The superconducting magnets of SuperKEKB

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https://indico.pnp.ustc.edu.cn/event/1948/

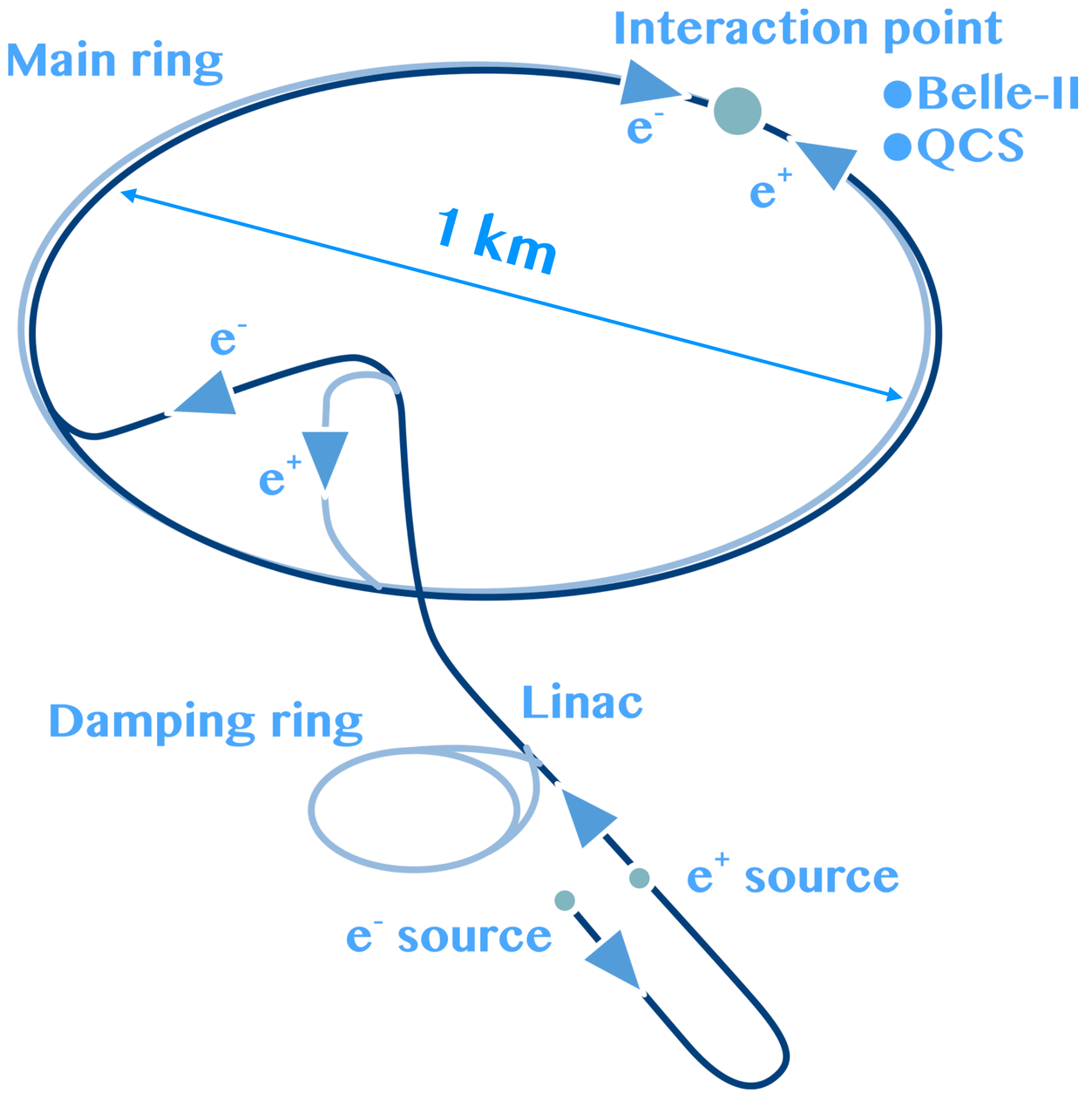
Contents

SuperKEKB accelerator

- Linac
  - Electron and positron beams are accelerated to 7 GeV and 4 GeV, respectively.
- Damping ring
  - Lower emittance for positron of 1.1 GeV.
- Main ring

	e-	e+
Beam energy	7 GeV	4 GeV
Stored energy	2.6 A	3.6 A
Vertical beam size at IP	62 nm	48 nm

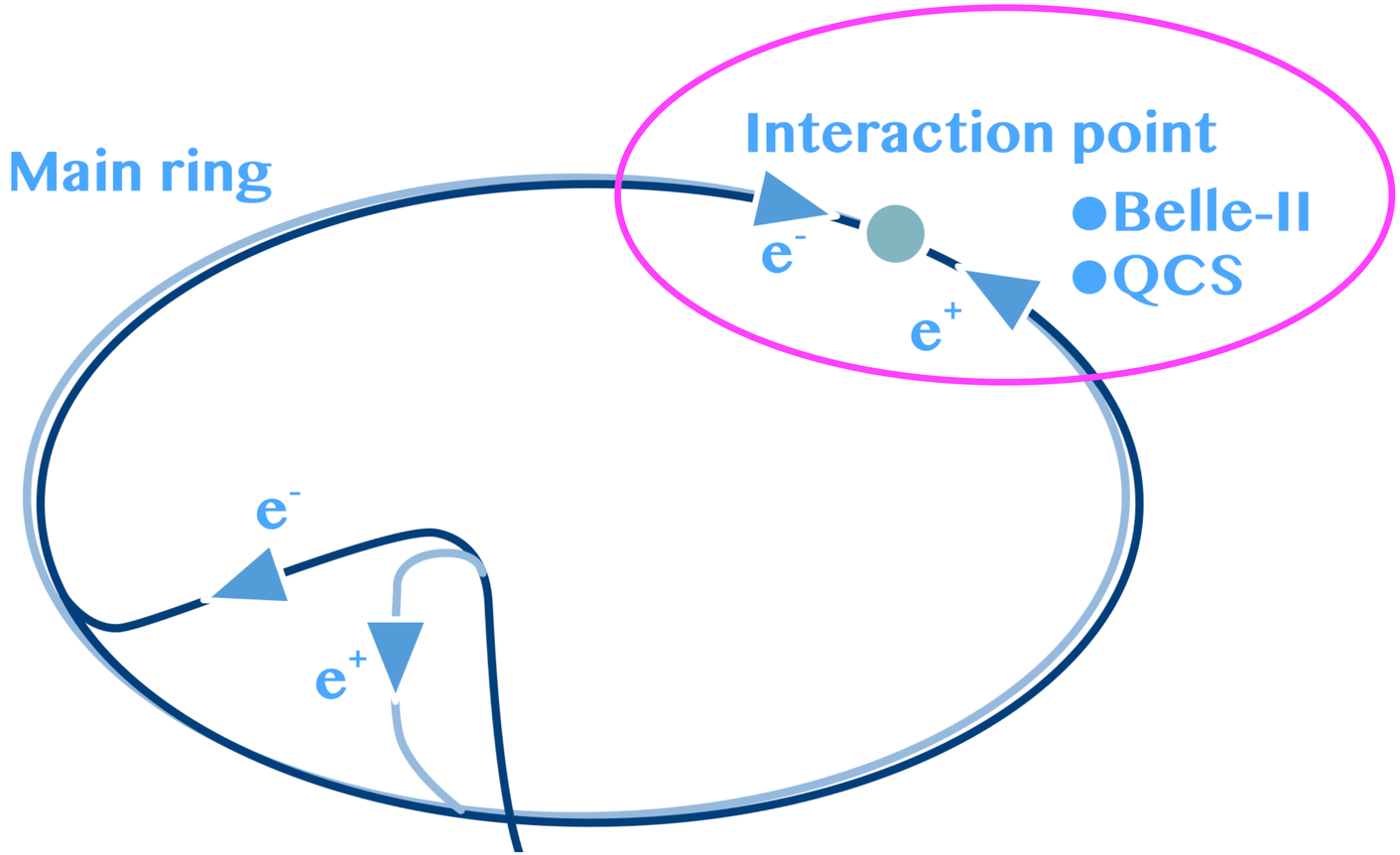
Target luminosity : 6×10^{35} s^{-1} cm^{-2}



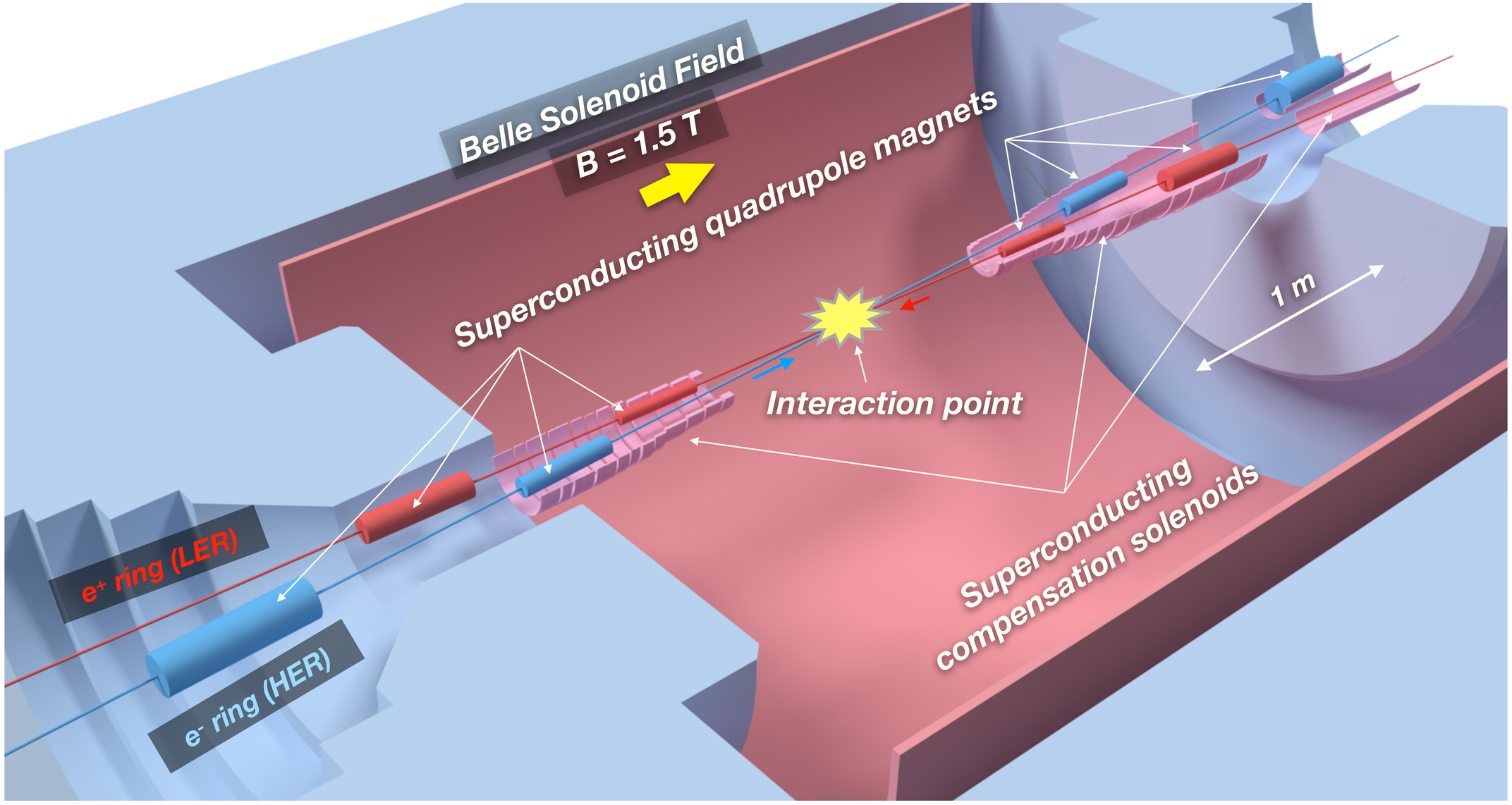
Superconducting final focus magnets (QCS)

Superconducting final focus magnet system (QCS)

SuperKEKB uses superconducting magnets only in IR for final focus



QCS configuration in the interaction region (IR)



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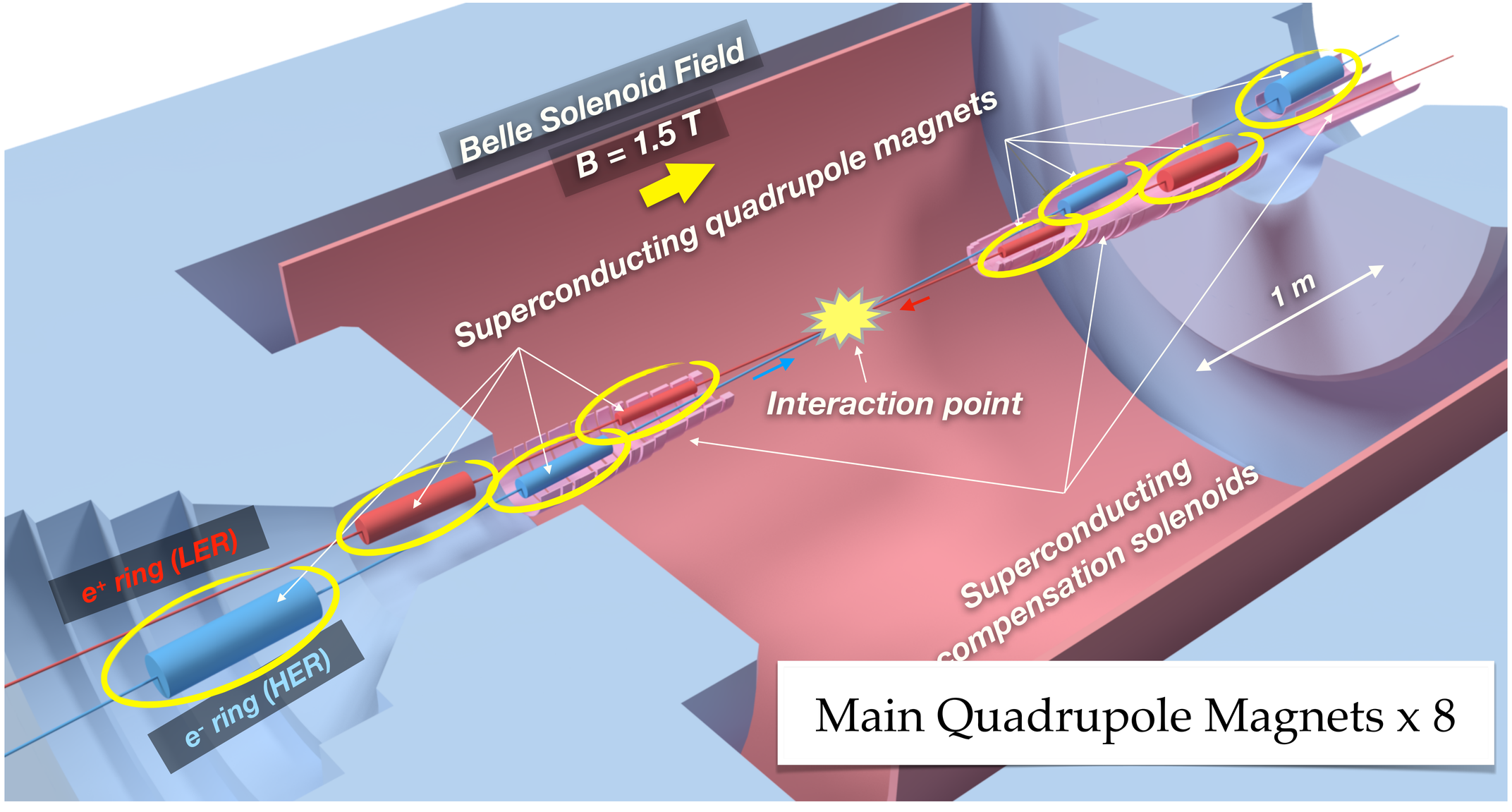

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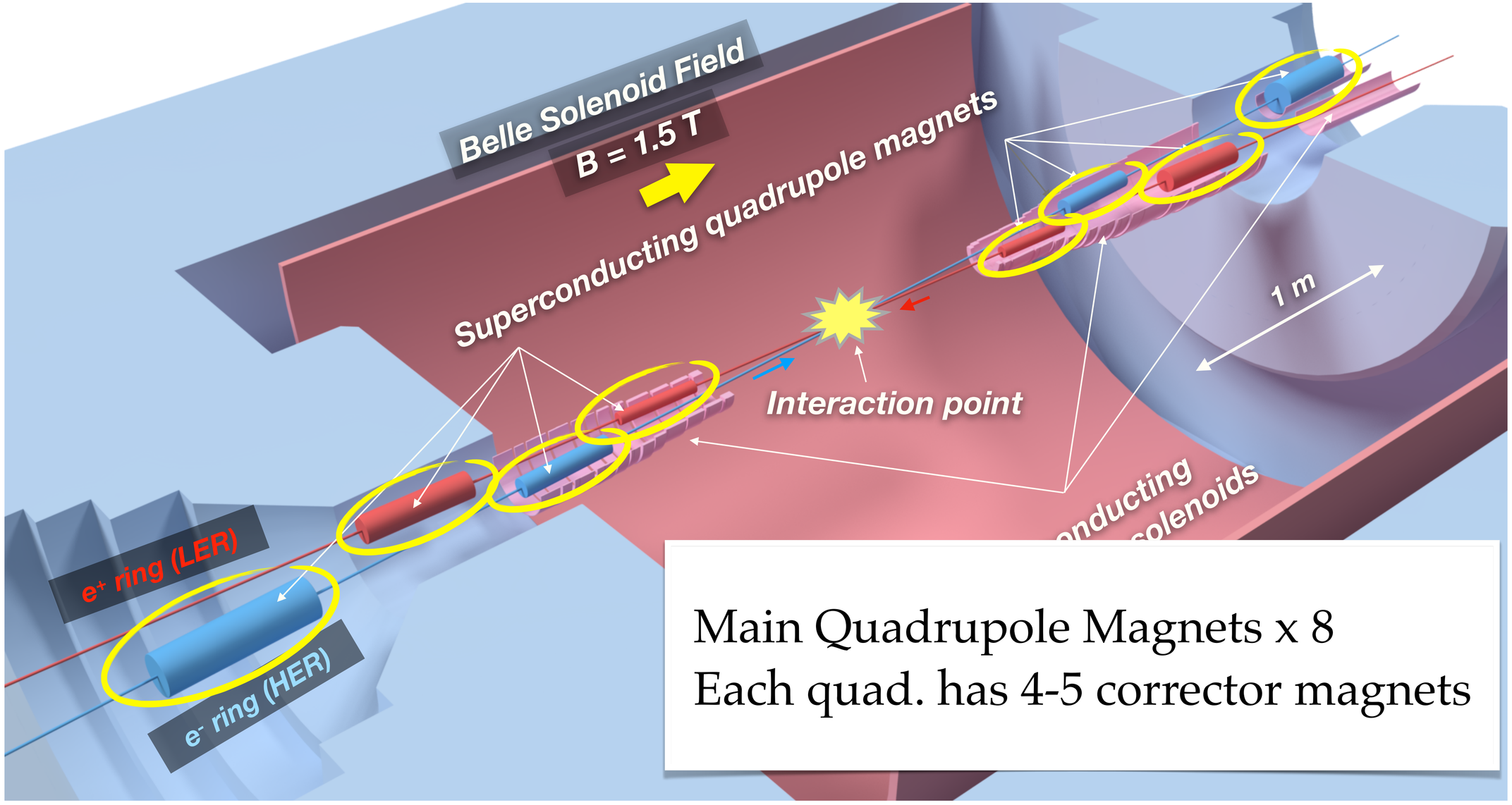
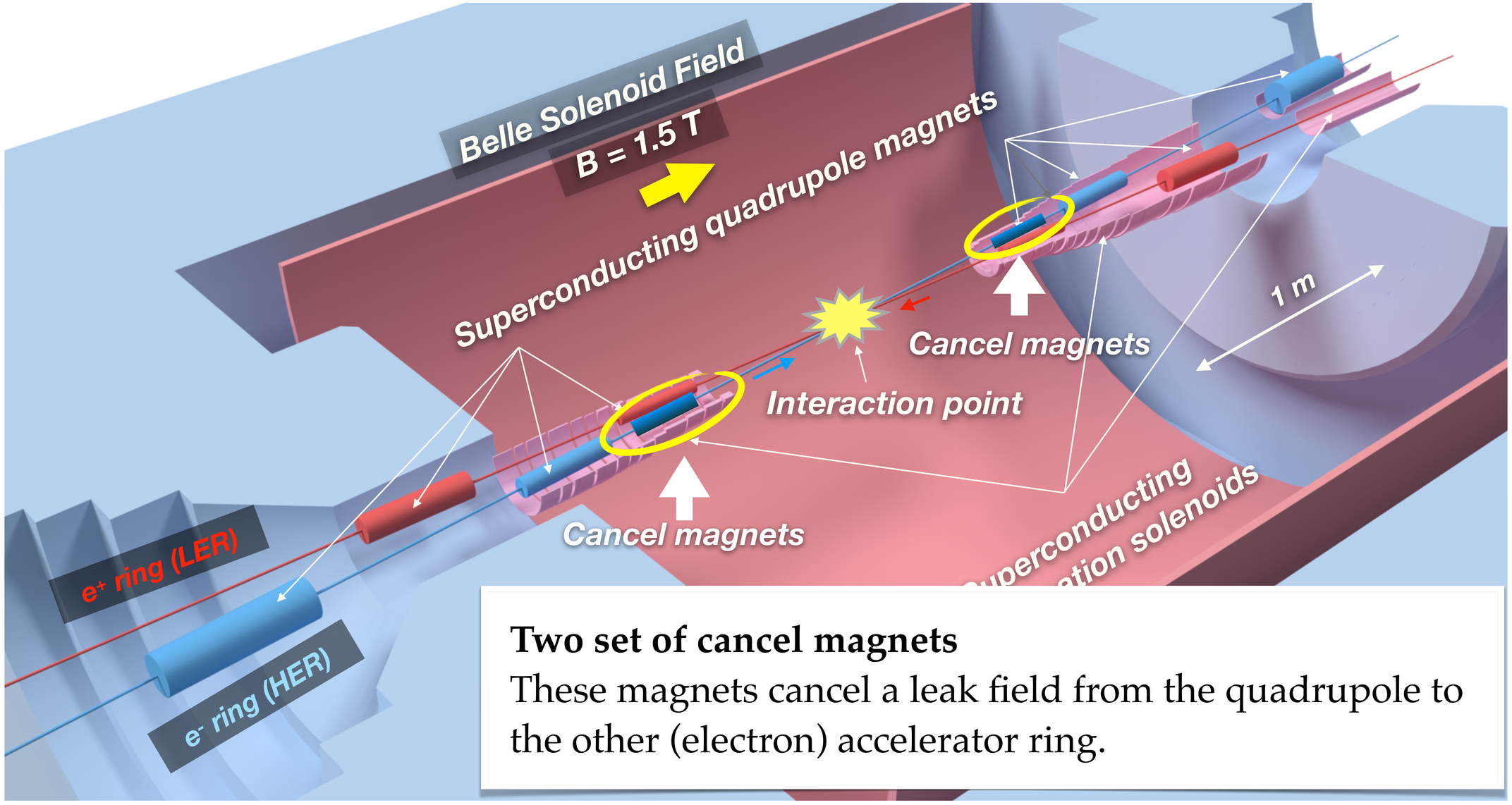


Main Quadrupole Magnets x 8
Each quad. has 4-5 corrector magnets

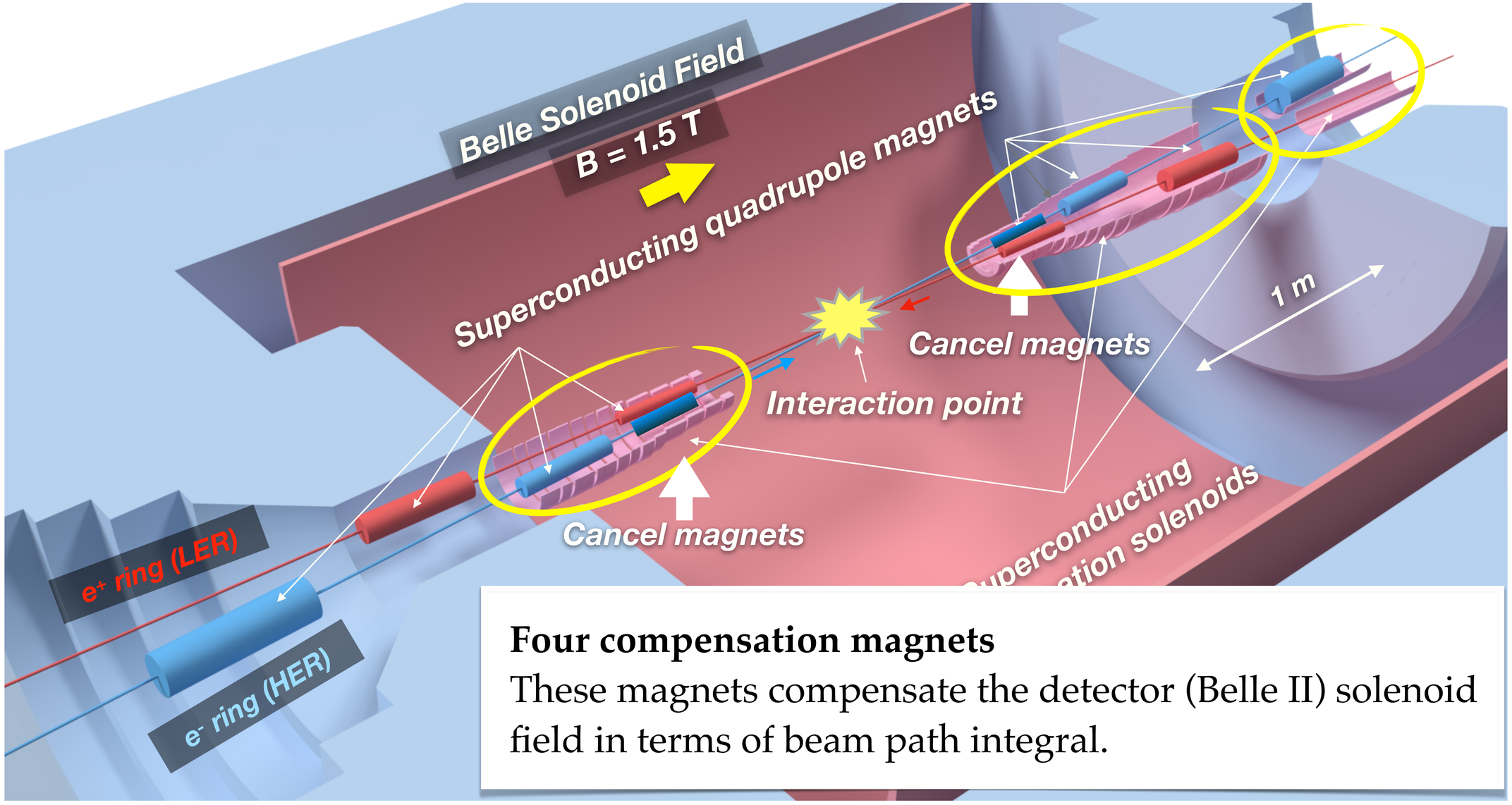
QCS configuration in the interaction region (IR)



Two set of cancel magnets

These magnets cancel a leak field from the quadrupole to the other (electron) accelerator ring.

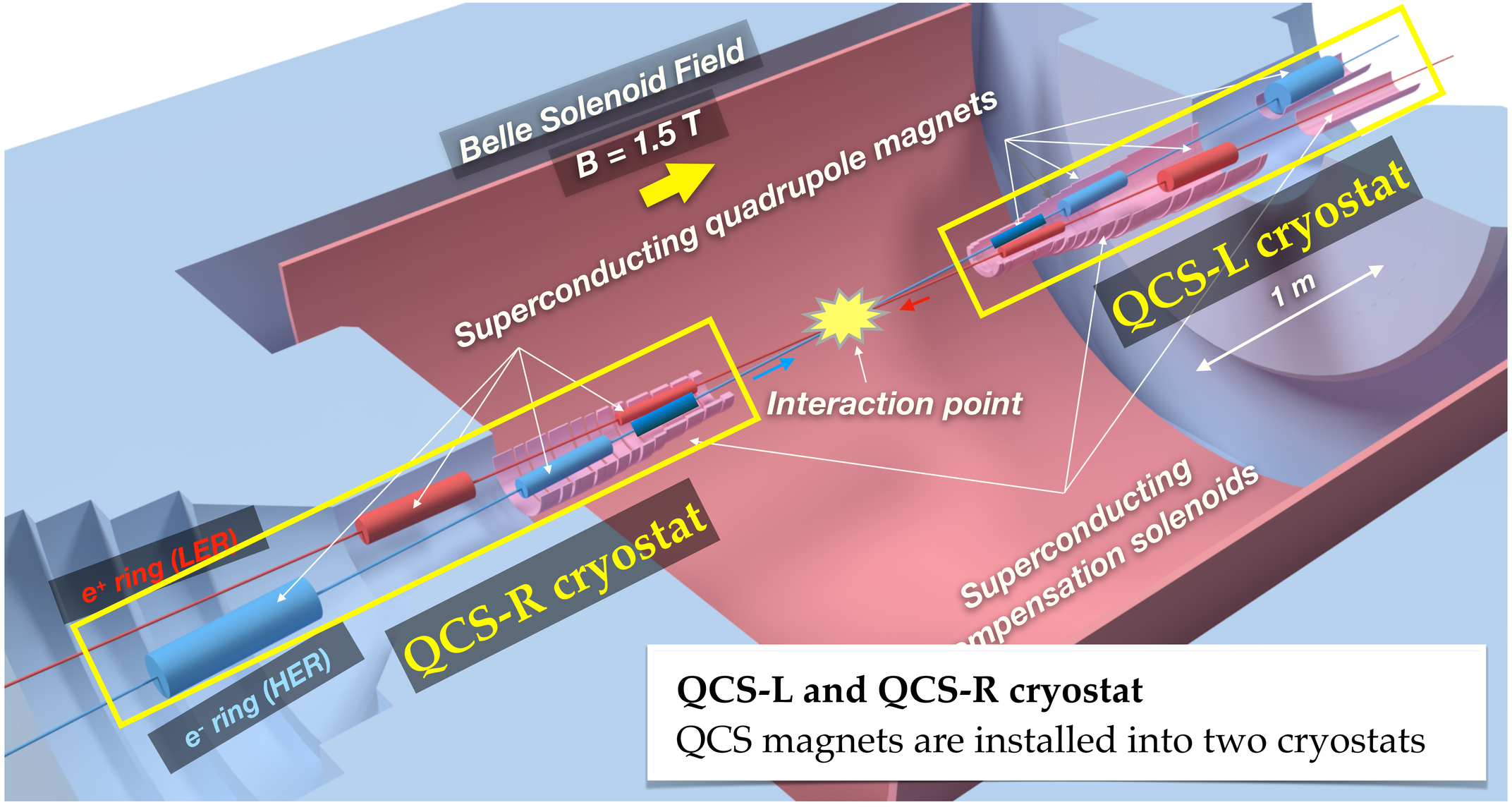
QCS configuration in the interaction region (IR)



Four compensation magnets

These magnets compensate the detector (Belle II) solenoid field in terms of beam path integral.

QCS configuration in the interaction region (IR)

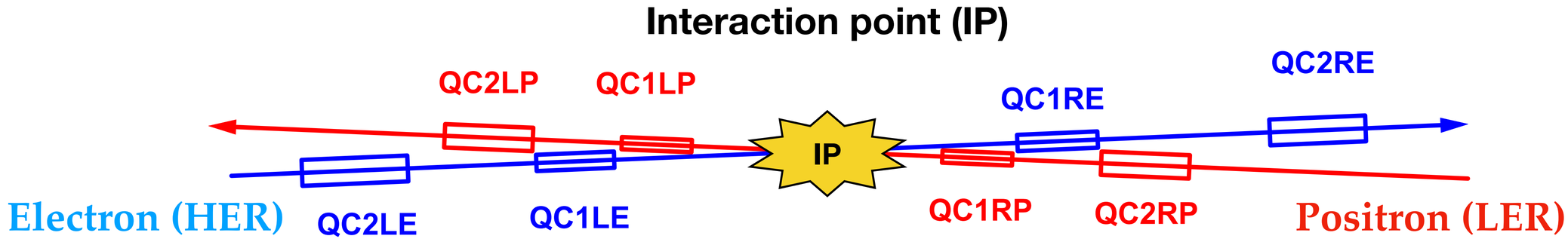


QCS-L and QCS-R cryostat

QCS magnets are installed into two cryostats

Superconducting quadrupole magnets

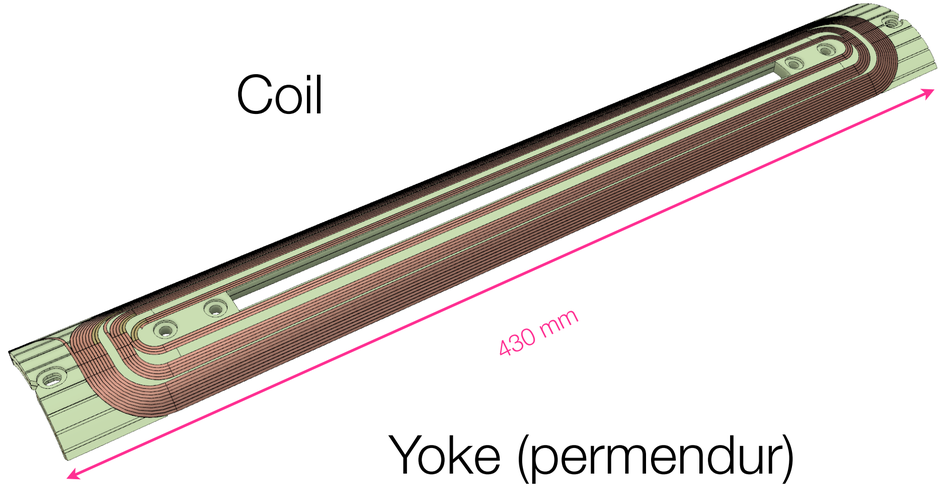
Main parameters of quadrupole magnets

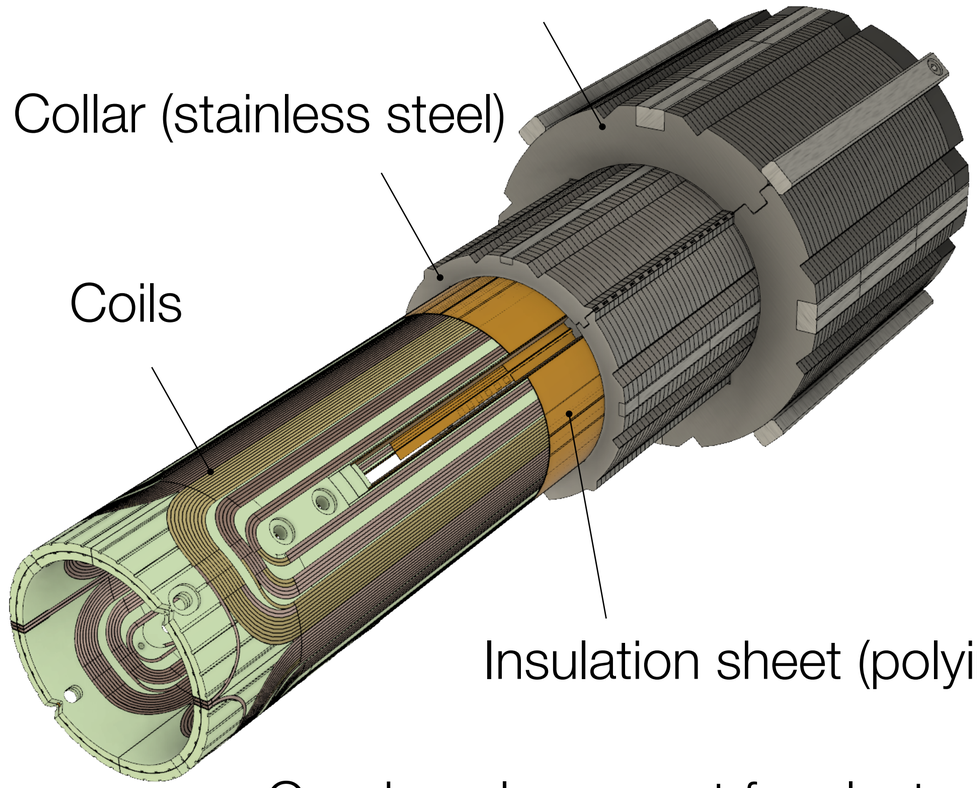


	Magnet Name	G [T/m]	I [A]	Inner Radius [mm]	Effective Length [mm]
Positron	QC1LP/QC1RP	68.9 / 68.9	1625 / 1624	25	334
Positron	QC2LP/QC2RP	28.1 / 26.3	877 / 822	53.8	410
Electron	QC1LE/QC1RE	72.2 / 70.9	1577 / 1486	33	373
Electron	QC2LE/QC2RE	28.4 / 32.4	977 / 1068	59.3	537/419

Quadrupole magnet mechanical design

- Coil
  - NbTi Rutherford cable with keystone angle
  - Double pancake / cos2θ winding
- Stainless collars to suppress Lorentz force
- Magnetic yoke: Reduce leak field. Made of permendur at high magnetic field.

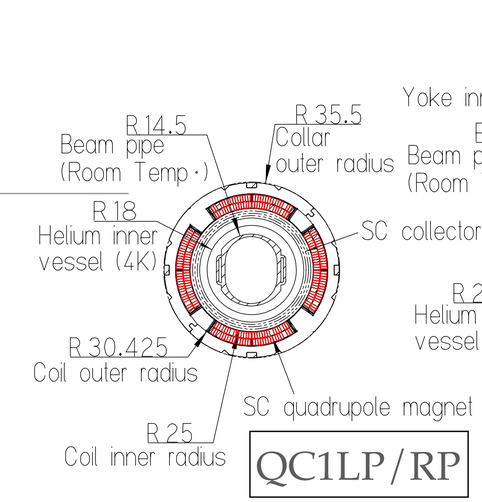


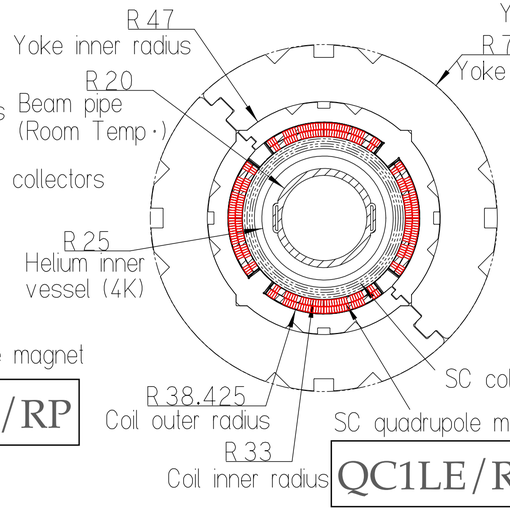


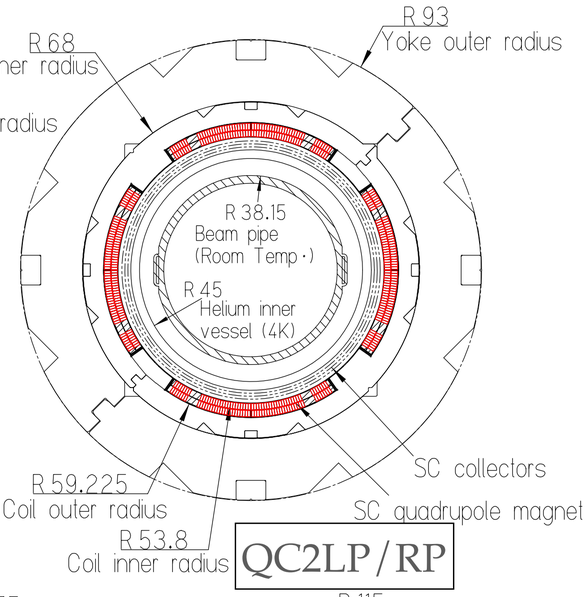
Quadrupole magnet for electron ring (QC1E)

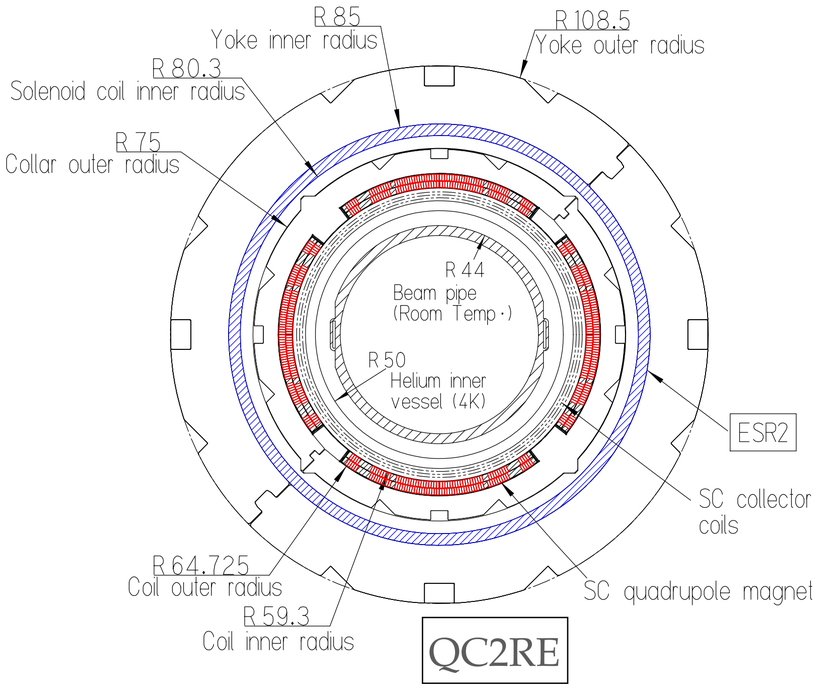
Cross sections of quads.

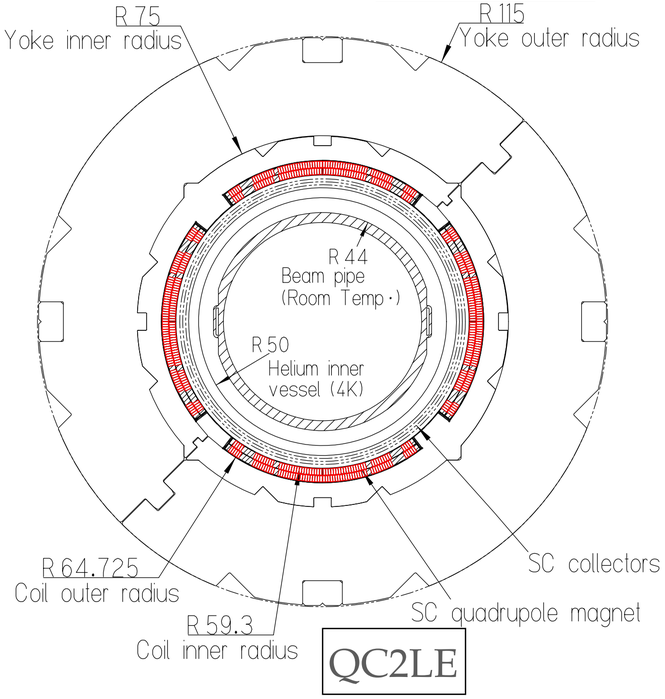
- QCS quads has five types of cross section.
- The red areas indicate conductors.
- The QC1LP/RP has the smallest inner diameter of 25 mm.
- The QC2LE/RE has the biggest inner diameter of 59.3 mm.
- QC2RE has the compensation solenoid at outside of quadrupole magnet (blue area).
- Corrector magnets are equipped inside quads. except for octupole corrector of QC1LP/RP.



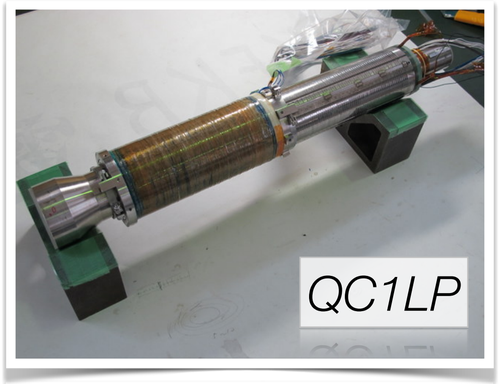


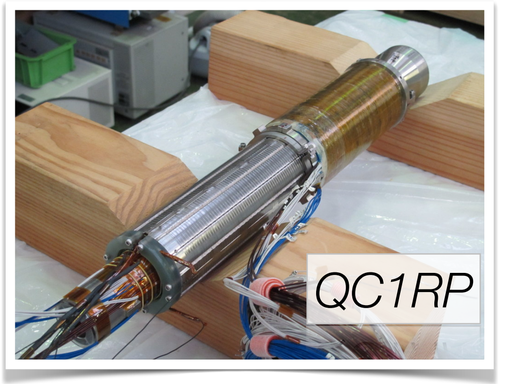


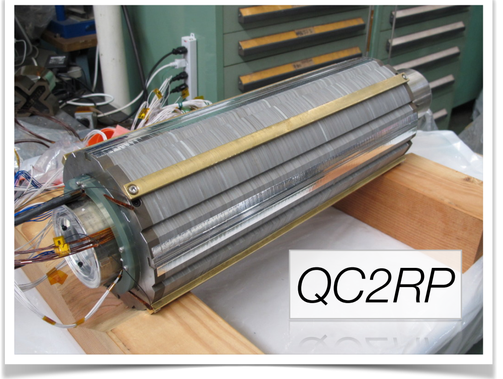


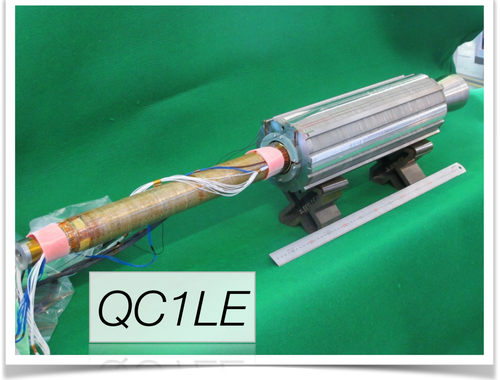


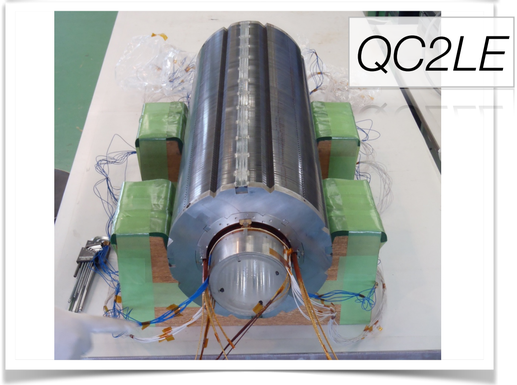
Main Quadrupole Magnets

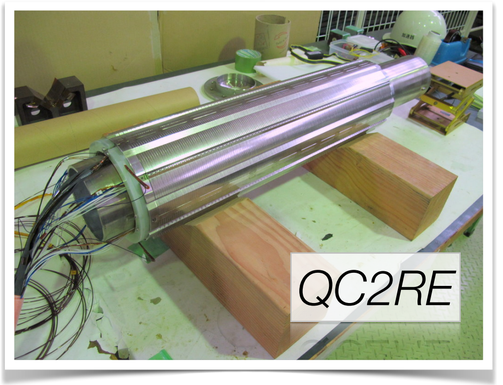








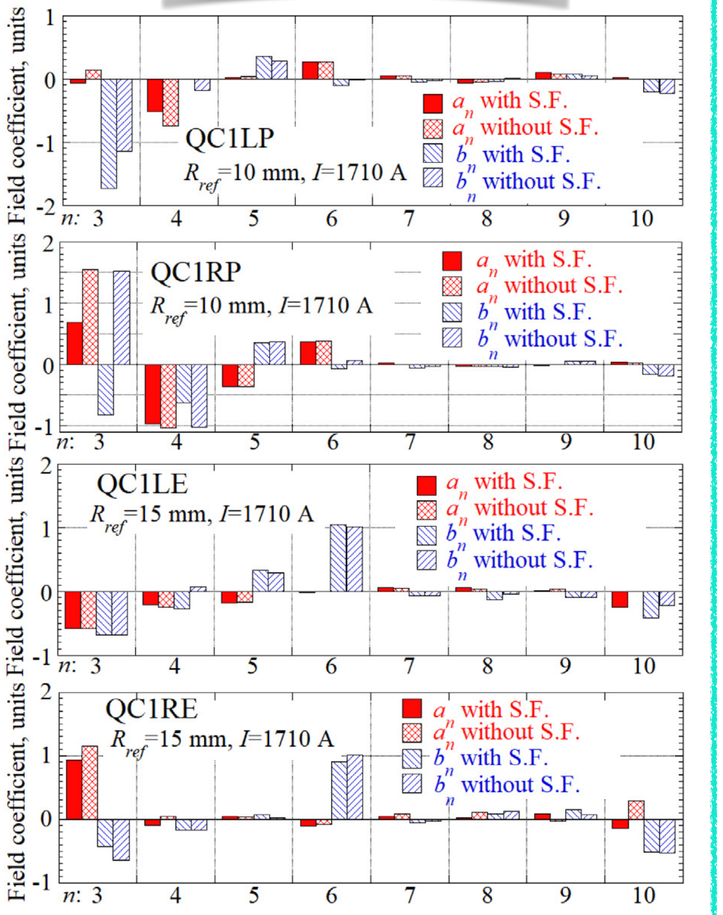




Magnetic field qualities of quads.

$$B_y + iB_x = B_2 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

Vertical focus quads.



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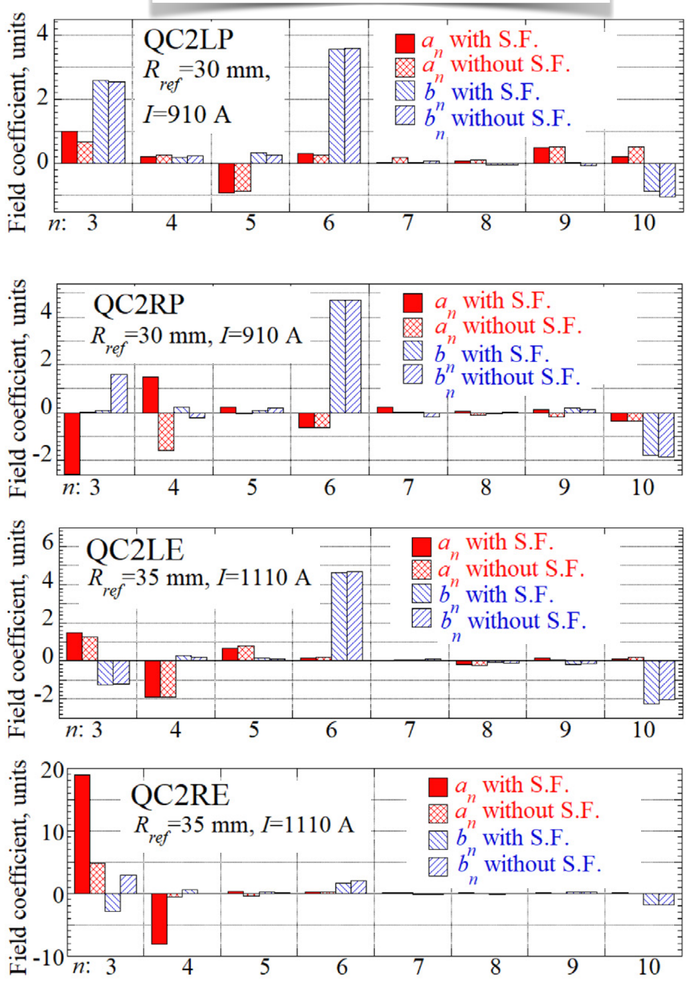

"units" definition

$b_n = B_n / B_2 \times 10^4$

$a_n = A_n / B_2 \times 10^4$

Tolerances Corrector magnet can correct

n=3 : < 10 units

n=4 (normal) < 5 units

The other components:

< 1 units

- The multipole for QC1L/RP and QC1L/RE are less than 1 units.
- QC2L/RP and QC2LE have a few units for several components.
- QC2RE shows large amplitude for sexupole and octupole

N. Ohuchi, *et.al.* Nucl. Instr. and Meth. A **1021** (2022) 165930.

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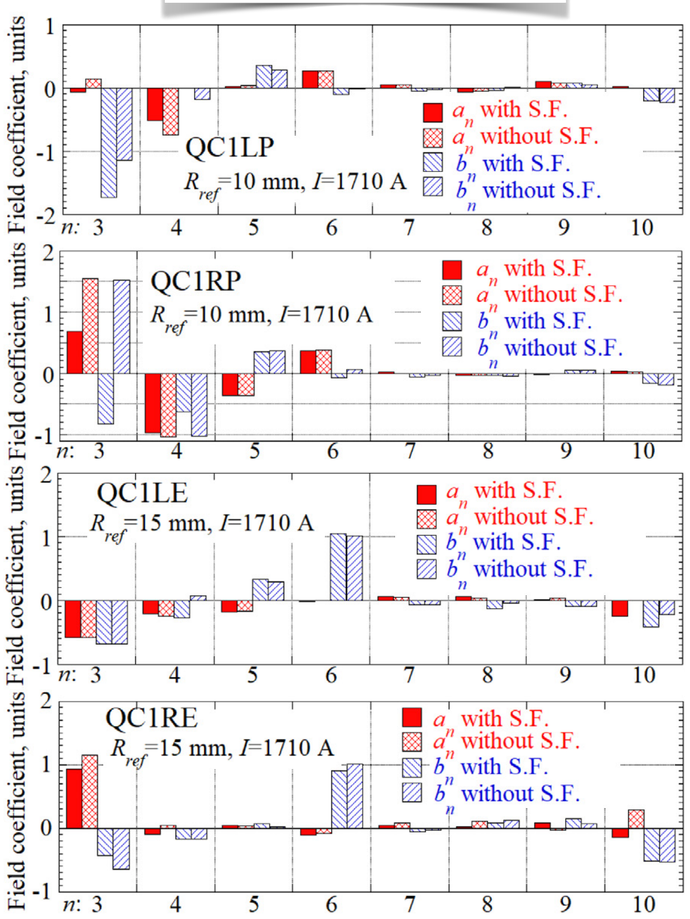

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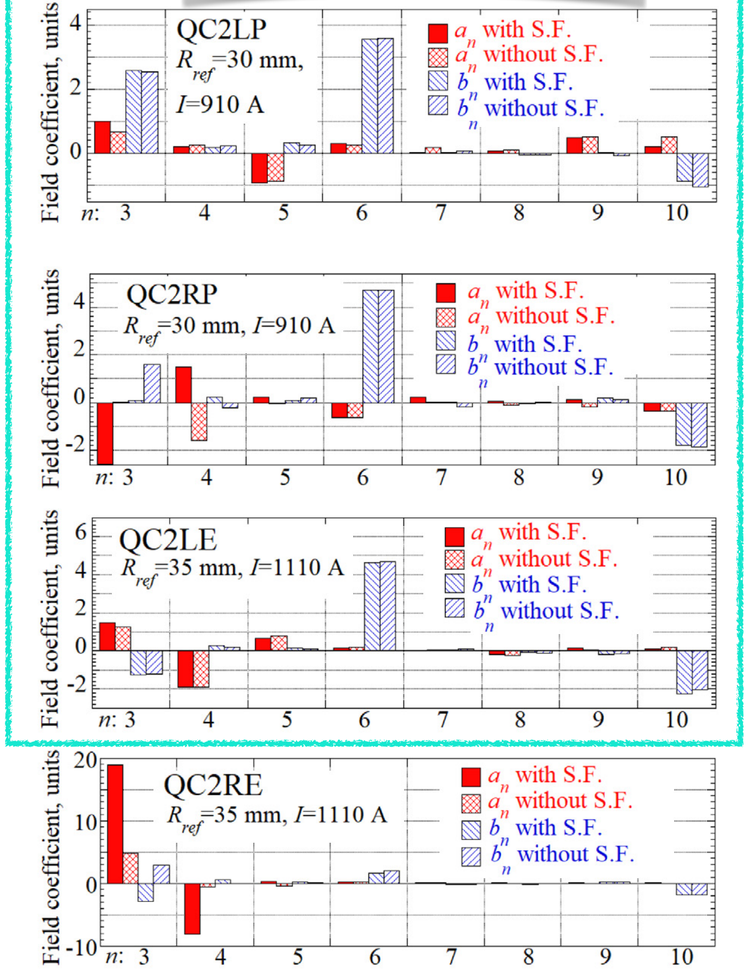

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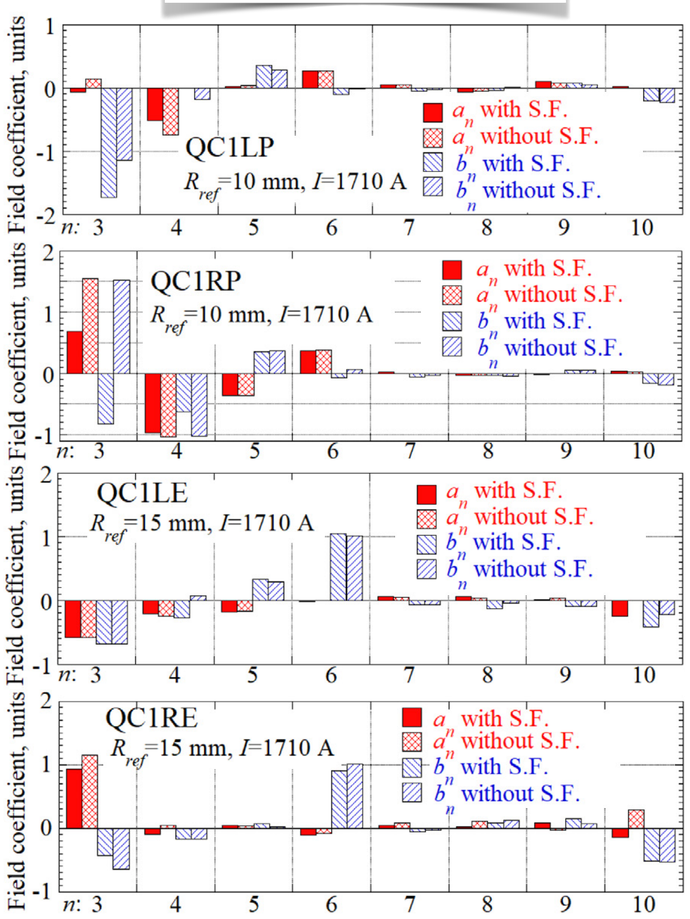

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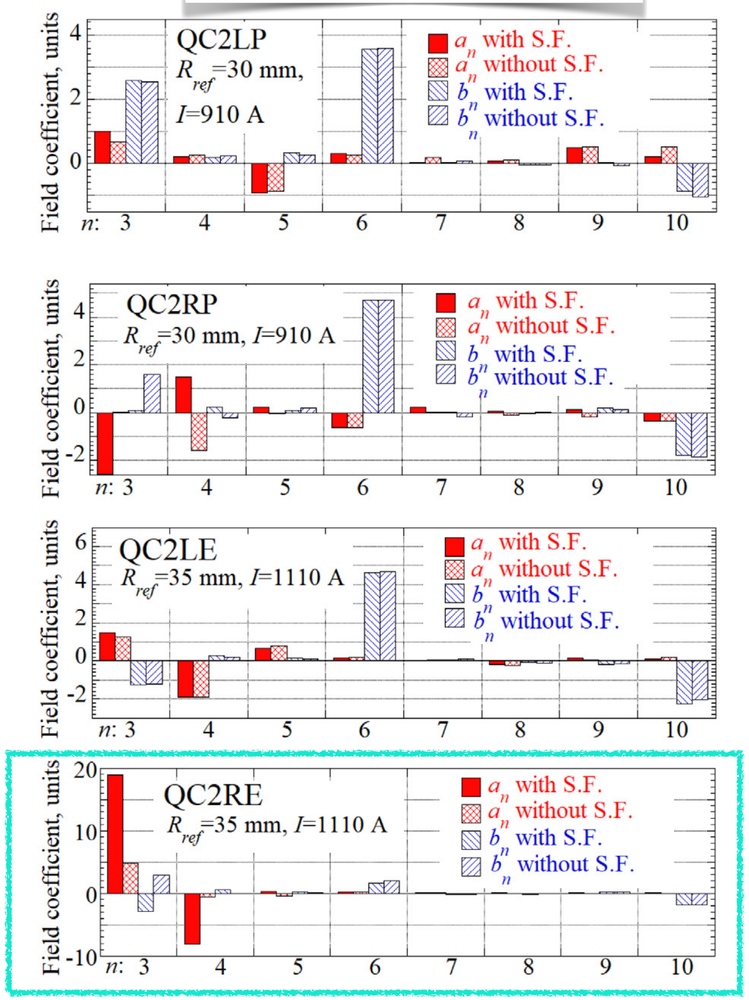

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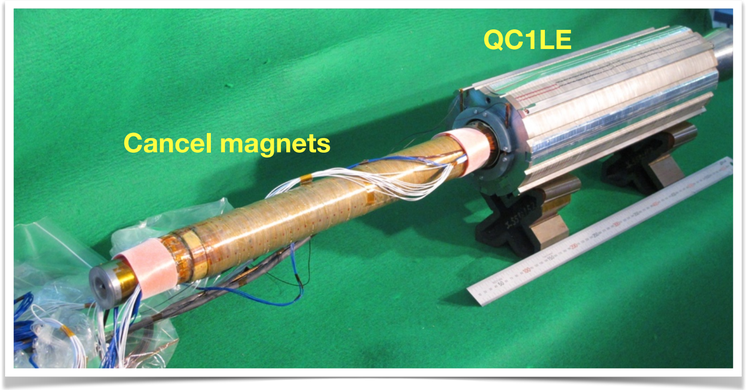
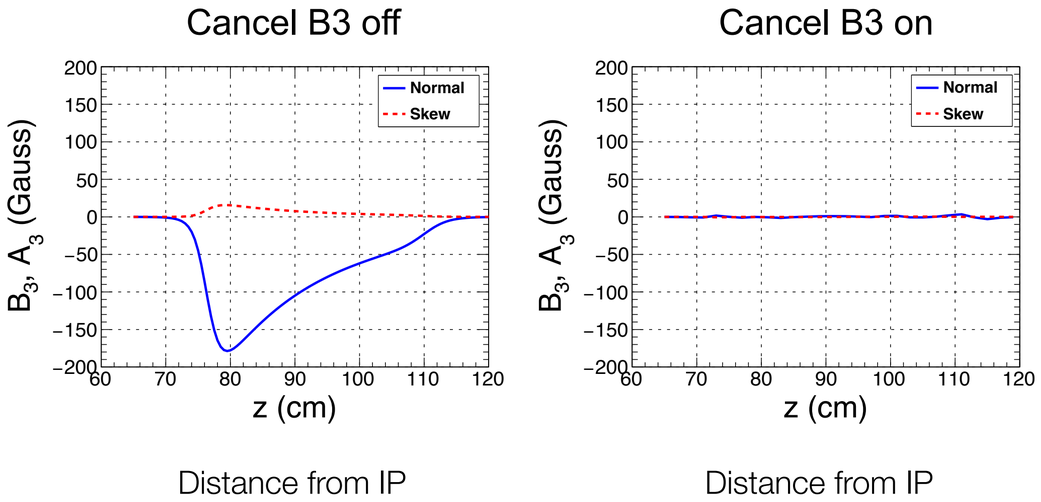
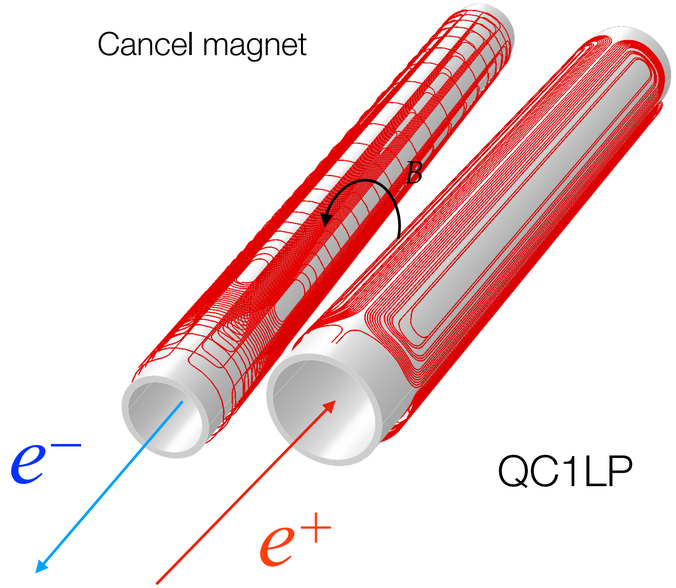
Cancel magnets

Cancel magnets

- Cancels leakage fields from the main quadrupole magnet to the opposing ring
- Cancels leakage fields from sextupole, octupole, decupole, and dodecupole magnets
- Fabricated by Brookhaven National Laboratory

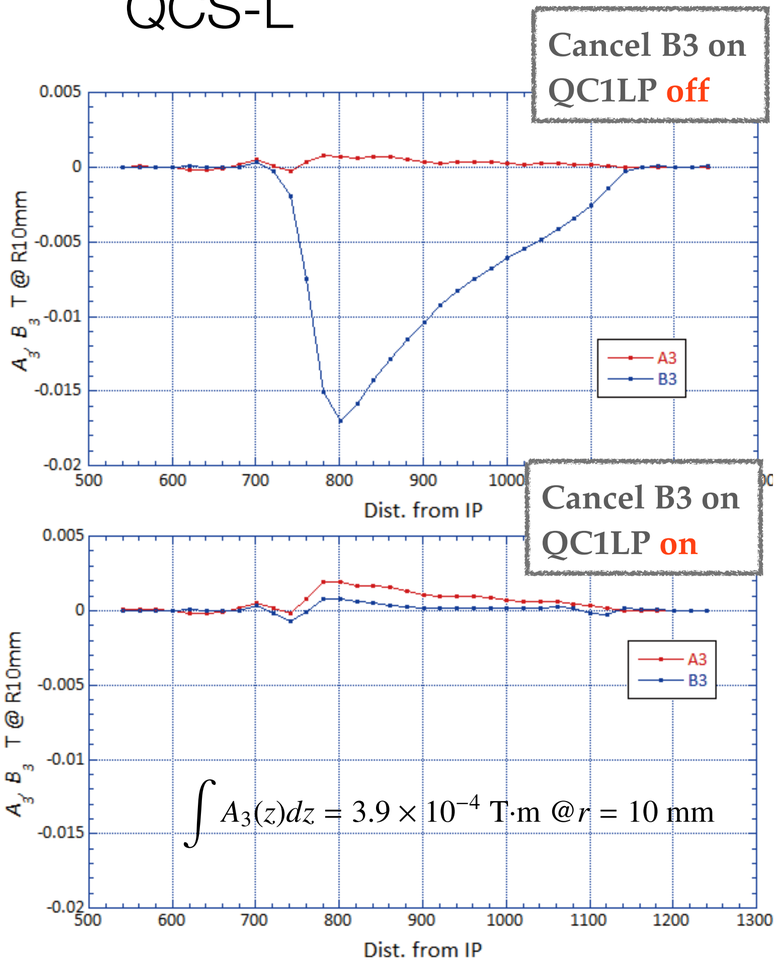




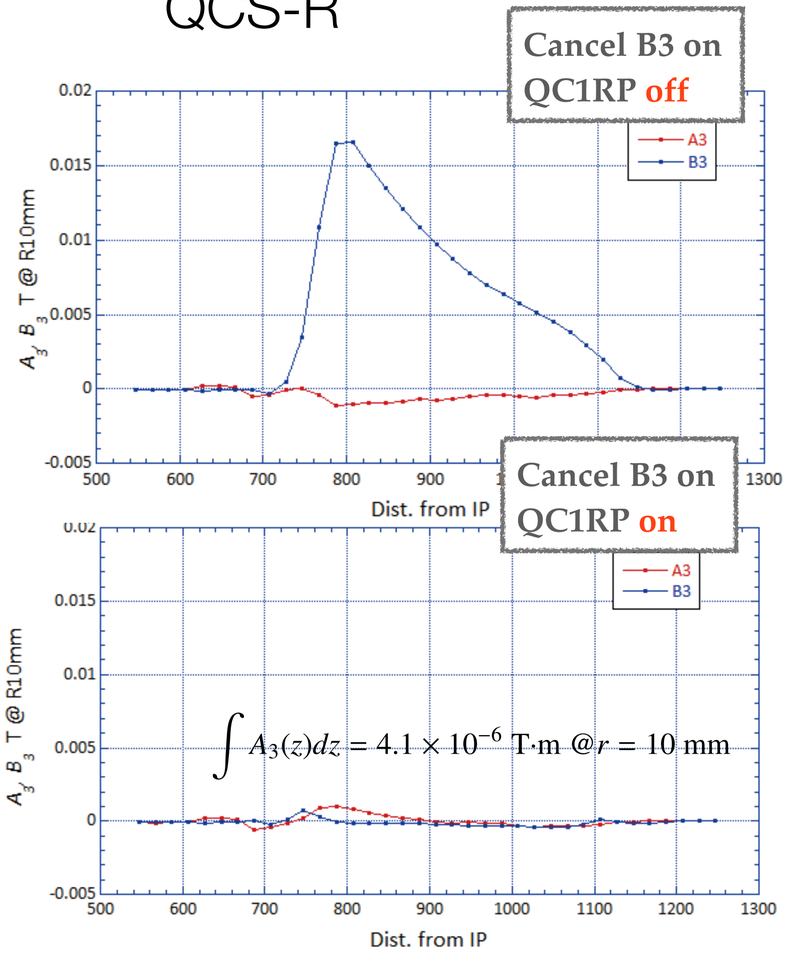


Sextupole components of Leak field on electron beam line

QCS-L



QCS-R



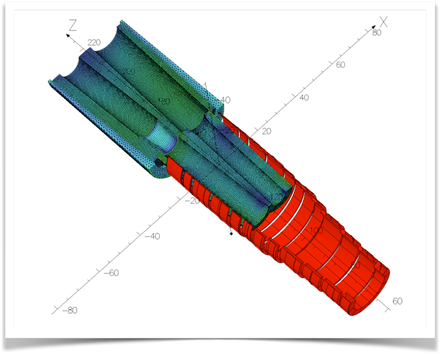
The energized current is optimized so that integral of B3 become to zero.
Sextupole components are reduced by the cancel magnet.

Compensation solenoids

The compensation solenoids cancel

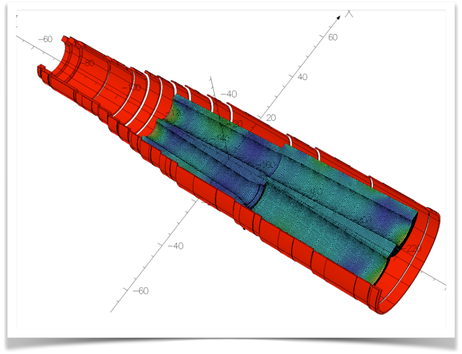
- The compensation solenoids cancel the B-field of the Belle II detector solenoid magnet (B=1.5T) by the integral magnetic field BzL.
- Number of solenoid magnet: 4
- Type of superconducting wire
  - 0.93 mm x 1.38 mm NbTi monolithic cable (rectangular cross section)

ESL



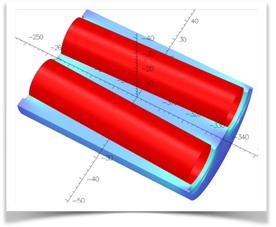
ESL consists of 12 coil blocks.

ESR1



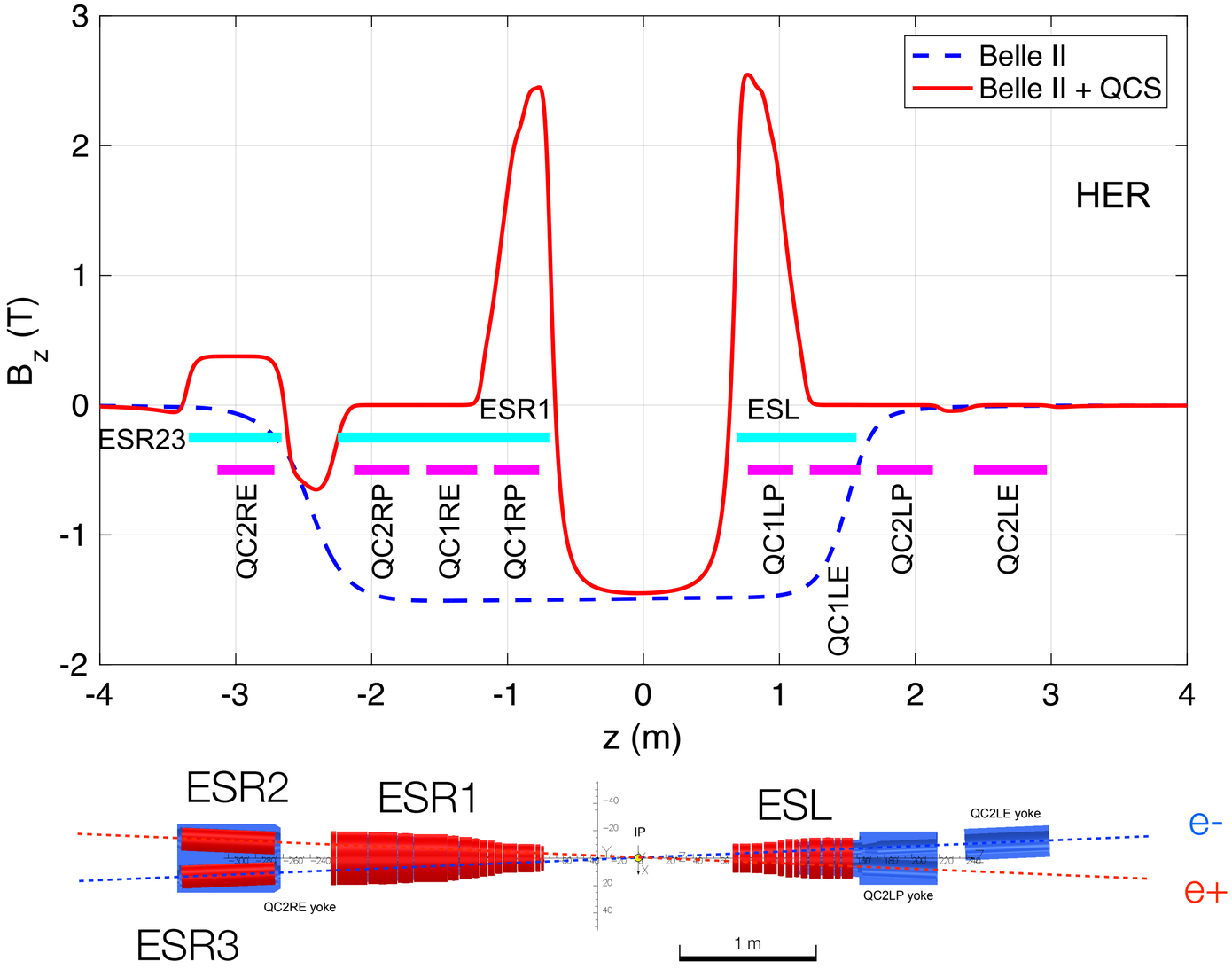
ESR1 consists of 15 coil blocks.

ESR23

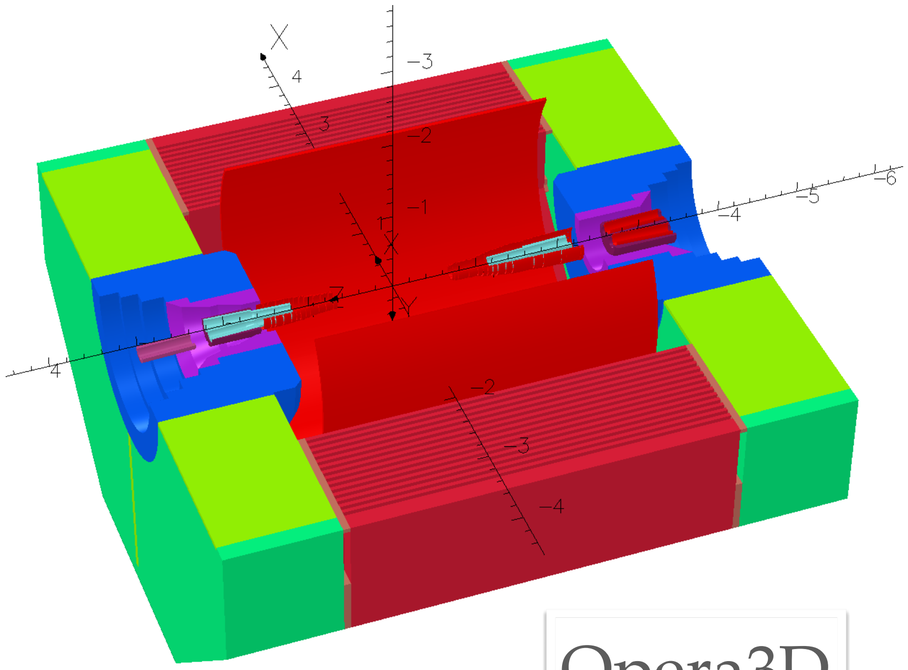


ESR23 consists of one solenoid on each beamline

Axial B-field Profile of Belle II + Compensation Solenoid



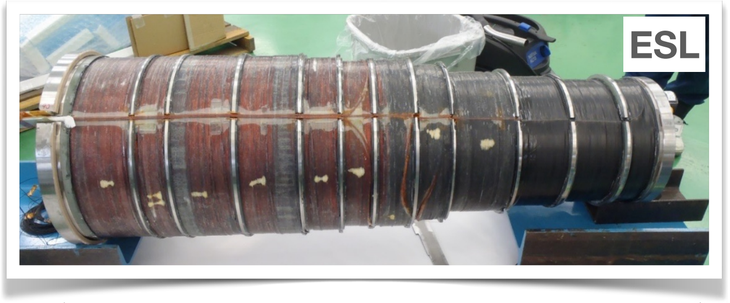
3D Calculation



Opera3D

Parameters of Compensation Solenoids

	ESL	ESR1	ESR2, 3
Number of coil blocks	12	15	1
Nominal operating current	404 A	450 A	151 A
Stored energy	118 kJ	244 kJ	1.6 kJ
Inductance	2.53 H	8.81 H	0.14 H
Maximum field in the coil	3.53 T	3.2 T	0.48 T
Load line ratio	0.53	0.51	0.11



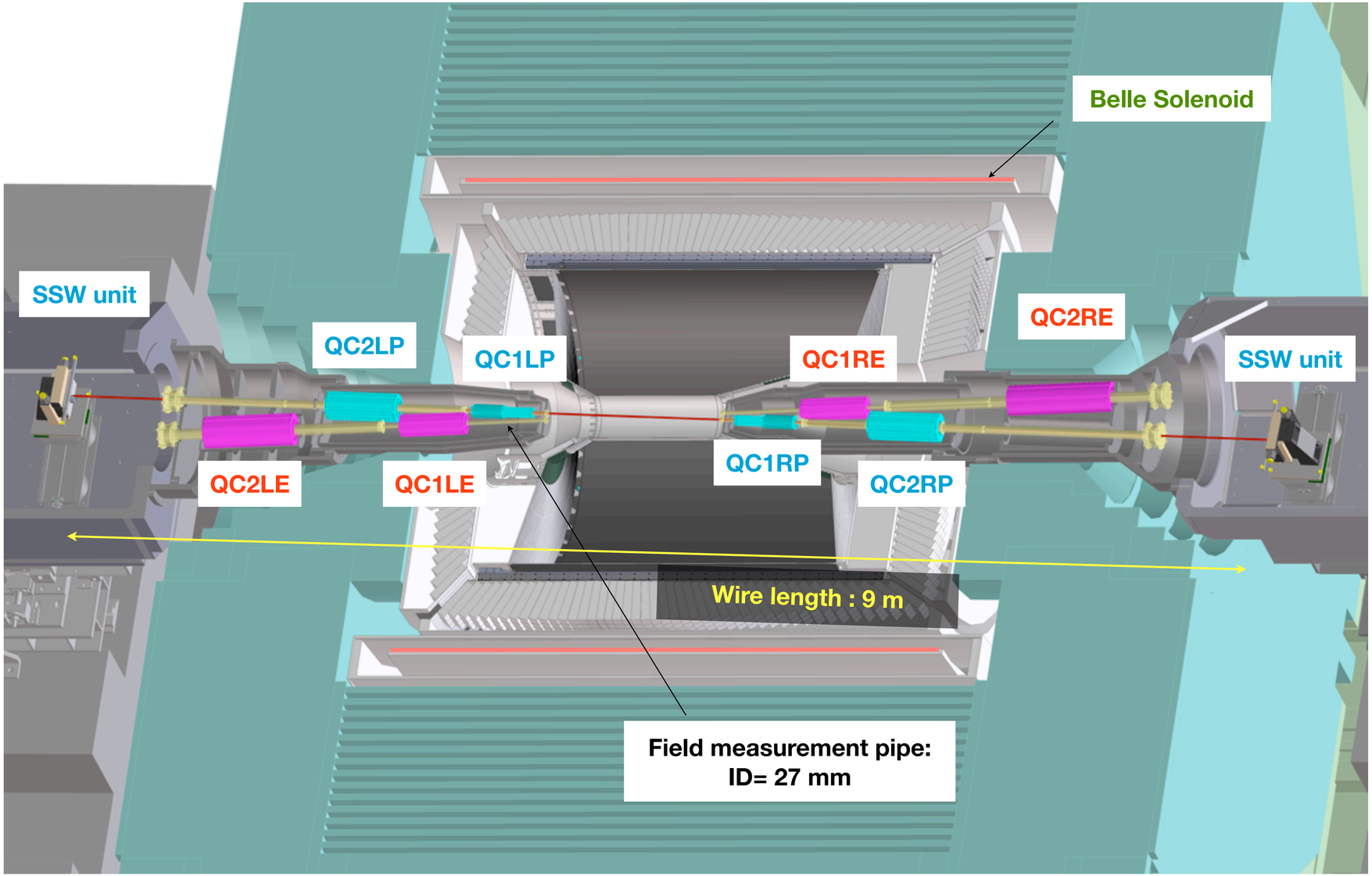
1 m

1.5 m

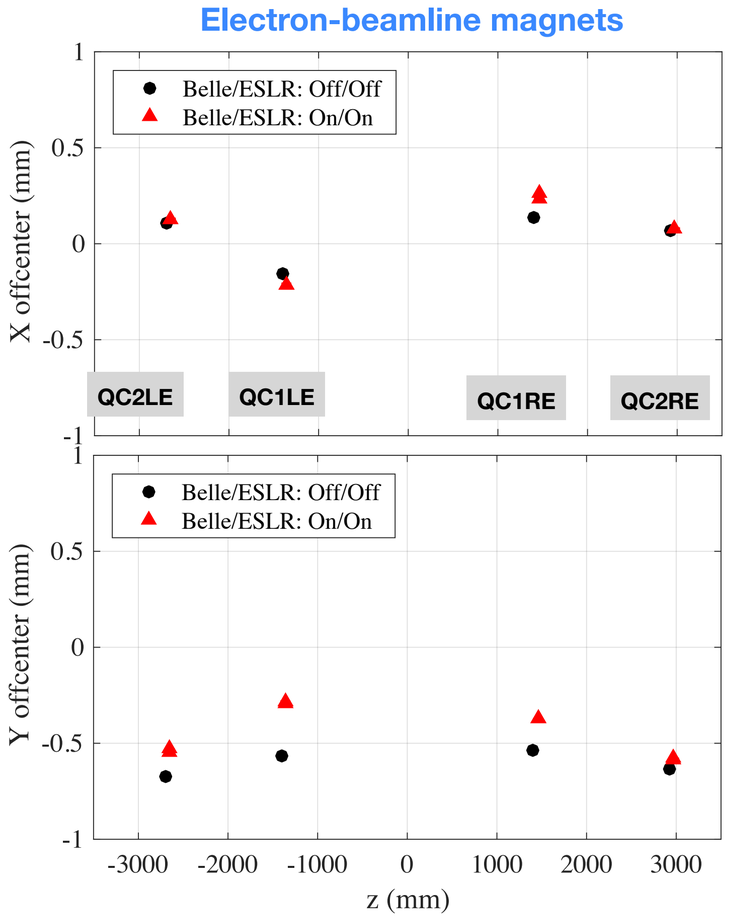
X. Wang

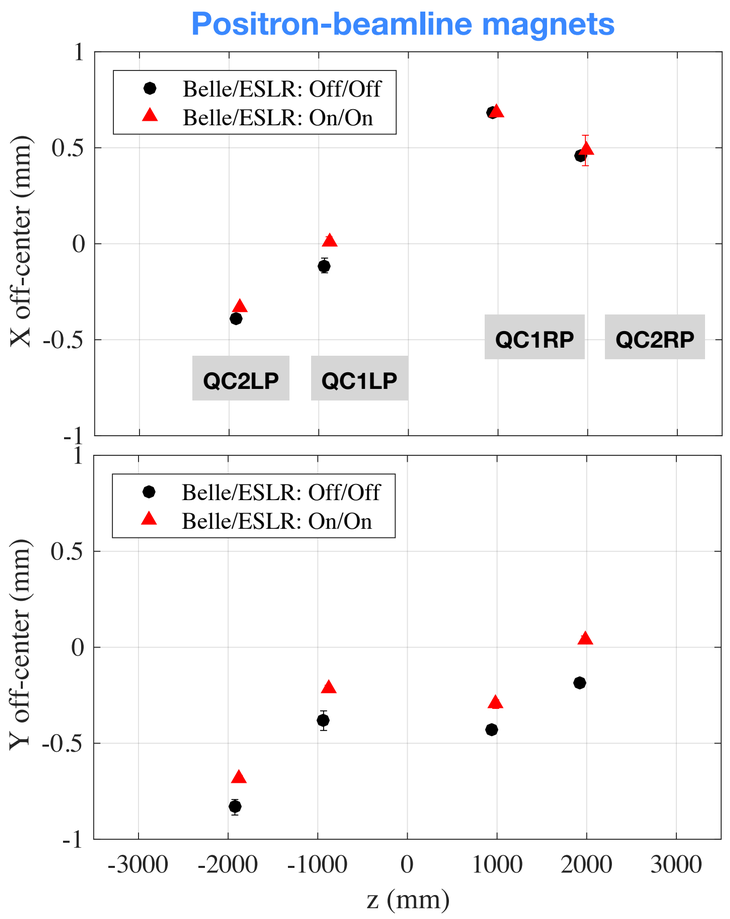
Magnet center measurement with single stretched wire

SSW measurement: setup



Magnet center for each magnet wrt design position





- Magnet field centers are varied, with the solenoid field turned on/off.
  - dx ~ 0.1 mm, dy~0.3 mm
- The maximum offset from the beamline is 0.7 mm for QC1RP in the x-direction.
- The maximum offset from the beamline is -0.6 mm for QC2LP in the y-direction.
- These offsets can be corrected with dipole correctors and normal conducting magnets near QCS.

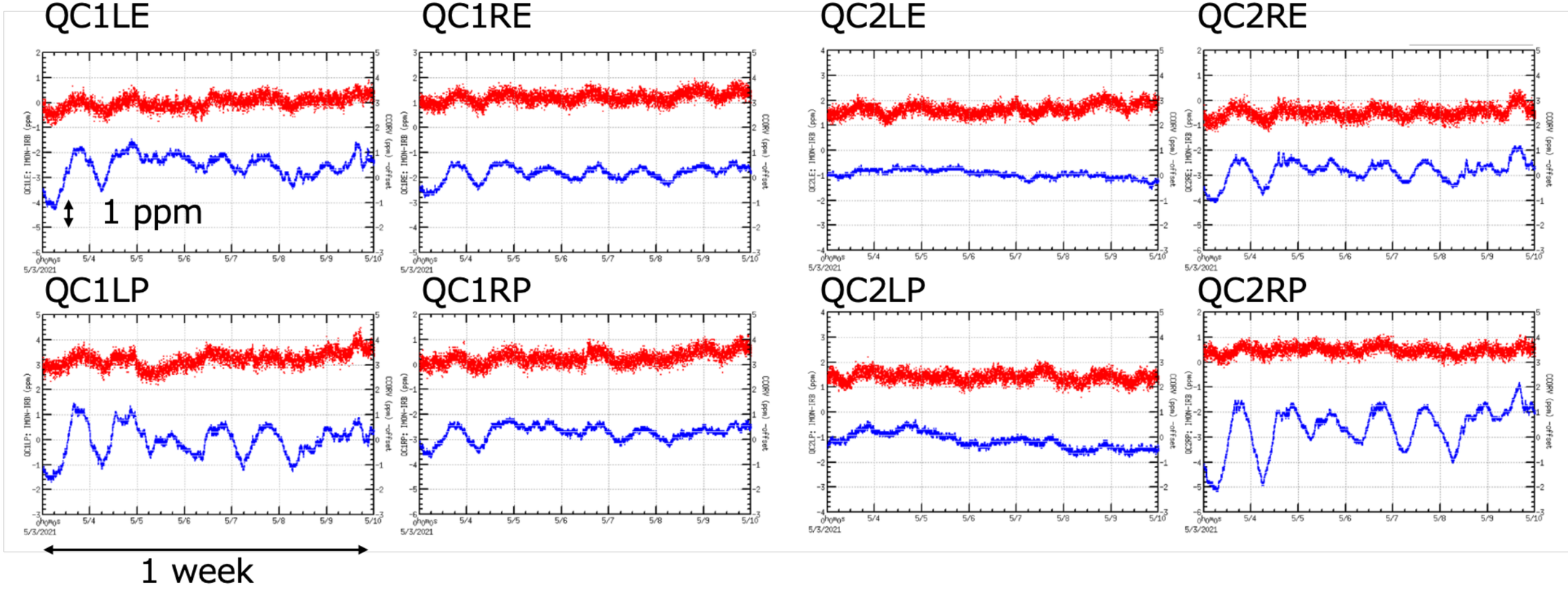
QCS Operation

One week stability of power supply for quadrupole magnets

Current stability of eight-quadrupole magnets (one week)

主四極8台の1週間の計測値(1 ppm/div)

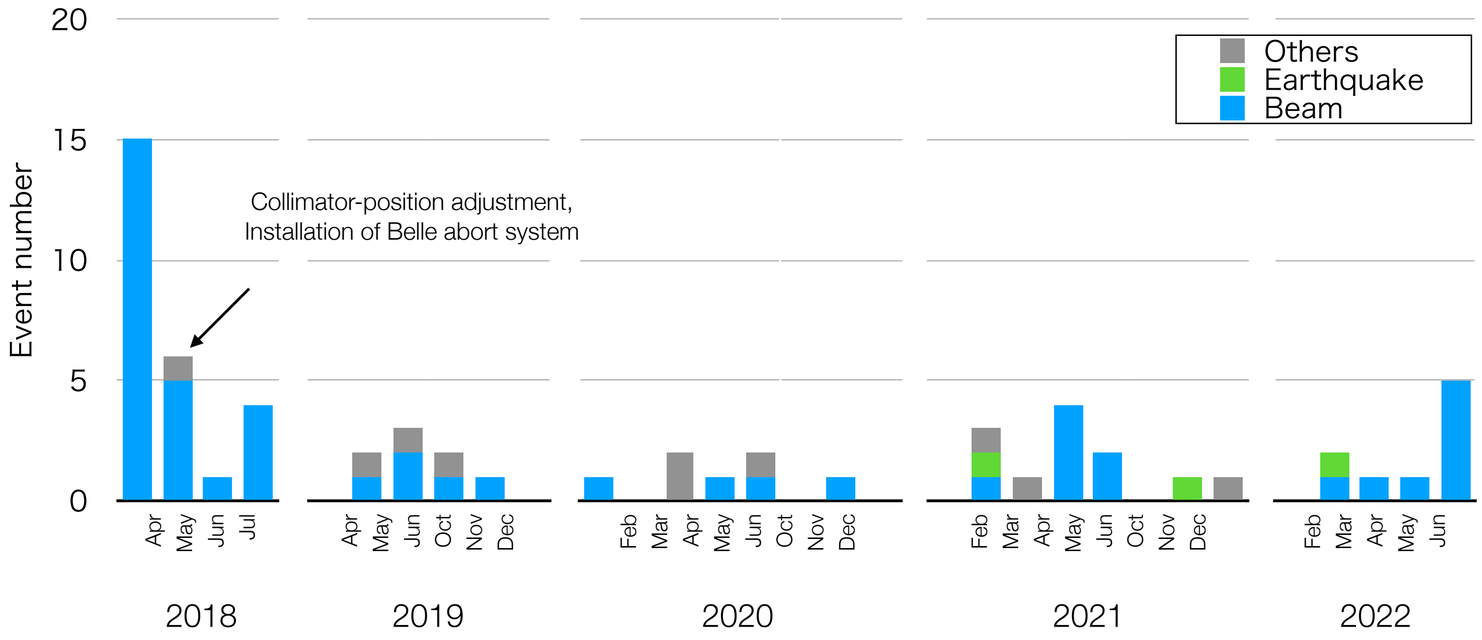
- Output current
- Correction value by digital feedback



We achieved good stability of 2 ppm per 1 week by digital feedback.

T. Oki

Accidental power shutdown of QCS magnets during beam operation



- Causes:
  - Quench induced by beam (~1-10 mJ)
  - Earthquake: not quench but induced voltage by change of coupling B-field between Belle solenoid and QCS solenoid over the threshold of a quench detector
  - Others: Power supply trouble (fixing every event and frequency is reducing), supply water trouble
- If a collimator in a ring is damaged, the frequency of the beam induced quench events increase.
- Recovery time from quench: 1 — ~10 hours (depend on quenched magnet)

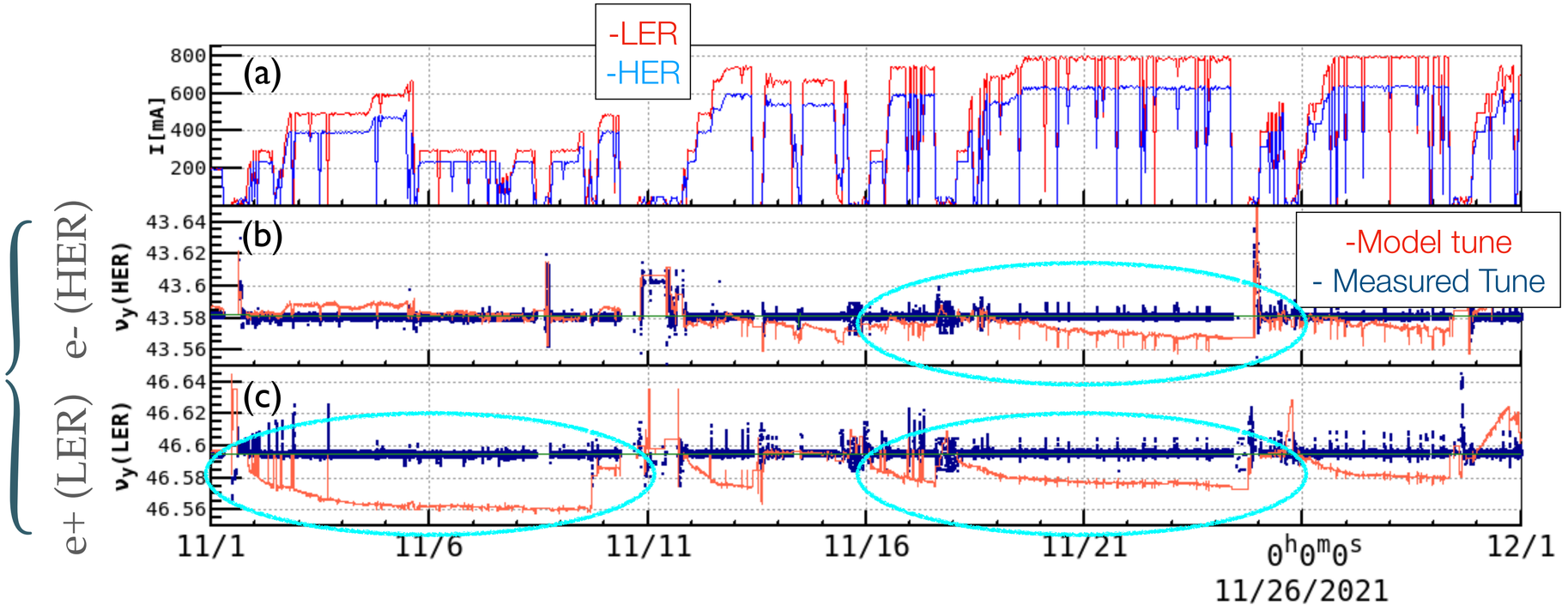
X. Wang

Long term drift of vertical model tune

- We observed that the vertical-setting (model) tune changed after powering off/on the quadrupole magnet in SuperKEKB operation.
- It corresponds to the variation of 10^{-4} of the quadrupole field of QCS in a few hours.

Beam current

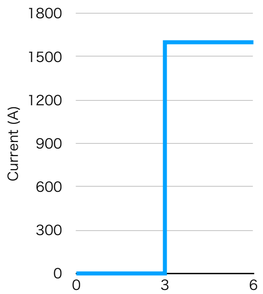
Vertical tune



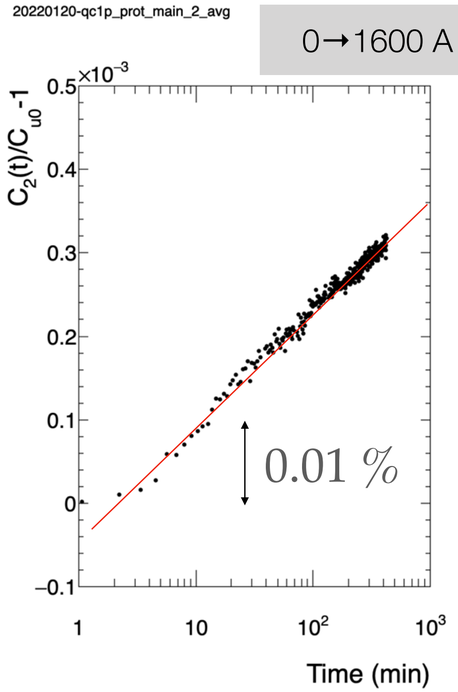
Drift of strength of quadrupole magnet

- We performed measurements with the QC1P R&D magnet and found that the quadrupole field is varied by 3×10^{-4} in 8 hours.
- We deduced that it is caused by flux creep in superconductor cable.
- We avoid this by changing the ramping pattern of the magnet.

Current ramp pattern

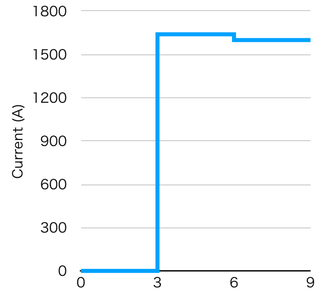


Variation: 3×10^{-4} per 7 hours

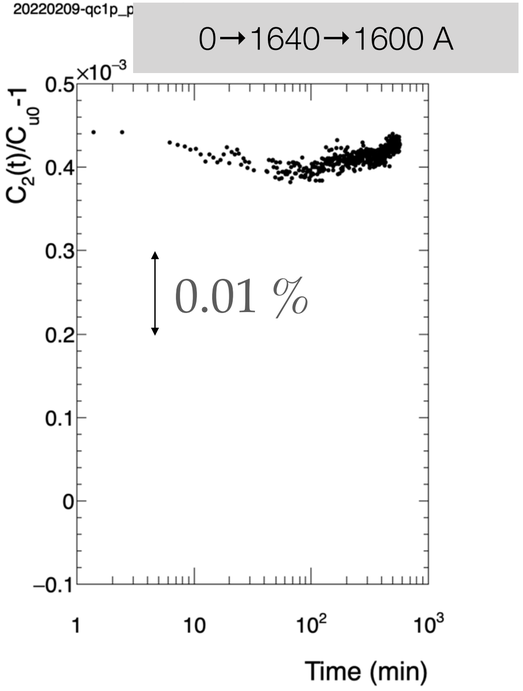


Change the initial ramping pattern

Current ramp pattern



Variation: 0.2×10^{-4} per 10 hours



Summary

- QCS consists of 8 SC quadrupole magnets, 43 sc correctors/cancel magnets, and 4 SC compensation solenoids.
- Field quality
  - Multipoles: unexpected multipoles were measured for QC2RE. Caused by irregular shape at iron structure inlet.
- Magnet center measurement (alignment measurement)
  - The magnetic field center was measured by SSW at the accelerator ring.
- Operation
  - We have many quenches induced by the beam.
  - Induced voltage by earthquake sometimes over the threshold of the quench detector.
  - We found that the strength of QC1 varied by 3×10^{-4} in 8 hours after we energized the QCS magnet.
    - We avoid this by modifying the ramping pattern.