IR Superconducting Magnets

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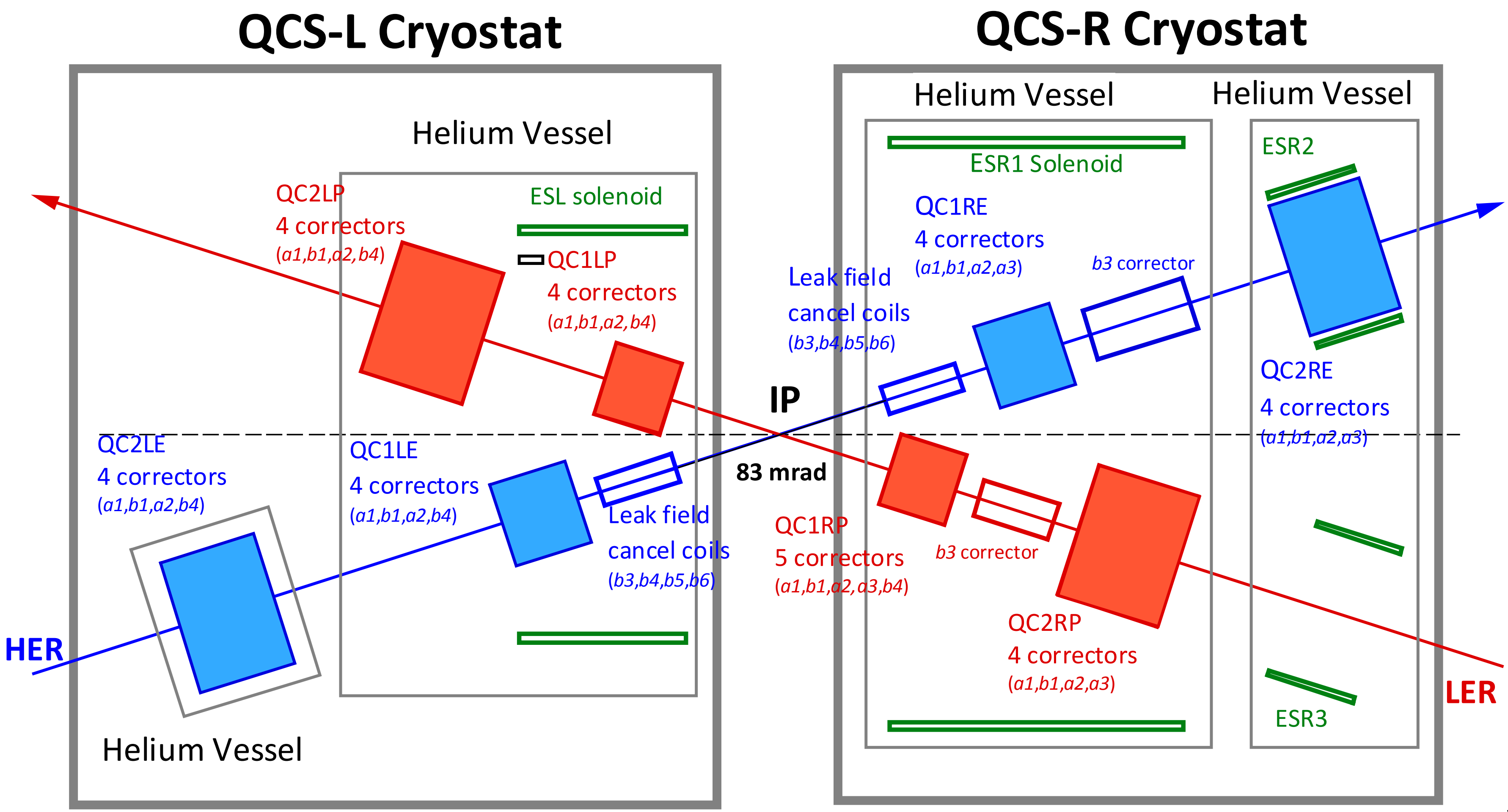
Contents

Production status of magnets

1. Collaring processes of the 8 SC quadrupole magnets have been completed in March 2014.
2. The four quadrupole magnets for QCSL were completed, and they were assembled with the corrector magnets in July 2014.
   - The cold tests of the magnets were performed with the vertical cryostat.
     - The quadrupole magnets and the corrector magnets were successfully excited to the design currents under the combined excitations without any quenches.
     - The field measurements were performed with the harmonic coils.
3. Production of all correctors magnets by BNL has been completed in January 2015.
4. The compensation solenoid, ESL, was constructed in December 2014.
   - ESL was tested at 4K, and it was excited to the design current without quench.
   - The solenoid field profile was measured with a Hall probe.

Production status of magnets



Tests during magnet production

QC1, 2 by Mitsubishi:
Field measurements in the factory
- Room temperature, Special harmonic coil
- After collaring: Field quality , focused on **sextupole error field**
- After assembling QC with corrector magnets: Field angles

Corrector magnets by **BNL**:
Field measurements at room temperature in BNL
Excitation and Field measurements at 4K in KEK

Cold tests of assembled magnets [QC1,2 + corrector magnets] in KEK:
- Field measurements and excitation tests at 4K
  QC1P, 1E : Harmonic coils [**R=12mm**, L=595mm n=100 and L=20mm n=120]
  QC2P, 2E : Harmonic coils [**R=20mm**, L=595 n=150 and L=20mm n=150]

Assembly of QC1,2+corrector magnets into the support block in **Mitsubishi**

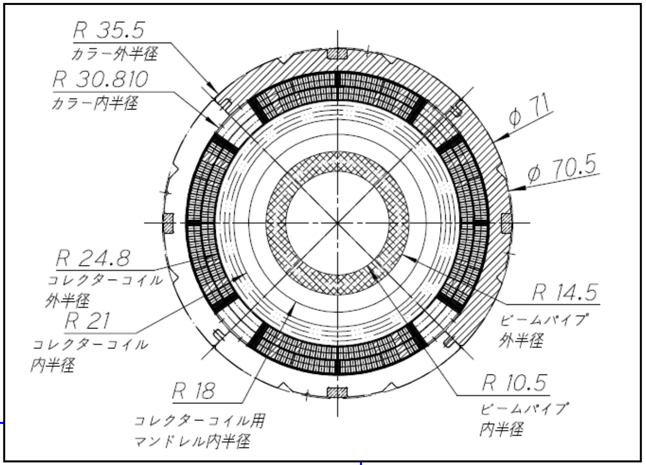
Now, here for QCSL

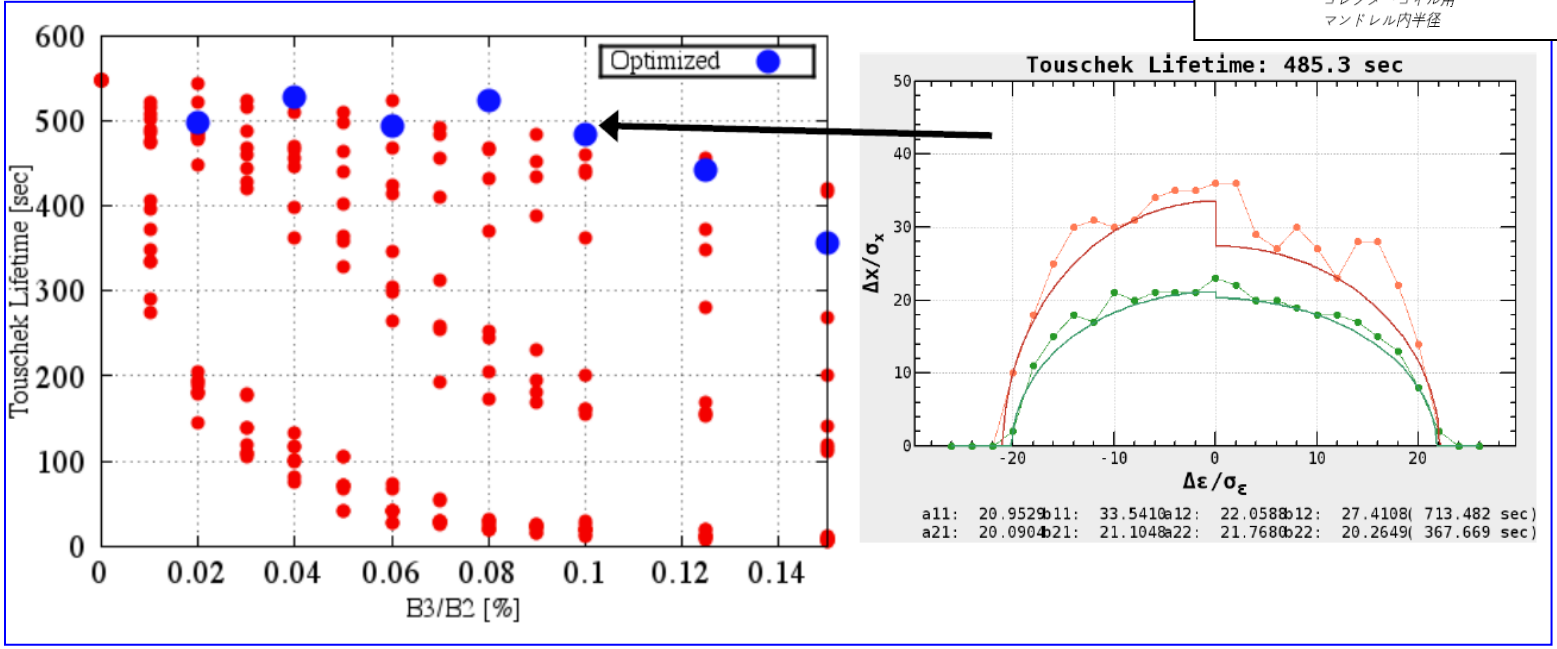
Field measurement for alignment of QC magnets in the block in KEK:
- Measurement of magnetic axes and angles of QC magnets at room temperature with the special harmonic coil

Cold test of combined excitation of QC1P, QC1E, QC2LP, corrector magnets, ESL/ESR in KEK:
- Excitation tests with QC1 and QC2 quadrupole magnets under the solenoid field
- Measurement of the cancelled leak field of QC1P magnet with the corrector magnets

Error field effect of quadrupoles

- Beam lifetime (Touschek lifetime) reduction by error fields of quadrupole magnets
  - **The sextupole field component** of 2 $\times 10^{-4}$ with respect to quadrupole field (B_3/B_2) is induced by the deformation of 8 μm in the coil shape.
  - The field component degrades the beam life time from 550 s to 150 s.
  - The reduced life time is recovered to 500 s with the sextupole corrector magnets.





From presentation by H. Sugimoto at 18th KEKB Review

Production of quadrupole magnets

Integral Field measurement results:QC1LP

	@ R = 10 mm, 1802A		Design @ R= 10 mm	
	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**
3	**0.45**	**3.04**	**0.00**	**0.00**
4	1.49	0.56	0.00	0.24
5	-0.24	-0.39	0.00	0.00
6	-0.39	0.08	0.00	0.54
7	0.11	0.14	0.00	0.00
8	0.03	-0.14	0.00	0.01
9	-0.08	0.04	0.00	0.00
10	0.08	-0.17	0.00	-0.21

Design field @1624.9A, r_0=10mm

– B_2L_{eff}/r_0 = 22.996 T

Measured field @1624.9A, r_0=10mm

– **B_2L_{eff}/r_0 = 22.903 T**

Production of quadrupole magnets

Integral Field measurement results:QC2LP

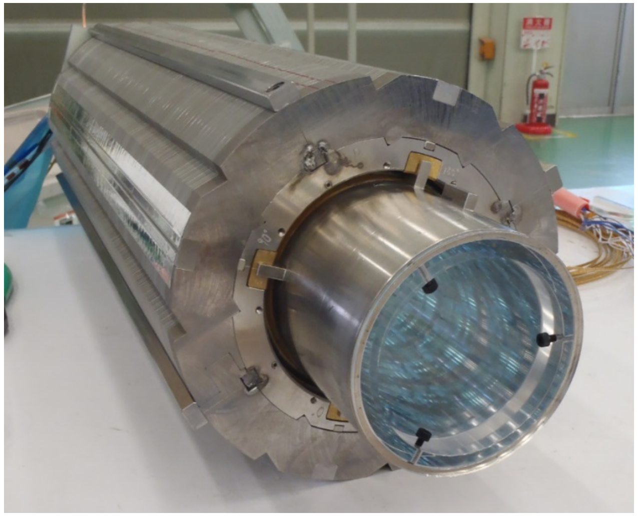
	@ R = 30 mm, 1002.3 A		Design @ R = 30 mm	
	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**
3	**1.79**	**-0.59**	**0.00**	**0.00**
4	0.00	0.45	0.00	-0.06
5	-0.39	-0.19	0.00	0.00
6	-0.14	3.40	0.00	0.28
7	0.32	-0.08	0.00	0.00
8	0.13	-0.20	0.00	0.11
9	0.20	0.07	0.00	0.00
10	0.18	-1.50	0.00	-1.43

Design field @877.4 A, r_0=30 mm

– B_2L_{eff}/r_0 = 11.497 T

Measured field @877.4 A, r_0=30 mm

– **B_2L_{eff}/r_0 = 11.402 T**



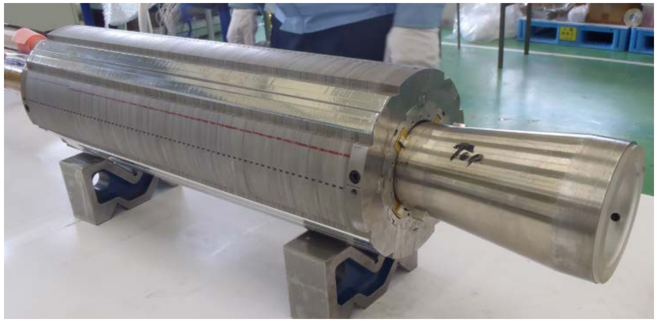
Production of quadrupole magnets

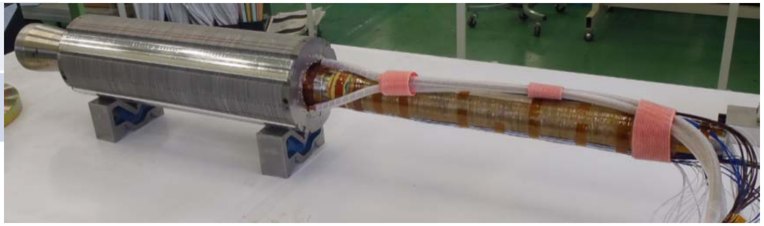
Integral Field measurement results:QC1LE

	@ R = 15 mm, 2004.2 A		Design @ R = 15 mm	
	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**
3	**2.26**	**-5.41**	**0.00**	**0.00**
4	-0.85	2.84	0.00	-0.02
5	0.15	0.86	0.00	0.00
6	-0.23	-0.26	0.00	-0.04
7	0.01	0.26	0.00	0.00
8	0.35	0.58	0.00	-0.42
9	-0.11	0.01	0.00	0.00
10	1.25	-0.66	0.00	0.05

Design field @1577.1 A, r_0=15 mm
- B_2L_{eff}/r_0 = 26.938 T

Measured field @1577.1 A, r_0=15 mm
- **B_2L_{eff}/r_0 = 26.435 T**





Production of quadrupole magnets

Integral Field measurement results:QC2LE

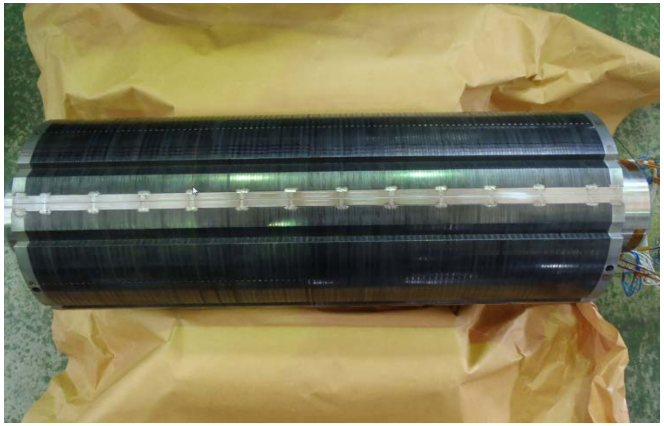
	@ R = 35 mm, 1252.8 A		Design @ R = 35 mm	
	a_n	b_n	a_n	b_n
n=1	0.00	0.00	0.00	0.00
2	0.00	**10000**	0.00	**10000**
3	**0.07**	**-1.04**	**0.00**	**0.00**
4	1.35	0.32	0.00	-0.02
5	-0.08	0.11	0.00	0.00
6	-0.46	4.41	0.00	-0.04
7	-0.06	-0.13	0.00	0.00
8	0.31	0.11	0.00	-0.42
9	-0.60	1.02	0.00	0.00
10	0.04	2.44	0.00	0.05

Design field@976.95 A, r_0=35 mm

- B_2L_{eff}/r_0 = 15.272 T

Measured field@ 976.95 A, r_0=35 mm

- $\boldsymbol{B_2L_{eff}/r_0}$ **= 14.844 T**



Production of corrector magnets

- Production of 43 corrector magnets were completed.
  - The cold tests of the 35 corrector magnets have been performed.
    - The field qualities of the magnets were measured at room temperature in BNL.
    - In KEK, the magnets were cooled to 4 K and they were excited to +/ー 60 A.
  - The 16 corrector magnets for QCSL were assembled with the QC magnet, they were tested at 4K under the combined excitations.
  - The corrector magnets for QC1RE and the QC1RP leak field cancel magnets have been constructed by BNL, and they are scheduled to be transported to KEK in February.

Field measurements of correctors

- 16 corrector magnets for QCSL

	Corrector	Optics requirement	Design at 60 A (without Yoke)	After assembled with QC magnets at 60 A
QC1LP	a1	0.016 Tm	0.0182 Tm	0.0176 Tm (No Yoke)
	b1	0.016 Tm	0.0150 Tm	0.0145 Tm (No Yoke)
	a2	0.64 T	0.843 T	0.788 T (No Yoke)
	b4	60 T/m^2	304 T/m^2	283 T/m^2 (No Yoke)
QC2LP	a1	0.03 Tm	0.0236 Tm	0.0351 Tm
	b1	0.03 Tm	0.0264 Tm	0.0406 Tm
	a2	0.31 T	0.511 T	0.634 T
	b4	60 T/m^2	148 T/m^2	159.6 T/m^2
QC1LE	a1	0.027 Tm	0.0232 Tm	0.0318 Tm
	b1	0.046 Tm	0.0408 Tm	0.0544 Tm
	a2	0.75 T	0.825 T	0.901 T
	b4	60 T/m^2	788 T/m^2	737 T/m^2
QC2LE	a1	0.015 Tm	0.0266 Tm	0.0396 Tm
	b1	0.015 Tm	0.0291 Tm	0.0460 Tm
	a2	0.37 T	0.580 T	0.732 T
	b4	60 T/m^2	131 T/m^2	142.4 T/m^2

Field measurements of correctors

- 19 corrector magnets for QCSR

	Corrector	Optics requirement	Design at 60 A (without Yoke)	Before assembled with QC magnets at 60 A
QC1RP	a1	0.016 Tm	0.018 Tm	0.0180 Tm
	b1	0.016 Tm	0.0164 Tm	0.0165 Tm
	a2	0.64 T	0.814 T	0.788 T
	a3	**7.6 T/m**	**9.2 T/m**	**9.59 T/m**
	b4	60 T/m^2	283 T/m^2	275 T/m^2
QC2RP	a1	0.03 Tm	0.038 Tm	0.0384 Tm
	b1	0.03 Tm	0.027 Tm	0.0273 Tm
	a2	0.31 T	0.49 T	0.495 T
	a3	**1.36 T/m**	**1.39 T/m^2**	**1.430 T/m^2**
QC1RE	a1	0.027 Tm	0.0226 Tm	Measurement in March
	b1	0.046 Tm	0.040 Tm	Measurement in March
	a2	0.75 T	0.77 T	Measurement in March
	a3	**7.0 T/m**	**21 T/m**	Measurement in March

Field measurements of correctors

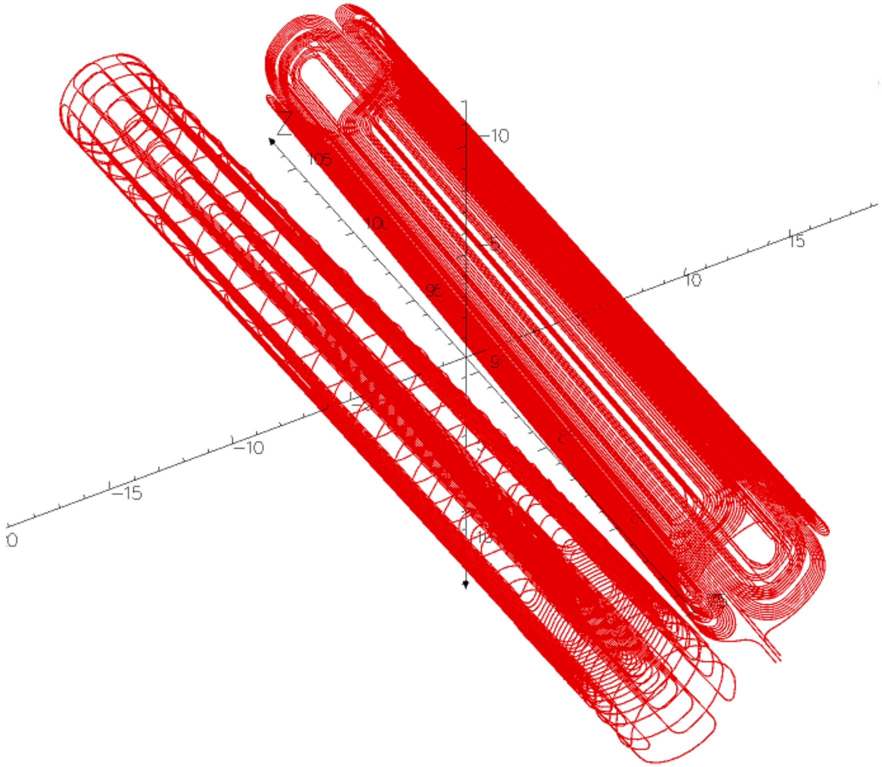
- 19 corrector magnets for QCSR

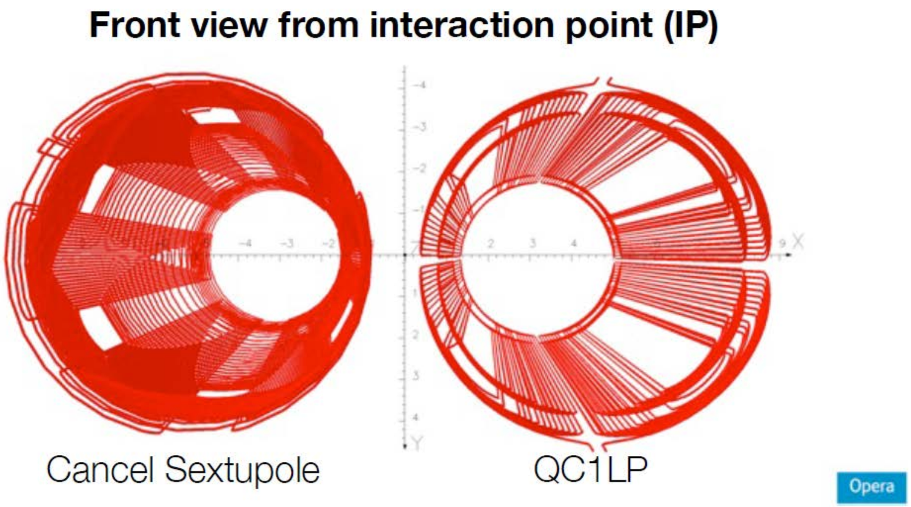
	Corrector	Optics requirement	Design at 60 A (without Yoke)	Before assembled with QC magnets at 60 A
QC2RE	a1	0.015 Tm	0.0224 Tm	0.0231 Tm
	b1	0.015 Tm	0.0257 Tm	0.0266 Tm
	a2	0.37 T	0.524 T	0.536 T
	a3	**1.5 T/m**	**6.2 T/m**	**6.38 T/m**
QC1-2RE	**b3**	**27 T/m**	**33.4 T/m**	**33.51 T/m**
QC1-2RP	**b3**	**17.2 Tm**	**18.4 T/m**	**18.87 T/m**

The four corrector magnets of QC1RE and the QC1RP leak field cancel magnets will be measured at 4K in March.

QC1LP leak field cancel magnets

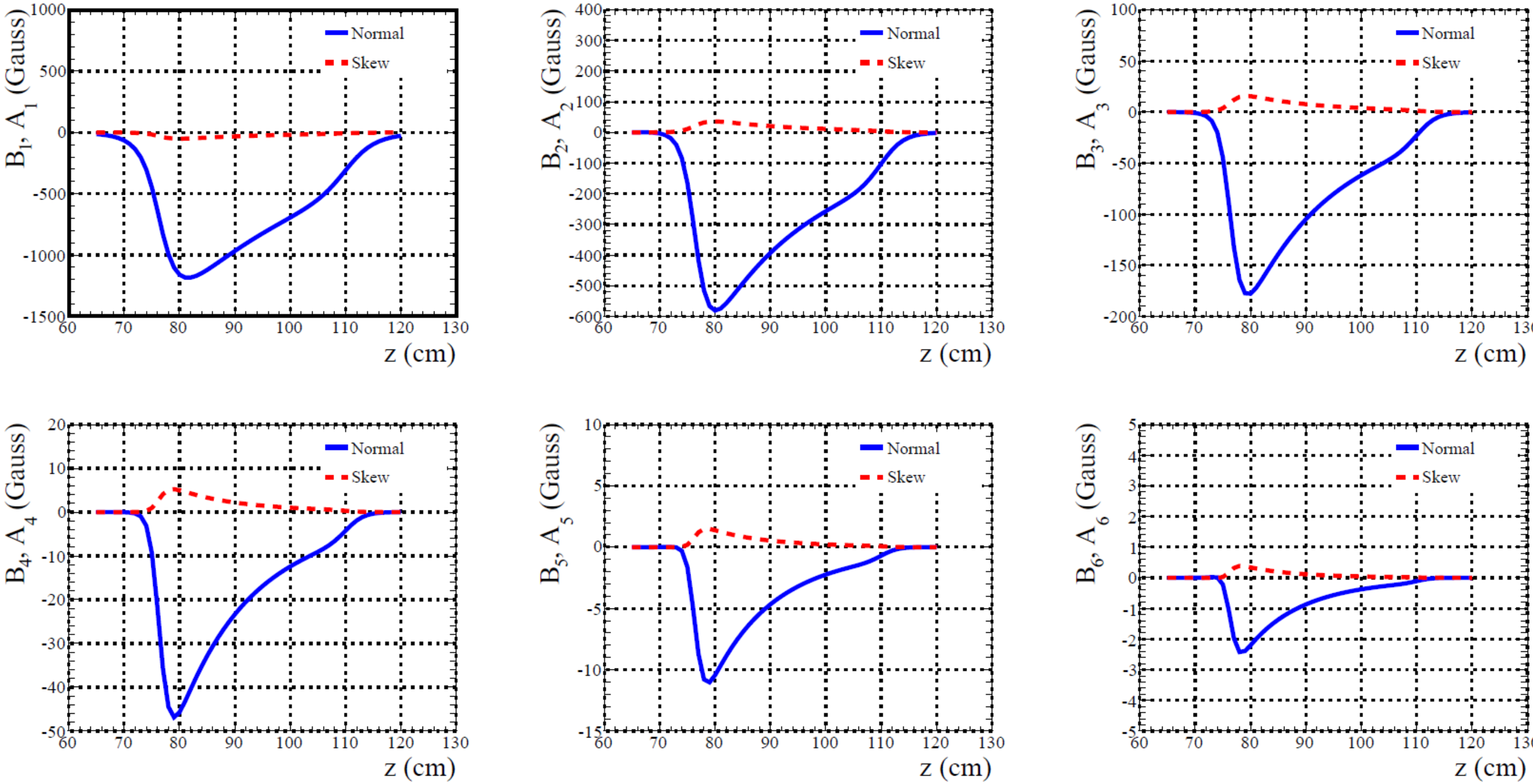
- LER and HER beam lines have difference of -1.5 mm in height.
  - The leak field of QC1LP has the skew field components on the HER beam line.
  - The leak field cancel magnets are designed to be rotated to cancel the skew components as with the normal components.





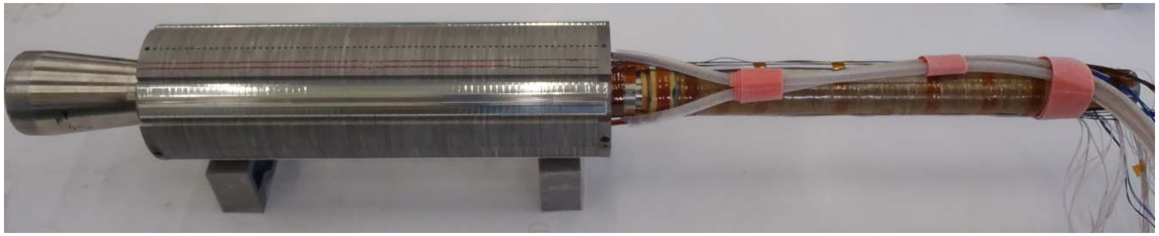
QC1LP leak field cancel magnets

- The leak field profile of QC1LP on the HER beam line



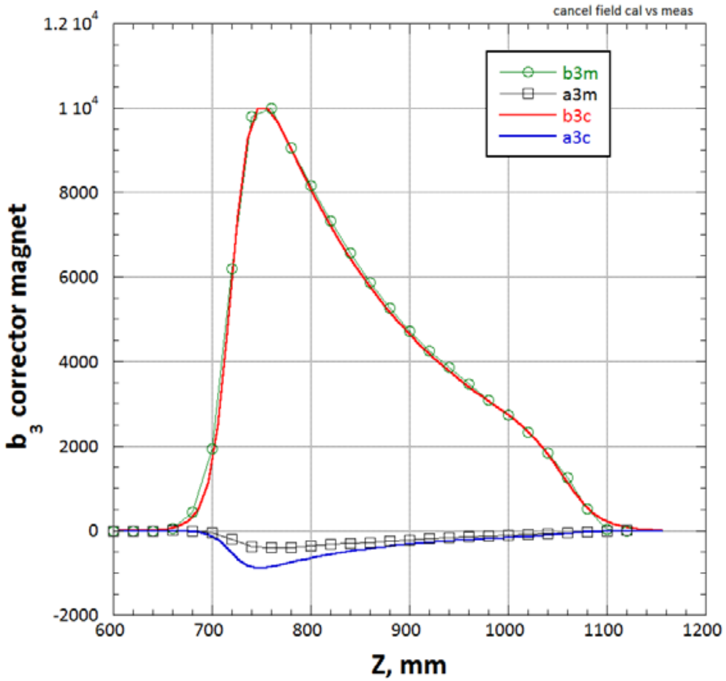
QC1LP leak field cancel magnets

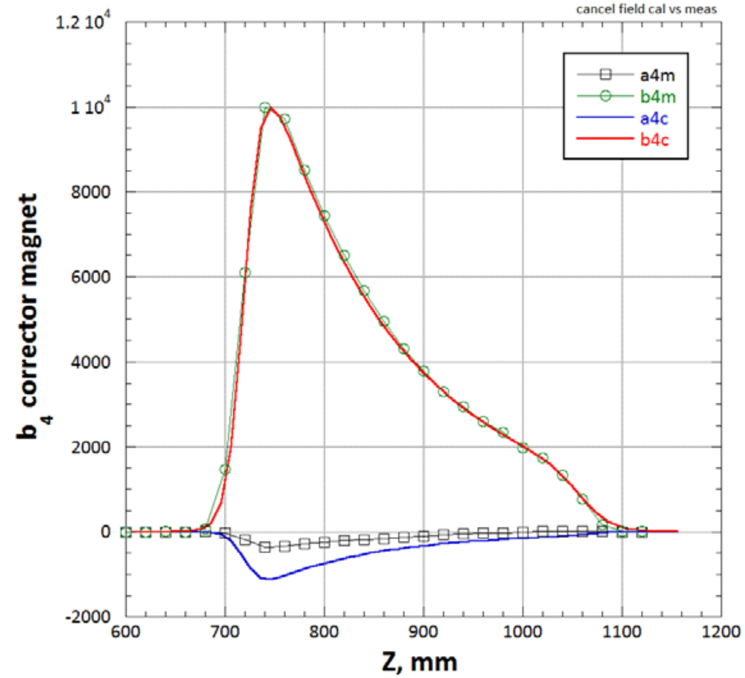
- Magnetic field measurement
  - The field measurements were performed with the vertical cryostat.
  - For measuring the normal and skew components of the corrector magnets, the phase angle of the measurement was referenced to the quadrupole angle of QC1LE.
    - The precise measurements are scheduled with the real cryostats and the horizontal measurement system.
    - In the measurement, the phase angle of the magnetic field is defined with the gravity.



QC1LE QC1LP leak field cancel magnet

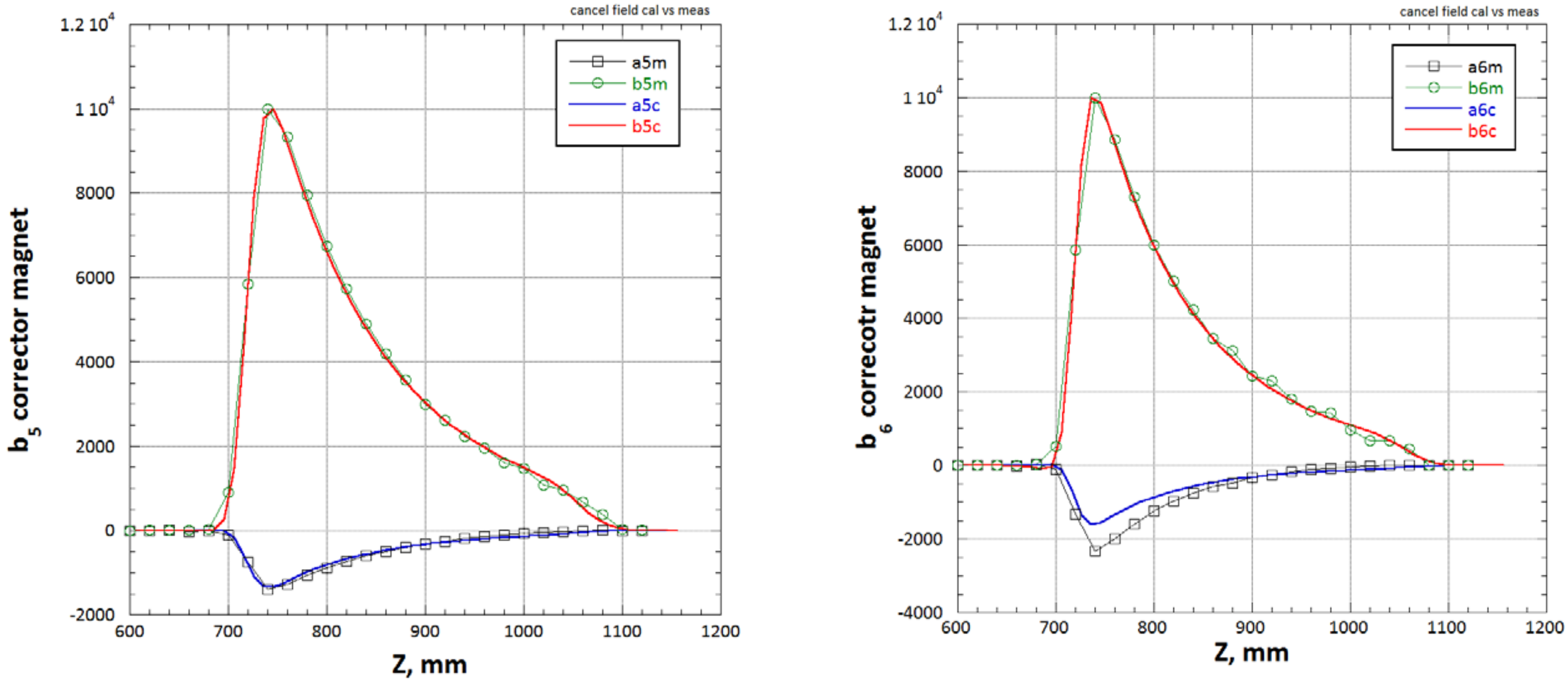
QC1LP leak field cancel magnets





- The comparison between the calculation and measurement
  - The peak of the normal components are normalized as 10000.
    - b_3 corrector magnet : $\int b_{3-cal}$ = 194.4 m, $\int b_{3-meas}$ = 197.4 m, $\int a_{3-cal} = -14.8$ m, $\int a_{3-meas} = -8.28$ m
    - b_4 corrector magnet : $\int b_{4-cal}$ = 168.7 m, $\int b_{4-meas}$ = 171.5 m, $\int a_{4-cal} = -16.5$ m, $\int a_{4-meas} = -4.79$ m
  - $\Delta = \int a_{3-cal} - \int a_{3-meas} = -6.52$ m corresponds to A_3 = 1.16 $\times 10^{-4}$ Tm @ R_{ref}=0.01 m
    - A_3 = 1.16 × 10-4 Tm @ R_{ref}=0.01 m is 5.5 % of the field strength of the A_3 corrector magnet in QC1RE at 60 A.
  - $\Delta = \int a_{4-cal} - \int a_{4-meas} = -11.71$ m corresponds to A_4 = 5.48 $\times 10^{-5}$ Tm @ R_{ref}=0.01 m
    - A_4 = 5.48 $\times 10^{-5}$ Tm @ R_{ref}=0.01 m is 2×10^{-4} of the integral field of QC1LP.

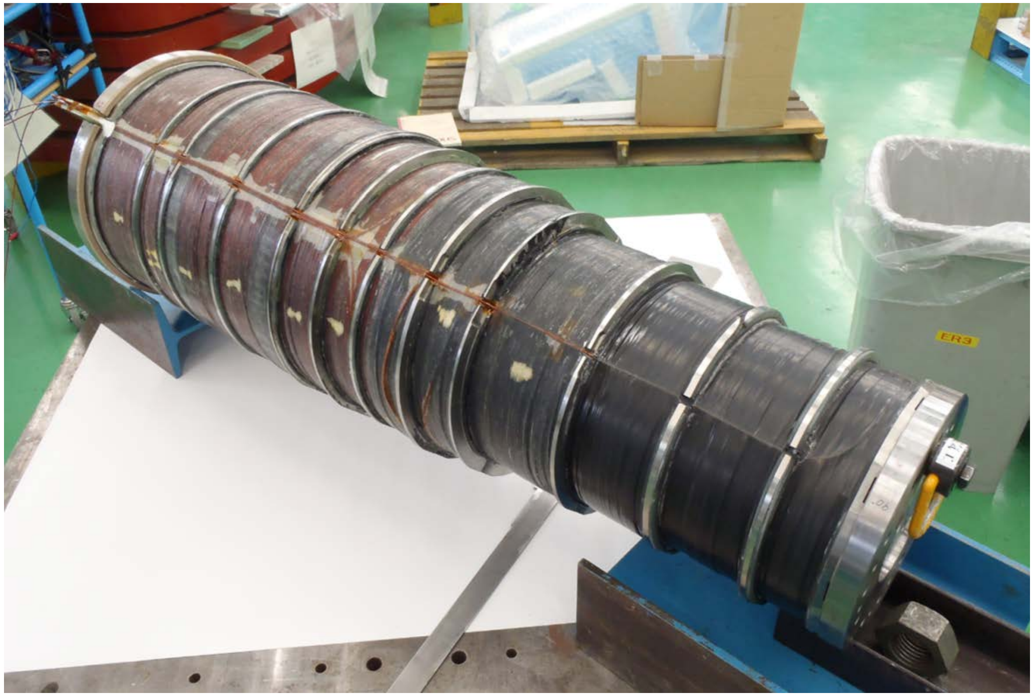
QC1LP leak field cancel magnets



- The comparison between the calculation and measurement
  - The peak of the normal components are normalized as 10000.
  - b_5 corrector magnet : $\int b_{5-cal} = 148.5$ m, $\int b_{5-meas} = 150.4$ m, $\int a_{5-cal} = -17.8$ m, $\int a_{5-meas} = -17.9$ m
  - b_6 corrector magnet : $\int b_{6-cal} = 131.5$ m, $\int b_{6-meas} = 133.2$ m, $\int a_{6-cal} = -18.7$ m, $\int a_{6-meas} = -24.6$ m
  - $\Delta = \int a_{6-cal} - \int a_{6-meas} = 5.9$ m corresponds to $A_6 = 1.43 \times 10^{-6}$ Tm @ R_{ref}=0.01 m
  - $A_6 = 1.43 \times 10^{-6}$ Tm @ R_{ref}=0.01 m is 6.2×10^{-6} of the integral field of QC1LP

Compensation solenoid, ESL

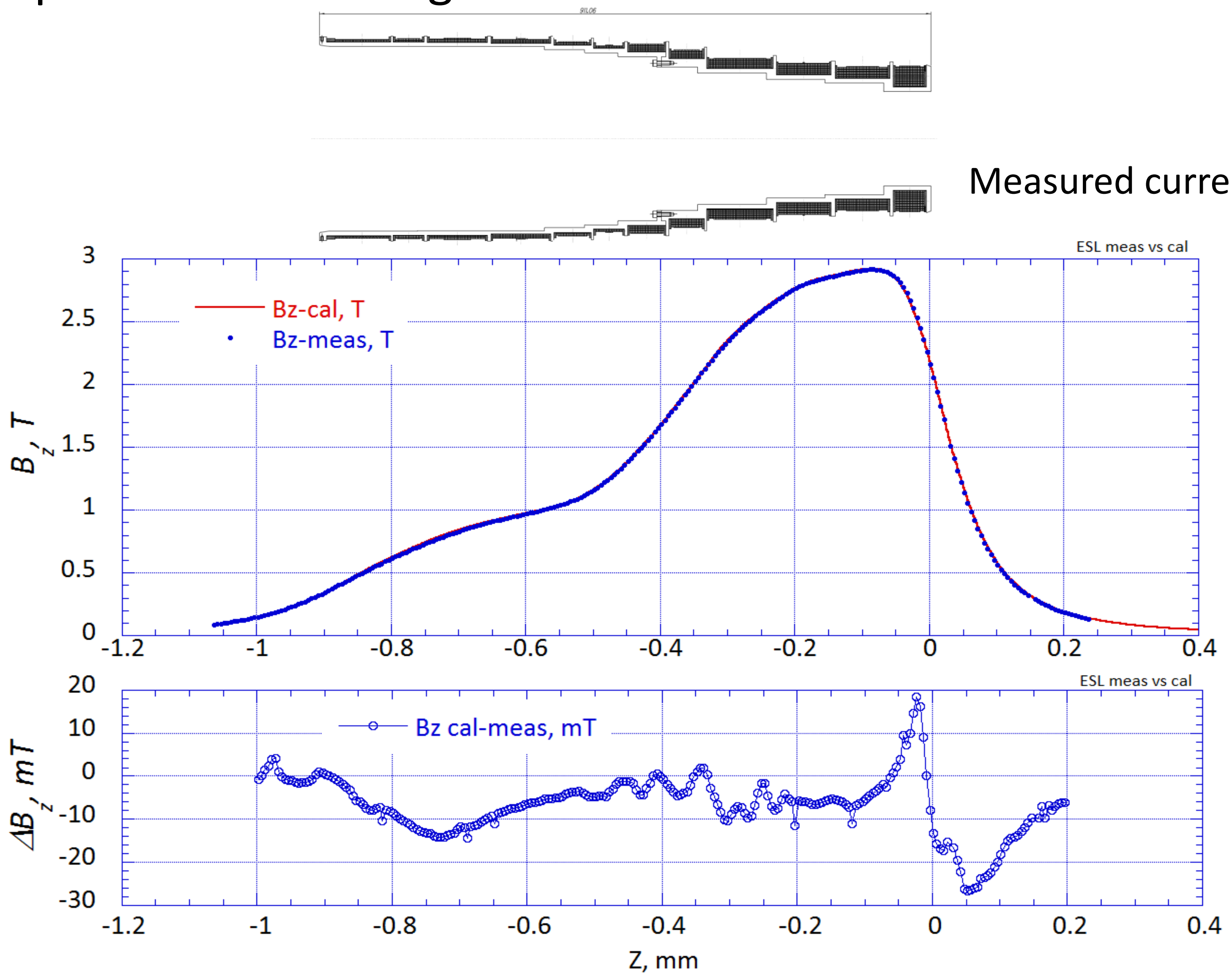
- ESL was constructed and delivered to KEK in December 2014.
  - The cold tests of ESL was performed in January 2015.
    - ESL was excited to the design current of 404 A without quench.
    - The field measurement by the hall probe was performed.
    - The field profile on the solenoid axis was measured.



Compensation solenoid, ESL

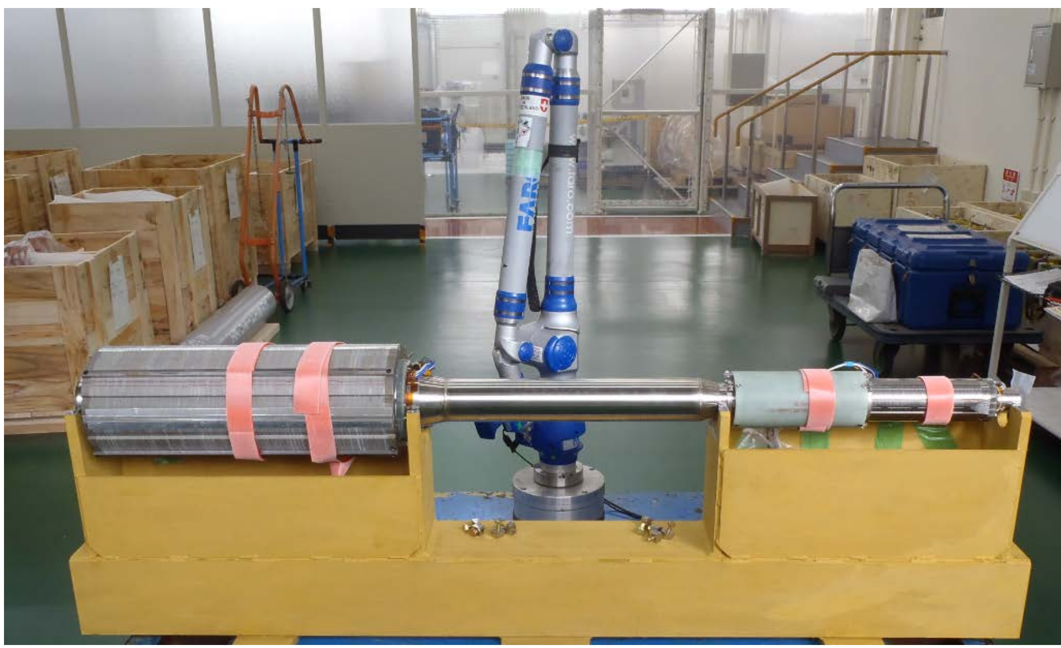
- Field profile of ESL along the solenoid axis

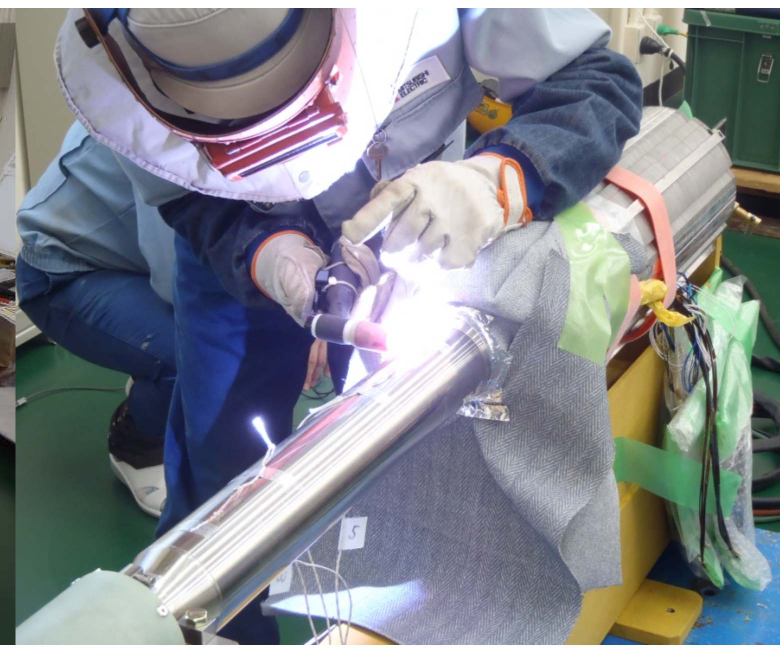
Measured current =295A



Assembly of quadrupoles

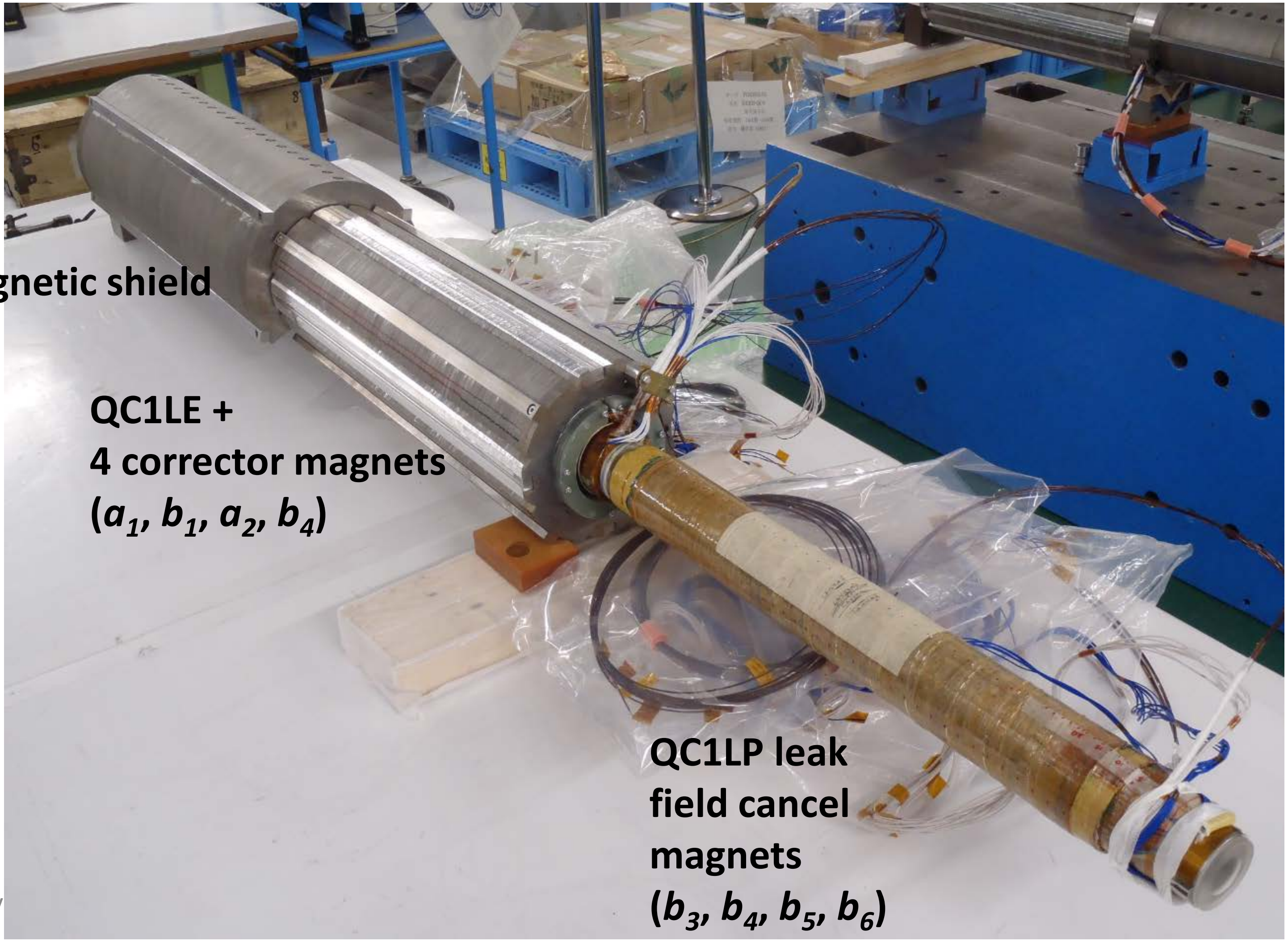
- Alignment of the magnets and components with the special jig
  - The magnets and the pipes are aligned with the special jig.
    - The shape of the jig was measured with the FARO 3D surveying instrument.
    - The magnets were assembled on the jig, and the position of the magnets were measured before and after welding the support bobbins and pipe.
    - The alignment errors were within 20 μm.





Assembly of quadrupoles

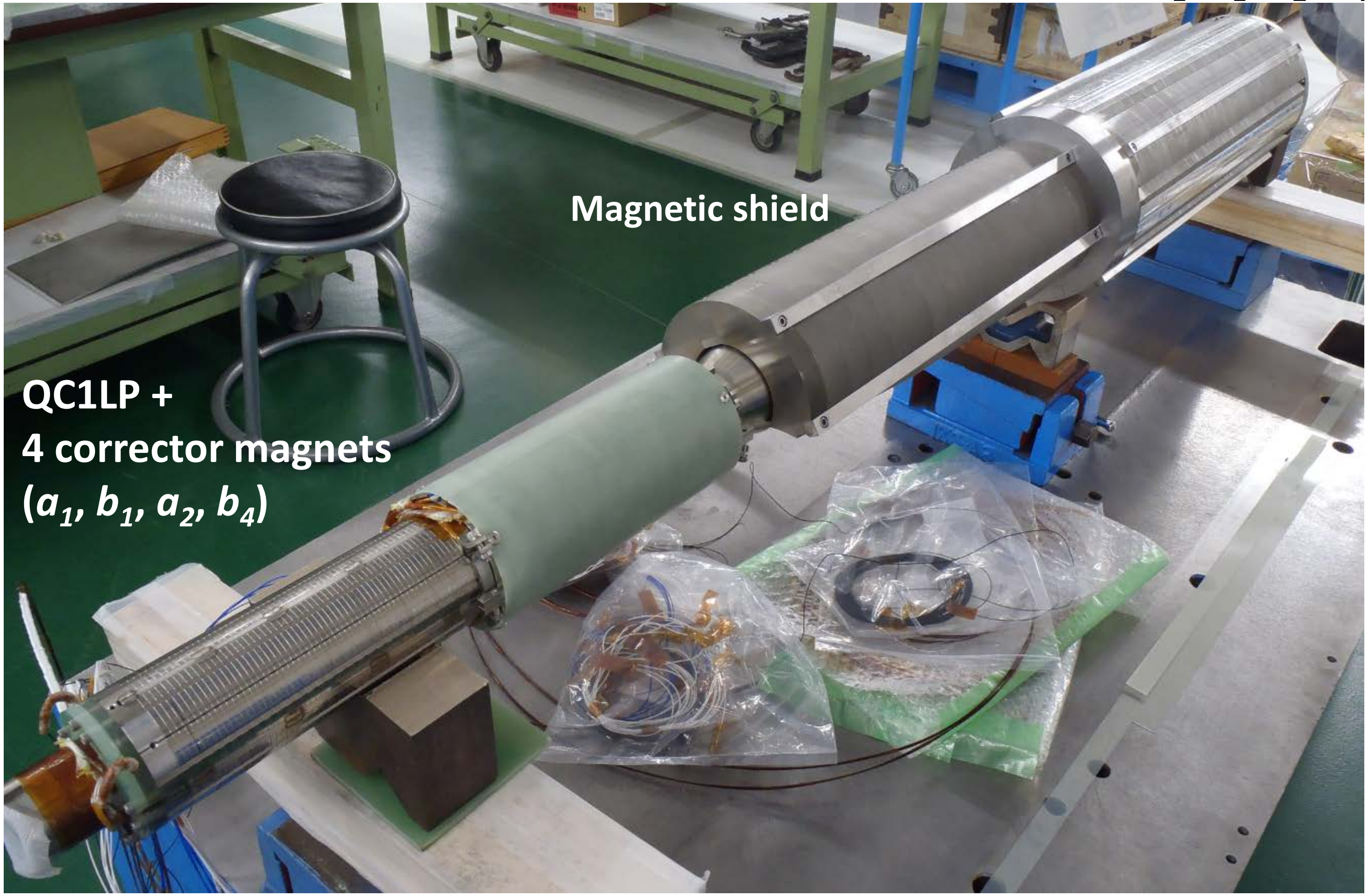
- Combined QC1LE, QC1LP leak field cancel magnets and magnetic shield



Assembly of quadrupoles

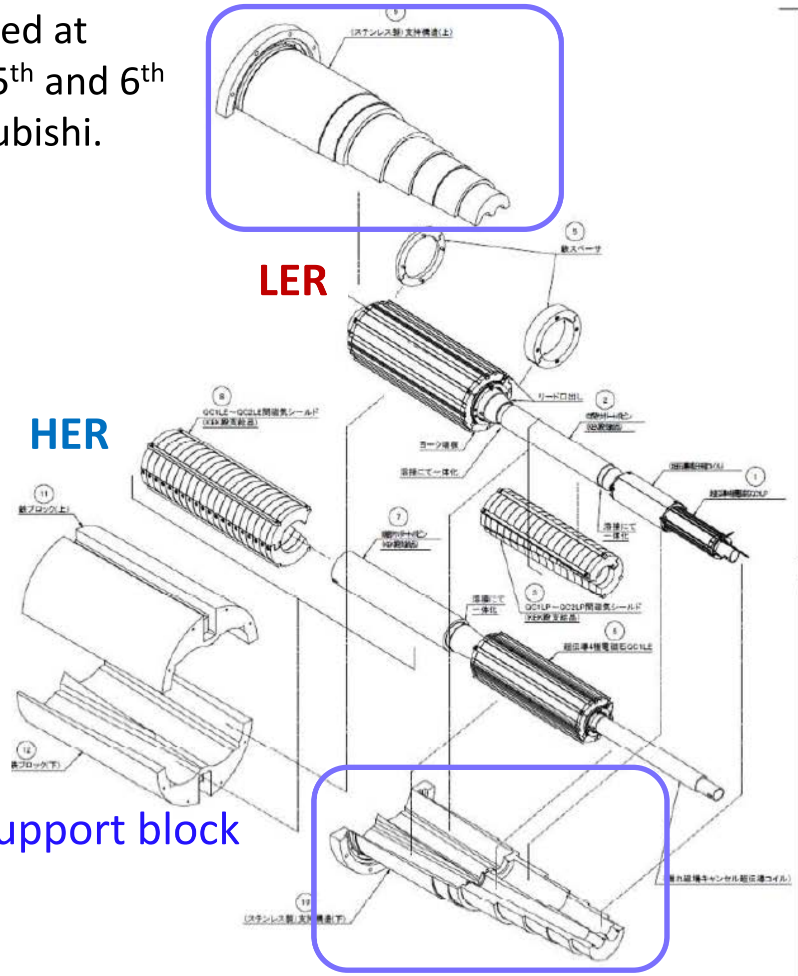
- Combined QC1LP, magnetic shield and QC2LP

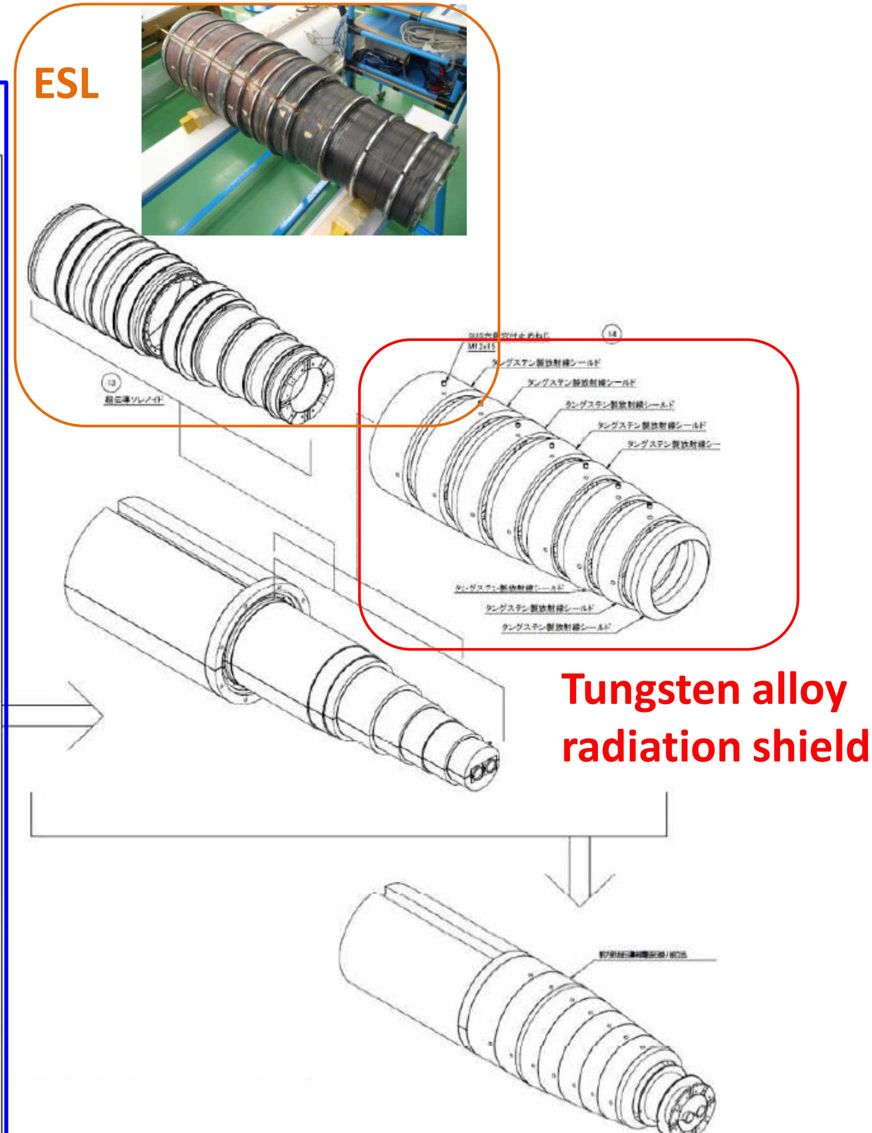
QC2LP +
4 corrector magnets
(a_1, b_1, a_2, b_4)



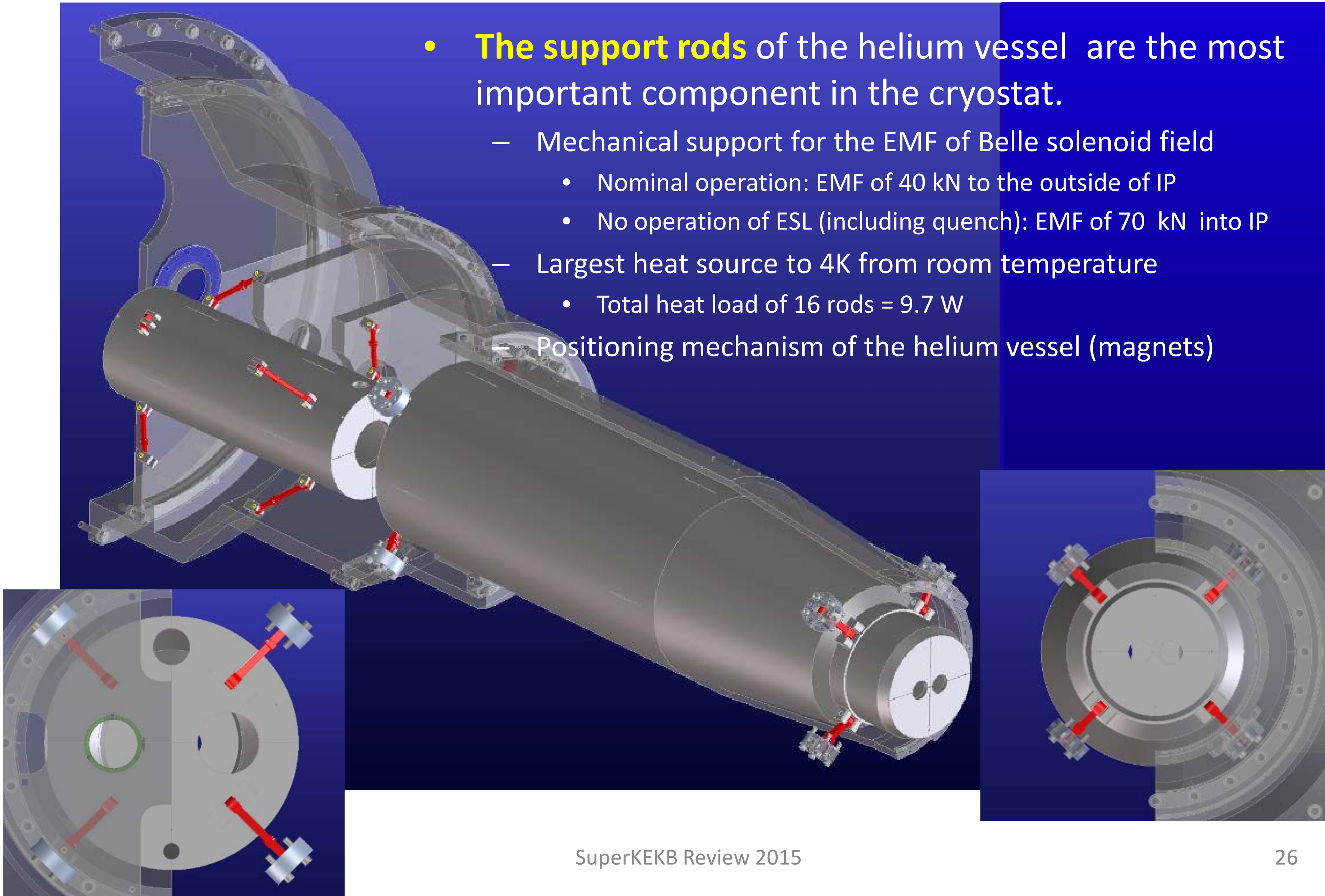
Assembly of quadrupoles

The assembly is scheduled at March 5th and 6th at Mitsubishi.





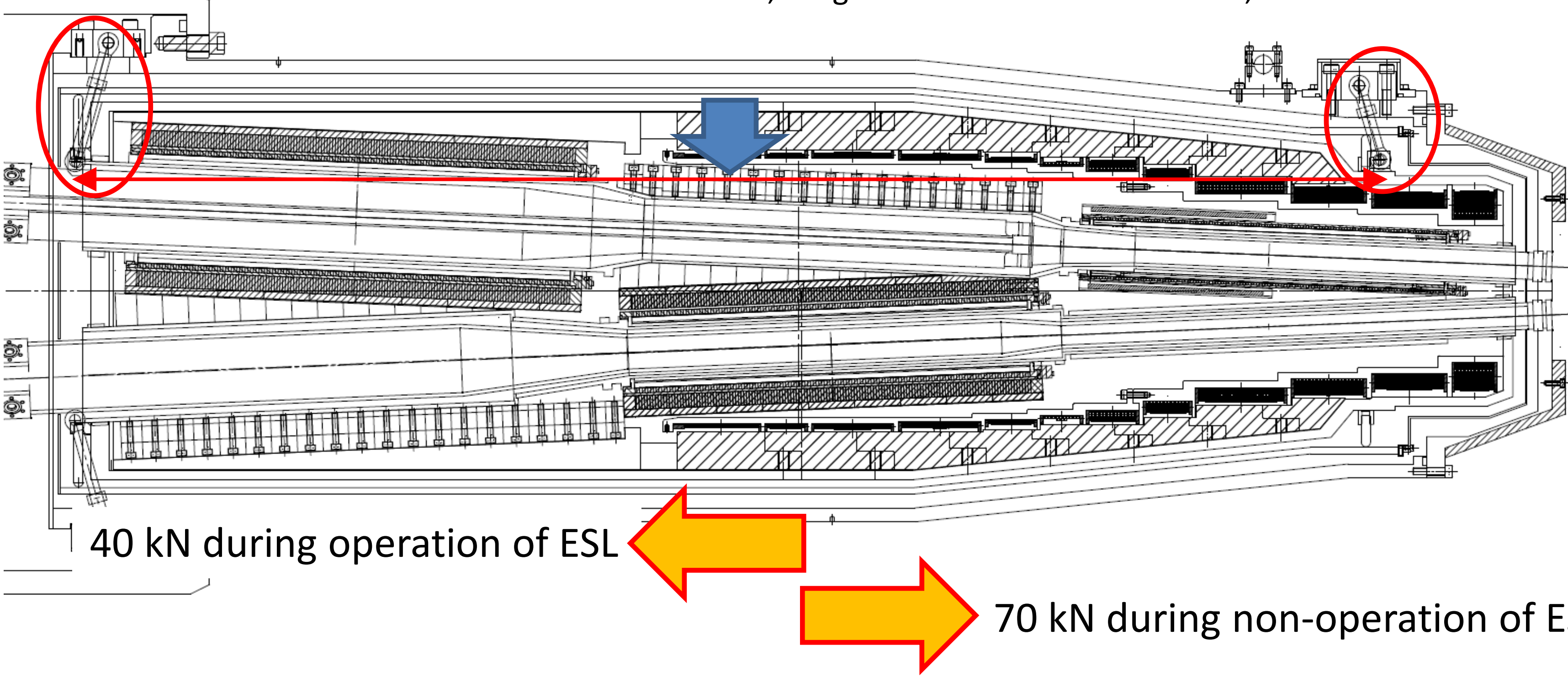
QCSL cryostat



- **The support rods** of the helium vessel are the most important component in the cryostat.
  - Mechanical support for the EMF of Belle solenoid field
    - Nominal operation: EMF of 40 kN to the outside of IP
    - No operation of ESL (including quench): EMF of 70 kN into IP
  - Largest heat source to 4K from room temperature
    - Total heat load of 16 rods = 9.7 W
  - Positioning mechanism of the helium vessel (magnets)

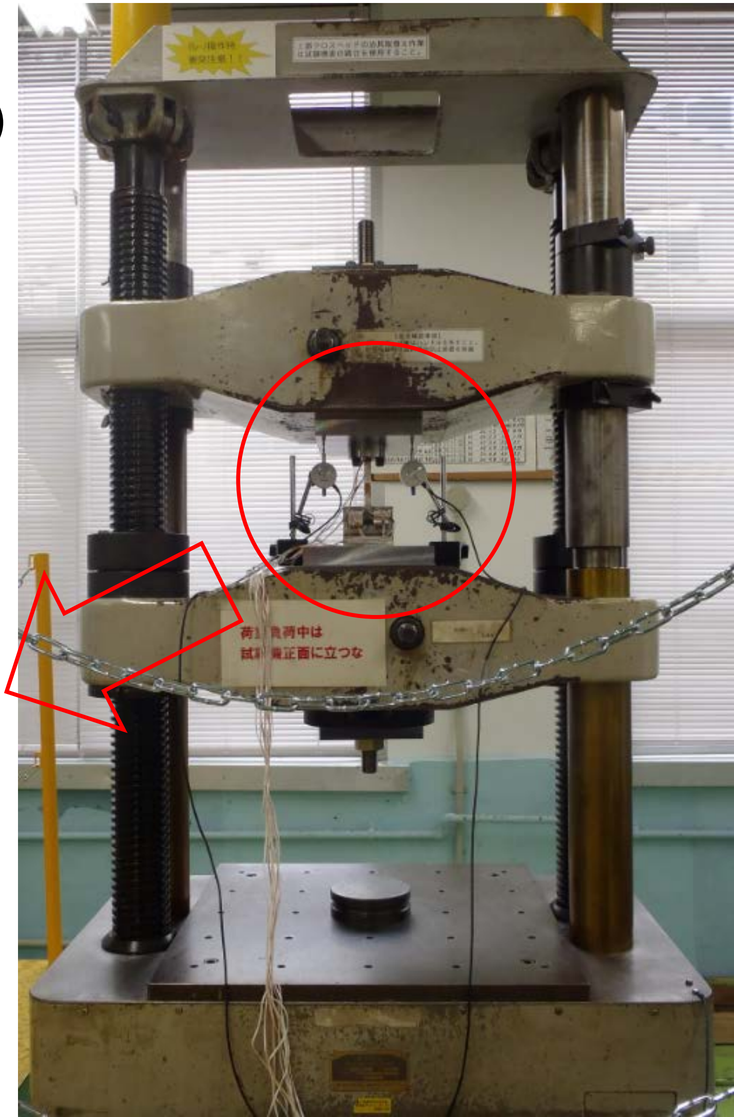
QCSL cryostat

- Design of the support QCSL rods
  - The liquid helium is supported with 8 rods.
  - The center position between the front and rear rods does not change by cool down from room temperature to 4K.
    - Angles of the front rod= 16.37 degree, the rear rod=15.70 degree
    - The magnet locations at 300K are designed to be at the specific positions by optics calculation at 4K.
  - The rod material: Ti-6Al-4V ELI
    - Rod cross section= □13.5mm ×13.5mm, Lengths of the front rod=83.5mm, the rear rod=33.5mm



QCSL cryostat

- The tensile and compression tests of the support rod were performed.
  - The applied forces to the sample:
    - Maximum force=64.4 kN (calculated max. load ×1.37)
    - 1.37: safety factor in Mitsubishi
  - 1st test
    - Materials of the test sample
      - Mount of the pin : Stainless steel (SUS304)
      - Pin: Ti alloy
      - Rod: Ti alloy
    - Permanent deformation at the hole for the pin in the mount
  - 2nd test
    - Improving materials
      - **Mount : Stainless steel (YUS170)**
      - Proof strength
        SUS304=170 MPa
        YUS170=460 MPa
    - No deformation in the system

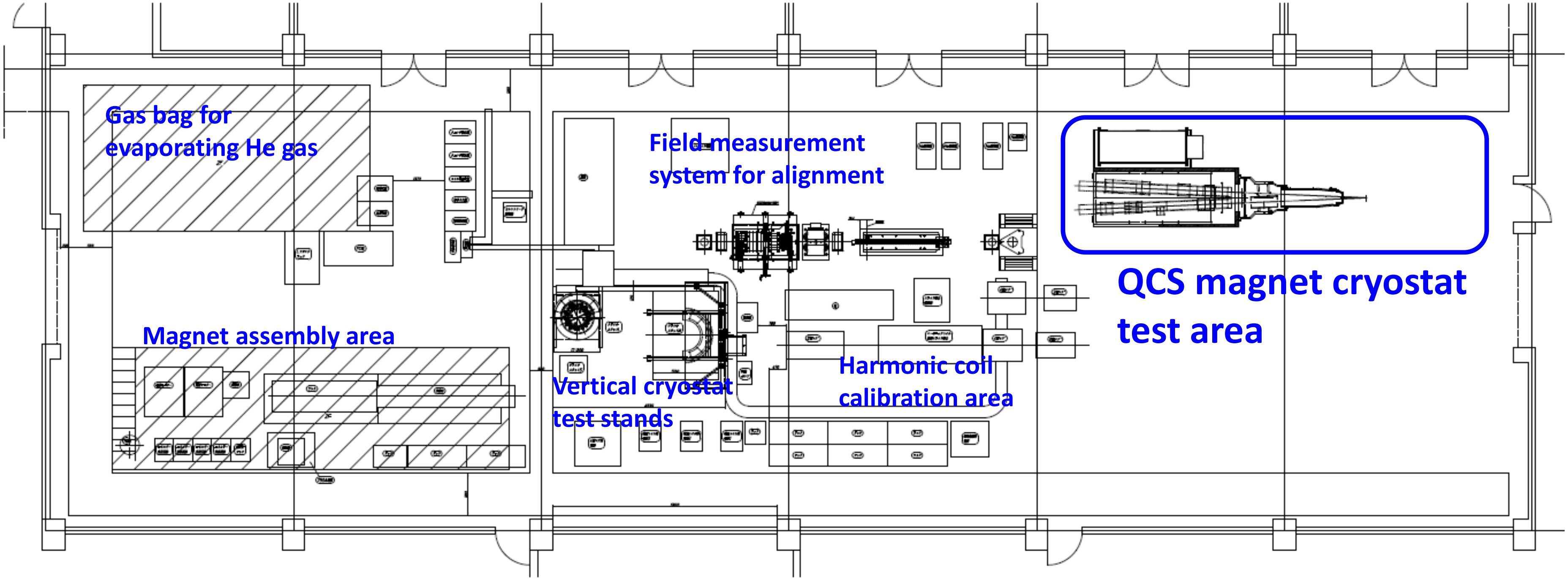


Cold tests of cryostats

- Cold tests of the magnet cryostats are scheduled in the experimental laboratory before installing them into the IR.
  - Tests and measurements in the experimental laboratory
    - Cooling the magnets down to 4K and exciting the magnets to the design currents
    - Field quality measurements of the magnets with the rotating harmonic coils
    - Field axes and angles of the quadrupoles with the single stretched wire (SSW) system
      - The **SSW** system is being developed with **FNAL** under the US-Japan research collaboration program.
    - Vibration measurements of quadrupole fields (in case that the vibration probe is ready)
      - The **pick-up coil type probe** is being developed with **BNL** under the US-Japan research collaboration program.
- Cold tests of the magnet cryostats in the IR
  - Tests and measurements in the IR
    - Cooling two cryogenic systems (QCSL and QCSR) down to 4K and exciting the magnets to the design currents under the Belle solenoid field
    - Measurement of the effect of the EMF by Belle solenoid field on the system
    - Field quality measurements of the magnets with the rotating harmonic coils
    - Field axes and angles of the quadrupoles with the single stretched wire (SSW) system
    - Vibration measurements of quadrupole fields (in case that the vibration probe is ready)

Cold tests of cryostats

- The QCSL cryostat will be completed in May 2015.
  - The cryostat is installed in the experimental laboratory.
  - The new cryogenic line for the liquid nitrogen was constructed in 2014.
  - The cool-down and excitation tests of the magnets are scheduled from July to August 2015.
  - The field measurements will start from September 2015.



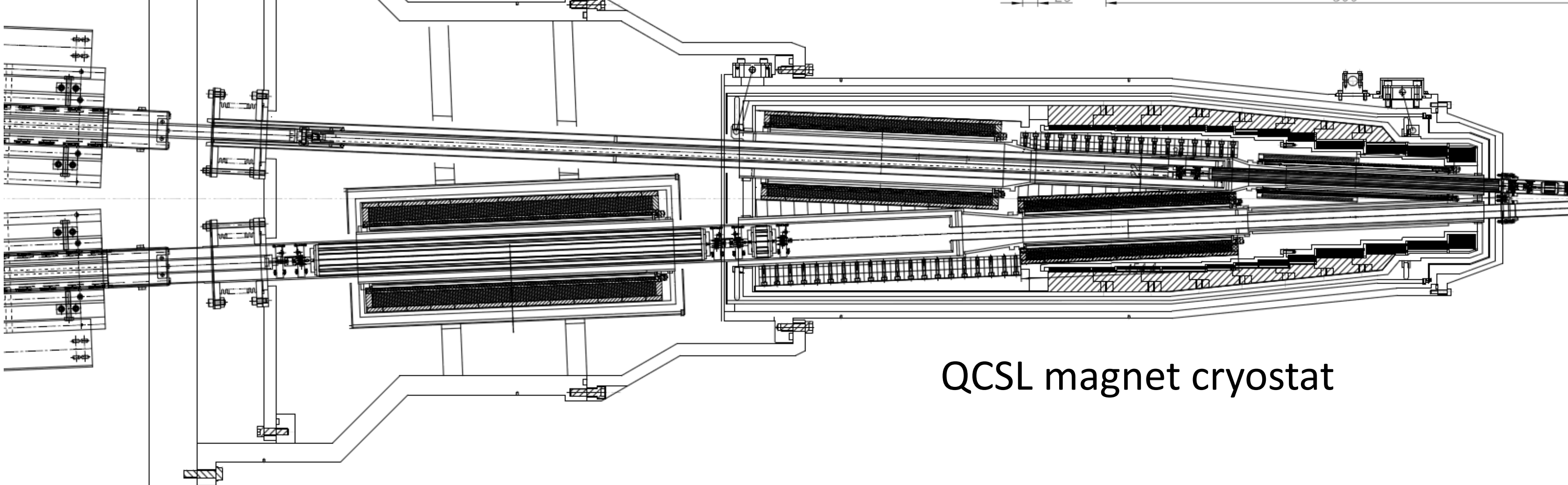
Cold tests of cryostats

- Three harmonic coils are being prepared for the measurements of the field qualities of the magnets.
  - Different reference radii of QC1 and QC2 magnets
    - QC1P=10 mm, QC1E=15 mm, QC2P=30 mm, QC2E=35 mm
    - The harmonic coil radius is properly designed for the individual magnet.

For QC1P and QC1E:
Coil radius=12.5 mm, Length=20mm, 600mm

For QC2P:
Coil radius=25 mm, Length=20mm, 700mm

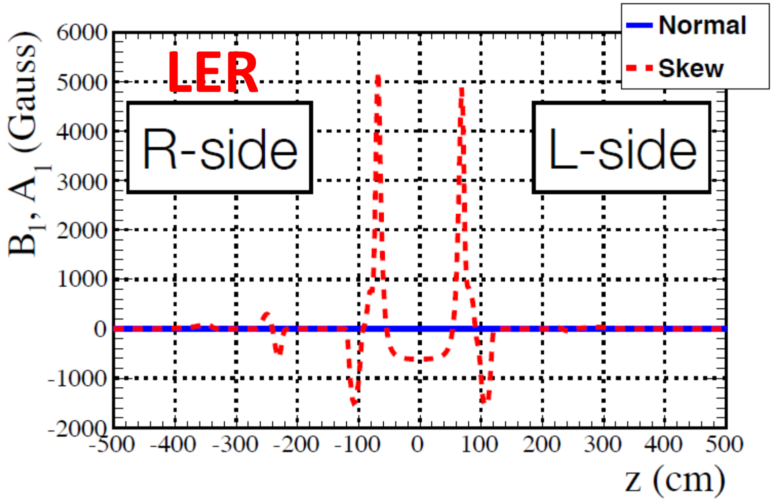
For QC2E:
Coil radius=33 mm, Length=20mm, 800mm

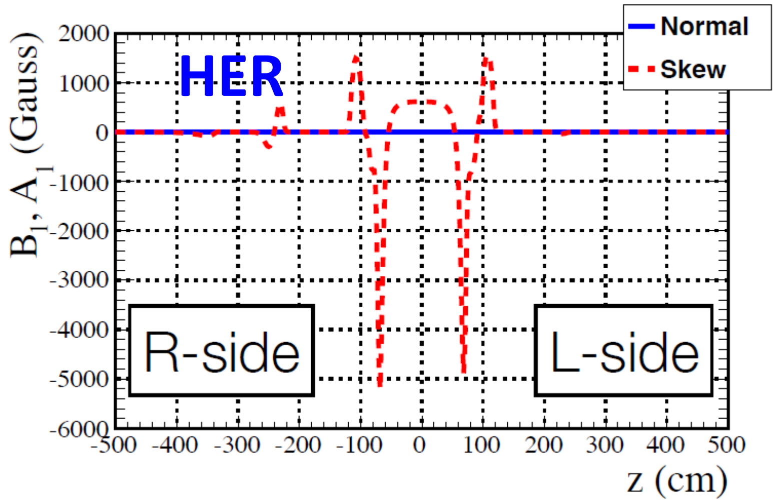


QCSL magnet cryostat

Cold tests of cryostats

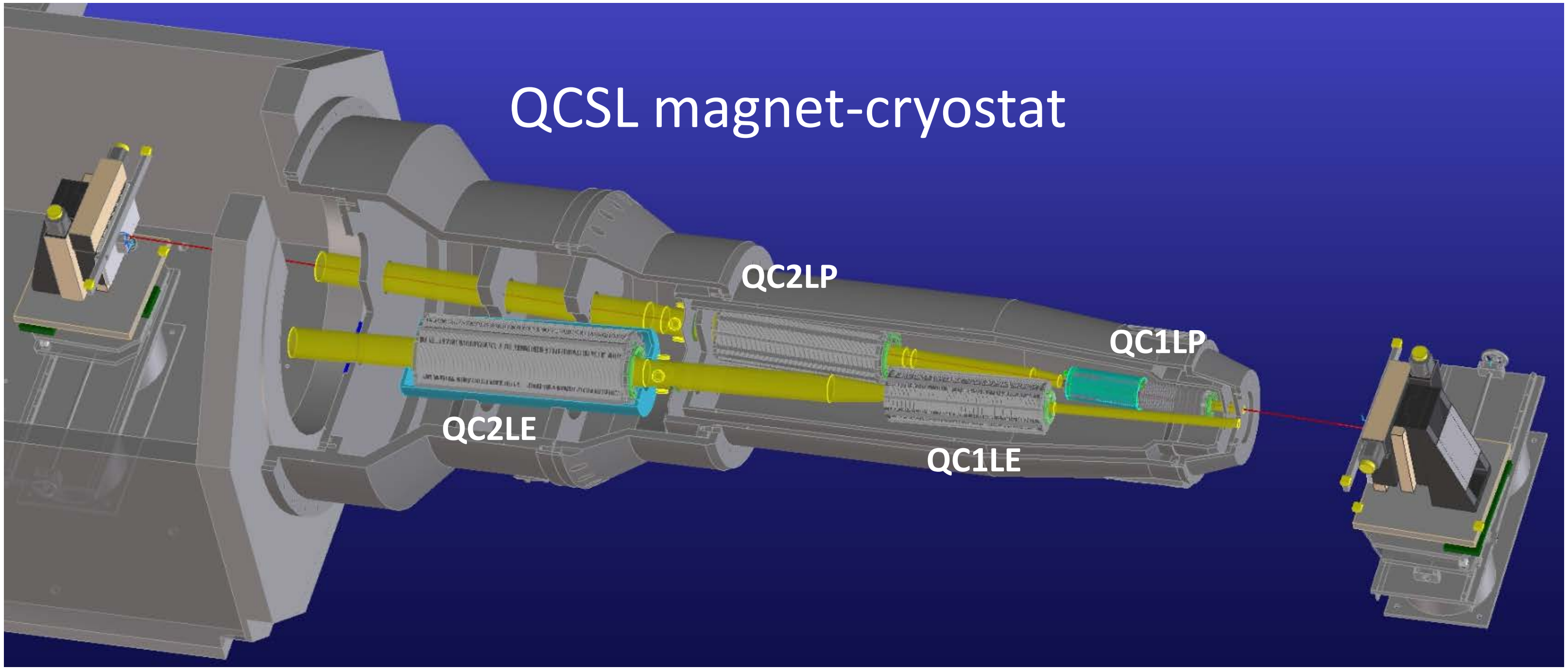
- Measurement of the quadrupole field axis and angle
  - Quadrupole axis measurement of KEKB QCS : rotating harmonic coil
    - Simple magnet configuration: one quadrupole magnet at each side
    - The design quadrupole axes were parallel to the solenoid field axis.
    - Decentering of the quadrupoles to the beam line was evaluated with the dipole field components of A_1 and B_1 to the quadrupole field of B_2.
  - Quadrupole axis measurement of SuperKEKB QCS : single stretched wire (SSW)
    - Complex magnet configuration: two quadrupole magnets in each side and each beam
    - The axes of the SuperKEKB quadrupole magnets have the angle of 41.5 mrad to the solenoid field axis.
      - In the QC1P area, the peak skew dipole field by the solenoid field is 0.5T, and it is 60 % of quadrupole field strength on the harmonic coil.





Cold tests of cryostats

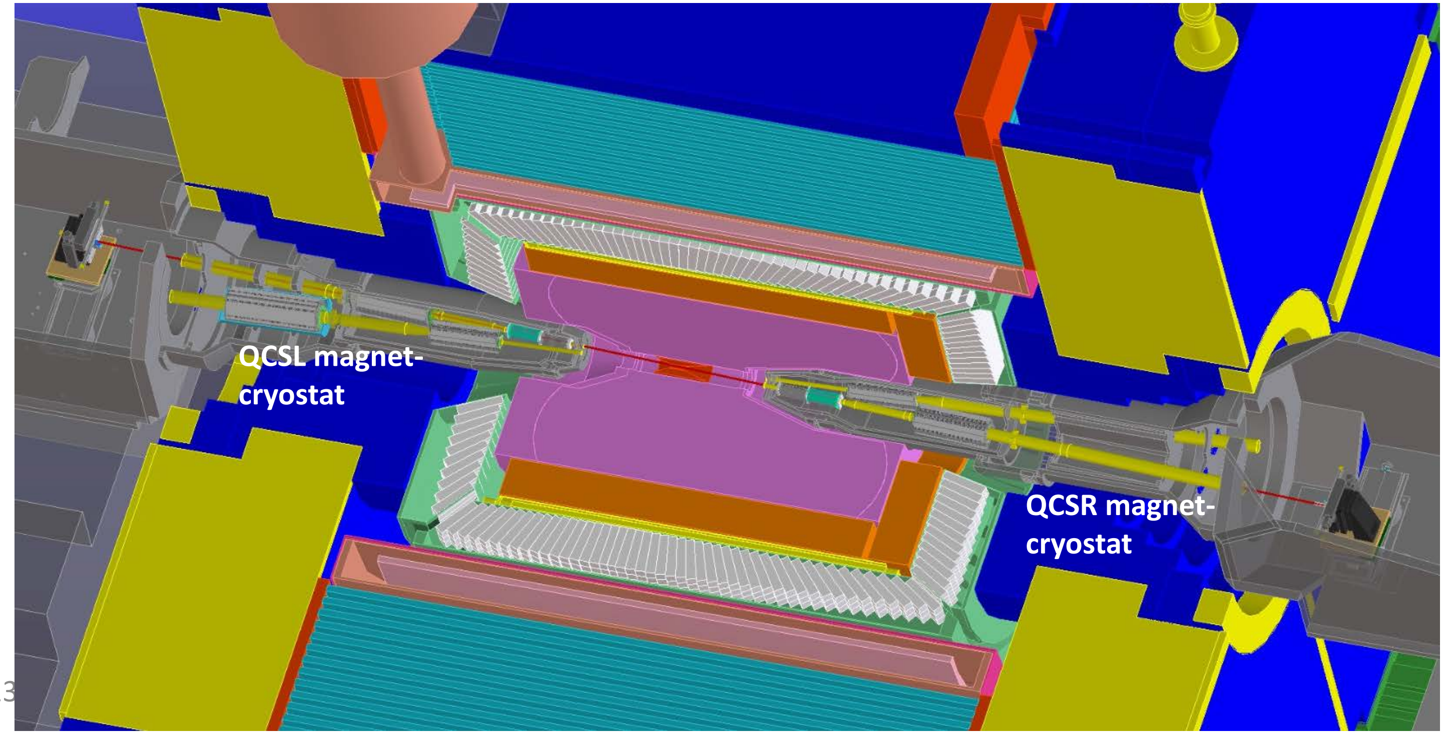
- SSW measurements of the magnet-cryostats in the experimental laboratory
  - The stretched wire is aligned with the alignment targets on the cryostat.
  - The quadruple magnet is excited individually, and the magnet axis and angle are measured to the wire.
  - The resolution of the measurement system is about 10 μm, and the precision of the measurement is about 50 μm.



Setup of the SSW system and the QCSL magnet-cryostat in the experimental laboratory

Cold tests of cryostats

- SSW measurements of the magnet-cryostats in the SuperKEKB IR
  - The stretched wire is aligned to the beam line.
  - Two magnet-cryostats of QCSL/R are aligned to the beam lines with the targets of the cryostats.
    - During the operation of the SC quadrupole magnets, the electro-magnetic force of 40 kN on two cryostats by the Belle II solenoid moves the quadrupole magnets.
  - The SSW system directly measures the field axes and the angles of the quadrupole magnets with respect to the beam lines with the precision of ± 0.1 mm.



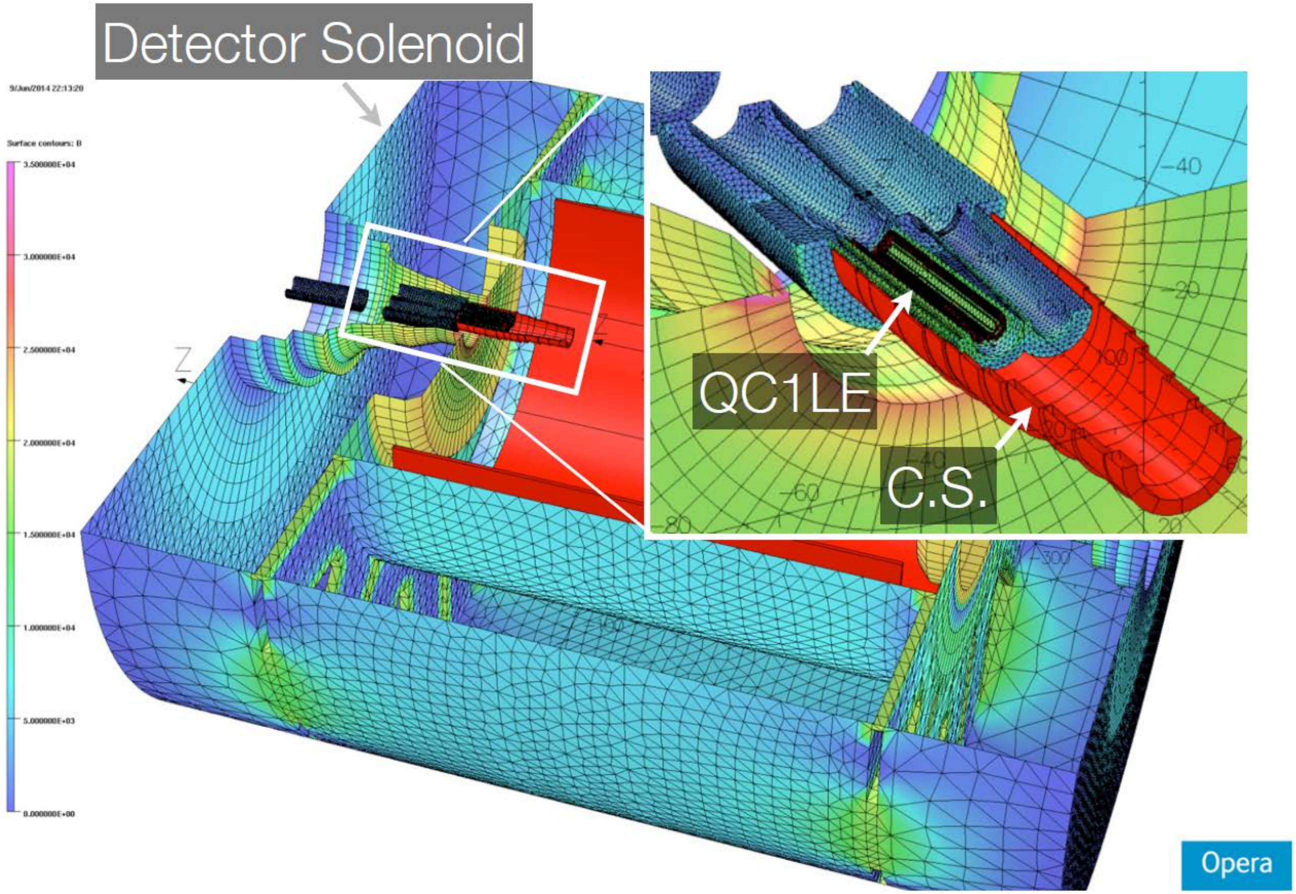
Cold tests of cryostats

- Scheduling of the field measurements in the experimental laboratory and on the beam lines
  - The measurement items are programed not to be overlapped in two sites.
    - The field measurements which correlate the measurements between two sites will be performed.
  - The 3D calculation results by OPERA will be used for reducing the total time of the field measurements.
    - The effect of the Belle end yoke on the magnetic fields of the corrector magnets are studied with the 3D calculation of OPERA.
    - The full set of the measurements of the corrector magnets in the IR are downsized.

Cold tests of cryostats

IR 3D model : all magnets with the corrector magnets are included.

- The calculation model is now being refined by Y. Arimoto.



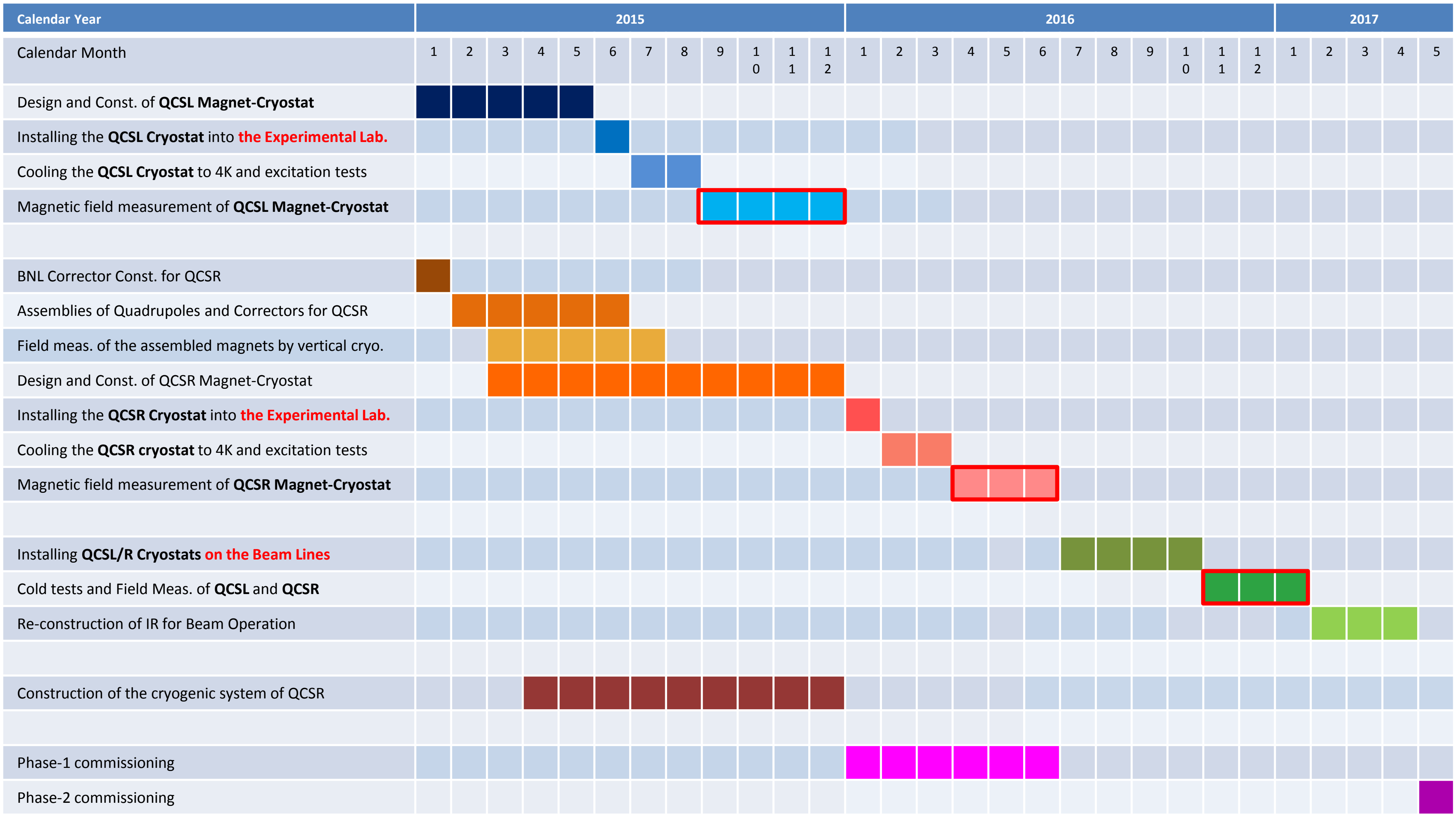
By Y. Arimoto

Cold tests of cryostats

	Experimental Laboratory	Beam Lines
Conditions	**Without Belle solenoid field** **One set of field measurement system** **Independent excitation of magnet**	**With Belle solenoid field** **Two set of field measurement system** **Combined excitations of magnets**
Integral field measure-ments by 600-800 mm long harmonic coils	QC1P, QC2P, QC1E, QC2E: 24 hours Corrector magnets of 4 QCs: 56 hours QC1P leak field cancel magnets: 24 hours Subtotal=104 hours	QC1P, QC2P, QC1E, QC2E: 12 hours Corrector magnets of 4 QCs: 8 hours QC1P leak field cancel magnets: 1 hours Subtotal=21 hours
Field mapping by 20 mm long harmonic coils	QC1P, QC2P, QC1E, QC2E: 108 hours (4s & 12 GeV) Corrector magnets of 4 QCs: 64 hours (± 60A) QC1P leak field cancel magnets: 64 hours (4s & 12 GeV) Subtotal=236 hours	QC1P, QC2P, QC1E, QC2E: 31 hours (4s & 12 GeV) Corrector magnets of 4 QCs: 32 hours (+ 60A) QC1P leak field cancel magnets: 16 hours (4s) Subtotal=79 hours
Solenoid field mapping by Hall probe	HER/LER beam lines: 12 hours	Belle field profile of HER/LER beam lines: 12 hours ES + Belle field profile of HER/LER beam lines: 12 hours
Field axis and angle measurement by FNAL SSW	With preparation of the measurement and set-up 40 hours (one week)	With preparation of the measurement and set-up 40 hours (one week)
Vibration measurement by BNL probe	With preparation of the measurement and set-up 40 hours (one week)	With preparation of the measurement and set-up 40 hours (one week)
Total hours	432 hours (8 hours × 54 days: ~11 weeks: ~3 months)	204 hours (8 hours × 25.5 days: ~6 weeks: ~1.5 month)

The measured time is for one magnet-cryostat.

Construction Schedule



Construction Schedule

Construction status of cryogenics

He refrigerator for QCSL

He refrigerator for QCSR

New He compressor building and He tanks for QCSR

He compressor for QCSR
Relocated from Oho exp. hall to the new comp. building in Tsukuba exp. hall.

Additional He gas tank for QCSL

These construction works were performed in collaboration with the Belle cryogenic group.

Summary

- Construction of SC magnets
  - The SC quadrupole magnets, corrector magnets and the compensation solenoid for QCSL showed the sufficient performances for the beam operation.
  - Assembly of the QC magnets and the correctors for QCSR started in February 2015. This is delay of 6 months in the original construction schedule.
- Magnet-cryostat
  - The design and tests of the support rods were completed. The degree of completion of the QCSL cryostat design is 80 %. The service cryostat design is not completed.
- Cold tests of magnet-cryostats
  - The magnet-cryostats are tested in the experimental laboratory and in the IR.
  - Tests
    - Cool-down and excitation tests, heat load measurements
    - Field measurements (harmonic coils, Hall probe, FNAL-SSW, BNL-probe)
- Schedule
  - The QCSL magnet-cryostat will be completed in May 2015.
  - The QCSR magnet-cryostat is scheduled to be completed in December 2015.

Back-up

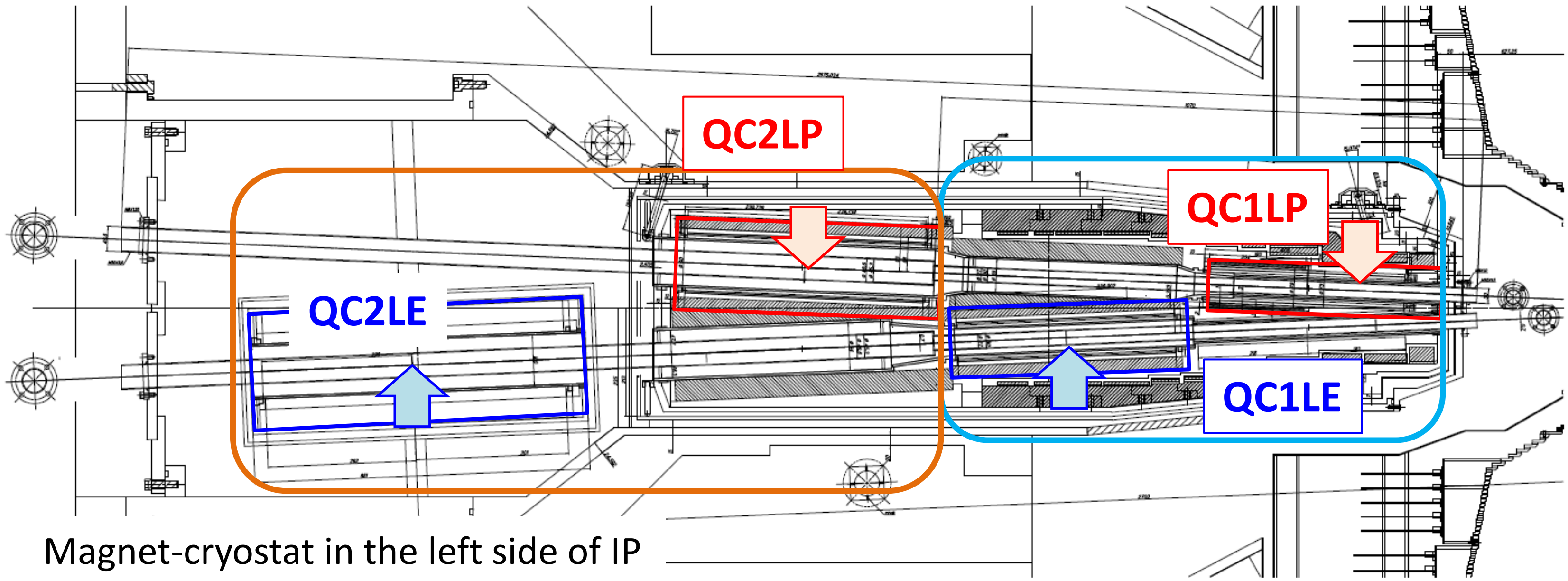
Vibration measurement

- The measurement system was being developed for ILC IR magnets. The system consists of a pick-up coil, the support and the vibration isolation table.
- **Resolution of a few nm** at frequency above a few Hz is achievable.
- The sensor can be inserted at the location of each magnet. The vibration of the magnet is measured, independently.

2500-turn coil

Vibration measurement

- From the beam study, two quadrupole magnets in HER and LER beam lines need to be measured at the same instant.



Magnet-cryostat in the left side of IP

– Measuring the correlation of vibrations in the two quads to ~ 5nm for f > 5Hz
(Vibration resonance of SuperKEKB cryostat = ~ 30 Hz)
– Two probes need to be installed simultaneously.

QCSL cryostat