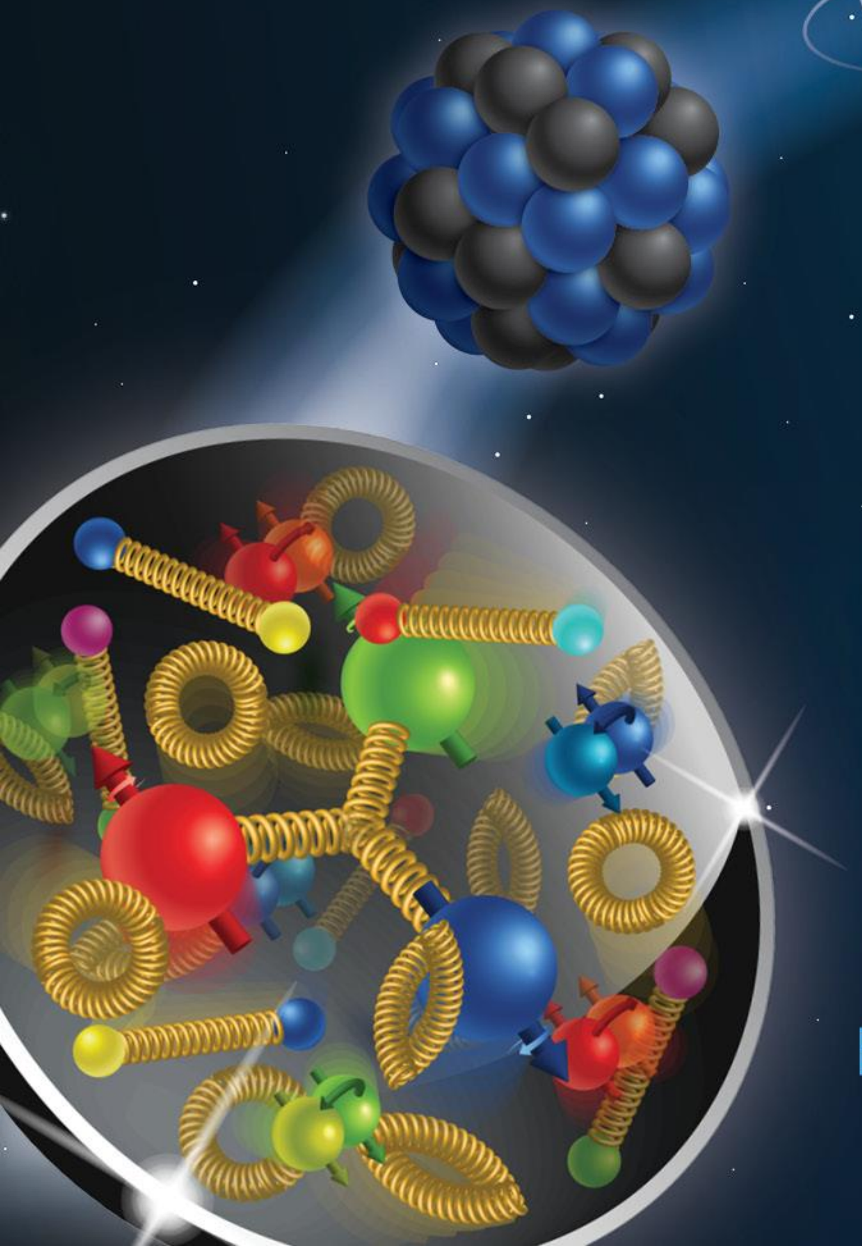


IR Design Status and Plans

Holger Witte

Mach 19, 2020

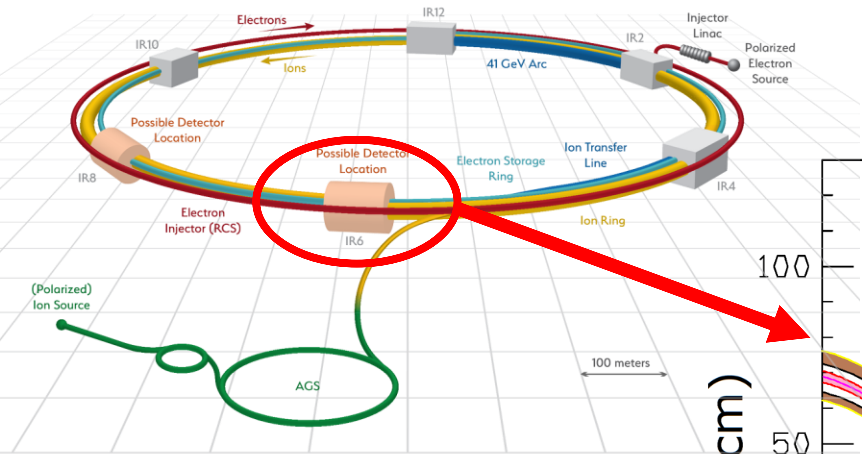
Electron Ion Collider – EIC at BNL

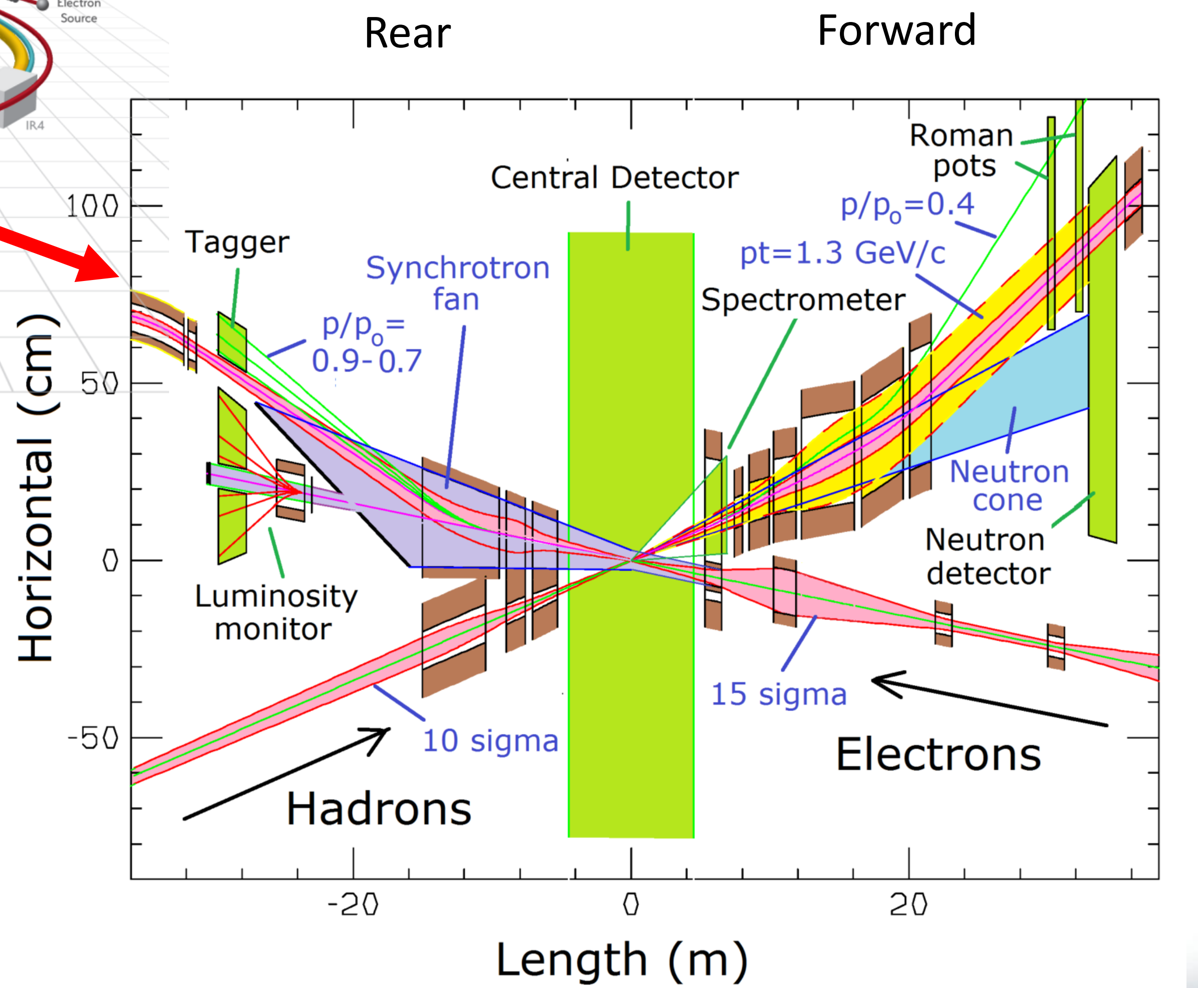
BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Overview IR
- Requirements / Considerations
  - Geometric constraints
  - Optics
- Components
  - Magnets
  - Vacuum chamber
- Plans
- Conclusion

EIC IR: Overview





RHIC yellow ring: EIC hadron ring

Add electron storage ring in existing tunnel

Possible IR location: IP6

IR Requirements

- EIC IR designed to meet physics requirements
  - Machine element free region: +/- 4.5m main detector
  - 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 ~40m from IP)
    - Rear lepton magnets: aperture dominated by sync fan

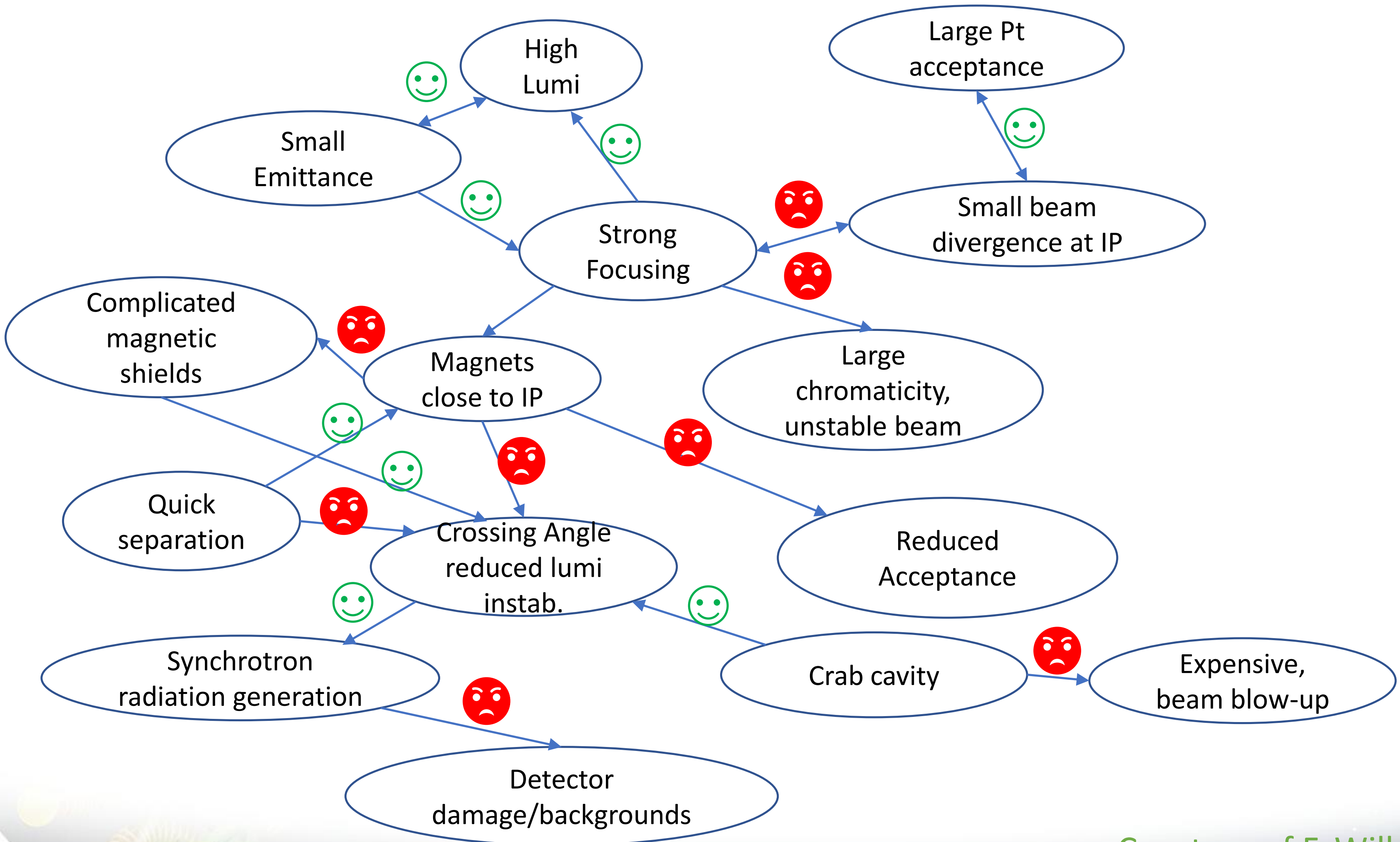
Considerations

- Geometry
  - RHIC tunnel (injection, RHIC magnets, RCS, eSR)
  - Experimental hall (IP6?)
  - Space for detector
- Physics considerations
  - See previous slide, other talks
- Accelerator/optics
  - Match into existing tunnel
  - Dispersion, chromaticity

Considerations (cont.)

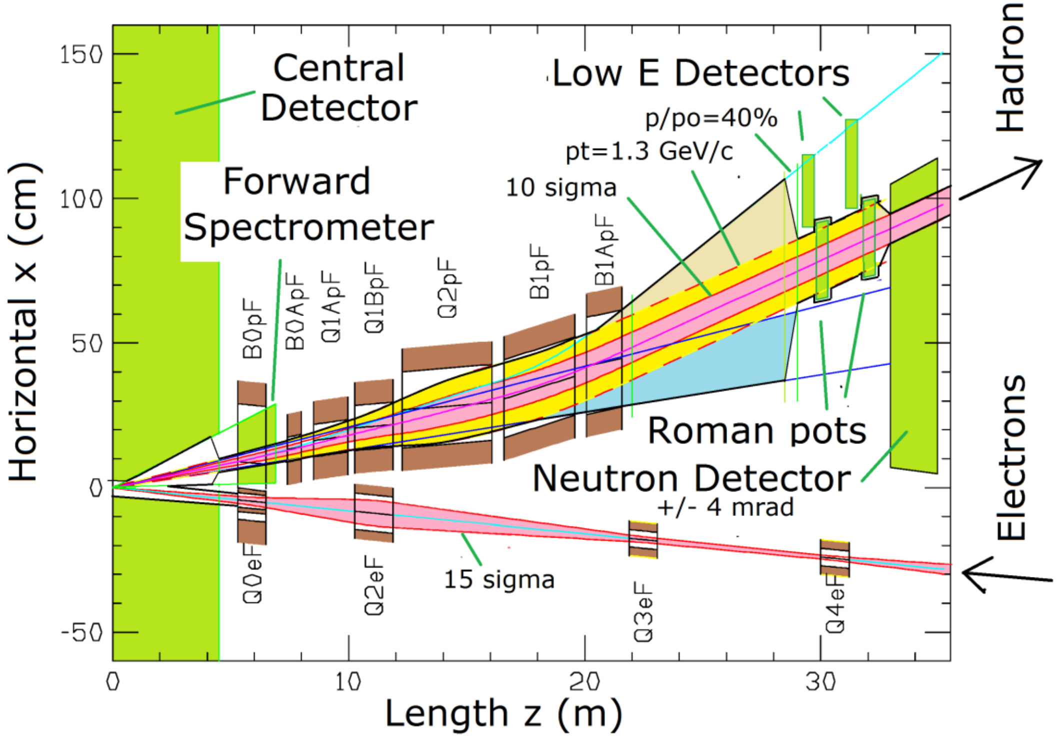
- Crab cavities
  - Location
  - Geometry
  - Beam optics constraints
- Engineering
  - Magnets: feasibility
  - Cryostating
  - Utilities
- Project
  - Cost, risk
  - R&D required
  - Vendors

IR Design Choices



Courtesy of F. Willeke

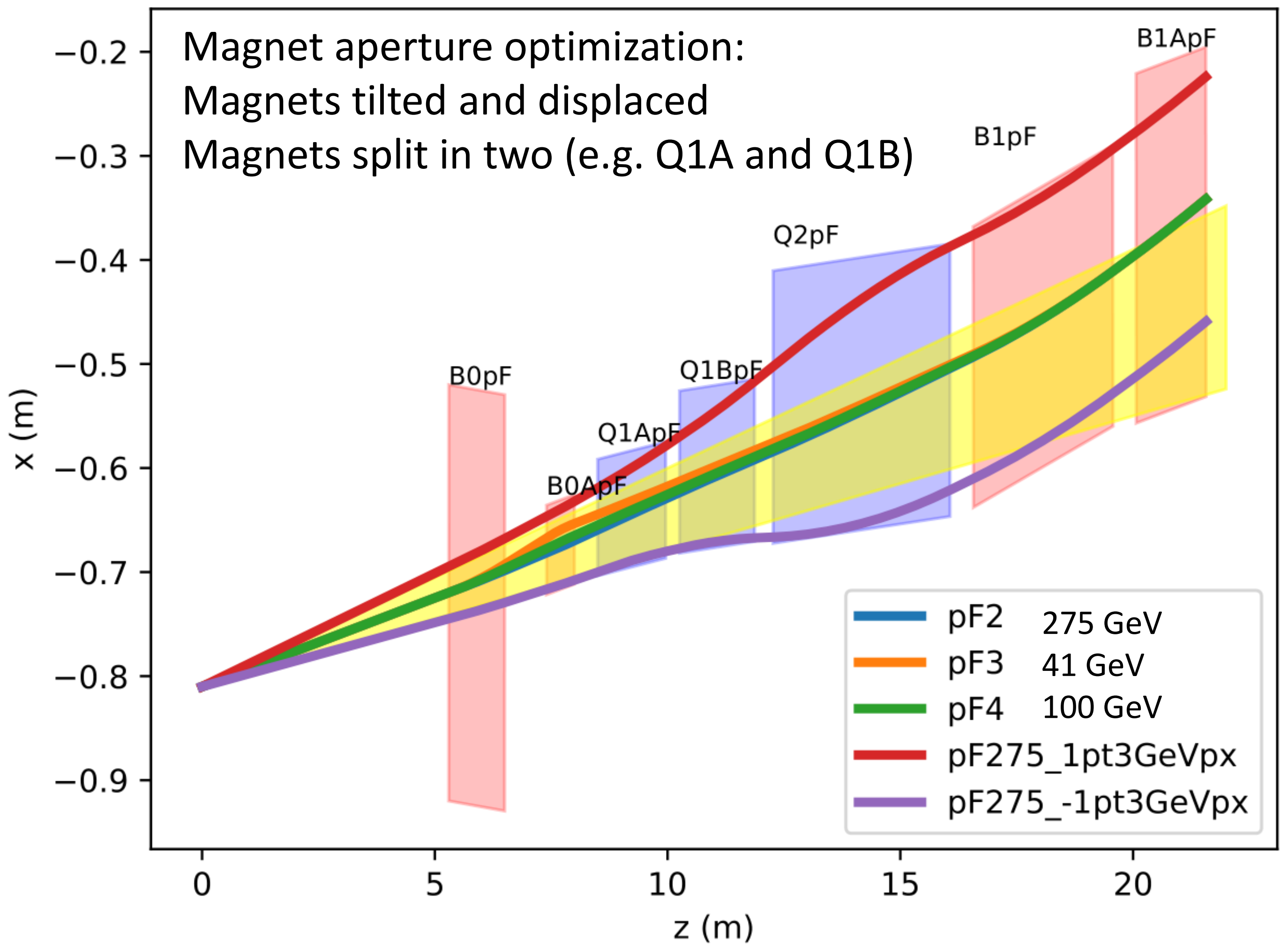
EIC IR: Forward Direction



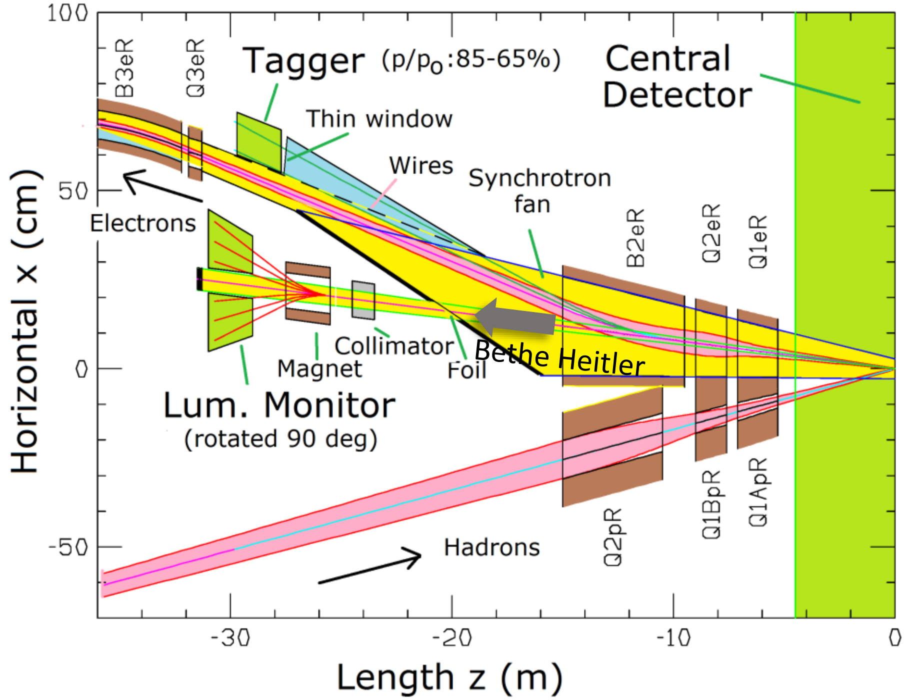
Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
B0ApF	0.043	0.6	-3.3	0	-3.3
Q1ApF	0.056	1.46	0	-72.608	-4.066
Q1BpF	0.078	1.61	0	-66.18	-5.162
Q2pF	0.131	3.8	0	40.737	5.357
B1pF	0.135	3	-3.4	0	-3.4

- Requirements for hadron beam direction
  - B0pF: Forward Spectrometer (6 - 20 mrad)
  - Neutron Detector (+/-4 mrad)
  - Roman pots (sensitive 1 to 5 mrad)
- Mostly interleaved magnets
  - Exception: B0 and Q1BpF/Q2eF
- Large apertures of proton forward magnets
  - See next slide

Hadron Forward - Apertures



EIC IR: Rear Direction

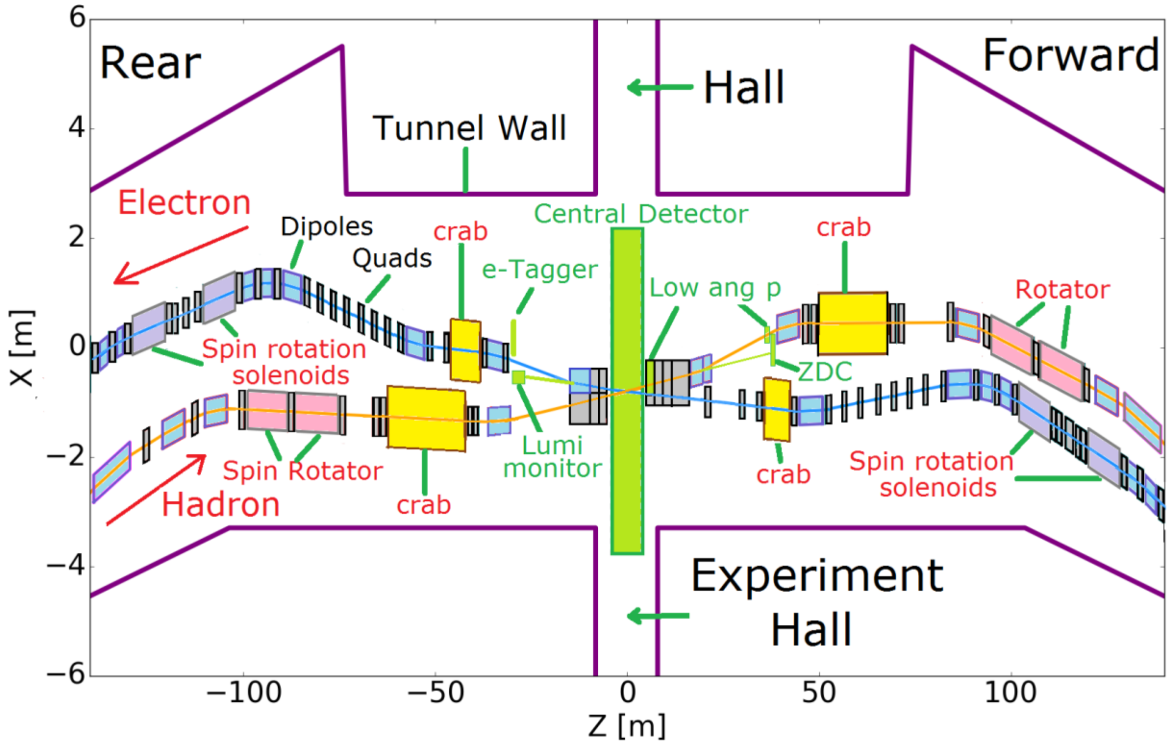


- B2eR: separate photons from beam, separate low Q^2 electrons from beam
- 2-in-1 magnets
  - Lepton magnet aperture defined by SynRad fan
  - Hadron magnets: 10σ beam size aperture

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

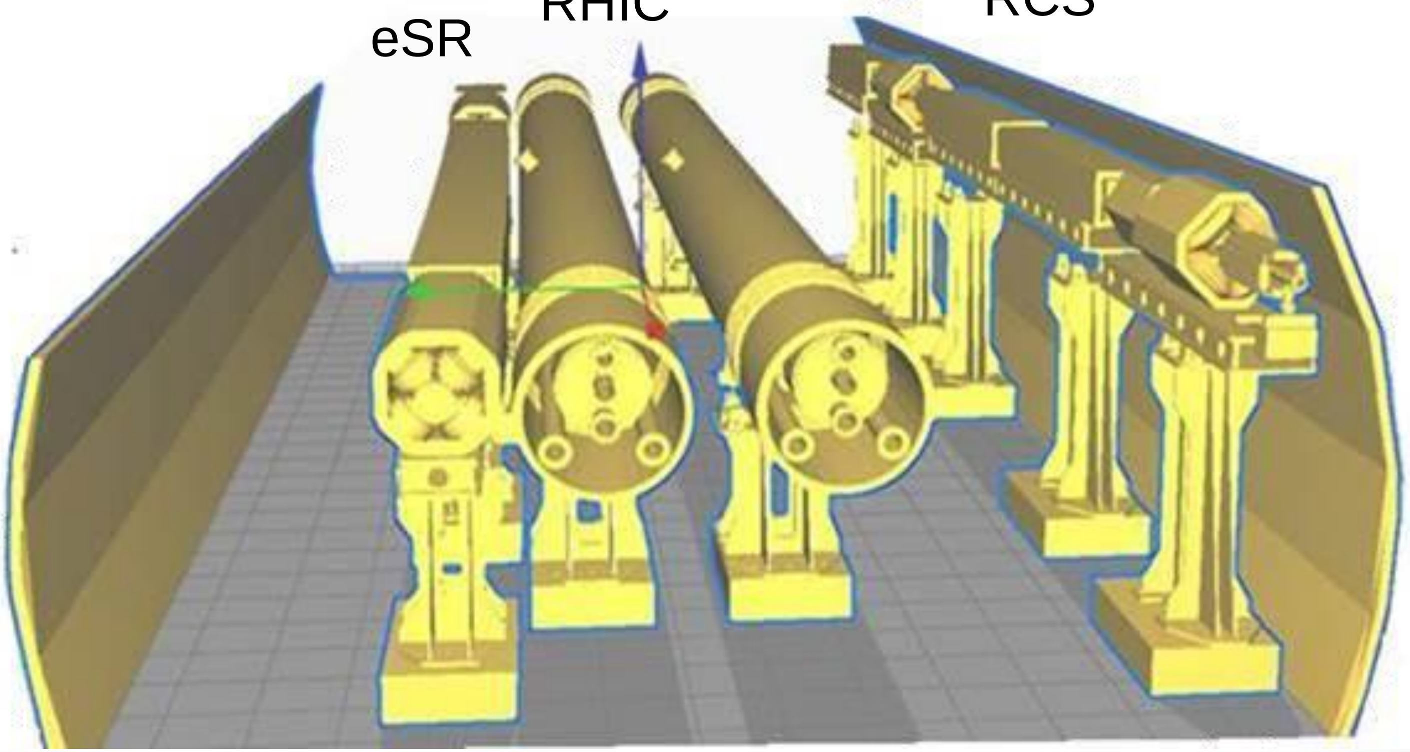
EIC IR



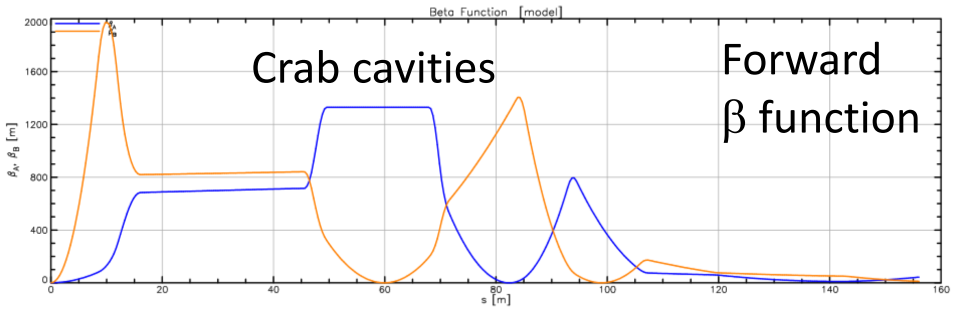
- IR fits into RHIC tunnel
- Lattice: sufficient space for crab cavities and spin rotators

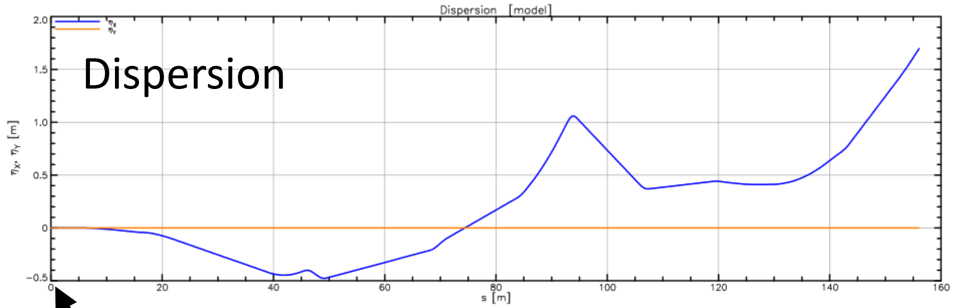
Tunnel Cross Section

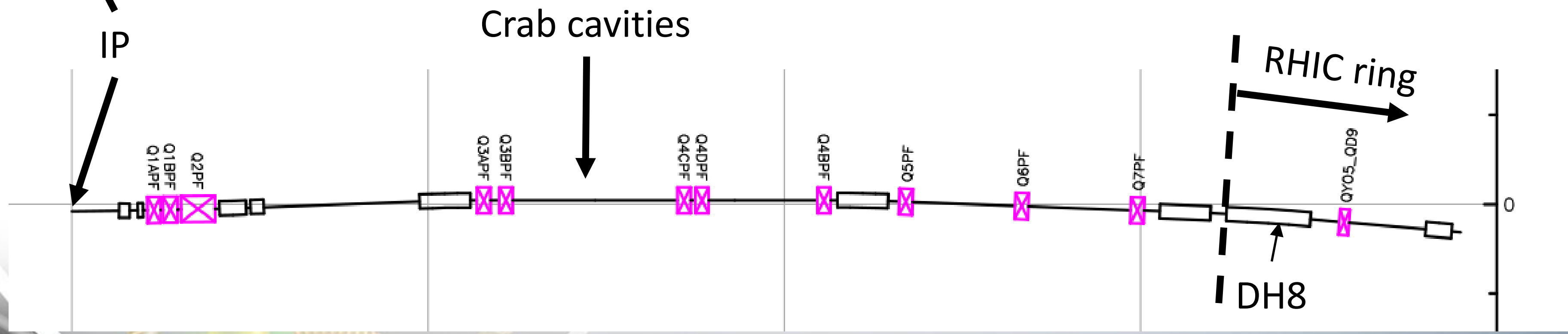
All accelerators fit into the existing tunnel



Match to Hadron Ring



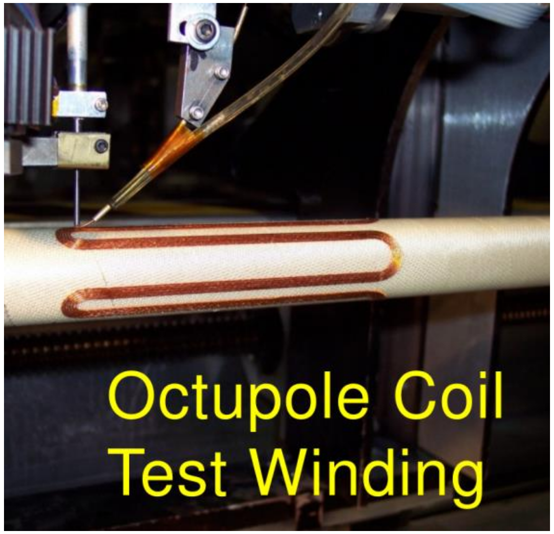




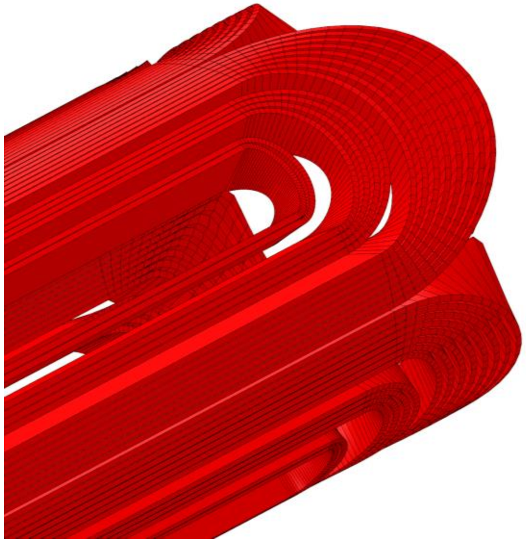
- Forward and rear hadron lattice matched into RHIC
- Requires
  - 6 dipoles
  - 17 quads
- Repurpose as many RHIC magnets as possible

IR Magnets - Overview

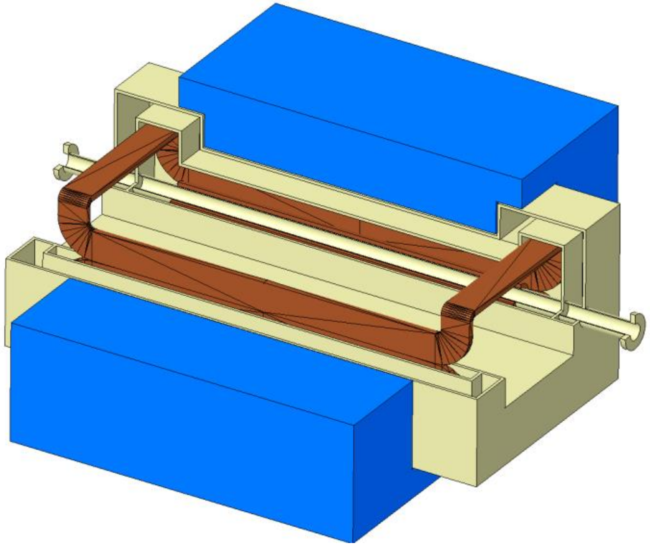
- Three groups of superconducting magnets
  - All NbTi
- (Also: normal conducting magnets, not addressed here)



9 Direct Wind Magnets (S-MD)



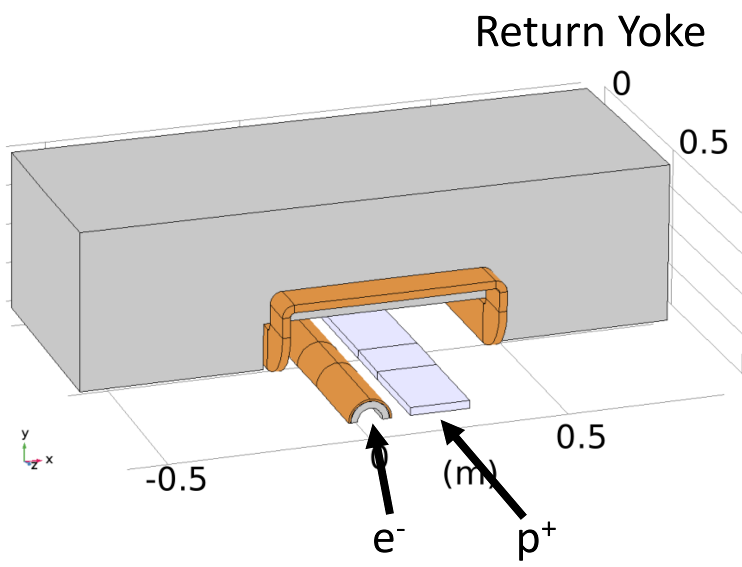
6 Collared Magnets

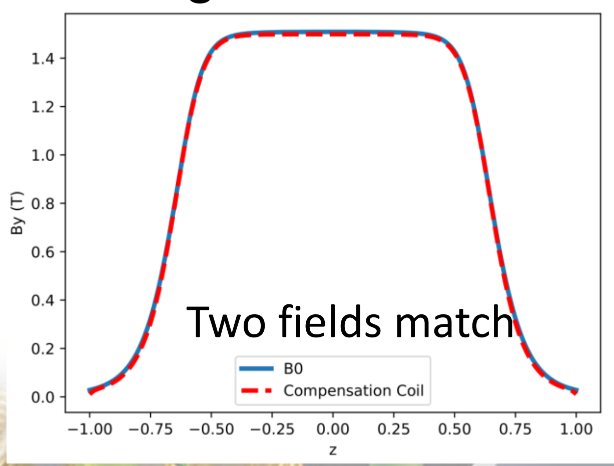


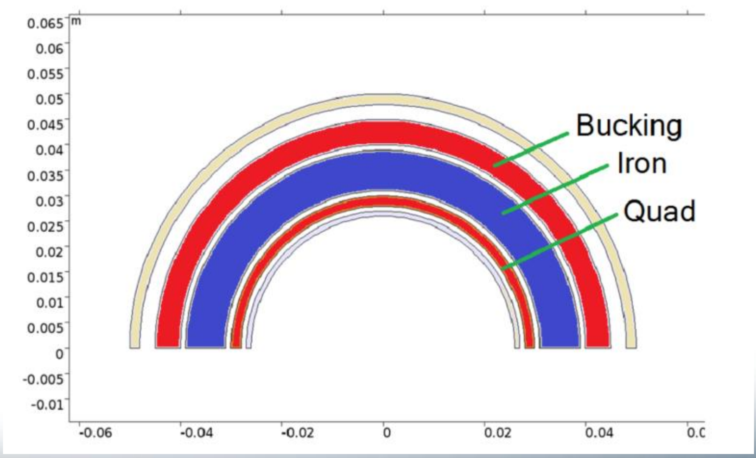
1 Special Magnet

B0pF Spectrometer Magnet

- Superferric 1.3T magnet
  - Fixed field
  - Option: normal conducting
- Aperture: 0.23x0.5m^2
- Electrons: 15T/m gradient
  - In B0pF aperture
  - Requires cancellation dipole field
  - Bucking coil and iron collar

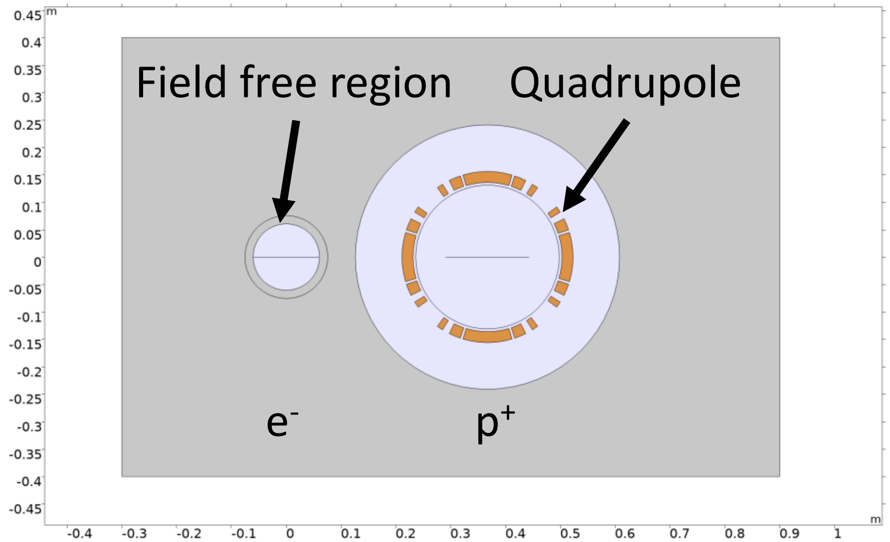


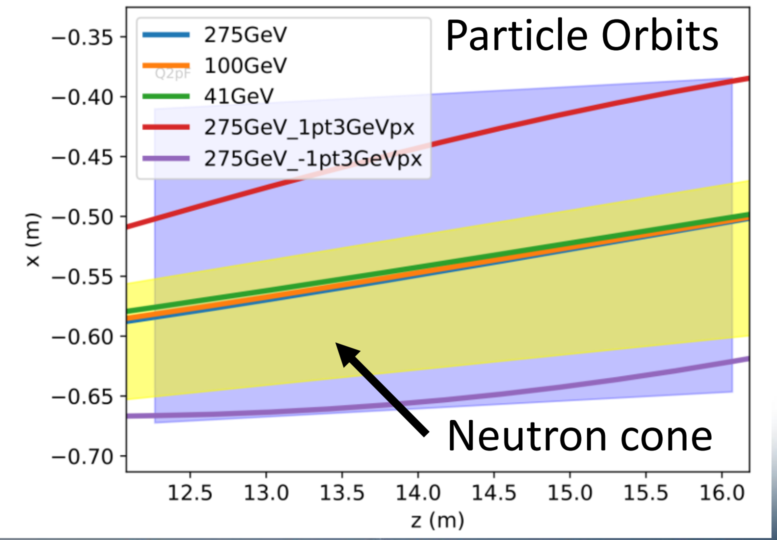




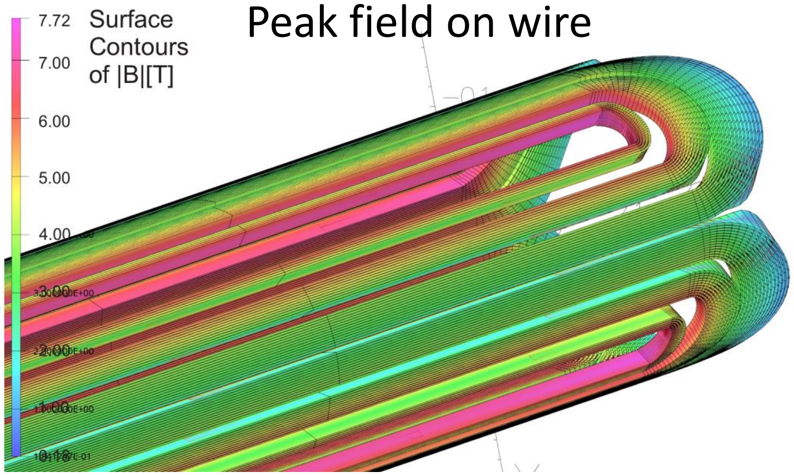
Q2pF – Collared Magnet

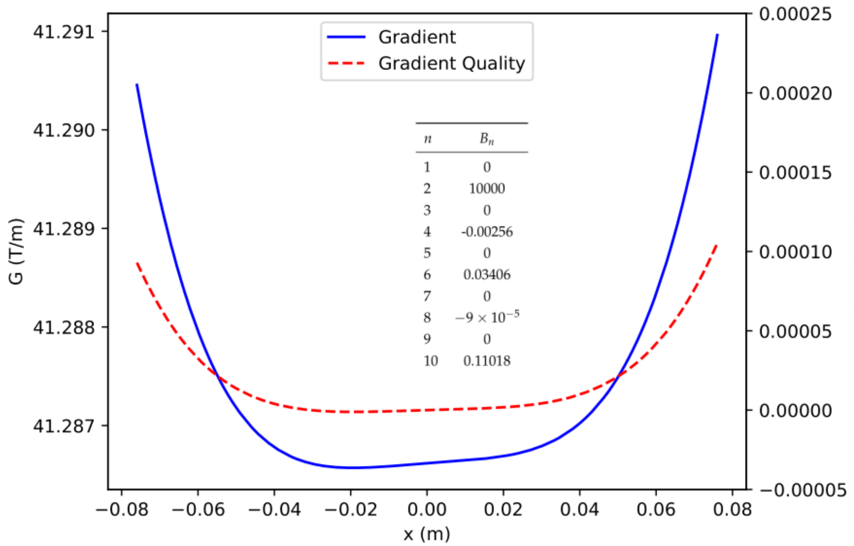
- Hadron quadrupole
  - Gradient: 41 T/m
  - 3.8m long
  - Aperture 262 mm
  - e-beam: 36-42cm distance
- Return yoke: 1.2x0.8 m^2
- Field-free region for electrons
- Magnet limitations
  - Gradient/field
  - Aperture
  - Stray field



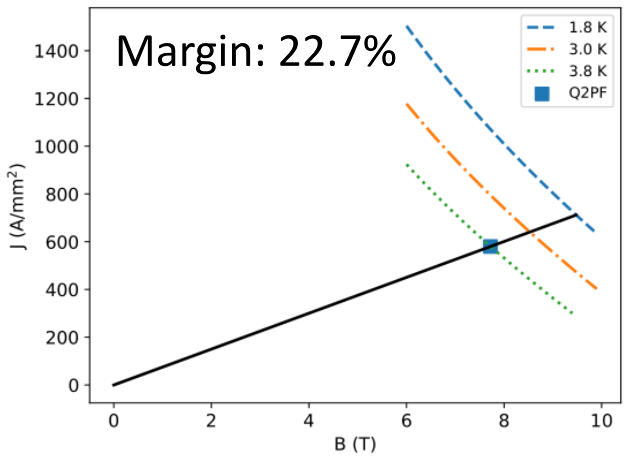


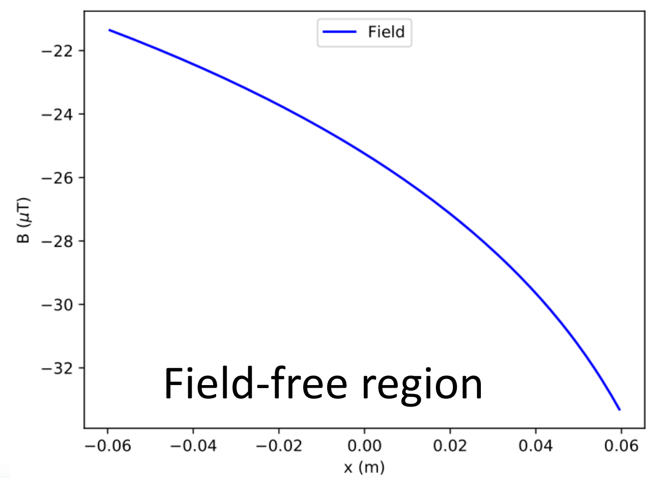
Q2pF Simulation Results





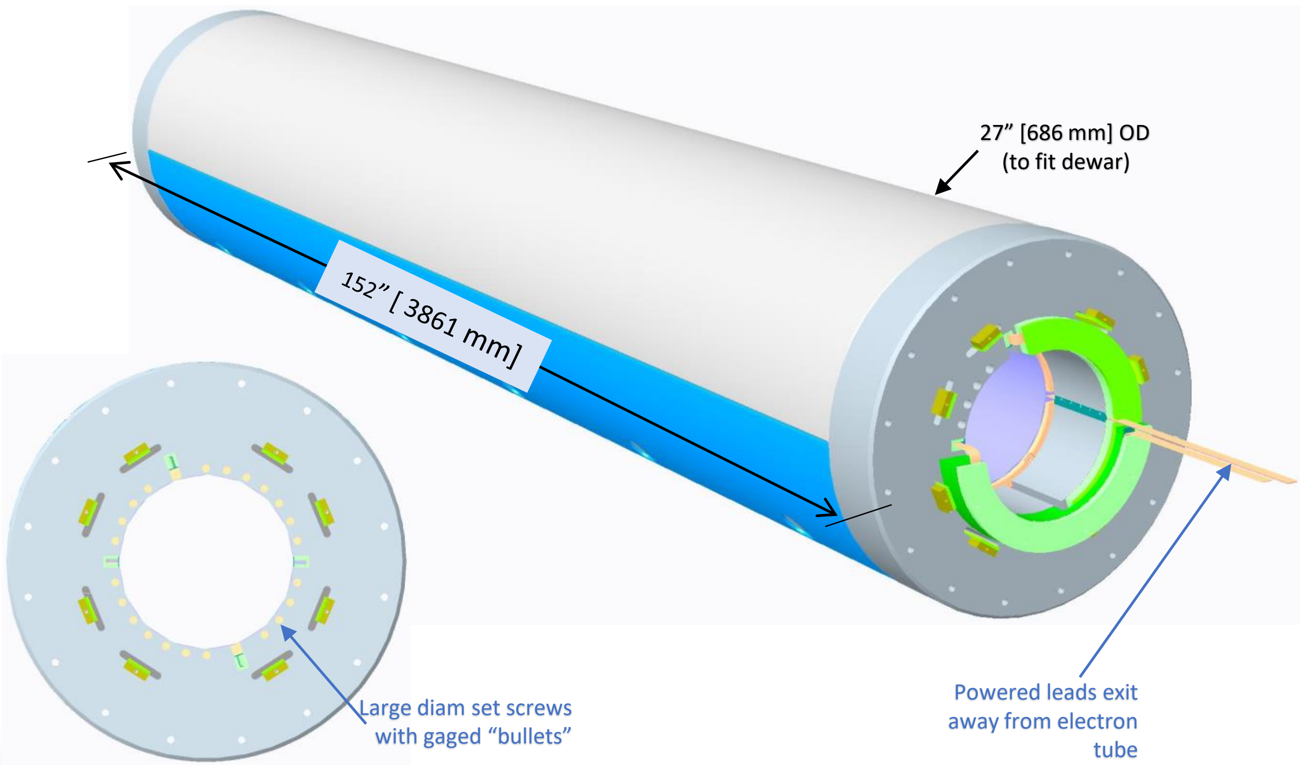
Load line

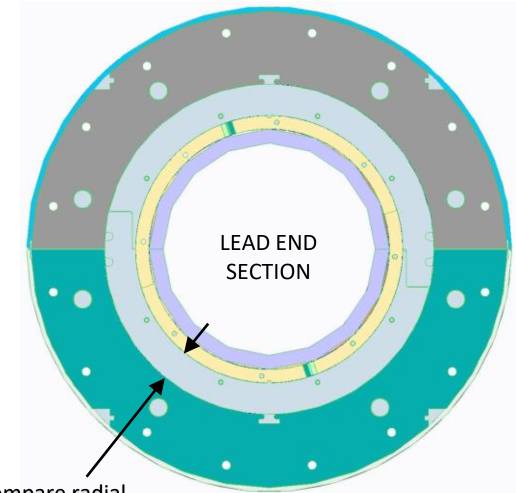


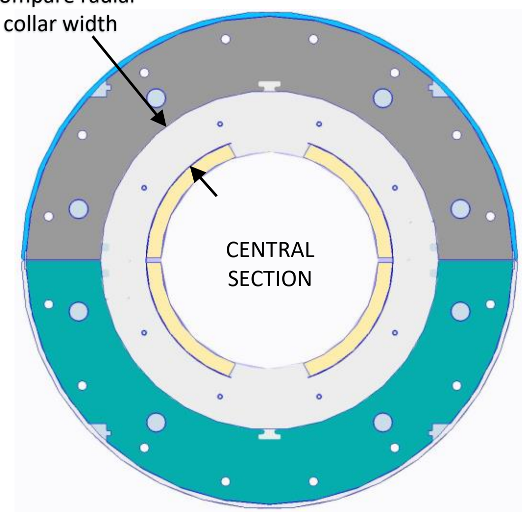


Cold Mass Concept

- Half shells welded to end plate
  - serves as helium containment vessel
  - Reacts longitudinal Lorentz forces
- Partial iron contained within shells (blocks? laminations?)
- Test vertically

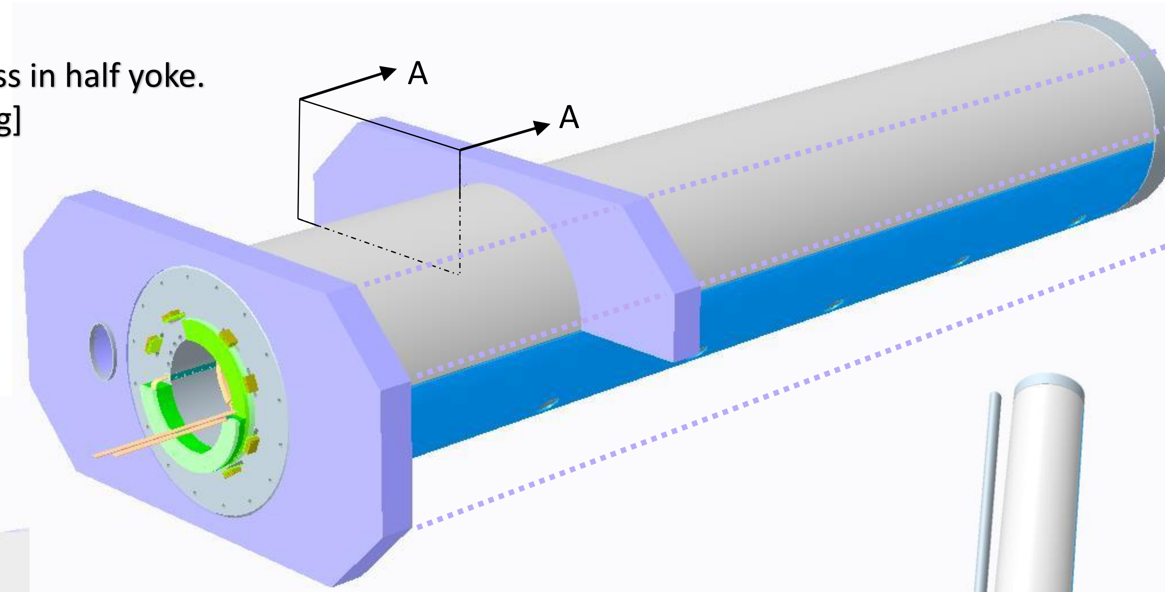


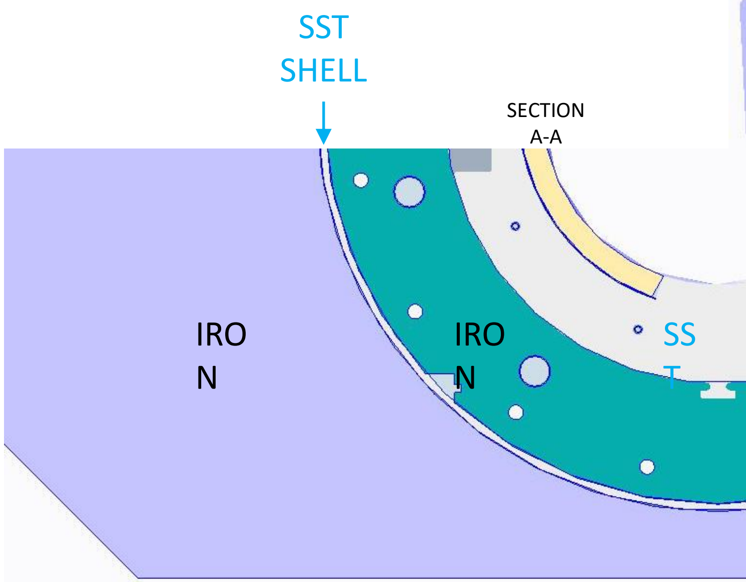


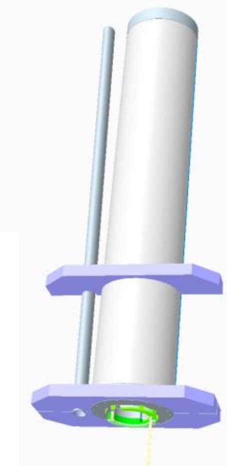


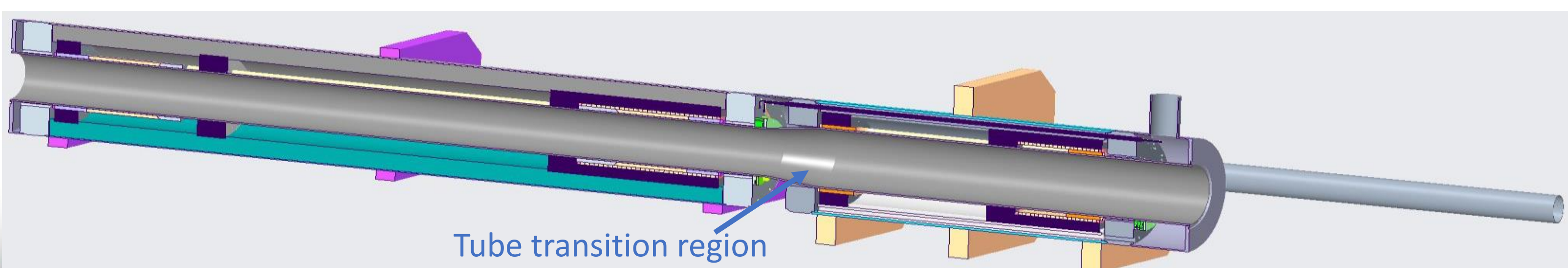
Cold Mass in Full Iron Yoke

- Outer yoke - stacked blocks. Place cold mass in half yoke.
- Total magnet weight ~68,000 lbs [30,800 kg]
- Support of yoke?

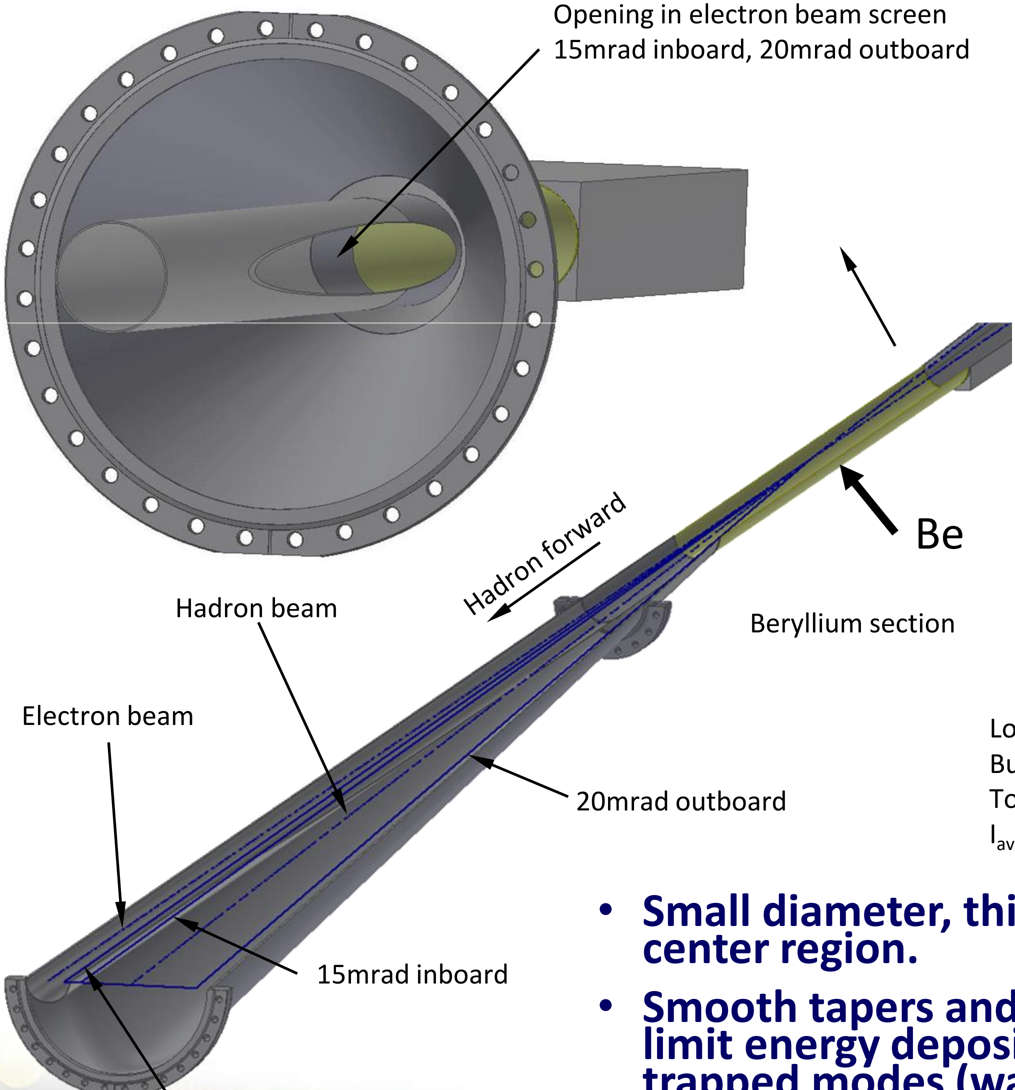


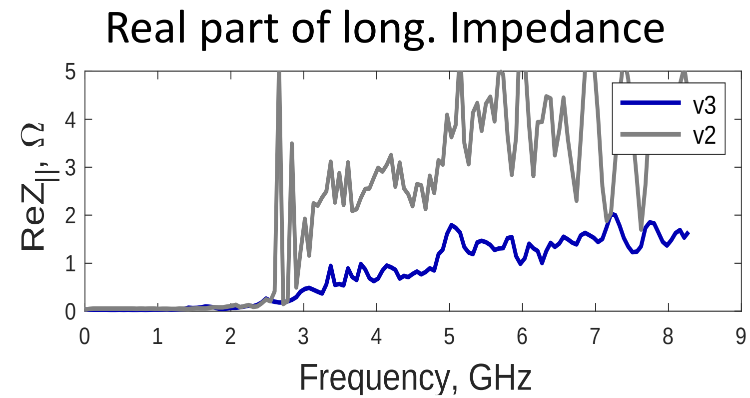


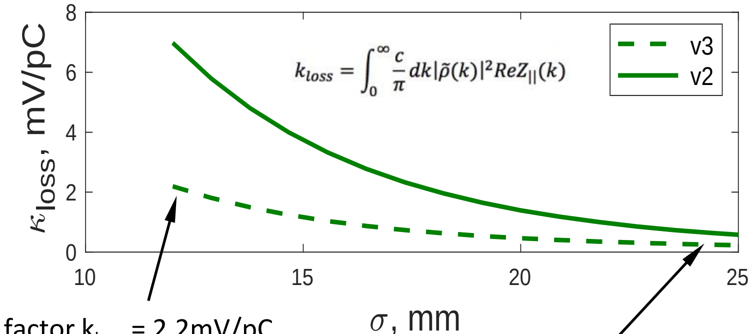




Central Vacuum Chamber







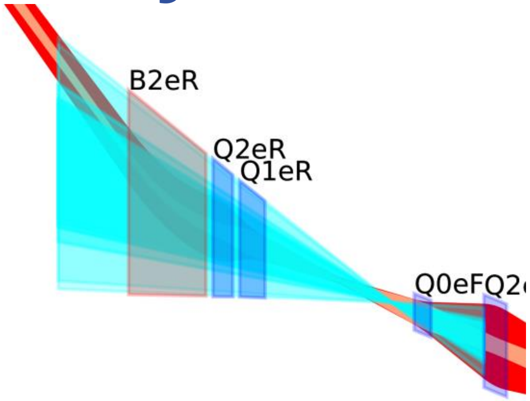
Loss factor k_{loss} = 2.2mV/pC
Bunch length σ_s = 12mm
Total power loss = 262W
I_{avg} = 2.48A, N = 660, T_o = 12.79µs

Loss factor k_{loss} = 0.2mV/pC
Bunch length σ_s = 24mm
Total power loss = 30W
I_{avg} = 2.48A, N = 660, T_o = 12.79µs

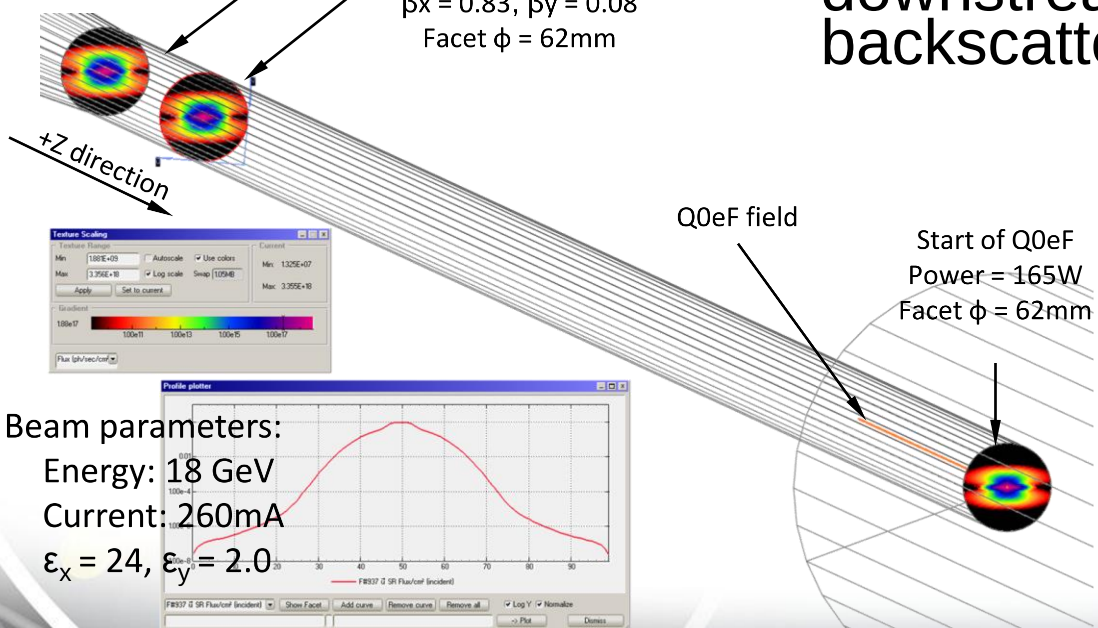
- **Small diameter, thin walled Be in center region.**
- **Smooth tapers and transitions to limit energy deposited by beam in trapped modes (wakes).**
- **Considering HOM absorbers**

$$P_{loss} = \frac{k_{loss} I_{av}^2 T_0}{M}$$

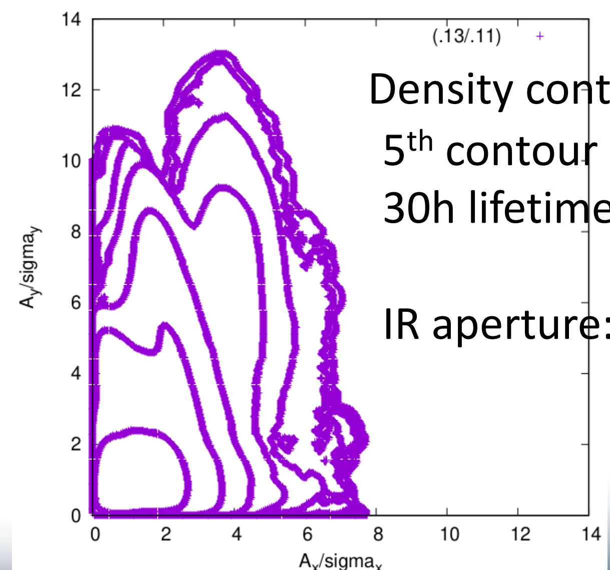
Synchrotron Radiation



- Generated by quads only
- Tails: can produce hard radiation
  - Non-Gaussian
- Aggressive collimation to a few sigma: extremely poor lifetime
- Most radiation has to be passed through detector, absorbed far downstream to minimize backscatter



Beam parameters:
Energy: 18 GeV
Current: 260mA
$\varepsilon_x = 24$, $\varepsilon_y = 2.0$



Density contours
5th contour line
30h lifetime

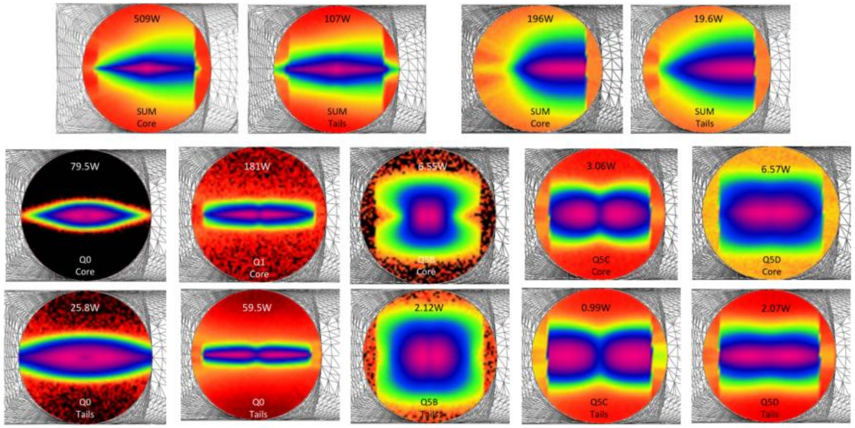
IR aperture: 13σ

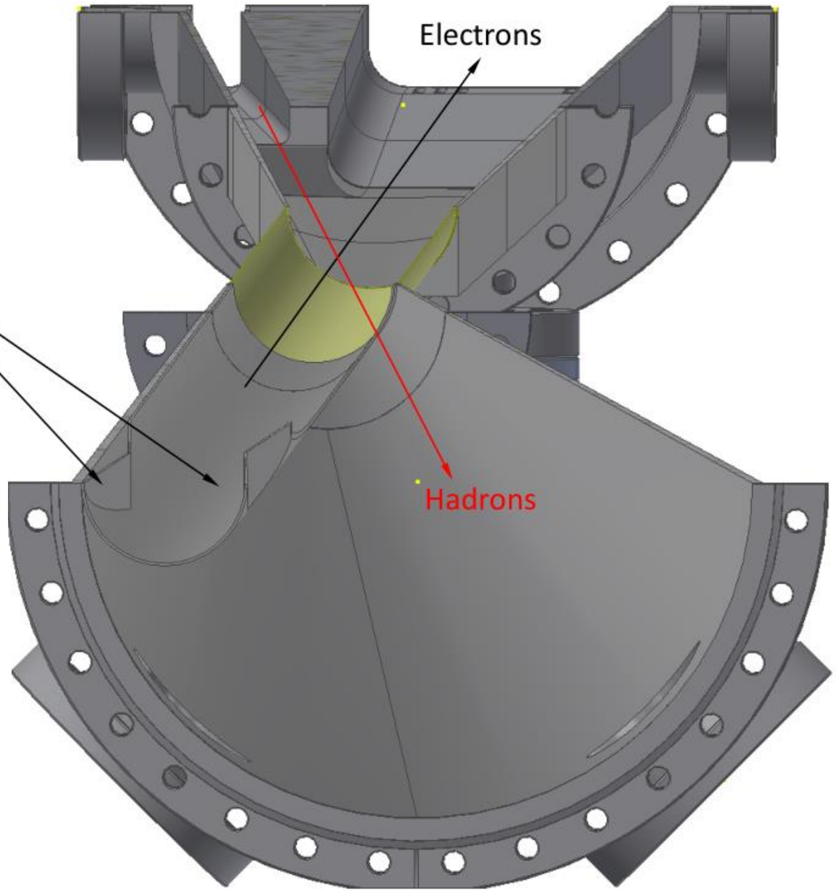
SynRad – 18 GeV, latest Lattice

Power on electron beam tube absorber

Total power on absorber: 78.3W

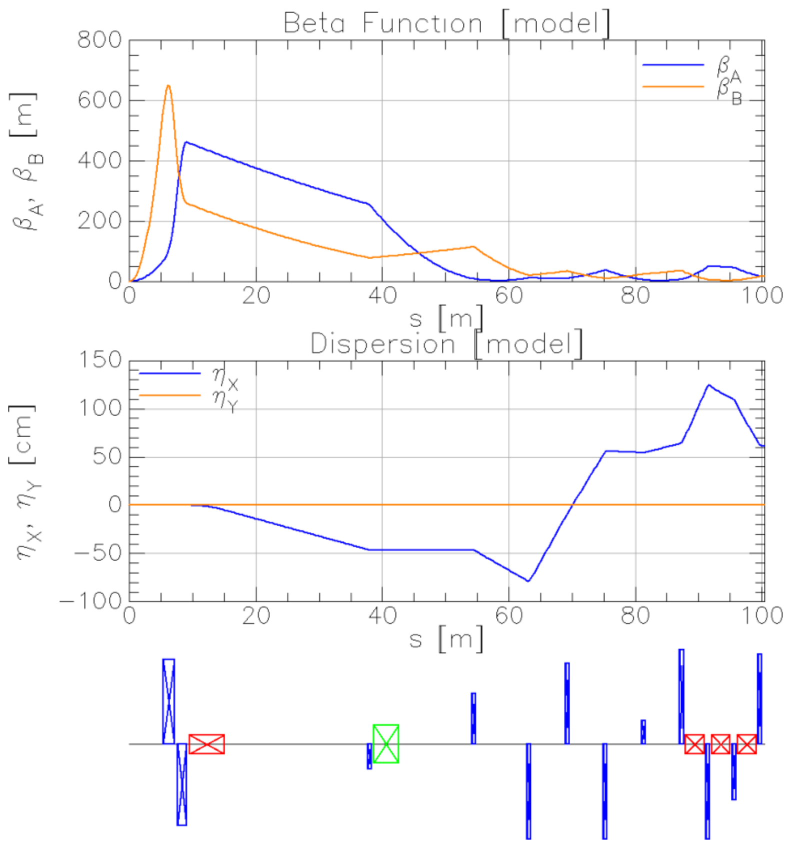
SynRad Results – Core and Tails for 18GeV





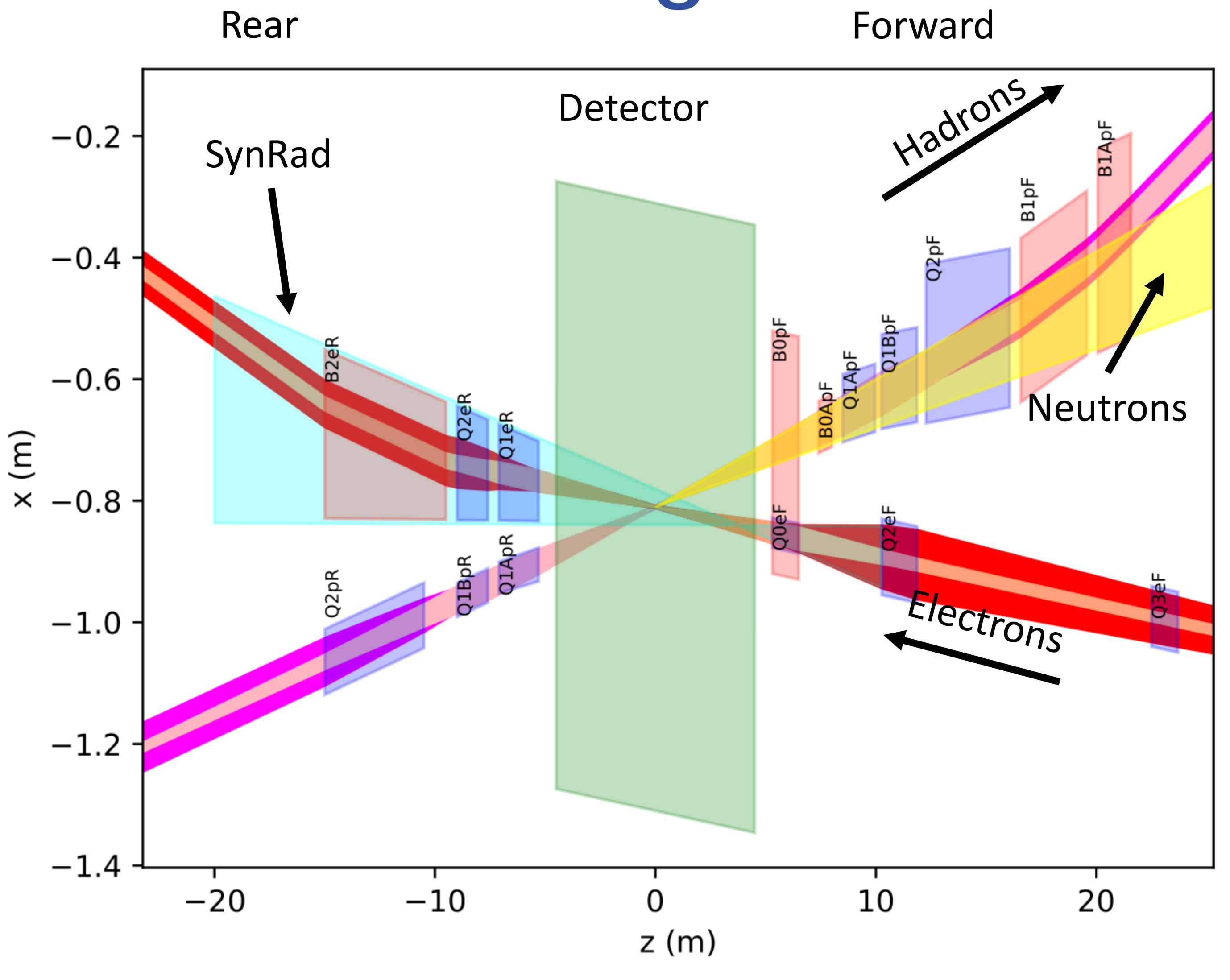
Electron Lattice

- New iteration just completed
- Reason:
  - Crab cavity location close/in neutron cone
  - Synchrotron radiation for crab cavities
- Matched into lattice of eSR



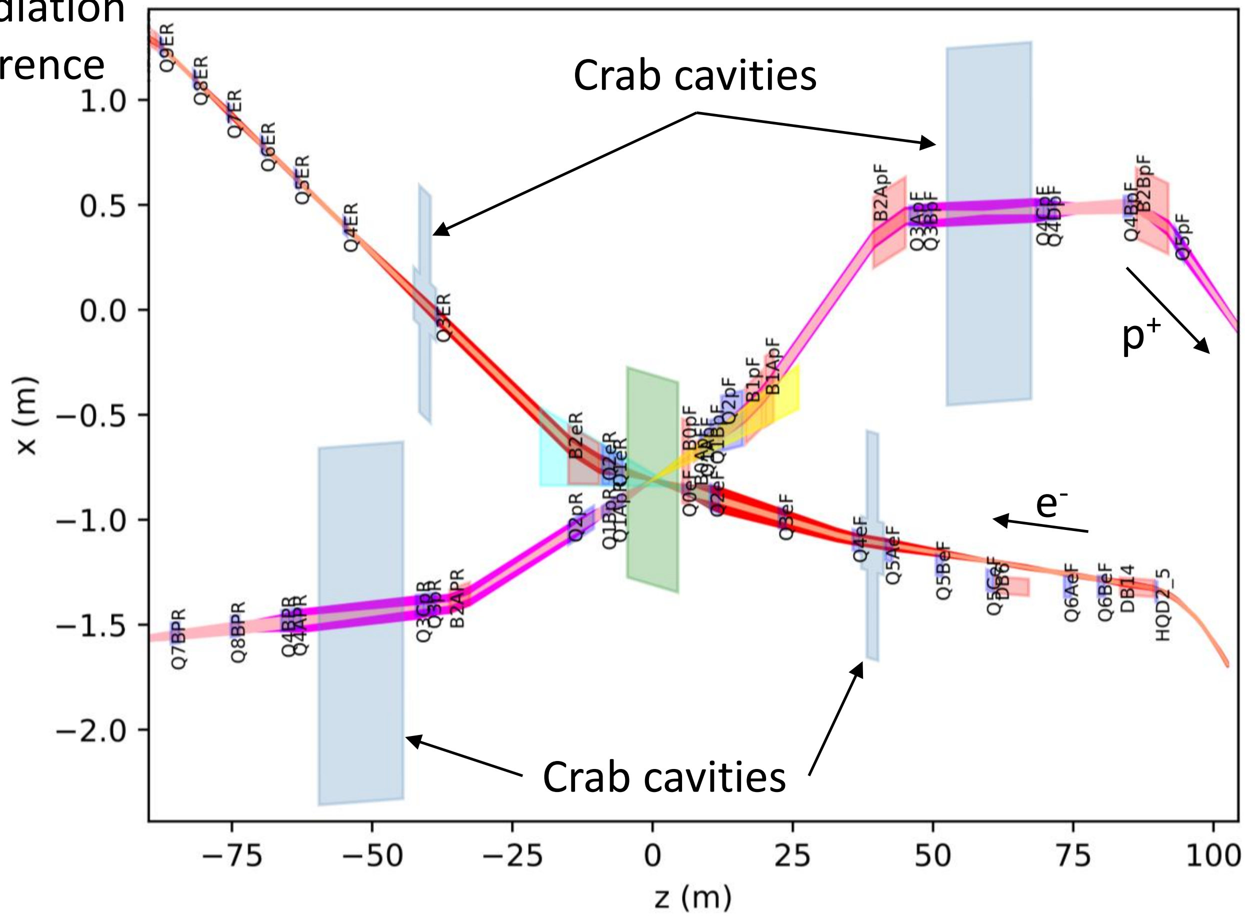
New rear solution

Present IR Design



Present IR Design

Issues addressed for crab cavities:
Synchrotron radiation
Physical interference



Plans

- Adopt new electron lattice as baseline
  - Needs to go through Change Control Board
- Several task forces in place/being setup (JLAB/BNL)
  - Effect/mitigation of detector solenoid on beam dynamics
  - Conceptual design of IR magnets (matching and spin rotators)
- Synchrotron radiation (SLAC/BNL)
  - Beam tails
  - Evaluate present lattice
  - Masking scheme (reduce synchrotron fan)
- Magnet development
  - Layout
  - Feasibility

Design Change Control (DCC)

- (Not exclusive to IR)
- Introduced to prevent uncontrolled changes
  - IR particularly vulnerable
- Organized way to introduce changes to baseline
- Start: potential change identified
  - Assess impact of all involved L2/L3 areas
  - DCC committee meeting/recommendation
  - Change accepted or dismissed

Summary

- IR developed in collaboration with BNL Physics
  - Meets requirements of ‘white paper’
  - Is there anything we have been missing?
- Many considerations went into this IR
  - Geometric constraints
  - Engineering feasibility
  - Magnets, cryostating
- Changes are possible
  - Need to go through DCC
    - What problem needs fixing?

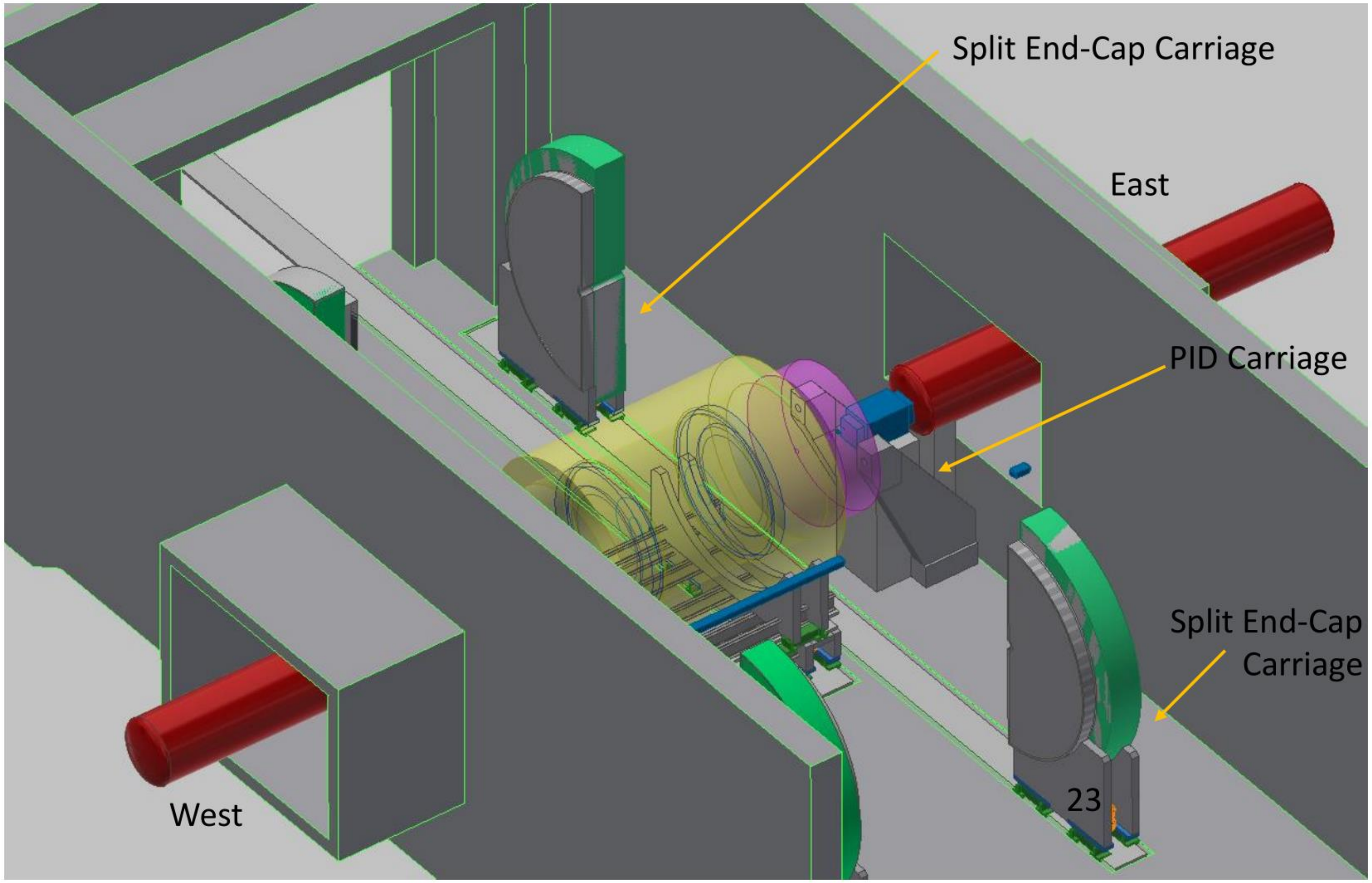
Acknowledgements

Mike Anerella, Elke Aschenauer, J Scott Berg, Alexei Blednykh, John Cozzolino, Dave Gassner, Karim Hamdi, Charly Hetzel, Doug Holmes, Henry Hocker, Alex Jentsch, Alexander Kiselev, Henry Lovelace III, Gary McIntyre, Christoph Montag, Guillaume Robert-Demolaize, Brett Parker, Bob Palmer, Stephen Plate, Mike Sullivan (SLAC), Steve Tepikian, Roberto Than, Peter Thieberger, Qiong Wu

Additional Slides

EIC Detector Infrastructure

Split Hadron End-Cap, E&H-Cal, and pull out PID – 9/19



Note: Rough design for Upper Stability Frame is still needed

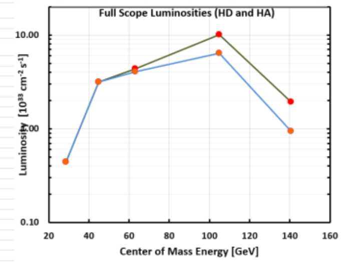
IR Development

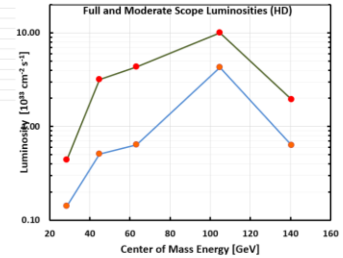
- Core group
  - Several experts matrixed (C-AD, NSLSII, SLAC)
- Meetings
  - Weekly IR meetings
  - Bi-weekly Synrad meetings
  - Future: Integration meetings
- How do we keep track?
  - Sharepoint: meetings, presentations, …
  - Lattice files with history
  - Concept specification documents
    - Being populated
- How do changes become the baseline?
  - Change control board (CCB)

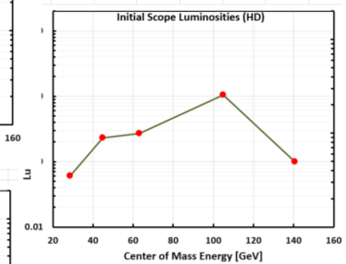
Baseline Parameters

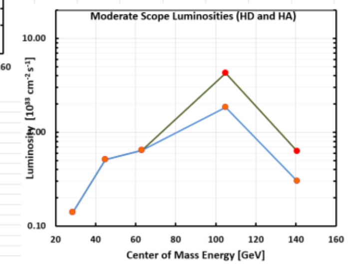
- Full set of parameters
- Initial vs full
- Hadron and electron beam

CME, GeV	Init-HA	Init-HD	Moder-HA	Moder-HD	Full-HA	Full-HD
28.6	0.06	0.06	0.14	0.14	0.44	0.44
44.8	0.23	0.23	0.51	0.51	3.16	3.16
63.2	0.27	0.27	0.64	0.64	4.07	4.35
104.9	0.59	1.05	1.85	4.28	6.40	10.05
140.7	0.06	0.10	0.30	0.63	0.94	1.93







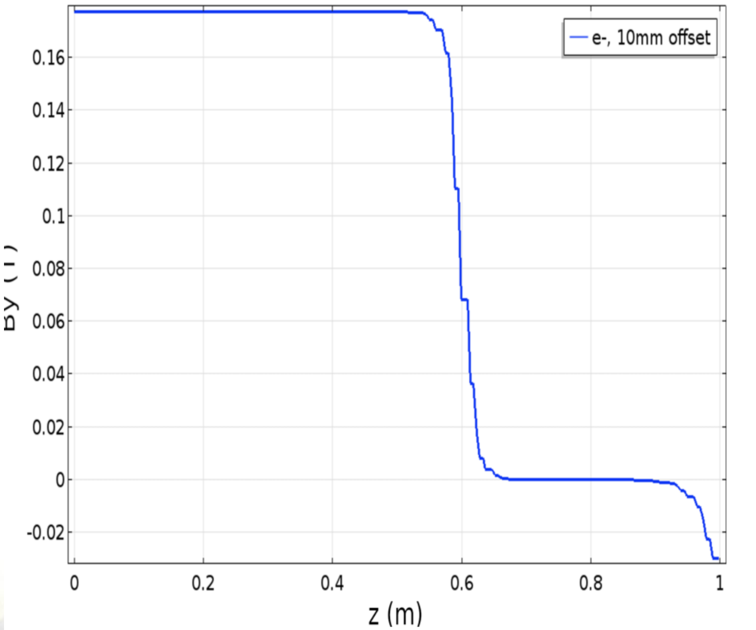


PARAMETERS	Proton	Electron	Proton	Electron	Proton	Electron	Proton	Electron	Proton	Electron
energy, GeV	275	18	275	10	100	10	100	5	41	5
relativistic factor	293.1	35225.1	293.1	19569.5	106.6	19569.5	106.6	9784.8	43.7	9784.8
bunch_intensity,E10	20.444	7.294	6.881	17.203	6.881	17.203	4.658	17.203	2.639	13.294
number_of_bunches	290		1160		1160		1160		1160	
beam_current,A	0.74	0.265	1	2.5	1	2.5	0.68	2.5	0.38	1.932
rms_normaliz._emittance,h/v_um	4.6/0.74	845/71.2	2.8/0.45	391/23.9	4.0/0.22	391/25.4	2.7/0.27	196/20.0	1.9/0.45	196/34.2
rms_emittance,h/v_nm	15.8/2.5	24.0/2.0	9.6/1.5	20.0/1.2	37.1/2.1	20.0/1.3	25.1/2.6	20.0/2.0	43.6/10.3	20.0/3.5
emittance_y/emittance_x	0.159	0.084	0.158	0.061	0.056	0.065	0.102	0.102	0.236	0.175
beta,h/v_cm	90/4.0	59/5.0	90/4.0	43/5.0	90/4.0	167/6.4	90/4.0	113/5.0	90/7.1	196/21.0
IP_beam_size,h/v_um	119/10.1	119/10.1	93/7.8	93/7.8	183/9.1	183/9.1	150/10.1	150/10.1	198/27.1	198/27.1
K=sgm_y/sgm_x	0.084		0.084		0.05		0.067		0.137	
IP_rms_ang_spread,h/v_urad	133/251	201/201	103/195	215/156	203/227	109/143	167/253	133/202	220/380	101/129
beam-beam_parameter,h/v	0.004/0.002	0.100/0.100	0.014/0.007	0.073/0.100	0.010/0.009	0.075/0.057	0.015/0.010	0.100/0.066	0.015/0.009	0.053/0.042
long._bunch_area,evs	0.68		0.68		0.4		0.4		0.2	
rms_bunch_length,cm	6	0.9	6	2	7	2	7	2	7.5	2
rms_energy_spread,e-4	6.6	10.9	6.6	5.8	9	5.8	9	6.8	10.4	6.8
max_space_charge	0.006	neglig.	0.003	neglig.	0.028	neglig.	0.019	neglig.	0.05	neglig.
Piwinski_angle,rad	5.5	0.8	7.1	2.4	4.2	1.2	5.1	1.5	4.2	1.1
Longit._IBS_time,h	2.1		3.41		2		2.6		3.8	
Transv._IBS_time,h	2		2		2.32/2.36		2/4.8		3.4/2.1	
lumi_factor	0.86		0.86		0.85		0.83		0.93	
luminosity,E33	**1.93**		**10.05**		**4.35**		**3.16**		**0.44**	
main RF frequency, MHz	591	591	591	591	591	591	591	591	197	591
main RF Voltage, MV	18	68	18	20	8.5	20	8.5	13	9	13
harmonic RF frequency, MZ				1773		1773		1773		1773
harmonic RF voltage, MV				6.6		6.6		4.3		4.3
SR loss power, MW		10.00		9.00		9.00		3.20		2.47
synchronous voltage, MV		37.8		3.6		3.6		1.28		1.28
transverse radiation damping time, ms		9.2		59.4		59.4		70.1		70.1
ST (de-)polarization time, h		0.53		9.92		9.92		11.7		11.7

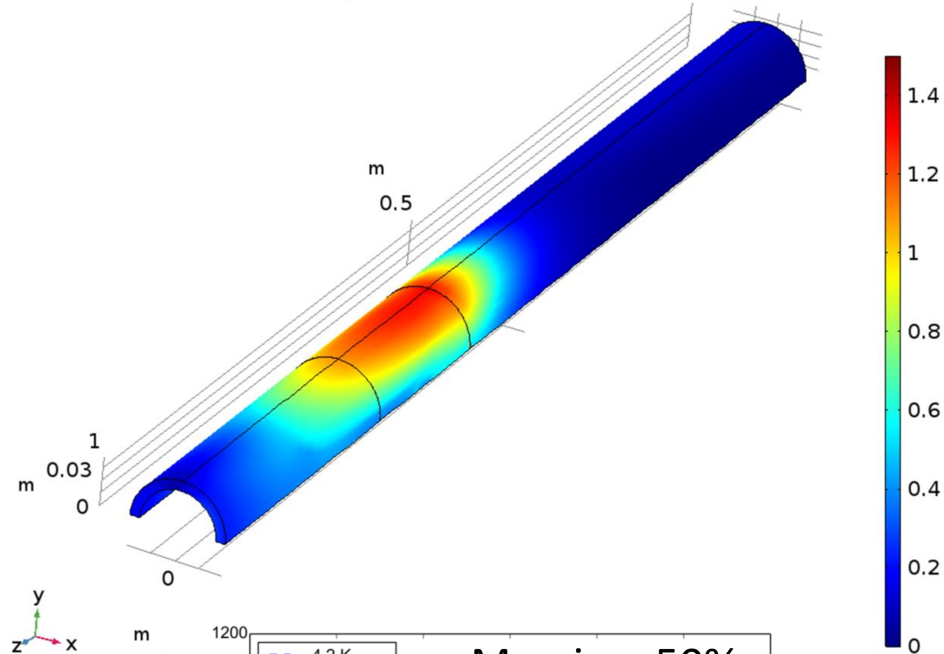
https://brookhavenlab.sharepoint.com/:x:/s/eRHIC/bnl&slac/ESBW8F9WAsdMqNAod1r127YB4wY1r1Xz-T0me06QpZMjPw?e=VHIW1V

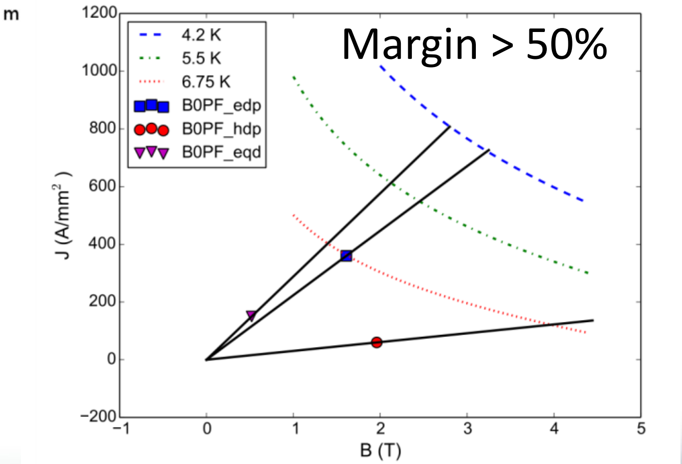
B0pF Simulation Results

- Challenging: shielding tube
  - End effects from dipole magnet



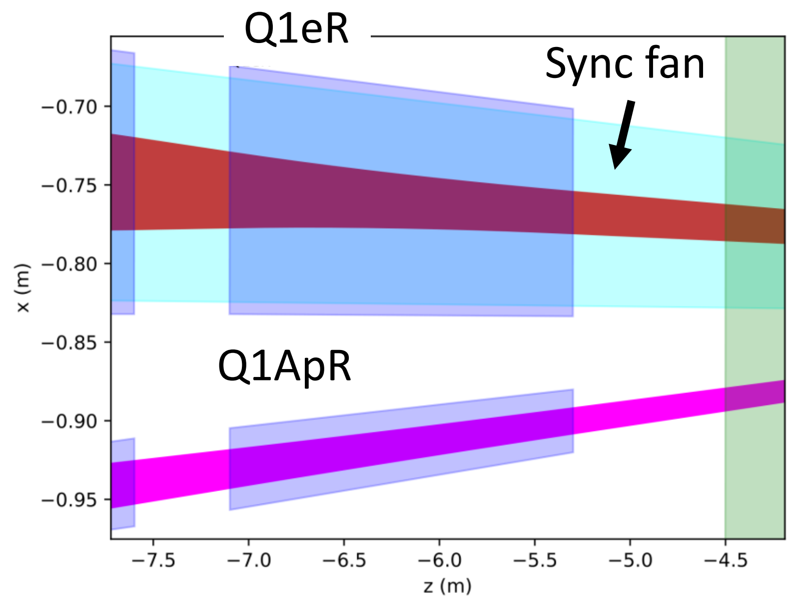
(b) at position of $x = 10\,\mathrm{mm}$

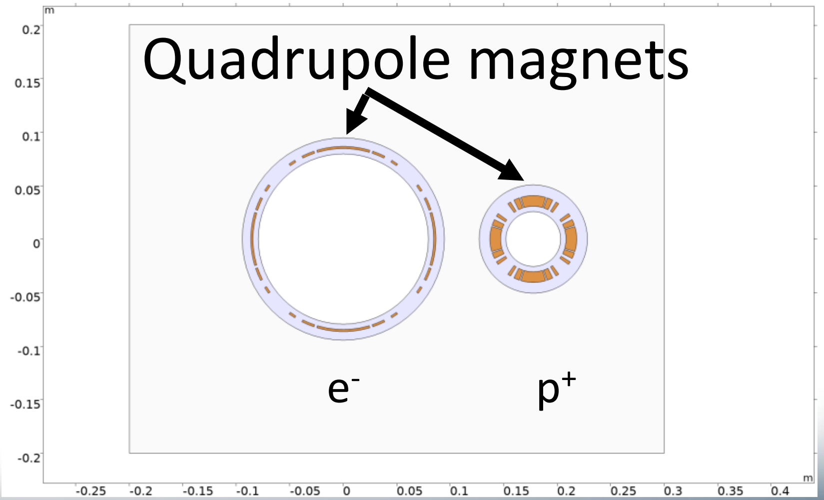




Rear Side Magnet Q1APR/Q1ER

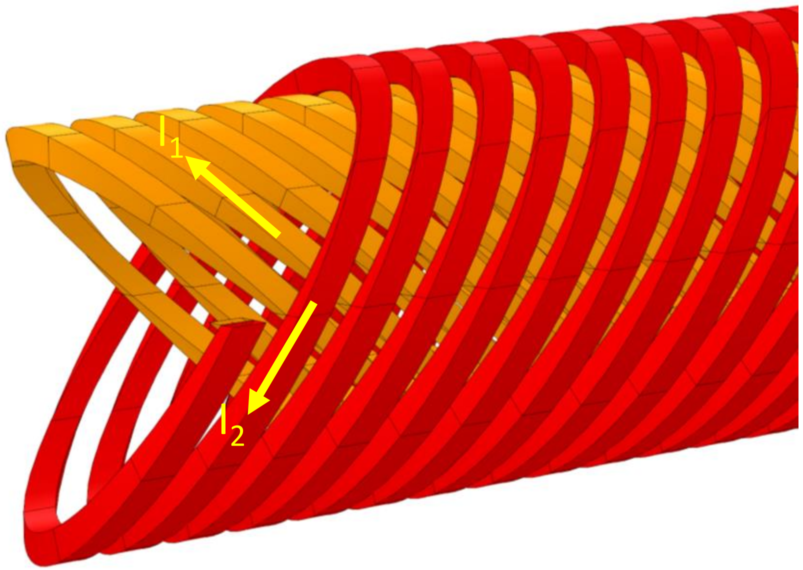
- Gradients
  - Q1eR: 14 T/m
  - Q1ApR: 78 T/m
- Large synchrotron radiation fan
  - Defines apertures of rear lepton magnets
- Quads as close as possible to IR
  - 2-in-1 magnets: apertures overlapping
  - Alternative: interleaving magnets
  - Or: taper magnets
- Tapered magnets: change in multipole field along magnet length





Tapered Double-Helix Coils

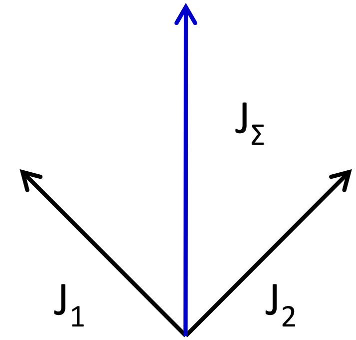
- Double helix (or CCT) known since 60s
  - ‘tilted solenoids’
- Field is generated by two layers
  - Each layer: multipole field and solenoidal field
  - Solenoidal field cancels
- More general: vector addition of two currents
  - Can create any current distribution outside cylinder
- Allows to change multipole fields at different locations



$$x = R\cos(\Theta)$$

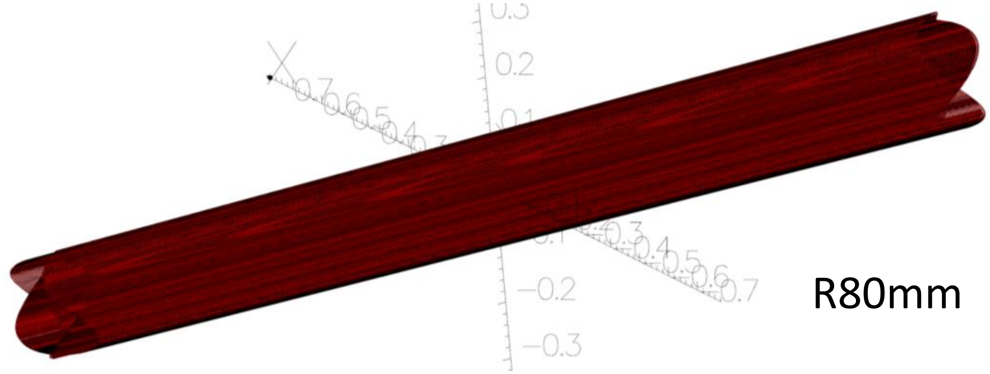
$$y = R\sin(\Theta)$$

$$z = \frac{R}{\tan\alpha}\sin(n\Theta)$$



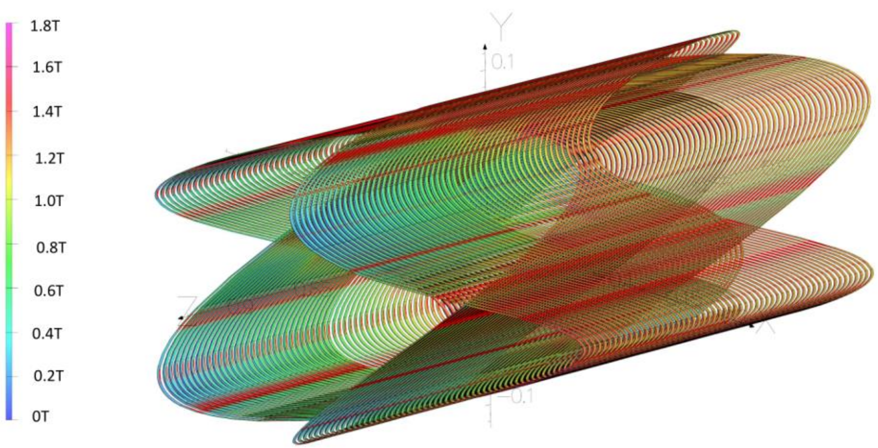
Q1eR

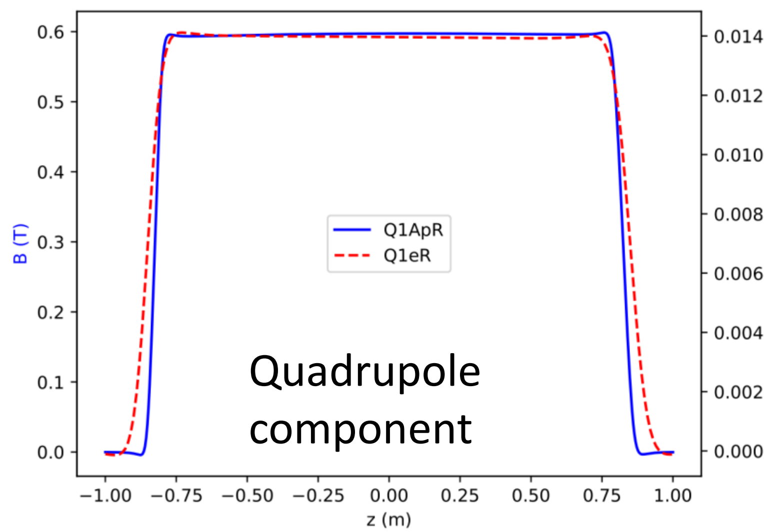
- Length: 1.8m
- Gradient: 14T/m
- NbTi conductor, 4.2K
- 74A
- Margin: 32%



R80mm

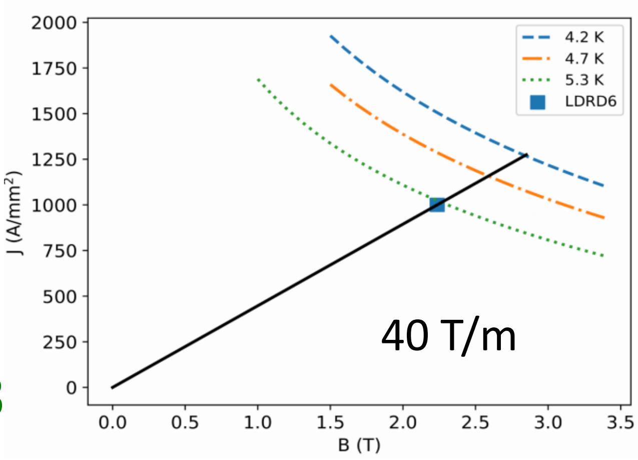
R65mm

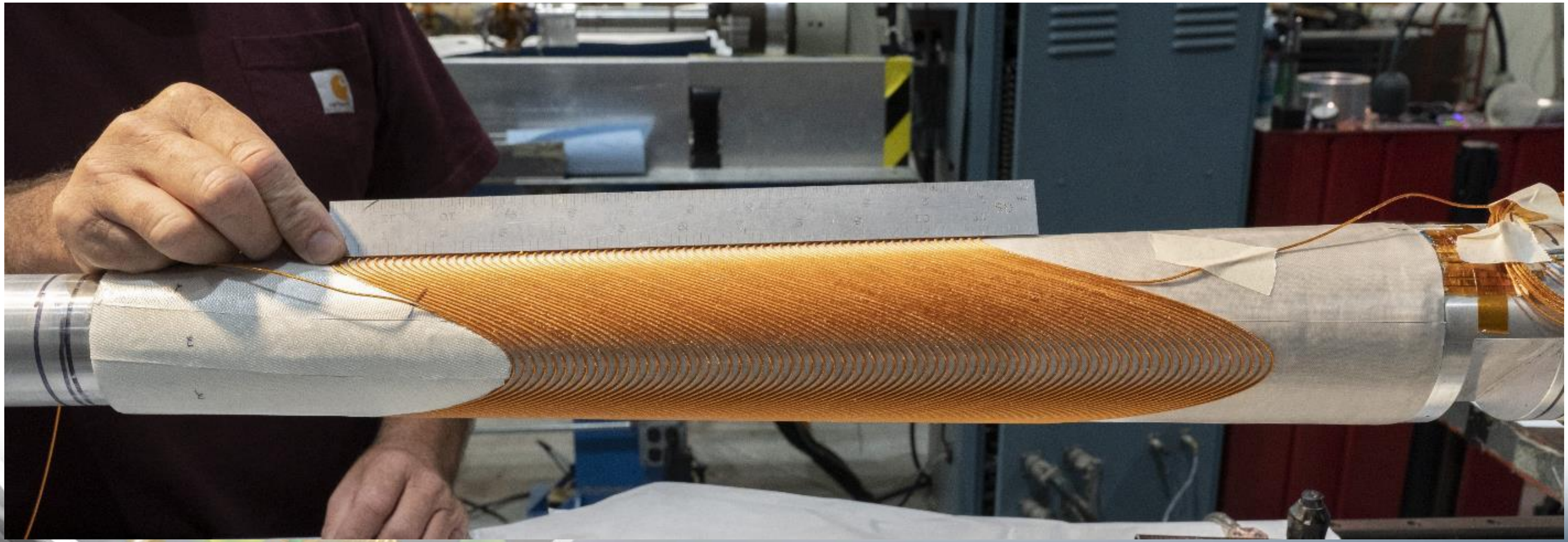




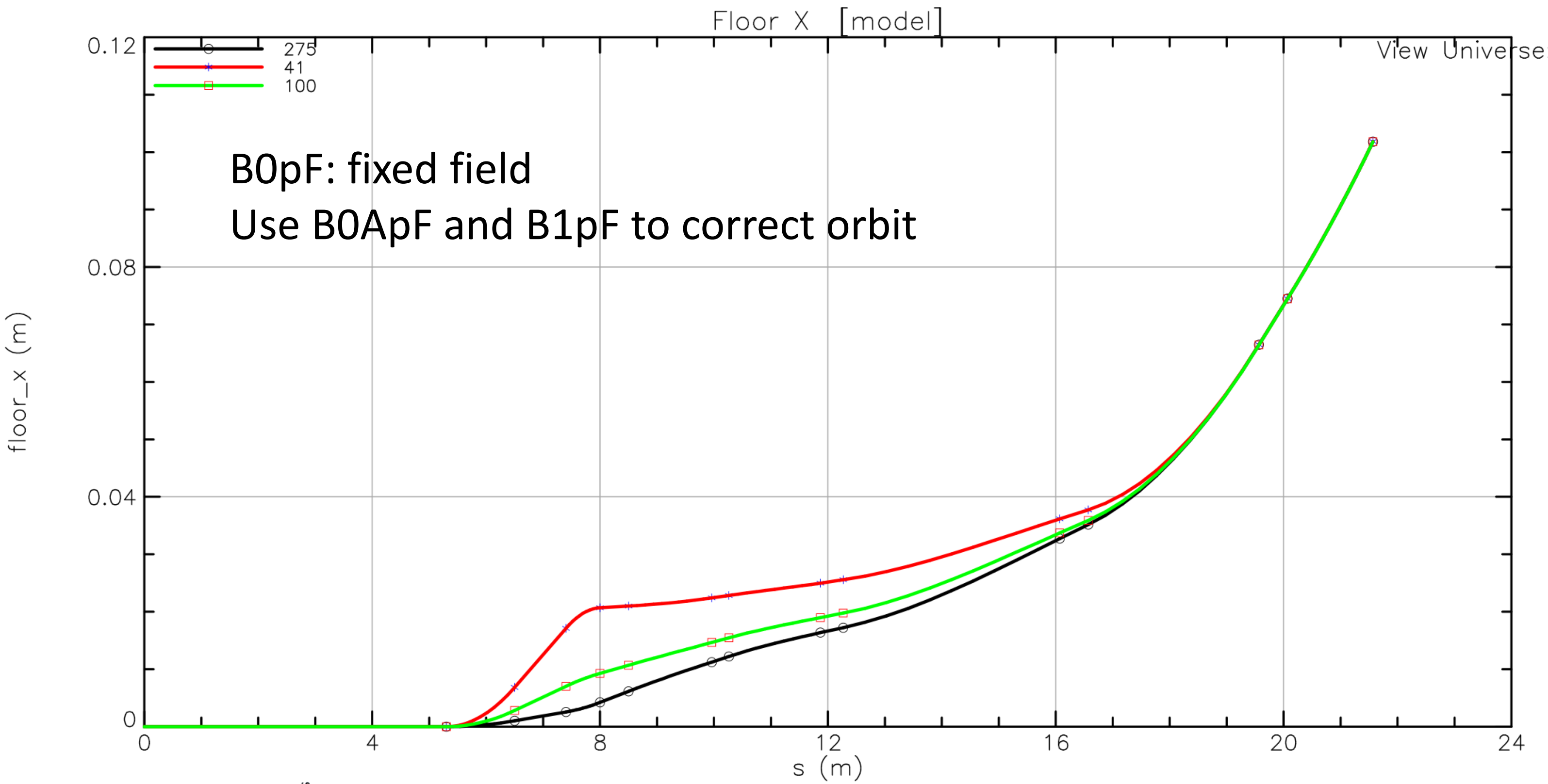
Tapered Double Helix Magnet

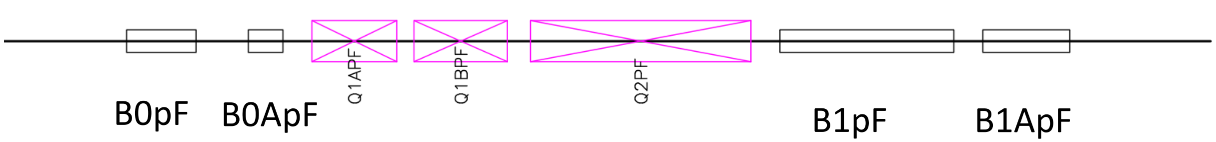
- Demonstrator presently under construction
- 4 layer coil
  - Aperture: 60..80mm
  - L=0.4m
- Compatible with direct wind process
- H. Witte et al. http://dx.doi.org/10.1109/TASC.2019.290298

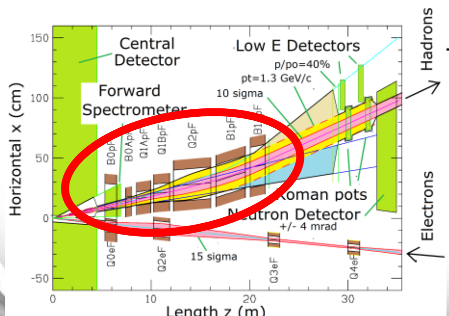




Hadron Forward – Orbit Bump







Electron Forward

- Move crab out of neutron cone
- Move geometry matching dipoles away from IR
  - Beta reduction at crab doesn't conflict with dispersion control
  - 0.083 T dipole fields
- ≈90 deg. to crab