EIC Interaction Region Requirements and Constraints

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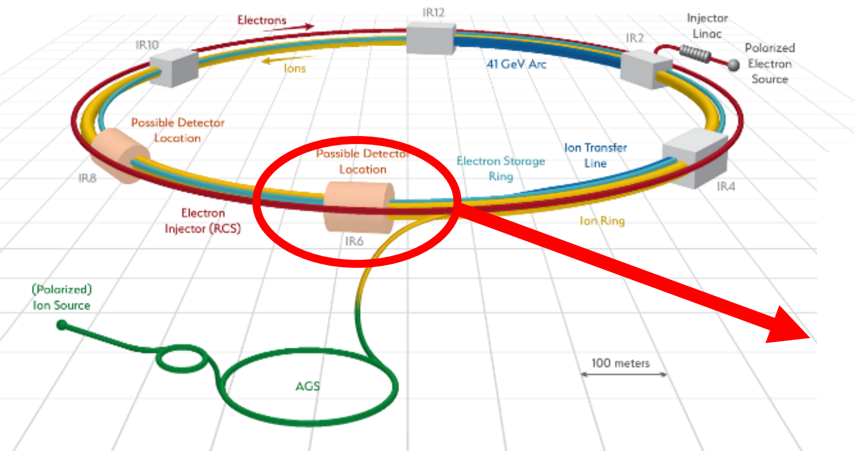
Electron Ion Collider – EIC at BNL

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

Outline

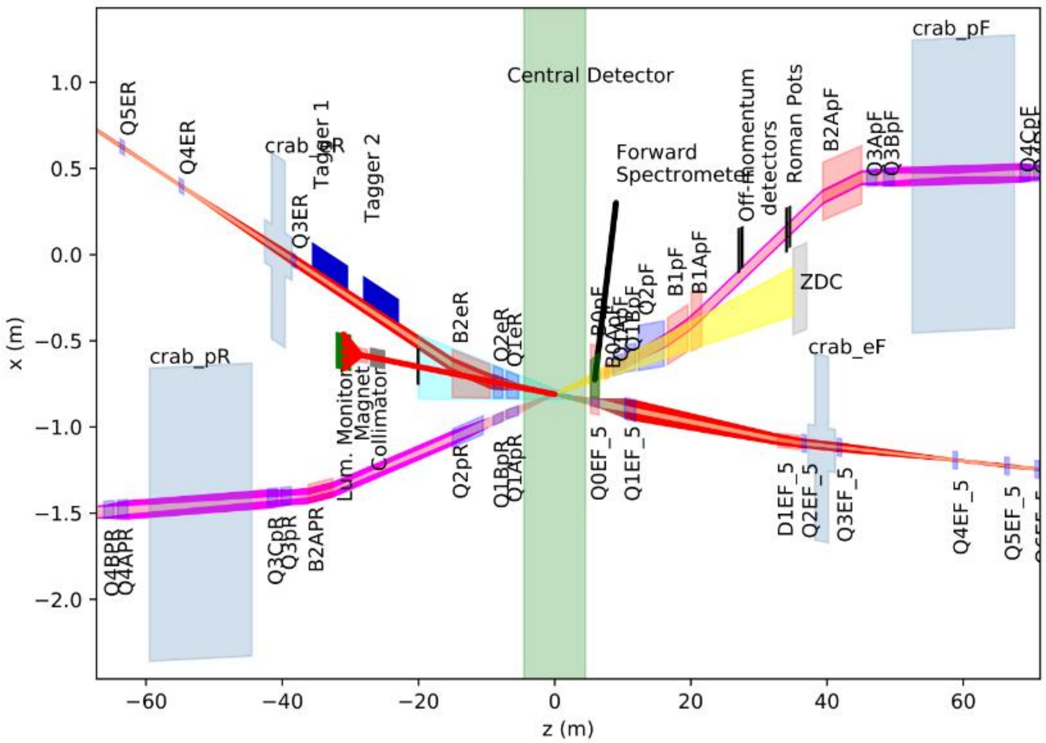
- Overview
  - Requirements
  - General constraints
  - Present IR
- Luminosity
  - Focusing
  - Crab crossing
- IR Magnets
  - Apertures and Challenges
  - Engineering

EIC IR: Overview



Rear

Forward



RHIC yellow ring: EIC hadron ring

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

IR location: IR6

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 GeV < p_t < 1.3 GeV
    - Neutron cone +/- 4 mrad
- Machine requirements
  - Small β^*_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

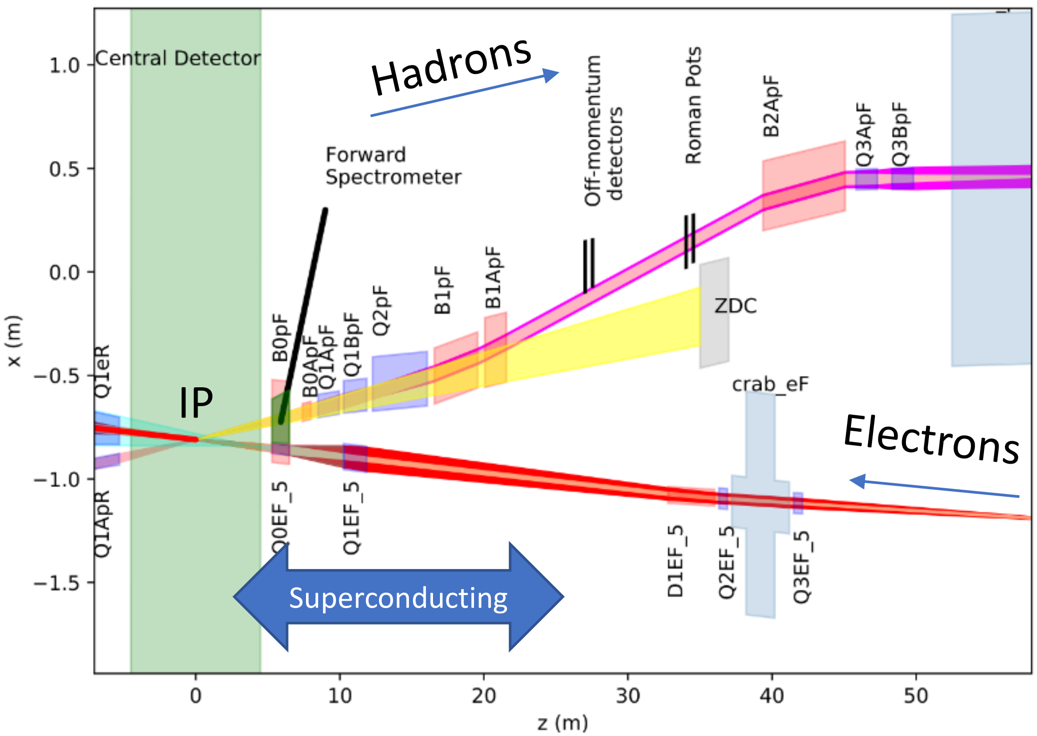
Considerations

- 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

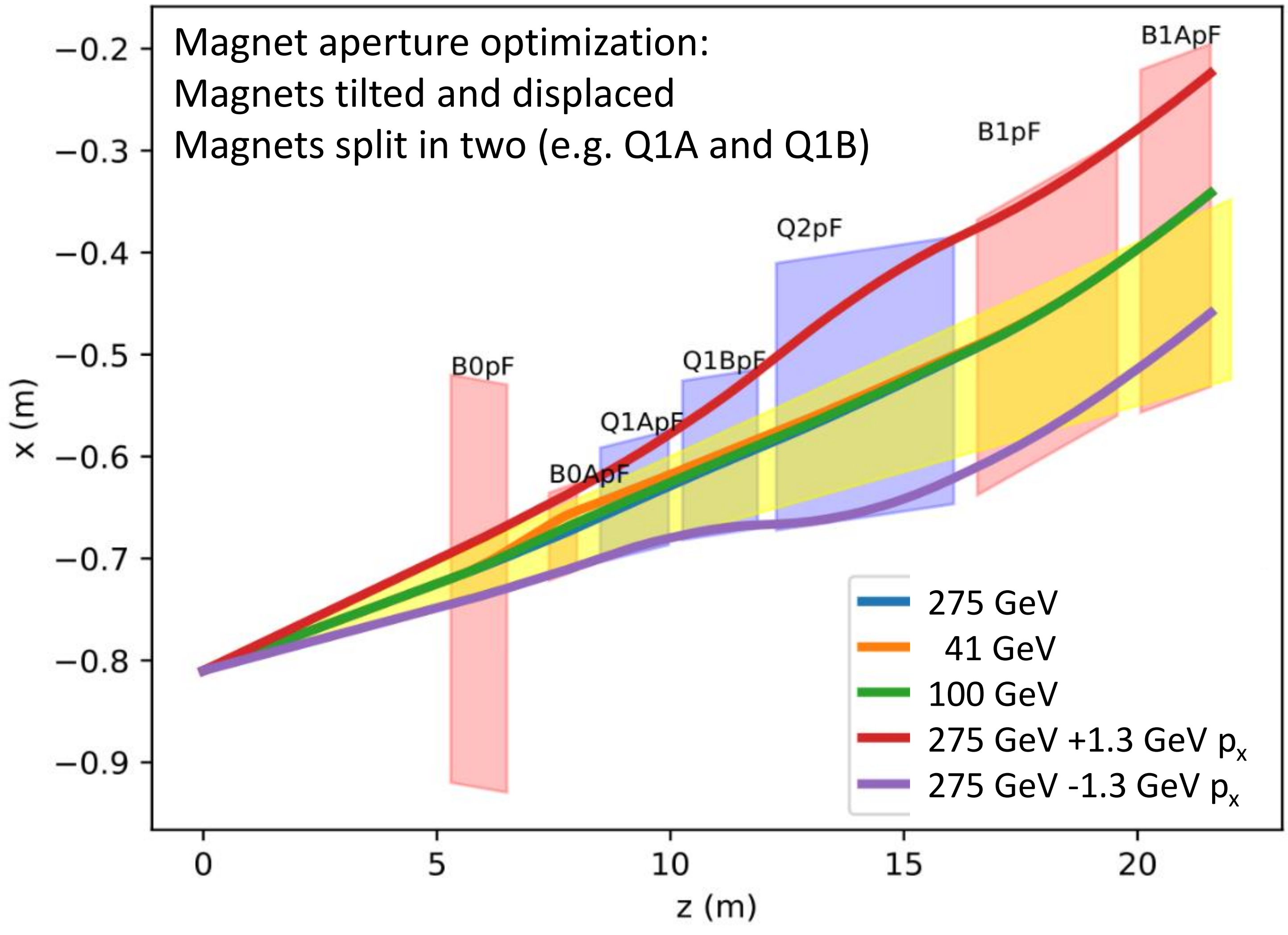
EIC IR: Forward Direction



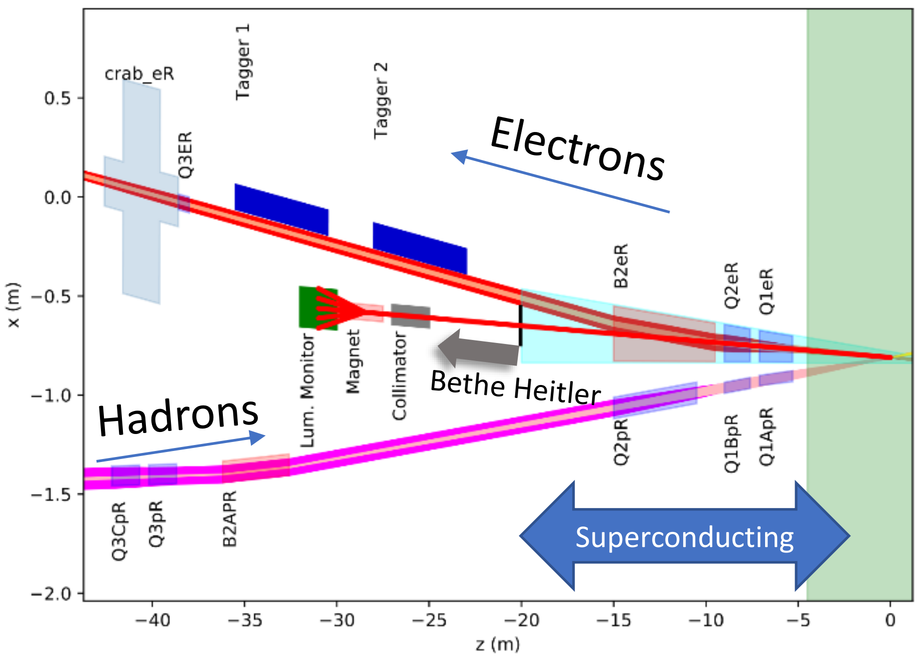
Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
B0ApF	0.043	0.6	-3.3	0	-3.3
Q1ApF	0.056	1.46	0	-72.608	-4.066
Q1BpF	0.078	1.61	0	-66.18	-5.162
Q2pF	0.131	3.8	0	40.737	5.357
B1pF	0.135	3	-3.4	0	-3.4

- 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

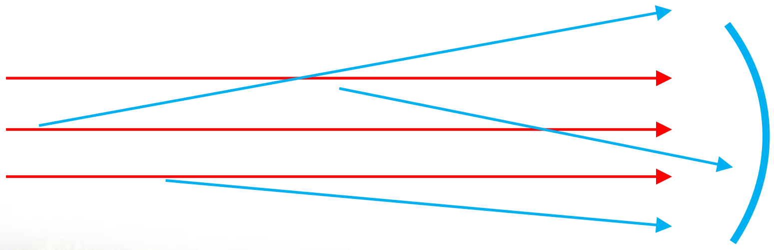
Name	R1	R2	length	grad	B pole
	[mm]	[mm]	[m]	[T/m]	[T]
Q1ApR	20	26	1.8	78.4	2.0
Q1BpR	28	28	1.4	78.4	2.2
Q2pR	54	54	4.5	33.8	1.8

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

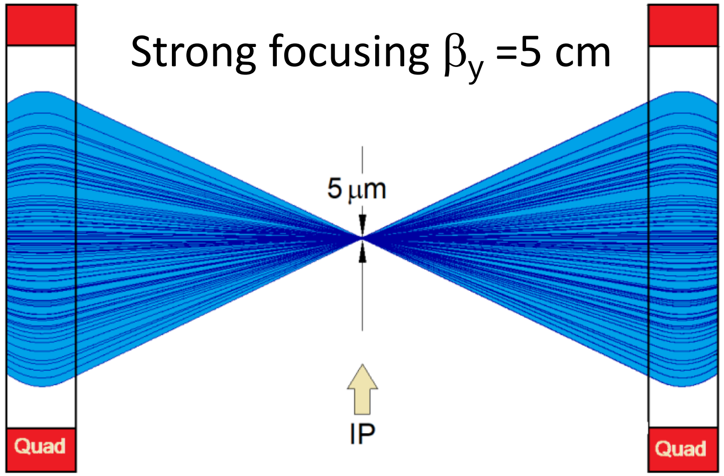
Luminosity and Focusing

- Luminosity ~ 1/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)

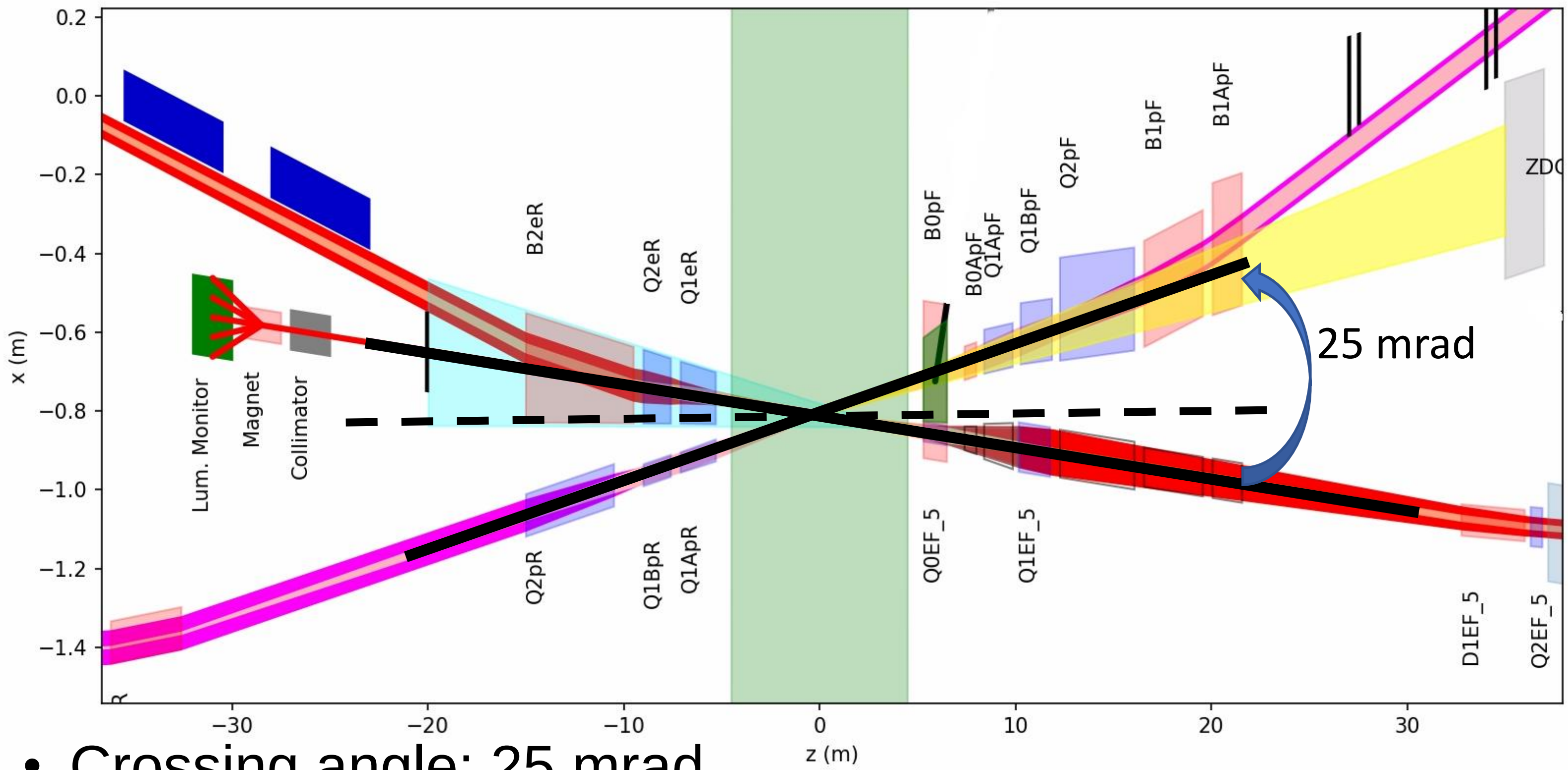


Divergence: ‘spread’ of the beam away from the central trajectory.



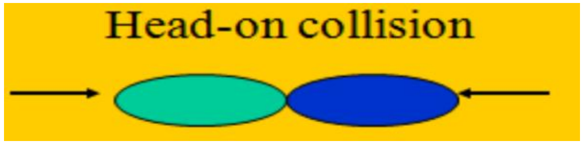
Focusing elements for both beams need to be as close as possible to the IP

Crossing Angle

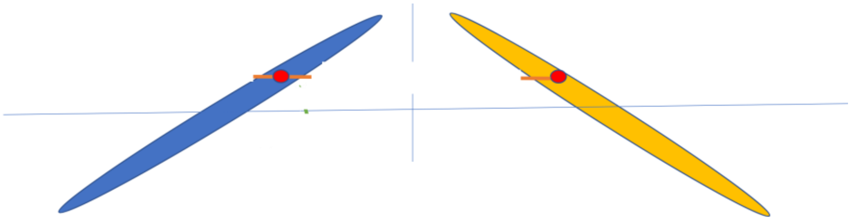


- Crossing angle: 25 mrad
  - Hadrons: 17 mrad
  - Electrons: 8 mrad
- Smaller crossing angle: beams less separated, magnet issues
- Larger crossing angle: magnet issues, crab cavities, beam dynamic issues

Crossing Angle and Luminosity



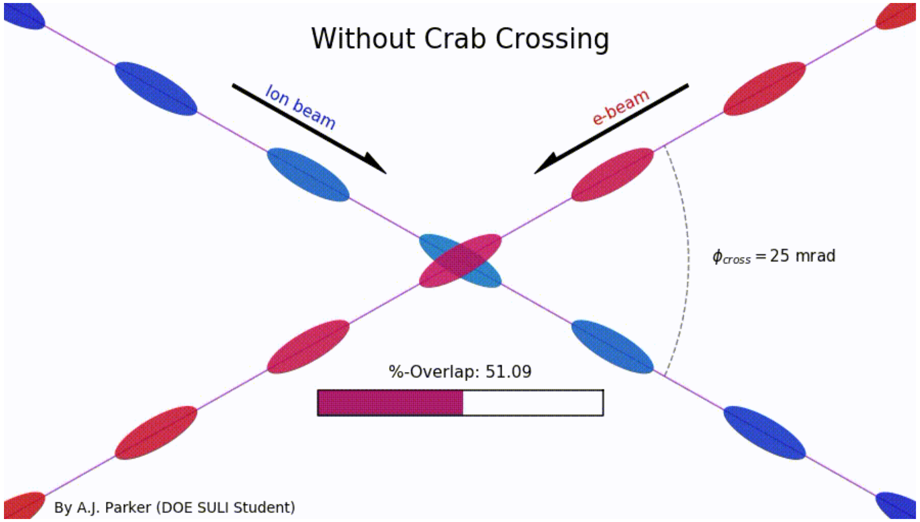
- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



- Long (~+/-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

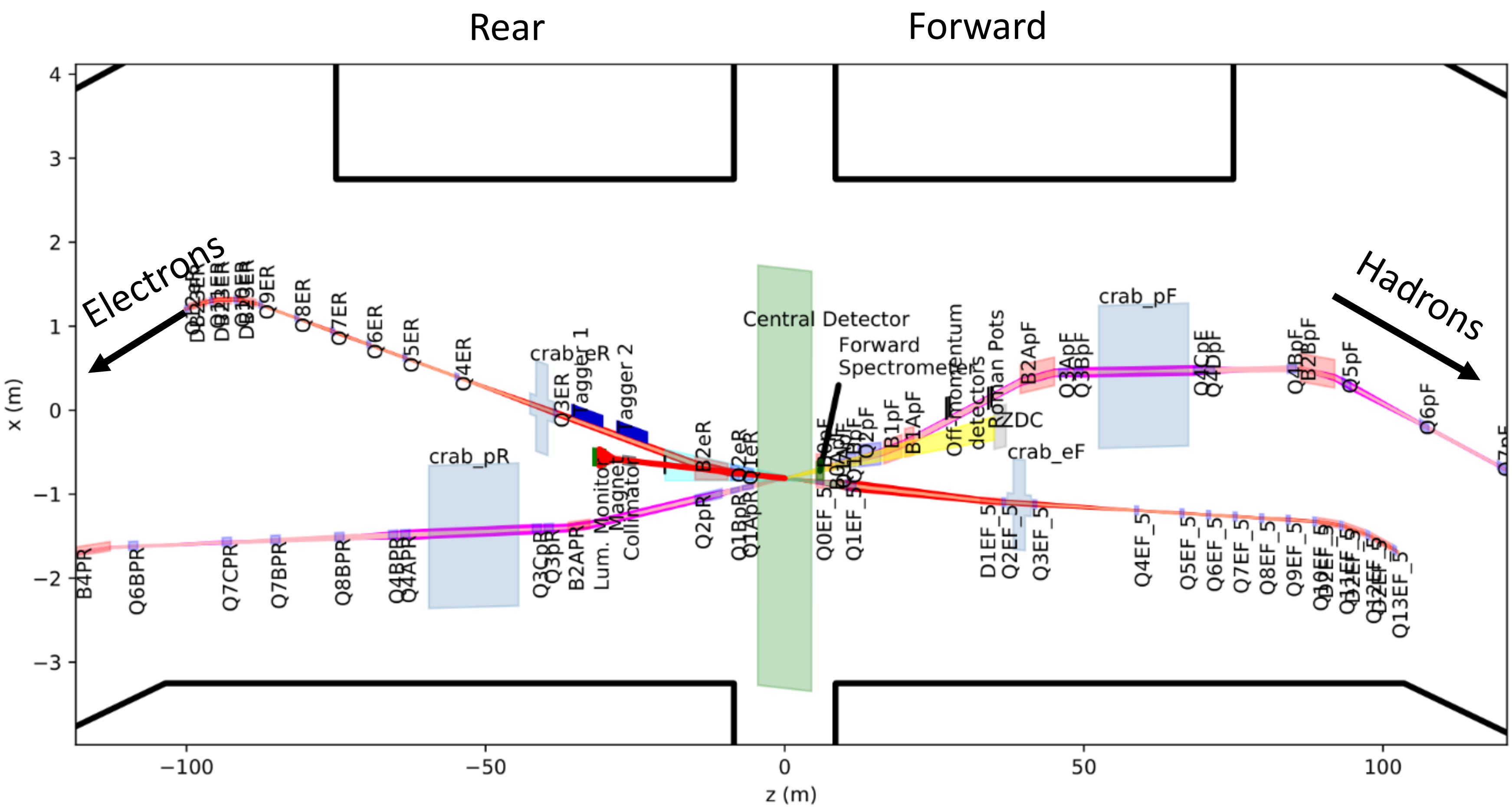
Crab crossing to the rescue

- 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
- 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: magnet cryostats are 94" dia



Larger crossing angle:

Cannot do more in hadron line (field/space issues)

Electrons: Synrad issues (kW of power already)

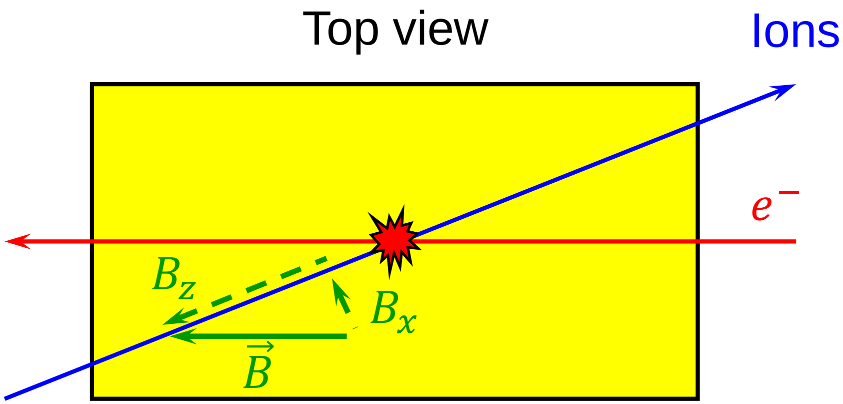
Detector Solenoid Effects

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

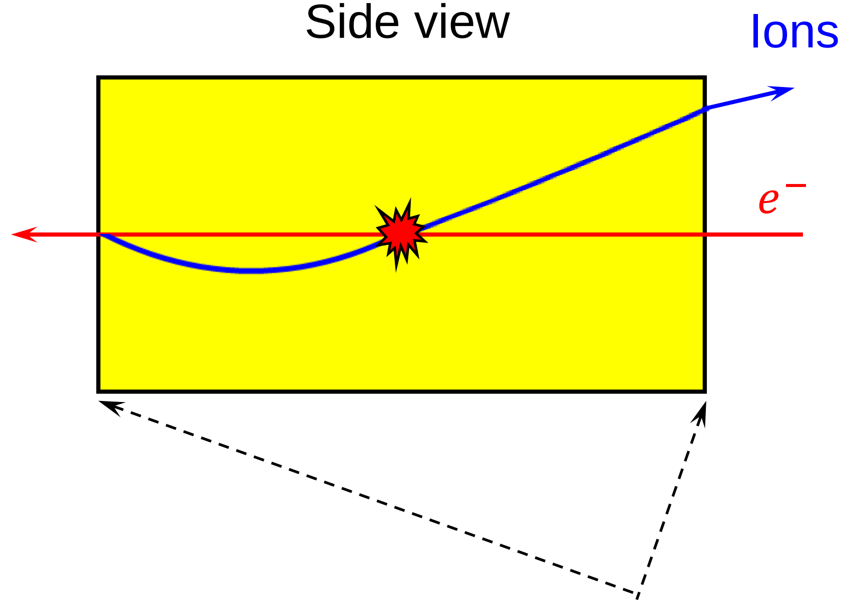
Coherent Distortion of Ion Orbit

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

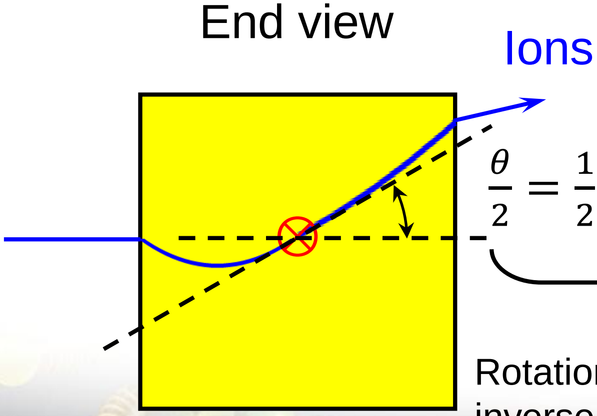
Top view



Side view



End view



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

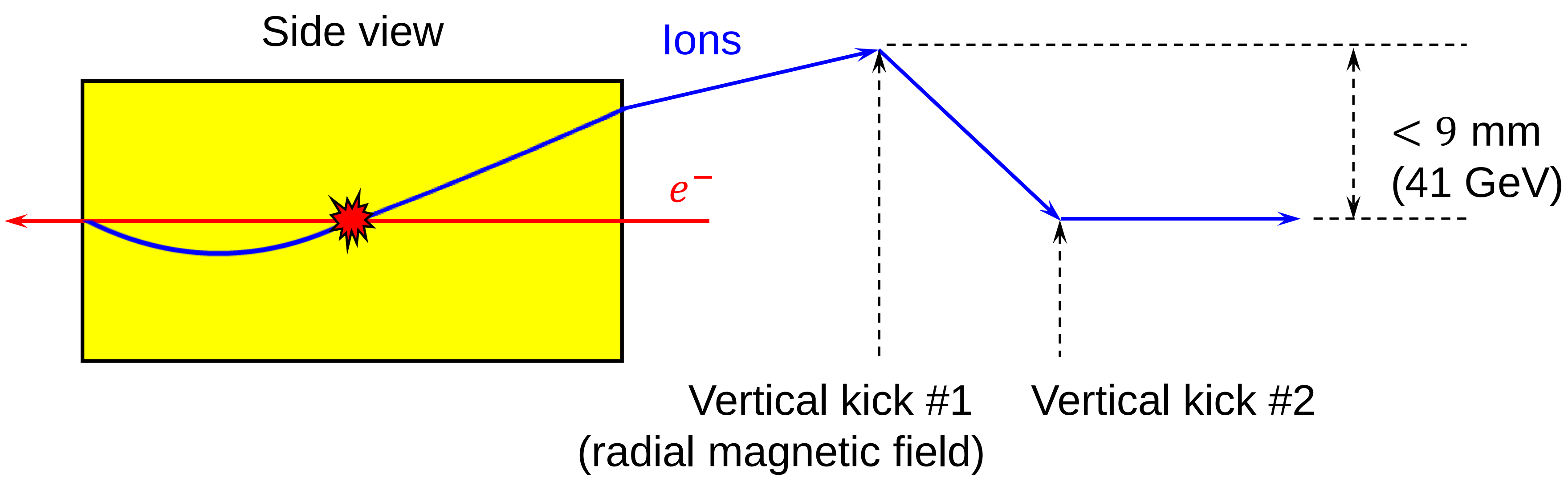
Rotation of the interaction plane inversely proportional to the beam energy

Vertical kicks by the solenoid fringe fields

Horizontal orbit distortion due to coupling

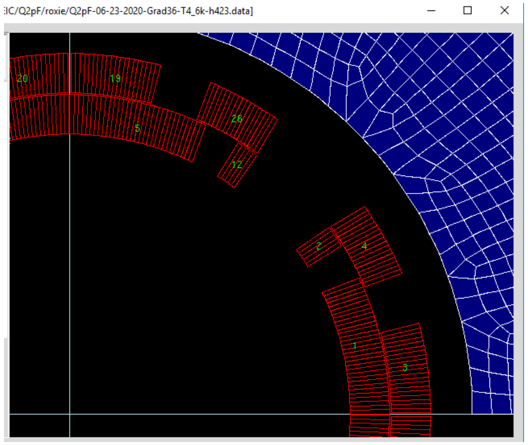
Correction of Ion Orbit

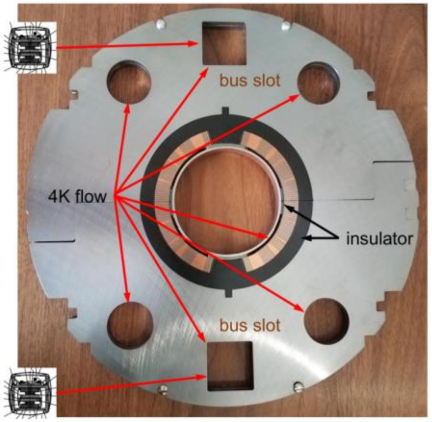
- The closer the kicks to the IP, the smaller the orbit excursion
- Orbit excursion inversely proportional to the beam momentum
- Concern for field non-linearity at large offsets

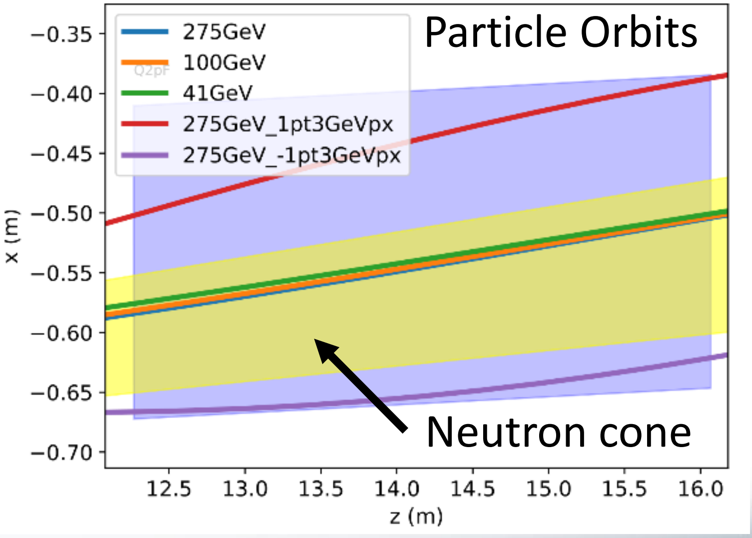


Q2pF – Collared Magnet

- 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

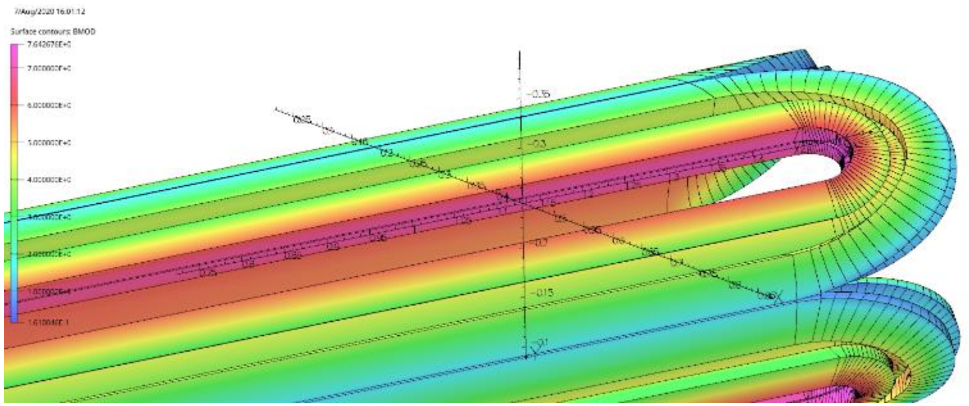




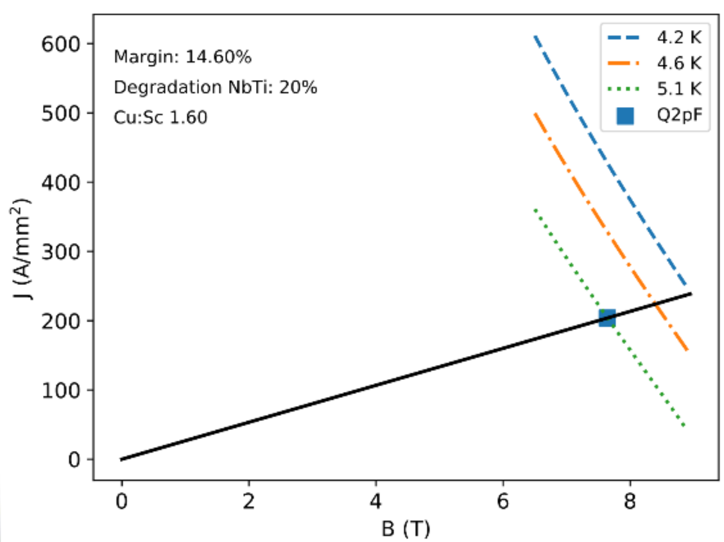


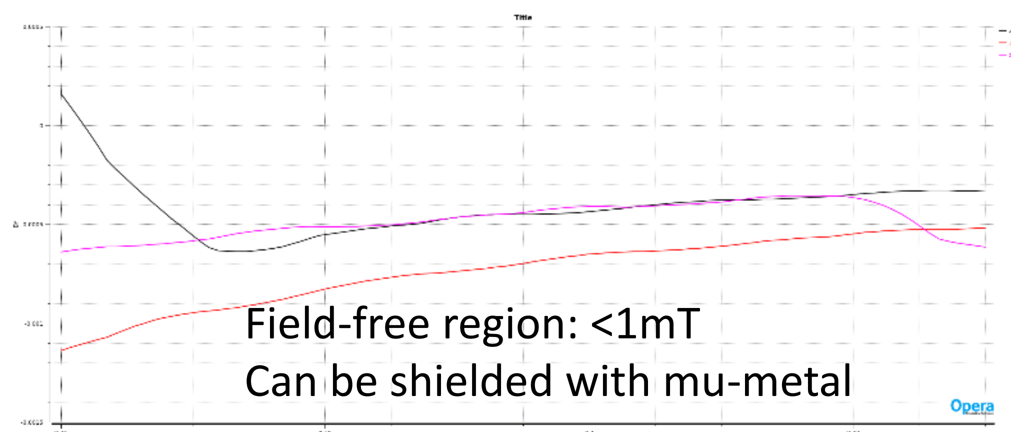
Q2pF Simulation Results

Peak field on wire: 7.6T



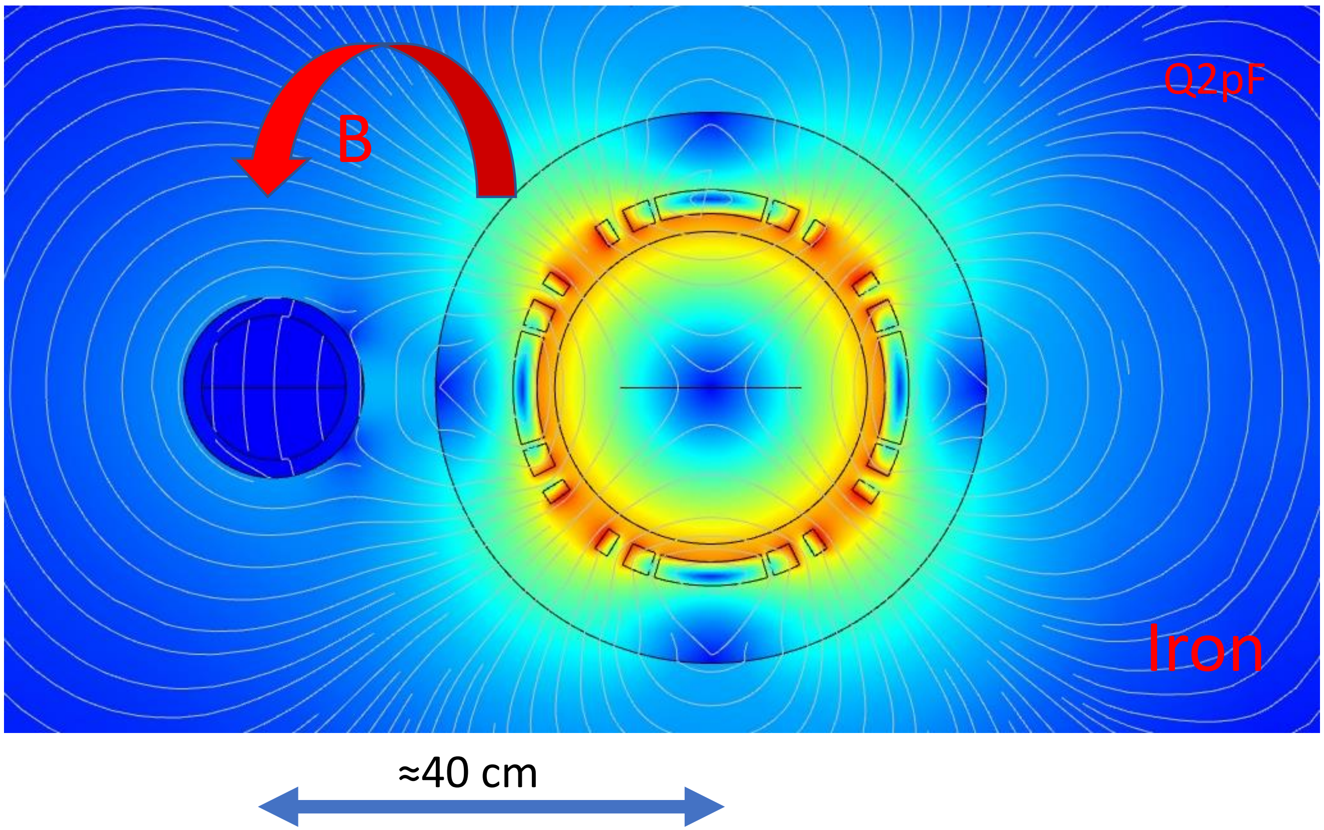
```
NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -0.00000  b 2:  10000.00000  b 3:      0.00000
b 4:      0.00788  b 5:      0.00000  b 6:     -0.32418
b 7:      0.00000  b 8:      0.00003  b 9:     -0.00000
b10:      0.62188  b11:      0.00000  b12:     -0.00013
b13:      0.00000  b14:     -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

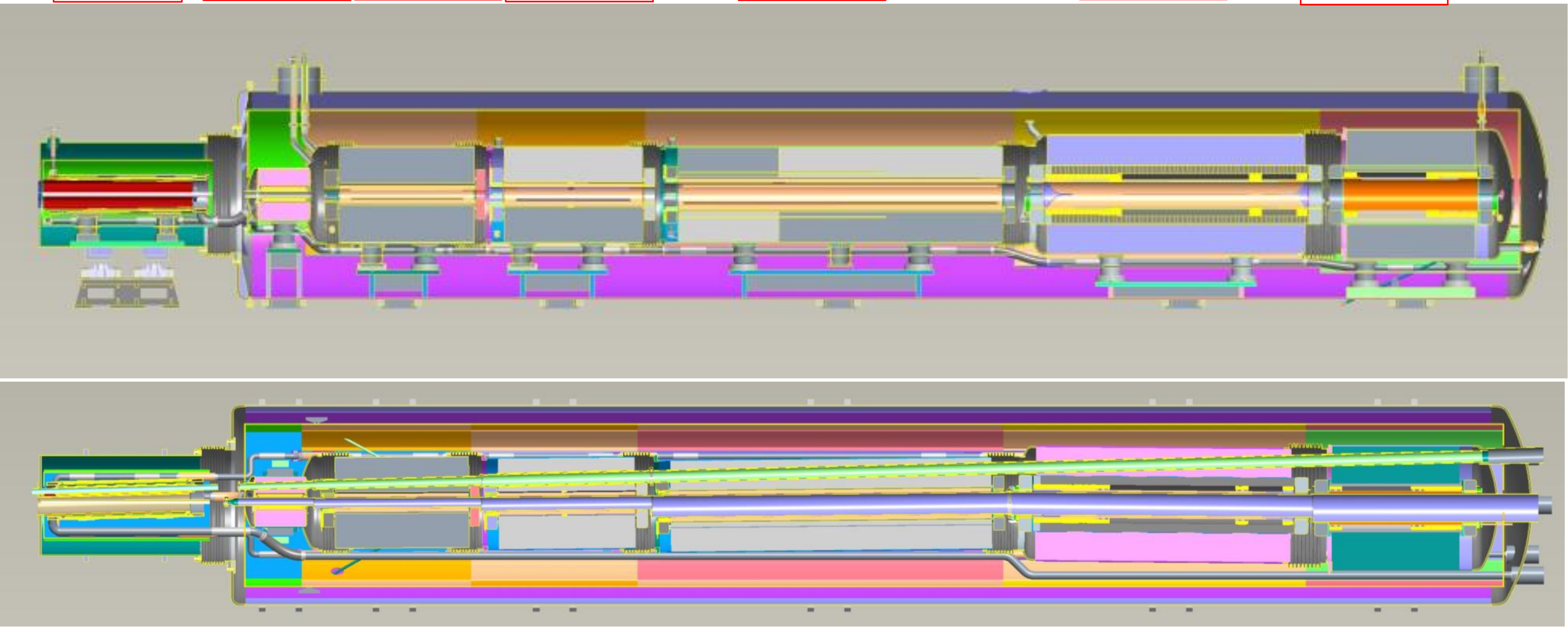


Refers to flux from one magnet leaking into the other
Leads to field quality issues
Depends on geometry and field/flux

Common issue for all IR magnets

Magnet Engineering

B0pF | B0ApF | Q1ApF | Q1BpF Q1eF | Q2pF | B1pF | B1ApF

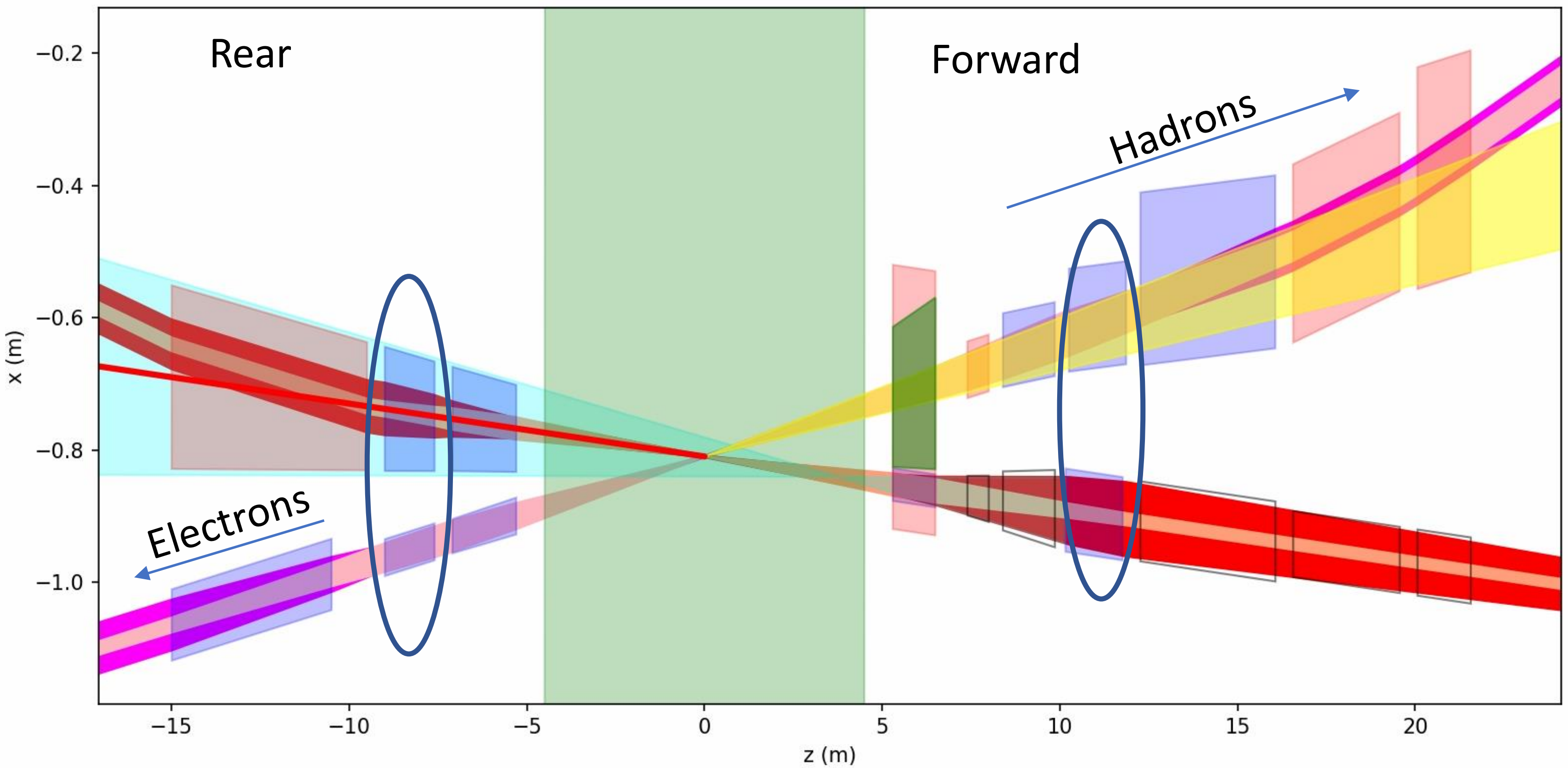


Standalone 48” cryostat

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

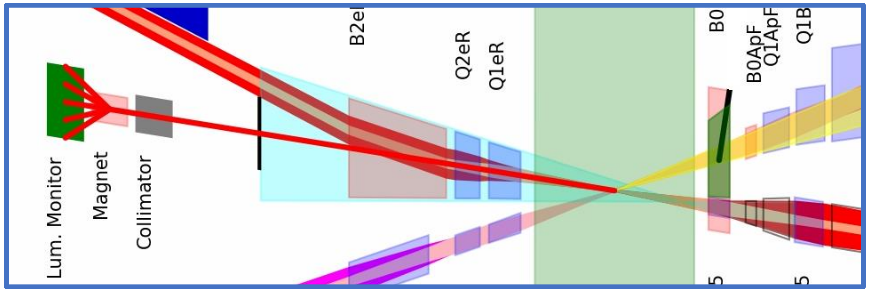
IR Layout

IR quadrants not independent of each other



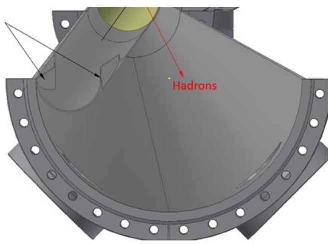
Changing one sector implies changing another one
Also: need to get back to RHIC ring (HSR)

Synchrotron Radiation

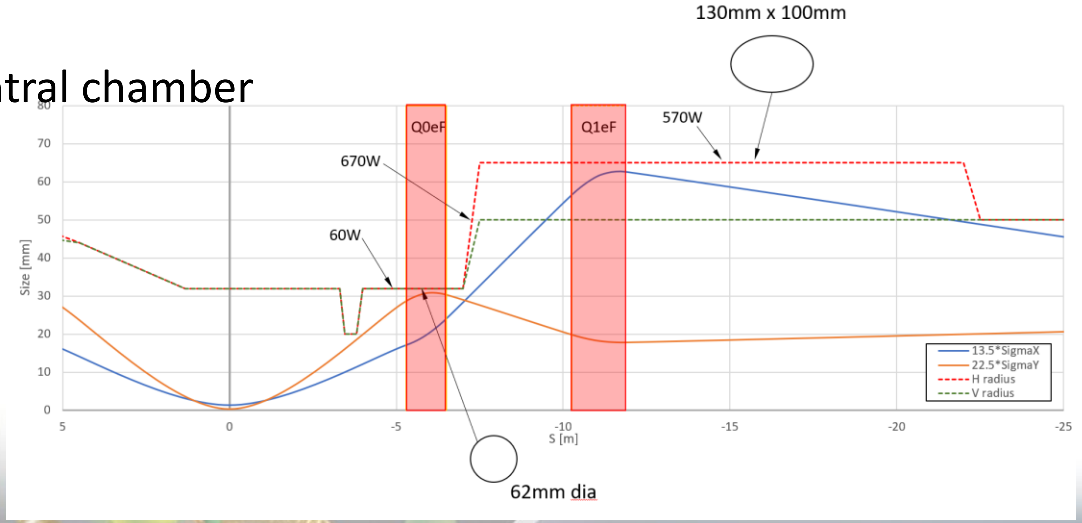


- Origin: quads and bending magnet upstream
- Tails: can produce hard radiation
  - Non-Gaussian
- Even with masking: significant heating to deal with

FPA



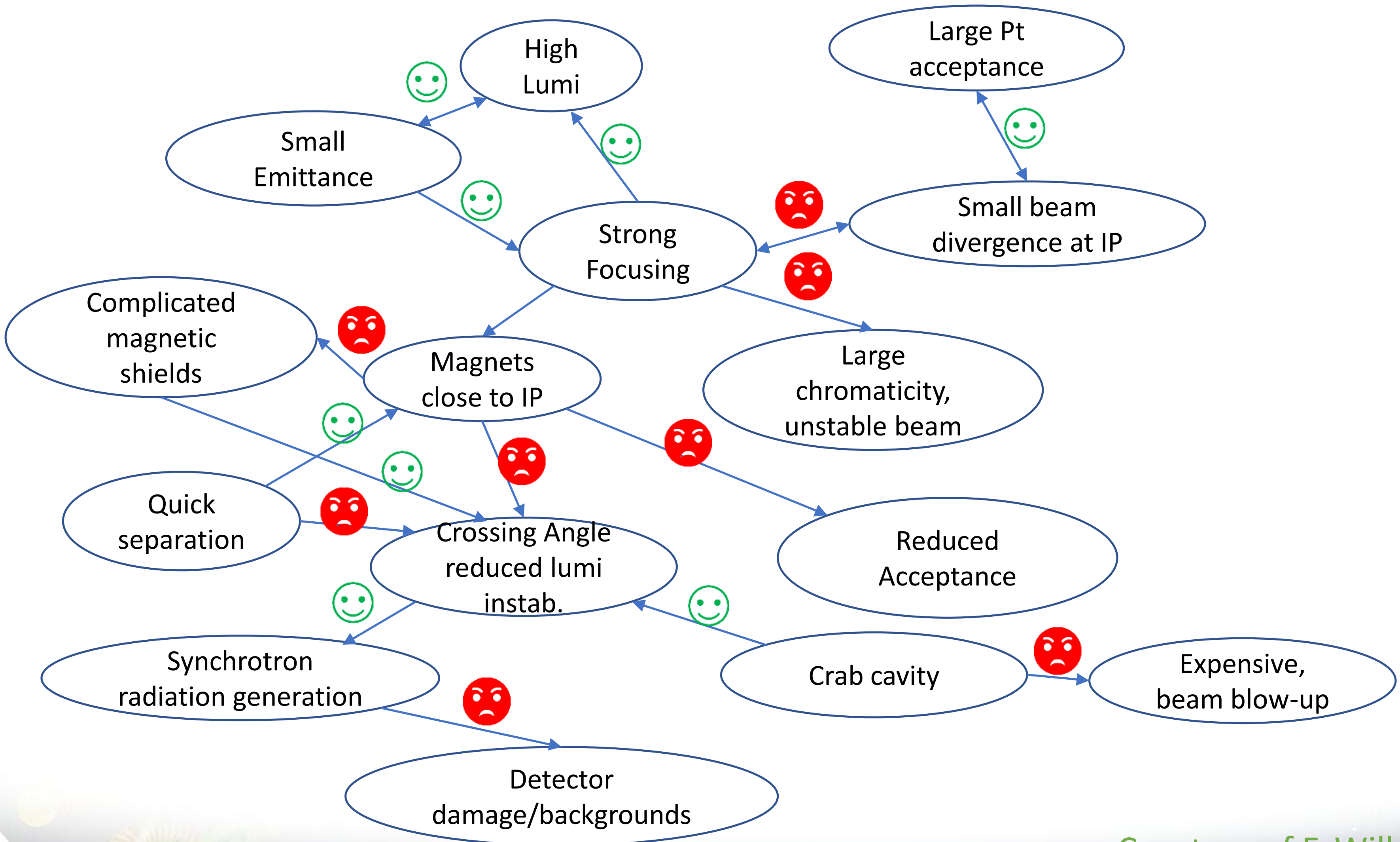
Central chamber



Beam pipe envelope and synrad heating

Courtesy C. Hetzel

IR Design Choices



Courtesy of F. Willeke

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

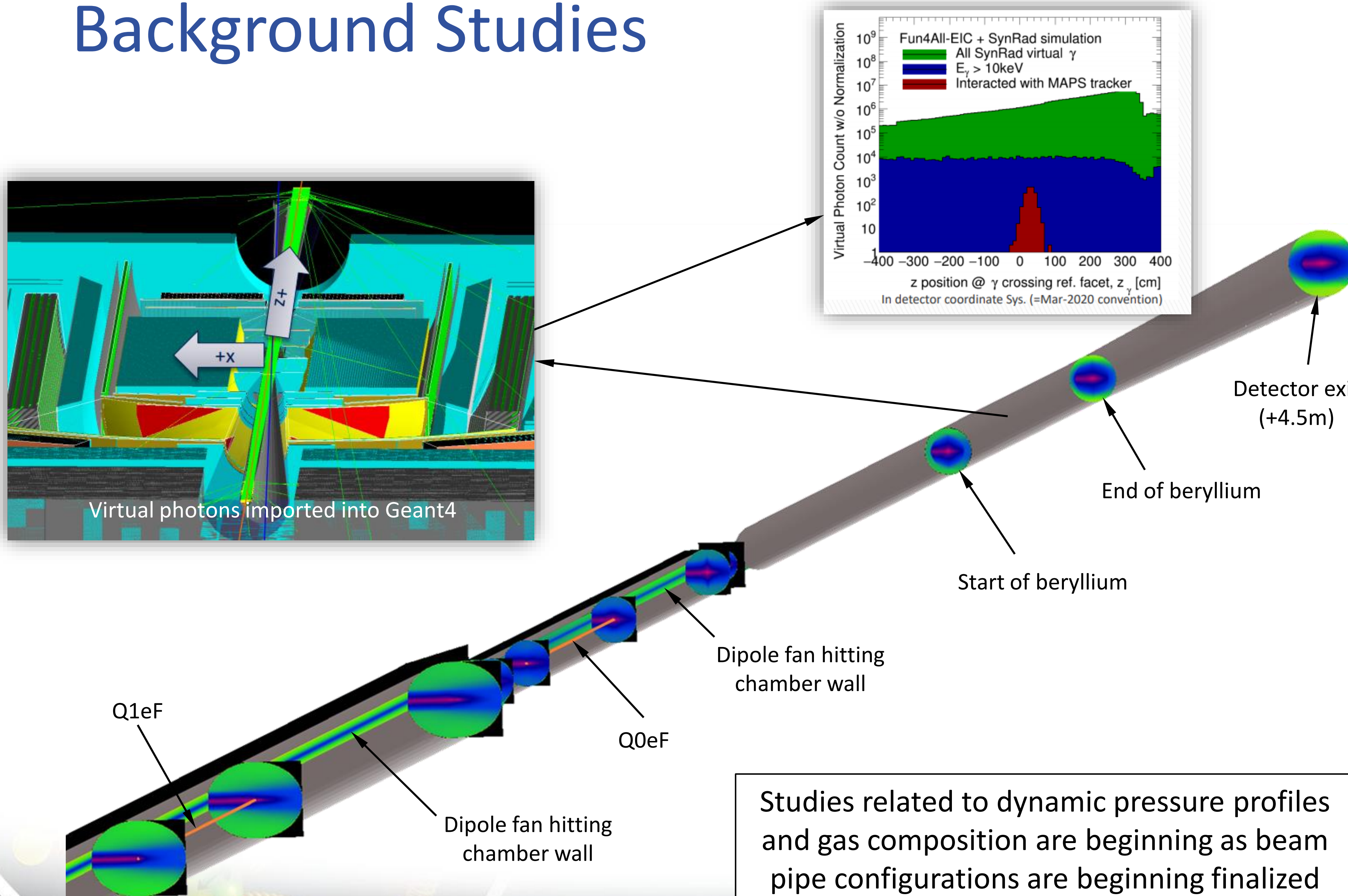
Acknowledgements

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!

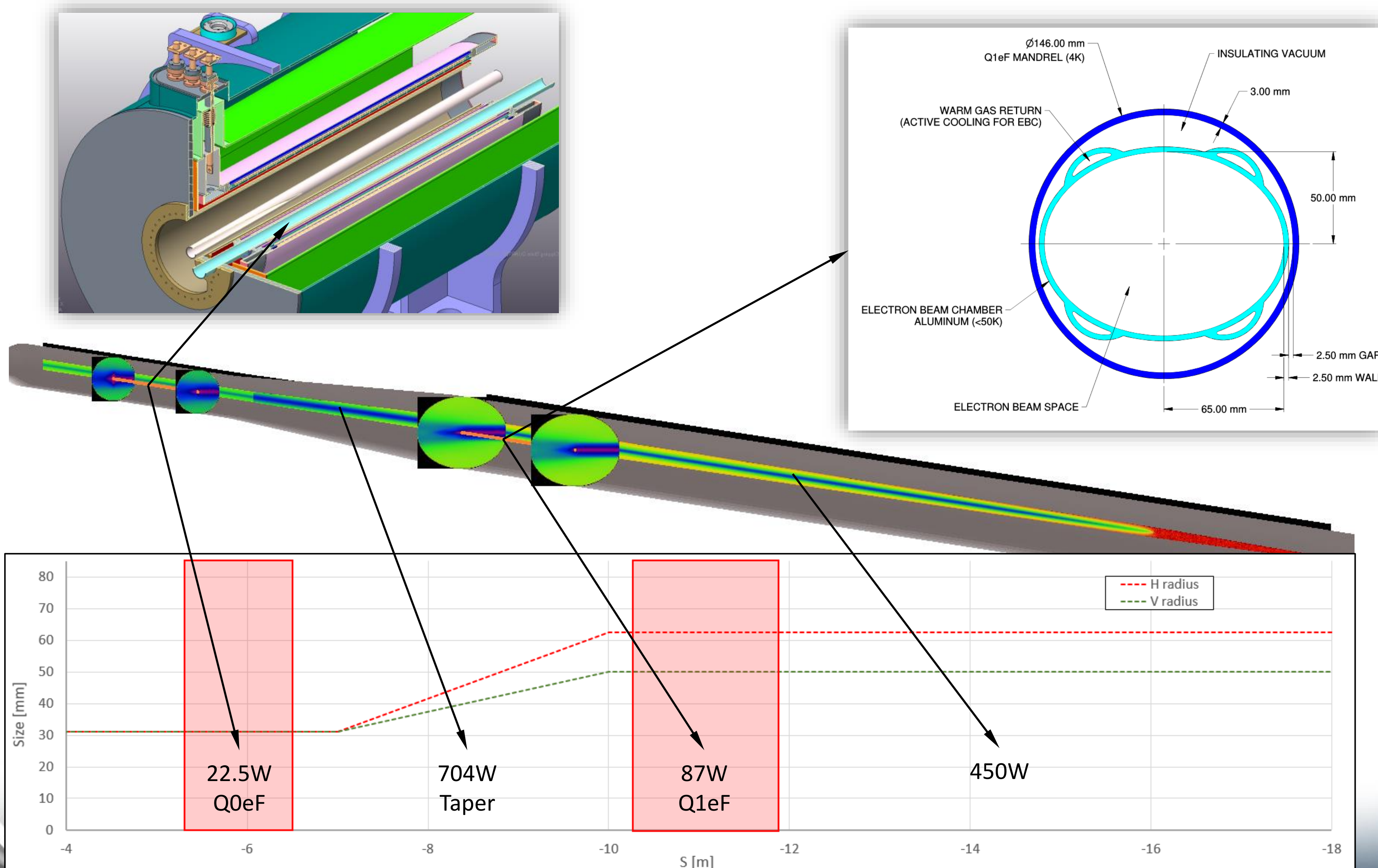
Additional Slides

Background Studies



Studies related to dynamic pressure profiles and gas composition are beginning as beam pipe configurations are beginning finalized

Heat Load in Cold Magnets

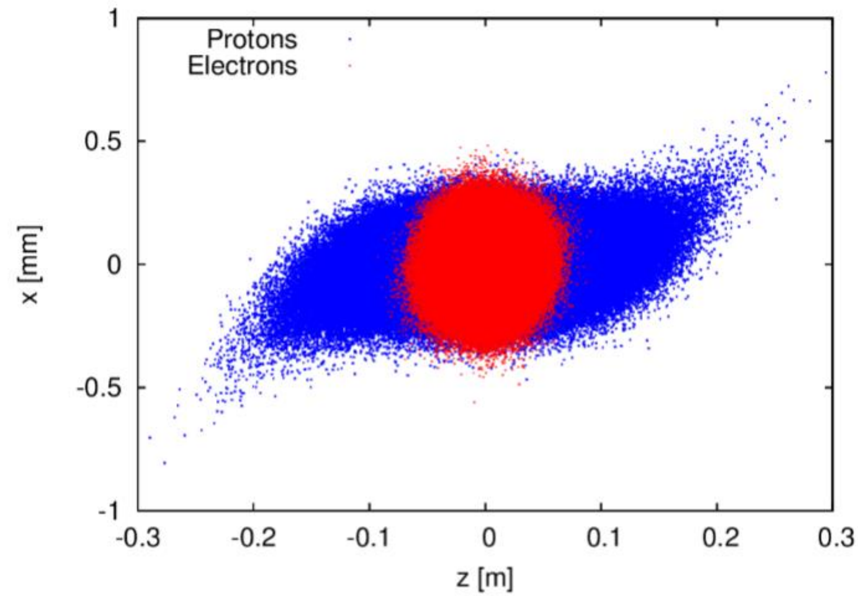


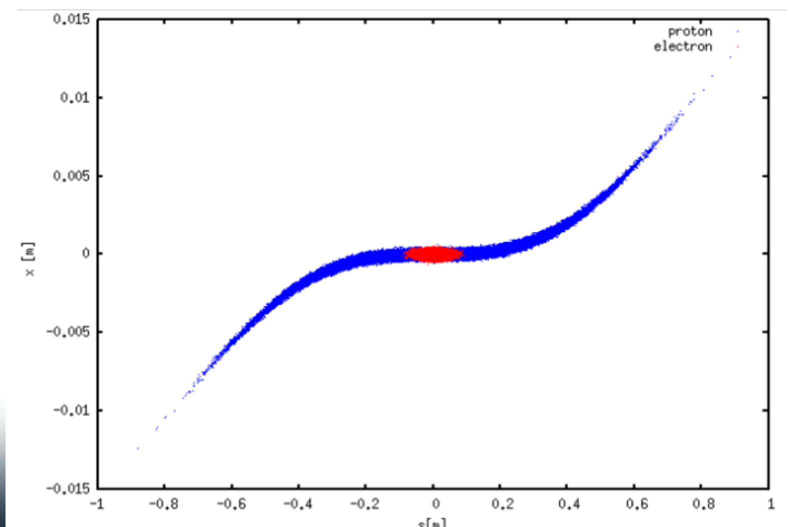
Crossing angle collisions

- 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

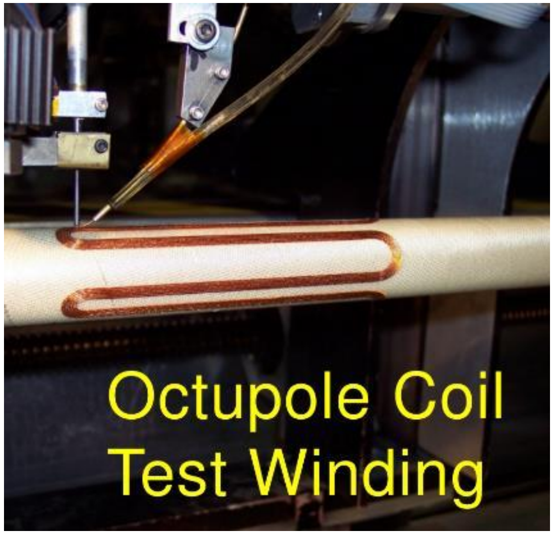
- Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
- Long hadron bunches are "S"-shaped during collision
- Distorted shape results in transverse offset between electron bunch and head and tail of proton bunch – reduced luminosity and severe beam dynamics 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)



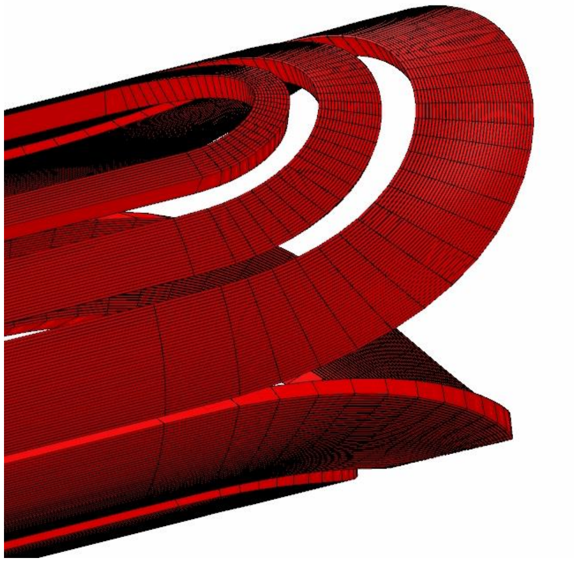


IR Magnets - Overview

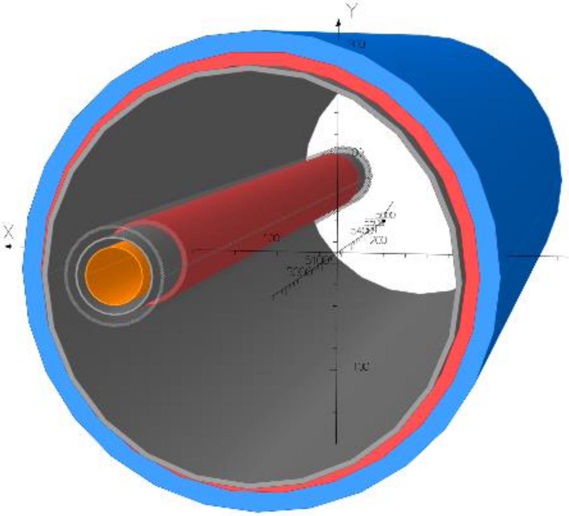
- Three groups of superconducting magnets
  - All NbTi
- (Also: normal conducting magnets, not addressed here)



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