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

SuperKEKB and Belle II interaction region modelling

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On behalf of the beam background and MDI groups

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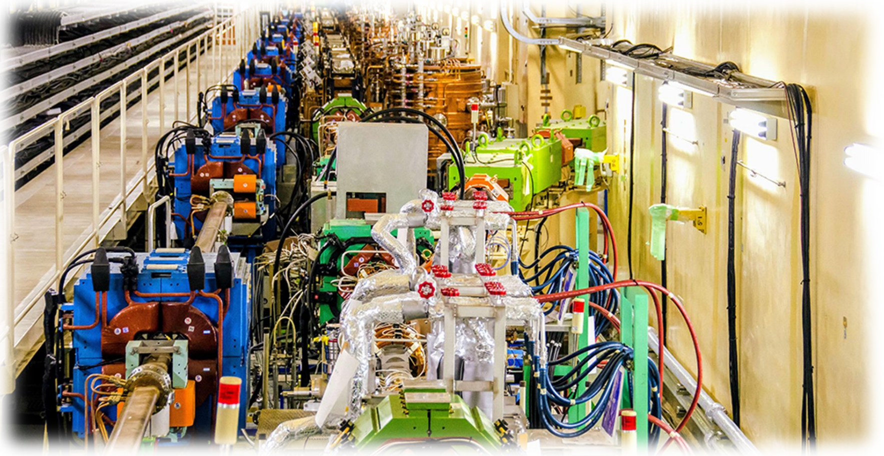
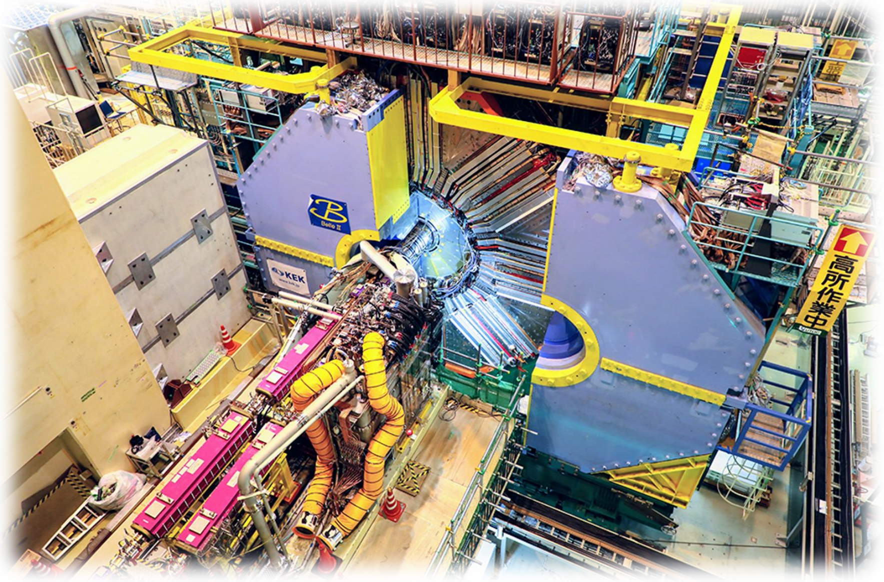
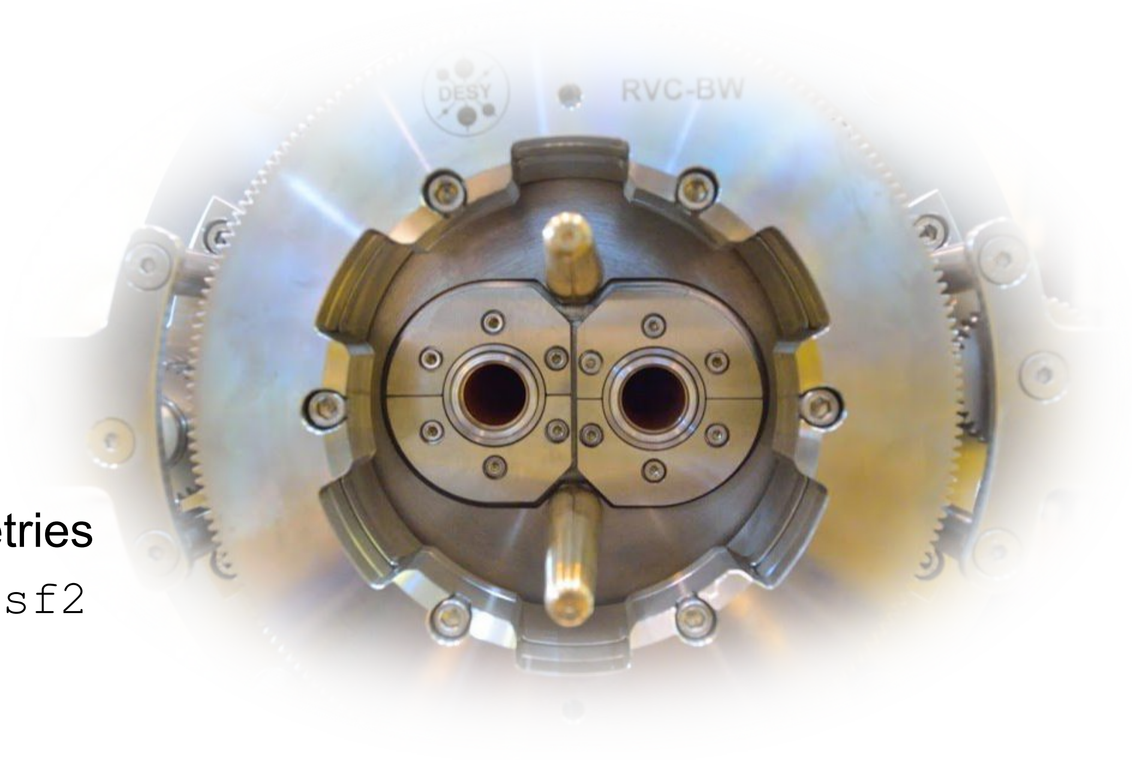




Outline

- KEKB to SuperKEKB
  - Upgrade timeline
  - Final focusing system
  - IR beam pipe
  - Belle II shielding
- Simulation software
- IR model
  - `SAD` and `Geant4` geometries
  - Magnetic field map in `basf2`
- Summary



KEKB to SuperKEKB

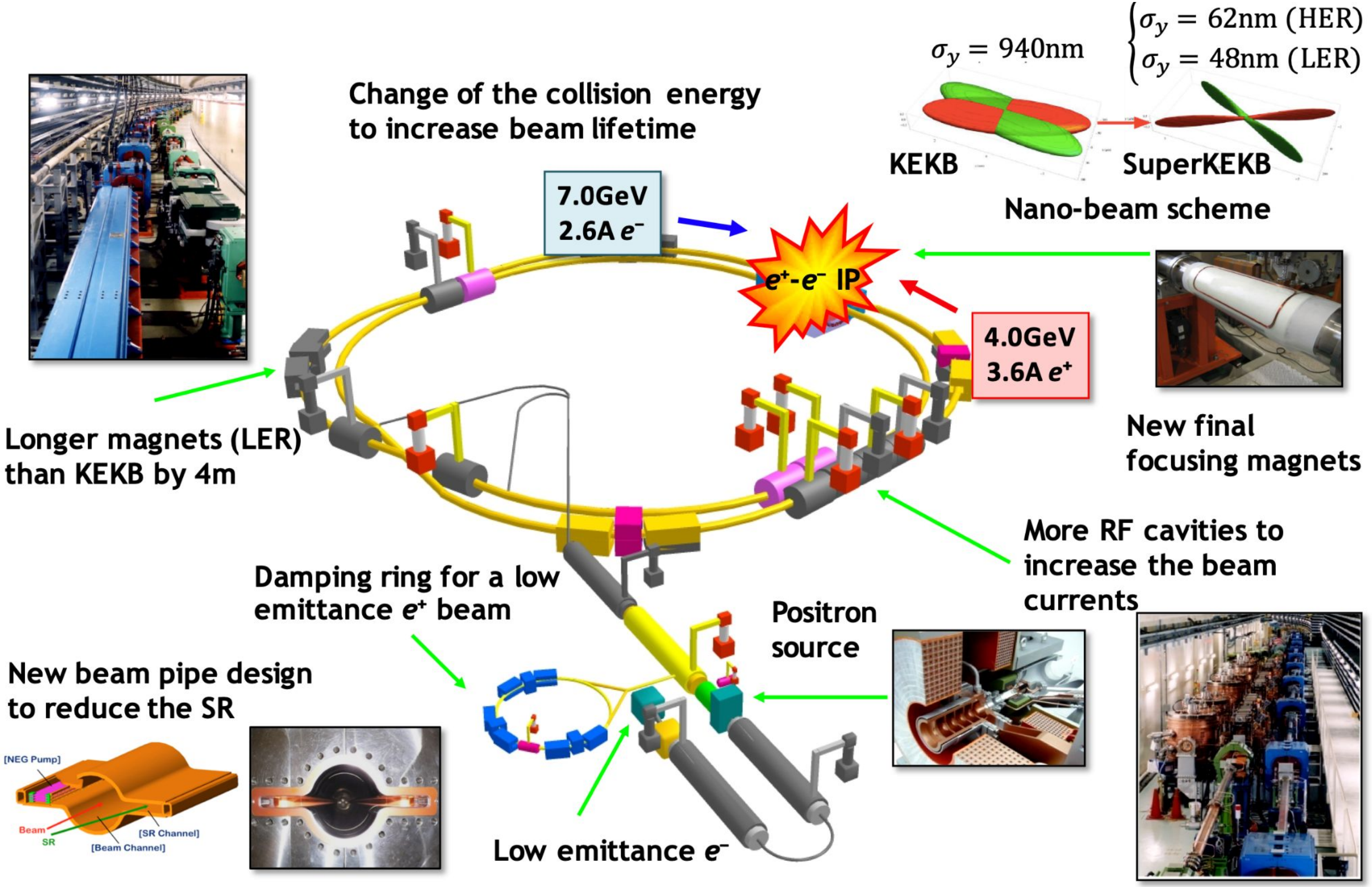
Machine modification

- Replaced short dipoles with longer ones (LER)
- Redesigned the lattices and IR (LER & HER)
- Installed antechambers (LER)
- Damping ring to reduce the emittance (LER)
- New superconducting final focusing quads (QCS) near the IP (LER and HER)
- Modified RF systems

Performance change

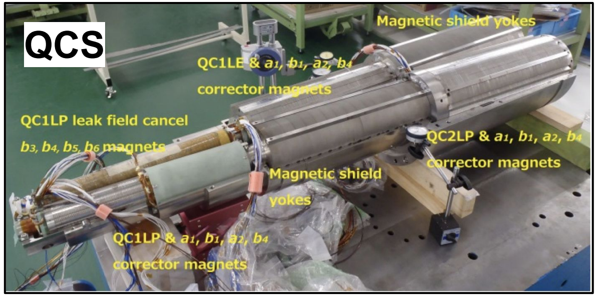
x40 collision luminosity (design)
x2 higher beam currents
x20 smaller IP beta function

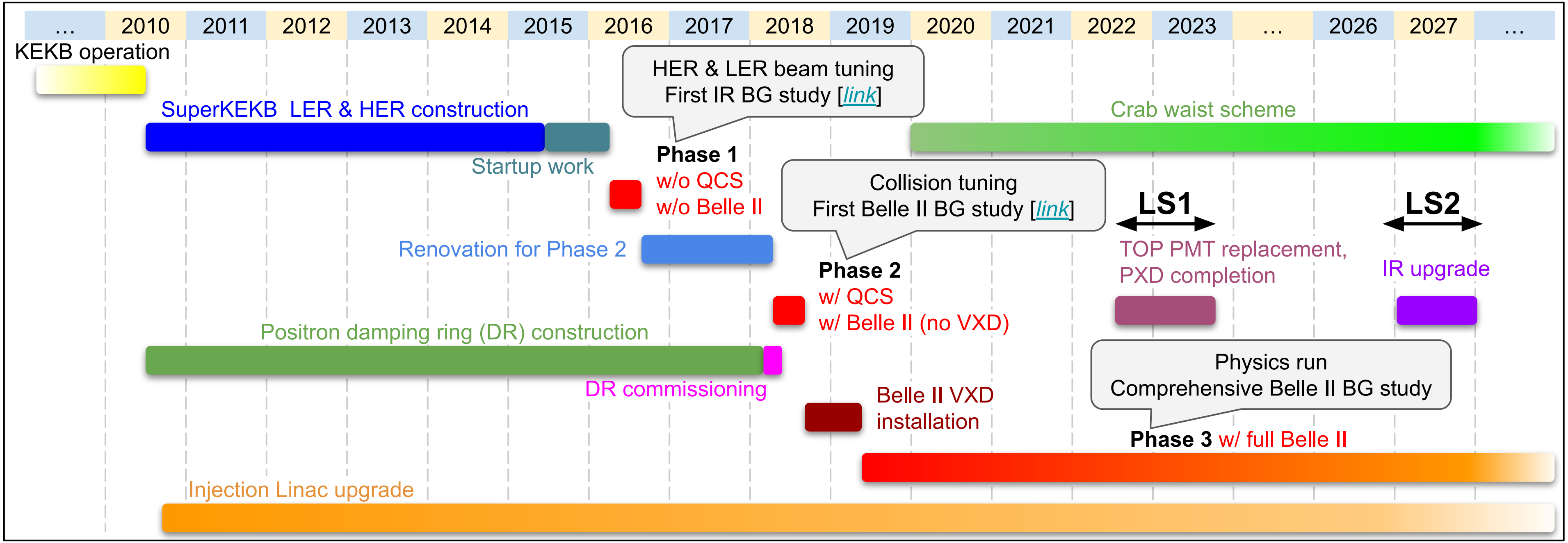
Much higher beam loss rates in the interaction region (IR) → **better BG protection is needed**



Timeline for machine upgrade

- **Phase 1** (2016) → Accelerator commissioning
- **Phase 2** (2018) → First collisions; partial detector; background study; physics possible
- **Phase 3** (2019) → Nominal Belle II start

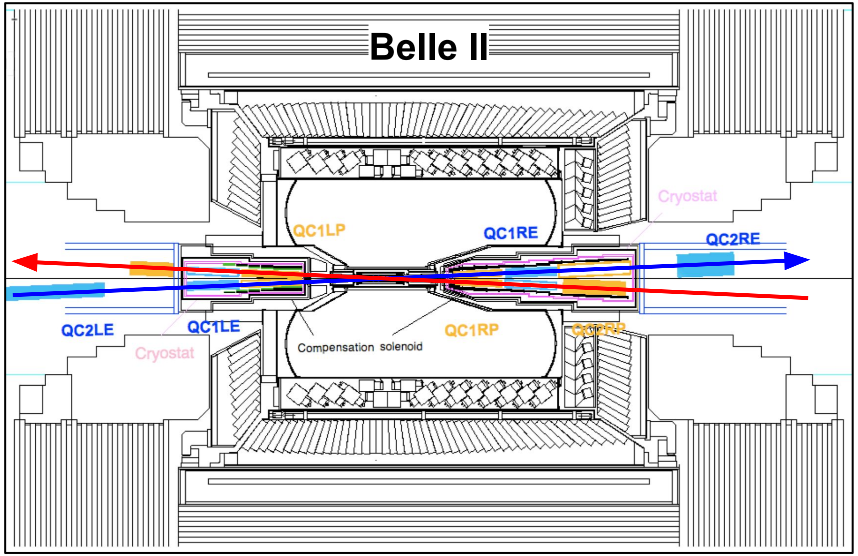


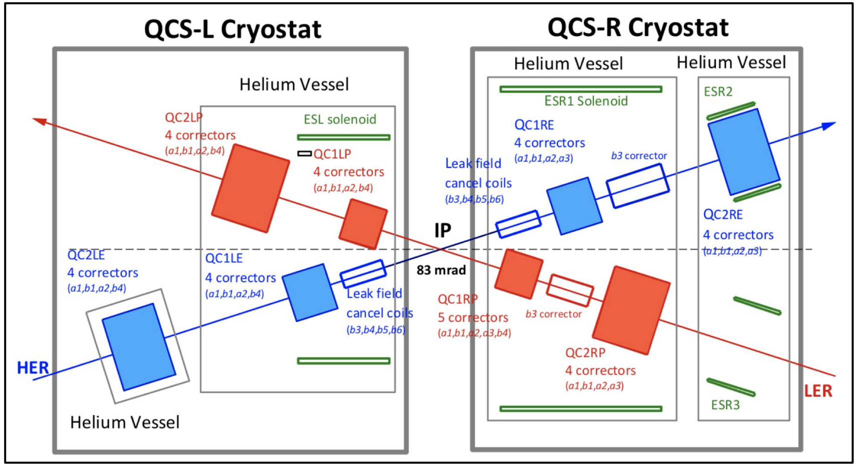


Final focusing system

To squeeze the beams at the IP and for fine beam tuning, the beam final focus system is installed in the Interaction Region (IR) [1]

- 8 superconducting (SC) main quadrupole magnets (QCS) (to focus and defocus the beams)
- 4 SC compensation solenoid magnets (to fully compensate the detector solenoid field of 1.5 T)
- 35 SC corrector magnets (to tune the beams)
- 8 magnets (to cancel the leak field from the QCS)



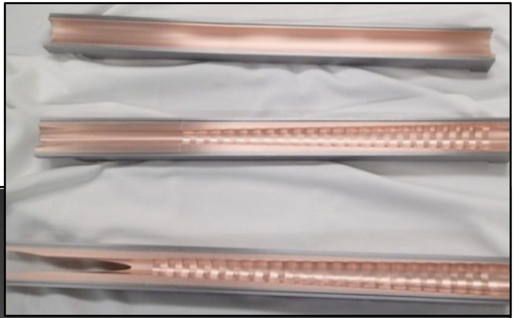


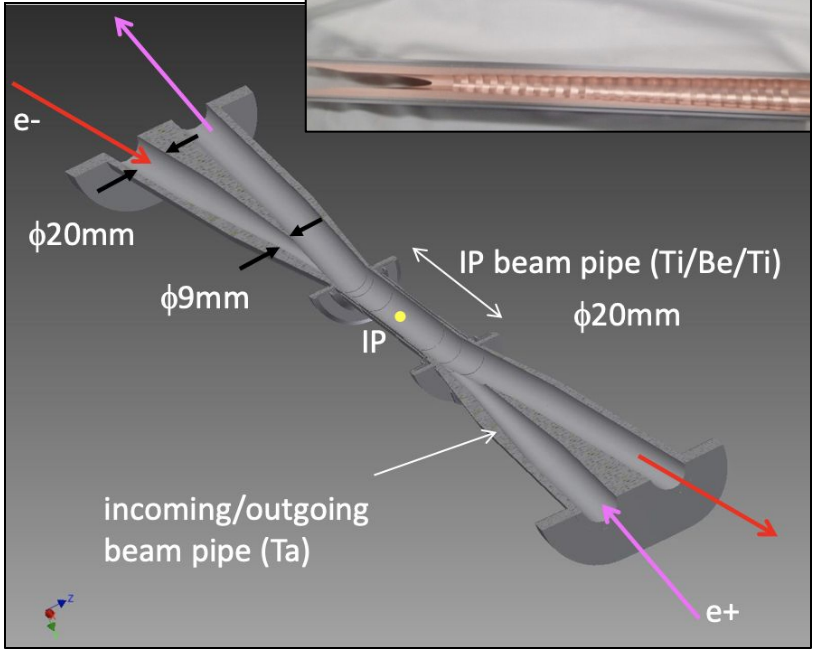
[1] N. Ohuchi, et al., “SuperKEKB beam final focus superconducting magnet system”, Nuclear Inst. and Methods in Physics Research, A 1021 (2022) 165930

IR beam pipe

- The beryllium beam pipe is coated with a thin gold layer to protect the VXD from X-rays
  - *Cylindrical, inner R = 10 mm, 10 μm Au, 0.6 mm Be, 1mm coolant (paraffin), 0.4 mm Be*
- Also, the ridge structure on the inner surface is used to avoid reflected SR hits at the detector
- Incoming beam pipes collimate most of SR photons thanks to the design geometry ⌀20 mm → ⌀9 mm
  - *Direct SR hits on the IP beam pipe are negligible*
- We are building a new IP beam pipe with an additional gold layer and slightly modified geometry to reduce the amount of the backscattered SR

Ridge structure of the inner beam pipe around the IP

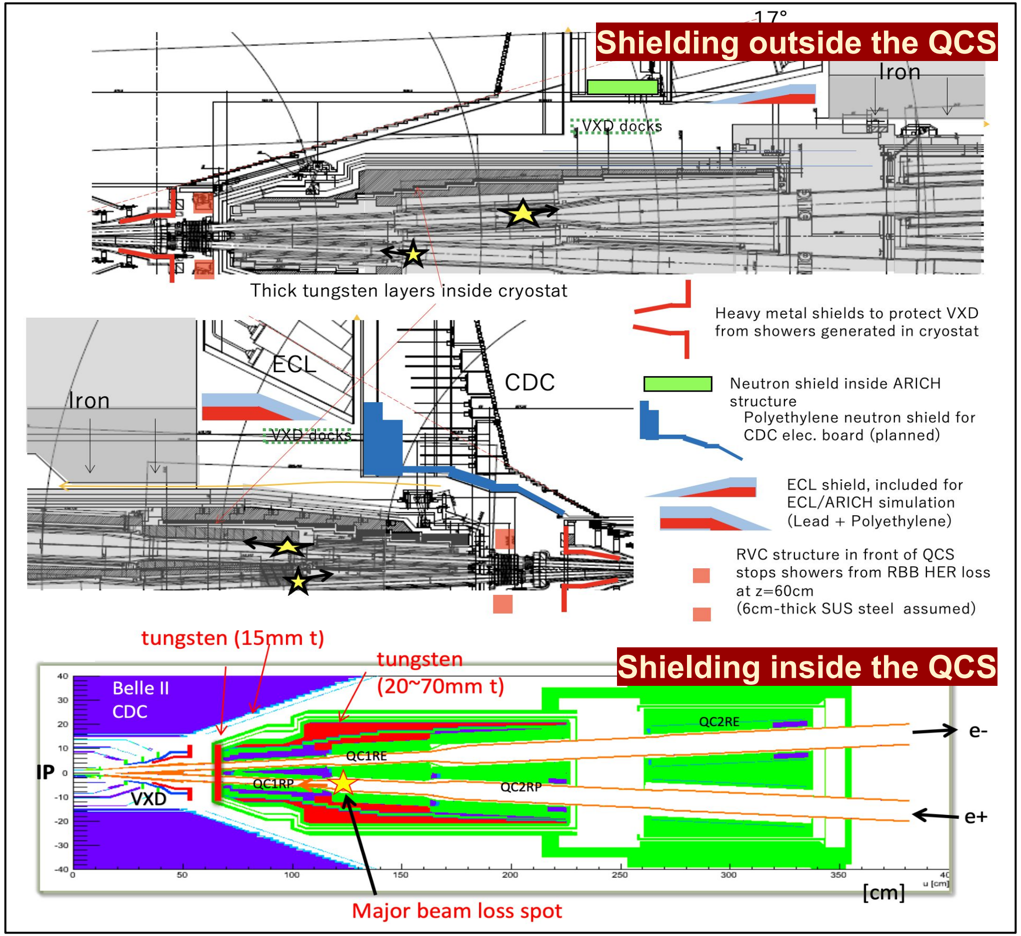




IP beam pipe geometry

Belle II shielding

- Most of IR beam losses occur inside the QCS
  - Partially considered in the TDR 2010 [1]
- In 2021-2022, detector saw single-event upsets (SEU) of FPGAs electronics boards
  - SEUs are presumably from neutrons created in the EM showers
  - Still acceptable level
- Installed additional detector protection
  - Heavy metal shield inside VXD
  - Polyethylene+lead shield inside ECL, ARICH & CDC
- Planned detector protection for the LS1 (2022-2023)
  - Additional EM and neutron shielding around QCS and Belle II to suppress SEUs



[1] T. Abe, et al., “Belle II Technical Design Report”, KEK-REPORT-2010-1, 2010, https://doi.org/10.48550/arXiv.1011.0352

Software for beam background simulation

Multi-turn particle tracking in `SAD` [1]
Beam-gas & Touschek [2]

- realistic collimator description
  jaw profile, chamber
- particle interaction with collimators
  a.k.a. tip-scattering
- measured vacuum pressure distribution
- random machine errors
  sextupole magnet offset

`Geant4` [3] + Belle II Analysis Software Framework (`basf2`) [4]

Single-beam background

Luminosity background
Two-photon [5] and Radiative Bhabha [6,7]

Synchrotron radiation

- realistic IR modelling (±30m from the IP)
  Belle II and SuperKEKB
- generating simulated data
- unpacking of real raw data
- reconstruction
  tracking, clustering, …
- high-level analysis
  applying cuts, vertex-fitting, …

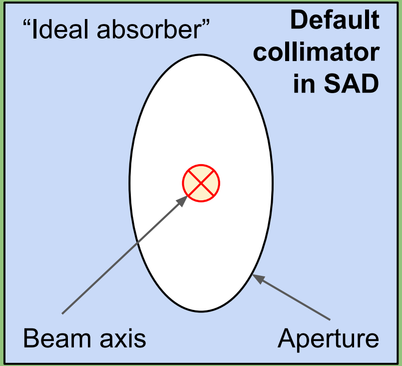
[1] Y. Ohnishi, et al., “Computer program complex sad for accelerator design, simulation and commissioning”, Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan (PASJ2019), WEOHP04, 2019
[2] Y. Ohnishi, et al., “Accelerator design at SuperKEKB”, Progress of Theoretical and Experimental Physics, Volume 2013, 2013, Pages 03A011
[3] Geant4 https://geant4.web.cern.ch
[4] A. Moll. The software framework of the belle II experiment. J. Phys. Conf. Ser., 331 (3):032024, 2011
[5] F.A. Berends, et al., “Complete lowest-order calculations for four-lepton final states in electron-positron collisions”, Nuclear Physics B, Volume 253, 1985, Pages 441-463
[6] R. Kleiss, et al, “BBBREM — Monte Carlo simulation of radiative Bhabha scattering in the very forward direction”, Computer Physics Communications, Volume 81, Issue 3, 1994, Pages 372-380
[7] S. Jadach, et al., “BHWIDE 1.00: O(α) YFS exponentiated Monte Carlo for Bhabha scattering at wide angles for LEP1/SLC and LEP2”, Physics Letters B,Volume 390, Issues 1–4, 1997,Pages 298-308

Evolution of the simulation accuracy in SAD

Data/MC ~ 10^{-3}–10^{3} → **Data/MC ~ 10^{-1}–10^{1}** → **Data/MC ~ 1**

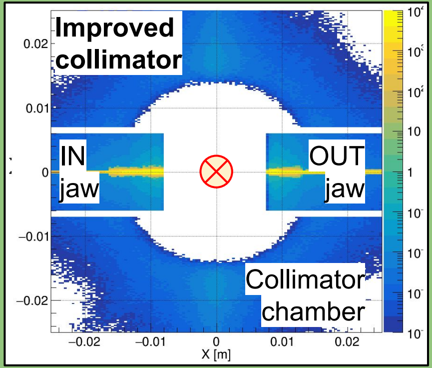
Phase 1 and Phase 2 experiences 2016–2018

IR beam pipe geometry improvement
+
Measured background decomposition methodology



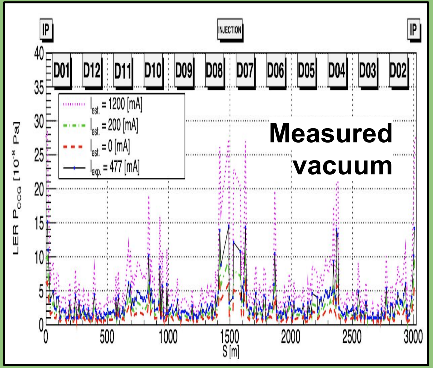
Early Phase 3 experiences 2019–2022

IR beam pipe geometry improvement
+
Realistic collimator profile
+
Particle interaction with collimator materials



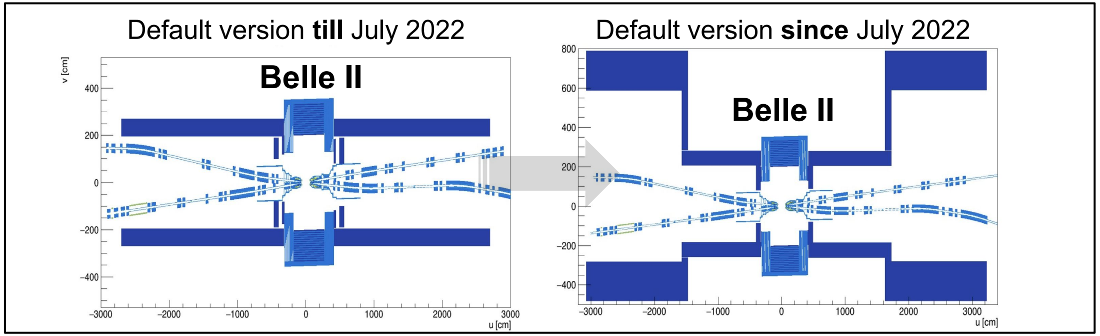
Early Phase 3 experiences 2019–2022

Measured beam pipe gas pressure
+
Accurate translation of beam losses from SAD to Geant4
+
Improved Geant4 model

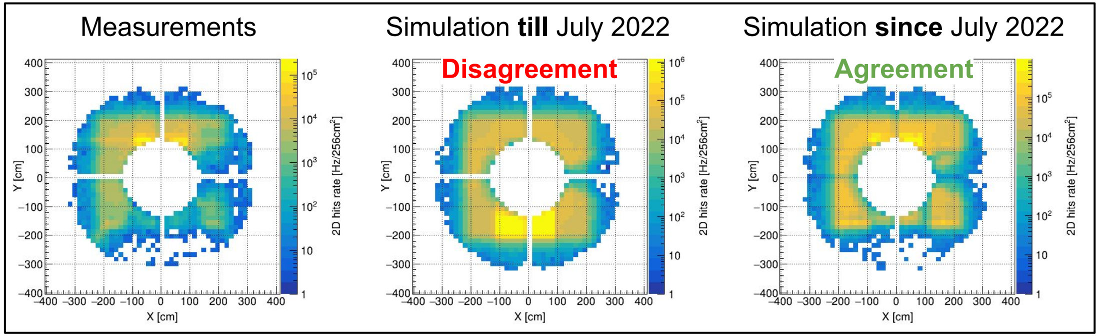


`Geant4` model evolution and impact on backgrounds

- In the past two years we put a lot of efforts to improve the `Geant4` modelling of the Belle II and SuperKEKB interaction region
- The latest version realistically describes detector materials and accelerator tunnel
  - Accurate IP beam pipe
  - Belle II shielding
  - Tunnel wall
  - Machine equipment (e.g. collimators)
- **Improved** the data/MC agreement
  - ARICH Lumi BG data/MC 10 → 1
  - Better end cap KLM hits 2D distribution
- Allows us to study the impact of the additional shielding planned for the LS1

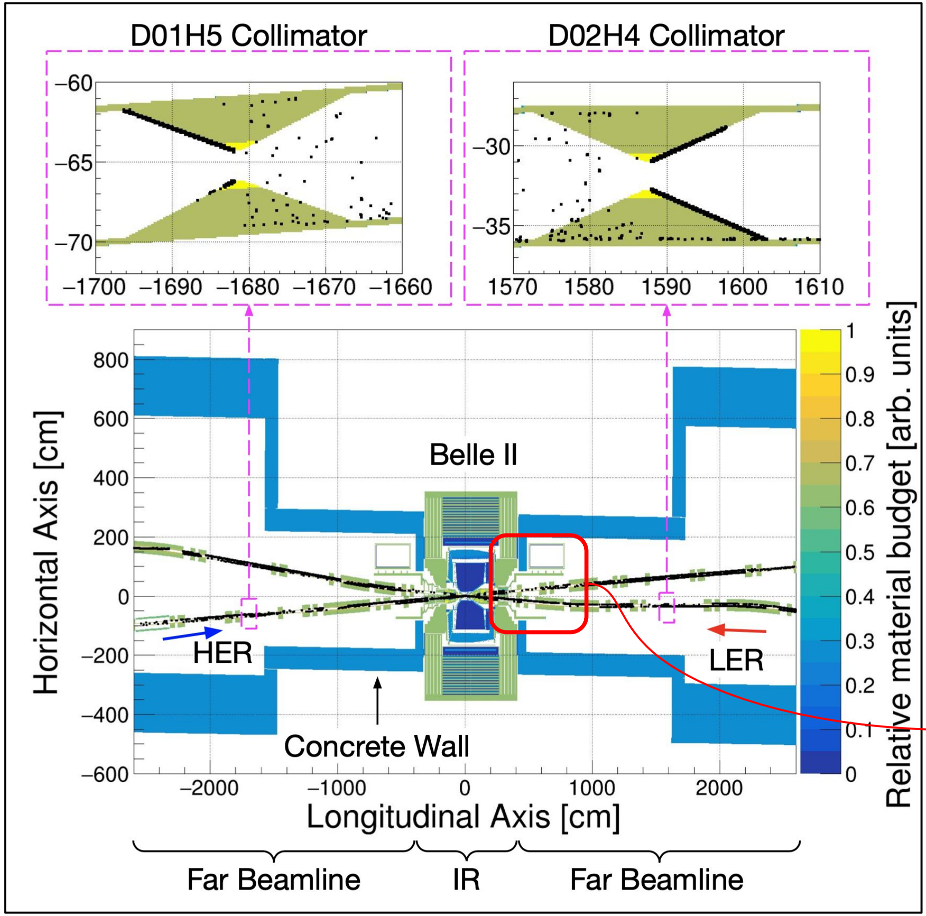


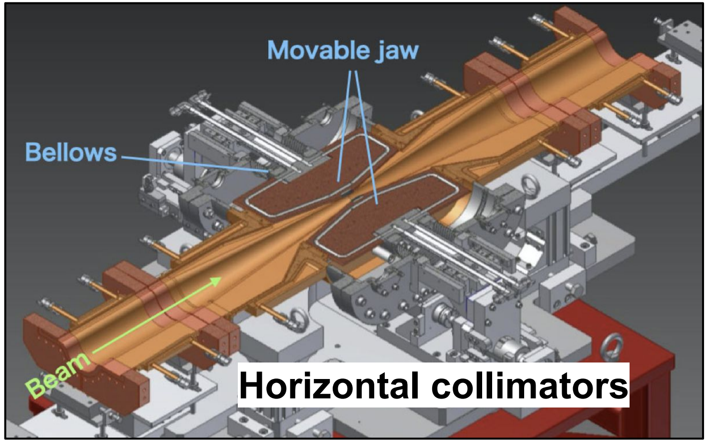
IR `Geant4` model improvement. Skipping intermediate steps

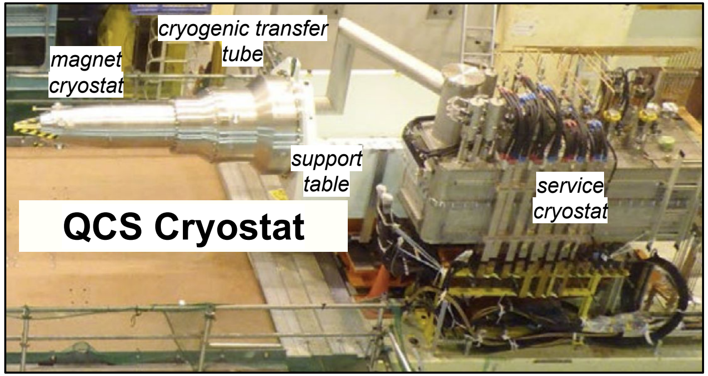


2D background hits on the outermost layer of the FWD KLM end cap

Current Geant4 model of the IR

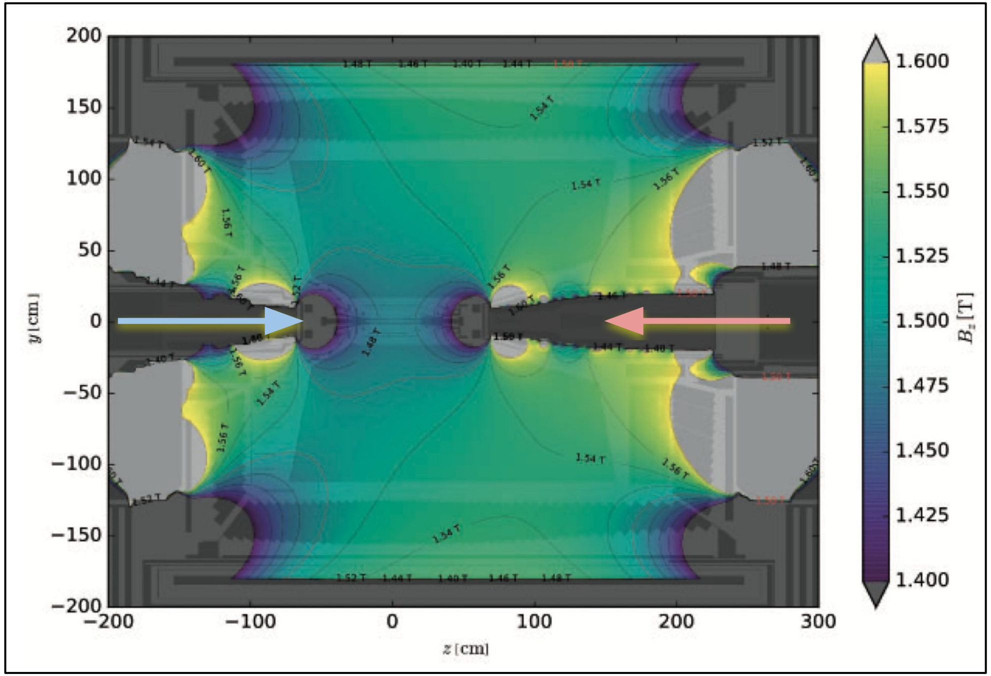






Magnetic field in `basf2`

- The magnetic field map [1] is used for
  - Charged tracks reconstruction
  - Precise track momentum calculation
- Uncertainties in magnetic fields would affect Belle II analyses and offline reconstruction causing systematic biases between measurements and simulation
- The `Opera3D/TOSCA` software [2] was used to produce a precise model of the magnetic field
  - The resulting 3D magnetic field map was incorporated into `basf2/Geant4`
- The magnetic field inside the QCS beam pipe is turned on only for beam particle tracking during the luminosity background simulation



The z component of the 3D magnetic field map

[1] E. Kou, et al., "The Belle II Physics Book", *Progress of Theoretical and Experimental Physics*, Volume 2019, Issue 12, December 2019, 123C01, https://doi.org/10.1093/ptep/ptz106
[2] Cobham Technical Services, Vector Fields Software, Oxford, England, Opera-3D User Guide Ver. 15R3 (Oct. 2012)

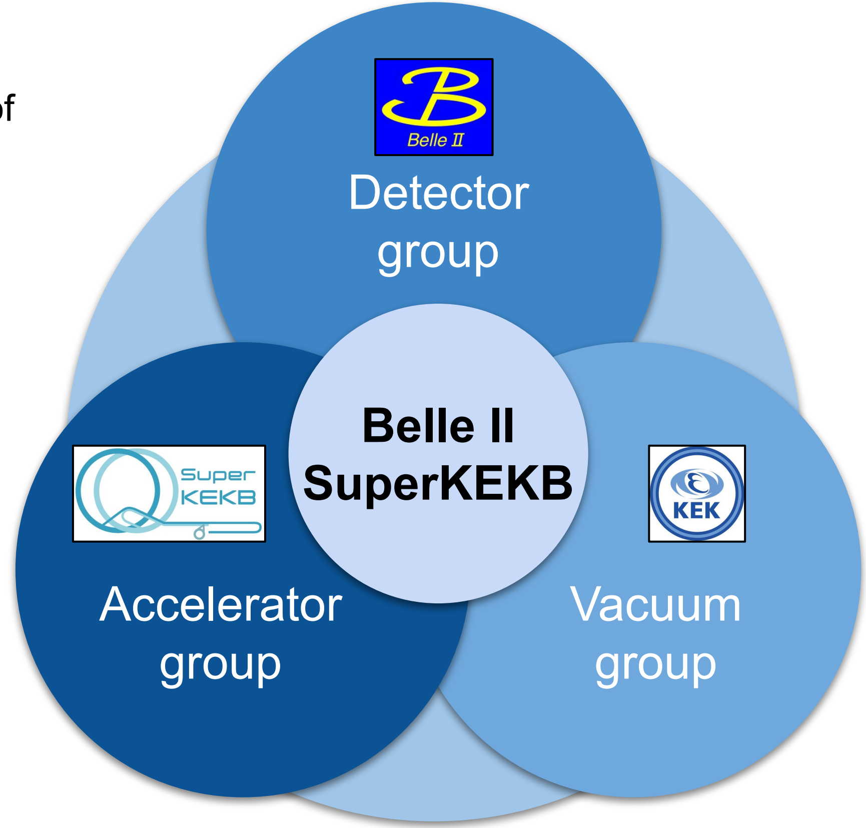
Summary

- SuperKEKB and Belle II have successfully rolled in as a new generation of *B*-factories
- A naive extrapolation from KEKB did not work well for the new collision scheme, and many detector protection modifications were implemented iteratively
- Improved beam-induced background simulation and careful IR modelling help to predict beam losses at various machine conditions
  - New types of collimators are designing
  - Additional shielding around Belle II is planned to be installed
  - Accurate beam backgrounds for the physics analysis is provided
- Several further machine and detector upgrades are under consideration to reach the target luminosity
- For new projects (e.g. ILC, FCC, EIC, CEPC), we recommend to reserve enough space at early stages of the design for the inner shielding between the final focusing and detector

Acknowledgements

Most of the presented materials are results of the hard work of my colleagues in the SuperKEKB and Belle II groups

I sincerely appreciate their tremendous efforts, time, experiences and knowledge to make the SuperKEKB/Belle II project real

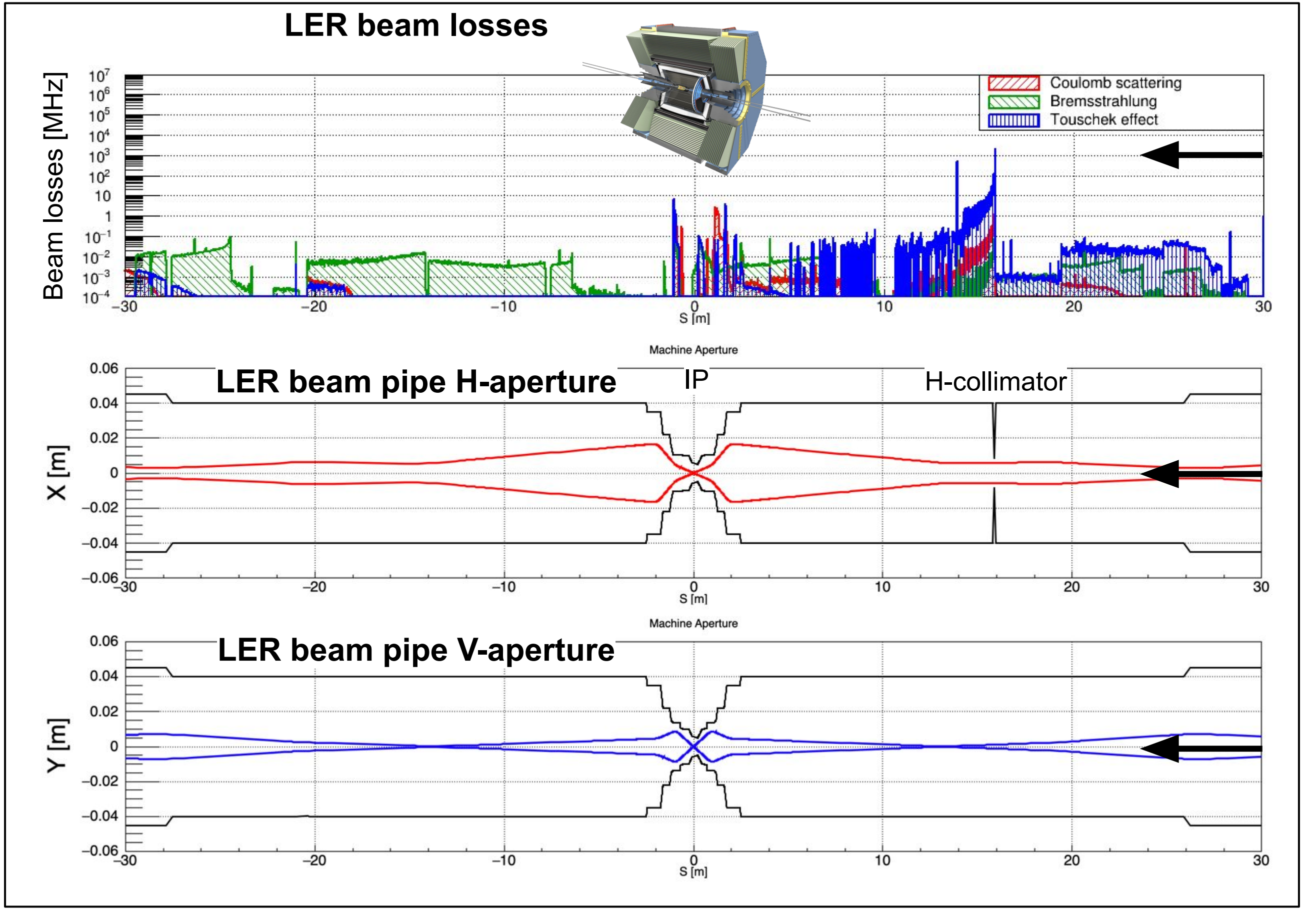


Thank you for attention!

Backup slides

IR single-beam losses

- In `SAD`, the IR beam pipe aperture is accurately described to follow the real geometry
- Particles which reach the beam pipe or collimators aperture are considered as lost and transferred to `Geant4`



IR magnet system

- Since SuperKEKB has a big crossing angle (83 mrad) between two beamlines, the axis of the Belle II solenoid (1.5 T) is placed on the bisection line of the two beamlines.
- This configuration was chosen as optimal since we know that the tilt (θ_{tilt}) between the solenoid axis and a beamline generates a vertical emittance growth which depends on the tilt angle ($\varepsilon_y \sim \theta_{tilt}^4$).
- Therefore, we use skew dipole correctors to compensate for the emittance growth down to ~2 pm. X-Y coupling and vertical dispersion are corrected by skew quadrupoles and dipoles, respectively.

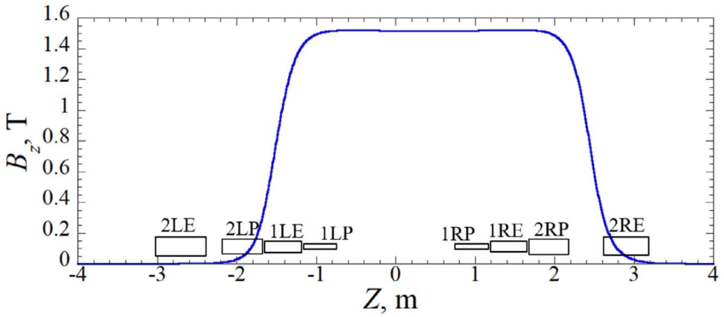


Fig. 4. Calculated magnetic field profile along the Belle II SC solenoid magnet. Z=0 corresponds to the IP position. The axial center of the solenoid magnet is located at Z=0.47 m. The quadrupole magnets with the distance from the IP are shown by the rectangle boxes.

Table 2
Main parameters of the final focus system.

Number of SC magnets	55
Main quadrupole	Integral field
QC1RP, QC1LP	22.96 T, 22.96 T
QC2RP, QC2LP	11.54 T, 11.48 T
QC1RE, QC1LE	25.39 T, 26.94 T
QC2RE, QC2LE	13.04 T, 15.27 T
Compensation solenoid	Integral field
ESR1 + ESR2 or ESR3	3.86 T•m
ESL	2.31 T•m
Magnet-cryostat	2 units
	Cold mass @ 4 K
QCS-R, QCS-L	3,139 kg, 1,522 kg
He refrigerator cryogenic system	2 units
Cooling power of one unit	250 W @ 4.5 K

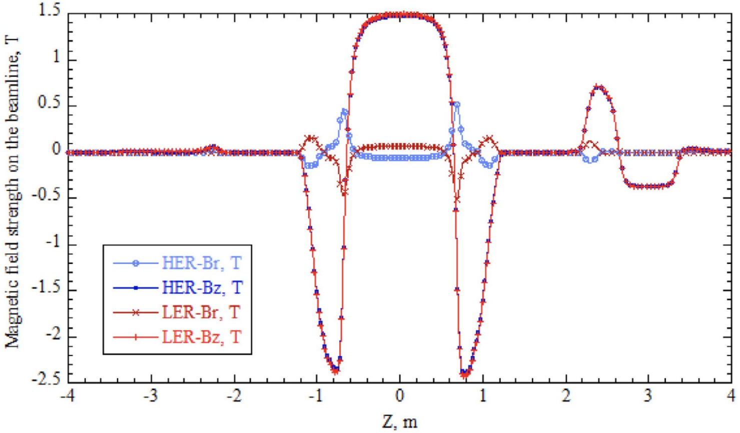


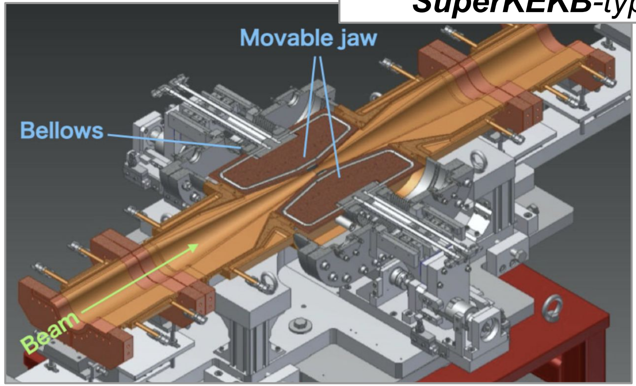
Fig. 16. Magnetic field profiles along the beam lines.

[1] N. Ohuchi, et al., "SuperKEKB beam final focus superconducting magnet system", Nuclear Inst. and Methods in Physics Research, A 1021 (2022) 165930

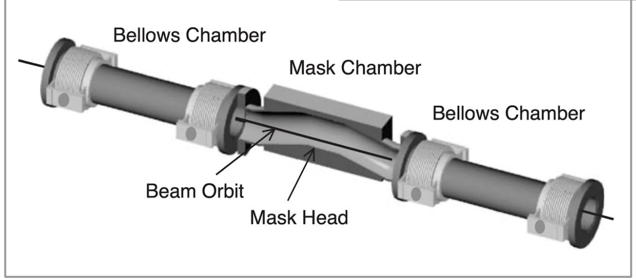
Collimation system

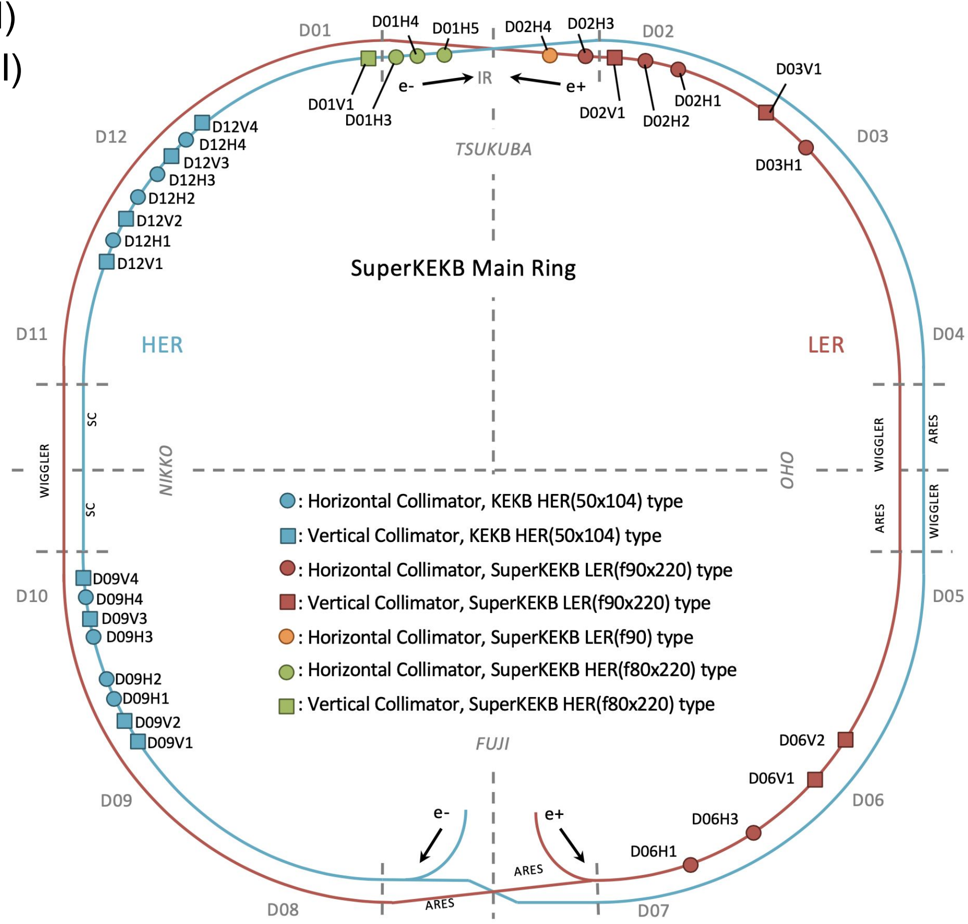
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

Two-sided collimator
***SuperKEKB**-type*

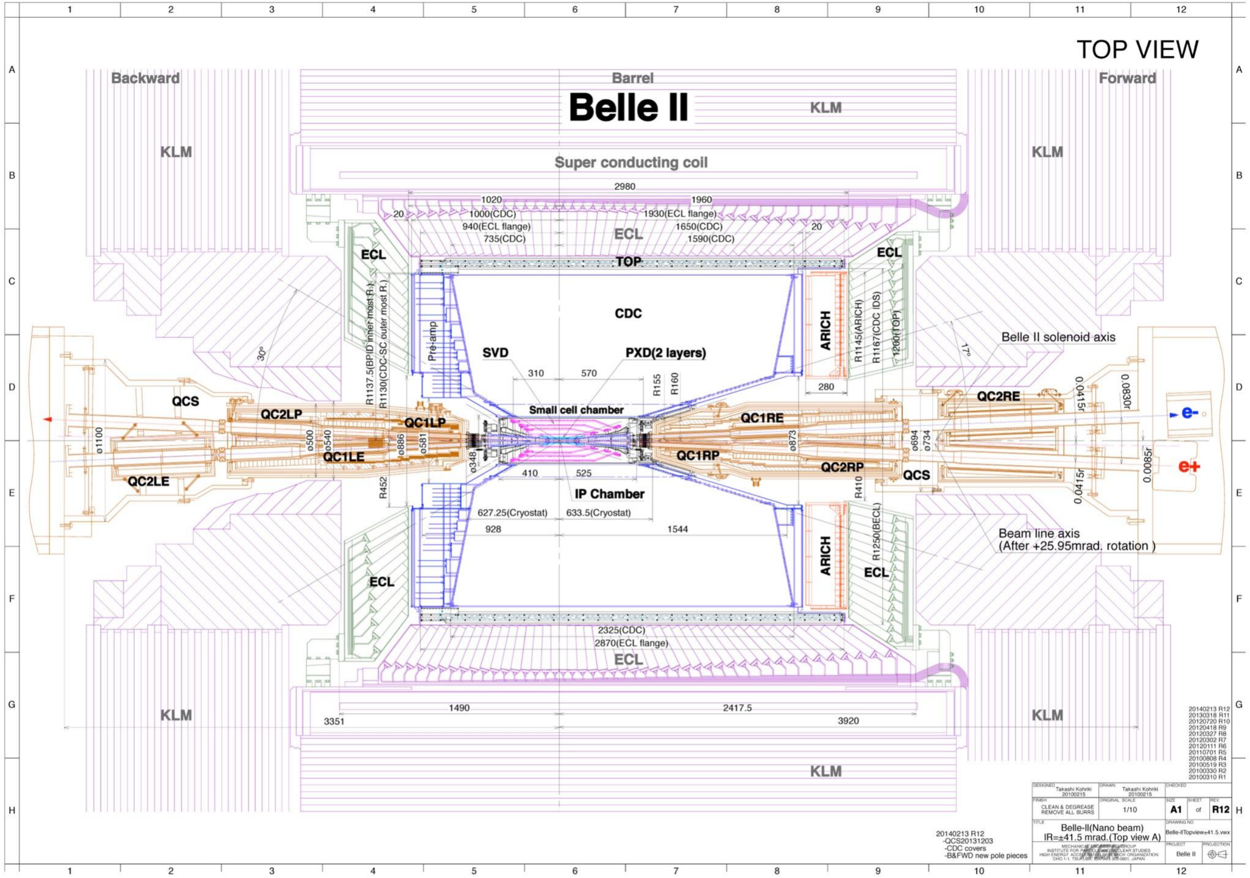


One-sided collimator
***KEKB**-type (D09 & D12)*





Belle II


TOP VIEW
Backward
Barrel
Forward
Belle II
KLM
Super conducting coil
ECL
TOP
CDC
SVD
PXD(2 layers)
ARICH
Pre-amp
Small cell chamber
IP Chamber
QCS
QC2LP
QC1LP
QC1LE
QC2LE
QC1RE
QC1RP
QC2RP
QC2RE
Belle II solenoid axis
Beam line axis
(After +25.95mrad. rotation)
e-
e+
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)