Lessons Learned from the SuperKEKB IR Magnet Upgrade and Plans for the Future

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- From KEKB to SuperKEKB
- QCS at SuperKEKB IR
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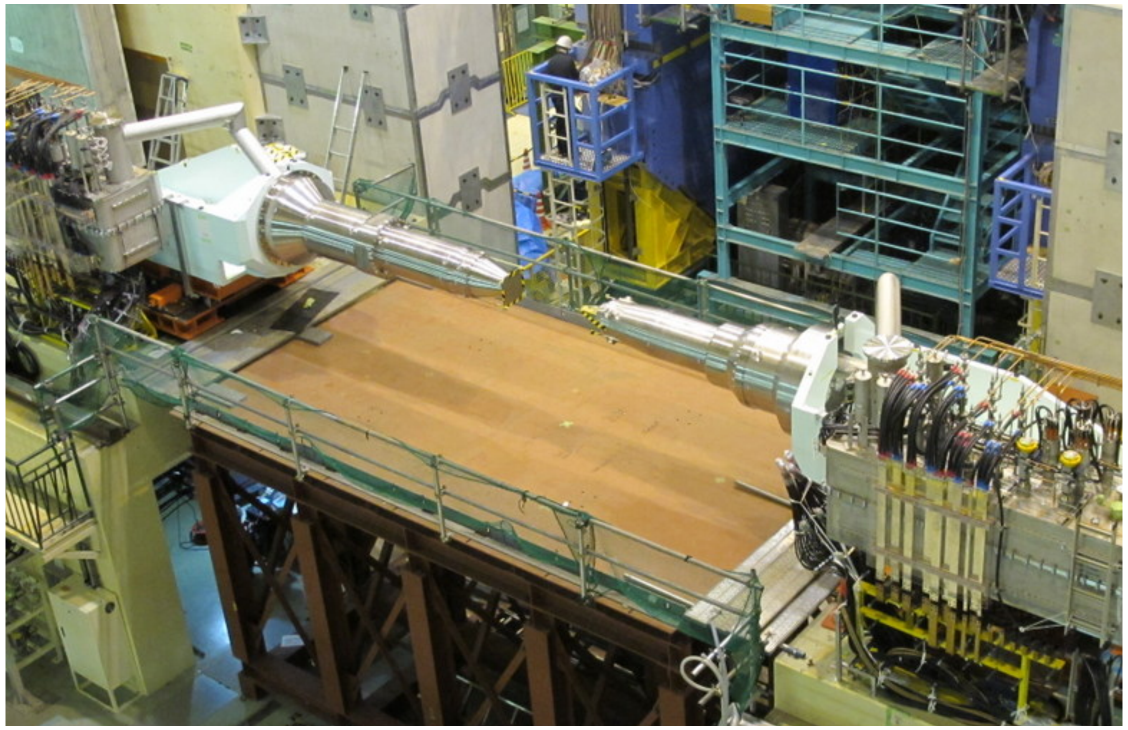
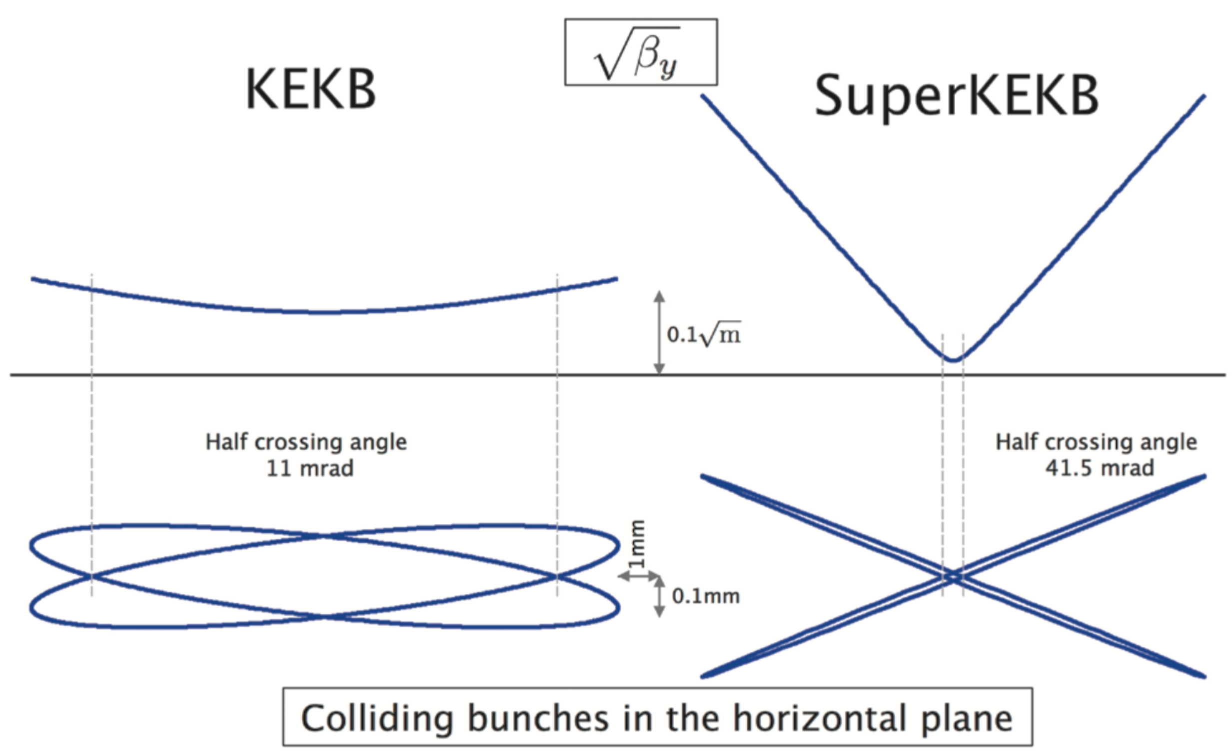
  - Field quality
  - Magnet center
- Operation
  - Stability of power supply for QCS quads.
  - Quench
  - Flux creep
- Upgrade options for QCS



From KEKB to SuperKEKB

Machine parameters of KEKB and SuperKEKB

	KEKB		SuperKEKB	
	LER	HER	LER	HER
Beam Energy [GeV]	3.5	8.0	4.0	7.0
Crossing angle [mrad]	22		83	
β_y^* [mm]	5.9	5.9	0.27	0.30
σ_y^* [nm]	900	900	48	62



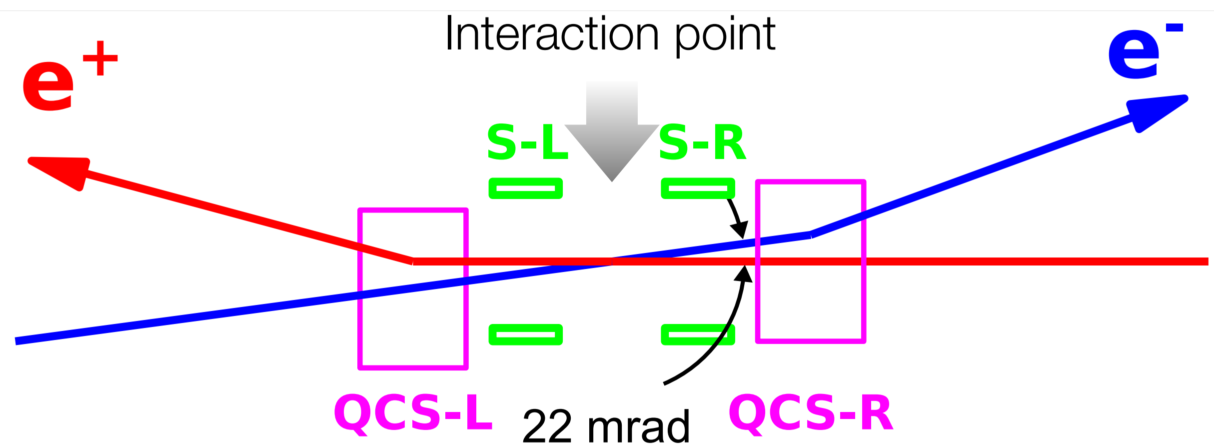
- Larger crossing angle
- Smaller beam size

K.Akai and H. Koiso, J. Particle Accelerator Society of Japan, Vol. 15, No. 4, 2018

QCS for KEKB and SuperKEKB

KEKB

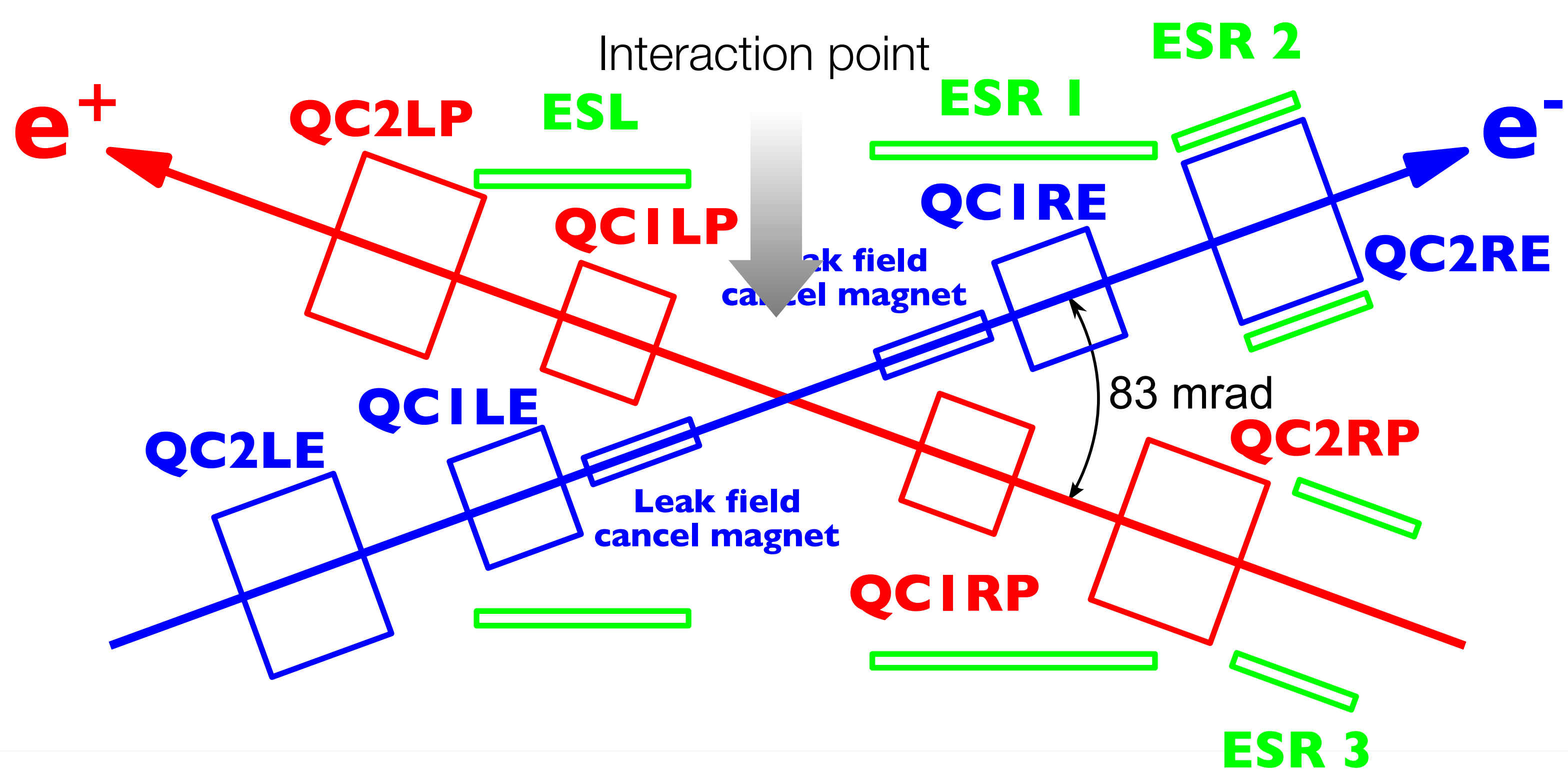
2 sc quads. and 2 sc solenoids



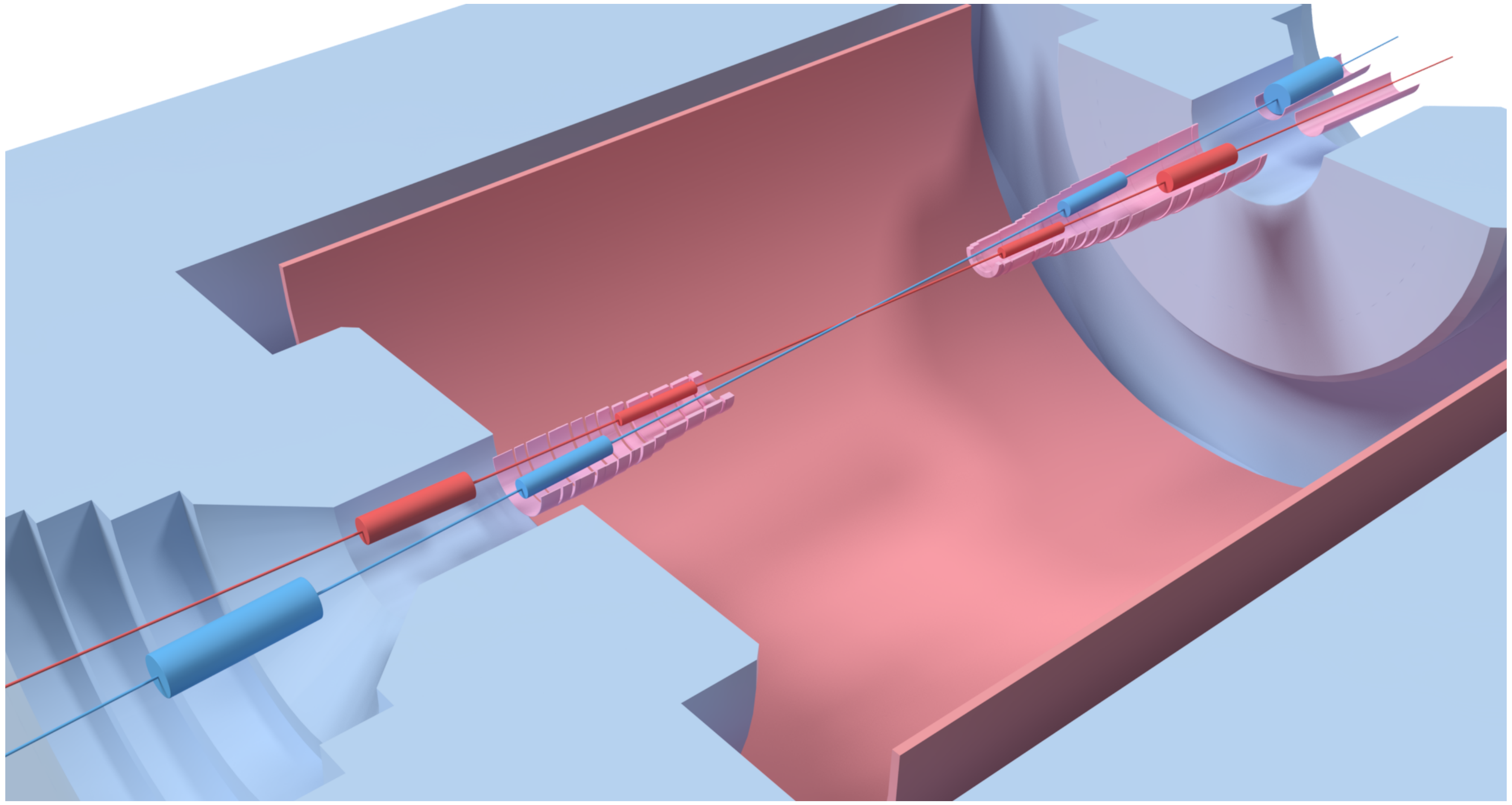
SuperKEKB

8 sc quads., 4 sc solenoids
and two cancel magnets

Electron and positron beam
have quadrupole doublets
independently.

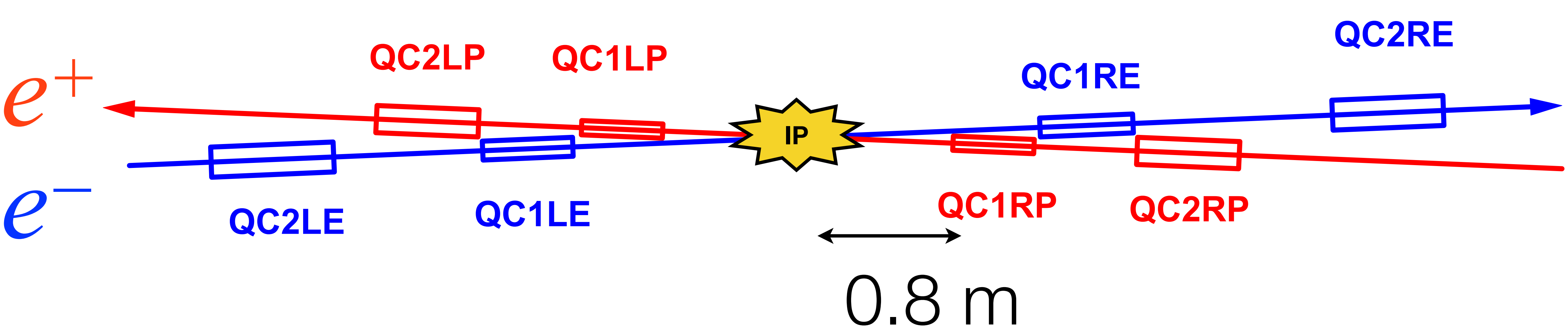


Final focus system: QCS



Final focus system (QCS) of SuperKEKB

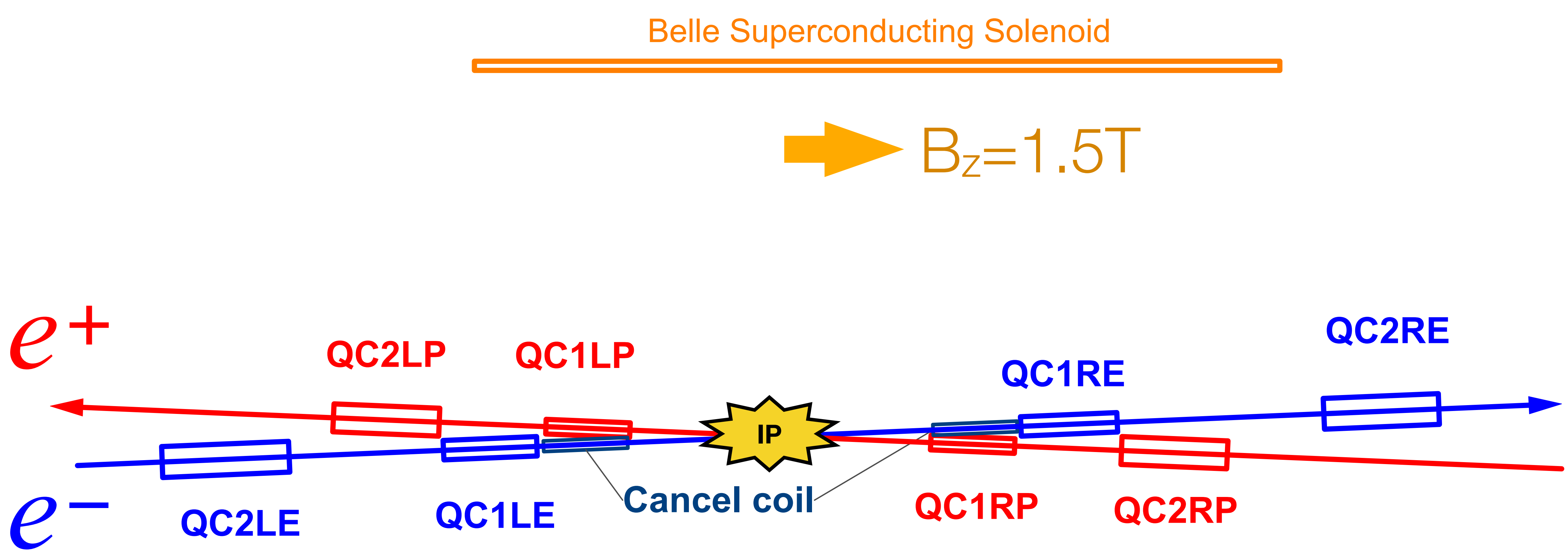
- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils



Final focus system of SuperKEKB

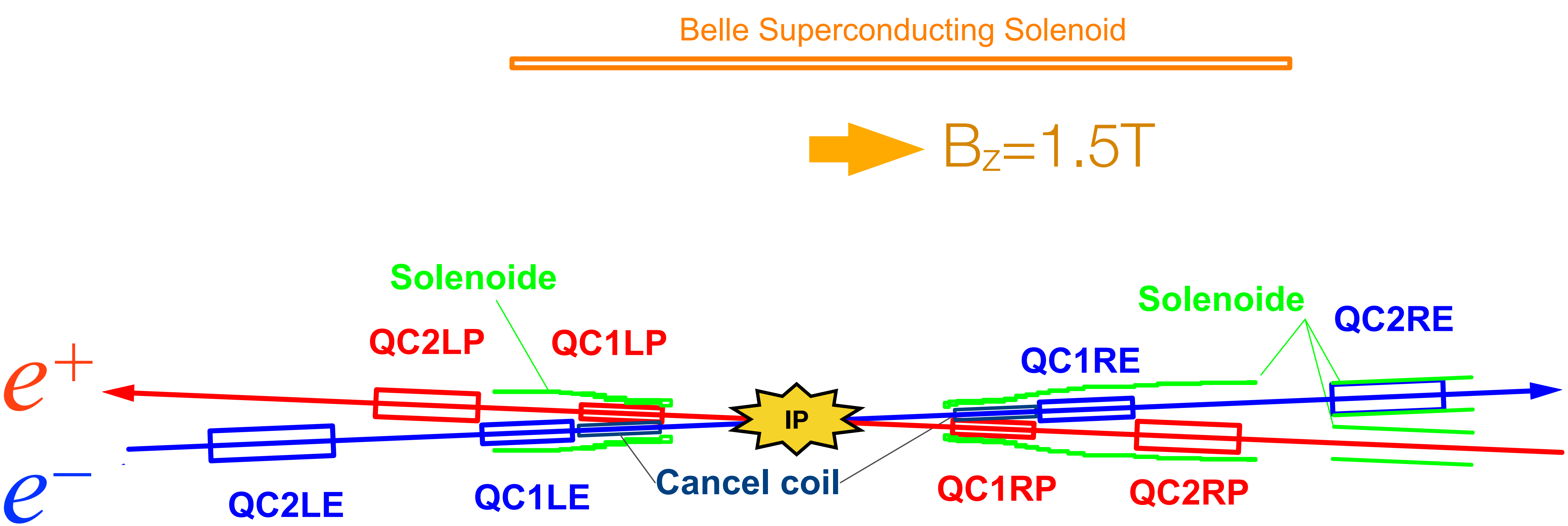
- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils

- The final focus system is located in the large detector solenoid

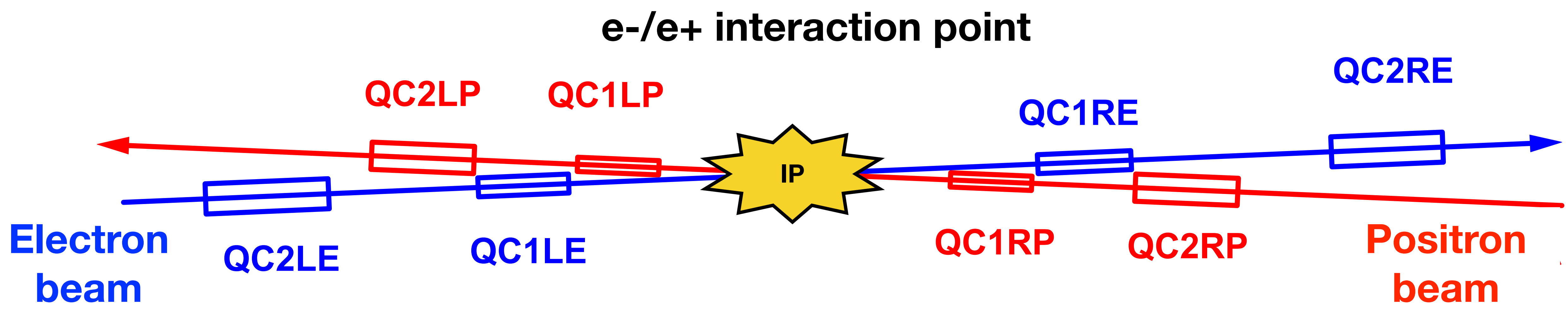


Final focus system of SuperKEKB

- QCS consists of
  - 4 quadrupole magnets (= 2 pairs of doublets) for each beam line
  - 43 corrector/cancel coils
  - 4 compensation solenoids (to compensate Belle II solenoid field)
- The final focus system is located in the large detector (Belle II) solenoid

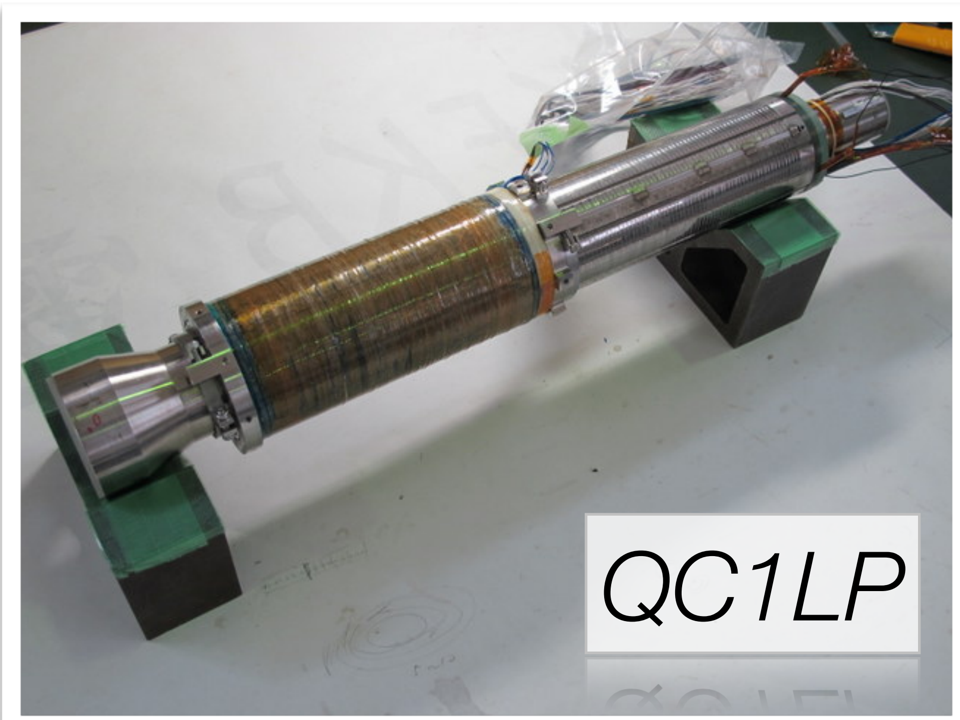


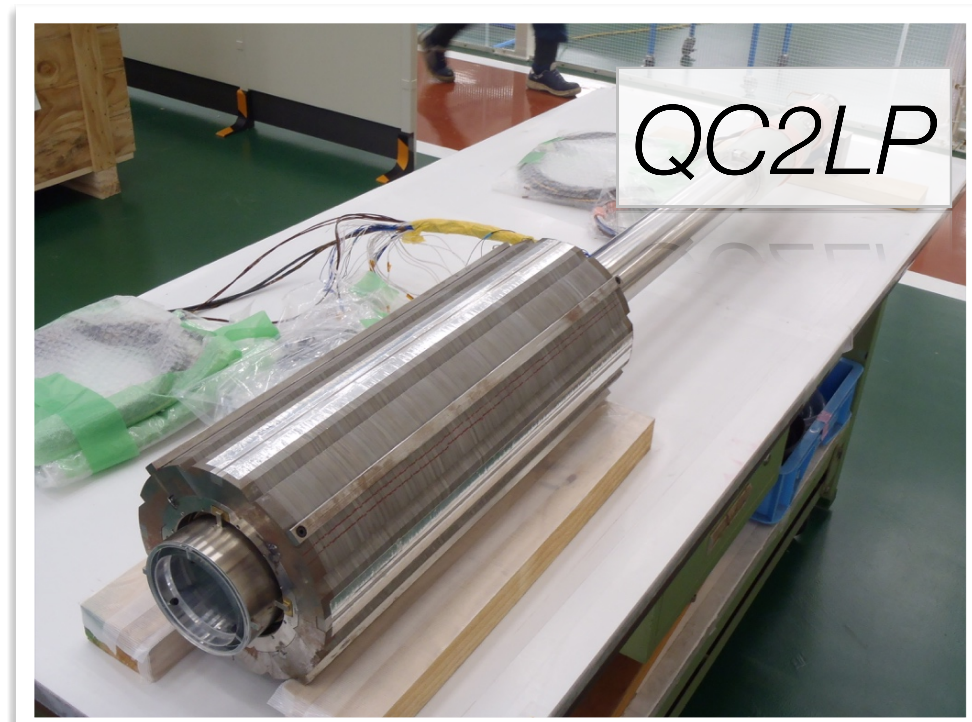
Main parameters of QCS quadrupoles

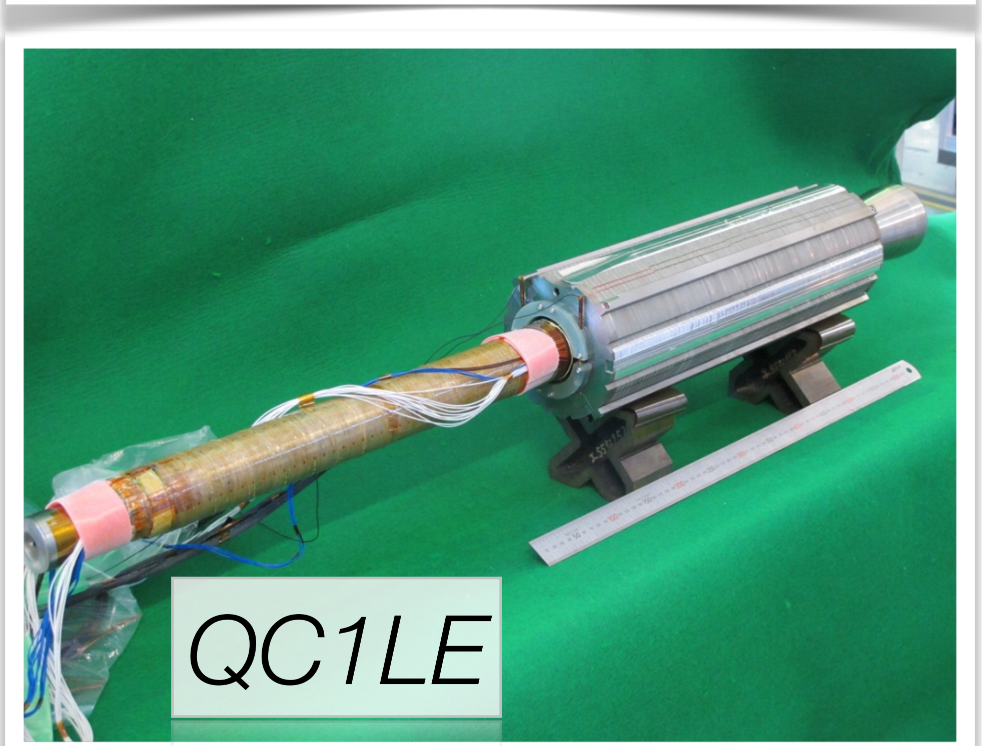


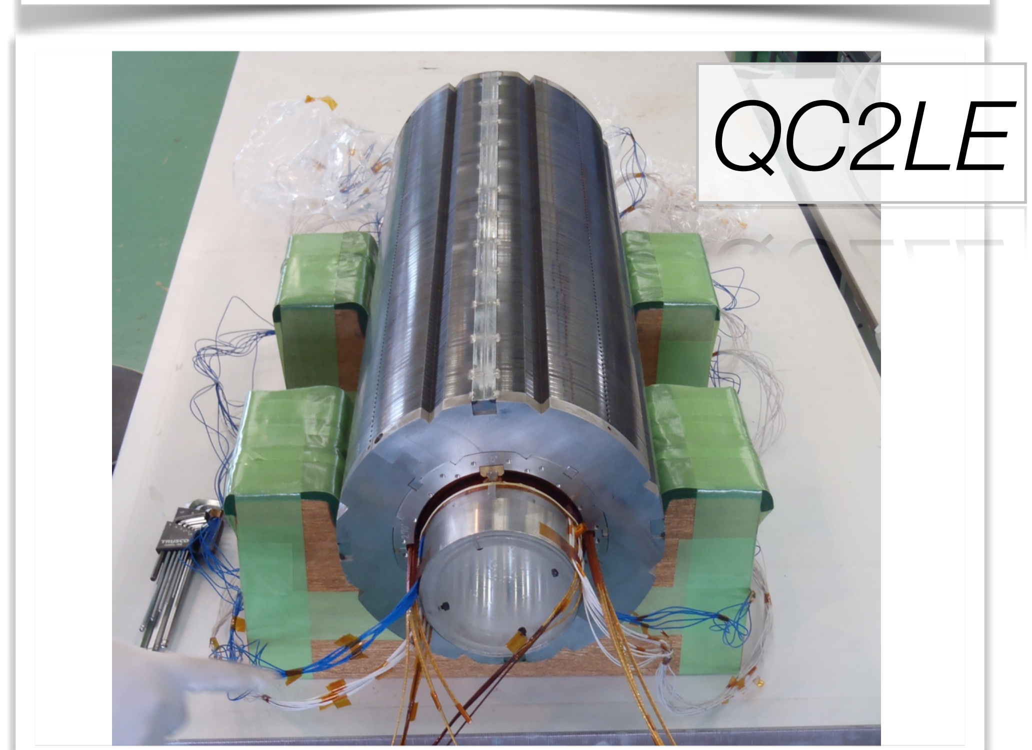
Magnet Name	G [T/m]	I [A]	Inner Radius [mm]	Effective Length [mm]
QC1LP/ QC1RP	68.9	1625 / 1624	25	334
QC2LP/ QC2RP	28.1 / 26.3	877 / 822	53.8	410
QC1LE/ QC1RE	72.2 / 70.9	1580 / 1490	33	373
QC2LE/ QC2RE	28.4 / 32.4	977 / 1070	59.3	537/419

Quadrupole magnets (on left side of IP)

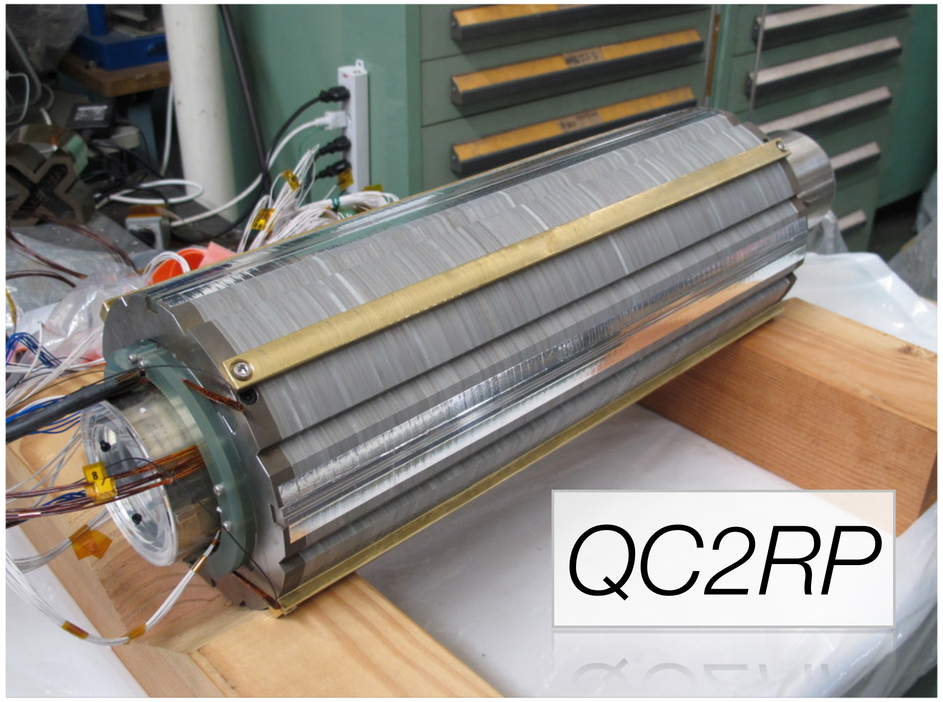


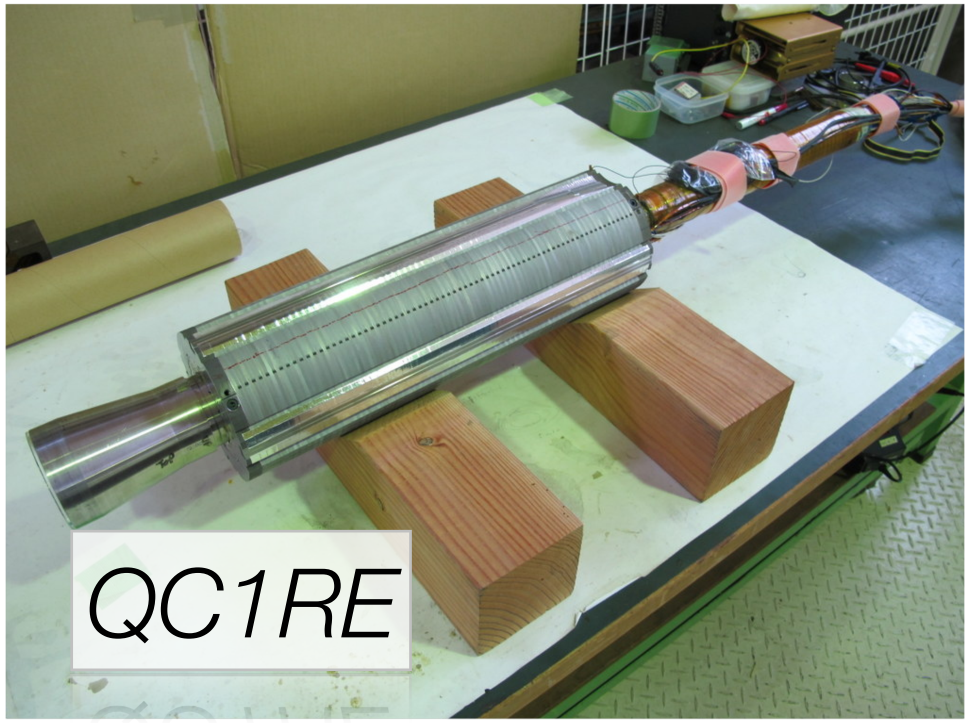




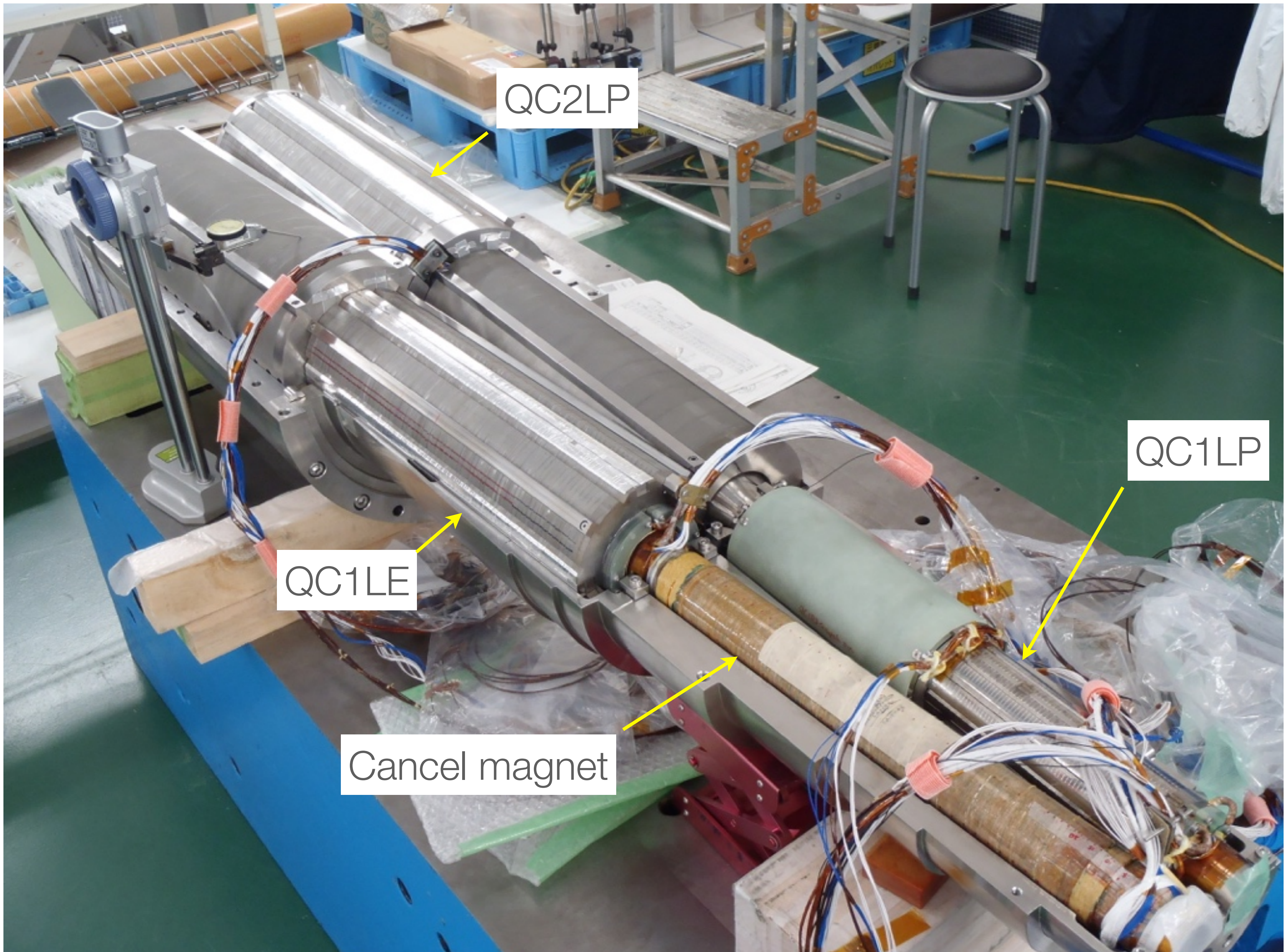


Quadrupole magnets (on right side of IP)





Assembled three quadrupole magnets



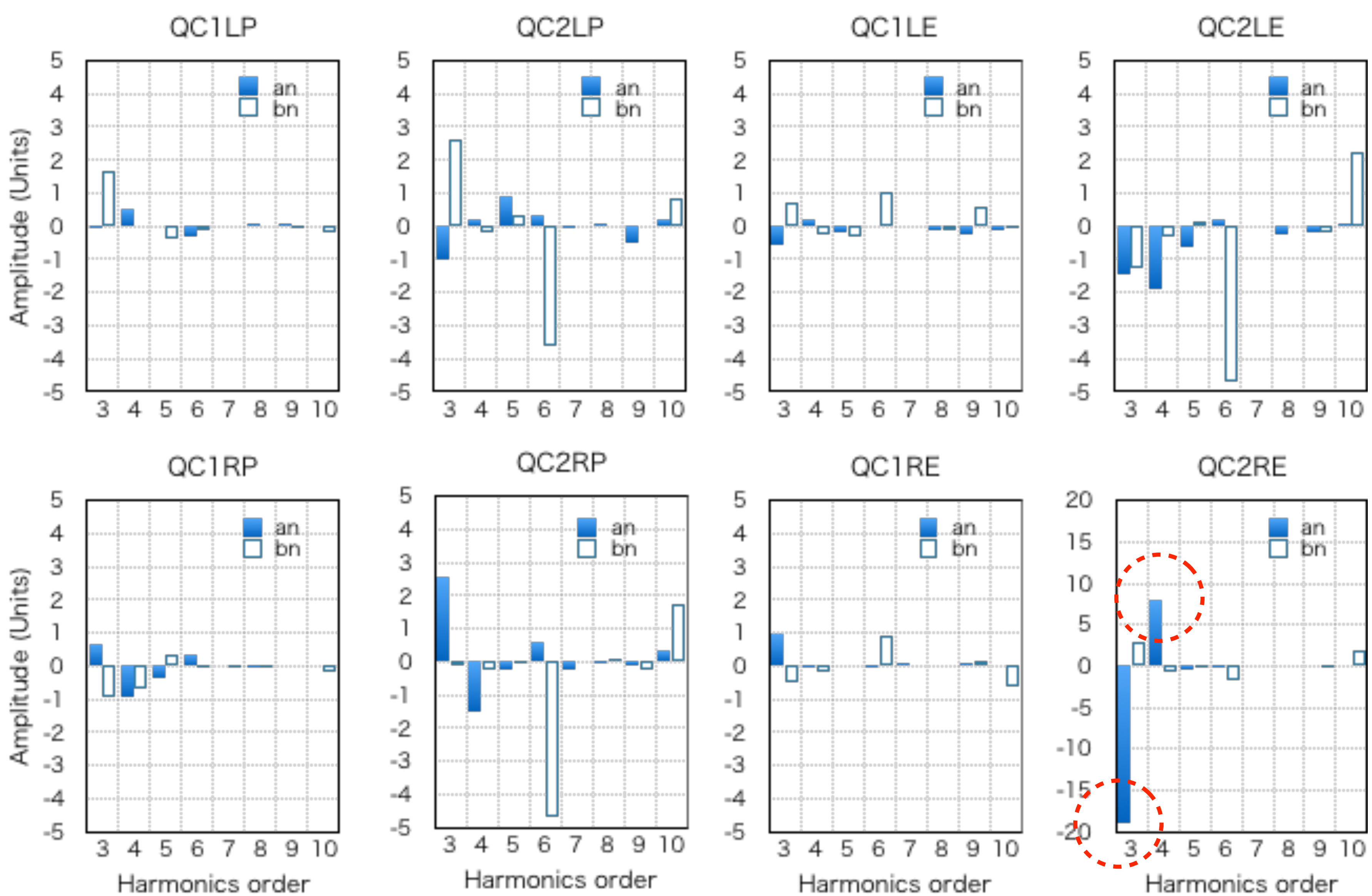
Magnetic measurements

Magnetic measurement for QCS at IR

- We performed several magnetic measurements at IR
  - We need to know combined field with Belle II solenoid and compensation solenoid.
  - We need to impact of magnetic force of solenoid to magnet alignment
- Magnetic measurements:
  - Measurement of B-field multipole with harmonic coil
  - Measurement of magnet center with single stretched wire method.
  - Measurement of solenoid field with Hall probe

Higher order harmonics of quadrupole magnets

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



"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

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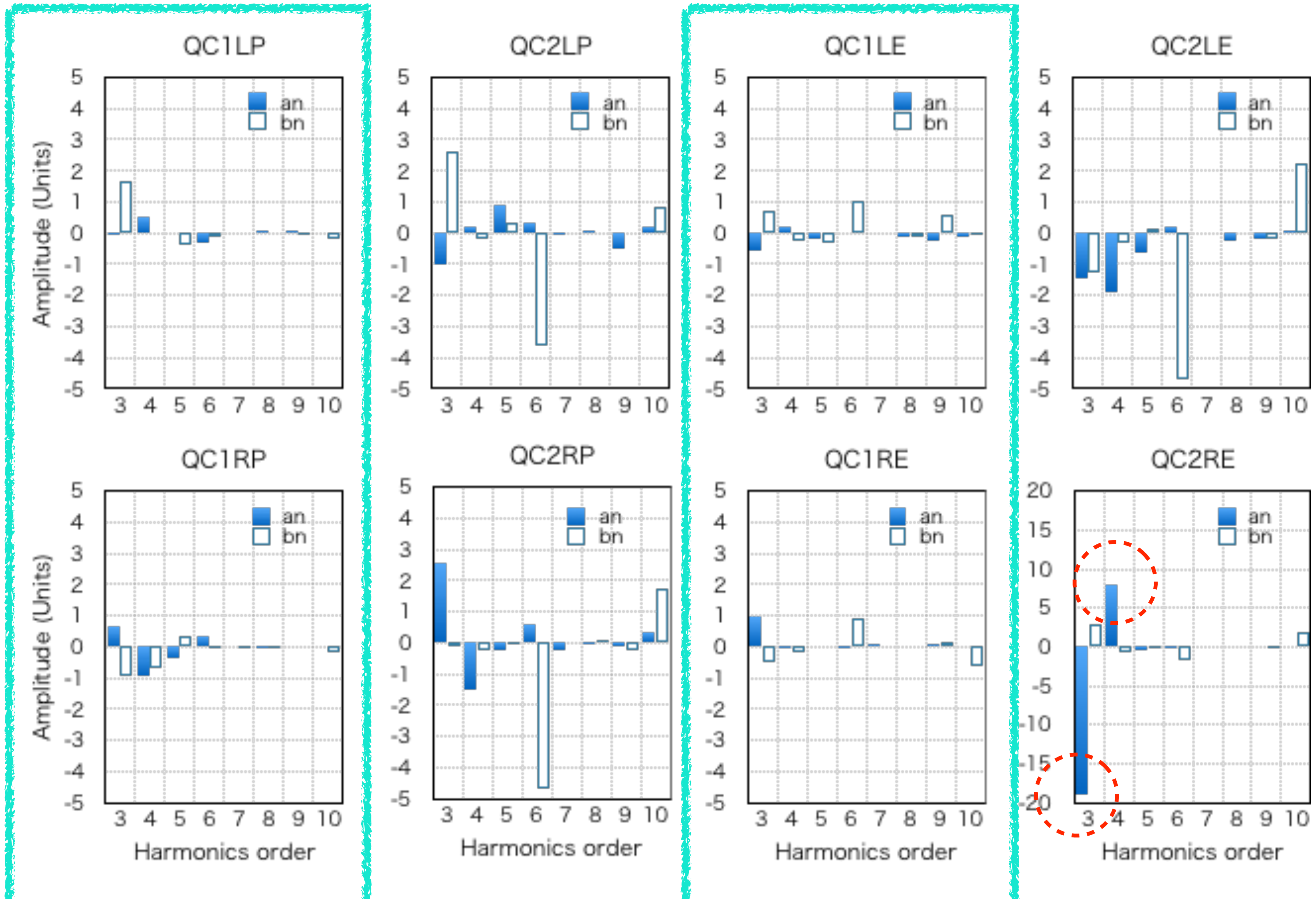

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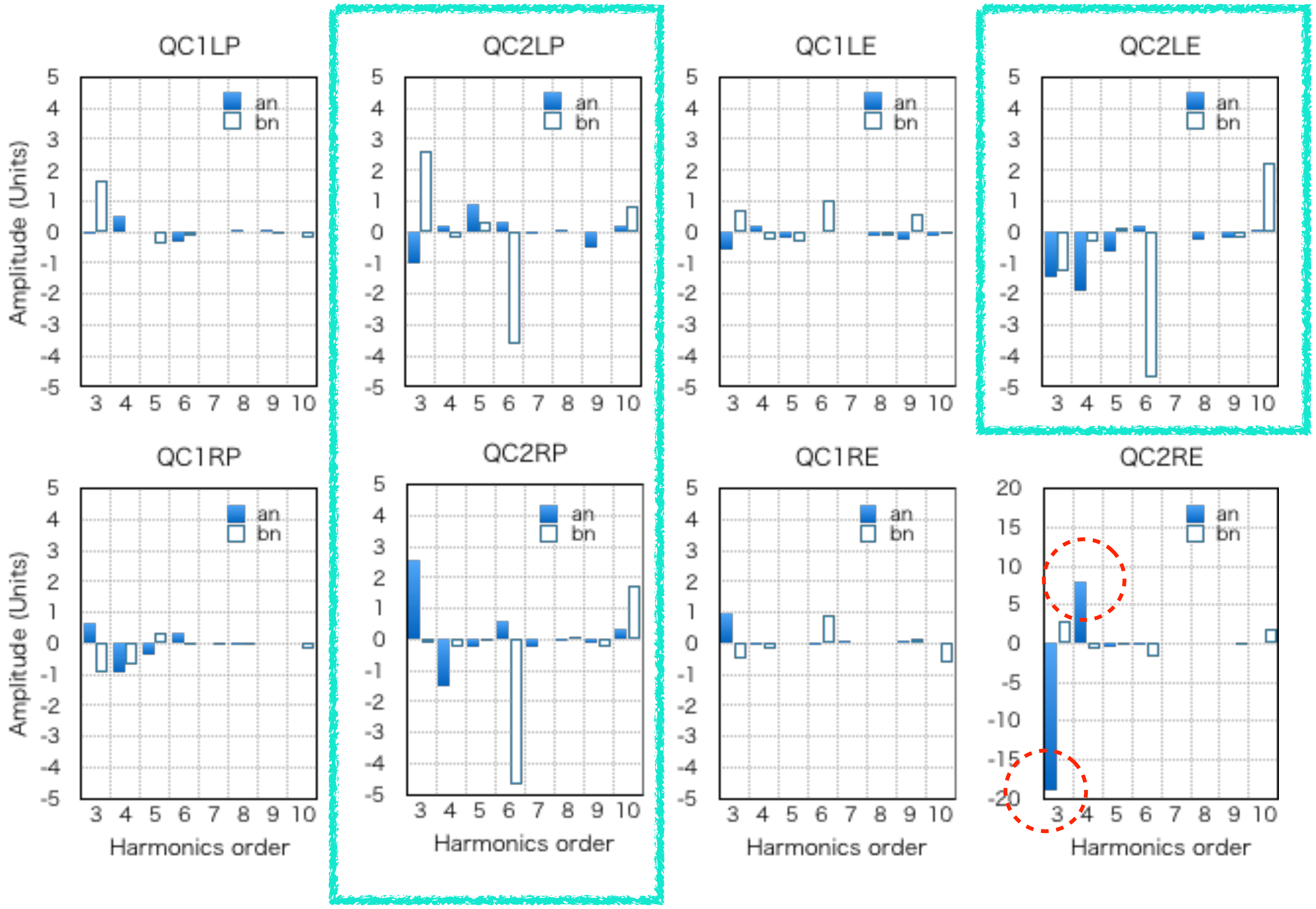
$$B_y + iB_x = B_2 \sum_{n=1}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$



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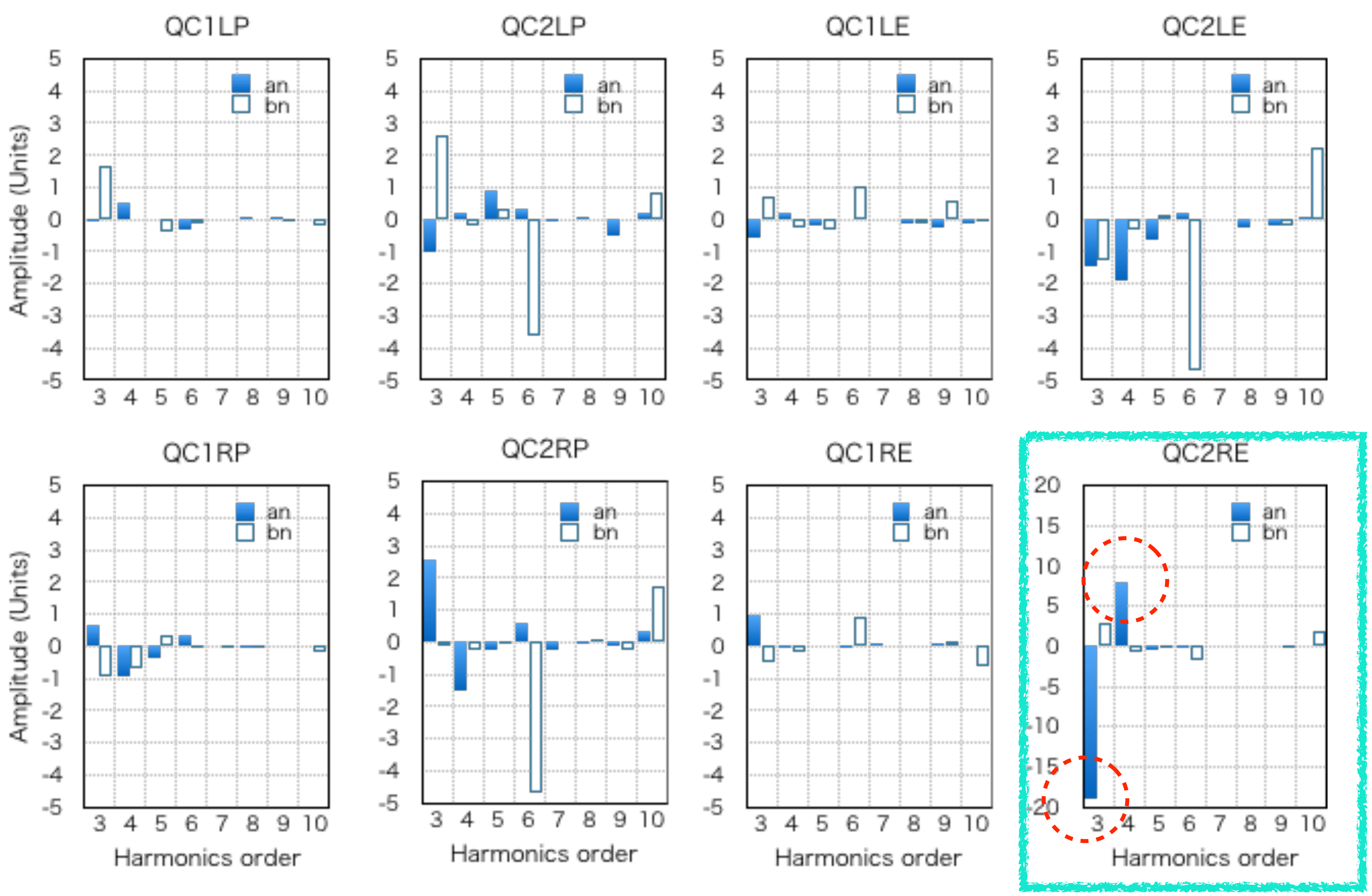


Tolerances

Corrector magnet can correct

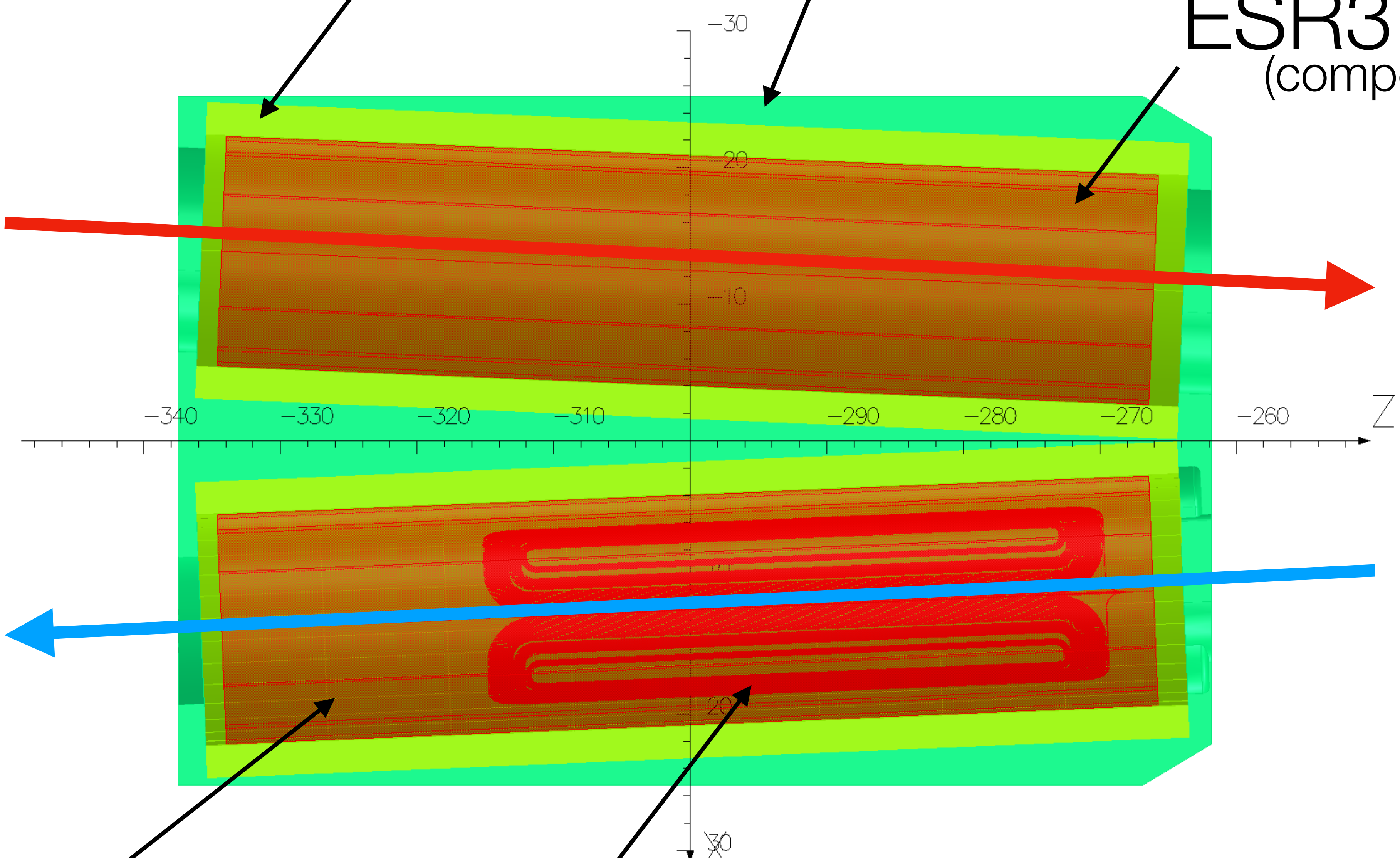
n=3 : < 10 units

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

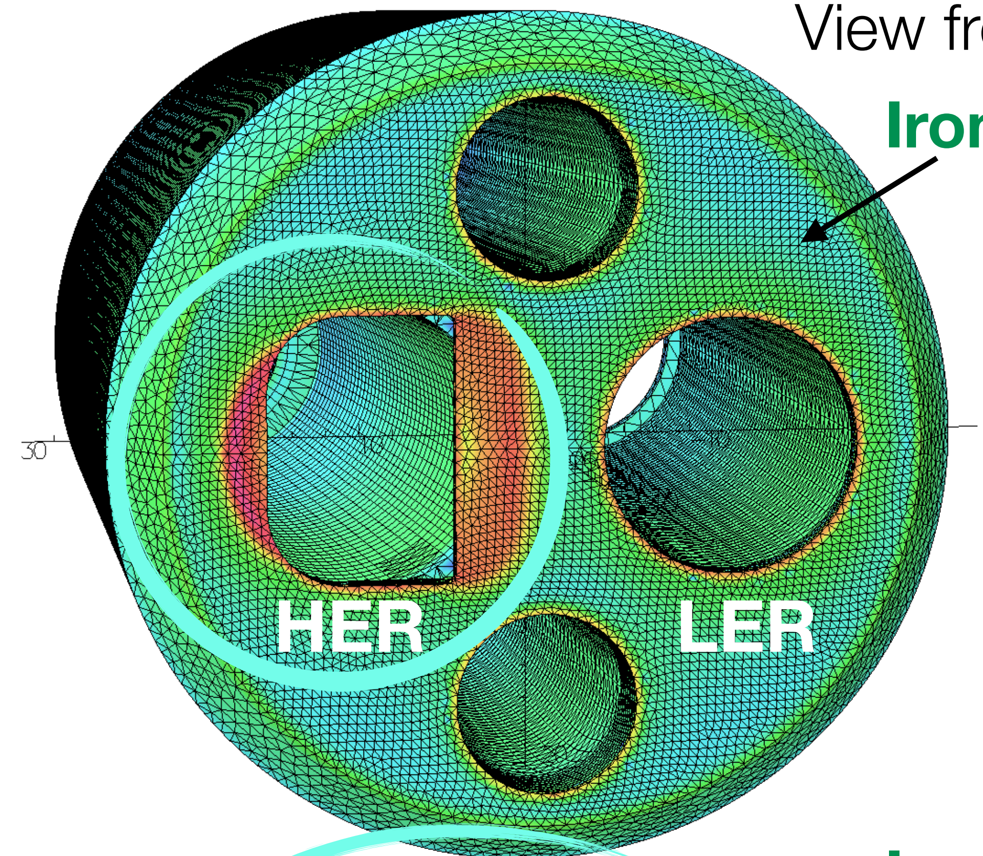
QCS-R rear cold mass with QC2RE



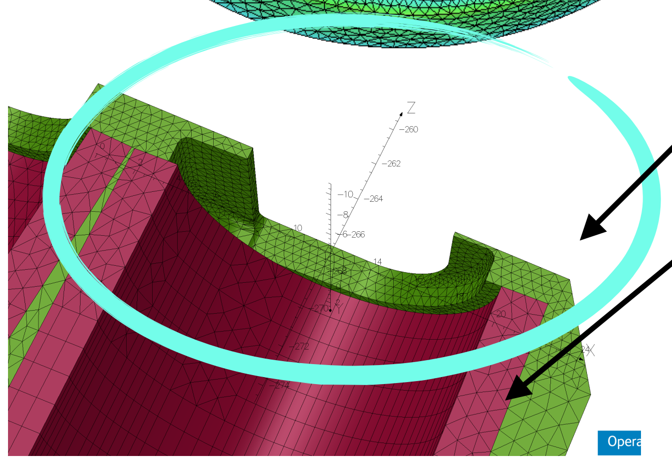
- QC2RE is inside iron structure and yoke and compensation solenoid

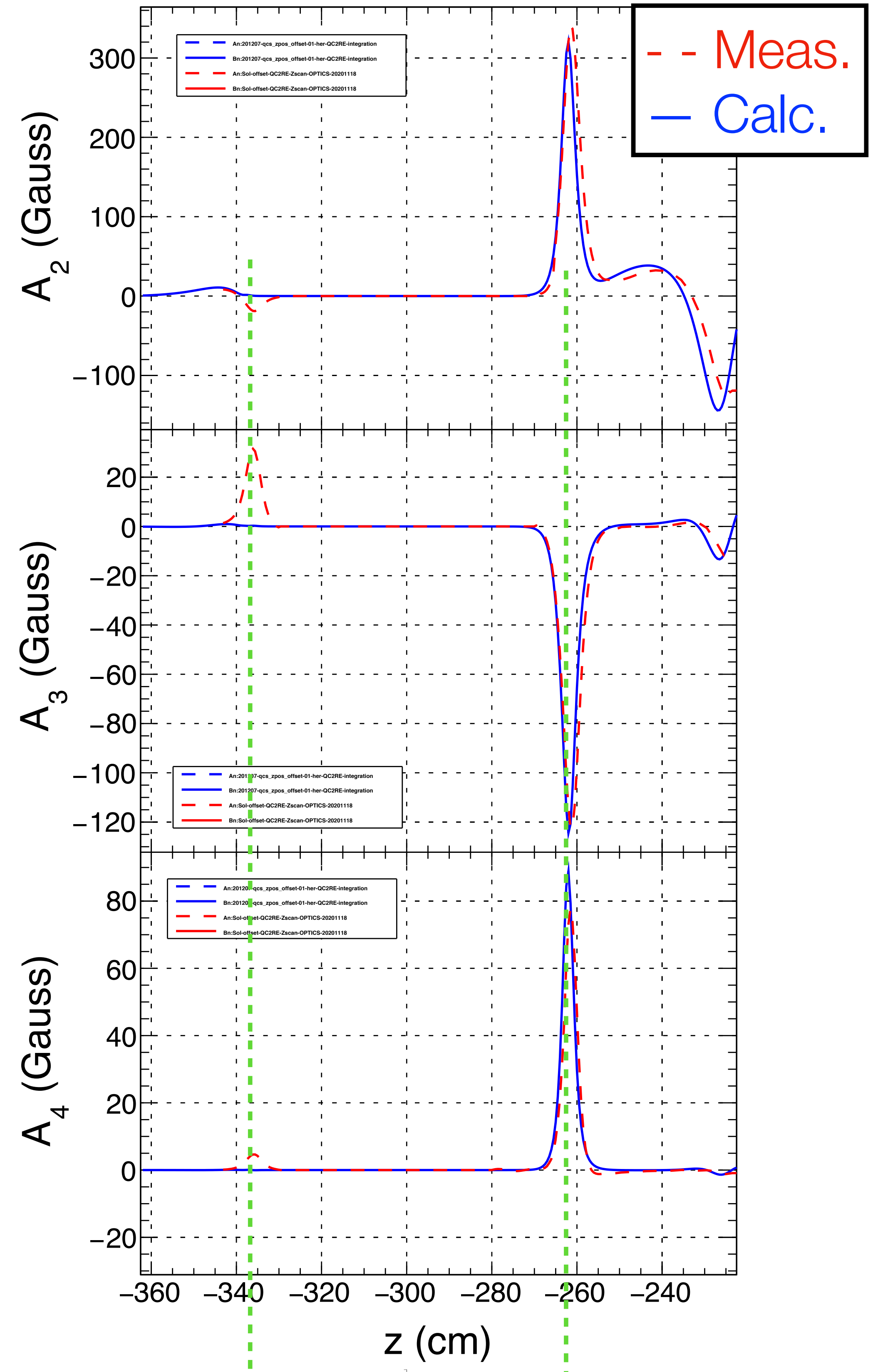
Axial profile of QC2RE region (on HER)

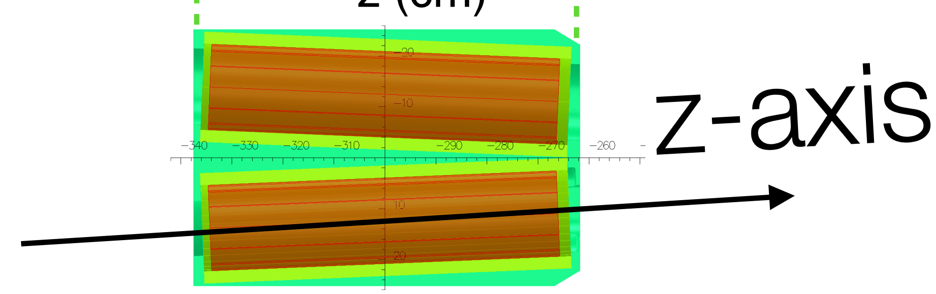
View from IP side



- No QC2RE
- Belle Sol: on
- Compensation solenoid: on

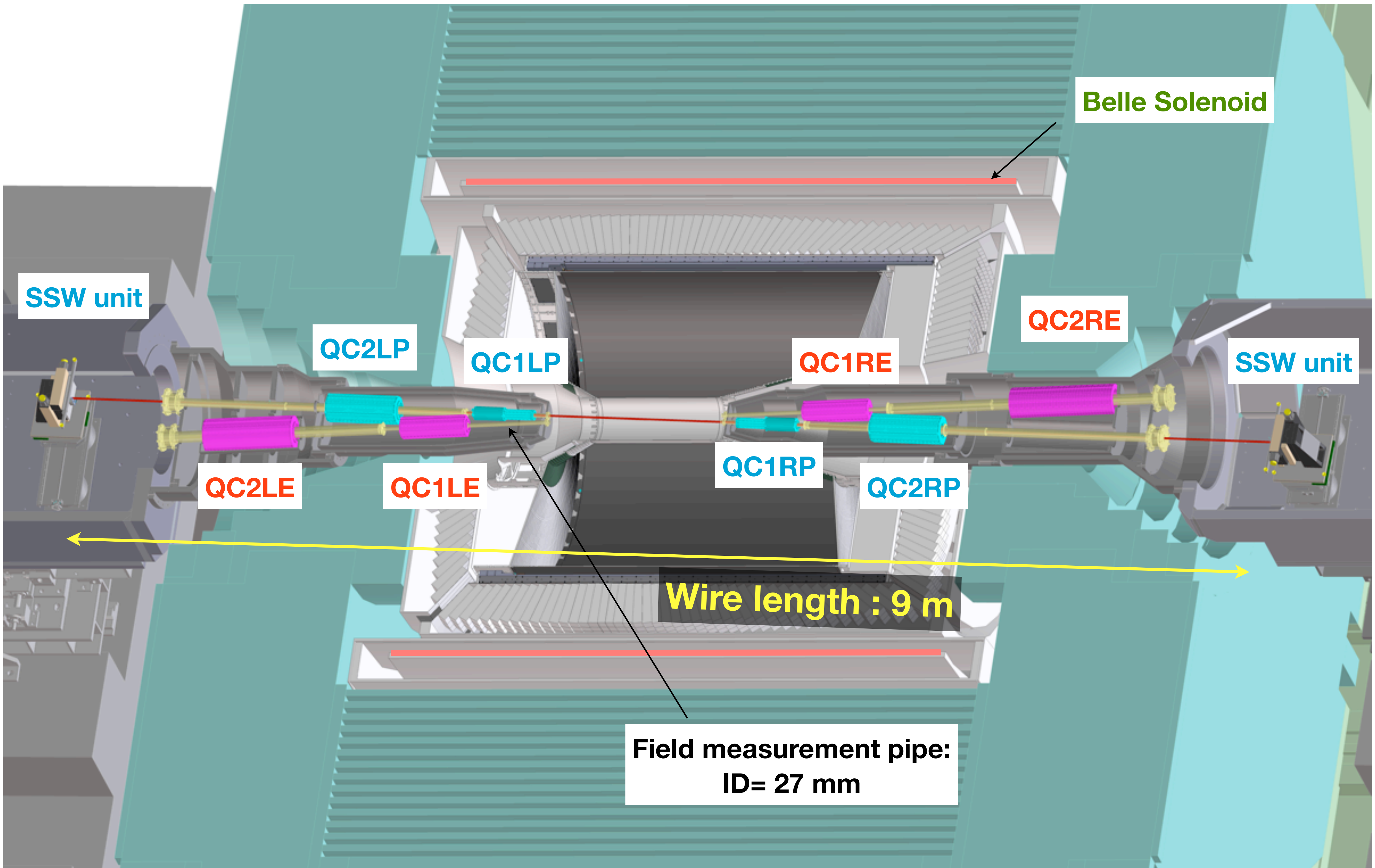




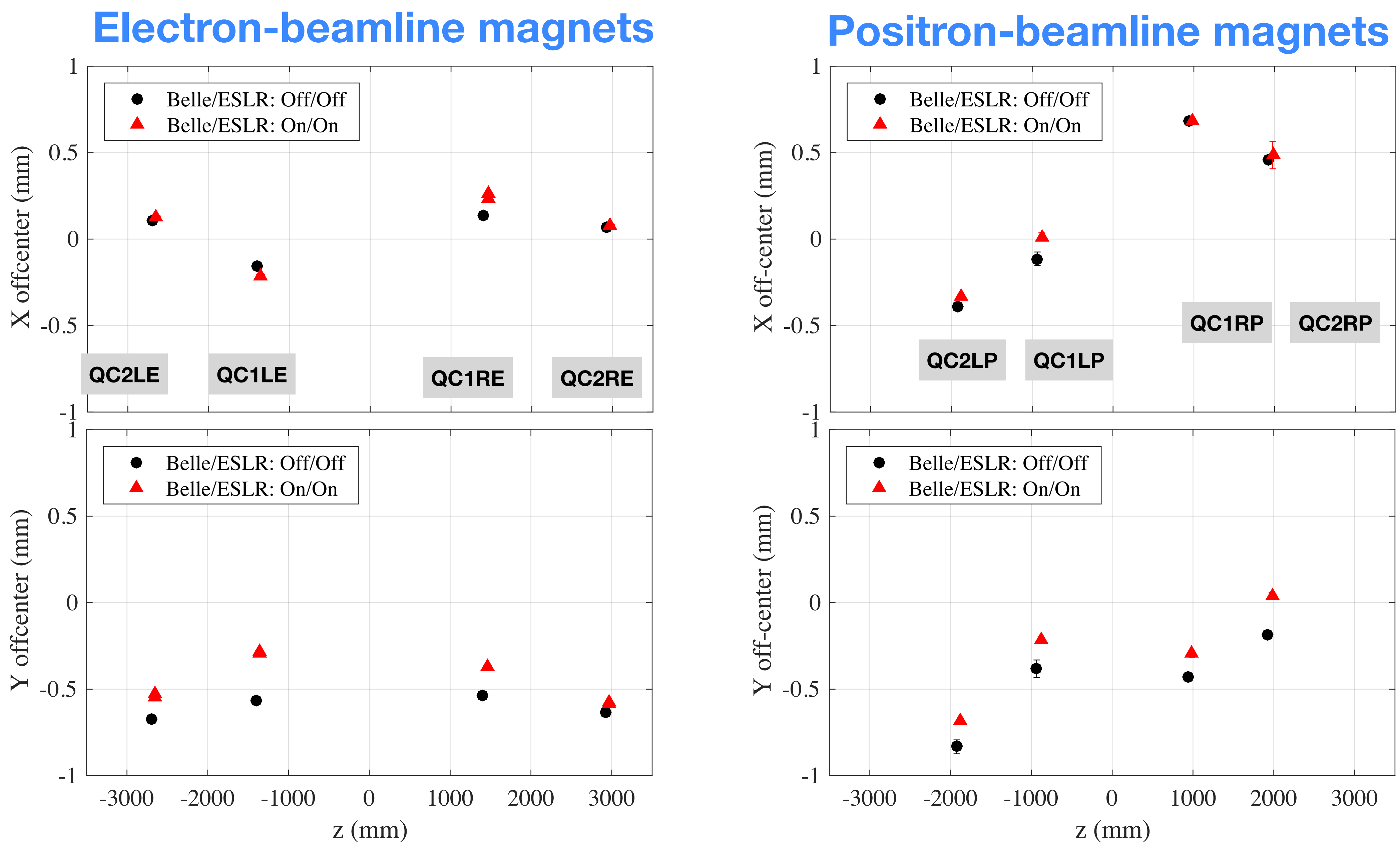


The source of the large skew components is an irregular shape (not circular shape) of the iron structure outlet with a solenoid field.
However, degradation of the beam optics by this error field is not observed up to now.

SSW measurement: setup



Magnet center for each magnet wrt design position



Magnet positions are varied with solenoid field turned on/off.
dx ~ 0.1 mm, dy~0.3 mm
The maximum offset from beam line are 0.7 mm for QC1RP in x-direction.
The maximum offset from beam line are -0.6 mm for QC2LP in y-direction.
These offset can be corrected with dipole correctors.

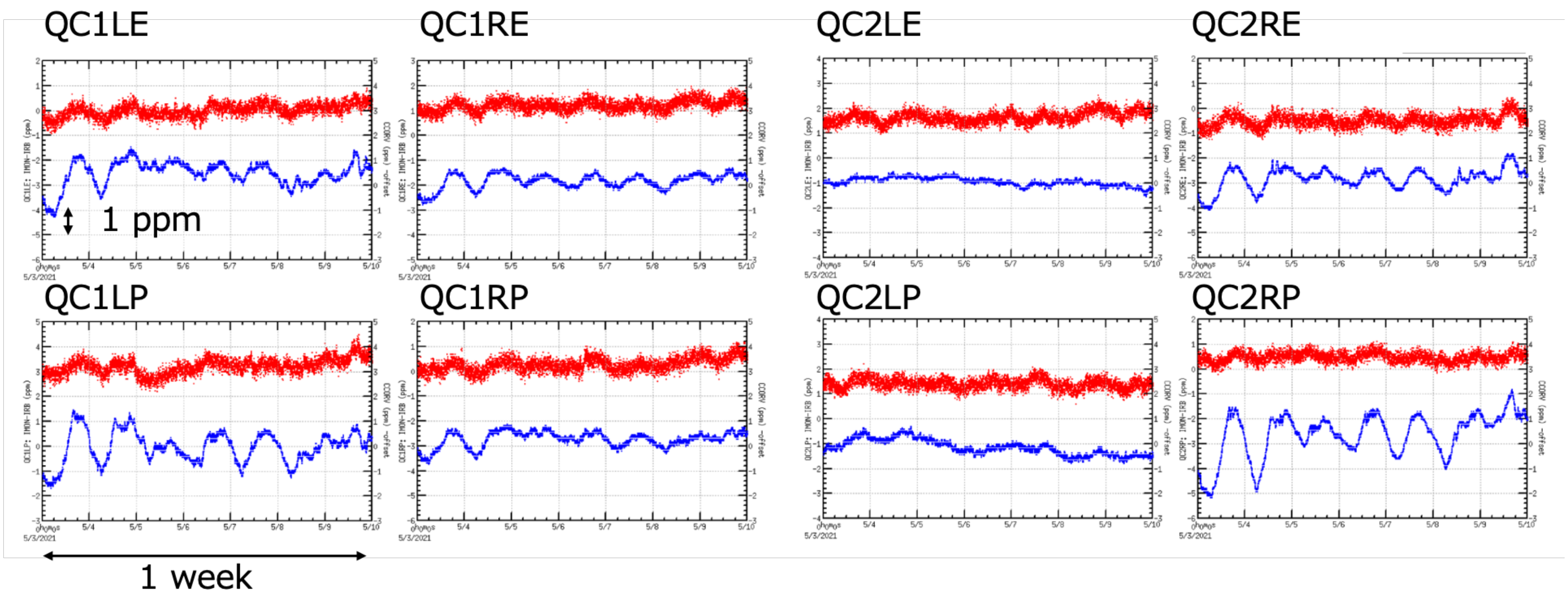
Operation

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)

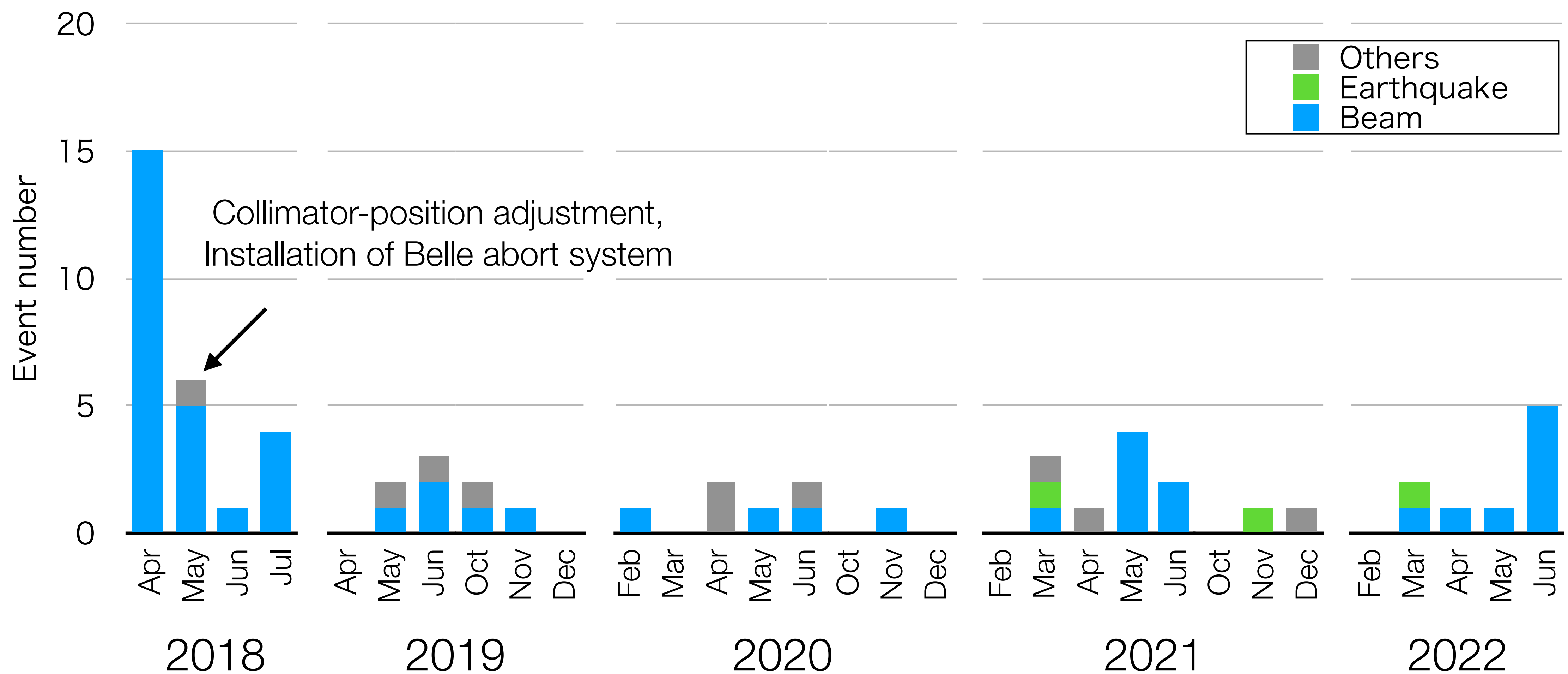
- Output current
- Correction value by digital feedback



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

T. Oki

Power shutdown of QCS magnets during beam operation



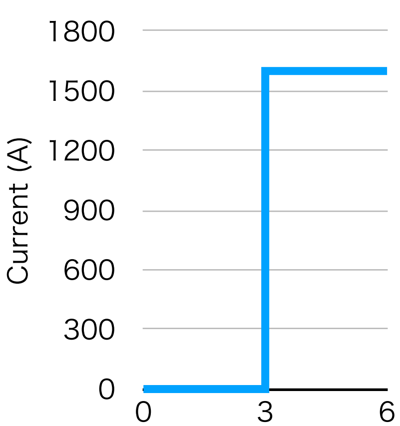
- Cause:
  - Quench induced by beam (~1-10 mJ)
  - Earthquake: not quench but induced voltage by change of coupling B-field between Belle solenoid and QCS solenoid over the threshold of a quench detector
  - Others: Power supply trouble (fixing every event and frequency is reducing), supply water trouble
- 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

Drift of strength of quadrupole magnet

- SuperKEKB is constant energy, so QCS operates in DC mode.
- We observed that the setting (model) tune changed after powering off/on the quadrupole magnet.
- It corresponds to the variation of 10^{-4} of the quadrupole field of QCS in a few hours.
- We performed measurements with the QC1P R&D magnet and found that the quadrupole field is varied by 3×10^{-4} in 7 hours.
- We deduced that it is caused by flux creep in superconductor cable.
- We avoid this by changing the ramping pattern of the magnet.

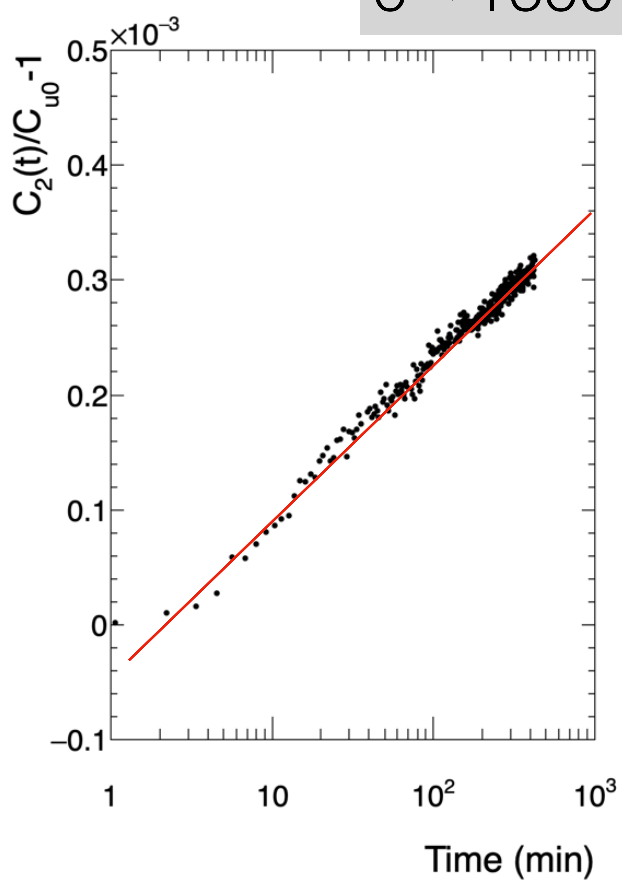
Current ramp pattern



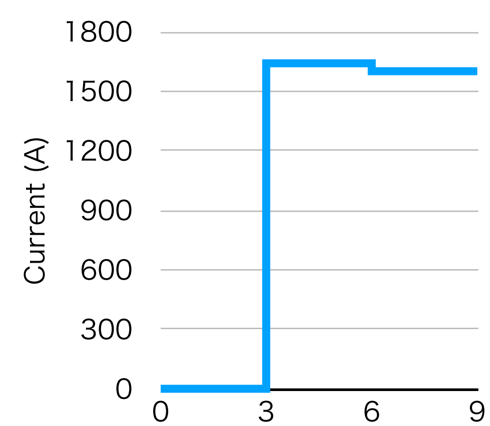
Variation: 3×10^{-4} per 7 hours

20220120-qc1p_prot_main_2_avg

0→1600 A



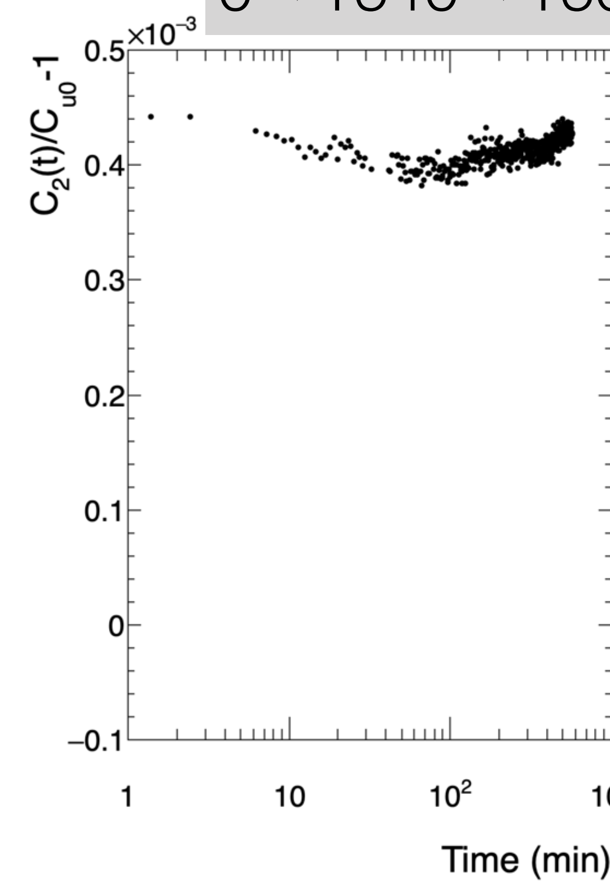
Current ramp pattern



Variation: 0.2×10^{-4} per 10 hours

20220209-qc1p_p

0→1640→1600 A



Upgrade options for QCS

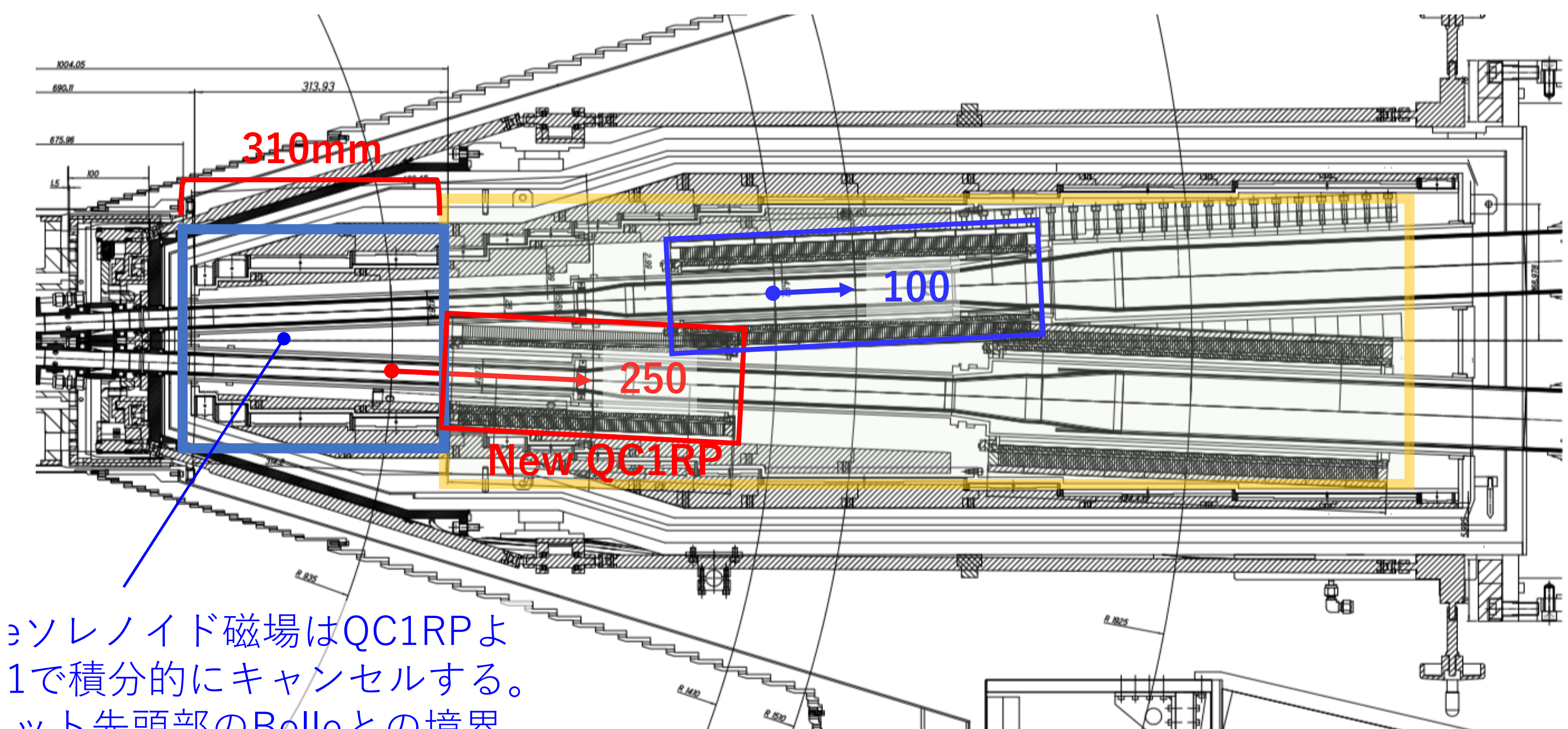
Upgrade plan

- SuperKEKB goal
  - Integrated luminosity: 50 ab^{-1} around 2030
  - Luminosity: ~6×10^{35} cm^{-2} s^{-1}
- Issues for a luminosity increase
  - Transverse Mode Coupling Instability
  - Beam lifetime / Injection efficiency ← QCS
  - etc.
- Upgrade schedule at IR
  - Long shutdown 2 (LS2) : 2026~

It is expected that QCS upgrade contributes to improvement of beam lifetime

Option A

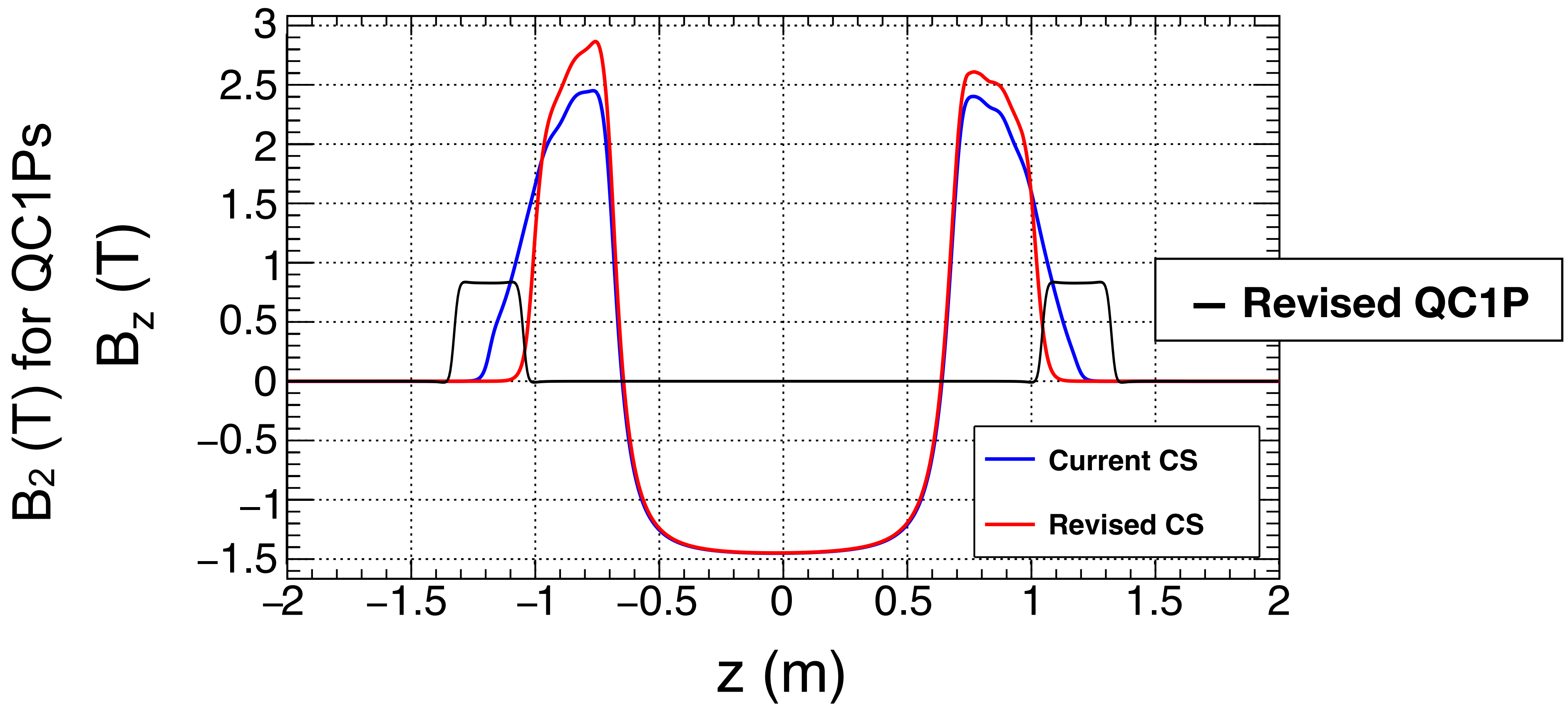
- Reduction of overlapping region compensation solenoid and QC1Ps (vertical final focus element for positron)
  - Move QC1RP and QC1LP by 250 mm away from IP
  - Enlarge QC1Ps aperture size as same as QC1Es
  - Move QC1RE and QC1LE by 100 mm away from IP
  - The compensation solenoid field region is shortened.



N. Ohuchi

Option A (cont.)

Axial profiles obtained from 3D model for OptionA and current version

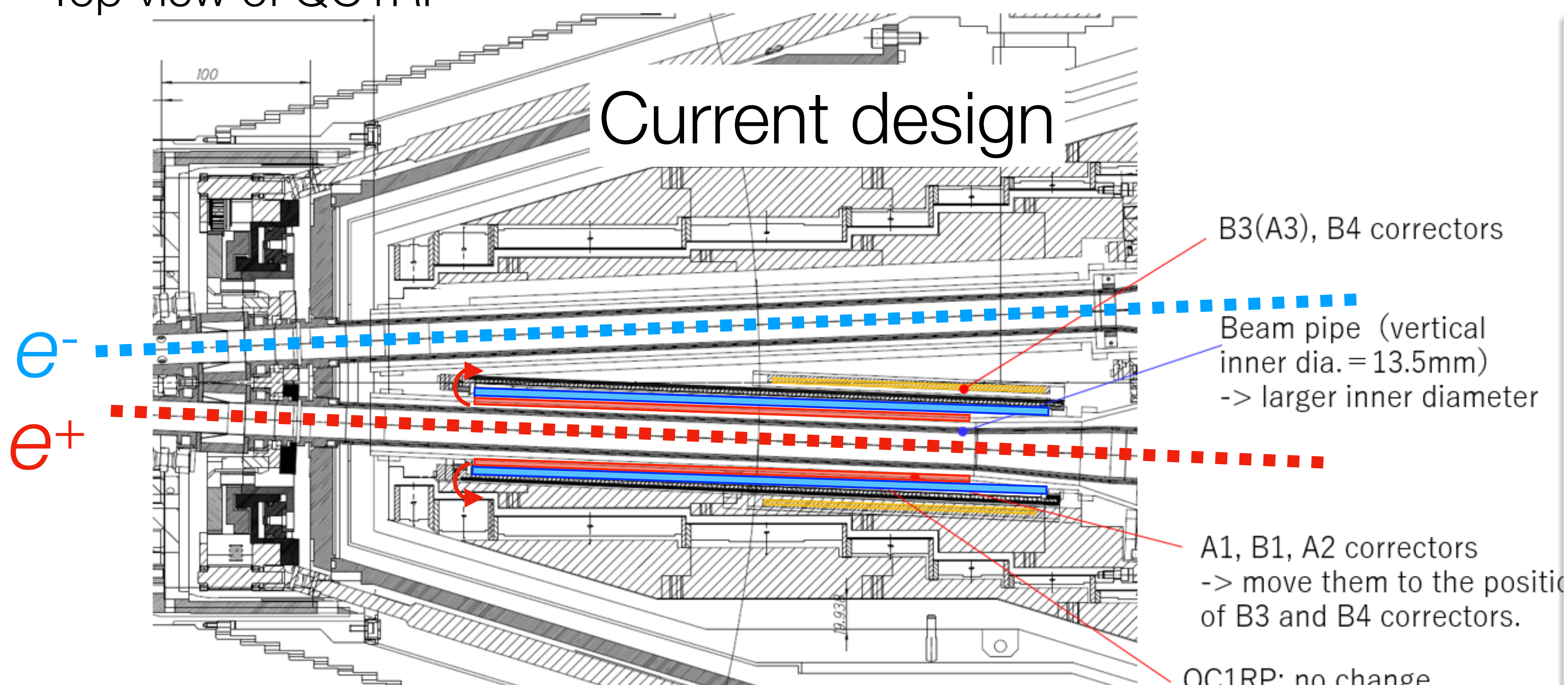


- The overlap region is reduced, and the increase of solenoid field strength is small.
- It is possible to make this magnet system.
- **However, no improvement in beam lifetime is expected.**

Option B

- Main quadrupole magnets, QC1s, QC2s are not modified.
- Corrector magnet inside QC1Ps are set on outside.
  - Corrector magnet for QC1Ps need to be reproduced.
- Enlarge the vertical aperture of beam pipe at QC1Ps

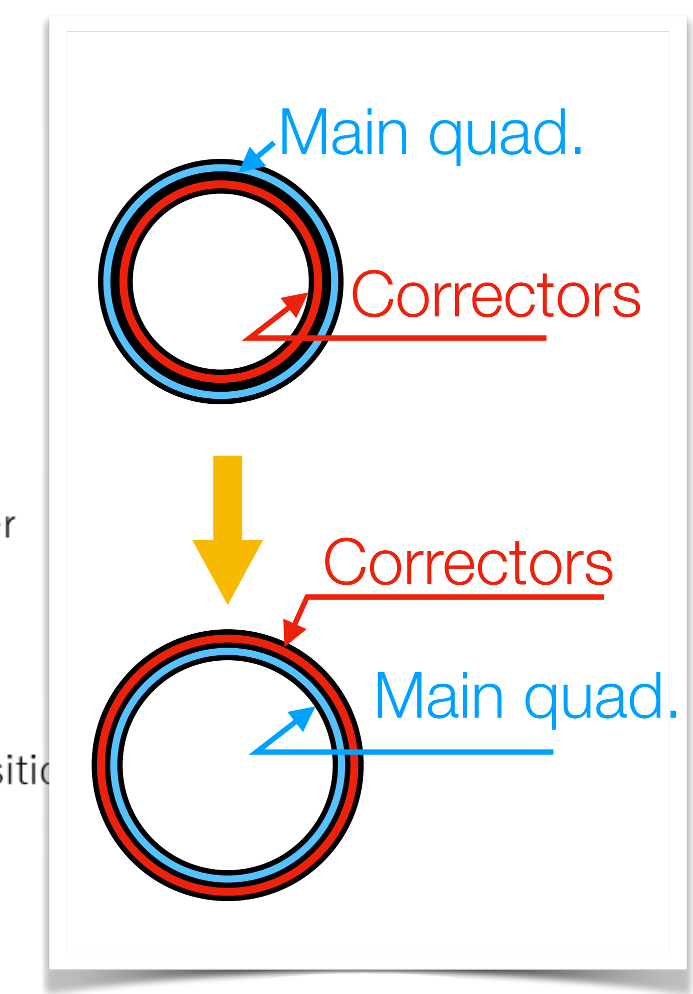
Top view of QC1RP



presented at the MDI meeting at Oc. 22, 2020

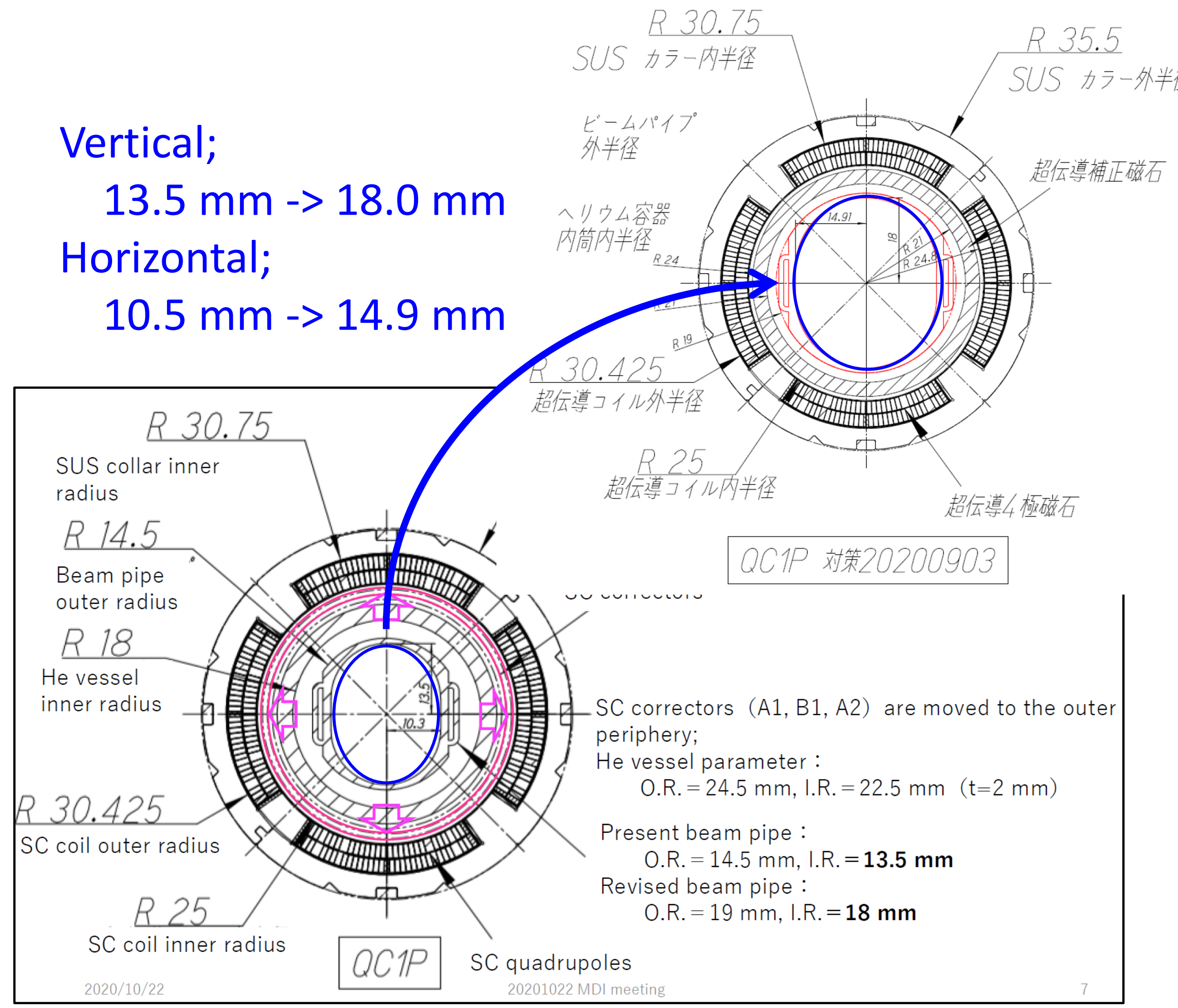
N. Ohuchi

QC1RP cross section



Option B (cont.)

- Corrector magnet design is underway (BNL)
- The vacuum group investigated the technical problem for the beam pipe modification.
- They found that we can enlarge beam pipe size
  - Vertical 13.5 mm → 18.0 mm
  - Horizontal: 10.5mm → 14.9 mm
- Effect
  - Get a larger collimator opening size
  - Reduce beam background
  - **<u>Does not improve beam lifetime</u>** because the dynamic aperture is smaller than the current beam pipe at QC1Ps

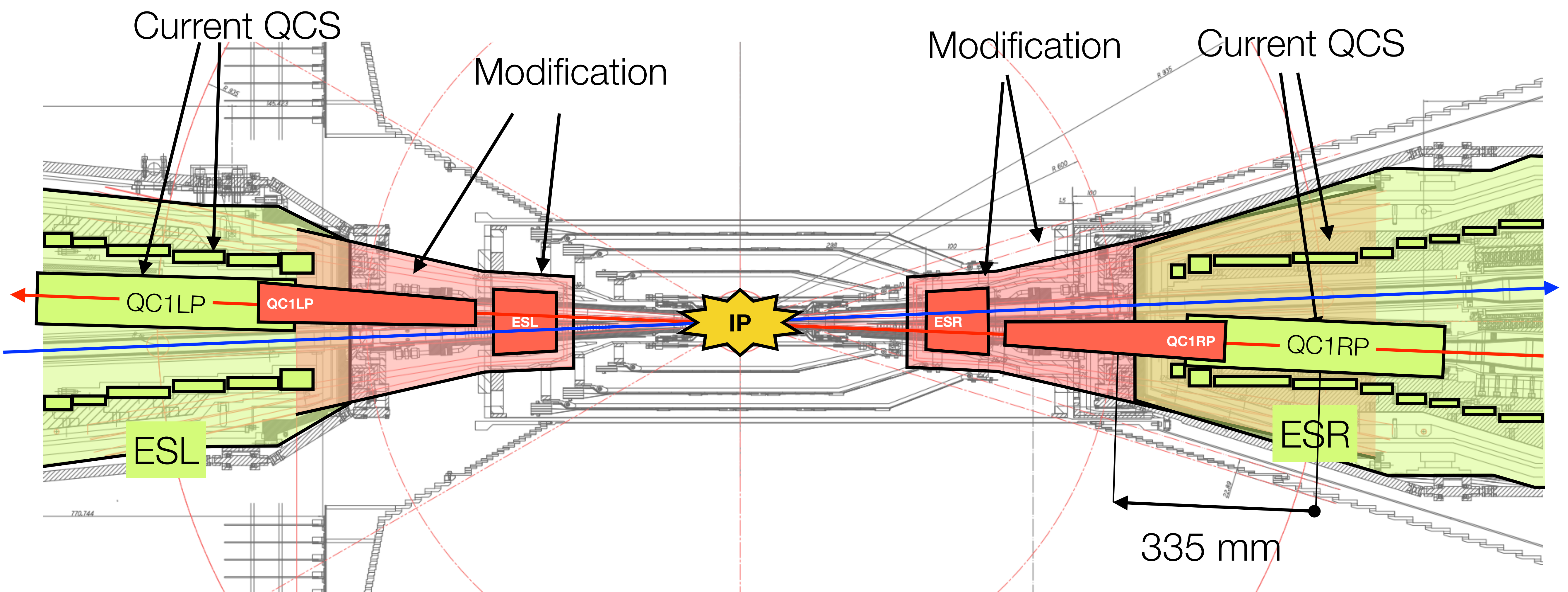


K. Shibata

We have not completely abandoned this option because it has some advantages.

Drastic modification at IR

- The solenoid and QC1s get closer to IP by 30 cm. However, modification of Belle II is needed.
- Lifetime increase by 2.5 times (from estimation with simple model by A. Morita)
- We have many issues which are needed investigations (no space for BPM, installation scheme, …)
- It is difficult to fit LS2 period.

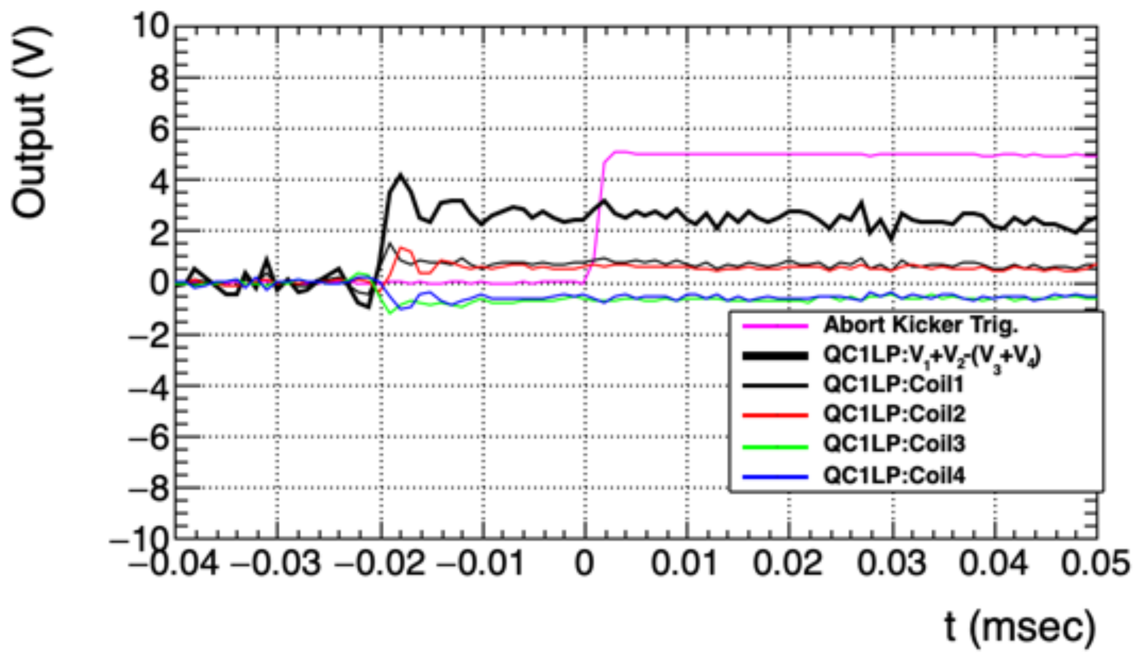


Summary

- We newly designed and constructed QCS for SuperKEKB
- QCS is consisted of 8 sc quadrupole magnets and 43 sc correctors/cancel magnets and 4 sc compensation solenoids.
- Magnetic measurement
    - Multipoles: unexpected multipoles were measured for QC2RE. Caused by irregular shape at iron structure inlet.
    - The magnetic field center was measured by SSW at the beamline.
- Operation
    - We have many quenches induced by the beam.
    - Induced voltage by earthquake sometimes over the threshold of quench detector.
- We investigated upgrade options for QCS. We still haven’t find any effective upgrade scheme for QCS.

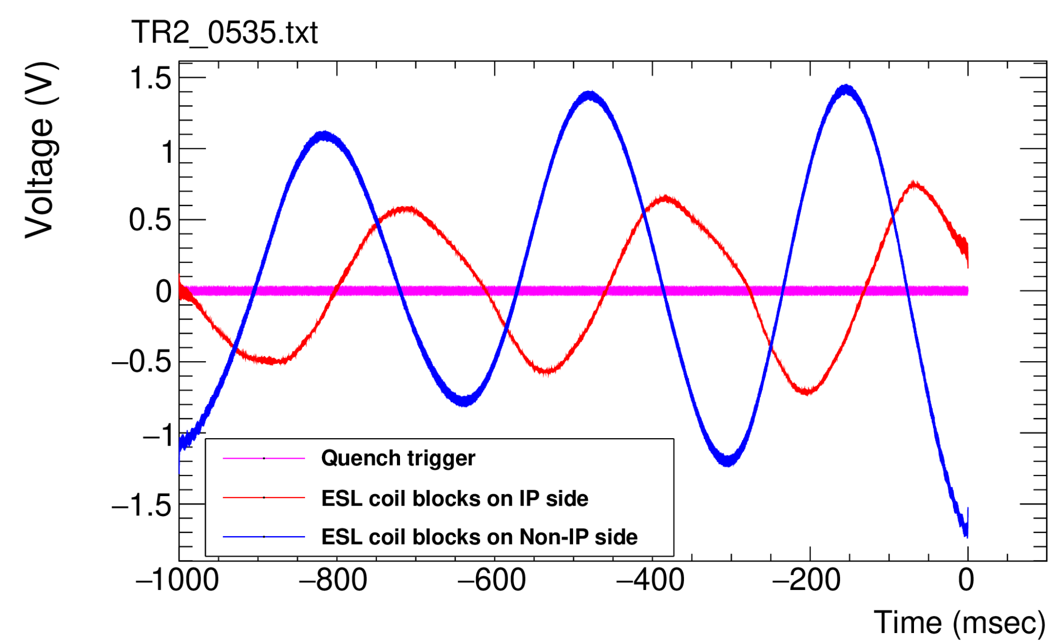
Difference of coil voltage profiles

Beam



Profiles of the main quadrupole coils

Earthquake



Profile of the compensation solenoid

- Beam: fast-rising (within 1 μsec)
- Earthquake: Slow oscillation pattern (~2 Hz)

Single stretched wire

- Purpose
  - Measurement of magnet centers of quadrupole magnets
- Motivation
  - The quadrupole magnets are inside cryostats.
  - These quadrupole magnets are installed in helium vessels and they are lifted by support rods fixed to vacuum chamber.
  - The helium vessels move by magnetic force of solenoids.
  - We cannot see the quadrupole magnet with optical alignment tool.
  - We should measure quadrupole center in magnetically.
  - Single stretched wire method can measure magnet center.
- Collaboration
  - The device is newly constructed by Fermi National Accelerator Laboratory.
  - The measurement was performed by collaboration of KEK and FNAL.