IR Magnets SuperKEKB

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(on behalf of KEK SC magnet group, IR group and BNL SC magnet group)

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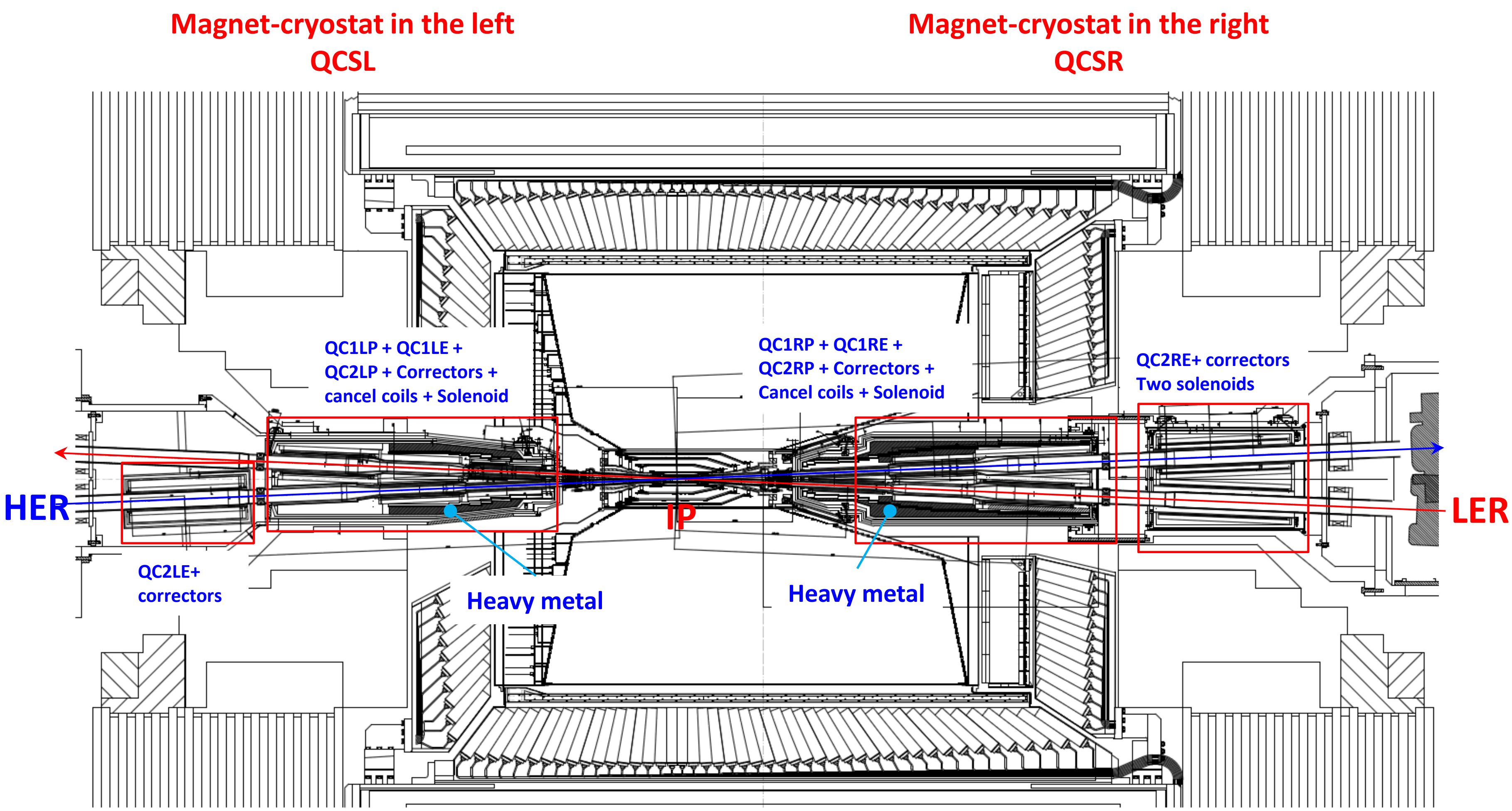
Progress from the last MAC

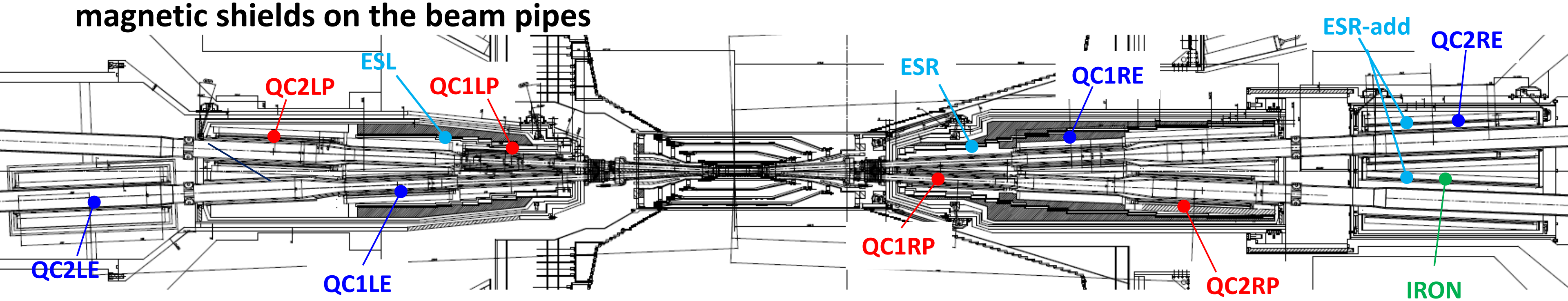
1. IR magnet and cryostat design
   - Improvement of the cross section design of all magnets from the prototype test results.
   - Permendur was chosen as the yoke material for QC1E and QC2P.
   - Heavy metal components are installed into the cryostats against the beam background noise.
   - The 3D designs of QC1/2 in the IR have started by OPERA under the research collaboration with BNL.
2. R&D
   - QC1P and QC1E proto-type magnets were constructed and tested in LHe.
   - Vibration study with the KEKB magnet cryostat
3. Construction
   - The company for construction of QCSL magnet cryostat was decided as Mitsubishi Electric Corporation.
   - The three real corrector coils for QC1LP have been completed, and measured at room temperature by BNL.
   - The cryogenic system in the left side has been completed in the 4th floor in Tsukuba experimental hall and cold tested.

IR magnets overview



S.C. magnets in SuperKEKB IR

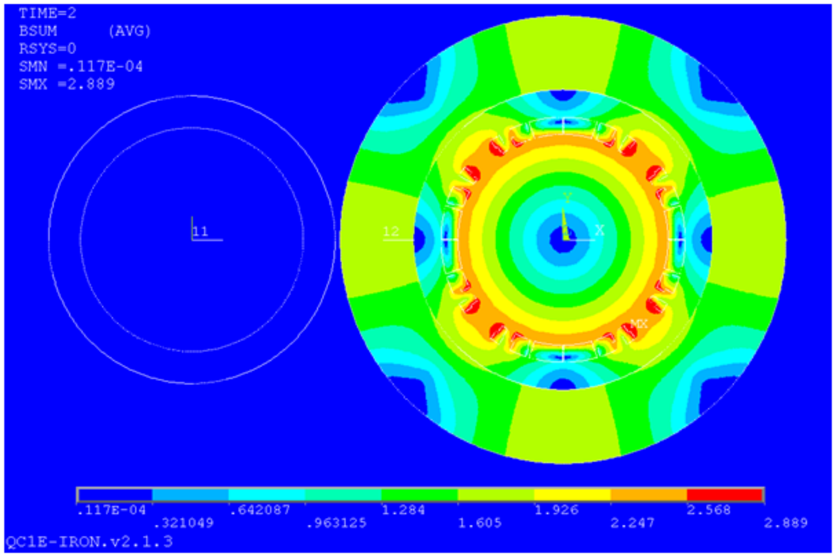
Design changes in the magnets: introducing Permendur yokes to QC1E and QC2P and Permendur magnetic shields on the beam pipes

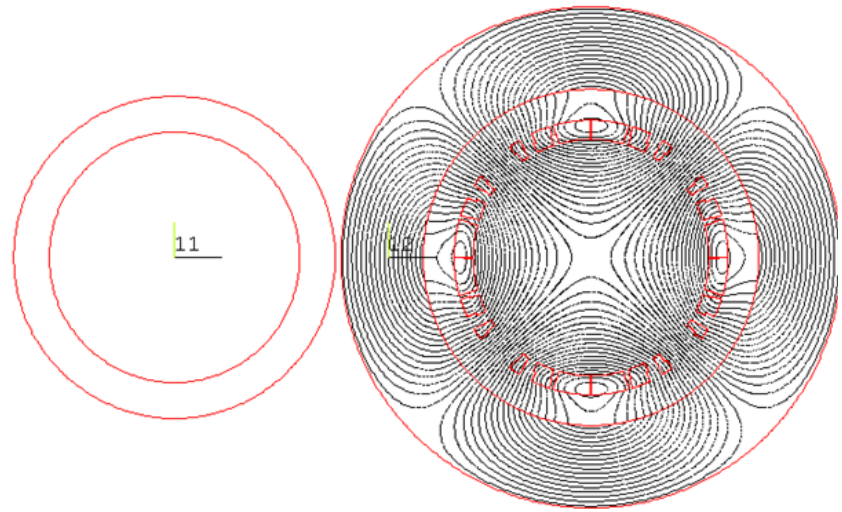


	Integral field gradient, (T/m)･m Solenoid field, T	Position from IP, mm	Magnet type	Corrector	Leak field cancel coil
QC2RE	13.58 [32.41 T/m × 0.4190m]	2925	**S.C. + Iron Yoke and mag. shield**	a_1, b_1, a_2, b_4	
QC2RP	11.56 [26.28 × 0.4099]	1925	**S.C. + Permendur Yoke and mag. shield**	a_1, b_1, a_2, b_4	
QC1RE	26.45 [70.89×0.3731]	1410	**S.C. + Permendur Yoke and mag. shield**	a_1, b_1, a_2, b_4	
QC1RP	22.98 [68.89×0.3336]	935	**S.C.**	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LP	22.97 [68.94×0.3336]	-935	**S.C.**	a_1, b_1, a_2, b_4	b_3, b_4, b_5, b_6
QC1LE	26.94 [72.21×0.3731]	-1410	**S.C. + Permendur Yoke and mag. shield**	a_1, b_1, a_2, b_4	
QC2LP	11.50 [28.05 × 0.4099]	-1925	**S.C. + Permendur Yoke and mag. shield**	a_1, b_1, a_2, b_4	
QC2LE	15.27 [28.44×0.5370]	-2700	**S.C. + Iron Yoke**	a_1, b_1, a_2, b_4	
ESR	4.3 T (max. field)		S.C. Solenoid		
ESR-add	0.3 T	Each beam	S.C. Solenoid + Iron Yoke		
ESL	4.7 T (max. field)		S.C. Solenoid		

Magnet design: Permendur yoke

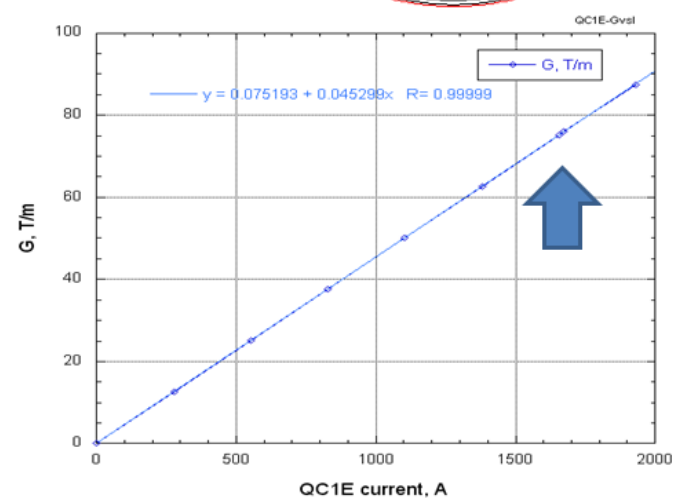
QC1E magnetic design (4s operation) : presented in 2012-KEKB-MAC





QC1E magnet design (QC1RE, QC1LE)

- 2 layer coils [double pancake]
- Magnet inner bore radius=33.0 mm
- Beam pipe (warm tube)
  - Inner radius=17.0 mm, outer radius=21.0 mm
- Magnet current= 1655 A
  - Current density = 599.6 A/mm^2 (in the coils), 1770 A/mm^2 (in NbTi)
- G_R = 75.94T/m
- Maximum field in the magnet=2.89 T
- Ratio of field enhancement by iron is 1.338.



Magnet design: Permendur yoke

- Choice of Permendur for QC1E and QC2P Yoke.
  1. Space between LER and HER beam lines along the QC1E is insufficient not to have leak field of QC1E in the LER beam area.
  2. Compensation of Belle solenoid field by the accelerator solenoid is not perfect in the local position.
     – The remanent solenoid field easily goes into the Yokes and the magnetic field in the yokes is enhanced.
  3. 12 GeV accelerator operation is the severer magnetic condition for the magnets than 4S (nominal) operation.

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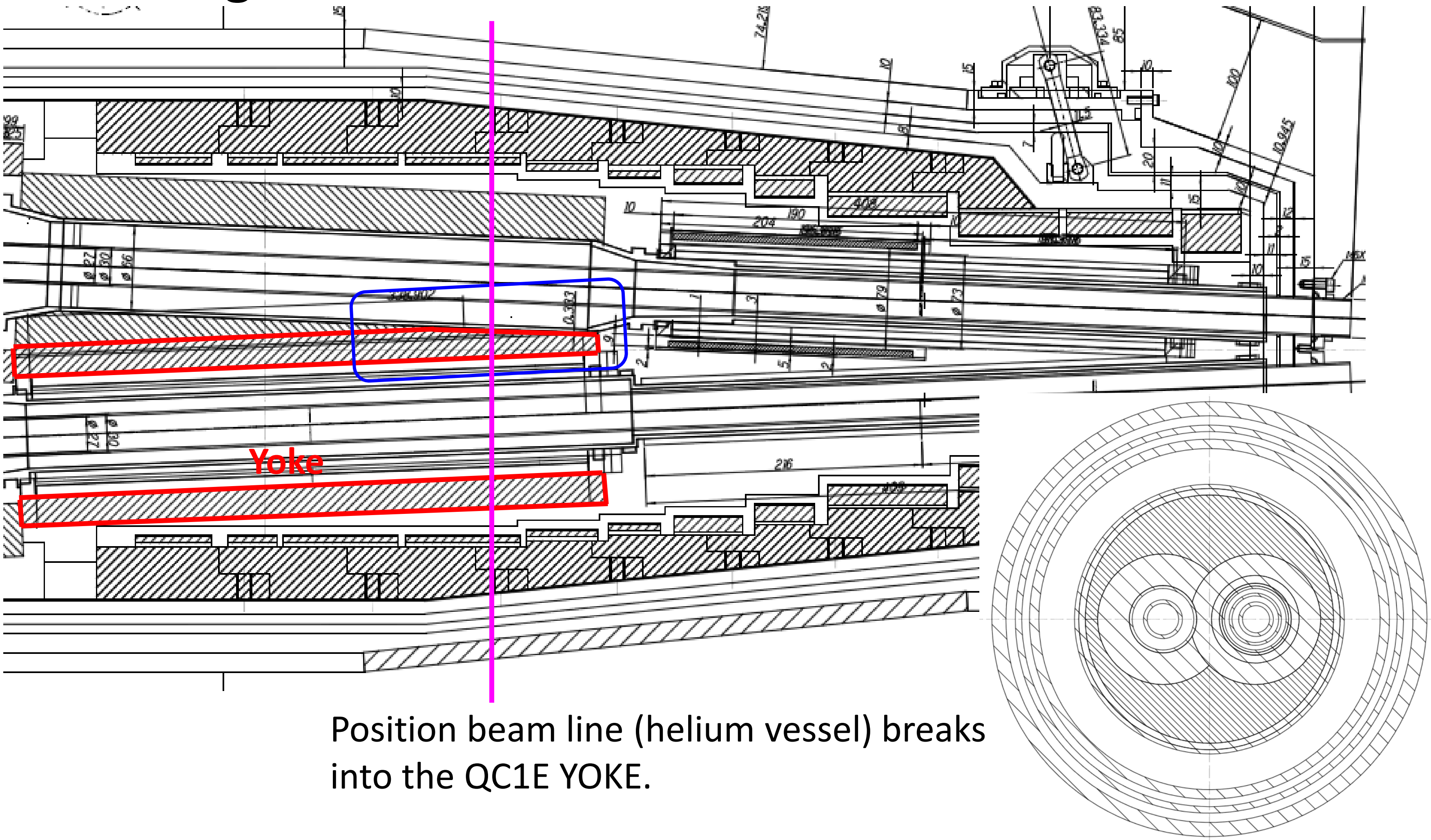
Permendur Yoke and Magnetic Shield

Magnet design: Permendur yoke

QC1E magnet and e+ beam line



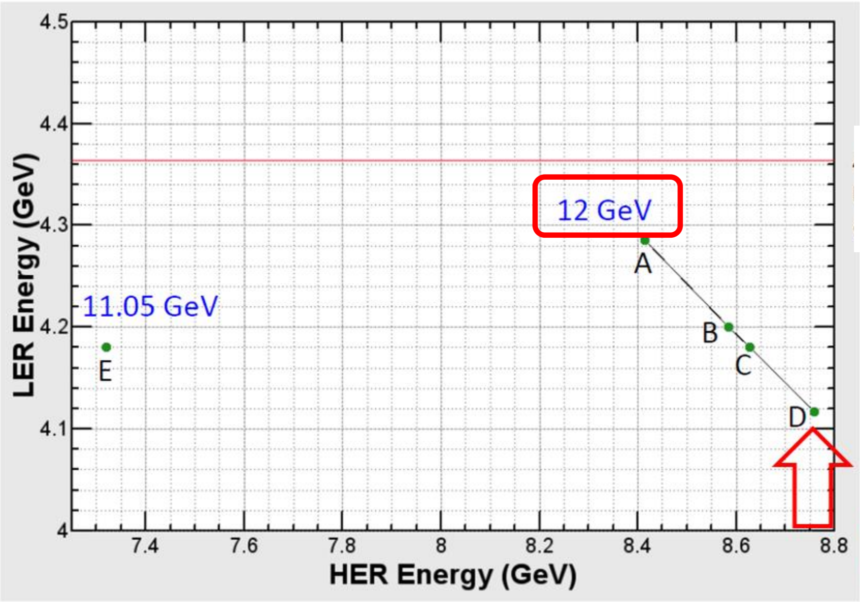
Position beam line (helium vessel) breaks into the QC1E YOKE.

Cross section of magnet-cryostat

Magnet design: Permendur yoke

SuperKEKB Operational Energy

Higher E_{cm}



4.364 GeV@860A
Maximum of the
power supply for LER

4.364GeV
(4.364/4=1.091)

8.75875GeV
(8.75875/7=1.25125)

E={7.32,4.18}

A={8.41415,4.28571} QC1LP(LER) 90%
B={8.58471,4.20056} HER:88.21 LER:88.21%
C={8.62694,4.18} HER:88.64 LER:87.78%
D={8.75875,4.11710} QC1LE(HER) 90%

For 12 GeV operation:

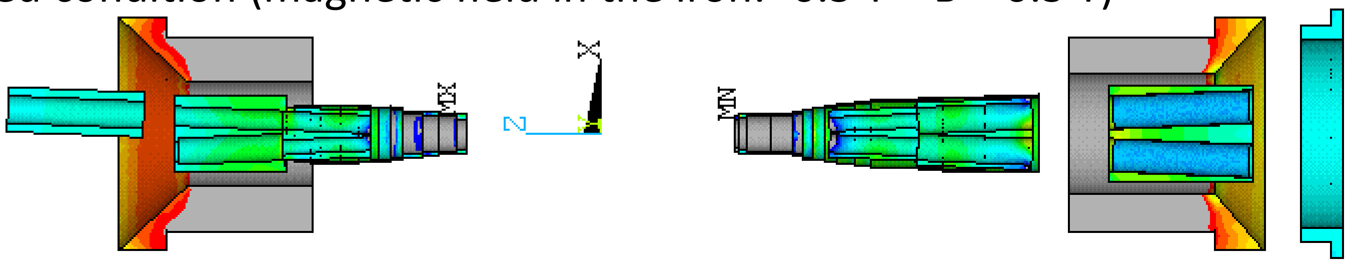
QC1E and QC2E current = 1.25 × current $_{@4s}$

QC1P and QC2P current = 1.09 × current $_{@4s}$

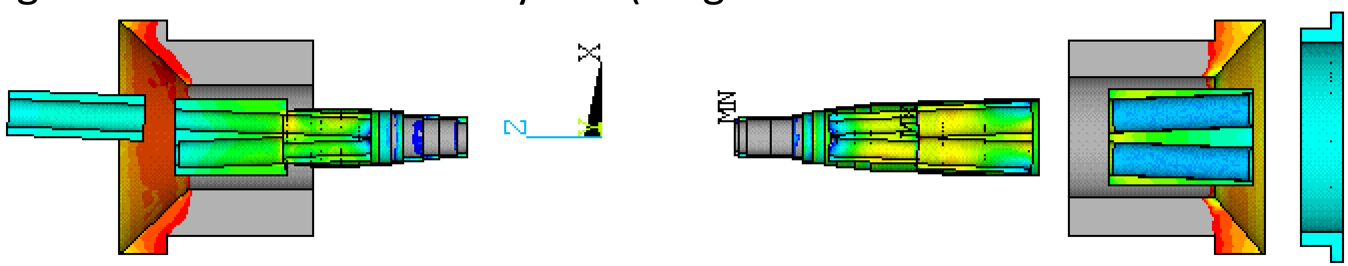
Magnet design: Permendur yoke

Field profile in the iron components (3D ANSYS)

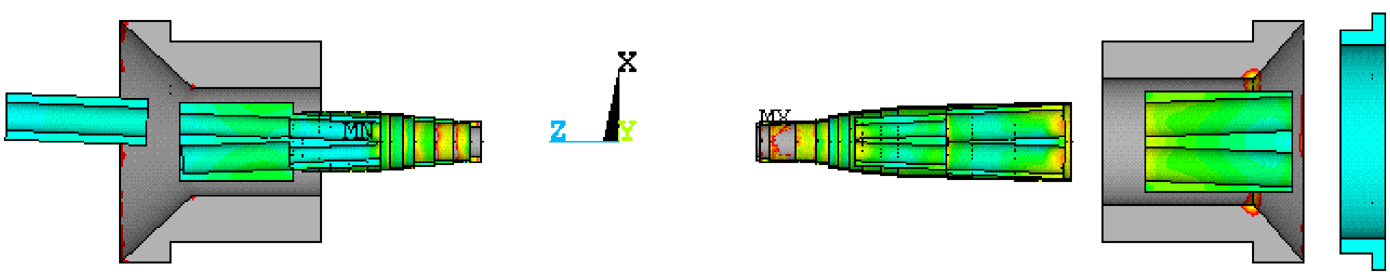
Optimized condition (magnetic field in the iron: -0.5 T < B < 0.5 T)

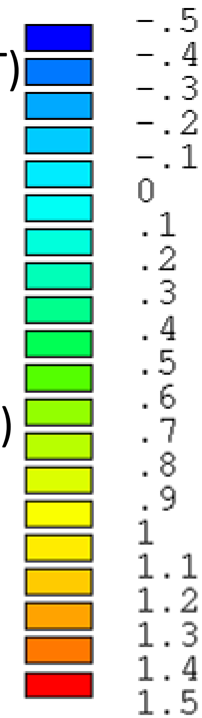


Increasing Belle solenoid current by 1 % (magnetic field in the iron: -0.5 T < B < 1 T)



Increasing acc. solenoid current by 1 % (magnetic field in the iron: -0.1 T < B < 1 T)

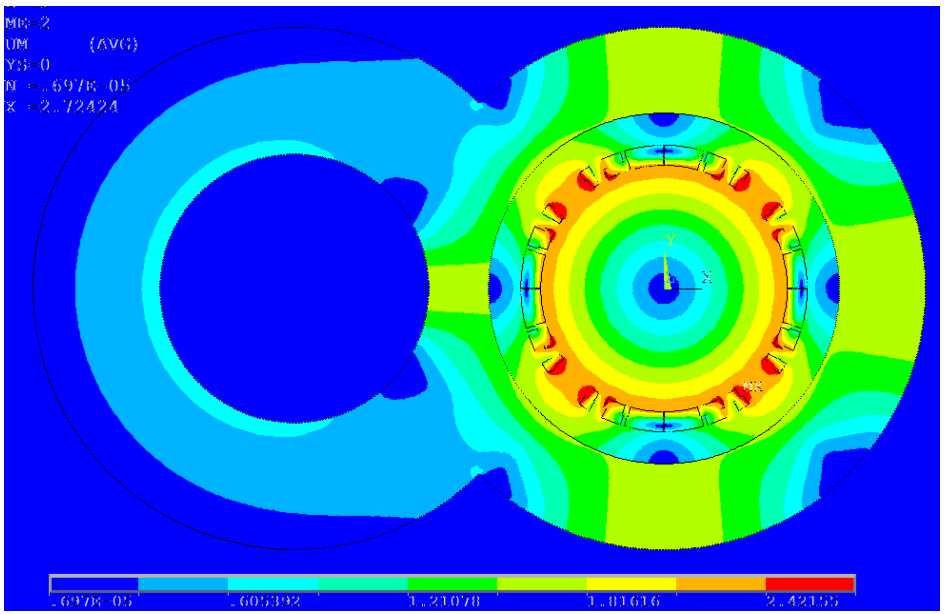




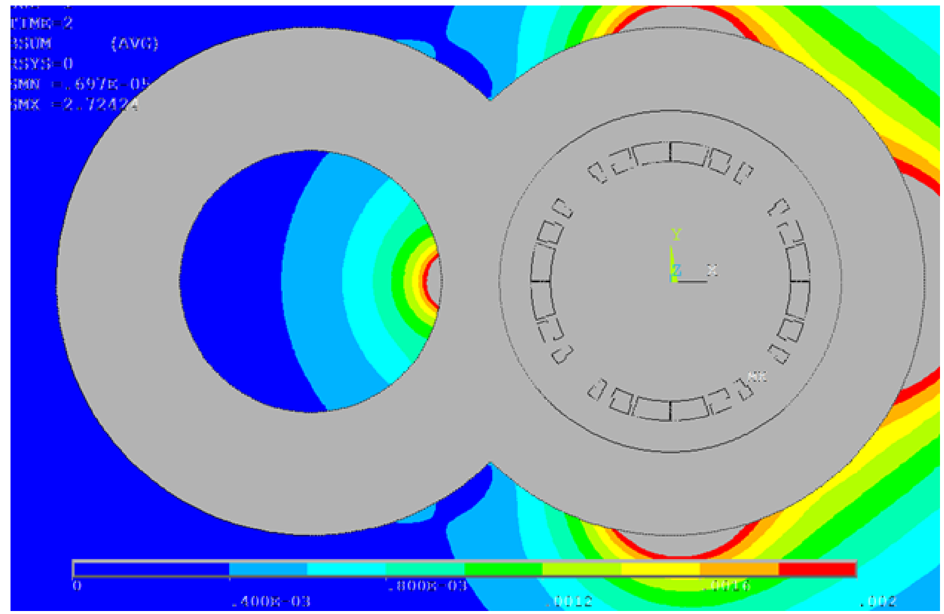
Magnet design: Permendur yoke

2D field calculation of QC1E (4s) : Yoke material= Iron

With 0T bias field



0 T **2.724 T**



0 Gauss **20 Gauss**

In the nominal operation of 4s:

Magnet current = 1577 A

G = 72.21 T/m

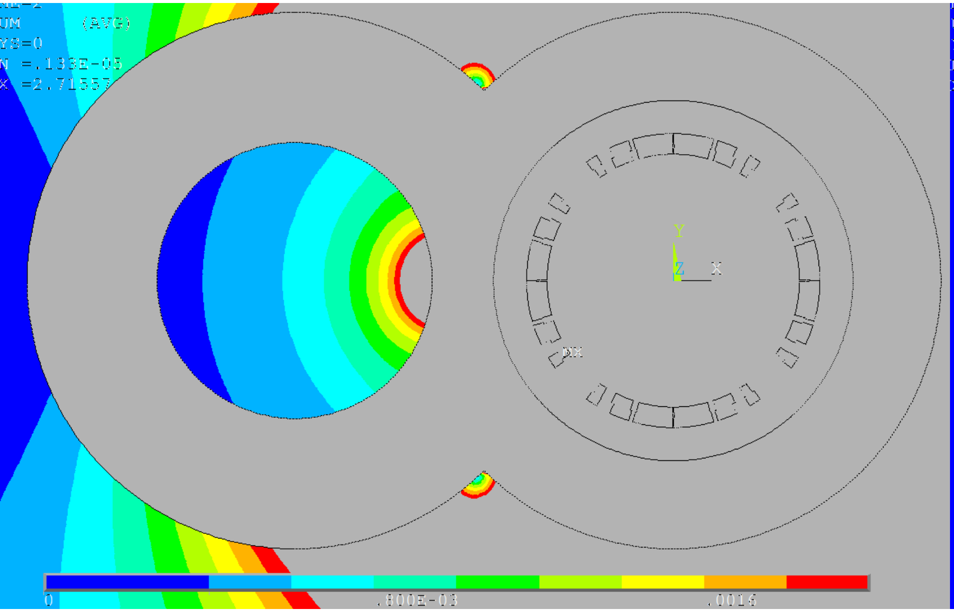
Max. field in the magnet = 2.724 T

Leak field in the e+ beam line center = 5 Gauss

Magnet design: Permendur yoke

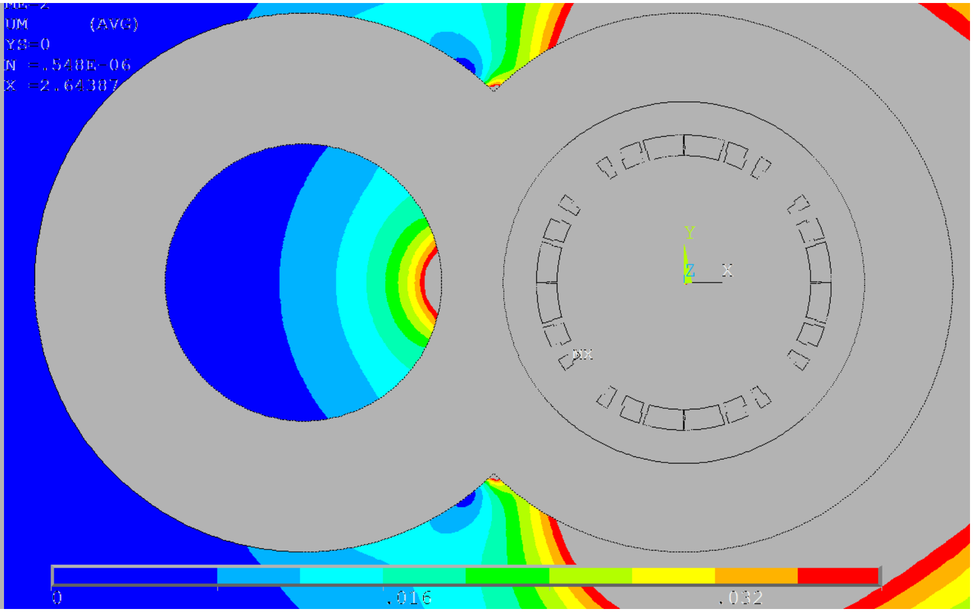
2D field calculation of QC1E (4s) : Yoke material= Iron

With 0.5 T field in the Iron Yoke



0 Gauss **20 Gauss**

With 1 T field in the Iron Yoke



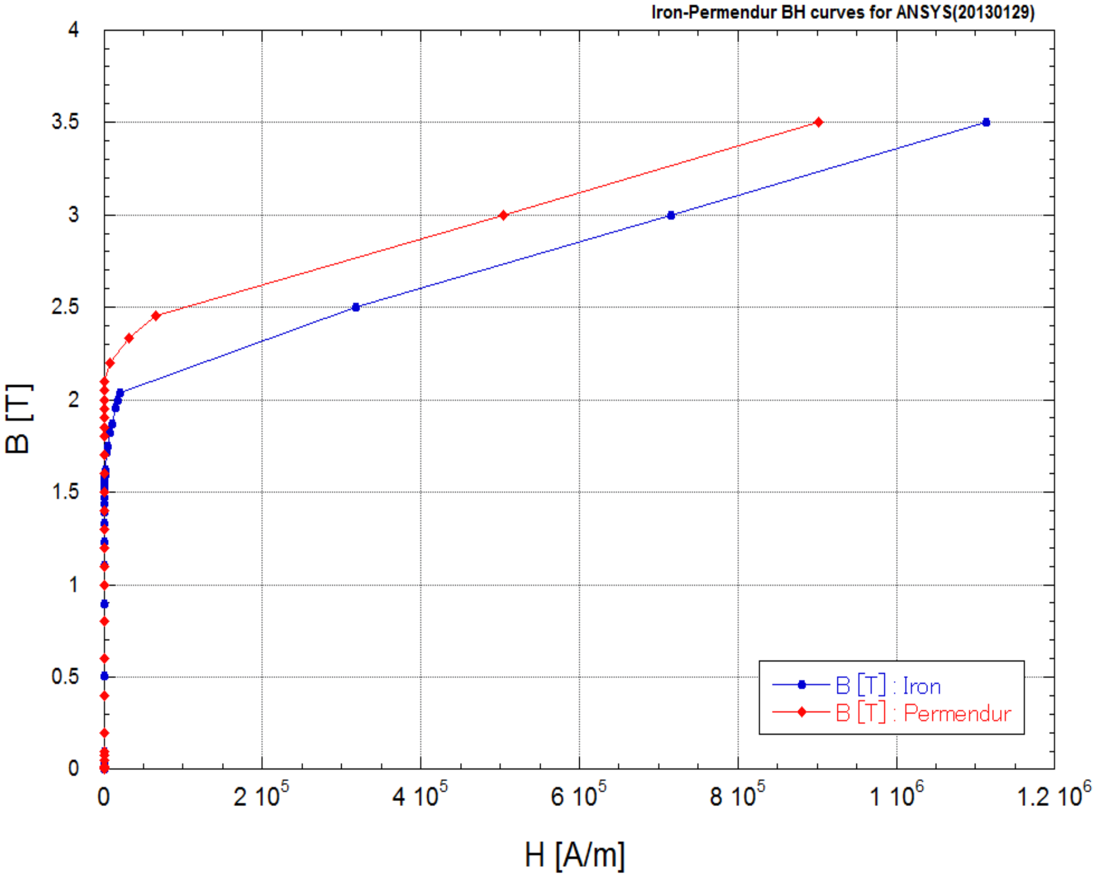
0 Gauss **400 Gauss**

Leak field at the e+ beam center = 6 Gauss

Leak field at the e+ beam center = 100 Gauss

Magnet design: Permendur yoke

B-H curves of Iron and Permendur



Permendur:

Fe=49.2%, Co=49 %, V=1.8%

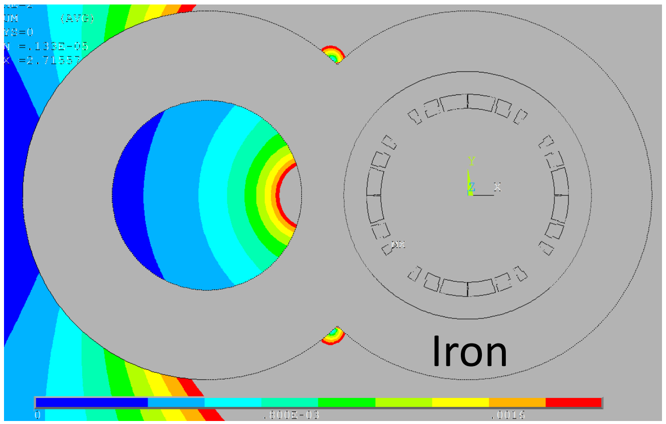
ρ= 8.3 g/cm^3

Bs > 2.35 T

Magnet design: Permendur yoke

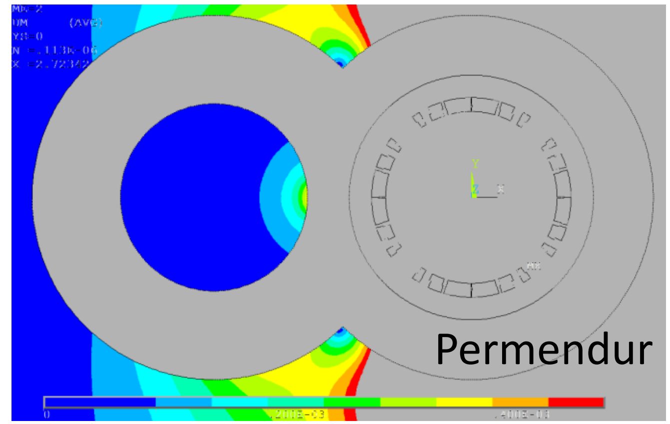
Comparison between Iron and Permendur

<u>With 0.5 T field in the Yoke (4s)</u>



0 Gauss **20 Gauss**

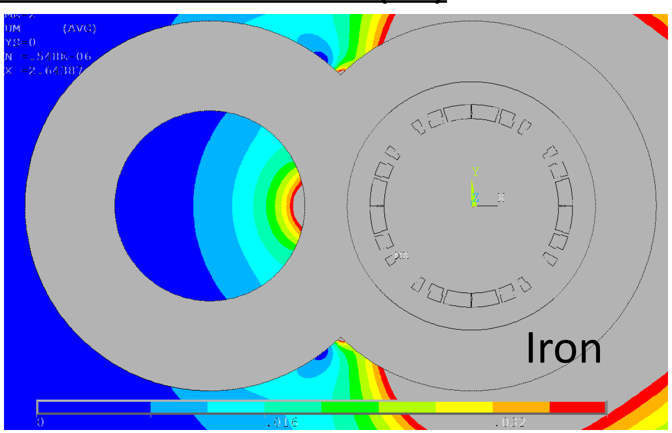
Leak field at e+ center = 6 Gauss



0 Gauss **5 Gauss**

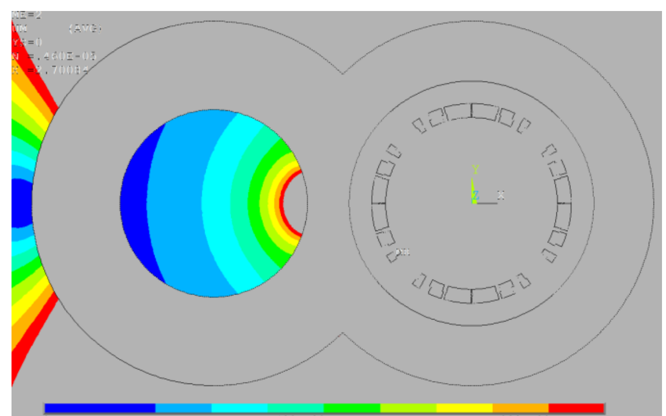
Leak field at e+ center <1 Gauss

<u>With 1 T field in the Yoke (4s)</u>



0 Gauss **400 Gauss**

Leak field at the e+ center = 100 Gauss



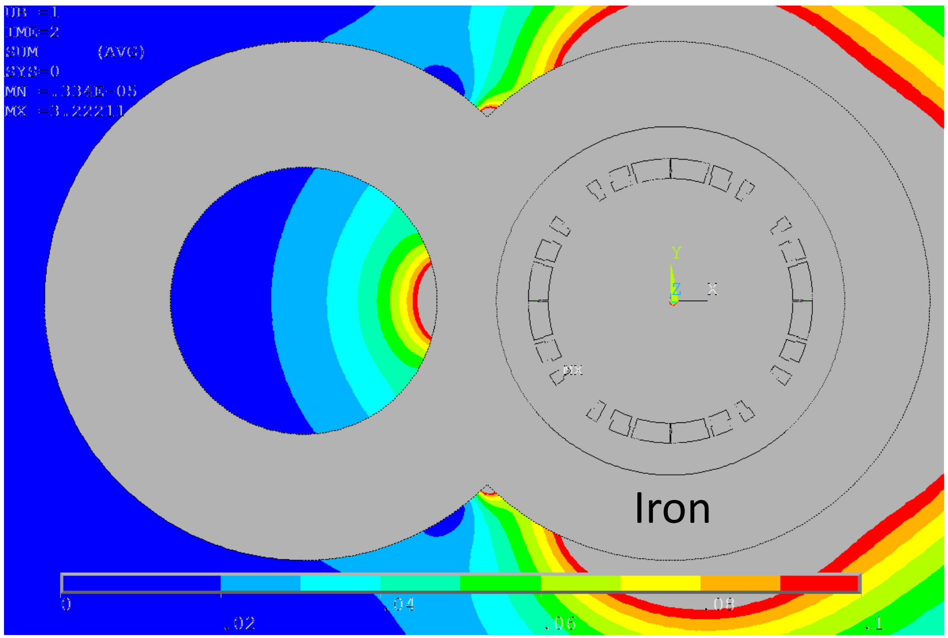
0 Gauss **10 Gauss**

Leak field at e+ center = 6 Gauss

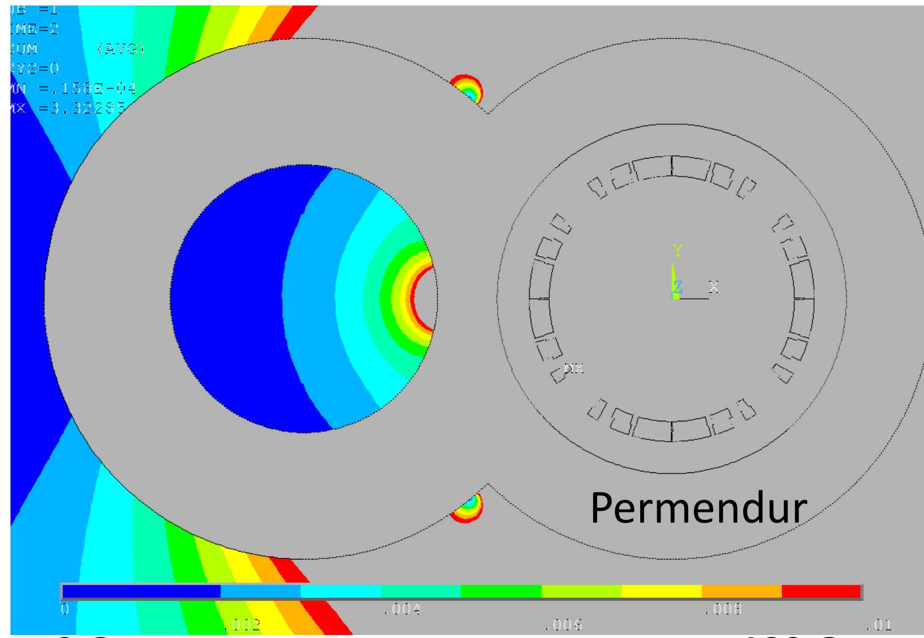
Magnet design: Permendur yoke

Comparison between Iron and Permendur

With 1 T field in the Yoke (12 GeV)



0 Gauss **1000 Gauss**



0 Gauss **100 Gauss**

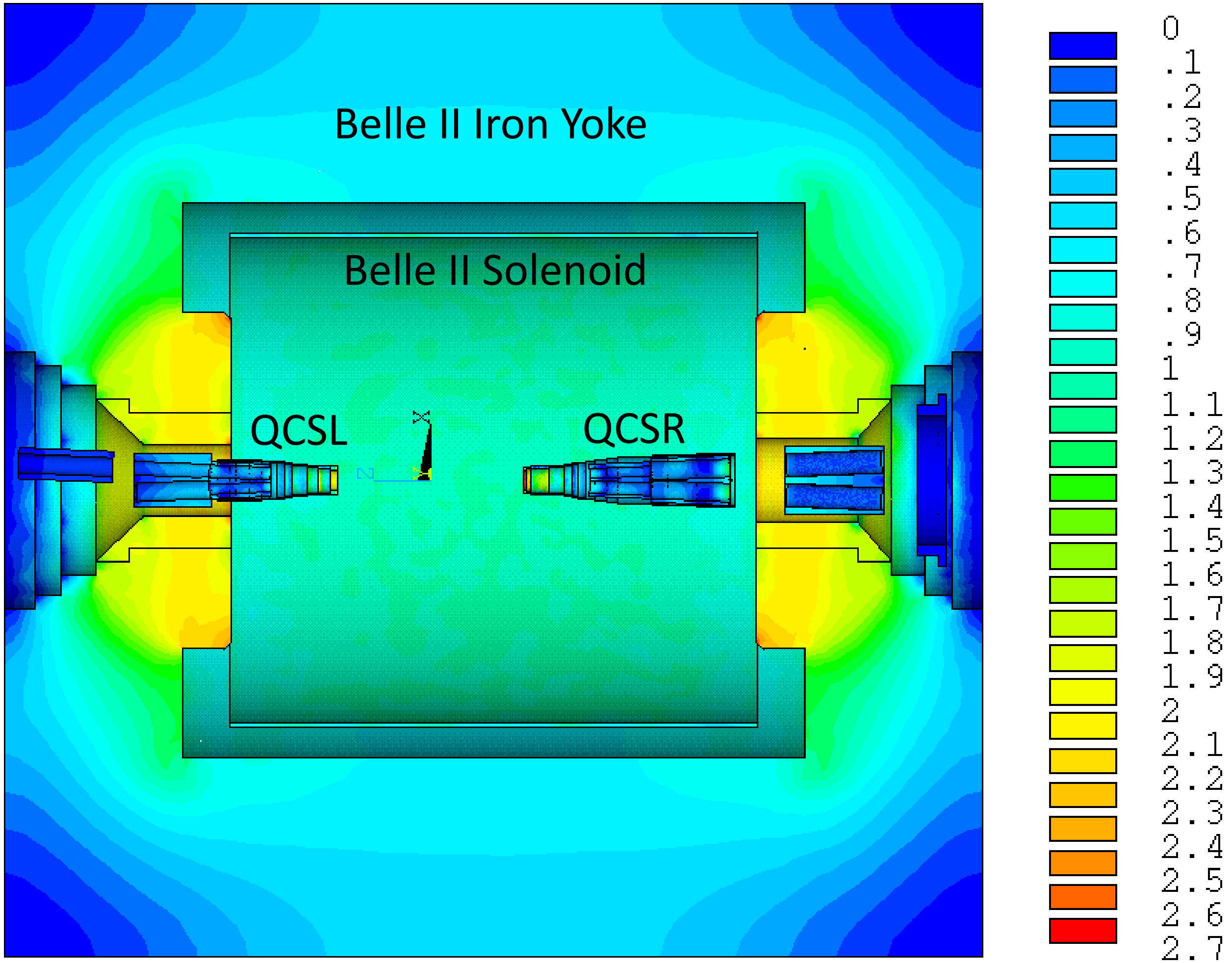
Cryostat mechanical design

- 3D Magnetic field calculation (Yamaoka-san)
  - Model with the Belle II solenoid + acc. solenoids + iron components
  - Calculation of the magnetic field and force
- Beam background noise study (Nakayama-san)
  - Installing the heavy metal components into the cryostats for the radiation shield

Mechanical calculation of the cryostat components by ANSYS

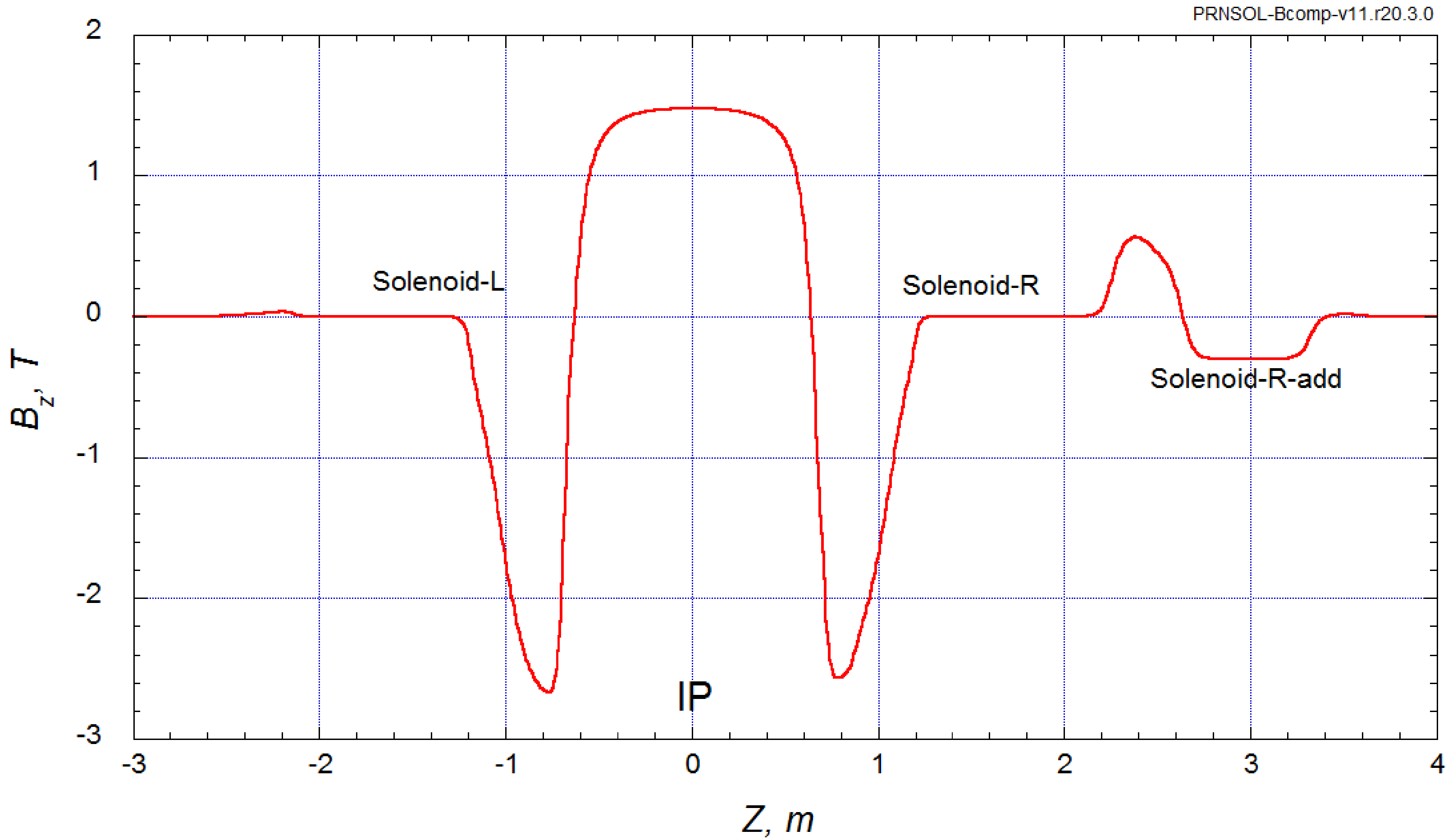
Cryostat mechanical design

- Magnetic field profile in the Belle II



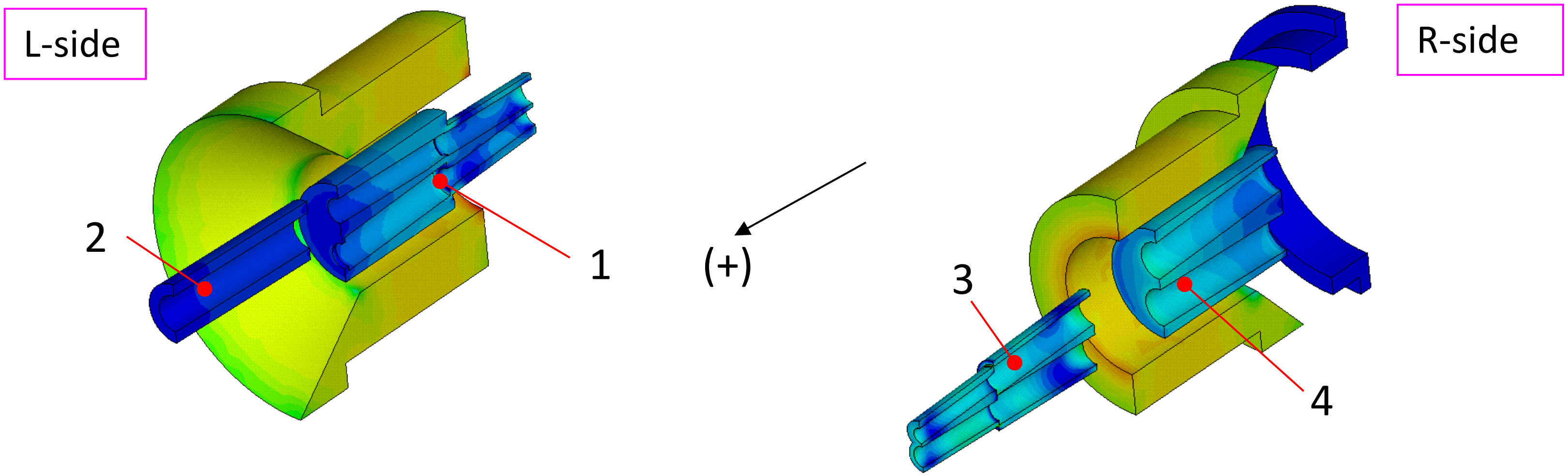
Cryostat mechanical design

- Magnetic field profiles along the beam lines



Cryostat mechanical design

- Electro-magnetic forces on the iron components and solenoids



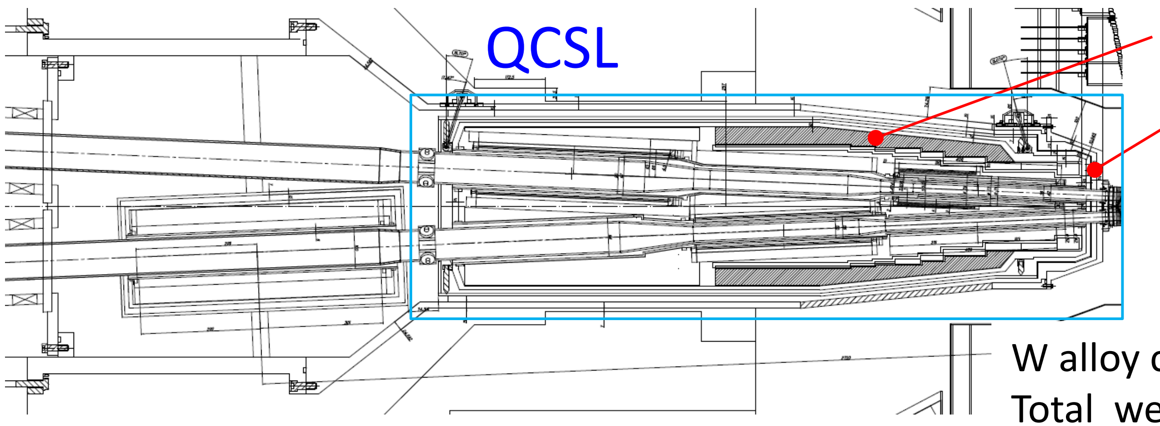
Electro-magnetic force, kN

	QCSL			QCSR		
	1	Solenoid	2	3	Solenoid	4
Acc. Solenoid ON	-0.81	48.3	-0.05	-1.89	-39.7	8.4
Acc. Solenoid OFF	-60.9	0	-0.15	6.01	0	15.3

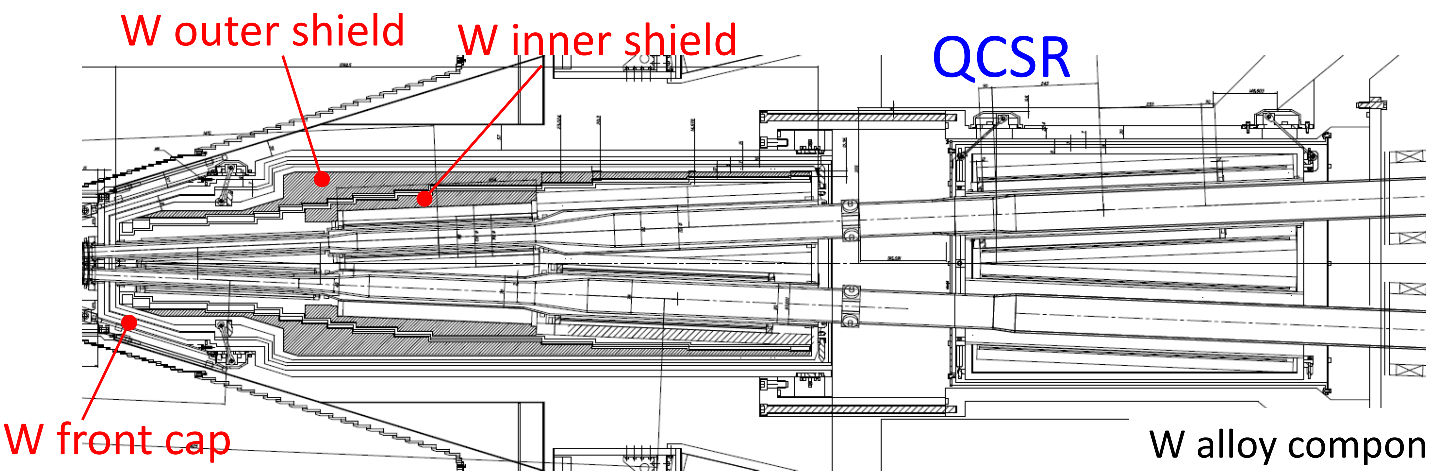
<u>The largest EMF for the one He vessel</u>

Cryostat mechanical design

- Heavy metal components in the cryostats
  - Material: W alloy [W>95%, ρ=18 g/cm^3], nonmagnetic



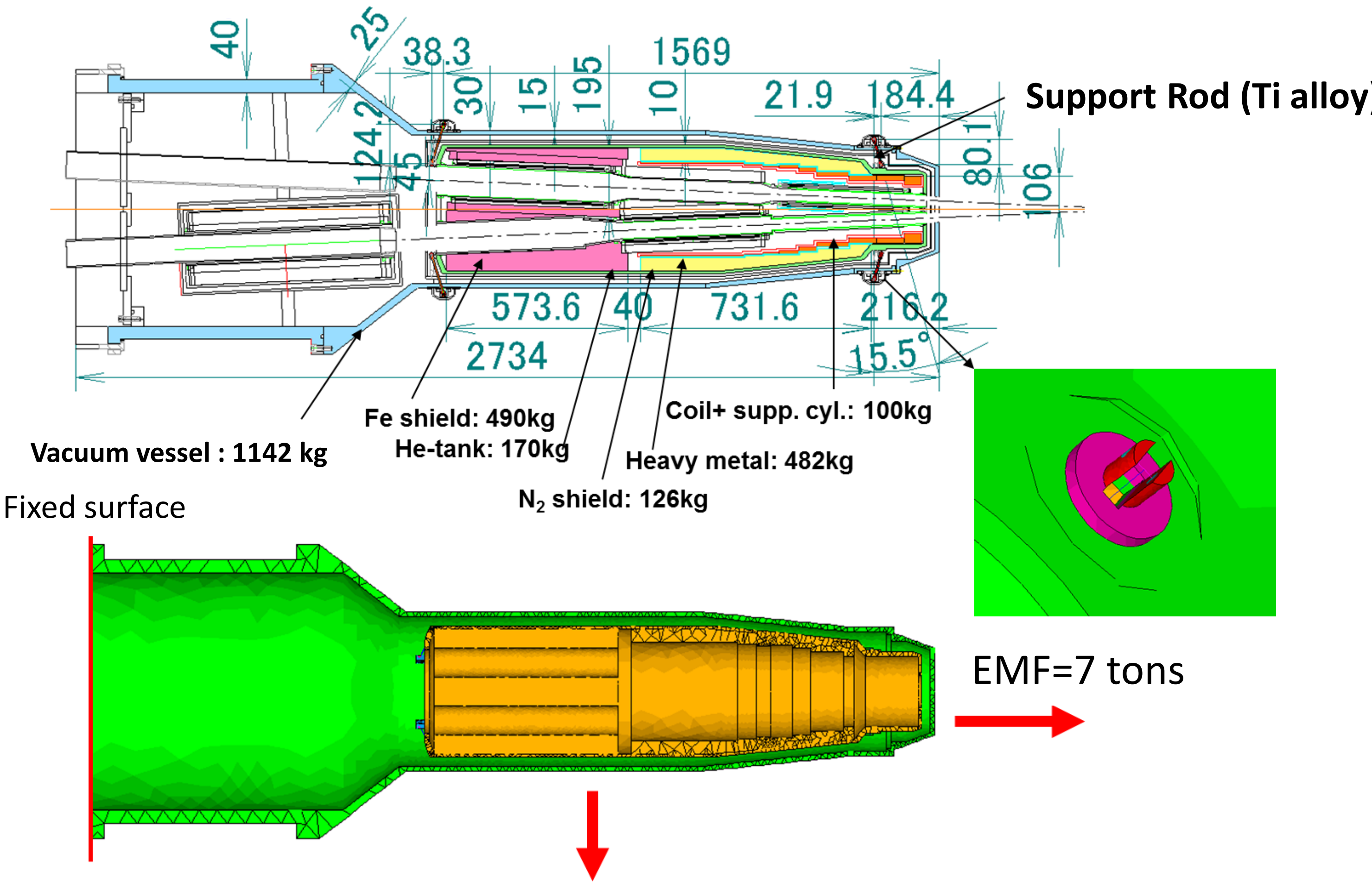
W alloy components = 480 kg
Total weight (cold mass) = 1400 kg



W alloy components = 800 kg
Total weight (cold mass) = 1700 kg

Cryostat mechanical design

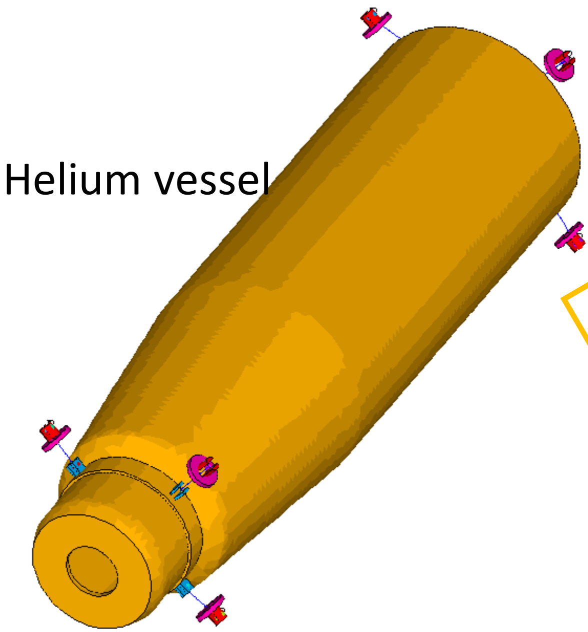
- Model for mechanical calculation by ANSYS

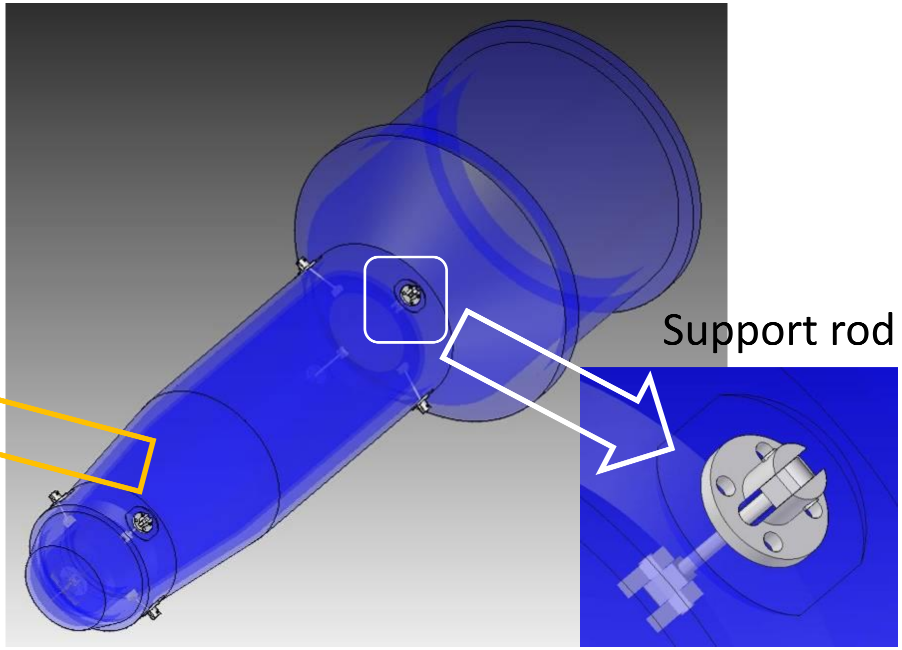


Total weight of the QCSL cryostat and magnets = 2510 kg
Cold mass = 1400 kg

Cryostat mechanical design

- Model for mechanical calculation by ANSYS





<u>Support rod design</u>

Most careful design: buckling in the support rods

Front rod: diameter=15 mm, length=80 mm, buckling stress of the rods=4550 MPa

Calculated stress in the rod = 224 MPa < 4550 Mpa

Rear rod: diameter=15 mm, length=132 mm, buckling stress of the rods=1670 MPa

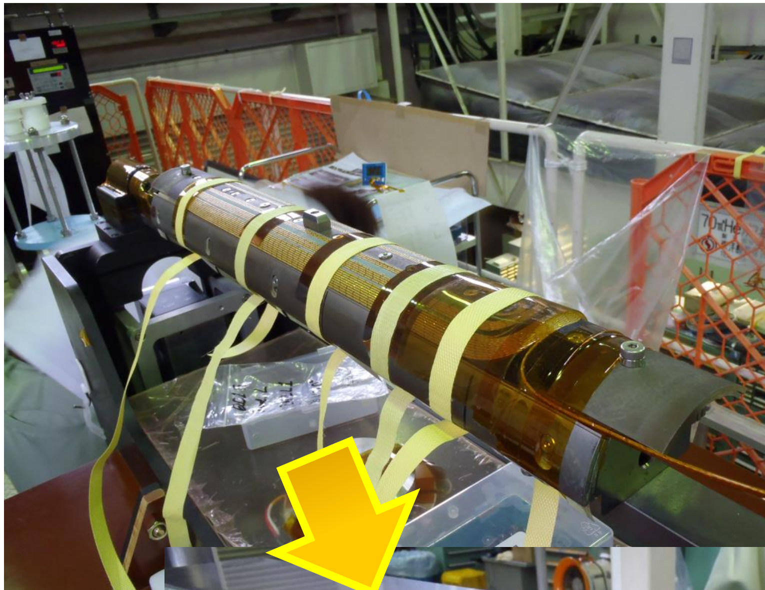
Calculated stress in the rod = 124 MPa < 1670 Mpa

QC1 proto-type construction

1. Prototypes of QC1E and QC1P were constructed.
   - QC1P has the smallest inner radius (R=25mm) in the four types magnets. Most difficult magnet to get the sufficient field quality.
   - QC1E has the second-smallest radius (R=33mm) and has the magnetic yoke.
2. QC1E Prototype
   - Magnet construction : May 28 – June 28
   - Cold test : July 7 – July 13
3. QC1P Prototype
   - Magnet construction : August 6 – September 7
   - Cold test : September 11 – September 20.

Proto-type QC1E coil production

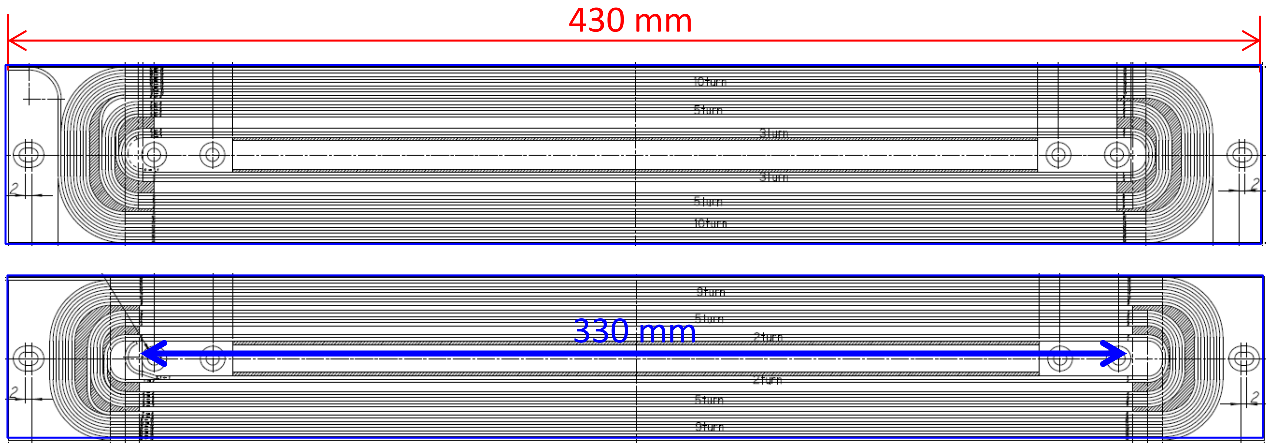
Coil winding on the mandrel



The coil was baked at 130 °C and pressed.

The wound coil was set in the forming block.

QC1E Prototype Magnet



2nd layer coil

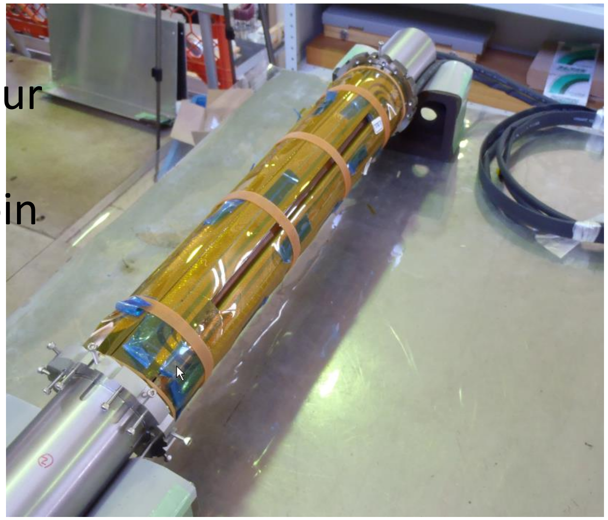
1st layer coil

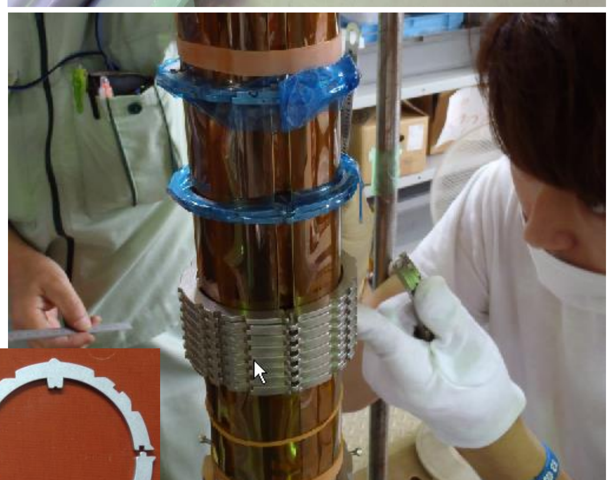
The coil length is 46 mm longer than QC1P.
The length of the coil straight section is 330 mm.

Four double layer coils

Collaring and yoking processes

Assembled four coils on the support bobbin



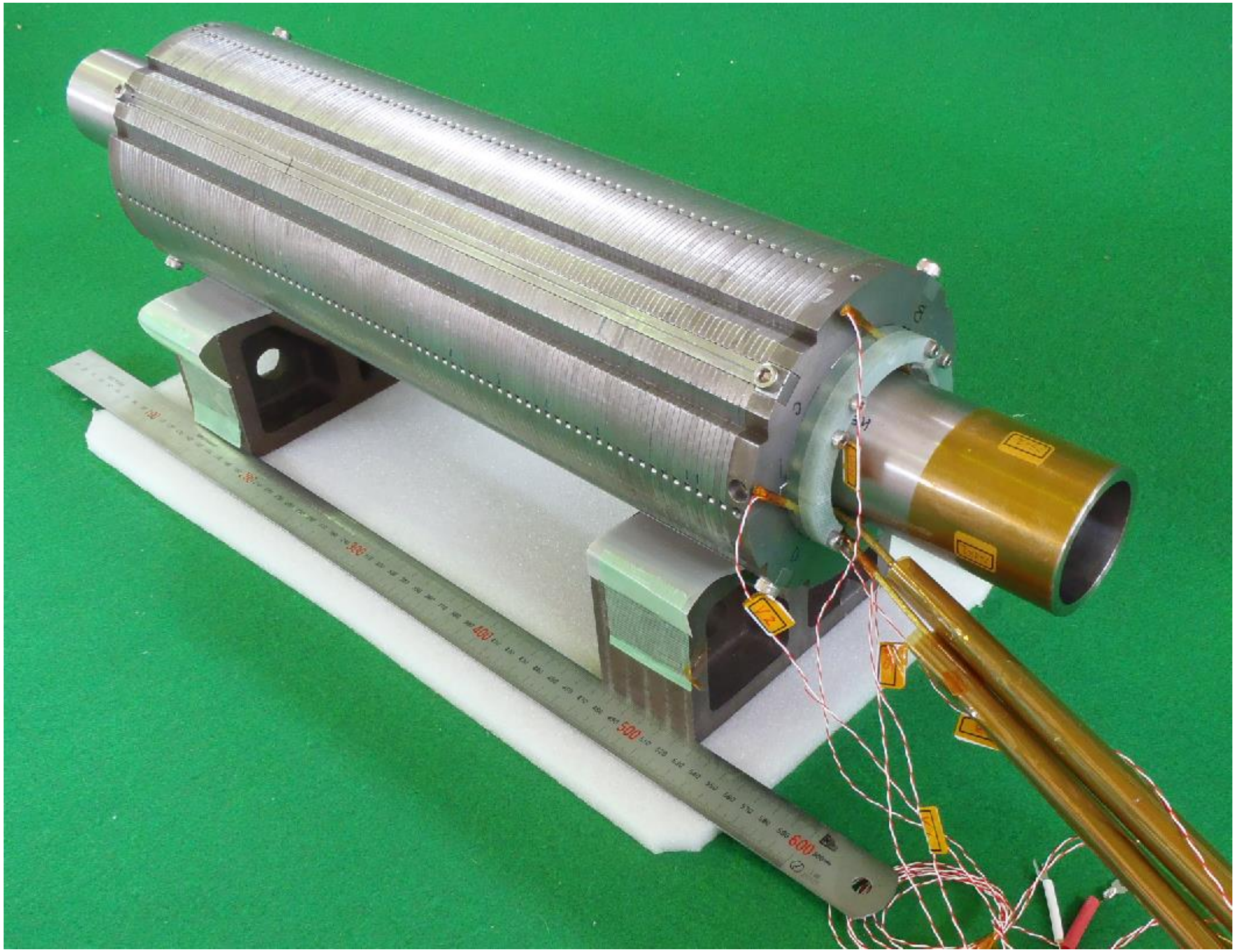


SS316LN collars

Collaring press

(Yoking process is same as the collaring process)

Yoked QC1E proto-type

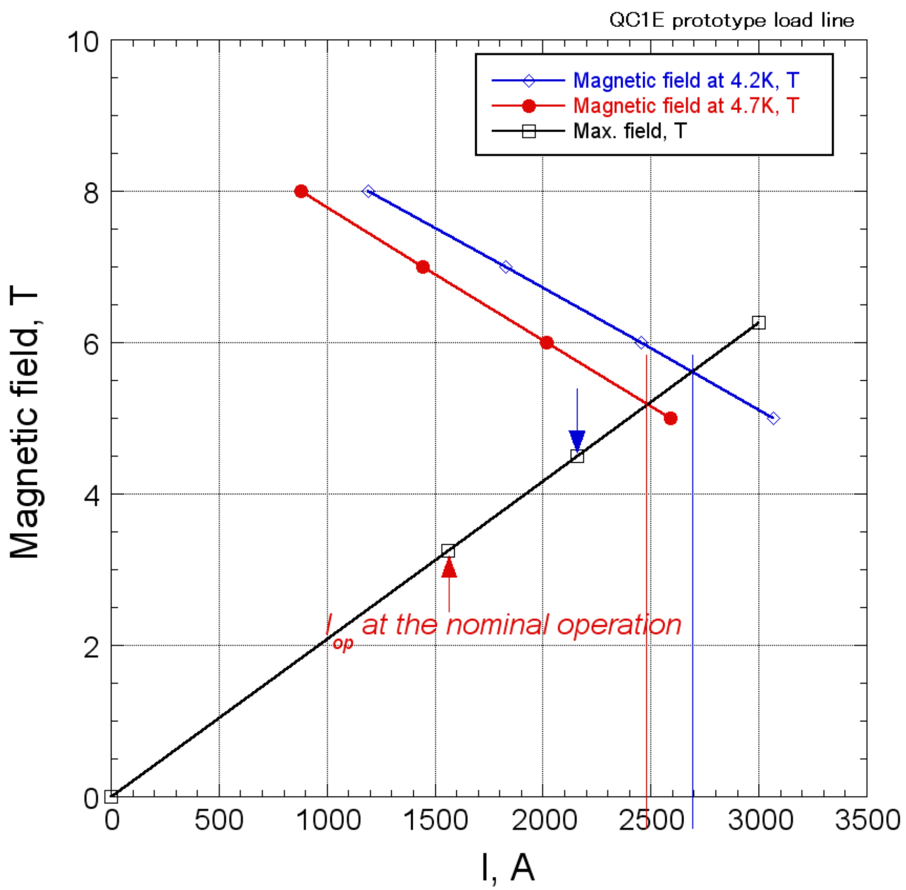


QC1E excitation test

QC1E magnet was excited up to 2157 A without quench.

Nominal operating current for 4S = 1558.5 A

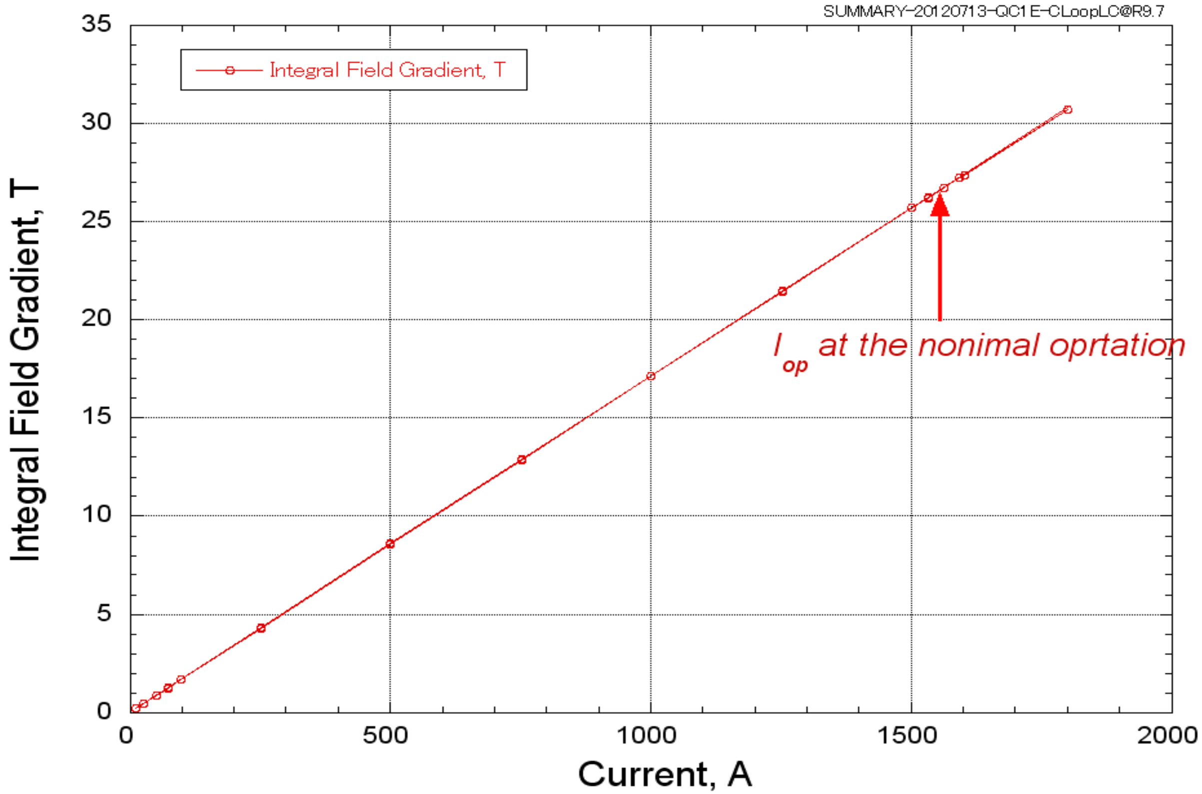
The current of 2157 A is the limitation of the power supply.



- On the load line of QC1E,
  - I_c at 4.7 K = 2480 A
  - $\boldsymbol{I_{op}/I_c}$ = 1558.5/2480 = **0.628**
  - I_{2157A}/I_c = 0.870
- For the operation at 12 GeV,
  - The maximum HER energy is assumed to be 8.75875 GeV.
  - QC1E current: $I_{8.75875}$ = 1950.1 A
  - $I_{8.75875} / I_c$ = 0.786

QC1E integral field measurements

Integral quadrupole field



- I_{op} = 1558.5 A for 4S
  - Optics requirement of the quadrupole field = 26.938 T
  - Measured quadrupole field = 26.660 T
    - The assembled magnet produces 1% less quadrupole field than the design.

QC1E integral field measurements

Error field (Multipole field comp.)

	R=9.54 mm at I=1561.7 A		R=15.0 mm at I=1561.7 A	
n	a_n	b_n	a_n	b_n
3	1.14	5.50	1.78	8.59
4	0.18	-0.28	0.44	-0.68
5	0.06	-0.48	0.23	-1.83
6	-0.06	-0.31	-0.39	-1.85
7	-0.01	0.01	-0.09	0.10
8	0.05	-0.00	0.69	-0.02
9	0.02	-0.00	0.51	-0.09
10	-0.00	-0.02	-0.10	-0.62

Reference radius= 9.54 mm

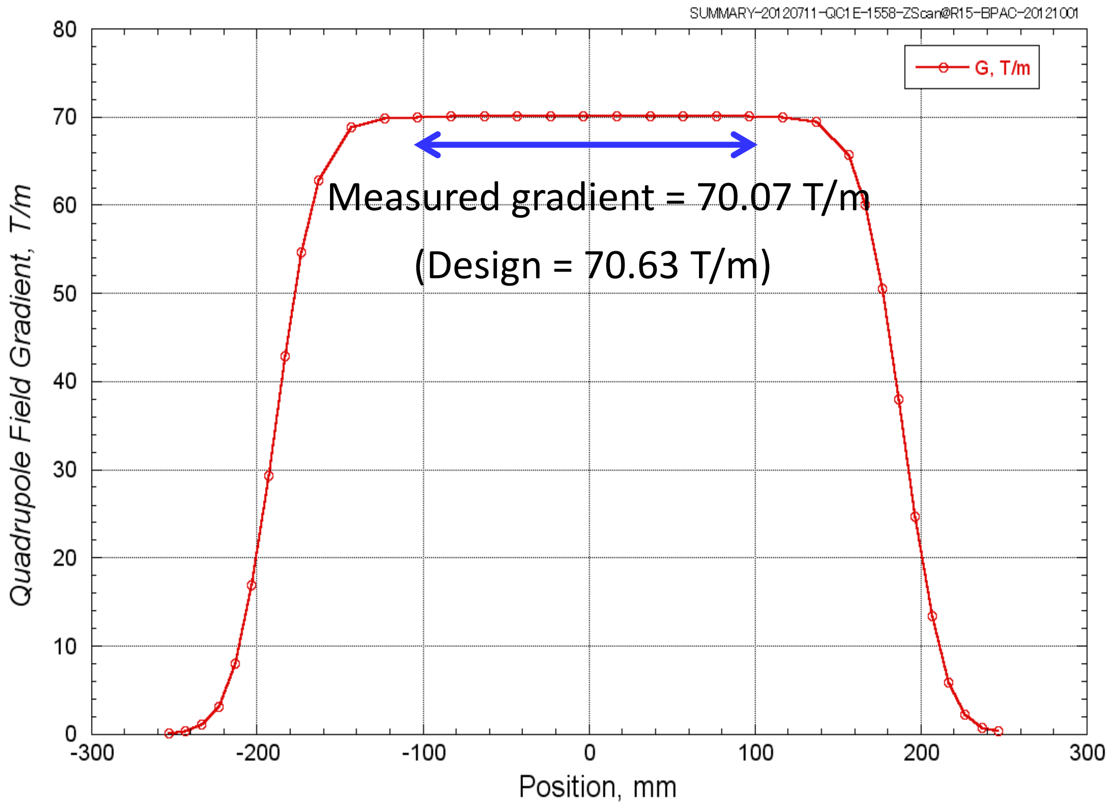
$a_n = A_n/B_2 \times 10000$

$b_n = B_n/B_2 \times 10000$

QC1E field profile measurements

Quadrupole field profile

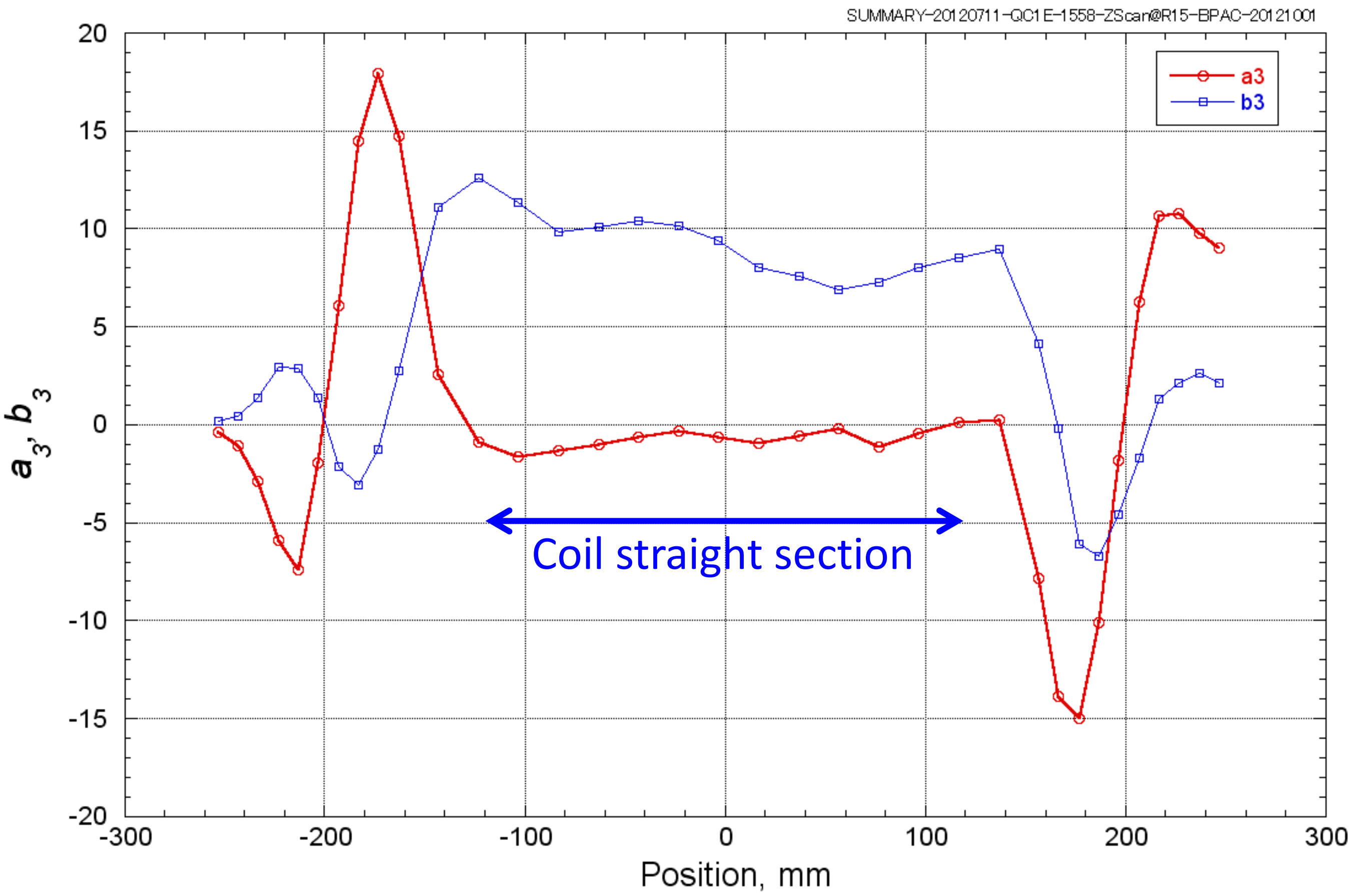
Field profile measurements were performed at *I*=1560.6 A.
The 40 mm HC was moved with a distance of 10 mm in the coil ends, and 20 mm in coil straight section.



The measured field gradient along the coil straight section was 0.86 % less than the design value.

QC1E field profile measurements

Sextupole field profile(a_3, b_3)

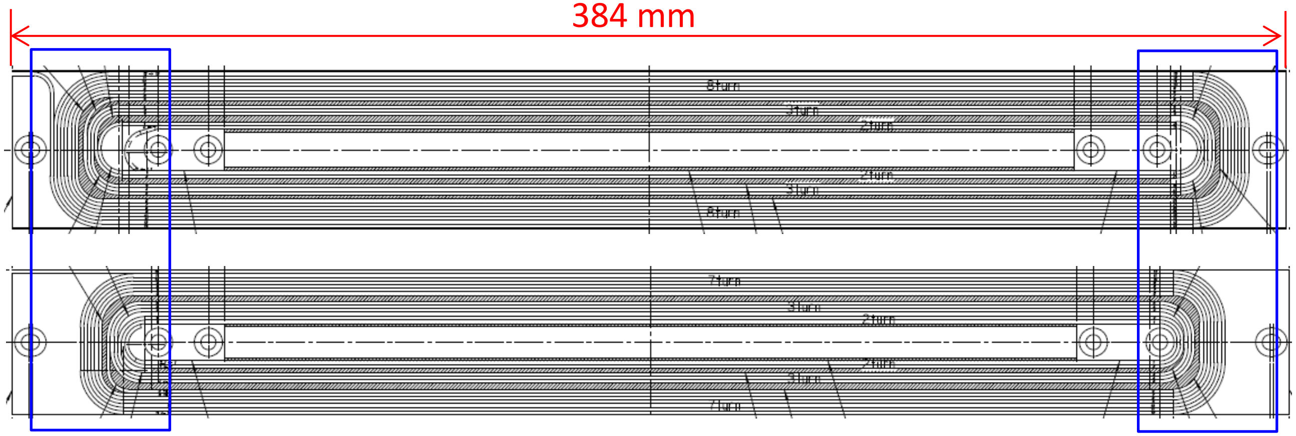


Reference radius= 15 mm

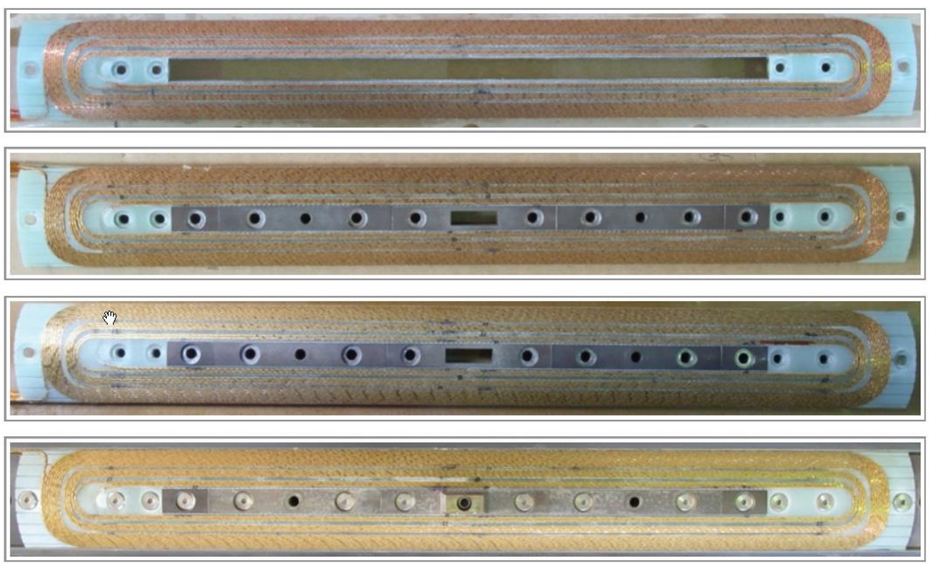
$a_n = A_n/B_{2@magnet\text{-}center} \times 10000$

$b_n = B_n/B_{2@magnet\text{-}center} \times 10000$

QC1P prototype magnet



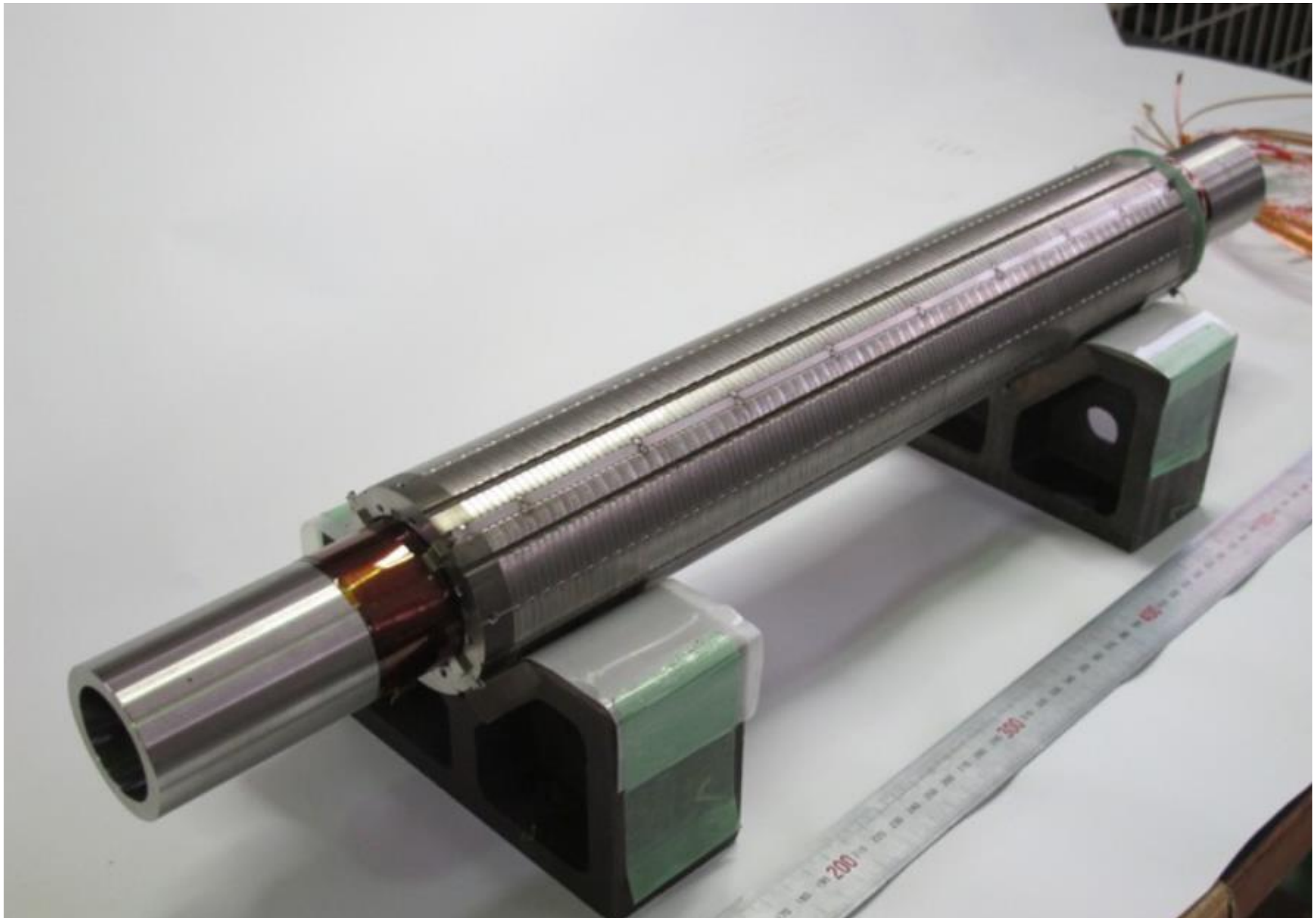
The designs of the coil ends are optimized as to the integral magnetic length and error field components.



Four double layer coils

QC1P prototype magnet

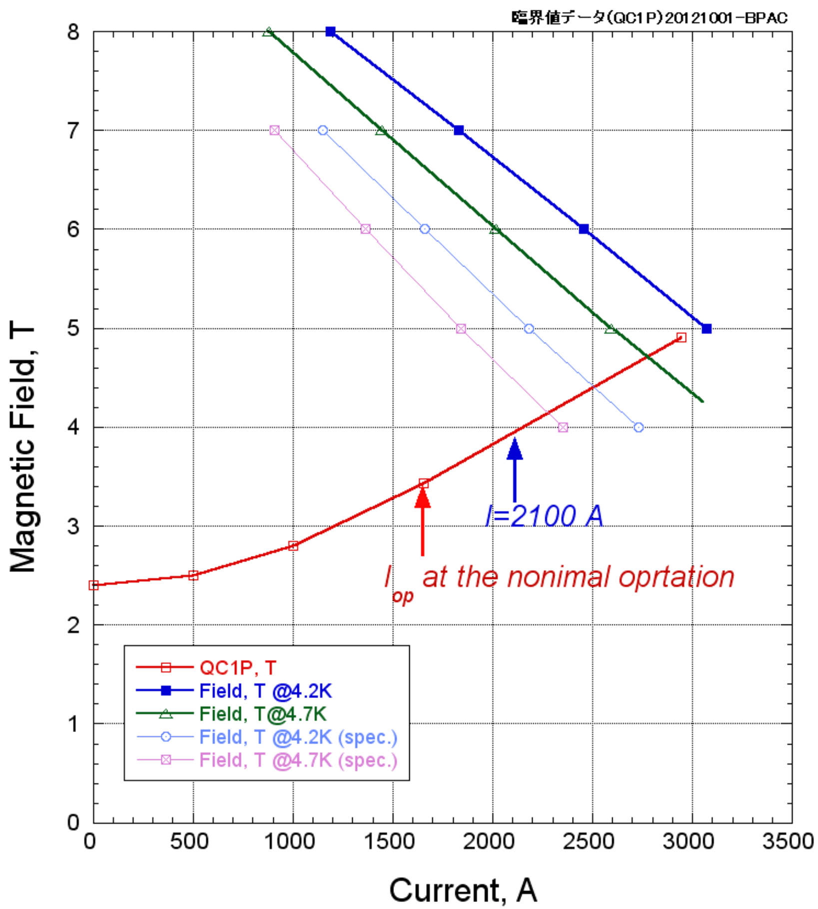
Completed QC1P prototype magnet (collared magnet without yoke)



QC1P excitation test

QC1P magnet was excited up to 2100 A without quench.

Nominal operating current for 4S = 1625 A

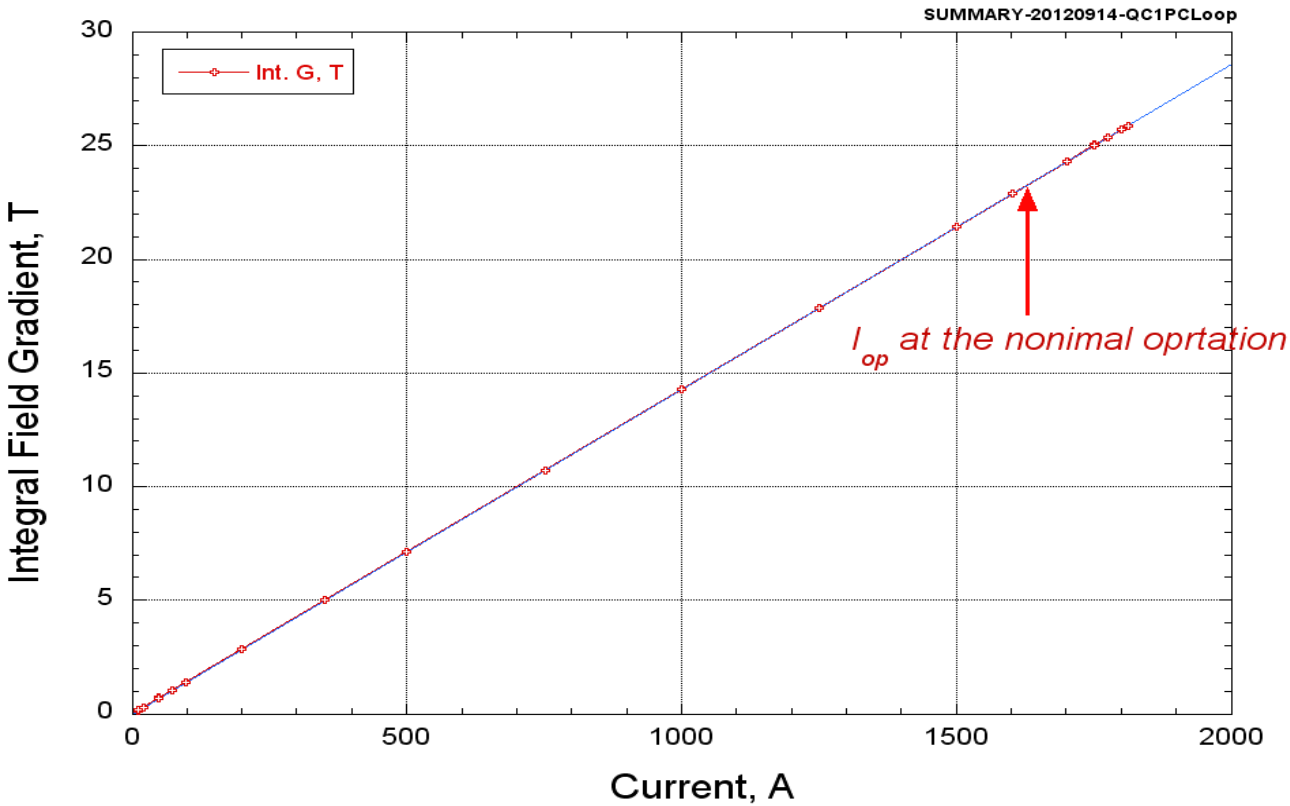


QC1P Load Line with Solenoid Field

- The SC cable performance was much better than the specification.
  - SC cable supplier: Furukawa Electric. CO LTD
- On the load line of QC1P,
  - I_c at 4.7 K = 2770 A
  - I_{op}/I_c = 1625/2770 = **0.58**
- For the operation at 12 GeV,
  - The maximum LER energy is assumed to be 4.364 GeV.
  - QC1P current: $I_{4.1171}$ = 1773 A
  - $I_{4.1171} / I_c$ = 0.64

QC1P integral field measurements

Integral quadrupole field



- I_{op} = 1624.93 A for 4S
  - Optics requirement of the quadrupole field = 22.966 T
  - Measured quadrupole field = 23.217 T
    - The assembled magnet produces 1% higher quadrupole field than the design.

QC1P integral field measurements

Error field (Multipole field comp.)

n	a_n	b_n
2	-0.000	10000
3	2.82	3.66
4	2.08	0.24
5	0.35	0.23
6	0.03	-0.59
7	0.07	0.13
8	0.03	0.01
9	-0.08	0.05
10	0.02	0.01

n : Multipole number

- $n = 2$: quadrupole field

Reference radius= 9.54 mm

$a_n = A_n/B_2 \times 10000$

$b_n = B_n/B_2 \times 10000$

A_n : skew field of the *n-th*

B_n : normal field of the *n-th*

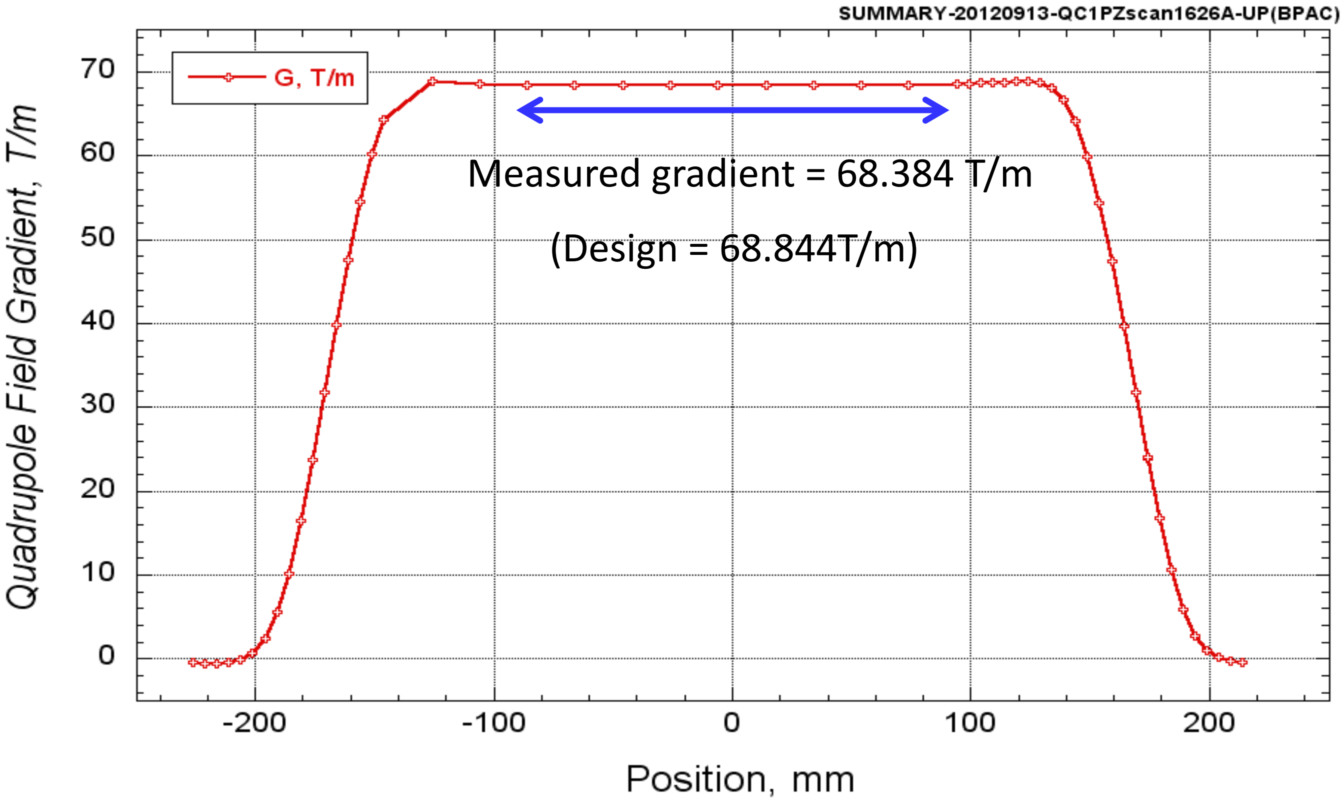
B_1 : normal dipole,

B_2 : normal quadrupole.

QC1P field profile measurements

Quadrupole field profile

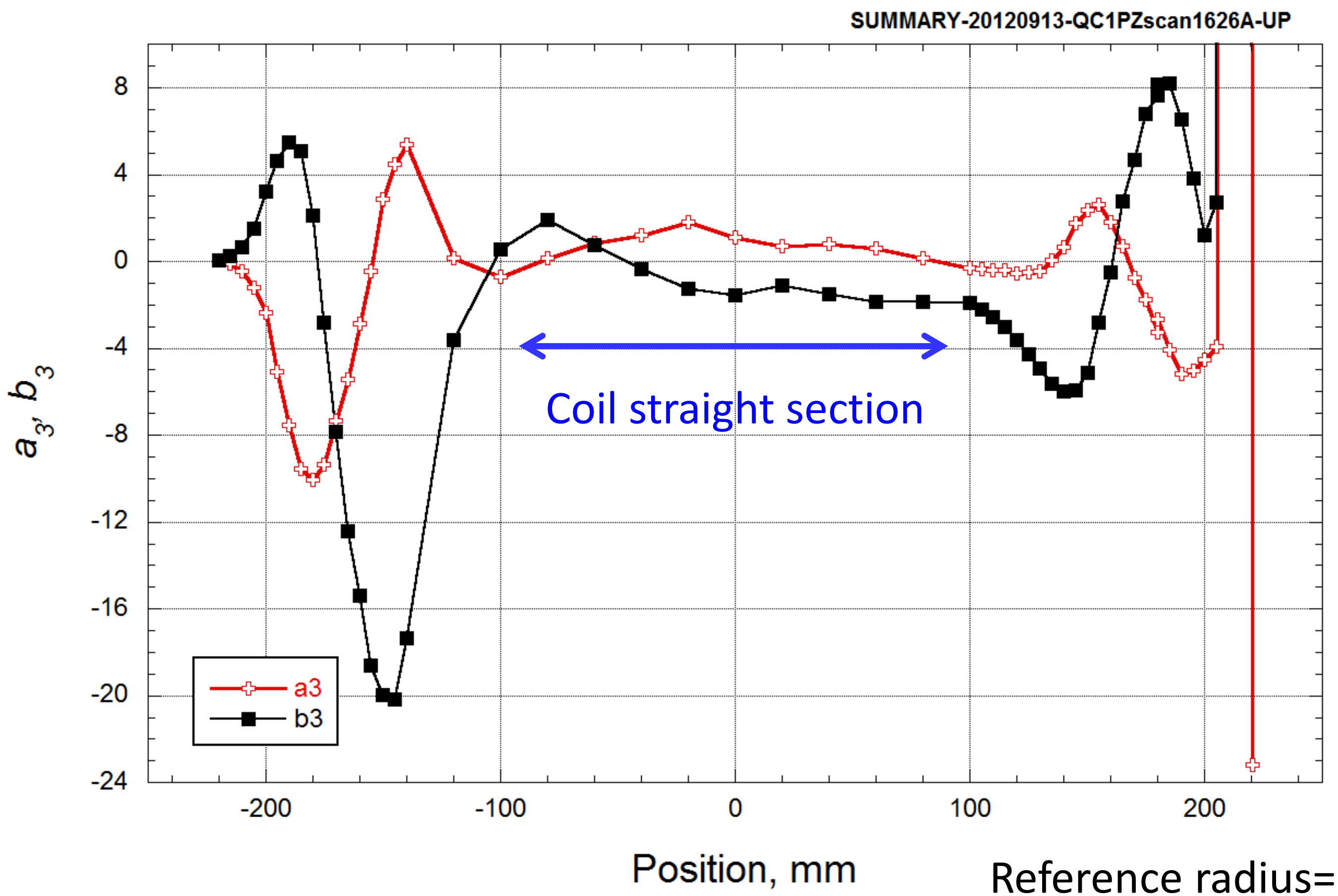
Field profile measurements were performed at *I*=1626 A.
The 40 mm HC was moved with a distance of 5 mm in the coil ends, and 20 mm in coil straight section.



The measured field gradient along the coil straight section was 1 % less than the design value.

QC1P field profile measurements

Sextupole field profile(a_3, b_3)



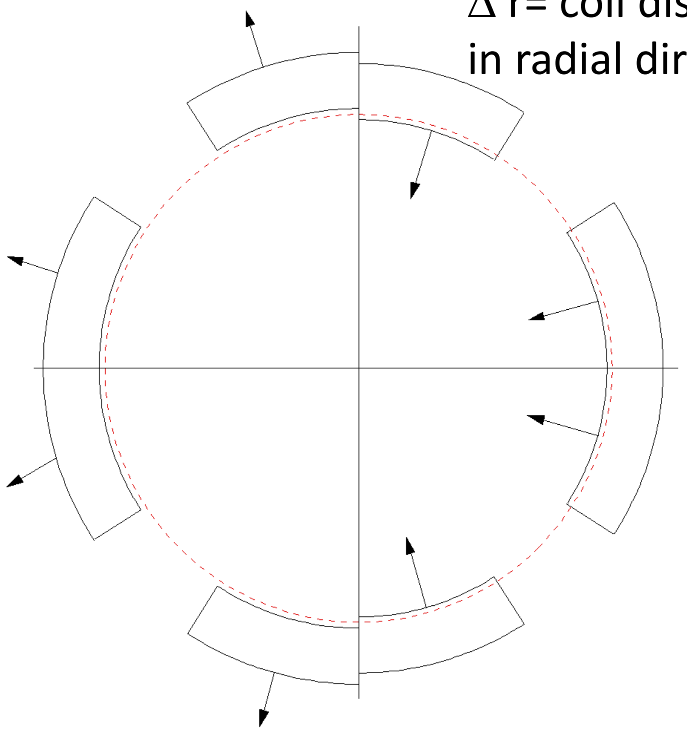
Reference radius= 10 mm

$a_n = A_n/B_{2@magnet\text{-}center} \times 10000$

$b_n = B_n/B_{2@magnet\text{-}center} \times 10000$

a_3 and b_3 error field

- Sextupoles are produced by the dipole deformation of four coils



- Δ r = 50 μm
  - $b_3 = 13.62 \times 10^{-4}$
  - $a_3 = 0$
  - $b_4 = 0$
  - $a_4 = 0$
  - $b_5 = -1.63 \times 10^{-4}$
  - $a_5 = 0$
- Δ r = 20 μm
  - $b_3 = 5.45 \times 10^{-4}$
  - $a_3 = 0$
  - $b_4 = 0$
  - $a_4 = 0$
  - $b_5 = -0.65 \times 10^{-4}$
  - $a_5 = 0$

$b_3 = 10 \times 10^{-4}$ corresponds to Δr = 36 μm.

QC1E: G=72.2 T/m

@ R=15 mm : b_3 = 14.75 Gauss (50 μm)、5.9 Gauss (20 μm)

Improper design in Quadrupoles

- a_3 and b_3 at 0.1% in the magnet straight section
  - The calculated displacement of the quadrant coil = 36 μm
- 0.1 % smaller produced magnetic field than the design
  - r_{in} of the QC1E coil : 280 μm larger than design
  - r_{in} of the QC1P coil : 250 μm larger than design
- During the collaring process of the four coils, the coils were squeezed on the support bobbin which had correctly the design radius.
  - There existed the gap of ~300 μm between the support bobbin and the coil inner surfaces.

↓

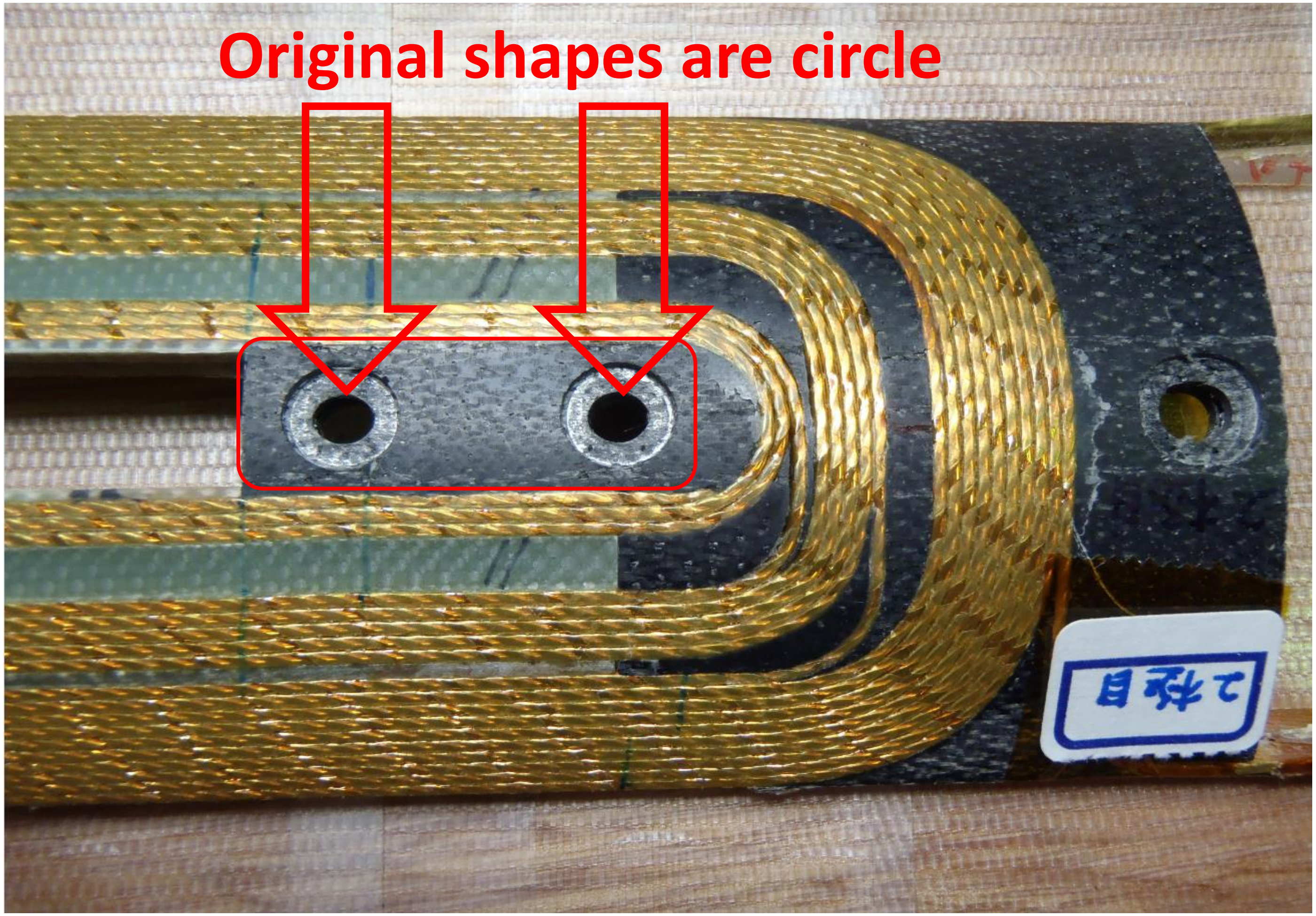
The mechanical parameters of SC cables were checked in the magnet cross section.

Improper design in Quadrupoles

- In the design of the magnet cross section
  - “EMF in the magnet + thermal contraction from room temp. to 4 K” is considered.
  - Under the conditions at 4 K, the inner stress in the coils should be left so that the cables do not move by the EMF.
  - In the magnet design, the inner stress at room temperature was designed at 30 MPa.
  - The magnet cross sections were designed with the cables at the compressed size with the stress.
- **The improper mechanical parameter: Young modulus**
  - Initial design: 648 MPa
  - Cable measurement: 8 GPa (In KEKB quadrupole, 6.86 GPa)
  - In the produced coils after collaring, the inner radius was larger than the design.
- **The designs of the cross sections and the coil ends in all magnets were modified with the proper Young modulus.**

Improper design in Quadrupoles

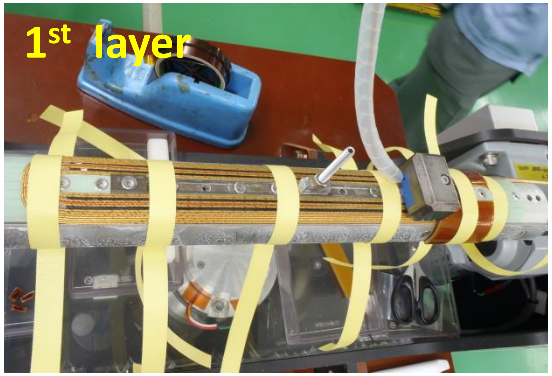
- QC1E coil end

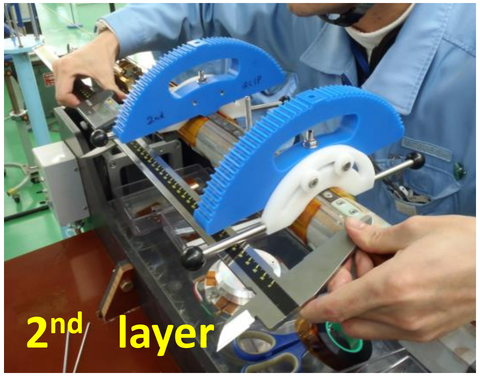


Construction status

1. QCSL QC1/2 SC quadrupoles at Mitsubishi

- Technical transfers of QC1LP, QC1LE, QC2LP and QC2LE magnet drawings, and all jig drawings have been almost completed.
- Tooling jigs, machines for QC1P/E and the SC cables were transported to Mitsubishi in December 2012.
- The winding machines were set in the factory of Mitsubishi.
- The first test winding of QC1P proto-type coil were performed in January 2013 by the technicians of Mitsubishi for their training.
  - The test winding has been completed with the same coil components and the QC1P cable four times up to now.
  - The final test winding with the actual coil end spacers is planed in April.



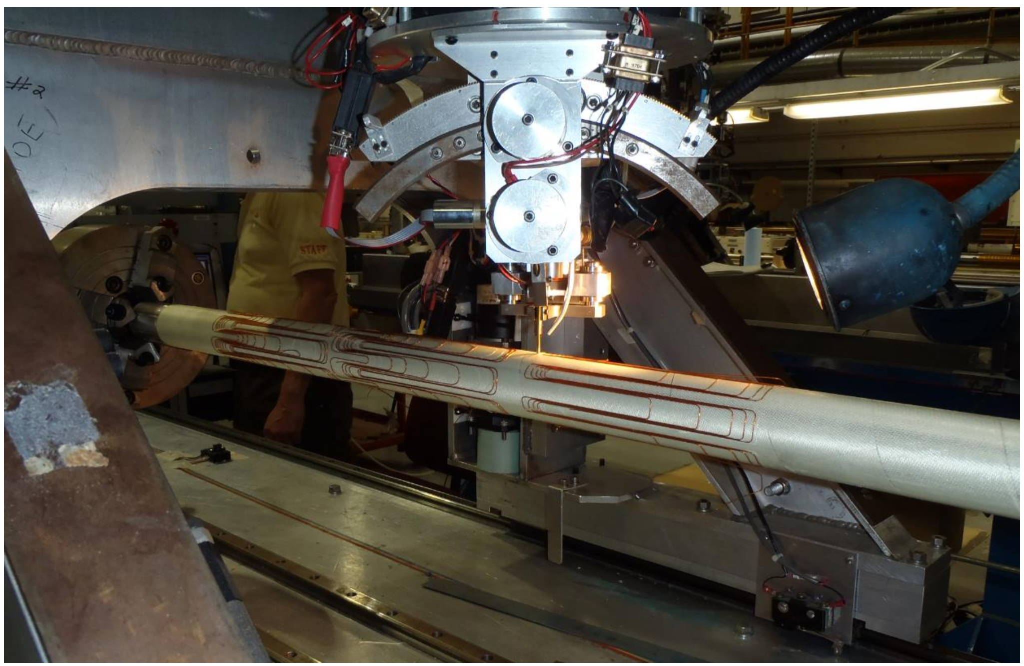


Construction status

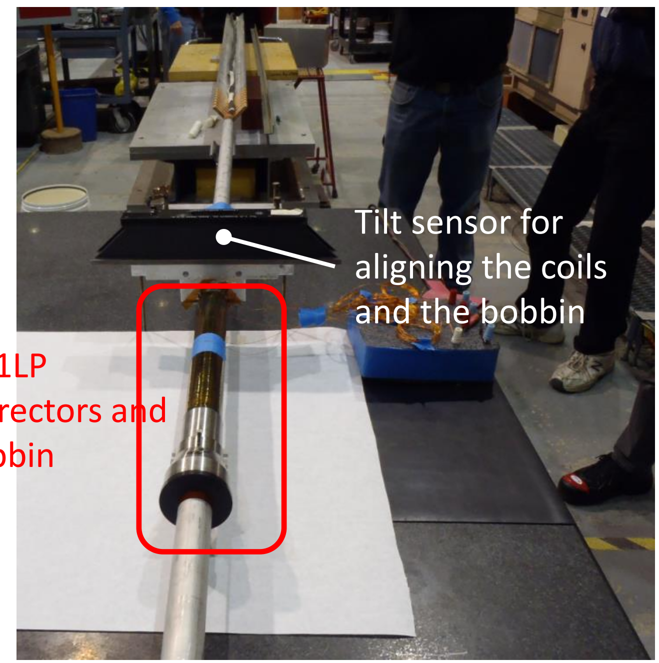
2. SC corrector coils at BNL

- The corrector coils (a_1, b_1 and a_2) for QC1LP were completed by BNL and measured at room temperature. The correctors and bobbins will be transported to KEK in April, and they will be cold tested in KEK.
- The corrector coils (a_1, b_1, a_2 and b_4) for QC1LE are now wound on the second winding machine.

Test winding of leak field cancel coil



Field measurement at room temp. in BNL



Field quality of the correctors for QC1LP

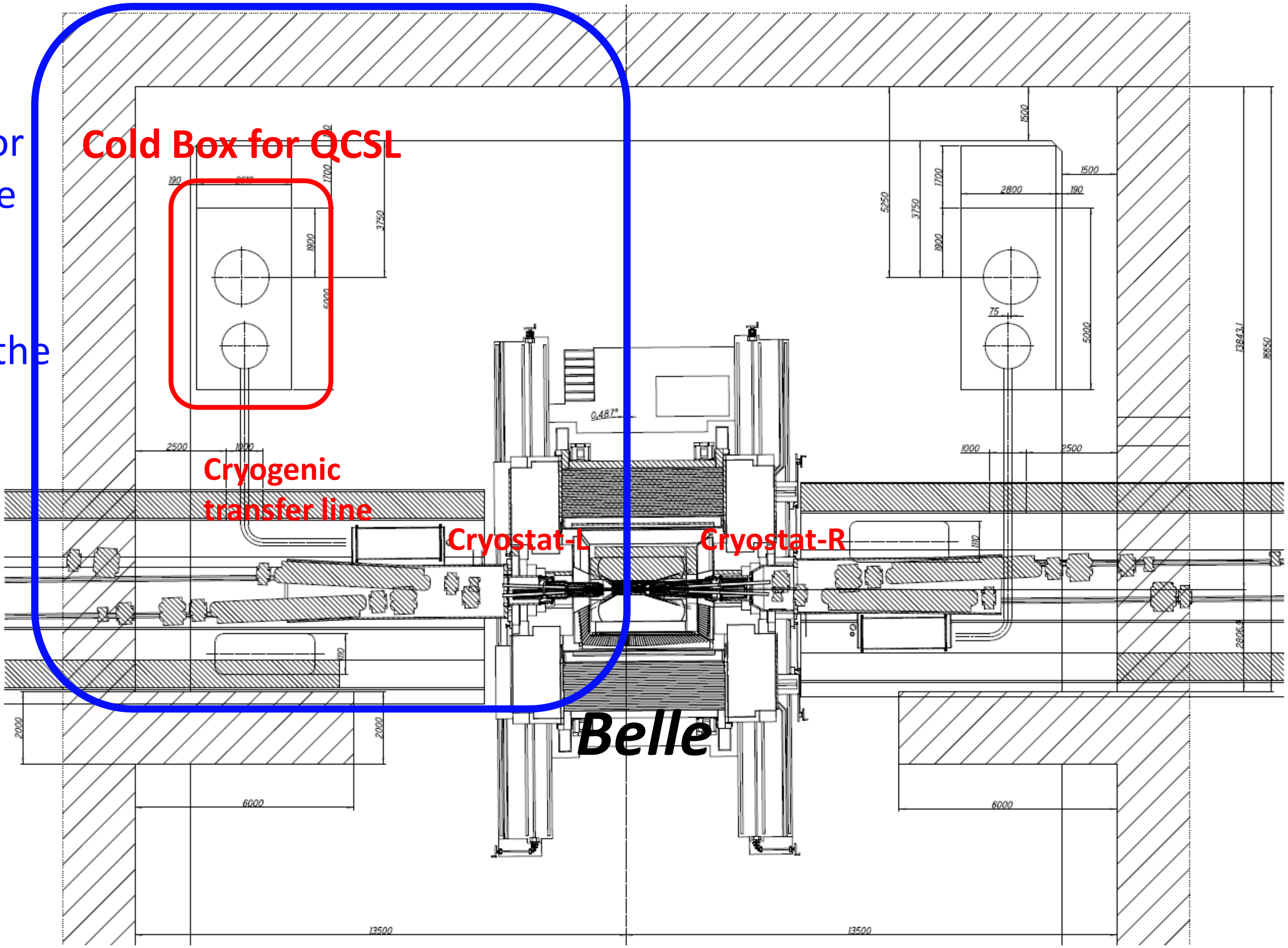
	a_1 coil		b_1 coil		a_2 coil	
n	b_n	a_n	b_n	a_n	b_n	a_n
1	0.0	10000.0	10000.0	0.0	0.0	0.0
2	3.6	-9.9	10.5	-4.9	0.0	10000.0
3	-2.1	6.4	-6.6	4.0	0.4	-1.5
4	-0.5	-5.2	-1.3	6.3	-0.1	-1.6
5	0.1	-1.0	-1.6	-0.2	-1.5	0.0
6	0.0	0.6	-0.1	0.9	-0.6	1.4
7	-0.2	0.0	-0.9	-0.3	-0.1	0.1
8	0.2	-0.2	0.1	1.6	-0.1	-0.2
9	0.1	0.4	-1.1	-0.1	-0.1	-0.1
10	-0.4	0.0	-0.1	0.3	0.0	0.1

Field strength@70A **0.0212T・m** **0.0175T・m** **0.982T**

Construction status

3. Cryogenic system for QCSL

The LHe refrigerator and subcooler were installed in the 4th floor underground and cold tested in the last month.

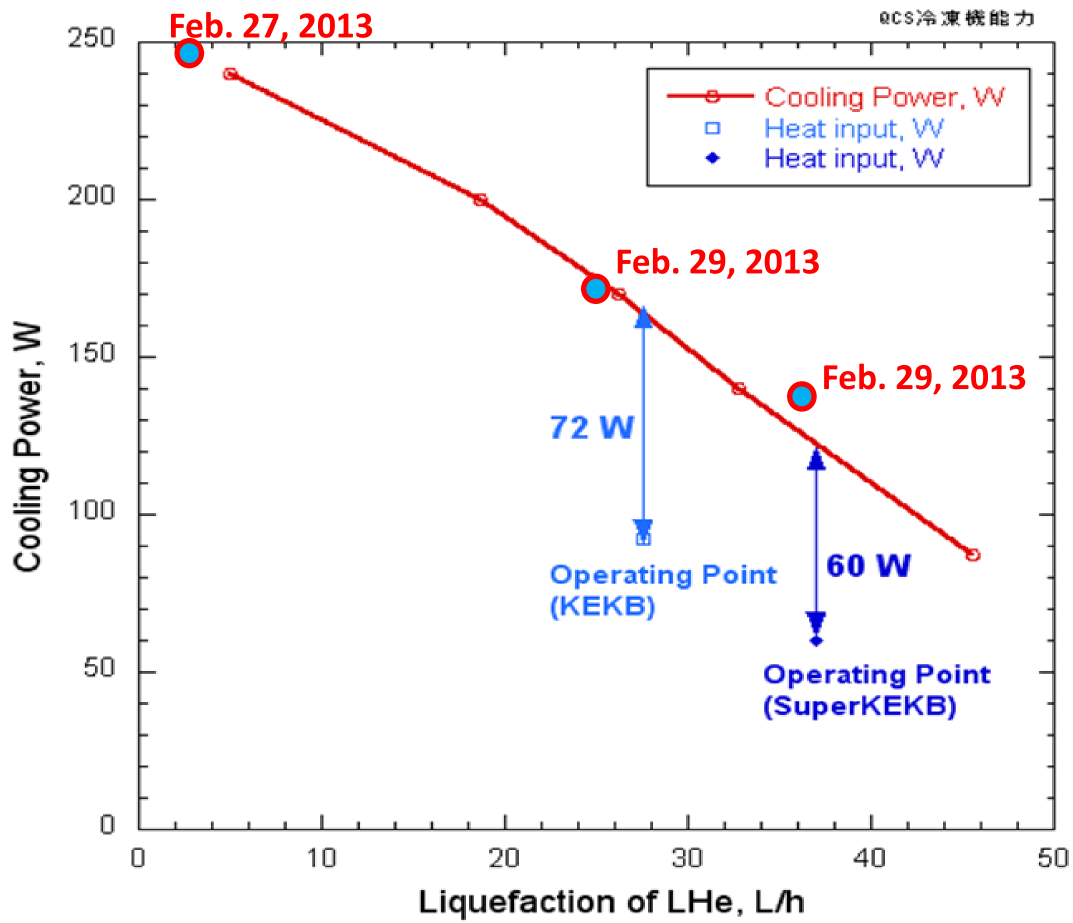


Construction status

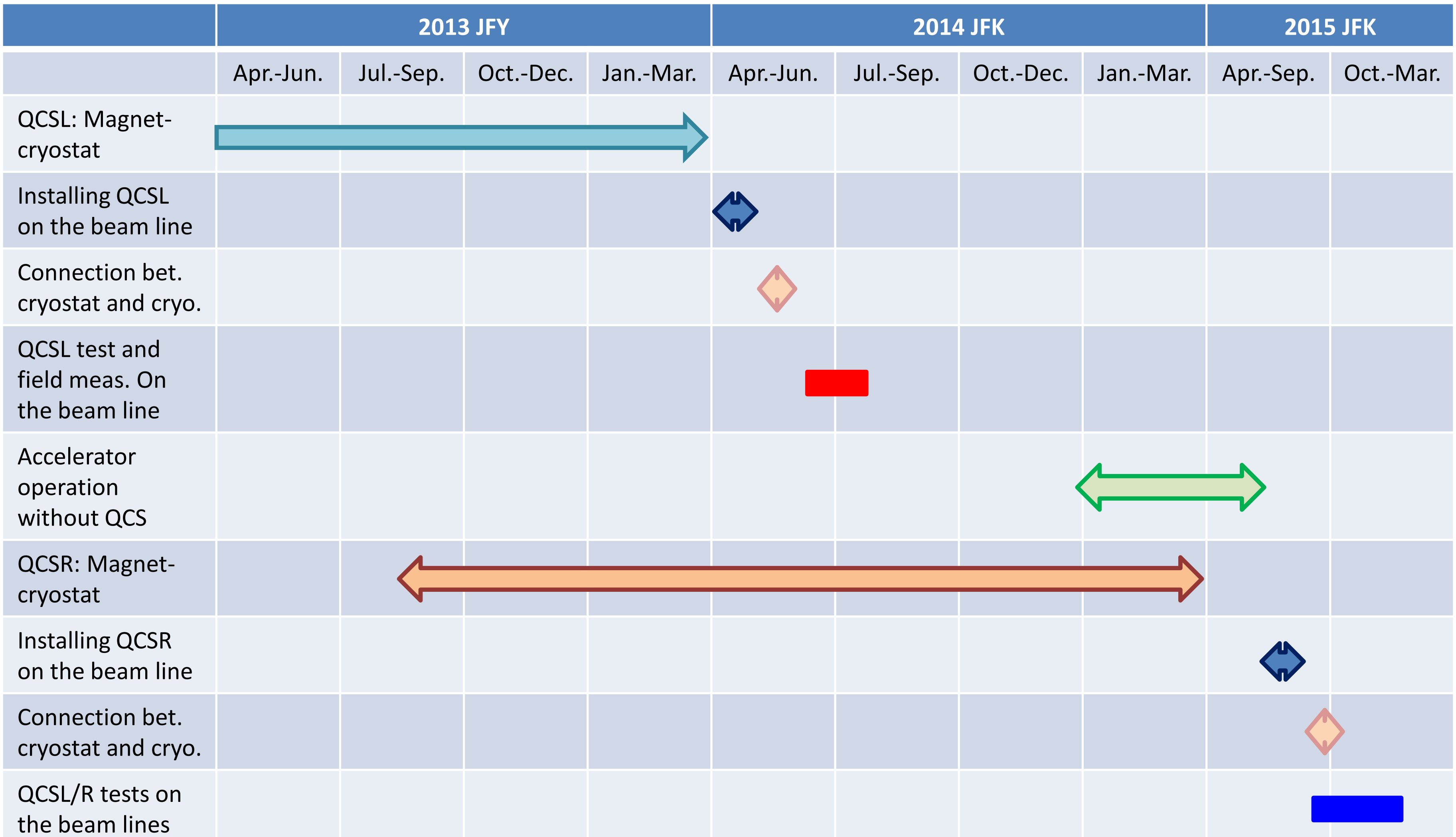
Cold box and subcooler unit

Construction status

- Performance test cold box
  - The cold box showed the cooling power as same as the power in 20 years ago.
  - Measured cooling power is 250 W at 4.3 K.



Construction schedule



Summary

- Magnet and IR design
  - Permendur yoke for QC1E and QC2P.
  - Redesign of all QC1/2 magnets.
- SC correctors and leak field cancel coils
  - Production of correctors has been started by BNL.
  - The completed coils showed good field quality at room temperature, and the final test at 4.2 K will be performed at April in KEK.
  - All coils for QCSL will be completed in December 2013.
- Prototype QC1E/P magnets
  - Prototypes showed good excitation results.
  - From the field measurement results, the improper parameter, Young modulus, in design was found. The correct parameter is already included in the all magnet designs.
- Completion of QCSL on the beam line in May 2014 is now very difficult, but our group will not give up.