Future SuperKEKB IR design upgrade Challenge for higher luminosity (D_RD_32)

Dr. Shuji TANAKA
Ing. Takashi KOHR IKI
Dr. Koji HARA
Dr. Katsuro NAKAMURA
*Ing. Takahiro KANAYAMA(**ITDC**)*
*Ing. Junichi SUZUKI(**ITDC**)*
*Dr. Yoshiyuki ONUKI(**U-tokyo**)*
*Dr. Takeo HIGUCHI(**IPMU**)*

Ing. Julien BONIS
Dr. Emi KOU
Ing. Didier AUGUSTE
Ing. Yann PEINAUD
Prog. François LE DIBERDER
Dr. Roman MIZUK

FJPPN-FKPPN Joint workshop of TYL/FJPPN and FKPPN 2026

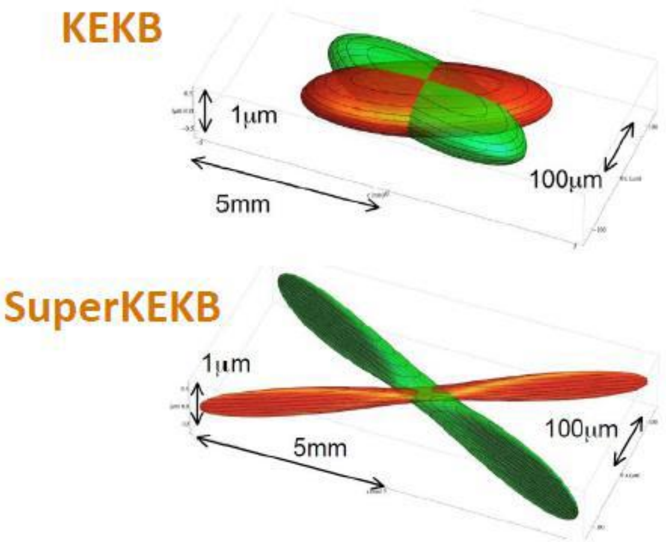
Introduction

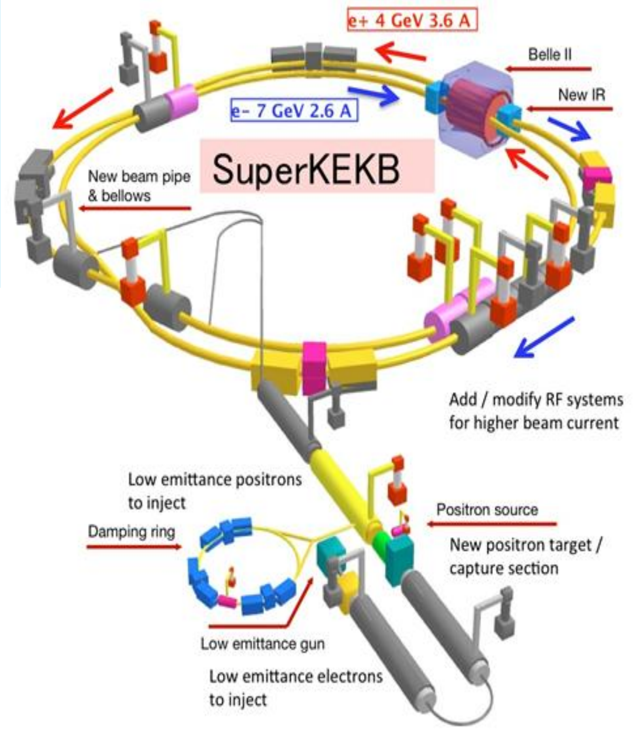
The Intensity Frontier: Studying rare particle decays of D and B mesons (also τ) to find a signal of the BSM

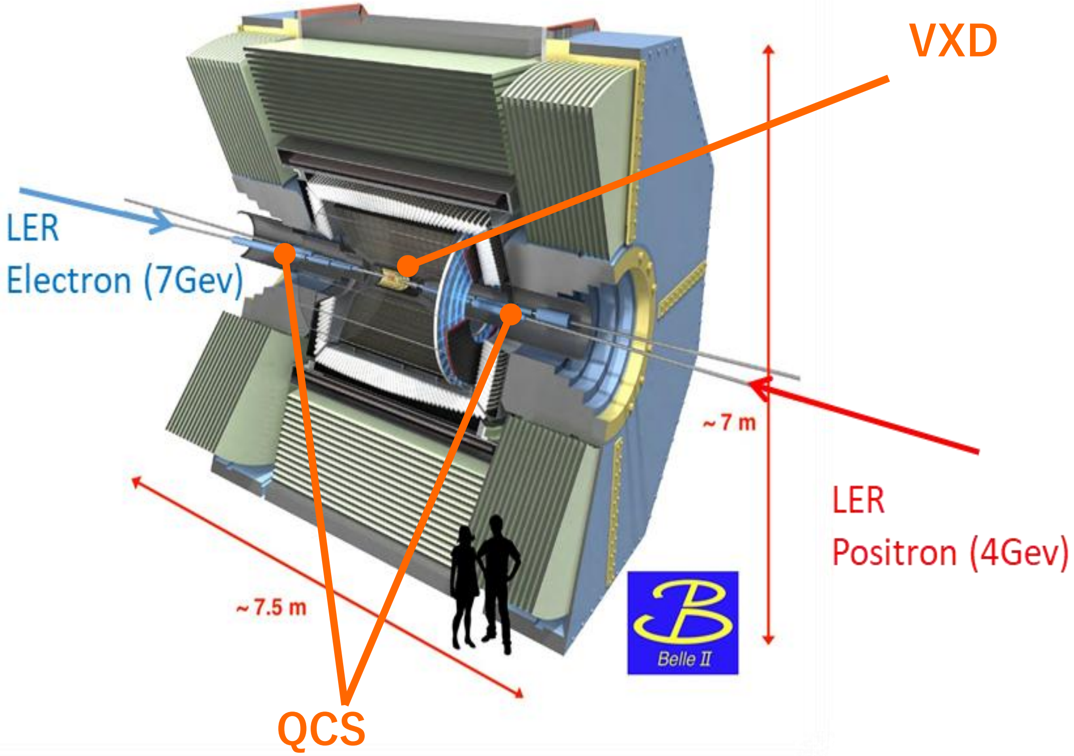
1. High luminosity accelerator: SuperKEKB
2. High-resolution and large area coverage detector: Belle II
3, Asymmetric energy electron-positron beam collision (identify boosted B meson decay products)
4. Ultimate goal: Integrated luminosity: 50 ab^{-1} by operating at $6x10^{35} cm^{-2}s^{-1}$

Accelerator complex consisting of
- Injector (Linac)
- Positron Damping Ring (DR)
- Beam Transport Lines (BT)
- Main Ring (MR)

with Belle II Detector





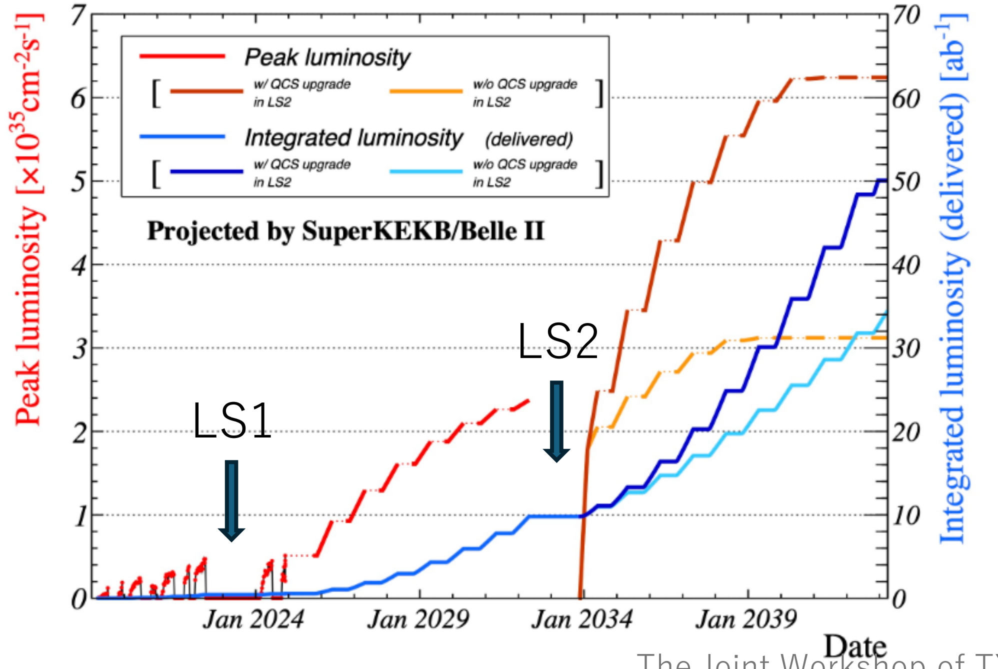


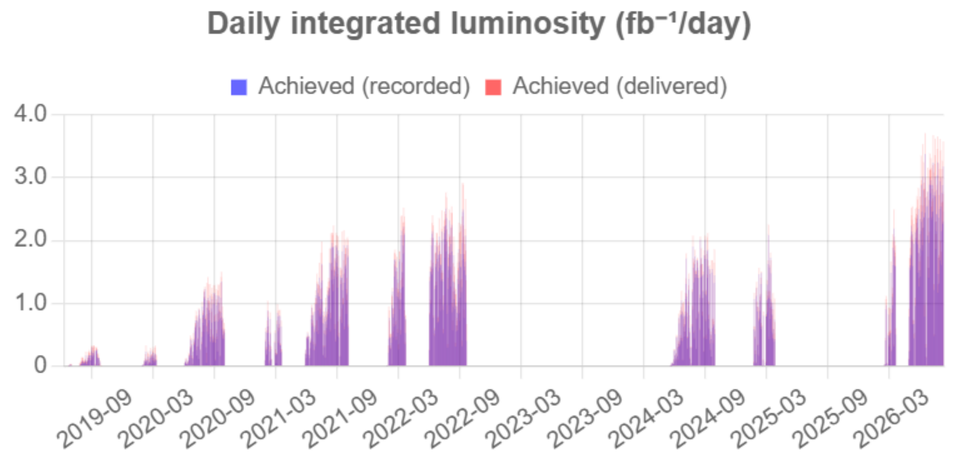
Beam lifetime ~10 minutes or less

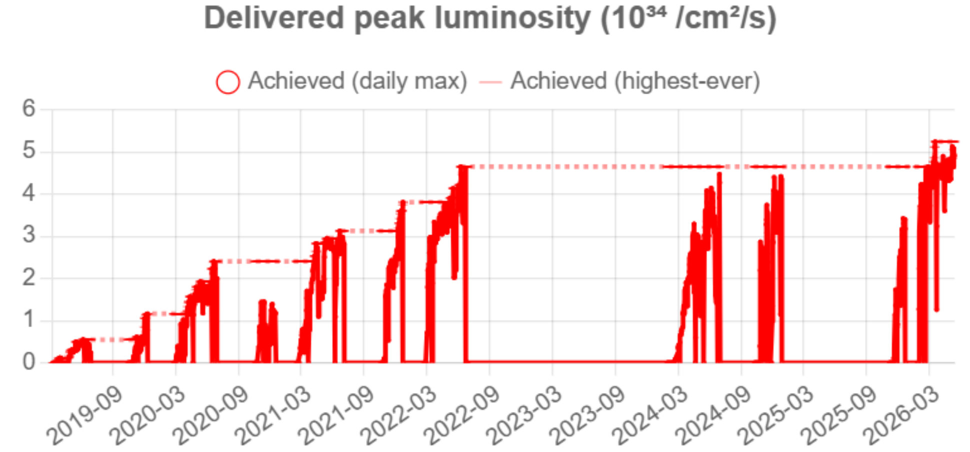
Current operation status and future plan

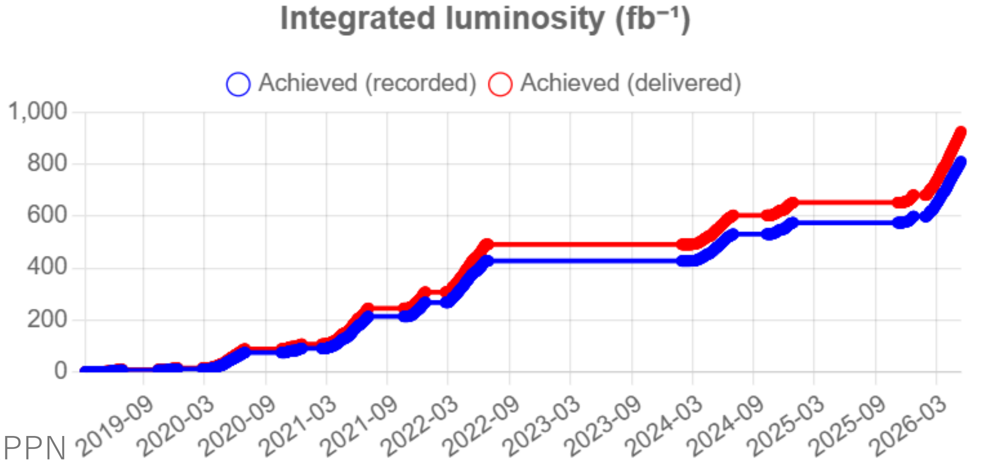
- Long Shutdown 2 (LS2) is expected around 2032.
- After LS2, luminosity projection shows two lines.
- luminosity improvement of x 1.3 is expected due to the beam current increase mainly by the RF reinforcement (beam current increasement).
- IR upgrade is assumed to be able to increase the luminosity much more.
- Technical feasibility of the IR upgrade and the exact luminosity gain remain uncertain.
- Operation needs to be continued by 2042 to deliver 50 ab^{-1} with IR upgrade.

Luminosity projection









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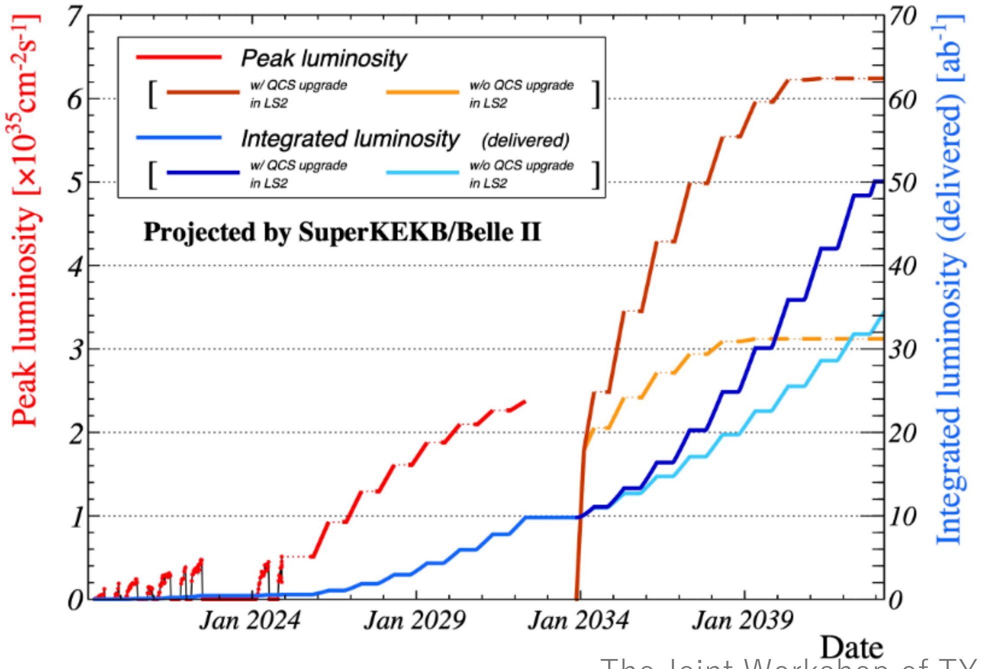
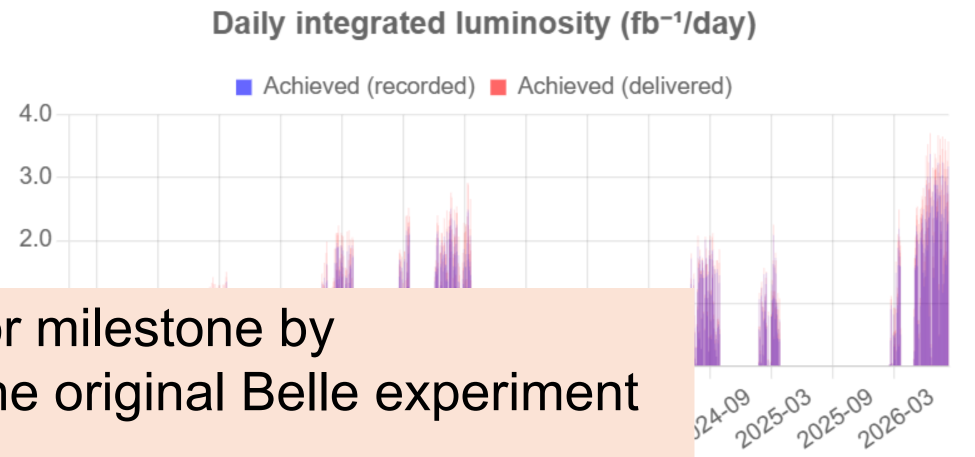
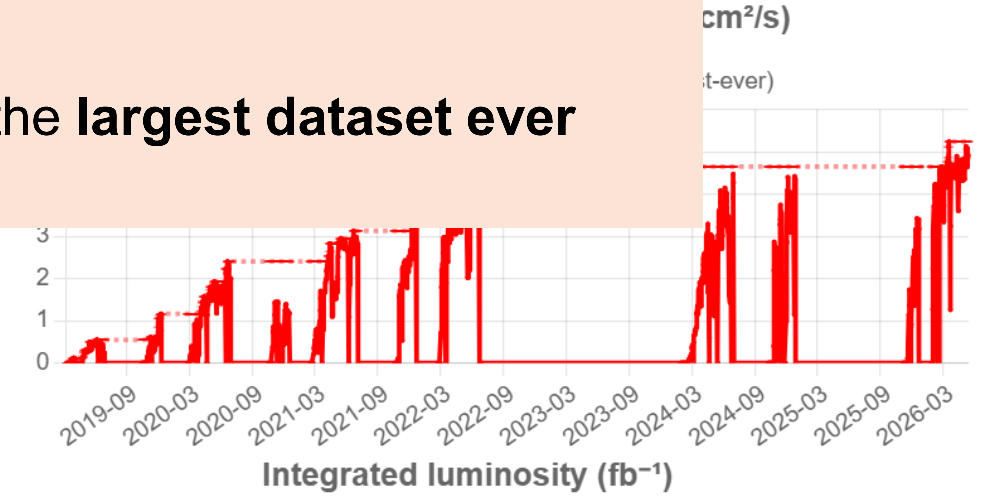
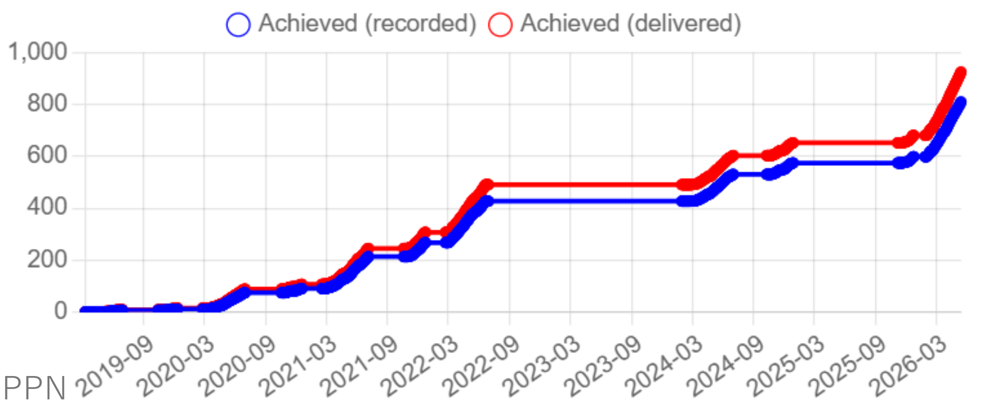
On **17 May 2026**, the **Belle II experiment** at KEK achieved a major milestone by surpassing the total integrated luminosity previously recorded by the original Belle experiment at the **Υ(4S) resonance**.

Belle II has now accumulated **more than 713.7 fb^{-1}**, establishing the **largest dataset ever collected at this energy**.



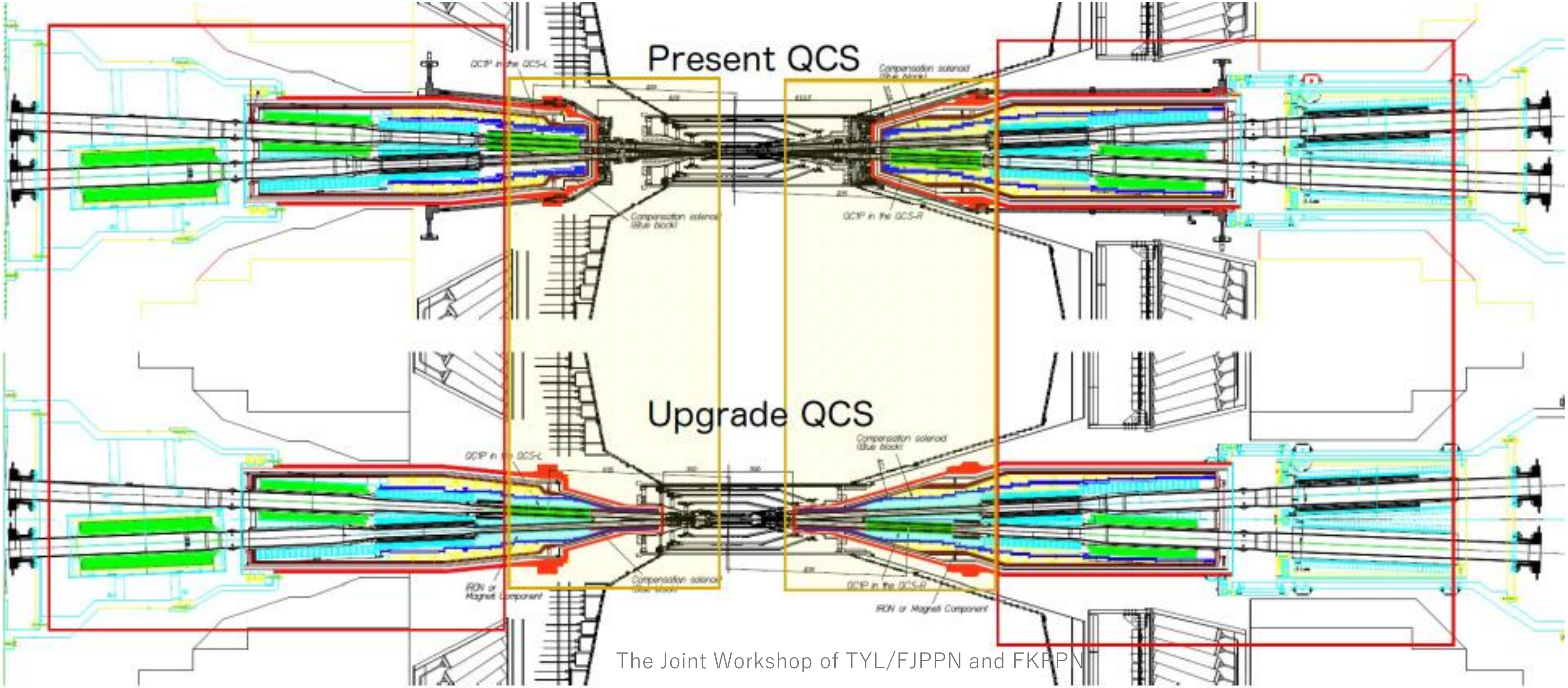






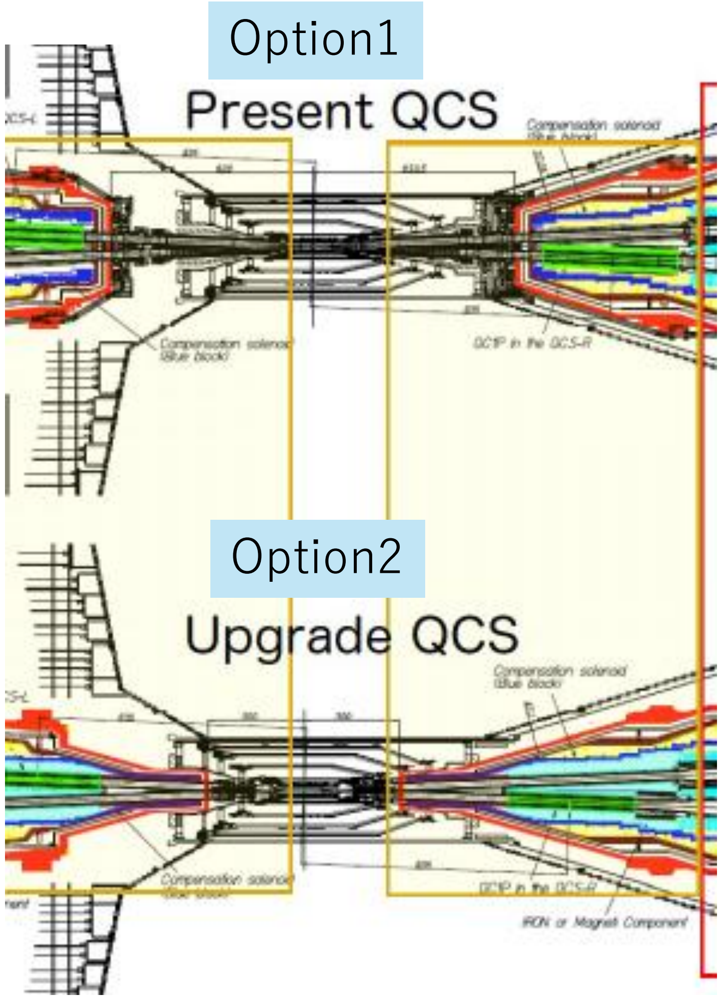
LS2 IR design upgrade

- Control beam–beam effects to optimize luminosity while maintaining adequate beam lifetime.
- Introducing individual cancel coils for the Belle solenoid and shifting the IP-side QC1 magnets enlarges the dynamic aperture. The resulting simpler beam orbit also contributes to lower background.



SuperKEKB IR design upgrade: (2024JFY)

The FJPPN project plays a central role in the Belle II upgrade, linking the IR, QCS, and the next-generation vertex detector. A key challenge is defining reliable procedures for installing, assembling, and cooling the VTX sensors, as well as assembling the IP beam pipe and radiation shields. These tasks cannot be improvised and depend strongly on the final QCS design.



Two integration scenarios of VTX/QCS are under consideration:

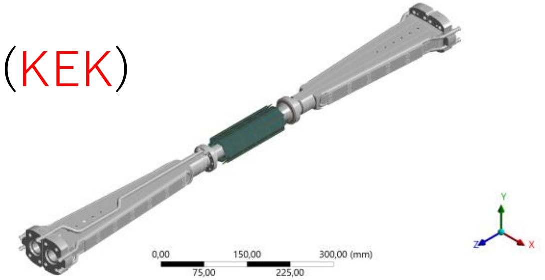
Option1:Maintain the current mechanical boundaries of the IR components.

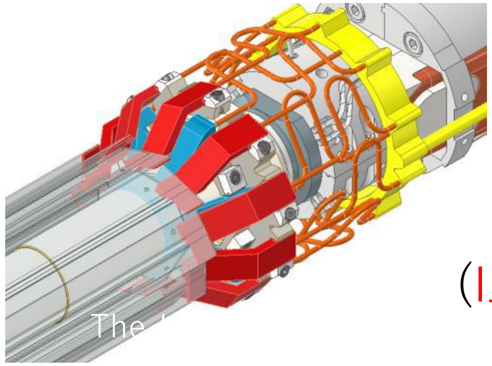
Option2: Fully rebuild the QCS and renovate the vertex detector.

In 2024, the Belle II upgrade working group selected Option 1 as the baseline plan. (for understanding VXD integration and issue)

The machine group continues feasibility studies for a new QCS design with Nb3Sn wire which is new challenge and if its feasibility is confirmed, the project will switch to Option 2.

(KEK)



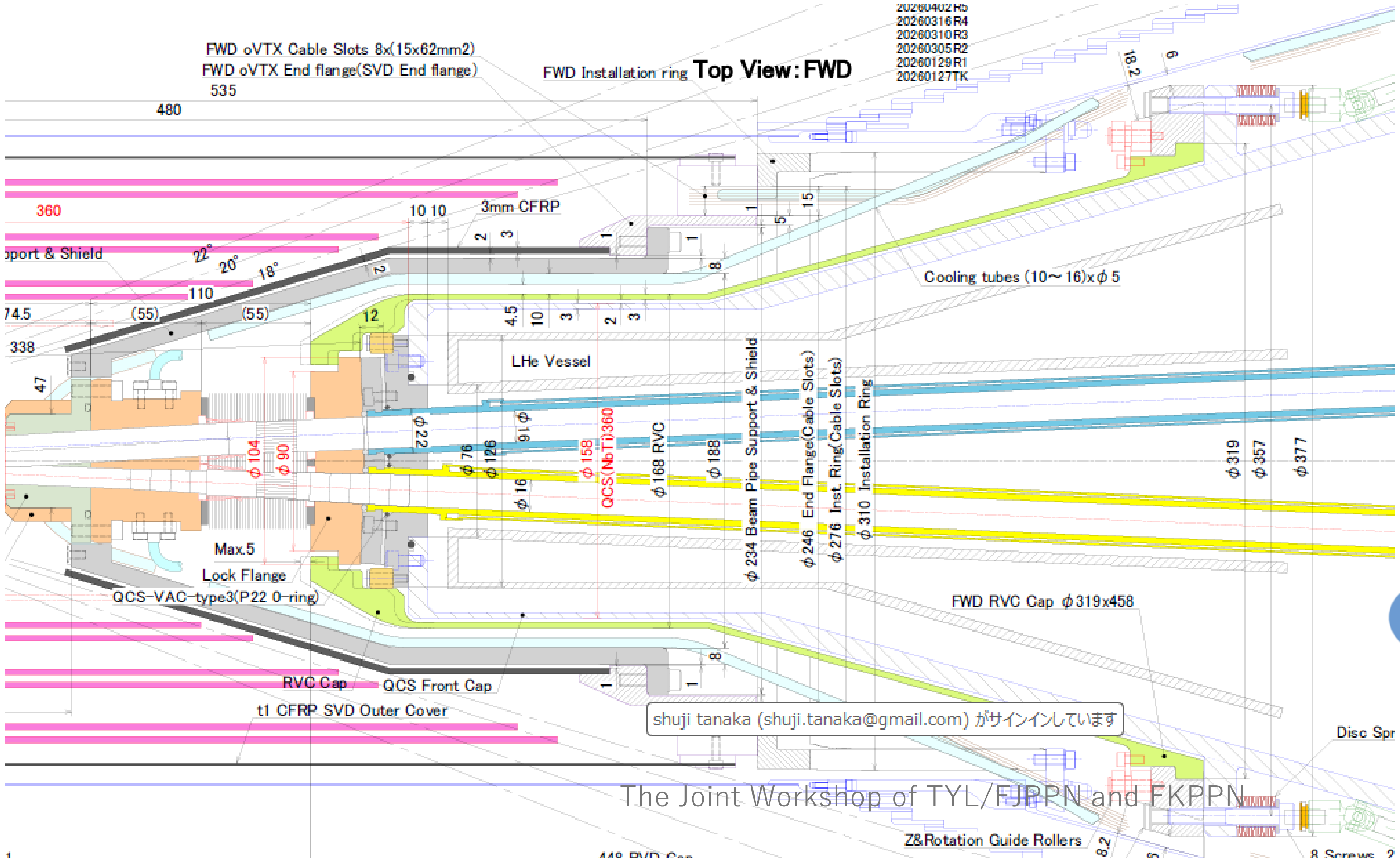


Proposed integration of iVTX around the beam pipe.

(IJClab, QMUL)

SuperKEKB IR design upgrade: (2025JFY)

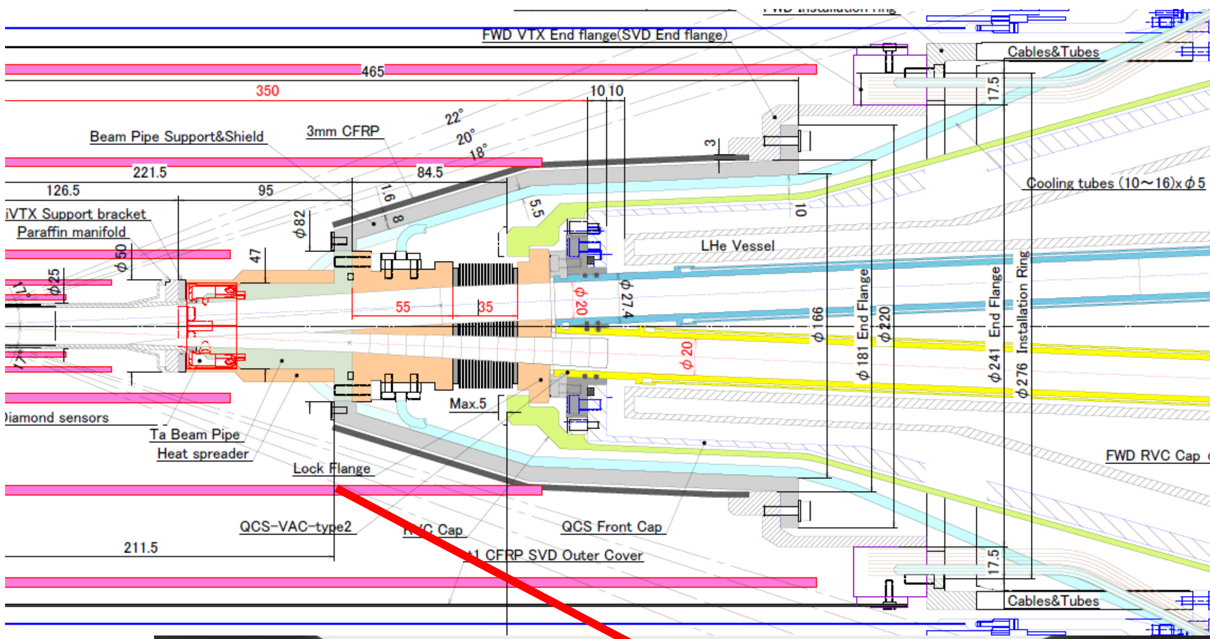
- KEK IR group and VTX group took agreement to change base scenario from Option1 to Option2 (Space allocation of QCS and VTX is completely changed from current IR design).
  - QC1 superconducting wire of LS2 QCS is considered as NbTi case which is fallback option of Nb3Sn scenario.
    - By this change, QCS cryostat outer dimension will be enlarged than Nb3Sn case (which means VTX space will be reduced),
    - If Nb3Sn wire option was confirmed later, we will switch to this option.

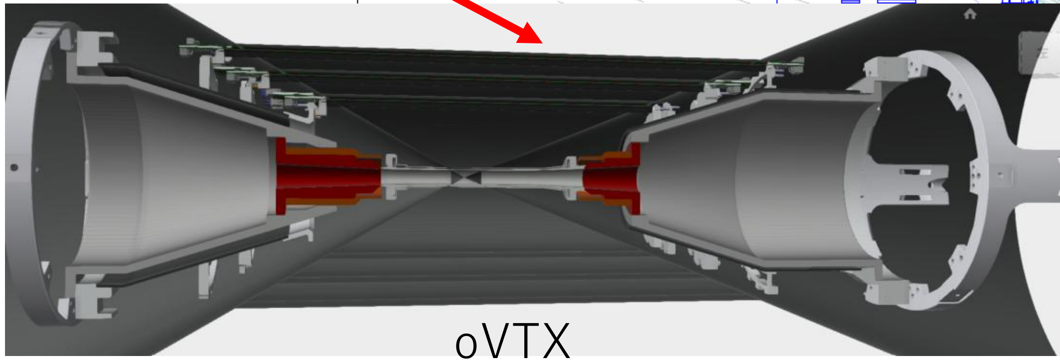


KEK VTX group

IR mechanics design check points

1. Optics design (Optics group)
   - Preparing models for LS2 upgrade
   - SAD simulation and (IR (Tsukuba straight section) design
2. BG estimation (BG group)
   - BASF2 implementation
   - Magnetic field implementation
   - BG estimation with SAD simulator
   - Finding Additional shield space <-> IR meeting
3. QCS design
   - Magnet allocation
   - Thermal management
   - Cryostat design -> VTX space allocation
   - Movement by QCS quench or earthquakes (open space decision)
4. Beam pipe integration
   - QCS beam pipe
   - RVC(next slide)
   - Bellows pipe (BPM+bellows, Diamond sensor)
   - IP beam pipe
5. Service space for IR and VTX
   - QCS -> RVC -> open space -> VTX services(pipe, cable) -> Shield -> oVTX, iVTX
6. oVTX design , iVTX design
7. VTX integration: similar step with VXD
   - IP beam pipe(+iVTX) + Heavy metal shield + Endf-lange (+oVTX)+ CDC inner ring
8. VTX installation: the same step with VXD

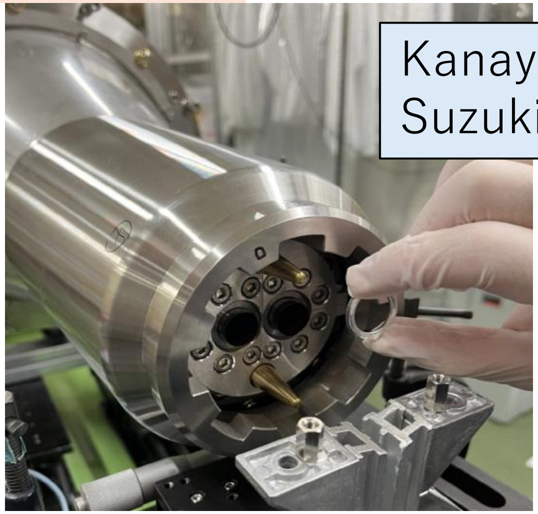




LS2 RVC (Remote Vacuum Connection) mock test

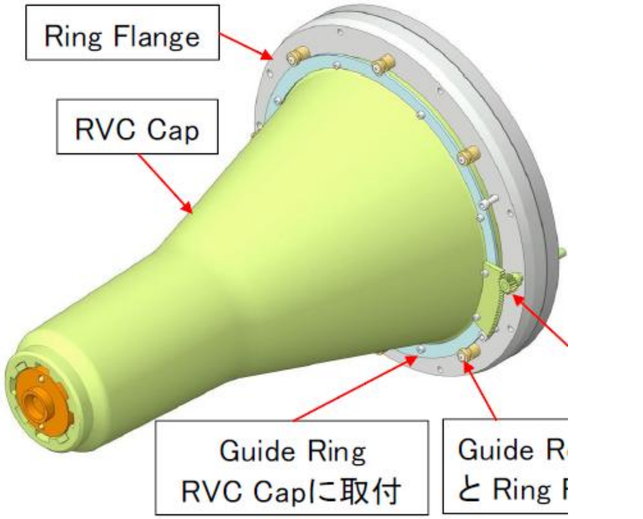
After the QCS insertion, this RVC controls vacuum beam pipe connection remotely.

Kanayama, Kohriki
Suzuki



HELICOFLEX®

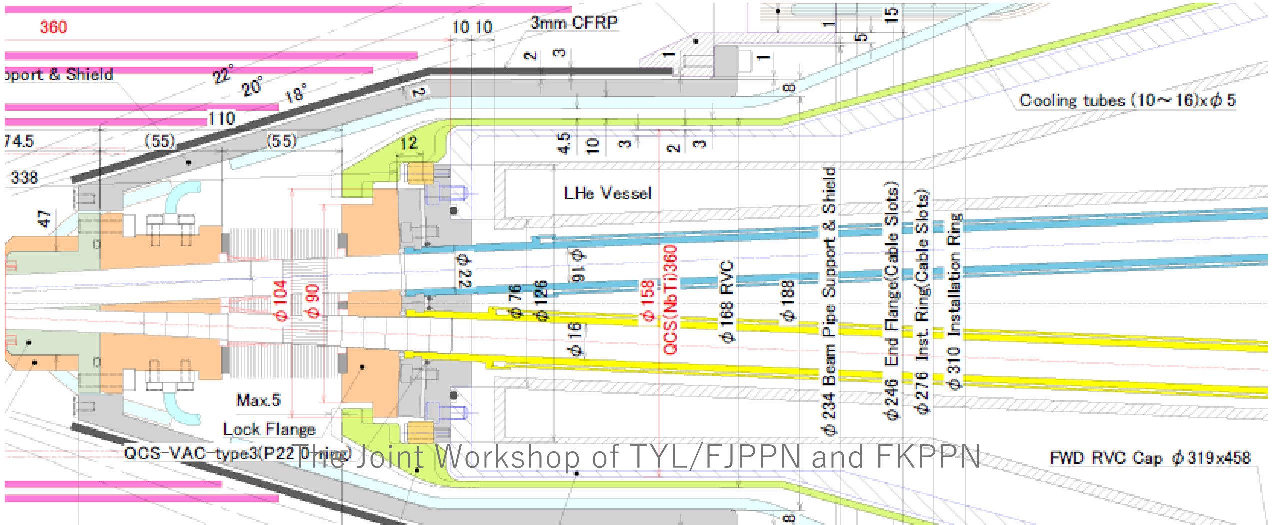
- RVC vacuum leak test has passed with remote rod control
- Seal test with asymmetric diameter o-ring is on preparation. Also metal o-ring positioning design



Main update of the LS2 IR design in 2025 JFY

- KEK VTX group has developed a basic mechanical integration design for the IR beam pipe, including the vacuum sealing structure, and has outlined preliminary procedures for VTX integration and material allocation. Due to the reduced available space in the new IR configuration, several modifications from the current design are required:

1. **Reduced beam pipe diameter** The beam pipe diameter near the IP is decreased from 20 mm to 16 mm to fit within the QCS tip region and to secure proper vacuum sealing.
2. **Integrated HER/LER bellows structure** To absorb relative displacement between the IP beam pipe and the QCS during quenches or earthquakes, the HER and LER bellows—previously separate—must be combined into a single integrated unit due to LS2 space constraints. A mock-up test is being prepared to validate its functionality.
3. **Defined VTX–QCS clearance** A 4.5 mm clearance between the VTX and QCS is specified to avoid mechanical interference during seismic events. Recent FEM studies indicate that the current support bracket design lacks sufficient seismic robustness, and appropriate support jigs will be installed in the near-term plan.



Latest issues and challenges on the IR mechanics

- **In 2027, Technical design report of LS2 program will be published.**
- KEK IR mechanics
  - Feasibility check for each component and Action for the issue
    - **(KEK IR) Feasibility check of the 16mm diameter beam pipe (i.e. sputtering process)**
    - **Feasibility check of VTX assembly procedure**
    - **FWD iVTX cooling pipe space check and oVTX cable slot issue (FEM,BG)**
    - **Mechanical stiffness check of new BWD installation ring**
    - **(Vacuum)** Bellows pipe movement (RF finger) for the earthquake
    - SR heating management (particularly around bellows)
    - **(QCS)** QCS head area stiffness (for standing RVC stress)
    - QCS design/test(Nb3Sn and NbTi)
    - Feasibility check of the vacuum sealing design around the QCS head
    - **(BG)** BG estimation and mitigation with additional shields
    - **(STR)** Additional Belle II support structure to mitigate displacement by the earthquake
- oVXD (Pisa, Vienna)
  - oVTX ladder mount on the End-ring
  - oVTX service management (cables and pipes)
  - oVTX cooling
- iVTX (IJClab, QMUL)
  - **iVTX ladder mount on the Beam pipe (design)**
  - **iVTX themal management study**
  - iVTX service management (PP space, Kapton flex , cooling pipes)
- Another check points (almost agreed)
  - Grounding policy
  - VTX position control (target precision of position control)

iVTX (inner Vertex Detecror) cooling. (IJClab)

(Snecario1: air flow cooling)

Numerical simulations show the following limitations of air cooling:

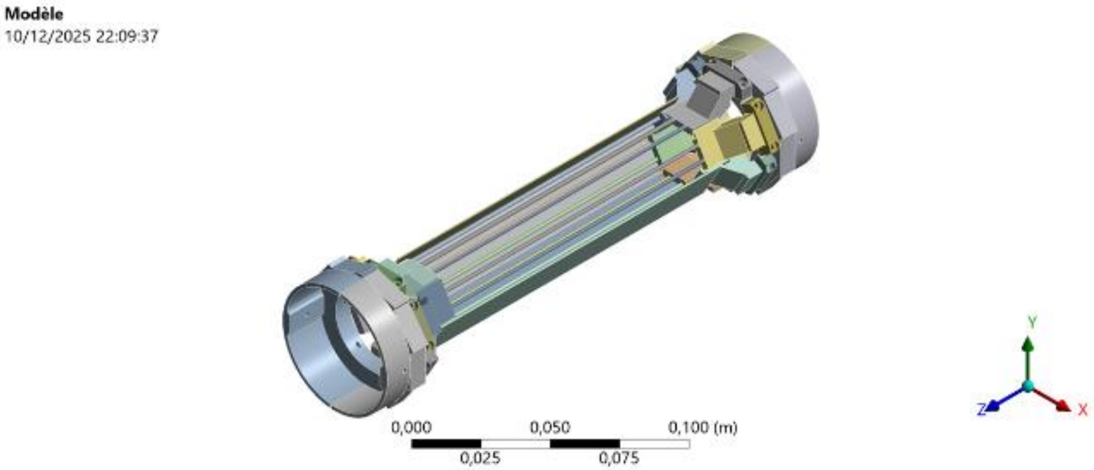
- The power density is too high relative to the limited heat capacity of air.
- Maintaining an acceptable sensor temperature close to room temperature is not feasible.
- The space available for cooling airflow is severely restricted.
- Service access space is extremely limited.

Therefore, air cooling is no longer a viable option.

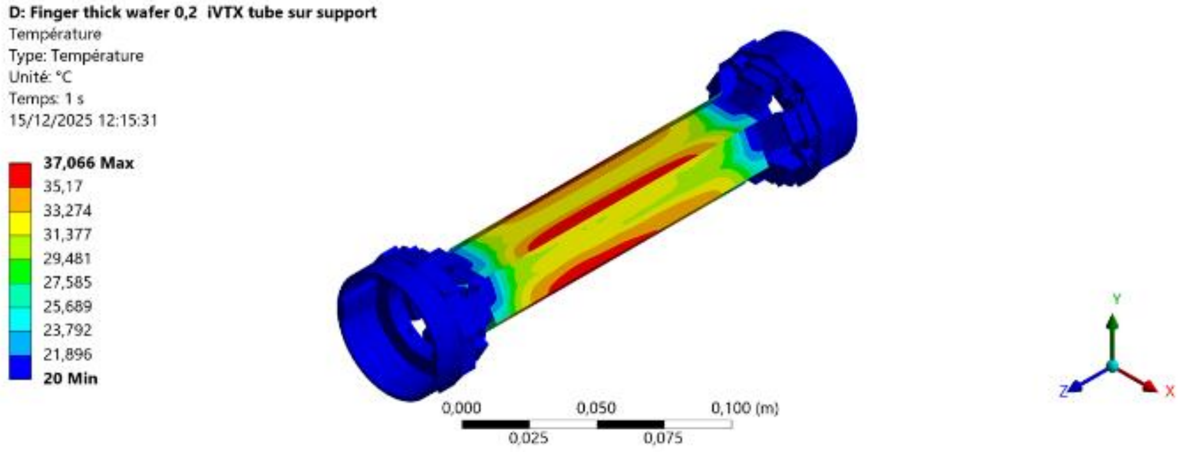
IJClab/KEK discussion
＊Satellite meeting of the Belle II VTX workshop
＊During B2GM (Belle II General meeting)

(Snecario2: water pipe cooling)

After **Investigated of cooling scenarios**: Possible options could be **liquid-cooling**.



CAD model of ladders on supports with liquid cooling pipes



FEM simulation of ladders on supports with liquid cooling pipes

However, **several significant technical drawbacks** remain.

- Material budget of cooling pipe
- Leakage risk. (damaging electronics)
- The complexity of the design and installation.

These substantial risks, together with the potentially severe consequences for the Belle II experiment, provide strong arguments against circulating fluid through thin tubes along the ladders.

The only viable alternative :
Dissipate thermal energy through **conduction to the support structures using solid materials** while keeping the system as transparent as possible to particles.

(Snecario3: Thermal conduction using TPG)
Thermal Pyrolytic Graphite (TPG).
TPG : extremely high thermal conductivity (> 1500 W/m·K),
A relatively large radiation length.

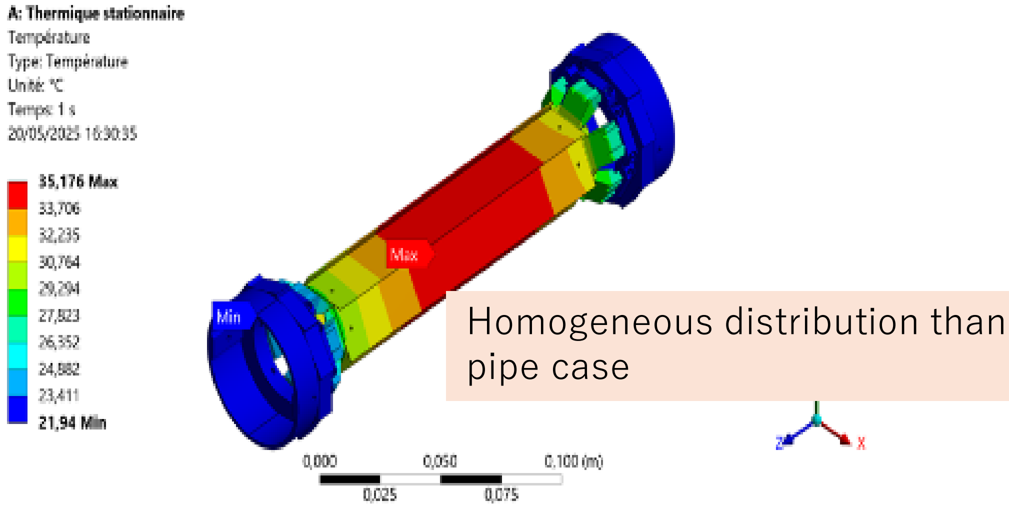
We were able to obtain extensive information and practical guidance on its use thanks to the work of the Goethe University Frankfurt team, in particular Mr. Franz Matejcek.

Thermal drainage with TPG would allow effective cooling of the iVTX ladders.

The thermal energy generated by the sensors would be transferred to the supports through a sheet made of pyrolytic graphite (TPG).

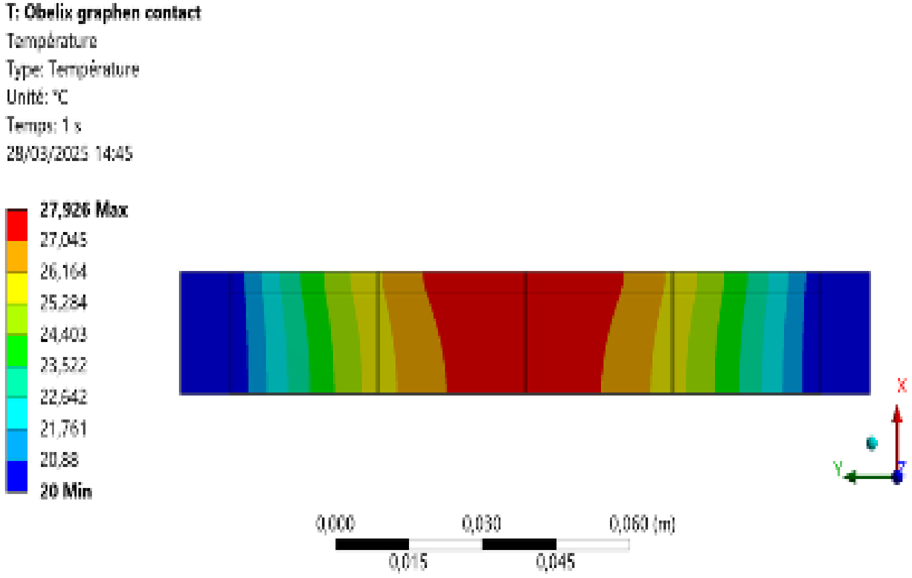
A possible **TPG iVTX ladder** composition is as follows:

- *Wafer thickness: 0.1 mm*
- *TPG thickness: 0.4 mm*
- *Adhesive thickness: 0.05 mm*
- *Copper mounting arms with adhesive at both end*

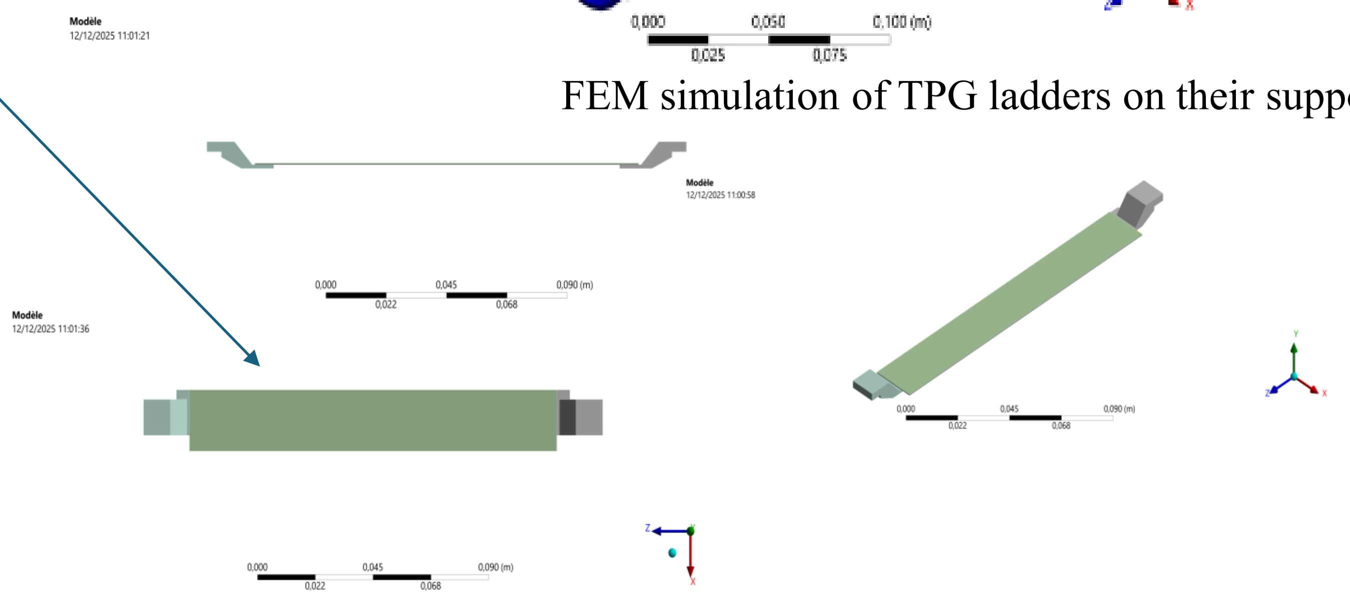


Homogeneous distribution than cooling pipe case

FEM simulation of TPG ladders on their supports



FEM simulation of TPG ladders alone



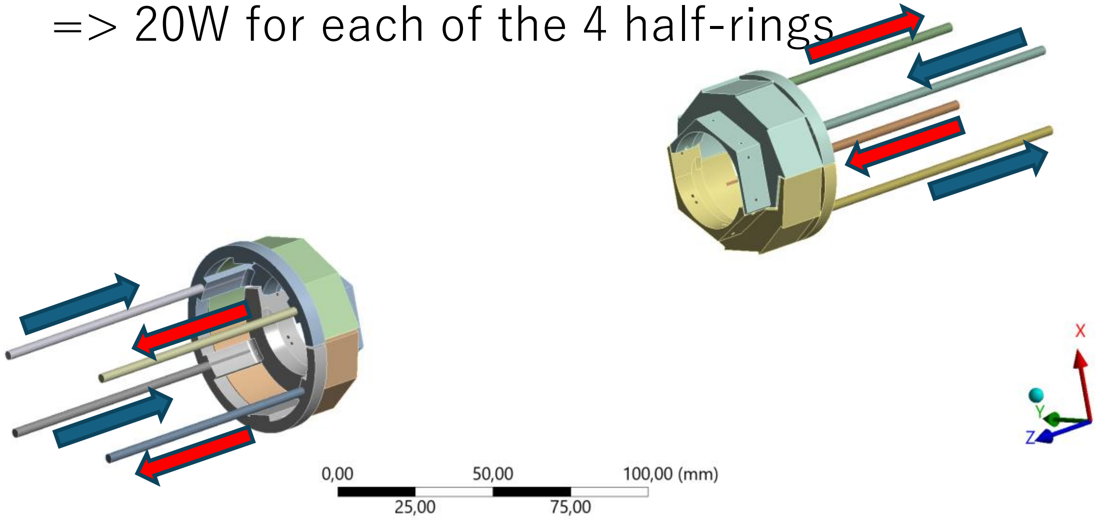
Complete ladder with TPG wafer and copper arms

iVTX support structure cooling

Water circulation remains cooling method.

Since the flow tubes are located outside the particle measurement area and their number is limited, they can be made sufficiently robust and easy to connect, thereby minimizing the risk of leakage. Nevertheless, further studies will be required to validate this approach.

If 5W per ladder
=> 80W for 16 ladders
4 water cooling loops
=> 20W for each of the 4 half-rings



We have estimated the water flow rates required to cool the iVTX supports.
The preliminary study indicates that the space allocated for iVTX services around the beam tube is sufficient to accommodate eight cooling-water pipes.

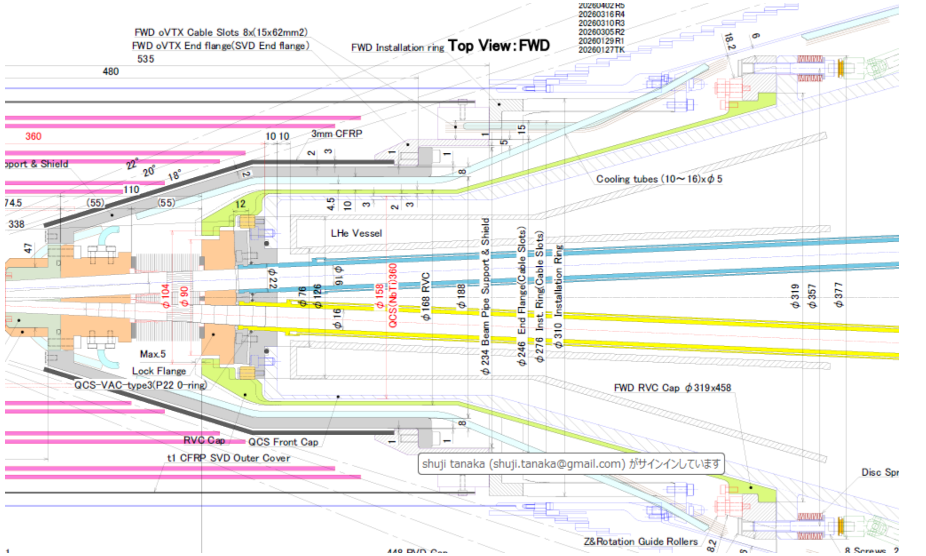
The next steps in our program are the feasibility study of the assembly procedure and the thermal-performance tests of the TPG-based ladders.

Conclusion and plan in 2026

- On the SuperKEKB/BelleII project, Long Shutdown 2 (LS2) is expected around 2032.
- By the LS2 upgrade, a luminosity improvement of approximately ×1.3 is expected, primarily due to the increased beam current enabled by the RF-system reinforcement. In addition, the IR upgrade will further enhance luminosity by providing a larger dynamic aperture.
- In 2025 JFY , KEK IR group and VTX group took agreement to change base scenario from Option1 to Option2 (Space allocation of QCS and VTX is completely changed from current IR design).
- LS2 IR component space allocation was agreed. (more detailed study is ongoing, i.e. service space)
- Feasibility of the new RVC mechanics was confirmed with mock test.
- In 2026 JFY, full function of the RVC check and New IP

Beam pipe with reduced diameter(20-> 16mm) will be studied.

(Also VTX mechanical integration procedure will be studied.)



- IJClab group tested several scenarios of silicon-sensor cooling:
  1. Air flow,
  2. Water-pipe attachment directory on the sensor and
  3. Thermal conduction using TPG
- As a result, third scenario-TPG based thermal conduction has emerged as a strong candidate.
- The feasibility study of the assembly procedure and the thermal-performance tests of the TPG-based ladders will be carried out in 2026.

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