IR Design Overview IP6

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Electron Ion Collider – EIC at BNL

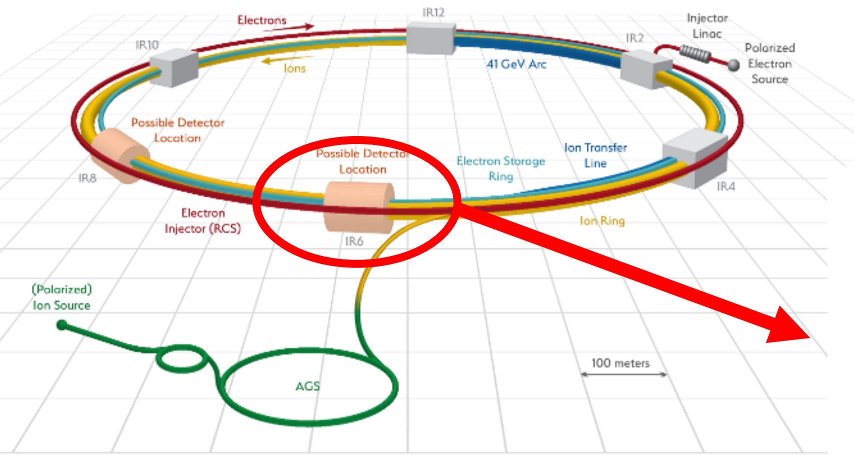
BROOKHAVEN NATIONAL LABORATORY

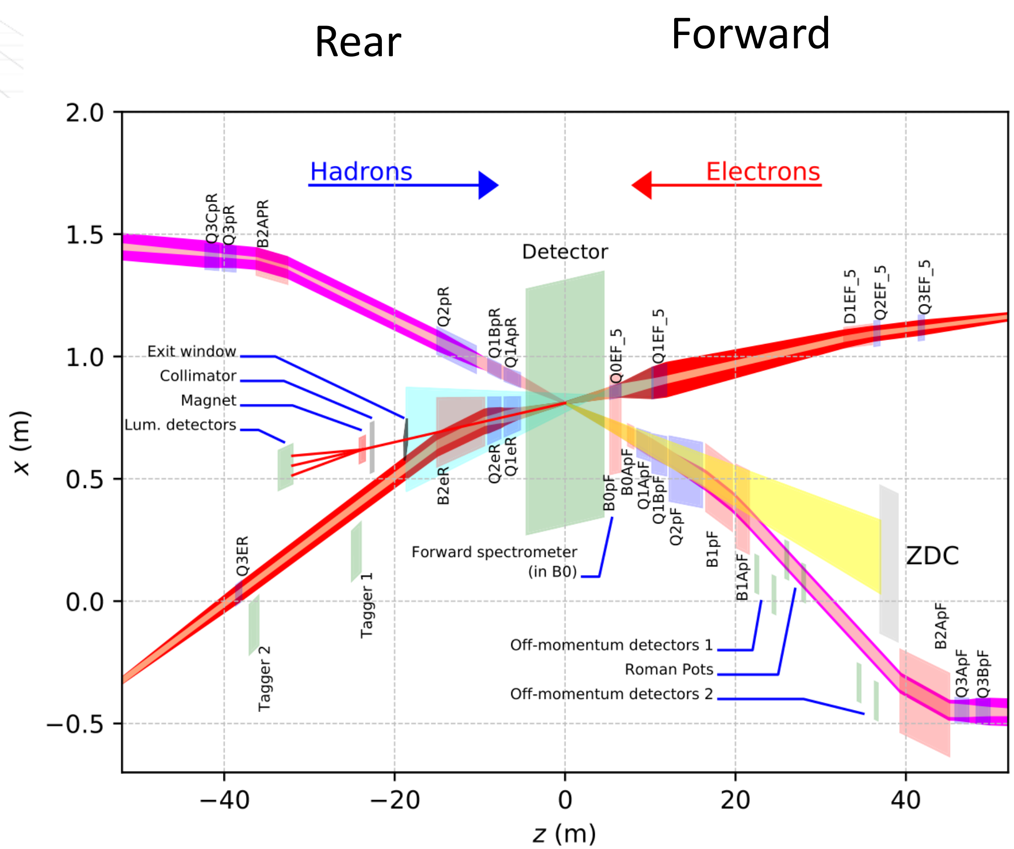
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Overview
  - Requirements
  - General constraints
  - Present IR
- Forthcoming Changes / Work in Progress
  - Tilt of ESR
  - Correctors
  - 0.5m shift forward direction
- IR Magnets
  - 2K Operation
  - B0pF
  - Q1ABpF

EIC IR: Overview





Hadron storage ring (HSR): 4 yellow and 2 blue RHIC arcs

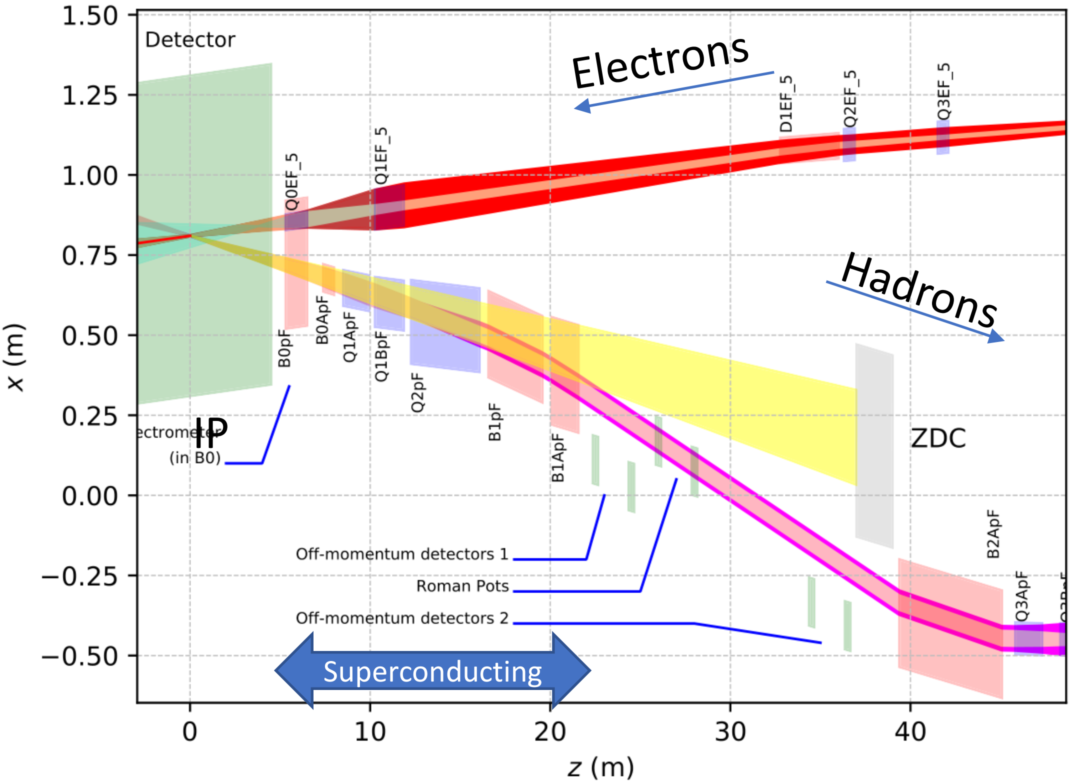
Add electron storage ring (ESR) in existing tunnel (and the RCS)

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

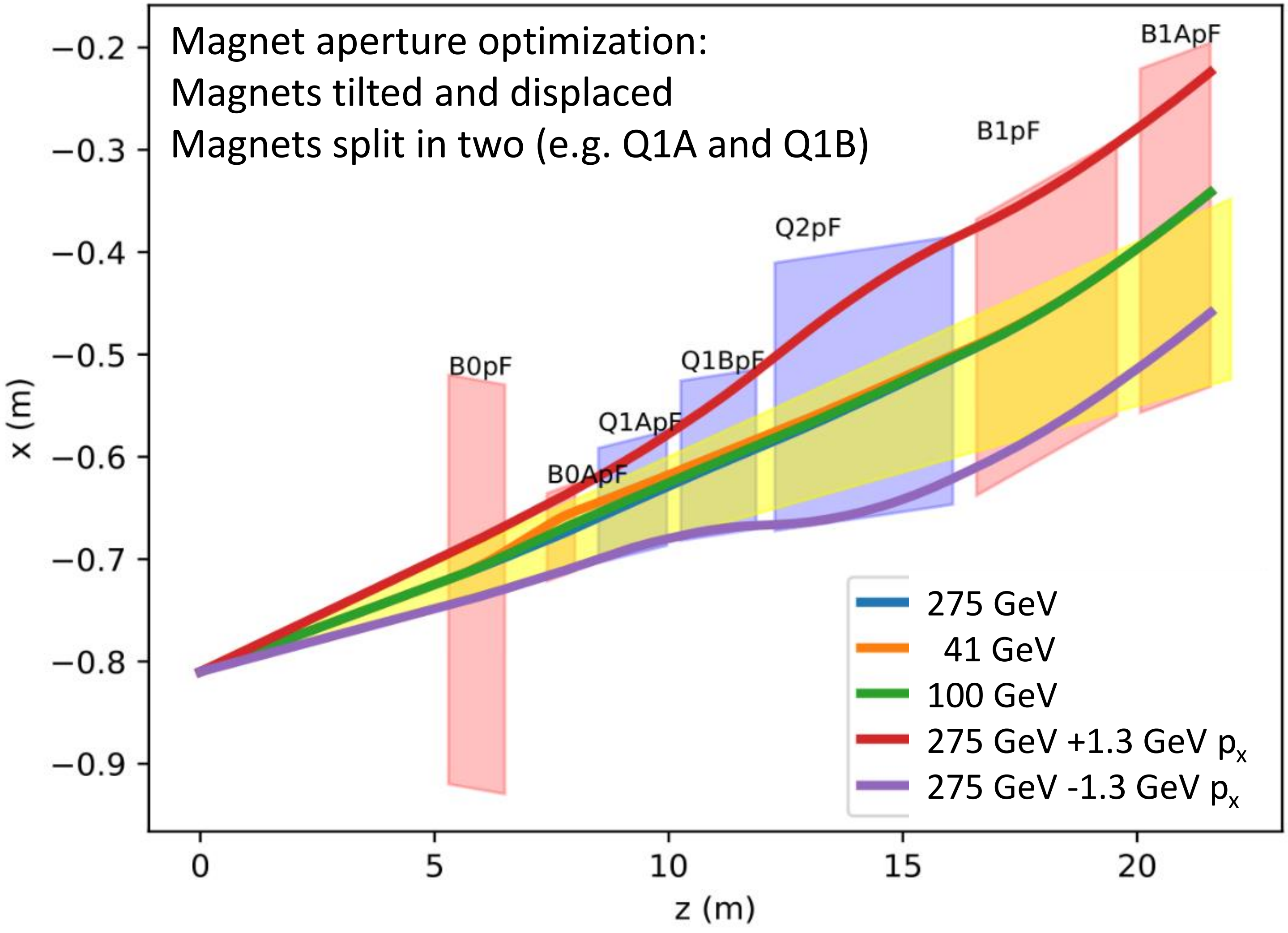
EIC IR: Forward Direction



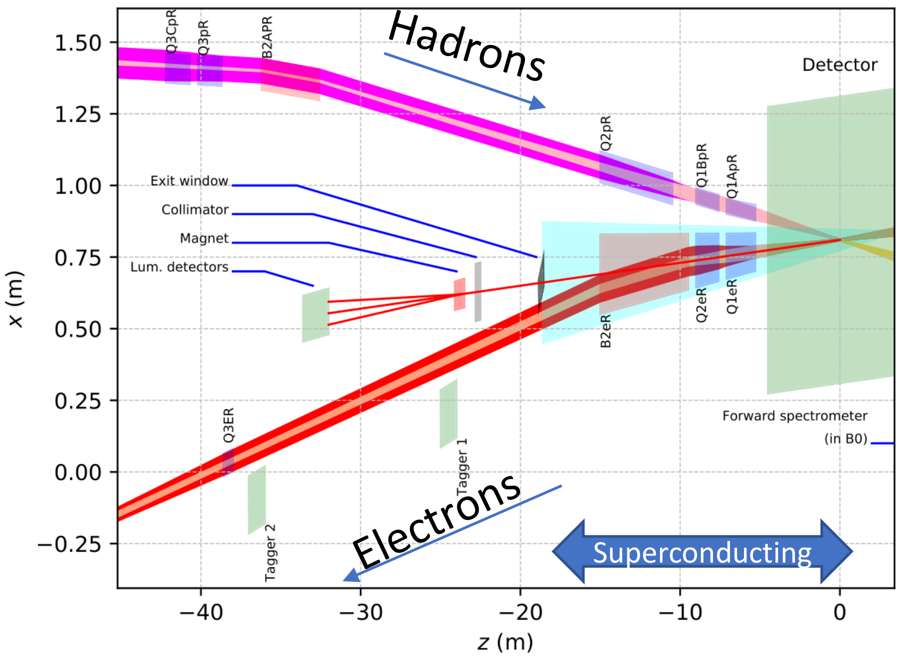
Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
B0ApF	0.043	0.6	-3.3	0	-3.3
Q1ApF	0.056	1.46	0	-72.608	-4.066
Q1BpF	0.078	1.61	0	-66.18	-5.162
Q2pF	0.131	3.8	0	40.737	5.357
B1pF	0.135	3	-3.4	0	-3.4

- 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

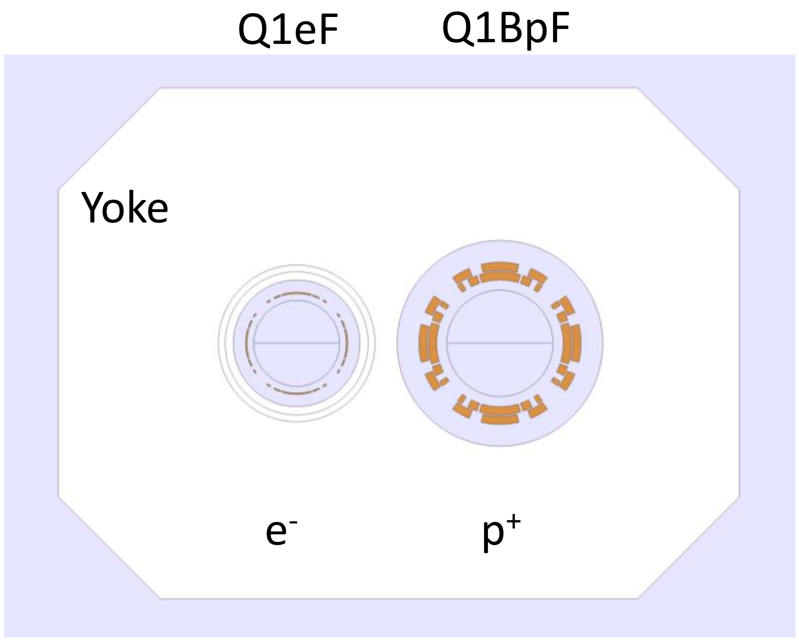
For technical reasons B2eR will be split into two magnets

Detector Solenoid Effects

- Coherent orbit distortion
- Transverse coupling
  - (Requires skew quads further away from IP)
- **Rotation of the crabbing plane**
  - **Requires skew quadrupoles in low-beta quads**
- Polarization tilt

Skew Quad Q1eF

- Additional windings on Q1eR, Q2eR, Q0eF and Q1eF
  - Gradient: 1.5T/m
- Changes Magnetization
- Potential crosstalk issue - looks ok so far
  - Checked Q1eR, Q1eF
  - need to look at other magnets



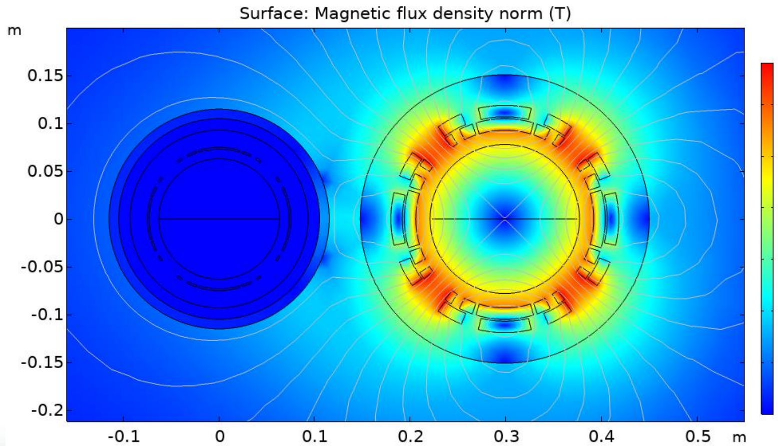
2.1.1 Skew components

Show 10 entries Copy CSV Excel Print PDF Search:

sf	a1	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15	a16	a17	a18	a19
0	0.0	0.0	-0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	-0.0	0.0	-0.0	-0.0	0.0	0.0	0.0	-0.0	-0.0
0.5	0.0	0.1	-0.0	0.0	-0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
1	0.0	**0.1**	-0.0	0.0	**-0.1**	0.0	-0.0	0.0	-0.0	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
1.5	0.0	**0.2**	-0.0	0.1	**-0.2**	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
2	0.0	**0.3**	0.0	0.1	**-0.3**	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
2.5	0.0	**0.4**	0.0	**0.1**	**-0.5**	0.0	0.0	0.0	-0.0	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
3	0.1	**0.5**	0.0	**0.1**	**-0.7**	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
3.5	0.1	**0.6**	-0.0	**0.1**	**-1.0**	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
4	0.1	**0.6**	-0.0	**0.2**	-1.2	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0
4.5	0.1	**0.7**	-0.0	**0.2**	-1.3	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	-0.0

Showing 1 to 10 of 17 entries

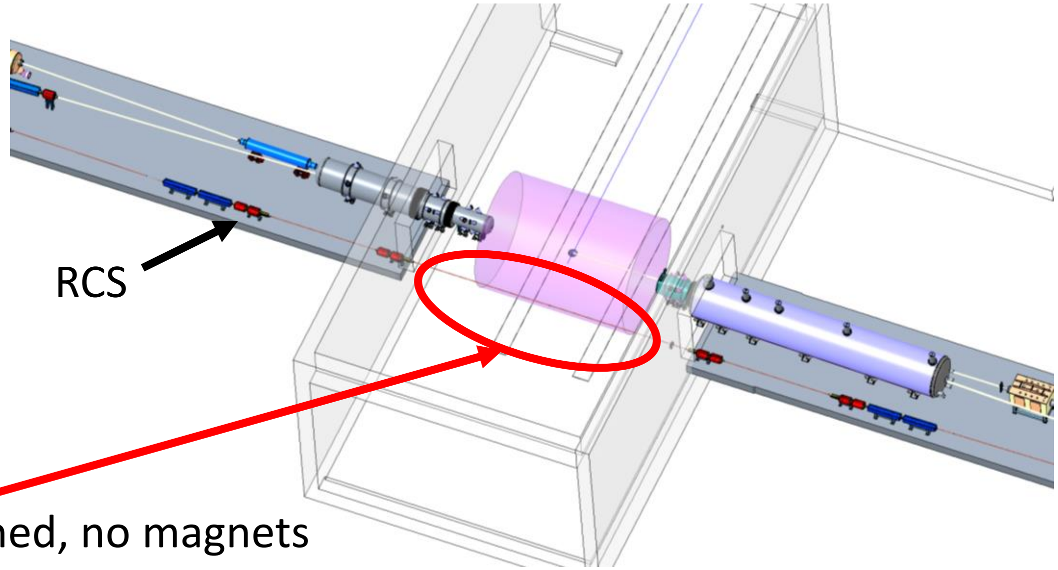
Previous 1 2 Next



IR6 Hall

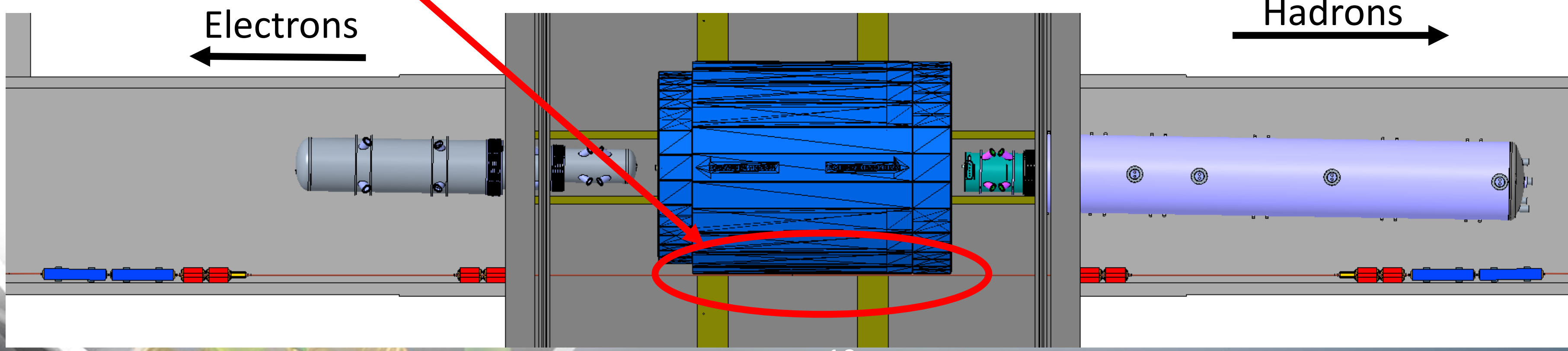
Rear

Forward



Change: RCS redesigned, no magnets behind detector

Detector



ESR Tilt

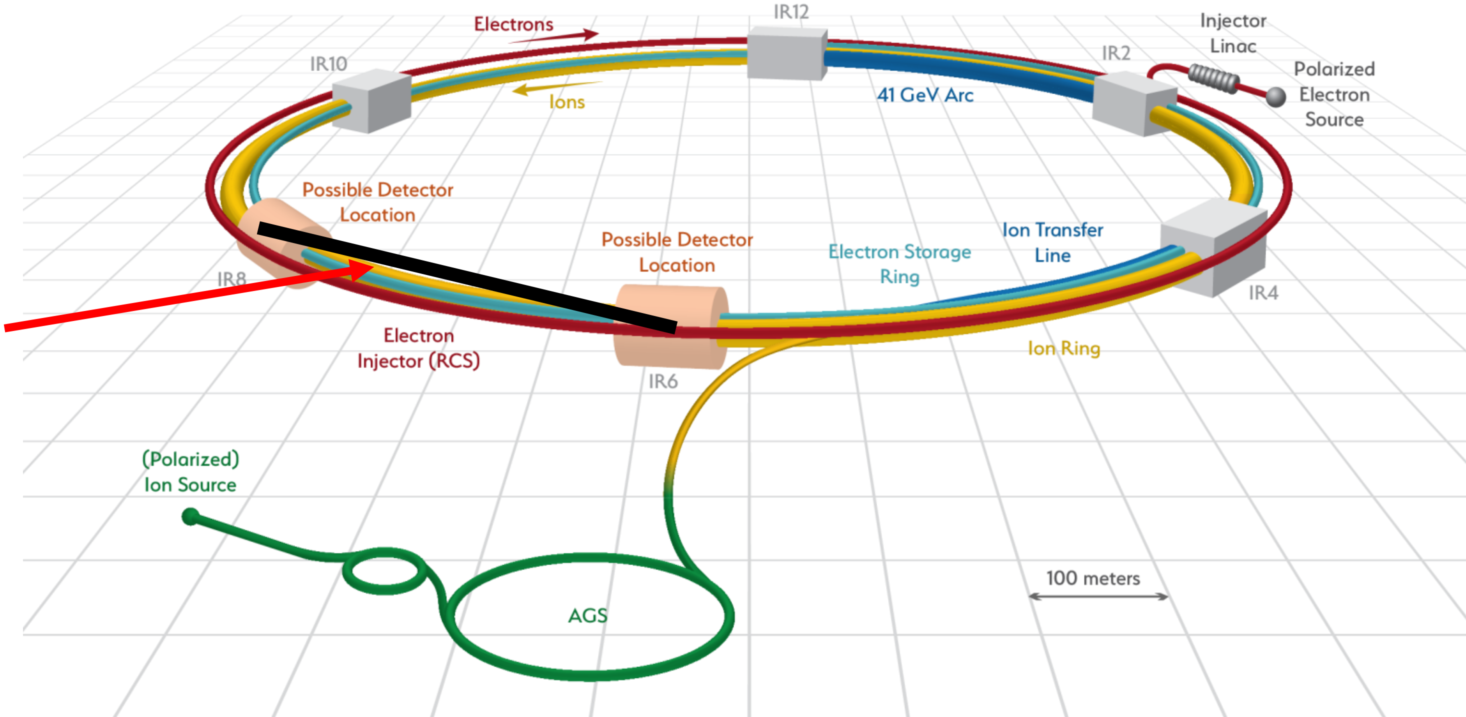
Elegant solution to space issues in tunnel

Tilt ESR: 200urad

Rotation axis: Line from IP6 to IP8

Accepted as baseline

Rotation axis

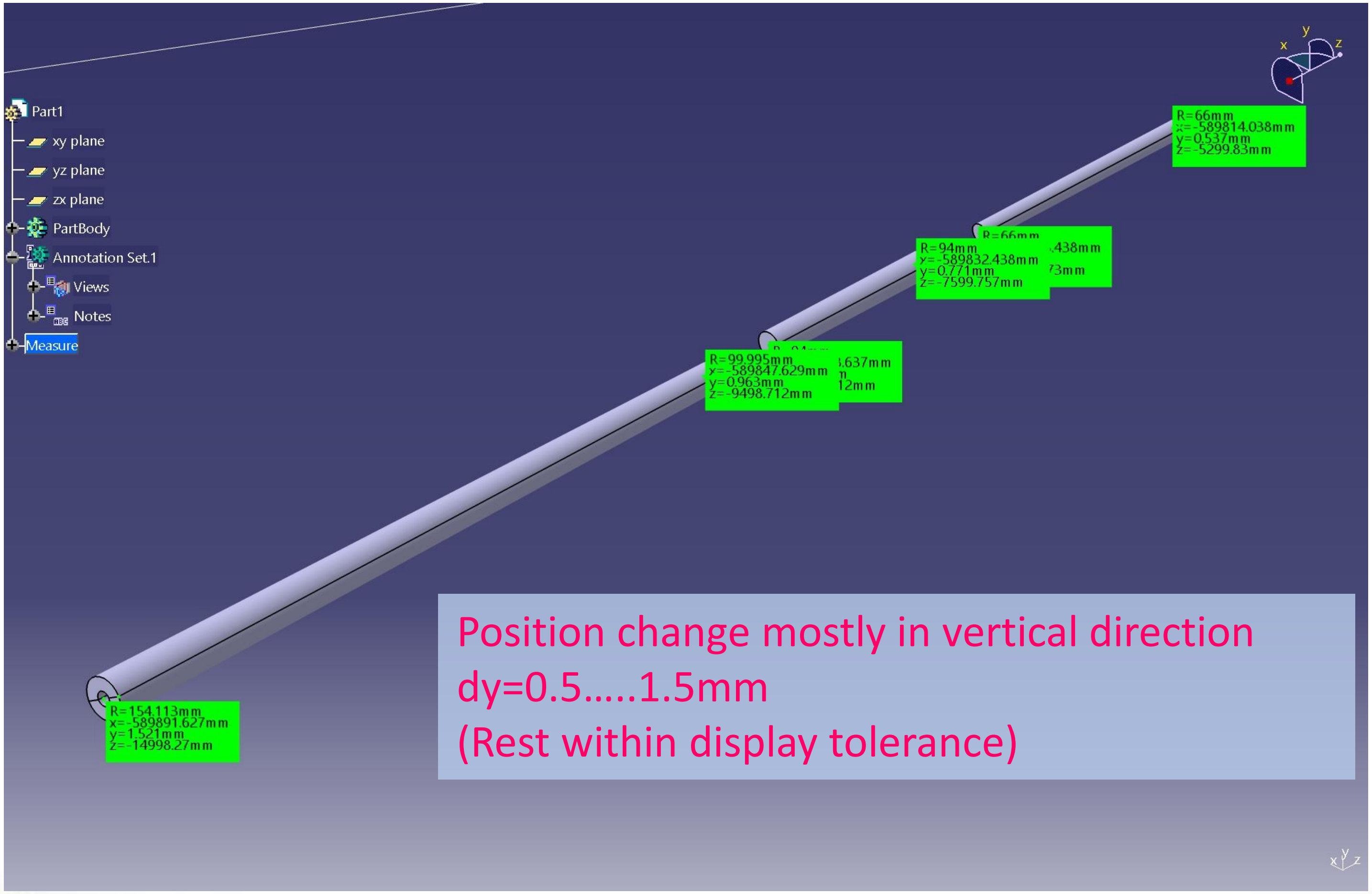


ESR and HSR cross in several places in tunnel (IP6, IP8, IR4 and IR12)

Eliminates vertical bumps in ESR, which is challenging due to spin transparency

Magnet Shifts

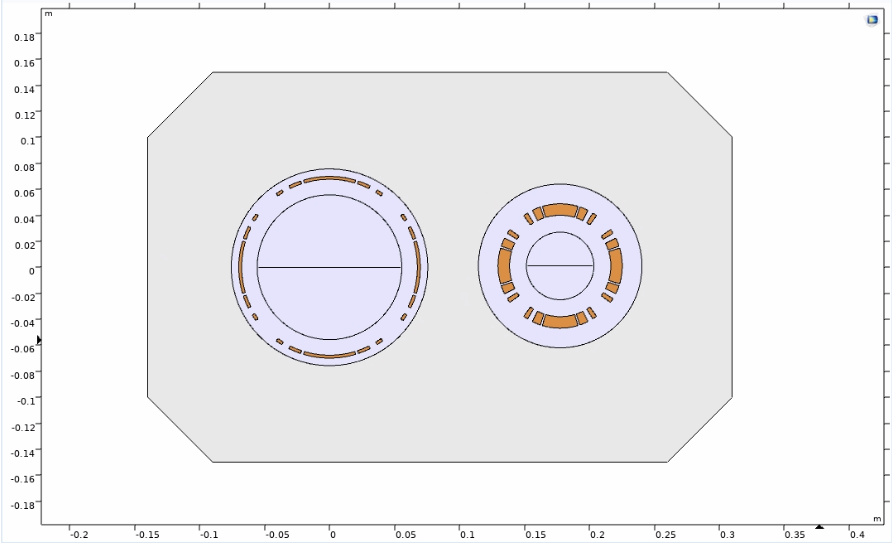
ESR tilt leads to hadron/electron magnet apertures shifting with respect to each other

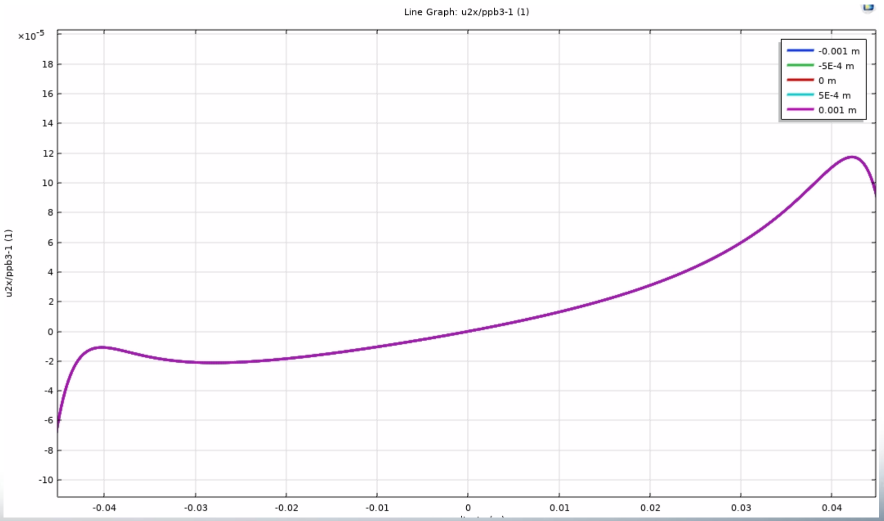


Position change mostly in vertical direction
dy=0.5…..1.5mm
(Rest within display tolerance)

Impact ESR Tilt

- 2D studies
- Looked at low-β quads
- No obvious change in field/gradient quality
- Special case B0pF
    - Beam will go through at an angle
    - Will need to look at harmonics
    - Check with field map

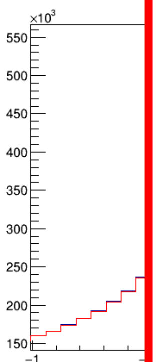




Impact on Physics

Below we show plots using 18x275 GeV with rotation of the ESR reference plane about a line through IP6 and IP8 by ~200 µRad .

→ for IP-6 this means a vertical shift of 1.521mm at the end of b2er (z=14998.27mm), that makes it a about 100µrad angle



ue: no rotation

d: with rotation

Summary

- No relevant impact on particle distribution from collisions was found
- No objection from the friends from physics  on this change
- Thanks to Brian Page and Jarda Adam for doing the simulations

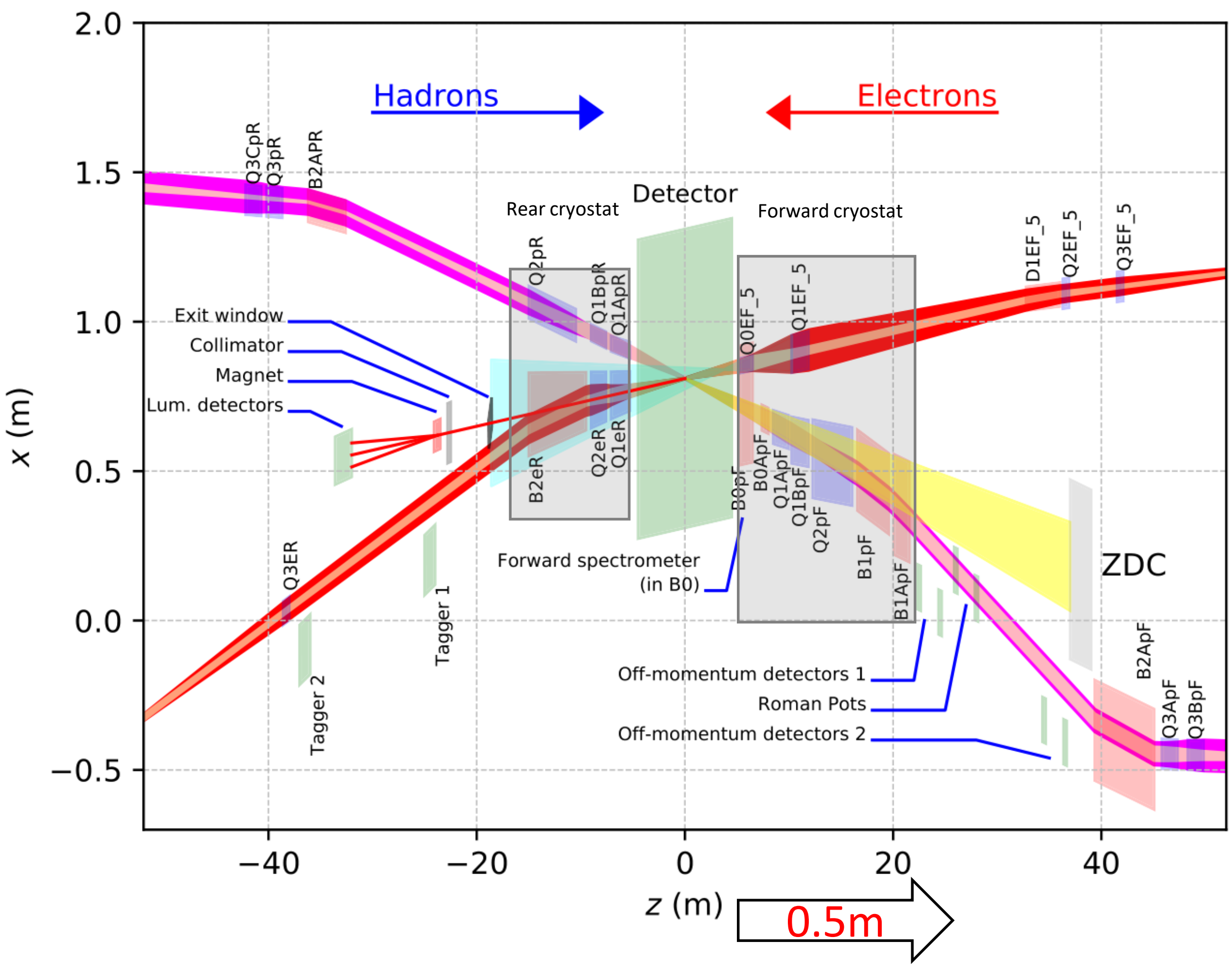
The left plot sho d crossing in Y. A very slight offset is seen, but I would not call it significant in any way.

The right plot shows the angle between the y and z components of the beam. The widths of the distributions are due to beam divergence and are equal. The red distribution is offset 0.0001 radians as expected.

0.5m Shift

- **Request from Physics community**
  - Need 0.5m more space for detector on forward side
- Submitted to Tech. Change Control Board
  - **Reminder: this does not have to be perfect**
  - **Purpose: establish baseline**
- Effects have been studied
  - Leave magnet apertures unchanged
- Results
  - Lattice/Match
  - Magnets / magnet locations
  - Synrad
  - Effect on physics results/clipping

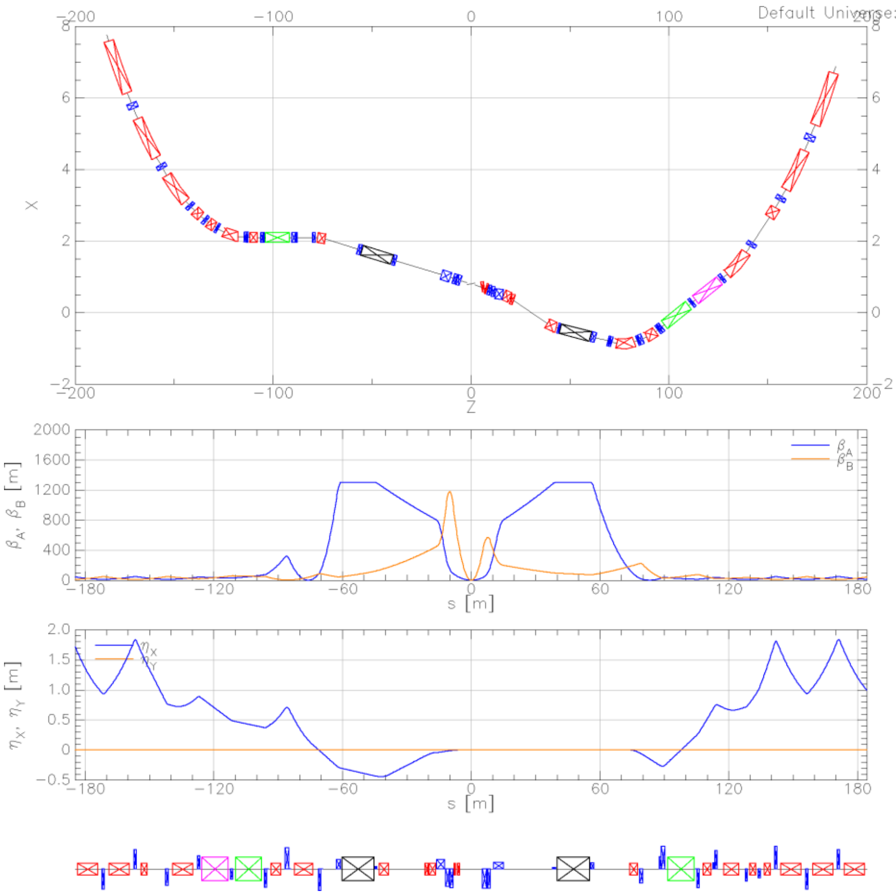
IR Region



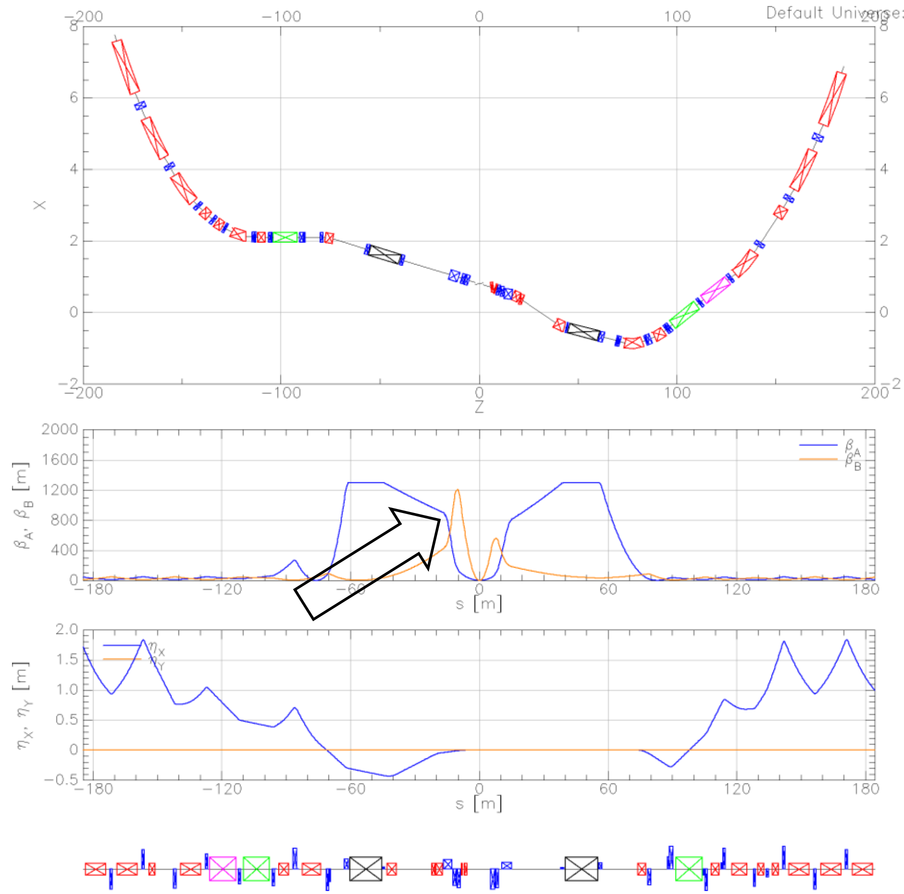
Space for detector grows in forward direction by 0.5m

Hadron Lattice

Before



After



Same β*

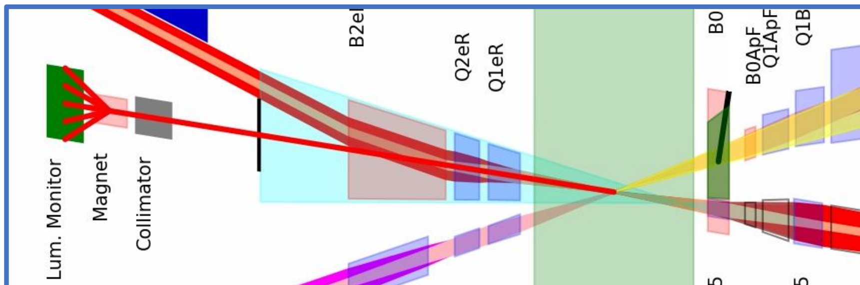
Larger β in low-beta quad on forward side (larger beam size)

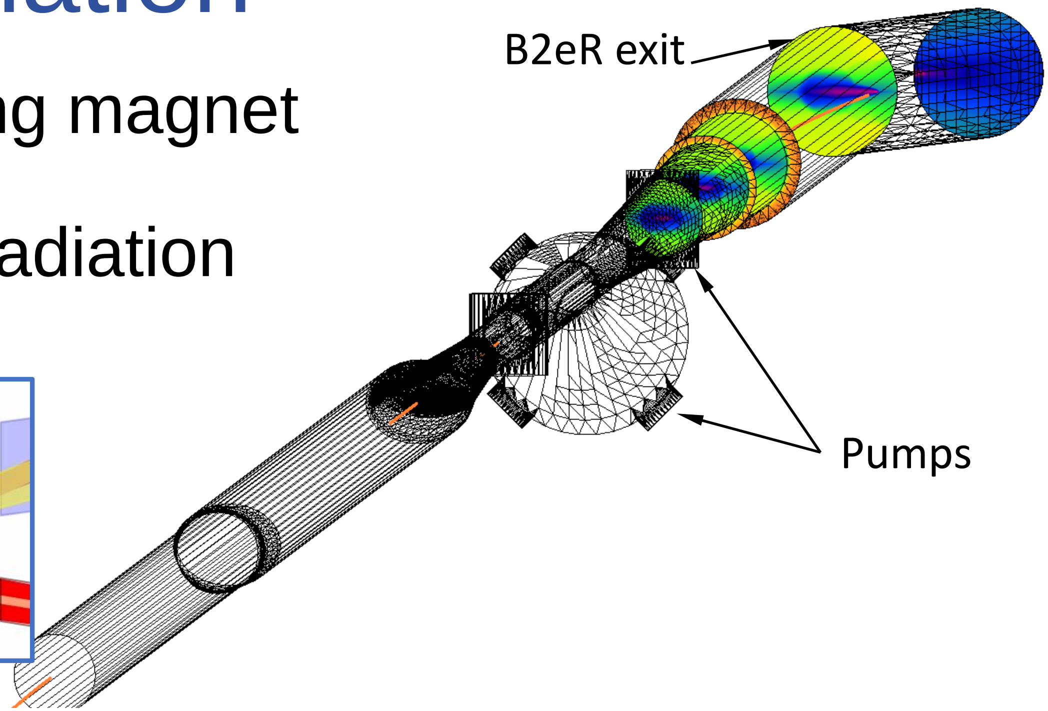
Magnet apertures unaffected

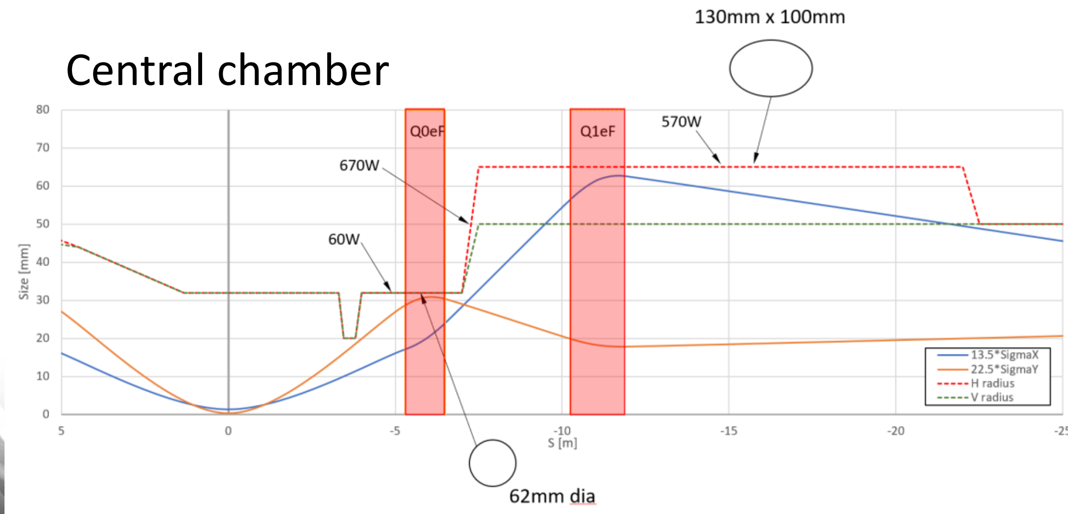
By J.S. Berg

Synchrotron Radiation

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







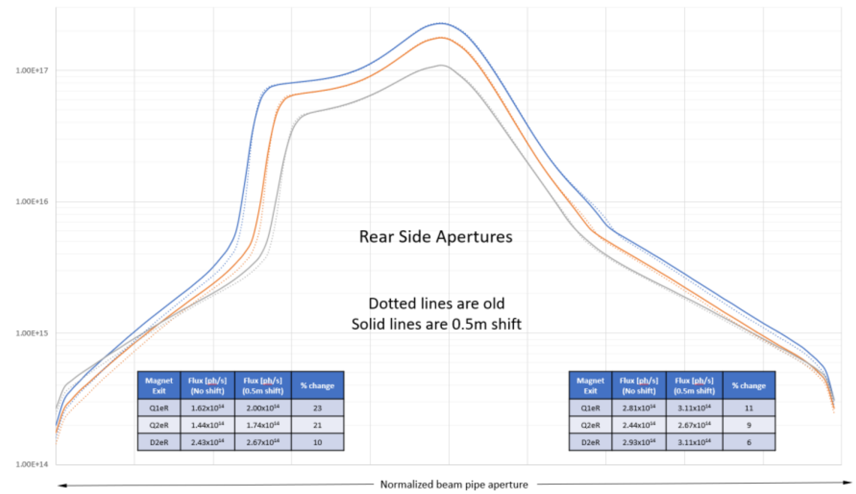
Beam pipe envelope and synrad heating

Even with masking: significant heating to deal with

Courtesy C. Hetzel

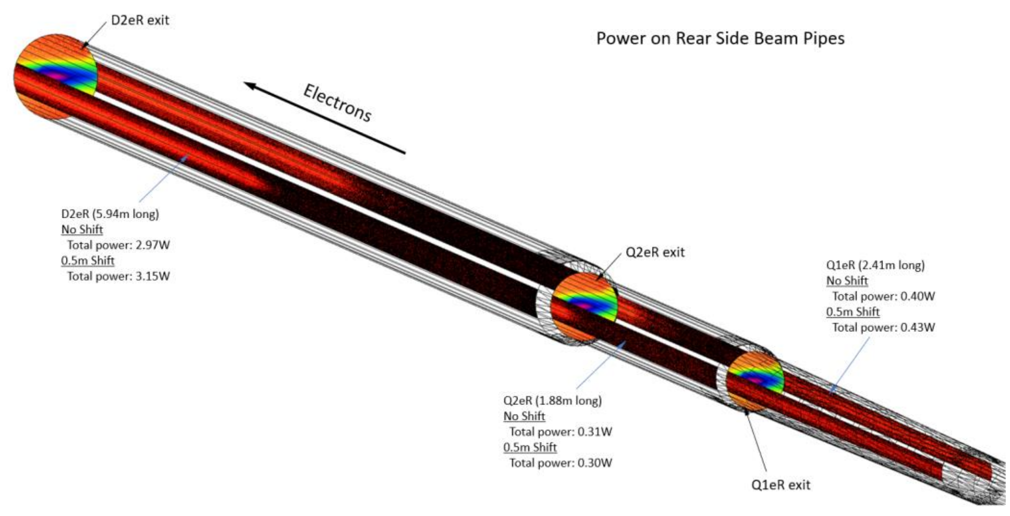
Synchrotron Radiation / 0.5m Shift

- Studied using Synrad3D
- Small changes in Synrad
- No significant increase in photon hits in central chamber
  - … and can probably still be improved



Magnet Exit	Flux [ph/s] (No shift)	Flux [ph/s] (0.5m shift)	% change
Q1eR	1.62×10^{14}	2.00×10^{14}	23
Q2eR	1.44×10^{14}	1.74×10^{14}	21
D2eR	2.43×10^{14}	2.67×10^{14}	10

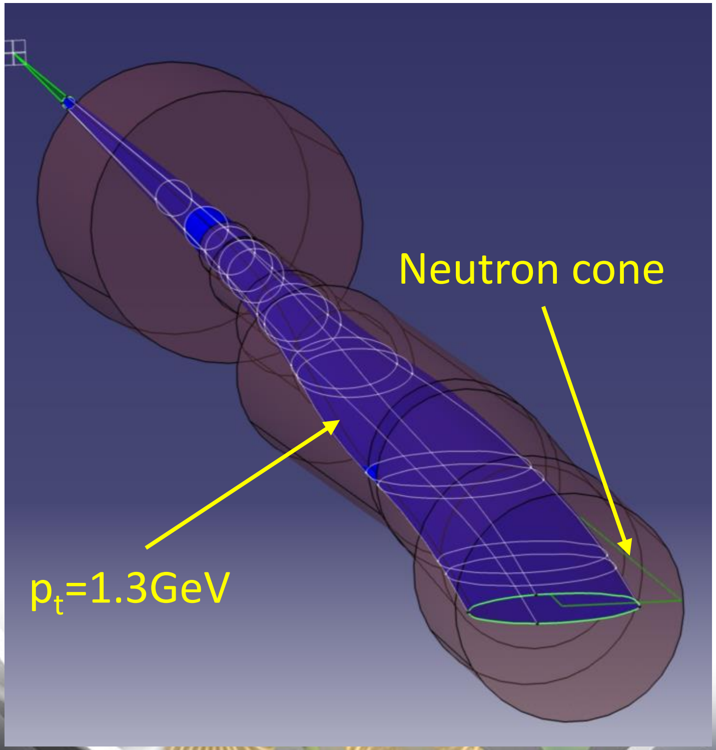
Magnet Exit	Flux [ph/s] (No shift)	Flux [ph/s] (0.5m shift)	% change
Q1eR	2.81×10^{14}	3.11×10^{14}	11
Q2eR	2.44×10^{14}	2.67×10^{14}	9
D2eR	2.93×10^{14}	3.11×10^{14}	6

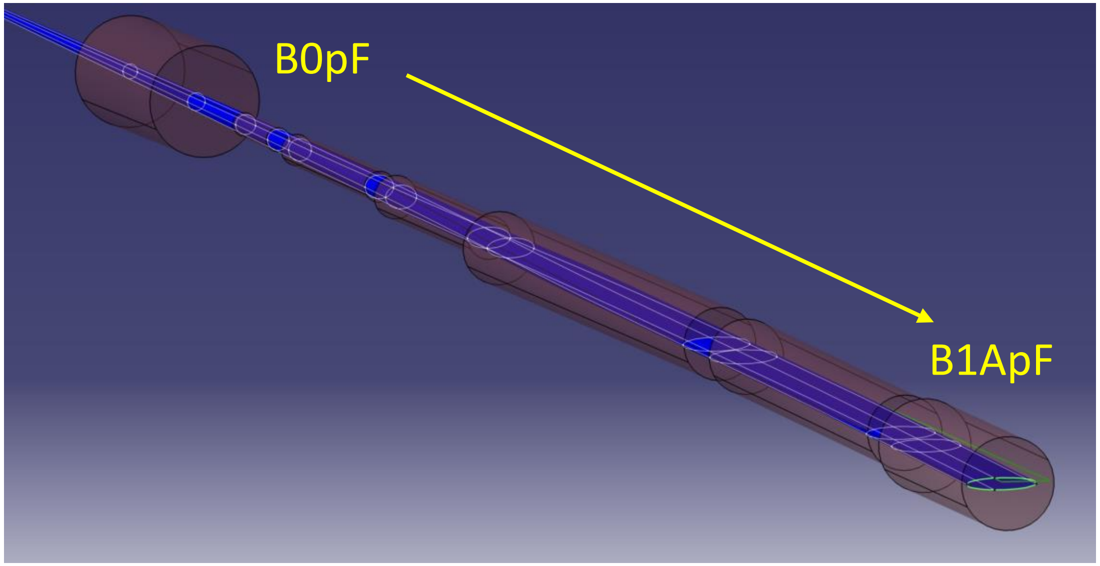


By C. Hetzel / M. Sullivan

Acceptance Studies

- Checked with two codes
  - BMAD – general purpose tracking code
  - Geant4 (friends from Physics)
- Cross-check allowed to identify error
  - Now perfect agreement



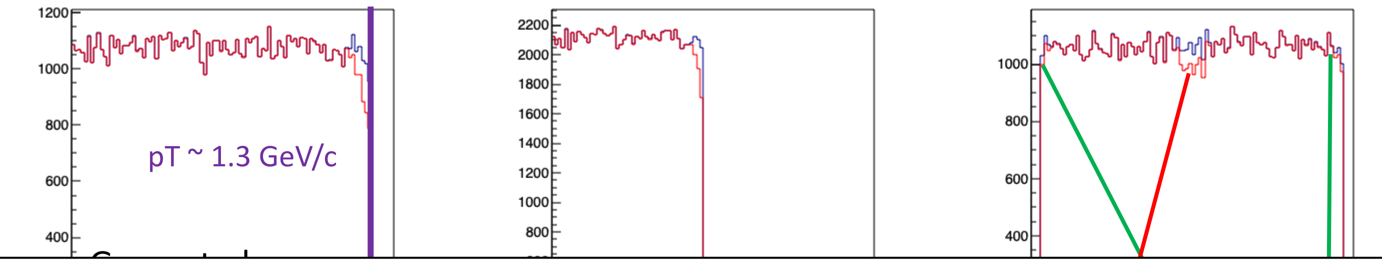


Generate cone for particles with p_t=1.3GeV
Rendered in CAD program with magnet apertures

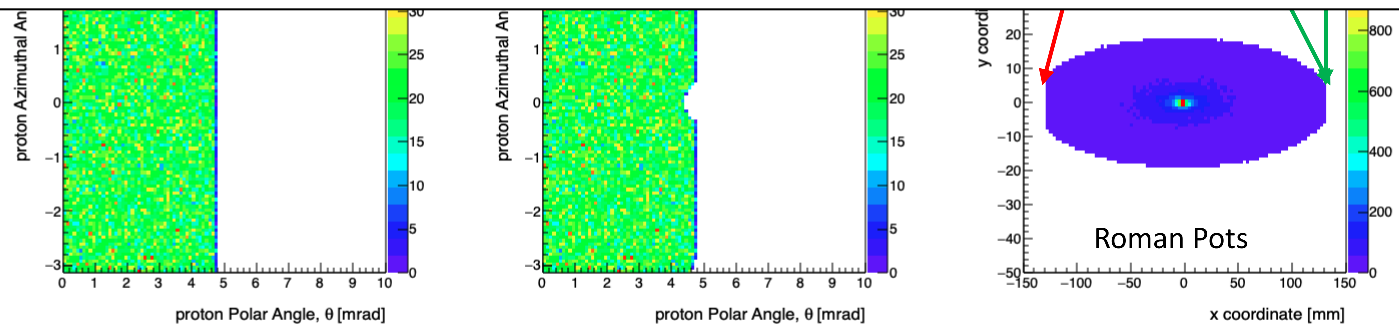
Summary of Detector Acceptance

- Alex passed a 100k events through the simulation after we worked out the technical issues in GEANT.

By A. Jentsch



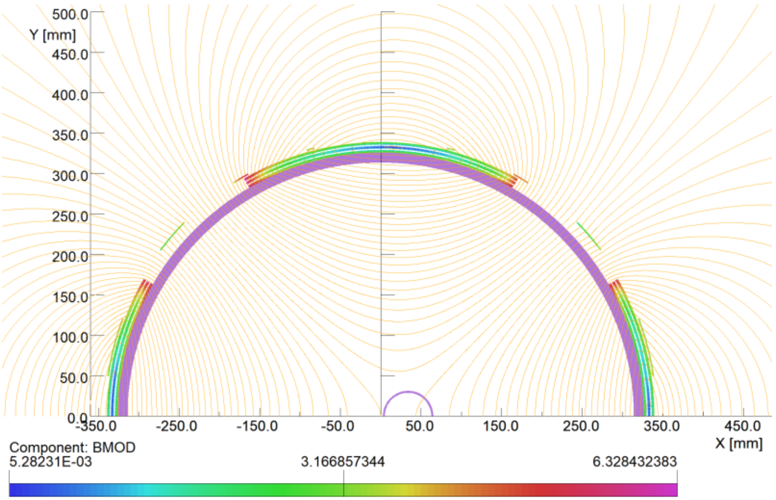
Overall, the shifted IR performs very similarly to the nominal one, and there are no red flags or showstoppers.

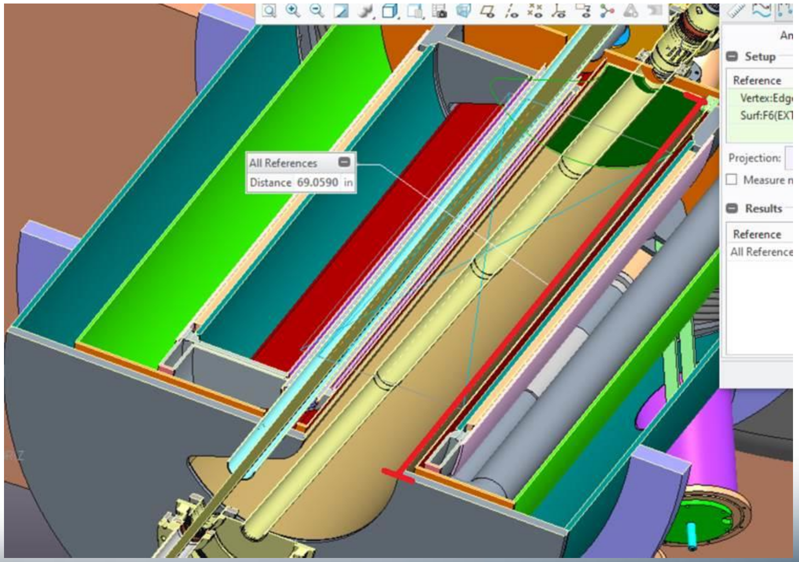


- Some very small amounts of clipping are observed on the edges (at phi = 0 and phi = pi), but overall the acceptance is 100% up to pt ~ 1.2 GeV/c

Forward Spectrometer

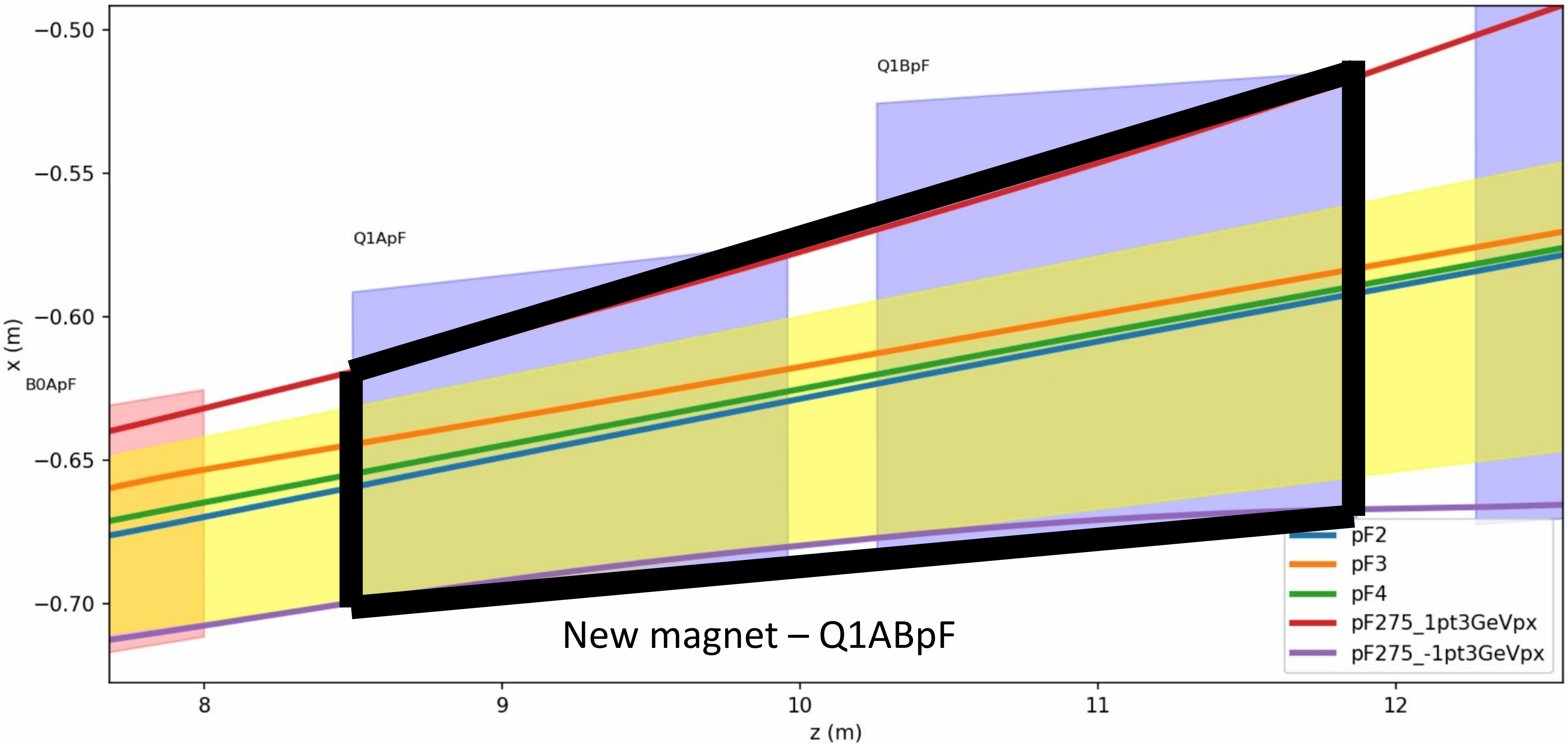
- Beams share magnet aperture
  - Hadrons: 1.3T field
  - Electrons: 14T/m gradient
- Implementation: combined function magnet
  - Large aperture quadrupole; zero field axis shifted with dipole
- Needs to be adopted for 0.5m shift
  - Requires 2K?





Q1ABpF – New Magnet Concept

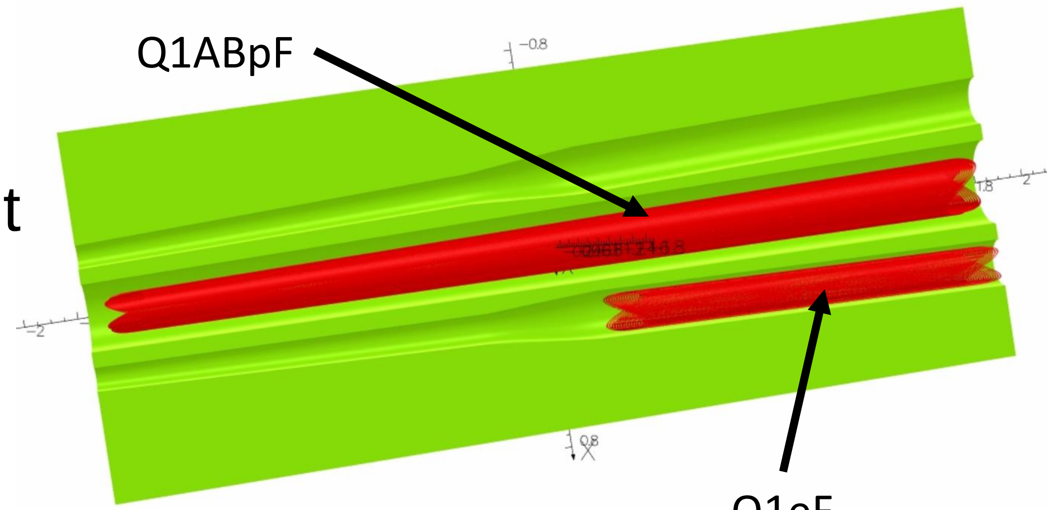
Recombining Q1ApF and Q1BpF

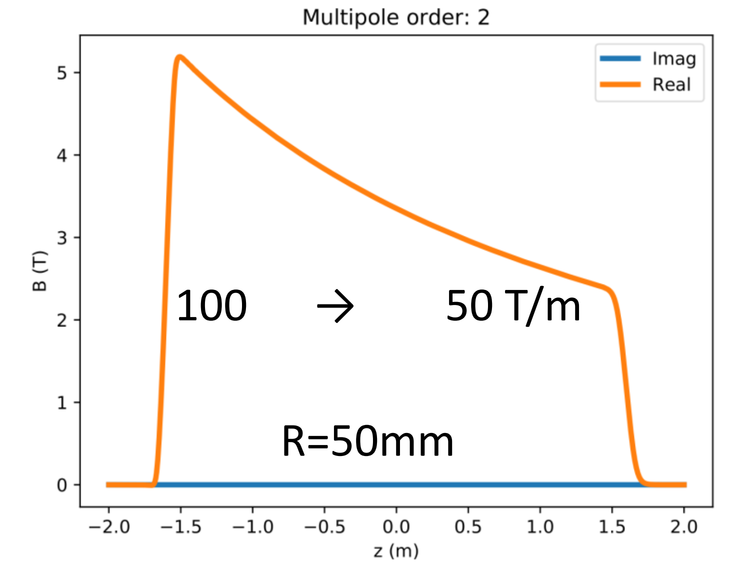


Advantages: No end plates, making use of additional space between magnets
Smaller aperture at IP side

Resolves Several Issues

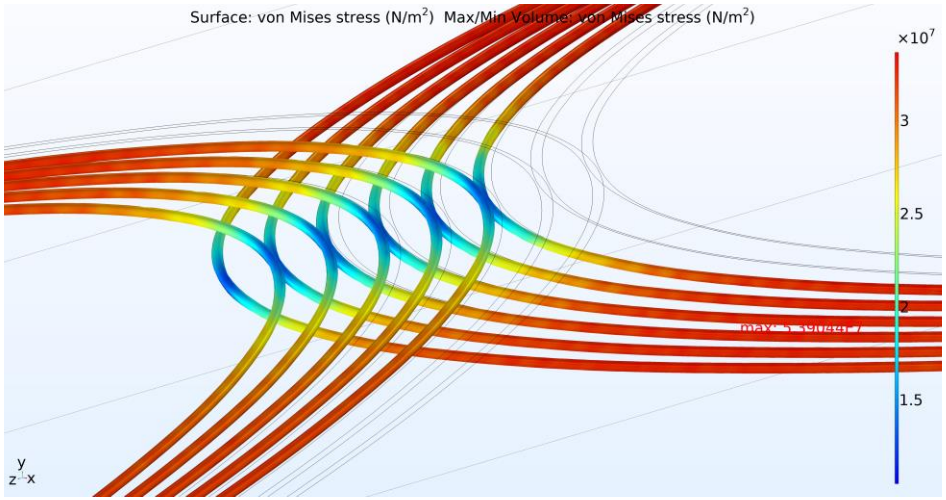
- Helps crosstalk / field quality
- Frontloading of gradient
  - Helps optics
- Financially attractive
  - Replaces two collared magnets
- Challenges
  - Need to prove that this works mechanically
- Needs TCC approval
  - Eliminates field reversal on forward side
  - (Note: nobody is asking for this at the moment…)

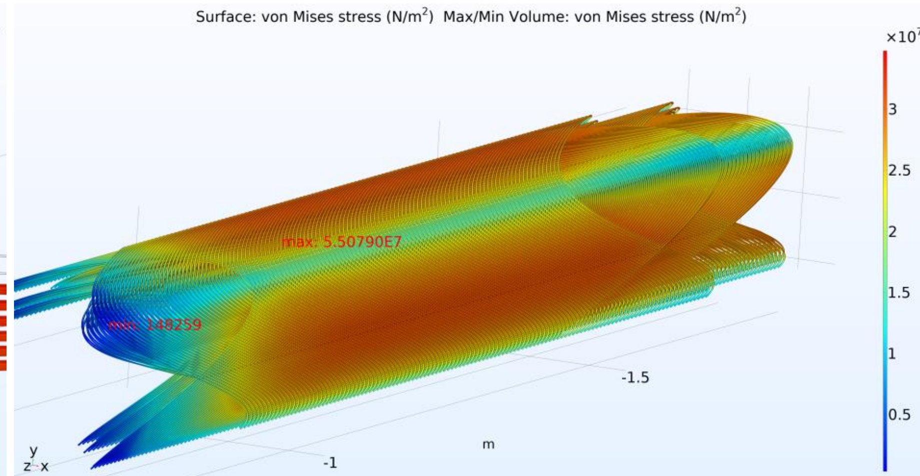


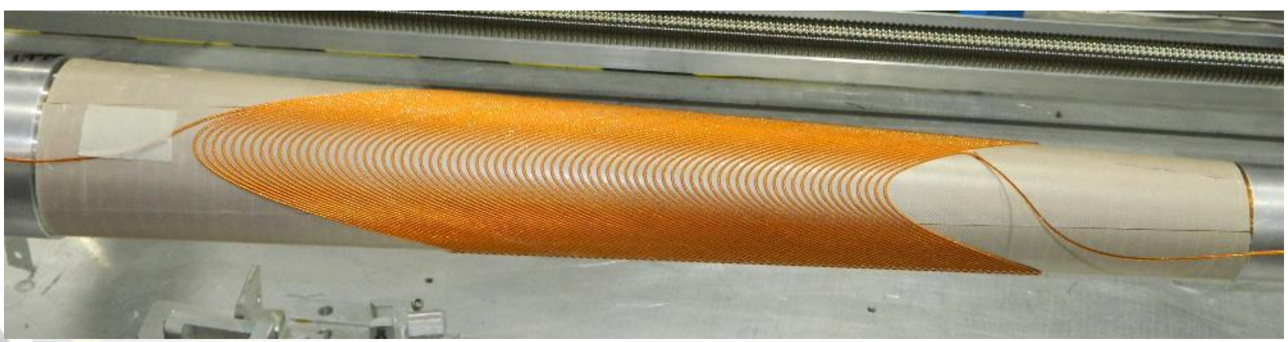


Mechanical Analysis

- Issue: complexity
    - 3D problem, need to model each strand







- Proof-of-principle
    - 7/16/2020
- BNL LDRD
- Implemented using direct-wind

What are we working on?

- Implementing 0.5m shift forward side ☑
  - re-optimizing magnet apertures/positions ☑
  - Submitted to 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

- Several changes ongoing
  - 0.5m shift, Q1ABpF, ESR tilt, correctors, …
- Increase in detector space: most involved
  - Submitted to TCC
  - If approved will defined new baseline
    - Cannot make more progress quickly
- Ongoing work…
  - Optimize lattice/apertures
  - Re-design B0pF
  - Need to implement 0.5m shift and ESR tilt in engineering layout

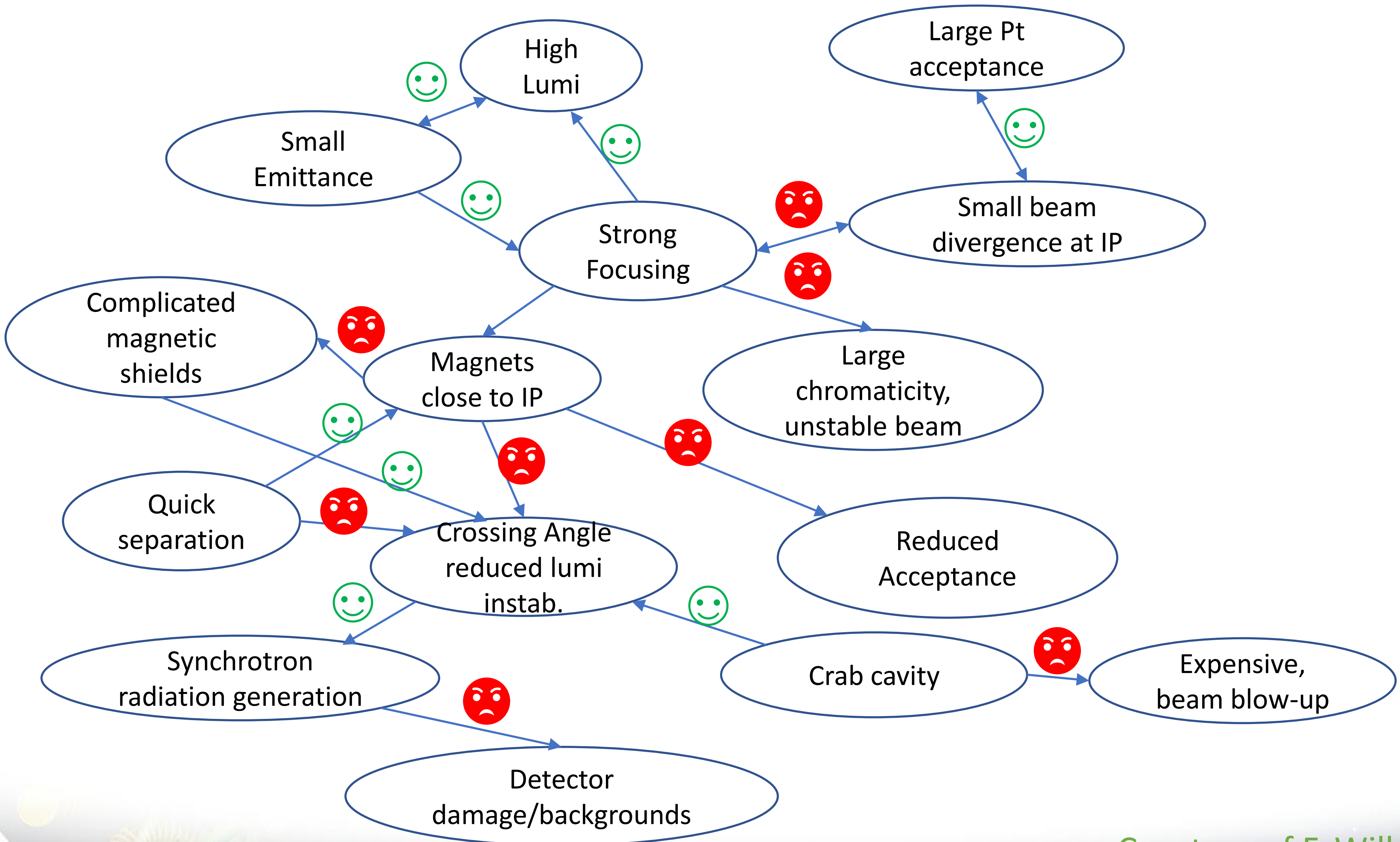
Acknowledgements

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!

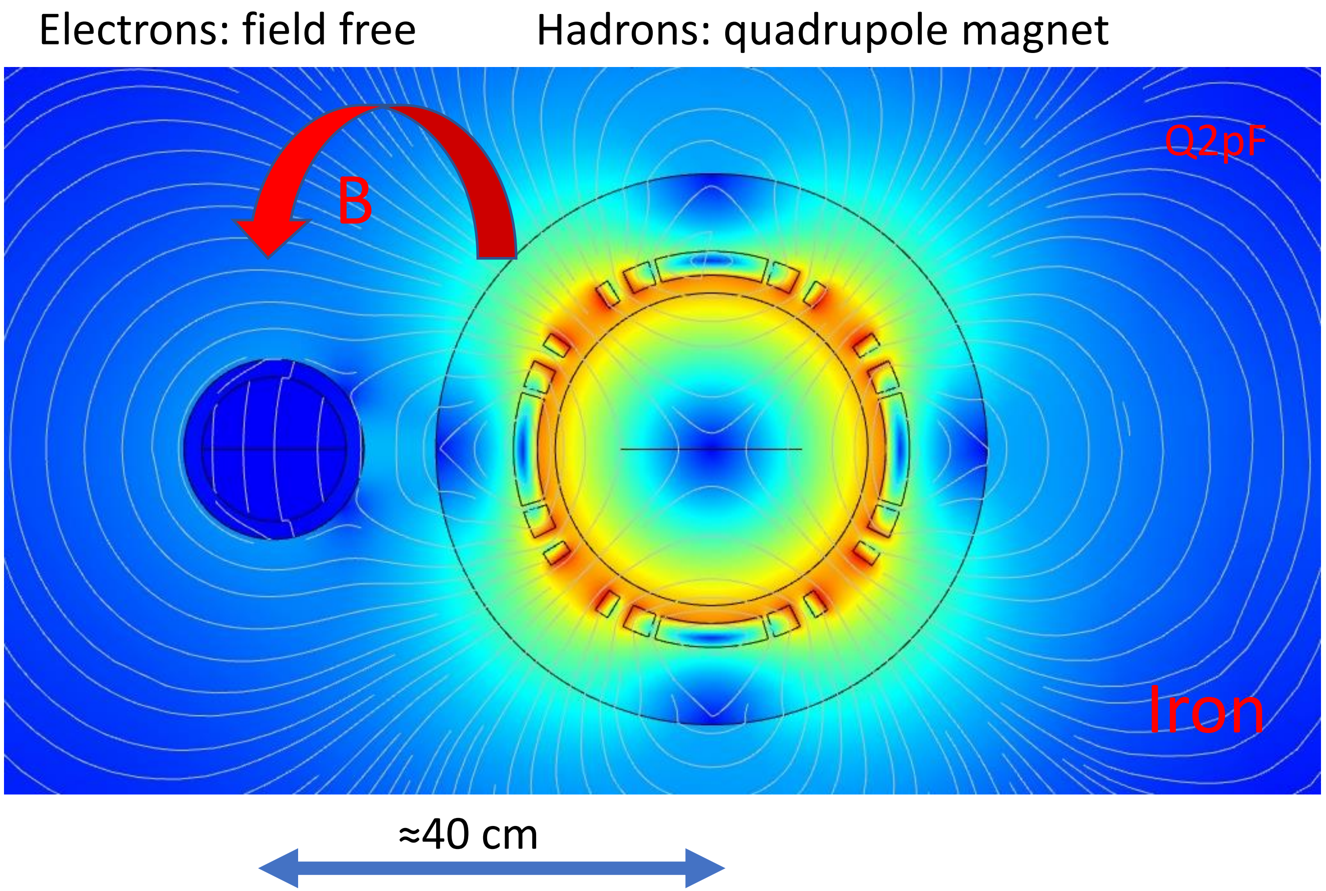
Additional Slides

IR Design Choices



Courtesy of F. Willeke

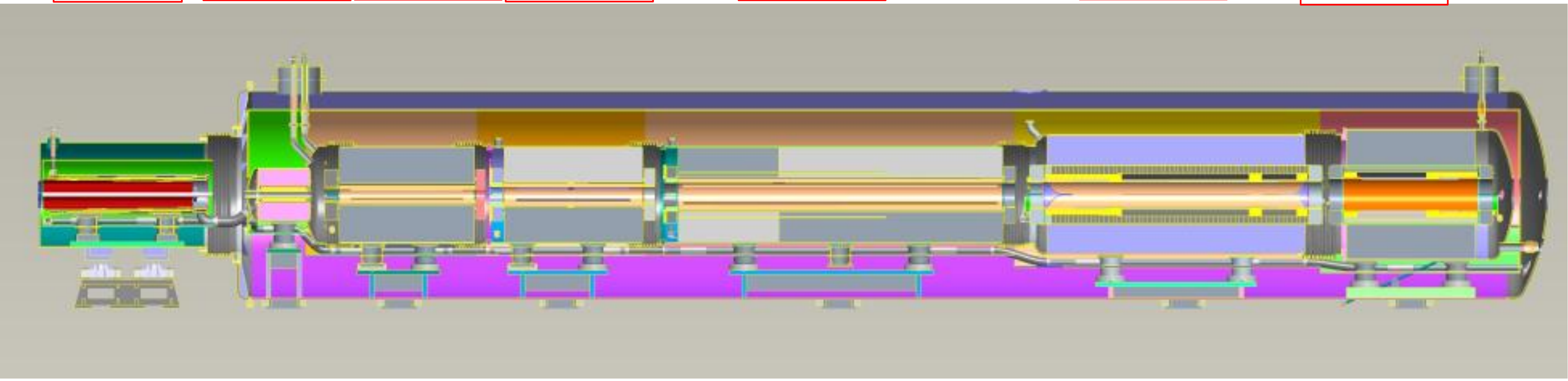
Crosstalk

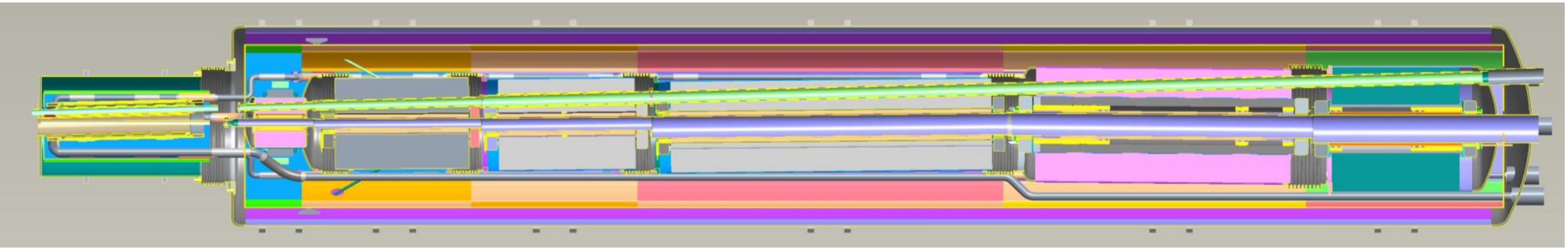


Refers to flux from one magnet leaking into the other
Leads to field quality issues
Depends on geometry and field/flux

Common issue for all IR magnets

Magnet Engineering





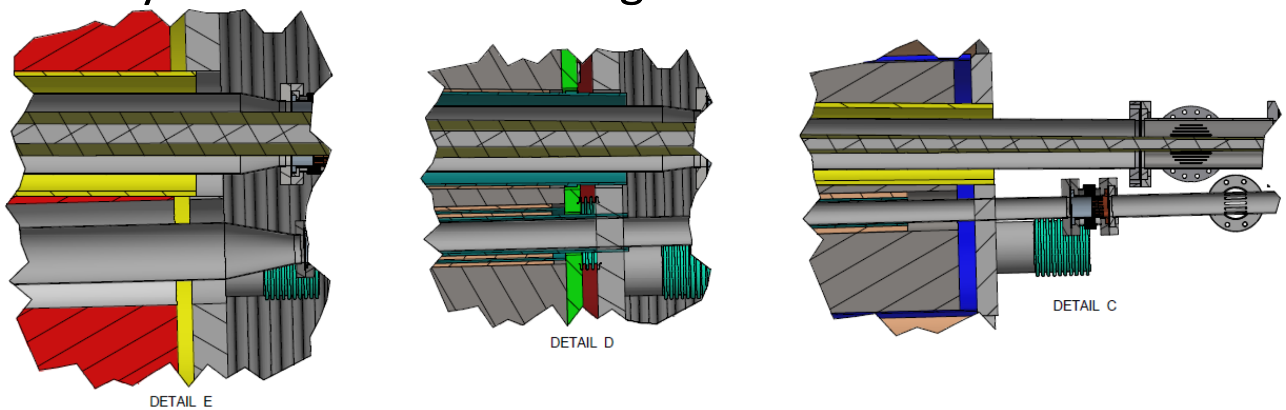
Standalone
48” cryostat

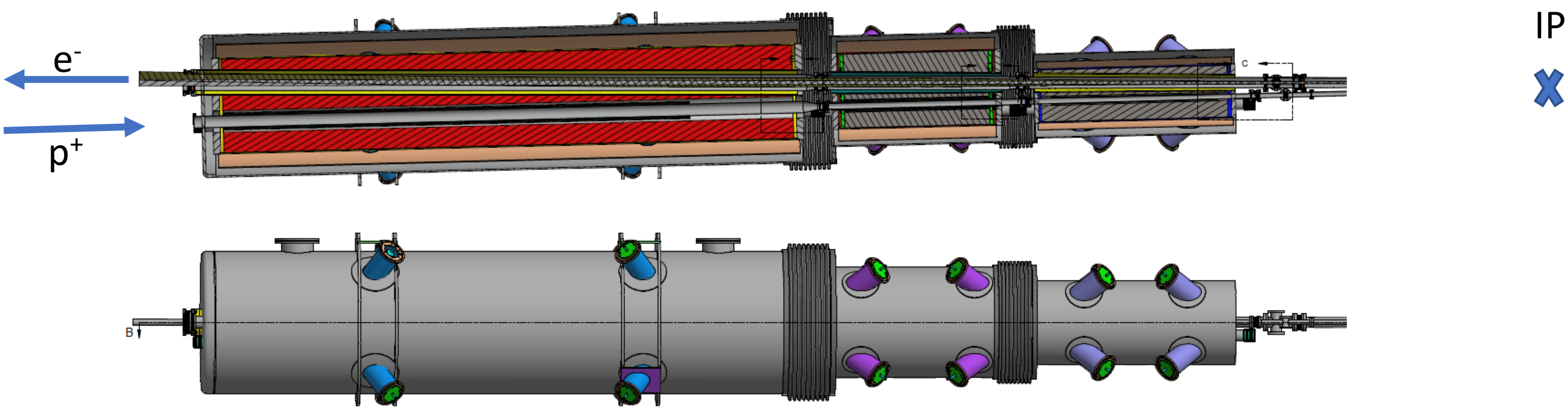
- Common split cryostat
- Cold mass adjustments within cryostat
- Each cold mass independently anchored
- Common helium vessel, with bellows between all magnets

Rear Side Integration / Beampipe

Separate cold masses - helium vessels

Separate circular cryostats with decreasing OD’s toward IP





Ø66”
Q2pR – B2eR

Ø54”
Q1BpR – Q2eR

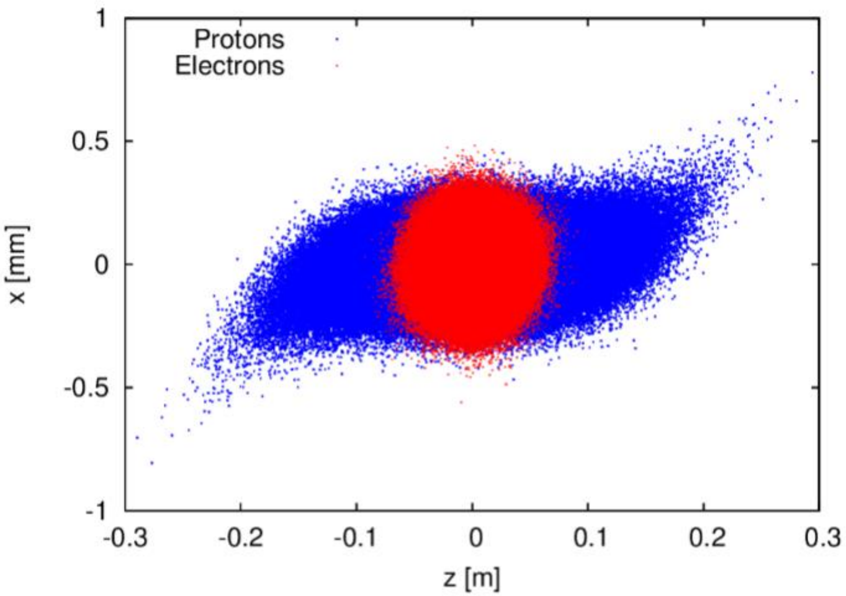
Ø42”
Q1ApR – Q1eR

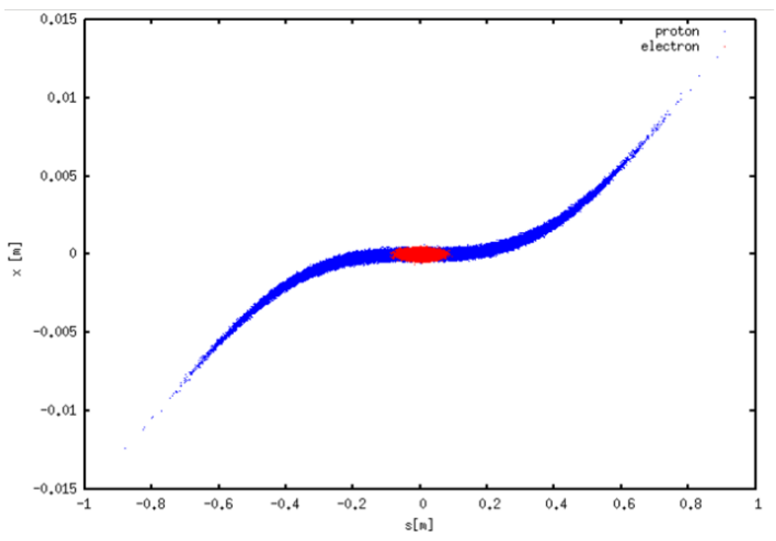
Crossing angle collisions

- 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

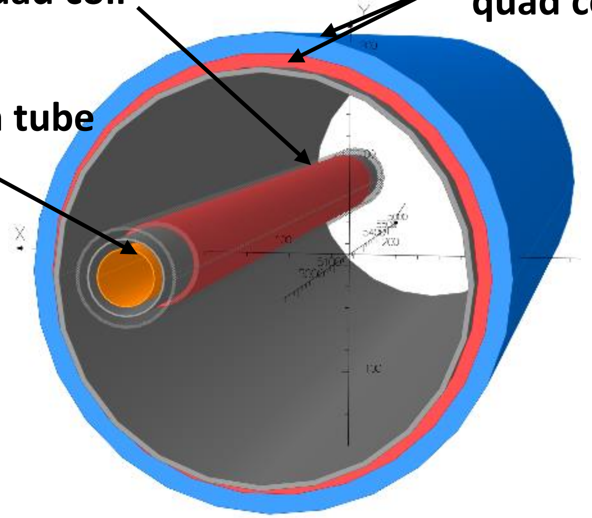
- Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
- Long hadron bunches are "S"-shaped during collision
- Distorted shape results in transverse offset between electron bunch and head and tail of proton bunch – reduced luminosity and severe beam dynamics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

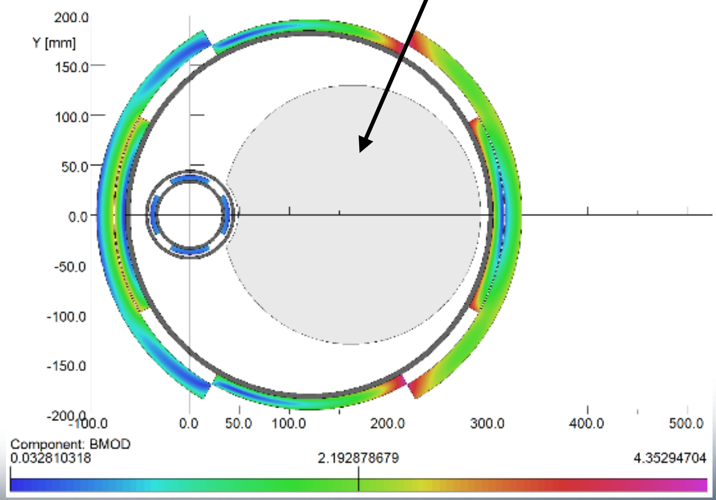




B0pF Spectrometer Magnet

- 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

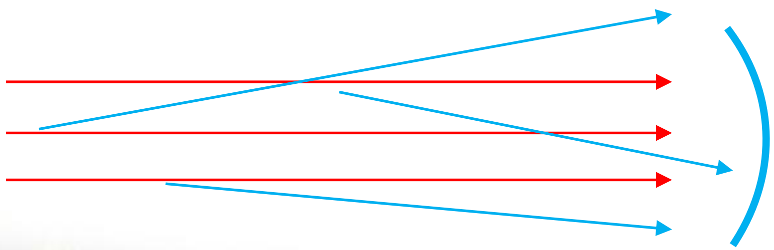
Chromaticities

- Hadrons
  - Increase by 0.3/0.8 units (hor./vert.)
  - Totals:
    - Crab to crab: 11.4/22.3
    - Arc-to-arc: 27.1/24.8
- Electrons
  - Increase 0.4/1.0
  - Total: 15.9/23.9

Luminosity and Focusing

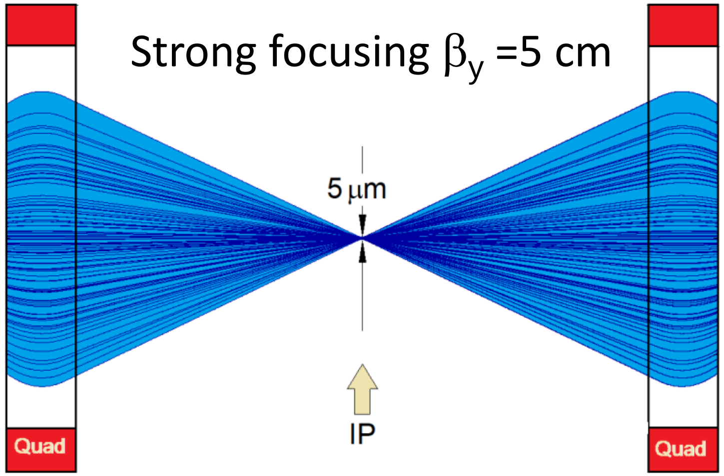
- Luminosity ~ 1/cross section
- A smaller spot size at the IP means more luminosity
- At the IP, (beam size)X(beam divergence)= const. in each plane (emittance)
- For a given beam (= fixed emittance), a smaller IP beam size means larger divergence

- 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)



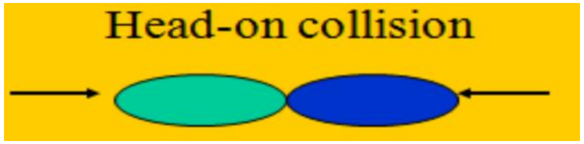
Divergence: 'spread' of the beam away from the central trajectory.

Strong focusing β_y =5 cm

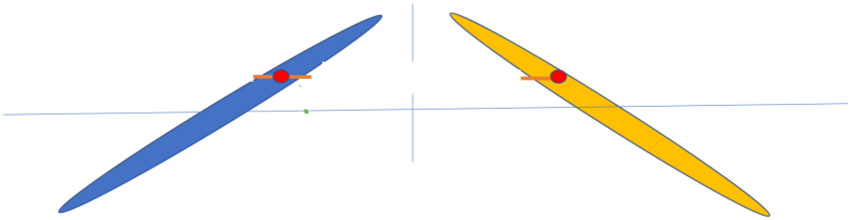


Focusing elements for both beams need to be as close as possible to the IP

Crossing Angle and Luminosity



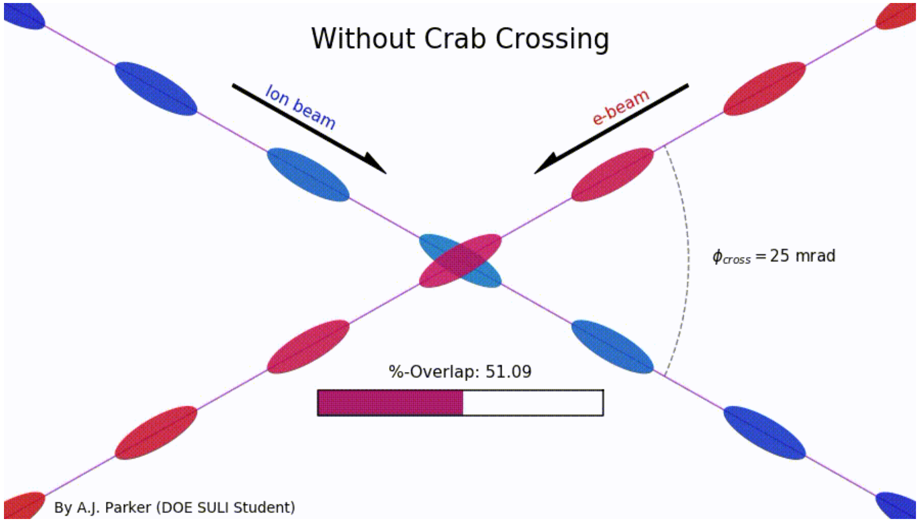
- In head-on collisions, every beam particle in one beam can potentially interact with every particle in the other beam



- 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

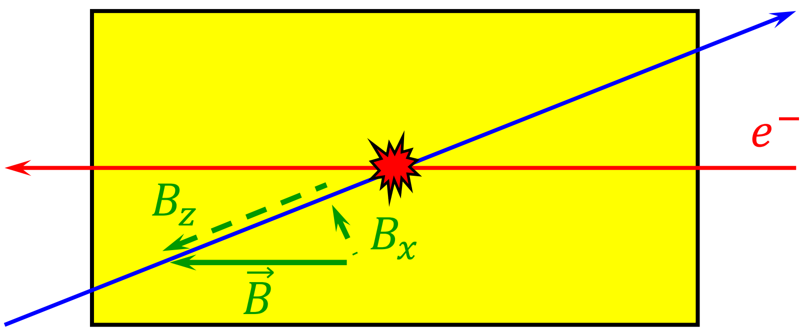
- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction
- Challenges
    - Bunch rotation (crabbing) is not linear due to finite wavelength of RF resonators (crab cavities)
    - Severe beam dynamics effects
    - Physical size of crab cavities



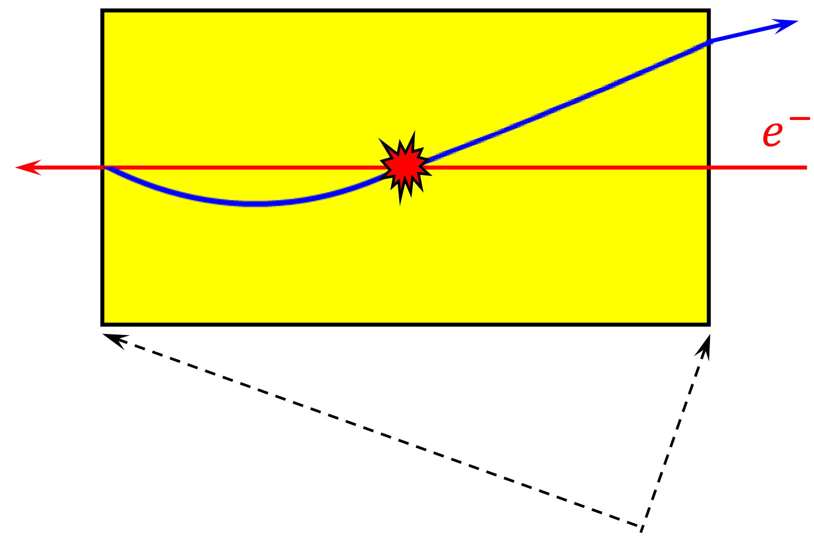
Coherent Distortion of Ion Orbit

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

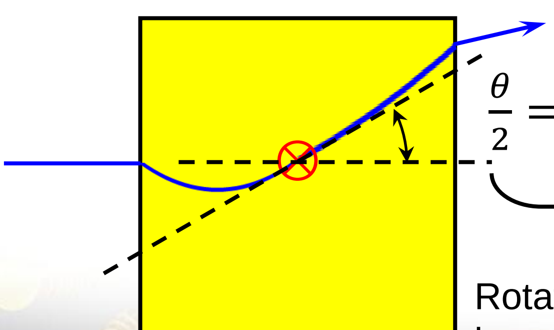
Top view



Side view



End view



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

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