IR Superconducting Magnets

N. Ohuchi

KEK

Contents

1. Production status of SC magnets
2. Production of quadrupole magnets
3. Production of correctors
4. Schedule
5. Summary

Production status of magnets

1. All superconducting coils for the quadrupole magnets have been completed.
   - Production of the first coil for QC1LP started from June 11, 2013.
   - The last coil for QC2RE was completed at January 16, 2014.
   - Total number of the coils is 32.
2. Collaring process of the QC1LP quadrupole magnet started from January 22, 2014.
   - Collaring processes of QC1LP, QC2LP, QC1LE and QC1RE were completed.
   - The collaring processes of all quadrupole magnets will be completed in March 2014.
3. Correctors and cancel coils for the left side have been completed in February 2014.
4. Production of correctors and cancel coils for the right side has started.

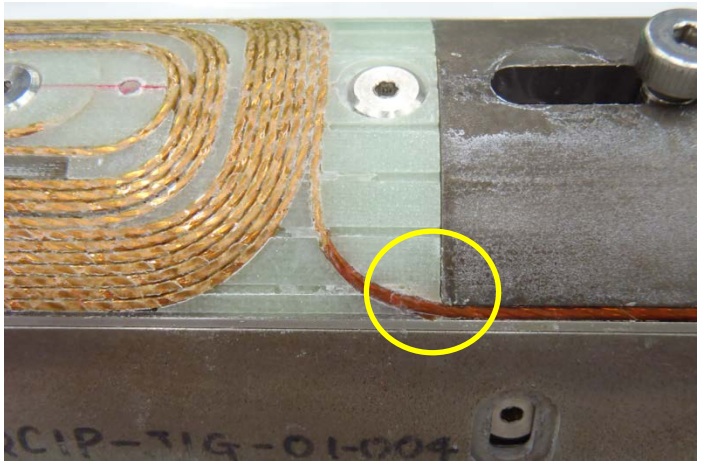
Production of quadrupole magnets

1. SC coil production
   - The SC coils of four type quadrupole magnets were wound with 5 sets of jigs and tools.
     - While QC2LEand QC2RE have the same cross section, the lengths were different.
   - After winding the coils, the coils are cured to the design shape with the forming blocks at temperature of 130 degree C and pressure of 20 MPa.

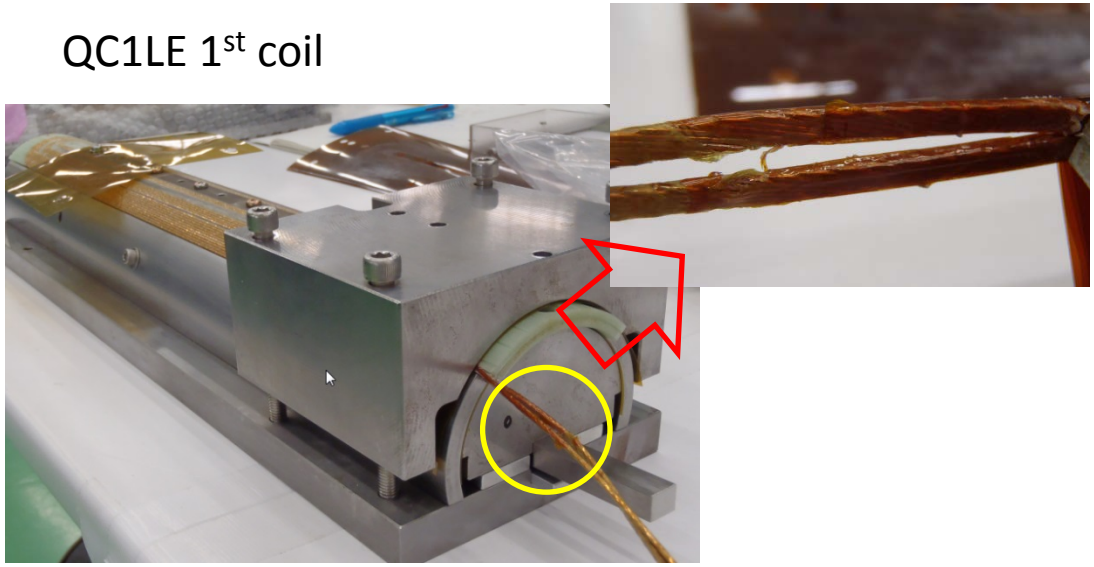
Production of quadrupole magnets

- QC1LP: 5 coils were built from 11 June 2013 ~ 17 July 2013.
  - The first coil was for training the technicians in Mitsubishi.
  - The third coil had a damage of the electrical insulation in the SC lead during a curing process. The damaged part was repaired.
  - The tools for the curing process was improved.
- QC1LE: 4 coils were built from 26 June 2013 ~ 11 July 2013, and the 5th coil was built from 9 October 2013 to 15 October 2013.
  - The SC cable in the 1st coil had a damage during a curing process. The coil was scrapped.

QC1LP 3rd coil



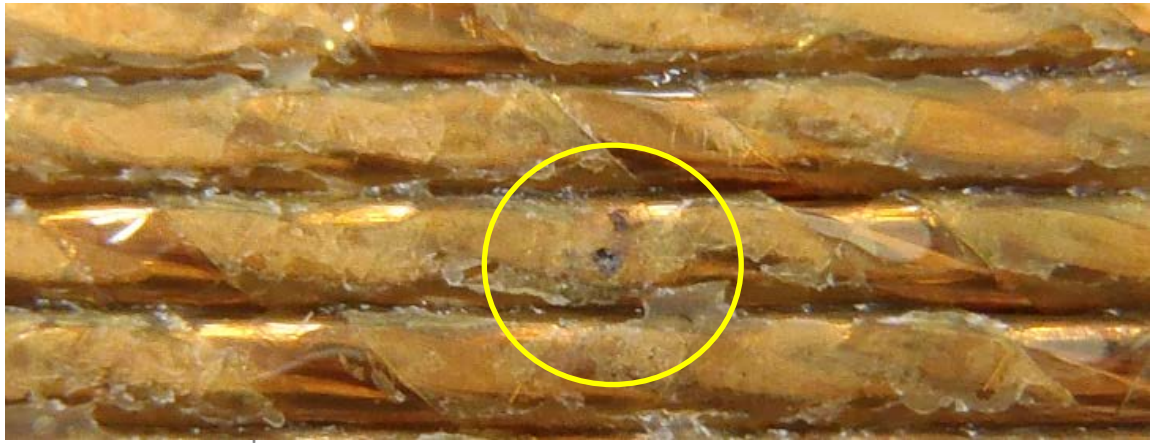
QC1LE 1st coil



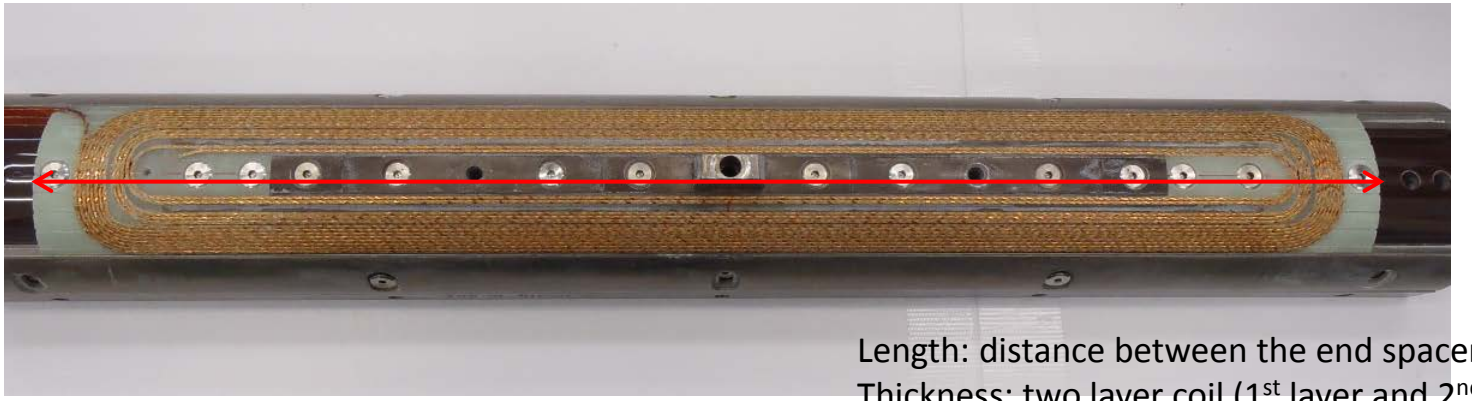
Production of quadrupole magnets

- QC2LP: 5 coils were built from 10 September 2013 ~ 17 October 2013.
  - The first coil was for training the technicians in Mitsubishi because the magnet had a large aperture.
  - The 5th coil had a damage of the electrical insulation by the metal flakes from the screw hole. The damaged part was identified and repaired with epoxy resin.
- QC2LE : 4 coils from 20 September 2013 ~ 4 October 2013.
- QC1RP: 4 coils from 19 November 2013 ~ 28 November 2013.
- QC1RE: 4 coils from 2 December 2013 ~ 7 December 2013.
- QC2RP: 4 coils from 16 December 2013 ~ 25 December 2013.
- QC2RE: 4 coils from 8 January 2014 ~ 16 January 2014.

QC2LP coil surface



Production of quadrupole magnets



Length: distance between the end spacers
Thickness: two layer coil (1st layer and 2nd layer)
STD: standard deviation of four coils

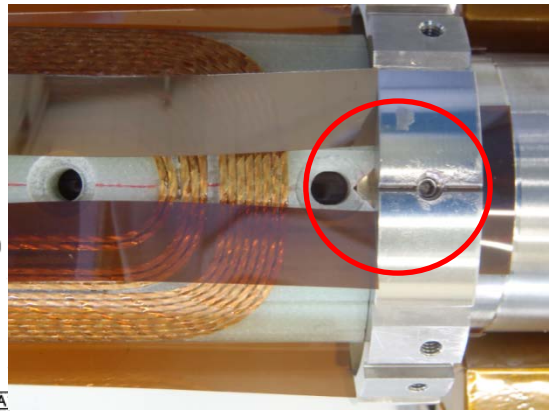
Coil shape	QC1LP	QC1LE	QC2LP	QC2LE
Length, mm (**Average**, STD) (Design)	**384.00**, 0.044 (384.0)	**429.98**, 0.041 (430.0)	**470.02**, 0.019 (470.0)	**593.05**, 0.012 (593.0)
Thickness, mm (**Average**, STD) (Design)	**5.418**, 0.006 (5.425)	**5.425**, 0.003 (5.425)	**5.419**, 0.003 (5.425)	**5.415**, 0.005 (5.425)

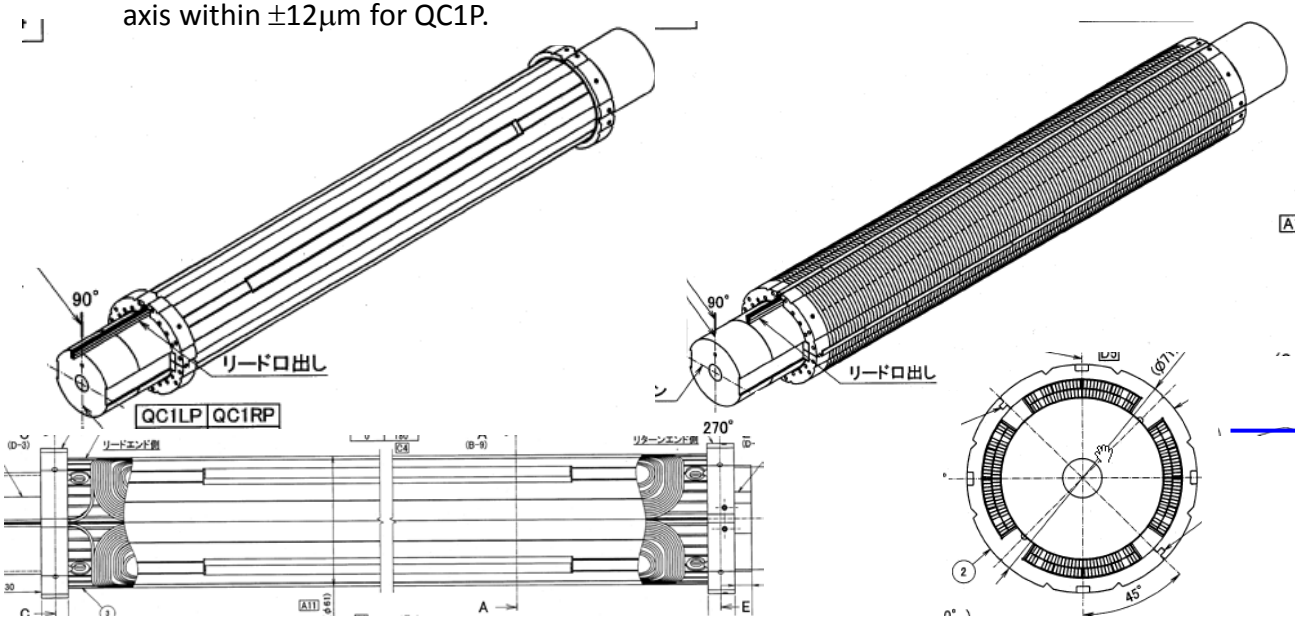
Coil shape	QC1RP	QC1RE	QC2RP	QC2RE
Length, mm (**Average**, STD) (Design)	**383.98**, 0.006 (384.0)	**429.92**, 0.010 (430.0)	**470.02**, 0.014 (470.0)	**535.05**, 0.070 (535.0)
Thickness, mm (**Average**, STD) (Design)	**5.423**, 0.002 (5.425)	**5.418**, 0.002 (5.425)	**5.420**, 0.007 (5.425)	**5.413**, 0.006 (5.425)

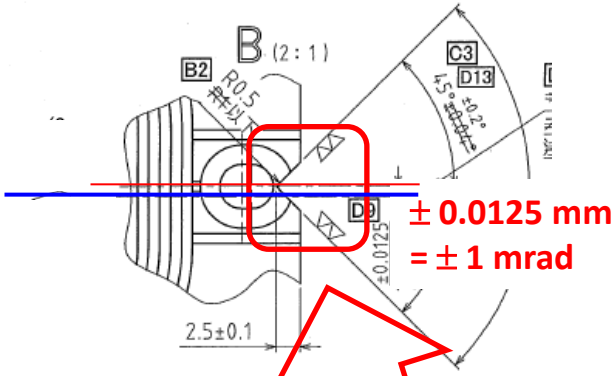
Production of quadrupole magnets

Machining of coil ends

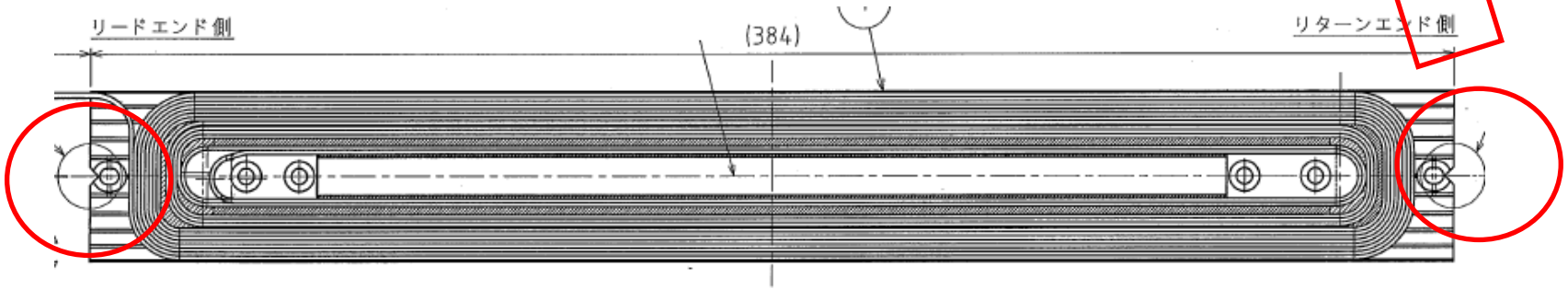
- The four coils are aligned with **the magnet end plates** with keys.
- The end plates are aligned of the support bobbin of the correctors with another keys.
- The support bobbin has the alignment keys to the cryostat.
- The mating surface (V-groove) center is required to be coincident with the coil center axis within ±12μm for QC1P.







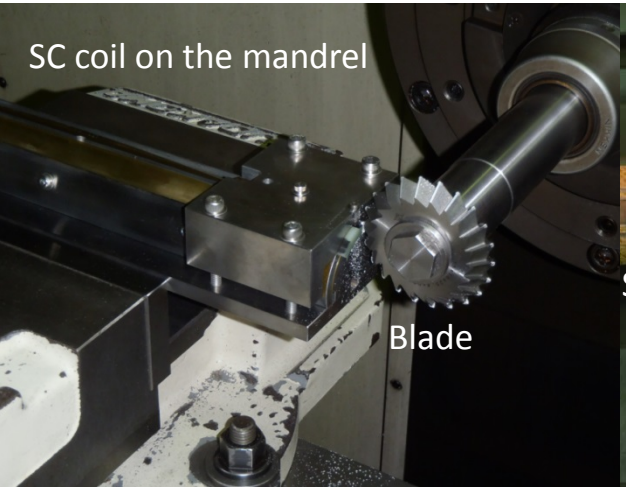
± 0.0125 mm
= ± 1 mrad

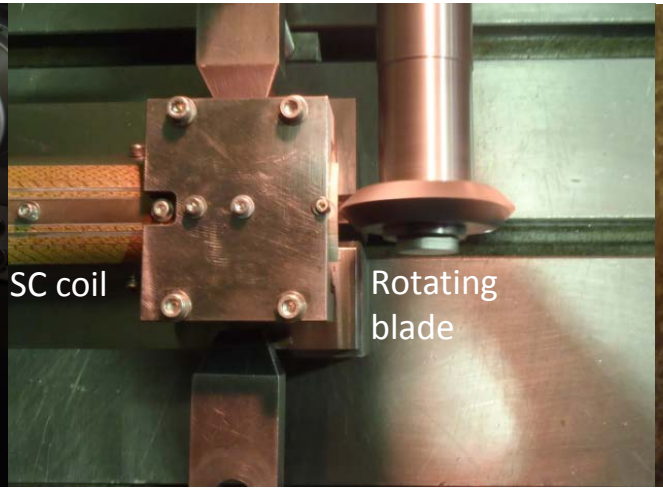


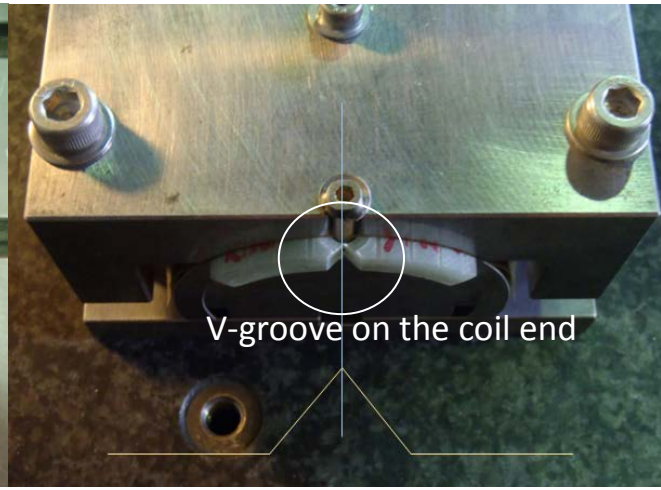
Production of quadrupole magnets

Machining of coil ends

- Machining of coil ends was performed with the rotating blade.
- The blade shape was shaped to the angle of 90 degree, and the blade surfaces have evenly the angle of 45 degree with respect to the plane including the top parts of the rotating blades.
- The coil was assembled on the special mandrel for this process to have a precise alignment to the blade.
- The blade position was decided from the mandrel.
- This process started from August 2013, and the machining method within the required precision was confirmed at December 25, 2013.





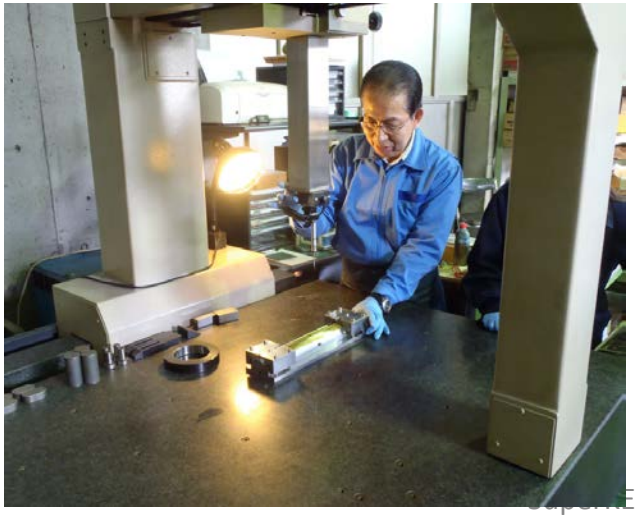


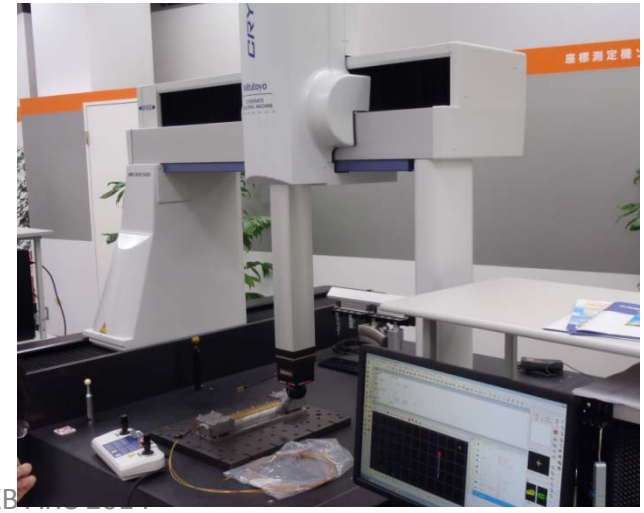
Production of quadrupole magnets

Measurement of the shape of V-groove on the coil ends

- At the beginning of the machining process, the shape of V-groove was measured by the 3D shape measurement instrument with manual operation.
  - The number of sampling points is limited, and the G10 material of coil ends was the combined material with epoxy and glass fiber.
  - Machining surface was not flat like metal.
  - The measured data did not have repeatability.
- Appling the newest type of 3D measurement instrument
  - With a kind collaboration of Japanese company (Mitsutoyo), we had a technical service for measuring the shape of V-groove.
  - The machine was operated with the automatic scanning of the surface with the sampling span of 2.3 μm. The resolution of the machine is 0.1 μm
  - The measured data were over 1000 points, and the data were processed statistically.
  - The accuracy and repeatability of the measured offset between the coil center axis and the V-groove center were measured with the ultimate precision.

Old type of 3D shape measurement instrument

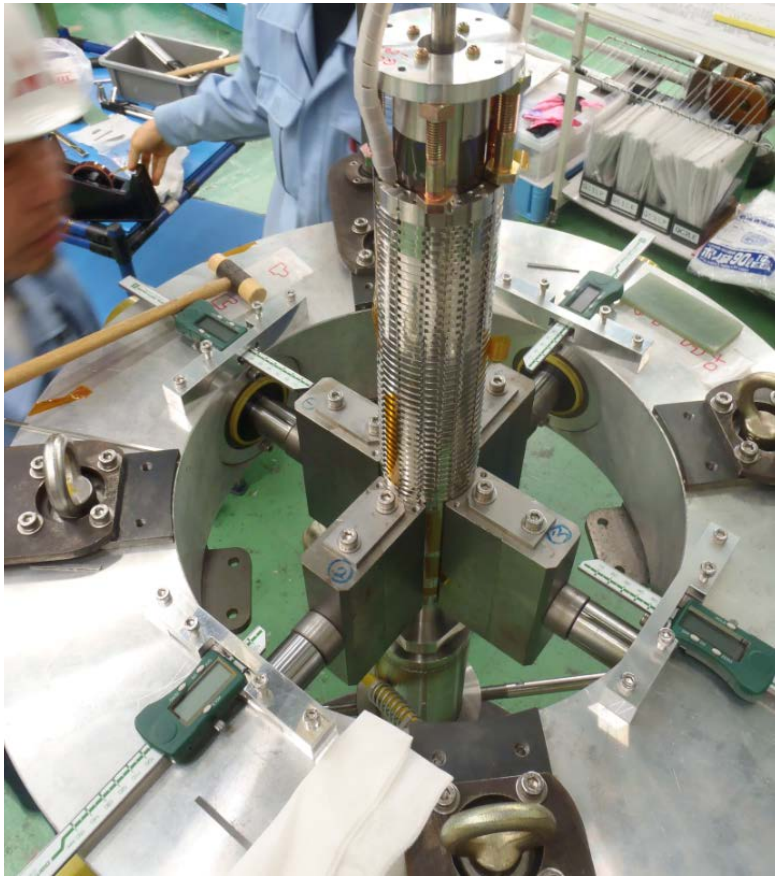




Newest type of 3D shape measurement instrument

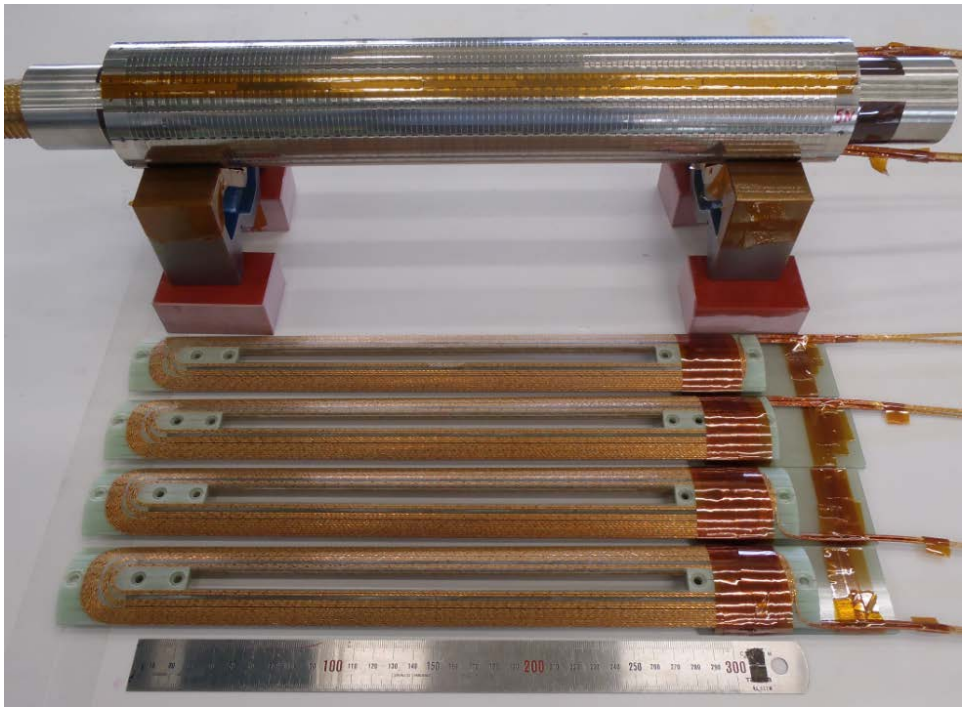
Production of quadrupole magnets

Collaring process of four coils



Collaring press and the QC1LP magnet

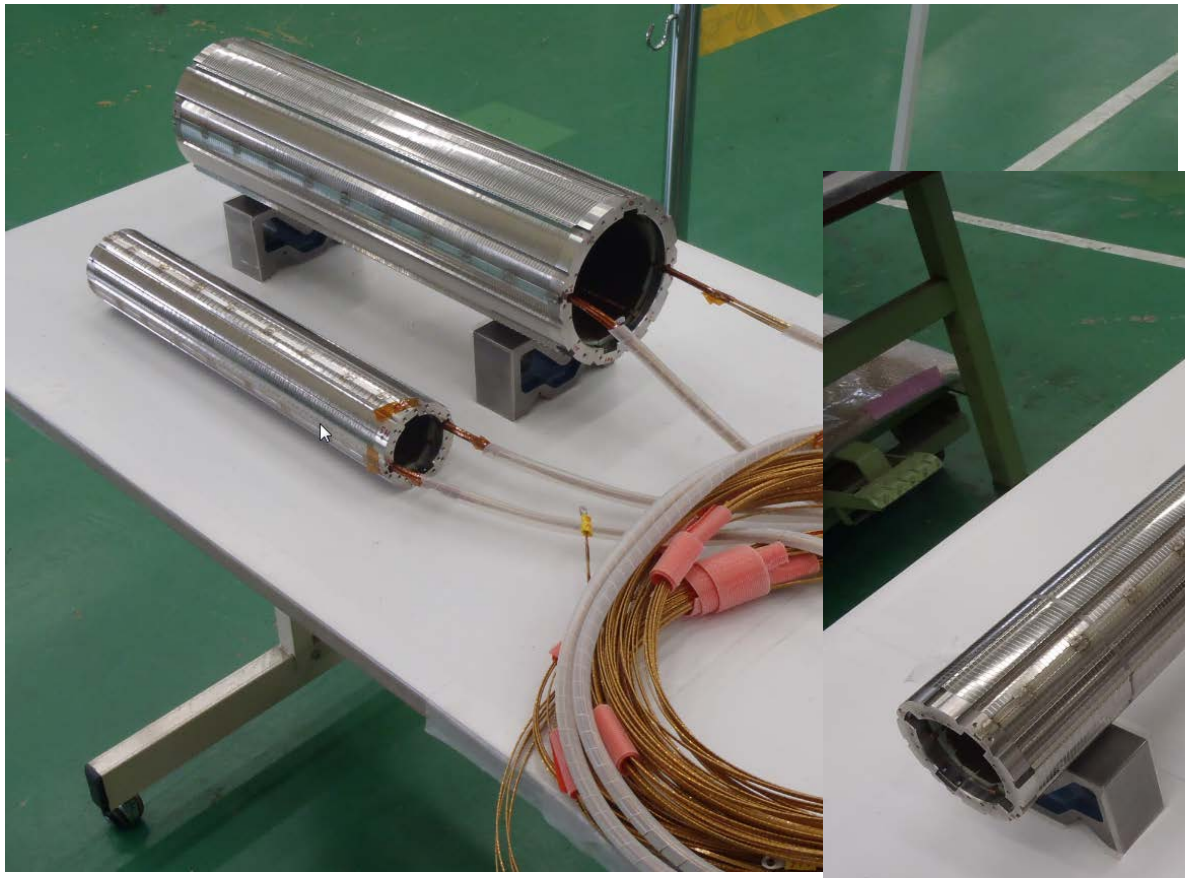
Collared QC1LP magnet after the 1st collaring



Coils for QC1RP magnet

Production of quadrupole magnets

Completed collared magnets



QC1LP & QC2LP

QC1LE & QC1RE

Production of quadrupole magnets

- QC1E proto-type test results
  - The sextupole error field at the level of 10^{-3} to the quadrupole field was measured.
  - Sextupole correctors were introduced into the magnet system in the right side.
- Fields of the collared magnets are measured at Mitsubishi.
  - When the amplitude of the sextupole field exceeds 10^{-3} w.r.p. the quadrupole field, the magnet is disassembled and the collaring process will be conducted again.

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

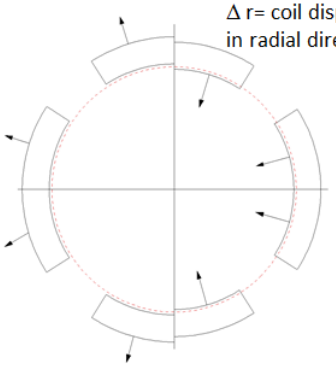
$a_n = A_n/B_2 \times 10000$

$b_n = B_n/B_2 \times 10000$

a_3 and b_3 error field

- Sextupoles are produced by the dipole deformation of four coils

Δ r= coil displacement in radial direction



- 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

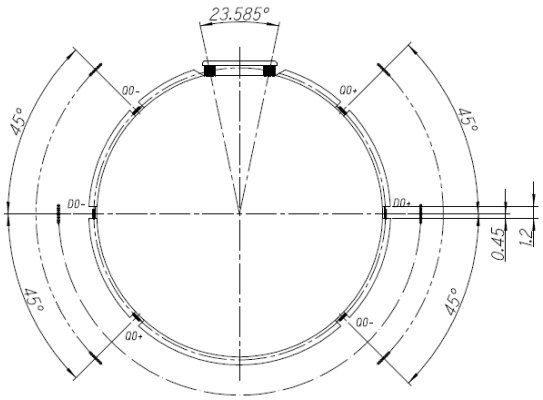
@ R=15 mm : b_3 = 14.75 Gauss (50 μm)、 5.9 Gauss (20 μm)

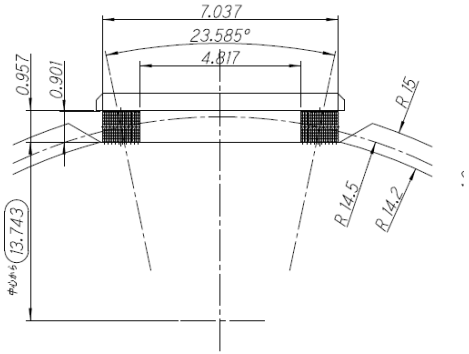
Presented at SuperKEKB ARC 2013

Production of quadrupole magnets

Field measurement at Mitsubishi

- Field measurement system (Harmonic coil)
  - The system measures the integral field of the magnet.
  - Harmonic coil length = 997.989 mm
  - Harmonic coil radius = 14.5 mm
  - Turn number of the coil = 100
- Magnet current at the measurement＝±1A
  - Design current at nominal operation = 1625A
  - The signal was magnified 200000 times larger with the pre-amplifier plus amplifier in the integrator.
- The field measurements were performed with the dipole and quadrupole bucking process.





Production of quadrupole magnets

Field measurement results:QC1LP

QC1LP field quality after collaring

	@ R = 14.5 mm		@ R = 10 mm		Design @ R= 10 mm	
	a_n	b_n	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00	0.00	0.00
2	-0.00	**10000**	0.00	**10000**	0.00	**10000**
3	**-3.16**	**0.89**	**-2.18**	**0.61**	**0.00**	**0.00**
4	1.32	-1.22	0.63	-0.58	0.00	0.24
5	1.07	-0.31	0.35	-0.10	0.00	0.00
6	-0.39	0.45	-0.09	0.10	0.00	0.54
7	-0.27	0.14	-0.04	0.02	0.00	0.00
8	-0.04	-0.38	-0.00	-0.04	0.00	0.01
9	-0.01	0.05	-0.00	0.00	0.00	0.00
10	0.07	-2.03	0.00	-0.10	0.00	-0.21

Production of quadrupole magnets

Field measurement results:QC2LP

QC2LP field quality after collaring

	@ R = 14.5 mm		@ R = 30 mm		Design @ R = 30 mm	
	a_n	b_n	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**	0.00	**10000**
3	**-0.21**	**-0.05**	**-0.43**	**-0.11**	**0.00**	**0.00**
4	0.03	-0.18	0.12	-0.77	0.00	-0.06
5	-0.11	0.06	-1.00	0.50	0.00	0.00
6	0.01	0.00	0.23	0.01	0.00	0.28
7	0.05	0.03	1.97	1.29	0.00	0.00
8	0.02	0.04	1.36	3.38	0.00	0.11
9	0.02	0.02	3.38	3.06	0.00	0.00
10	-0.03	0.00	-9.92	0.93	0.00	-1.43

Production of quadrupole magnets

Field measurement results:QC1LE

QC1LE field quality after collaring

	@ R = 14.5 mm		@ R = 15 mm		Design @ R = 15 mm	
	a_n	b_n	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**	0.00	**10000**
3	**0.27**	**0.89**	**0.28**	**0.92**	**0.00**	**0.00**
4	0.47	-0.23	0.50	-0.25	0.00	-0.02
5	0.07	-0.02	0.08	-0.02	0.00	0.00
6	-0.02	-0.01	-0.03	-0.02	0.00	-0.04
7	-0.02	0.02	-0.02	0.02	0.00	0.00
8	-0.02	-0.04	-0.02	-0.05	0.00	-0.42
9	-0.02	-0.00	-0.03	-0.00	0.00	0.00
10	-0.07	-0.08	-0.10	-0.10	0.00	0.05

Production of quadrupole magnets

Field measurement results:QC1RE

QC1RE field quality after collaring

	@ R = 14.5 mm		@ R = 15 mm		Design @ R = 15 mm	
	a_n	b_n	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**	0.00	**10000**
3	**1.06**	**-1.09**	**1.10**	**-1.13**	**0.00**	**0.00**
4	-0.10	-1.34	-0.11	-1.44	0.00	-0.02
5	-0.10	-0.14	-0.11	-0.15	0.00	0.00
6	0.18	-0.16	0.21	-0.19	0.00	-0.04
7	0.06	0.02	0.07	0.03	0.00	0.00
8	0.01	-0.02	0.01	-0.03	0.00	-0.42
9	-0.00	0.06	-0.00	0.08	0.00	0.00
10	-0.14	-0.16	-0.18	-0.21	0.00	0.05

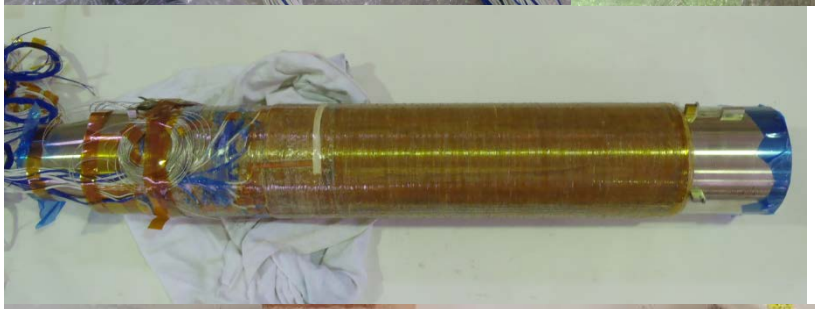
Production of quadrupole magnets

- Four magnets (QC1LP, QC2LP, QC1LE and QC1RE) are accepted for the next step in the assembly process.
- Assembly of QC1LP and correctors into one unit:
  - The assembly is scheduled from 17 March, 2014 at Mitsubishi.
  - The mid-planes and magnetic centers of the QC1LP and corrector fields are measured.
  - The cold test of the assembled magnet will be performed in April at KEK.
- Assembly of QC2LP and correctors into one unit:
  - The assembly is scheduled from 25 March, 2014 at Mitsubishi.
  - The mid-planes and magnetic centers of the QC2LP and corrector fields are measured.
  - The cold test of the assembled magnet will be performed in May at KEK.

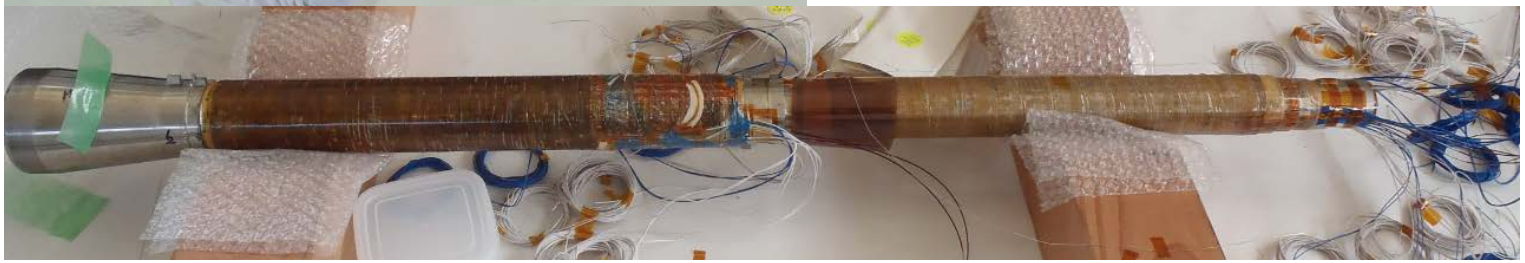
Production of correctors

Production status of correctors in the left side:

QC1LP correctors : a_1, b_1, a_2, b_4



QC2LP correctors : a_1, b_1, a_2, b_4



QC1LE correctors : a_1, b_1, a_2, b_4

QC1LP leak field cancel coils : b_3, b_4, b_5, b_6

The correctors for the QC2LE magnet will be delivered from BNL in March.
The cold test of the correctors is scheduled in March.

Production of correctors

All correctors in KEK were tested in the vertical cryostat.

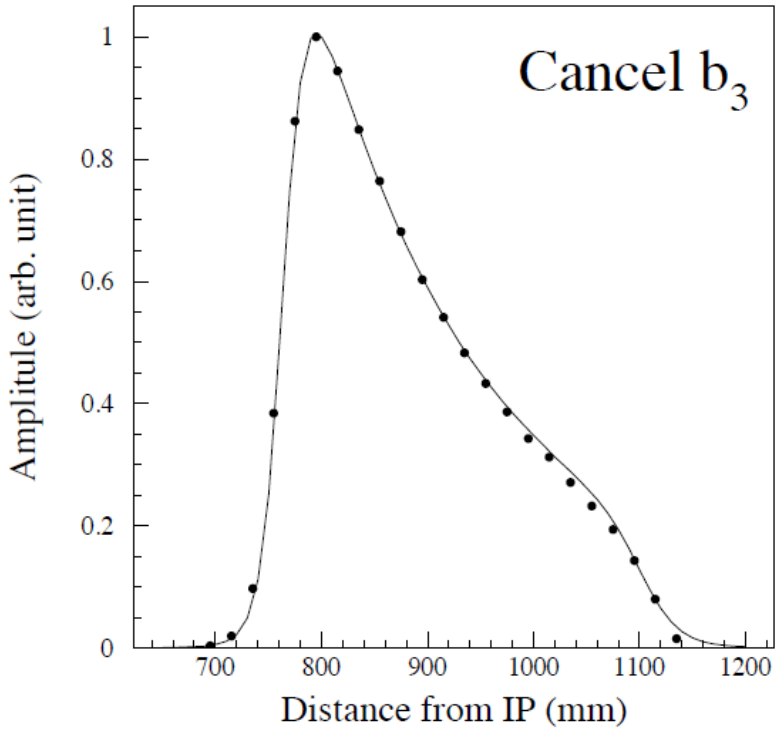
- The correctors were excited up to 70 A without quench.
- The field measurements were performed.

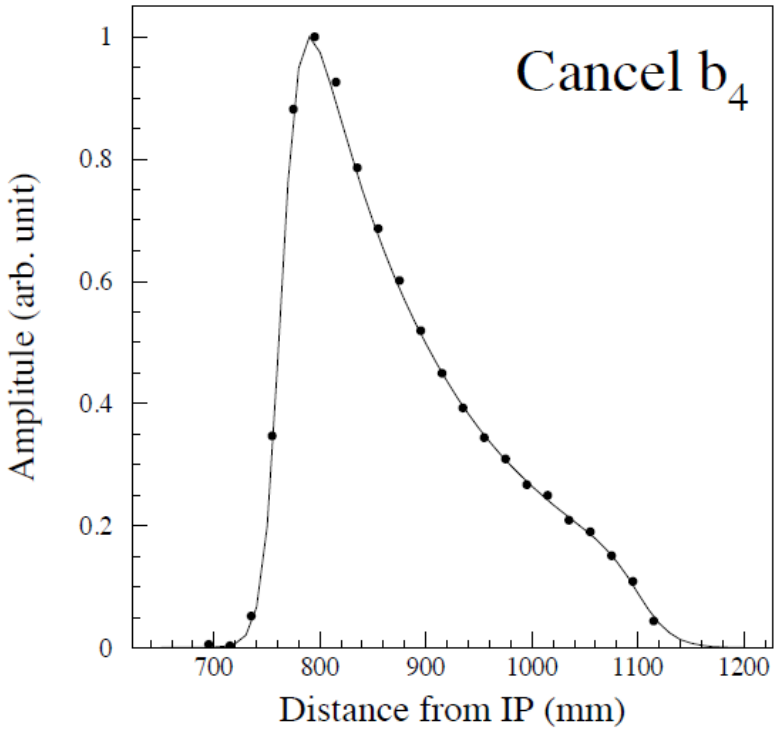
	Corrector	Specification (Required field)	Design field at 70 A	Meas. field at 70 A
QC1LP	a1	0.016 Tm	0.0212 Tm	0.0214 Tm
	b1	0.016 Tm	0.0175 Tm	0.0176 Tm
	a2	0.64 T	0.9839 T	0.9921 T
	b4	60 T/m^2	354.6 T/m^2	329.6 T/m^2
QC2LP	a1	0.03 Tm	0.02752 Tm	0.02756 Tm
	b1	0.03 Tm	0.03079 Tm	0.03084 Tm
	a2	0.31 T	0.5964 T	0.5894 T
	b4	60 T/m^2	172.3 T/m^2	166.8 T/m^2
QC1LE	a1	0.027 Tm	0.02707 Tm	0.02702 Tm
	b1	0.046 Tm	0.04756 Tm	0.04655 Tm
	a2	0.75 T	0.9624 T	0.9504 T
	b4	60 T/m^2	919.3 T/m^2	875.1 T/m^2

Production of correctors

Field measurements of the QC1LP leak field cancel coils (b_3, b_4, b_5, b_6)

- The field profiles of the cancel coils need to be measured with the 20 mm long harmonic coil.



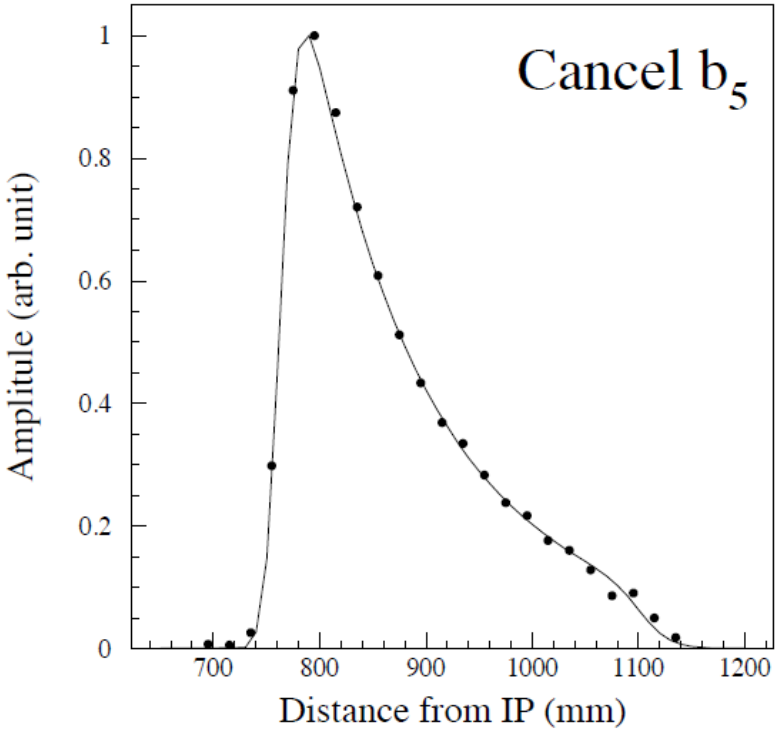


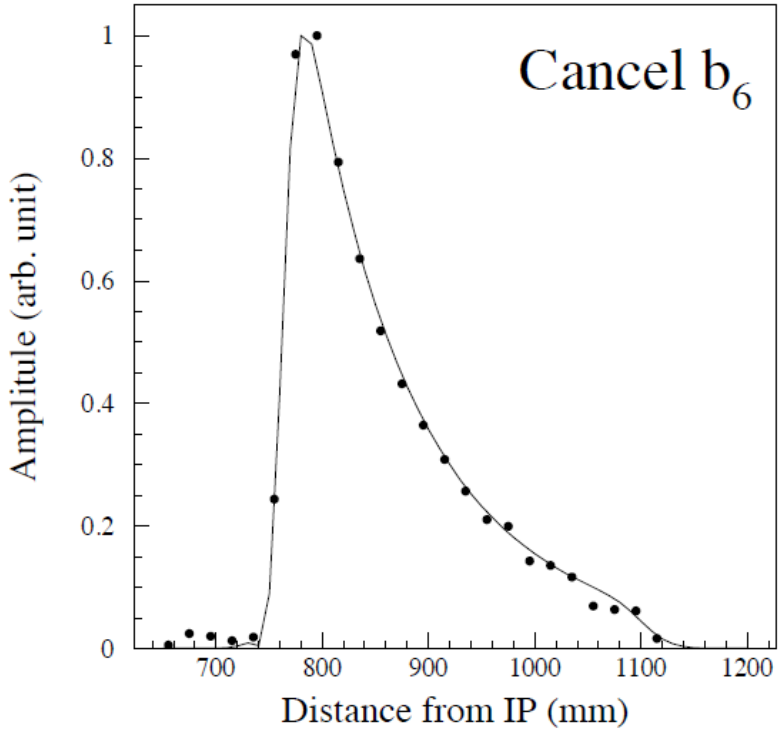
Line : Opera3D (Leak field from QC1LP)

Dot : Measurement

Production of correctors

Field measurements of the QC1LP leak field cancel coils (b_3, b_4, b_5, b_6)





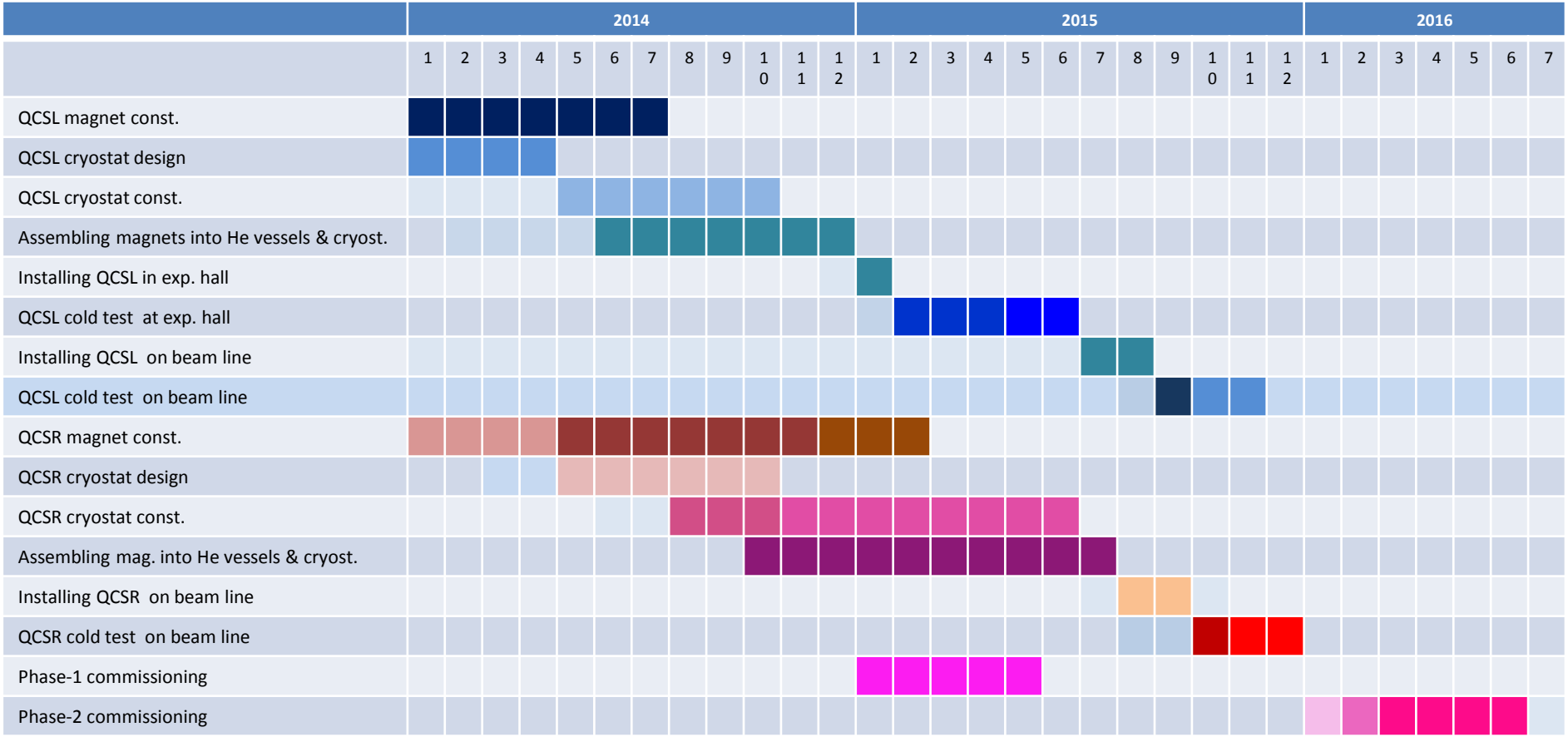
Line : Opera3D (Leak field from QC1LP)

Dot : Measurement

Production of correctors

- Construction schedule of correctors in the right side
  - The design and the construction of the correctors for the right side already start.
  - All correctors for the right side are scheduled to be completed in 2014 JFY.
    - QC1RP [a_1, b_1 and a_2] : March 21, 2014
    - QC1RP [b_4 and a_3] : April 2, 2014
    - QC2RP : May 21, 2014
    - QC1RP－QC2RP sextupole : July 30, 2014
    - QC1RE ＋cancel coils : September 22, 2014
    - QC2RE : July 14, 2014
    - QC1RE－QC2RE sextupole : September 4, 2014

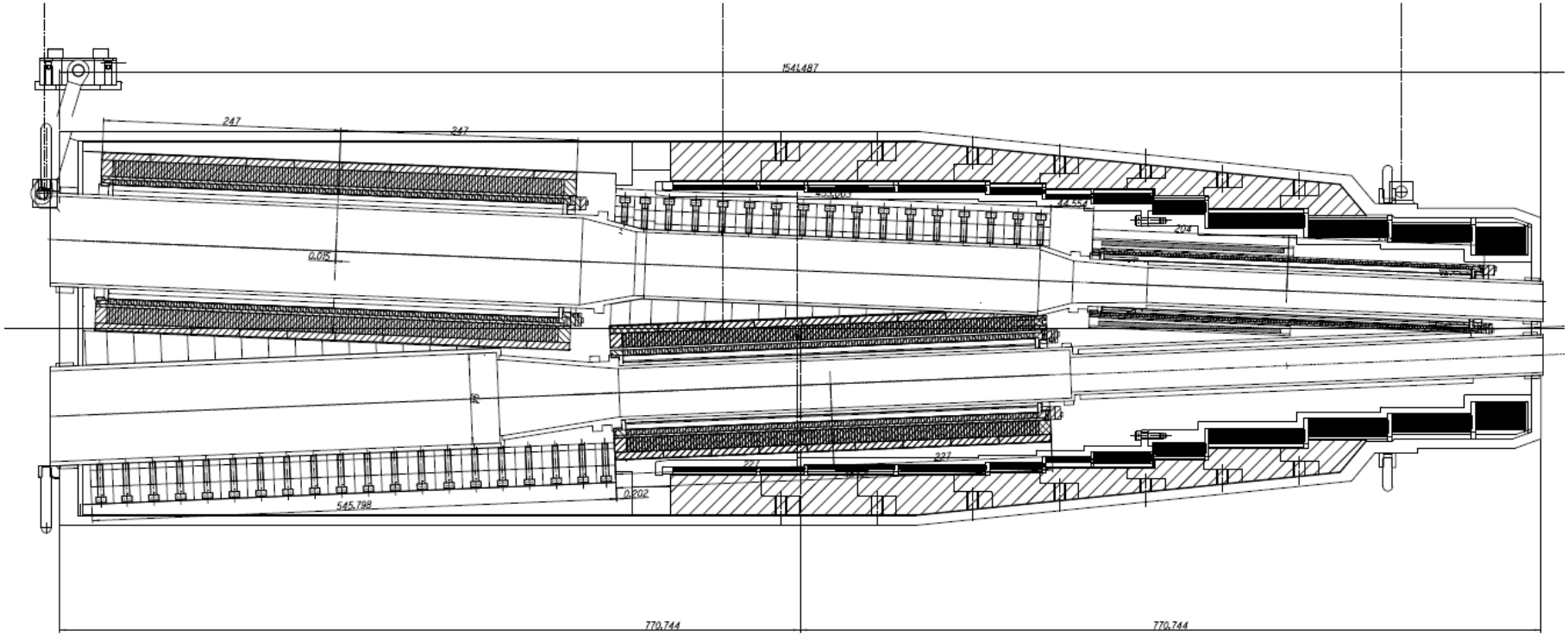
Construction Schedule



Detail schedule for L-side

- Magnet construction
  - QC2LE collaring: March 3 ~ March 7, 2014
  - Assembly of QC magnets and correctors: March 17 ~ April
    - QC2LE need to be cold tested in March
  - Yoking of 4 collared magnet: April ~ May
    - The permendur yokes and magnetic shields have been completed and transported to Mitsubishi.
  - Cold tests of 4 assembled magnets: April ~ June
  - Design of solenoid for construction: March ~ April
  - Construction of solenoid: May ~ July (all magnets for the left side come to be present.)
- Cryostat
  - The detail design of the cryostat is under way.
    - Design of support rods
    - Thermal shrinkage effect on the components
  - The design need to be completed in April.
  - The radiation shield (Tungsten alloy) have been machined in the final shape.
- Assembled magnet-cryostat
  - It is scheduled to be completed and transported to KEK in December 2014.

Detail schedule for L-side



Details of the magnets and magnet components in the front helium vessel of the left cryostat

Summary

- Quadrupole magnet construction
  - All SC coils for the main quadrupoles were completed.
  - The collaring processes of four quadrupoles were completed, and they are accepted from the field measurement results.
  - Collaring all magnets will be completed in March.
- SC corrector construction
  - The correctors in the left side were completed.
  - The transported correctors from BNL to KEK were tested at 4 K in KEK, the coils showed good performances in excitation and field quality.
  - Construction of all coils by BNL will be completed in September 2014.
- Schedule
  - The magnet-cryostat in the left side will be completed in December 2014.
  - The magnet-cryostat in the right side will be completed in July 2015.
  - The tests on the beam line are scheduled from September to December 2015.