Plans for LS2 (IR upgrade)

Y. Arimoto
2025-01-15 ARC

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Answer to recommendations from the last ARC

Overview

- Masuzawa-san reported on IR Upgrade at last year's ARC
- She presented an option to bring QC1P closer to 100 mm IP.
- To apply this, QC1P coils should be made of Nb_3Sn, not NbTi.
- We have started the development of Nb_3Sn QC1P to support this option.
- We obtained budgets from the Japan-US Science and Technology Cooperation this fiscal year and started development in collaboration with FNAL and Furukawa Electric Co.

Answers to recommendations from the last ARC

- R26.1: Determine which SuperKEKB accelerator studies need to be done during the next few years, and when, to allow technical decisions related to the future upgrades to be made at an appropriate time.
- **A**: We plan to test the prototype QC1P within the next three years. The results of these tests will provide important insights for future technical decisions.
- R26.2: Encourage laboratory tests of crucial technologies (e.g. thin Nb_3Sn coils) to be done over the next few years.
- **A**: Yes, we are currently working on testing the prototype Nb3Sn quadrupole. Efforts are already underway, including magnet design, tooling design, coil winding practice, and short sample testing of superconducting conductors.

Answers to recommendations from the last ARC (cont.)

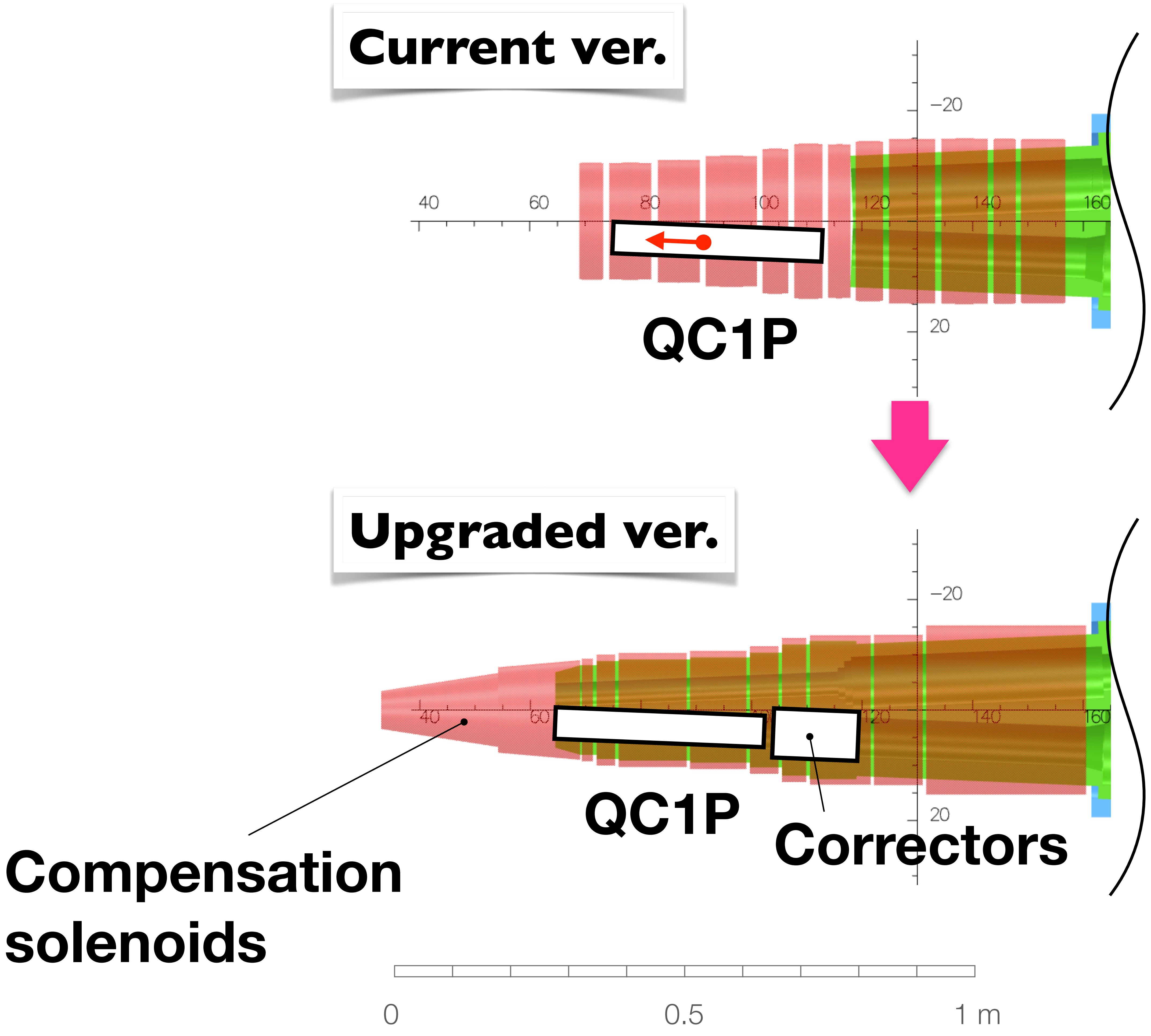
- R26.3: Periodically monitor the composition of the upgrade study group to make sure all the relevant skills sets are included.
- **A**: We hold two main technical meetings on a ~monthly basis:
  - Nb3Sn Magnet Development: Involves KEK, FNAL, and Furukawa.
  - IR Mechanical Study: Involves the Belle II group and the Accelerator group. Additionally, meetings about optics issues are held with the optics group as needed.
- R26.4: Continue the development work on the new Nb_3Sn quadrupoles.
- **A**: Yes, we are continuing development work on the new Nb_3Sn quadrupoles.

Upgrade scheme

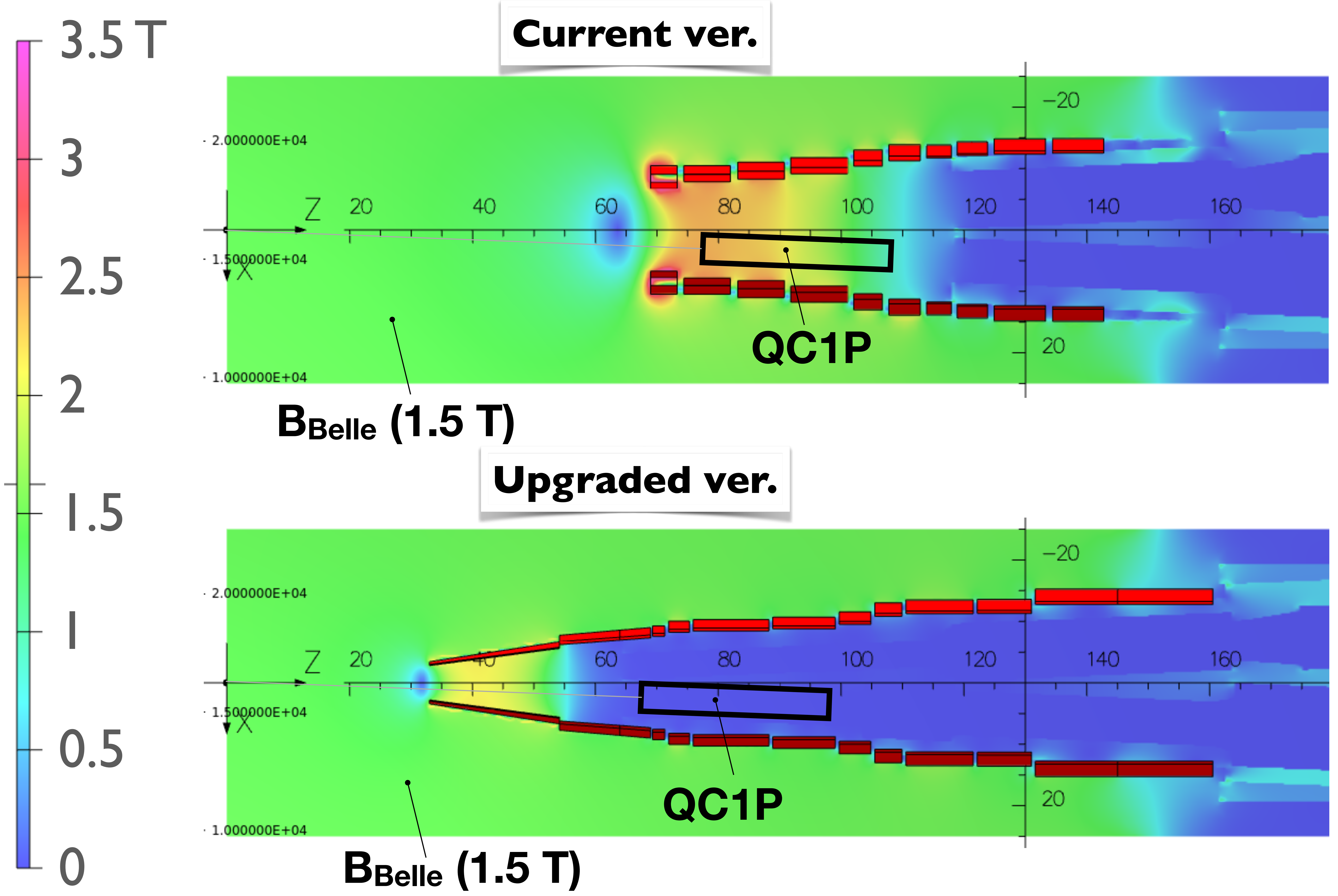
Proposed QCS modifications

- QC1P 100 mm closer to IP
  - Enlarge dynamic aperture of LER
  - Extend the beam lifetime
- Change conductor of QC1P from NbTi to **Nb_3Sn**
  - Decrease risk of beam-induced quench
- Install a compensation solenoid between the IP and QC1P
  - Simplify IR optics
  - Reduce chromatic xy coupling
  - Reduce emittance growth at IR

QCS-R and QCS-L



Solenoid field at QC1P



- The current QC1P is exposed to a large solenoid field; on the other hand, the upgraded one is almost solenoid field-free.

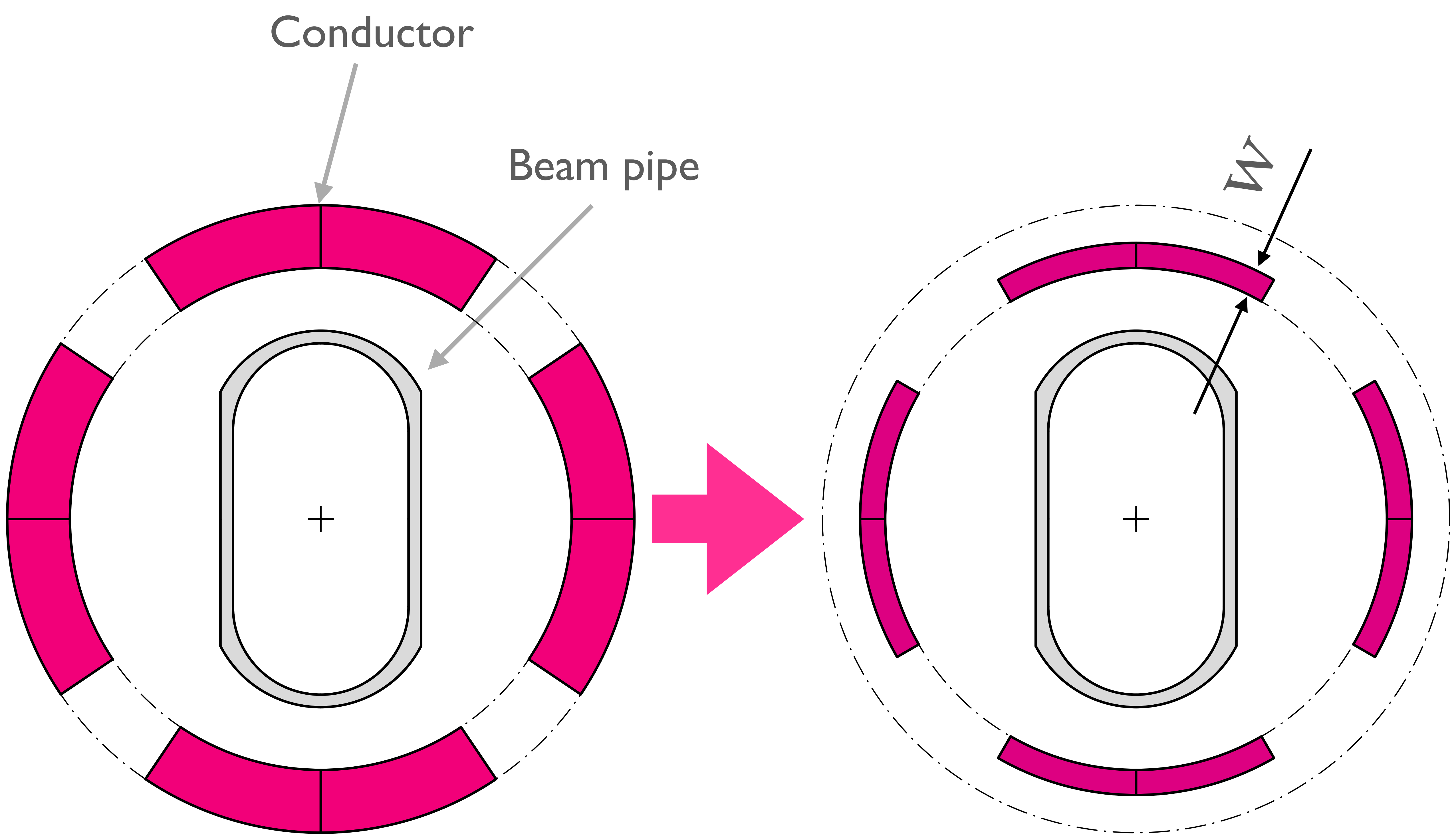
Distance between QC1P and electron beam at different distances from IP

The distance between the beam pipes becomes shorter as the beamline gets closer to the IP.

To avoid interference with e-beam pipes

Thinner conductor cross section!
(< 2 mm)

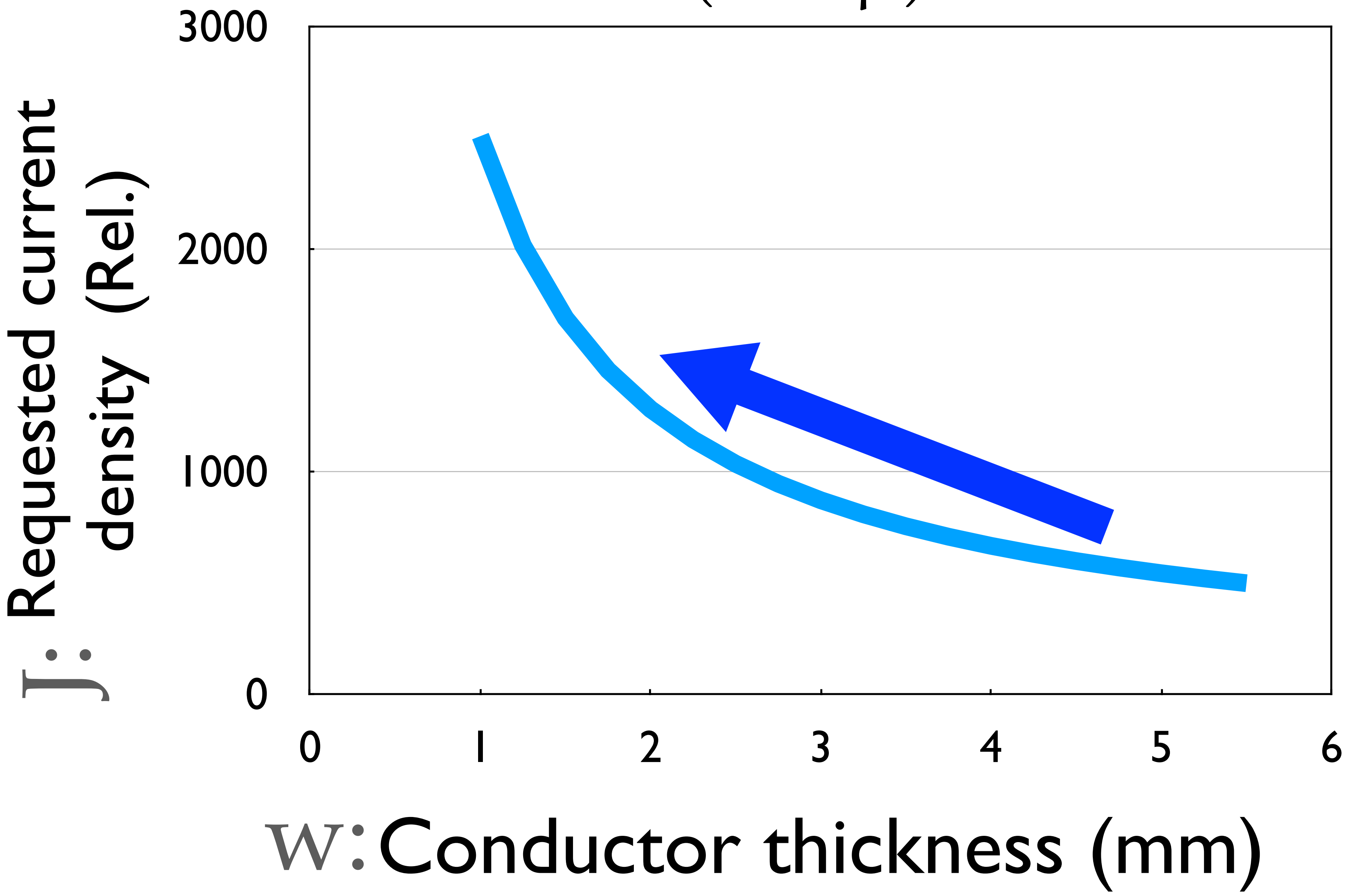
Higher current density !



Magnetic field gradient (G) vs. current density (J), coil width (w)

$$G = \frac{2\mu_0 J}{\pi} \ln\left(1 + \frac{w}{r}\right) \sin 2\theta$$

$$J \propto \ln\left(1 + \frac{w}{r}\right)^{-1}$$



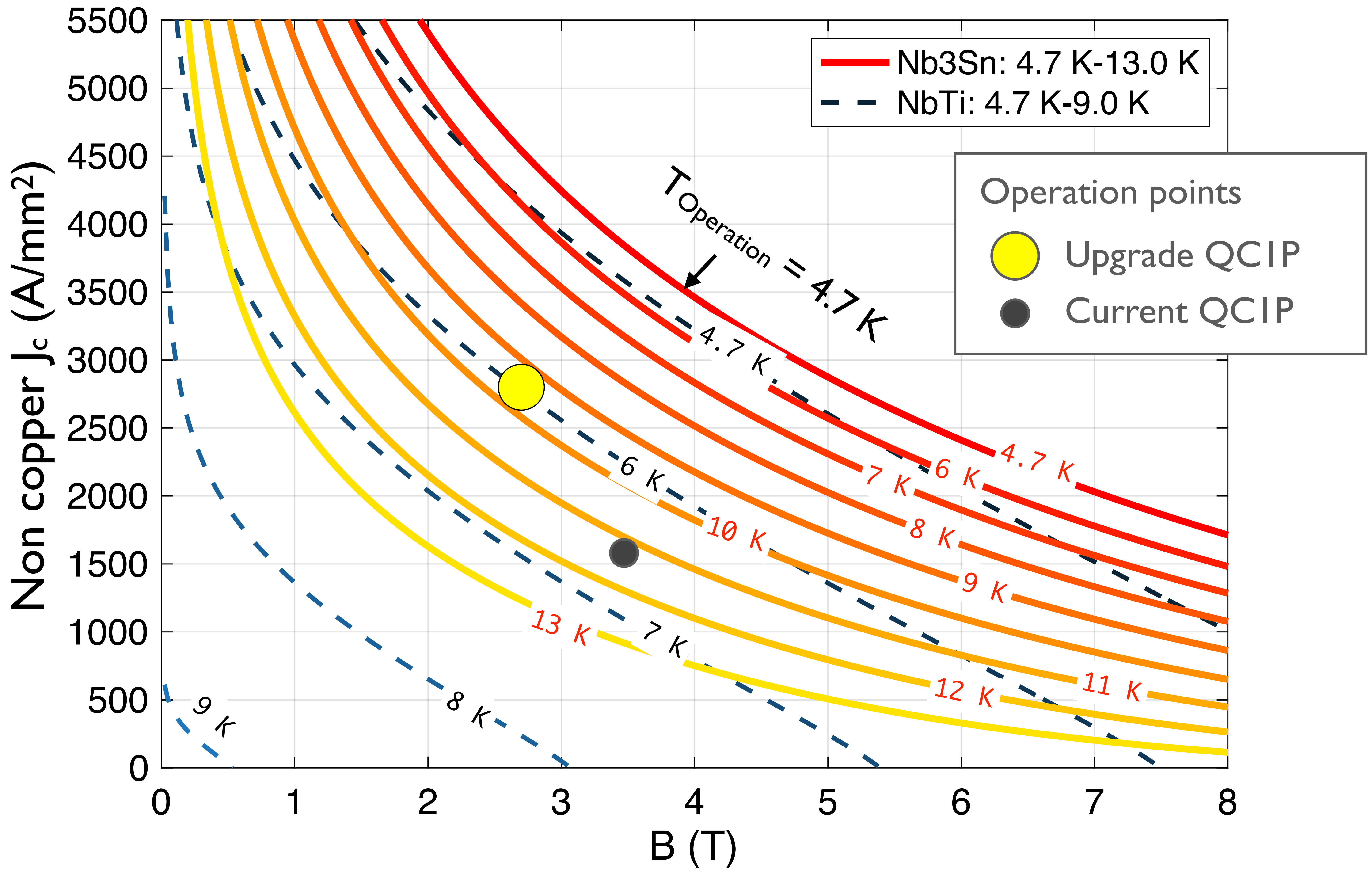
Critical surface and operation points

- Operation point of upgrade QC1P magnet move to larger J region.
- Temperature margin:
  - ΔT ~ 1 K (for NbTi)
  - ΔT ~ 4 K (for Nb_3Sn)
- Compared to the current QC1P, the temperature margin is twice as large

	ΔT [K]	
	Nb3Sn	NbTi
One layer	4	1
Current	-	2

$T_{Operation}$ = 4.7 K

Contour lines of critical surface for Nb3Sn and NbTi



- Nb_3Sn: by K. Suzuki and X. Xu
- NbTi: L. Bottura, A practical fit for the critical surface of NbTi, IEEE Trans. Appl. Supercond. 10 (2000), no. 1, 1054–1057.

Nb3Sn conductor performance required for upgrade QC1P

- Due to limited space, a thin coil is needed
  - Conductor width < 2 mm
  - Large packing factor: rectangle cross section
- For sustainable operation against quench,
  - High-temperature margin > 4 K
- For small flux creep (to avoid drift of magnetic field),
  - Small filament diameter < 5 μm
  - Production using the bronze method can achieve this.

Example of commercial conductor

1.13 mm x 1.7 mm

Filament size: 3.2 μm

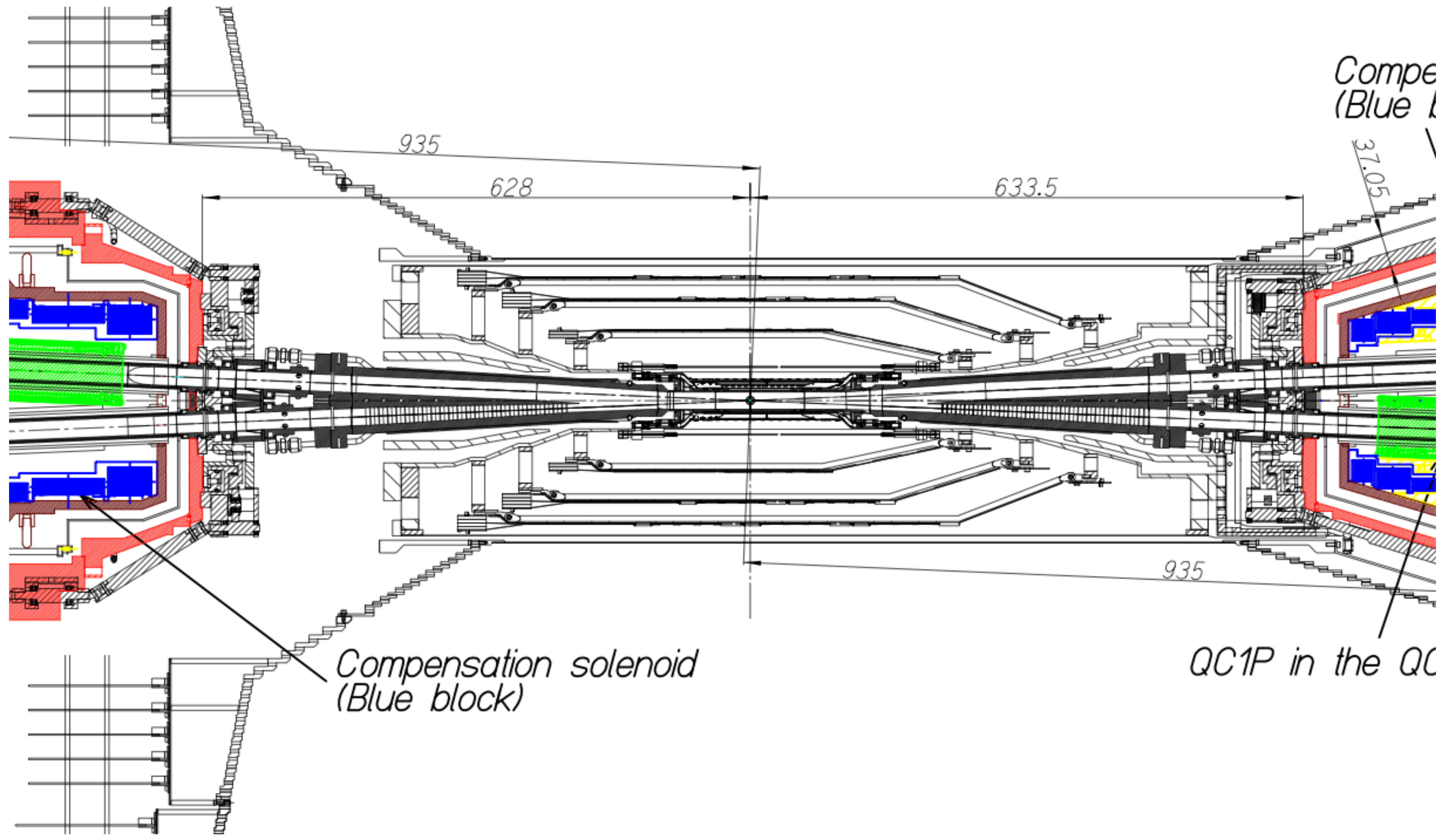
Sugimoto, etc. , Furukawa Electric Review, No. 55 2024

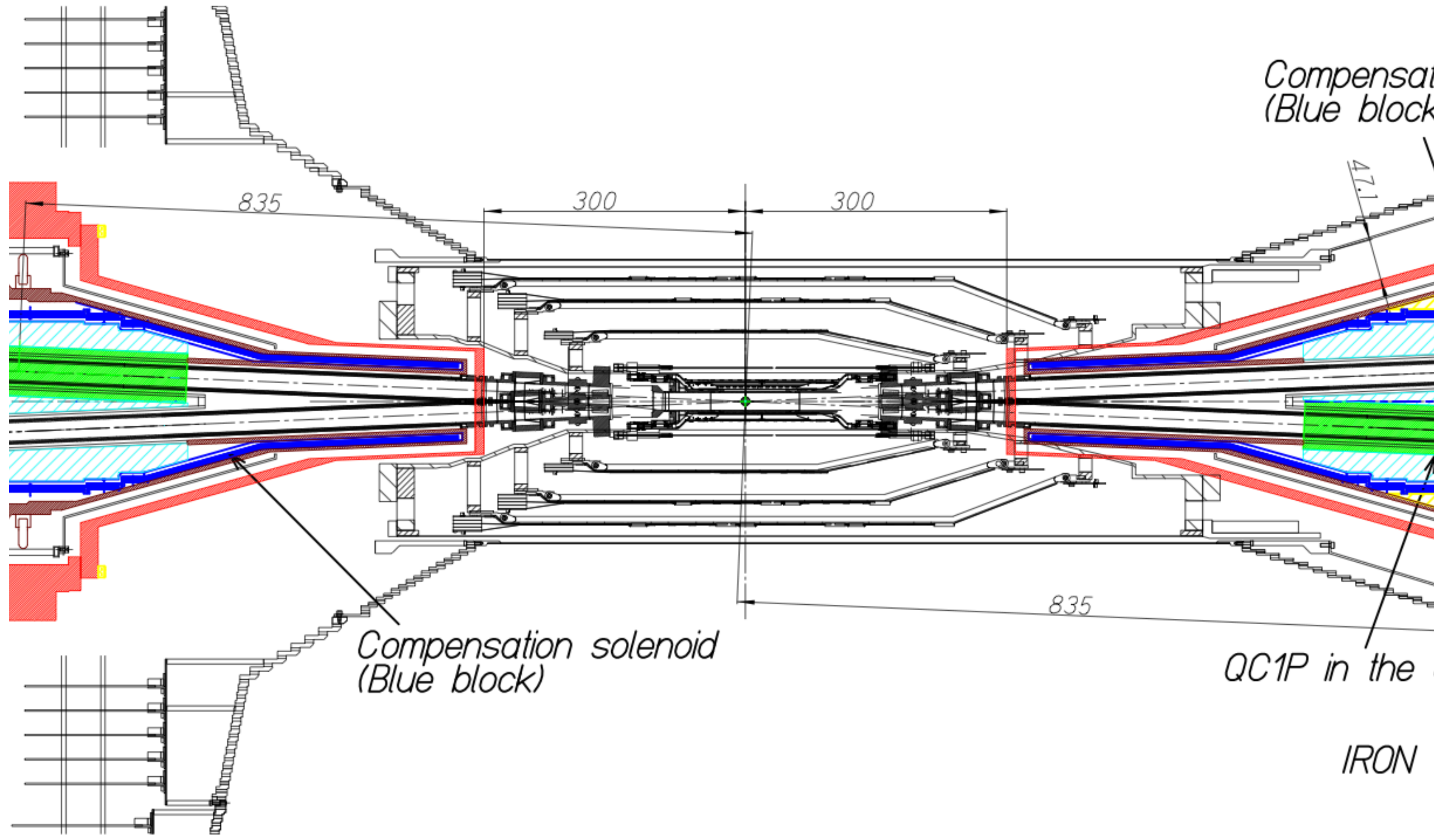
It is necessary to produce conductors that fit the QC1P requirements.

The conductor will be delivered in this February

Impact of QC1P upgrade to other instruments

- Impact of QC1P upgrade to
  - Beam pipe
  - RVC
  - Vertex detector system
  - BPM
- We have monthly meeting about this issues.
  - The RVC modification proceeded by Belle II gr. They will perform first mock up test, in Jan-Feb /2025.





Nb_3Sn QC1P development

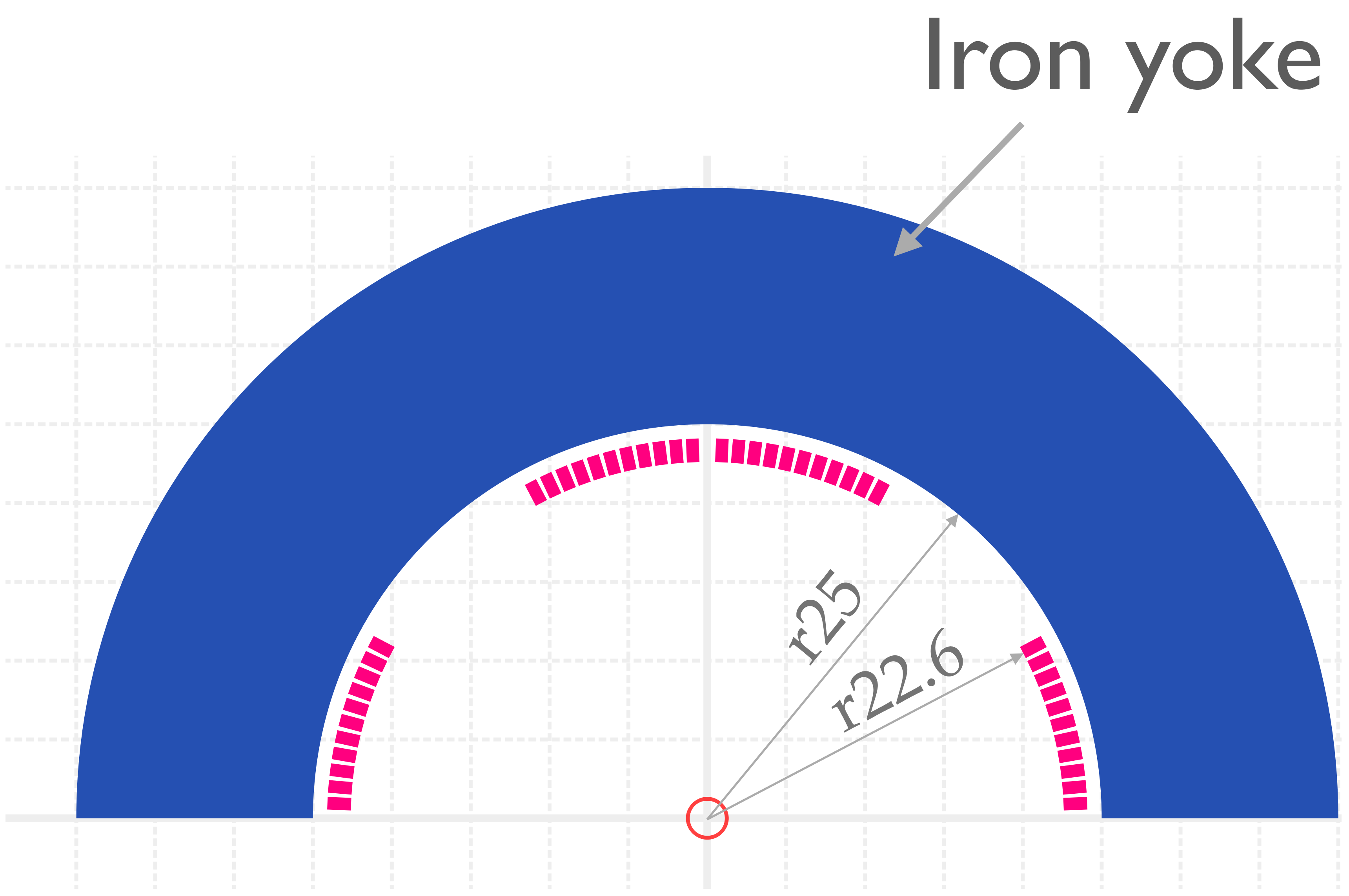
Collaborations

- We develop this Nb_3Sn magnet collaborating with FNAL, Furukawa Electric Co., Sophia U.
    - Two students newly participate from Sophia University.
- KEK and Sophia U.: Magnet design, Nb_3Sn winding, design quench protection, tooling for winding, magnetization measurement, measurement of conductor mechanical property
- FNAL: Reaction of coil, impregnation, mirror magnet design, magnetization measurement
- Furukawa: Production of rectangular Nb_3Sn conductor

Parameters of upgrade QC1P

Parameters	Values
G: B-Field Gradient	80 T/m
GL: G-Integral	26.7 T
L: Effective length	334 mm
Current	1680 A
J (Non-Cu)	< 3000 A/mm^2
Inner radius of coil	22.5 mm
Coil thickness	< 2 mm
T_c@B=2.5 T	> 8.7 K*
Relative multipole error	< 1×10^{-4}

* Assuming temperature margin of 4 K at operating temperature of 4.7 K



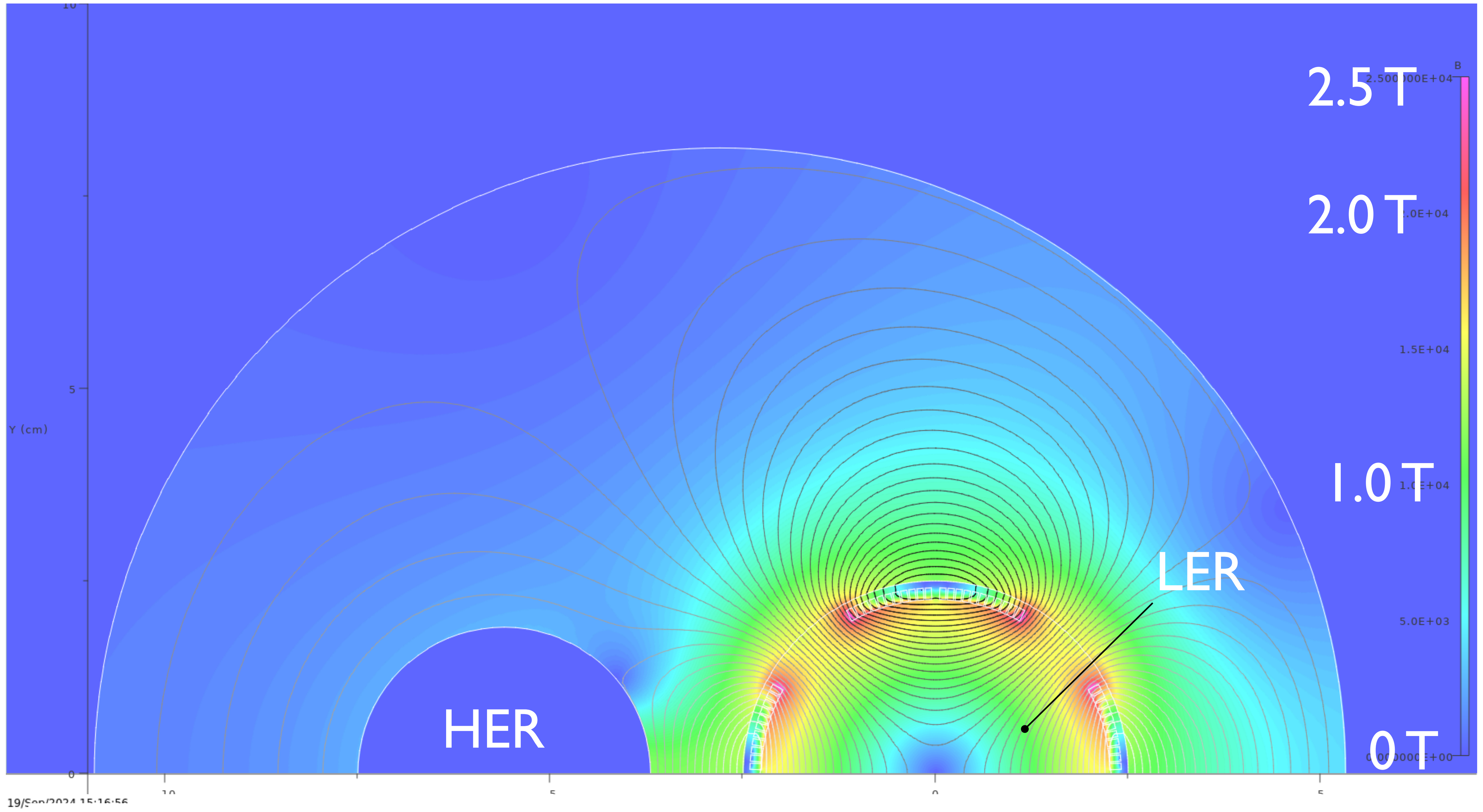
Magnet type:

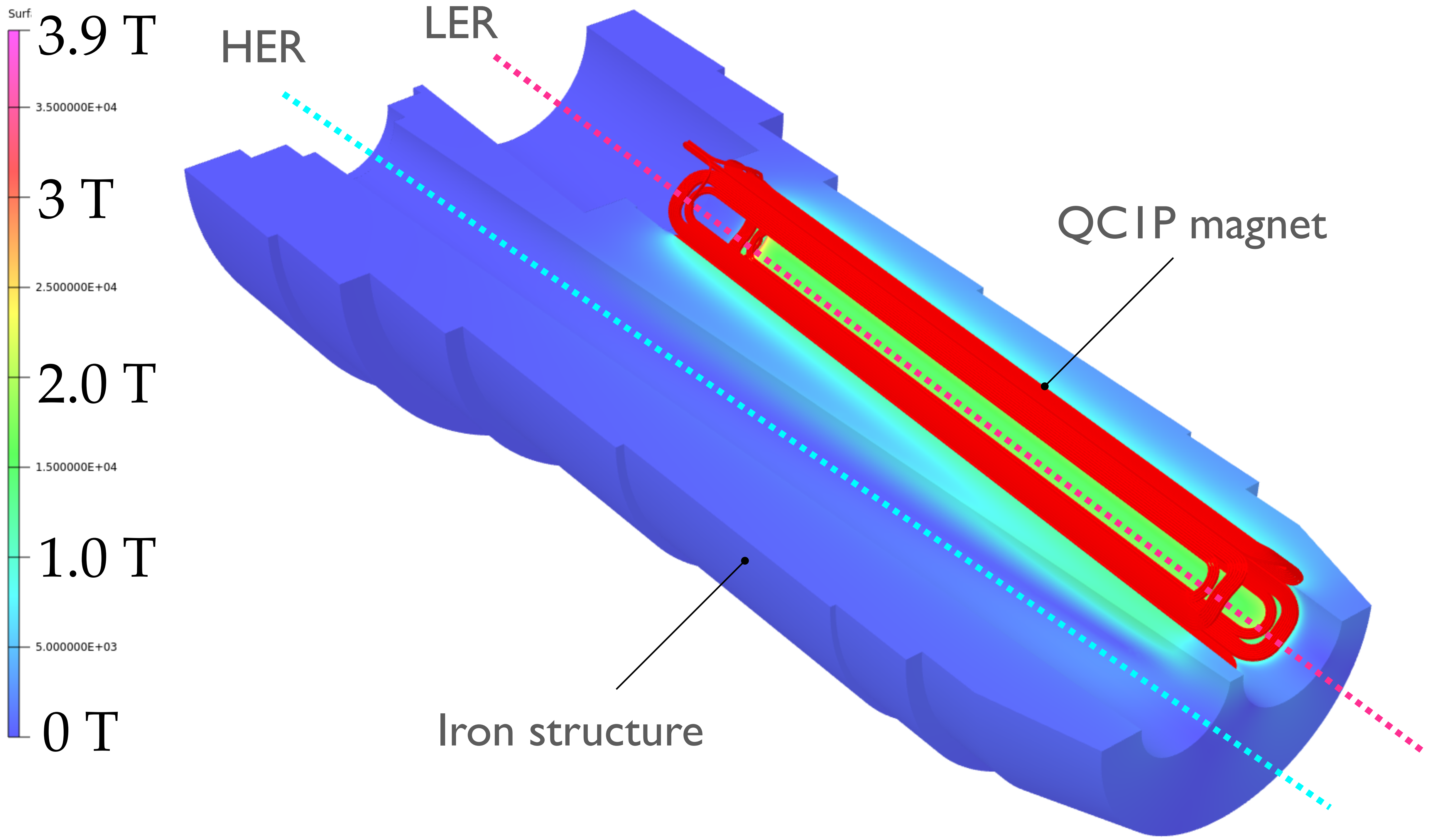
Cos 2θ magnet with a yoke

One layer coil

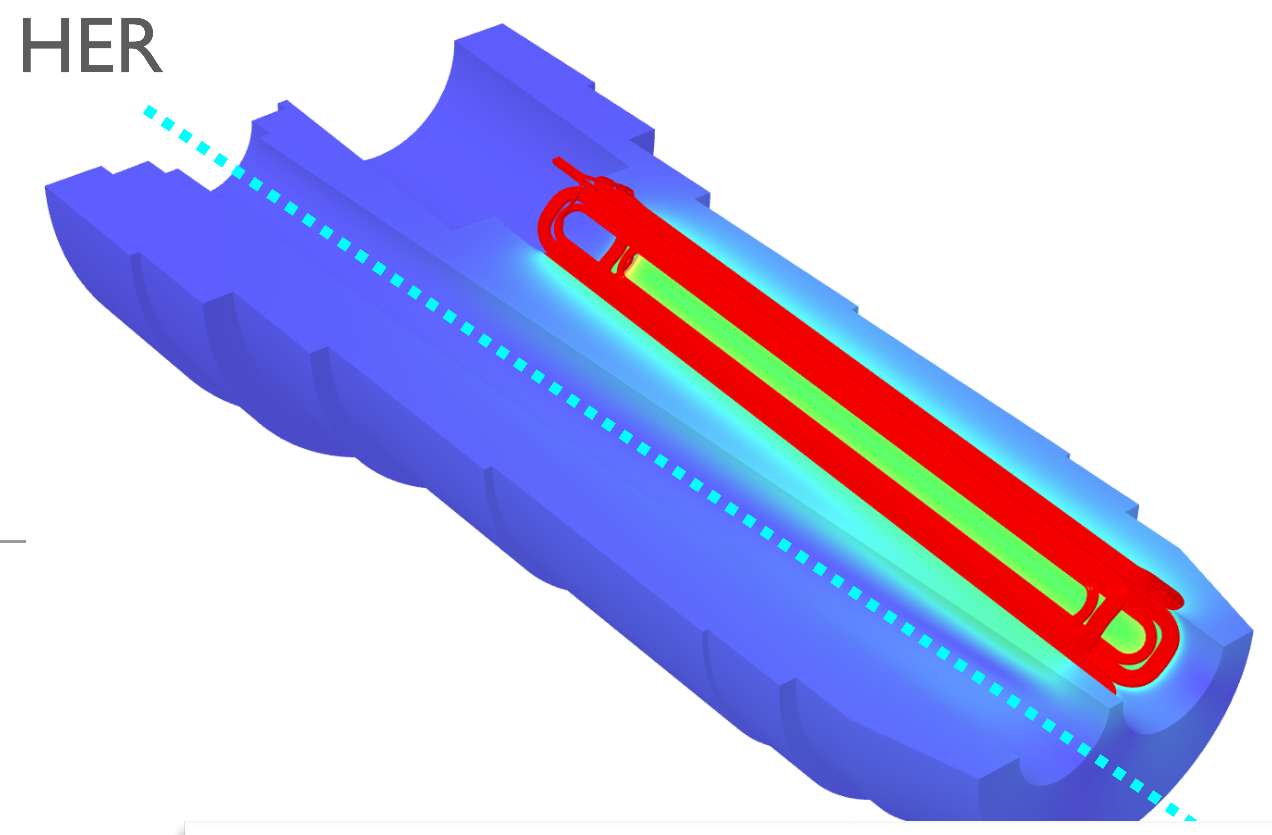
Magnet and iron structure

- QC1P is located in iron structure.
- The iron structure has functions as follows,
  - Increase field gradient,
  - Shield a leak field to HER
  - Shield the Belle II solenoid field with combination of the compensation solenoids
  - Reduce a peak B-field at conductor



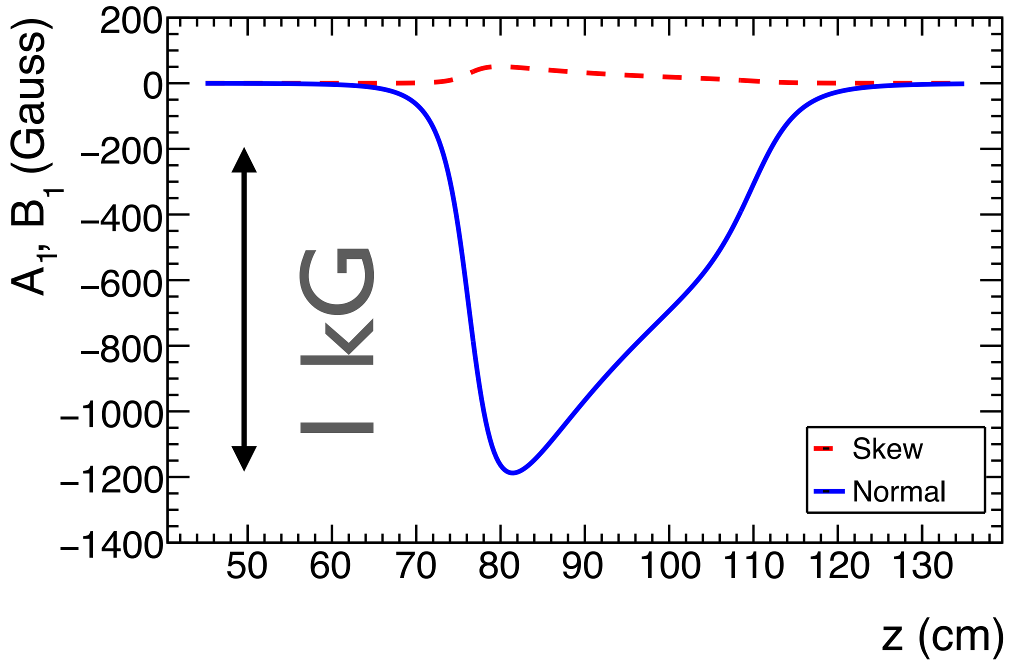


Leak field on HER

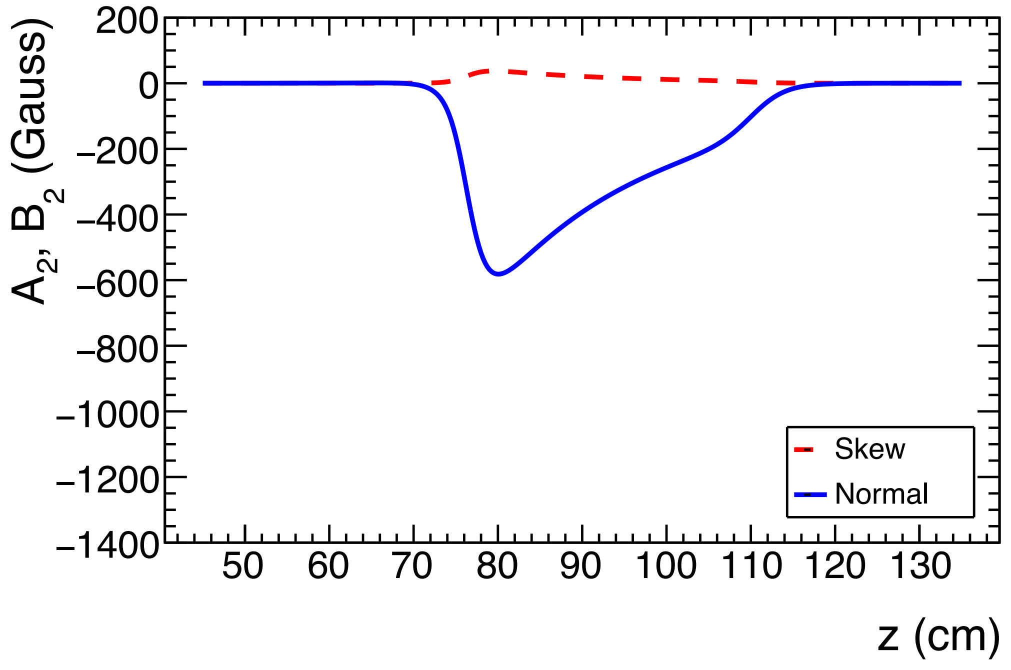


Current ver.

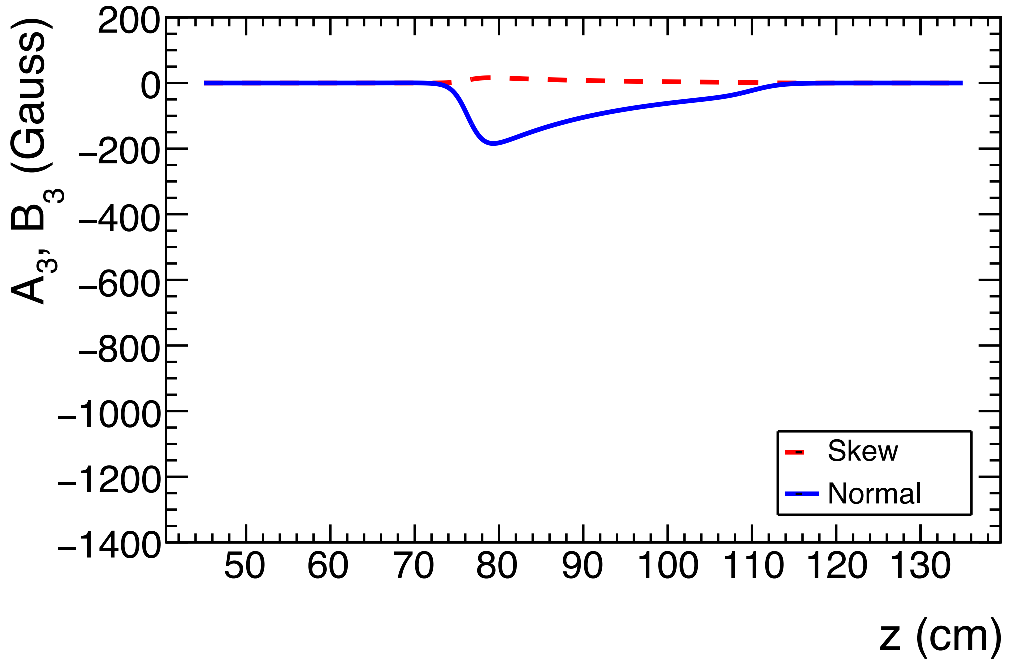
QC1LP_and_QC1RP-2 **Dipole (n=1)**



QC1LP_and_QC1RP-22 **Quad. (n=2)**



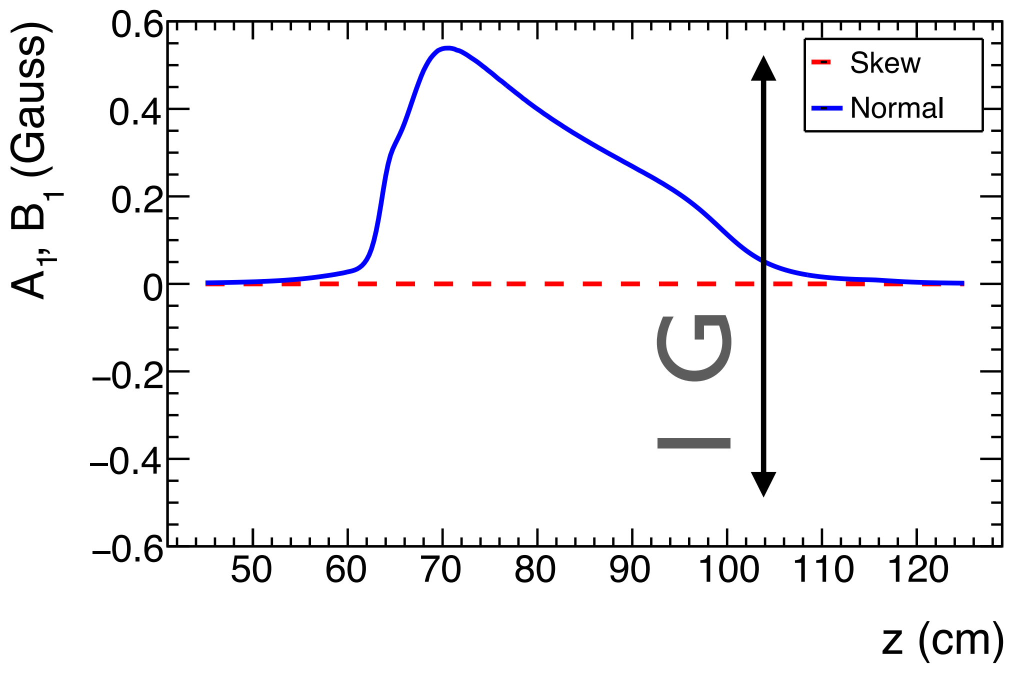
QC1LP_and_QC1RP-2212 **Sext. (n=3)**



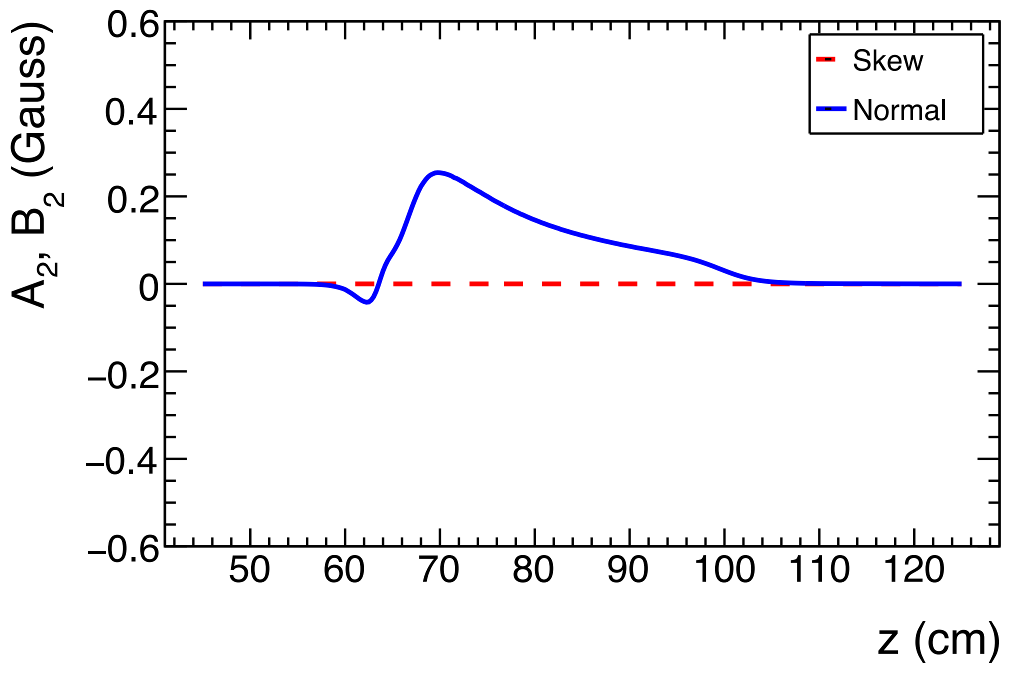
I=1626 A, R_{ref} = 10 mm

Upgraded ver.

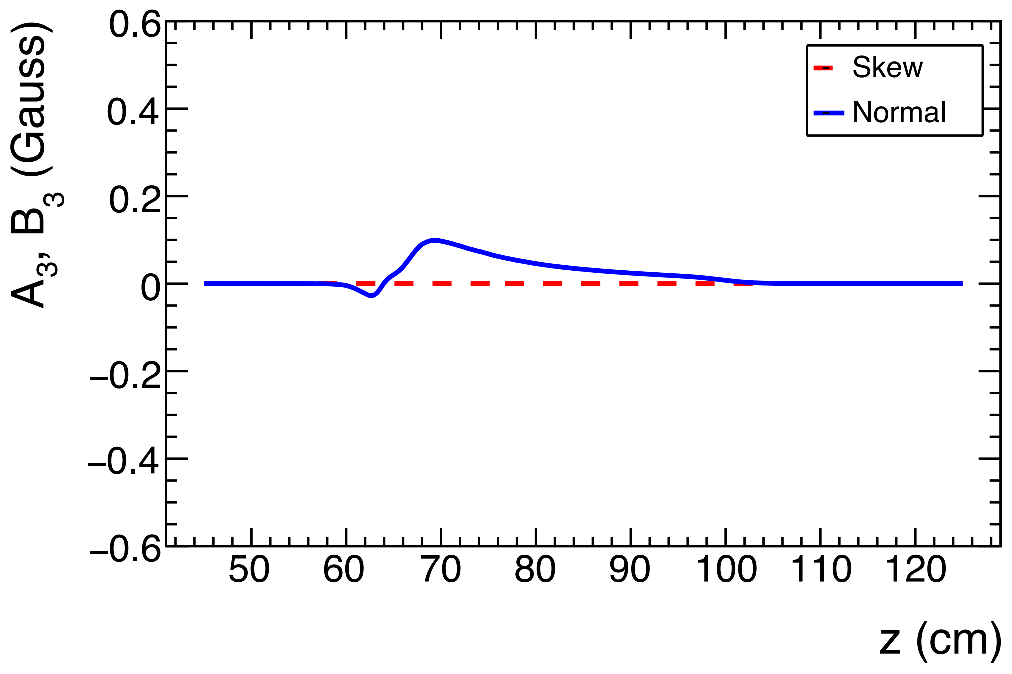
240807-qc1p_ug_front-13_tc **Dipole (n=1)**



240807-qc1p_ug_front-13_tol_ **Quad. (n=2)**



240807-qc1p_ug_front-13_tol_3 **Sext. (n=3)**

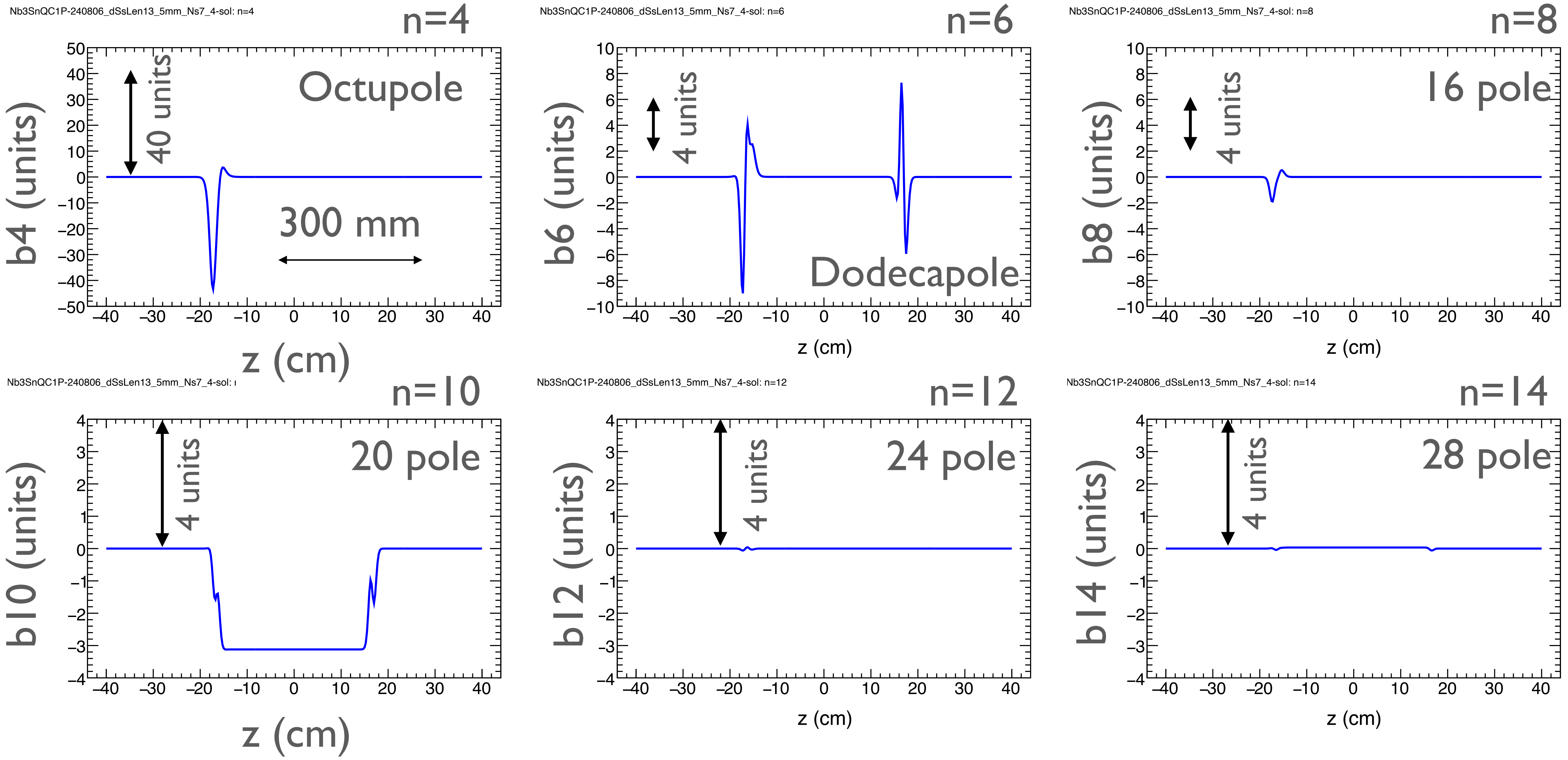


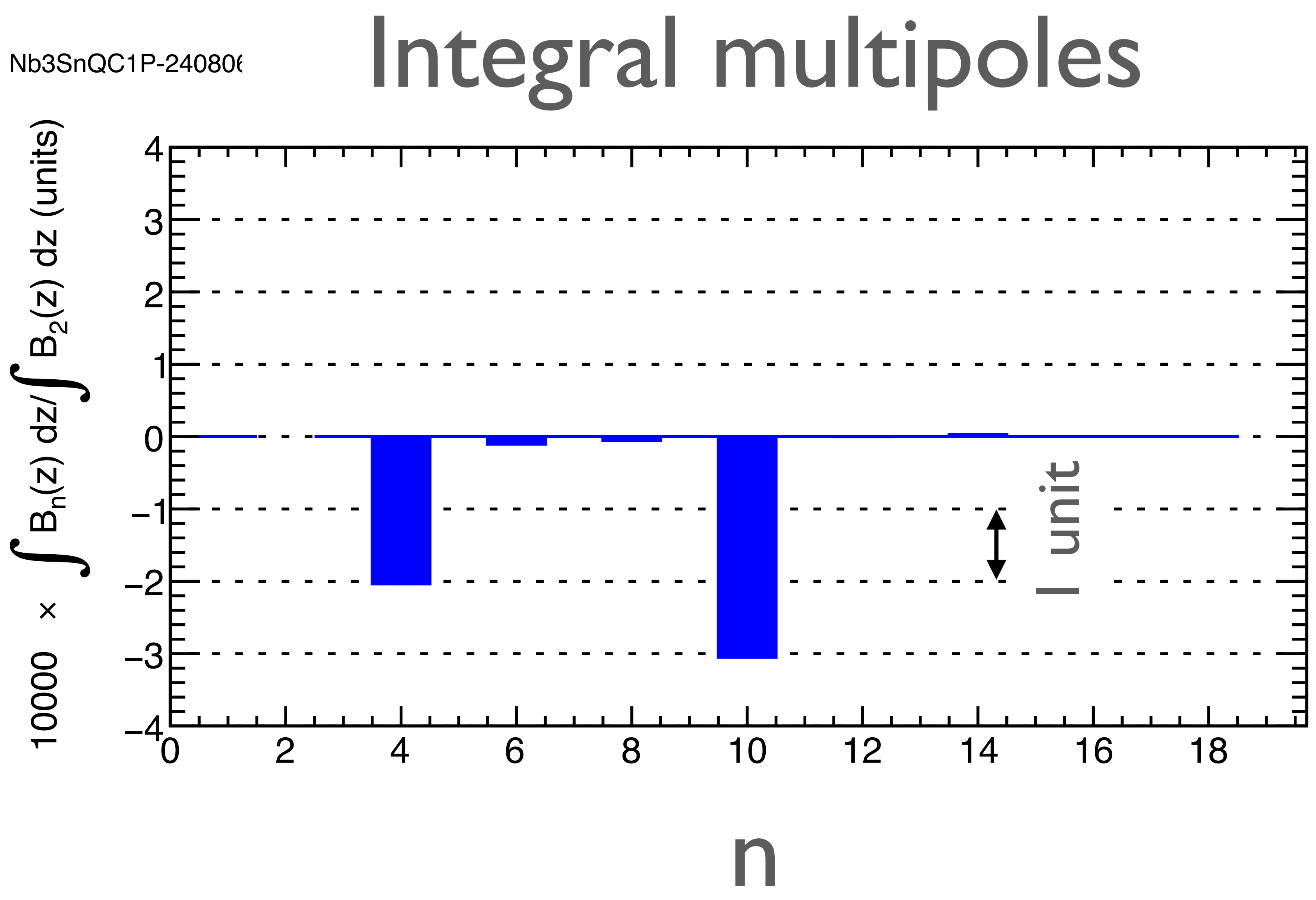
I=1704 A, R_{ref} = 10 mm

- Current version has large leak fields.
- Cancel magnets can cancel higher multipoles of n=3, 4, 5, 6 for current ver.
- Dipole (n=1) and quad. (n=2) components are not canceled.

- Upgrade version has small leak fields. (less then 0.6 Gauss)
- No cancel magnet is needed for upgrade ver.

3D calculation (no yoke), LER, Rref = 10 mm, I=1704 A



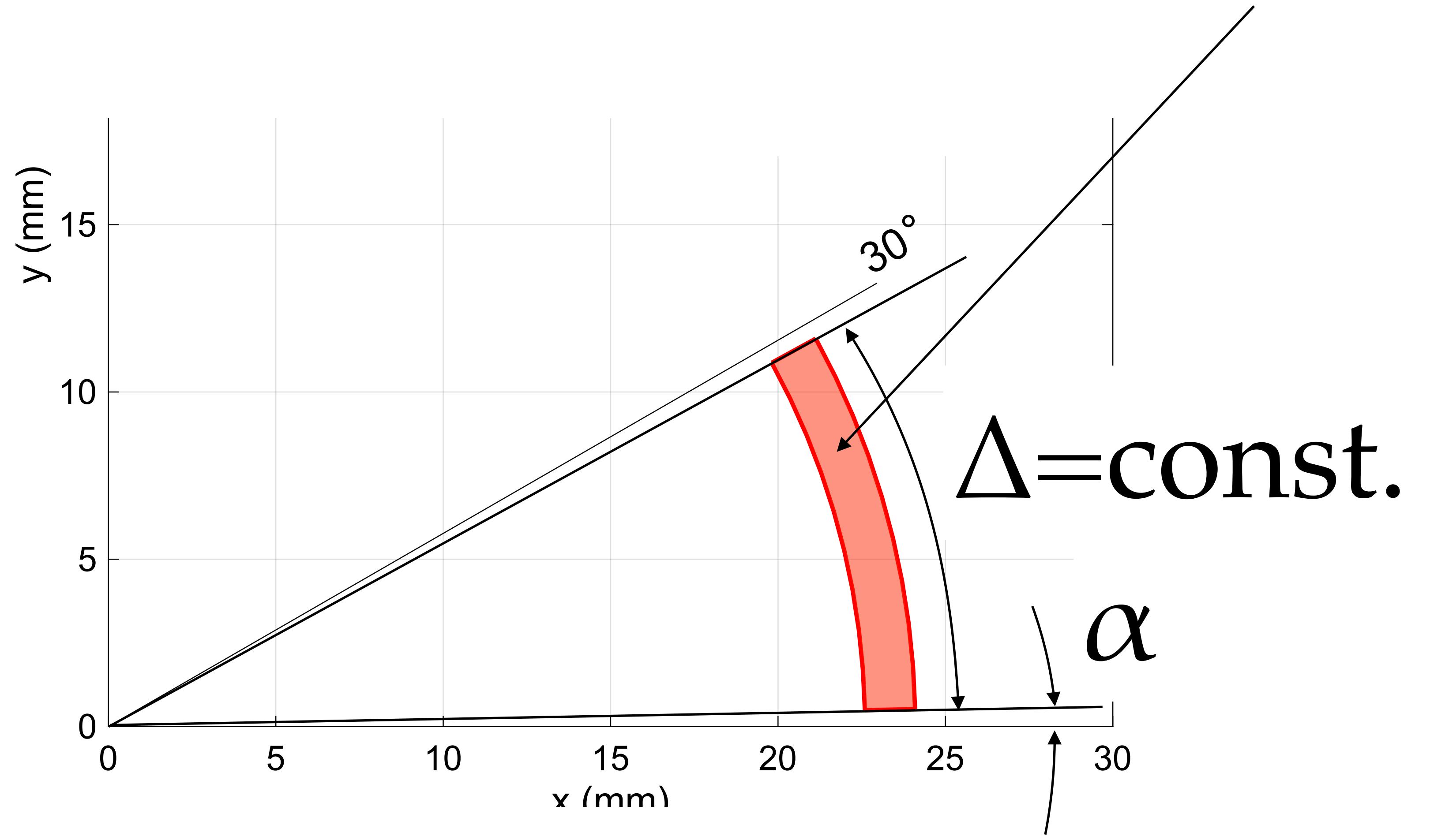


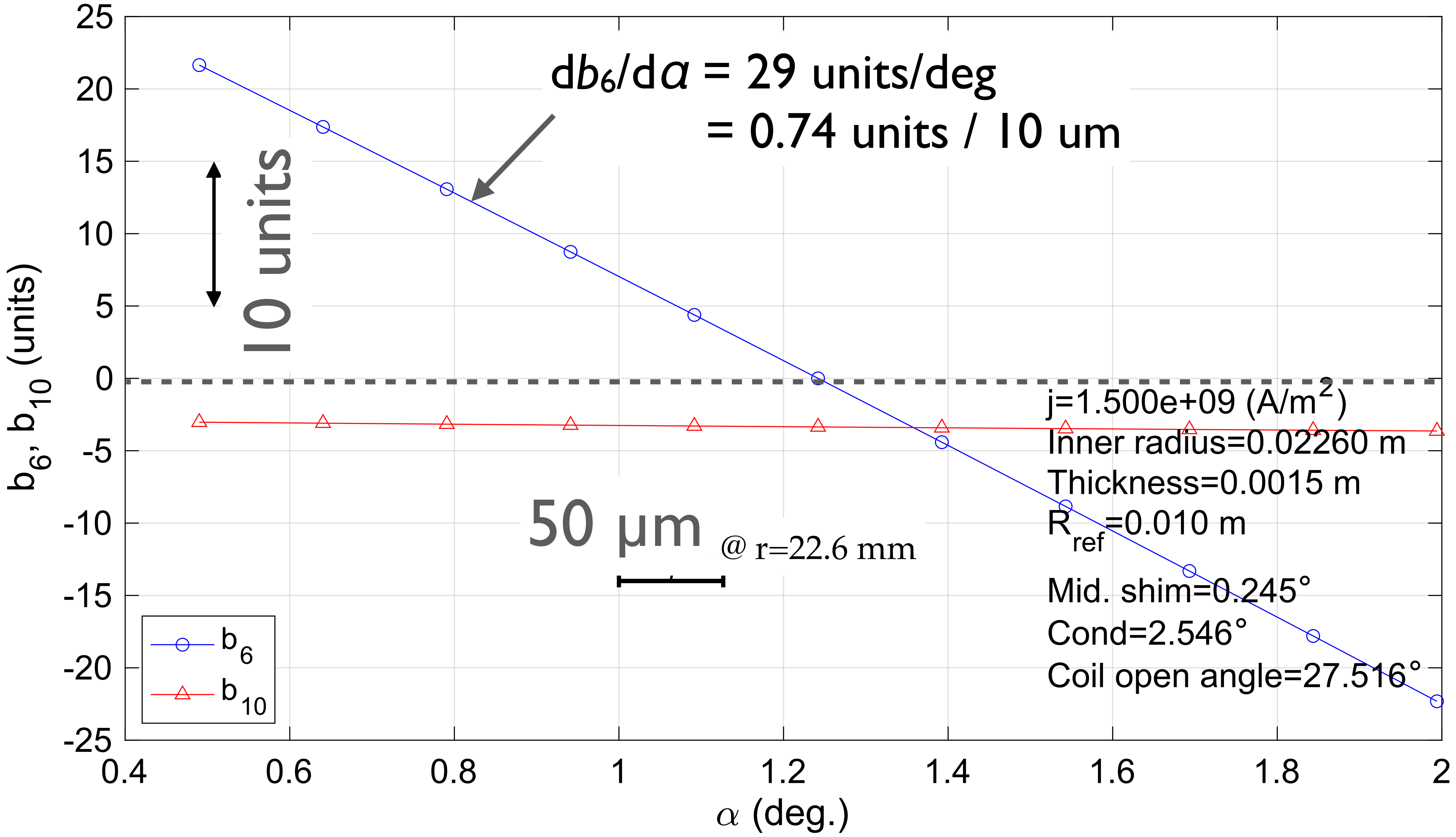
- At the lead end, a large octupole is generated
  - Need more adjustment for the lead end winding
- At straight section constant b10 is generated.
  - This does not significantly impact the beam optics.

Angular offset dependence of b6 and b10

- Variations of b6 and b10 are calculated by changing the azimuthal angle under the opening angle, Δ is constant.
- b6 is sensitive to the angular offset of coil block (α), while b10 is not sensitive.
- Position error in the azimuthal direction of 10 um at r=22.6 mm makes 0.7 units error field.
- Based on our experience of NbTi QC1P production, we can achieve this machinery accuracy.

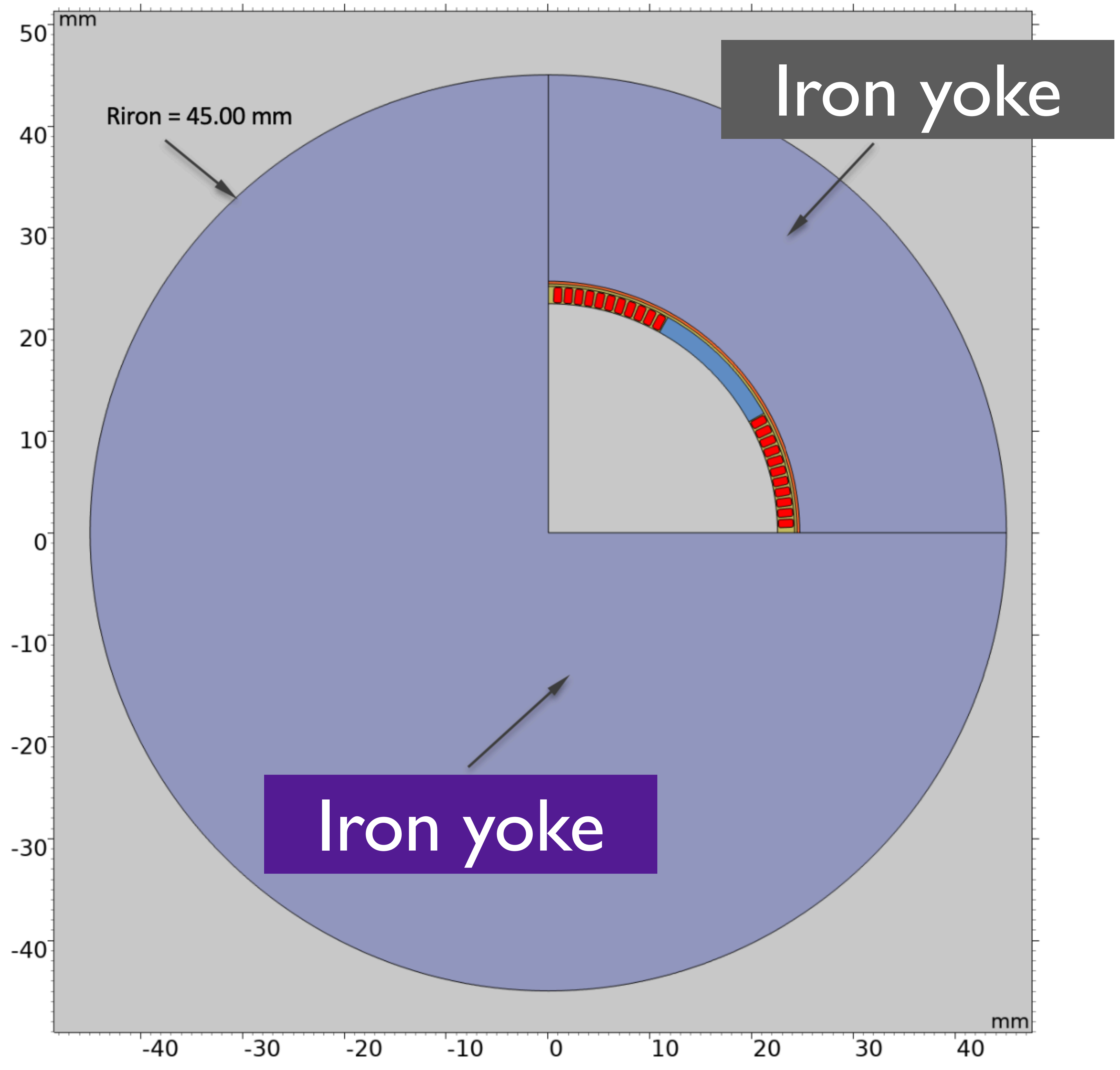
Coil cross section





Mirror magnet design

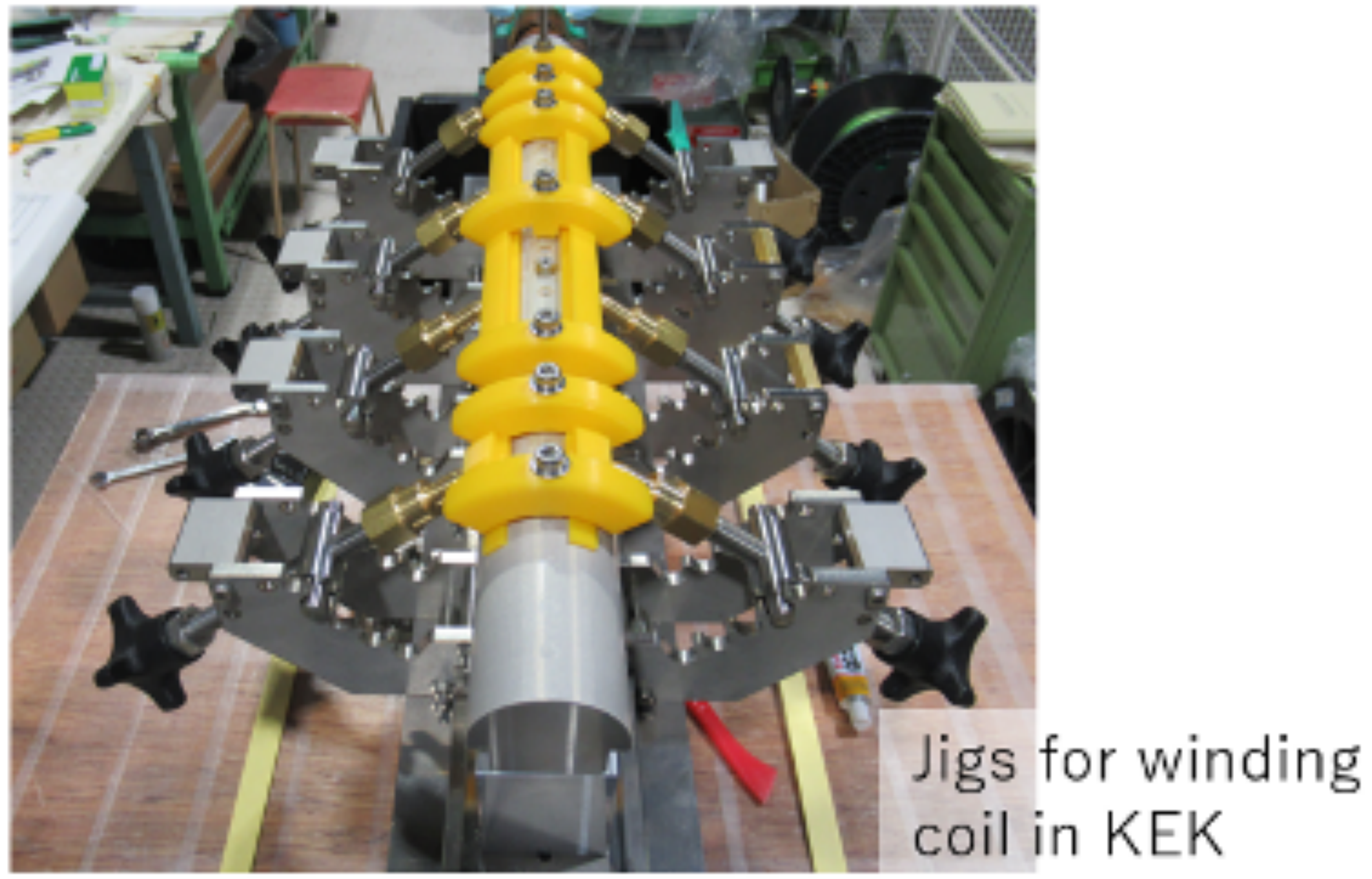
- The mirror magnet will test the mechanical property, thermal property, and quench protection performance.
- The magnet consist of a Nb_3Sn coil and mirror iron yoke. This configuration generate same B-field and magnetic force to the coil as a full coil magnet.
- Designs of toolings and engineering design of magnet are under way.
- We will produce the magnet and test next fiscal year.

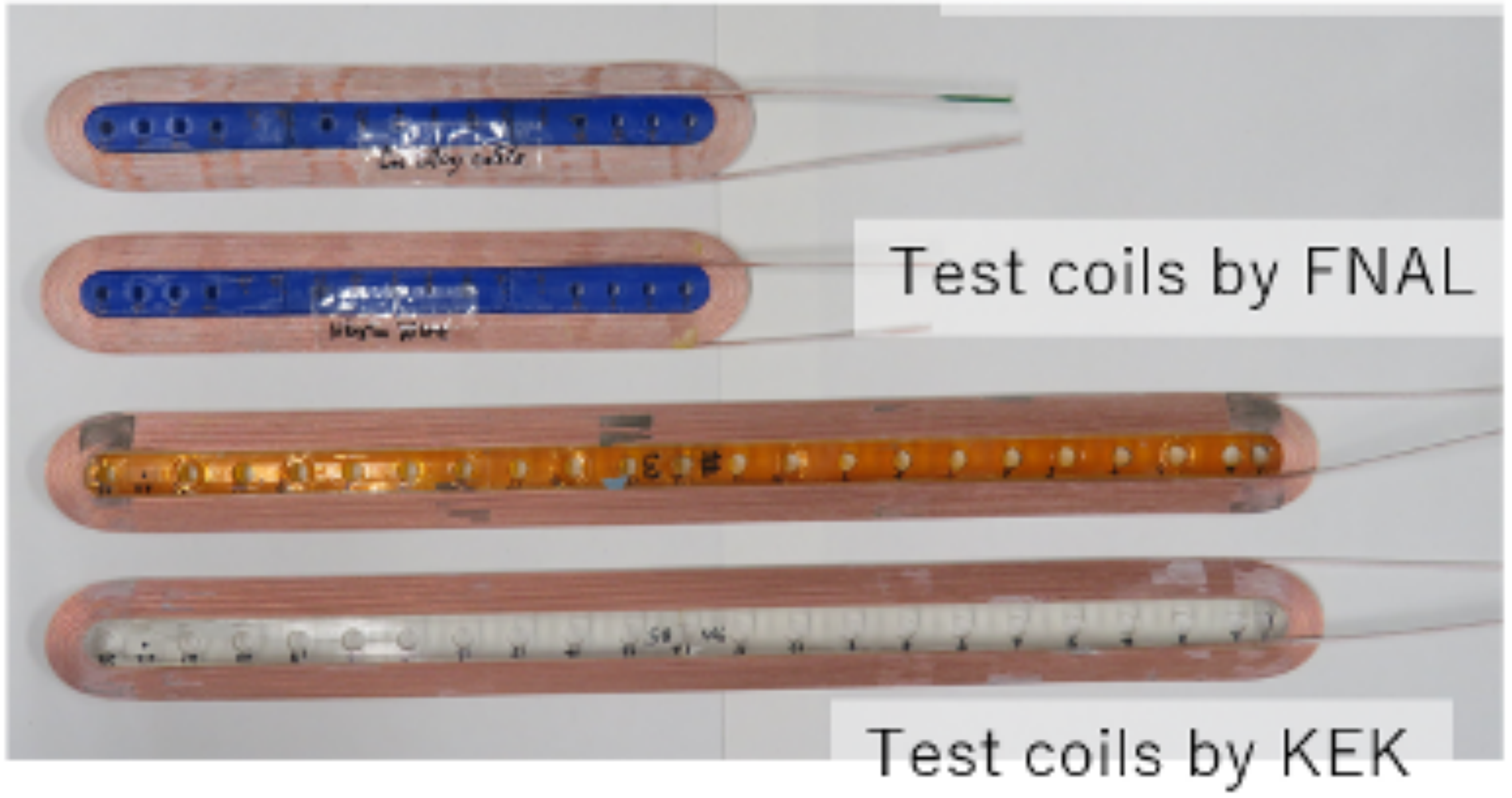


by Vadim Kashikhin (FNAL)

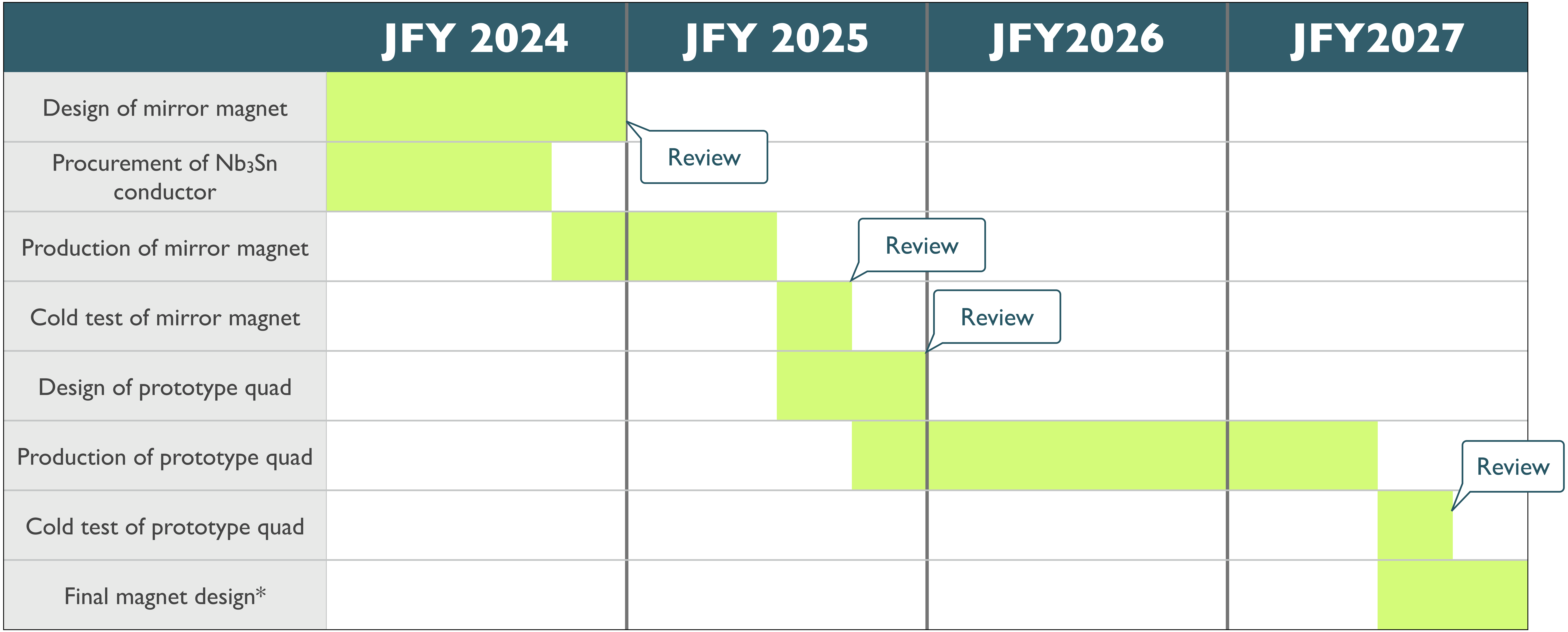
The other works

- Nb_3Sn conductor will be delivered this February.
- We practicing wiring using wire made of CuNi which has same geometry with Nb_3Sn conductor.
- We are preparing to measure mechanical property of Nb_3Sn conductor.
- We are preparing to measure time dependence of magnetization at KEK.
- Quench protection design is underway.





Schedule



* Depends on a decision of the SuperKEKB/Belle II project

Summary

- FNAL and Furukawa Electric Co. have been working together, and two students from Sophia University have joined us this fiscal year.
  - The research activity by the two students is supported by "Exploration of the particle physics frontier at the Super B-factory and cultivation o f young researchers".
- In the next fiscal year, we plan to fabricate a mirror magnet to verify the thermal and mechanical performance of the coils.
- After that, we will conduct a review and start to fabricate a prototype by the end of 2027.

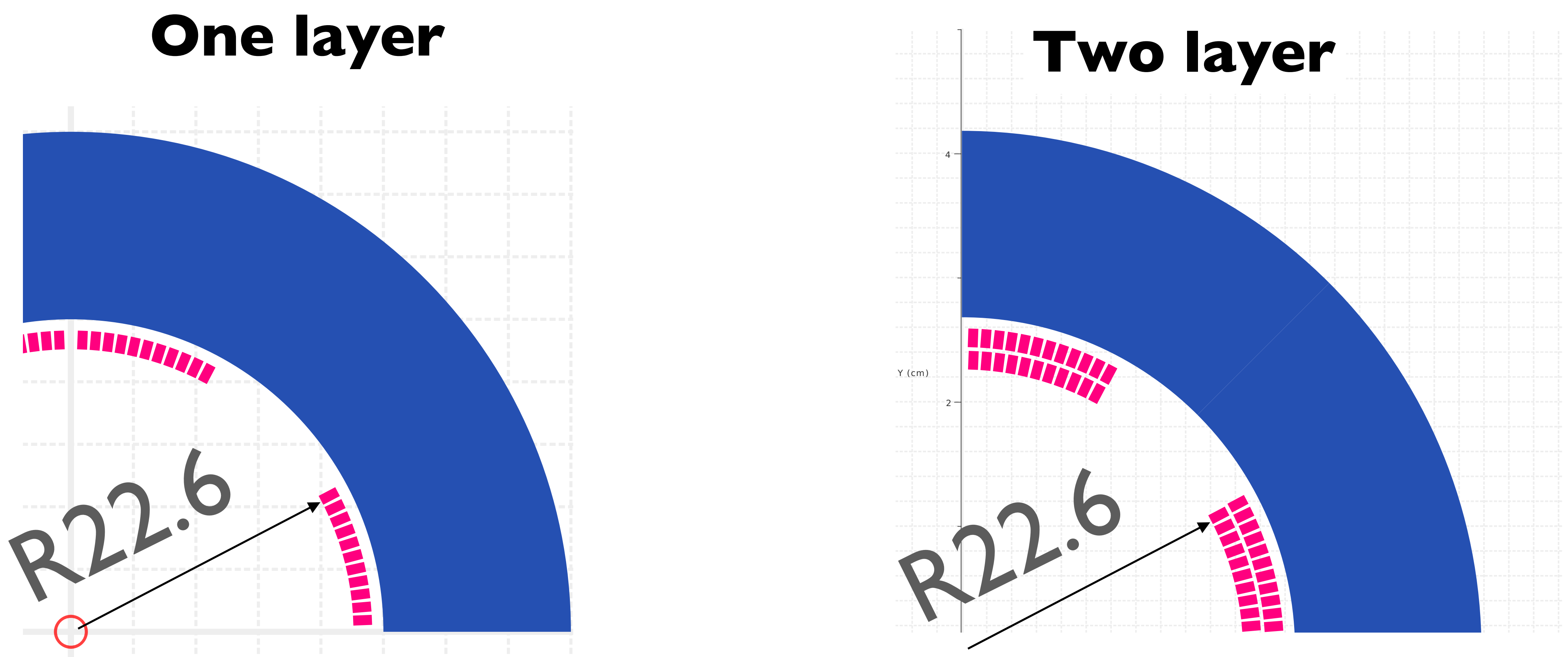
Backup

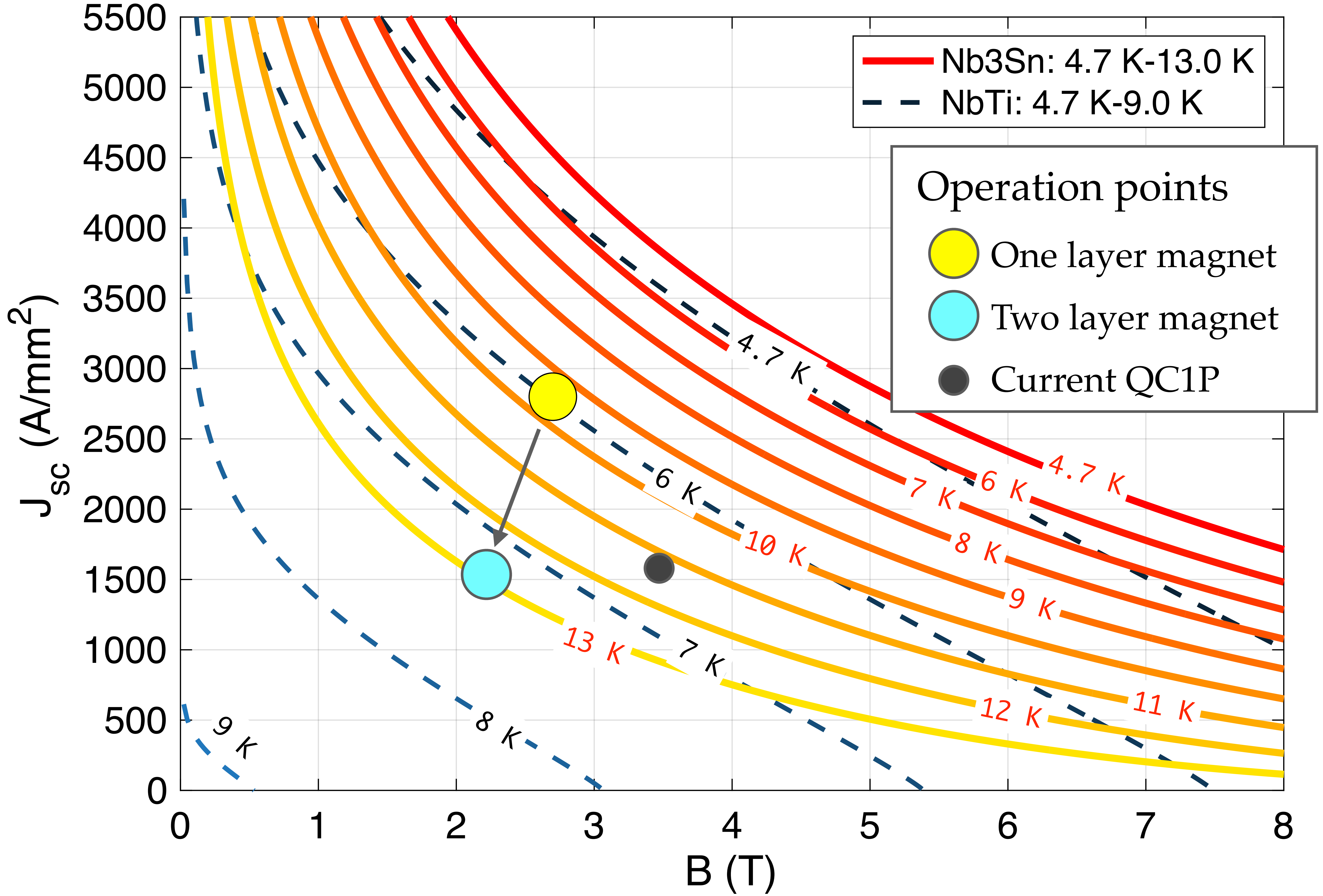
Two layers magnet

- We have a two-layer-coil option
- In this option, the conductor is wound in two layers, keeping the inner coil diameter at the same value as one layer.
- This type reduces current density to about half
- The temperature margin increase
- 20 pole components will be reduced
- NbTi conductor becomes a candidate.

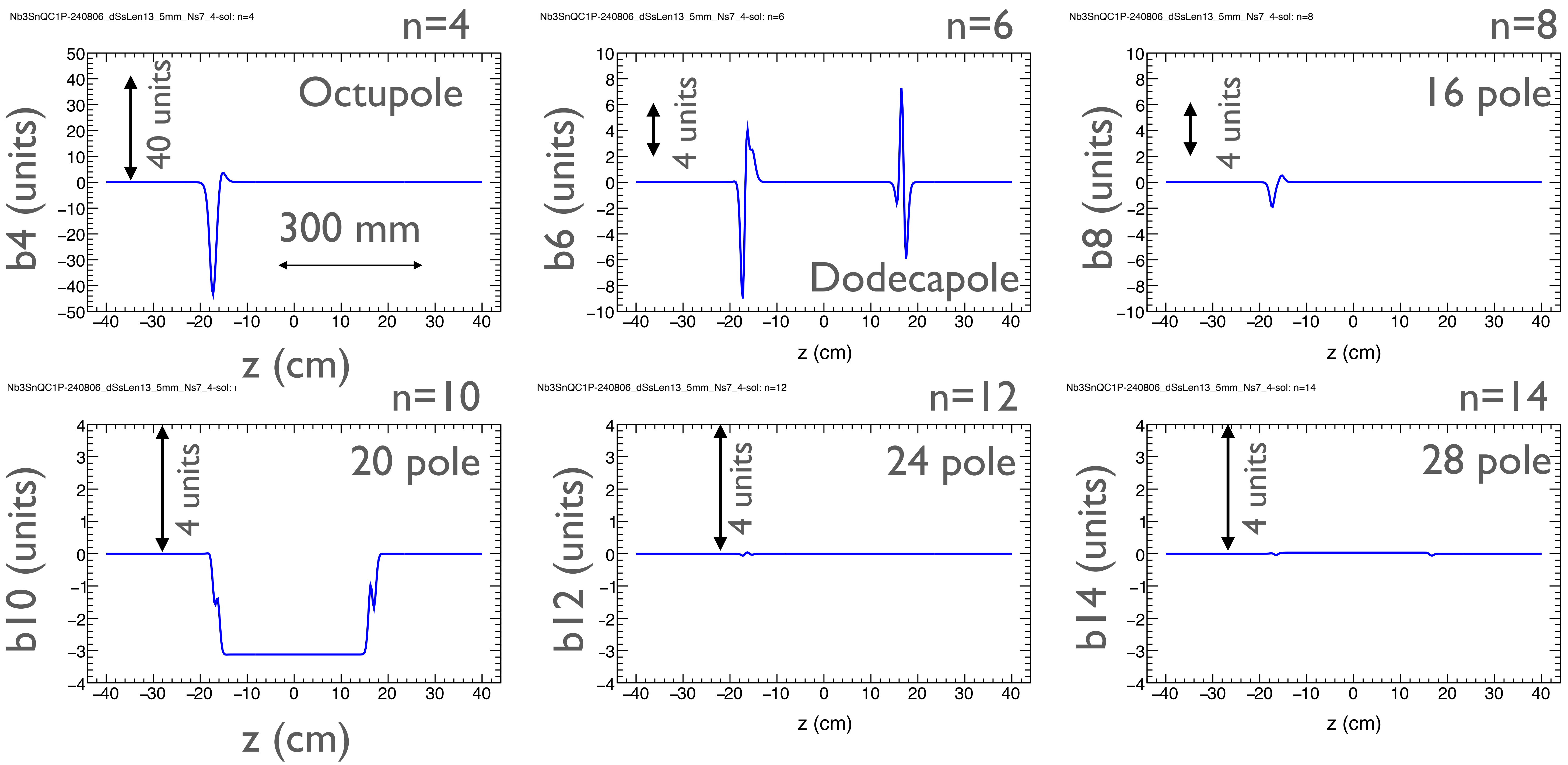
	ΔT: Temperature margin [K]	
	Nb3Sn	NbTi
One layer	4	1
Two layer	8	2.5
Current	-	2

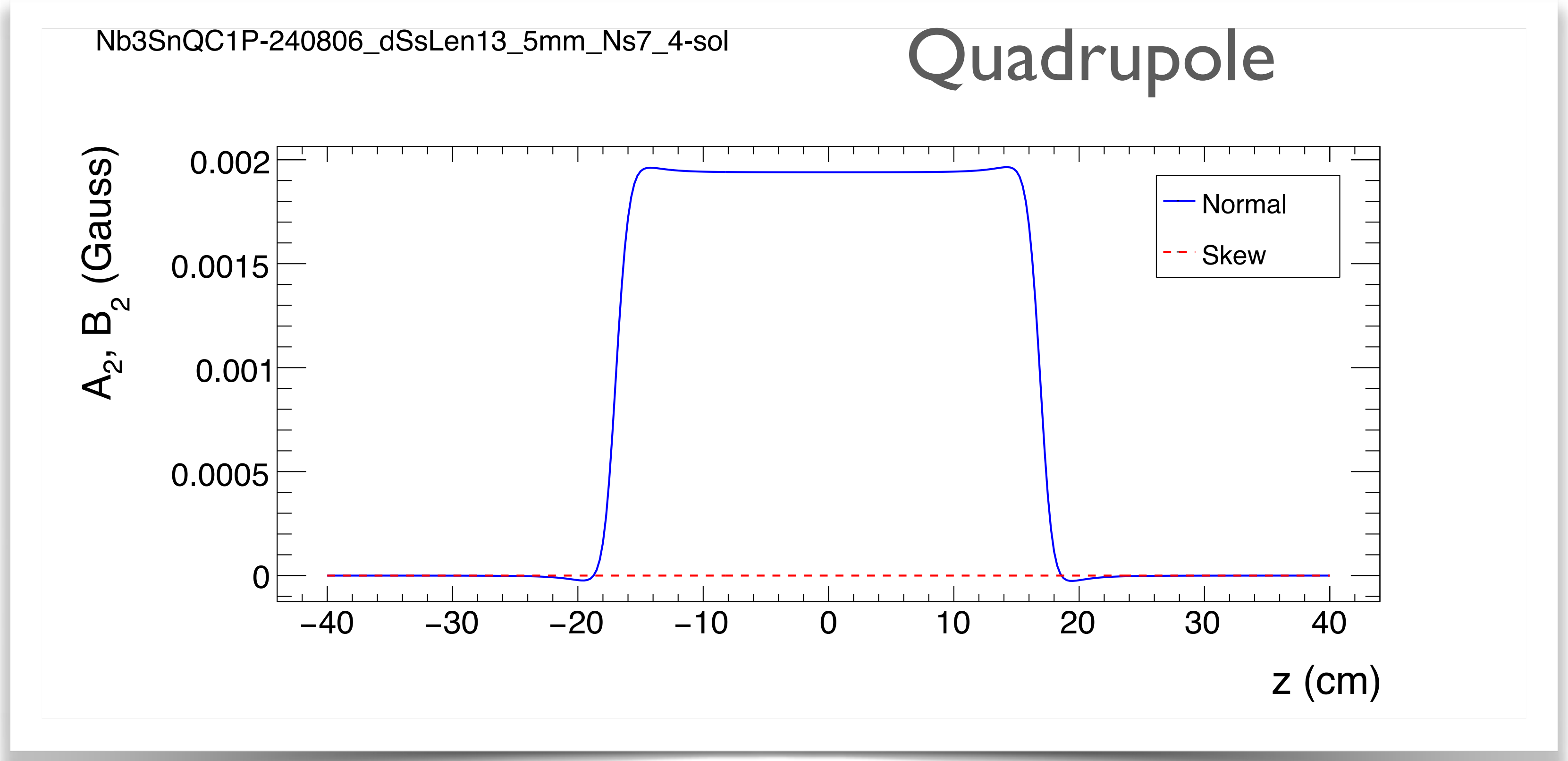
$T_{Operation}$ = 4.7 K



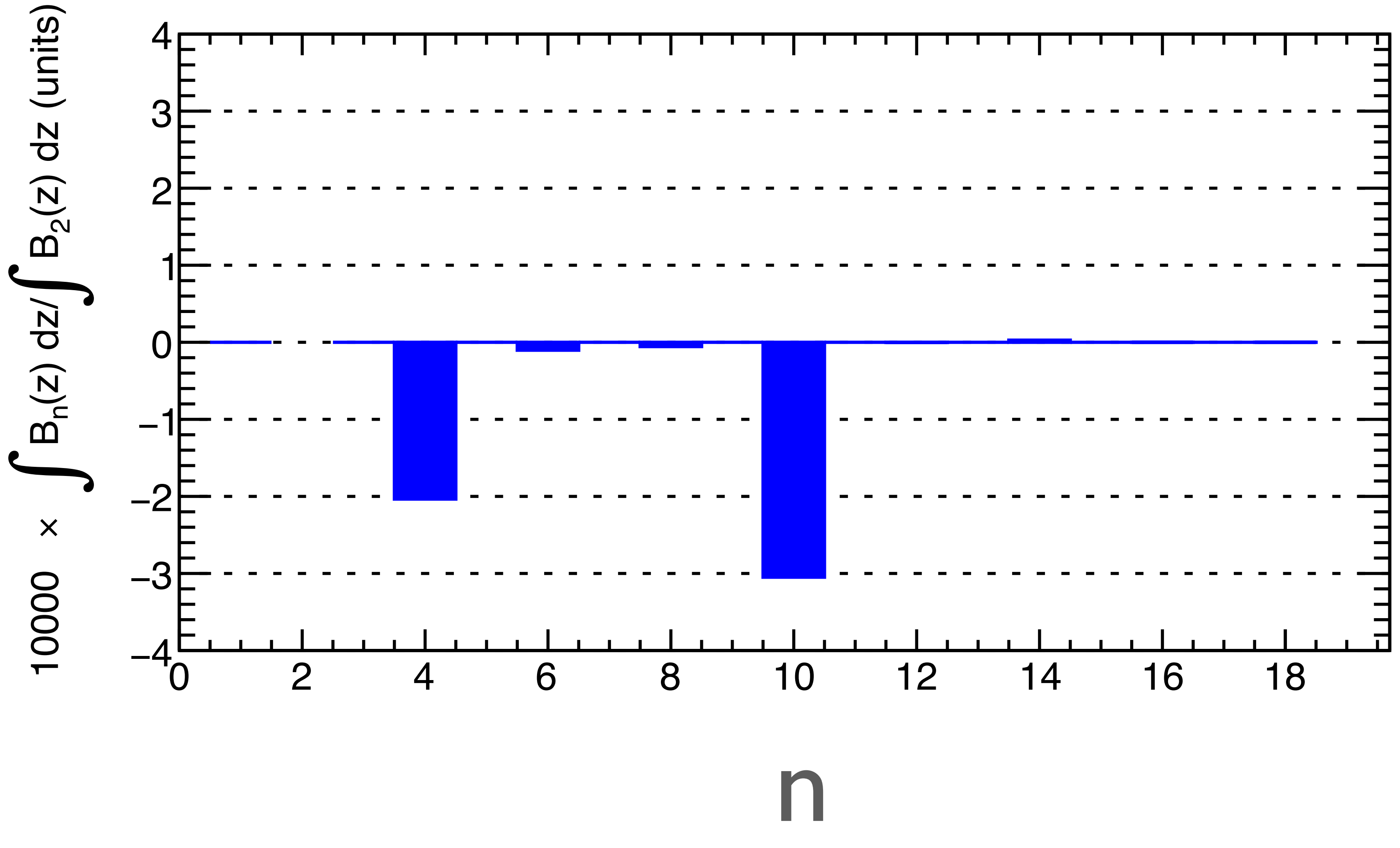


3D calculation (no yoke), LER, Rref = 10 mm, I=1704 A



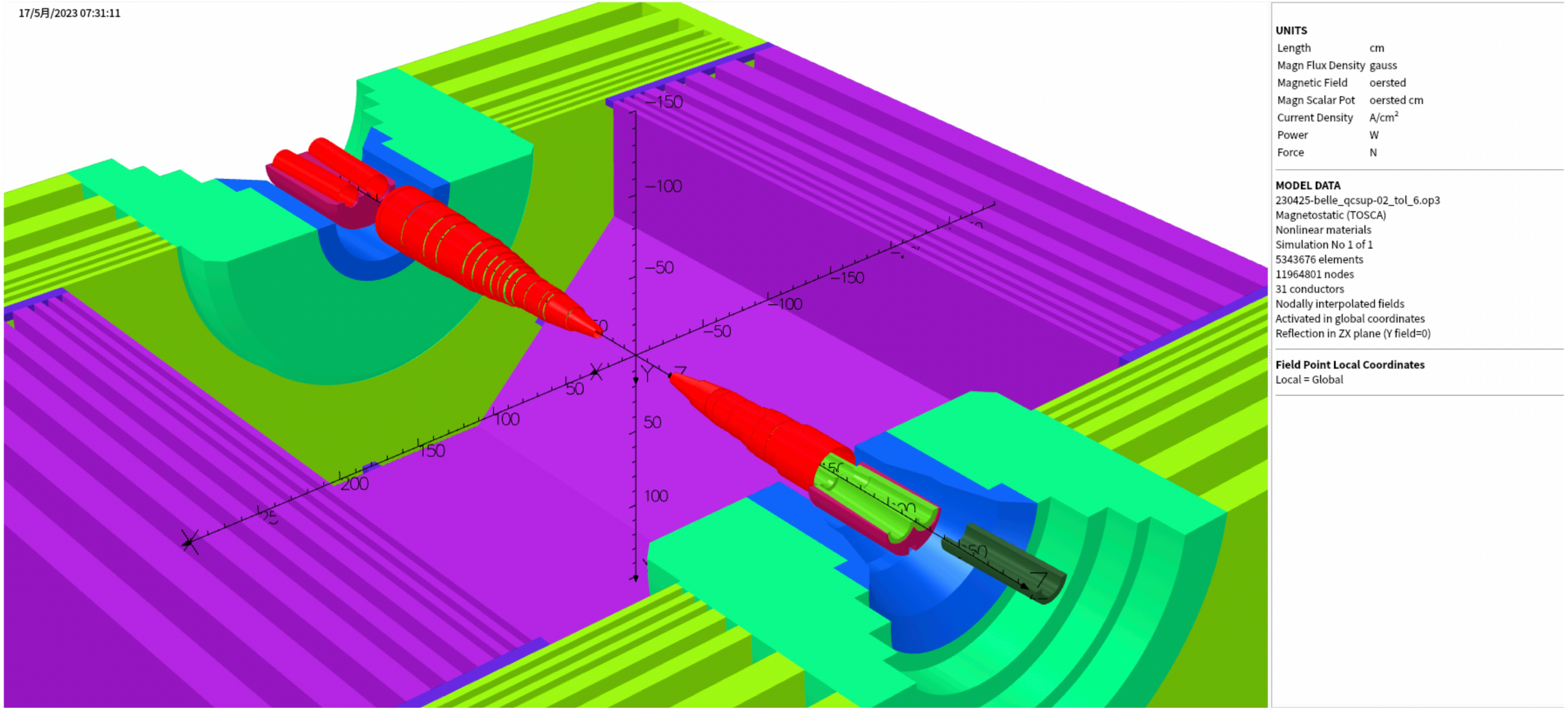


Integral multipoles



- At the lead end, a large octupole is generated
  - Need more adjustment for the lead end winding
- At straight section constant b10 is generated.
  - This does not significantly impact the beam optics.

3D Entire model

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Animations
Images
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Run Comi
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Command Files
User Variables
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View
Units
Set AC Time
Field Buffers
Model Symmetry
Model LCS
Field Options
Options
Model
Graphs
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Magnetic Field oersted
Magn Scalar Pot oersted cm
Current Density A/cm^2
Power W
Force N
MODEL DATA
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Nonlinear materials
Simulation No 1 of 1
5345771 elements
11967501 nodes
34 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in ZX plane (Y field=0)
Field Point Local Coordinates
Local = Global
New QC1P
Inside this yoke
Min (1.103734) at (-2.155556,0.921159,98.73605), Max (23269.88) at (-18.20316,1.442757,-216.9316)


New Anti-solenoid
12/Jul/2023 09:16:44
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1.000000E+04
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Magn Flux Density gauss
Magnetic Field oersted
Magn Scalar Pot oersted cm
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Power W
Force N
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Magnetostatic (TOSCA)
Nonlinear materials
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5345771 elements
11967501 nodes
34 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in ZX plane (Y field=0)
Field Point Local Coordinates
Local = Global
Min (1.103734) at (-2.155556,0.921159,98.73605), Max (23269.88) at (-18.20316,1.442757,-216.9316)

Solenoid axial profiles (LER)