EIC Accelerator Physics/Technology

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For the EIC Project and EIC Collaboration

CFNS/CTEQ School Lecture 1
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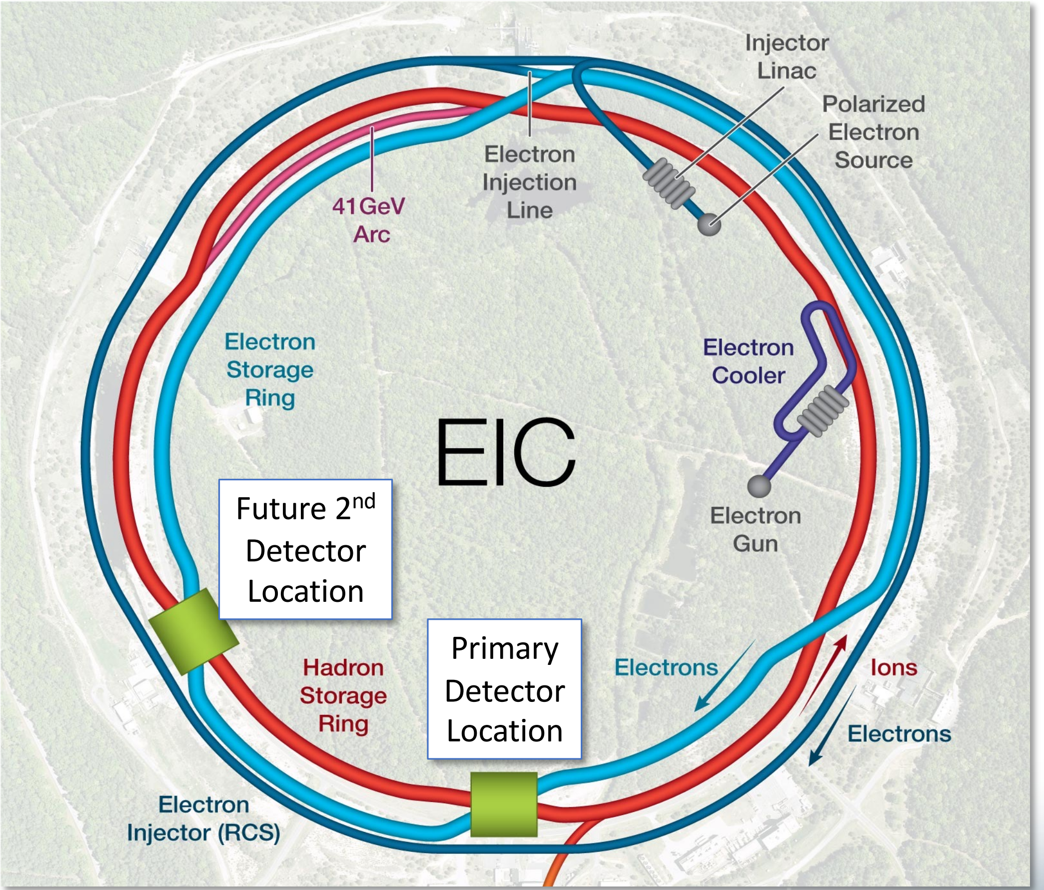
EIC: Electron-Ion Collider

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

Outline (Hour 1)

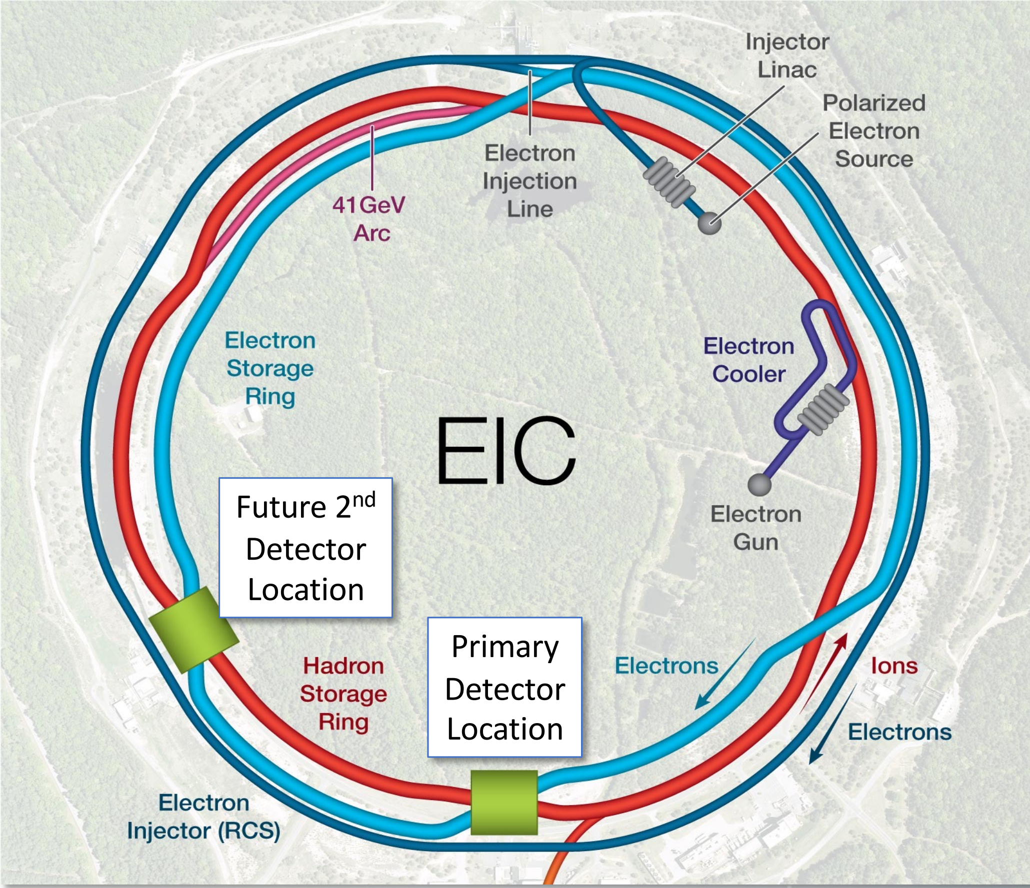
- EIC overview
  - From an accelerator physicist ☺
- Relevant accelerator physics
  - Synchrotrons
  - (Brief) beam dynamics
  - Phase space, emittance, “beta”
- Luminosity
- Collider interaction regions
  - ”Low-beta” squeeze



Outline (Hour 2)

Please give feedback/make requests!

- EIC interaction region
- Luminosity revisited
- Lumi optimization and limitations
  - Superconducting magnets
  - Crab cavities, crossing angle
  - Beam sizes and cooling
  - Space charge
  - Synchrotron radiation
  - Cooling
- Luminosity ramp-up



(May look familiar from 2022 Gordon Conference talk)

EIC Requirements

- **EIC design goals**
  - High luminosity: **$L = (0.1\text{-}1)\cdot 10^{34}\ cm^{-2}\ s^{-1}$**
    - ➔ 10-100 fb^{-1} "High"
  - Collisions of highly **polarized (>70%)** e and p (and light ion) beams Unique
    - with flexible bunch by bunch spin patterns
  - Large range of CM energies:
    - **E_{cm} = 20-140 GeV** "Low"
  - Large range of ion species:
    - Protons – Uranium Diverse
  - Ensure accommodation of a second IR
  - Large detector acceptances; good background
    - Hadron particle loss
    - IR synchrotron radiation backgrounds

uniquely challenging

EIC Accelerator Design Overview

- **Hadron storage ring (HSR): 40-275 GeV (existing)**
  - up to 1160 bunches, 1A avg beam current (3x RHIC, polarized)
  - bright vertical beam emittance (1.5 nm); new vac sleeves
  - hadron beam cooling
- **Electron storage ring (ESR): 2.5–18 GeV (new)**
  - up to 1160 polarized bunches
    - high polarization by continual reinjection from RCS
  - 2.5 A avg beam current ➔ 9 MW SR power
  - superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV (new)**
  - 2 bunches at 1 Hz; spin transparent due to high periodicity
- **High luminosity interaction region (new; future 2nd IR)**
  - L = 10^{34} $cm^{-2}s^{-1}$ = 10 kHz-uba, superconducting magnets
  - 25 mrad crossing angle with crab cavities/crab crossing
  - spin rotators (produce longitudinal polarization at IP)

Comparable to new mature B-factory, e.g. SuperKEKB

Current 6x NSLS-II

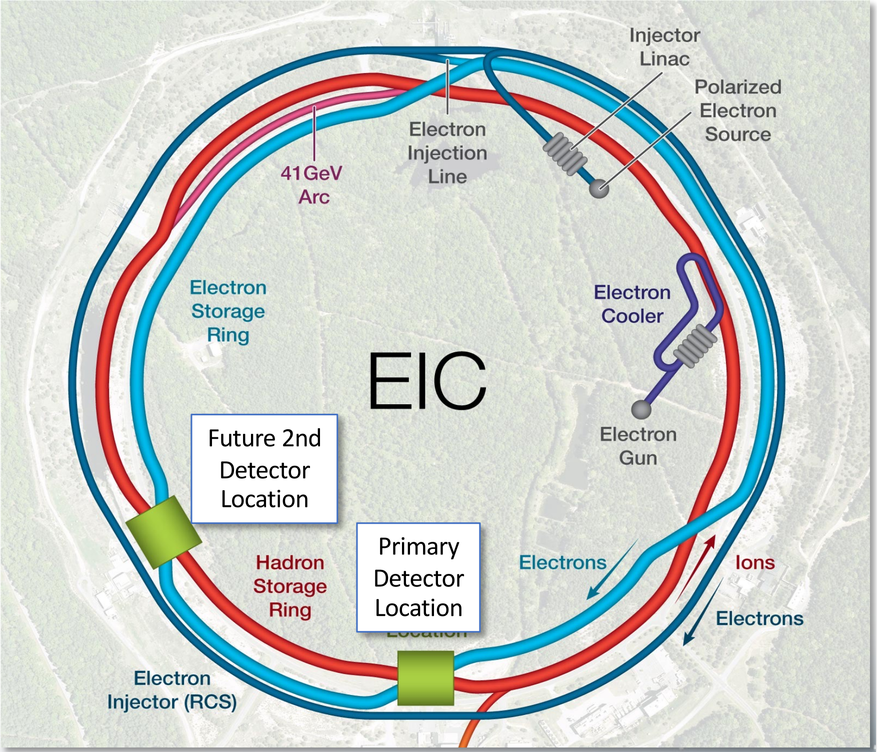


Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

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Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
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Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

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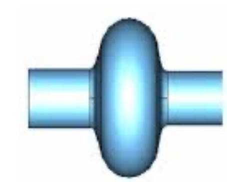
Whoa, wait! Emittance?

- Oops - let's start with some **background, scales, and definitions**
- To zeroth order a separated Lorentz force rules: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - Charged particle beams are **ensembles of oscillators**
    - Manipulated **longitudinally** by time-varying **electric fields** from **RF cavities**
      - Typically 10s kV to MV at frequencies of 10s MHz to GHz
      - Longitudinal **focusing** creates **bunches** (EIC: $10^{10\text{-}11}$ particles/bunch)
      - Sinusoidal weak restoring force => **slow pendulum-like oscillator**



    - Manipulated **transversely** by (conservative) **magnetic fields** from **magnets**
      - Typically 10s G (very low energy) to ~4 T+ (superconducting IR)
      - Transverse **focusing** keeps bunches transversely confined
      - Linear strong restoring force => **fast SHO-like oscillator**

- Higher orders add messy nonlinearities, coupling, environmental interactions

Focusing on the transverse focusing

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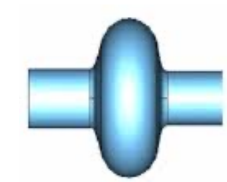
One dynamical dimension



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Two separate dynamical dimensions

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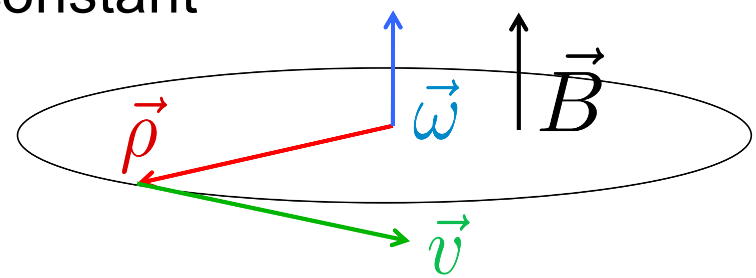
Charged Particle Bending by Magnetic Fields

- In a constant magnetic field, charged particles move in circular arcs of radius ρ with constant angular velocity ω:



$$\vec{F} = \frac{d}{dt}(\gamma m \vec{v}) = \gamma m \frac{d\vec{v}}{dt} = q\vec{v} \times \vec{B}$$

$$\vec{v} = \vec{\omega} \times \vec{\rho} \qquad \Rightarrow \qquad q\vec{v} \times \vec{B} = \gamma m \vec{\omega} \times \frac{d\vec{\rho}}{dt} = \gamma m \vec{\omega} \times \vec{v}$$

- For $\vec{B} \perp \vec{v}$ (magnets with fields transverse to particle motion)

$$qvB = \frac{\gamma m v^2}{\rho} \qquad p = \gamma m(\beta c) = q(B\rho) \qquad \boxed{\frac{p}{q} = (B\rho)} \qquad \omega = \frac{v}{\rho} = \frac{qB}{\gamma m}$$

(Cyclotrons)

Rigidity: Bending Radius vs Momentum

Beam (particles)

$$\frac{p}{q} = (B\rho)$$

Accelerator (magnets, geometry)

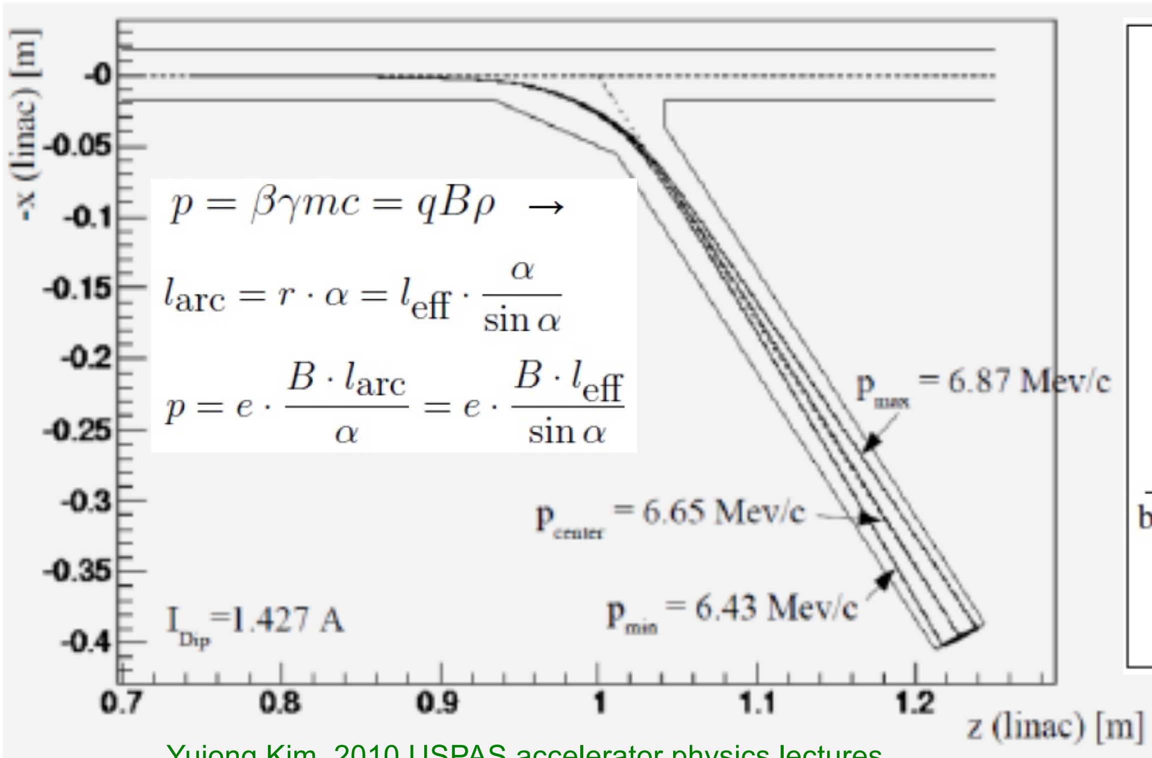
$$p = \beta\gamma mc$$

- This is such a useful expression in accelerator physics that has its own name: **rigidity**
- Ratio of momentum to charge
  - How hard (or easy) is a particle to magnetically deflect?
  - Often expressed in [T-m] (right side! Easy to calculate B)
  - Be careful when q≠e!!
- A possibly useful expression

$$\frac{p[\mathrm{GeV/c}]}{q[e]} \approx 0.3\, B[\mathrm{T}]\, \rho[\mathrm{m}]$$

Application: Particle Spectrometer

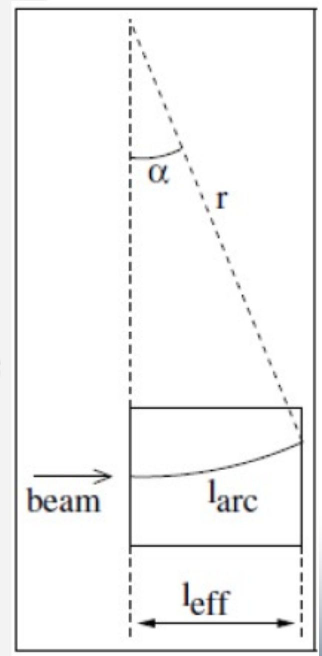
- Measure particle momentum by measuring bend angle α from a calibrated magnetic field B



$$p = \beta\gamma mc = qB\rho \rightarrow$$

$$l_{\mathrm{arc}} = r \cdot \alpha = l_{\mathrm{eff}} \cdot \frac{\alpha}{\sin\alpha}$$

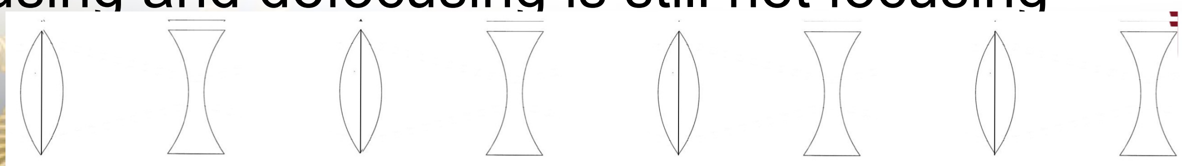
$$p = e \cdot \frac{B \cdot l_{\mathrm{arc}}}{\alpha} = e \cdot \frac{B \cdot l_{\mathrm{eff}}}{\sin\alpha}$$

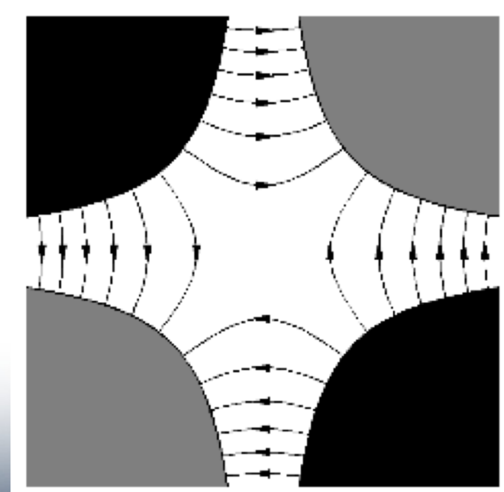


Yujong Kim, 2010 USPAS accelerator physics lectures

Transverse Charged Particle (De)Focusing

- **Dipoles** (constant uniform field) **bend** particles: change $x' \equiv dx/ds$
- **Quadrupoles** (constant dB/dx and dB/dy) **linearly (de)focus** particles
  - e.g. in horizontal B(x)=x*(dB/dx); Lorentz force is linear in x
  - Free space Maxwell's equations **require** that dB/dx=-dB/dy
    - **Discussion**: Convince yourself this is true
- Horizontal focusing = vertical defocusing
- Vertical focusing = horizontal defocusing
- Thankfully classical optics tells us alternating focusing and defocusing is still net focusing

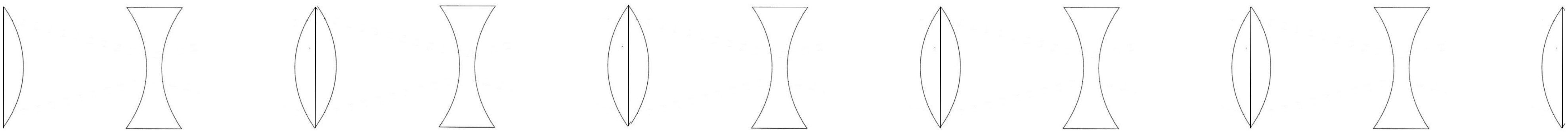




http://www.toddsatogata.net/2017-USPAS/Lectures/2017-01-18-Chapter5.pdf

FODO Lives

By convention horizontal focusing/defocusing is shown; vertical is opposite



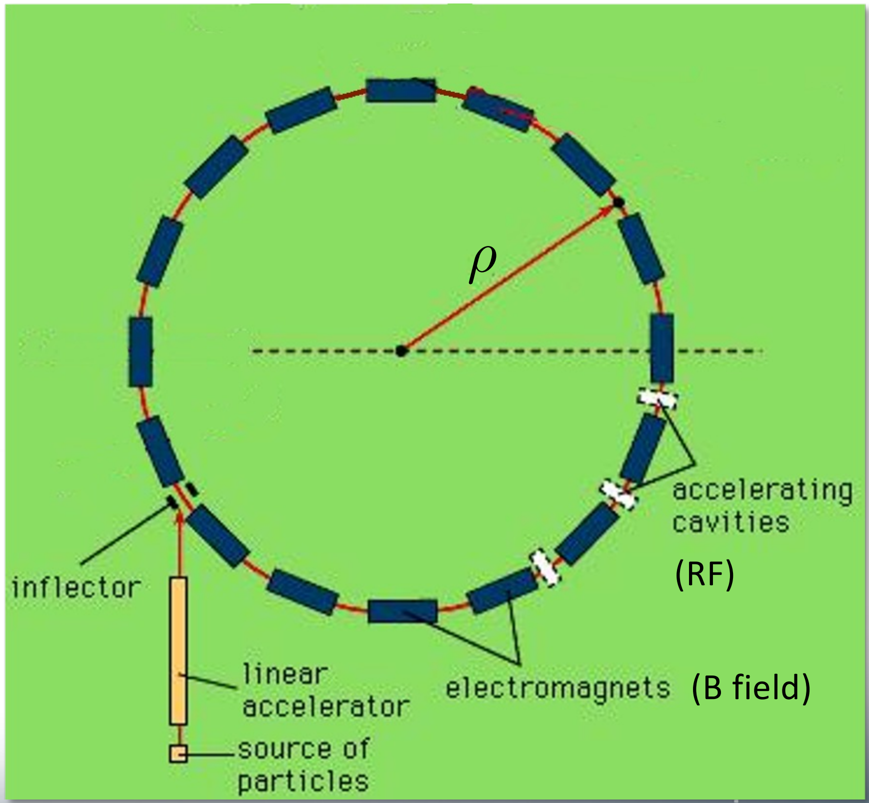
- Most accelerator lattices (including EIC) are designed in modular ways
  - Design and operational clarity, separation of functions
- One of the most common modules is a FODO module
  - Alternating focusing and defocusing “strong” quadrupoles
  - Spaces between are combinations of drifts and dipoles
  - Strong quadrupoles dominate the focusing
  - **Periodicity** is **one FODO “cell”**
  - **Horizontal beam size largest at centers of focusing quads**
  - **Vertical beam size largest at centers of defocusing quads**

EIC HSR/ESR/RCS are Synchrotrons

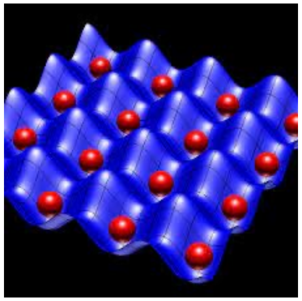
- ”Ring accelerator”
- Synchronize bending magnetic field B, beam momentum p
  - ~constant design (average) “radius” ρ

$$B\rho = \frac{p}{q} \qquad \Rightarrow \qquad \rho = \frac{1}{q}\left(\frac{p(t)}{B(t)}\right)$$

- Separate RF (longitudinal focusing, acceleration) and magnets (transverse bending/focusing)
- Circumference also ~constant
  - Revolution frequency and RF frequency change with particle relativistic velocity β, momentum p



Synchrotrons: Periodic Focusing Systems



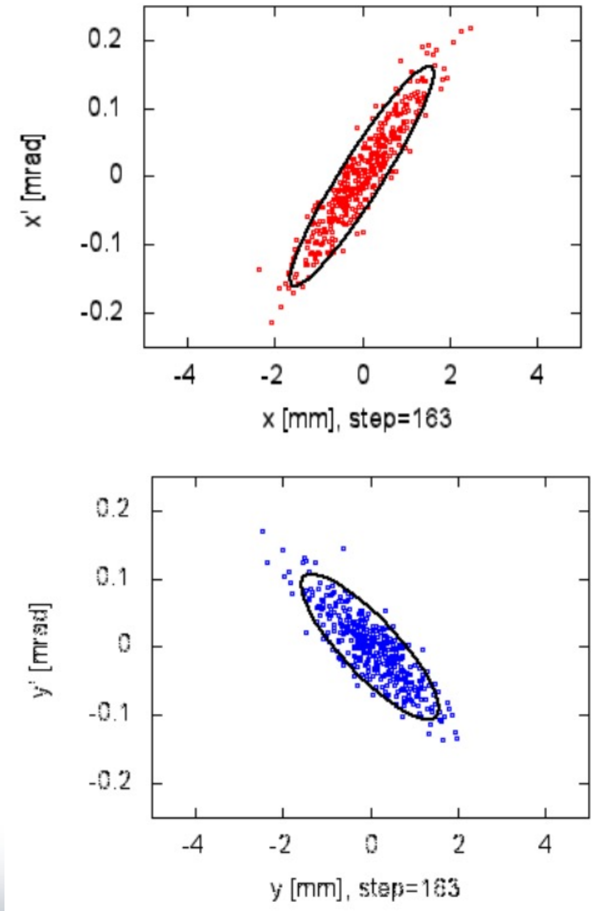
- Periodic focusing systems with periodic boundary conditions
  - A long academic history!
  - Solid state, quantum mechanics...
- Periodic **1D linear** focusing system
  - Hill's Equation (homogeneous)

$$x'' + K(s)x = 0 \qquad K(s) \equiv \frac{1}{(B\rho)} \left(\frac{\partial B_y}{\partial x} \right)(s) \qquad K(s + C) = K(s)$$

  - Overall synchrotron is periodic, as are repeated FODO "cells"
- Symmetry is locally broken for "insertions"
  - Match boundary conditions between sections with different K values (focusing)

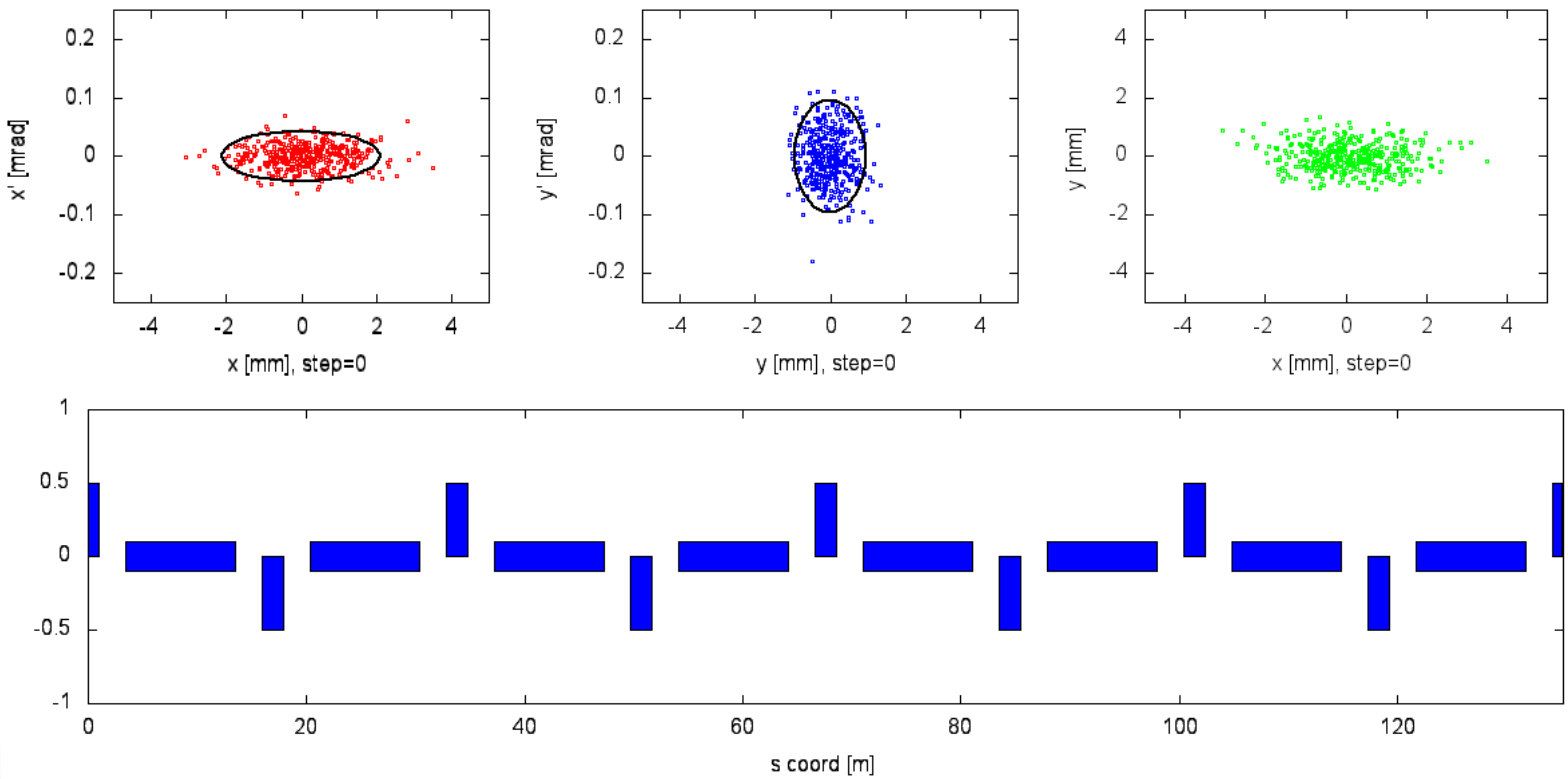
Phase Space and Emittance

- Equations of motion are **second-order differential equations**
- Like classical mechanics, particle trajectories are determined by their **equation of motion** (Hill's equation) and **two initial conditions**
  - **Horizontal** $(x, x' \equiv dx/ds)$ x',y' are angles
  - **Vertical** $(y, y' \equiv dy/ds)$
- x',y' are small for high-energy accelerators
  - Paraxial optics approximations apply
- Transverse distributions are **usually Gaussian**
  - RMS distribution ellipse area: **emittance** [mm-mrad]



Longitudinal similar but different

Electron-Ion Collider



Typical alternating FODO beam size behavior

Ellipse areas are horizontal and vertical emittances

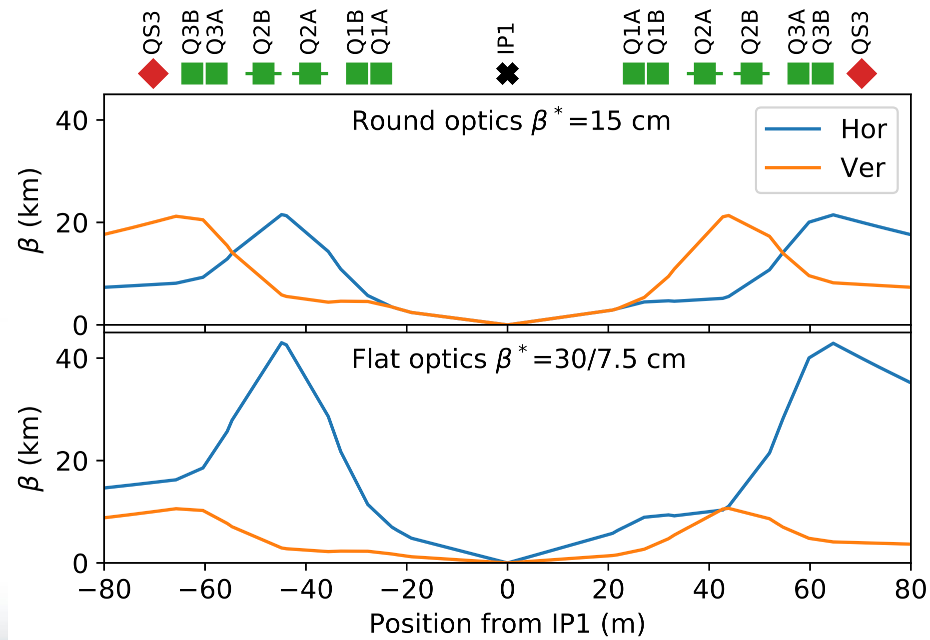
- Emittance ϵ is ”conserved” for linear particle motion
  - Cooling, synchrotron radiation, IBS, noise etc. violate this conservation
- **Beam size depends on emittance and optics “beta function”** $\sigma = \sqrt{\beta\epsilon}$

“Blah blah beta star blah blah”

lattice/magnets → beam

- Beam size depends on emittance and optics “beta”: $\beta(s) = \sigma(s)^2/\epsilon$
- Recall dipoles change $x' \equiv dx/ds$
- Quadrupoles change $\beta' \equiv d\beta(s)/ds$
  - Look for kinks in beta function plots
- Design and control of **periodic focusing** (**beta functions**, **beam sizes**): quadrupole layout/strengths
- Betas are the main beam size knobs

$$\beta^\star : \quad \beta \text{ at Interaction Point}$$



PHYS. REV. ACCEL. BEAMS 23, 041001 (2020)

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Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [µm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
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β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
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RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
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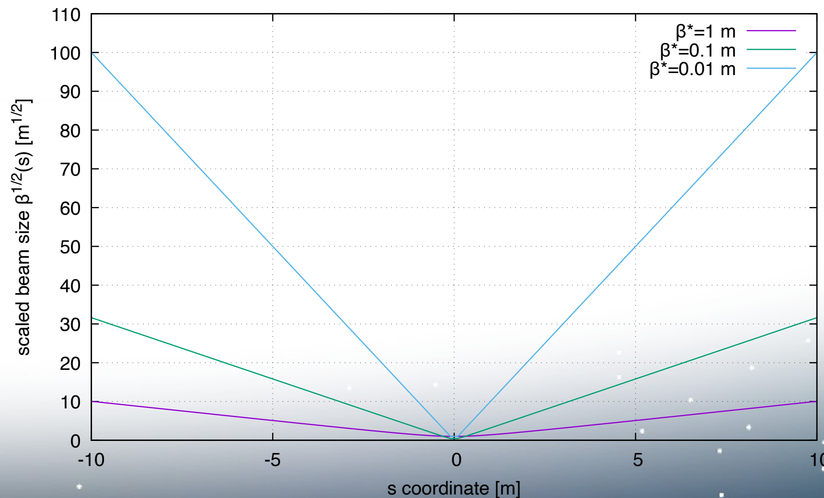
Beta in Free Space

- FODO has minimum beta in quadrupoles
  - You don't want **our** magnets in **your** detector
  - BUT we all want small beam sizes for **high luminosity**
- Can minimum beam size be achieved in "free space"
  - Yes! We can demonstrate in free space

$$\beta(s) = \beta^\star + s^2/\beta^\star$$

  - **Design tensions**:
    - Low beta* for high luminosity
    - Proximity of quadrupoles to IP
    - Large-aperture quads feasibility/quality
    - (Beam divergence near IP; "hourglass")
    - (Downstream secondary focus)



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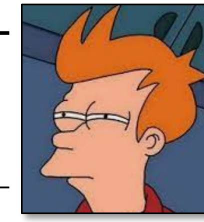

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Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

Luminosity (Lumi) Limits In One Slide™

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

f_{coll} : collision frequency

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

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

Every parameter optimized separately and collectively in the EIC design

Try multiplying out the given numbers – should be very close to 10^{34} $cm^{-2}s^{-1}$

- **Maximize collision frequency (~90 MHz)**
  - Limited by kicker rise times
  - Limited by parasitic collisions (crabbing)
- **Maximize particles per bunch (~10^{11})**
  - Limited by sources, space charge
  - Limited by collective effects
    - Interaction of beam with impedances
    - Also total currents: $I_{1,2}=q_{1,2}N_{1,2}f_{\mathrm{coll}}$ ~1-3A
- **Minimize beam sizes at IP (~250/25 um)**
  - Limited by IR focusing, magnets
  - Limited by chromatic dynamic aperture
  - Limited by emittance growth (IBS)

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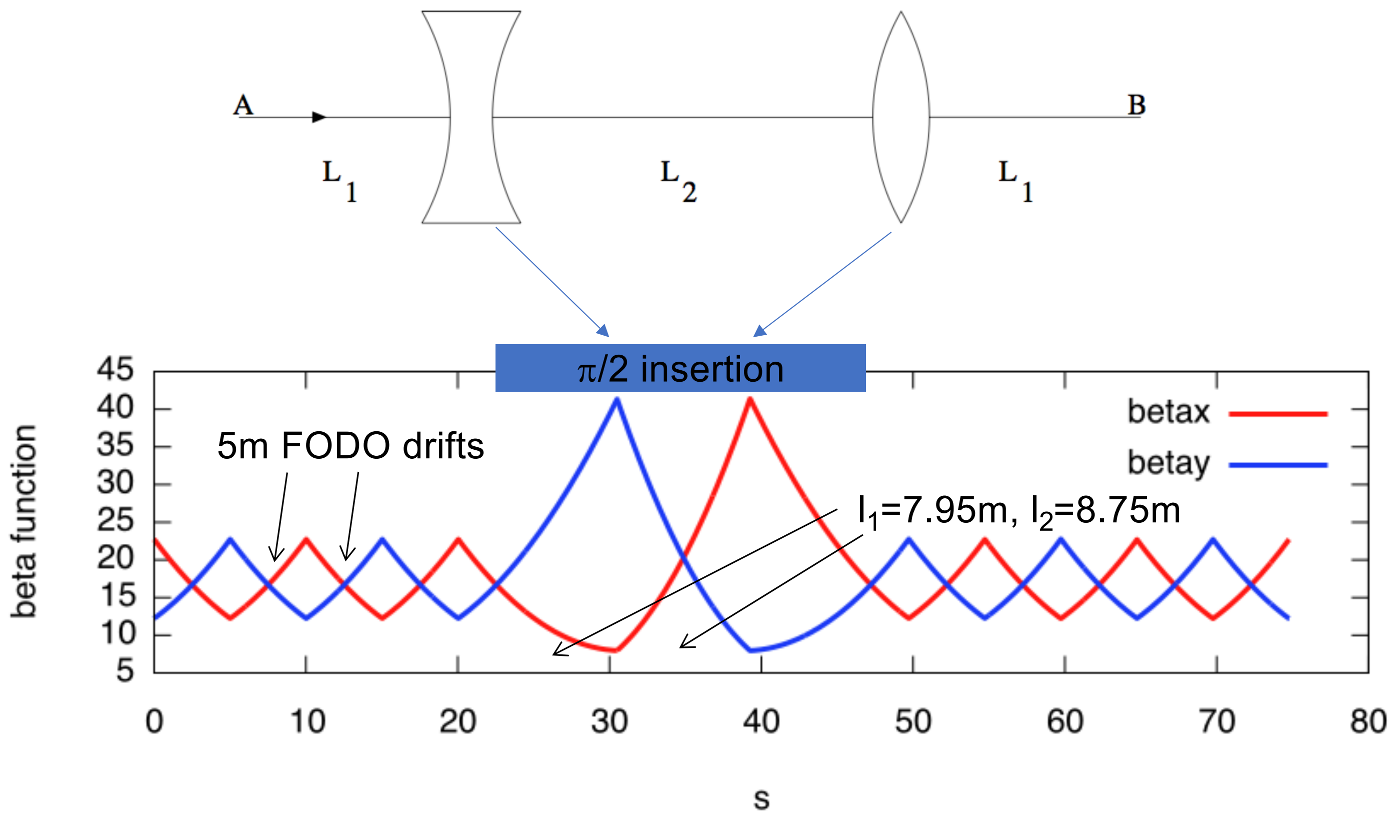
"π/2" Insertion

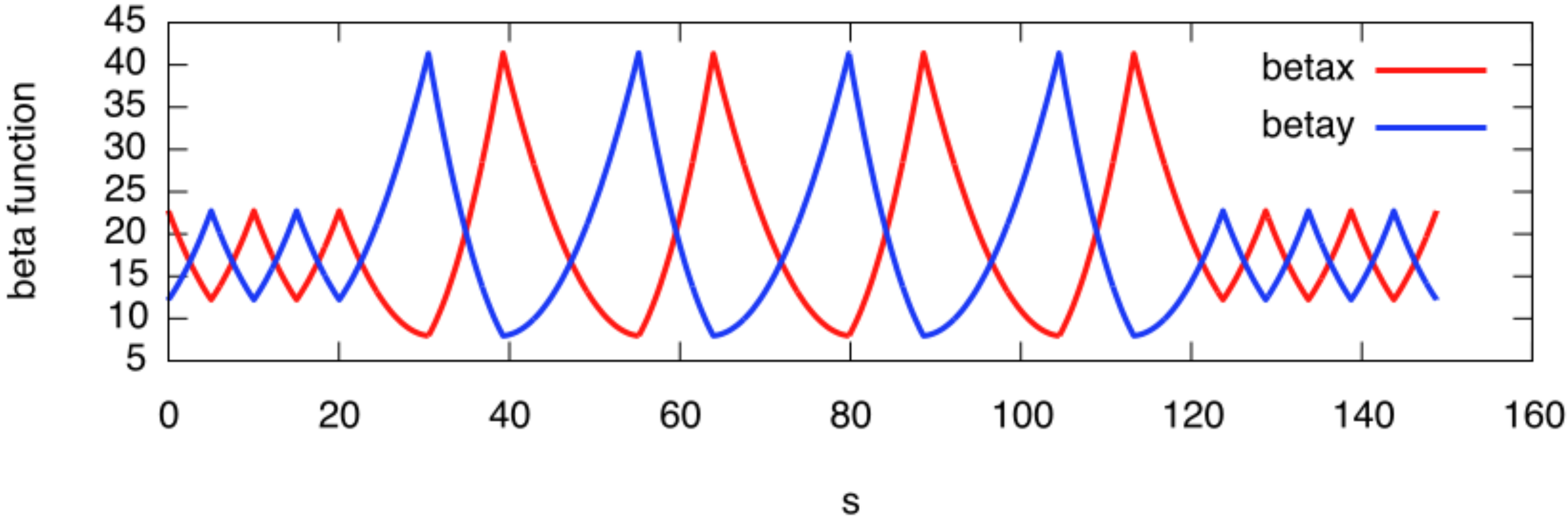
- "Make smaller beam size in longer magnet-free region"
- Among simplest insertions
- Match boundary conditions at insertion ends



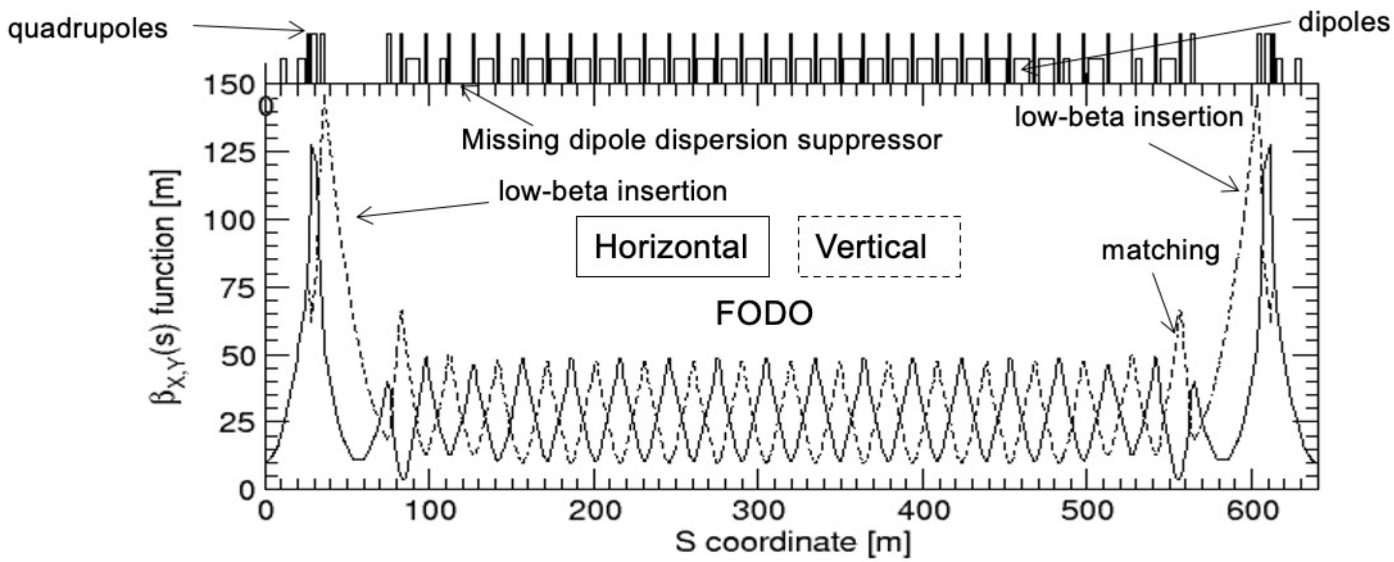
Multiple π/2 Insertions

$$\mathbf{M}^4 = \mathbf{I}$$

I = Identity Matrix



(1/6 of) RHIC Lattice

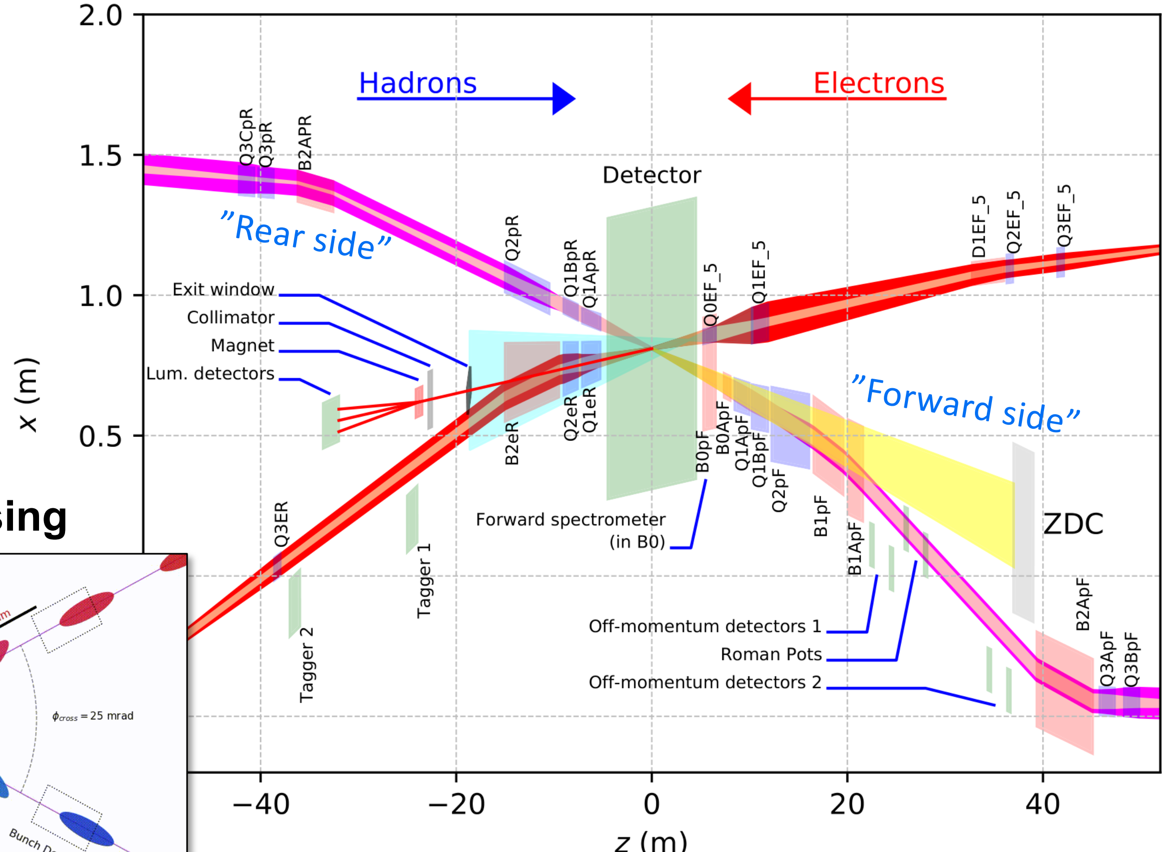


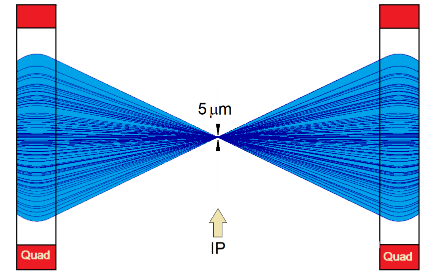
- Note modular, symmetric design, including low-beta insertions
  - Used for experimental collisions
  - Minimum beam sizes $\sigma_{x,y}$, Maximize luminosity
  - Large $\sigma_{x,y}$, beam sizes in "low beta quadrupoles"
- Other facilities also have longitudinal bunch compressors
  - Minimize longitudinal beam size (bunch length) for, e.g, FELs

EIC Primary Interaction Region

Existing tunnel and experiment halls

Different axis scales!





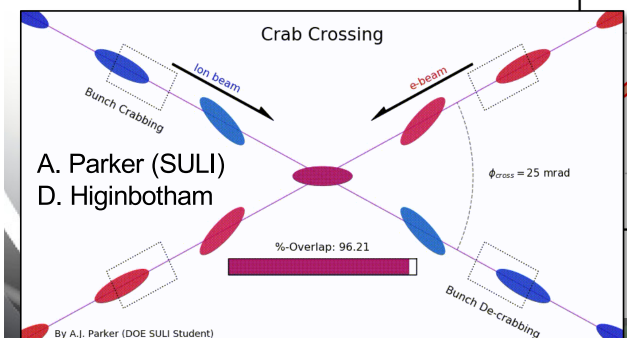
Focusing (quads) as close to IP as possible (~5m!)

Tensions in magnet requirements:

- high field
- large apertures
- e/p magnet proximity near IP

Chromaticity: focusing dependence on particle energy

25 mrad crab crossing



A. Parker (SULI)
D. Higinbotham

Final Focus/Luminosity Game

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

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

http://stephenbrooks.org/ap/beam2d/

Can **you** achieve a peak luminosity of 10^{34} cm^{-2} s^{-1}?

(NB: You may have to click on up/down rather than using the arrow keys)