Brookhaven National Laboratory

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U.S. DEPARTMENT OF ENERGY

EIC Accelerator Physics - part 2

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Electron-Ion Collider

Outline

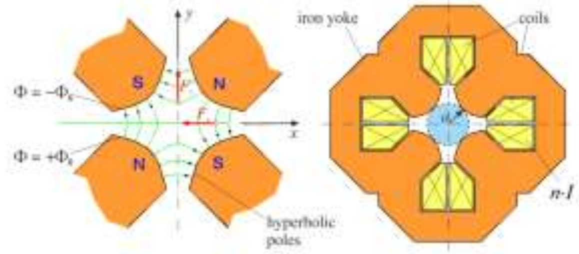
- Recap – how to describe particle trajectories and optics
- Application: the EIC interaction region
  - Luminosity
  - Focusing
  - Beam separation
  - Crab crossing
  - Luminosity limitations
  - Transport of low-p_t particles
  - Polarized beams
- Summary

Recap – what have we learned so far?

- (Linear) motion of single particles is described by transfer matrices:

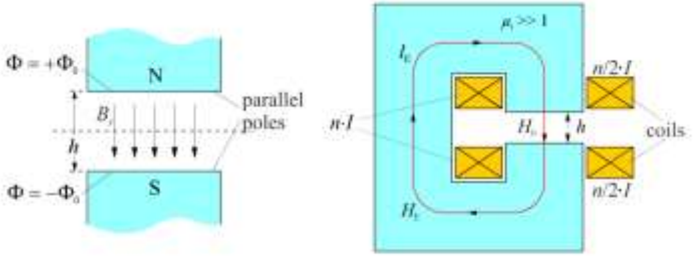
Horizontally focusing quadrupole (⇒ vertically defocusing):

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} \cos(\sqrt{|k|}z) & \frac{1}{\sqrt{|k|}}\sin(\sqrt{|k|}z) & 0 & 0 \\ -\sqrt{|k|}\sin(\sqrt{|k|}z) & \cos(\sqrt{|k|}z) & 0 & 0 \\ 0 & 0 & \cosh(\sqrt{|k|}z) & \frac{1}{\sqrt{|k|}}\sinh(\sqrt{|k|}z) \\ 0 & 0 & \sqrt{|k|}\sinh(\sqrt{|k|}z) & \cosh(\sqrt{|k|}z) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix}$$



Horizontally bending dipole (⇒ vertically just a drift):

$$\mathrm{M}_{\mathrm{drift}} = \begin{pmatrix} \cos\left(\frac{z}{R}\right) & R\sin\left(\frac{z}{R}\right) & 0 & 0 \\ -\frac{1}{R}\sin\left(\frac{z}{R}\right) & \cos\left(\frac{z}{R}\right) & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



- Transport of a beam ensemble is described by Twiss parameters:

$$\beta(s),\ \alpha = -\frac{1}{2}\frac{d\beta}{ds},\ \gamma = \frac{1+\alpha^2}{\beta}$$

- Define “beta-matrix”:

$$\mathbf{B} = \begin{pmatrix} \gamma & \alpha \\ \alpha & \beta \end{pmatrix}$$

- Transformation of this beta-matrix using element-by-element transport matrices:

$$\mathbf{B} = \mathbf{M} \cdot \mathbf{B}_0 \cdot \mathbf{M}^T$$

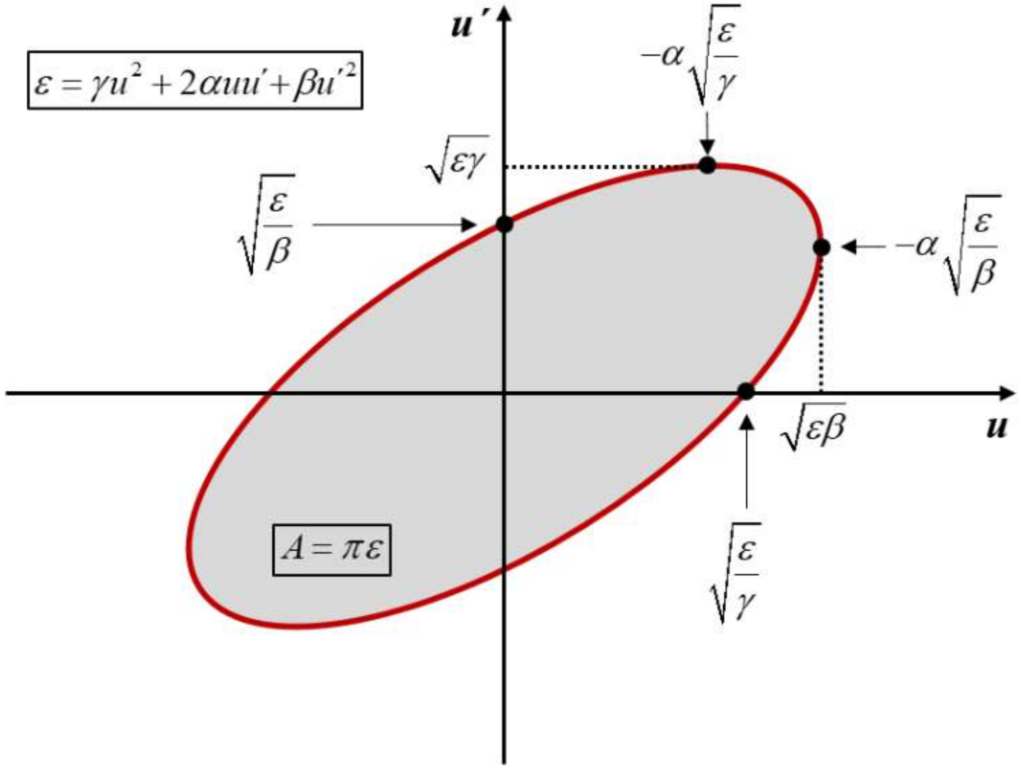
The Phase-space Ellipse

- At any location s in the machine, the phase-space ellipse is described by the Twiss parameters β(s), α(s), and γ(s)
- The RMS size of the ellipse is determined by the beam emittance:

$$\sigma=\sqrt{\varepsilon * \beta(s)}$$

$$\sigma'=-\alpha(s)\sqrt{\frac{\varepsilon}{\gamma(s)}}$$

- Ellipses do not intersect



Dispersion

- Momentum deviation has a non-negligible impact on the particle trajectory only in dipoles
- Equation of motion in a dipole with nominal bending radius R:

$$\frac{d^2x(s)}{ds^2} + \frac{1}{R^2}\mathrm{x(s)} = \frac{1}{R}\frac{\Delta p}{p}$$

- Define a special trajectory D(s) for a particle with $\frac{\Delta p}{p}$=1:

$$\frac{d^2D(s)}{ds^2} + \frac{1}{R^2}\mathrm{D(s)} = \frac{1}{R}$$

D(s) is called dispersion function

- Solution in matrix form:

$$\begin{pmatrix} D \\ D' \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\left(\frac{z}{R}\right) & R\sin\left(\frac{z}{R}\right) & R\left(1-\frac{z}{R}\right) \\ -\frac{1}{R}\sin\left(\frac{z}{R}\right) & \cos\left(\frac{z}{R}\right) & \sin\left(\frac{z}{R}\right) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} D_0 \\ D_0' \\ 1 \end{pmatrix}$$

- To describe the trajectory of an off-momentum particle, we add a 5th row and column to the 4x4 transport matrices:

5 × 5 dipole matrix:

$$\mathrm{M}_{\text{dipole}} = \begin{pmatrix} \cos\left(\frac{z}{R}\right) & R\sin\left(\frac{z}{R}\right) & 0 & 0 & R\left(1-\frac{z}{R}\right) \\ -\frac{1}{R}\sin\left(\frac{z}{R}\right) & \cos\left(\frac{z}{R}\right) & 0 & 0 & \sin\left(\frac{z}{R}\right) \\ 0 & 0 & 1 & z & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Quadrupoles and drifts:

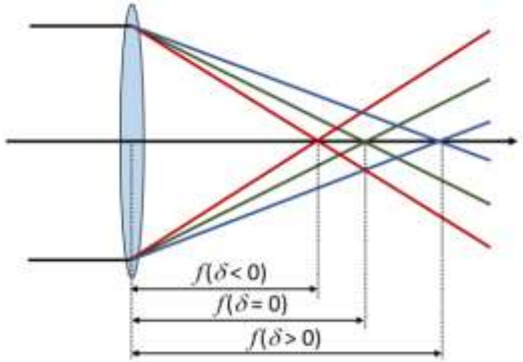
$$\mathrm{M} = \begin{pmatrix} m_{11} & m_{12} & 0 & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} & 0 \\ 0 & 0 & m_{43} & m_{44} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ \Delta p/p \end{pmatrix} = \mathrm{M} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \\ \Delta p/p \end{pmatrix}$$

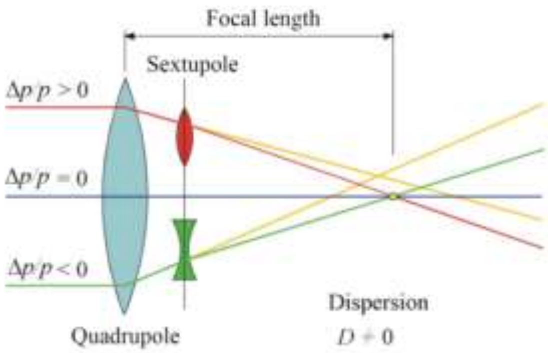
- The relative momentum offset $\frac{\Delta p}{p}$ is added as a 5th coordinate to the coordinate vector

Chromaticity

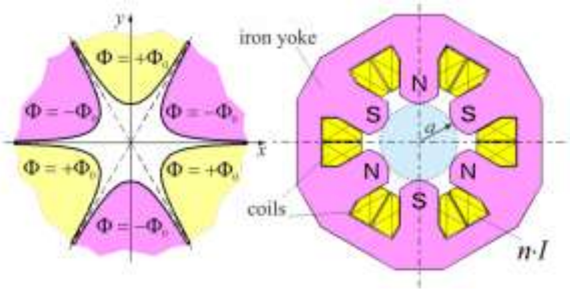
- Momentum offsets result in focusing errors – "chromaticity"
- Particles with higher momentum get under-focused, those with lower momentum are over-focused
- Chromaticity is proportional to the quadrupole strength, and to the β-function at that quadrupole



- These focusing errors are corrected using sextupoles
- Particles are transversely sorted by momentum due to dispersion

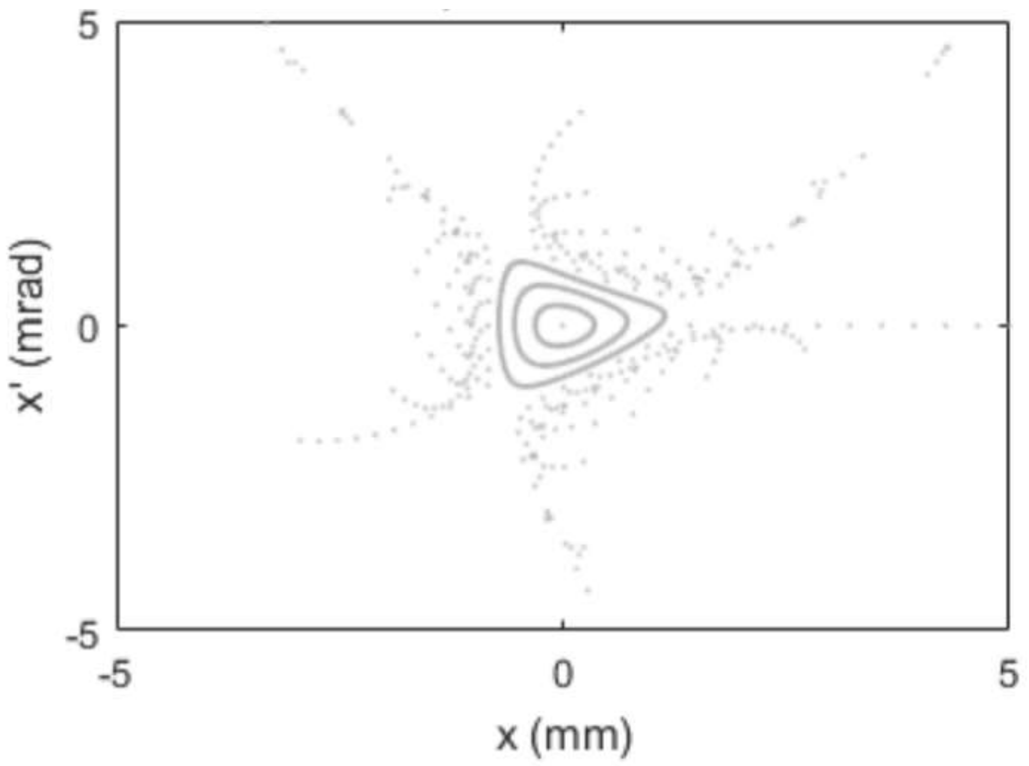


- A sextupole can be considered a "position-dependent quadrupole"



Dynamic Aperture

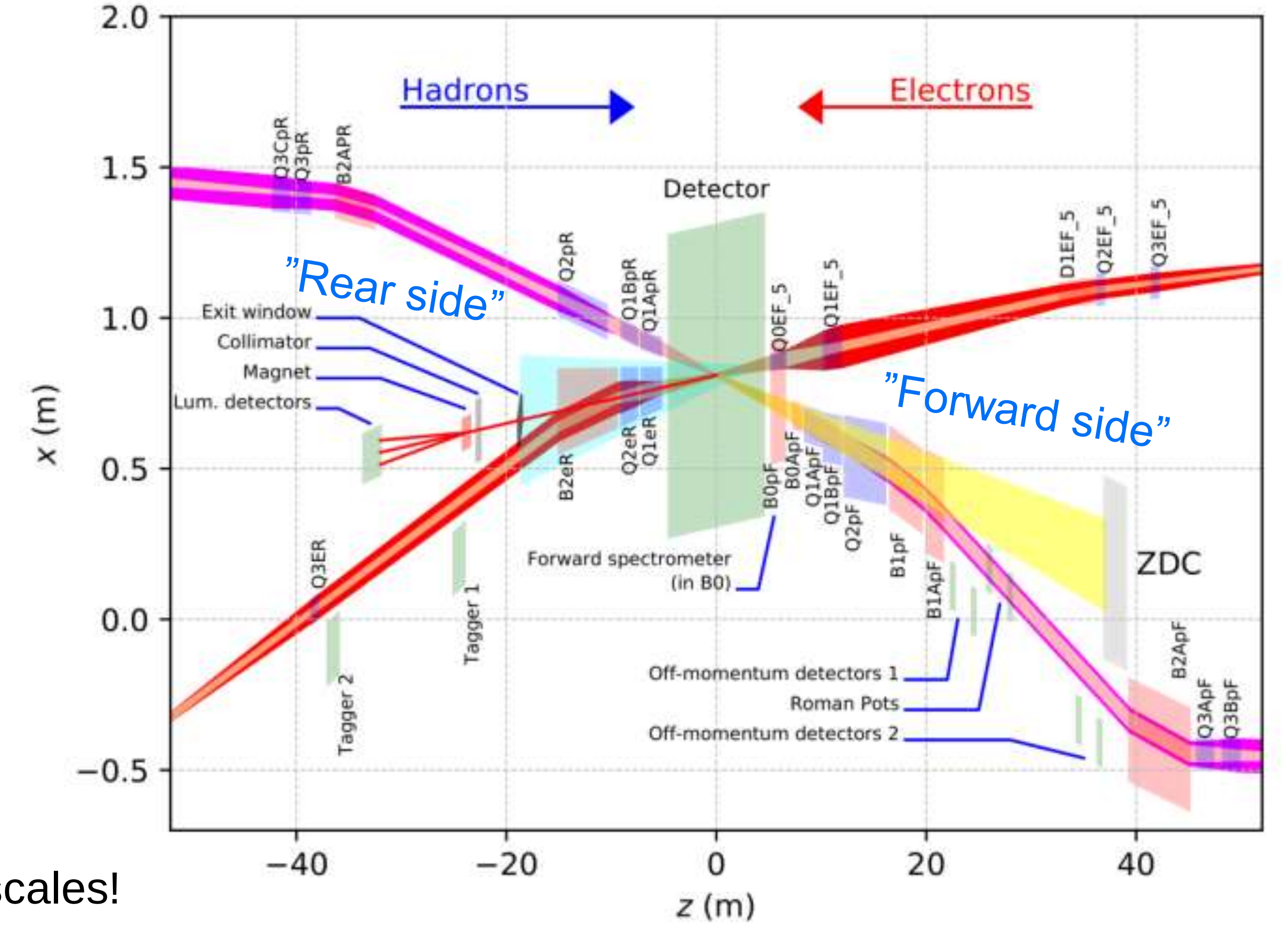
- Sextupoles are non-linear elements
- While small amplitude dynamics is still (almost) linear, large amplitude motion becomes more and more non-linear
- Beyond a certain threshold, particle motion is unstable and particles are lost
- This threshold is called “dynamic aperture”
- Note: non-linear multipole errors due to magnet imperfections impact dynamic aperture as well



Tying it all Together - the Interaction Region

IR requirements:

- High luminosity
- Space for central detector
- Multi-stage separation – hadrons from electrons, electrons from photons, hadrons from neutrons
- Detection of low-p_t particles
- Longitudinal polarization at the IP



Note different axis scales!

Luminosity

$$L \propto f_{\mathrm{coll}} N_1 N_2 / \sigma_x^\star \sigma_y^\star$$

f_{coll} : collision frequency

$N_{1,2}$: particles per bunch

$\sigma_{x,y}^\star$: (equal) beam sizes at IP

- **Maximize collision frequency (~100 MHz)**
  - Limited by kicker rise times
  - Limited by parasitic collisions, injection system, etc.
- **Maximize particles per bunch (~10^{11})**
  - Limited by sources, space charge
  - Limited by collective effects
    - Interaction of beam with impedances
    - Also total currents: $I_{1,2}=q_{1,2}N_{1,2}f_{coll}$ ~1-3A
- **Minimize beam sizes at IP (~100/10 um)**
  - Limited by IR focusing, magnets
  - Limited by chromatic dynamic aperture
  - Limited by emittance growth (IBS)

IR Focusing

- At the IP, we have $\alpha(s=0) = 0$
- Using the beta-matrix

$$\mathrm{B} = \begin{pmatrix} \gamma & \alpha \\ \alpha & \beta \end{pmatrix}$$

and its transformation

$$\mathrm{B} = \mathrm{M} \cdot \mathrm{B}_0 \cdot \mathrm{M}^T$$

with M describing the drift from the IP to the first quadrupole at position s

$$\beta(s)=\beta(IP) + \frac{s^2}{\beta(IP)}$$

- The RMS beam size $\sigma=\sqrt{\varepsilon\beta(s)}$ grows approximately linearly with distance from the IP

- Important consequence:

  The smaller β(IP), the larger it (and the beam) get at the first quadrupole

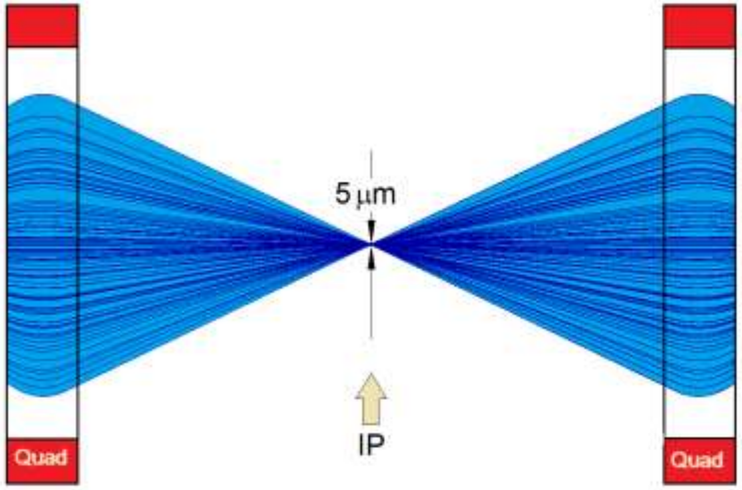
- With the first quadrupole outside the central detector, s = 5 meters
- The required quadrupole strength (=gradient) is nearly independent of β(IP), but the magnet aperture has to accommodate the large beam
- Large aperture at fixed gradient means high magnetic fields at the poles

  ⇒ superconducting IR magnets

- Reasonable limit is about 6 T at the pole
- Also remember: chromaticity is proportional to β

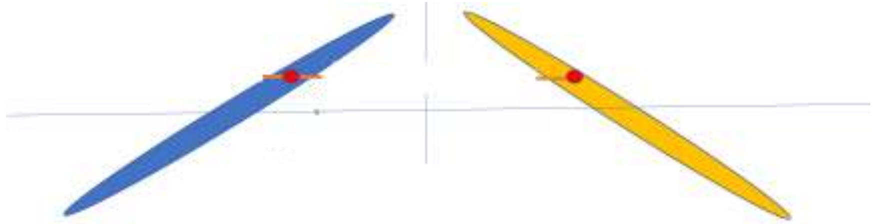
  ⇒ need stronger sextupoles

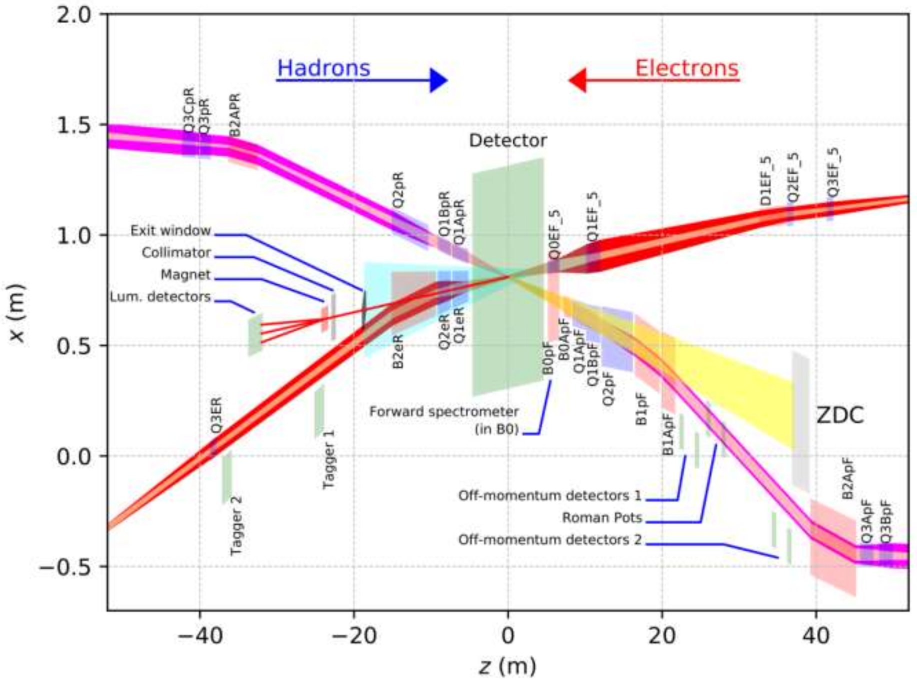
  ⇒ reduced dynamic aperture



Beam Separation

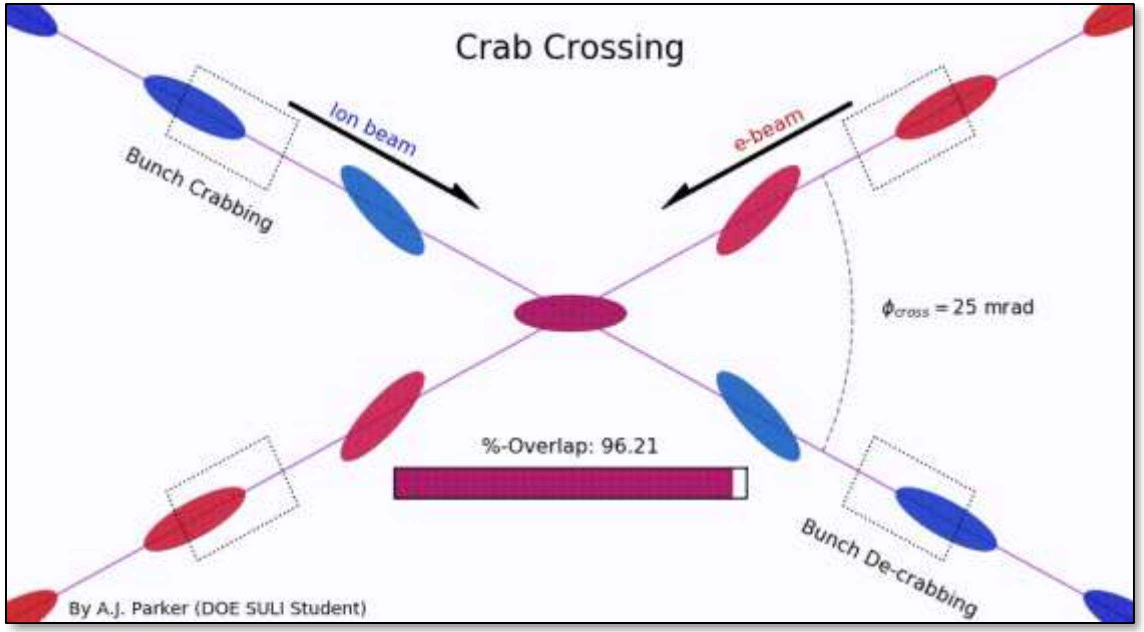
- Electron and hadron beams in EIC have vastly different energies
  → they need separate focusing channels at the IR
  beams need to be separated close to the IP
- Most effective, simple separation is a crossing angle (EIC: 25 mrad total crossing angle)
- However, a crossing angle reduces the overlap between the two beams and therefore the luminosity





Crab Crossing

- To restore head-on collisions despite the crossing angle, head and tail of each bunch are kicked in opposite directions when they approach the IP, using “crab cavities”
- As a result, electron and hadron bunches are lined up with each other at the IP, as in a head-on collision scheme
- This kick (or rotation) has to be un-done after leaving the IP
- Note: “crab crossing” does not only restore the luminosity loss caused by the crossing angle, but it is also necessary for stable beam dynamics



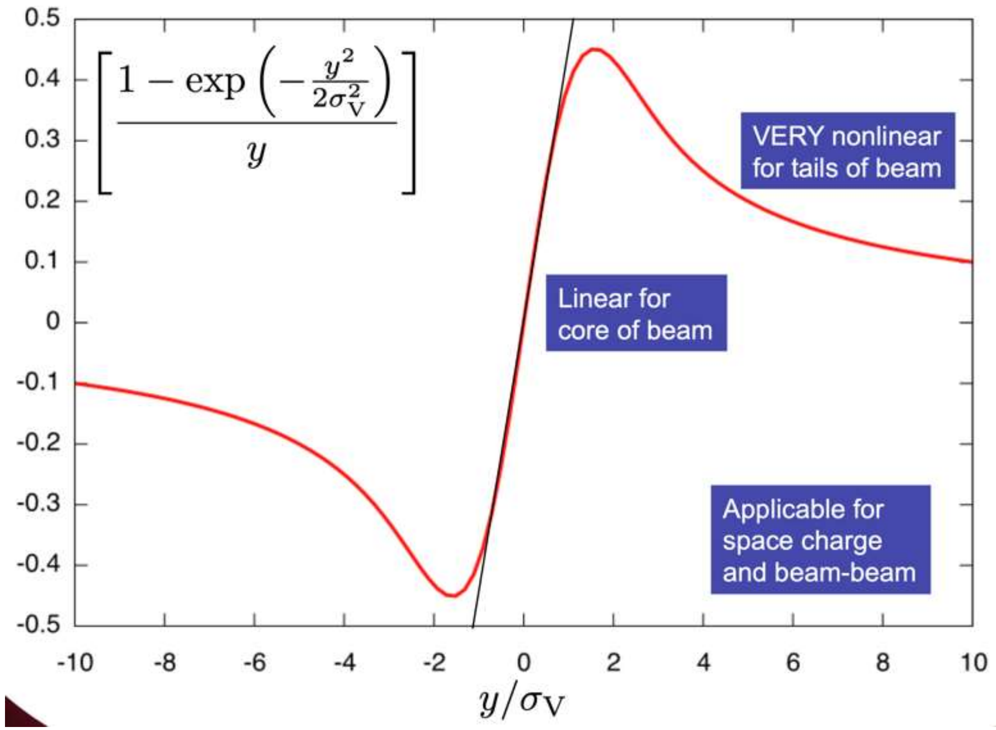
Luminosity Limitations: Beam-Beam

- Colliding beams see each other's collective charge distributions
- Creates **nonlinear** beam-beam force and equation of motion similar to space charge
  - Force is almost linear within ~1σ around beam center
  - Highly nonlinear beyond ~1σ
  - Vanishes for large amplitudes

  ⇨ Amplitude dependent focusing

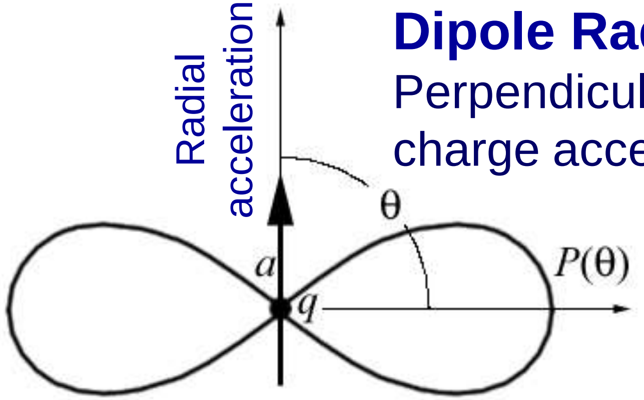
  ⇨ Amplitude dependent tune
- Tolerable "beam-beam tune spread" of 0.015 for hadrons, 0.1 for electrons limits highest EIC luminosity

$$F(r) = \frac{Nq^2}{2\pi\epsilon_0 l}\frac{1+\beta^2}{r}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$



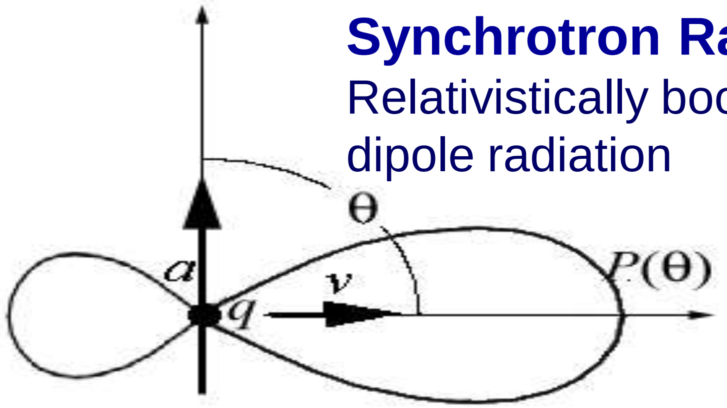
Lumi Limitations: Electron SR Power

- Accelerated charged particles emit photons
  - Electrons in synchrotron: radially accelerated
  - **Synchrotron radiation** emitted in forward cone
    - Cone opening angle $\propto 1/\gamma$
    - Radiated power $P_\gamma = \frac{2}{3}\frac{e^2 c}{4\pi\epsilon_0}\frac{(\gamma\beta)^4}{\rho^2}$
  - γ scaling **much** worse for electrons
    - 18 GeV e: γ=3.5x10^4 vs 255 GeV p: γ=3x10^2
- **Design: 9 MW** @ 18 GeV (facility limit 10 MW)
- **Expensive:** Power must be provided by SRF



Dipole Radiation
Perpendicular to charge acceleration

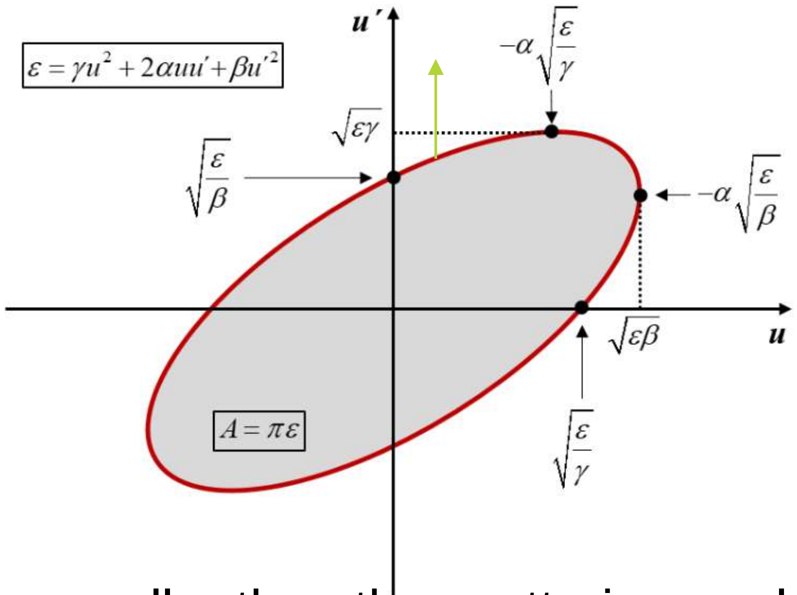
Relativistic Boost



Synchrotron Radiation
Relativistically boosted dipole radiation

Transport of low-p_t particles

- Particles scattered at the IP receive a transverse momentum kick p_t.
- This kick directly translates into an angle $x' = \frac{dx}{ds}$
- In transverse phase space:
- A scattering event kicks the particle on a new phase space ellipse – same shape as before, same center, but different size
- For detection at transverse position *x* at a Roman pot, this ellipse has to be “outside” the beam – typically at 10 σ



→ At the IP, the height of the 10 σ ellipse has to be smaller than the scattering angle x'

→ This limits the RMS beam divergence $\sigma' = \sqrt{\frac{\varepsilon}{\beta}}$ at the IP, and therefore the luminosity

→ Trade-off between acceptance and luminosity

Polarized Beams

- Physics program requires bunches with spin "up" and spin "down" (in the arcs) to be stored simultaneously
- Polarized light ion beams are generated at the source
- Sokolov-Ternov self-polarization of electrons would produce only polarization anti-parallel to the main dipole field, $\tau \sim \gamma^{-5}$
- 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

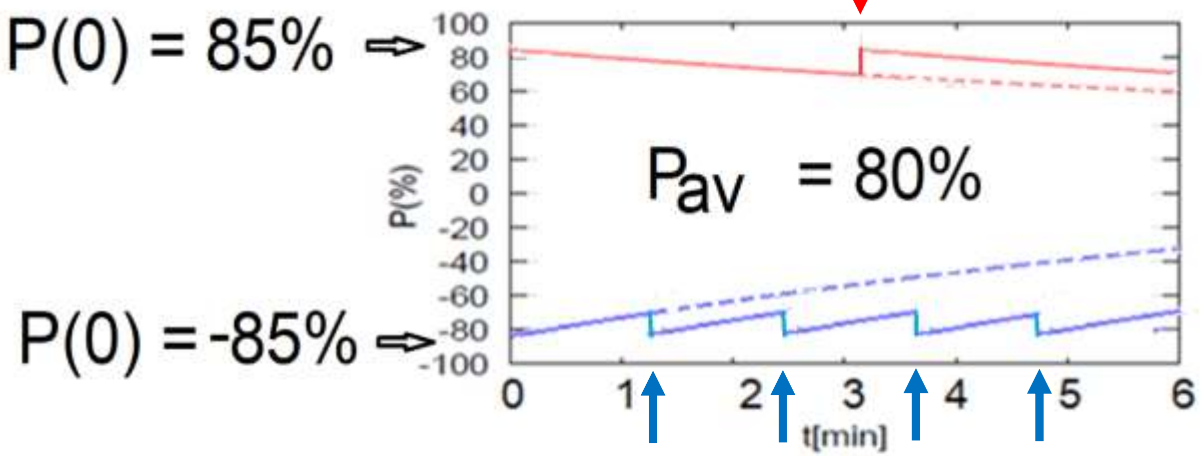
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



P_∞= 30% (conservative)

Re-injections

Spin Manipulation

Spin precession in magnetic fields is described by the Thomas-BMT equation

$$\frac{\mathrm{d}\vec{P}}{\mathrm{d}t} = \vec{\Omega}_0 \times \vec{P}$$

with

$$\vec{\Omega}_0 = -\frac{Ze}{m\gamma}\left[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel\right]$$

- Spins want to be aligned with magnetic field lines
- An orbit bending angle φ in a transverse field results in a spin rotation by Gγ*φ. Gγ is called the "spin tune"
- Polarization in the arcs is vertical
- Spin precession can be utilized to manipulate spin orientation

Polarization on the Ramp – Siberian Snakes

- Depolarizing resonances lead to polarization loss on the ramp
- In a nutshell, each particle in the beam samples magnetic fields with varying directions as it travels around the machine, which rotate the spin slightly away from the ideal, vertical direction
- Over many turns, these effects would accumulate, and polarization would be lost
- A "Siberian snake" rotates the spins by 180 degrees, so they point in the opposite direction. Simplest realization is a solenoid magnet.
- As a result, the spin motion during one turn is (largely) reversed on the next turn, thus counteracting depolarizing effects

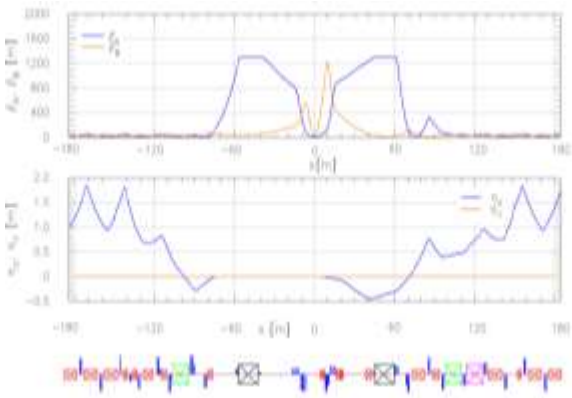
Caution: This is a severely simplified, hand-waving explanation of the effect of Siberian snakes! In reality, multiple snakes are needed to preserve polarization

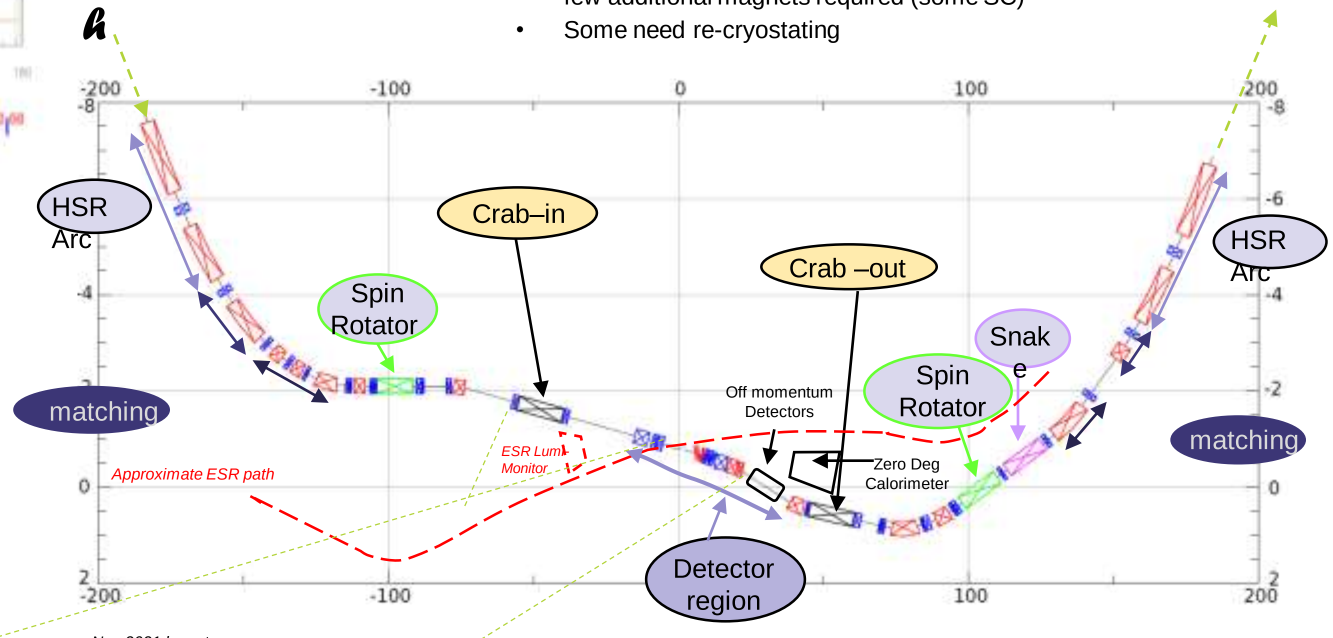
Spin Rotators

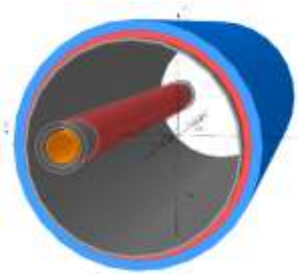
- Spins are vertical in the arcs, but experiments want longitudinal spin
- Need spin rotators
- For hadrons, helical dipoles serve as spin rotators (not covered here)
- For electrons, spin rotators consist of a combination of solenoids and dipoles:
  - Vertical spin from the arc is rotated into radial direction by a solenoid. The solenoid strength has to be matched to the beam energy
  - A well-defined net dipole bending angle φ between solenoid and IP rotates the spin by 90 degrees into the longitudinal direction, using $G\gamma*\varphi=\pi/2$
  - On the opposite side of the IP, this process is reversed so spins are vertical in the arc again

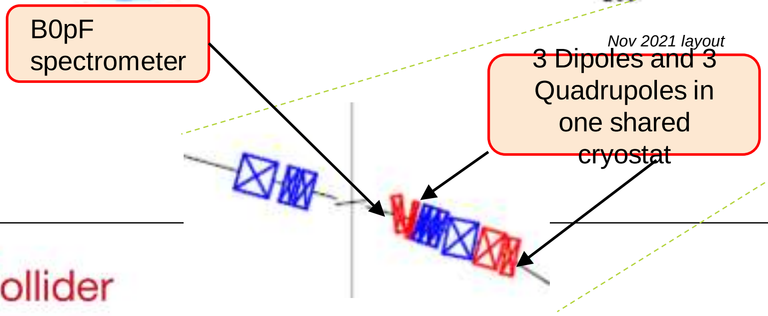
HSR layout in IR6

- 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





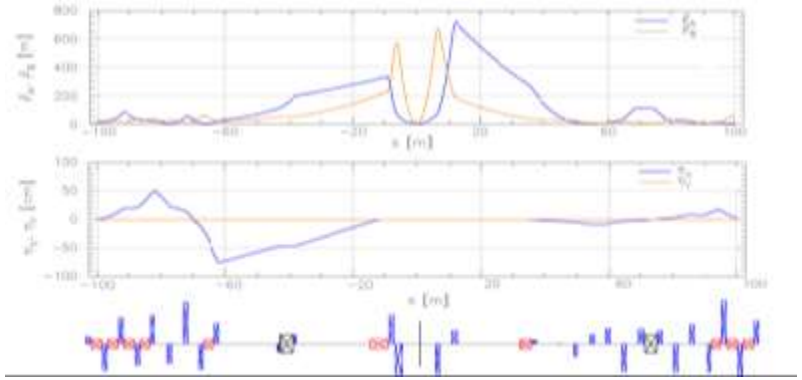


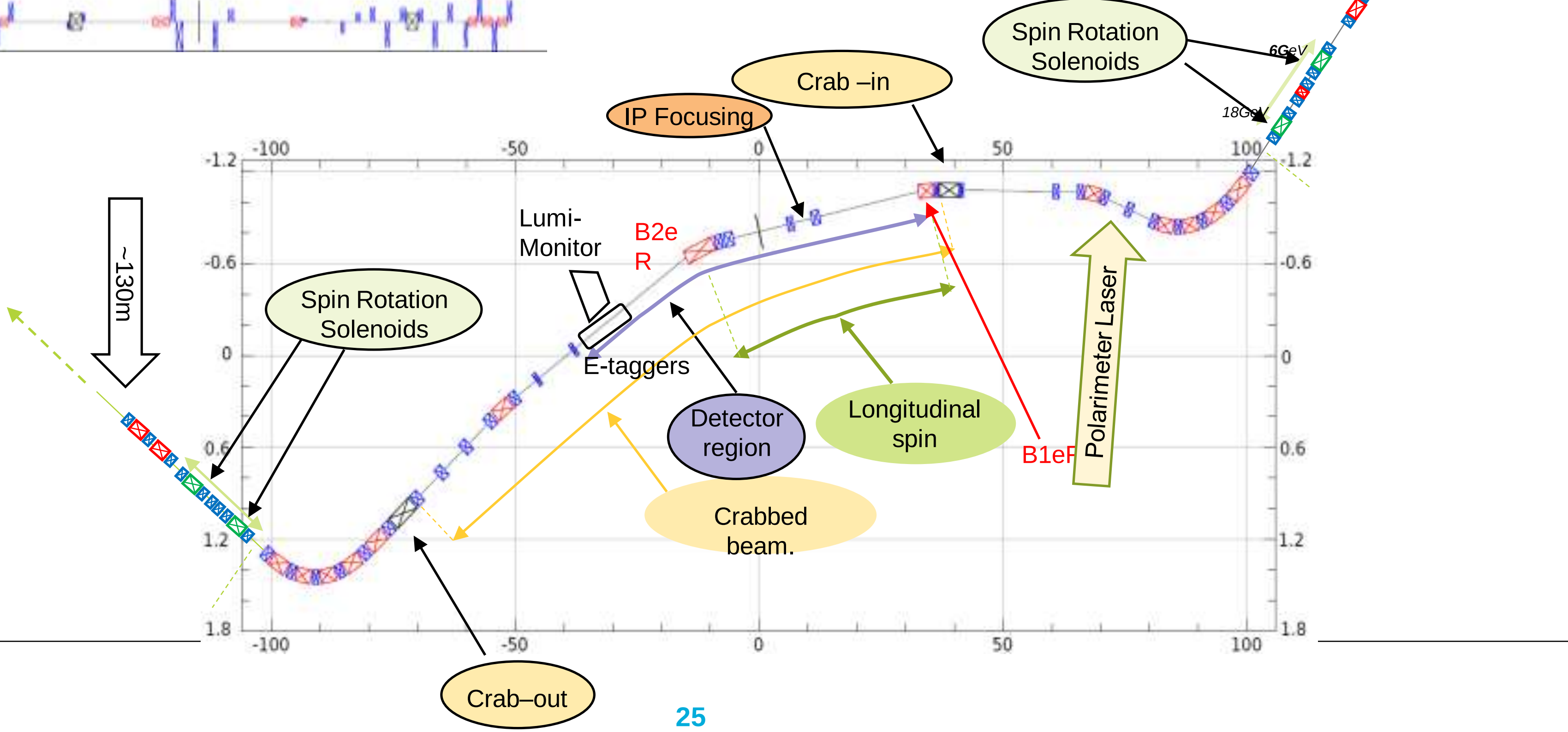


ESR layout in IR6

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





Summary

- The EIC is a highly complex collider
- The interaction region has to fulfill many requirements – high luminosity, beam separation, p_t acceptance, longitudinal polarization, …
- Any IR design is always a compromise between these requirements

Any Questions?