October 26, 2026
ARC

Current status of QCS upgrade

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On behalf of the QCS group

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• KEK (in particular)
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• Sophia University: Characterization of Nb_3Sn wires, simulation of magnetic field decay
S. Hoshino, K. Kaneko, T. Yagai

• Furukawa Electric: R&D of Nb_3Sn wires
K. Mun, R. Taniguchi

• FNAL: Technical support for the Nb_3Sn QC1P development
S. Stoynev, V. Kashikhin, G. Ambrosio, M. You, S. Krave, X. Xu, G. Velev, S. Gourlay

• BNL: Design for corrector magnets
V. Teotia, B. Parker

Contents

- Answers to recommendations from the reviewers at the last ARC
- Overview of the QCS upgrade
- Nb_3Sn QC1P development
- Corrector magnets and compensation solenoid

Answers to recommendations from the reviewers at the last ARC

R15.2: Complete the study of whether the radiation doses to the SC magnet coils due to SBLs, other beam aborts, and accumulated backgrounds will ultimately degrade the integrity of the SC magnet.

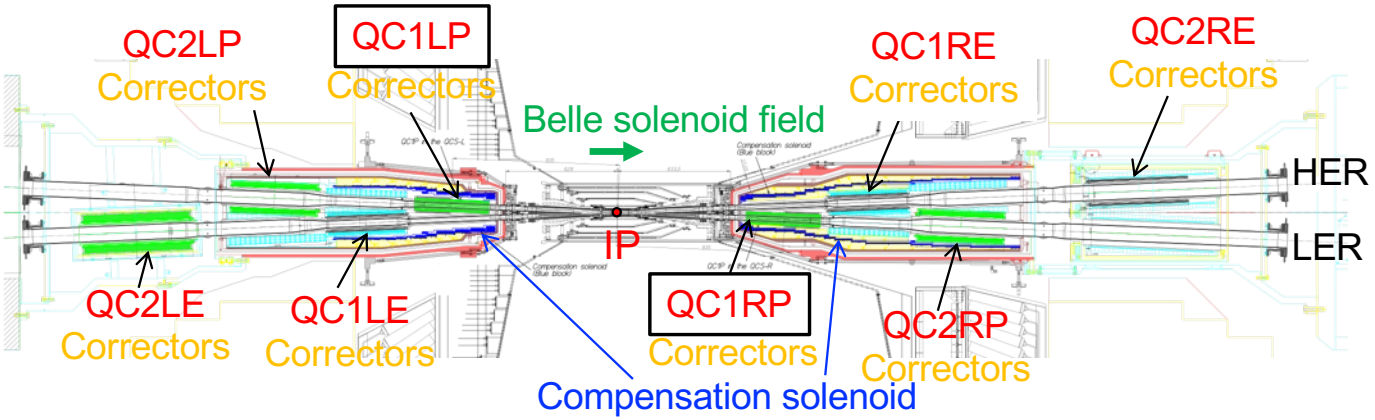
We have answered this comment in the previous talk given by Arimoto.

R22.2: Before embarking on the manufacture of tooling, study the possibility and implications of using a two-layer coil, and compare manufacturing, cost and performance issues with those associated with the single layer coil design shown in the presentation.

After the last ARC, we discussed which coil design option to choose within our group and FNAL. Then, we concluded that, in such a small coil, there will be a risk of mispositioning of the Nb_3Sn wire and insulation damage in a two-layer coil. Thus, we prioritized R&D for single-layer coils. We are repeating the fabrication of practice single-layer coils, but we have recognized some difficulties such as mispositioning of the ramp lead. In parallel with developing the single-layer coils, we have started R&D for two-layer coils. We will report on the results of the first practice winding for a two-layer coil in this presentation.

Overview of the QCS upgrade

Why is the QCS upgrade needed?



Layout of current QCS

– Main quadrupoles are exposed to the detector solenoid field in the current QCS

Install the main quadrupoles with rotation and offset
Large chromatic x-y coupling → IR optics need to be simplified.

– Moving QC1P forward to IP

Larger dynamic aperture and longer beam lifetime were expected in an early study.
A more severe space constraint → Replacing Nb-Ti coils with Nb_3Sn coils having a higher critical current density

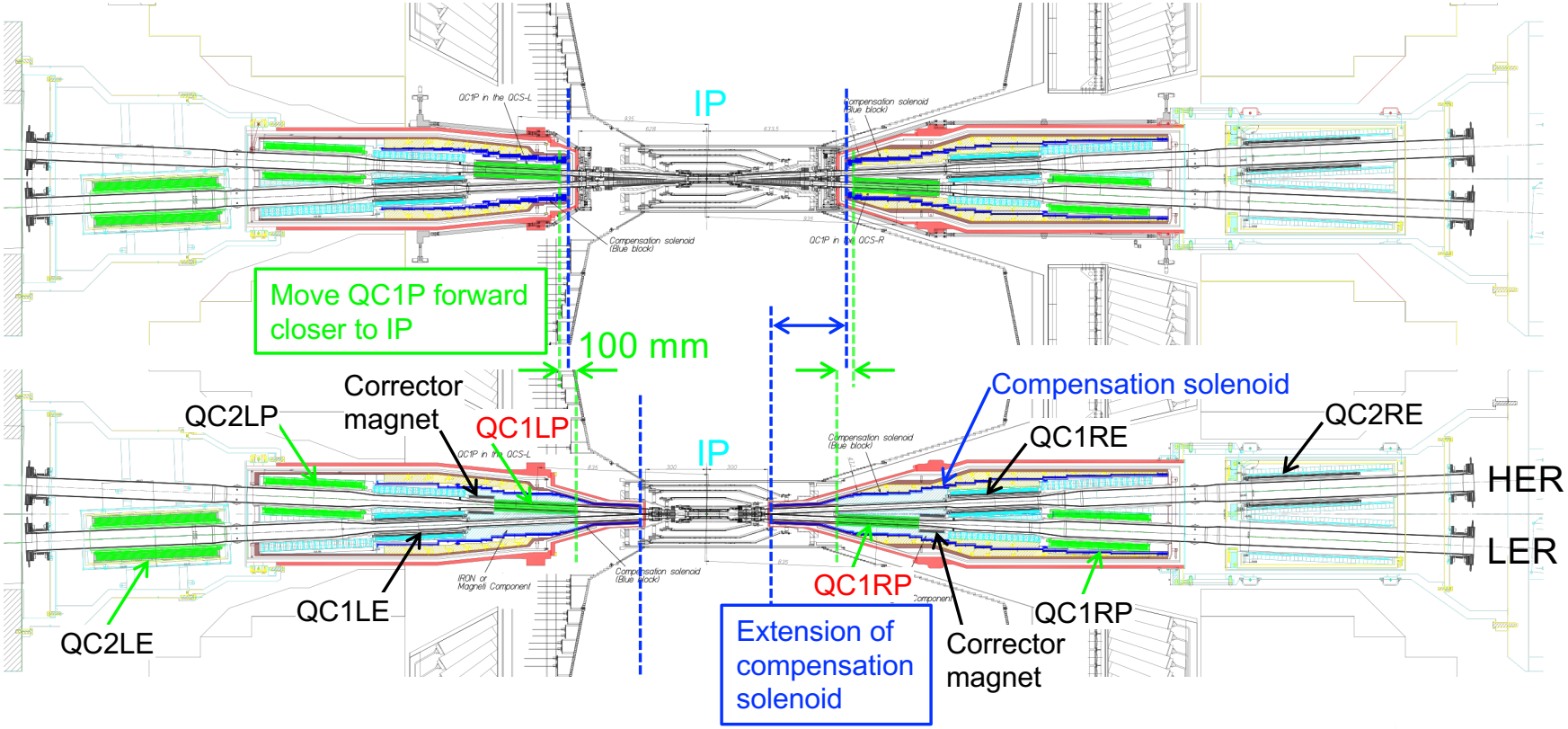
– Mitigation of beam-induced quench

Larger temperature margin by adopting Nb_3Sn with a higher critical temperature

QCS upgrade

Current QCS

Upgraded QCS

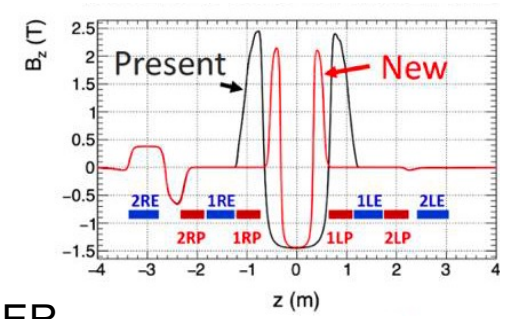


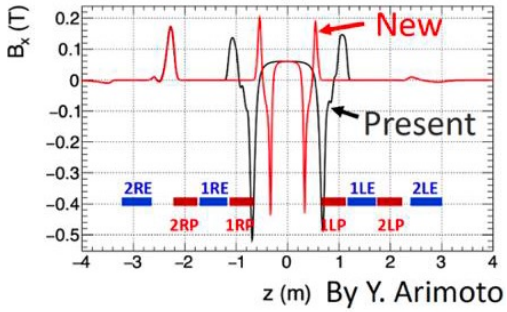
- Extension of compensation solenoid

  The detector solenoid field is canceled ahead of QC1P.
  → Simplified IR optics

- Place Nb_3Sn QC1P with iron yoke 100 mm closer to IP

  → Thinner coil size, larger temperature margin
  Lower operating current, reducing magnetic crosstalk to HER by iron yoke





By Y. Arimoto

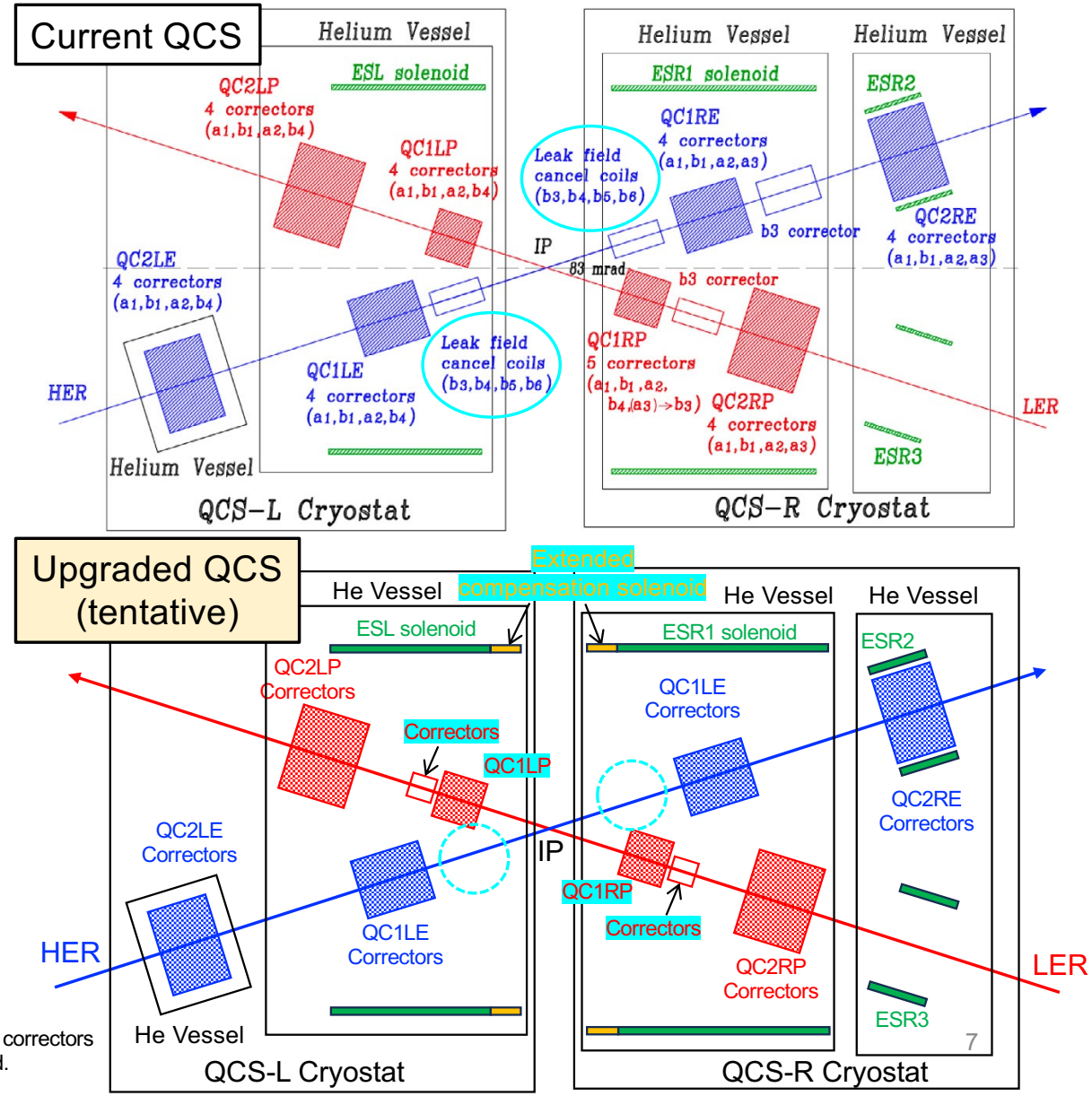
Layout of QCS magnets

Specifications of magnets for the current QCS

Main quadrupoles			
	Field gradient (R, L) (T/m)	Design current, I_d (R, L) (A)	Peak field at I_d (R, L) (T)
QC1P	76.37	1800	4.56
QC1E	91.57	2000	3.50
QC2P	31.97	1000	2.43
QC2E	38.56, 36.39	1562.5, 1250	2.81, 2.63
Compensation solenoids			
	Design current, I_d (A)	Peak field at I_d (T)	Coil inner radius (mm)
ESL	390	3.56	78~(145)
ESR1	450	3.05	70~189
ESR2 ESR3	151.1	0.3 T	81.1

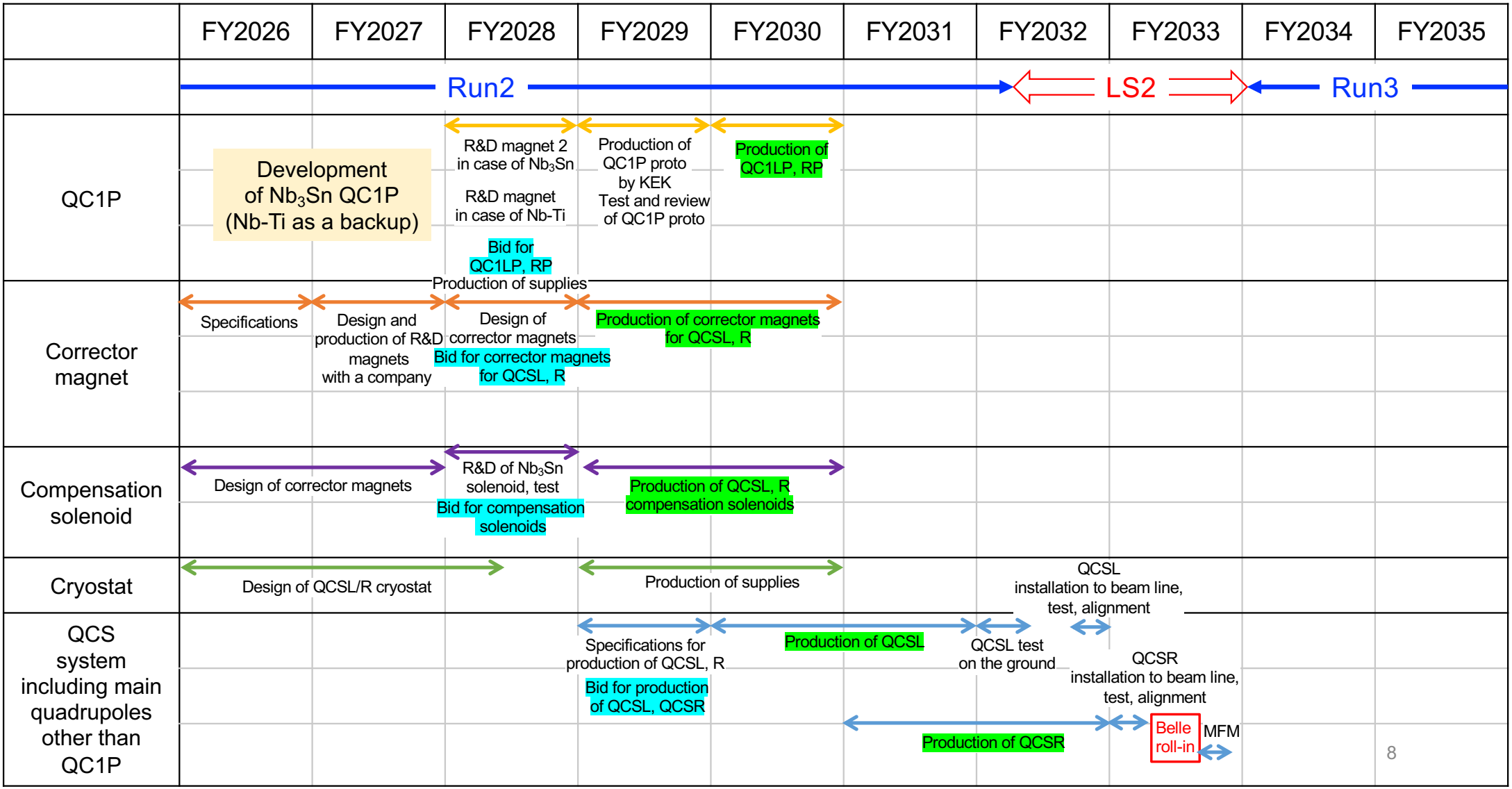
Main changes in upgraded QCS

- Extension of compensation solenoid
- Relocation of QC1P with iron yoke
  (Nb_3Sn is the baseline, Nb-Ti as a backup)
- New correctors for QC1P
- No leak field cancel coils



*Multipole order of correctors has not been fixed.

Tentative schedule of QCS production

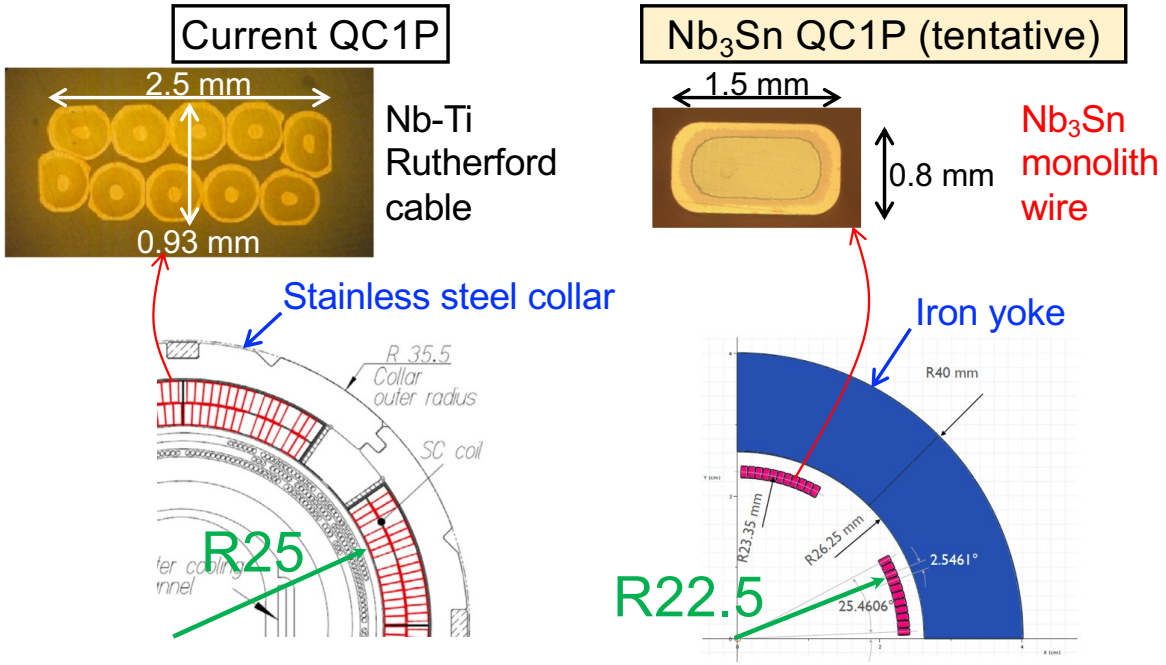


Nb_3Sn QC1P development

New Nb_3Sn QC1P

- The coil thickness needs to be reduced to install the magnet into a narrower space
  - Nb_3Sn monolith wires will be used instead of Nb-Ti Rutherford cables
  - Two options for the coil design: single-layer or two-layer

- Collaring with iron yoke
  - Coil pre-stress as high as 100 MPa during assembly to keep the Nb_3Sn coils in compression after cooling



Main Design Parameters of QC1P (Tentative)

	Units	Present	Upgrade
Conductor material		Nb-Ti	Nb_3Sn
Integral Gradient	T	22.96	26.7
Operation current	A	1600	1832
Field gradient	T/m	68.74	80
Field Quality		$< 10^{-4}$	
Material of magnetic yoke		-	Iron
Inner radius of coil (1st layer)	mm	25.0	22.5
Outer radius of coil (1st layer)	mm	27.65	24.2
Inner radius of coil (2nd layer)	mm	27.78	-
Outer radius of coil (2nd layer)	mm	30.43	-
Inner radius of collar or yoke	mm	30.75	26.25
Outer radius of collar or yoke	mm	35.5	40.0
Physical length	mm	409.3	< 400
Effective magnetic length	mm	333.6	334
Stored energy	kJ	1.43	0.484
Inductance	mH	0.88	0.29
Cross sectional size of strand	mm	Φ 0.498	0.8 x1.5
Cu/SC ratio		1	0.83
Filament diameter	μm	7.7	< 5
Number of strands		10	1
Cable width	mm	2.5	1.5
Cable thickness	mm	0.93	0.8
Magnet operation temperature	K	4.7	4.7
Load line ratio	%	72	80
Temperature margin to Tcs	K	1.9	4.6
I_c at 7 T, 4.2 K	A	193	-
I_c at 12T 4.2 K	A	-	> 500

Coil design: Single-layer or Two-layer

Single-layer coil

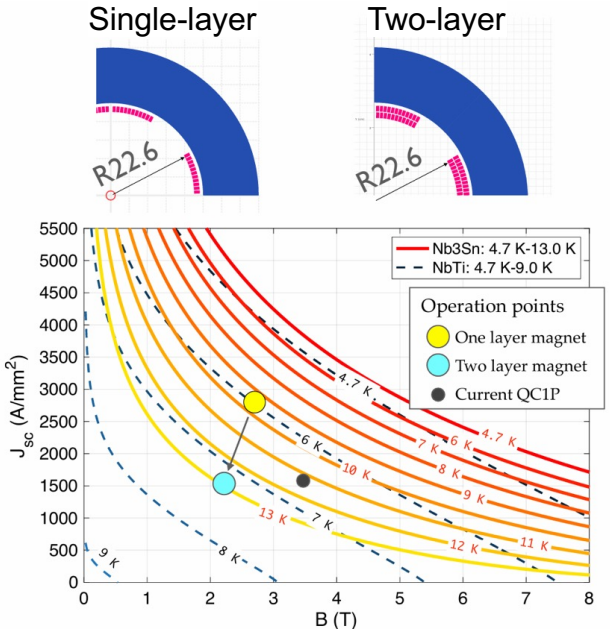
Pros
- Simple coil winding
- A thinner coil

Cons
- Higher operating current and smaller temperature margin than that of two-layer coils
- Position control of ramp lead
- Difficult mechanical support for ramp lead

Two-layer coil

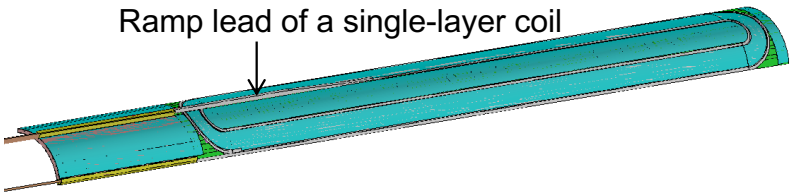
Pros
- Lower operating current and larger temperature margin
- Easy lead support
- Layer jump can be placed at the coil end.

Cons
- More complex coil winding, which can cause misalignment of turns
- A risk of wire insulation damage during coil winding



	ΔT: Temperature margin [K]	
	Nb_3Sn	NbTi
One layer	4	1
Two layer	8	2.5
Current	-	2

$T_{Operation}$ = 4.7 K



Both options have pros and cons.
We will decide which coil design to choose after the mirror magnet tests.

Flow of the Nb_3Sn QC1P development

Establishment of coil fabrication technology



Individual performance test of coils using a mirror magnet



Selection of either single-layer coil or two-layer coil

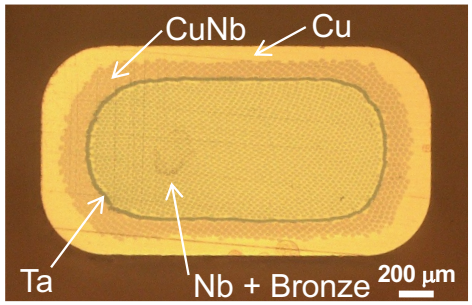


Fabrication of R&D quadrupole magnet, Performance verification test



Review of Nb_3Sn QC1P at the end of FY2027
(If the technical maturity of the Nb_3Sn magnet is deemed insufficient,
we will switch to the Nb-Ti option.)

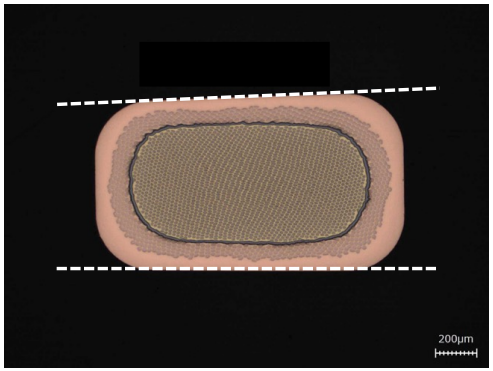
CuNb-reinforced Nb_3Sn wire



Rectangular wire for R&D

Reduction in the time decay of the magnetic field → Fine filaments
Large pre-stress during assembly → CuNb-reinforced wire

Size: 0.80±0.02 mm x 1.50±0.02 mm
Areal ratio: non-Cu 50±5%, CuNb 23±5%, Cu 27±5%
Filament diameter: 2.3 μm (nominal)
Reinforcer: CuNb (Cu-20vol%Nb)
Barrier: Ta
Insulation: S-2 glass braid
Size of insulated wire: 1.00±0.035 mm x 1.70±0.035 mm
I_c at 12 T, 4.2 K: >500 A
RRR: >100

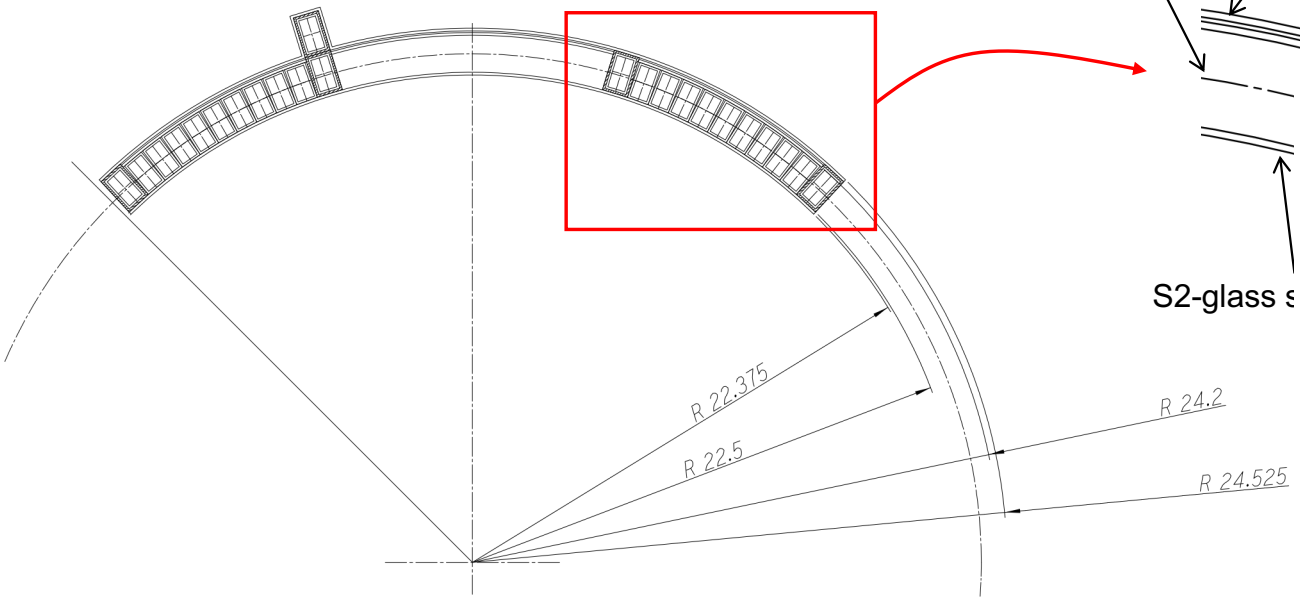


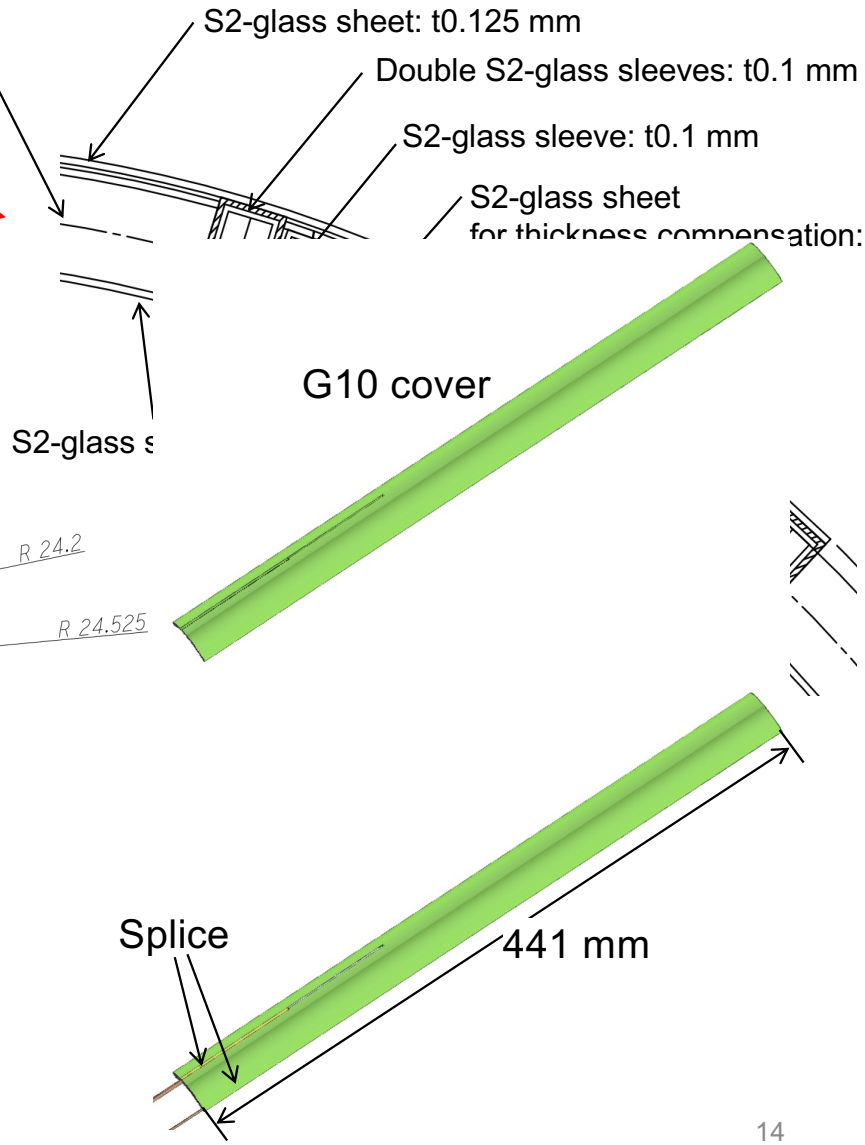
Wire with a keystone angle

- Furukawa Electric fabricated Nb_3Sn wire with a keystone angle of 2.29° as a trial.
- Quench occurred during I_c measurements for short straight samples.

→ A further study will be conducted at KEK.

Structure of single-layer coil

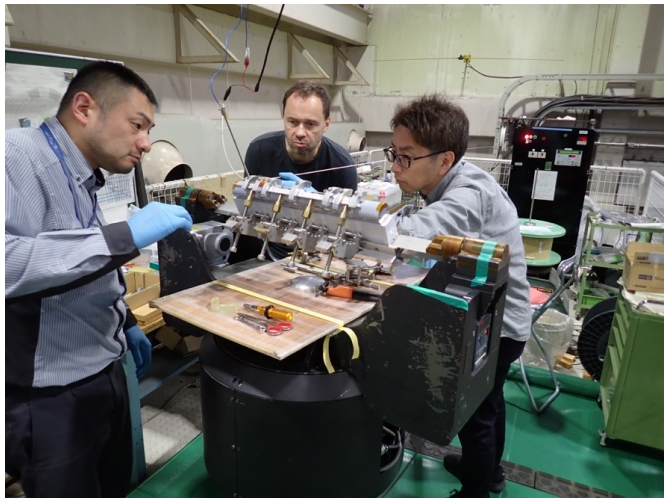


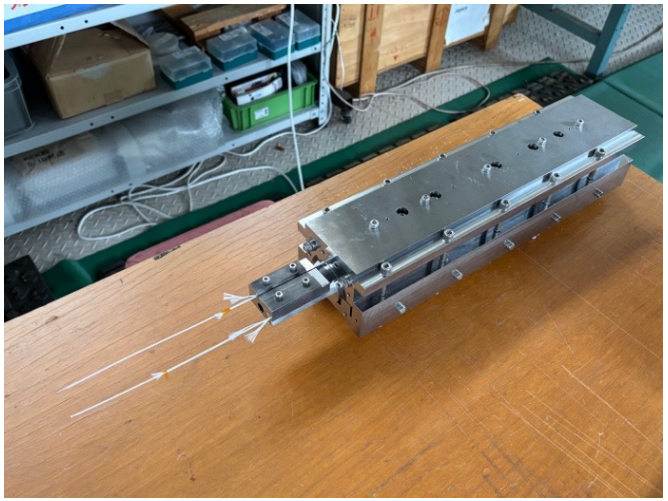


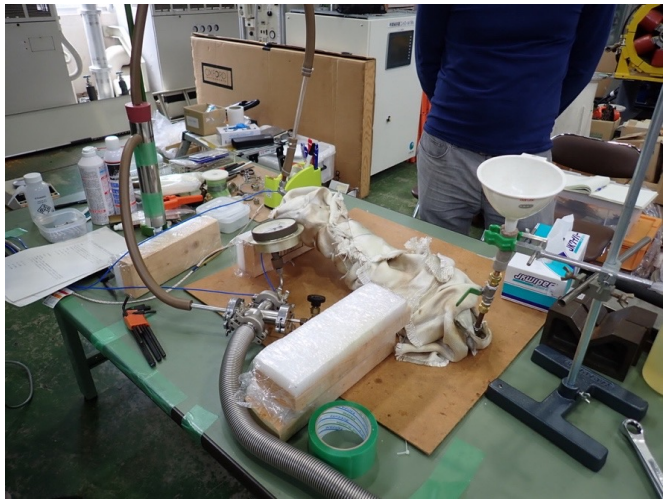
- Coil inner radius: 22.375 mm, coil outer radius: 24.525 mm
- Coil mechanical length: 441 mm
- Number of turns: 11
- Insulation
  - Double S2-glass sleeves for the pole and mid-plane turn
  - S2-glass sheet for thickness compensation
  - S2-glass sheet to cover the inner and outer surfaces
- A G10 cover is impregnated with a coil for mechanical support of the ramp lead.

Fabrication of single layer Nb_3Sn coils

Coil winding → Heat treatment → Epoxy impregnation





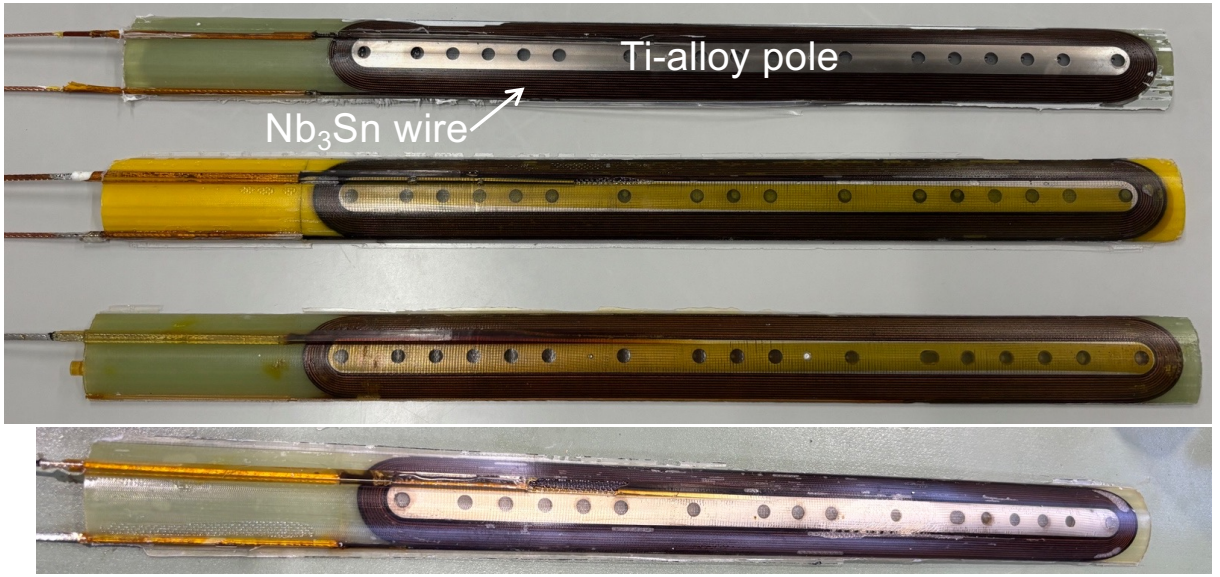






- A coil is not cured before reaction.
- Multi-step heat treatment over 2 weeks (Max. temperature = 650°C)
- Impregnation with CTD-101K (Epoxy resin)

Practice coils (Single-layer coils)



PC1

PC2

PC3

PC4

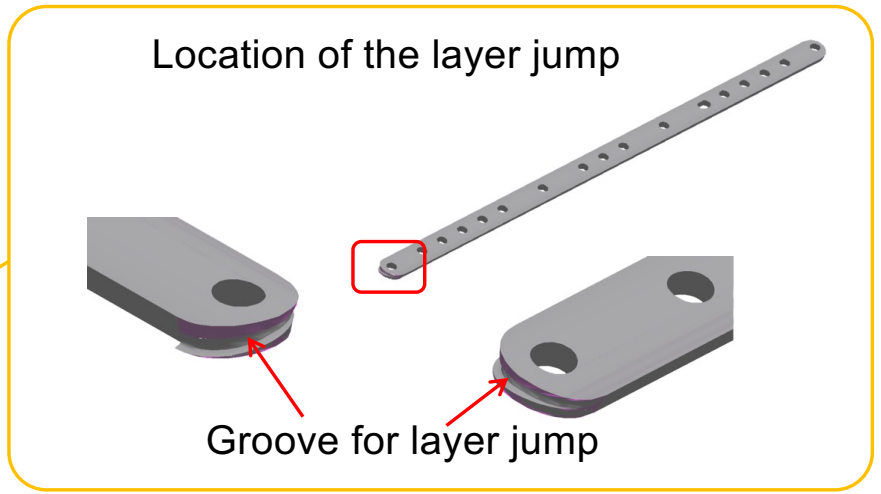


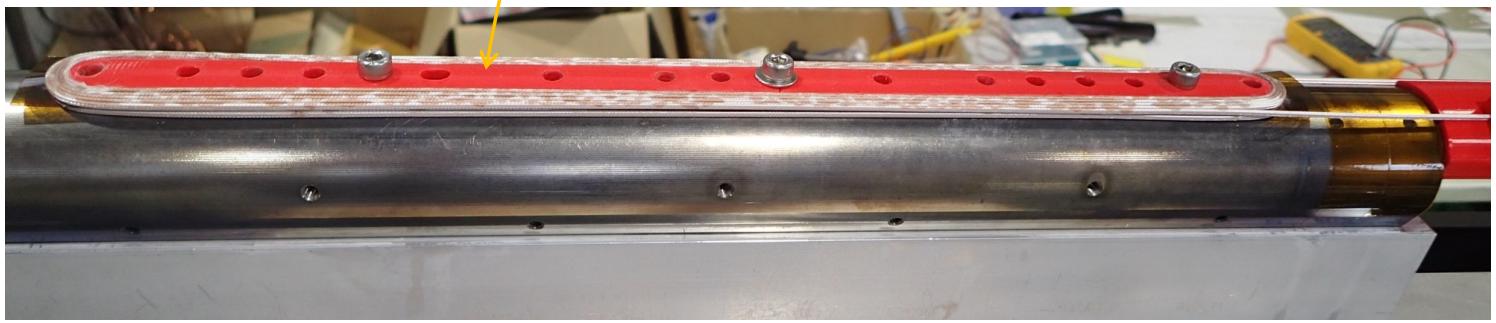
Cross-section of PC3

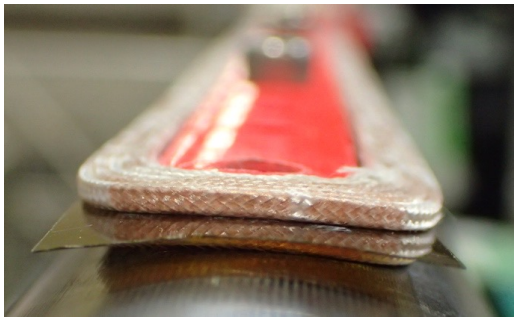
The coil fabrication process has not been fully established.

ID	Purpose	Insulation between pole turn and Ti-alloy pole	Heat treatment	Epoxy	Electrical test result (Hi-pot test btw pole and conductor)
PC1	Check winding, heat treatment, and epoxy impregnation tooling	Single S2 glass sleeve	Shortened pattern	EPO-TEK 301	Electrically shorted in a Hi-pot test → NG
PC2	Slightly modified tooling to accommodate additional glass sleeve, check the electrical insulation	Double S2 glass sleeves	Shortened pattern	EPO-TEK 301	Leak current of 15.7 μA at 1 → NG
PC3	The same tooling as PC2, check the electrical insulation, first coil impregnated with CTD101-K	Double S2 glass sleeves	Shortened pattern	CTD101-K	No leak current at 2 kV → OK
PC4	Minor modification from the tooling for PC3, full reaction for coil size measurement, electrical test	Double S2 glass sleeves	Full reaction	CTD101-K	Leak current of 206 μA at 0.09 kV → NG

R&D of two-layer coil

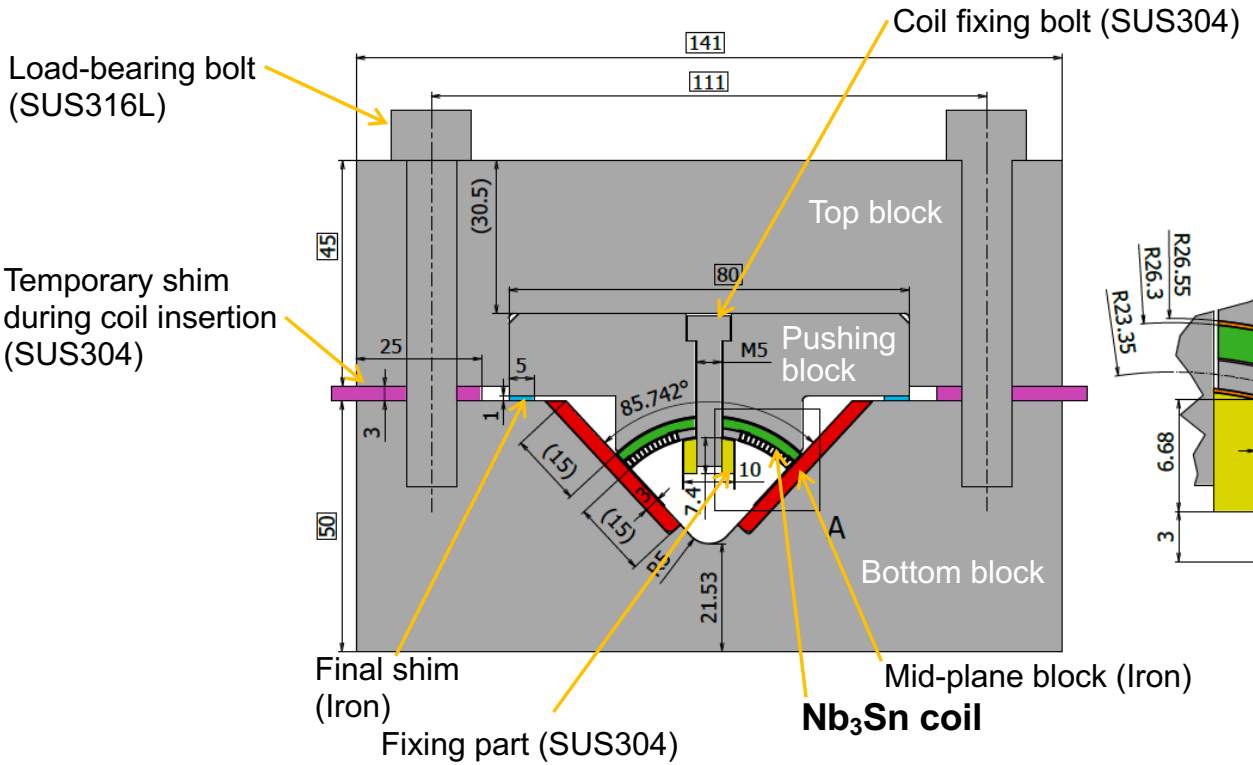




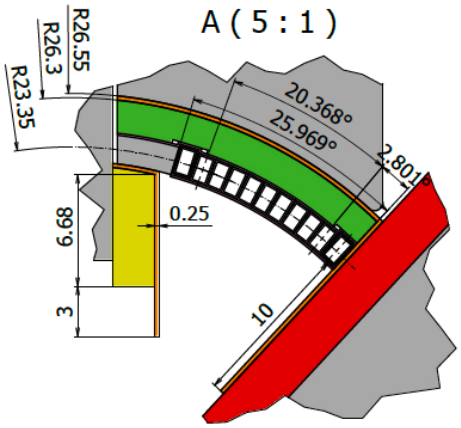


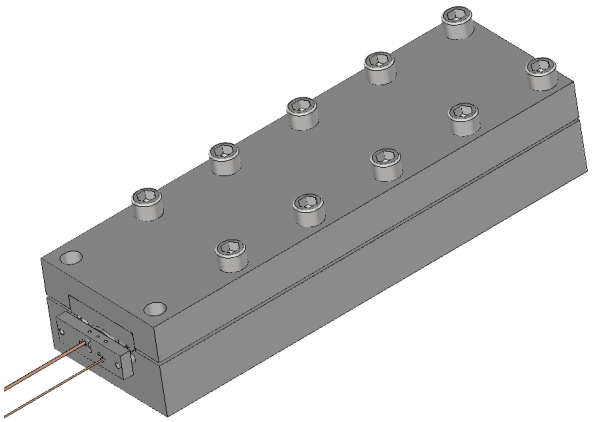
- Practice winding of a two-layer coil with 3D-printed parts has started.
- Each layer was temporarily secured by instant glue to simulate the curing process.
- The layer jump lead could be wound along the groove located at the coil end.
- Design of coil fabrication tooling for two-layer coils will start soon.

Mechanical structure of mirror magnet



2D cross-section



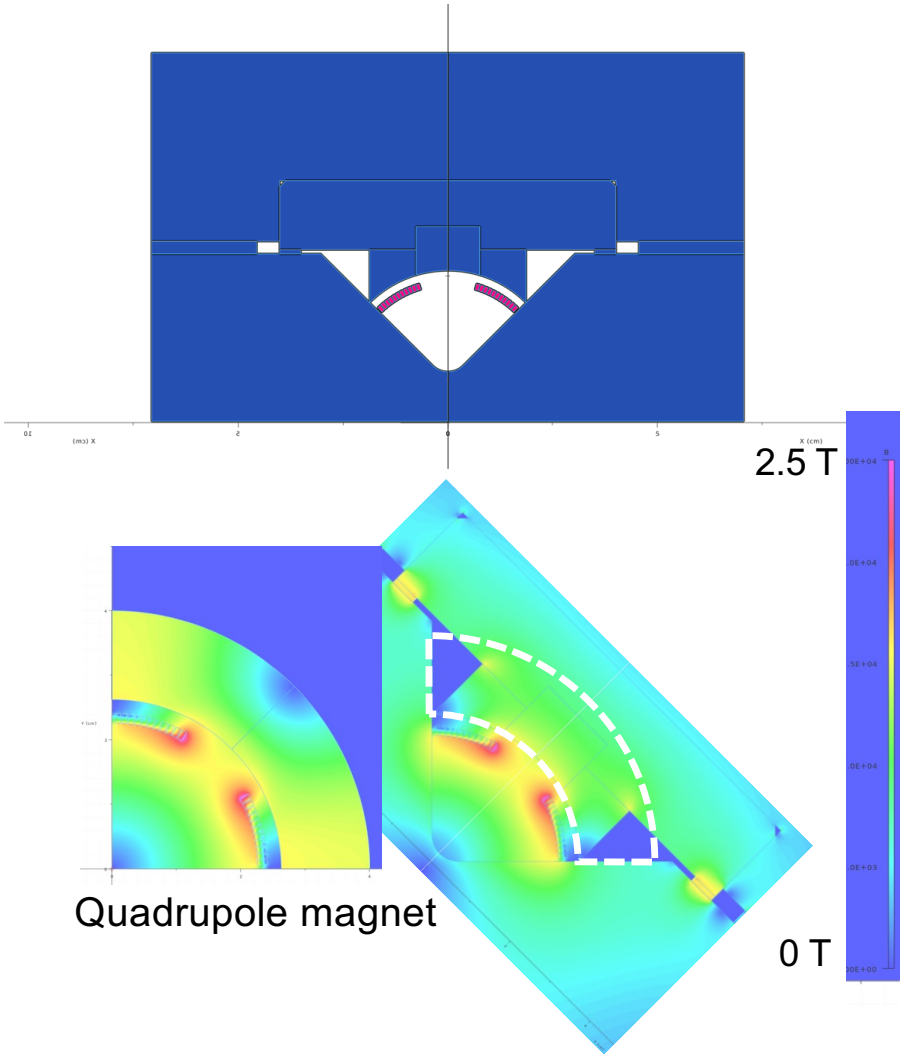


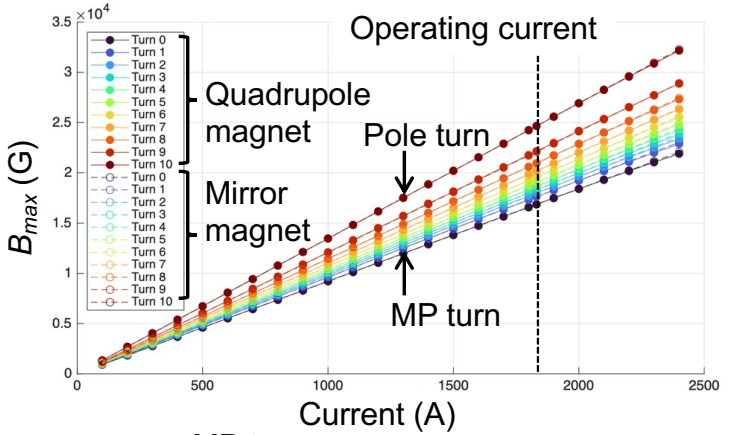
3D model with end structure

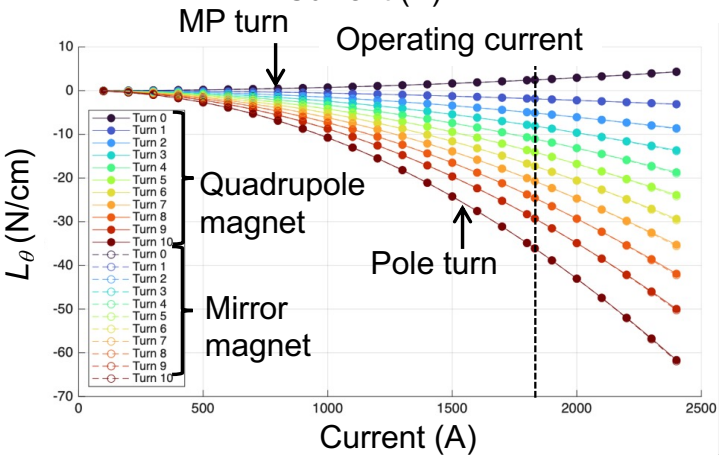
- A “Mirror magnet” can reproduce the magnetic field distribution and Lorentz force within a quadrupole magnet.
  → Relatively easy performance test for a Nb_3Sn coil
- Monitoring coil stress during assembly, cooldown, and excitation by strain gauges
  → Verify the validity of the mechanical design for brittle Nb_3Sn coils
- Training performance will be checked by excitation tests at 4.2 K.

Magnetic design of mirror magnet

Y. Arimoto







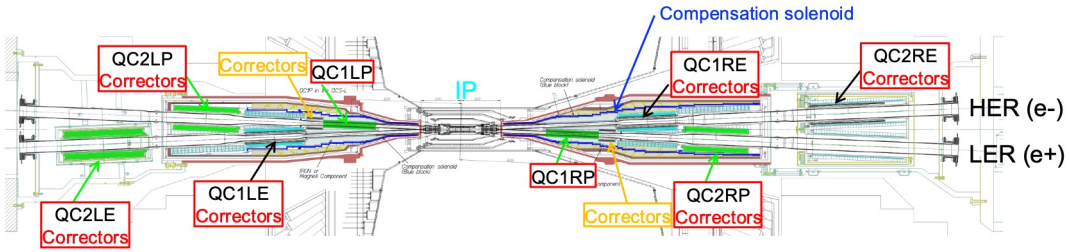
- Difference in magnetic field within a coil between a quadrupole magnet and a mirror magnet < 0.25%
- Difference in Lorentz force exerted on a coil between a quadrupole magnet and a mirror magnet ~3%

→ A mirror magnet reproduces a similar magnetic field distribution and the stress of a quadrupole magnet.

ANSYS simulation for more detailed structural analysis is ongoing.

Corrector magnets and compensation solenoid

Corrector magnets



Required corrector magnets

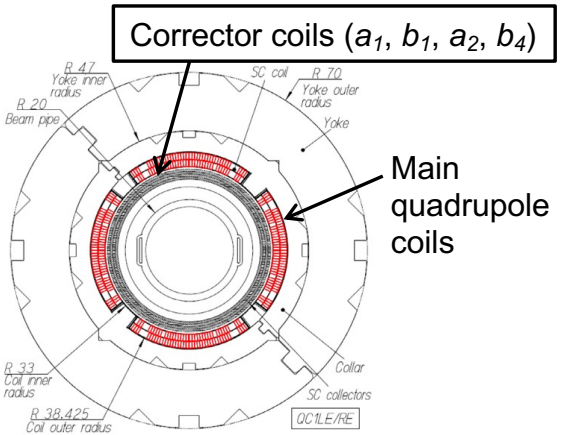
- Corrector coils for main quadrupoles other than QC1P
  - Almost the same design as those for the current QCS

- Corrector magnet for new QC1P
  - Limited longitudinal space → Higher magnetic field to keep the same field integral

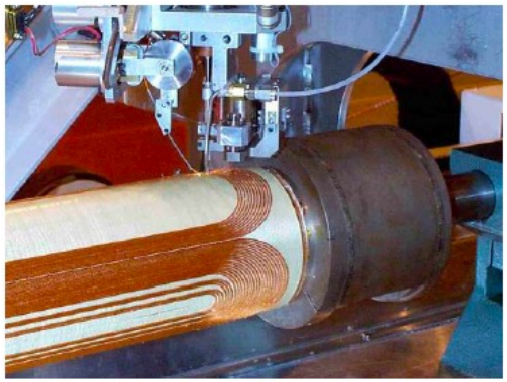
- Required multipole orders of the correctors and field integral for each coil are being discussed with the optics team.

Strategy for design and fabrication

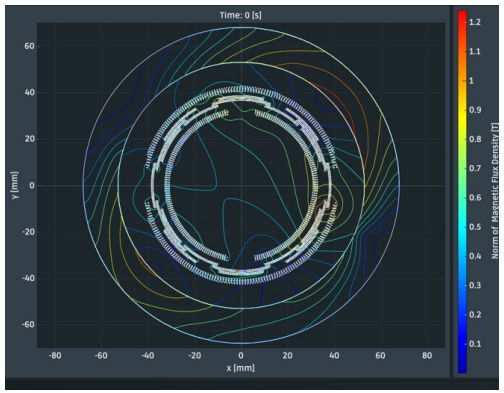
- Correctors for the current QCS were designed and fabricated by BNL based on the direct winding technology.
- In the QCS upgrade, BNL is responsible only for the design of the correctors, while a Japanese company will manufacture the magnets.
- KEK plans to place an order for a trial fabrication of corrector coils with the candidate company in FY2027.



Cross-section of current QC1E



Direct winding technology developed by BNL

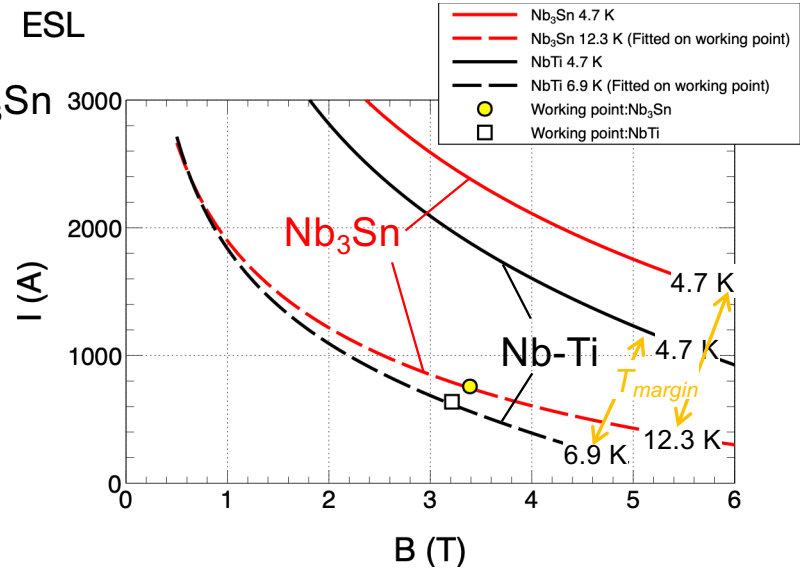


Design study for corrector magnet for new QC1P

Compensation solenoid

- The front end of the extended compensation solenoid will be made of Nb_3Sn for a smaller coil size and mitigation of beam-induced quench.
- Nb_3Sn “solenoid coils” are widely used in commercial products.
- Assuming the same Nb_3Sn wire as QC1P
- A design study has started for ESL for QCS-L.
- Thinner coil with a comparable current margin and a larger temperature margin in the Nb_3Sn option than in the Nb-Ti one
- For the rest of the compensation solenoid, Nb-Ti coils will be adopted, which is the same as the current QCS.

ESL



Critical current – magnetic field curves

NbTi: current margin 35%

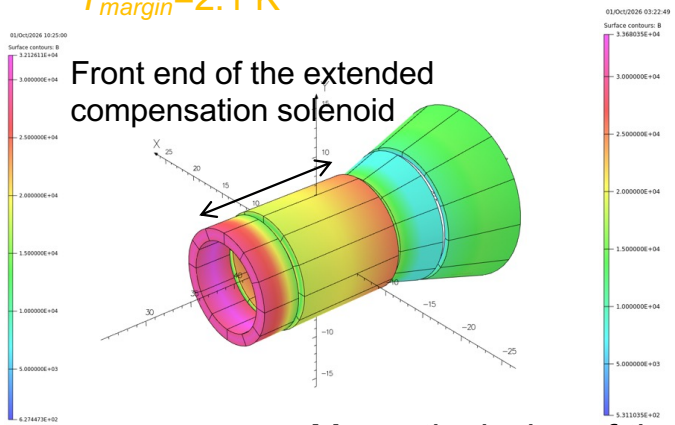
B_{peak}=3.21 T at J=304 A/mm^2

T_{margin}=2.1 K

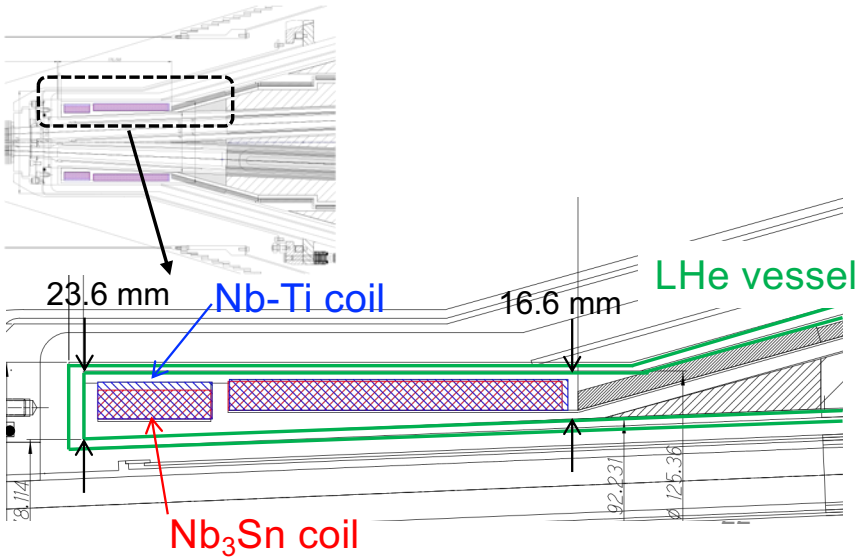
Nb3Sn: current margin 40%

B_{peak}=3.39 T at J=631 A/mm^2

T_{margin}=7.6 K



Magnetic design of the extended ESL



Summary

- QCS upgrade is planned during LS2. The main changes include the extension of the compensation solenoid, moving QC1P with Nb_3Sn coils forward to the IP, and a new corrector magnet for QC1P.
- R&D on Nb_3Sn QC1P is currently underway at KEK. If the technical maturity of the Nb_3Sn magnet is deemed insufficient at the end of FY2027, we will switch to the Nb-Ti option.
- BNL is responsible for the design of corrector magnets, while a Japanese company will manufacture the magnets.
- The Nb_3Sn option will be adopted for the front end of the extended compensation solenoid, considering a thinner coil size and larger temperature margin.

Appendix

Plan for electrical test

- Coil resistance
  before splice
  after splice

- Coil inductance

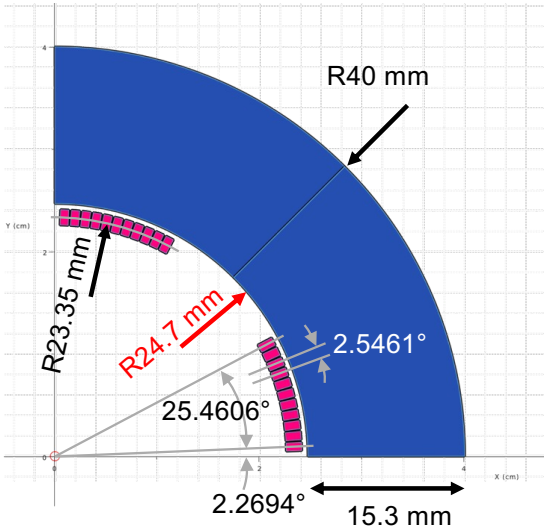
- Hi-pot test
  Voltage is applied between Ti-pole and wire.
  Max voltage estimated from quench simulation: 184 V (Kento Suzuki, “QC1P_250521.pptx”)
  Criteria adopted for HL-LHC magnets
  – Max voltage: (184 x 2 + 500) x 2 =1736 V → **1.8 kV**
  – Leak current < 10 μA
  – Duration time = 30 sec



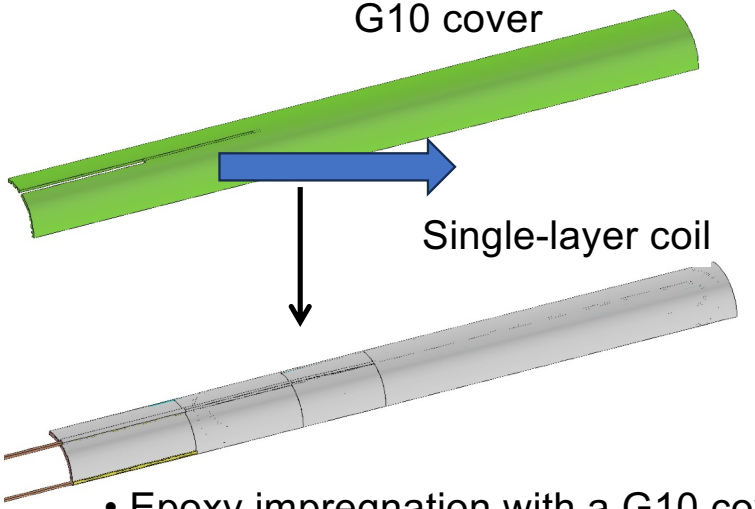
- Impulse test
  184 / 4 = 46 V/coil
  Max voltage: (46 x 2 +500) x 2 = 1184 V → **1.2 kV**
  We need to check if the max current during the test is acceptable.



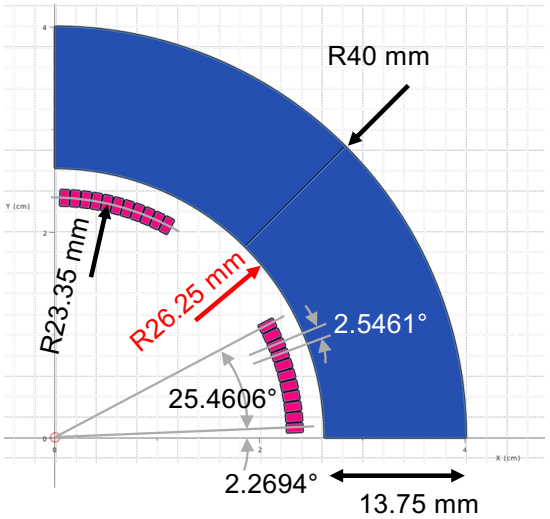
Magnetic design of single-layer coil (2D, 3D)



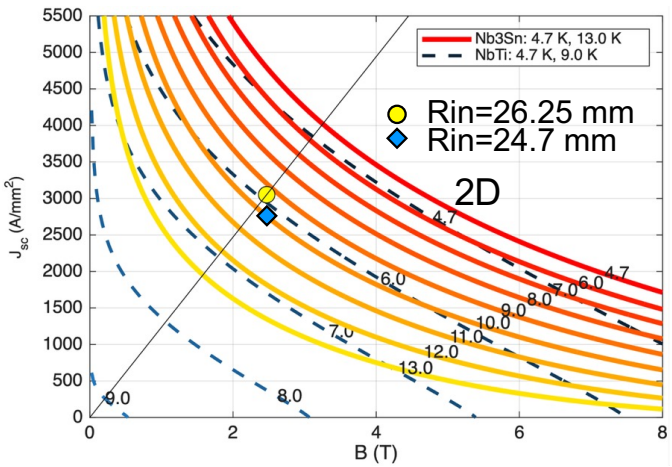
SingleLayer_v1



- Epoxy impregnation with a G10 cover
- Enlargement of yoke inner diameter to 26.25 mm



SingleLayer_v2

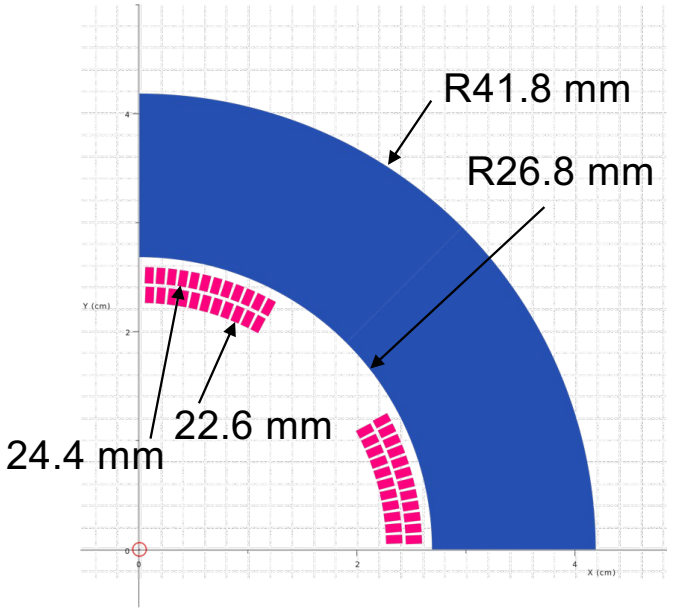


* Current at G=80 T/m at the longitudinal center of the straight section

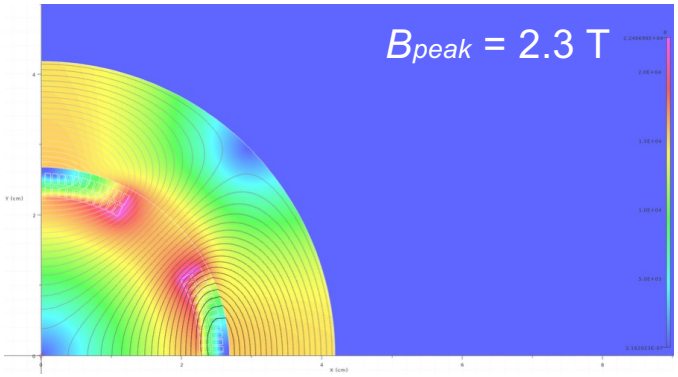
	SingleLayer_v1		SingleLayer_v2	
	2D	3D	2D	3D
Yoke ID (mm)	24.7		26.25	
Yoke OD (mm)	40		40	
B_{max} (T)	2.47	2.84	2.47	2.77
I at G=80 T/m (A)	1656	1658*	1831	1832*
J (non-Cu) (A/mm^2)	2760	2763	3052	3054
Load line ratio	0.72	0.76	0.76	0.80

Two-layer magnet

- Two layer magnet is designed with 2D analysis.
- Number of turns
  - 11 turn (inner coil)
  - 12 turn (outer coil)
- Inner radius
  - 22.6 mm (inner coil) (same as single-layer magnet)
  - 24.4 mm (outer coil)



J_{nc} is half the value of the single-layer option.



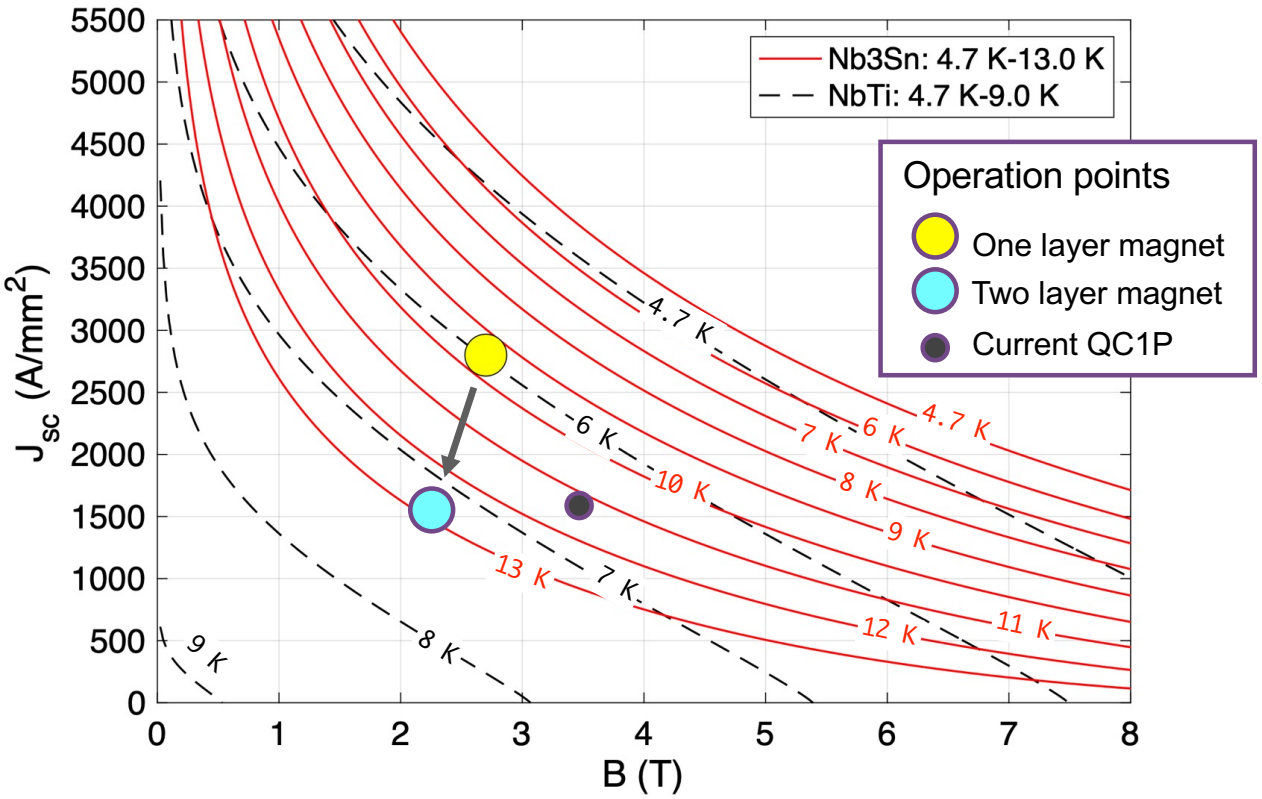
R_{ref} = 10 mm

	I (A)	A (mm^2)	J_{nc} (A/mm^2)	B_2 (T)	b_6 (units)	b_{10} (units)
Single-layer	1700	1.2	2833	0.8042	0	-2.2
Two layer (12 turn)	920	1.2	1533	0.8017	-0.1	-1.7
Two layer (11 turn)	960	1.2	1600	0.8040	0	-1.9

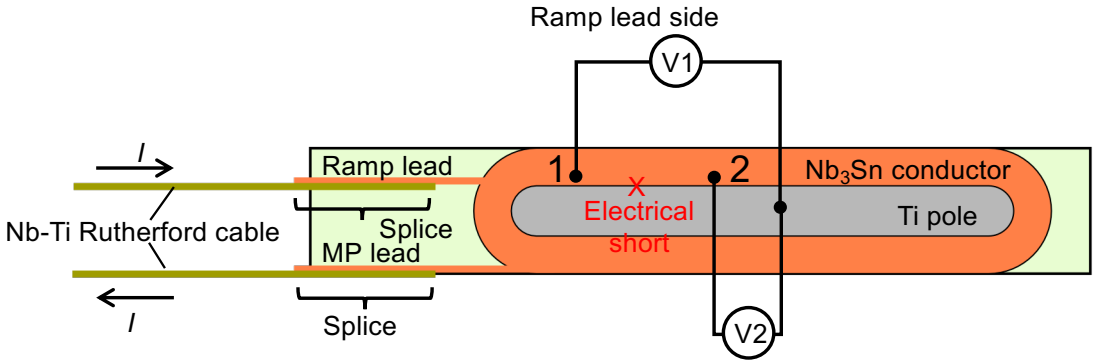
Critical surface and operation points

- The operating point of the two-layer magnet moves to the lower *J* region.
- The temperature margin increases by twice for Nb_3Sn.

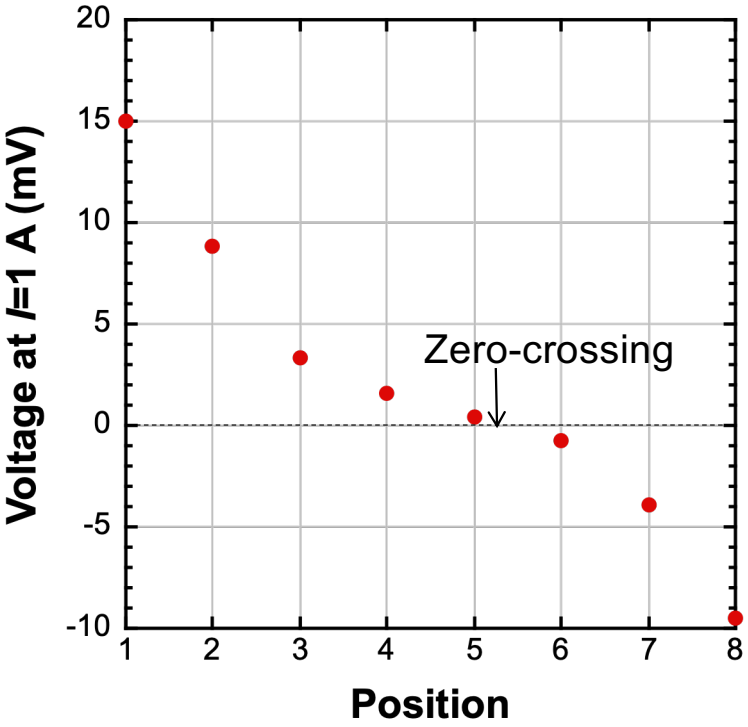
	Temperature margin (K)	
	Nb_3Sn	NbTi
Single-layer	4	1
Two-layer	8	2.5
Current QC1P	-	2

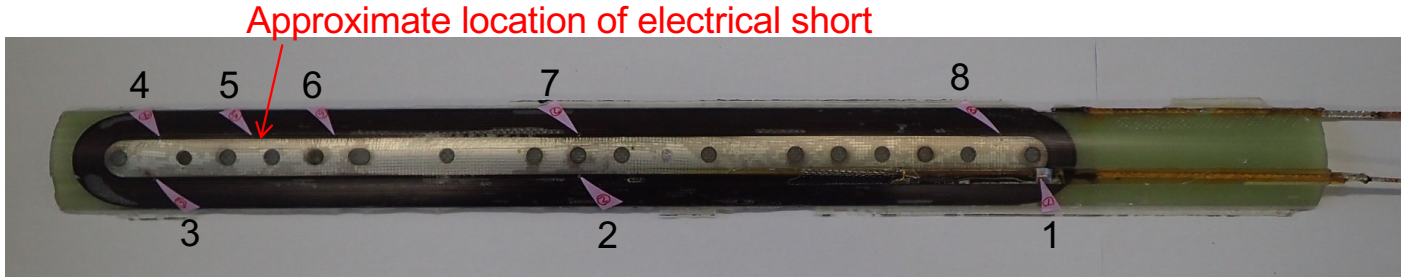


Location of electrical short in PC4



If an electrical short is located between Points 1 and 2, a sign of V1 and V2 is reversed.

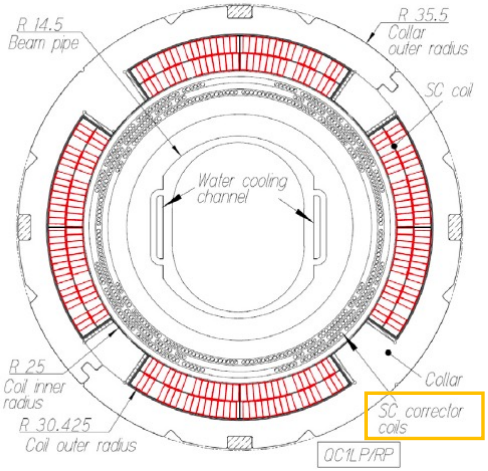


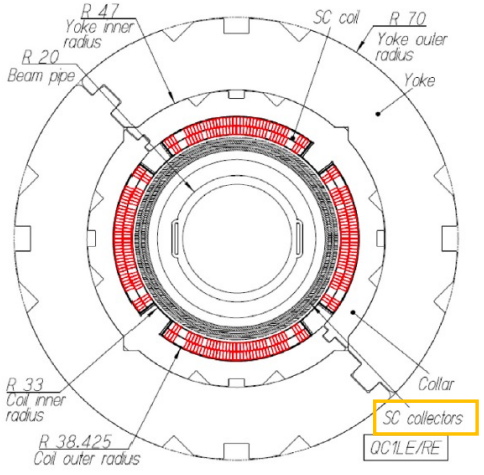


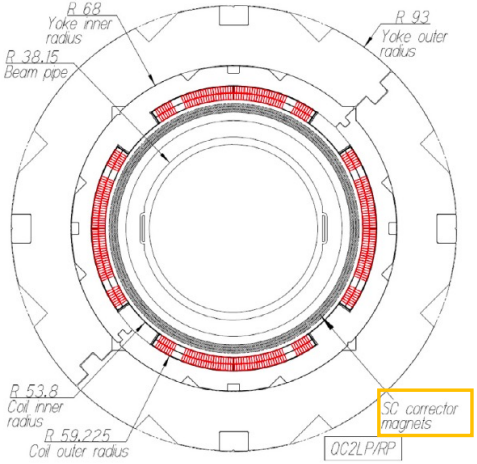
Resin and glass insulation were removed at Points 1-8 to measure the voltage between the pole piece and the conductor.

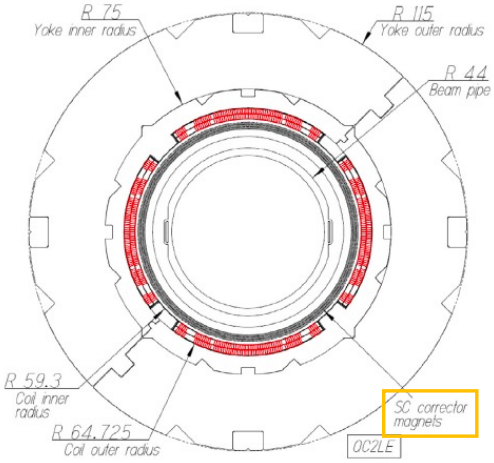
- The location of an electrical short was identified between 5 and 6 by a voltage measurement.

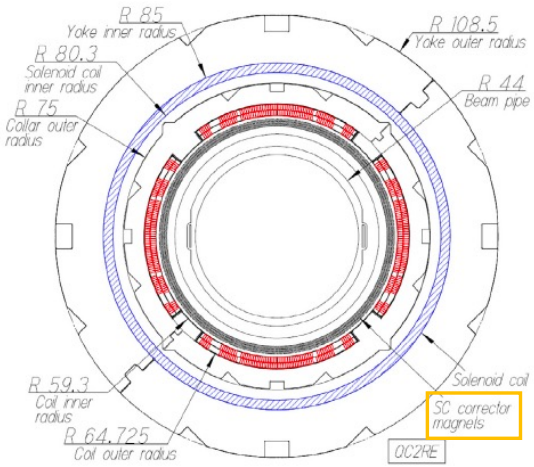
Corrector magnets in the current QCS

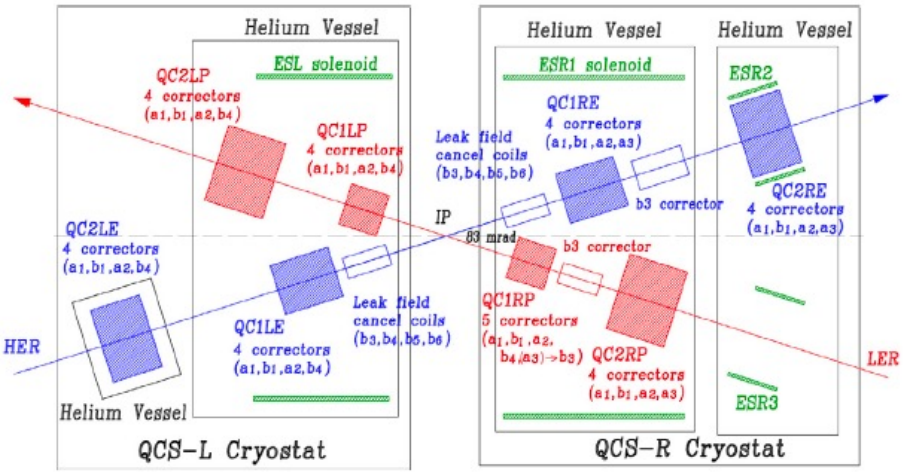






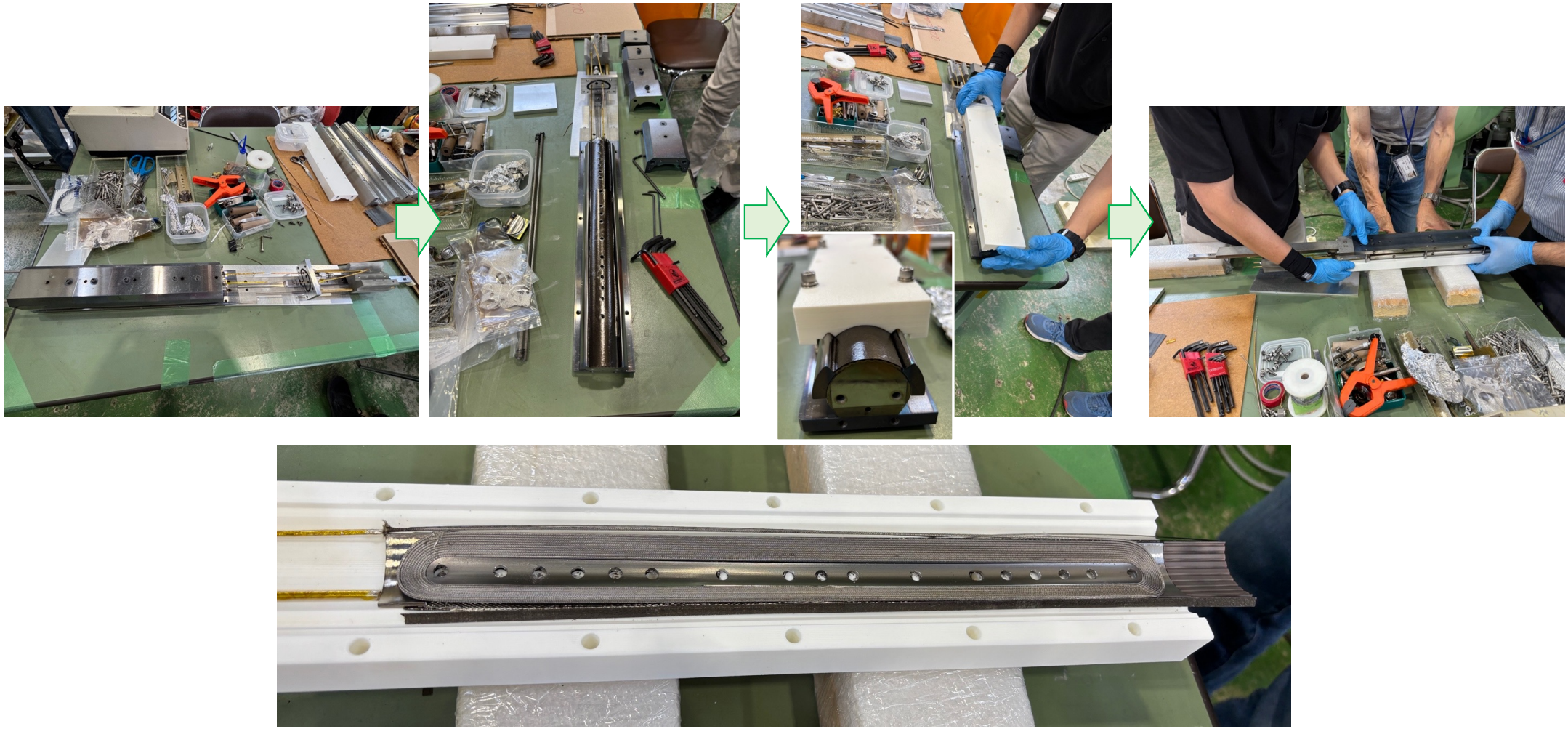






	Multipole orders
QC1P	a_1, b_1, a_2, b_4
QC1RP	a_1, b_1, a_2, b_4, b_3^*
QC1LE	a_1, b_1, a_2, b_4
QC1RE	a_1, b_1, a_2, a_3
QC2LP	a_1, b_1, a_2, b_4
QC2RP	a_1, b_1, a_2, a_3
QC2LE	a_1, b_1, a_2, b_4
QC2RE	a_1, b_1, a_2, a_3
QC1-2RE	b_3
QC1-2RP	b_3

Possible reason for mispositioning of ramp lead



Before epoxy impregnation, a coil is completely released from the heat treatment jig, and then the coil is turned upside down to put a glass sheet on the coil inner surface. Since the coil is not cured, the ramp lead would be easily twisted. → Curing would be necessary even for a single-layer coil.