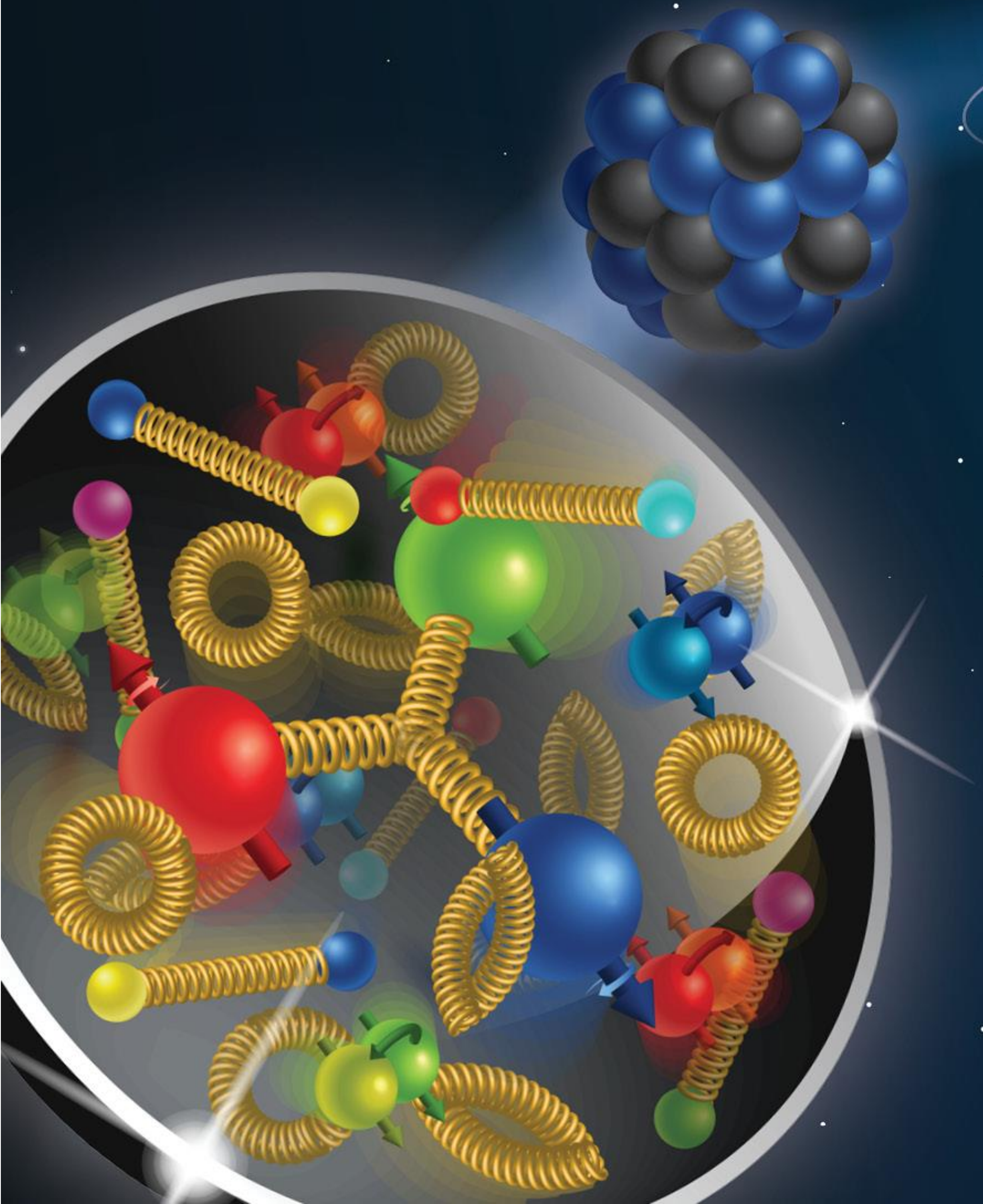


Update about the Accelerator and IR

Christoph Montag, BNL
ePIC Meeting, Warsaw
July 26 - 29 2023

Electron-Ion Collider

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

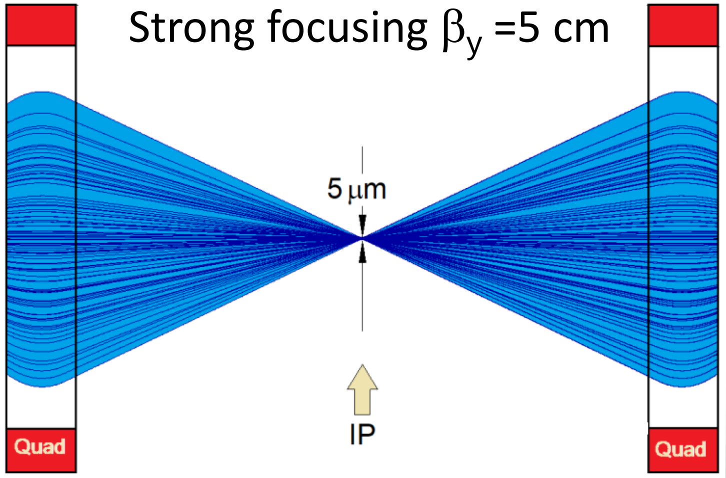
EIC Interaction Region Requirements

- High luminosity
- High p_t acceptance
- Detection of neutral particles (neutrons, photons,…)
- Longitudinal polarization
- Safely pass synchrotron radiation through the detector

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 ε)
- Beam-beam force scales as 1/ε – beam dynamics prefers large emittance
- For a given beam (= fixed emittance), a smaller IP beam size means larger divergence
- Two configurations: High luminosity vs. high p_t acceptance
- 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

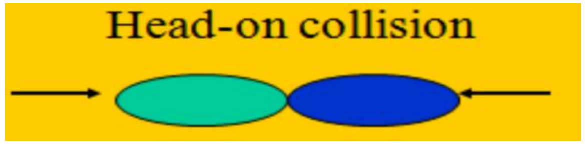


Focusing elements for both beams need to be as close as possible to the IP

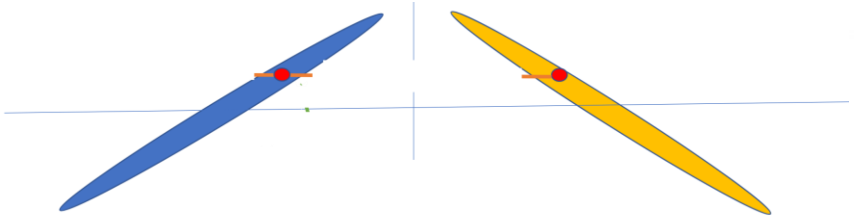
Crossing Angle Collisions

- 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



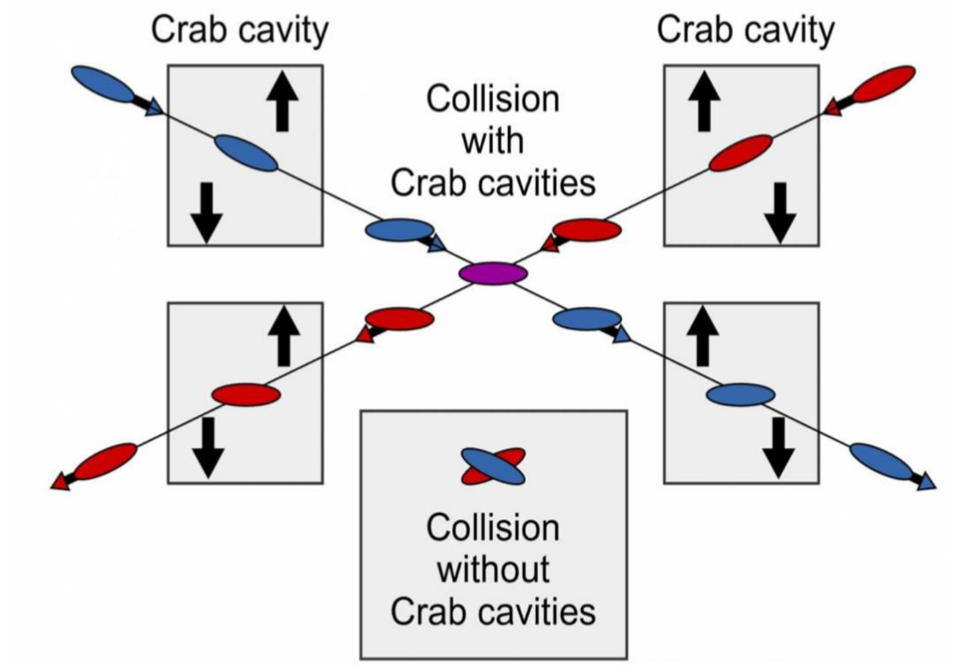
- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



- 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

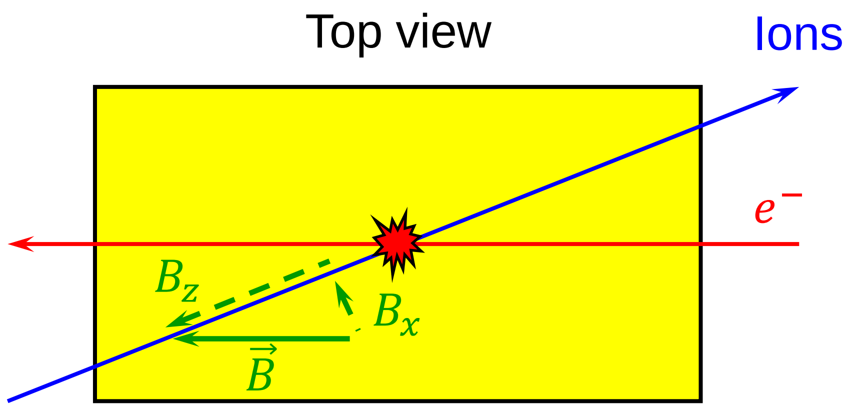
- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction

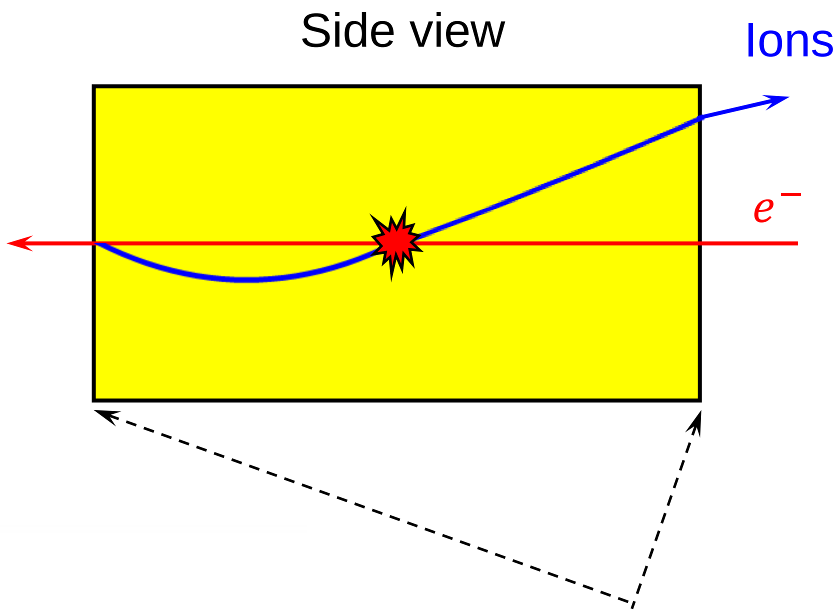


Detector Solenoid Effects

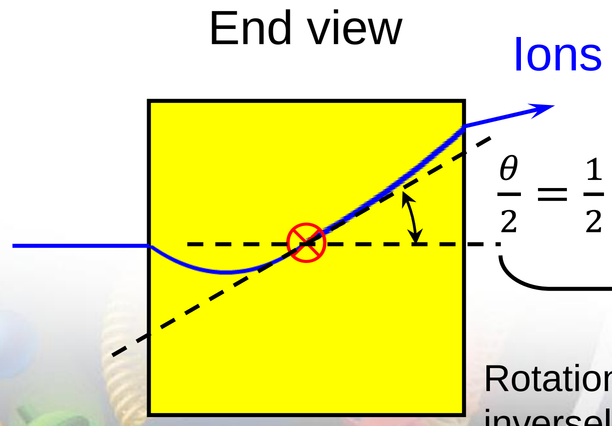
- Coherent orbit distortion
- Transverse coupling
- Rotation of the crabbing plane
- Polarization tilt

Coherent Distortion of Ion Orbit





Vertical kicks by the solenoid fringe fields



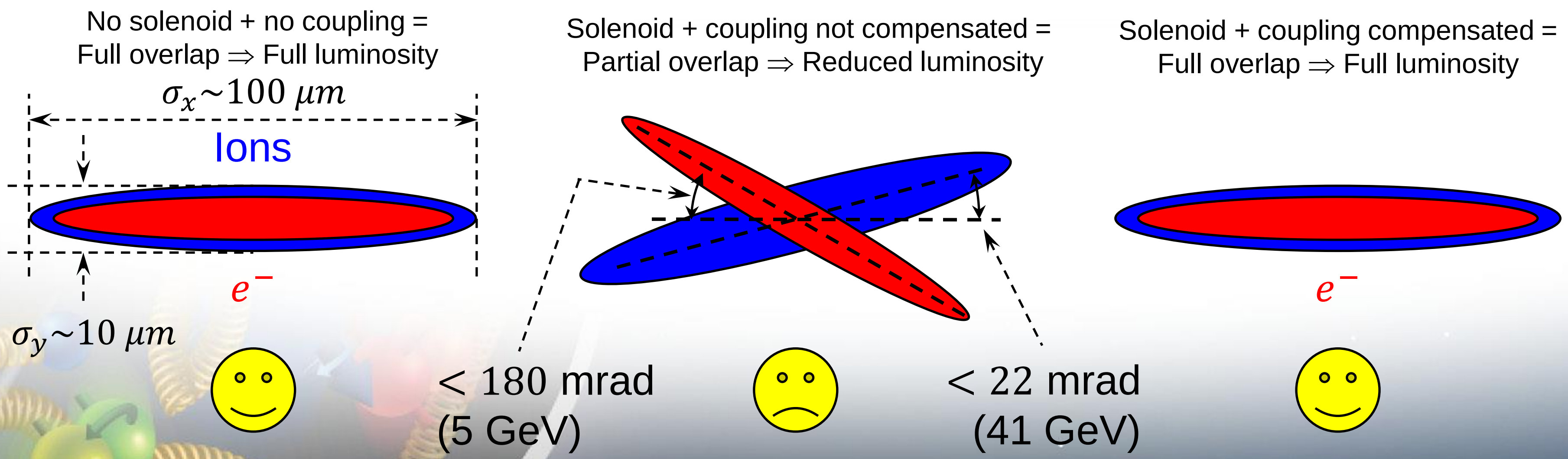
$$\frac{\theta}{2} = \frac{1}{2}\frac{B_{sol}L}{2B\rho} < 22\ \text{mrad (41 GeV)}$$

Rotation of the interaction plane inversely proportional to the beam energy

Transverse Coupling

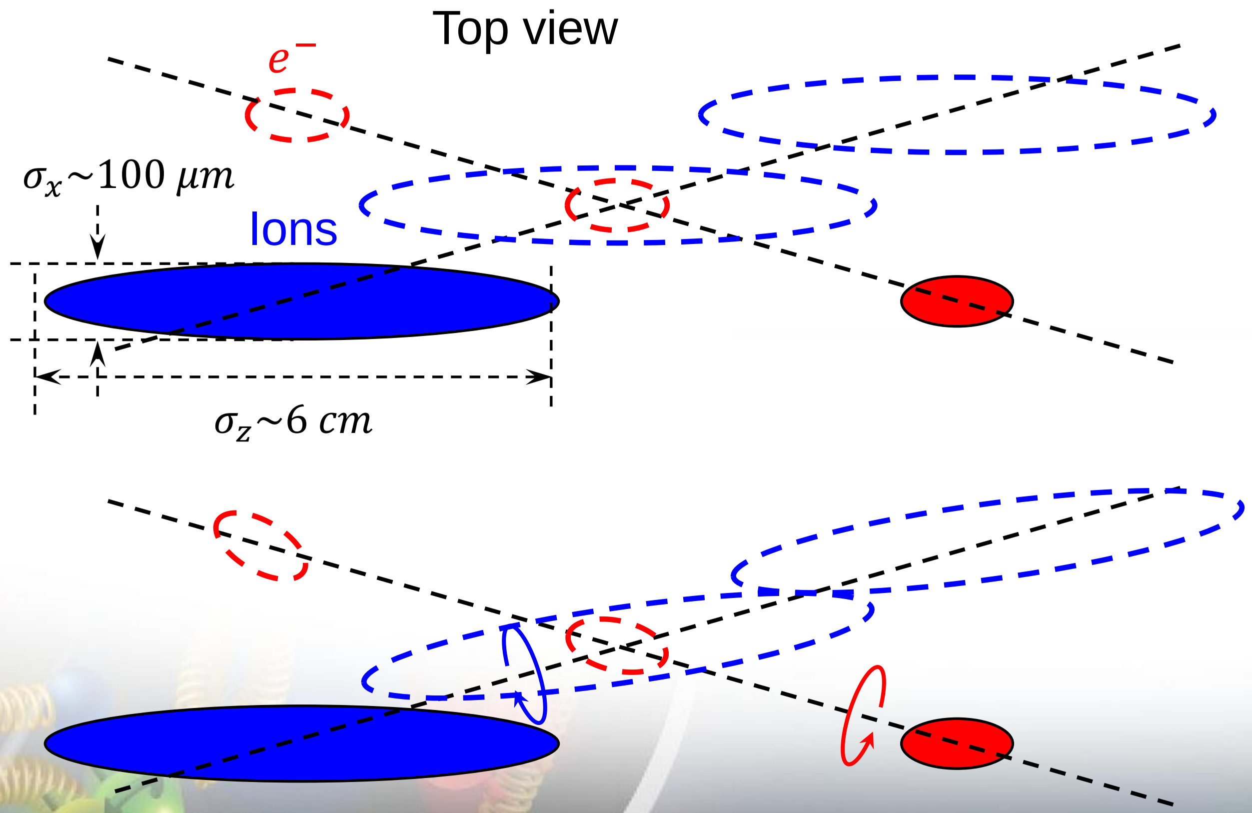
- Coupling is in general a global effect and involves consideration of the entire ring or the entire coupled section
- Potential for negative dynamic effects
- Can leads to redistribution of the horizontal and vertical emittances $\Rightarrow$ smaller beam “flatness” $\Rightarrow$ luminosity reduction
- If not locally compensated at the IP can lead to change in the transverse beam shape $\Rightarrow$ potential for luminosity reduction (beams enter solenoid uncoupled):

$\sigma_x/\sigma_y \sim 10\ \mu m$



Rotation of Crabbing Plane

- Another aspect of coupling
- Potential for negative dynamic effects
- Impact on luminosity

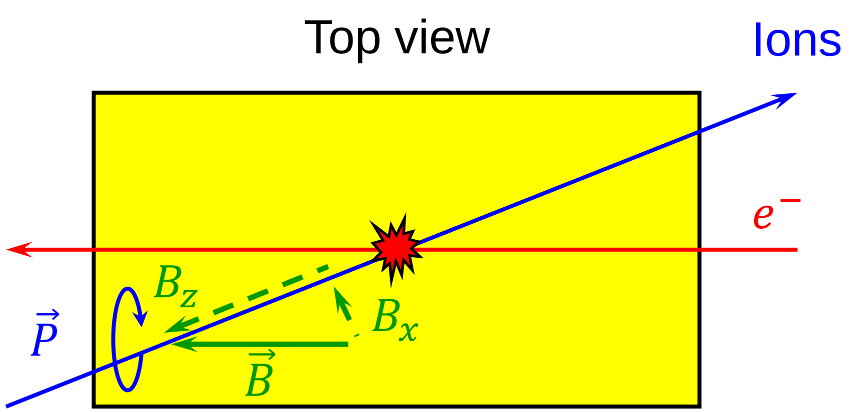


No solenoid + no coupling =
Full overlap ⇒ Full luminosity

Solenoid + rotation not compensated =
Partial overlap = Reduced luminosity

Polarization Tilt

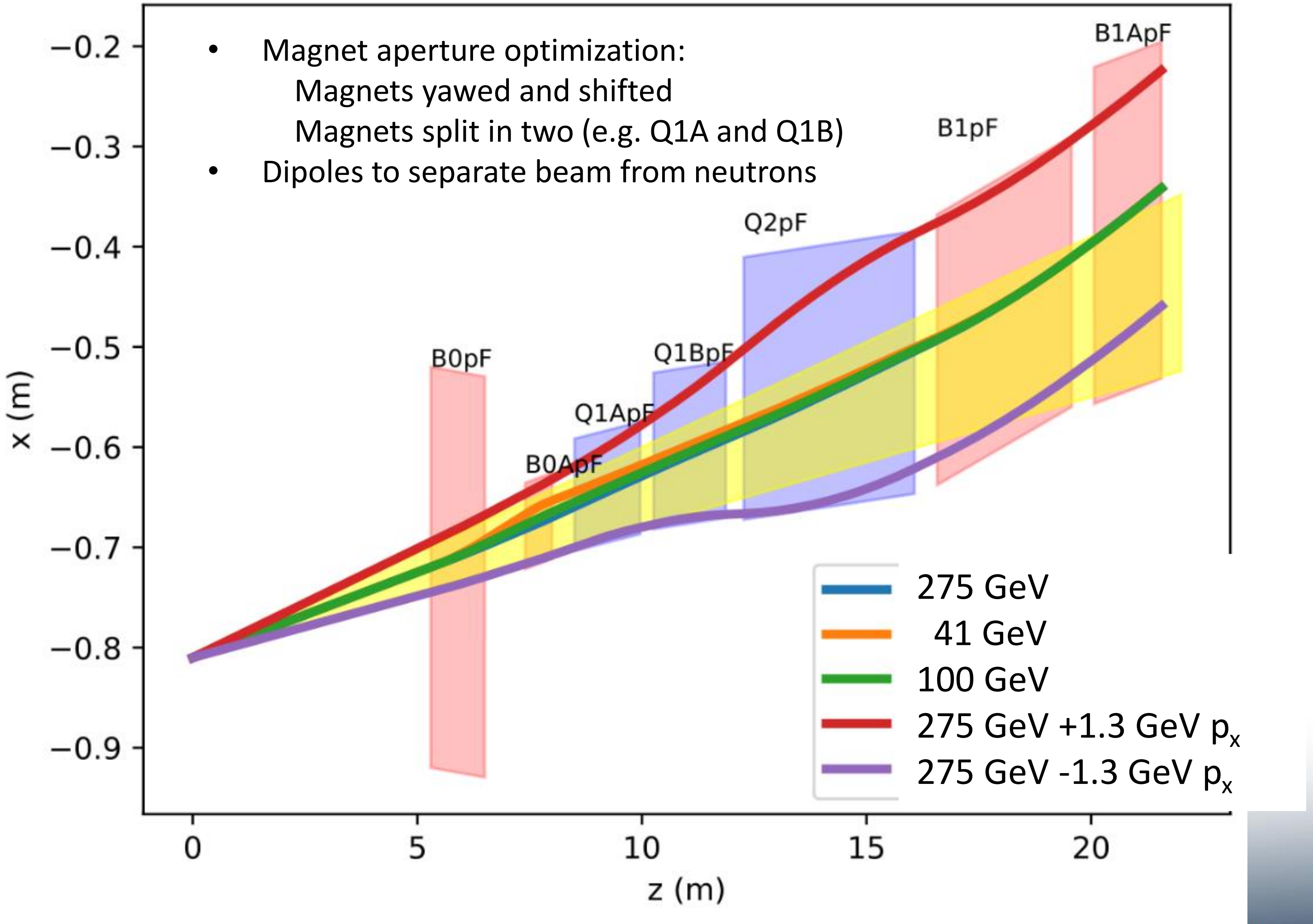
- The baseline scheme has no strong correctors on the rear side, so the polarization tilt is due to the rear side of the solenoid



Energy $[GeV]$	Long. n_x	Rad. n_y	Vert. n_z	φ_s $[2\pi]$
41	0.94	-0.34	0.02	0.01
100	0.76	-0.65	0.01	0.01
200	0.50	-0.87	0.01	0.008
275	0.39	-0.92	0.007	0.007

- Polarization orientation at the IP in this scenario is compensated by the rear ion spin rotator
- The net spin effect of the entire IR involves account of the contribution of the forward side
- The forward spin rotator compensation the remaining net effect

Hadron Forward – Large Apertures for low p_t Acceptance



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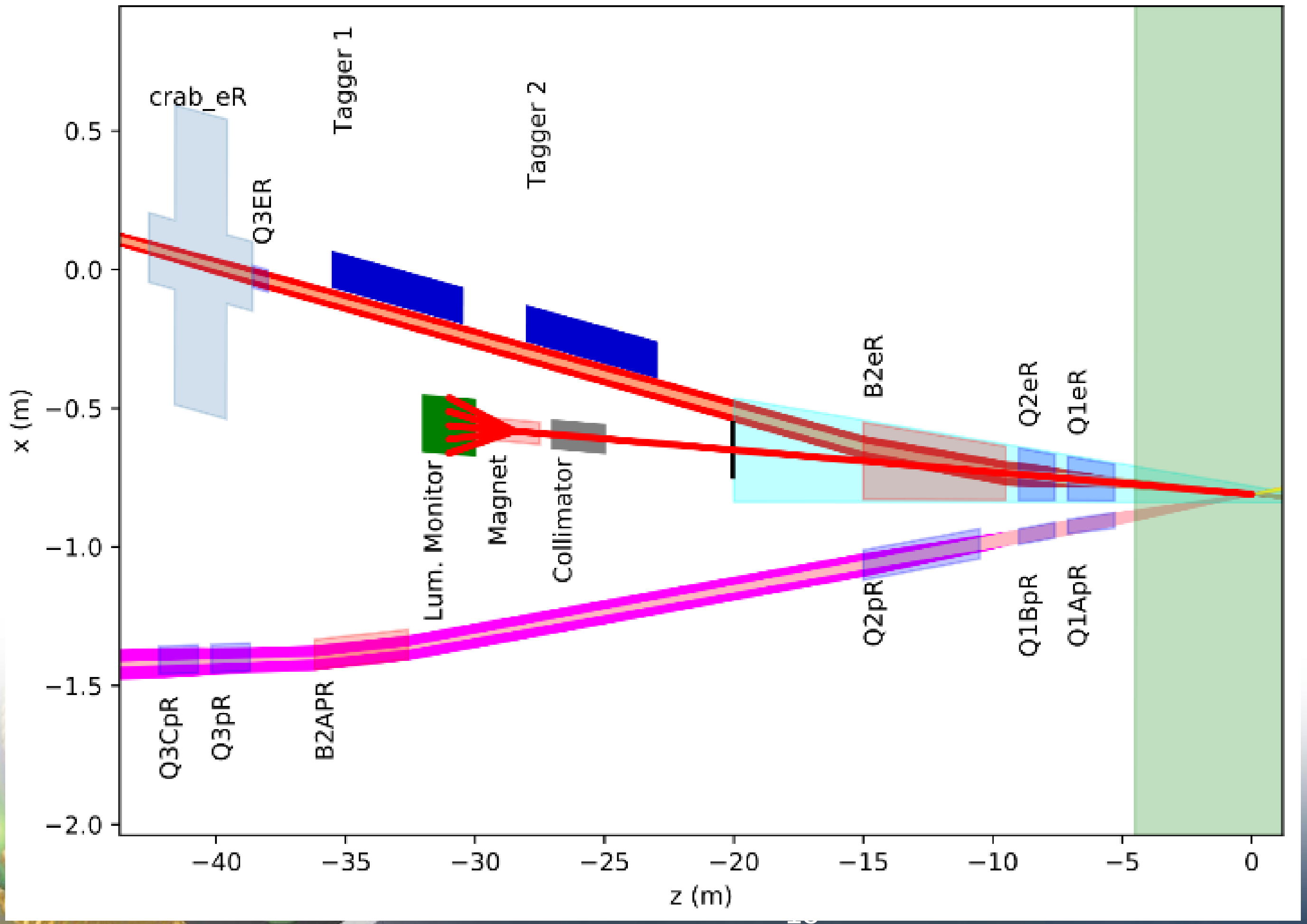
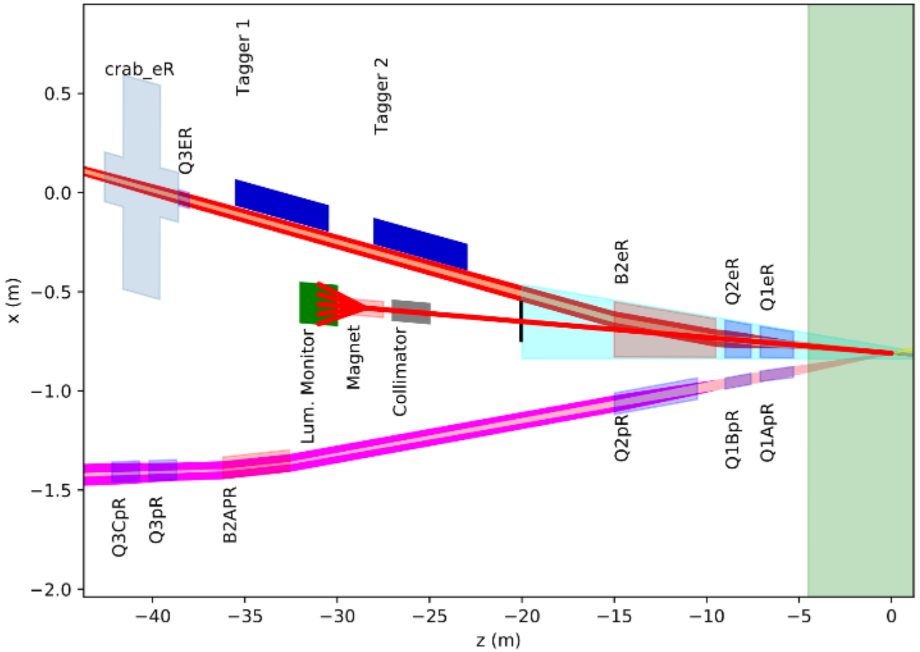
Electron Rear: Large Apertures to Pass Synchrotron Radiation Fan

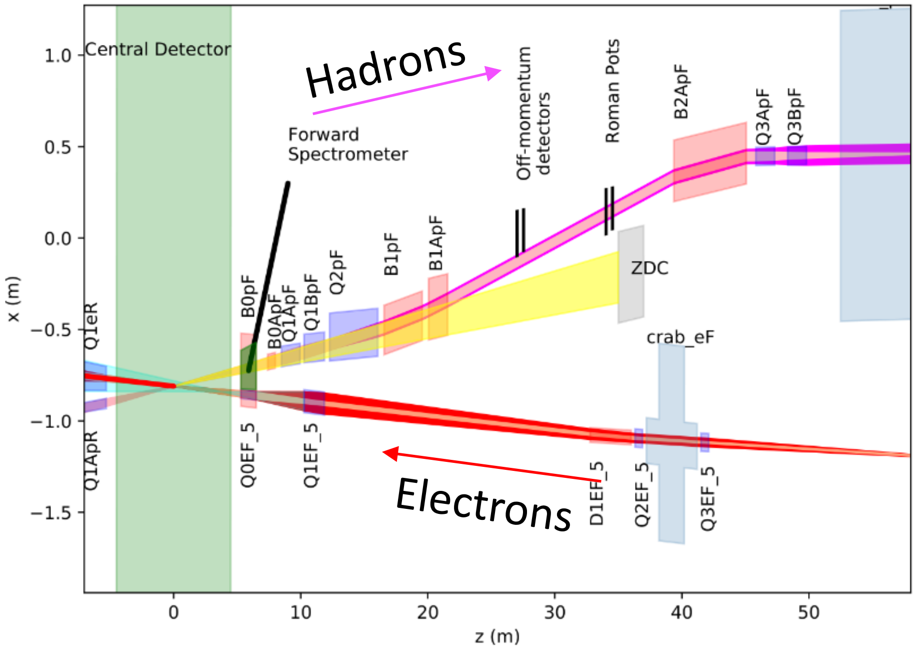


IR Magnets

Rear: RHIC sec 6



Forward: RHIC sec 5

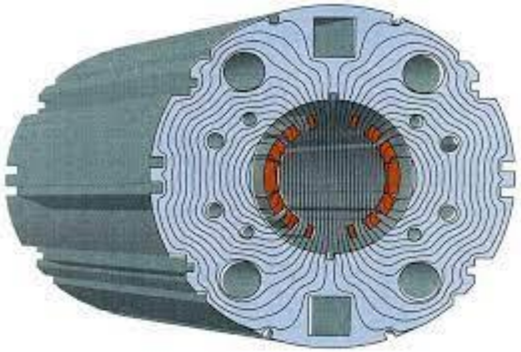


- 16 SC magnets to be built (4.5 K and 1.9 K)
- 10 direct wind magnets:
  - Q1eR, Q2eR, B2eR, Q1ApR, Q1BpR, Q2pR, Q0eF, B0pF, B0ApF, Q1eF
- 6 collared magnets (incl. B2pF)
  - Q1ApF, Q1BpF, Q2pF, B1pF, B1ApF, B2pF

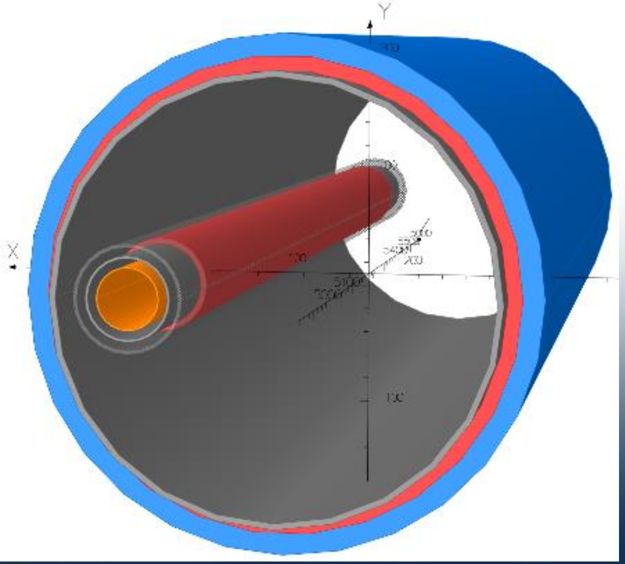
Superconducting IR magnets

- 10 direct-wind magnets

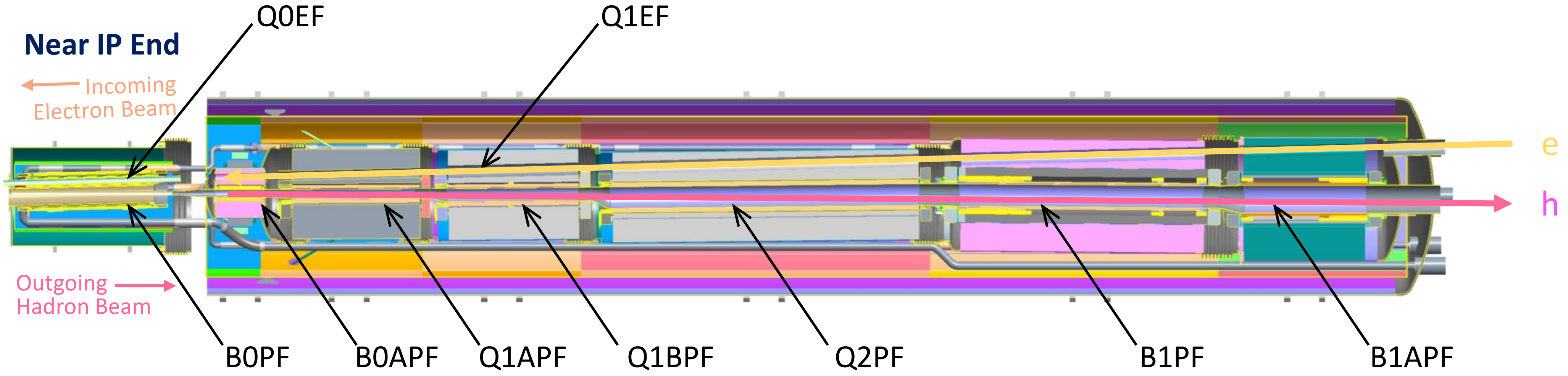
- 6 collared magnets



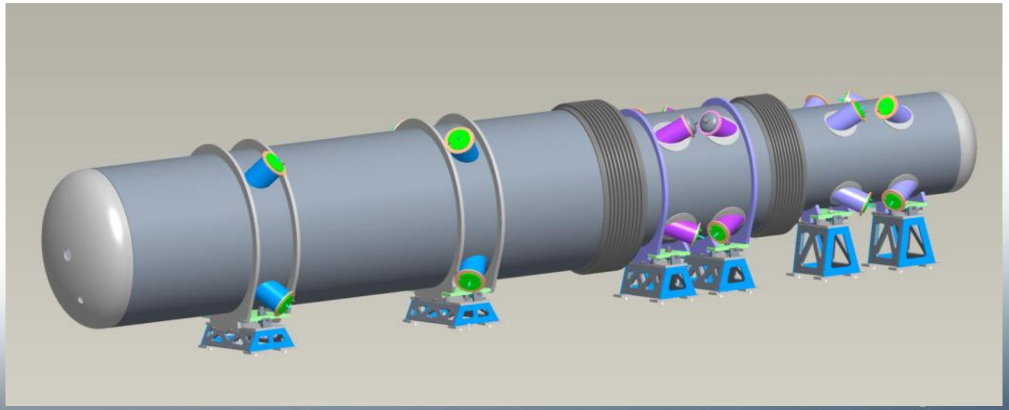
- B0 – an electron quadrupole
  inside a hadron spectrometer dipole



IR Magnet cryostats



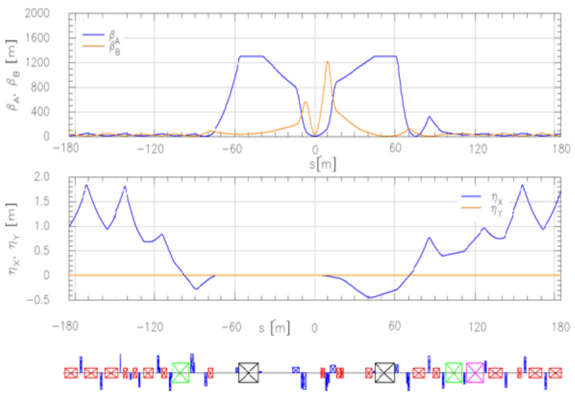
Electron and hadron magnets densely packed, side-by-side in a common cryostat on either side of the detector



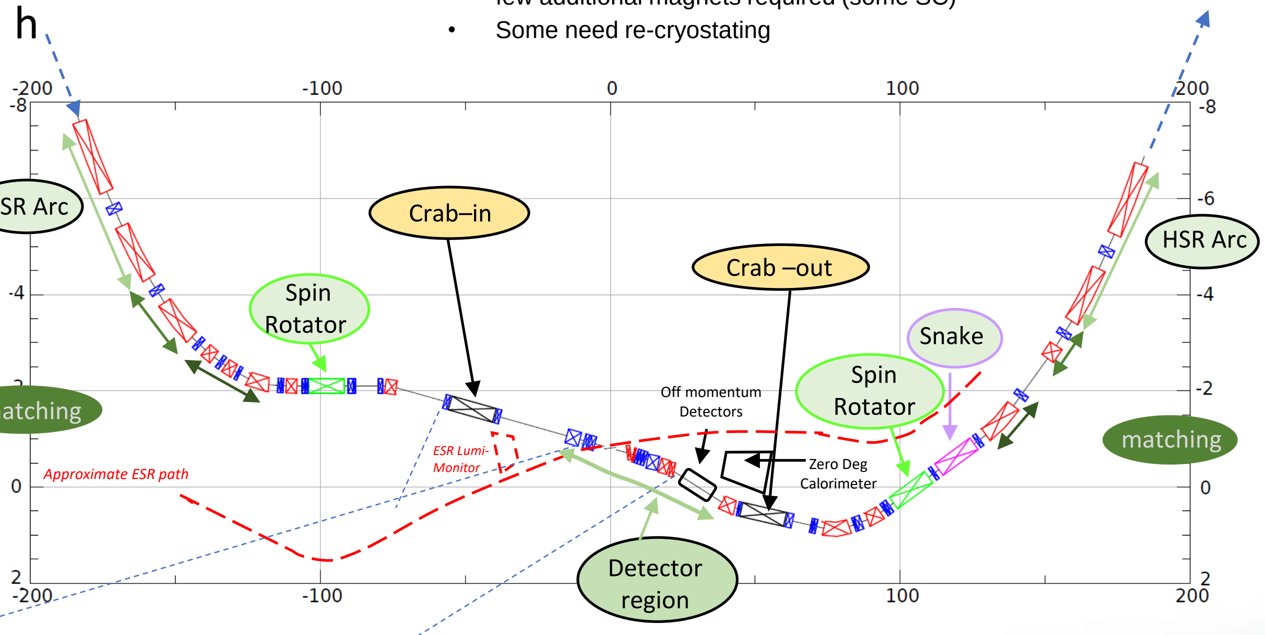
Spin Rotators

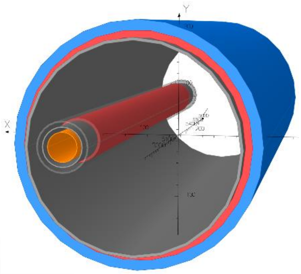
- Both electrons and protons will have longitudinal polarization at the IP
- Hadron spin rotators will be taken from present RHIC (helical dipoles)
- Electron spin rotators are based on solenoid magnets with subsequent dipole – large (> +/- 100 m) chunk of beamline with fixed geometry, challenging to fit into existing tunnel

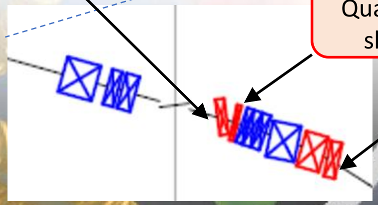
HSR layout in IR6



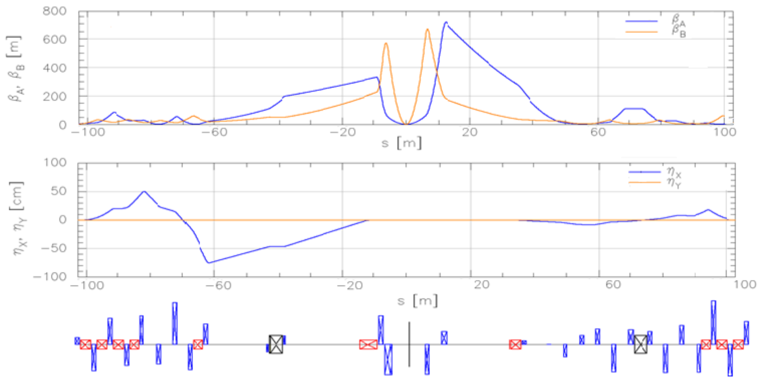
- Forward and rear hadron lattice matched into RHIC
  - Snake at correct angle
  - Beta = 1300m at crab cavities
    - Hor. phase advance 90º
  - Matching Magnets
    - Mostly repurposed RHIC magnets
    - few additional magnets required (some SC)
    - Some need re-cryostating





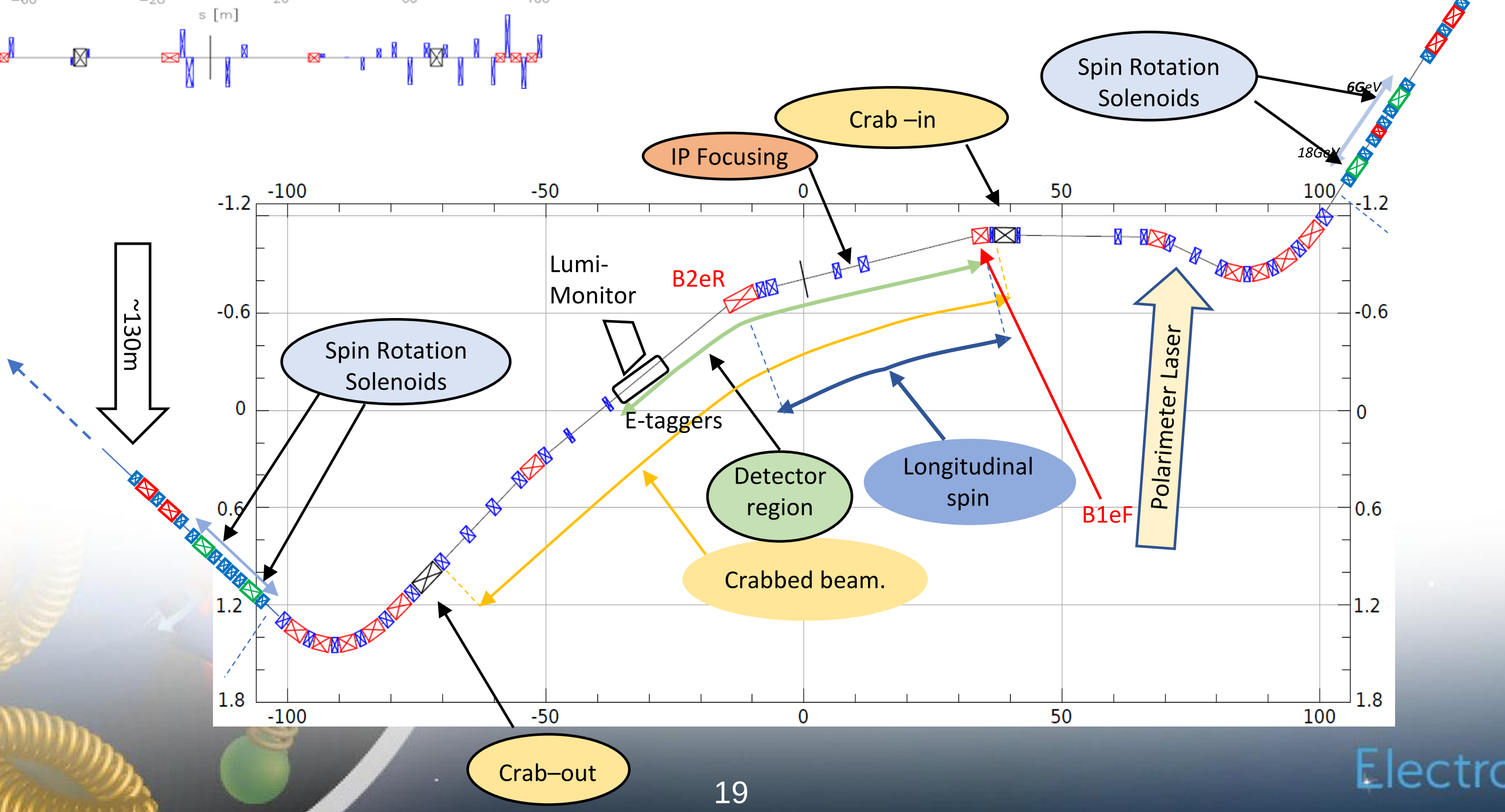


ESR layout in IR6



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



Luminosity Sharing with two IRs

- Both electrons and hadrons are at the beam-beam limit with one collision point – they would not "survive" a second IR
- To enable two collision points, both electron and hadron bunch intensity would have to be reduced by a factor two – resulting luminosity at each IR would be factor 4 smaller
- Instead, we modify the fill pattern such that half the bunches collide in IR6, while the other half collides in IR8
- As a result, total luminosity is preserved, and each detector gets half of the total – a maximum 5e33 each instead of 1e34 with a single IR

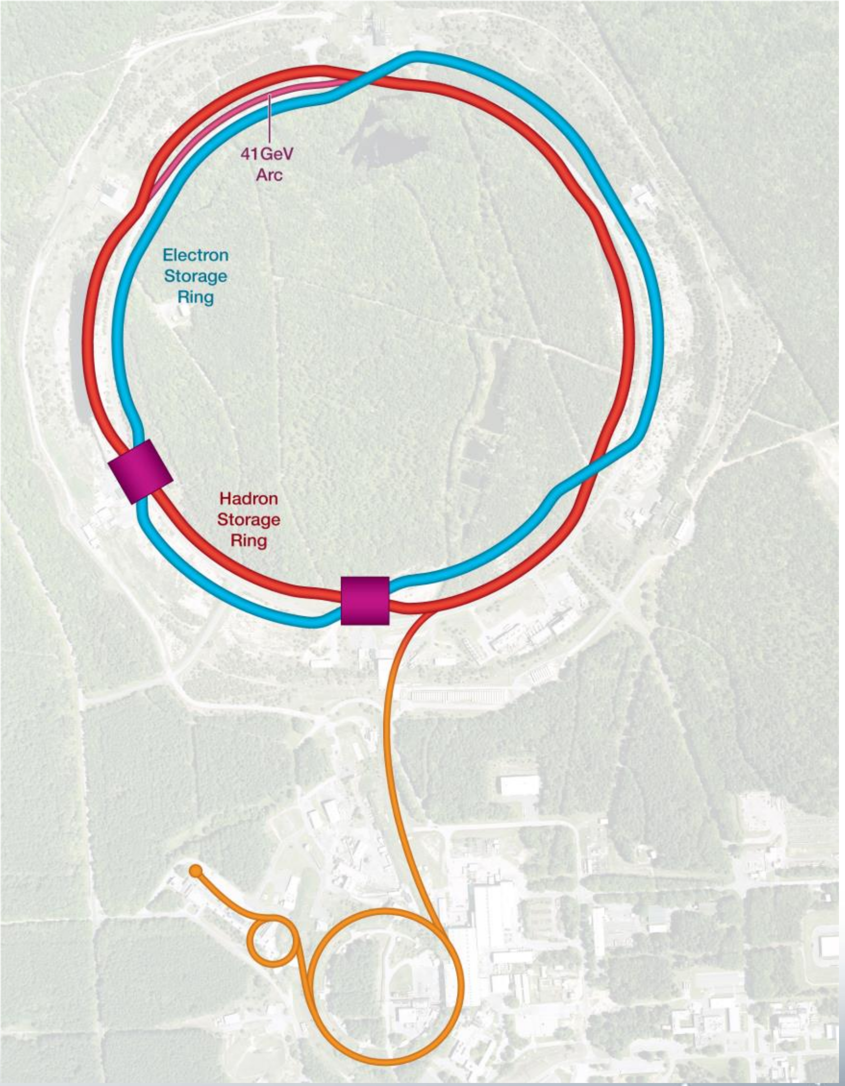
Summary

- EIC interaction region is highly optimized, but any IR design is always a compromise between luminosity, acceptance, cost, risk, …
- Design is driven by physics and detector needs, in close collaboration with experimenters
- Inner IR is practically frozen
- Remaining work concentrates on small geometric adjustments in the matching section towards the arcs, to fit everything into the tunnel

Supplemental Slides

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 (protons), 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 proton beam energy



Emittance Control in the ESR

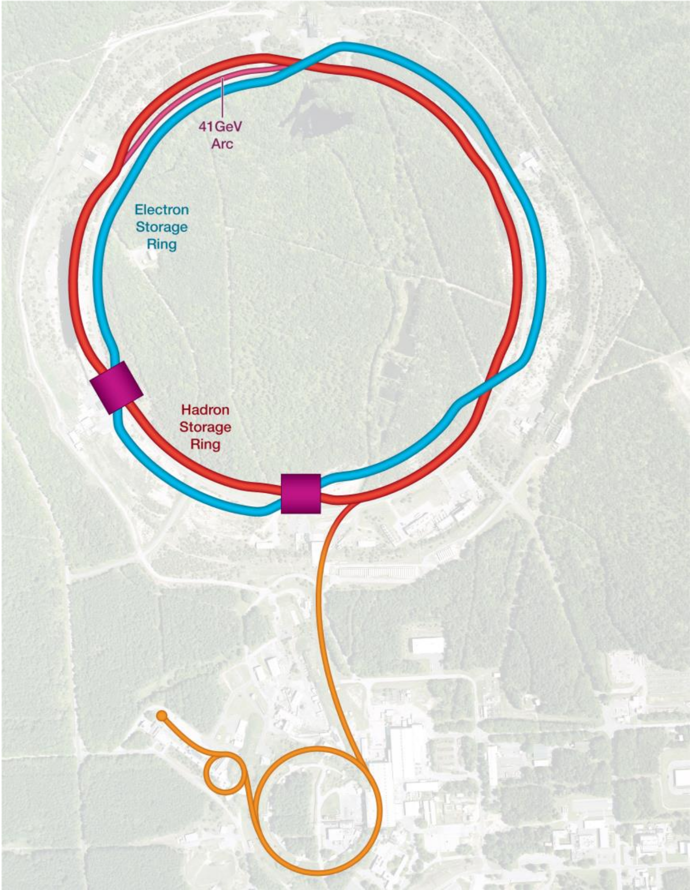
- EIC needs 24 nm emittance from 5 to 18 GeV for optimum luminosity, but equilibrium emittance in an electron storage ring depends on beam energy:

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

- 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 both yield ~24 nm
- "super-bends" for emittance generation below 10 GeV

Beam Energies

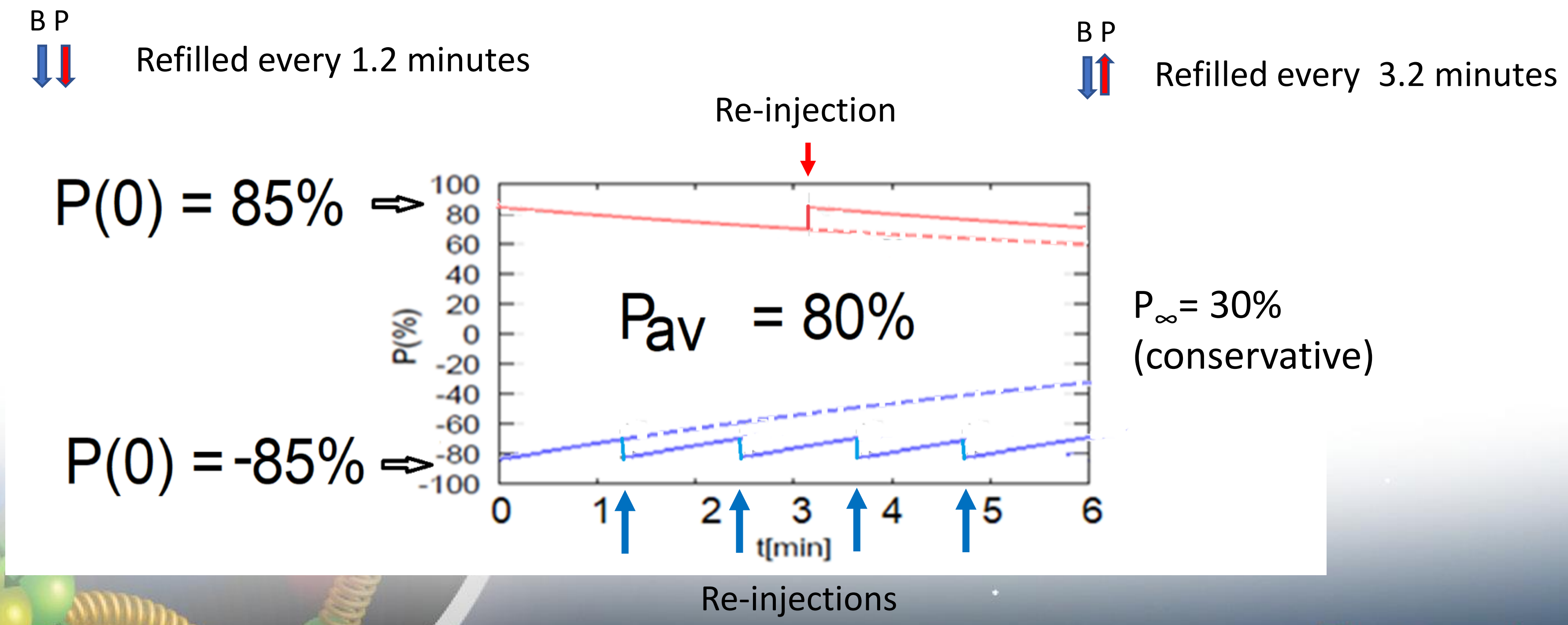
- γ range for hadrons:
  - γ = 43.7 through “41 GeV arc”
  - 107 < γ < 293 with radial shift
- Maximum hadron energy:
  - E [eV] < 916*c [m/sec]*Z/A
- Electron energies:
  - 5 to 10 GeV, with 60 degree lattice and super-bends
  - 18 GeV, with 90 degree lattice
  - Energies between 10 and 18 GeV are feasible, but at somewhat reduced luminosity due to non-optimum emittance, scaling as γ^2



Electron-Ion Collider

High Average Electron Polarization

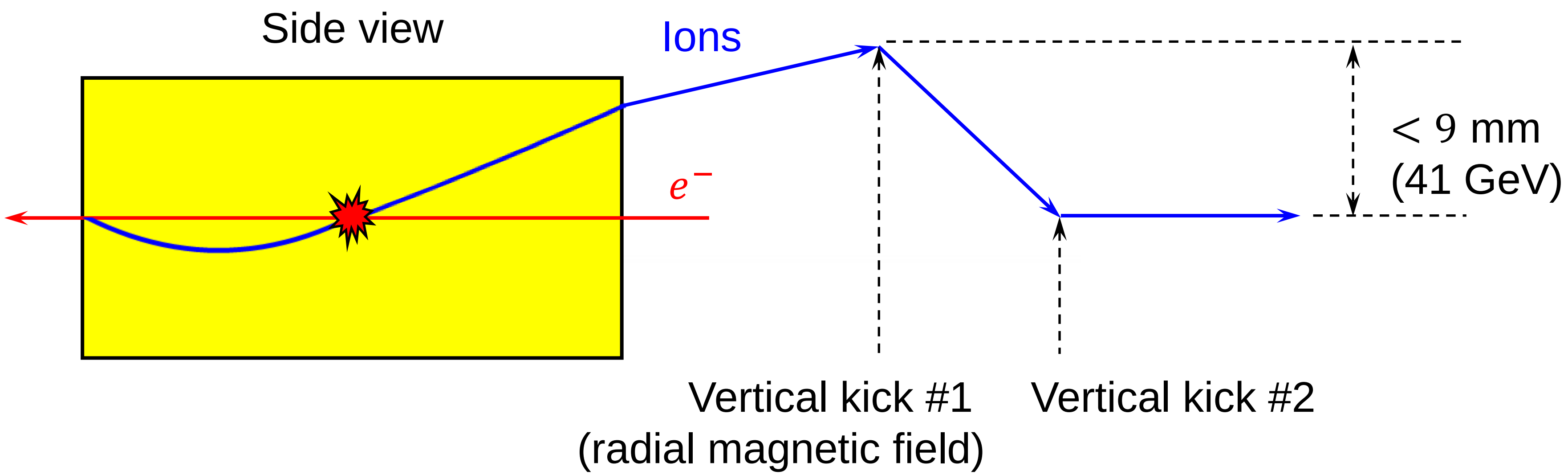
- Frequent injection of bunches with high initial polarization of 85%
- Initial polarization decays towards P_∞
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 2Hz



Electron-Ion Collider

Correction of Ion Orbit

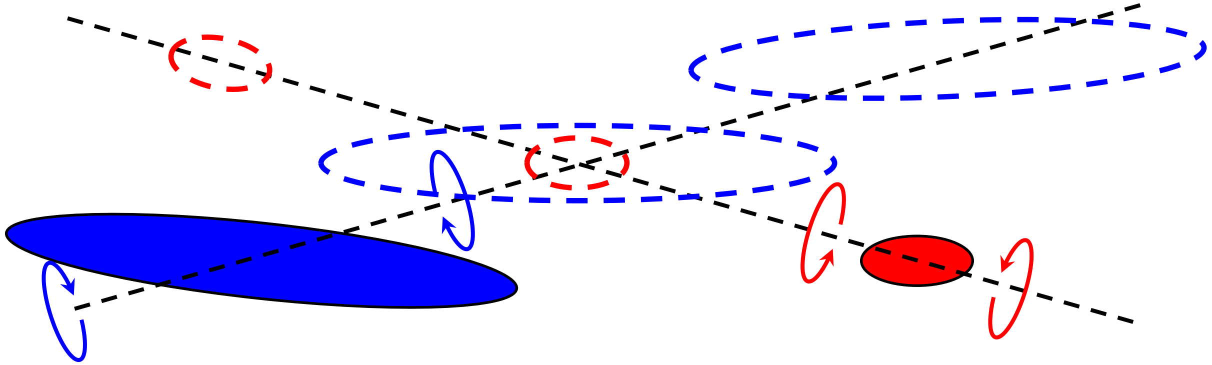
- The closer the kicks to the IP, the smaller the orbit excursion
- Orbit excursion inversely proportional to the beam momentum
- Concern for field non-linearity at large offsets



Rotation of Crabbing Plane Solution

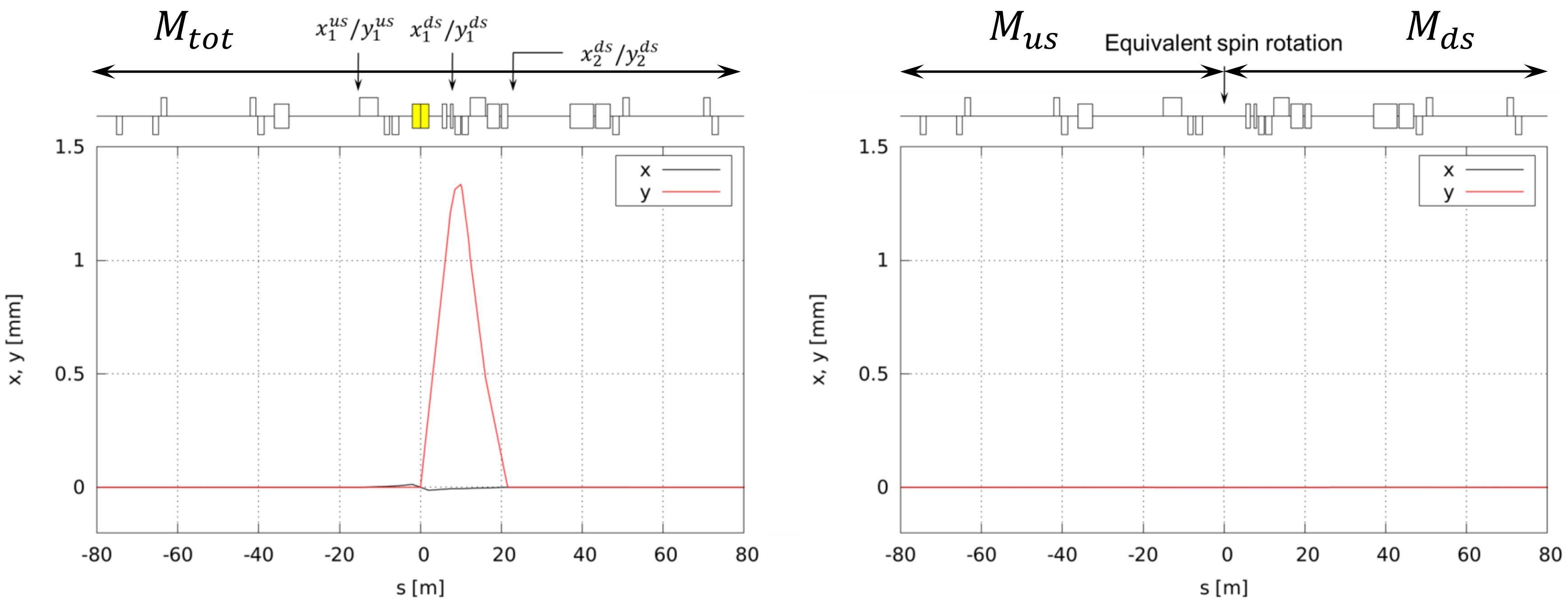
- Pre-rotated the crabbing plane using vertical crabbing kicks: ~140 kV for ions and ~430 kV for electrons

Top view



Solenoid + rotation compensated =
Full overlap ⇒ Full luminosity

Net Effect of IR on Ion Spin



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41	0.98	0.18	-0.076	0.038
100	0.97	0.23	-0.047	-0.035
200	0.93	-0.37	-0.029	0.021
275	0.88	-0.48	-0.025	-0.035