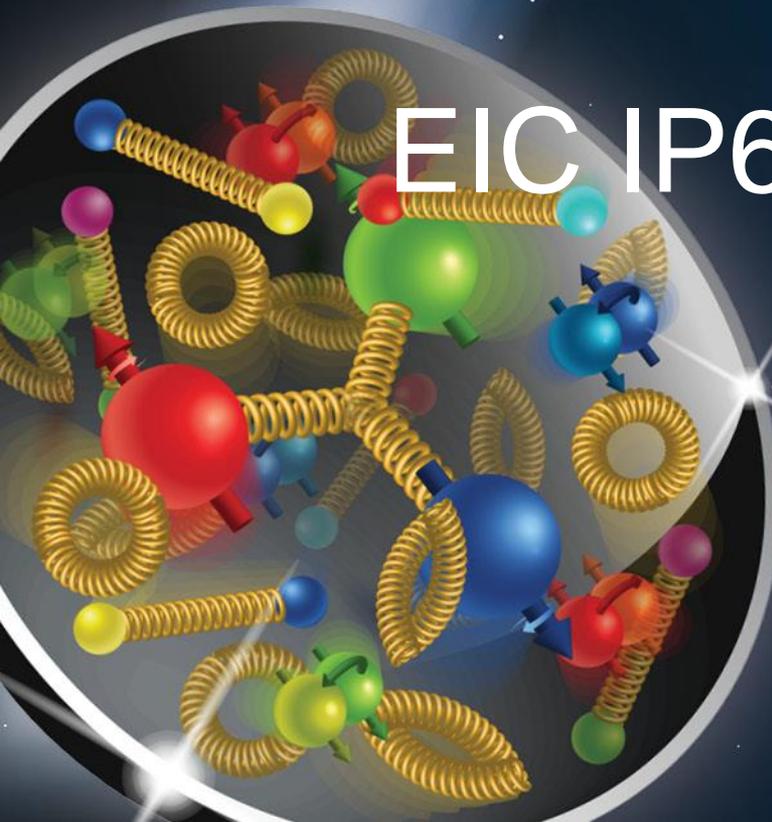


# EIC IP6 IR Design Overview

Holger Witte

March 12-13, 2021

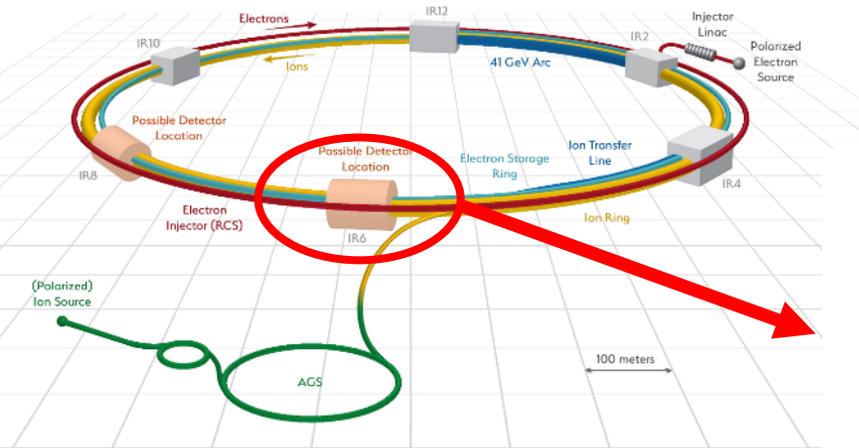
Electron Ion Collider – EIC at BNL



# Outline

- Overview
  - Requirements
  - General constraints
  - Present IR
- Luminosity
  - Focusing
  - Crab crossing
- IR Magnets
  - Apertures and Challenges
  - Engineering

# EIC IR: Overview



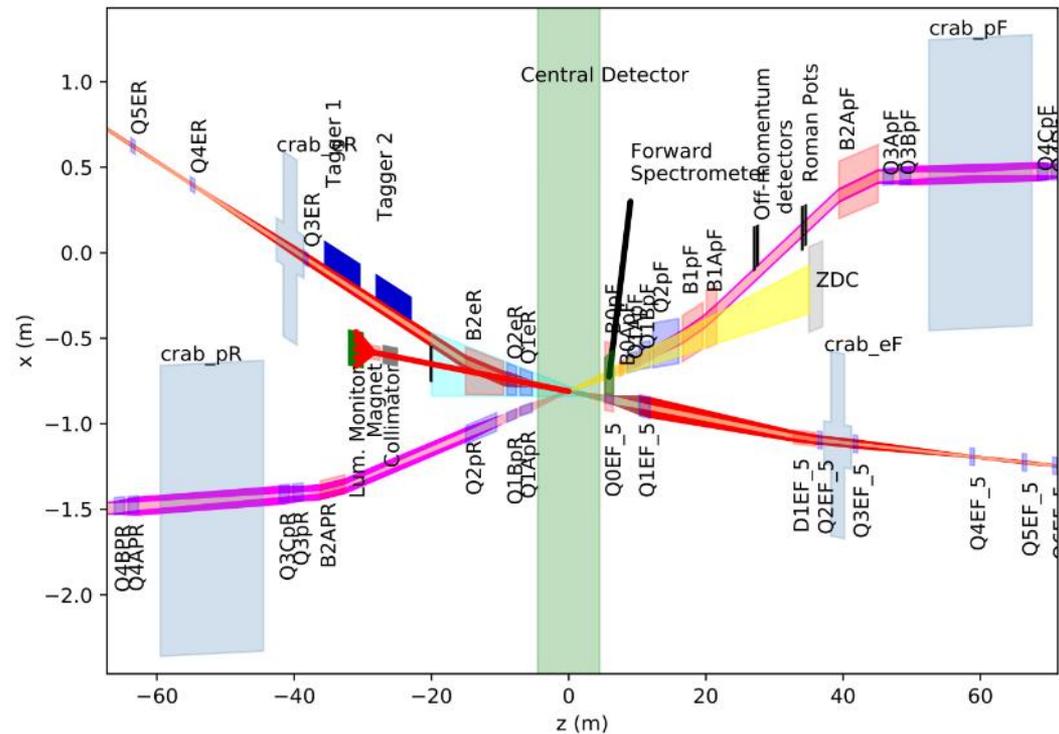
RHIC yellow ring: EIC hadron ring

Add electron storage ring in existing tunnel (and the RCS)

IR location: IR6

Rear

Forward



# IR Requirements

- EIC IR designed to meet physics requirements
  - Machine element free region: +/- 4.5m main detector
    - (Efforts underway to increase this to -4.5/+5m)
  - ZDC: 60cm x 60cm x 2m @ ~30 m
  - Scattered proton/neutron detection
    - Protons  $0.2 \text{ GeV} < p_t < 1.3 \text{ GeV}$
    - Neutron cone +/- 4 mrad
- Machine requirements
  - Small  $\beta_y^*$ : quads close to IP, high gradients for hadron quads
  - Crossing angle: as small as possible to minimize crab voltage and beam dynamics issues
    - Choice: 25 mrad
  - Synchrotron radiation background
    - No bending upstream for leptons (up to ~35m from IP)
    - Rear lepton magnets: aperture dominated by sync fan

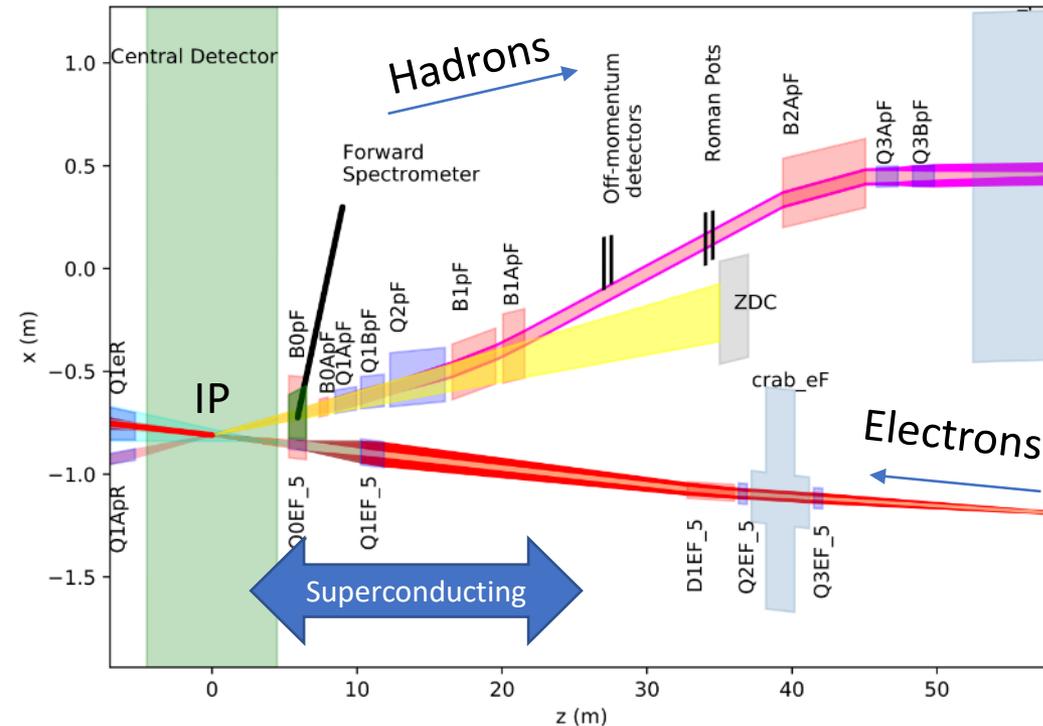
# Considerations

- Geometry
  - RHIC tunnel (injection, RHIC magnets, RCS, eSR)
  - Experimental hall (IR6)
  - Space for detector
- Physics considerations
  - See requirements, other talks
- Accelerator/optics
  - Match into existing machine
  - Dispersion, chromaticity

# Considerations (cont.)

- Crab cavities
  - Location
  - Geometry
  - Phase advance
- Engineering
  - Magnets: feasibility
  - Cryostating
  - Utilities
- Project
  - Cost, risk
  - R&D required
  - Vendors

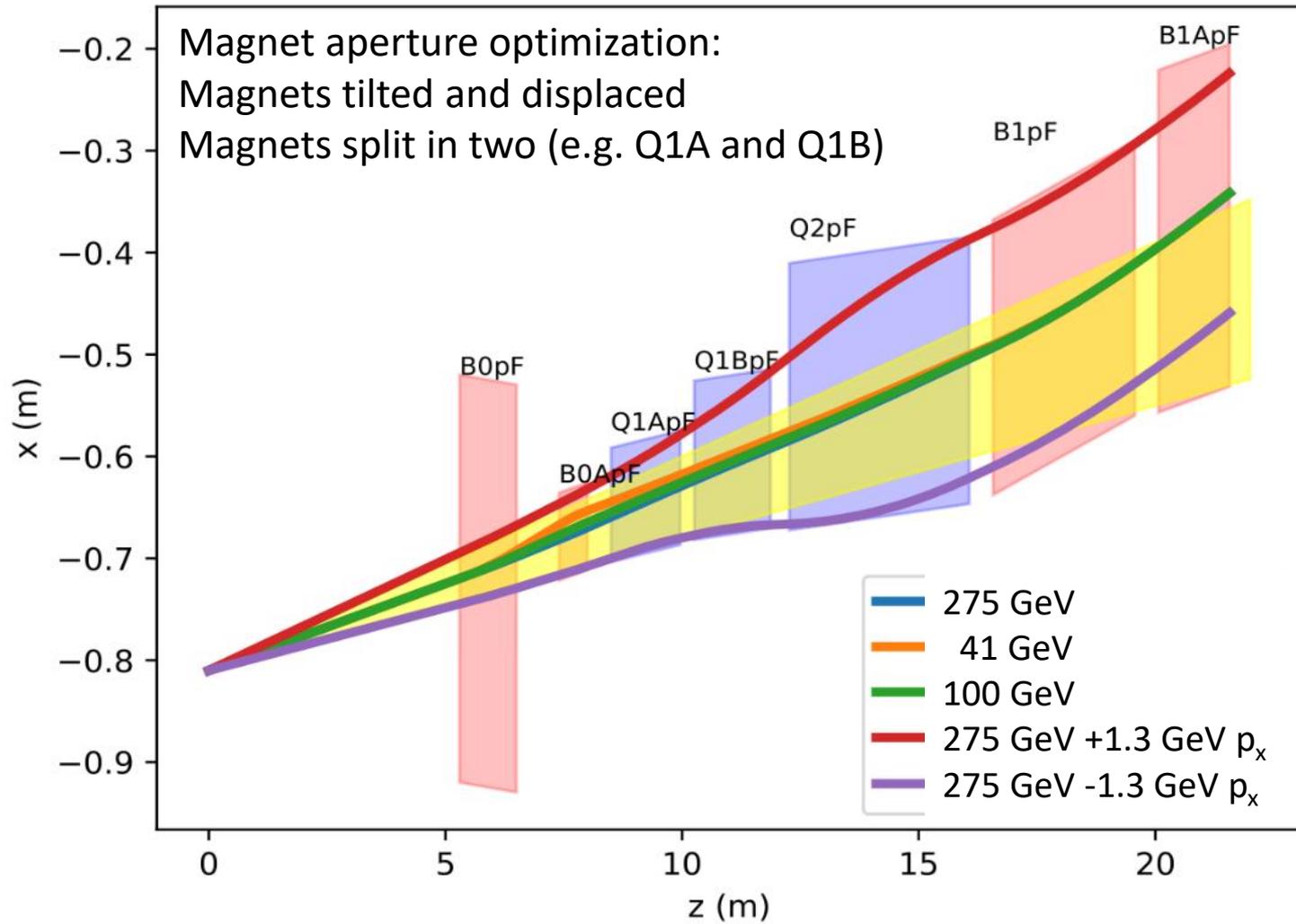
# EIC IR: Forward Direction



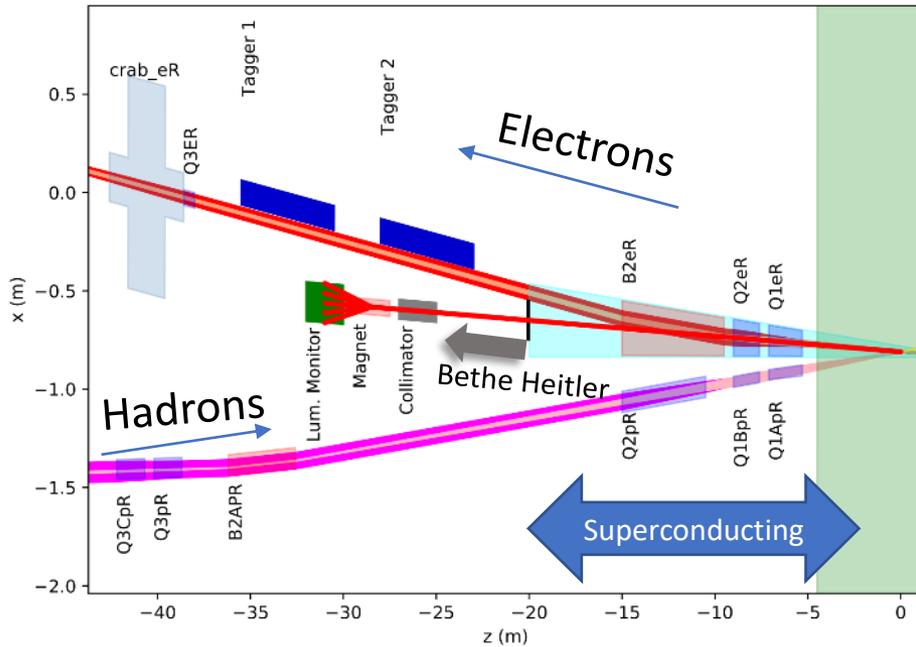
Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
B0ApF	0.043	0.6	-3.3	0	-3.3
Q1ApF	0.056	1.46	0	-72.608	-4.066
Q1BpF	0.078	1.61	0	-66.18	-5.162
Q2pF	0.131	3.8	0	40.737	5.357
B1pF	0.135	3	-3.4	0	-3.4

- Interleaved magnet scheme
  - Adding magnets is challenging
- Why are these magnets difficult?
  - Required field
  - Aperture
  - Geometric constraints
- Field
  - Accelerator physics
  - Hall/ring geometry
  - Magnet technology constraints
- Large apertures of magnets
  - Proton forward: physics
  - Rear electron: Synrad

# Hadron Forward - Apertures



# EIC IR: Rear Direction



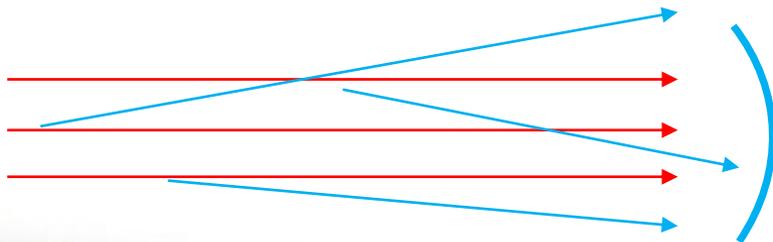
- 2-in-1 magnets
  - Common yokes
- Main issue: space between magnets
  - Crossing angle
- Large aperture due to synrad fan
  - Comes from low-beta quads

Name	R1	R2	length	grad	B pole
	[mm]	[mm]	[m]	[T/m]	[T]
Q1ApR	20	26	1.8	78.4	2.0
Q1BpR	28	28	1.4	78.4	2.2
Q2pR	54	54	4.5	33.8	1.8

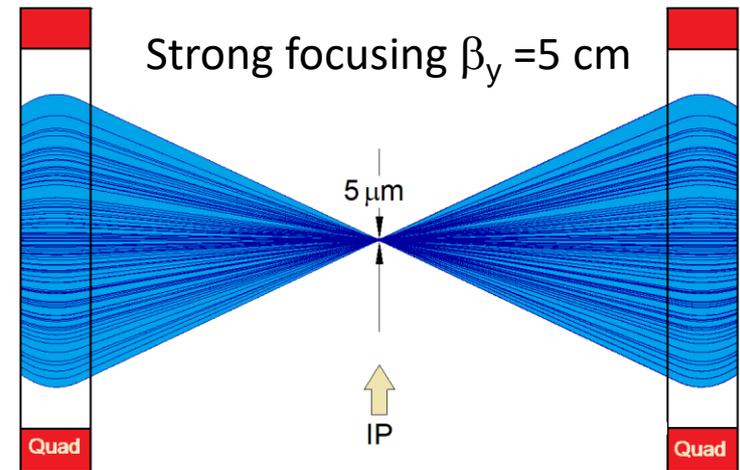
Name	R1	R2	length	B	grad	B pole
	[mm]	[mm]	[m]	[T]	[T/m]	[T]
Q1eR	66	79	1.8	0	14	-1.1
Q2eR	83	94	1.4	0	14.1	1.3
B2eR	97	139	5.5	0.2	0	-0.2

# Luminosity and Focusing

- Luminosity  $\sim 1/\text{cross section}$
- 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 (also: crosstalk)**

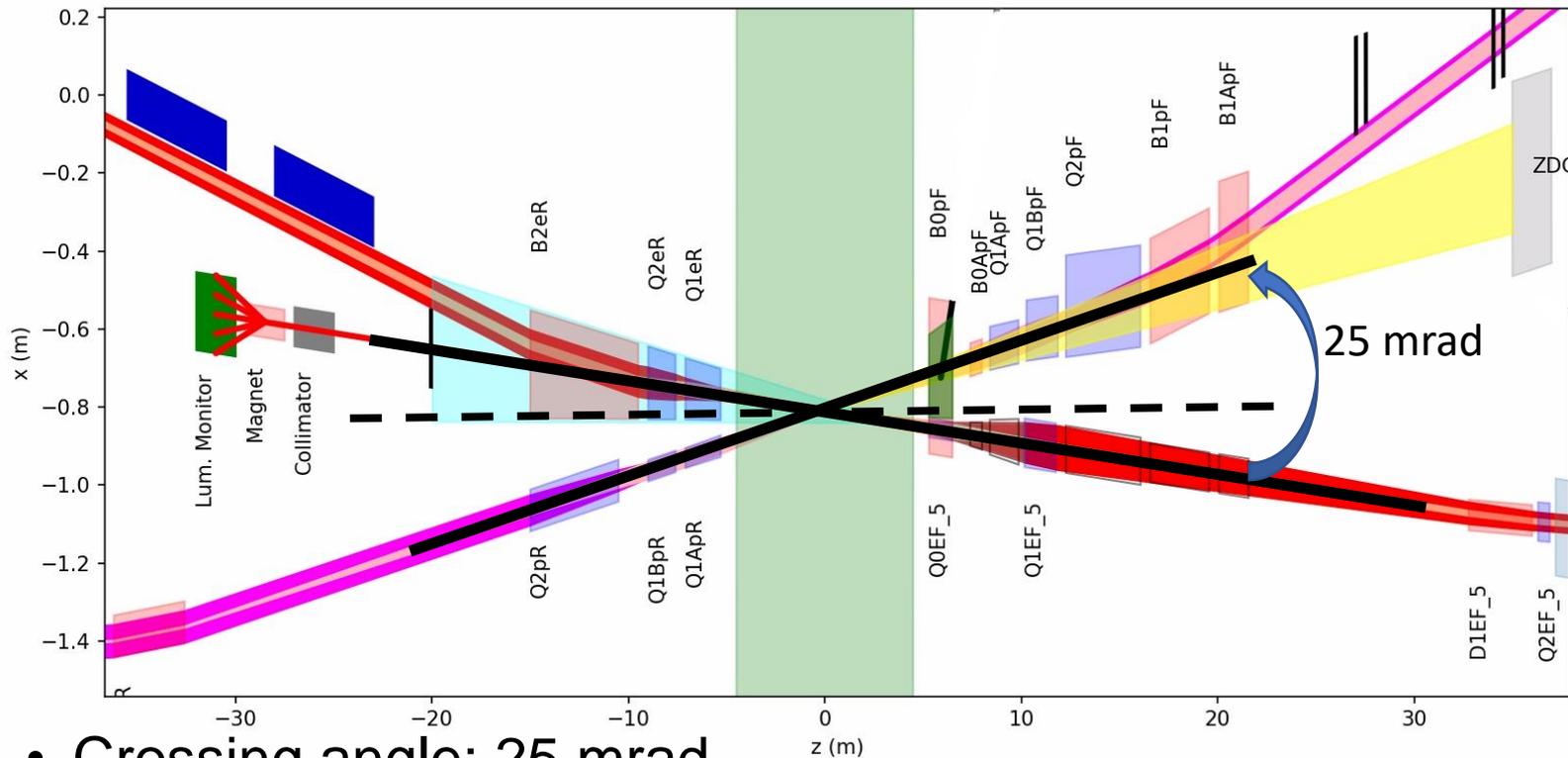


Divergence: 'spread' of the beam away from the central trajectory.



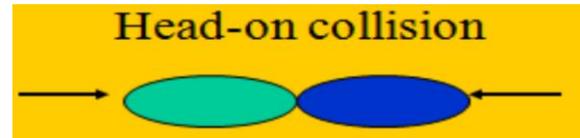
Focusing elements for both beams need to be as close as possible to the IP

# Crossing Angle

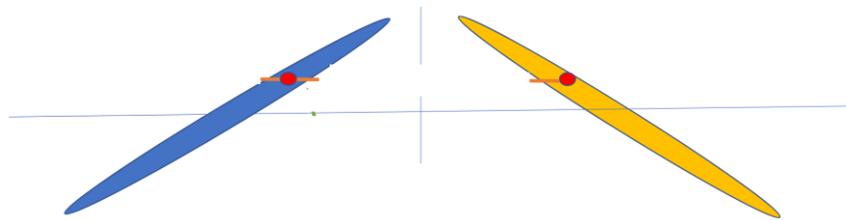


- Crossing angle: 25 mrad
  - Hadrons: 17 mrad
  - Electrons: 8 mrad
- Smaller crossing angle: beams less separated, magnet issues
- Larger crossing angle: magnet issues, crab cavities, beam dynamic issues

# Crossing Angle and Luminosity



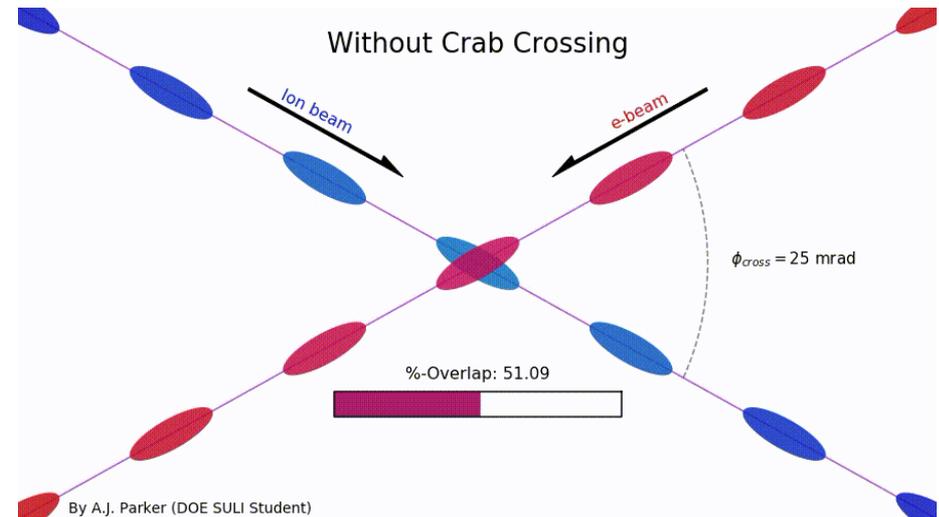
- In **head-on** collisions, **every beam particle** in one beam can potentially interact with **every particle** in the other beam



- Long ( $\sim \pm 6$  cm), skinny (100  $\mu\text{m}$ ) bunches colliding at an angle have **very little overlap**
- With **25 mrad crossing angle**, each particle can only interact with a  **$\pm 4$  mm thick slice** of the  $\pm 6$  cm long oncoming bunch

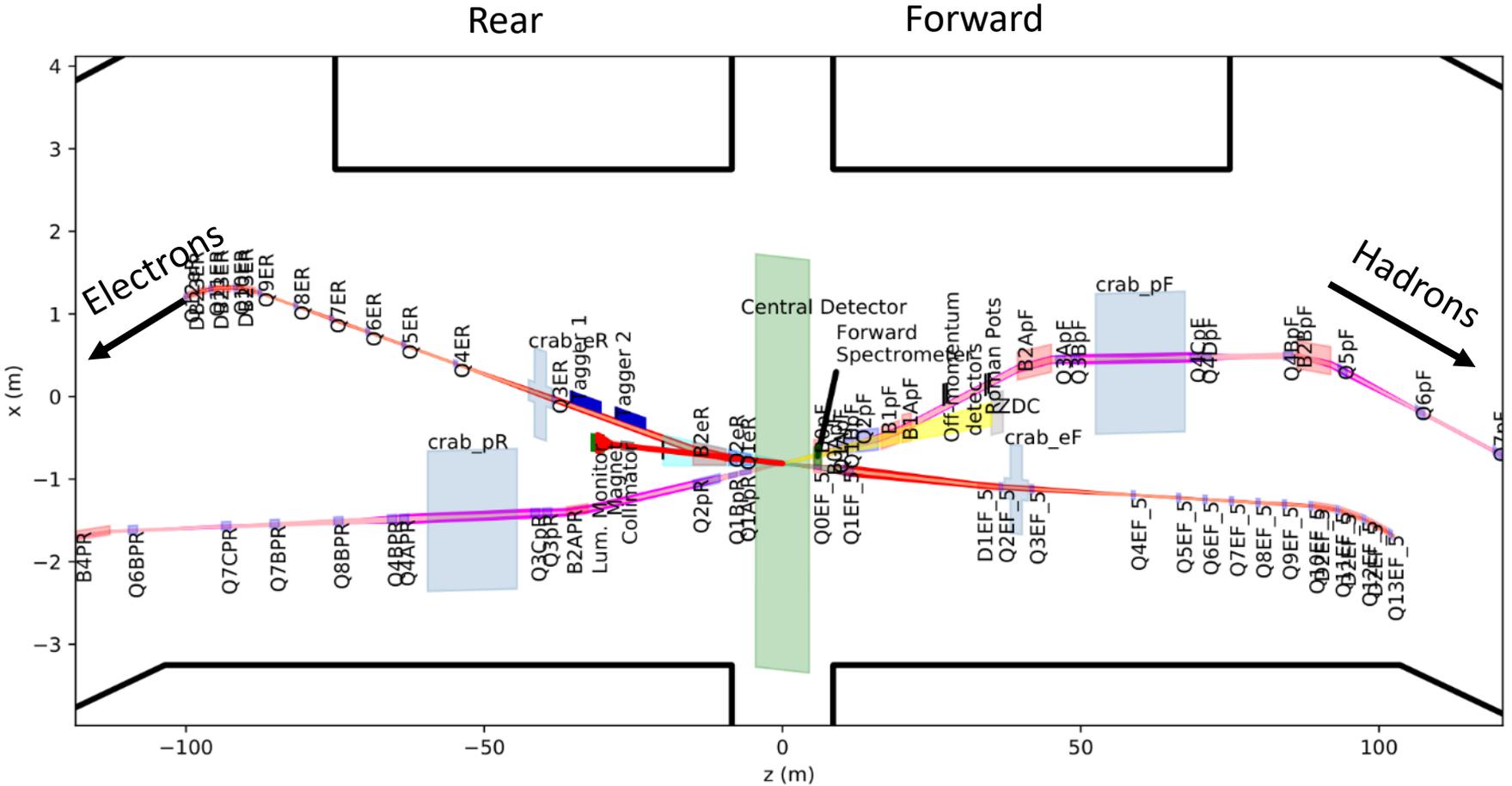
# Crab crossing to the rescue

- 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
- Challenges
  - Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
  - Severe beam dynamics effects
  - Physical size of crab cavities



# EIC IR

Note: forward magnet cryostat is 94" dia

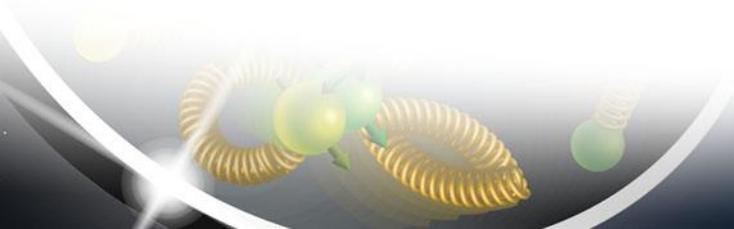


- Larger crossing angle:
- Cannot do more in hadron line (field/space issues)
- Electrons: Synrad issues (kW of power already)



# Detector Solenoid Effects

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

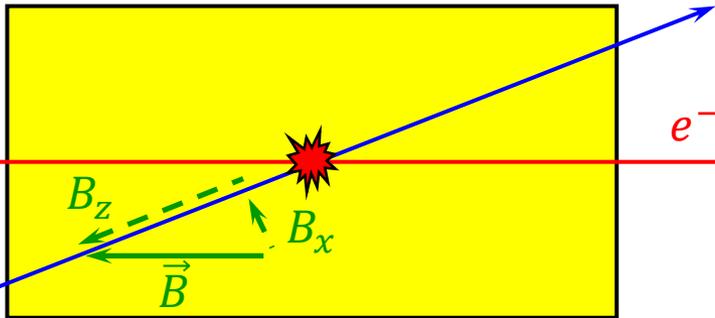


# Coherent Distortion of Ion Orbit

Particles traveling at angle through solenoid: orbit distortion due to end fields

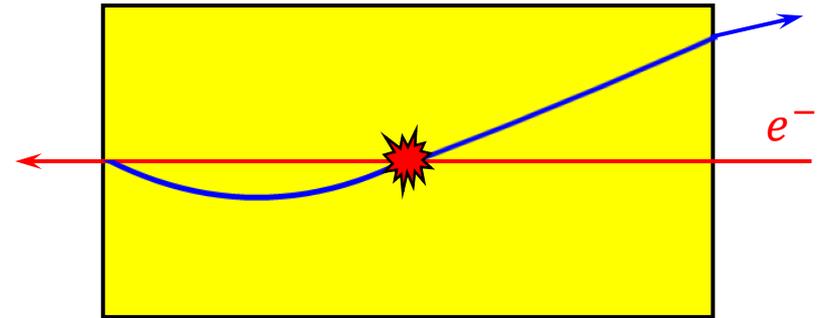
Top view

Ions



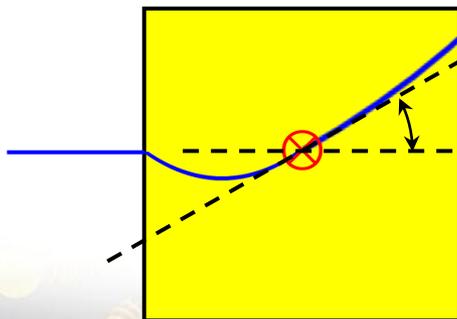
Side view

Ions



End view

Ions



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

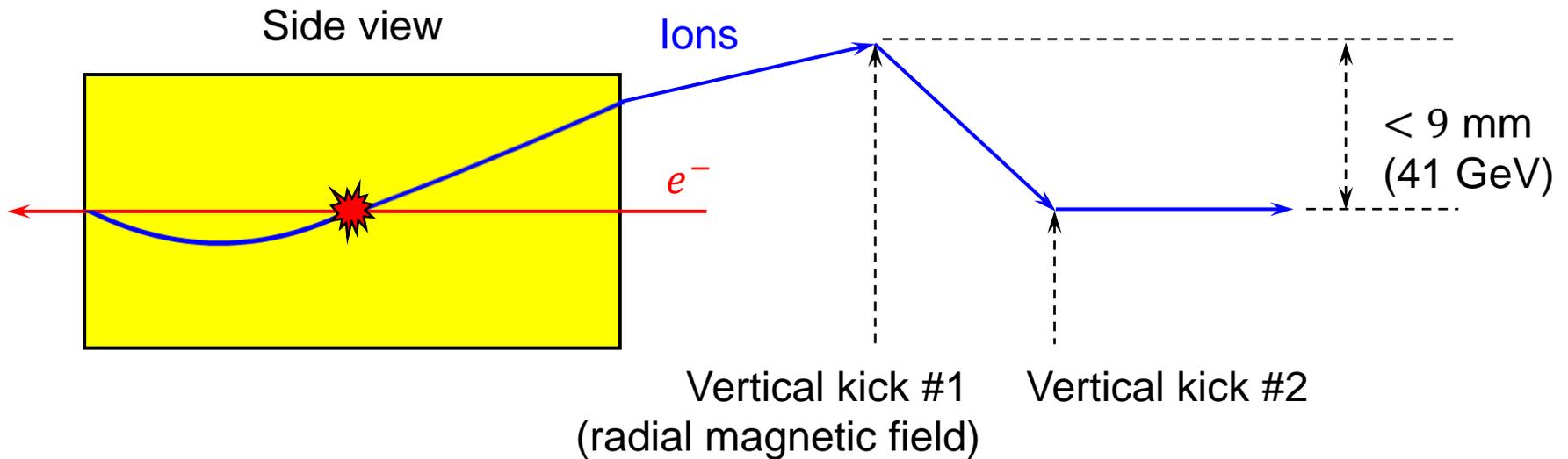
Rotation of the interaction plane  
inversely proportional to the beam energy

Vertical kicks by the  
solenoid fringe fields

Horizontal orbit  
distortion due to  
coupling

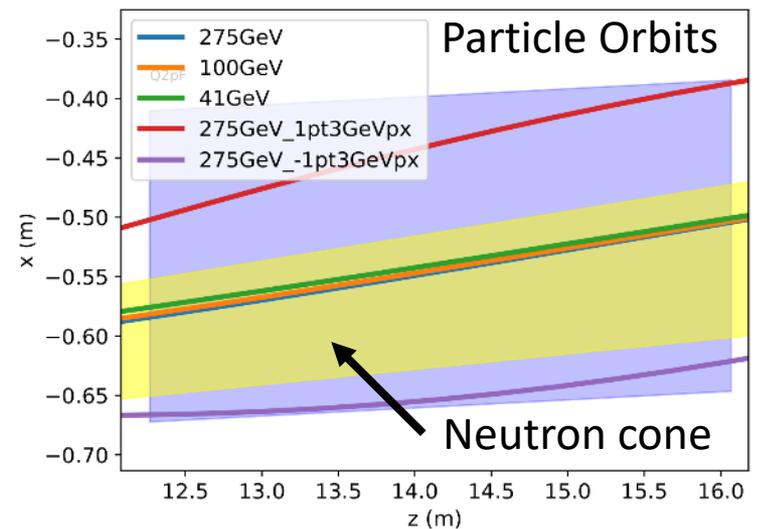
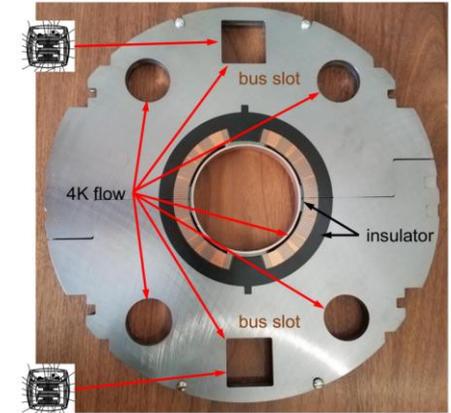
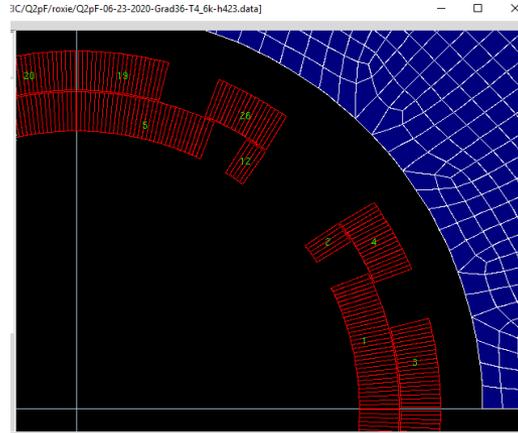
# Correction of Ion Orbit

- 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



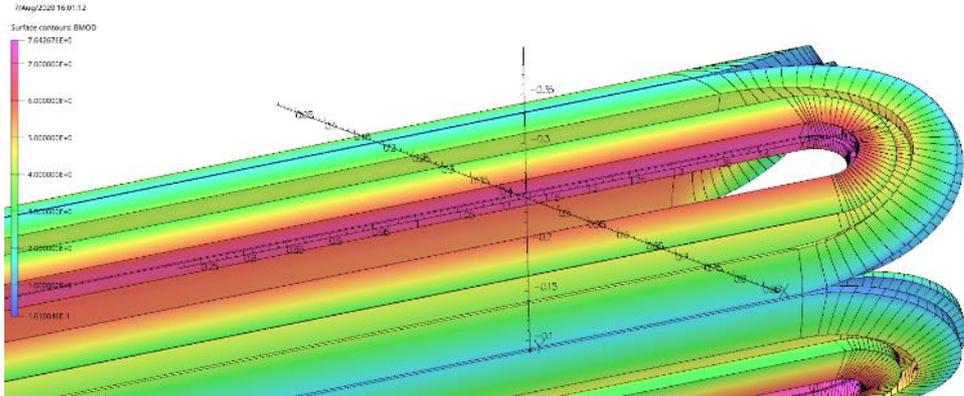
# Q2pF – Collared Magnet

- Hadron quadrupole
  - Gradient: 41 T/m
  - 3.8m long
  - Aperture 262 mm
    - Coil R=140mm
    - Pole tip field: 5.74T
  - e-beam: 36-42cm distance
- **Field-free region for electrons**
- Magnet limitations
  - Gradient/field
  - Aperture
  - Stray field



# Q2pF Simulation Results

Peak field on wire: 7.6T

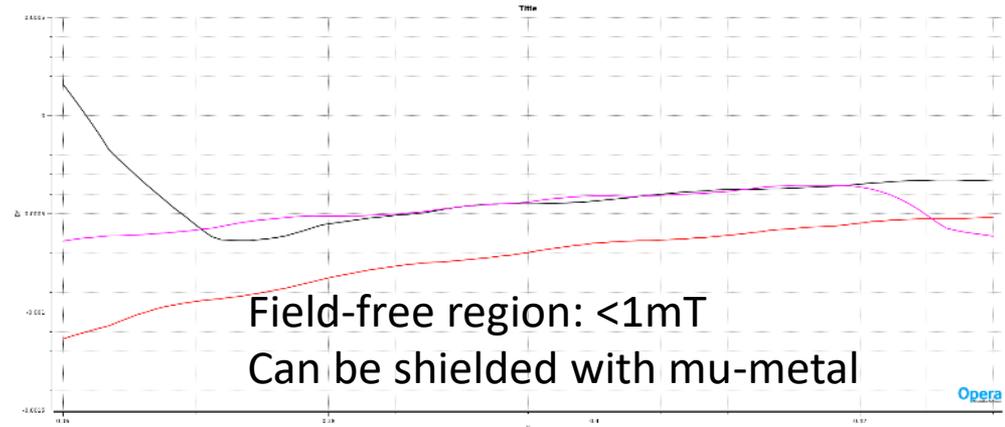
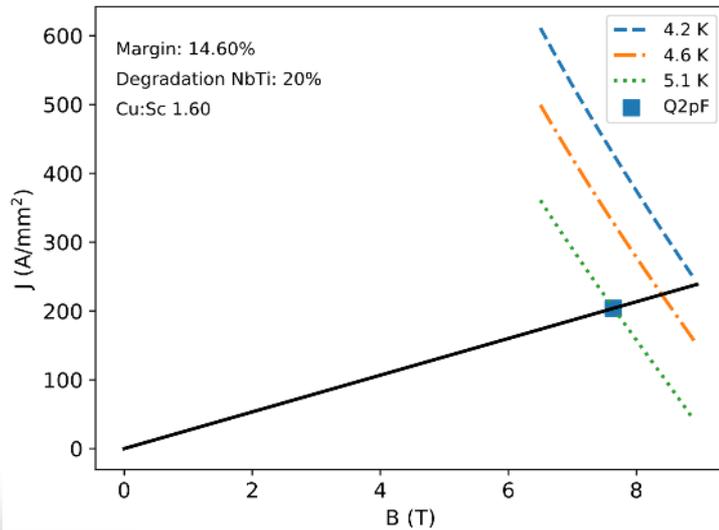


NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):

b 1:	-0.00000	b 2:	10000.00000	b 3:	0.00000
b 4:	0.00788	b 5:	0.00000	b 6:	-0.32418
b 7:	0.00000	b 8:	0.00003	b 9:	-0.00000
b10:	0.62188	b11:	0.00000	b12:	-0.00013
b13:	0.00000	b14:	-0.22462	b15:	-0.00000
b16:	0.00001	b17:	0.00000	b18:	0.01234
b19:	0.00000	b20:	0.00000	b	

SKEW 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):

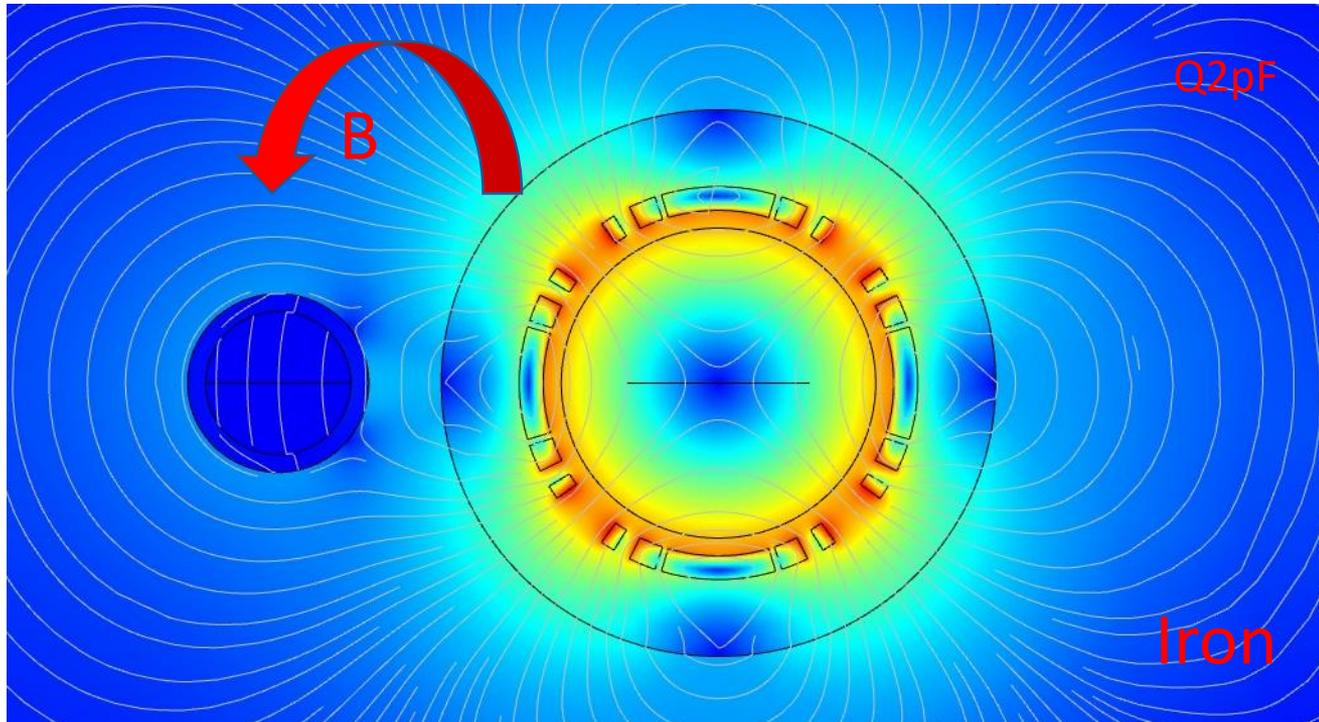
a 1:	-0.00000	a 2:	-0.00000	a 3:	-0.00000
a 4:	0.00000	a 5:	0.00000	a 6:	-0.00000
a 7:	-0.00000	a 8:	0.00000	a 9:	-0.00000
a10:	0.00000	a11:	-0.00000	a12:	-0.00000
a13:	0.00000	a14:	-0.00000	a15:	-0.00000
a16:	-0.00000	a17:	0.00000	a18:	0.00000
a19:	0.00000	a20:	0.00000	a	



# Crosstalk

Electrons: field free

Hadrons: quadrupole magnet



≈40 cm

Refers to flux from one magnet leaking into the other  
Leads to field quality issues  
Depends on geometry and field/flux

Common issue for  
all IR magnets

# Magnet Engineering

B0pF

B0ApF

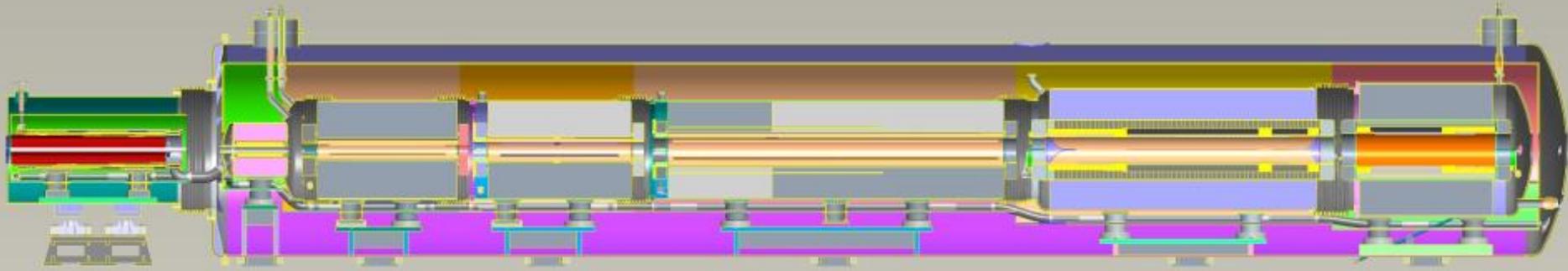
Q1ApF

Q1BpF  
Q1eF

Q2pF

B1pF

B1ApF



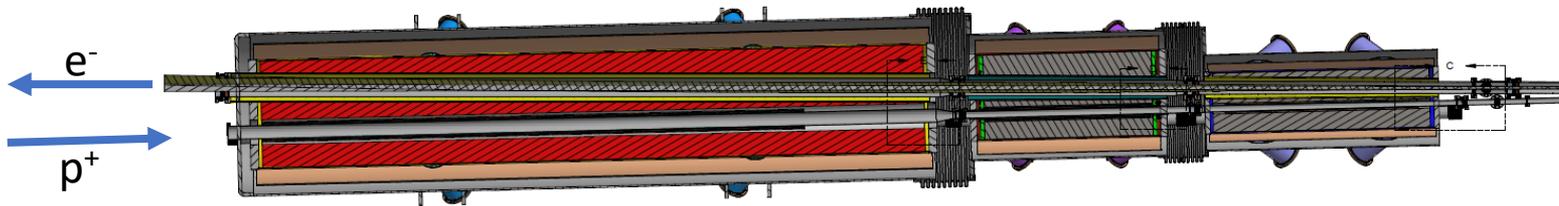
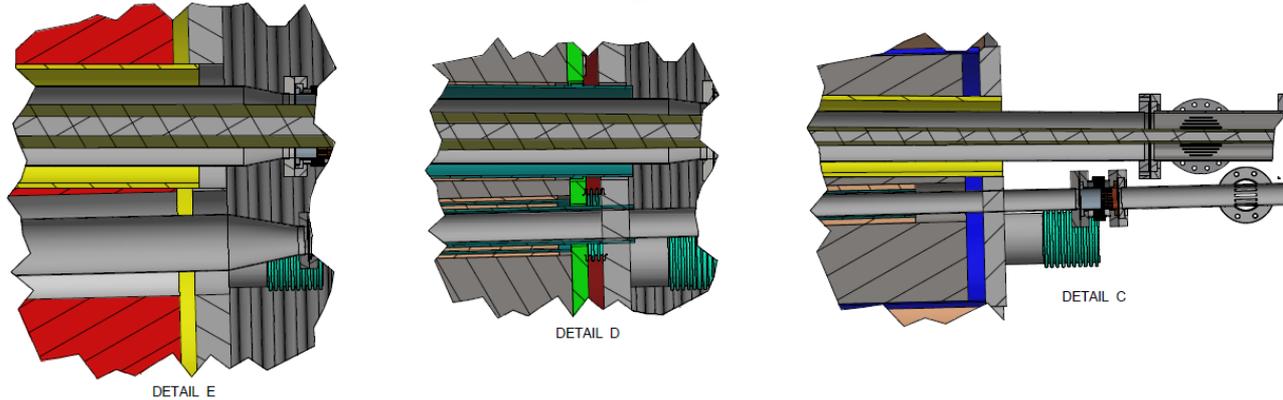
Standalone  
48" cryostat

- Common split cryostat
- Cold mass adjustments within cryostat
- Each cold mass independently anchored
- Common helium vessel, with bellows between all magnets

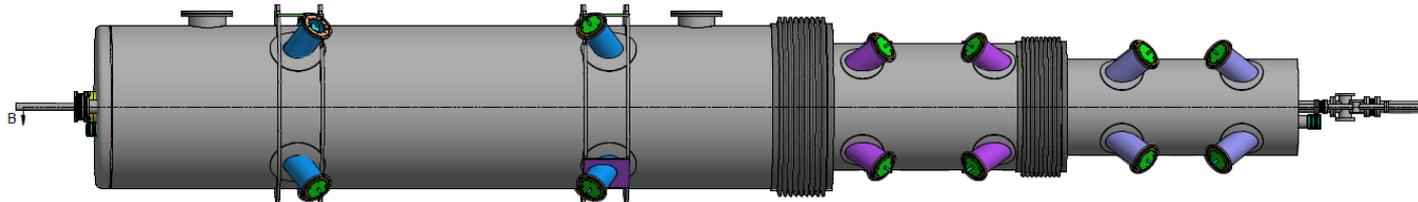
# Rear Side Integration / Beampipe

Separate cold masses - helium vessels

Separate circular cryostats with decreasing OD's toward IP



IP  
X



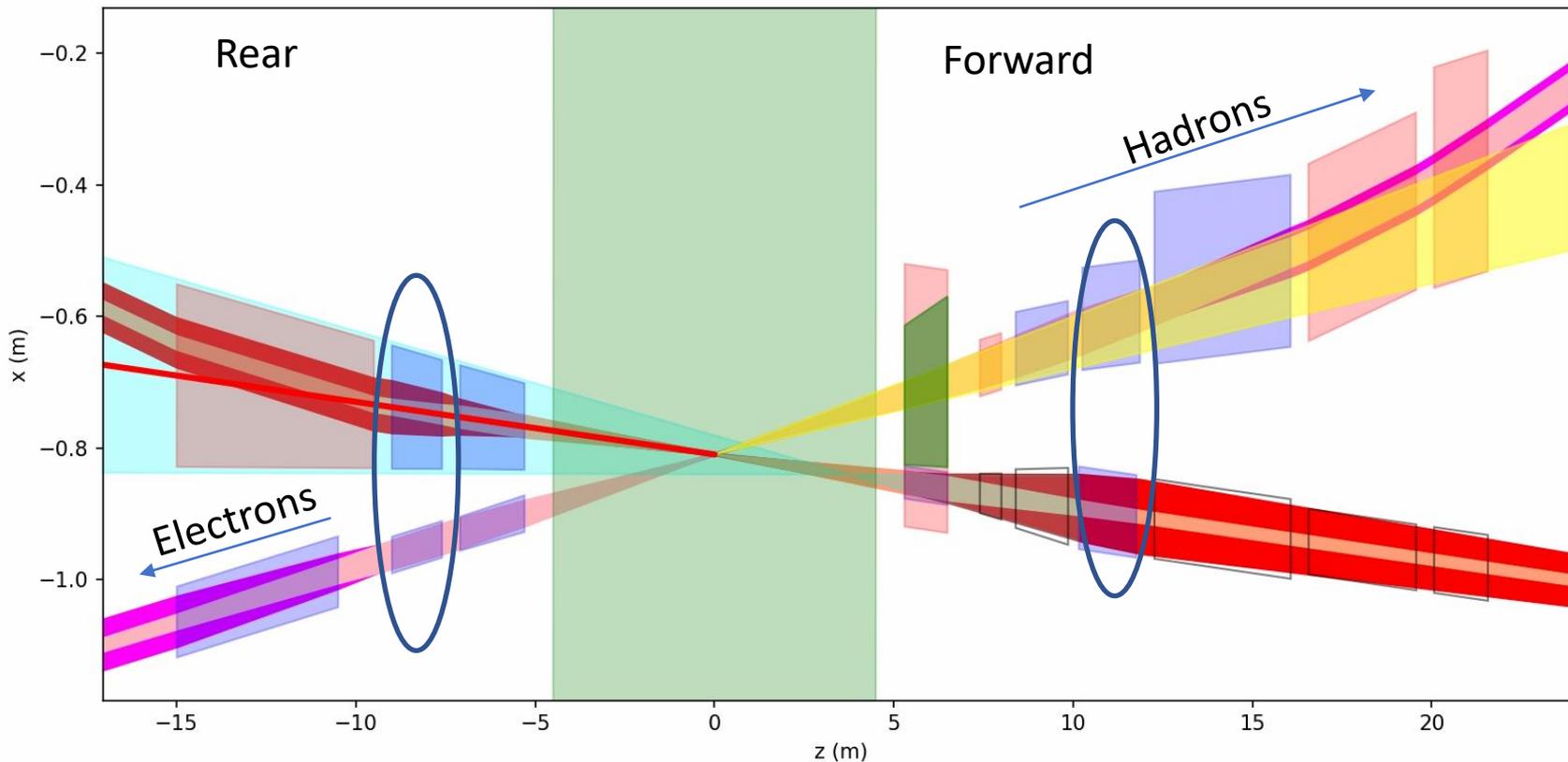
Ø66"  
Q2pR – B2eR

Ø54"  
Q1BpR – Q2eR

Ø42"  
Q1ApR – Q1eR

# IR Layout

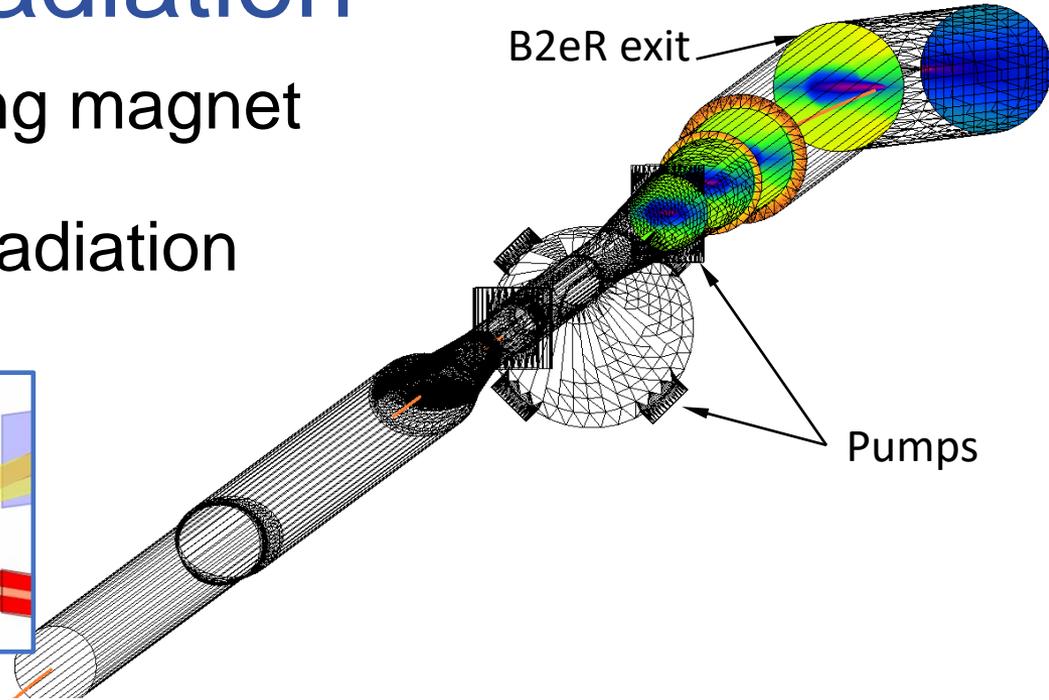
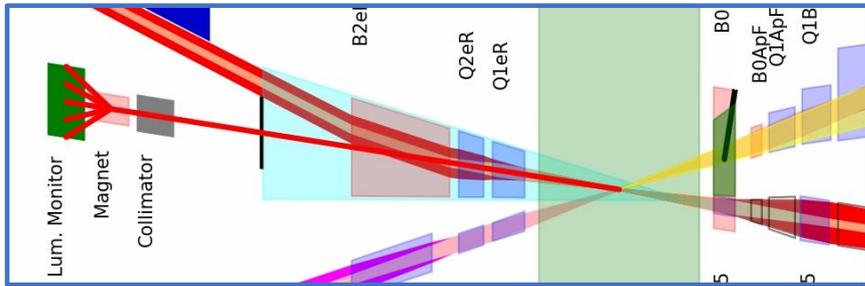
IR quadrants not independent of each other



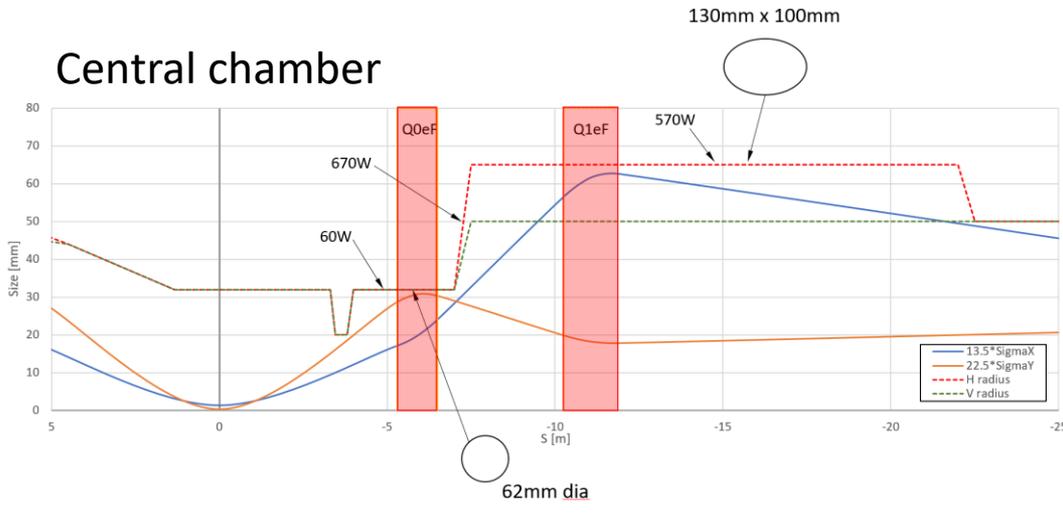
Changing one sector implies changing another one  
Also: need to get back to RHIC ring (HSR)

# Synchrotron Radiation

- Origin: quads and bending magnet upstream
- Tails: can produce hard radiation
  - Non-Gaussian



Central chamber



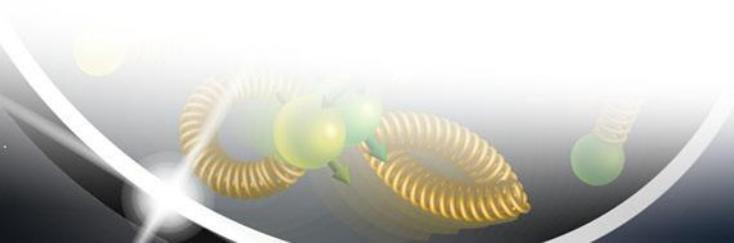
Beam pipe envelope and synrad heating

Even with masking: significant heating to deal with

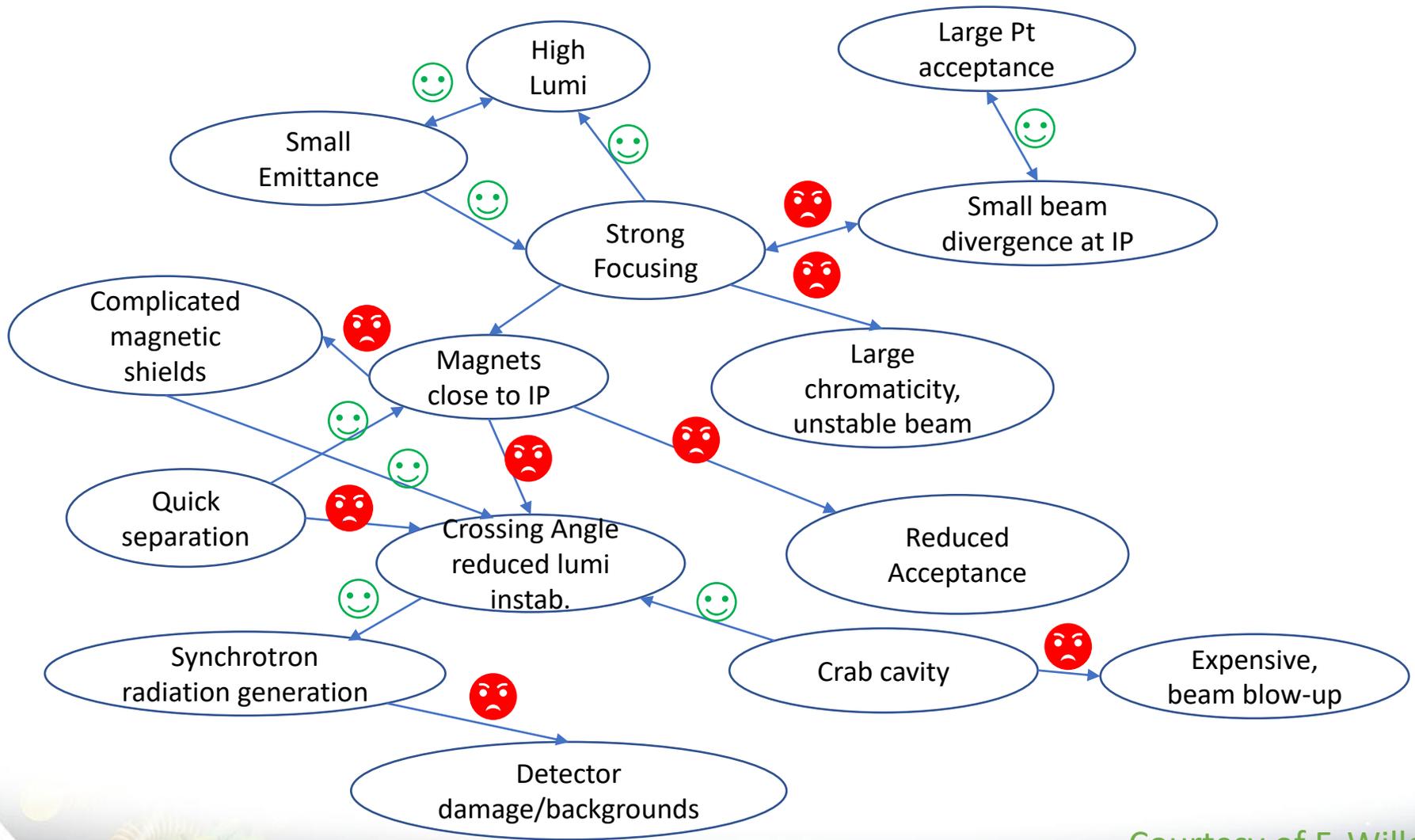
Courtesy C. Hetzel

# EIC IR Effort

- Ongoing effort for >4 years
  - This is when I got involved...
- Involves >40 people
  - Part/full-time
- Work split into several sub-groups/task forces
  - Synrad, magnets, spin rotators, correctors
  - Connections with multiple other areas/groups
- **Devil is in the details**
- Total effort?



# IR Design Choices



Courtesy of F. Willeke

# What are we working on?

- Implementing 0.5m shift forward side
  - Affects layout, re-optimizing magnet apertures/positions
  - Needs to be approved by Change Control Board
- Implement correctors
  - Skew-quadrupoles, solenoid compensation
  - Orbit correction
- Magnet design work
- Lots of challenging detailed work to be done
  - Beampipe
  - BPMs



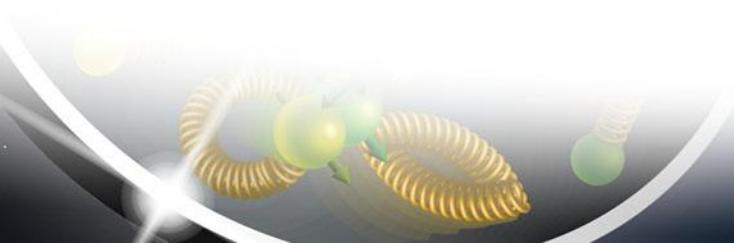
# Summary

- IR developed to meet physics requirements
  - Meets requirements of ‘white paper’
  - **See Alex Jentsch’s talk**
  - Is there anything we have been missing?
- Many considerations went into this IR
  - Geometric constraints
  - Engineering feasibility
  - Magnets, cryostating

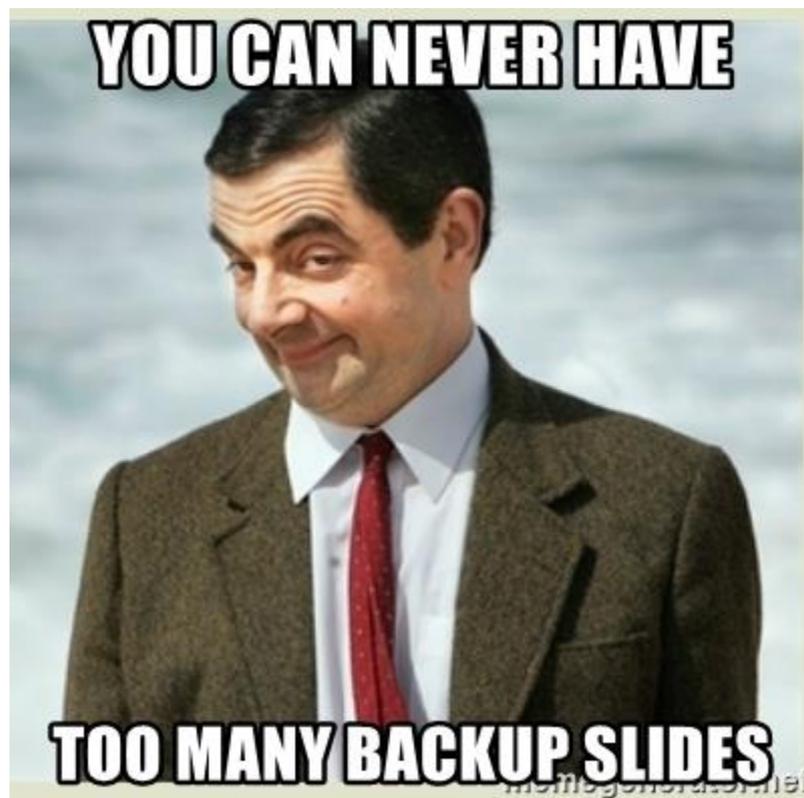
# Acknowledgements

J. Adam, M. D. Anerella, J.S. Berg, W. Christie, J. Cozzolino, C. Montag, E. C. Aschenauer, A. Blednykh, A. Drees, D. Gassner, K. Hamdi, C. Hetzel, H. M. Hocker, D. Holmes, A. Jentsch, H. Lovelace III, A. Kiselev, G. McIntyre, R. B. Palmer, G. Mahler, B. Parker, S. Peggs, S. Plate, V. Ptitsyn, G. Robert-Demolaize, K. S. Smith, S. Tepikian, P. Thieberger, J. Tuozzolo, F. J. Willeke, M. Blaskiewicz, J. Tuozzolo, Y. Luo, H. Witte, Q. Wu, Z. Zhang, M. Stutzman, R. Gamage, P. Ghoshal, T. Michalski, V. Morozov, W. Wittmer, M. K. Sullivan, Y. Nosochkov, A. Novokhatski

**... and many more!**

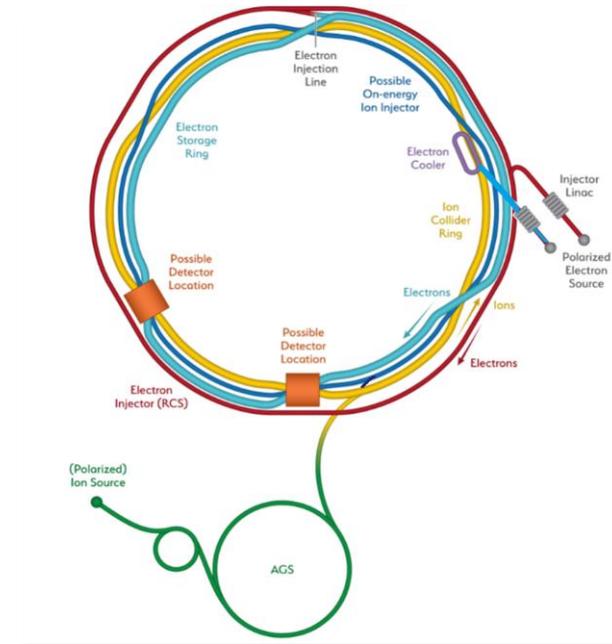
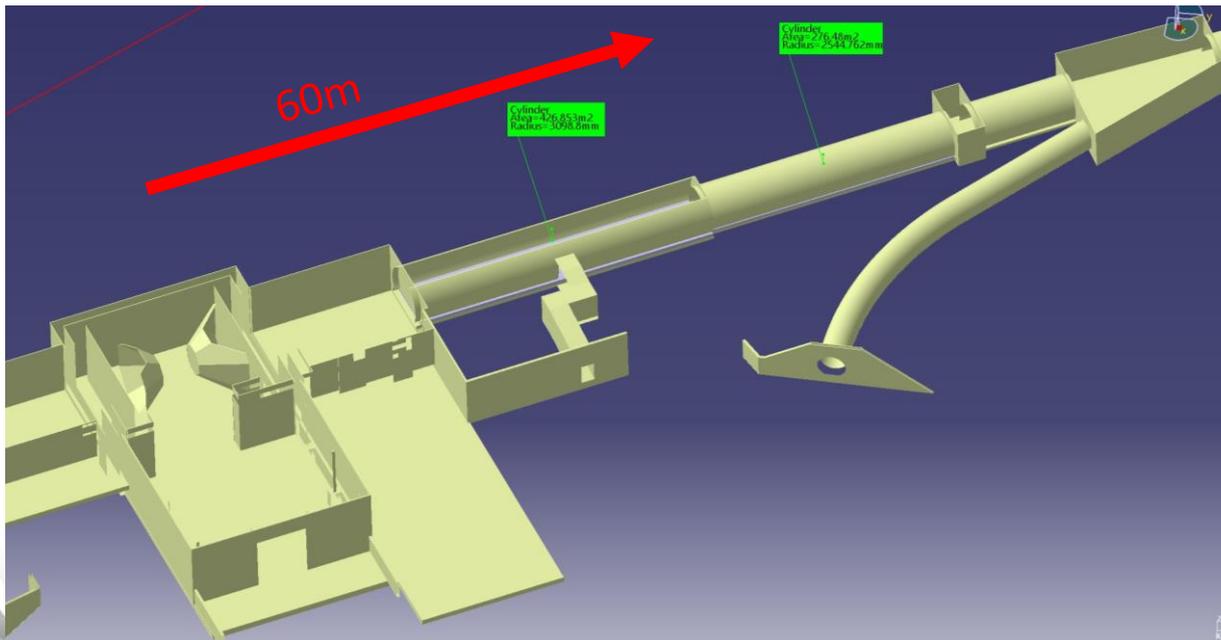


# Additional Slides



# Considerations IP8

- Going from outer arc into inner arc
  - IP6: from inner to outer arc
- Present IR not portable to IR8
- Geometric issues



IR8: Tunnel dia. 6.3m to 60m  
(then 5.3m dia)

IR6: 7m dia. +/- 140m

# Considerations IP8

- If using IP6 forward dipole configuration (HSR bends away from ESR)
  - Beam is bent further inside
  - Can't bend back until we reach the crabs
  - Requires creating a roughly 2 m transverse displacement over around 50 m length; lots of extra dipoles, issues with dispersion matching
- If we put ZDC on the outside, bending HSR toward the ESR
  - 25 mrad crossing angle not possible: lines diverge slowly, crab cavity transverse size creates collision between HSR/ESR lines

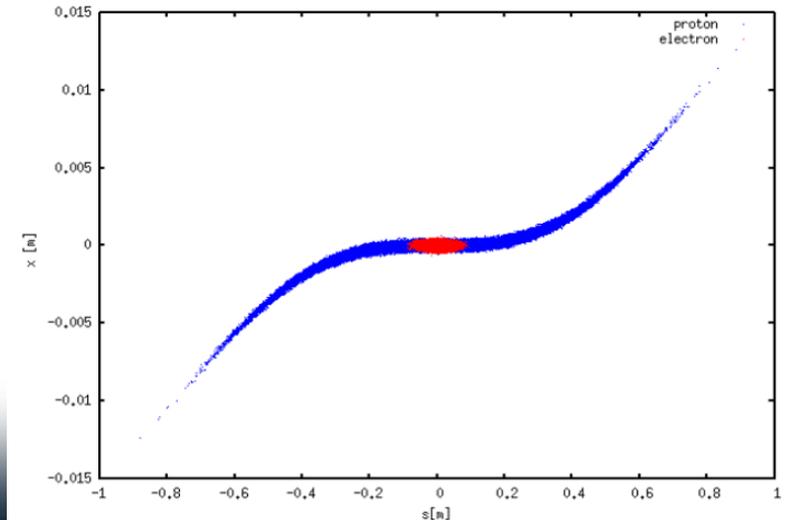
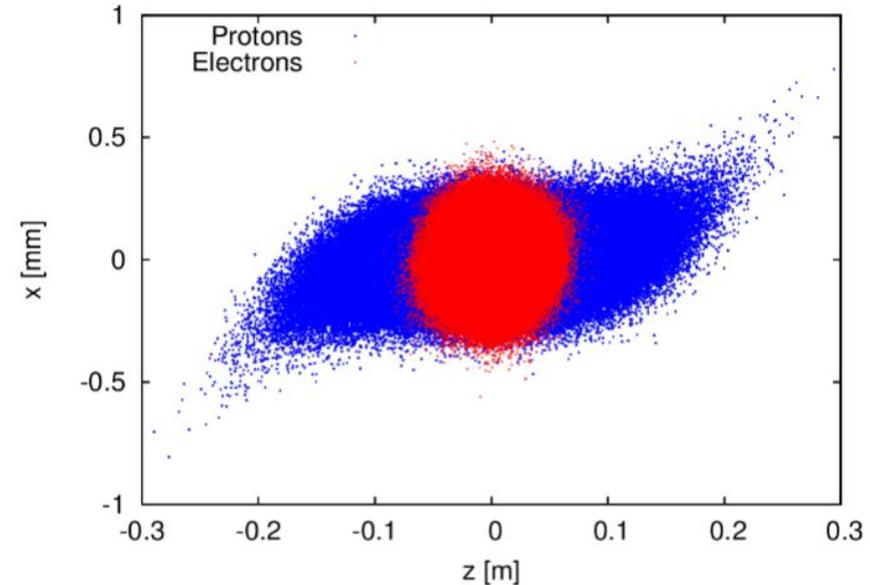


# Crossing angle collisions

- **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!**

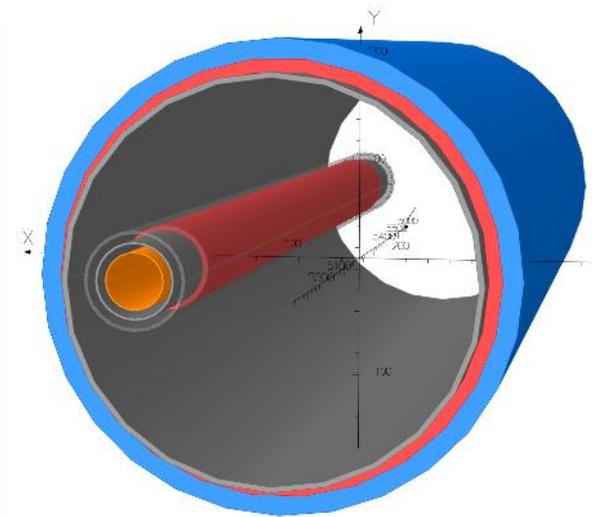
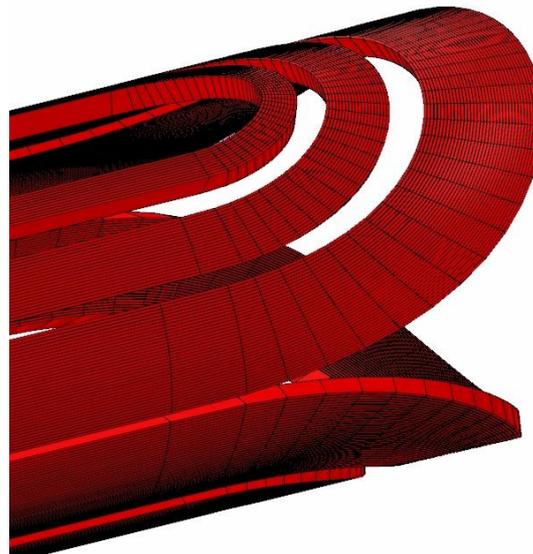
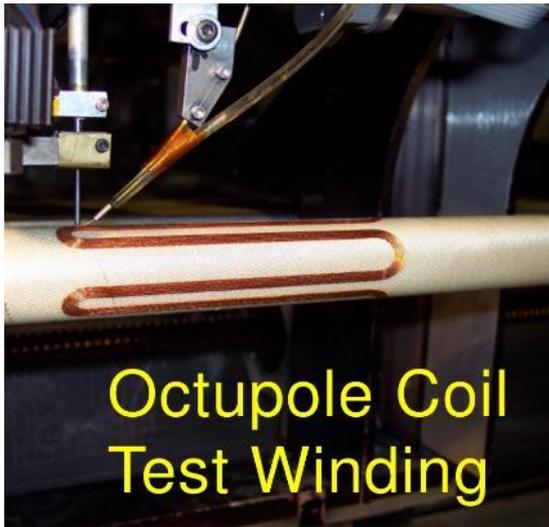
# Nobody's perfect

- 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)



# IR Magnets - Overview

- Three groups of superconducting magnets
  - All NbTi
- (Also: normal conducting magnets, not addressed here)



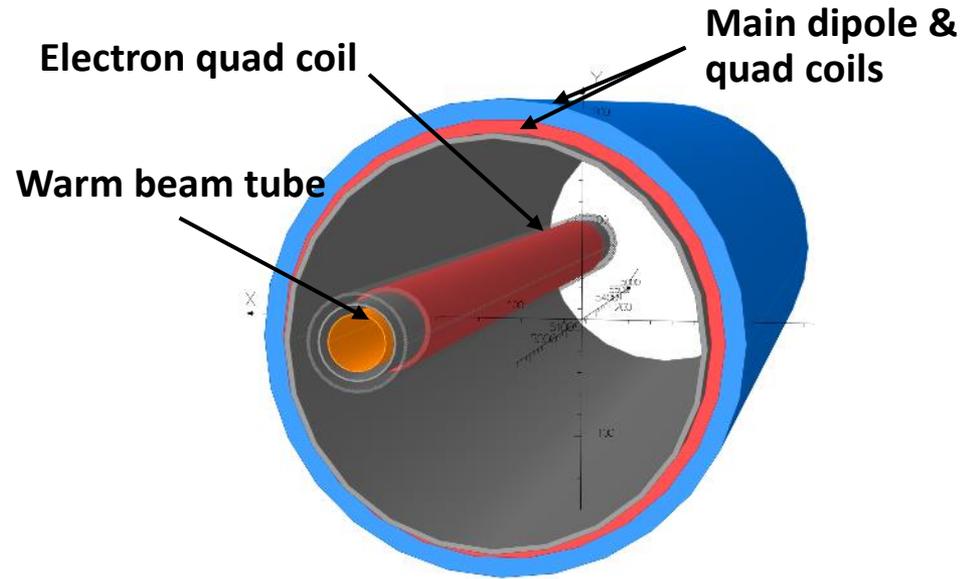
9 Direct Wind Magnets  
(S-MD)

6 Collared Magnets

1 Special Magnet

# B0pF Spectrometer Magnet

- Superconducting combined function magnet
  - 1.3T for hadrons
  - Created by quadrupole magnet
- Inner clear aperture of 180 mm radius
- Electrons: 15T/m gradient
  - In B0pF aperture
  - Use dipole to create zero dipole field for electrons
  - Use electron quad to tune gradient



Quadrupole

