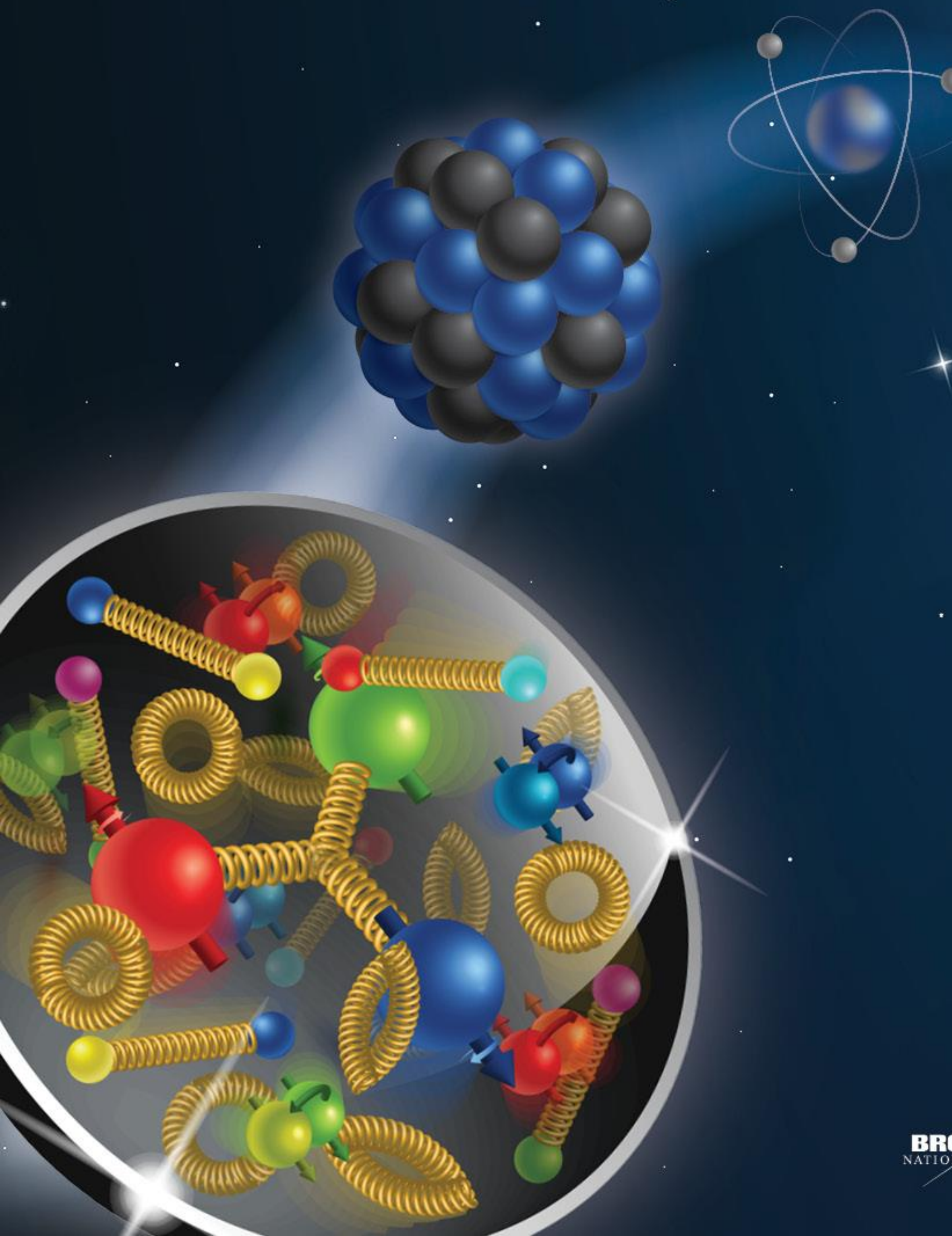


EIC MDI & IR Magnet Design

Holger Witte

Head Magnet Systems, L3 IR

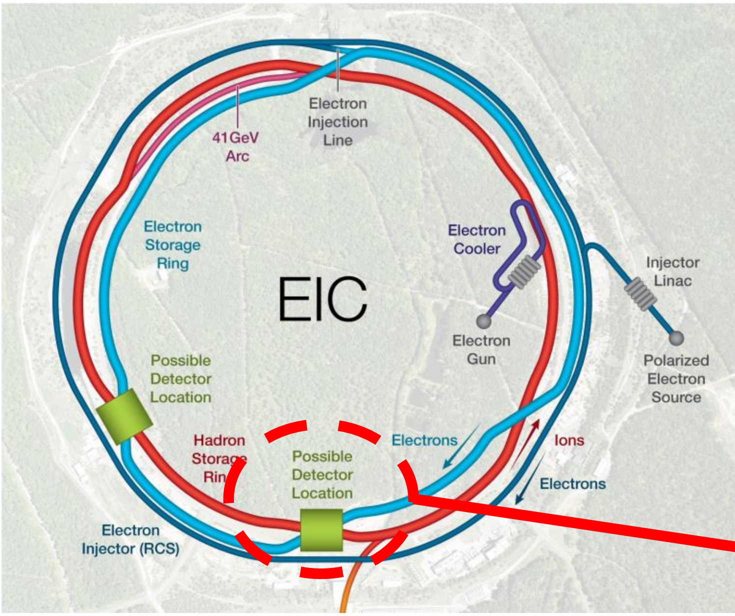
eeFACT 2022

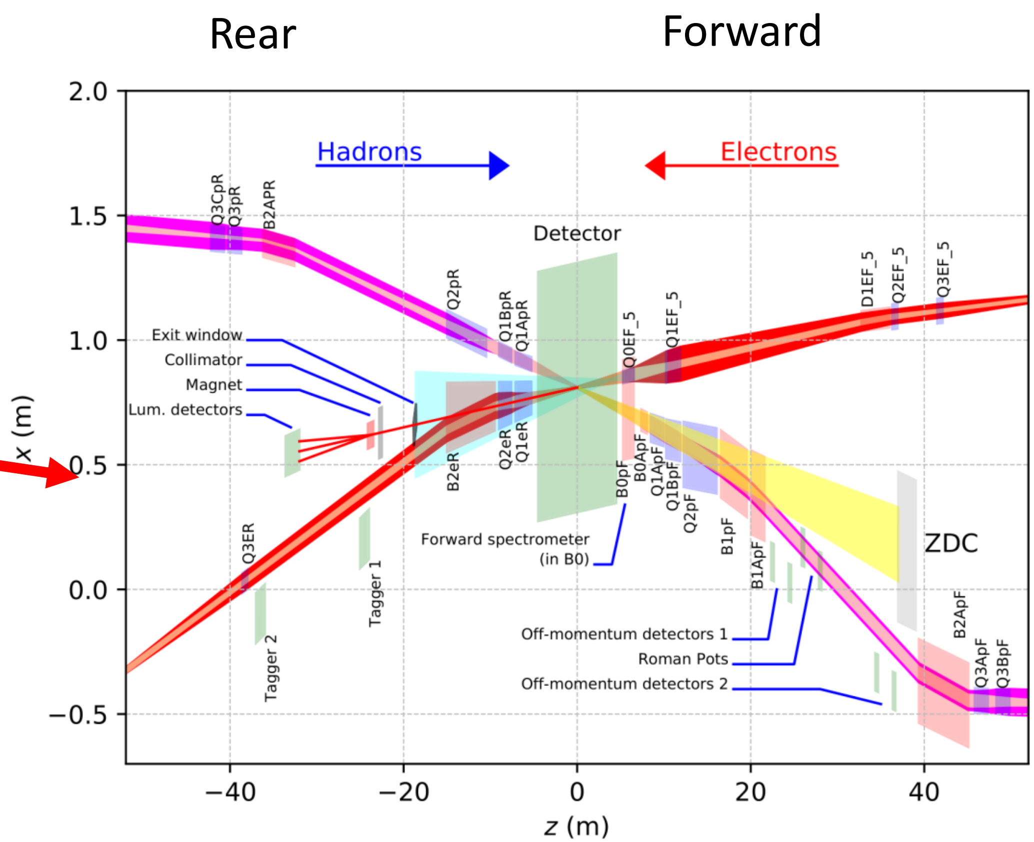
September 13th 2022

Electron-Ion Collider

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

EIC IR: Overview



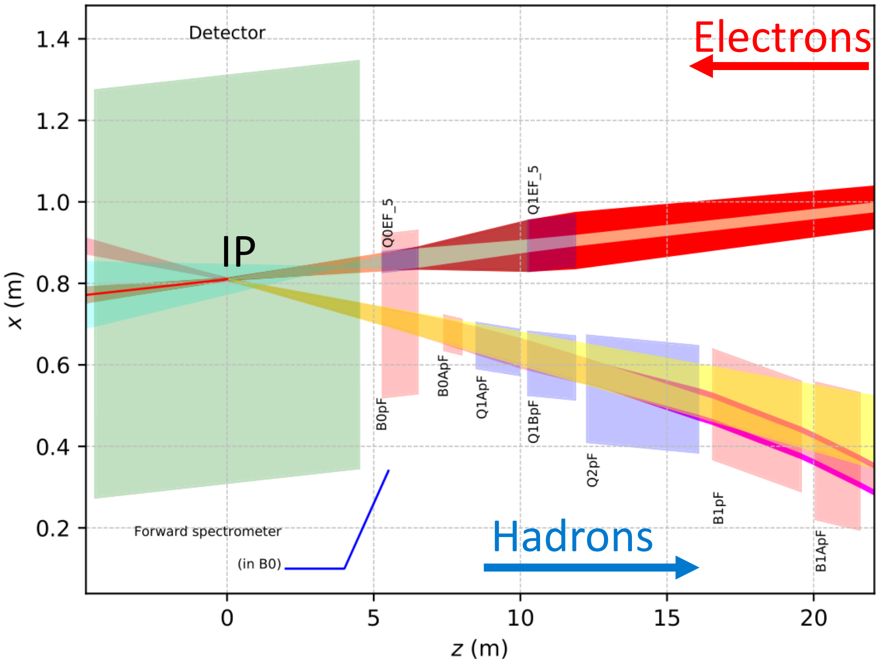


Hadron storage ring (HSR): 4 yellow and 2 blue RHIC arcs

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

IR location: IR6

EIC IR: Forward Direction

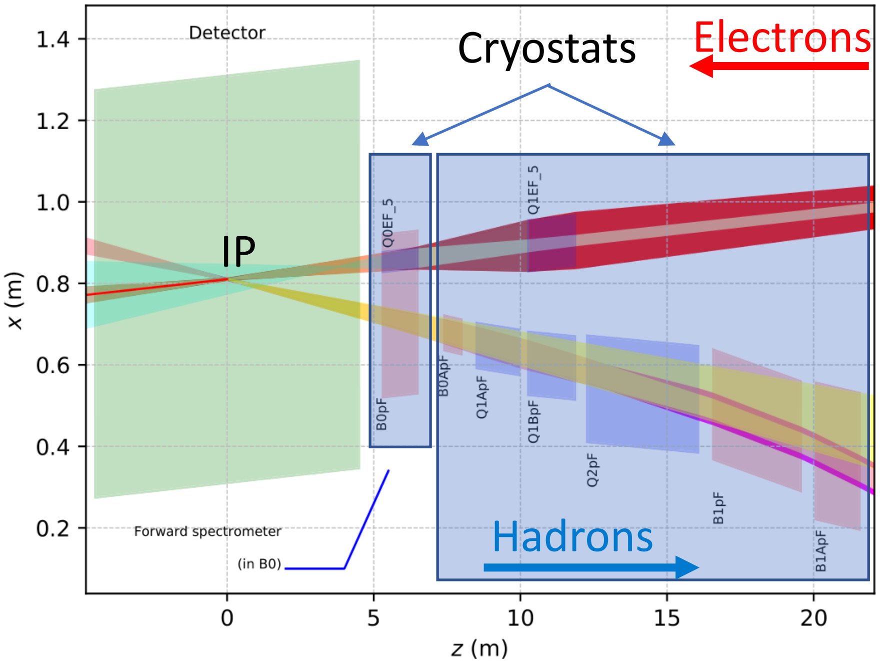


Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
B0ApF	0.043	0.6	-3.3	0	-3.3
Q1ApF	0.056	1.46	0	-72.608	-4.066
Q1BpF	0.078	1.61	0	-66.18	-5.162
Q2pF	0.131	3.8	0	40.737	5.357
B1pF	0.135	3	-3.4	0	-3.4

- Interleaved magnet scheme
  - Adding magnets is challenging
- Why are these magnets difficult?
  - Required field
  - Aperture
  - Geometric constraints
- Hadron forward magnets: collared magnets
  - Large apertures: physics
- Electron forward magnets/B0pF: direct wind magnet
- All magnets NbTi, 2K (Q0eF: 4K)

Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
Q0eF	0.025	1.2	0	13.5	0.4
Q1eF	0.063	1.61	0	8.1	0.5

EIC IR: Forward Direction



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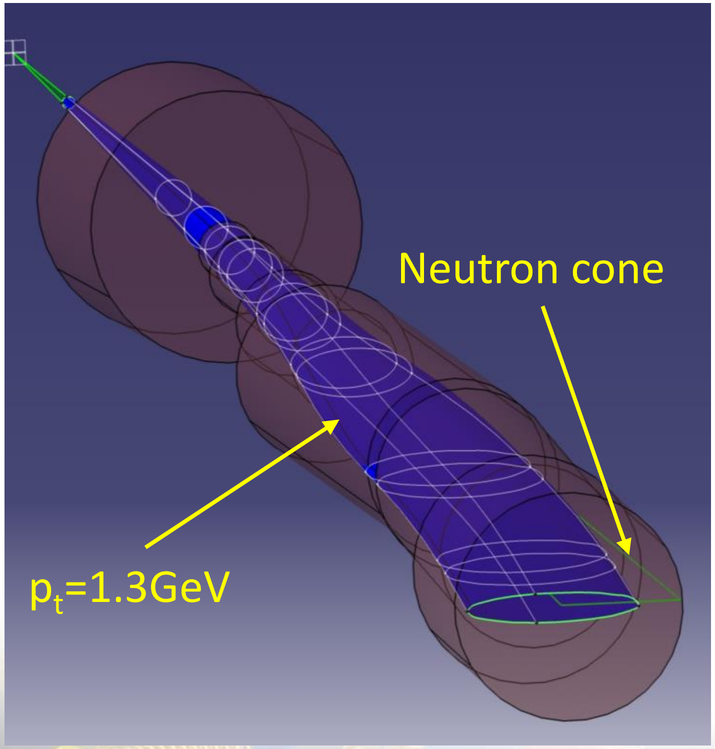
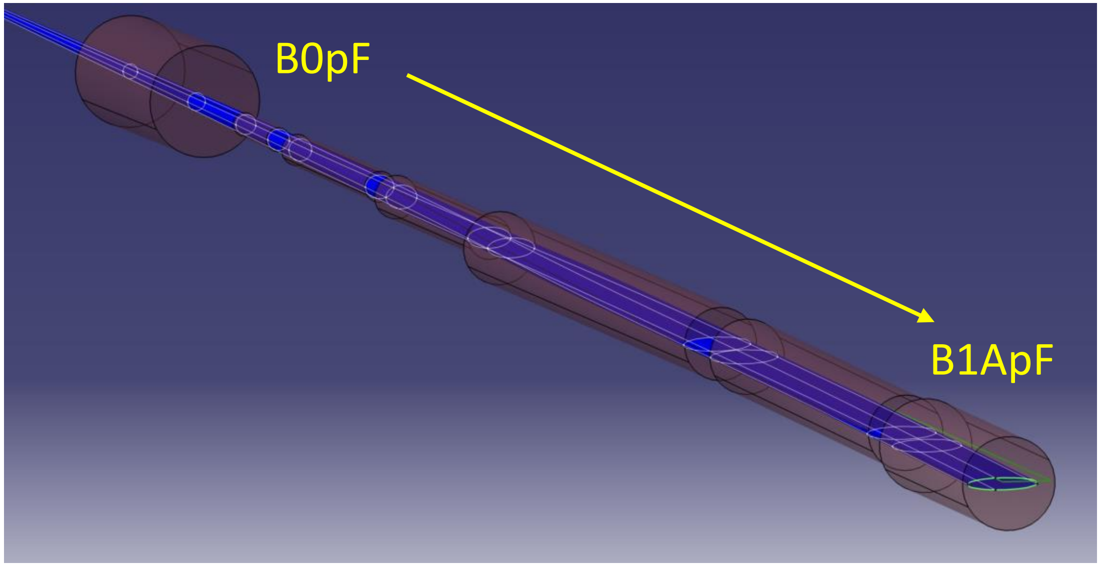
  - Required field
  - Aperture
  - Geometric constraints
- Hadron forward magnets: collared magnets
  - Large apertures: physics
- Electron forward magnets/B0pF: direct wind magnet
- All magnets NbTi, 2K (Q0eF: 4K)
- Two cryostats

Name	R1	length	B	grad	B pole
	[m]	[m]	[T]	[T/m]	[T]
Q0eF	0.025	1.2	0	13.5	0.4
Q1eF	0.063	1.61	0	8.1	0.5

Hadron Forward - Apertures

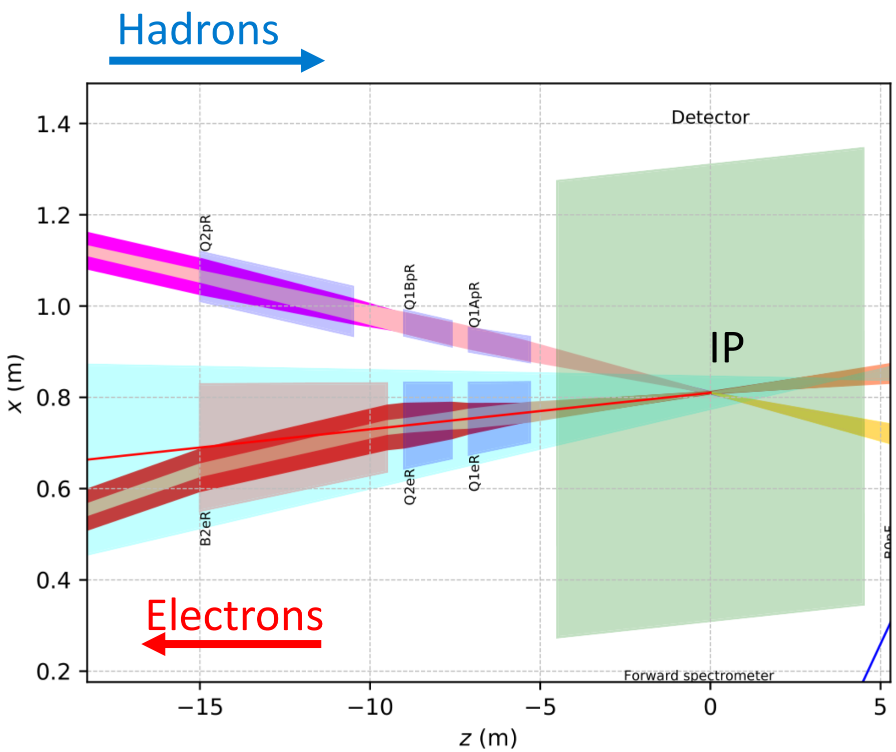
- To optimize aperture: magnets tilted and displaced
- Verified with two codes
  - BMAD – general purpose tracking code
  - Geant4 (friends from Physics)





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

EIC IR: Rear Direction



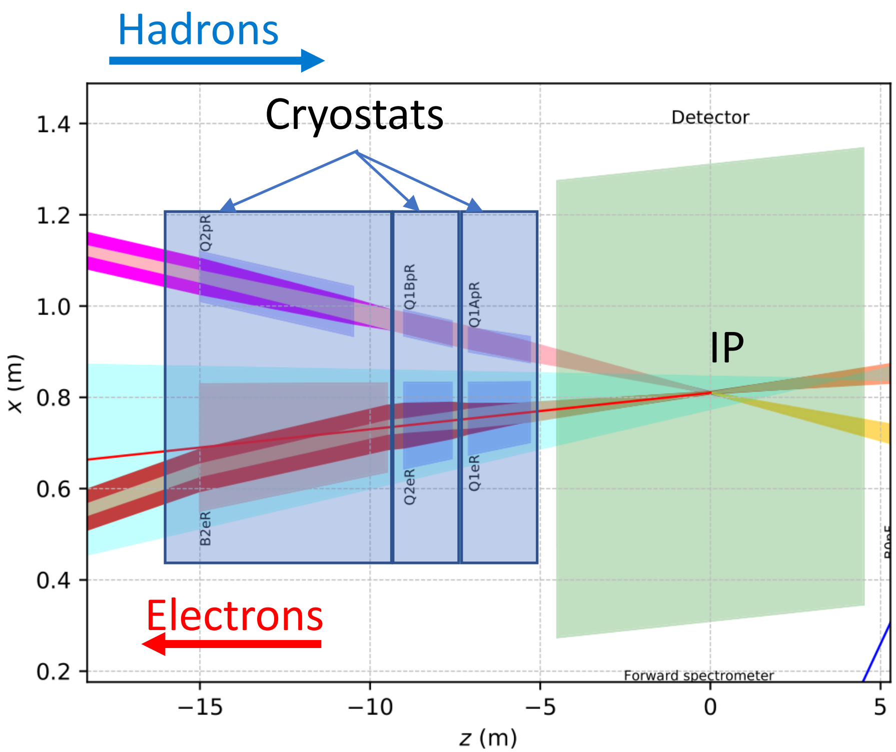
- 2-in-1 magnets
  - Common yokes
- Main issue: space between magnets
  - Crossing angle
- Large aperture due to synrad fan
  - Comes from low-beta quads
- All magnets NbTi, 4.2K
- All magnets direct wind

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
B2AeR	90.45	90.45	2.0	0.192	0	0.192
B2BeR	111.45	111.45	3.45	0.238	0	0.238

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

B2eR: split into two magnets, not shown in figure

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
- All magnets NbTi, 4.2K
- All magnets direct wind
- Three cryostats

Name	R1	R2	length	B	grad	B pole
	[mm]	[mm]	[m]	[T]	[T/m]	[T]
Q1eR	66	79	1.8	0	14	-1.1
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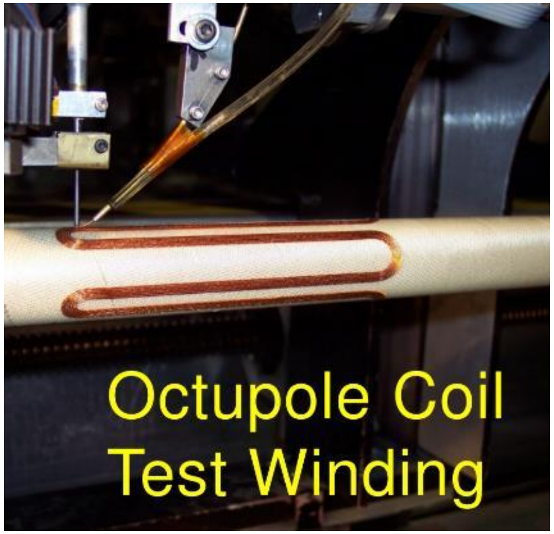
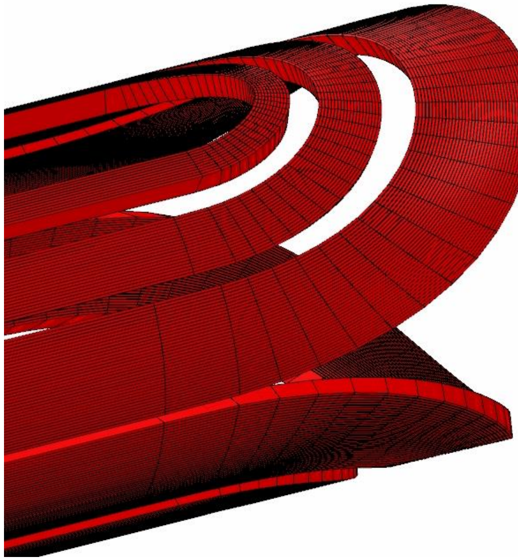
B2eR: split into two magnets, not shown in figure

IR Magnets – Fabrication Techniques

- Three groups of superconducting magnets
  - All NbTi



10 Direct Wind Magnets (S-MD)
Patterns: serpentine and CCT

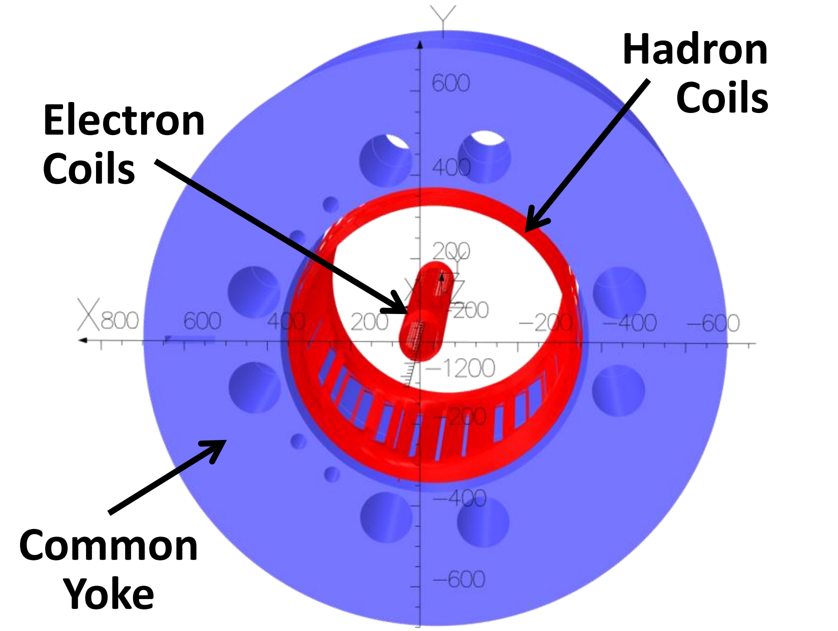


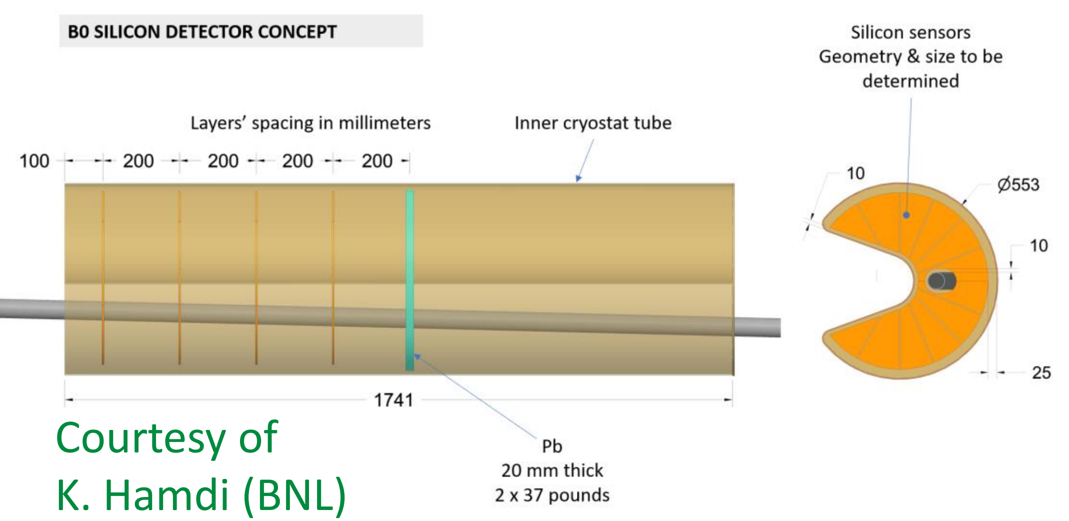
5 Collared Magnets

1 Special Magnet (also direct wind)

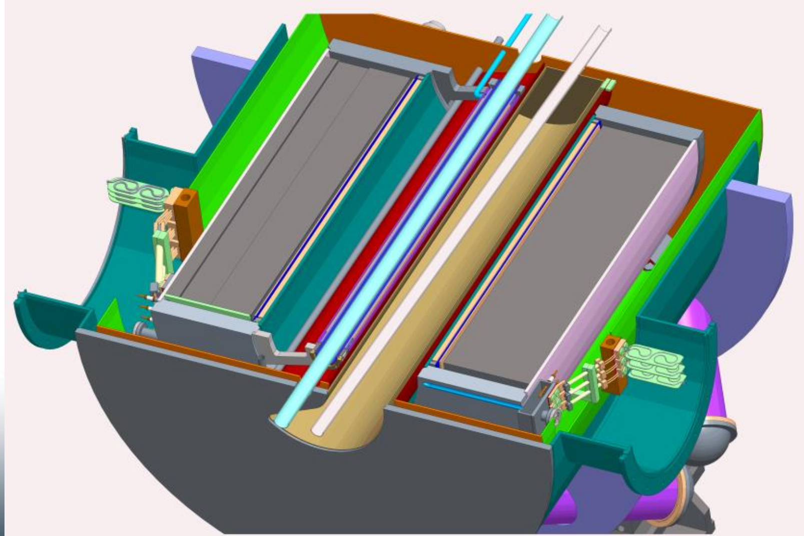
B0pF Forward Spectrometer

- 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
- Space constraints/large aperture
  - Requires 2K
- Courtesy of B. Parker (BNL)



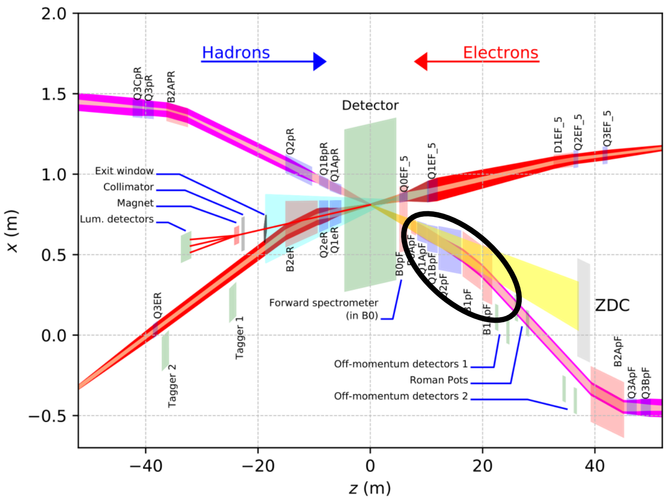


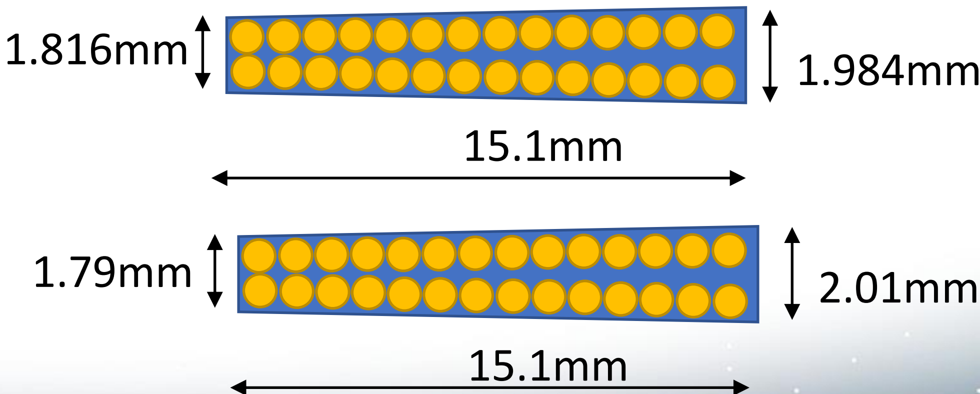
Courtesy of K. Hamdi (BNL)



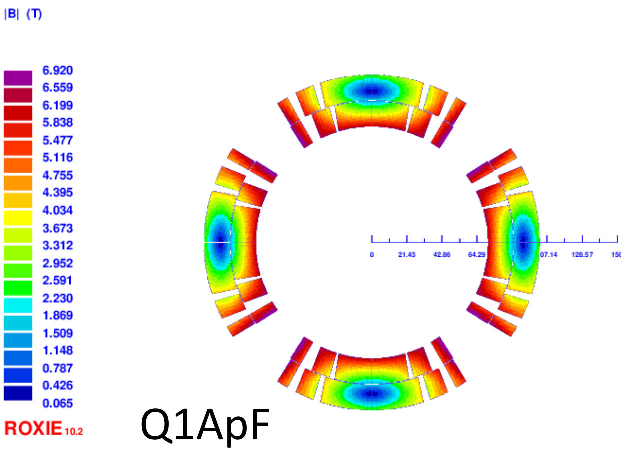
Hadron Forward Cable Magnets Status

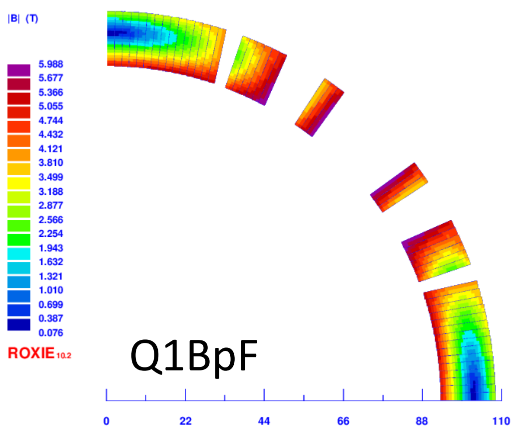
- Re-design for 2K
  - 4K did not converge
  - Better margins
  - Risk reduction
- New cable geometry: LHC style, 15mm wide
  - Two keystones
  - Similar to LHC cable
  - 28 strands
- 2D work complete
  - 3D work ongoing
  - Structural analysis



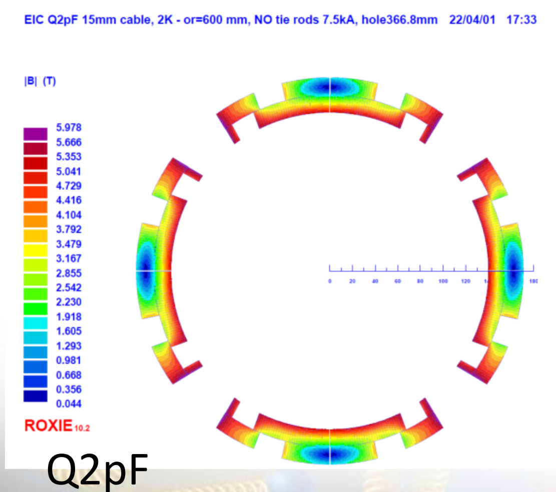


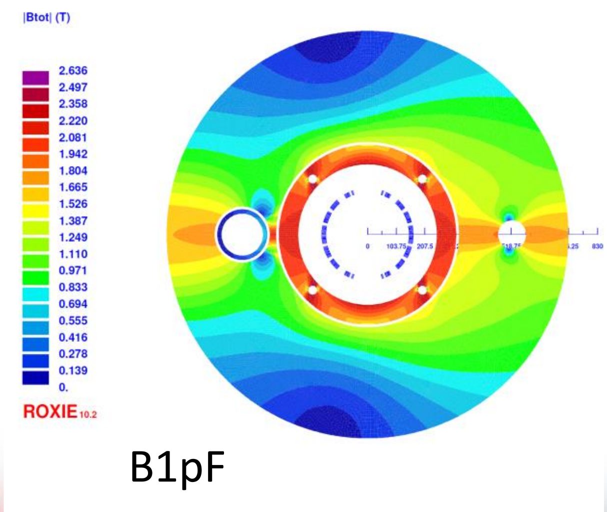
2D Cross-Sections

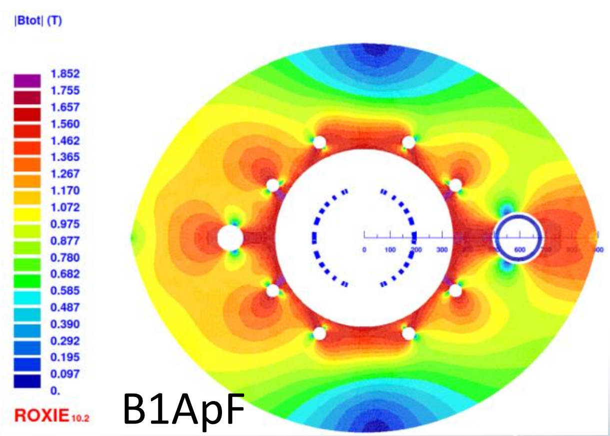




- 2D cross-sections for all collared magnets
- Sufficient field quality and temperature margin at 2K
- Iron yoke – magnetization management



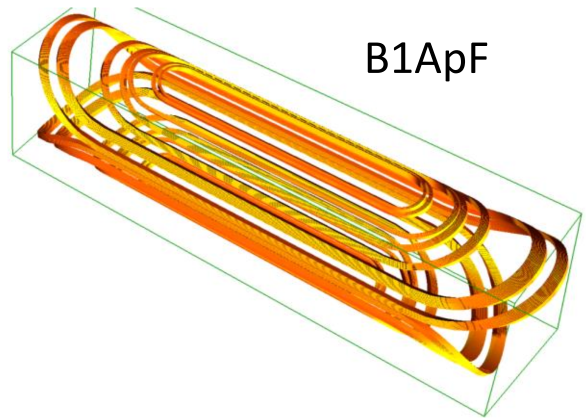




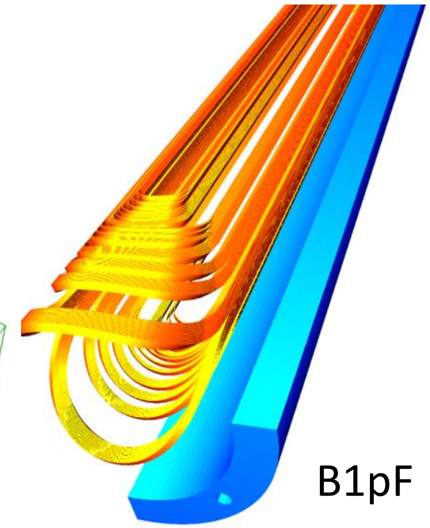
Courtesy of BNL SMD

3D Designs

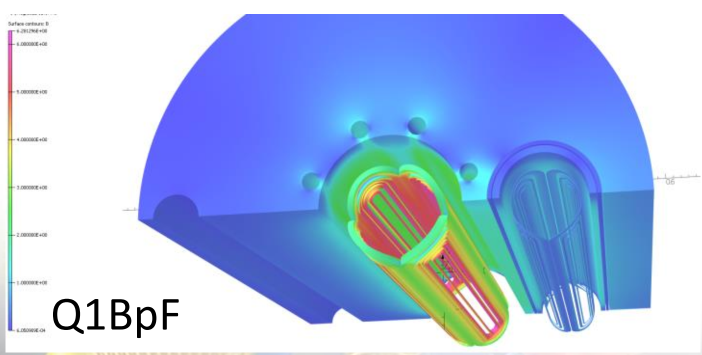
- Preliminary designs for all magnets
  - Minimized peak field in ends
  - Good harmonics
- Sufficient margin (>30%)

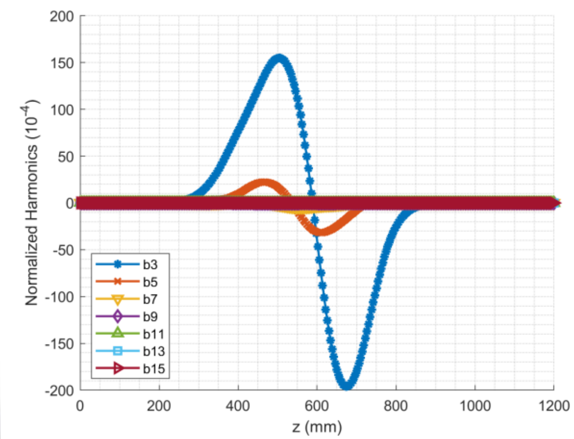


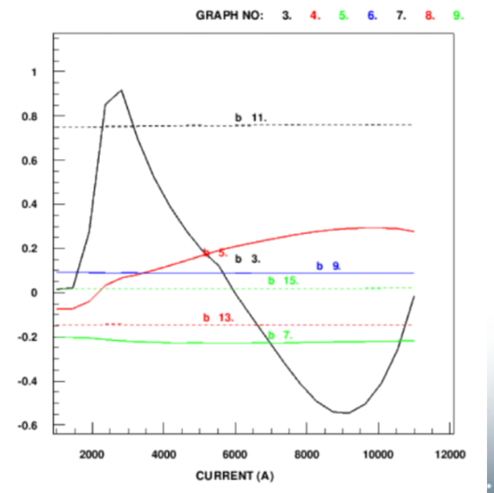
B1ApF



B1pF

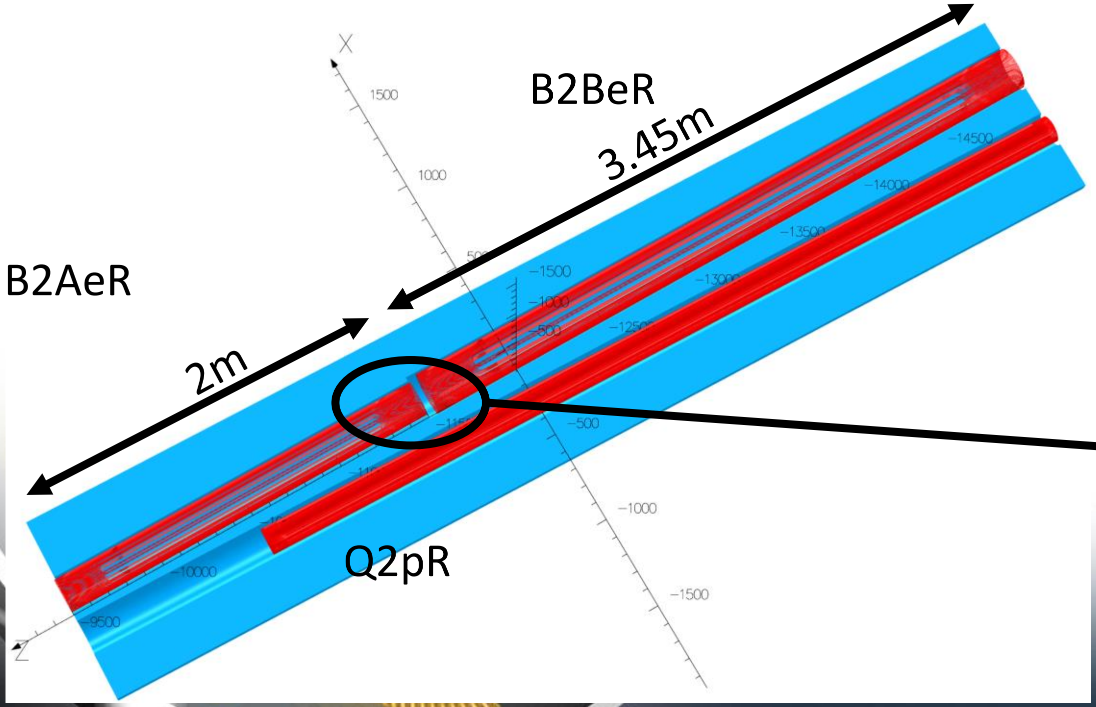


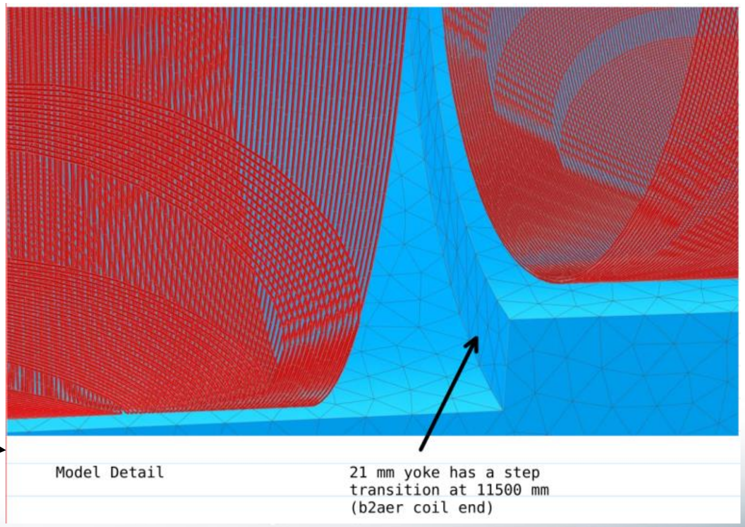




Direct Wind Magnets - Status

- Preliminary magnet designs complete
- Recent changes
  - B2eR split into two magnets to optimize magnet aperture/cost
  - B0pF length reduction
- Implementation of correctors

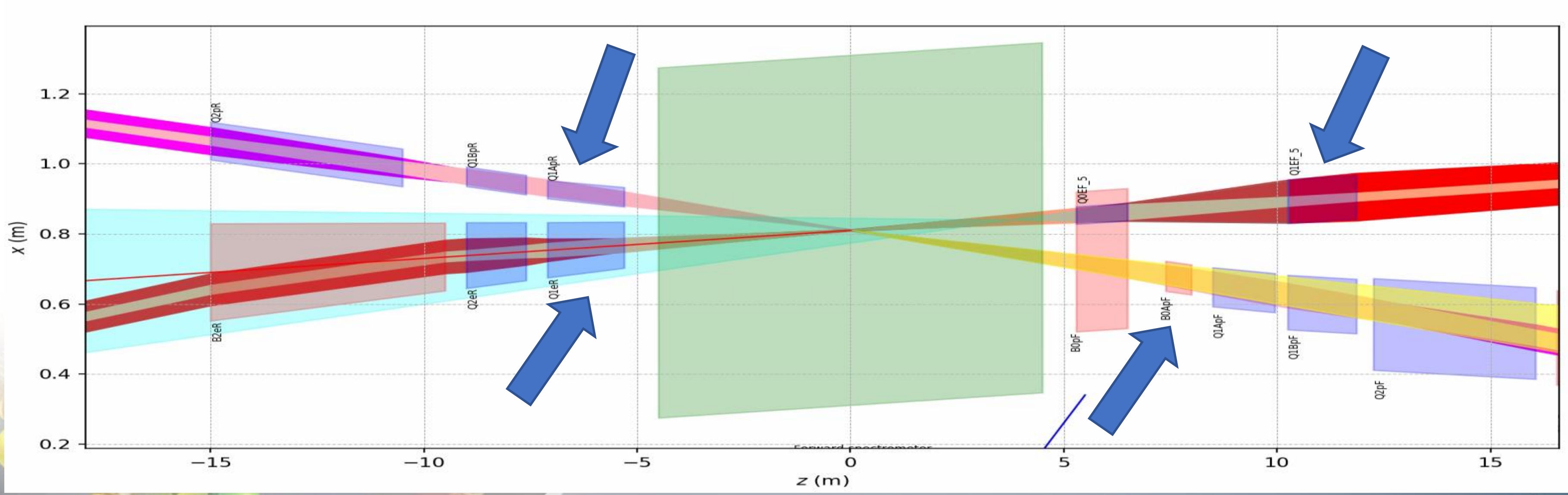




Courtesy of B. Parker (BNL)

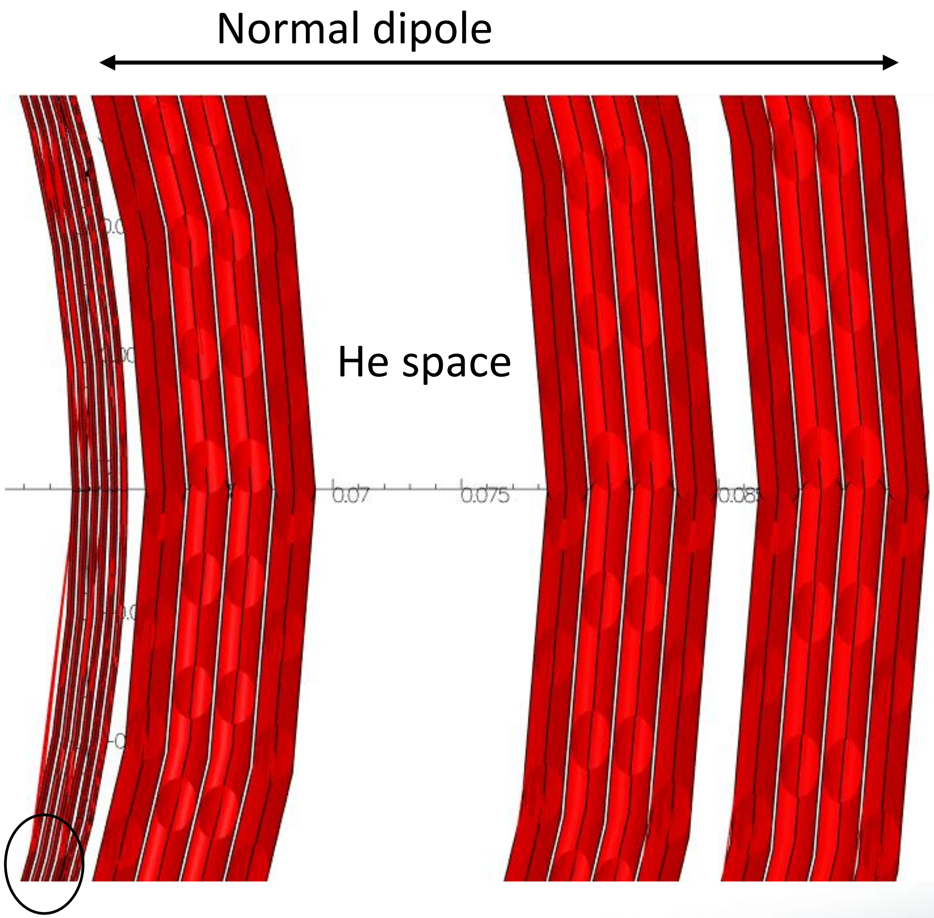
Detector Solenoid Compensation

- Need four skew quadrupole magnets
  - 0.6T/m over 1.8m (assuming 3T solenoid)
- Possible locations
  - Hadrons: B0ApF, Q1ApR
  - Electrons: Q1eF, Q1eR
    - Q0eF: technically possible, but cuts into acceptance



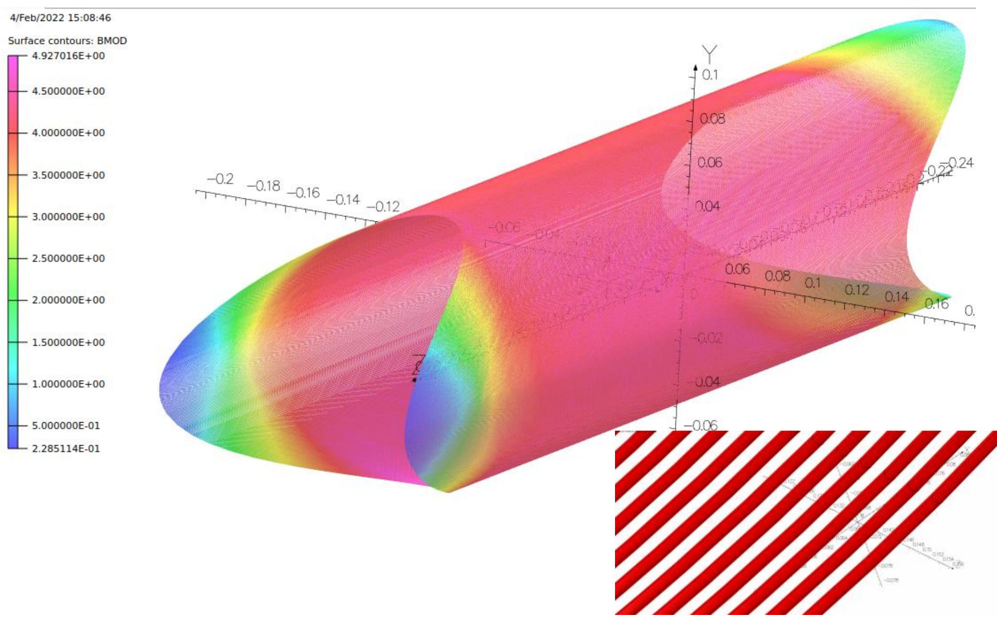
B0ApF – Corrector Dipole

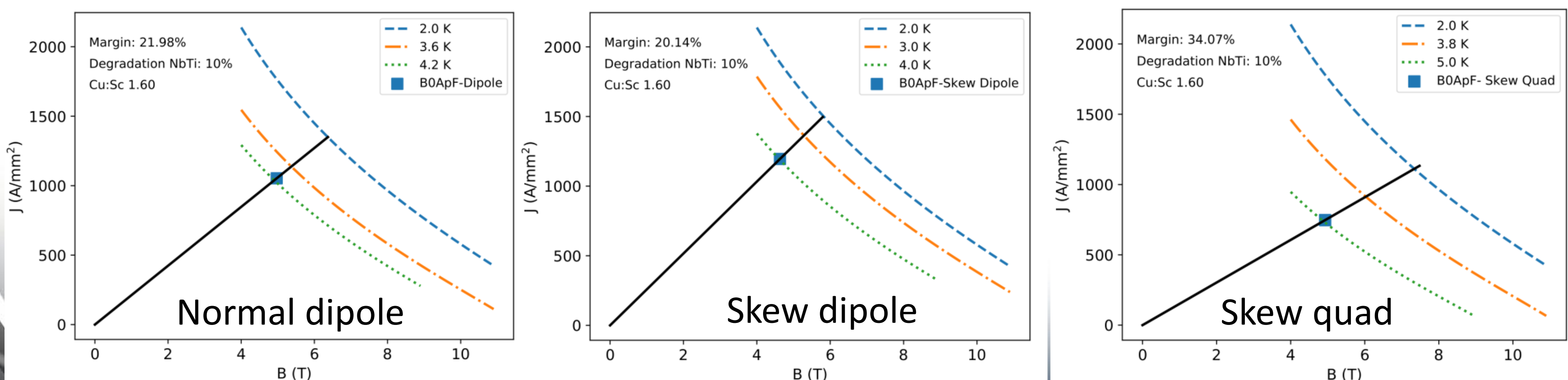
- Horizontal corrector, 3.3T, 0.6m long
  - Reason: B0pF is fixed field magnet
  - Different energies: different orbits
  - B0ApF and B1(A)pF: same orbit
- Also: vertical corrector
  - Detector solenoid compensation
- Also: possible location for skew quadrupole



Skew Quad, Hadron Forward

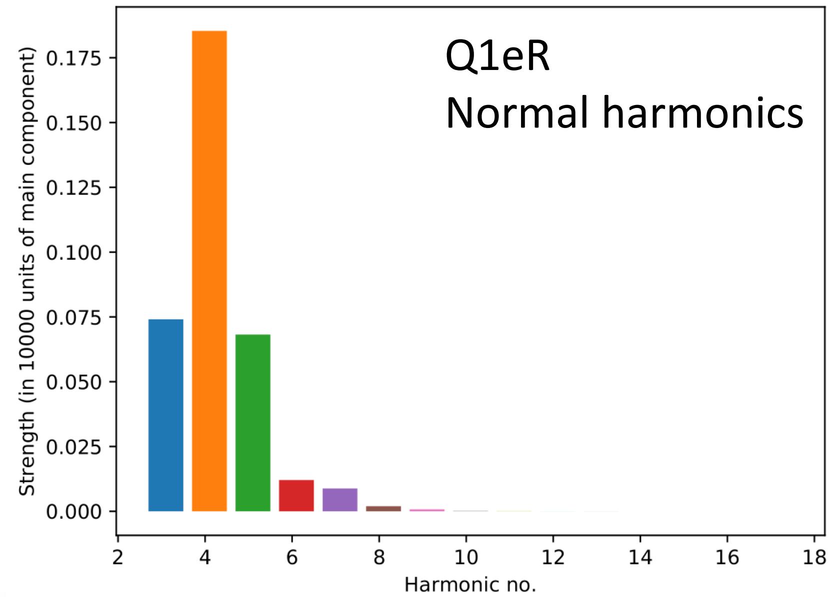
- Implementation: CCT
  - Serpentine pattern could be more efficient
- Sufficient margin for all multipoles at 2K
- Lower detector solenoid field: margins will increase

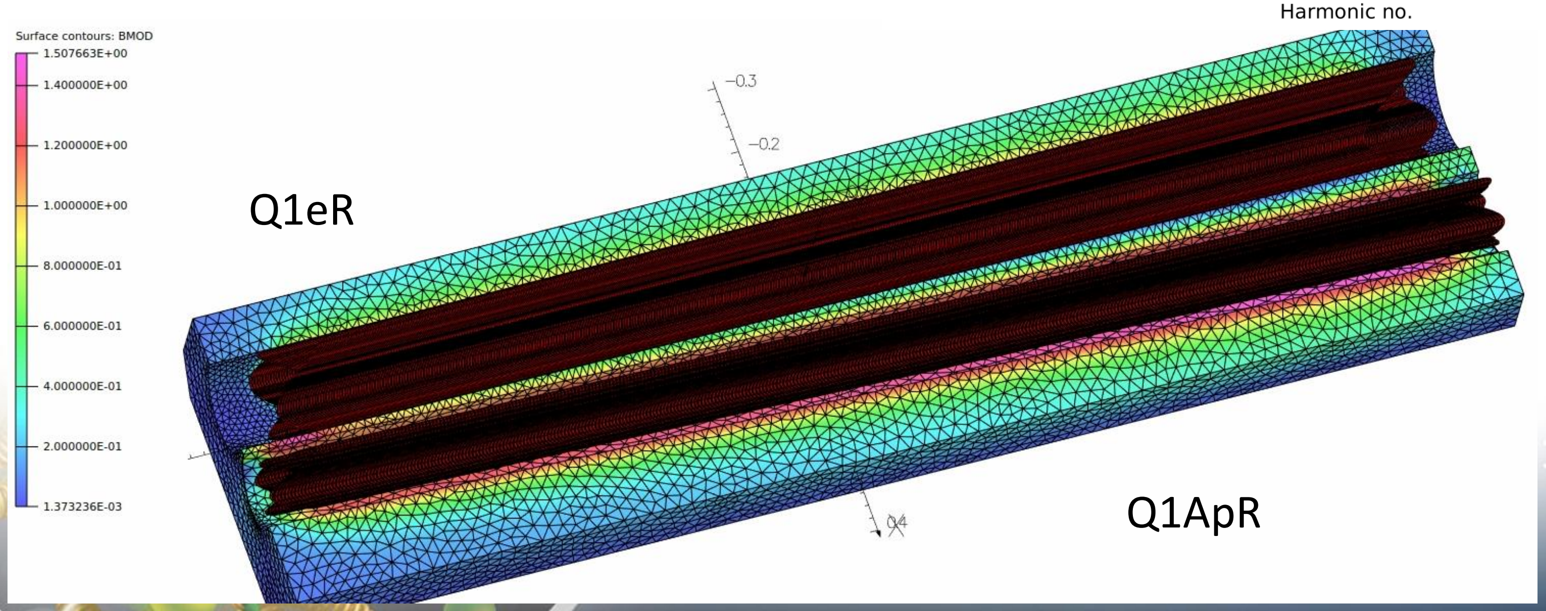




Q1ApR/Q1eR Tapered Quads

- Tapered CCT FF quadrupole magnets
- Clear apertures
  - Q1eR: IR 47.6... 55.7 mm
  - Q1ApR: IR 20…26 mm
- Gradient
  - Q1ApR: 78T/m
  - Q1eR: 14T/m
- Harmonics: <0.25 units





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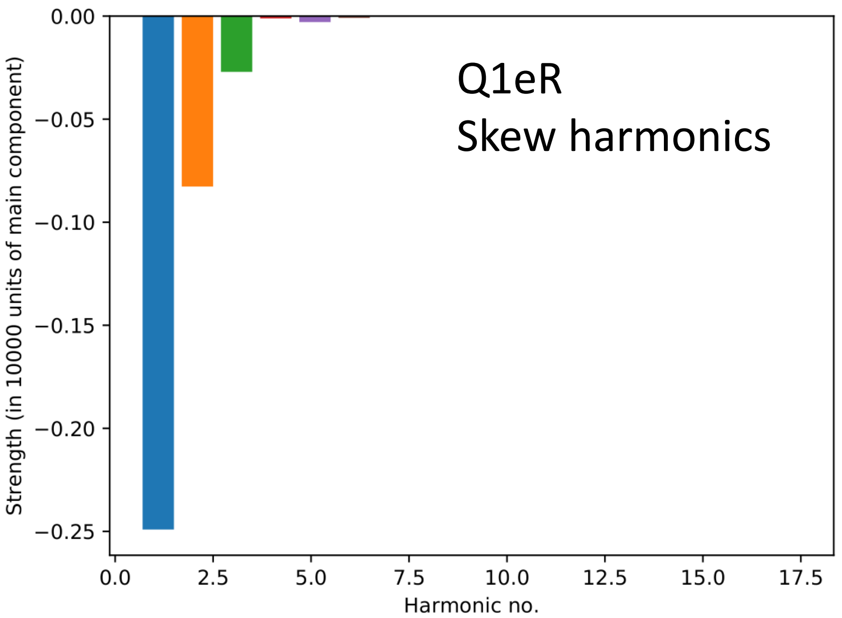
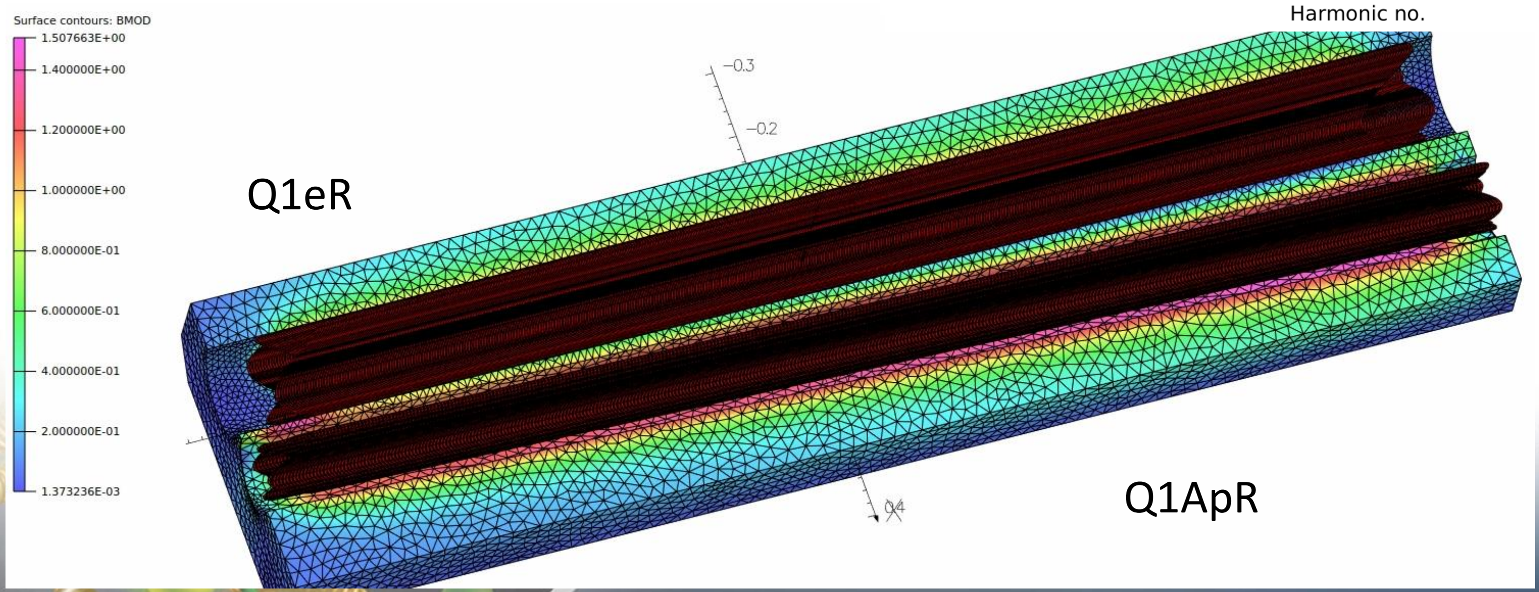
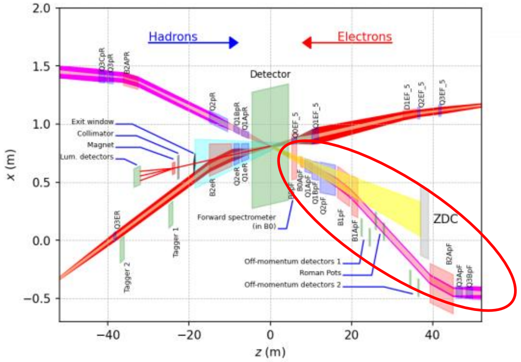
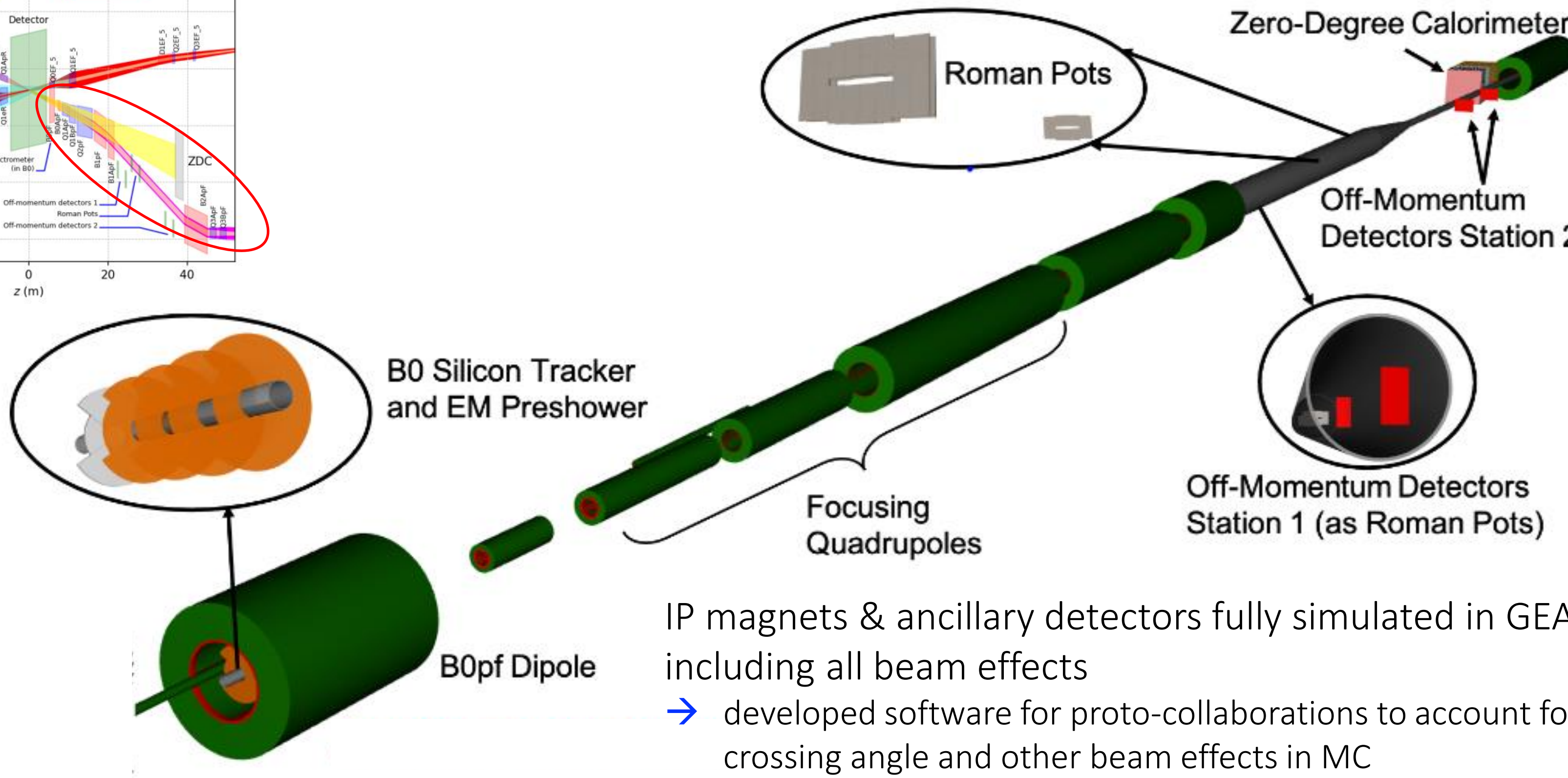




Progress – Integration to IR

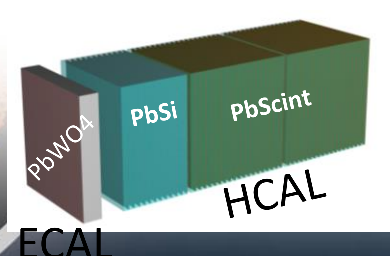


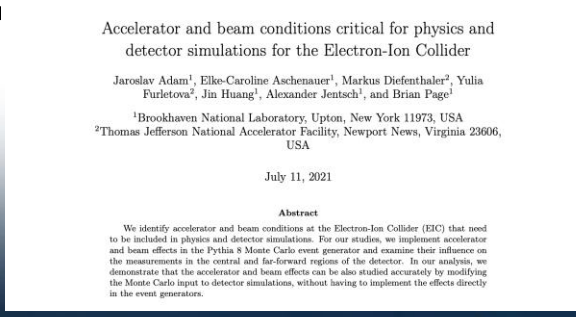


IP magnets & ancillary detectors fully simulated in GEANT including all beam effects

- → developed software for proto-collaborations to account for crossing angle and other beam effects in MC
- → to be published http://www.eicug.org/web/sites/default/files/Accelerator_and_beam_condition

Courtesy of
E. Aschenauer & group (BNL)




Accelerator and beam conditions critical for physics and detector simulations for the Electron-Ion Collider

Jaroslav Adam[1], Elke-Caroline Aschenauer[1], Markus Diefenthaler[2], Yulia Furletova[2], Jin Huang[1], Alexander Jentsch[1], and Brian Page[1]

[1]Brookhaven National Laboratory, Upton, New York 11973, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

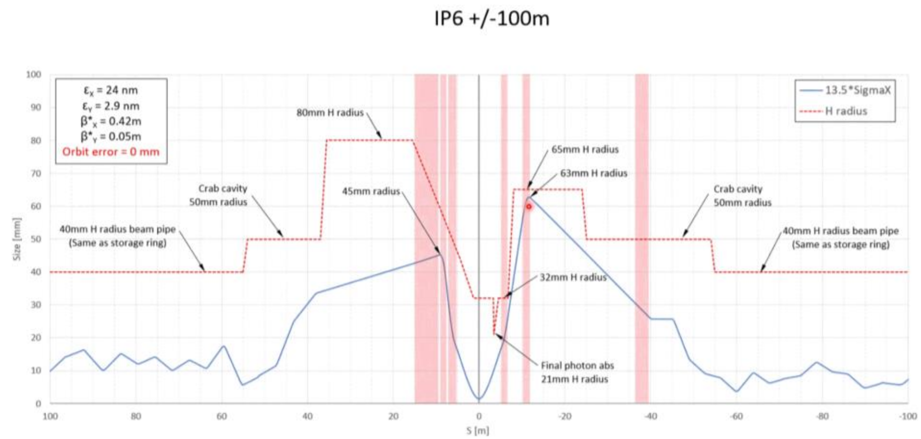
July 11, 2021

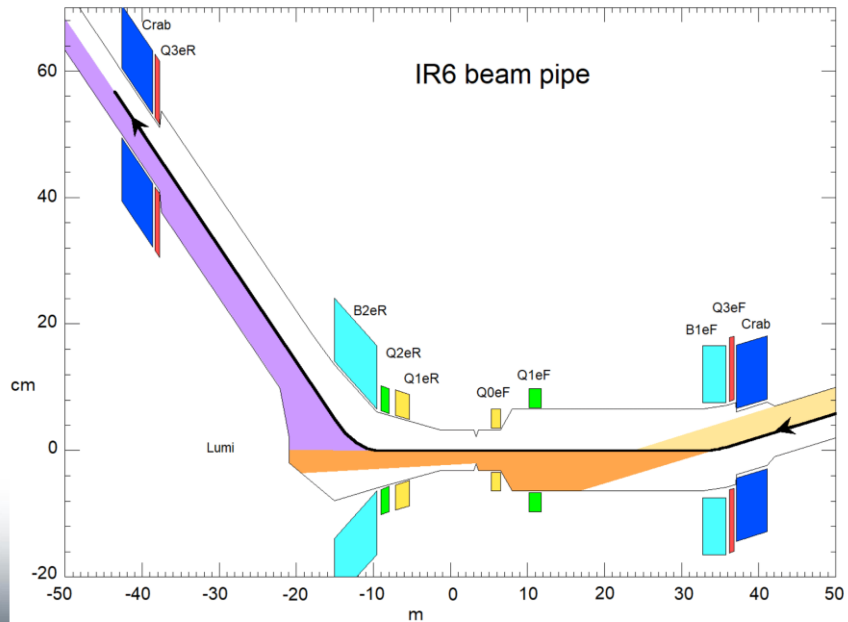
Abstract

We identify accelerator and beam conditions at the Electron-Ion Collider (EIC) that need to be included in physics and detector simulations. For our studies, we implement accelerator and beam effects in the Pythia 8 Monte Carlo event generator and examine their influence on the measurements in the central and far-forward regions of the detector. In our analysis, we demonstrate that the accelerator and beam effects can be also studied accurately by modifying the Monte Carlo input to detector simulations, without having to implement the effects directly in the event generators.

Synchrotron Radiation

- Extensive simulations of SR by dedicated working group
  - Including photo desorption
  - SR photon spectrum provided to collaborations
- Two separate codes with good agreement
  - Synrad3D
  - SYNC_BKG (Mike Sullivan)
- Focus on
  - Central chamber
  - Lumi window
  - Polarimeter
  - Heat loads inner IR
  - Spin rotators/crab cavities



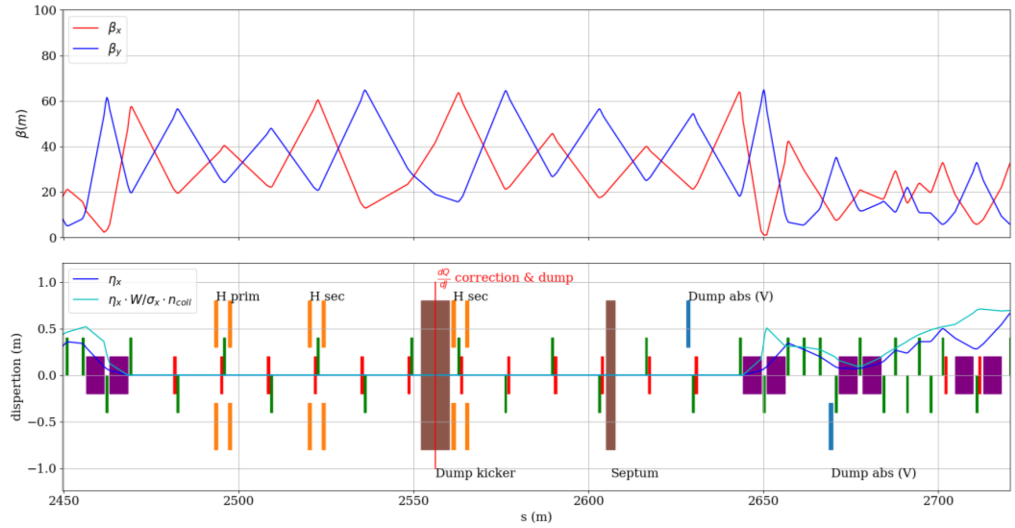


Courtesy of C. Hetzel (BNL) / M. Sullivan (SLAC)

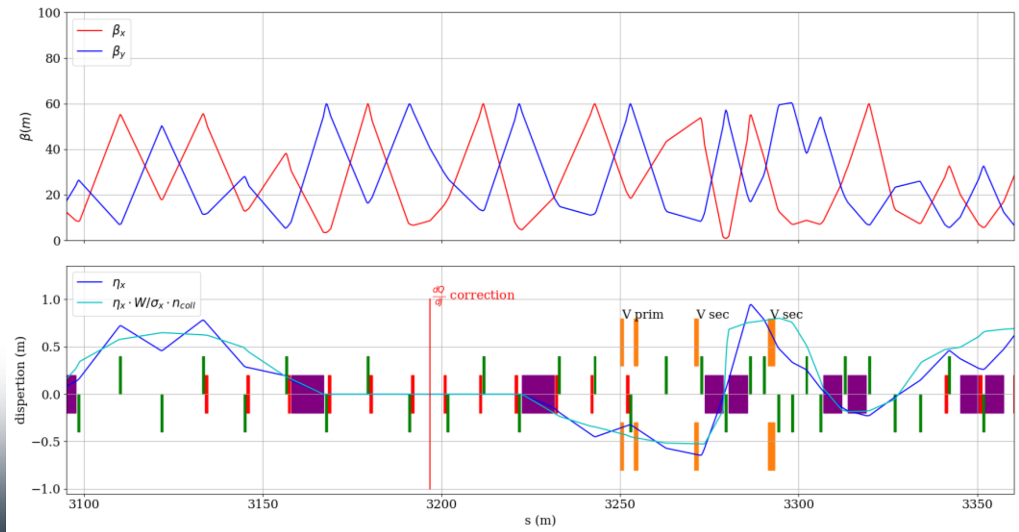
Collimators

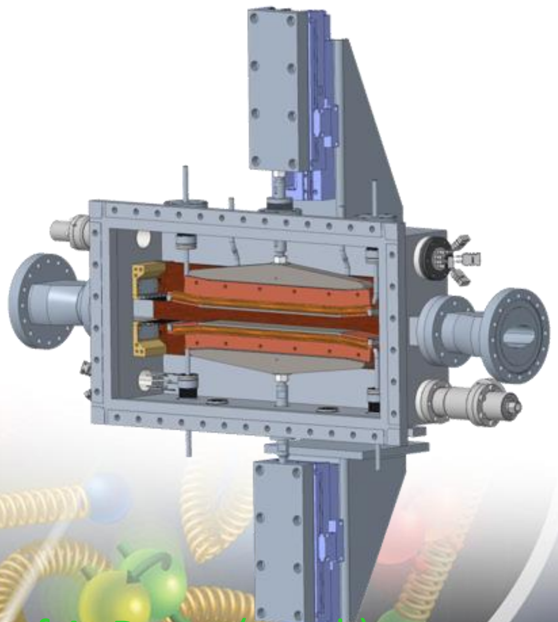
- ESR
  - Planned in IR2 & 4
  - 2-sided prim. + 2 sec. for cleaning and flexibility with phase advances and optics

IR2 - Horizontal



IR4 – Vertical

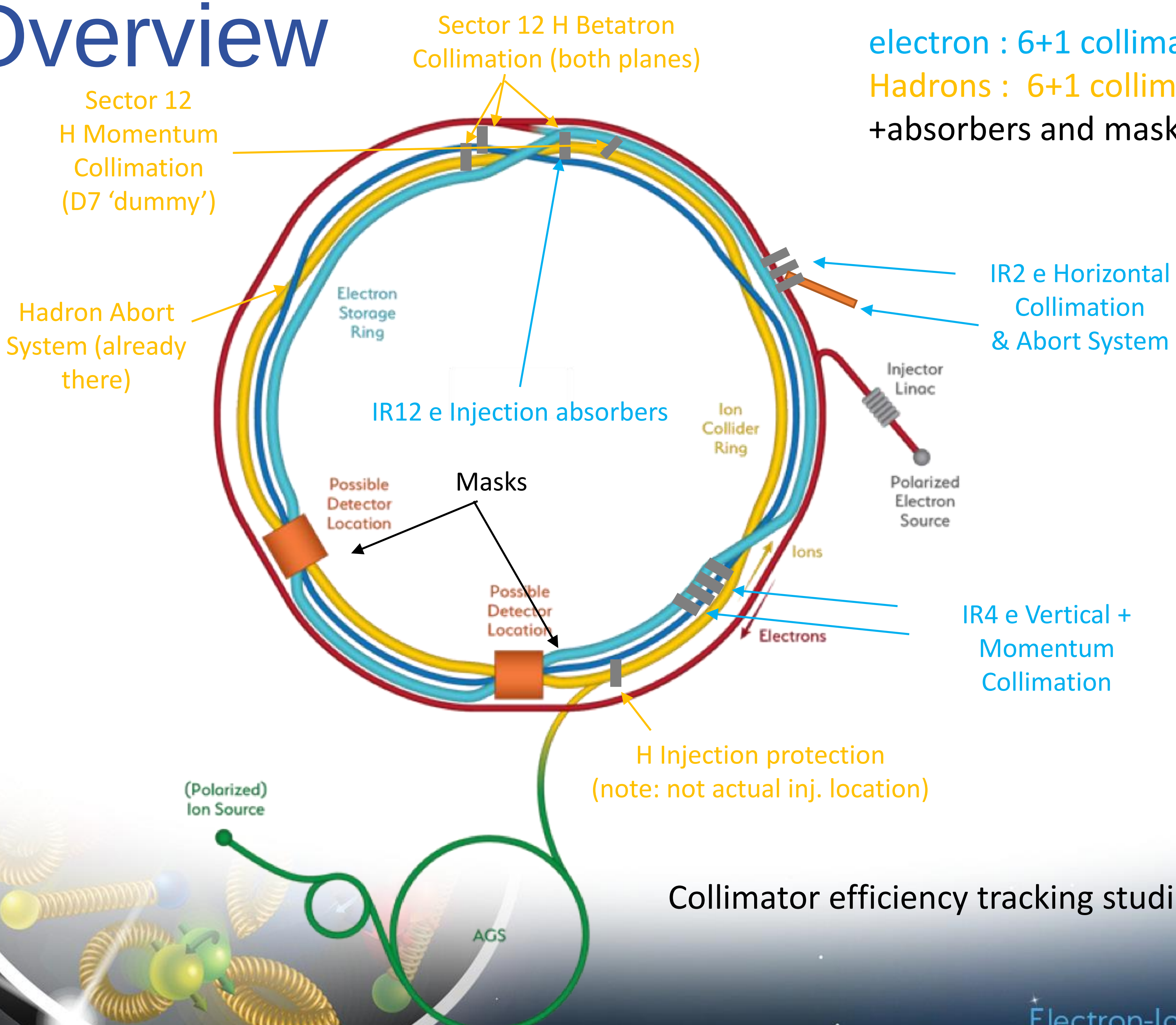




Courtesy of A. Drees (et. al.)

Overview

electron : 6+1 collimators
Hadrons : 6+1 collimators
+absorbers and masks



Collimator efficiency tracking studies ongoing

Summary

- IR design is mature
- Collared magnets: preliminary design complete
  - 2D/3D
  - 2K operation
- Most magnets: direct wind manufacturing technique
  - Preliminary designs complete
  - Including corrector magnets into designs
- Synchrotron radiation
- Detector integration
- Collimator design progressing

Acknowledgements

BNL

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SLAC

M. Sullivan, Y. Nosochkov, A. Novokhatski

ORNL

V. Morozov

. . . and many more!

Additional Slides

Forward Hadron Magnets

	Length	IR1	Pole tip field R1	Dipole Field	Gradient
	m	cm	T	T	T/m
B0pF	1.2	17		-1.3	
B0ApF	0.6	4.3		3.3	
Q1ApF	1.46	5.6	4.07	0	-77.903
Q1BpF	1.61	7.8	5.16	0	-63.028
Q2pF	3.6	11.3	5.36	0	39.736
B1pF	3	13.5		3.4	
B1ApF	1.5	16.8		2.7	

IR1: inner radius (= clear aperture) at coil beginning
Pole tip field R1: IR1*gradient

Collared coils, apart from B0pF and B0ApF (direct wind)

Forward Electron Magnets

	Length	IR1	IR2	Pole tip field R1	Pole tip field R2	Gradient
	m	cm	cm	T	T	T/m
Q0eF	1.2	2.5	2.5	0.4	0.4	13.5
Q1eF	1.61	6.3	6.3	0.5	0.5	8.1

IR1: inner radius (= clear aperture) at coil beginning
IR2: inner radius (= clear aperture) at coil end
Pole tip field R1: IR1*gradient
Pole tip field R2: IR2*gradient

All direct wind coils

Rear Hadron Magnets

	Length	IR1	IR2	Pole tip field R1	Pole tip field R2	Gradient
	m	cm	cm	T	T	T/m
Q1ApR	1.8	2.0	2.56	1.56	2.	78
Q1BpR	1.4	2.8	2.8	2.184	2.184	78
Q2pR	4.5	5.4	5.4	1.84	1.84	34

IR1: inner radius (= clear aperture) at coil beginning
IR2: inner radius (= clear aperture) at coil end
Pole tip field R1: IR1*gradient
Pole tip field R2: IR2*gradient

All direct wind coils
Q1ApR: tapered

Rear Electron Magnets

	Length	IR1	IR2	Pole tip field R1	Pole tip field R2	Dipole Field	Gradient
	m	cm	cm	T	T	T	T/m
Q1eR	1.8	4.76	5.57	0.67	0.78	0	14
Q2eR	1.4	6.43	6.43	0.91	0.91	0	14.1
B2AeR	2.0	90.45	90.45	0.192	0.192	0.192	0
B2BeR	3.45	111.45	111.45	0.238	0.238	0.238	0

IR1: inner radius (= clear aperture) at coil beginning
IR2: inner radius (= clear aperture) at coil end
Pole tip field R1: IR1*gradient
Pole tip field R2: IR2*gradient

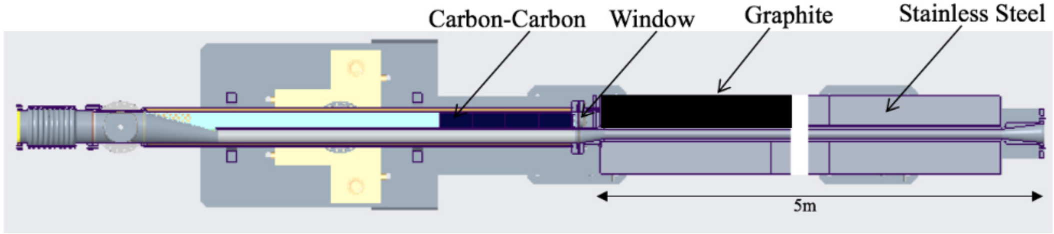
All direct wind coils
Q1eR: tapered double-helix coil

Abort systems: HSR & ESR

- HSR:

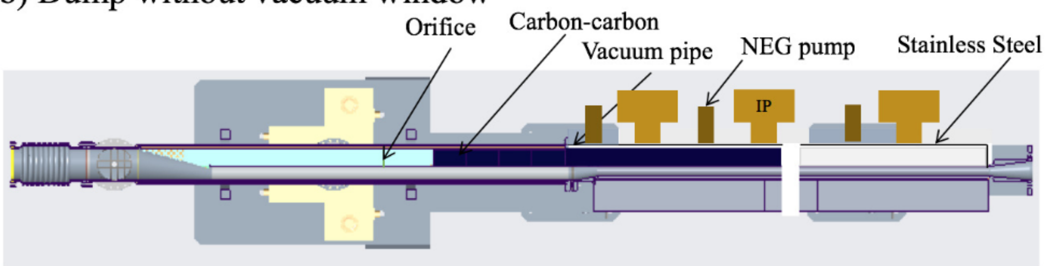
The plan is to keep the current RHIC system w. necessary upgrades

(a) Existing dump with vacuum window



0.5 m C-C blocks, 2.6 m graphite blocks and 2.0 m SS blocks

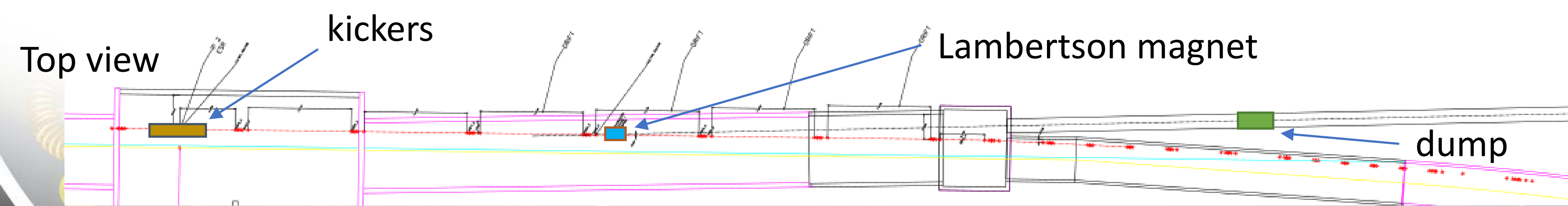
(b) Dump without vacuum window



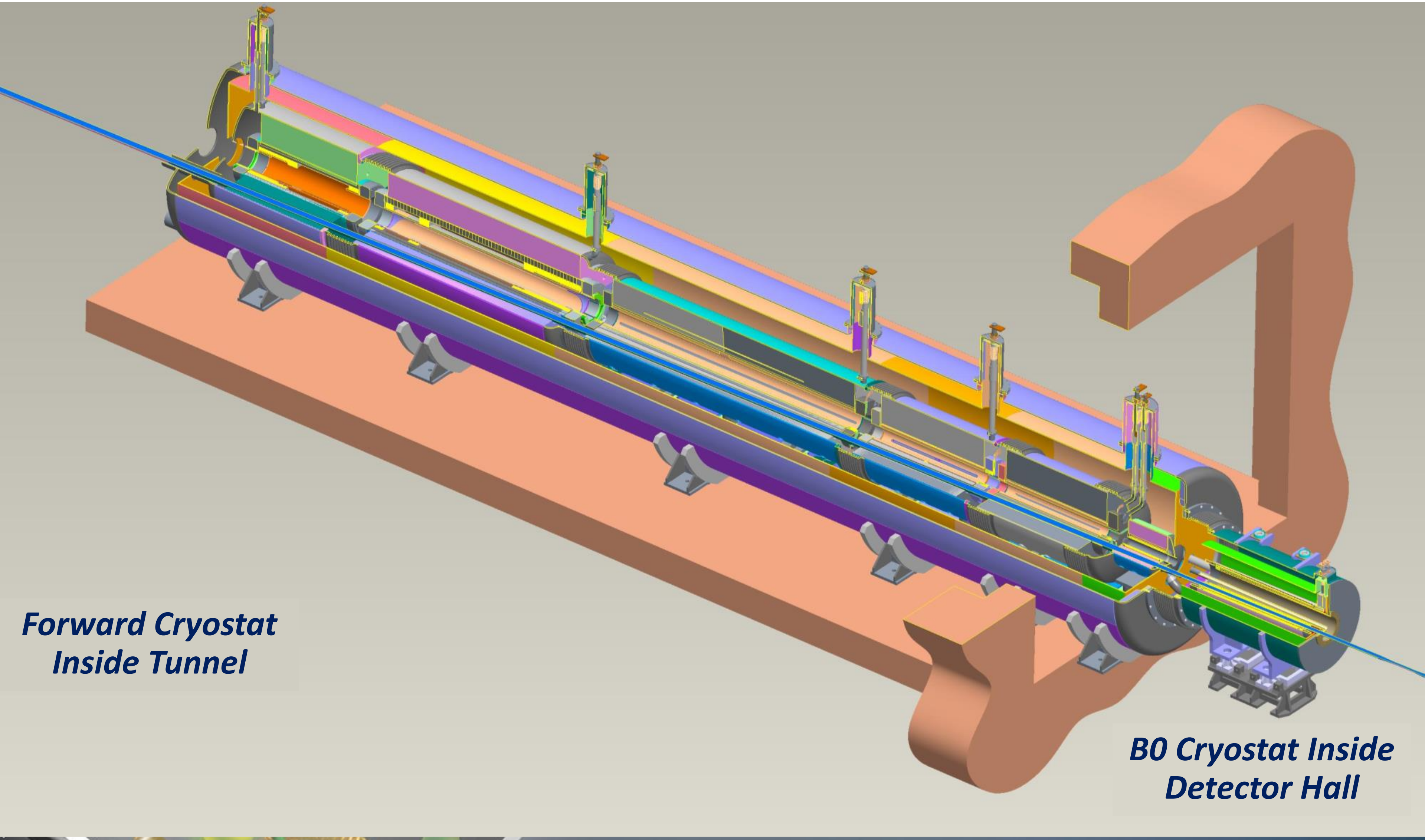
3.2 m C-C blocks and 2.0 m SS blocks

- ESR:

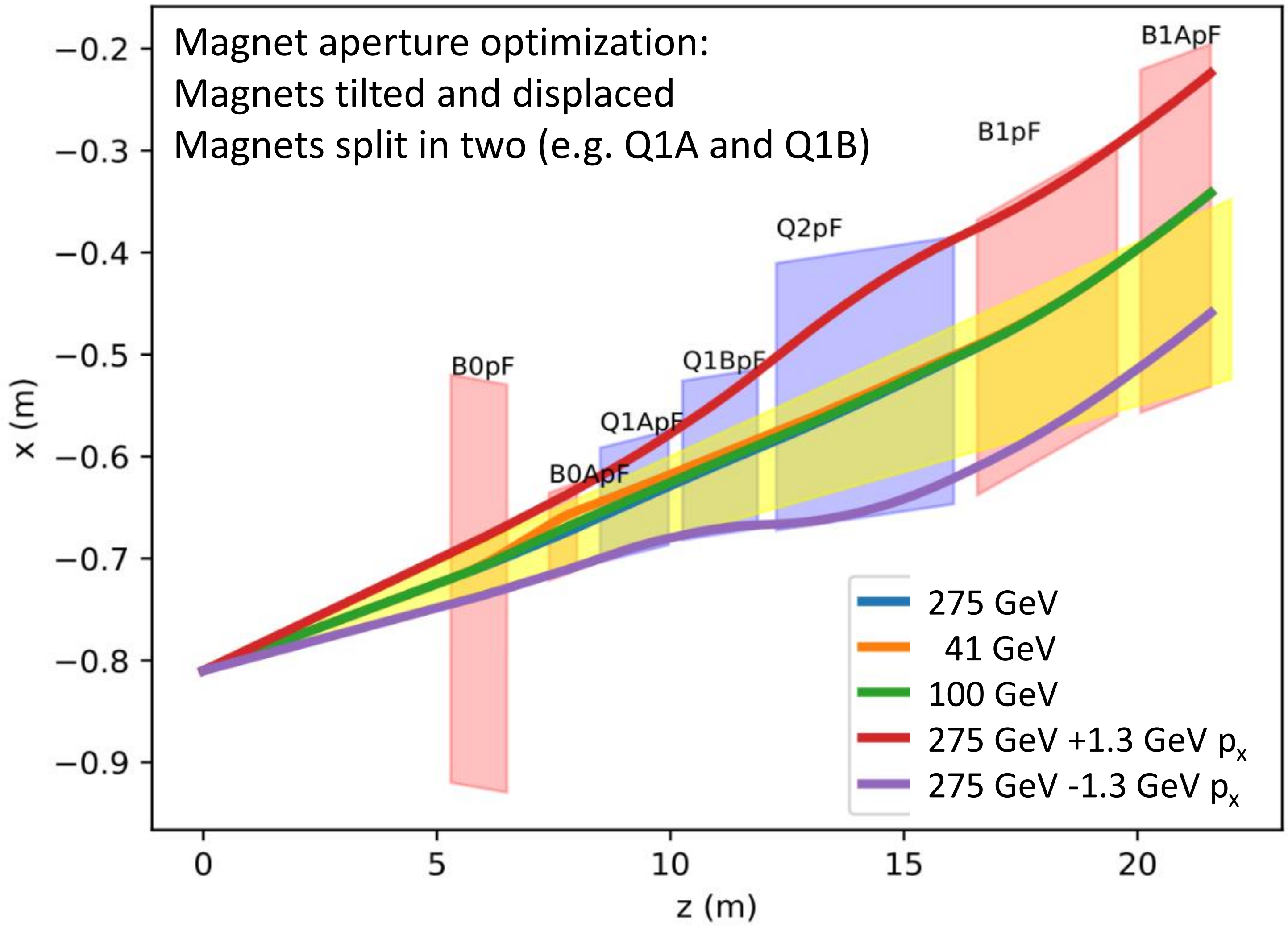
Plan to use an unused spectrometer tunnel in IR2 which will allow extracting the 300-kJ beam away from other IR2 users. It features 6 x 2-mrad vertical kickers, a 2° Lamberton magnet & a 50m-long transfer line with 6 warm quads.



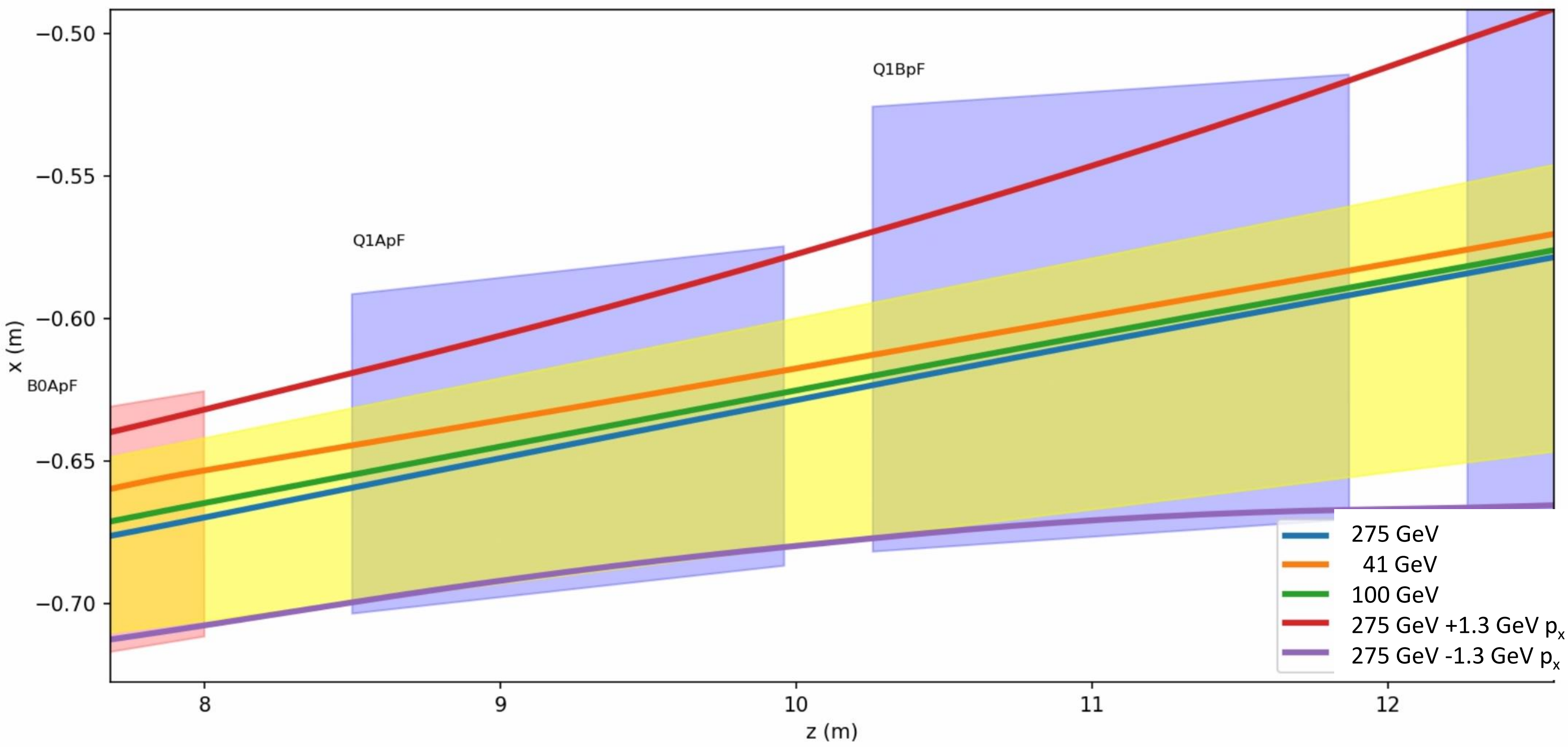
Forward Side, Two Cryostat Layout



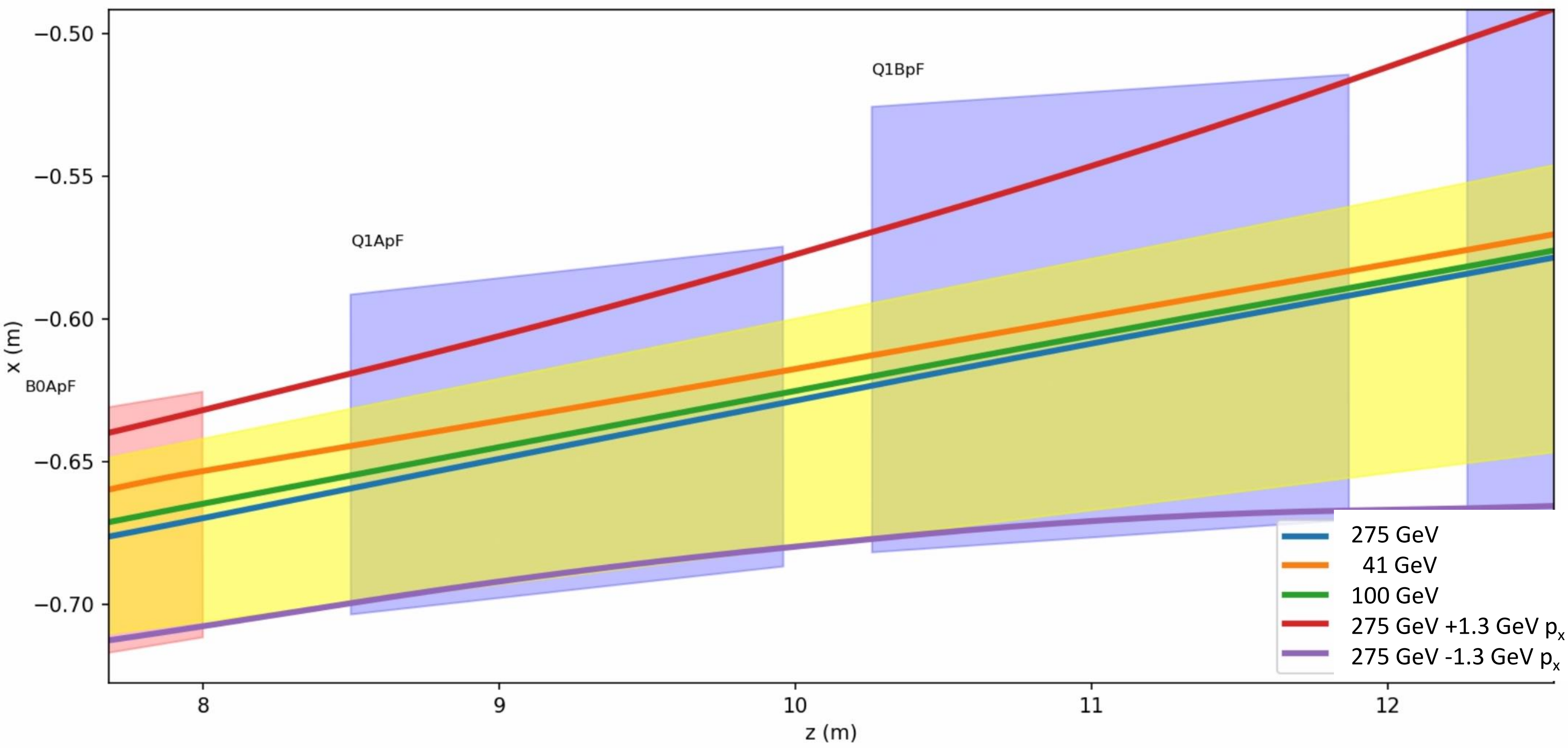
Hadron Forward - Apertures



Q1ABpF – New Magnet Concept

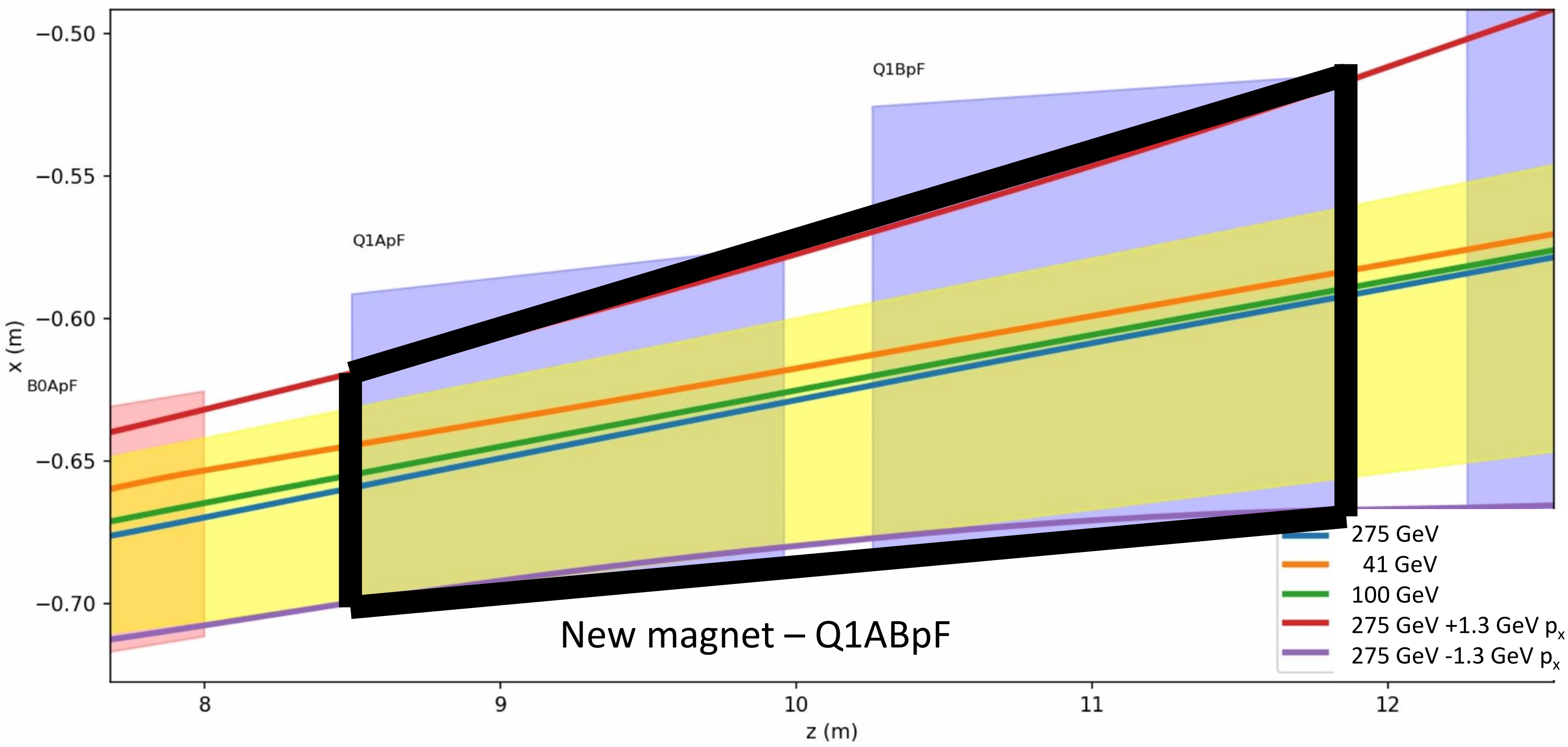


Q1ABpF – New Magnet Concept



Q1ABpF – New Magnet Concept

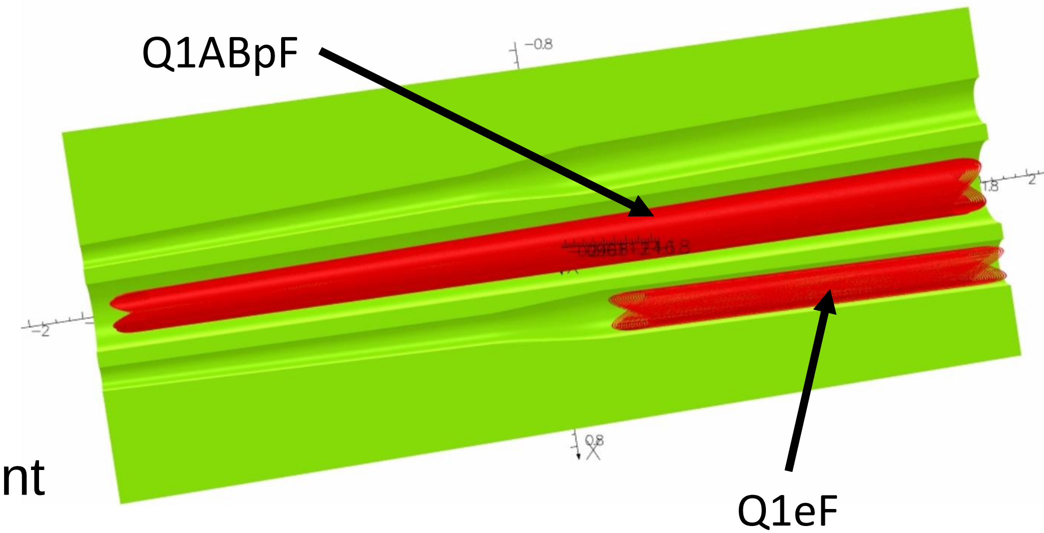
Recombining Q1ApF and Q1BpF

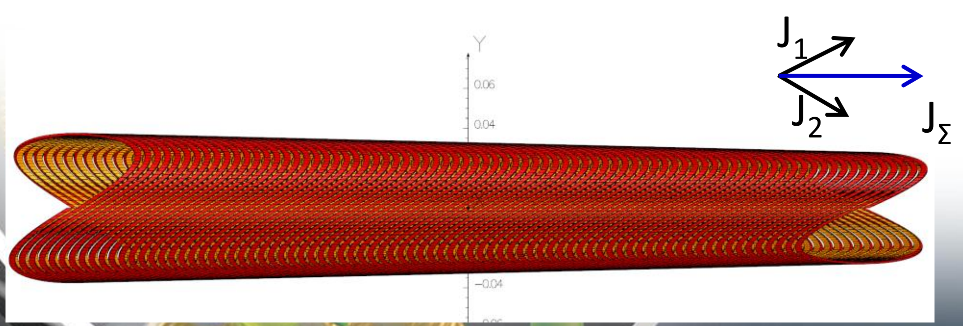


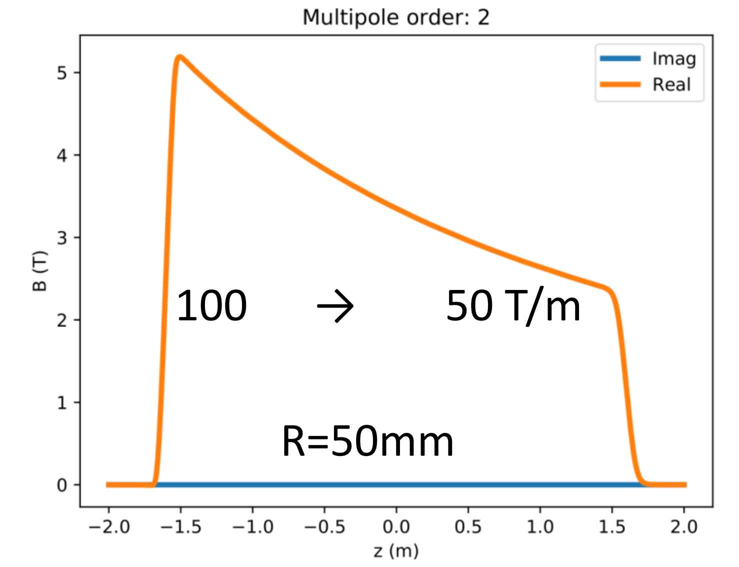
Advantages: No end plates, making use of additional space between magnets
Smaller aperture at IP side

Q1ABpF: Implementation

- CCT
  - Allows to cancel unwanted harmonics
  - Modulation of gradient
- Frontloading of gradient
- Helps crosstalk / field quality
  - Better utilization of space
  - Can tailor maximum gradient
- Challenges
  - Need to prove that this works mechanically
  - No collar

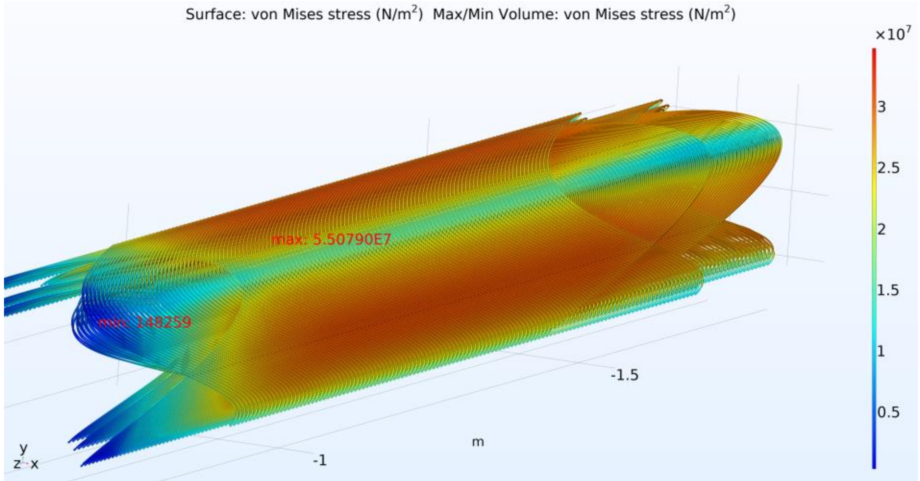


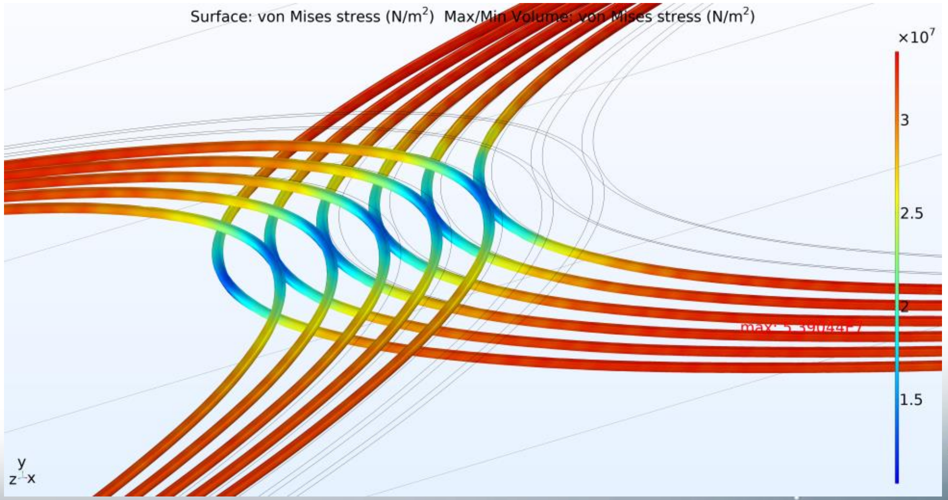


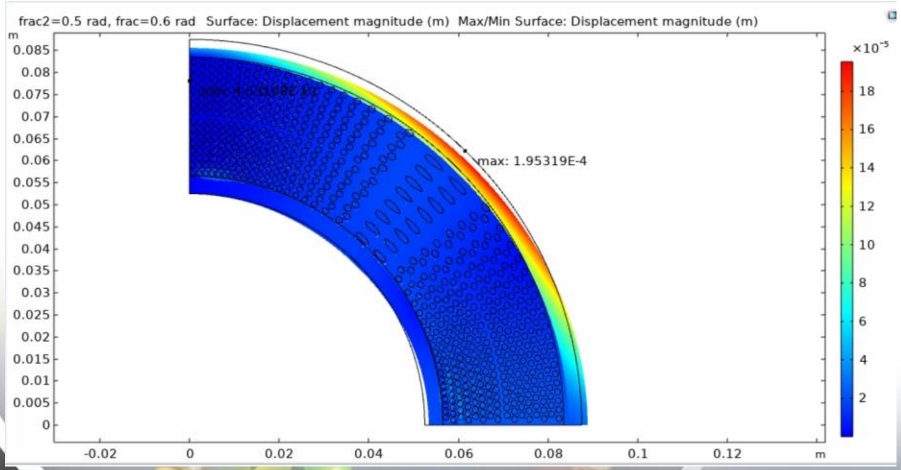


Mechanical Analysis

- Ongoing work
  - 2D/3D
- Modeling details 3D
  - Opera 3D: Forces
  - CATIA: Geometry and fill
  - COMSOL: Structural analysis
  - Complexity: 1TB RAM
- COMSOL 2D
  - Contact elements
  - Pre-stress, cooldown and Lorentz force

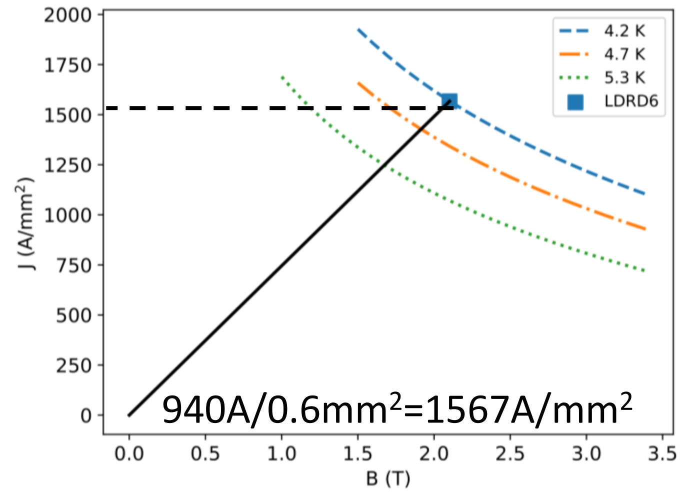


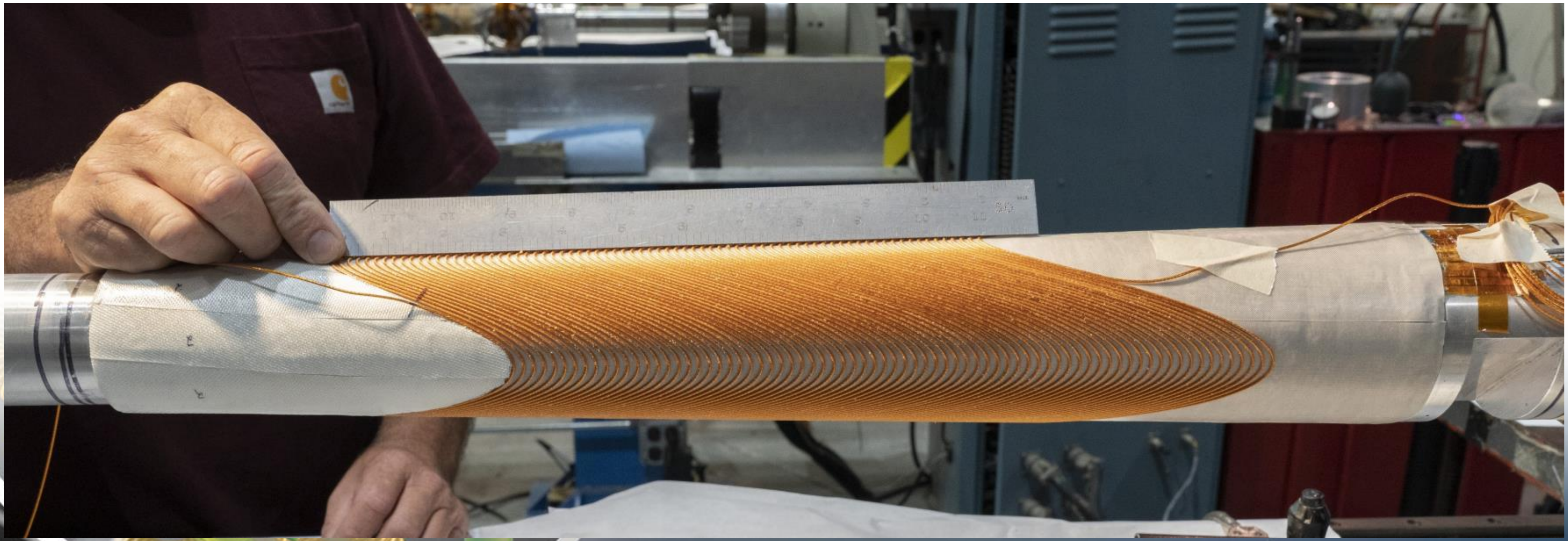




Tapered Double Helix Magnet

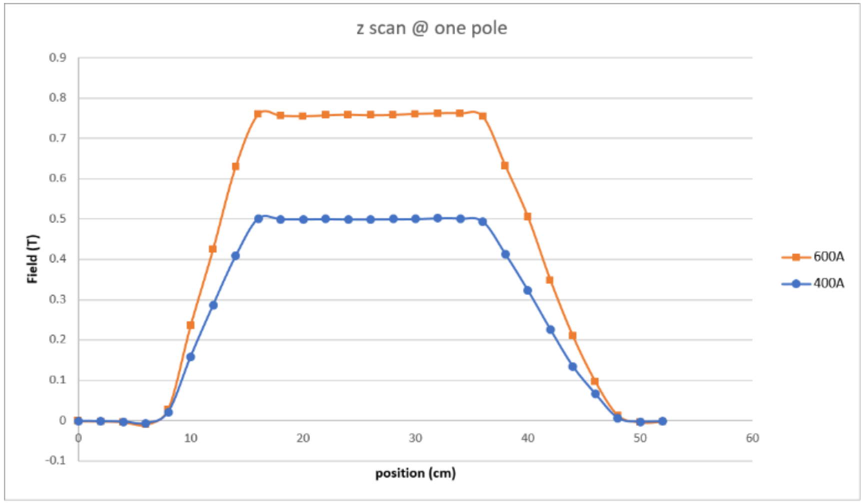
- Tapered double helix demonstrator
- 4 layer coil, NbTi, 4.2K
  - Aperture: 60..80mm
  - L=0.4m
- Tested successfully 7/16/2020
  - 40 T/m, no quench up to short sample

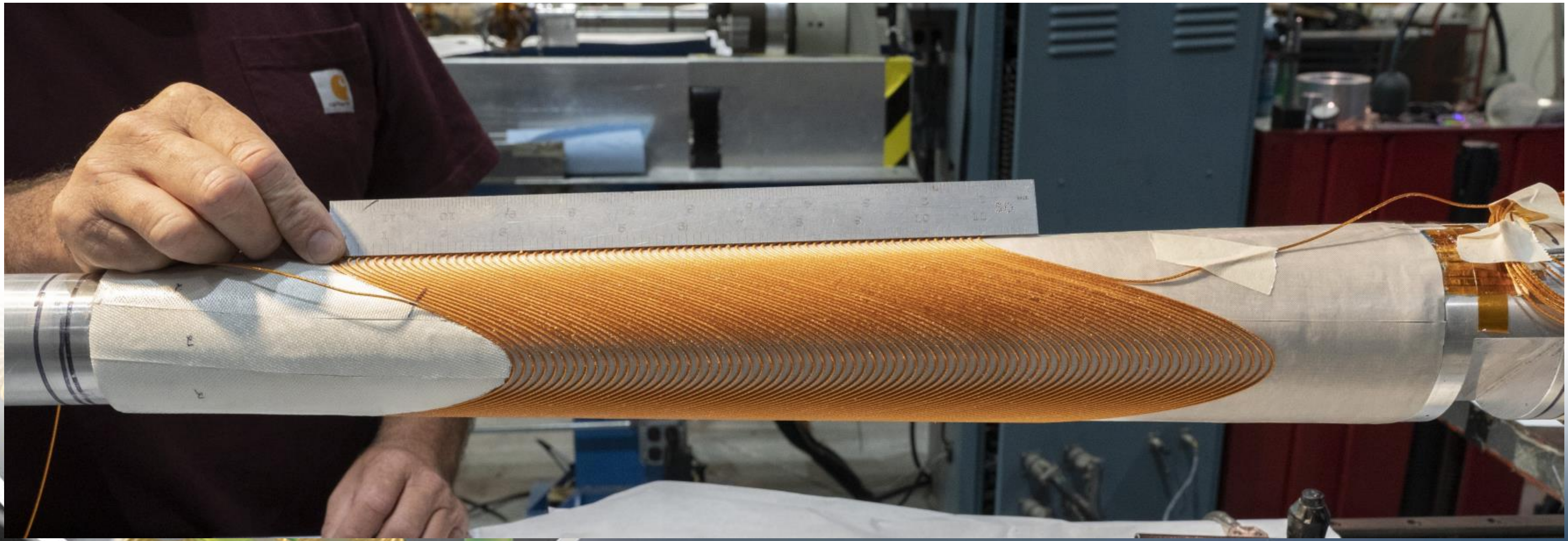




Tapered Double Helix Magnet

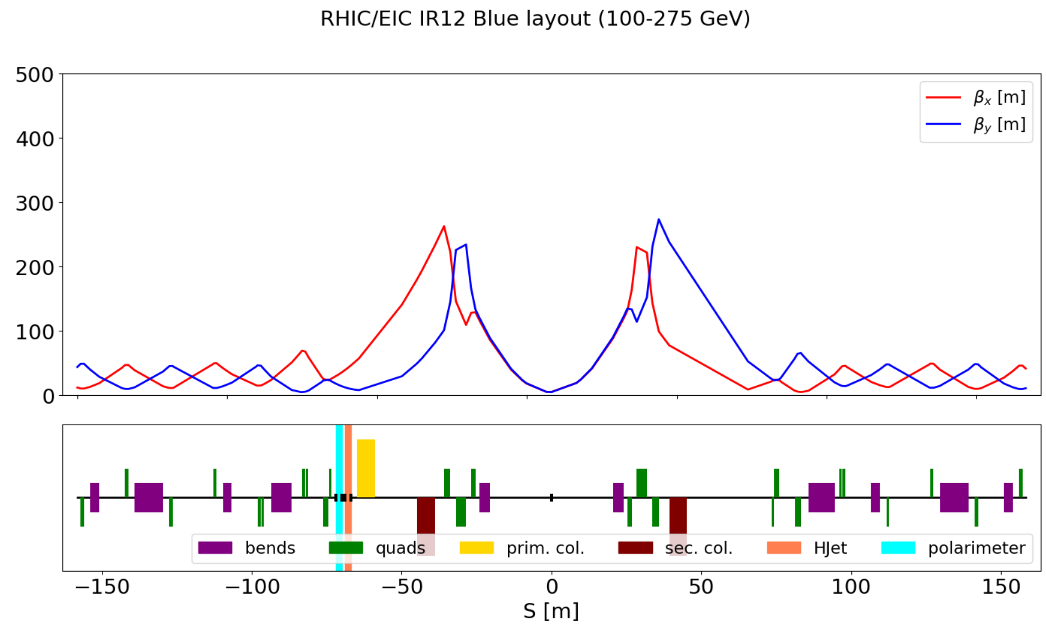
- Tapered double helix demonstrator
- 4 layer coil, NbTi, 4.2K
  - Aperture: 60..80mm
  - L=0.4m
- Tested successfully 7/16/2020
  - 40 T/m, no quench up to short sample
- Constant gradient despite taper
- H. Witte et al. http://dx.doi.org/10.1109/TASC.2019.2902982

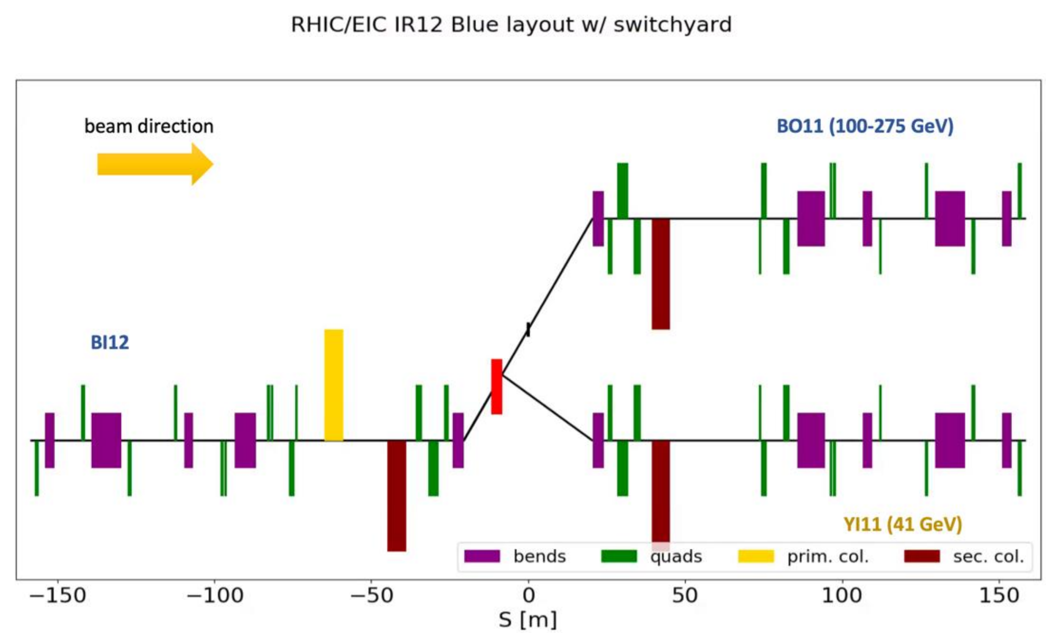




HSR Collimators

- Different constraints:
  - Different loss behavior for protons/ions
  - Cold ring requires good cleaning efficiency in the arcs
  - More flexibility on the optics
- We can benefit from RHIC and LHC experience.
- Planned in IR12 :
  - issues with other users due to radiation
  - switchyard doubles the second secondary
  - Real estate
- Momentum collimators are planned for the sector 12 ”D7” dummy.
  - Requires cryo-bypass!





Courtesy of G. Robert-Demolaize