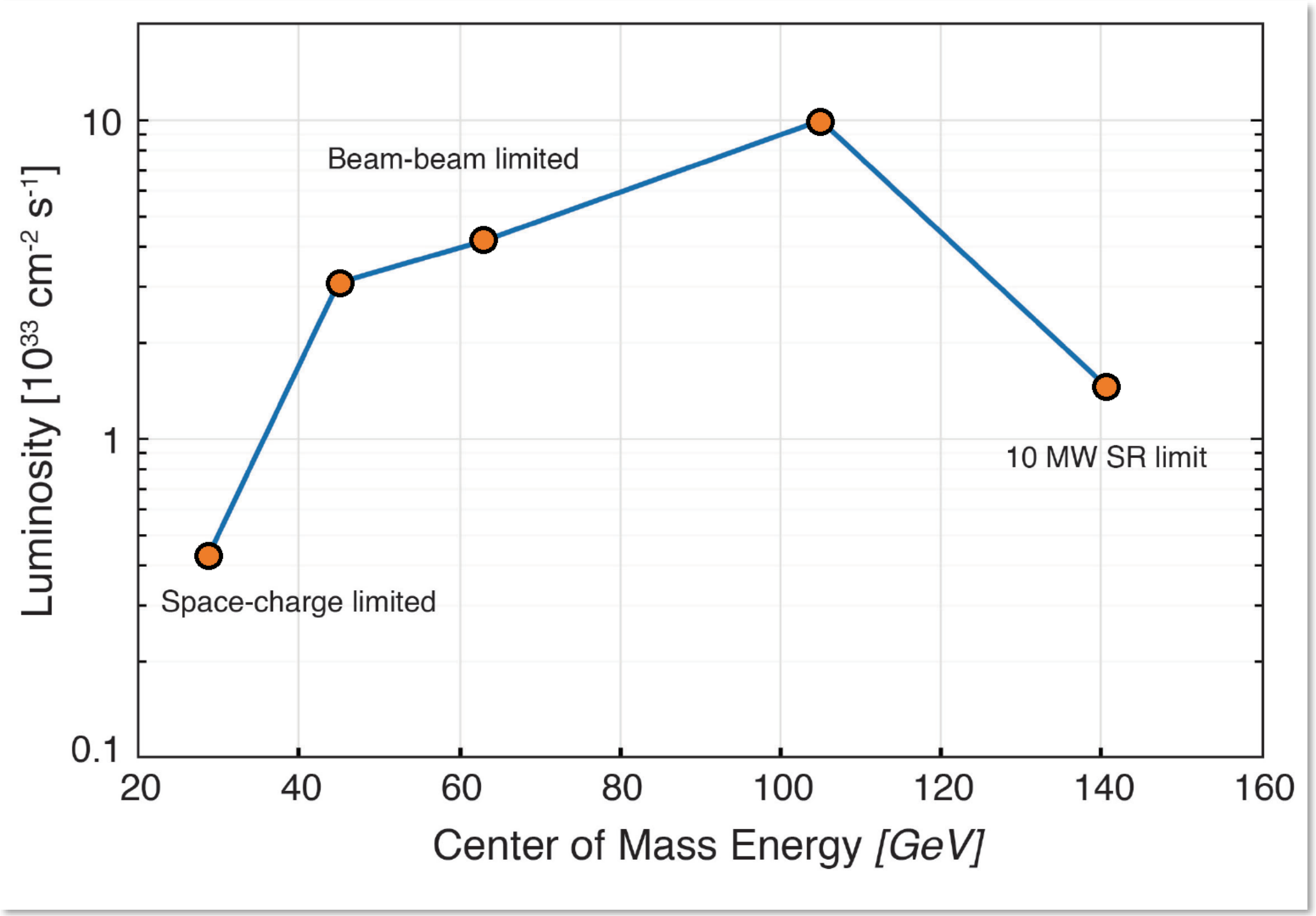


Facility layout

- "Yellow" RHIC ring as EIC Hadron Storage Ring
- RHIC hadron injector complex, with new, room temperature injection line to IR4
- 5 – 18 GeV Electron Storage Ring (ESR) in the same tunnel
- 750 MeV to 18 GeV Rapid Cycling Synchrotron (RCS) as electron injector in a separate, 1.4 km circumference tunnel
- Interaction Region (IR) with ePIC detector in IR6



Luminosity versus Center-of-Mass Energy



Parameters for Highest Luminosity

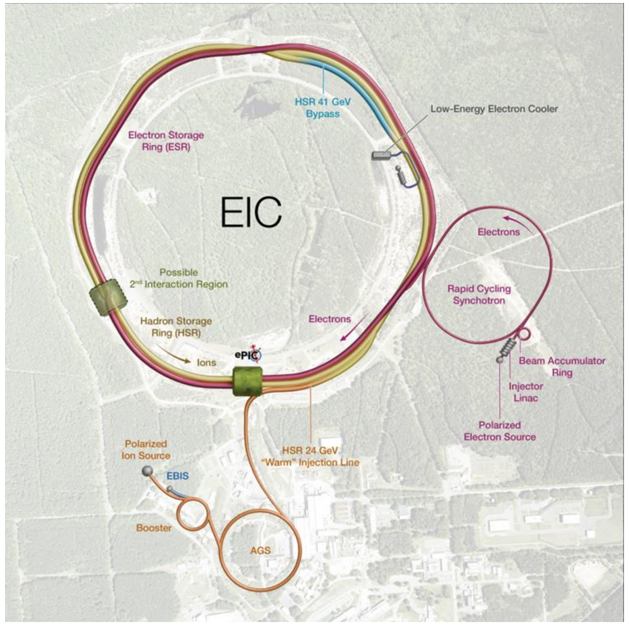
	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} (hor./vert.) [nm]	9.6/1.5	20/1.2
β^* [cm]	90/4	43/5
beam-beam parameter (hor./vert.)	0.014/0.007	0.073/0.100
σ_s [cm]	6	0.7
$\sigma_{dp/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} (transv./long.) [h]	3.4/2.0	N/A
L [10^{33} cm^{-2}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 (PEP-II, KEKB)

The EIC Hadron Storage Ring HSR

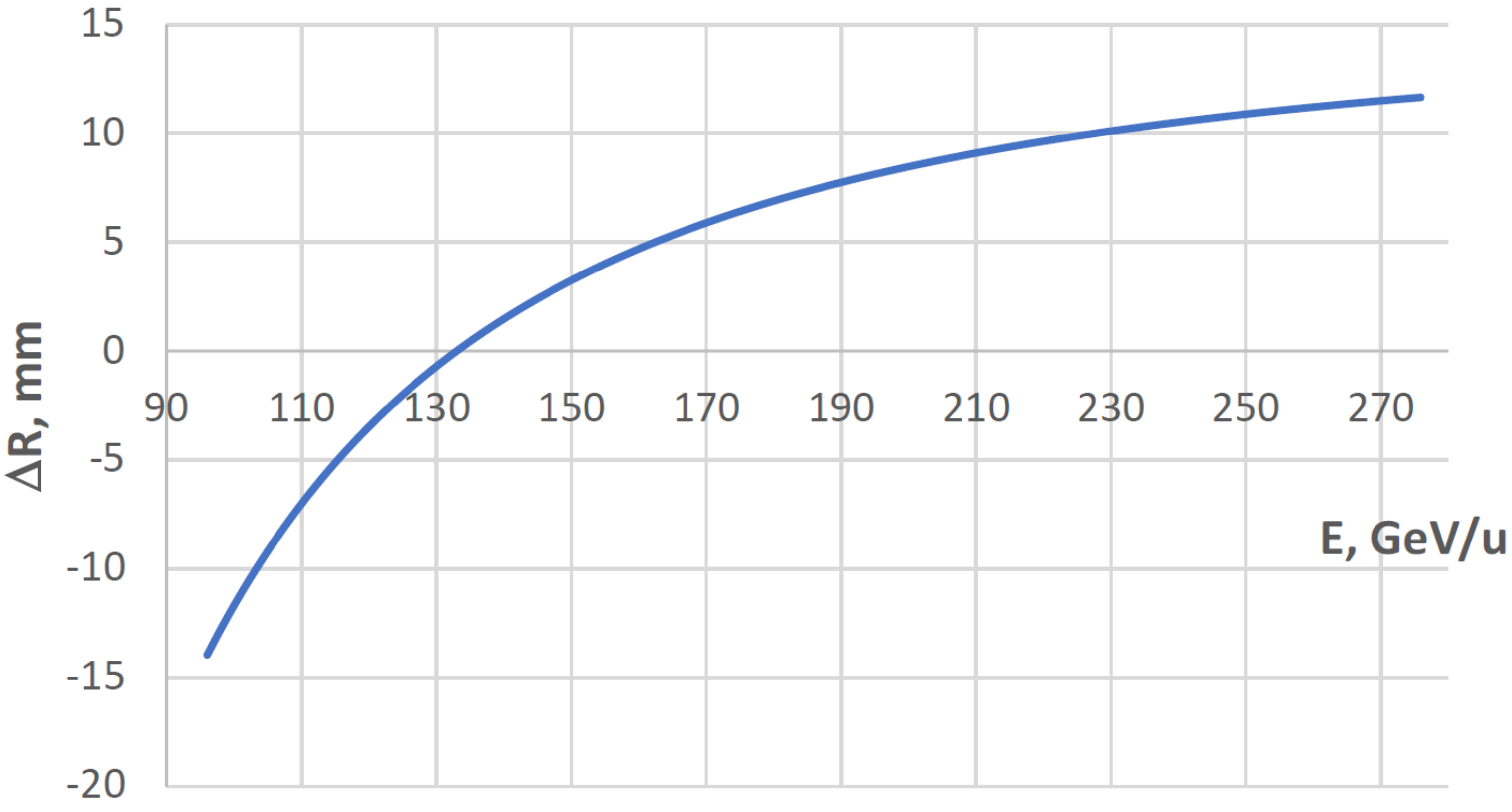
Tripled beam current, shorter bunch length, shorter bunch distance, ‘flat’ beams with small vertical emittance

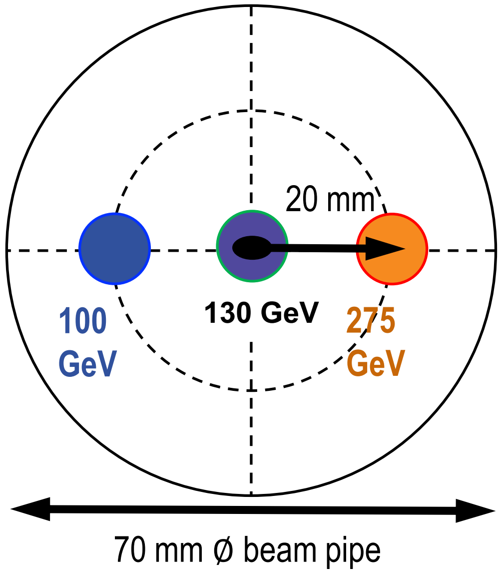
- EIC HSR to be composed of existing arcs of the Yellow RHIC ring (remove unused magnets)
- Insert sleeves coated with copper and amorphous carbon into superconducting magnet beam pipes to improve conductivity and reduce secondary electron yield (-> electron cloud)
- Add new RF cavities
- Add hadron cooling to create ‘flat’ bunches
- Add crab cavities, new IR SC magnets
- Add a collimation system



CD-3A: Actively Cooled Beam Screen Material procurement

Beam Energy and Average Orbit Radius in the HSR

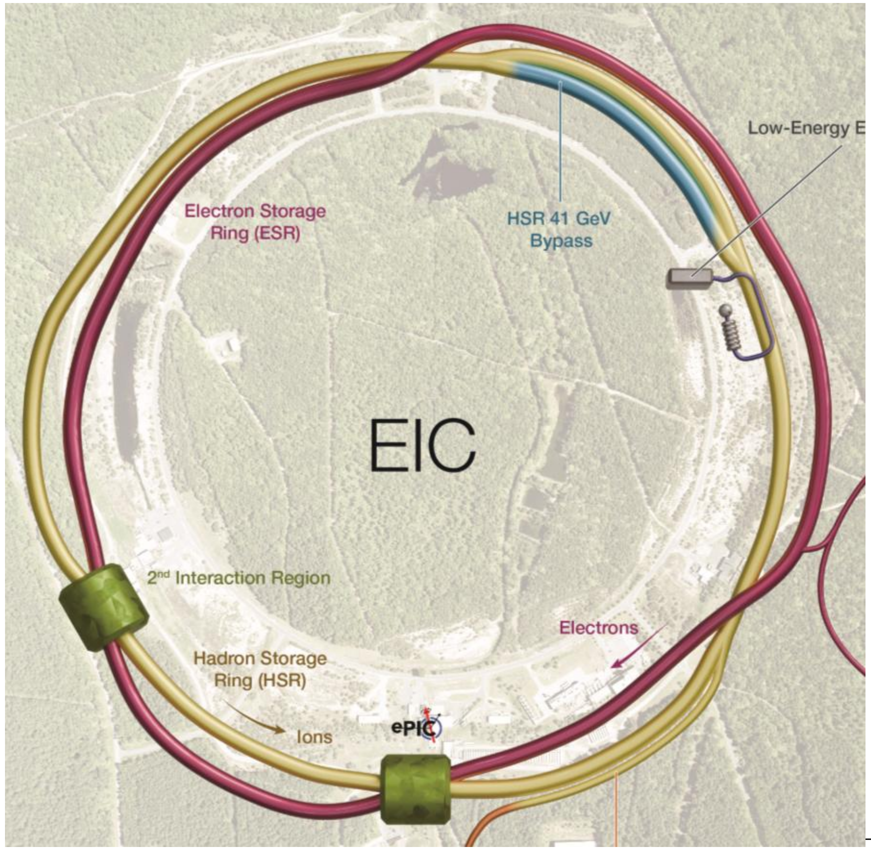




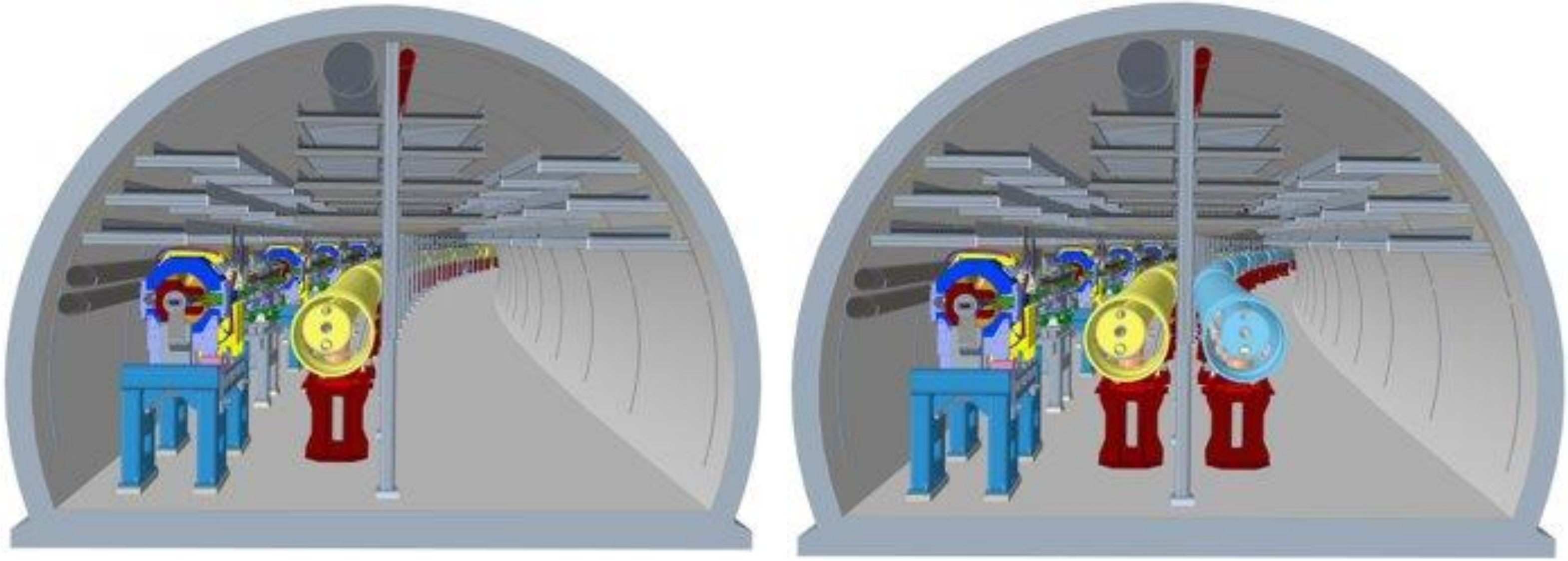
Since the electron revolution frequency is fixed, the hadron orbit must be adjusted with energy to keep the collisions in sync.

Demonstrated at RHIC

The 41-GeV ‘bypass’



Sector 1 without and with the 41-GeV bypass line

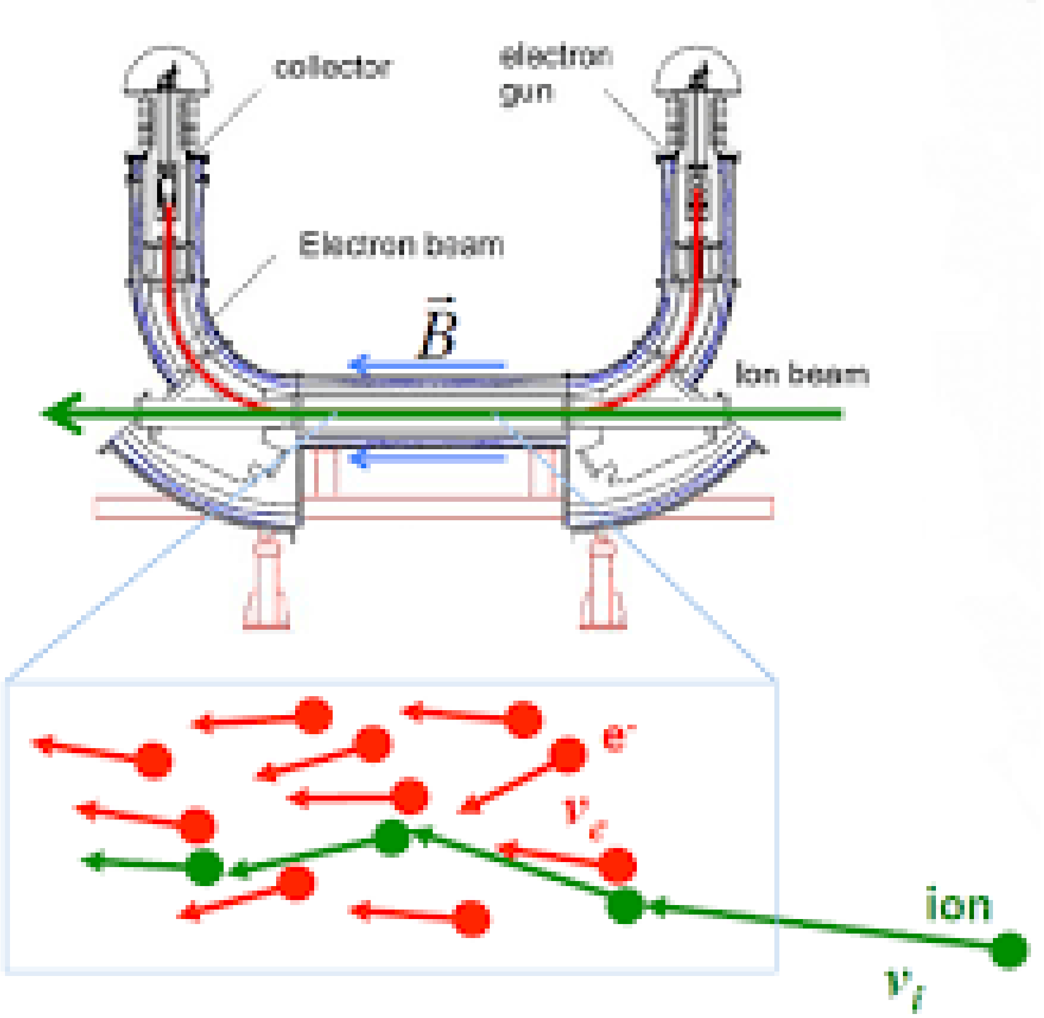


Intra-beam Scattering (IBS)

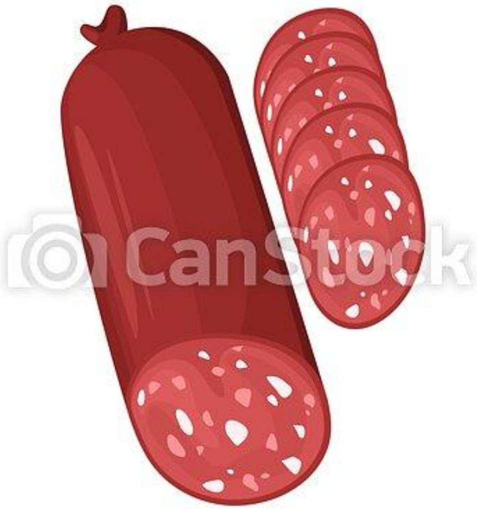
- Individual particles in the beam are focused by the magnets
- As a result, individual particles are constantly moving within the bunch
- As particles pass each other, they scatter off each other
- This multiple scattering results in emittance growth – the denser the bunch, the faster the growth
- If 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

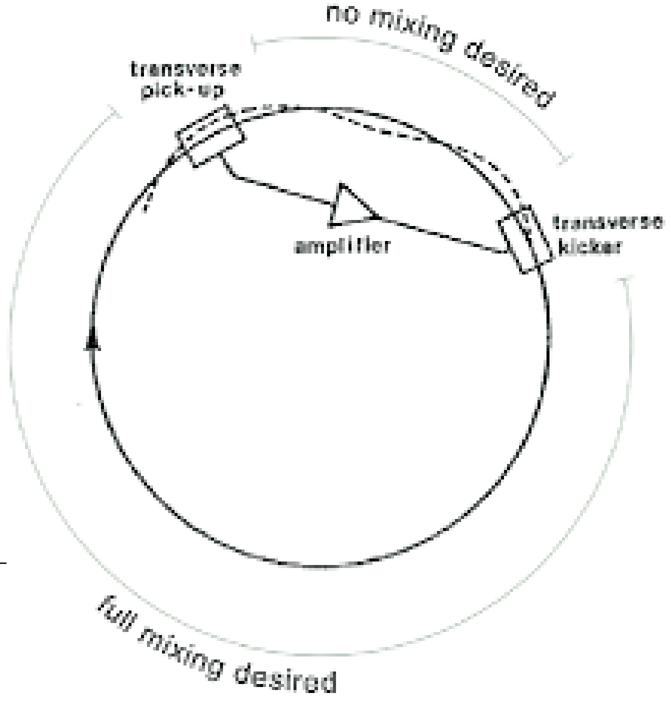
- Conventional electron cooling
  - Energy exchange between stored hadrons and an intense, “cold” (= low emittance) electron beam
  - Transverse cooling times scale as γ^5 - very challenging (but not impossible) above a few GeV



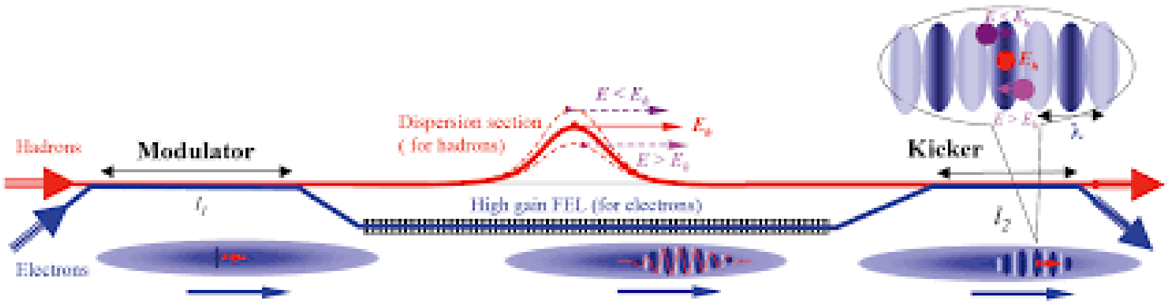
Hadron Beam Cooling



- 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



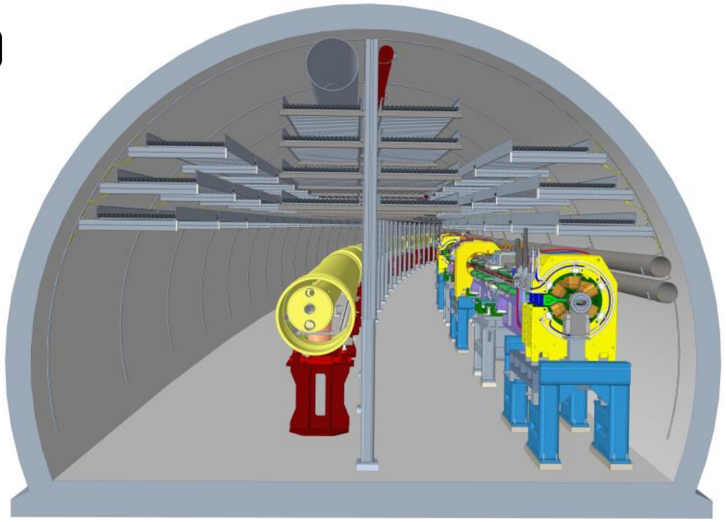
Hadron Beam Cooling

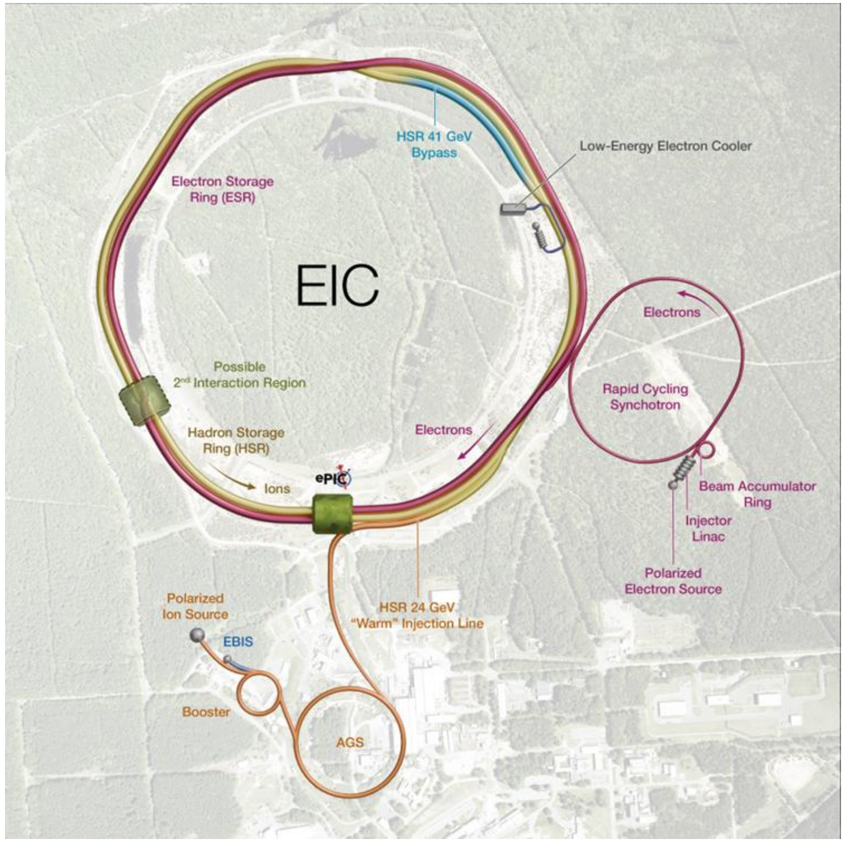


- Coherent electron cooling
  - Essentially, an ultra-high bandwidth stochastic cooling system
  - Instead of conventional pick-up, amplifier and kicker, and electron beam serves as pick-up and kicker
  - Hadron beam distribution is imprinted on electron beam
  - This imprinted signal is amplified, for 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

EIC 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)



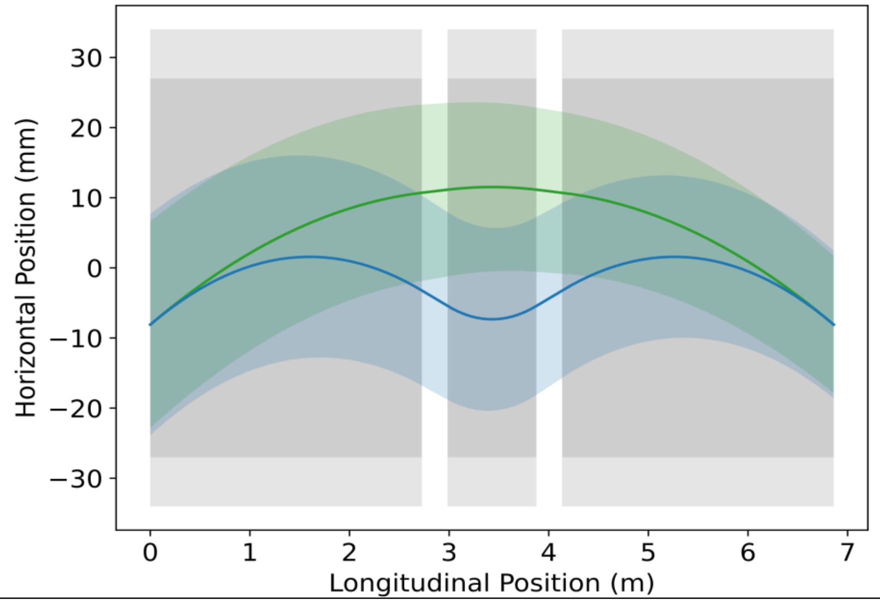


Emittance Control in the ESR

- EIC needs nearly constant (20 to 24 nm) emittance from 5 to 18 GeV for optimum luminosity, but equilibrium emittance in an electron storage ring depends on beam energy:

$$\epsilon_x = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2}, \qquad \text{with} \quad C_q = \frac{55}{32\sqrt{3}}\frac{\hbar c}{mc^2}$$

- 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 yield 20 nm at 10 GeV, 24 nm at 18 GeV
  - "Super-bends" (reverse bends) for emittance generation below 10 GeV – pole width accommodates the ~20 mm orbit variation
  - Rotating coil field measurements to be taken along different paths to reflect these orbit changes
  - Feed-down due to off-center orbits taken into account in dynamic aperture tracking

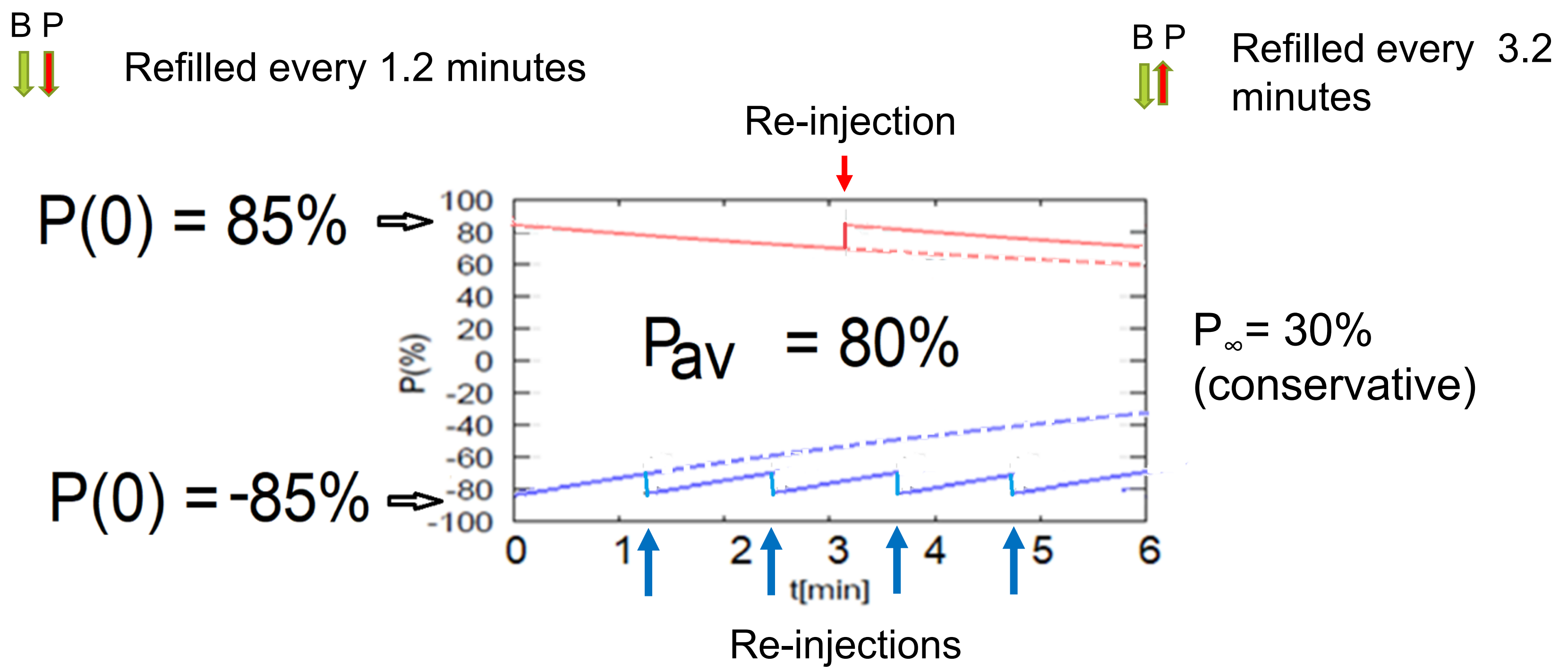


EIC Electron Polarization

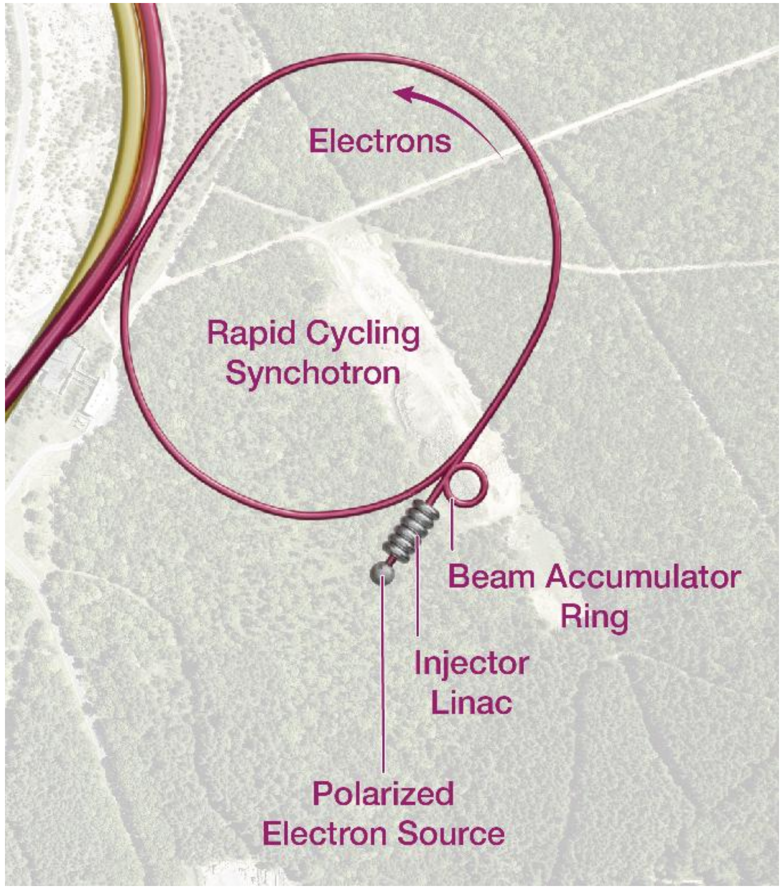
- Physics program requires bunches with spin "up" and spin "down" (in the arcs) to be stored simultaneously
- Sokolov-Ternov self-polarization would produce only polarization anti-parallel to the main dipole field
- Only way to achieve required spin patterns is by injecting bunches with desired spin 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

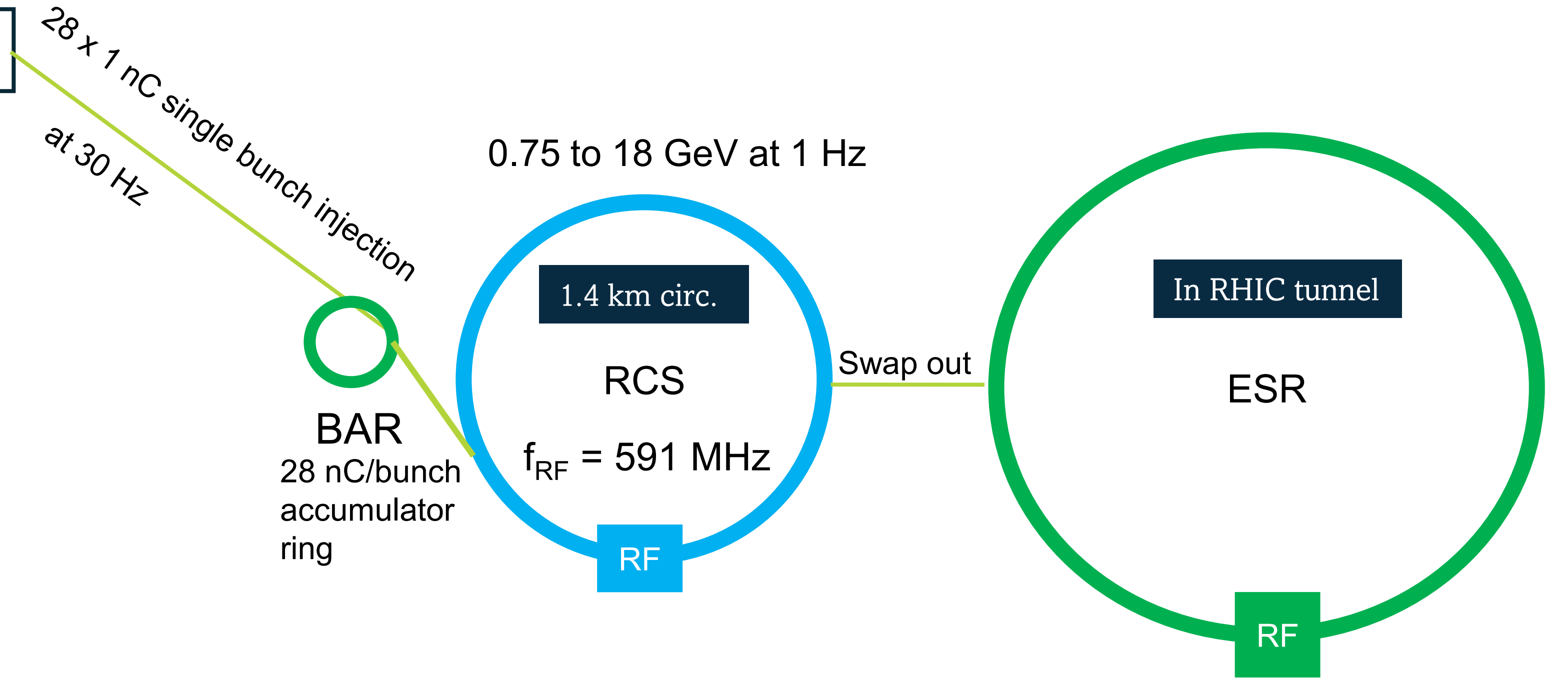
Electron polarization in the ESR

- Frequent injection of bunches with high initial polarization of 85%
- Initial polarization decays towards P_∞
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 1Hz



Electron Injector System





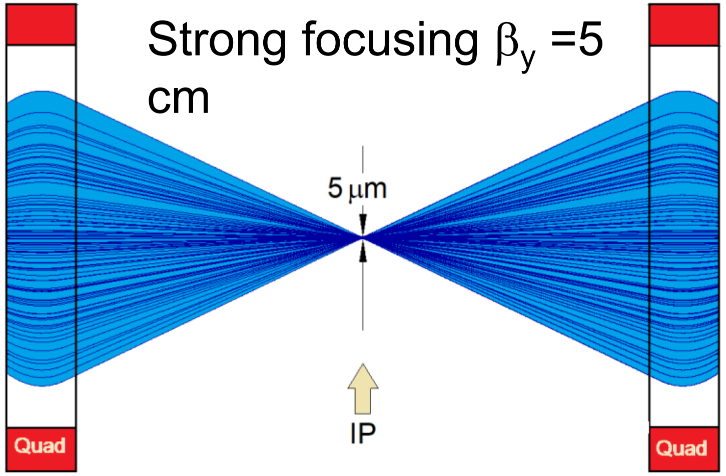
Rapid Cycling Synchrotron in new, separate 1.4 km tunnel

- Spin transparent due to high periodicity, high vertical tune
- Frees up valuable space in collider tunnel

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

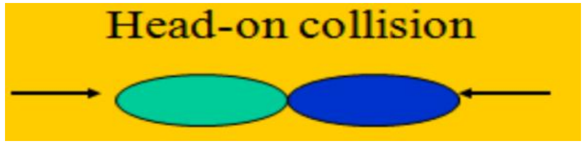


Focusing elements for both beams need to be as close as possible to the IP

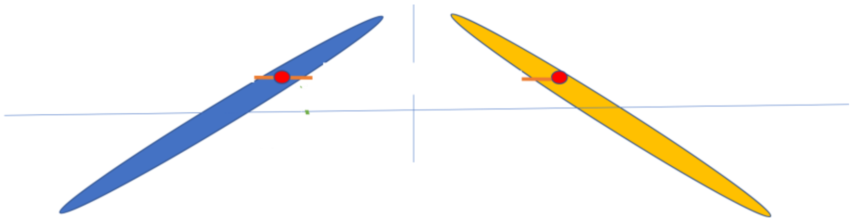
Crossing angle collisions

- 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



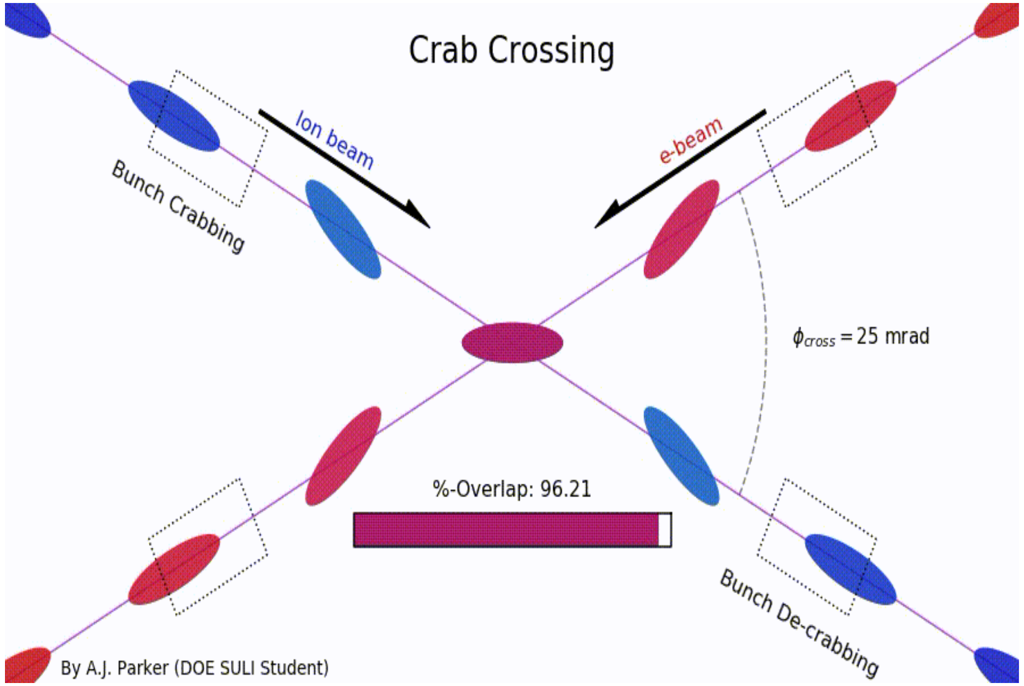
- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



- 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

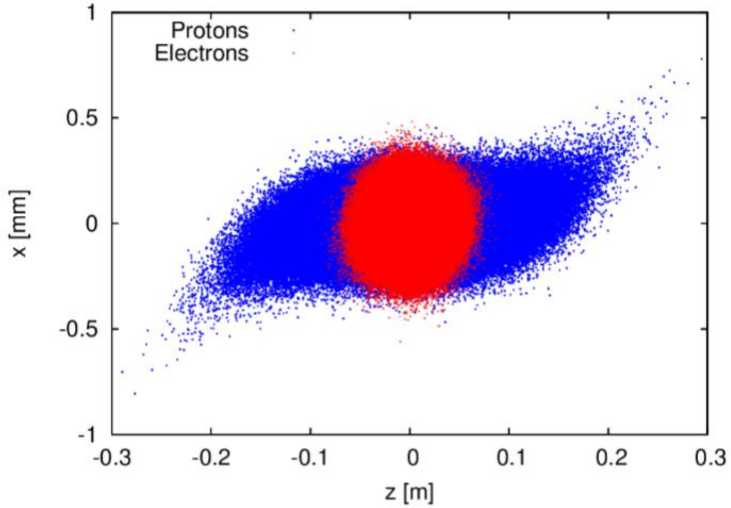
Crab Crossing to the Rescue

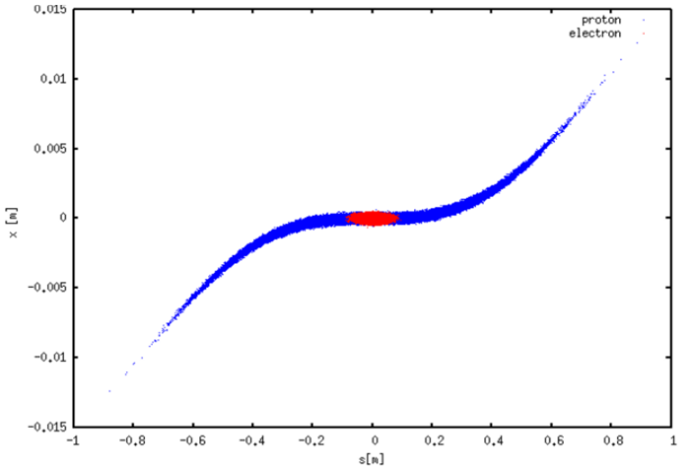
- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction



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)



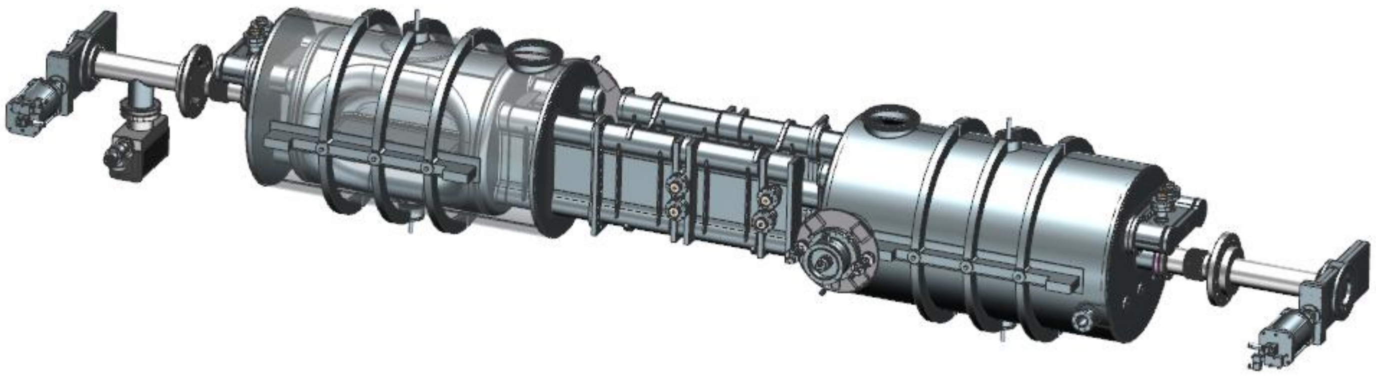


Au's RMS bunch length: 18 cm !

197 MHz Crab Cavity - Design & Prototyping

Cryomodule

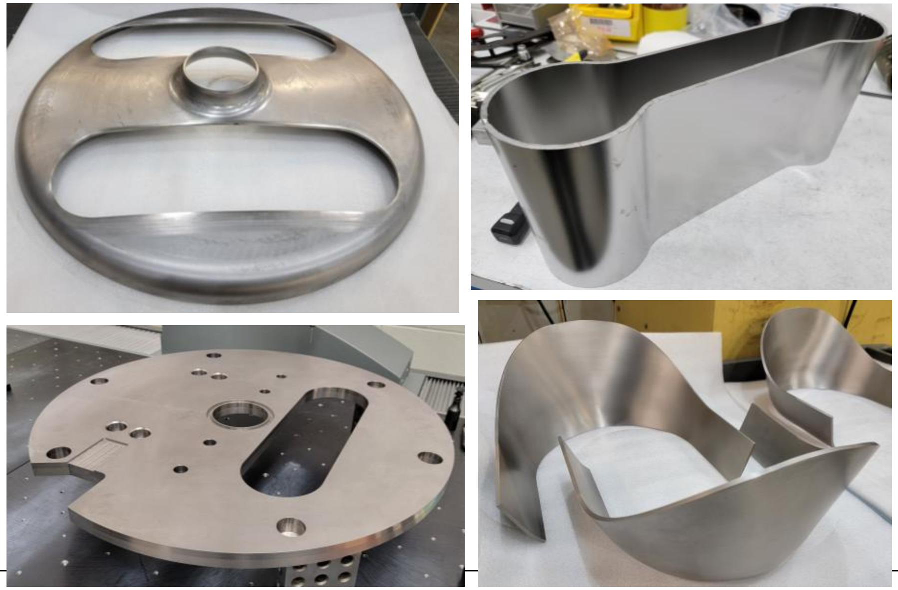
- Each cryomodule has two 197 MHz crab cavities
- HOM Dampers are installed on superconducting 'dogbone' waveguides, shown between the cavities
- The size of the cavities and cryomodule create challenges in assembly and integration into the tunnel
- The cavity string went through a Preliminary Design Review in 2024



197 MHz Cavity String

Design Verification Component (DVC)

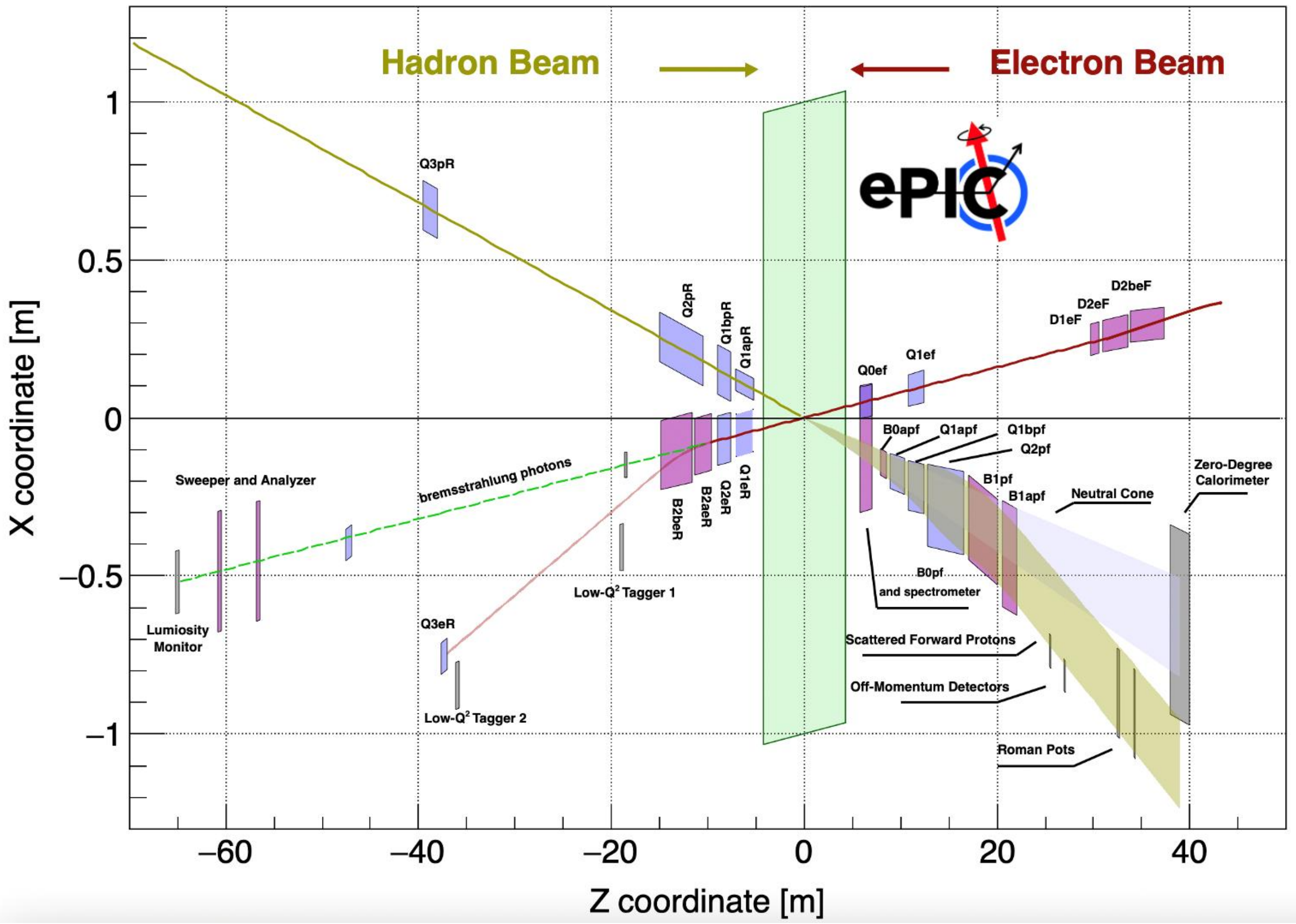
- A prototype (DVC) cavity is being fabricated in-house at JLab
- The cavity will be tested at 2K in the JLab VTA
- EBW of niobium parts for the cavity is currently underway



EIC Near-detector IR Layout

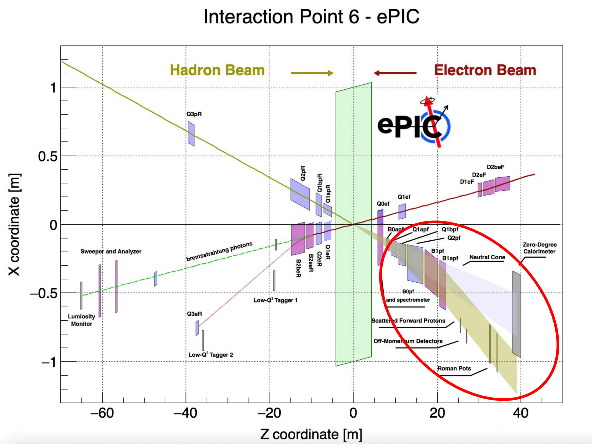
- IR based on 25 mrad total crossing angle, compensated by crab crossing
- No electron dipoles within ~30 meters upstream of detector
- Large aperture superconducting magnets to accommodate forward scattered particles and synchrotron radiation photons
- Note: Colored “boxes” indicate magnet *apertures*

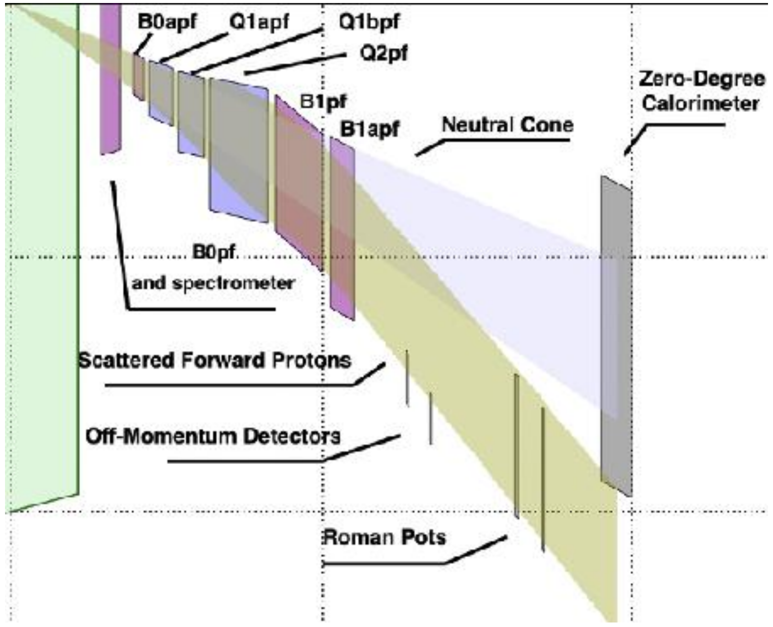
Interaction Point 6 - ePIC



Forward Acceptance

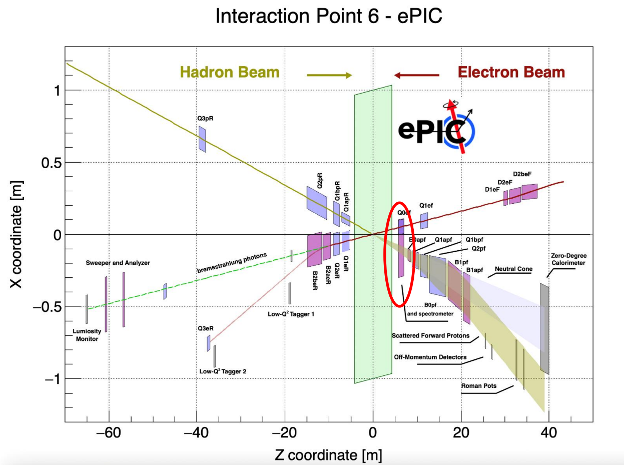
- Physics requires detection of charged particles with transverse momentum 200 MeV/c < p_t< 1.3 GeV/c
- These particles are detected by “Roman Pots” along the forward hadron beamline, at about 10σ from the central orbit
- For scattered particles to be detectable in Roman pots at 10σ, their scattering angle at the IP must be greater than 10σ'. This constrains the beam divergence and therefore the lowest hadron β^*
- For p_t = 1.3 GeV/c, and for the +/- 4 mrad neutron cone, hadron magnet apertures in the forward direction must be large enough to allow these particles to pass through

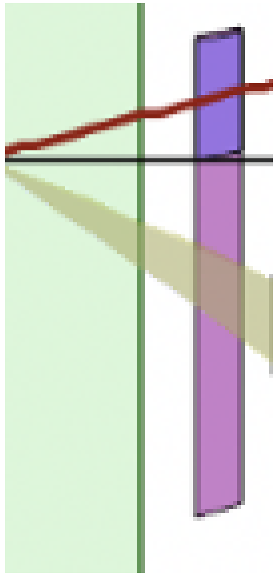




Forward Spectrometer – the B0pF Magnet

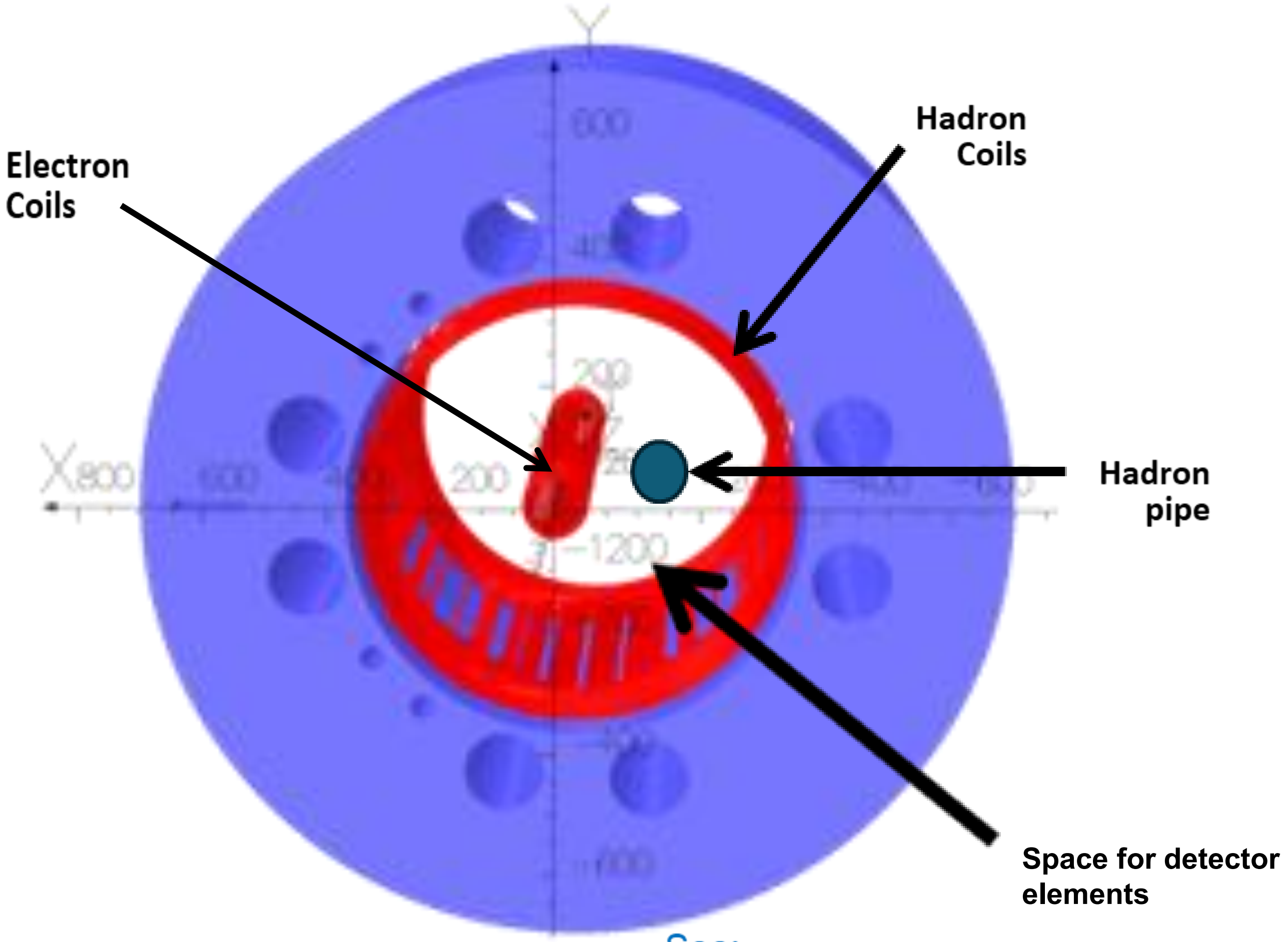
- Spectrometer “dipole” B0pF adjacent to main detector on “forward” side
- Large aperture combined function magnet, with detector elements inside
- Electron quadrupole Q0eF inside B0pF aperture





Forward Spectrometer – the B0pF Magnet

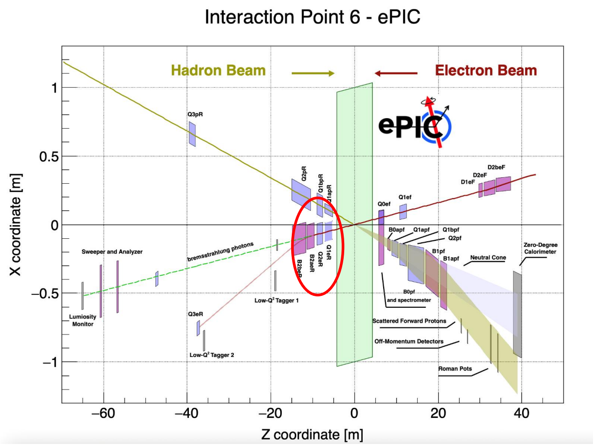
- B0pF is actually a combined function magnet aligned with electron orbit, thus minimizing dipole field on electron orbit
- Quadrupole component of B0pF matches required quadrupole field for 10 GeV electrons
- Q0eF quadrupole to adjust gradient on electrons at 5 and at 18 GeV
- External field of Q0eF quadrupole impacts multipole harmonics on hadron beam

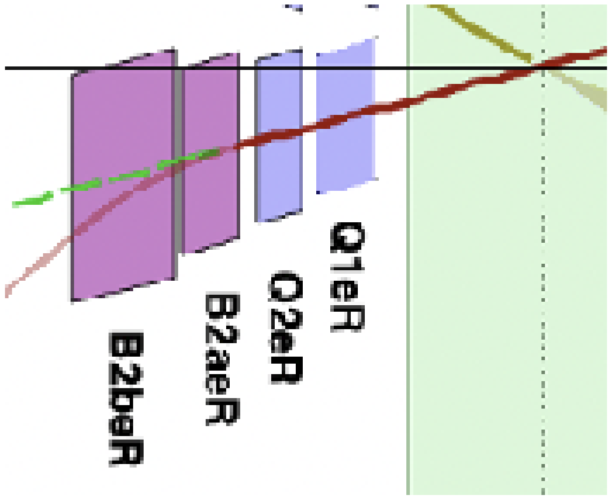


See:
IR SC magnets status, B. Wahl
IR SC magnets overview, P. Ferracin

Synchrotron Radiation

- Synchrotron radiation is generated in upstream ("forward") magnets
- Dipoles are placed far away and split into two segments (weak and strong bend) to further reduce synchrotron radiation power
- To avoid high photon background rates, radiation fan has to be passed through the detector beam pipe as well as through downstream ("rear") magnets to a faraway absorber
- Rear electron magnet aperture requirements are determined by synchrotron radiation photon fan, not by the much smaller electron beam itself

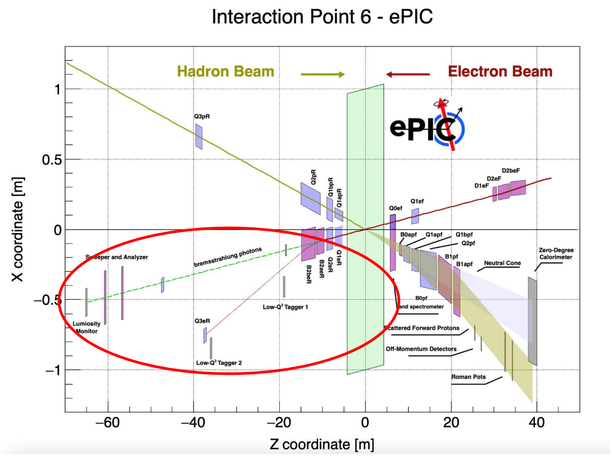


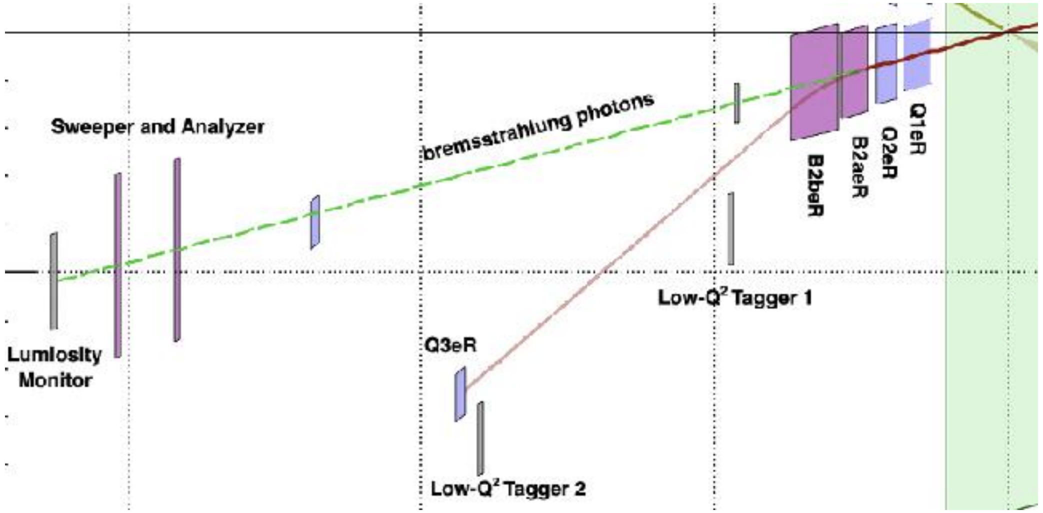


See:
Collimation and MPS, A. Natochii

Luminosity Measurement

- Luminosity measurement is based on Bethe-Heitler (bremsstrahlung) photons generated at the IP
- Bethe-Heitler photons travel within the synchrotron radiation fan
- Photon energy is much higher than synchrotron radiation – separation by exit window
- Exit window converts high energy photons into e+e- pairs that are detected in a tagger

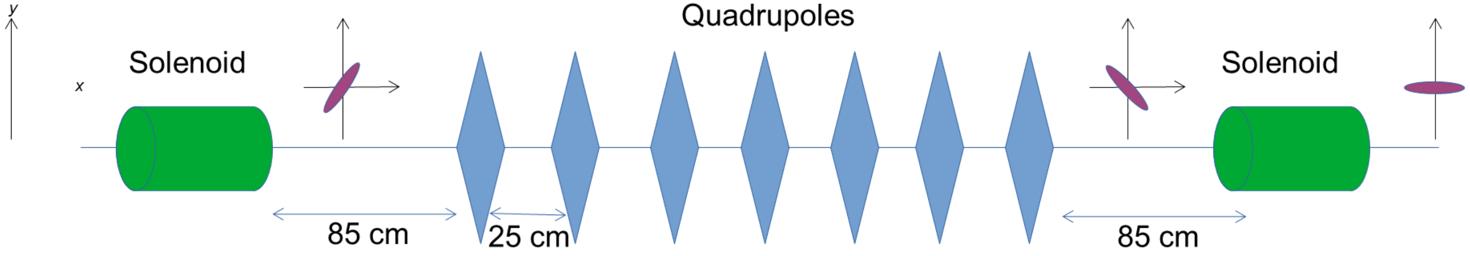




Spin Rotators

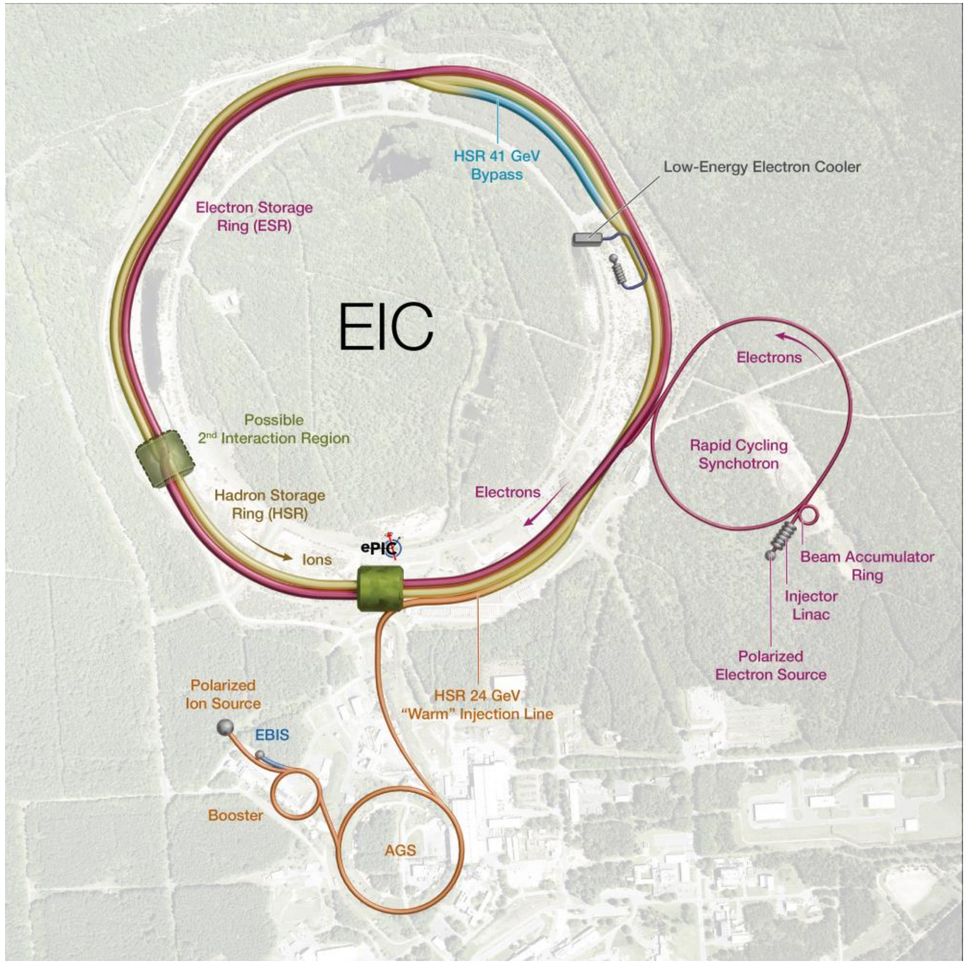
- Hadron spin rotators are based on helical dipoles – same as RHIC

- Electron spin rotators are based on superconducting solenoids – one set for 5 GeV (lowest energy) and one set for 18 GeV (highest)
- Each solenoid is split into two halves with normal-conducting quads in-between for local decoupling (no skew quads)



Summary

- The EIC is a very complex, challenging machine:
  - High luminosity
  - Polarized beams
  - Crab crossing
  - Beam cooling
  - Large energy range
  - Flat hadron beams
  - …
- EIC meets requirements laid out in the CD-0 Mission-need Statement
- A couple of crucial design changes were made, notably on the RCS
- Design is well underway, preparing for CD-2/3
- CD-4 envisioned in 2034



Backup Slides

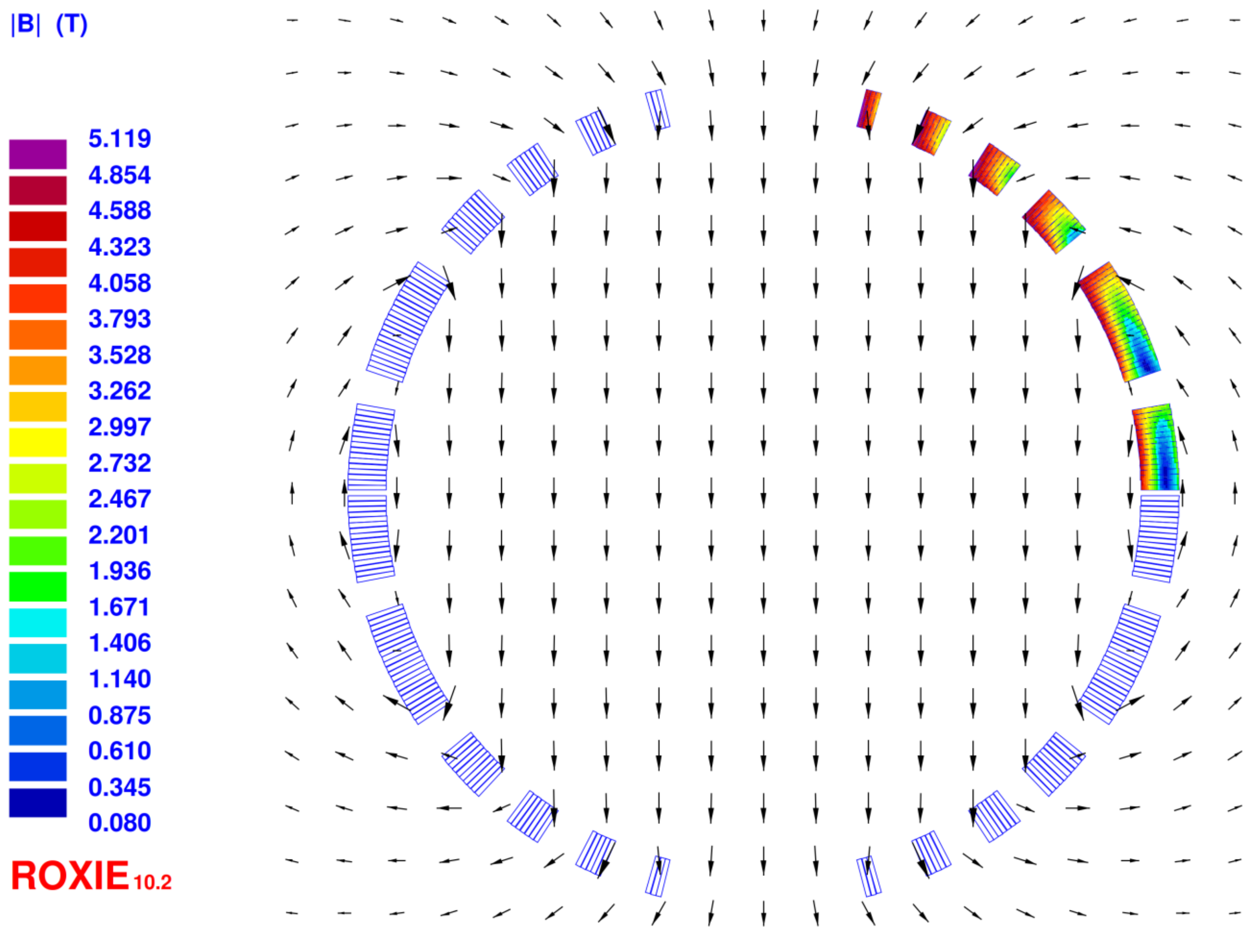
B1pF – Prototype Collared Magnet

Design Goals

Parameter	Requirement
Nominal Integrated Field	**10.344 T.m**
Total slot length	**3.0 m**
Aperture radius	**150 mm**
Reference Radius	**75 mm**
Operating Temperature	**1.9 K**
Harmonics	**All <1 unit**
Field in electron beam tube	**As low as possible**

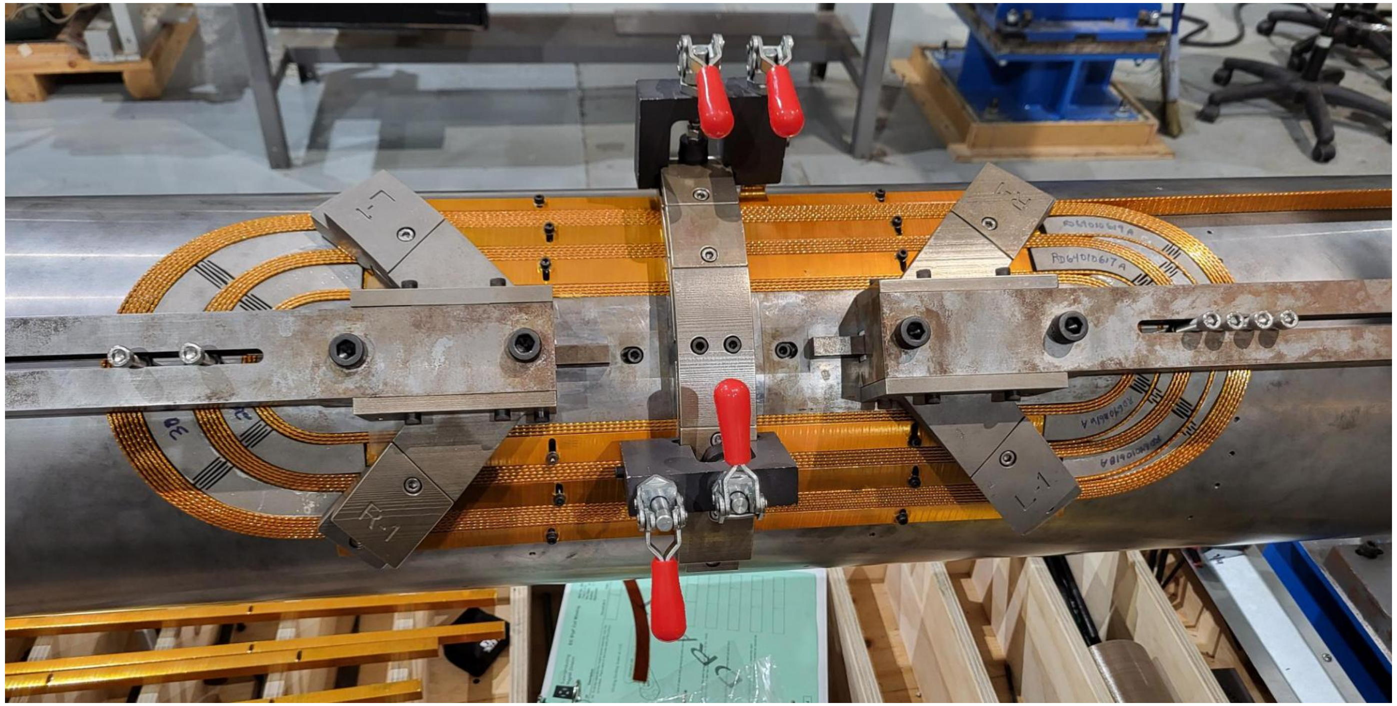
Optimized coil specs

Magnet Cross-section	Value
Number of Conductors per quadrant	63
Margin on the loadline	42.4 %
Reference Radius	75 mm
Nominal Current	11900 A
Central Field (R_{ref}=75 mm)	4.128 T
Diff. Inductance	26.7 mH
Max. peak field (on block 6)	5.1 T
Stored energy	1.89 MJ



SC Magnet Updates: Current status of B1pF prototype

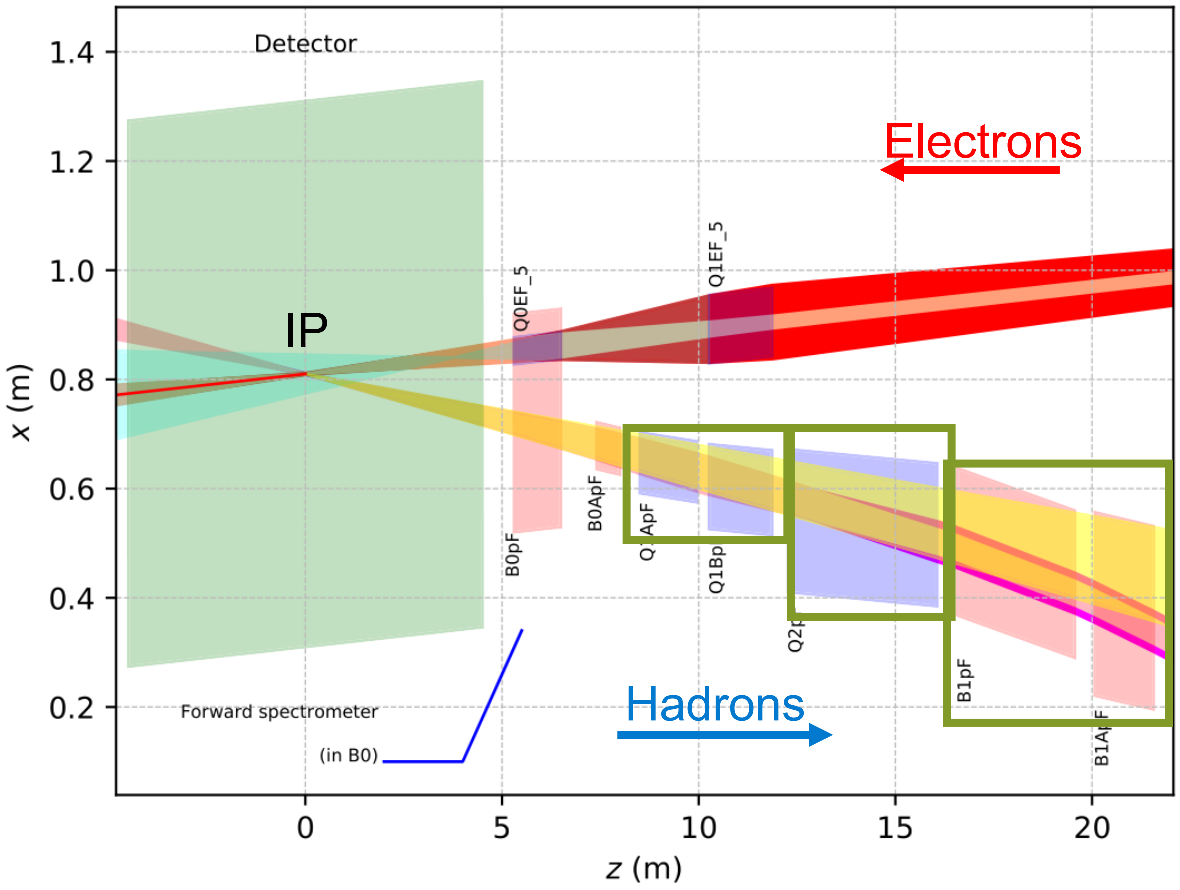
- Shown below are pictures of the B1pF Cable magnet prototyping effort underway at SMD.
- The image on the right is a complete half length coil just prior to being moved into the curing press.



Shown above is a test wind that was performed in July/Aug 2024

Tapered CCT Magnets Hadron Forward Side

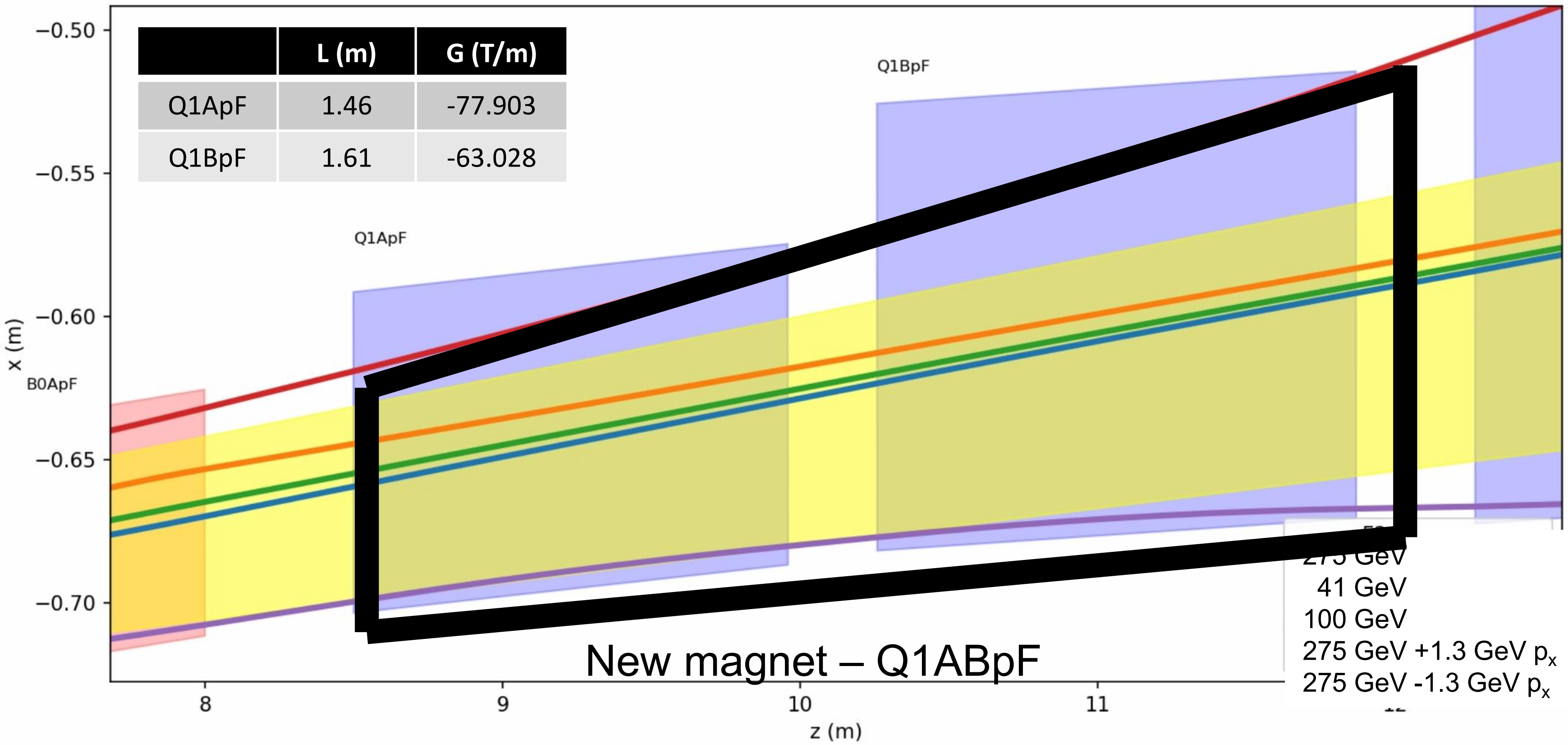
- Idea: replace hadron forward collared magnets
- Instead of 5 collared magnets: 3 tapered CCT magnets
  - Q1ABpF
  - Q2pF
  - B1/B1ApF
- Technically and financially attractive
  - Eliminates/reduces beam going through quads at an angle/off center
  - Frontloading of gradient
  - Reduces crosstalk



Q1ABpF – New Magnet Concept

Recombining Q1ApF and Q1BpF
(similar for other magnets)

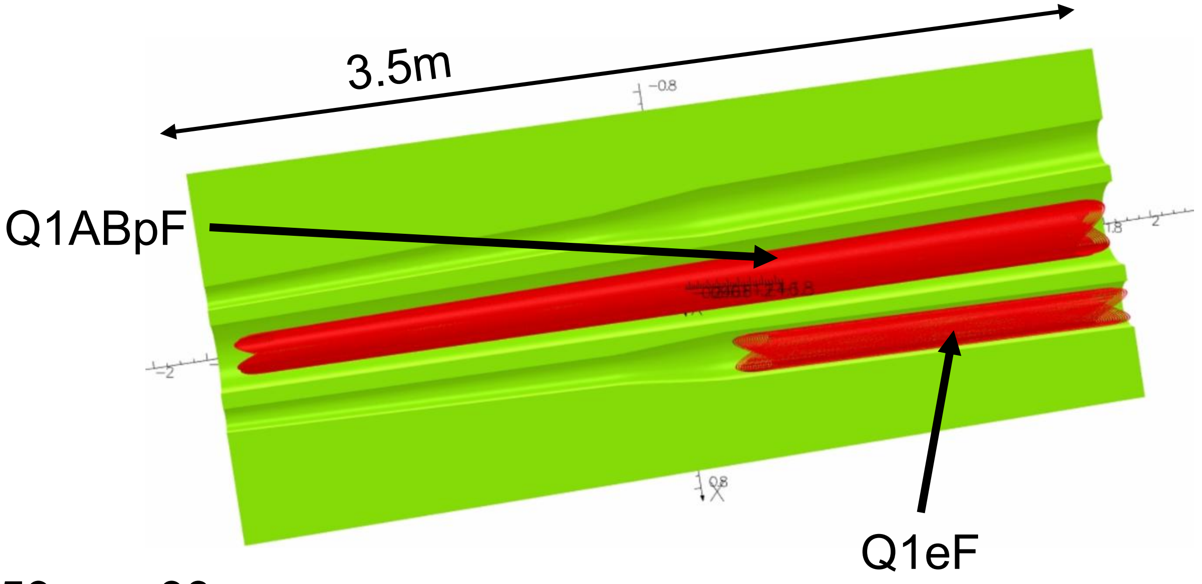
	L (m)	G (T/m)
Q1ApF	1.46	-77.903
Q1BpF	1.61	-63.028



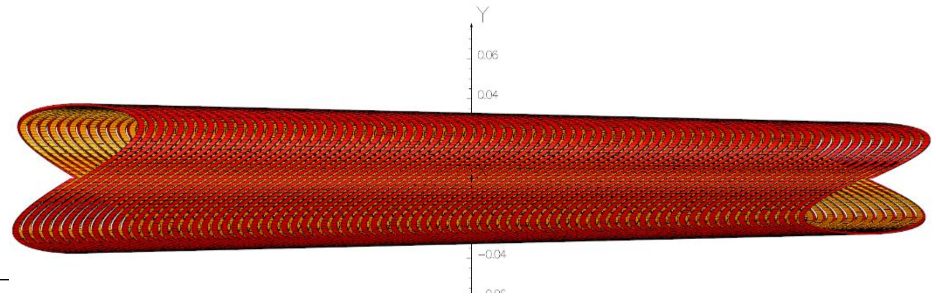
Advantages: No end plates, making use of additional space between magnets
Smaller aperture at IP side, can tune field/gradient for crosstalk

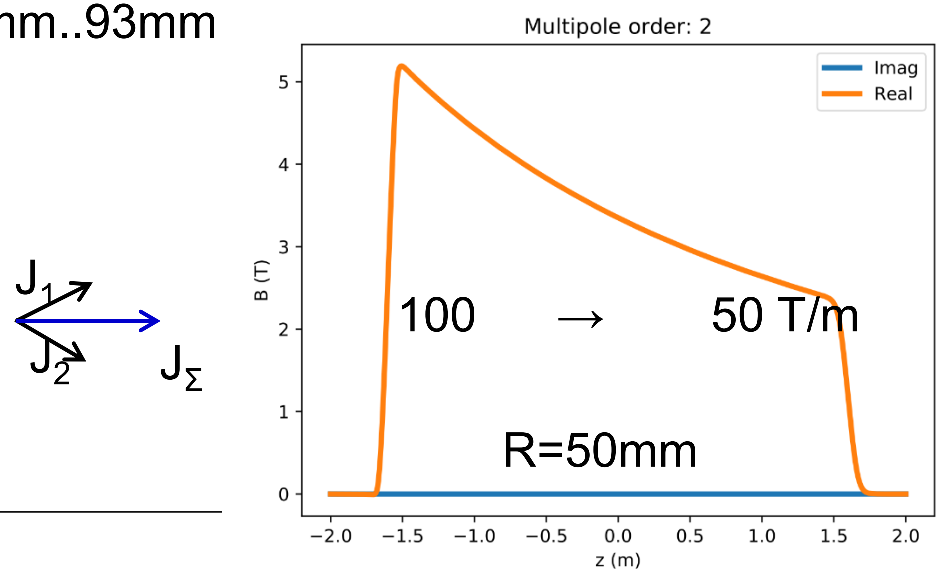
Q1ABpF: Implementation

- CCT
  - Allows to cancel unwanted harmonics
  - Modulation of gradient
- Frontloading of gradient
- Helps crosstalk / field quality
  - Better utilization of space
  - Can tailor maximum gradient
- Challenges
  - Need to prove that this works mechanically (no collar)
- Requirements
  - Integrated gradient 215T
  - Very good field quality
- **Design needs to be updated**
  - Q1ABpF prototype experience



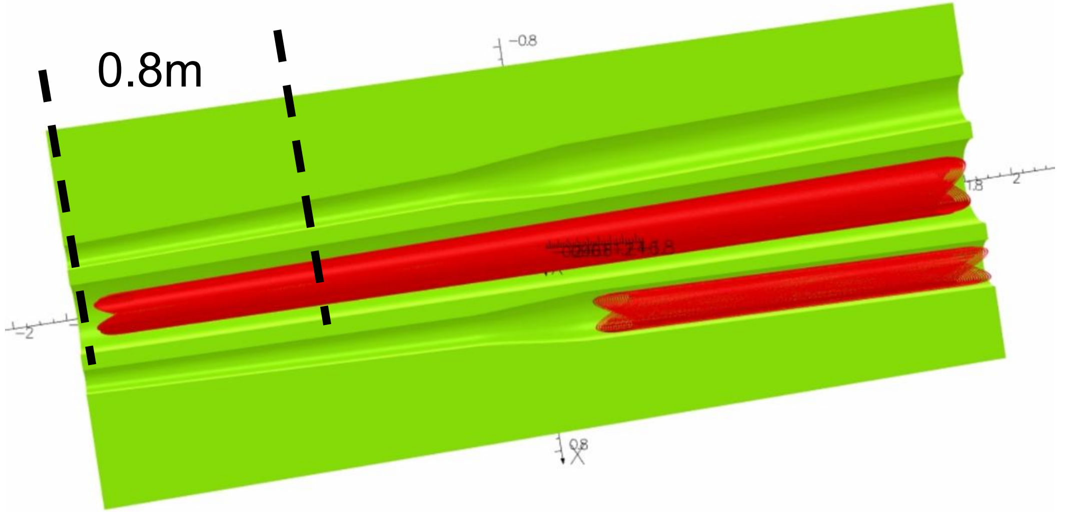
Radius=59mm..93mm

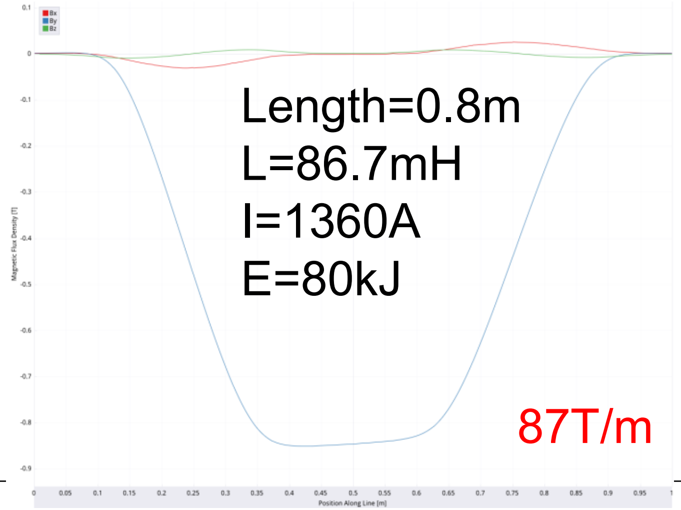




Q1ABpF – Short Prototype

- Short Q1ABpF: driven by schedule considerations
- Design features
  - ~0.84m from IP end
    - High gradient/field
  - Can be done with cable/strand at hand
  - Reduction of layers from 16 to 12
    - Accomplished by adjusting spacing/tilt angle
    - Reduces winding time
    - Crosstalk
- Goals
  - Demonstrate feasibility of Q1ABpF (full length version)
  - Feasibility of large aperture, high gradient direct wind quadrupole

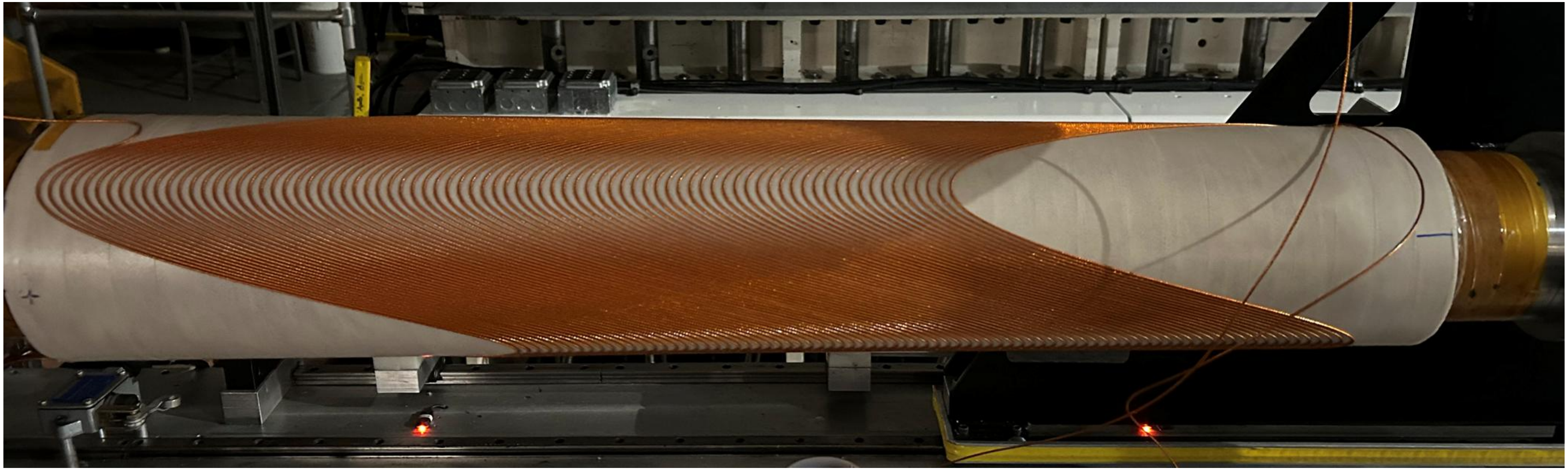




SC Magnet Updates : Current status of Q1ABpF

Tapered dipole

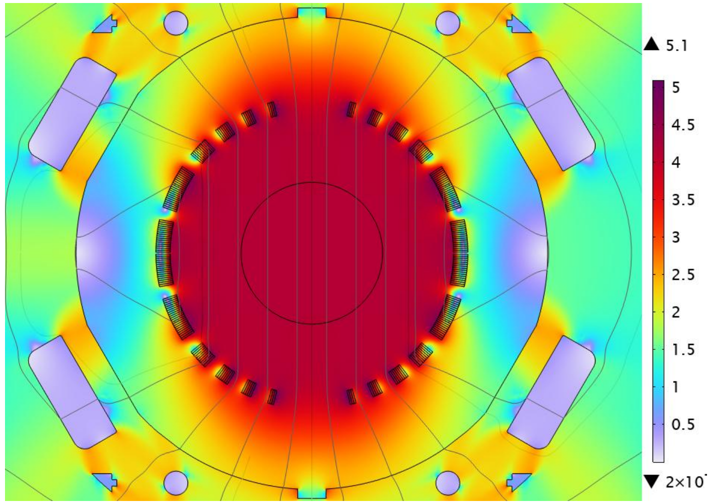
All 12 layers successfully completed in February

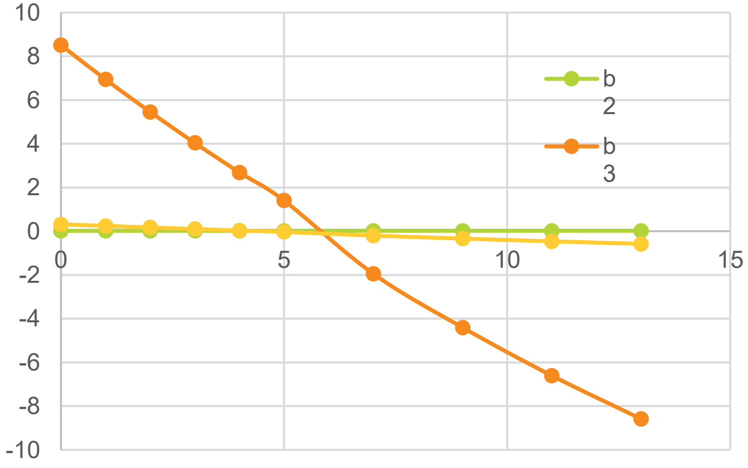


First layer

Magnet Shimming – Tunability

- Using two shims in dedicated cutouts, b3 can be tuned by a range of (+9.8→ -8.6) units
- B5 can be tuned to (+0.5→-1.0) units
- Additional tunability can be achieved by adding further shims on the coil wedges





Harmonics as a function of Shim 1 depth