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

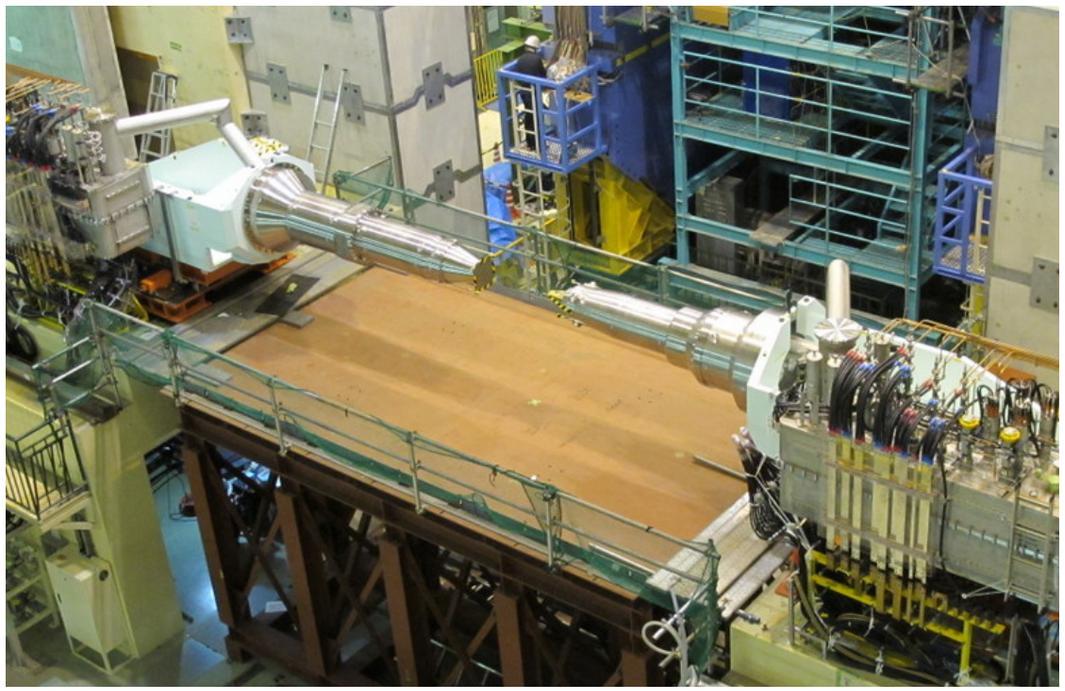
Y. Arimoto / KEK

Sep/14/2022

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular $e^+e^-$ Colliders (eeFACT2022)

# Contents

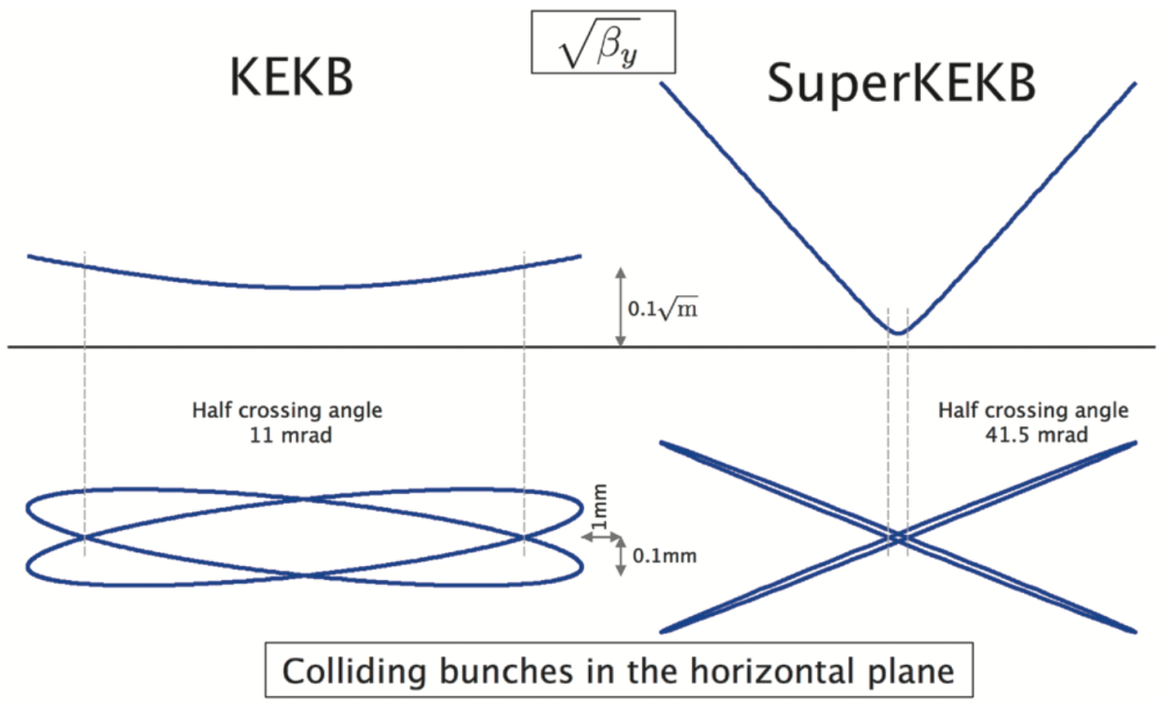
- From KEKB to SuperKEKB
- QCS at SuperKEKB IR
  - Magnet system
- Magnetic measurements
  - Field quality
  - Magnet center
- Operation
  - Stability of power supply for QCS quads.
  - Quench
  - Flux creep
- Upgrade options for QCS



# 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 | |
| $\beta_y^*$ [mm] | 5.9 | 5.9 | 0.27 | 0.30 |
| $\sigma_y^*$ [nm] | 900 | 900 | 48 | 62 |



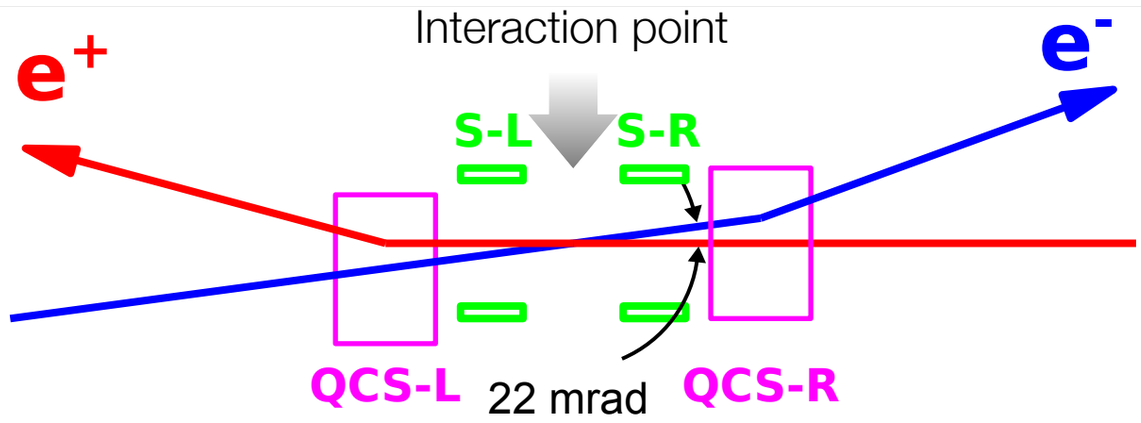

- Larger crossing angle
- Smaller beam size

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

# QCS for KEKB and SuperKEKB

## KEKB

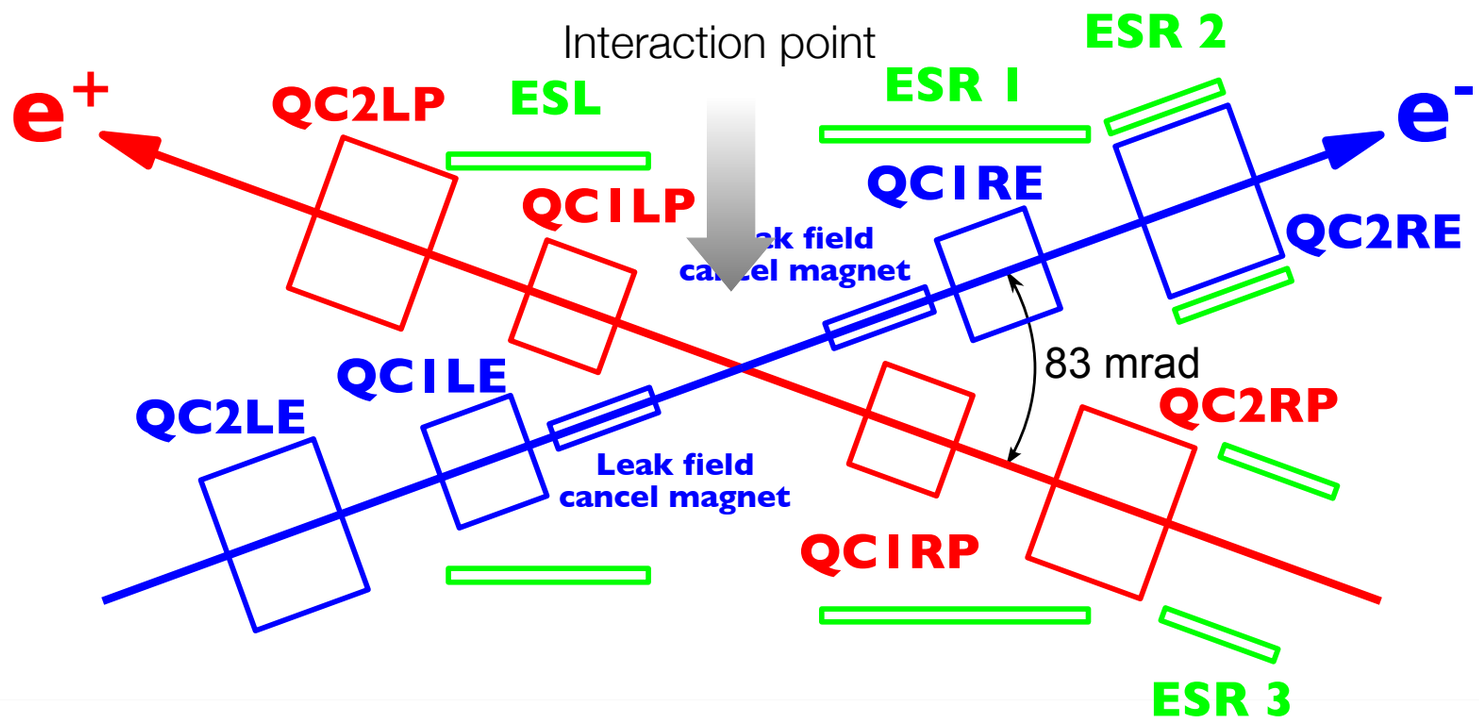
**2 sc quads. and 2 sc solenoids**



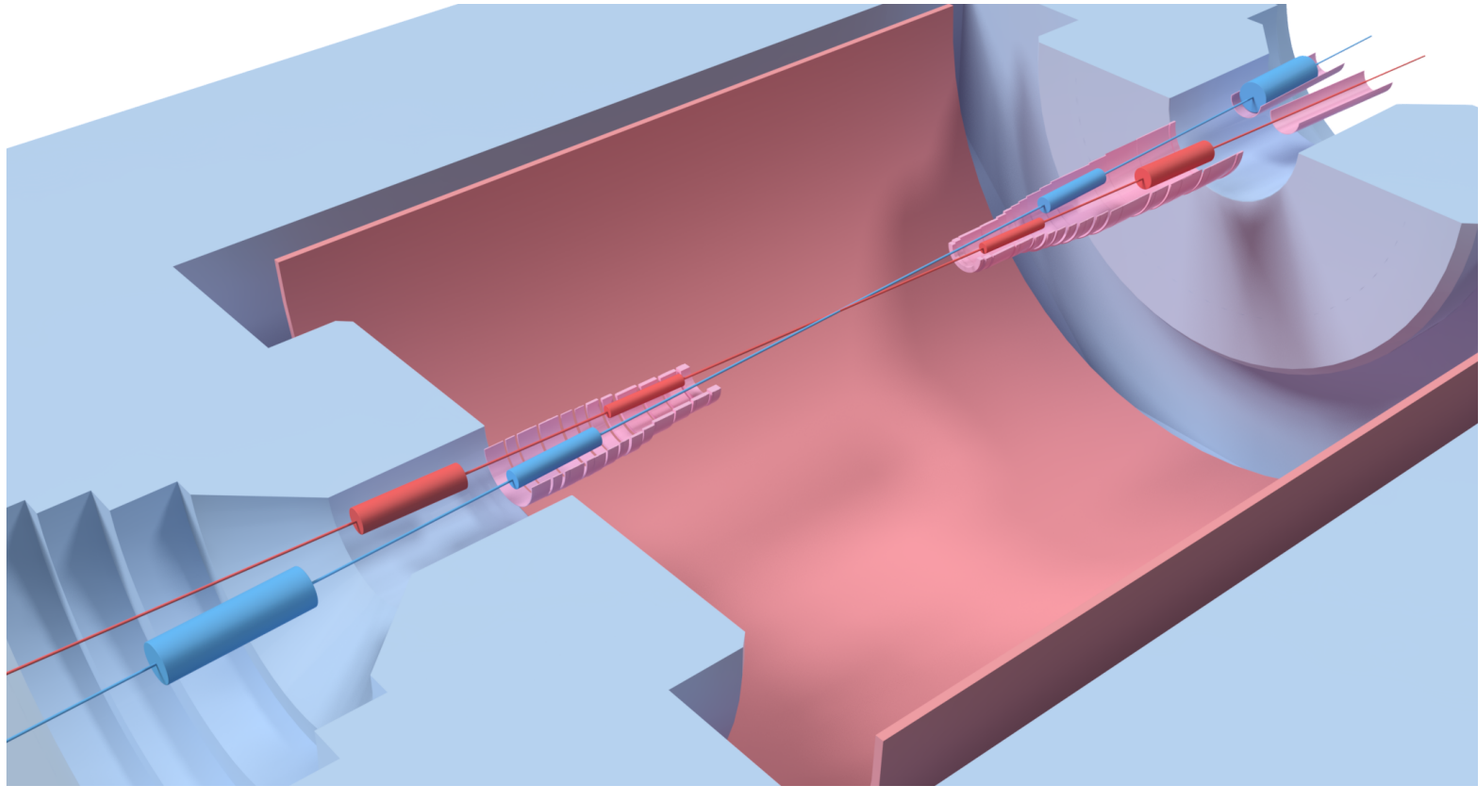

## SuperKEKB

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

**Electron and positron beam have quadrupole doublets independently.**

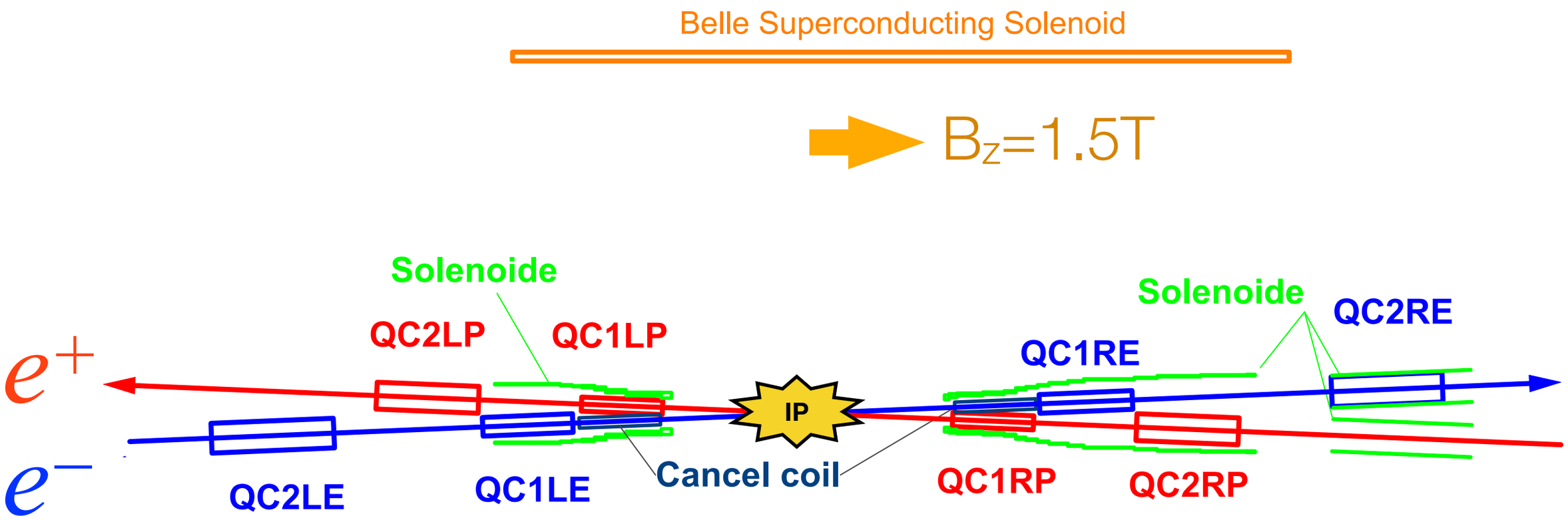


# Final focus system: QCS

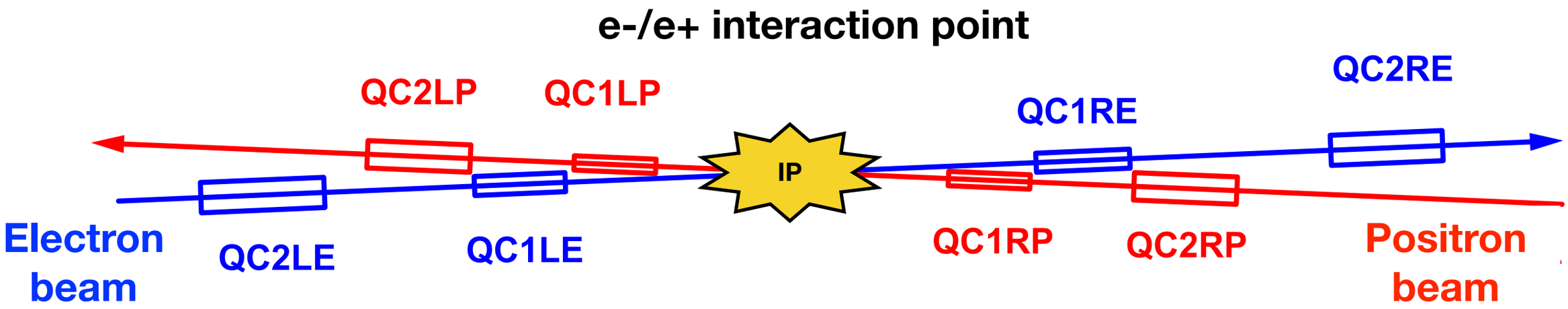


# Final focus system of SuperKEKB

- 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

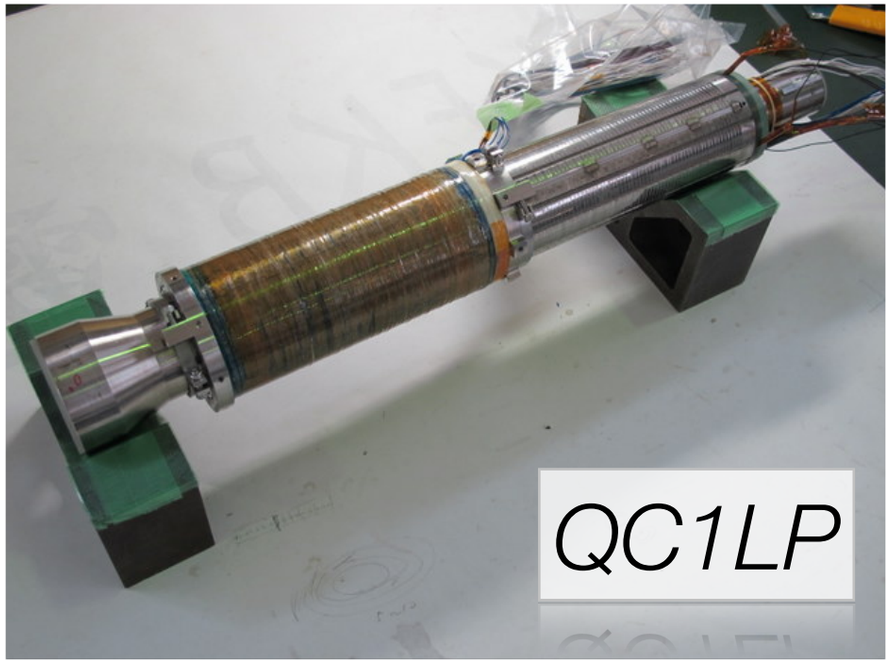


# Main parameters of QCS quadrupoles

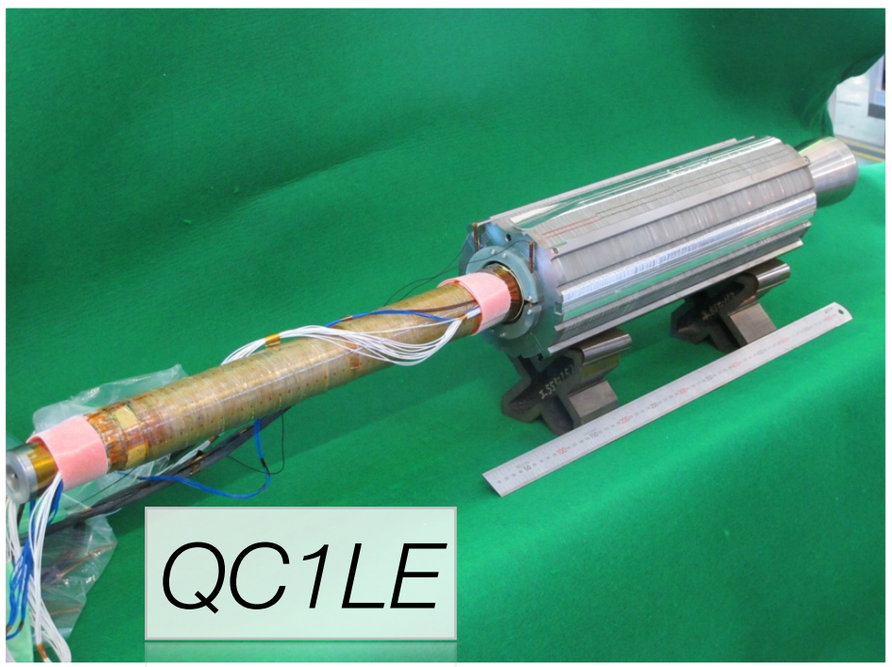


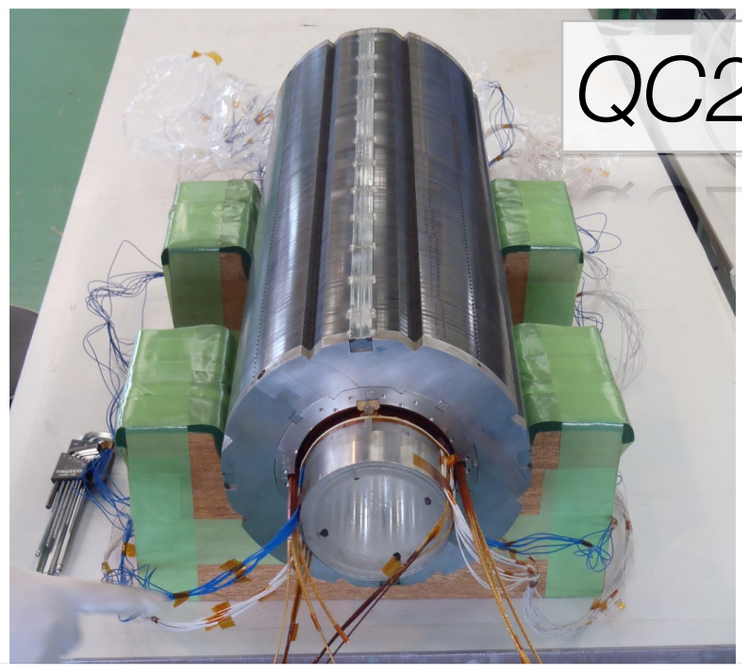

| Magnet Name | G [T/m] | I [A] | Inner Radius [mm] | Effective Length [mm] |
|---|---|---|---|---|
| QC1LP/ QC1RP | 68.9 | 1625 / 1624 | 25 | 334 |
| QC2LP/ QC2RP | 28.1 / 26.3 | 877 / 822 | 53.8 | 410 |
| QC1LE/ QC1RE | 72.2 / 70.9 | 1580 / 1490 | 33 | 373 |
| QC2LE/ QC2RE | 28.4 / 32.4 | 977 / 1070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

# Quadrupole magnets ( on left side of IP )

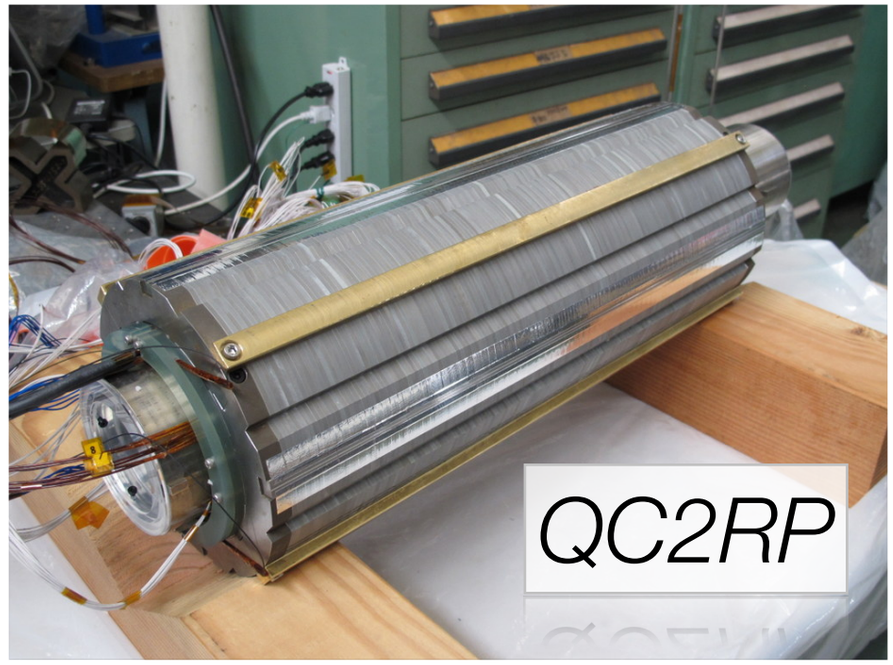


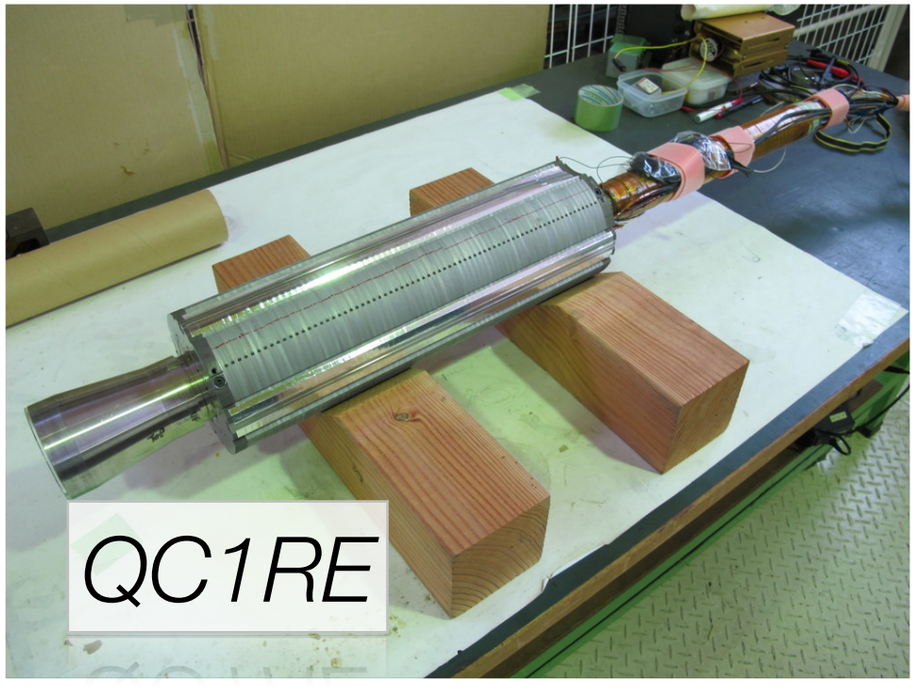




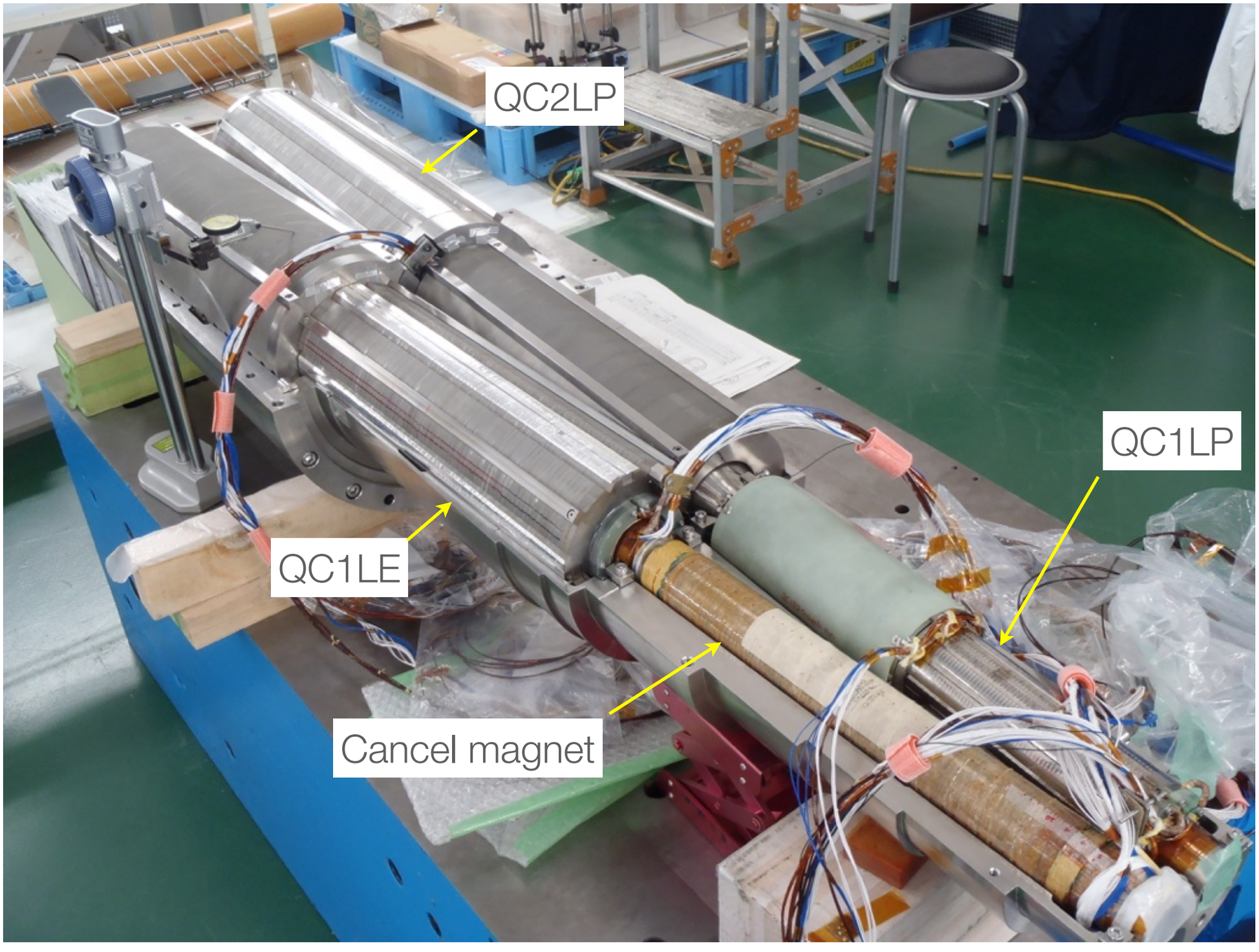



# Quadrupole magnets ( on right side of IP )


# 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

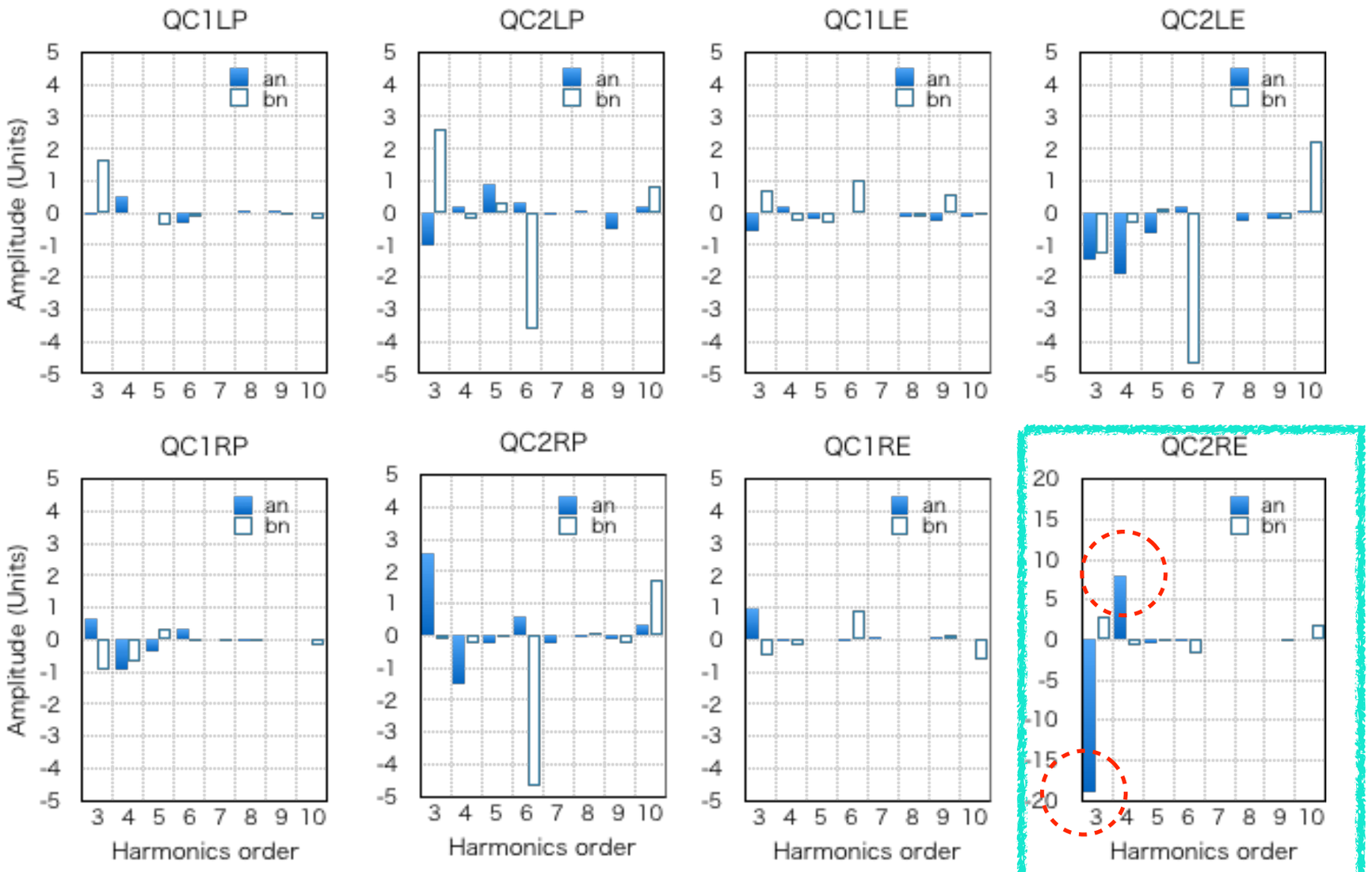
# Higher order harmonics of quadrupole magnets

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

**"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

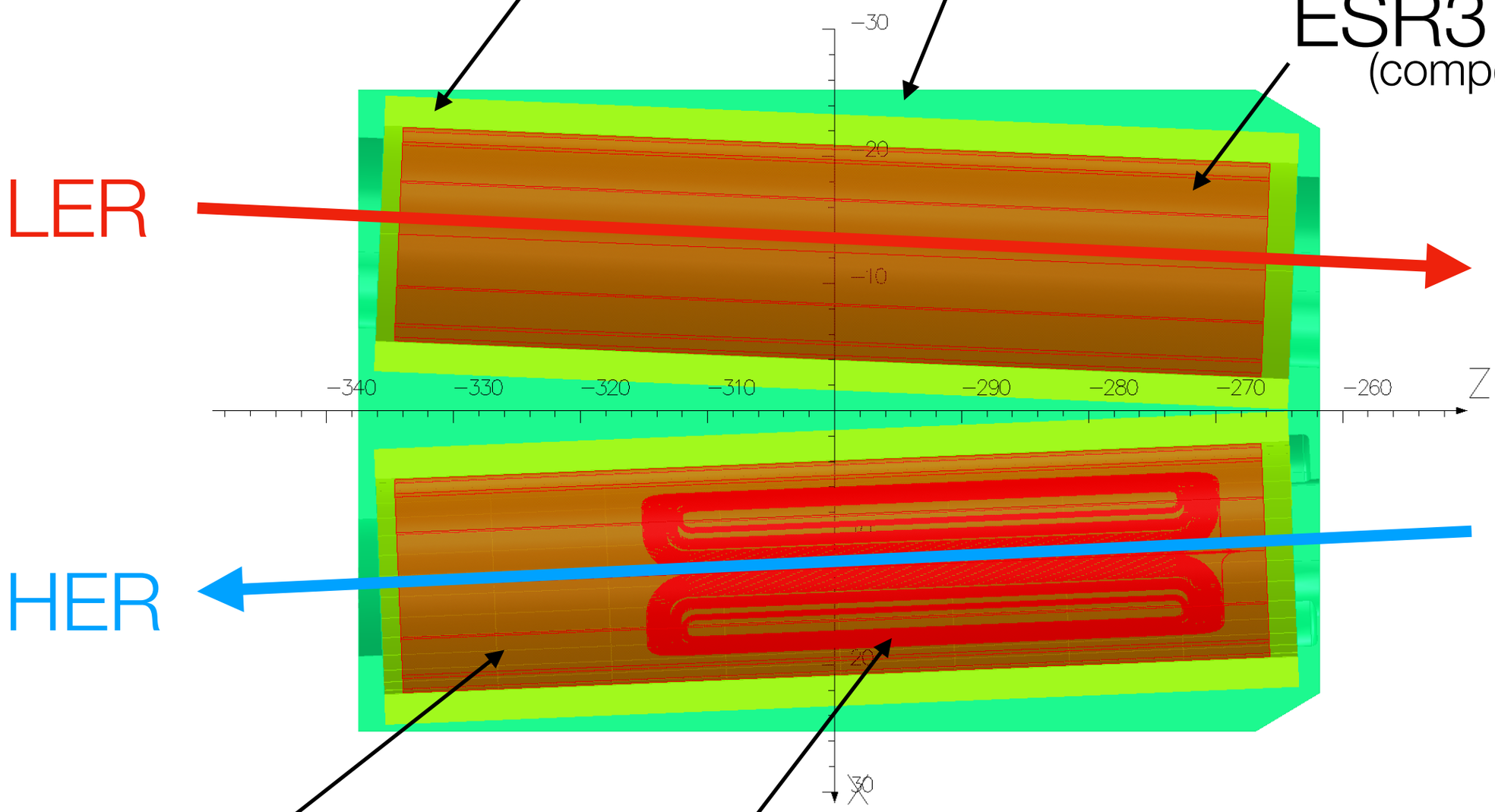
# QCS-R rear cold mass with QC2RE

Top view

Iron yoke

Iron structure

ESR3
(compensation solenoid)




LER

IP Side

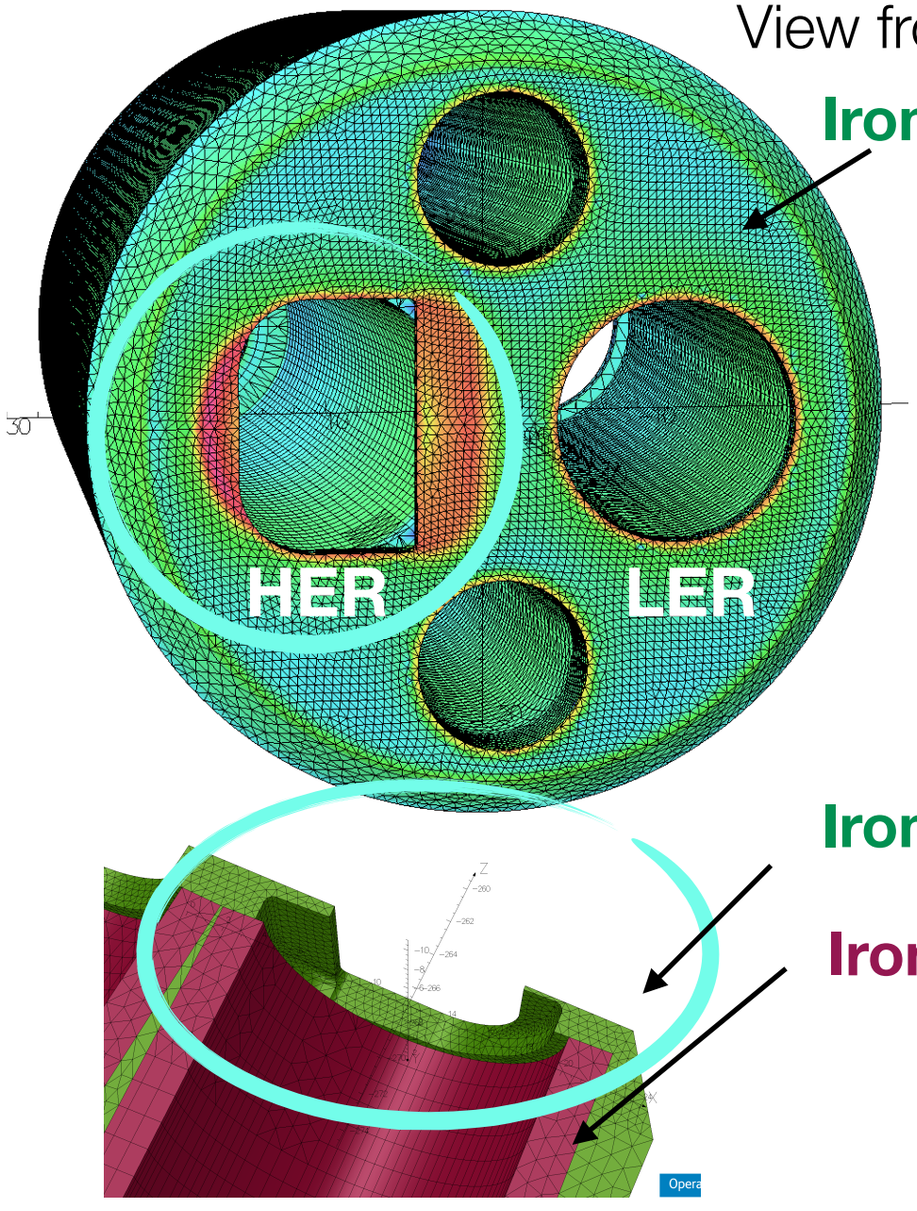
HER

ESR2
(compensation solenoid)

QC2RE

- QC2RE is inside iron structure and yoke and compensation solenoid

# Axial profile of QC2RE region (on HER)




View from IP side

**Iron structure**

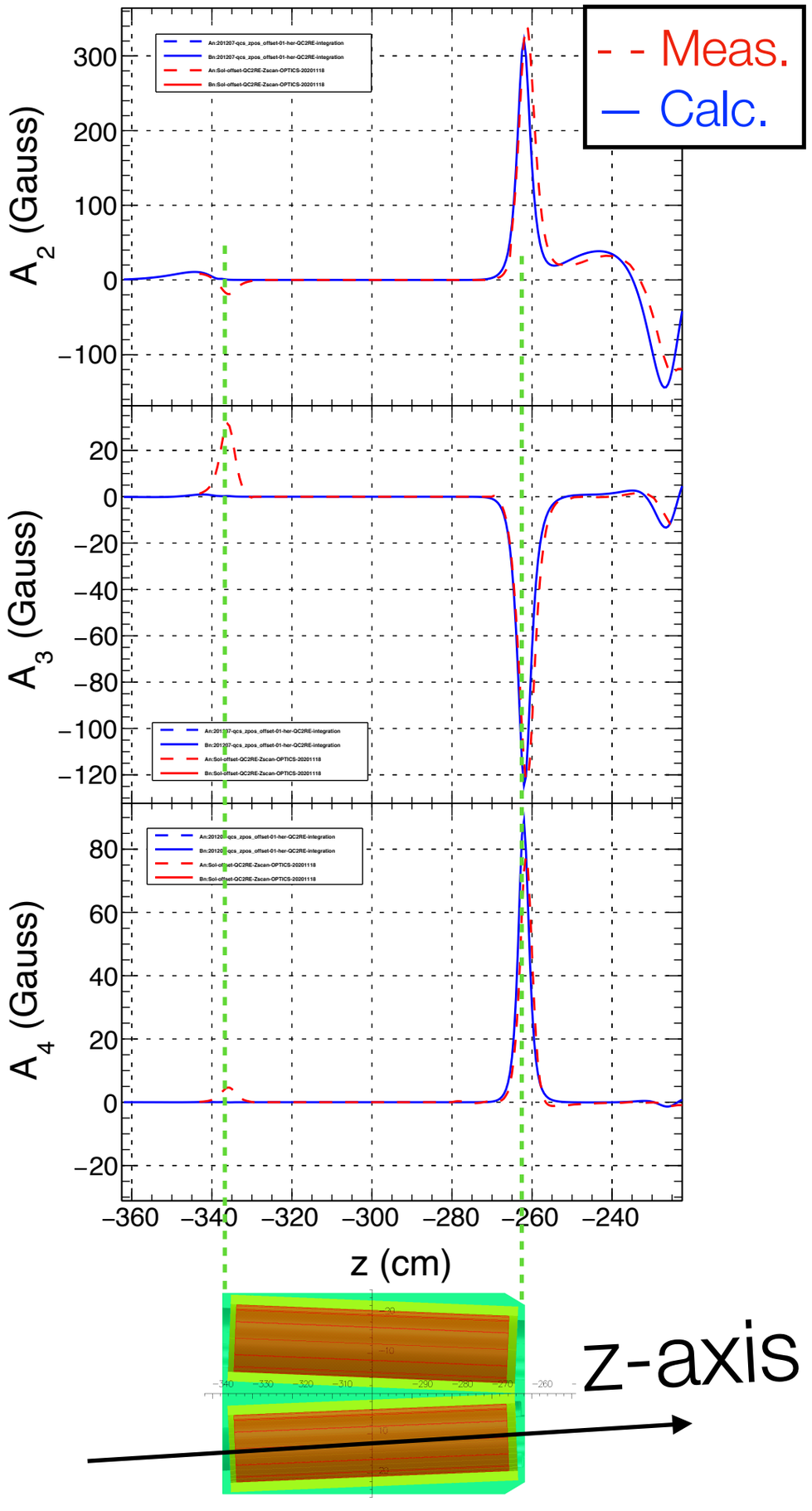
- No QC2RE
- Belle Sol: on
- Compensation solenoid: on



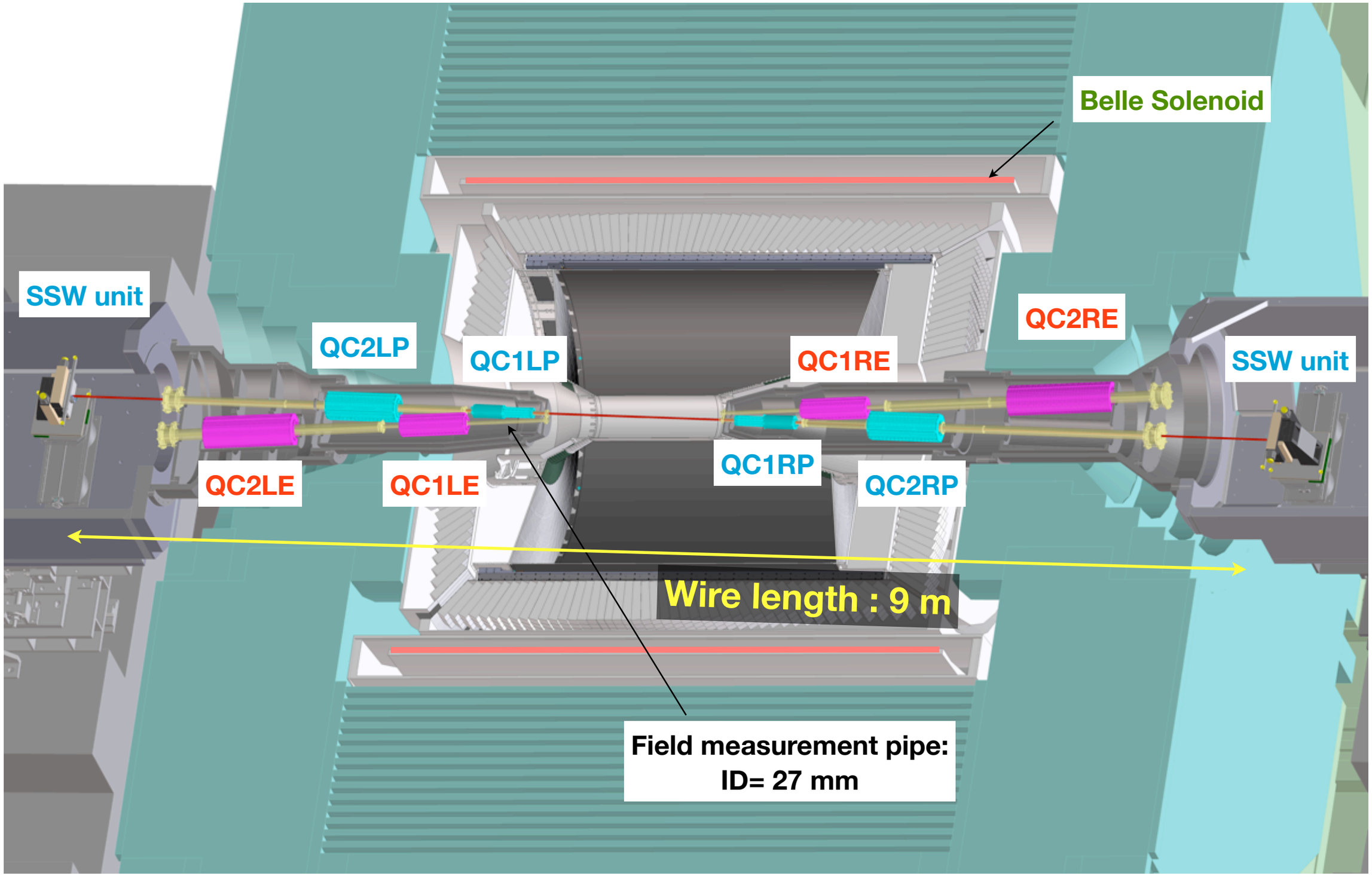
**Iron structure**

**Iron yoke**

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.

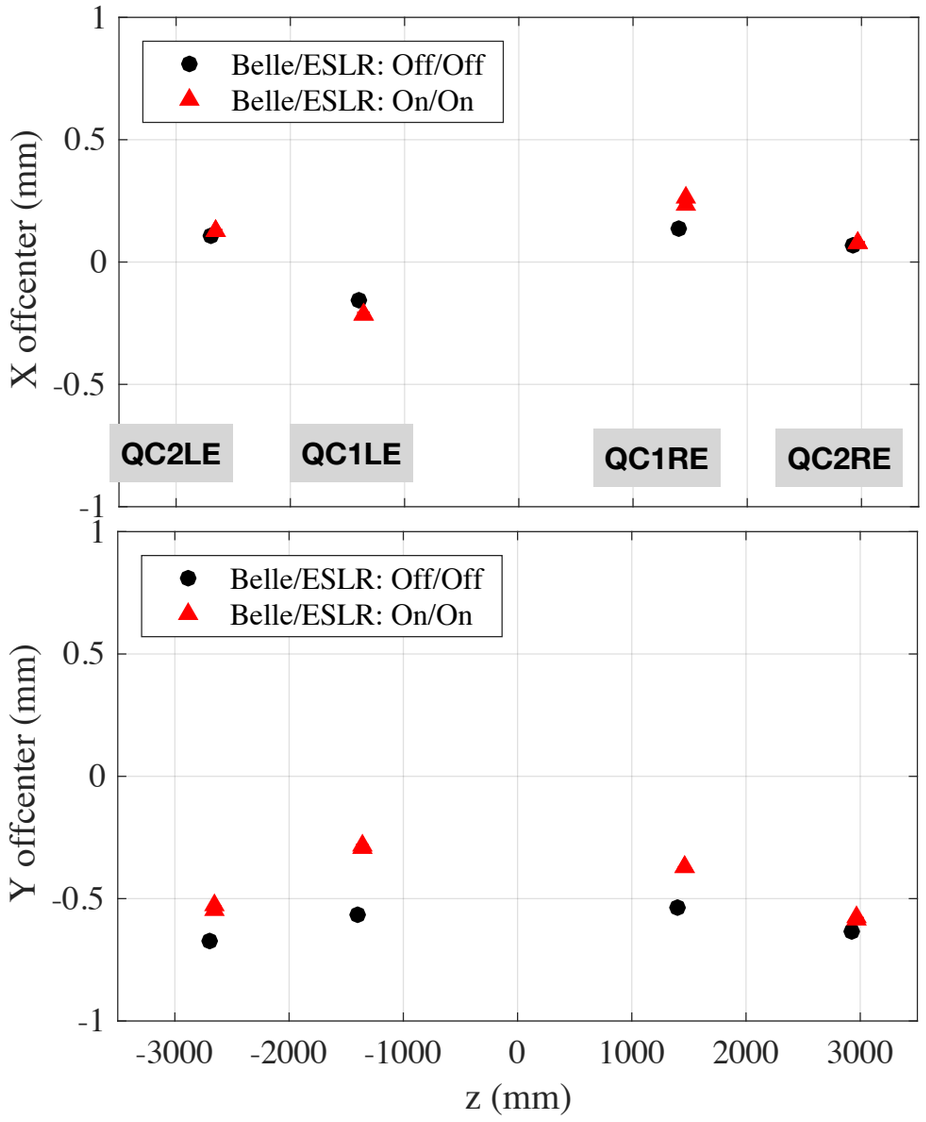


# SSW measurement: setup

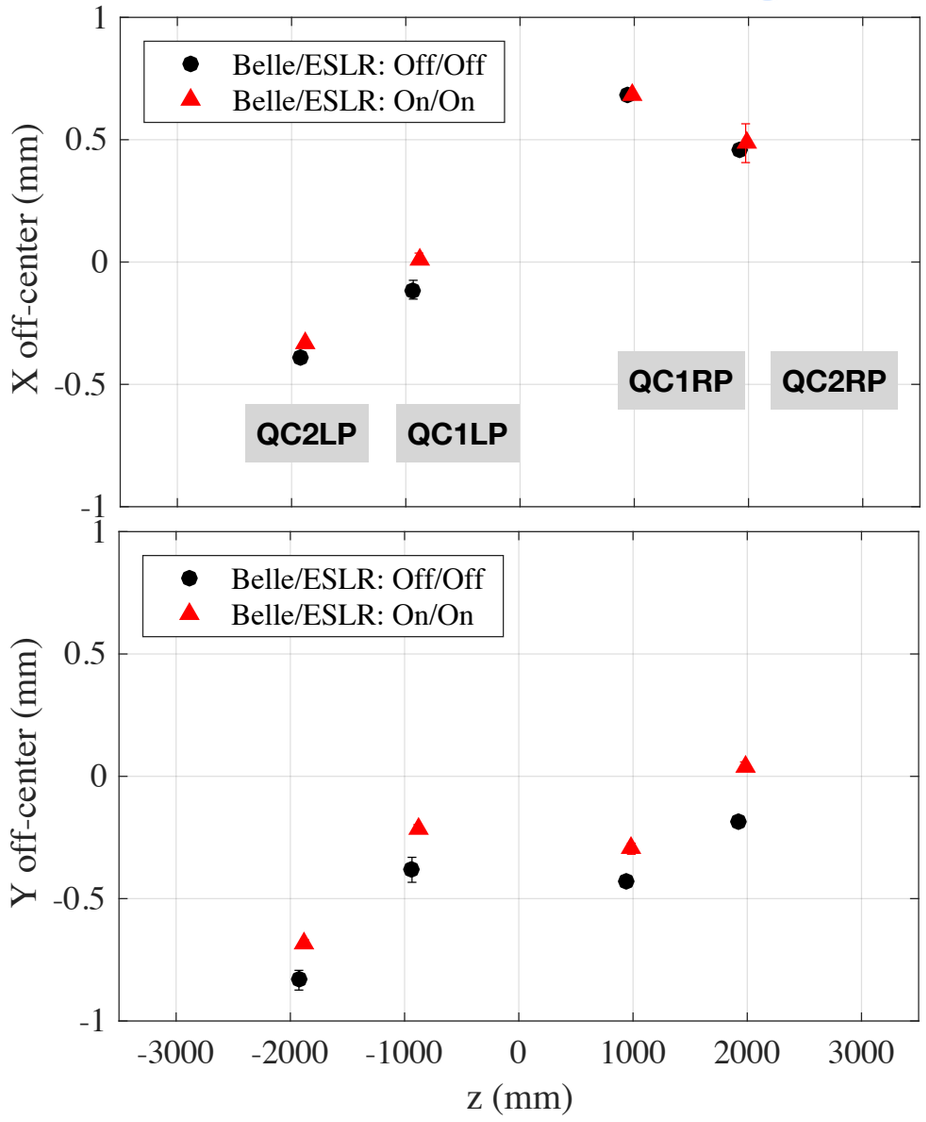


# Magnet center for each magnet wrt design position

## Electron-beamline magnets




## Positron-beamline magnets




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.

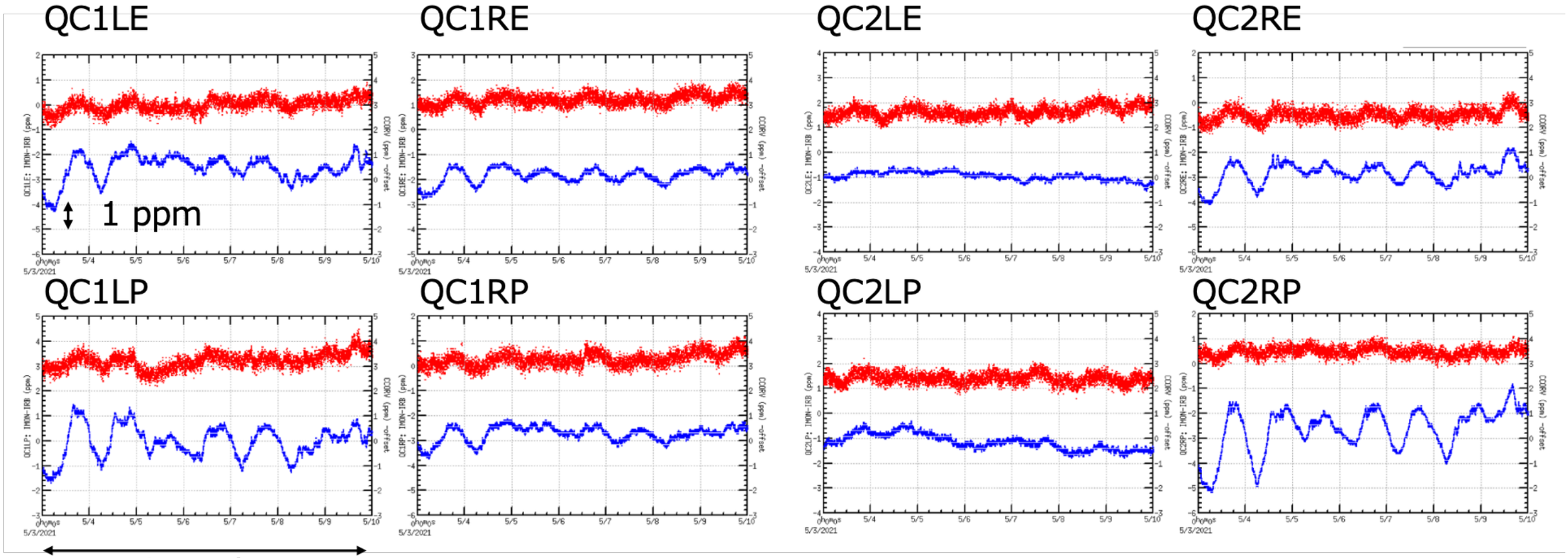
# Operation

# 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)

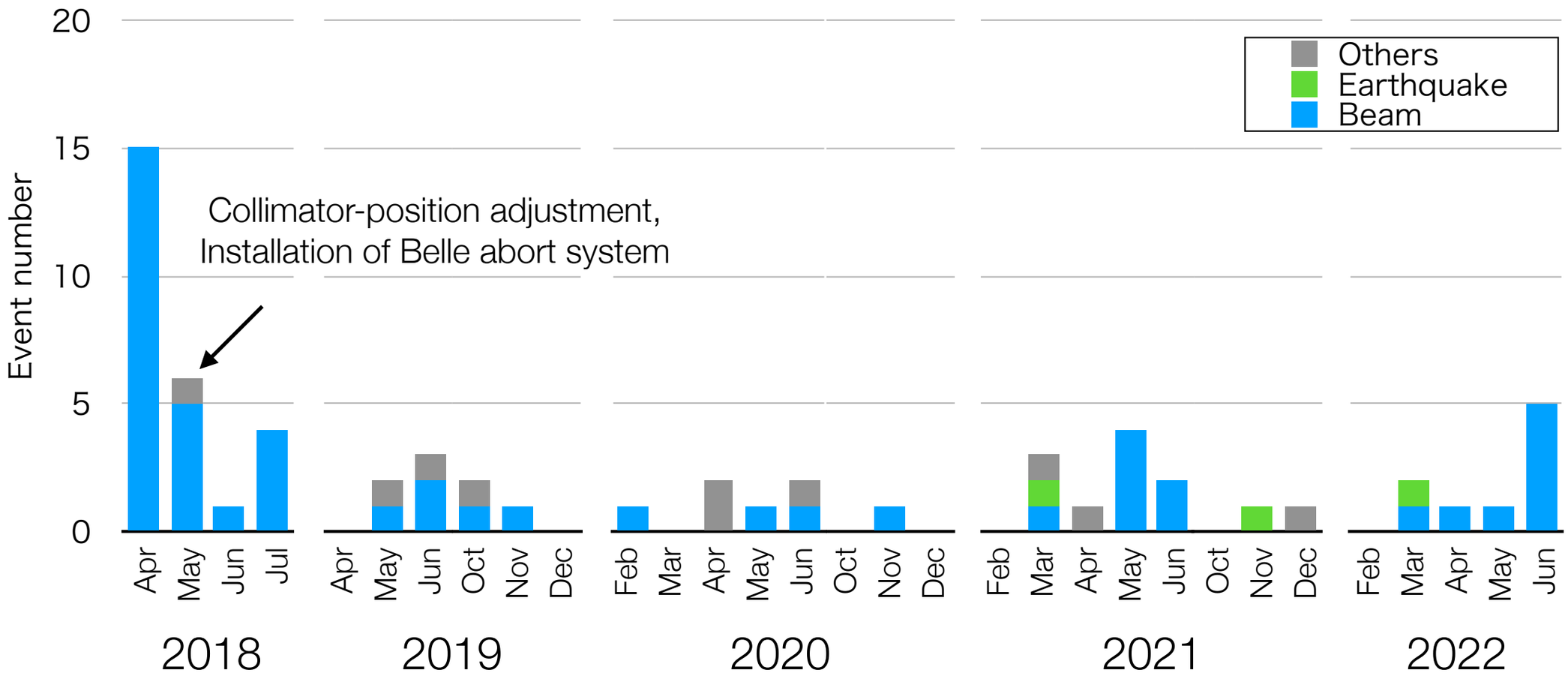
- Output current
- Correction value by digital feedback




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

T. Oki

# Power shutdown of QCS magnets during beam operation



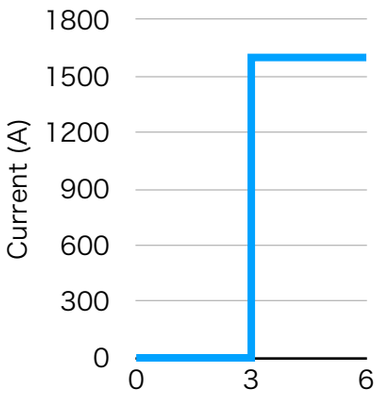

- Cause:
  - Quench induced by beam ( ~1-10 mJ )
  - Earthquake: not quench but induced voltage by change of coupling B-field between Belle solenoid and QCS solenoid over the threshold of a quench detector
  - Others: Power supply trouble (fixing every event and frequency is reducing), supply water trouble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

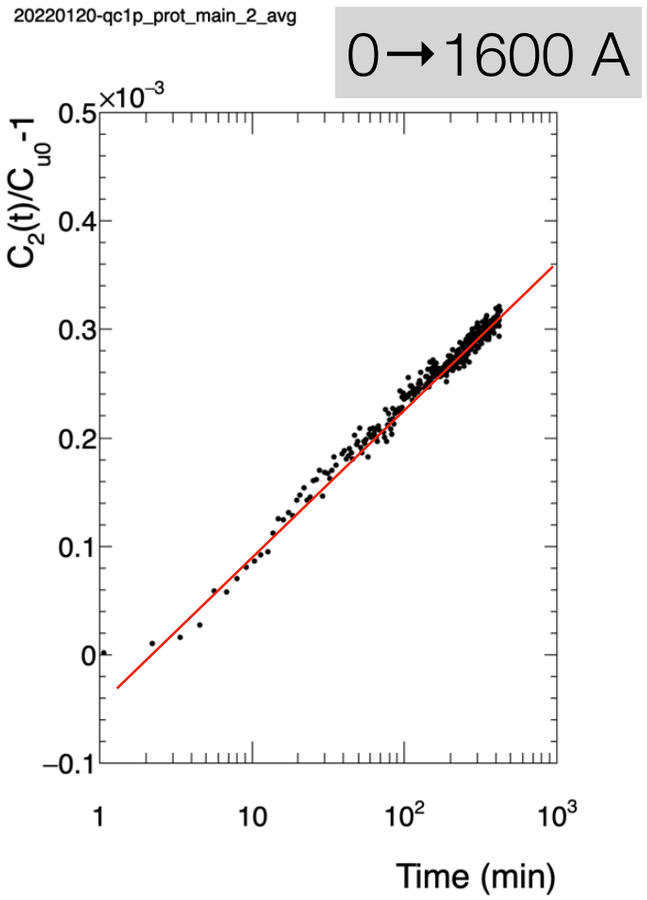
# Drift of strength of quadrupole magnet

- 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 $3\times10^{-4}$ 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.

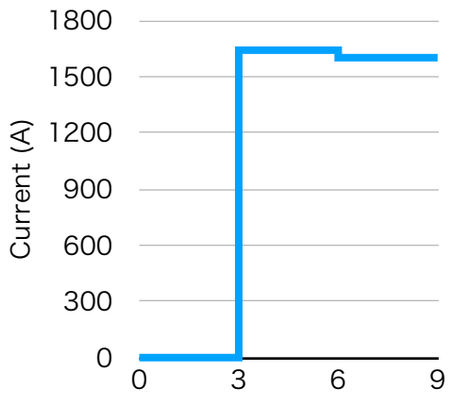
Current ramp pattern



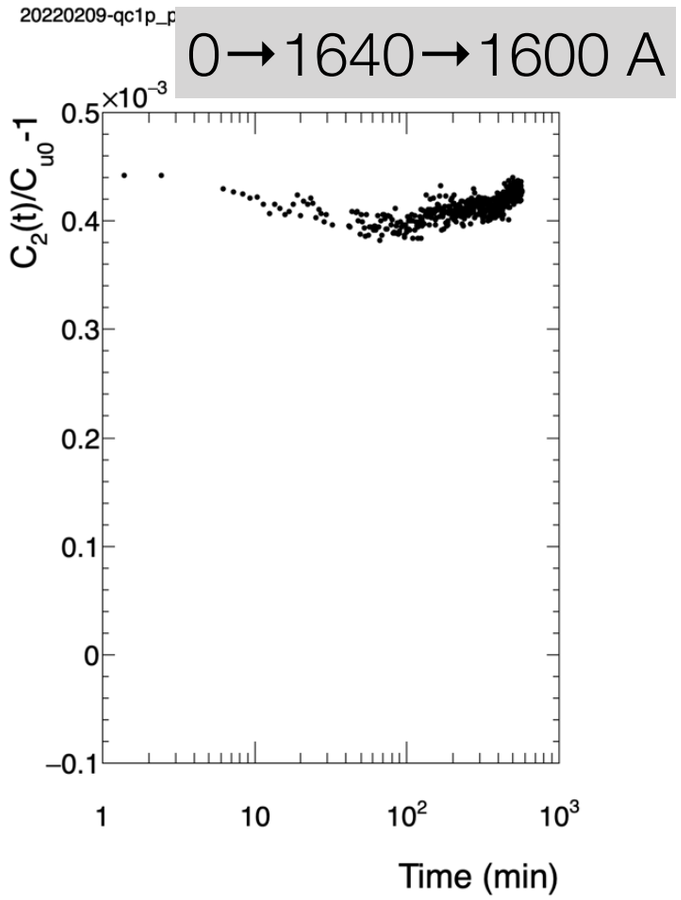

**Variation: $3\times10^{-4}$ per 7 hours**




Current ramp pattern



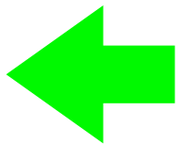

**Variation: $0.2\times10^{-4}$ per 10 hours**



# Upgrade options for QCS

# Upgrade plan

- SuperKEKB goal
  - Integrated luminosity: 50 $ab^{-1}$ around 2030
  - Luminosity: ~$6x10^{35}$ $cm^{-2}$ $s^{-1}$
- Issues for a luminosity increase
  - Transverse Mode Coupling Instability
  - Beam lifetime / Injection efficiency
  - etc.
- Upgrade schedule at IR
  - Long shutdown 2 (LS2) : 2026~

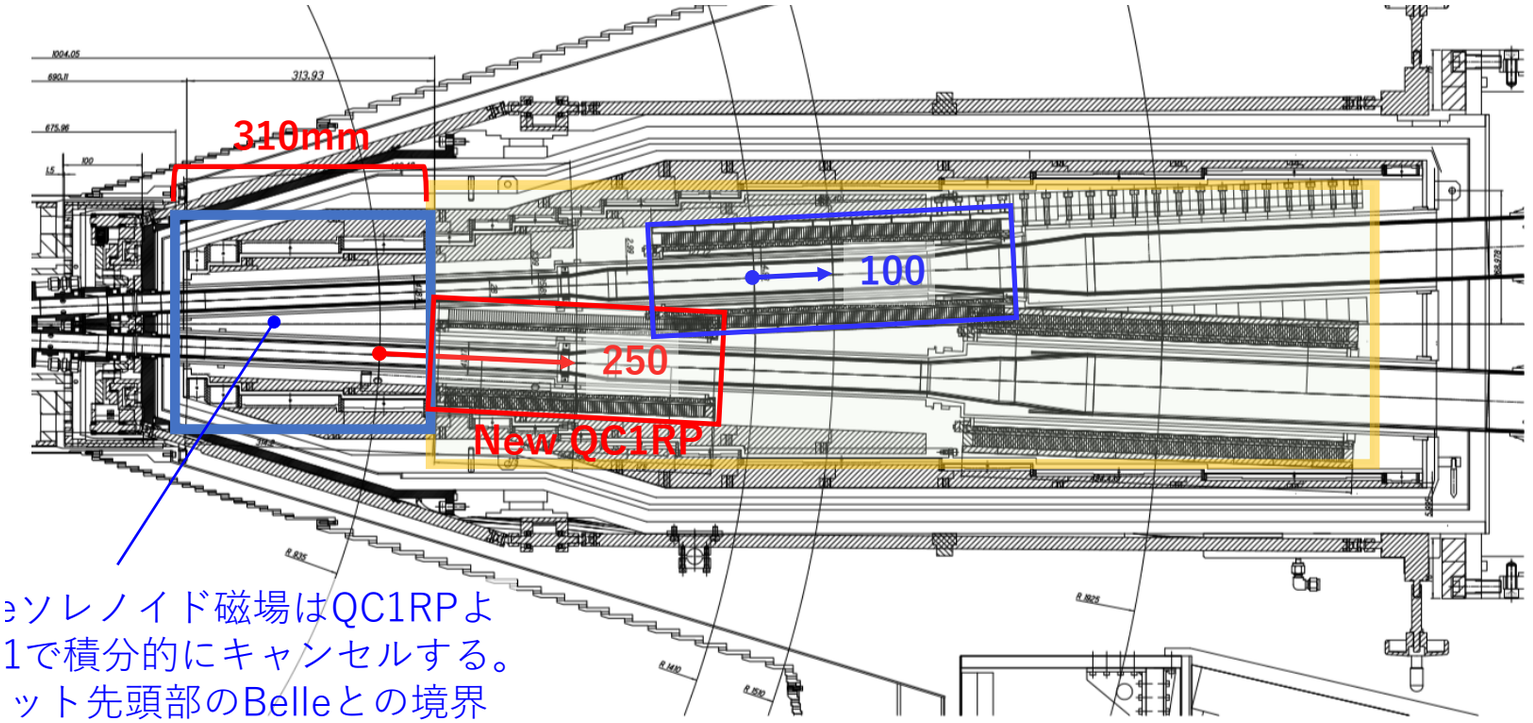


QCS

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

# Option A

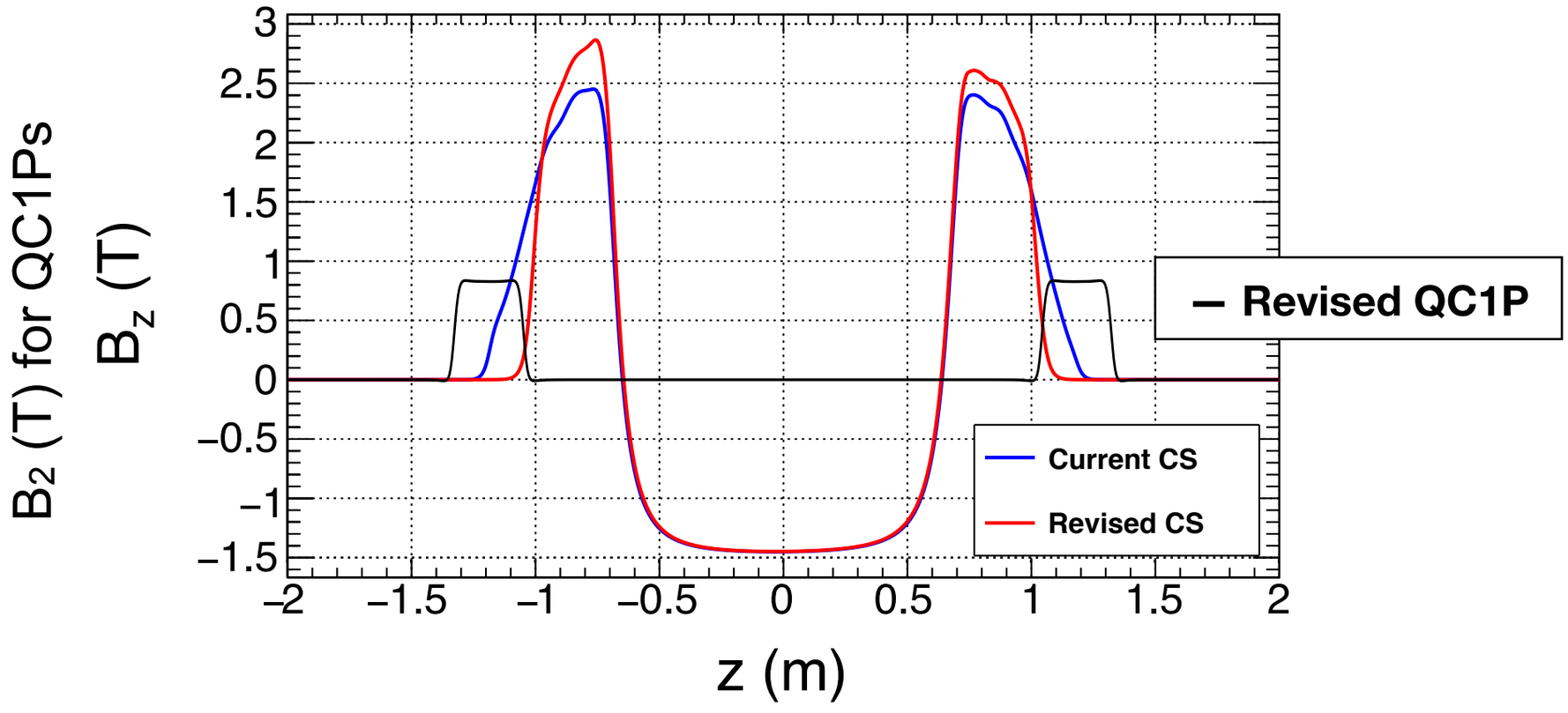
- Reduction of overlapping region compensation solenoid and QC1Ps ( vertical final focus element for positron )
  - Move QC1RP and QC1LP by 250 mm away from IP
  - Enlarge QC1Ps aperture size as same as QC1Es
  - Move QC1RE and QC1LE by 100 mm away from IP
  - The compensation solenoid field region is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




N. Ohuchi

# Option A (cont.)

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

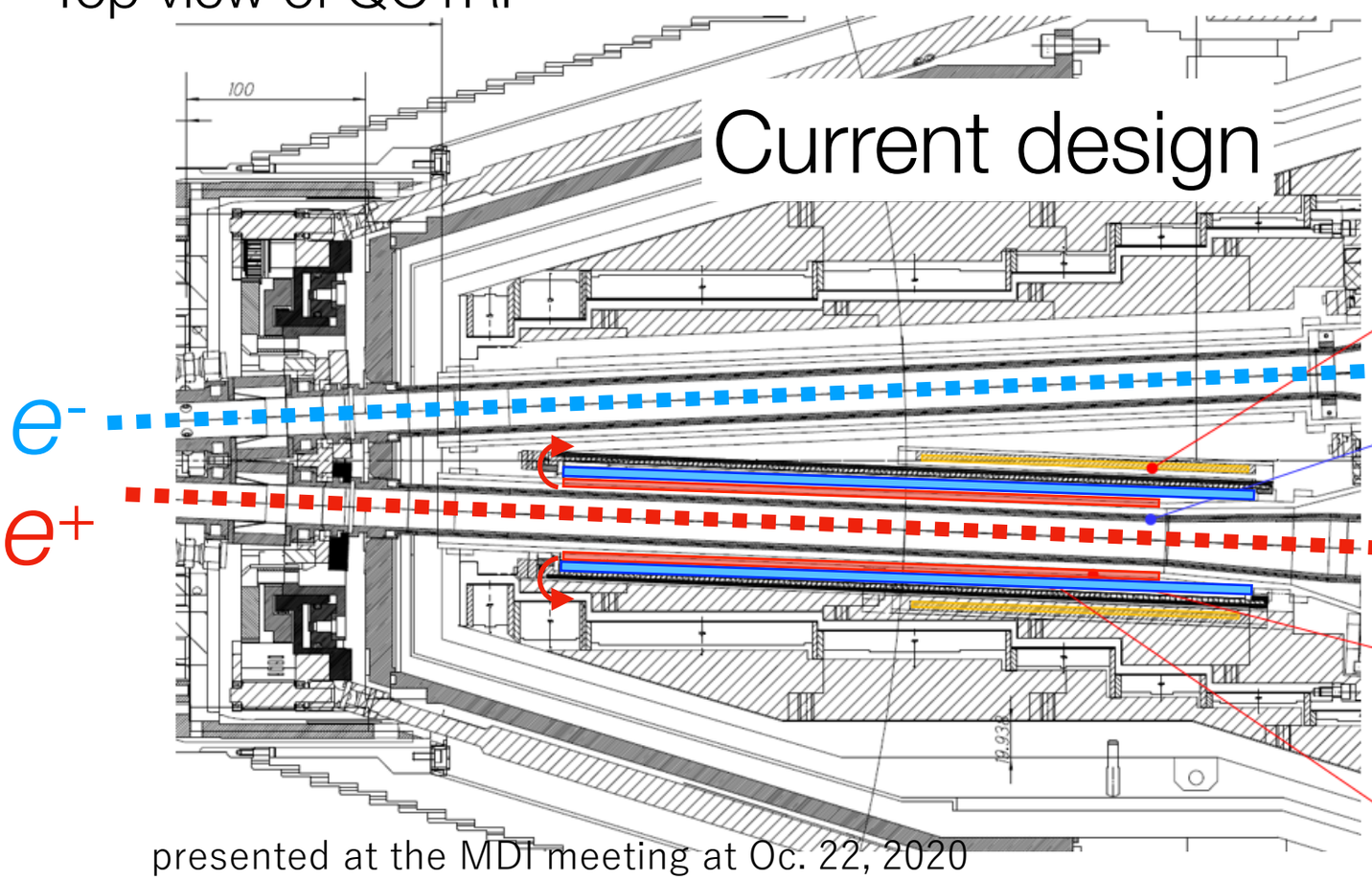



- The overlap region is reduced, and the increase of solenoid field strength is small.
- It is possible to make this magnet system.
- **However, no improvement in beam lifetime is expected.**

# 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

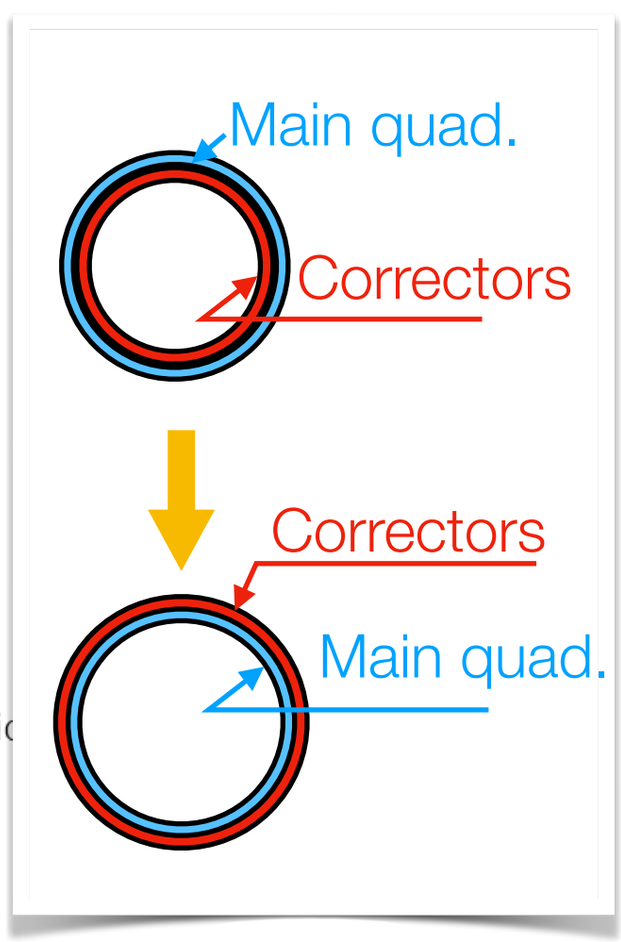
Top view of QC1RP




presented at the MDI meeting at Oc. 22, 2020

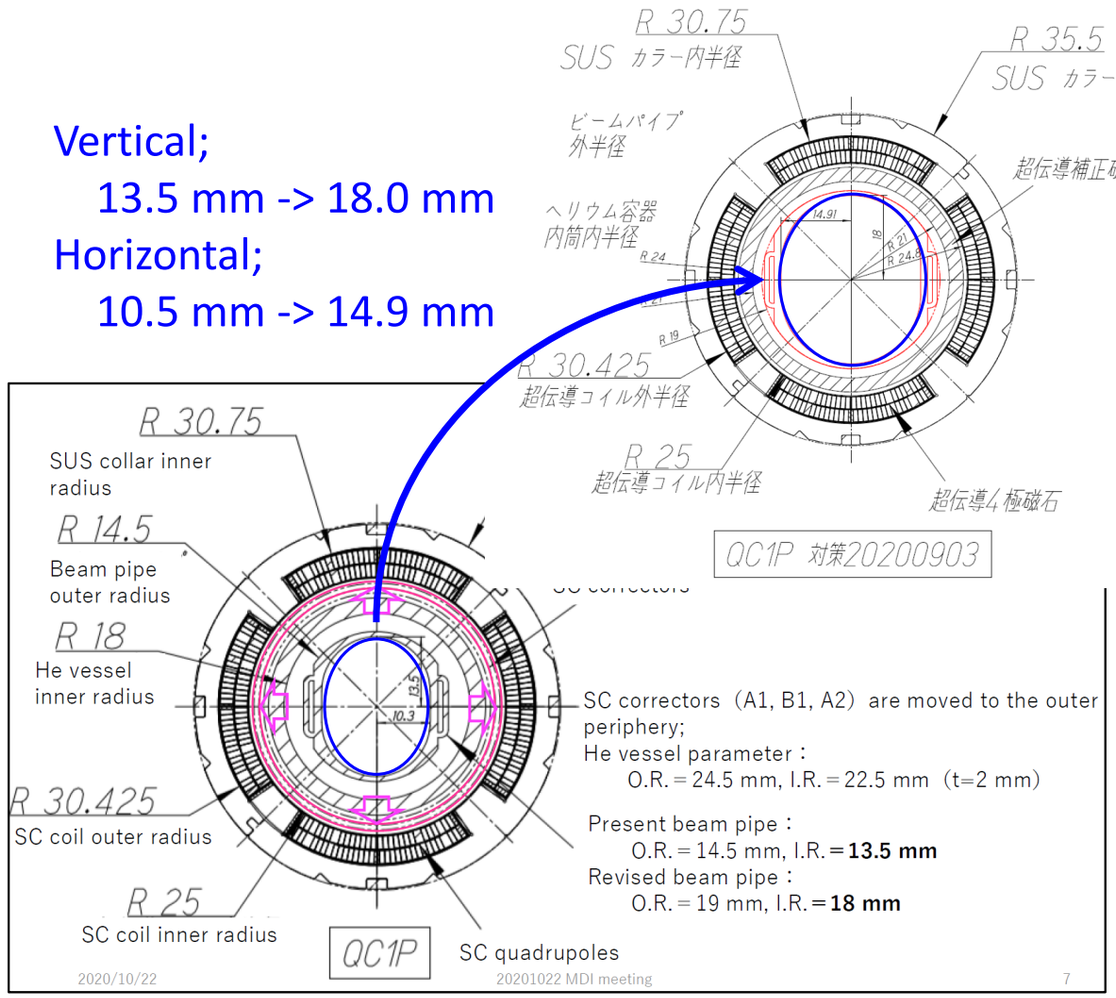
N. Ohuchi

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
  - **Does not improve beam lifetime** because the dynamic aperture is smaller than the current beam pipe at QC1Ps

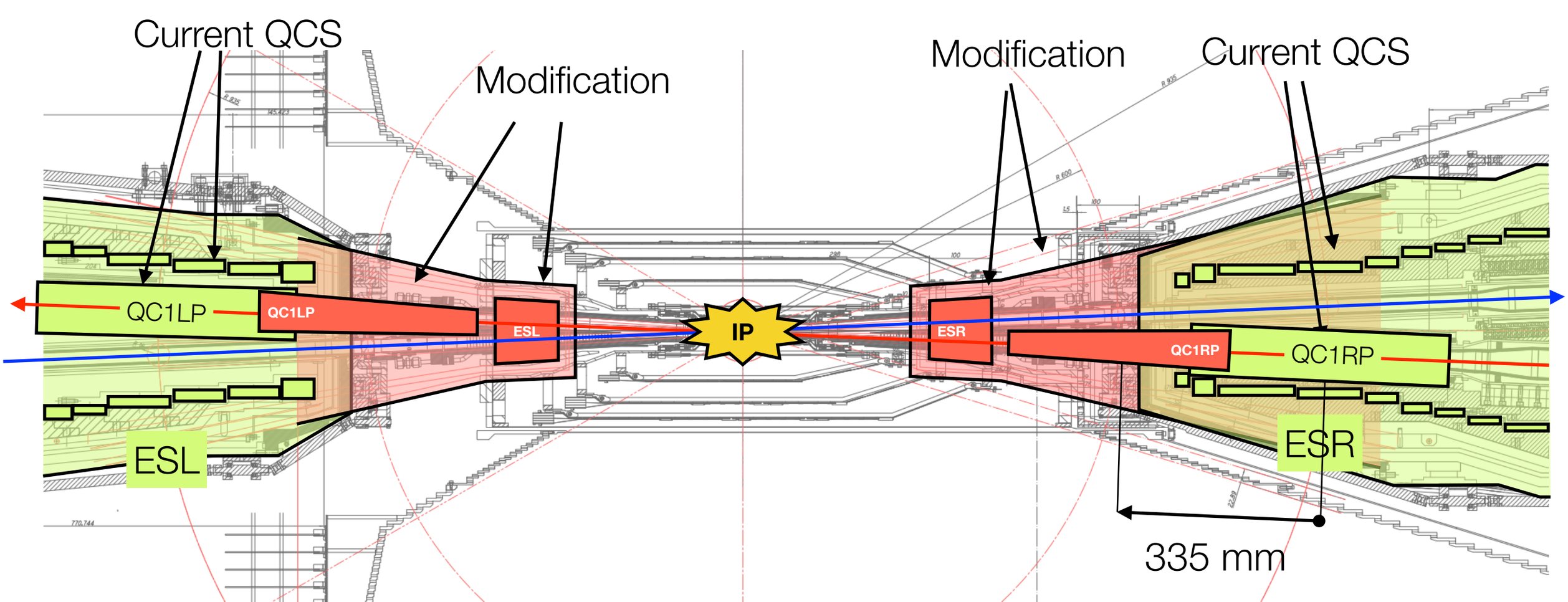



K. Shibata

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.