SuperKEKB upgrade

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2026/7/7　B2GM

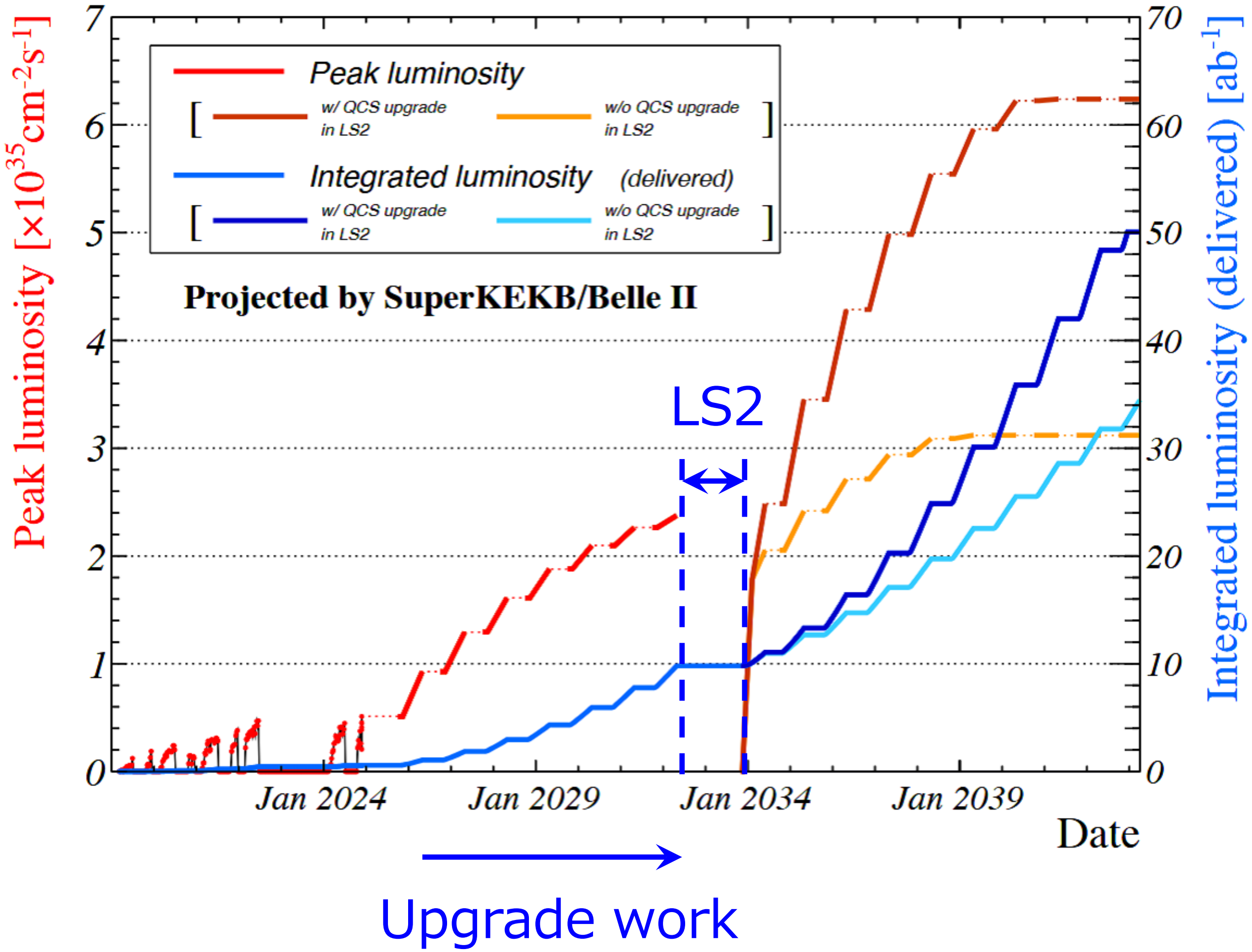
Major pillars for the upgrade under consideration

- **Injector linac**
  Modernising the Linac for highly stable, high-efficiency top-up continuous sourcing without operational limits.

- **HER RF System**
  Enhancing ring RF systems to storage massive high-current beams.

- **Final focus system (QCS)**
  Redesigning QCS to optimise the beam orbit at the interaction point.

- **Aging measures, stabilisation**



Injector linac

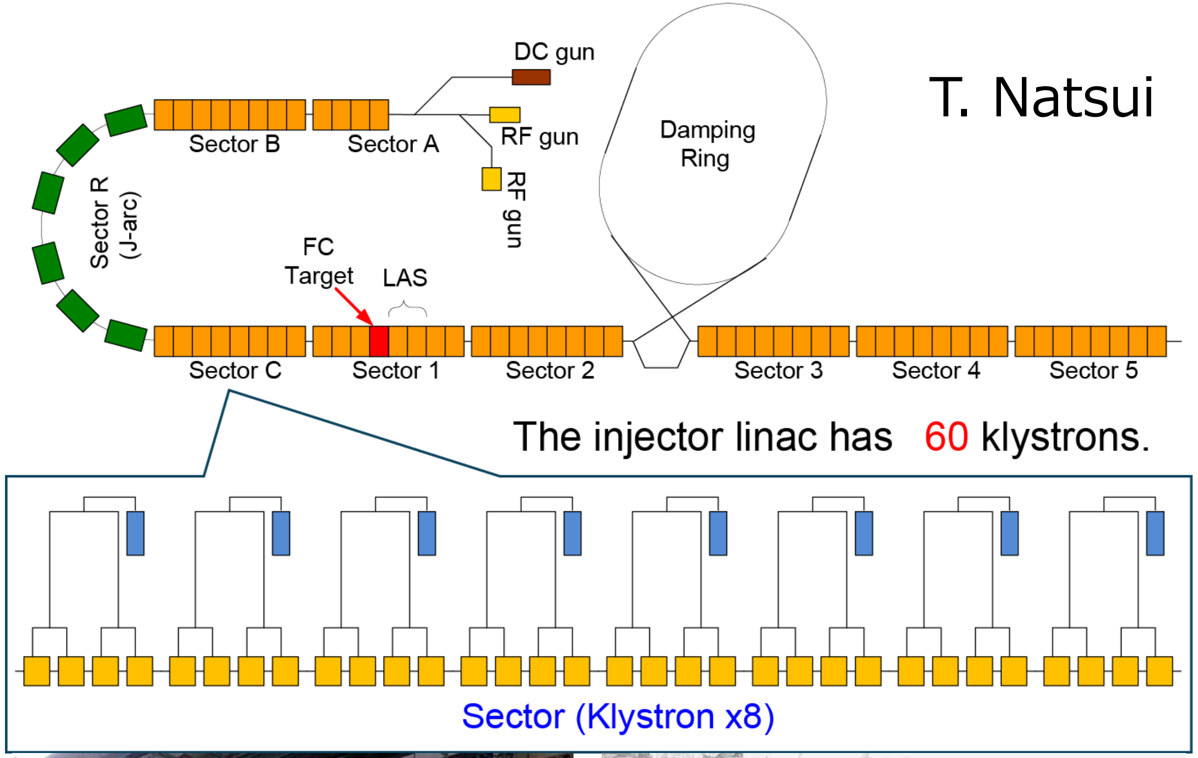
T. Natsui

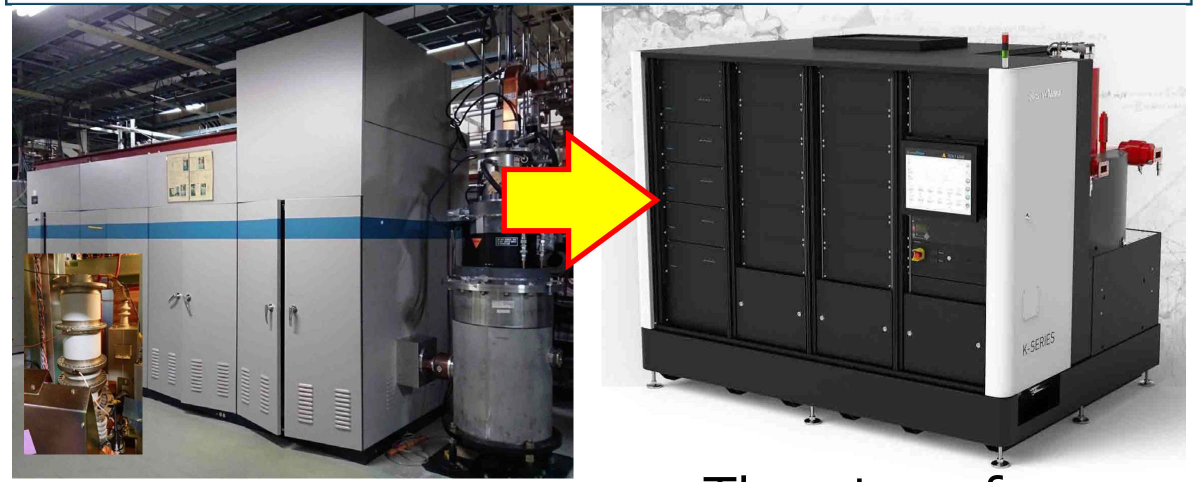
- Issue

  Difficulty in getting thyratrons for aging legacy modulators. With 63 units in operation, 8 must be replaced annually as consumables to maintain the system based on lifetime. High prices (>10M JPY/unit) hinder buying enough spares, which concerns stable operation.

- Solution

  Systemic replacement of legacy vacuum-tube modulators with modern, high-stability solid-state modulators. And introduction of next-generation, high-efficiency Multi-Beam Klystrons (MBK).





Thyratron-free modulator

HER RF System

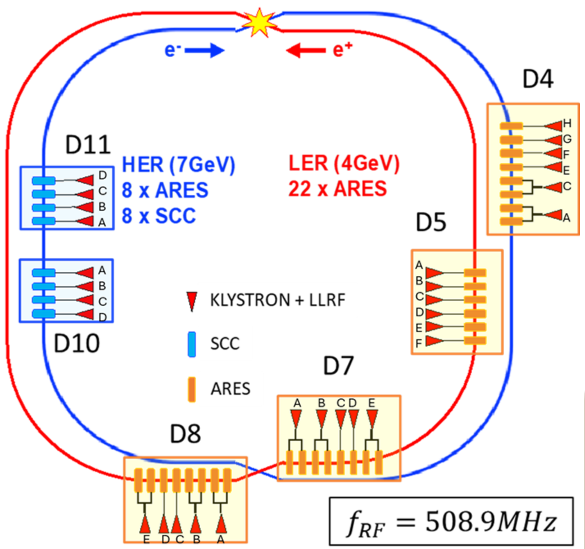
T. Yamaguchi

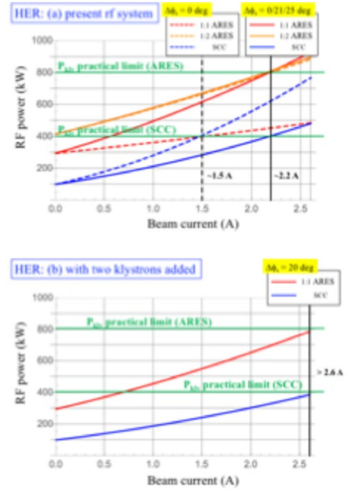
- Issue

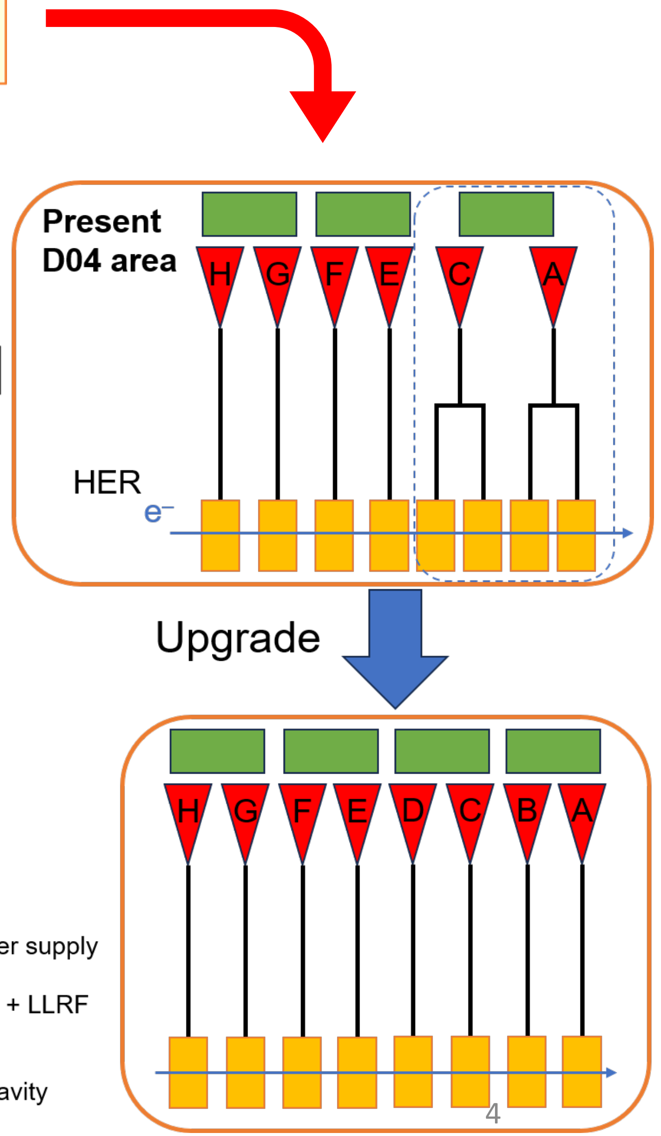
  The current 1:2 RF configuration, in which one klystron drives two cavities, **limits the HER beam current to 2.0 A** due to the input power (~400 kW) and klystron linearity (~800 kW) limits.

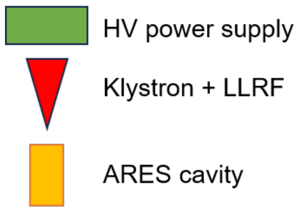
- Solution

  The D4 sector will be upgraded to a 1:1 ARES configuration, with one klystron driving each cavity. The upgrade includes two new klystrons and one additional high-voltage power supply. Optimising the 20° between ARES and SCC correlated phase difference will significantly increase the RF power available to the beam.



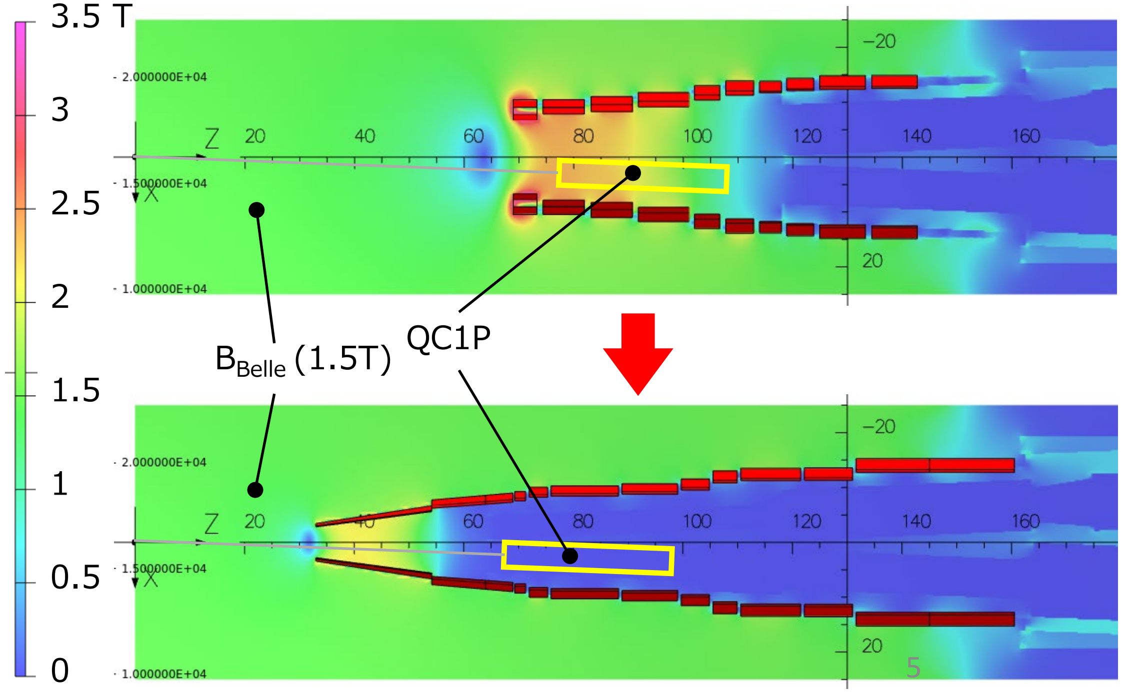


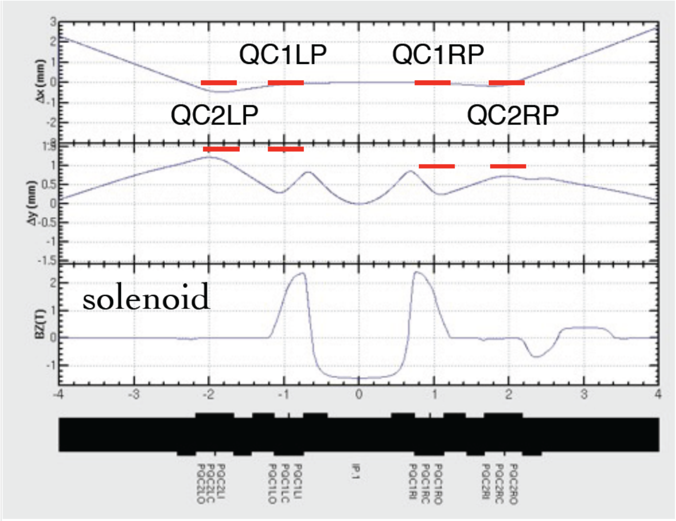




Constraint of the current IR

- **The current QC1P is exposed directly to the 1.5 T detector solenoid field** without magnetic shielding due to severe space constraints.
- This induces severe chromatic coupling and heavy orbit tilts. To mitigate these effects, the current magnets are installed with intentional physical offsets and rotations.
- Aiming to eliminate these elaborate and complex corrections, we are trying to cancel the solenoid field at QC1P to align the beam trajectory parallel to the magnet axes.





offset/rot.	QC2LP	QC1LP	QC1RP	QC2RP
Δy (mm)	+1.5	+1.5	+1.0	+1.0
Δθ (mrad)	-3.725	-13.65	+7.204	-2.114

Redesigning the QCS Final Focusing Magnets

Chromatic Coupling Mitigation:

(1) Additional compensation solenoid in front of the QC1P magnet.

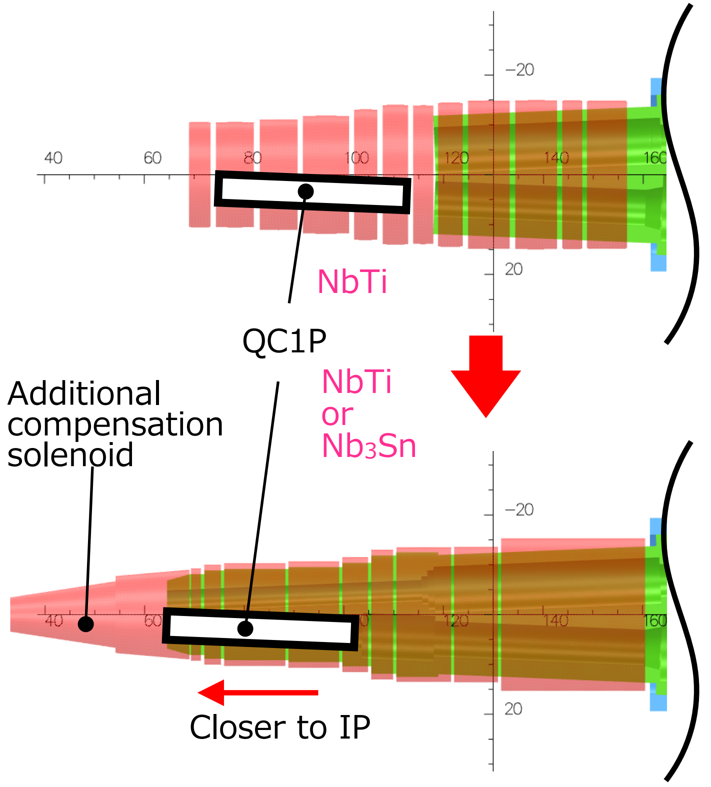
(2) Fully encasing the QC1P assembly within a new ferromagnetic iron yoke to shield from detector fields.

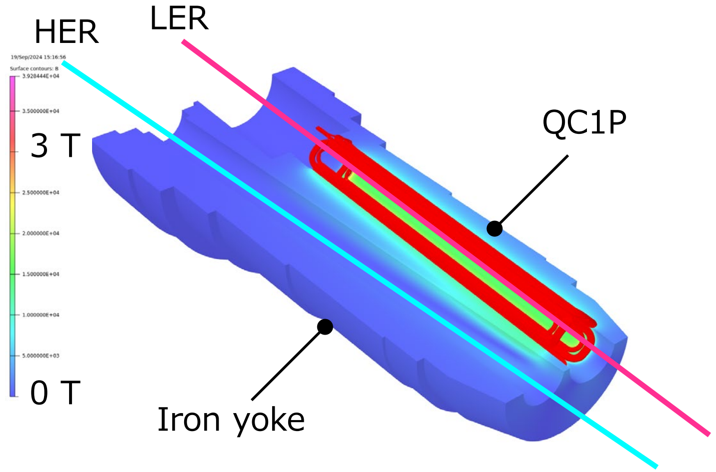
<u>The Ultimate Design Benefit</u>

Establishes a completely straight, unperturbed beam orbit through the final focus region. Completely eliminates the need for complex forced offsets, physical roll angles, and all 8 legacy cancelling coils.

Dynamic Aperture Expansion:

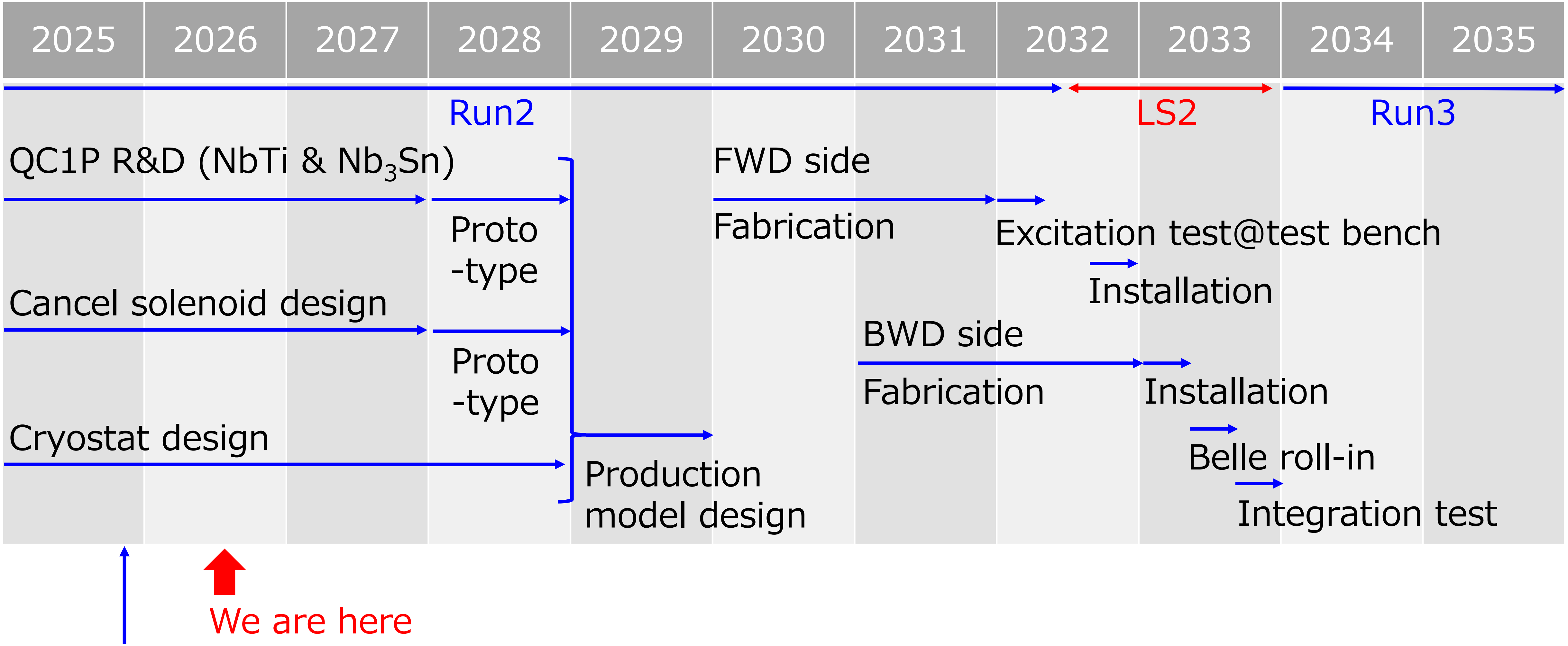
(3) Physically shifting the QC1P closer to the Interaction Point (IP).





QCS upgrade schedule

A budget request for JFY2027 has been submitted to MEXT.

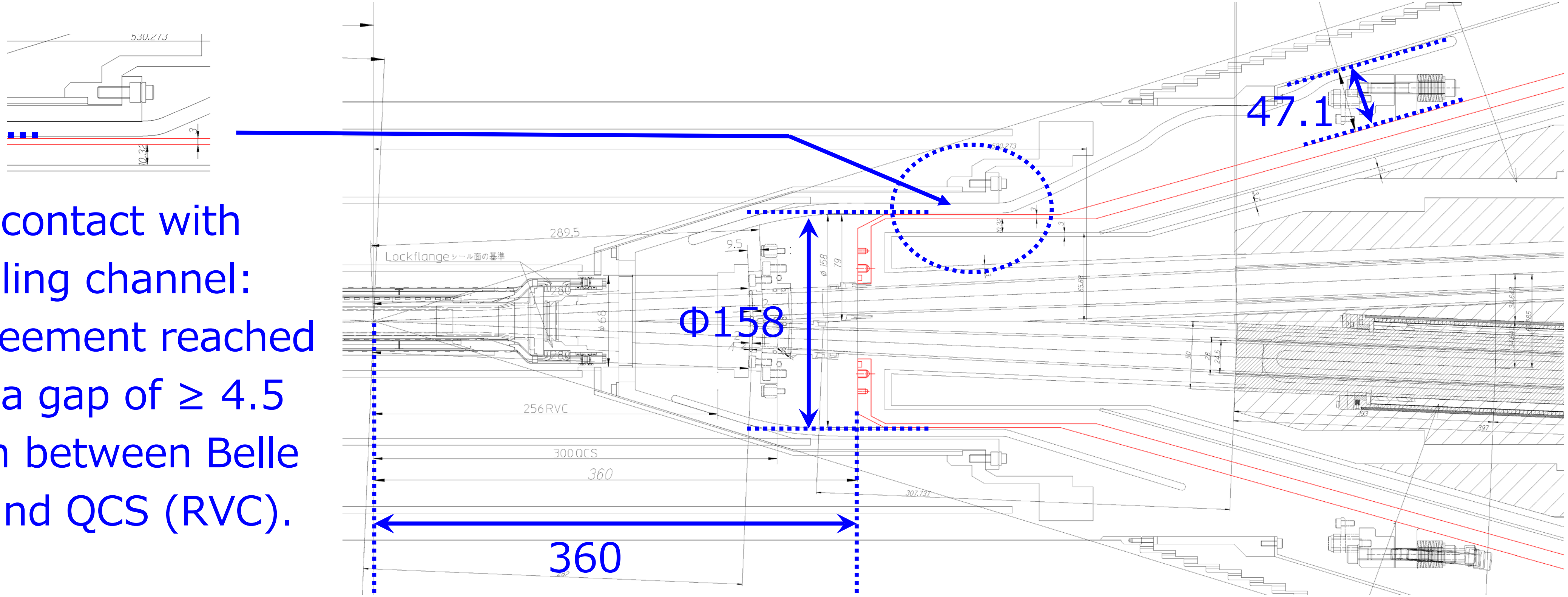


Boundary with Belle II detector was agreed with the Belle II group in Feb. 2026.

Boundary with Belle II detector

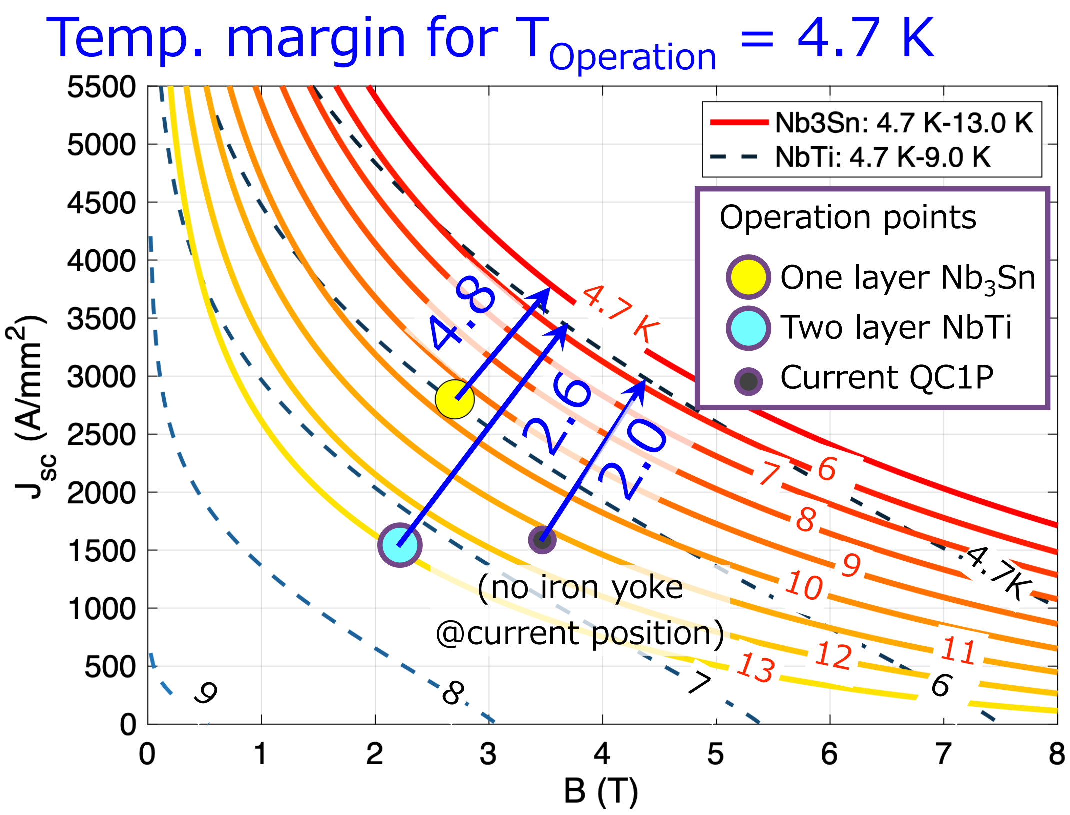
- In February 2026, the maximum conservative external dimension of the QCS cryostat was agreed with the Belle II group. While internal structure optimization continues, the outer dimension is finalised and will not increase. The cross-section assumes an additonal cancel solenoid in front of QC1P (shifted 100 mm closer to the IP), which does not affect this cryostat boundary.

No contact with cooling channel: agreement reached for a gap of ≥ 4.5 mm between Belle II and QCS (RVC).

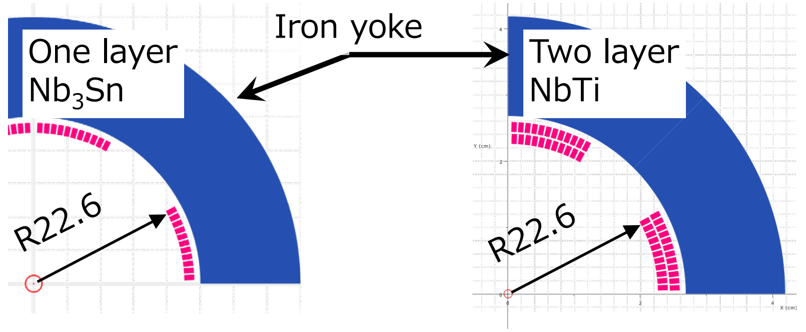


Possibility of NbTi coil for new QC1P

- NbTi is a commonly used material for superconducting magnet and is employed in the current QC1P. NbTi can be considered for the new QC1P coils.
- The temperature margins are compared here: the new QC1P made by Nb_3Sn (4.8 K), NbTi (2.6 K) and the current QC1P (2.0 K).
- While Nb_3Sn offers the advantage of a high temperature margin, it requires more extensive R&D.
- The newly introduced iron yoke expands the temperature margin by reducing the surrounding magnetic field.

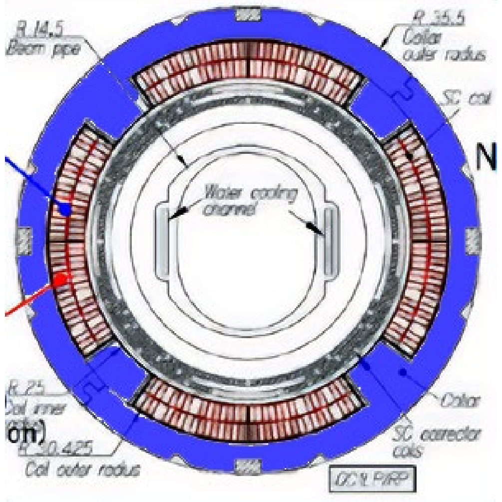


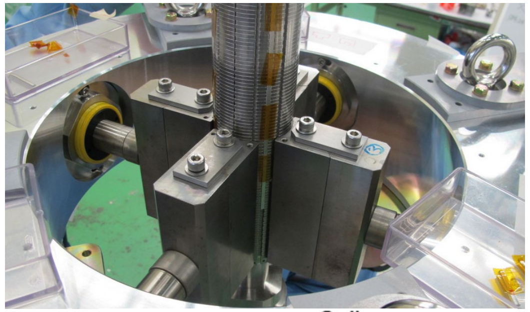
Here, followings are assumed: moving QC1P 100mm closer to the IP, enclosing it within an iron yoke, and positioning the cancellation solenoid closer to the IP in front of QC1P.

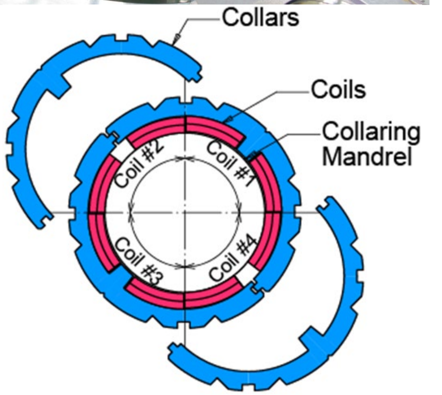


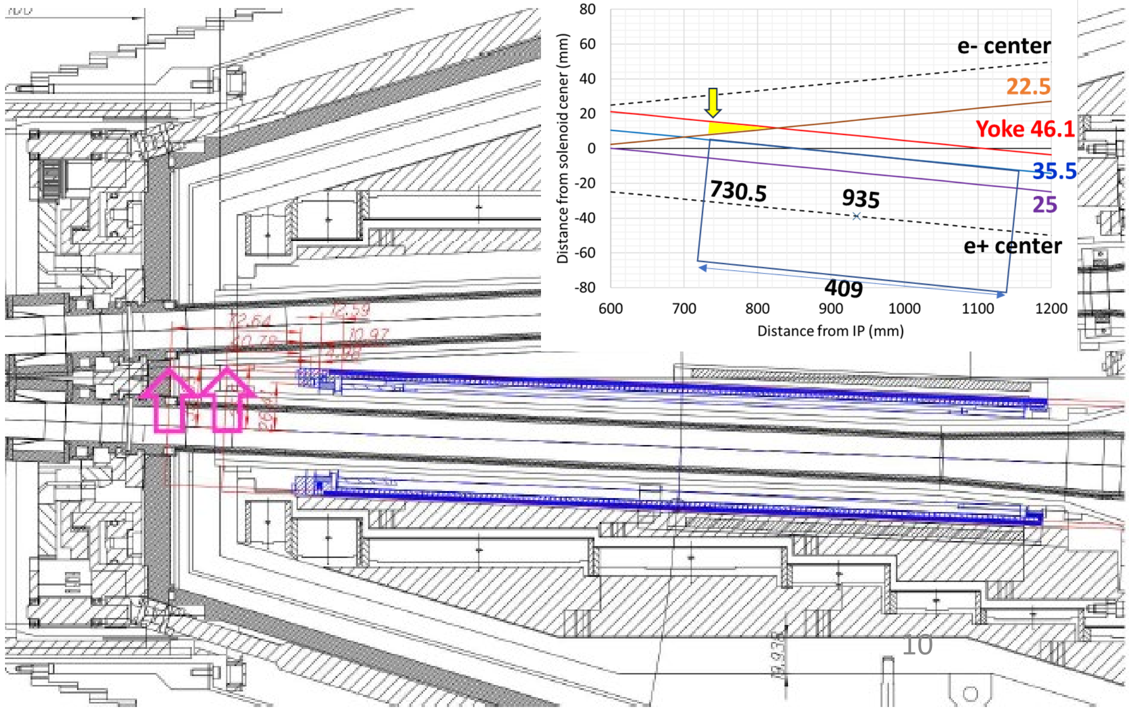
Iron yoke as collar for new QC1P

- Conventional stainless-steel collar restrains the coil to maintain its precise geometry, and this approach is adopted in the current QC1P.
- However, if an iron yoke is to be introduced for upgrade under more severe space constraints, such a SS collar cannot be adopted.
- Replacing the conventional SS collar with a structure made of iron that also functions as the magnetic yoke is being considered.
- The procedures for collaring with iron yoke for Nb_3Sn coils is being considered carefully so that brittle coils are not locally damaged due to stress concentration. Such an R&D is also necessary for NbTi QC1P.









Coil Production Workflow: NbTi and Nb_3Sn

	NbTi	Nb_3Sn
Conductor Characteristics	Ductile and easy to handle.	Intermetallic Nb_3Sn phase is intrinsically brittle.
Fabrication Process	React and Wind	Wind and React
Heat Treatment (Reaction)	NbTi phase is already formed before coil winding.	Heat treatment to form Nb_3Sn phase must be performed after coil winding.
Processes after coil winding	Curing for turn-to-turn bonding	Heat treatment and epoxy impregnation
Pre-stress control	Sufficient azimuthal pre-stress needs to be applied at RT to keep the coil stress in compression at cold.	Precise pre-stress control is required not to damage brittle coils.

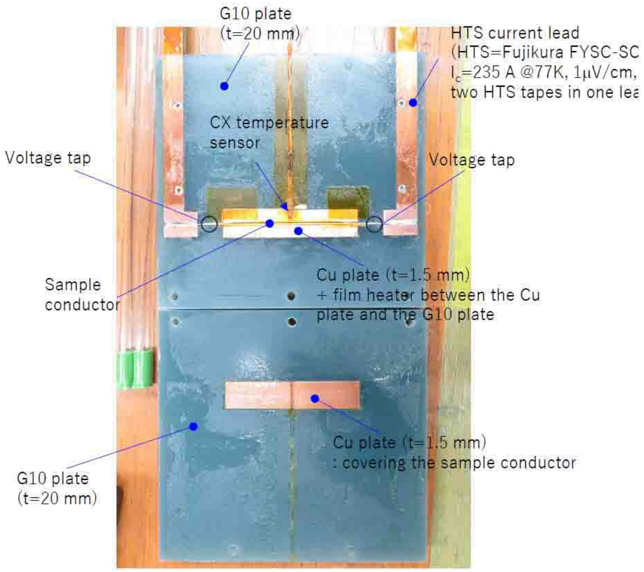
- **Difficulty in the development of Nb_3Sn magnets**: Volume change of Nb_3Sn conductors during heat treatment makes it difficult to precisely control the conductor positions, which is necessary to achieve the target magnetic field quality.

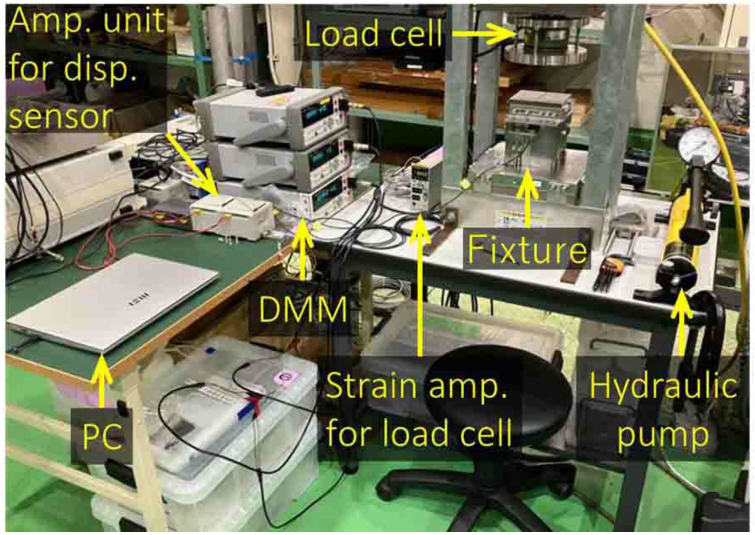
Nb_3Sn magnet R&D – Characterisation of material properties

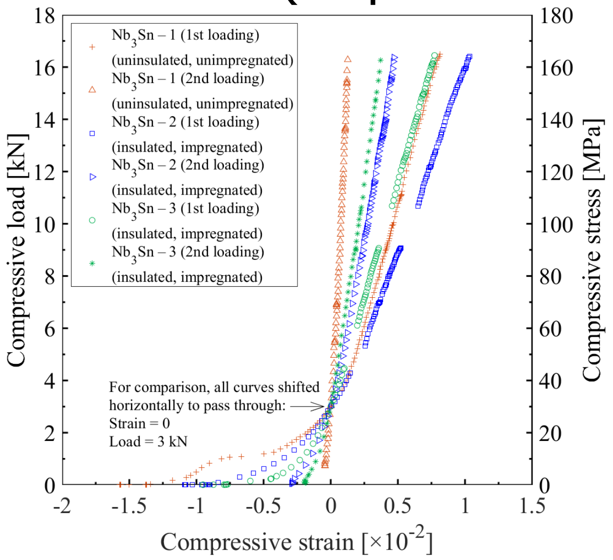
- ***J_c-B-T* curves for Nb_3Sn wire**: A Nb_3Sn wire with CuNb reinforcement will be applied to the coils for QC1P. Critical current density under various external magnetic fields and temperatures (J_c-B-T characteristics) is being evaluated, which is essential to magnetic design.

- **Compression test of stack samples**: Mechanical properties of Nb_3Sn coils need to be characterised for precise control of coil pre-stress during magnet assembly. A compression test of stack samples composed of glass-sleeve-insulated Nb_3Sn wires and epoxy resin is underway.

K. Kaneko (Sophia Univ.)







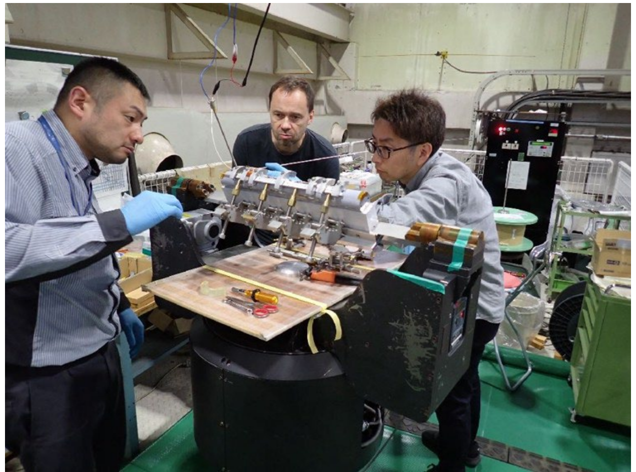
Nb_3Sn magnet R&D – Fabrication of practice coils

- Three single-layer Practice coils have been produced to establish the procedures for coil winding, heat treatment, and epoxy impregnation in collaboration with FNAL.

PC1: The pole turn and Ti-alloy pole piece were electrically shorted.

PC2: Even though an additional glass sleeve was inserted into the pole turn to consolidate electrical insulation between the turn and the pole piece, the insulation between them was still insufficient.

PC3: The impregnation resin was changed. The coil impregnated with CTD-101K passed a Hi-pot test up to 2 kV.

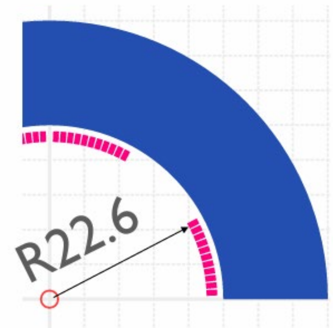


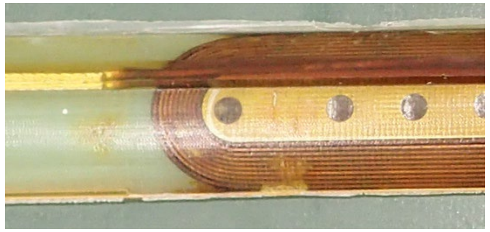
Nb_3Sn magnet R&D – Items to be considered in coil design and fabrication

- **Coil design (Single or double layer)**: Compared to the single-layer coil, the double-layer option has advantages of a larger temperature margin, more robust mechanical support for the ramp lead, and a reduction in error fields caused by the leads at the coil end. Design of a double layer coils is in progress.

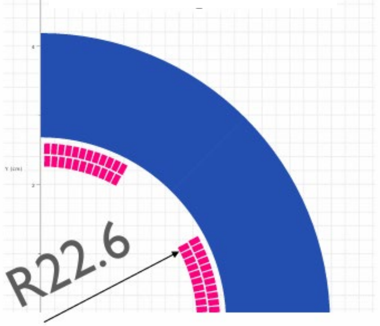
- **Coil size measurement**: The size of a coil needs to be precisely measured for controlling coil pre-stress and estimating the magnetic field quality. A preliminary measurement using a 3D scanner-type CMM has just started.

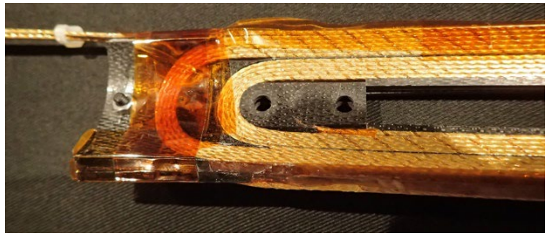
Single layer

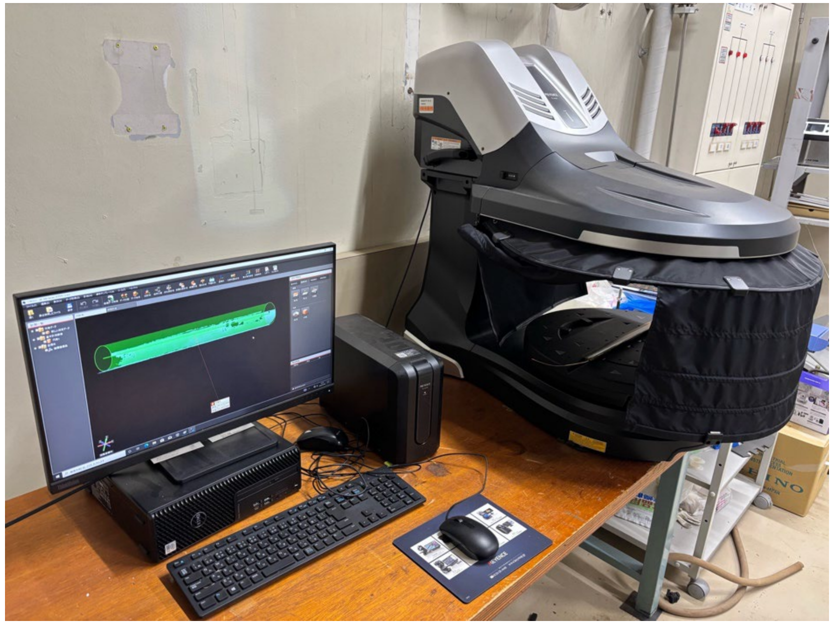




Double layer





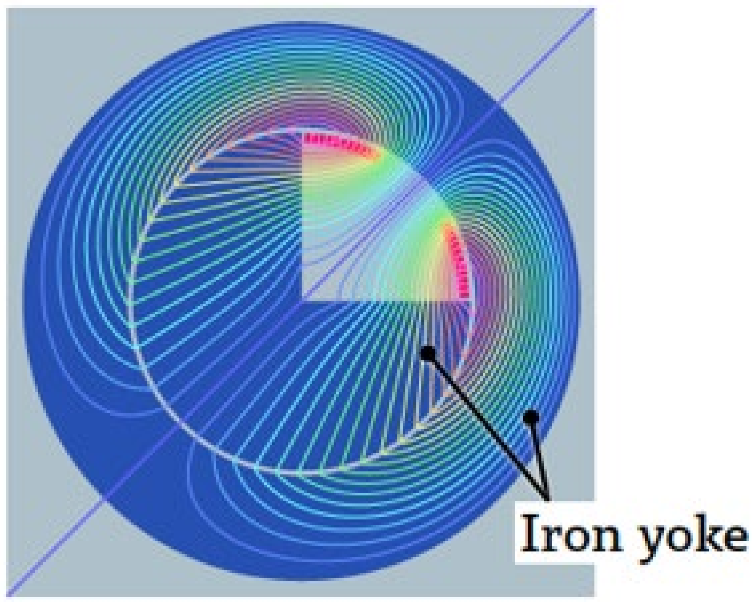


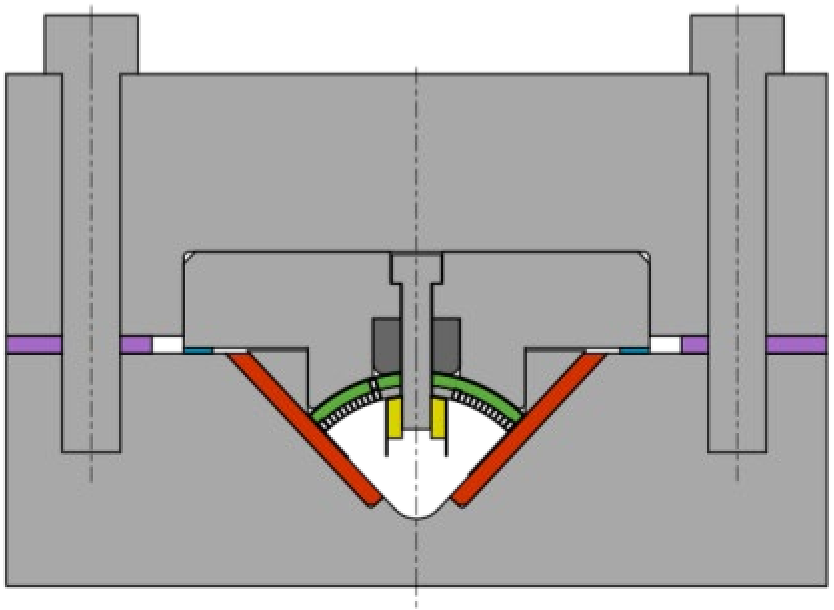
Nb_3Sn magnet R&D – Mirror magnet

- The soundness of Nb_3Sn coils will be confirmed by assembly, cooldown, and excitation of a "mirror magnet".

- To reproduce the magnetic field distribution and Lorentz force similar to those experienced by a coil inside a quadrupole magnet, a single coil is enclosed within iron blocks.

- Mechanical design of a mirror magnet is ongoing.





NbTi QC1P R&D

- In parallel with Nb_3Sn QC1P, the NbTi option is also being considered. The following items need to be addressed.

- Availability of a Rutherford cable with thinner wires or a monolith wire with fine filaments.

- Coil winding with a monolith wire and yoking trial without SS collar.

- Design of the magnet cross-section depending on the installation location.

Summary

- During LS2 (2032-), major upgrades of SuperKEKB are planned. The three major pillars of these upgrades are the modernisation of the injector linac, the enhancement of the HER RF system, and the modification of the IR.
- The IR upgrade focuses on installing an additional compensation solenoid and optimising QCS placement.
- Installing a compensation solenoid in front of QC1P reduces chromatic coupling and emittance growth. Placing QC1P closer to the IP increases the dynamic aperture and beam lifetime.
- The maximum external dimensions of the QCS cryostat were agreed as the boundary with the Belle II detector.
- Active R&D is progressing on both Nb3Sn and NbTi magnets for QC1P, and we will select one of them by the end of FY2027.