Superconducting Magnets for SuperKEKB Interaction Region

Norihito Ohuchi
1. SC magnet system of the SuperKEKB IR
2. Main quadrupole magnets
3. Correctors and leak field cancel coils
4. Compensation solenoids
5. Assembly of magnet-cryostat
6. Summary
IR Magnets Overview

Belle-II particle detector
S.C. Magnet System

**QCS-L Cryostat**

- **Helium Vessel**
  - QC2LP: 4 correctors ($a_{1}, b_{1}, a_{2}, b_{4}$)
  - QC1LP: 4 correctors ($a_{1}, b_{1}, a_{2}, b_{2}$: inner bore, $b_{2}$: magnet periphery)
  - QC1LE: 4 correctors ($a_{1}, b_{1}, a_{2}, b_{1}$)
  - QC2LE: 4 correctors ($a_{1}, b_{1}, a_{2}, b_{1}$)
  - Leak field cancel coils ($b_{3}, b_{4}, b_{5}, b_{6}$)

**QCS-R Cryostat**

- **Helium Vessel**
  - QC1RE: 4 correctors ($a_{1}, b_{1}, a_{2}, a_{2}$)
  - QC1RP: 5 correctors ($a_{1}, b_{1}, a_{2}$: inner bore, $b_{4}, a_{2}$: magnet periphery)
  - QC2RE: 4 correctors ($a_{1}, b_{1}, a_{2}, a_{2}$)
  - QC2RP: 4 correctors ($a_{1}, b_{1}, a_{2}, a_{2}$)

- **IP**
  - 83 mrad

**Target luminosity** = $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$

**Beam size at IP**: $e^{-}$ = 62 nm, $e^{+}$ = 46 nm

S.C. quadrupole: 8
S.C. solenoid: 4
S.C. corrector: 43
S.C. Magnets

- **Main quadrupoles [QC1, QC2]**
  - Consisting final beam focusing system with quadrupole doublets.

- **Correctors \([a_1, b_1, a_2, a_3, b_3, b_4]\)**
  - \(a_1, b_1, a_2\): magnetic alignment of magnetic center and mid-plane of main quadruple.
  - \(a_3, b_3\): correction of sextupoles induced by magnet construction errors.
  - \(b_4\): increasing the dynamic transverse aperture (increasing the Touschek life time).

- **Compensation solenoid [ESR, ESL]**
  - Canceling the integral solenoid field by the particle detector (Belle II).
  - By tuning the \(B_z'\) profile, the beam vertical emittance can be minimized.
  - The compensation solenoids are designed to be overlaid on the quadrupoles and correctors.

- **Leak field cancel coils \([b_3, b_4, b_5, b_6]\)**
  - Canceling the leak field on the electron beam line from QC1P (collared magnet).
### S.C. magnets in SuperKEKB IR

<table>
<thead>
<tr>
<th>QC2RE</th>
<th>13.58 [32.41 T/m × 0.419m]</th>
<th>Iron Yoke</th>
<th>2925</th>
<th>0</th>
<th>-0.7</th>
<th>0</th>
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<tbody>
<tr>
<td>QC2RP</td>
<td>11.56 [26.28 × 0.410]</td>
<td>Permendur Yoke</td>
<td>1925</td>
<td>-2.114</td>
<td>0</td>
<td>-1.0</td>
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<tr>
<td>QC1RE</td>
<td>26.45 [70.89×0.373]</td>
<td>Permendur Yoke</td>
<td>1410</td>
<td>0</td>
<td>-0.7</td>
<td>0</td>
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<tr>
<td>QC1RP</td>
<td>22.98 [68.89×0.334]</td>
<td>No Yoke</td>
<td>935</td>
<td>7.204</td>
<td>0</td>
<td>-1.0</td>
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<tr>
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<td>22.97 [68.94×0.334]</td>
<td>No Yoke</td>
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<td>-13.65</td>
<td>0</td>
<td>-1.5</td>
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<tr>
<td>QC1LE</td>
<td>26.94 [72.21×0.373]</td>
<td>Permendur Yoke</td>
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<td>+0.7</td>
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<tr>
<td>QC2LP</td>
<td>11.50 [28.05 × 0.410]</td>
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<td>-3.725</td>
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<tr>
<td>QC2LE</td>
<td>15.27 [28.44×0.537]</td>
<td>Iron Yoke</td>
<td>-2700</td>
<td>0</td>
<td>+0.7</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Integral field gradient, (T/m) • m**
- **Solenoid field, T**
- **Magnet type**
- **Z pos. from IP, mm**
- **θ, mrad**
- **ΔX, mm**
- **ΔY, mm**
Cross section of four quadrupoles
QC1P (No iron yoke)

QC1P magnet design (QC1RP, QC1LP)
- Same design for QC1RP and QC1LP
- 2 layer coils [double pancake]
- **SC correctors [designed by BNL]**
  - $a_2, b_1$ and $a_1$ inside of the magnet bore
  - $b_4, a_3$ outside of the magnet collar
- Cryostat inner bore radius=18.0 mm
- Beam pipe (warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

Superconducting cable (NbTi)
- Cable size : 2.5 mm × 0.93 mm
- **Keystone angle = 2.09 degree**
  - Each magnet has the optimized angle.
- Number of strands = 10
- Strand diameter = 0.5 mm
- Cu/SC ratio = 1.0
- Critical current (measured) = 3160 A @5 T & 4.2 K
Mirror symmetry for reducing the skew quadrupole field in the lead end.
Field profile of QC1R/LP

Lead end locates at IP side in the cryostat.

Multipole field at R=10 mm
Integral $b_4 = 2.38 \times 10^{-5}$
Int. $b_6 = 5.42 \times 10^{-5}$
Int. $b_8 = 1.10 \times 10^{-6}$

Peaks of $B_4 = \pm 18$ Gauss at 1625 A
Peaks of $B_6 = +4.4/-3.3$ Gauss at 1625 A
QC1E magnet design: Permendur yoke

QC1E magnet design (QC1RE, QC1LE)
- Yoked magnet: Permendur yoke
- 2 layer coils [double pancake]
- $I_{op@4K} = 1577$ A for QC1LE
  - $G = 72.2$ T/m, $L_{eff} = 0.373$ m
- **SC correctors**
  - $a_2$, $b_1$, $a_1$ inside of the magnet bore
  - $b_4$ [QC1LE], $a_3$ [QC1RE] inside of the magnet bore
- Cryostat inner bore radius=25.0 mm
- Beam pipe (warm tube)
Proto-types of QC1 magnets

• QC1P and 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.

QC1P Proto-type Magnet
Measured $G = 68.38$ T/m at $I = 1626$A
Design $G = 68.84$ T/m

<table>
<thead>
<tr>
<th>$n$</th>
<th>$a_n$</th>
<th>$b_n$</th>
</tr>
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<tbody>
<tr>
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<td>0.35</td>
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<td>6</td>
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<td>7</td>
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<td>8</td>
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<td>0.01</td>
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<tr>
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<td>0.05</td>
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<tr>
<td>10</td>
<td>0.02</td>
<td>0.01</td>
</tr>
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</table>

Integral field components at R=9.54 mm

QC1E Proto-type Magnet
Measured $G = 70.07$ T/m at $I = 1560.6$A
Design $G = 70.63$ T/m

<table>
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<th>$a_n$</th>
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<tbody>
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<td>10000</td>
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<tr>
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<td>1.78</td>
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<td>10</td>
<td>-0.10</td>
<td>-0.62</td>
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</table>

Integral field components at R=15 mm
$a_3$ and $b_3$ error field

- Sextupoles are produced by the dipole deformation of four coils

\[ \Delta r = \text{coil displacement in radial direction} \]

\[ \Delta r = 50 \, \mu\text{m} \]

\[
\begin{align*}
b_3 & = 13.62 \times 10^{-4} \\
a_3 & = 0 \\
b_4 & = 0 \\
a_4 & = 0 \\
b_5 & = -1.63 \times 10^{-4} \\
a_5 & = 0
\end{align*}
\]

\[ \Delta r = 20 \, \mu\text{m} \]

- $b_3 = 5.45 \times 10^{-4}$
- $a_3 = 0$
- $b_4 = 0$
- $a_4 = 0$
- $b_5 = -0.65 \times 10^{-4}$
- $a_5 = 0$

\[ b_3 = 8.6 \times 10^{-4} \text{ corresponds to } \Delta r = 32 \, \mu\text{m}. \]

The geometry error of 32 \, \mu\text{m} is comparable to the machining accuracy of the magnet components. The $a_3$ and $b_3$ correctors are designed to be 0.1 \% of the $b_2$ field.
Effect of $a_3$ on beam life time

Skew Sextupole Error Field

- Analogous calculation for skew sextupole error field.
- Different feature compared to the normal sextupole case.
- DA Improvement is not enough level.
### Integral field quality of the real magnets
(measured under solenoid fields)

<table>
<thead>
<tr>
<th></th>
<th>QC1LP at R=10mm, I=1.71kA</th>
<th>QC1RP at R=10mm, I=1.71kA</th>
<th>QC2LP at R=30mm, I=0.91kA</th>
<th>QC2RP at R=30mm, I=0.91kA</th>
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<tbody>
<tr>
<td>n</td>
<td>$a_n$</td>
<td>$b_n$</td>
<td>$a_n$</td>
<td>$b_n$</td>
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<td>790.2</td>
<td>232.9</td>
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<td>-0.10</td>
<td>0.37</td>
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<tr>
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<td>0.04</td>
<td>0.05</td>
<td>0.01</td>
<td>-0.06</td>
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<tr>
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<td>0.07</td>
<td>-0.03</td>
<td>-0.04</td>
<td>-0.04</td>
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<td>-0.06</td>
<td>-0.01</td>
<td>0.05</td>
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<td>-0.18</td>
<td>0.04</td>
<td>-0.18</td>
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Integral field quality of the real magnets
(measured under solenoid fields)

<table>
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<tr>
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<th>QC1LE at R=15mm, I=1.71kA</th>
<th>QC1RE at R=15mm, I=1.71kA</th>
<th>QC2LE at R=35mm, I=1.11kA</th>
<th>QC2RE at R=35mm, I=1.11kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>$a_n$</td>
<td>$b_n$</td>
<td>$a_n$</td>
<td>$b_n$</td>
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<td>0.03</td>
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<td>-0.08</td>
<td>-0.02</td>
<td>-0.60</td>
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</tbody>
</table>

Without excitation of solenoids
QC2RE field profile along the beam line
(measured under solenoid fields)

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
QC1LP field profile along the beam line
(measured under solenoid fields)

- Field profile of QC1LP along the beam line

![Graphs of field profiles](image)

With the field profiles, the distances of the main quadrupole magnet centers from IP are calculated. The field profiles will be built in the optics calculation model, and the influence on the beam operation will be studied.
Magnet design: Permendur yoke

- The final focus system is designed to be operated under the Belle II solenoid field at 1.5 T.
- This field is cancelled with the accelerator compensation solenoids along the beam line. This cancellation is not perfect.

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)

At the good cancelling condition, the insides of iron components have magnetic field at 0.5T.
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.
Magnet design: Permendur yoke

Comparison between Iron and Permendur

With 0.5 T field in the Yoke (4s)

Iron

Permendur

Leak field at e+ center = 6 Gauss

Leak field at e+ center <1 Gauss

Iron

Permendur

0 Gauss

20 Gauss

0 Gauss

5 Gauss

0 Gauss

400 Gauss

0 Gauss

10 Gauss

Leak field at the e+ center = 100 Gauss

Leak field at e+ center = 6 Gauss
## SC correctors

<table>
<thead>
<tr>
<th>Magnet</th>
<th>( R_0 ) mm</th>
<th>( I_{\text{max}} ) A</th>
<th>( A_1 ) T·m</th>
<th>( B_1 ) T·m</th>
<th>( A_2 ) T</th>
<th>( A_3 ) T/m</th>
<th>( B_3 ) T/m</th>
<th>( B_4 ) T/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC1LP</td>
<td>10</td>
<td>70</td>
<td>0.016 (0.69 mm)</td>
<td>0.016 (0.66 mm)</td>
<td>0.64 (13.9 mrad)</td>
<td>60</td>
<td>60</td>
<td></td>
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<tr>
<td>QC2LP</td>
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<td>70</td>
<td>0.03 (2.61 mm)</td>
<td>0.03 (2.61 mm)</td>
<td>0.31 (13.5 mrad)</td>
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<tr>
<td>QC1LE</td>
<td>15</td>
<td>70</td>
<td>0.027 (1.43 mm)</td>
<td>0.046 (2.42 mm)</td>
<td>0.75 (15.9 mrad)</td>
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<tr>
<td>QC2LE</td>
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<td>70</td>
<td>0.015 (1.6 mm)</td>
<td>0.015 (1.6 mm)</td>
<td>0.37 (16.7 mrad)</td>
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<td>QC1RP</td>
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<td>0.64 (13.9 mrad)</td>
<td>16</td>
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<td>0.31 (13.5 mrad)</td>
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<td>0.75 (15.9 mrad)</td>
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<td>0.015 (1.6 mm)</td>
<td>0.37 (16.7 mrad)</td>
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<td>4.8</td>
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</table>

The number of correctors is 35, and they are wound in multi-layer for each main quadrupole. The correctors are operated under the bias fields of solenoids and the quadrupole magnets.

- The figures in parentheses are the correctable errors of magnetic axes and quadrupole angles, and parts of these fields are used in the optics design.
SC correctors

- SC correctors were constructed by BNL under the US-Japan research collaboration program.
- The spaces for the correctors were very tight, and then the coils were wound by the direct winding method.
  - Diameter of the S.C. conductor = $\phi$ 0.35 mm, Critical current = 154 A at 4 T and 4.2 K
  - Multi-layered coils: Maximum layer number = 4 (from the space constraint between the bore of the main quadrupole magnet and the inner helium pipe.)

BNL direct winding machine

Dipole corrector magnet for QC1LE

Sextupole QC1P leak field cancel magnet

S.C. coil for QC1E magnet
SC leak field cancel coils

- QC1P for the e+ beam line is non-iron magnet and the e- beam line is very close to QC1P. The leak fields along the e- beam line by QC1P are calculated.
- \( B_3, B_4, B_5 \) and \( B_6 \) components of the leak fields are designed to be canceled with the SC cancel coils.
- \( B_1 \) and \( B_2 \) components are not canceled, and they are included in the optics calculation.
  - \( B_2 \) component is used for focusing and defocusing the e- beam.

QC1RP leak field profile along the e- beam line
SC leak field cancel coils

- The leak field cancel coils were designed and constructed by BNL under the US-Japan research collaboration program.
- The field models were constructed with the collaboration between BNL and KEK.

Cancel coil designed by B. Parker [BNL]
Sextupole cancel coil : 2 layer serpentine coils
Quadrupole magnets assembly

QC1LP & $a_1, b_1, a_2, b_4$
corrector magnets

QC1LP leak field cancel
$b_3, b_4, b_5, b_6$ magnets

Magnetic shield yokes

QC1LE & $a_1, b_1, a_2, b_4$
corrector magnets

QC2LP & $a_1, b_1, a_2, b_4$
corrector magnets
- In the left cryostat, one solenoid (12 small solenoids) is overlaid on QC1LP and QC1LE.
- In the right cryostat, the 1st solenoid (15 small solenoids) is overlaid on QC1RP, QC1RE and QC2RP.
  - The 2nd and 3rd solenoids on each beam line in the QC2RE vessel.

**Length of solenoid = 0.7 m**
Compensation Solenoids

**ESL:**
- Magnet length = 914 mm
- Maximum field at 403 A = 3.53 T
- Stored Energy = 118 kJ

**ESR1:**
- Magnet length = 1575 mm
- Maximum field at 450 A = 3.19 T
- Stored Energy = 244 kJ
- Cold diode quench protection system
Assembly of magnet-cryostats
Magnet-cryostats in SuperKEKB-IR
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Summary

• KEK has constructed the SuperKEKB accelerator with IR magnets.
  – The target luminosity = $8 \times 10^{35}$ cm$^{-2}$ s$^{-1}$

• IR SC magnet system is the most important and complicate hardware in SuperKEKB.
  – The construction of the final focusing system with 8 quadrupoles, 4 compensation solenoids and 43 corrector coils was completed.
  – Commissioning the system and the field measurements were performed from May to August, 2017.
  – From the field measurement results:
    • Some problems were confirmed.
      1. The outer correctors of the QC1RP were assembled with 90 degree rotation to the design.
         » $A_3$ corrector -> $B_3$ corrector
         » QC1LP and QC1RP have pretty small $A_3$ components, and then the effects of the function loss is not considered to be crucial.
      2. The iron block for the QC2RE has the multipole fields at the level of 0.2 % of the QC2RE quadrupole field at the surface of this component.
         » The $A_3$ field components induced by the iron block for both beams can be handled with the $A_3$ correctors in the QC2RE and QC2RP quadrupole magnets.