SuperKEKB status and Plans

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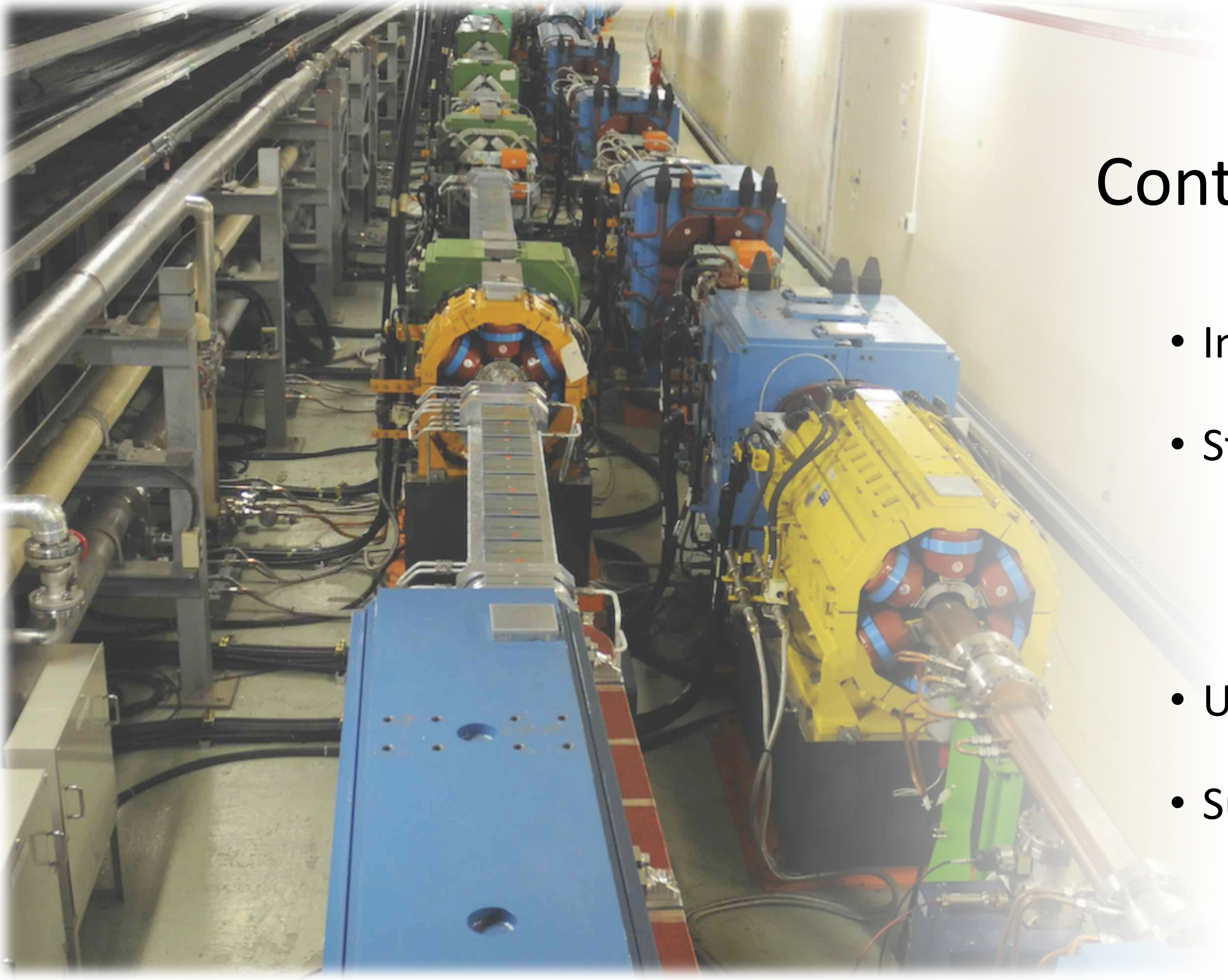
(KEK Accelerator)



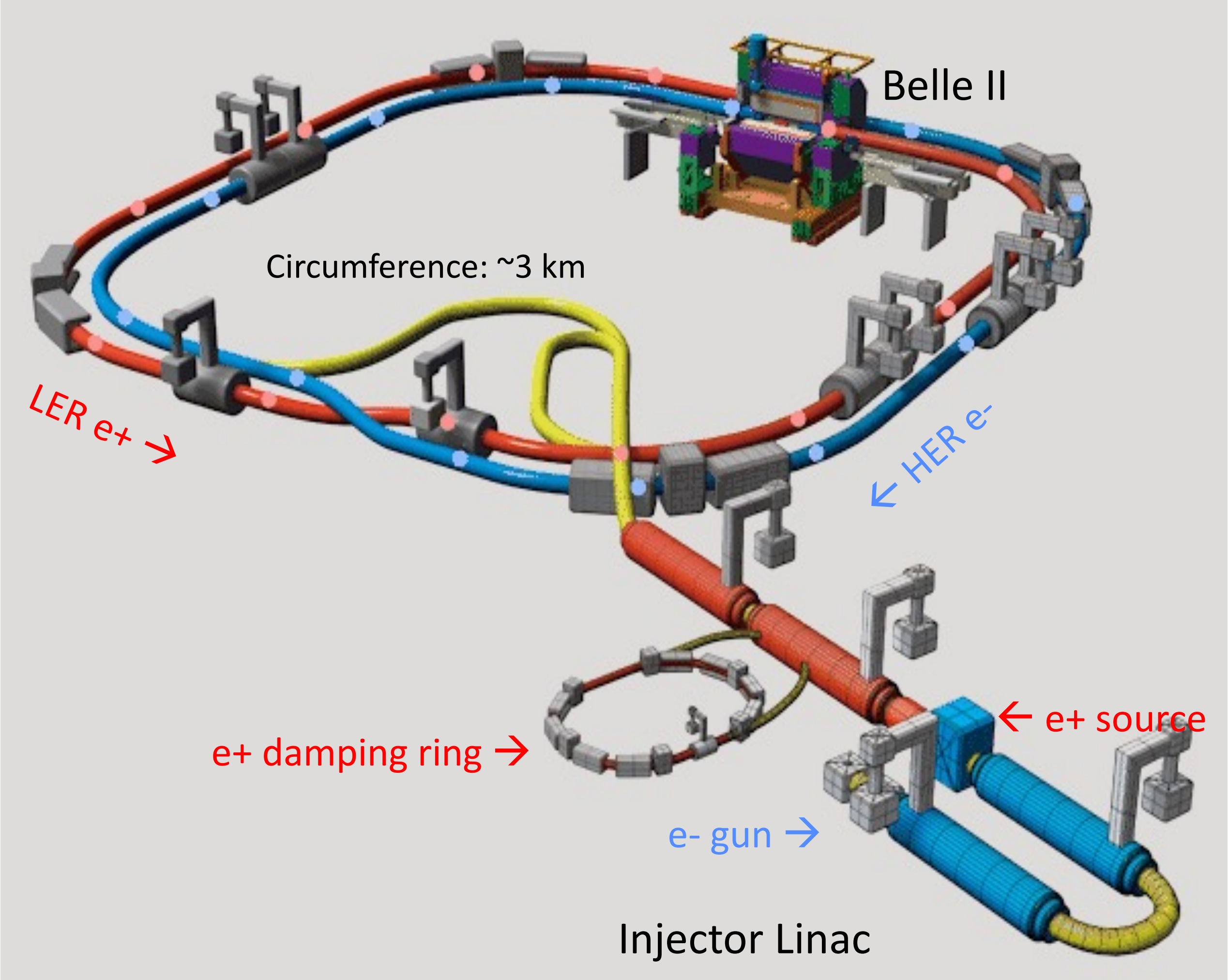
Contents

- Introduction
- Status
  - Before LS1
  - LS1 work
  - After LS1
- Upgrade ideas
- Summary

1. Introduction

1. Introduction

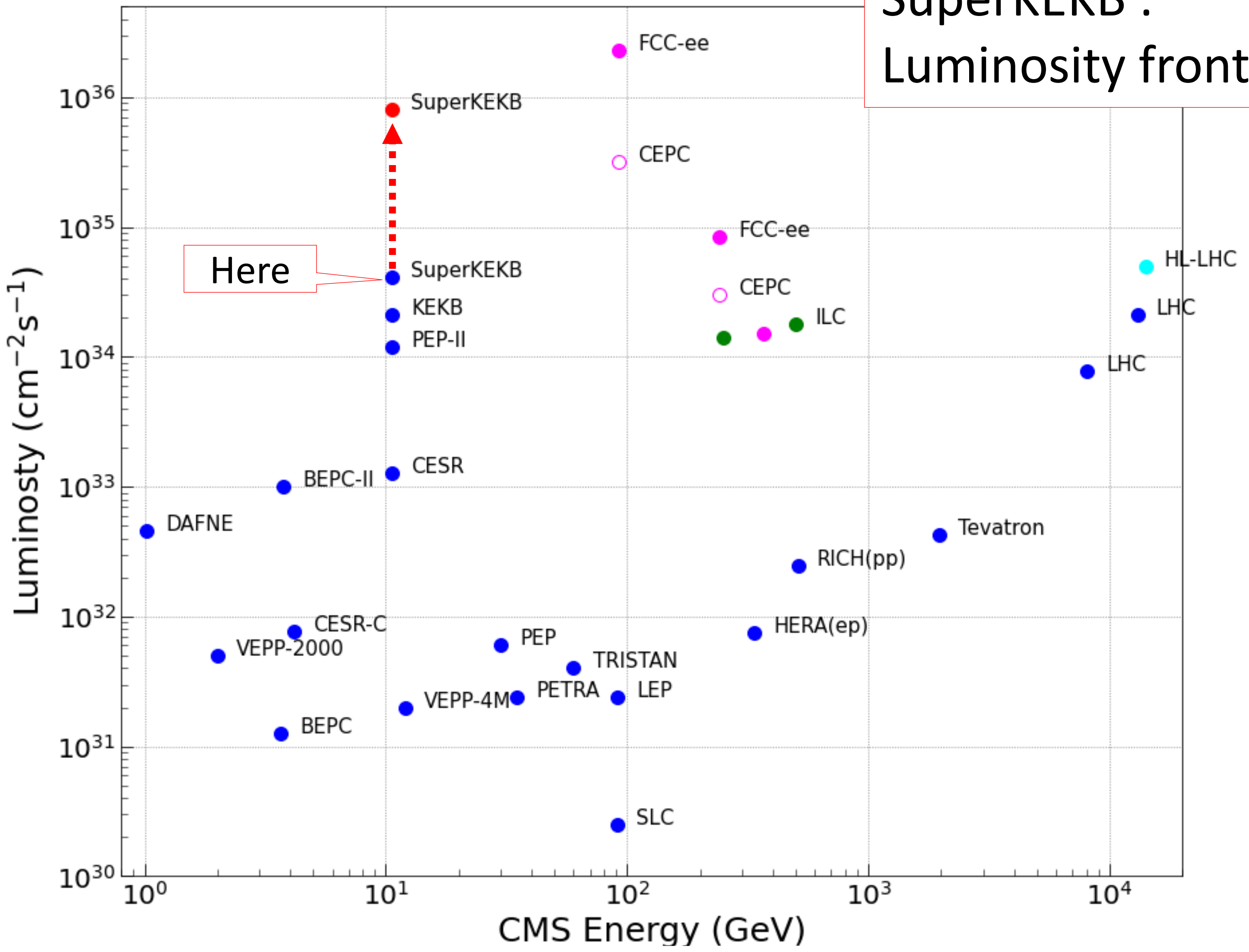
Electron-positron collider in Japan



- Upgraded from KEKB B-factory (KEKB)
- Stored-beam energies
  - **H**igh **E**nergy **R**ing (**HER**) : 7.0 GeV (e^-)
  - **L**ow **E**nergy **R**ing (**LER**) : 4.0 GeV (e^+)
- $E_{\mathrm{cms}} \approx M_{\Upsilon(4S)}$
- Stored-beam currents (design)
  - HER : 2.6 A
  - LER : 3.6 A
- Toward 6.0×10^{35} $\mathrm{cm^{-2}s^{-1}}$
  - Higher beam currents than those at KEKB
  - Squeezing β_y^* with the nano-beam collision scheme

The world's first practical application of the nano-beam scheme

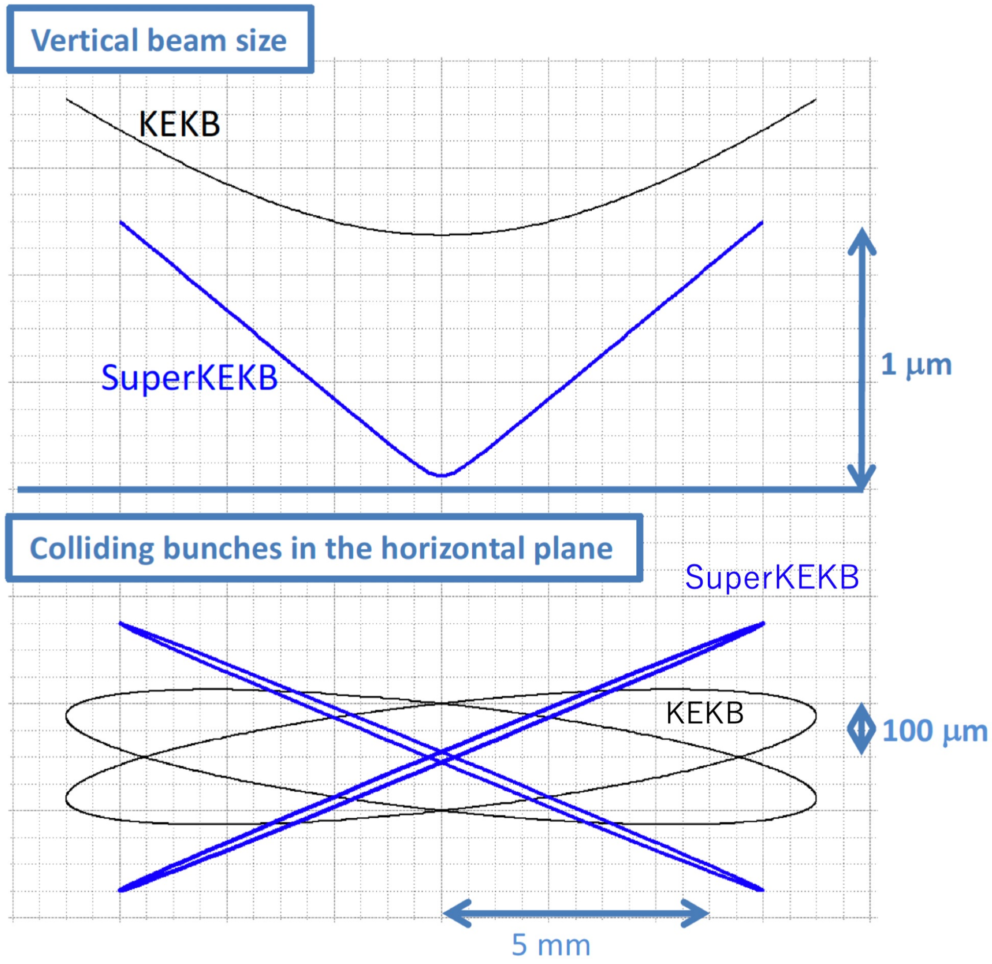
1. Introduction



SuperKEKB :
Luminosity frontier e^+e^- collider

1. Introduction

SuperKEKB Design concepts, strategy

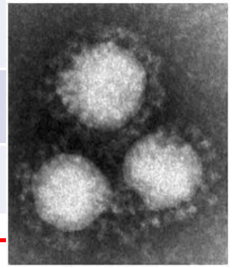


Collision with very small spot-size beam.

Low emittance ("nano-beam") scheme
⇒ first proposed by P. Raimondi.

	KEKB (LER/HER)	SuperKEKB(LER/HER)
Beam Energy (GeV)	3.5/8.0	4.0/7.0
Beam Current (A)	1.64/1.19	3.6/2.6
# of bunches	1584/1584	2500/2500
$\beta_x^* / \beta_y^* \ (mm)$	1200/5.9, 1200/5.9	32/0.27, 25/0.3
$\sigma_x^* / \sigma_y^* \ (\mu m)$	147/0.94, 170/0.94	10.1/0.048, 10.7/0.062
Half crossing angle $\theta_x \ (mrad)$	11	41.5
Piwinski angle (rad)	0 (w crab crossing)	~20
Luminosity $(\times 10^{34} cm^{-2} s^{-1})$	2.1	60

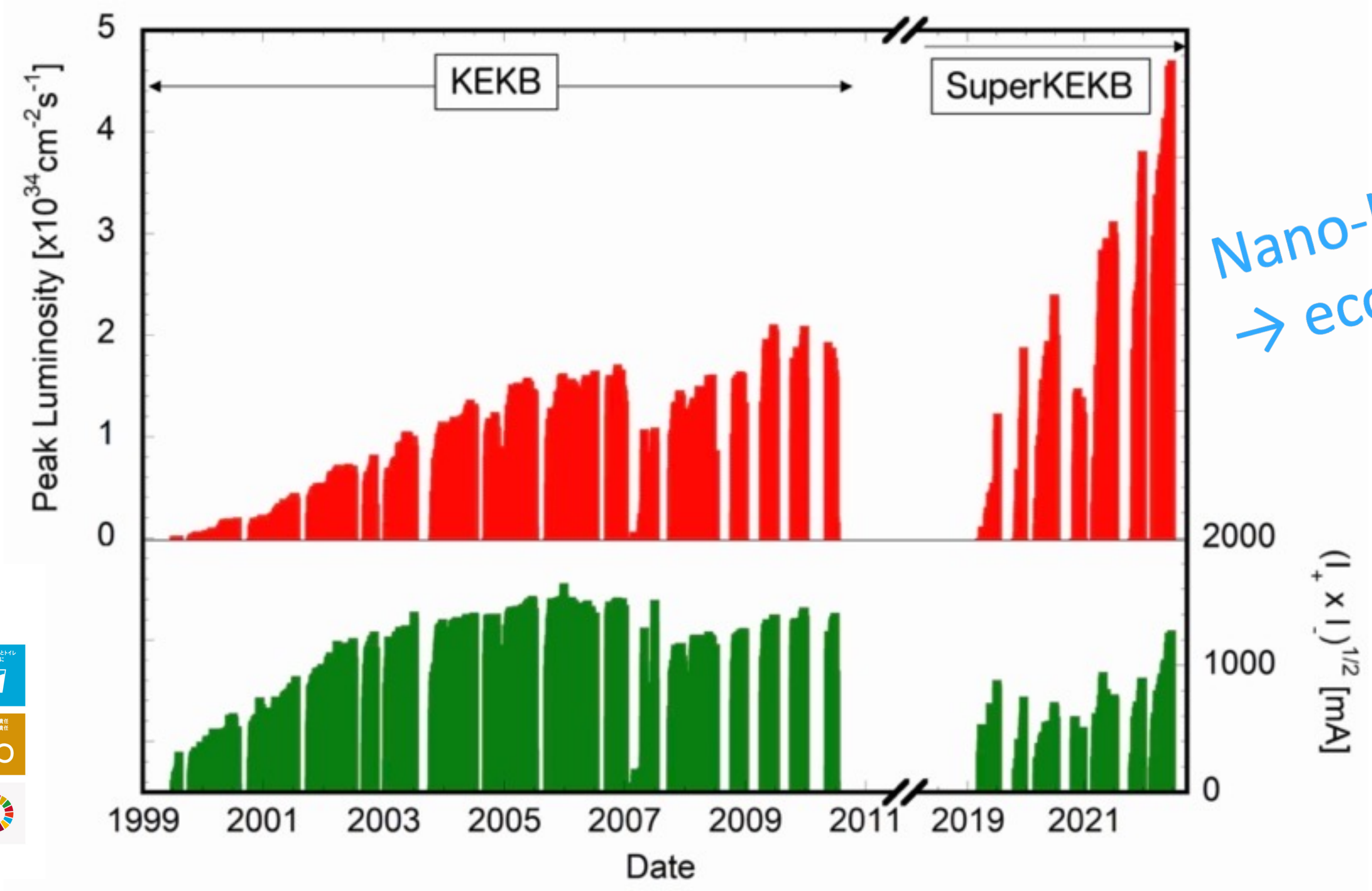
$$\phi_{Piw} \equiv \theta_x \sigma_z / \sigma_x^*$$



COVID-19

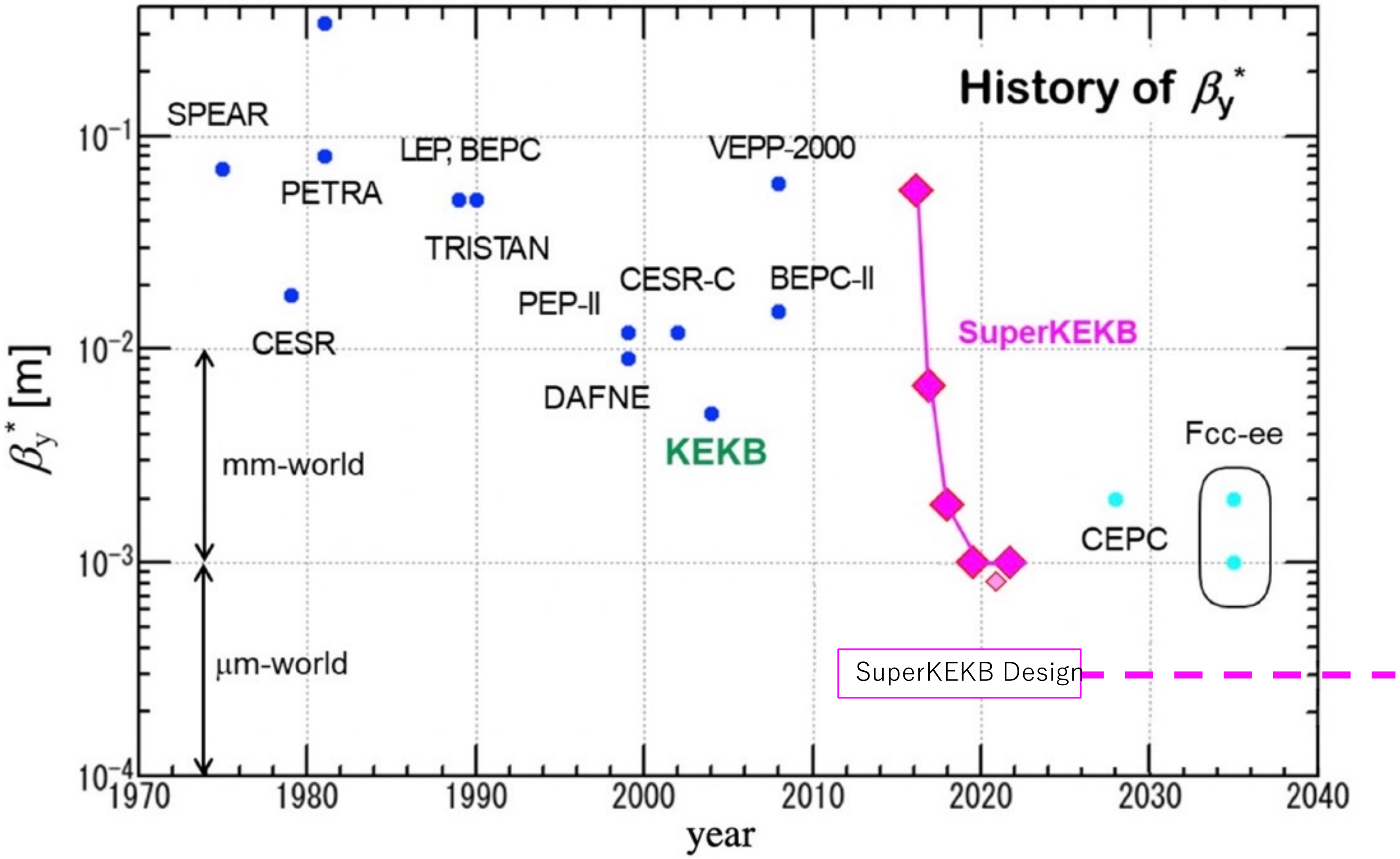
1. Introduction

Nano-beam SuperKEKB
can provide higher peak luminosity with lower beam current than KEKB

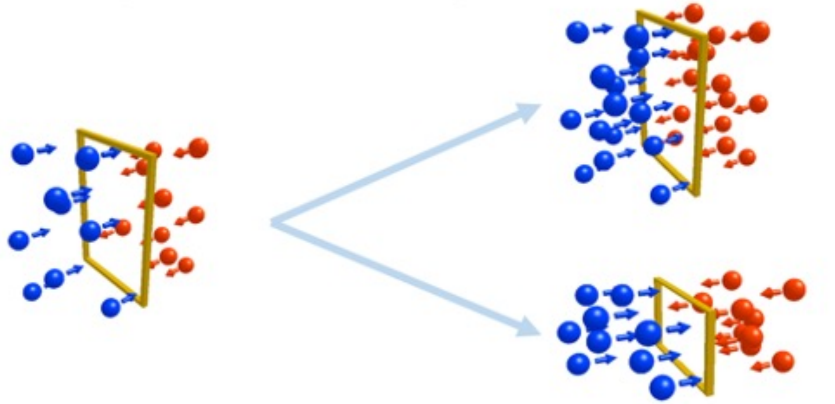


Nano-beam scheme
→ eco, sustainable

1. Introduction



Much larger beam currents



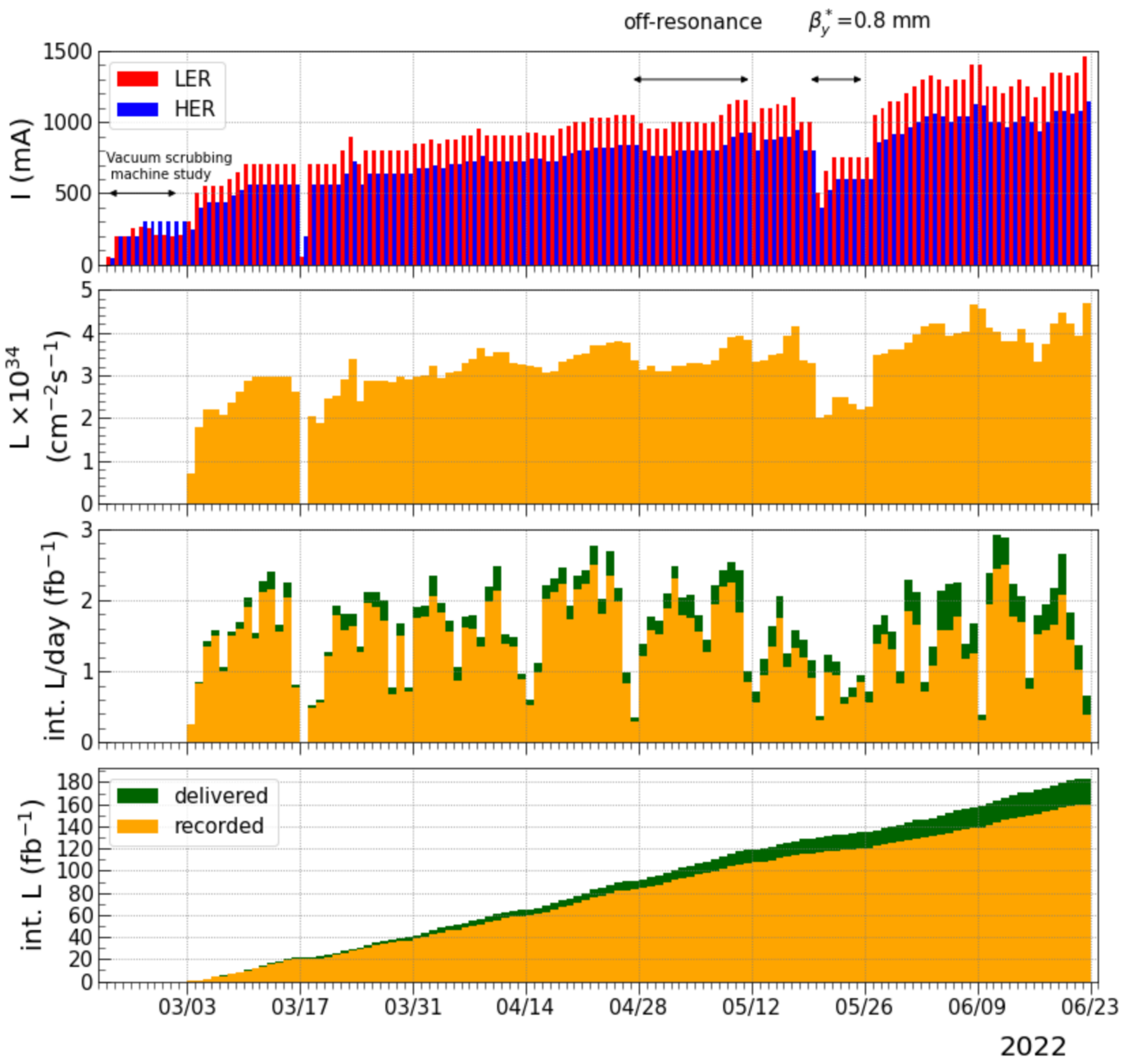
Much smaller beam size

$\beta_y^* = 1\ mm$

For most of the time

2. Status: Before LS1:accomplised

Records

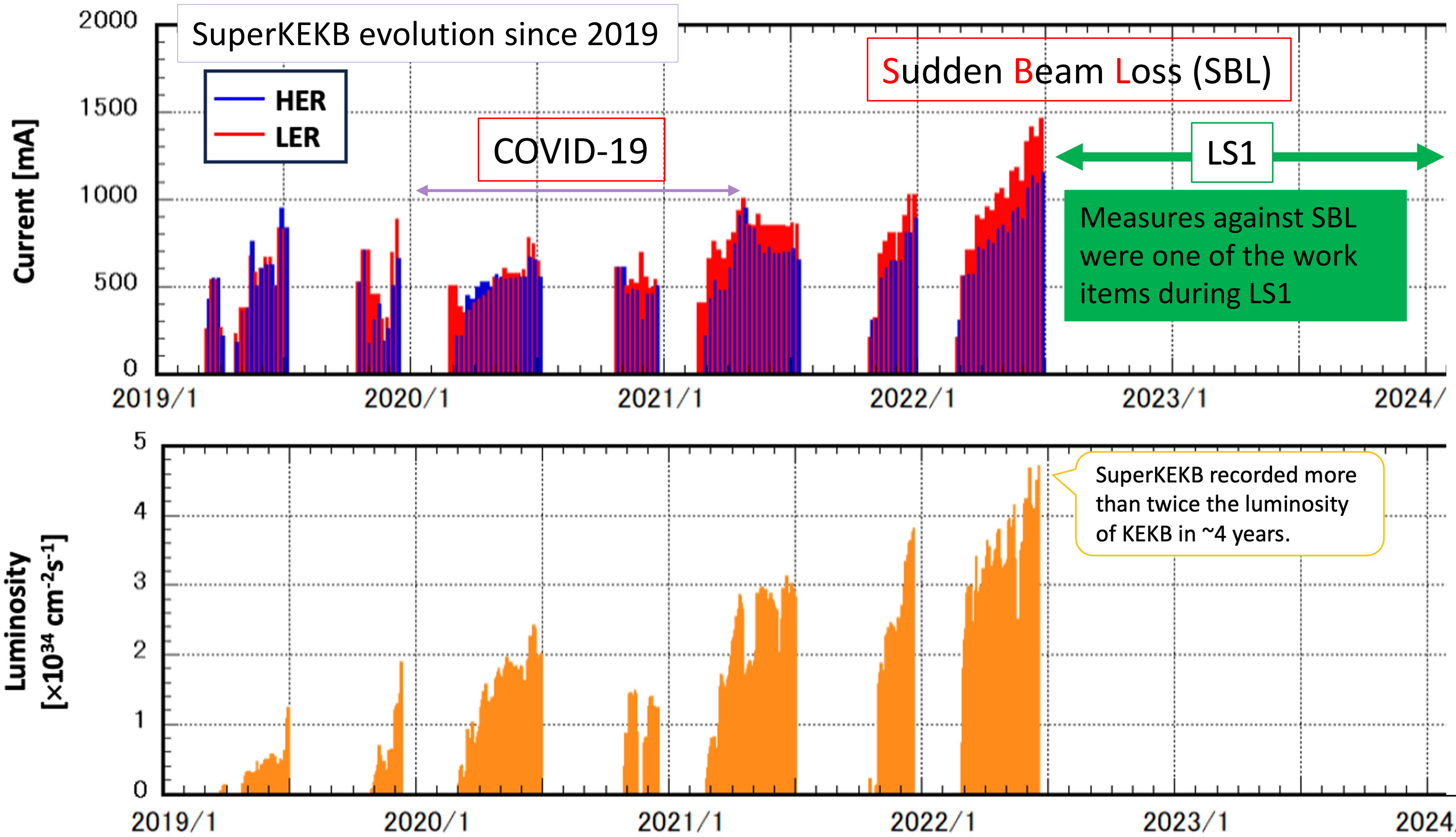


- Peak luminosity 4.65 x10^{34} (cm^{-2}s^{-1}), June 8, swing, 2022
- Belle II HV ON

Parameter	LER	HER	Unit
Beam Current	1321	1099	mA
Number of Bunches	2249		
Bunch Current	0.587	0.489	mA
Beam-Beam Parameter ξ_y	0.0407	0.0279	
Σ_y^*	0.303		μm
σ_y^*	0.215		μm
Tunes (x/y)	44.525 / 46.589	45.532 / 43.573	
Specific Luminosity (x10^{31})	7.21		cm^{-2}s^{-1}/mA^2
Luminosity (x10^{34})	4.65		cm^{-2}s^{-1}

Crab waist ratio 80% 40%

2. Status: Before LS1:Challlenges

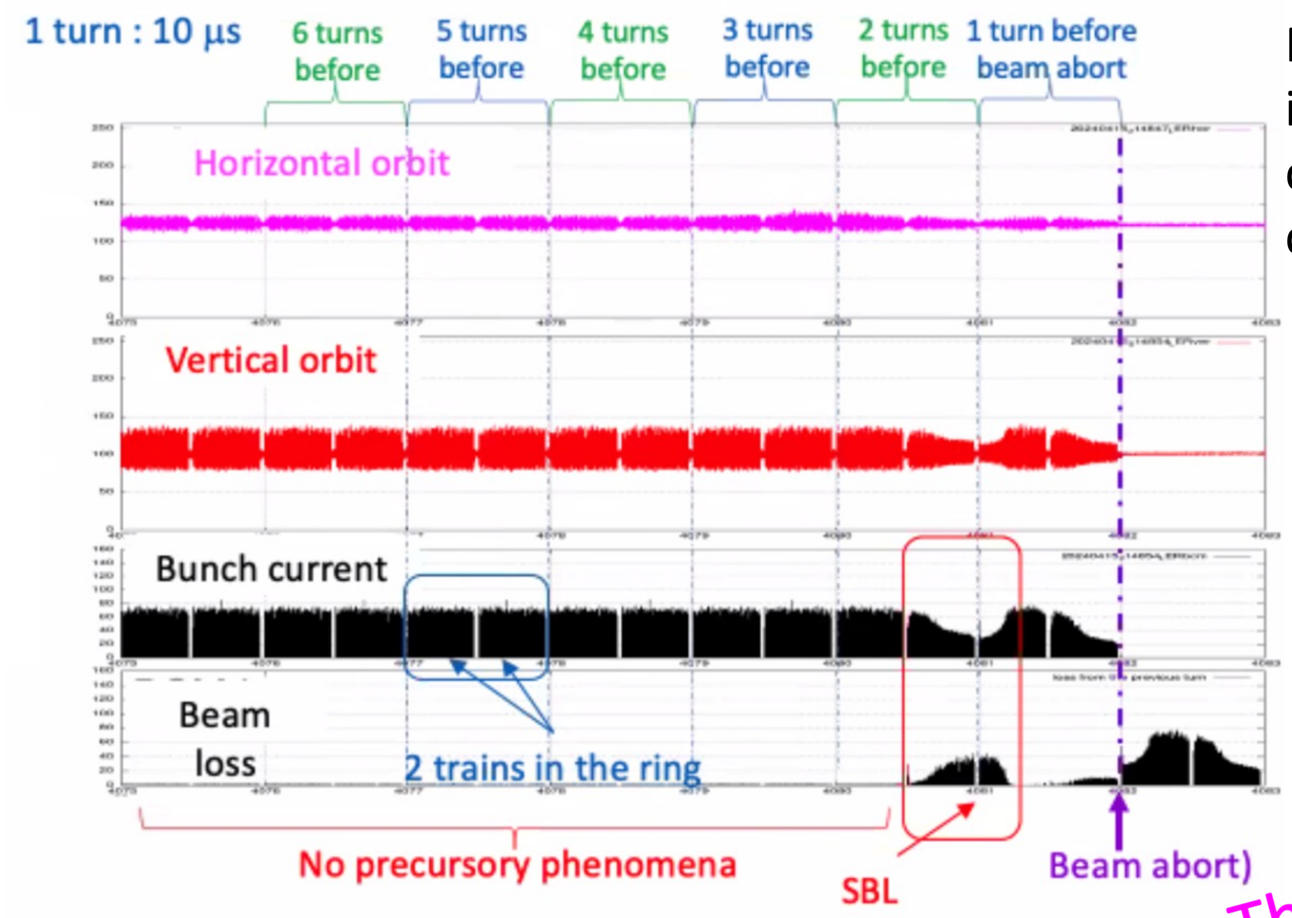


SBL

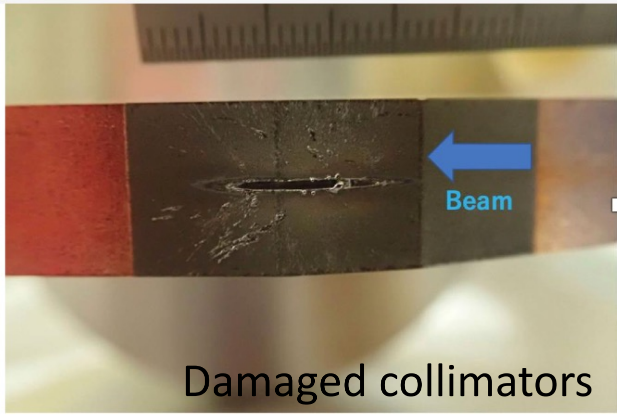
Major obstacle to increase the beam currents toward the end of June 2022.

SBL causes damages to collimators and detectors, and QCS quench

2. Status: Before LS1:Challlenges



SBL:
Phenomenon that part of the beam is suddenly lost in ~1 turn. Uncontrolled beams can cause QCS quenches, damage to accelerator component and detector.



D02V1 top side (95 µSv/h)

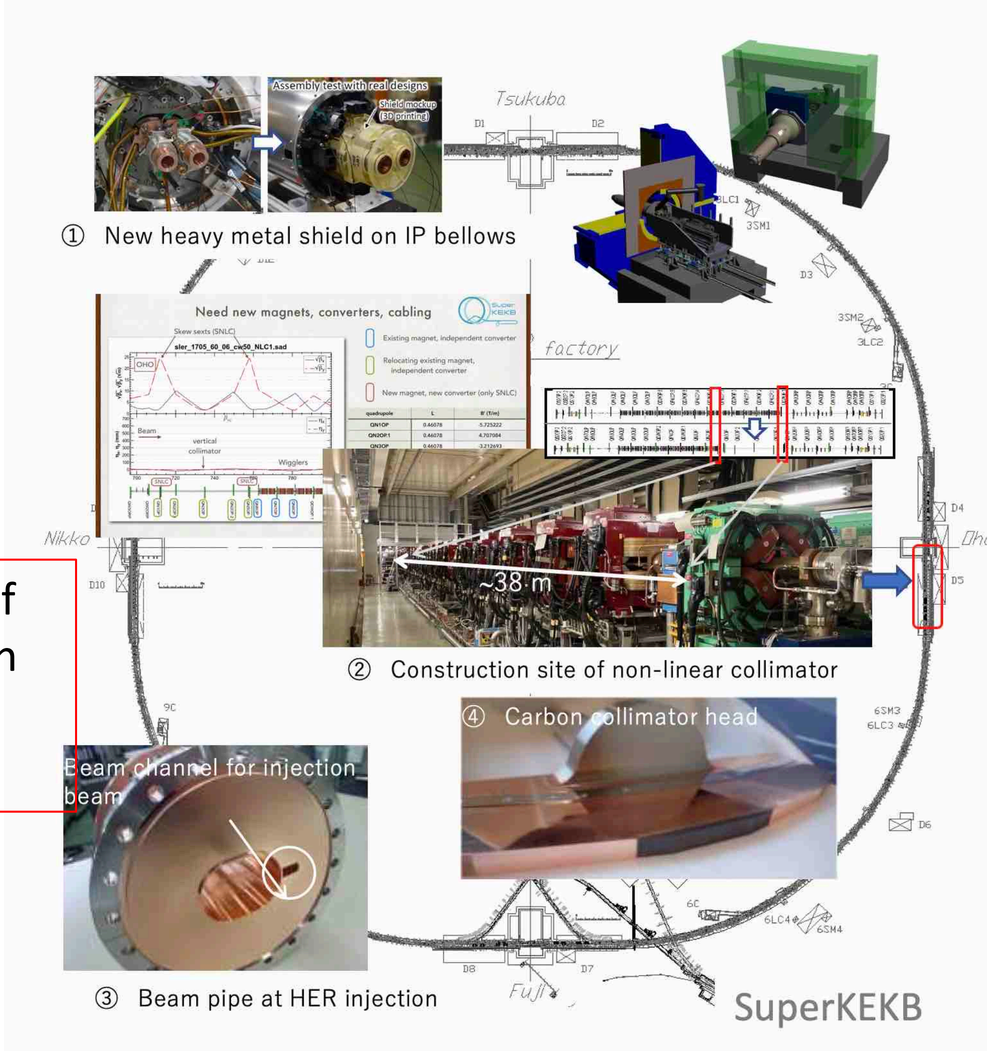
H. Ikeda's talk on Thursday

Fireball hypothesis?
SBL is triggered by a hot microparticle "fireball", similar to the mechanism as is observed in vacuum breakdown of accelerating cavities.
Counter-measure: Coat collimator heads with copper (the same material as the duct)

2. Status: LS1 work

Injector complex upgraade

Chamber modification of the HER injection section
→ injection efficiency improvement



Reinforcement of radiation shielding around the IP, replacement of the cap at the head of the QCS cryostat → Background reduction

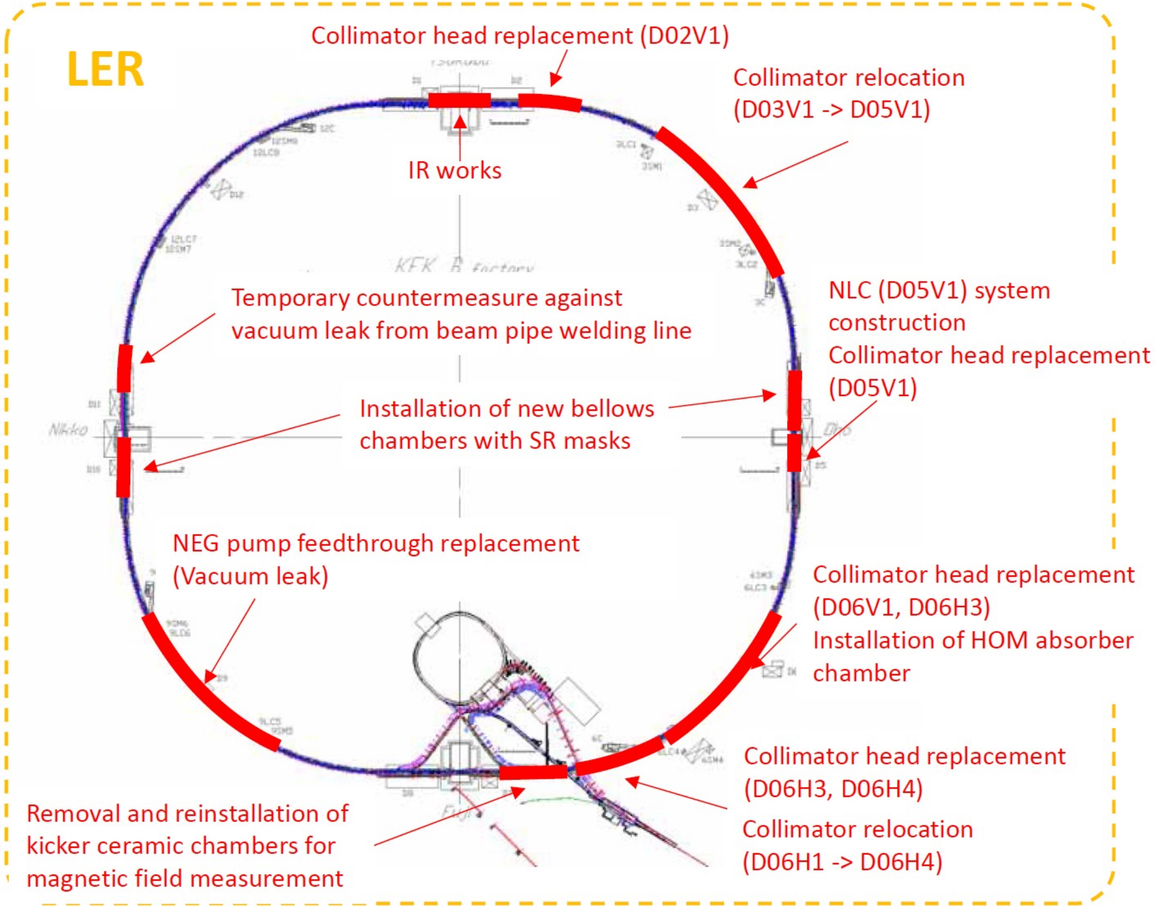
Installation of a new type of collimator (Non-Linear Collimator) in the Oho straight section → reduction of beam instability caused by the collimator, collimator protection, and etc.

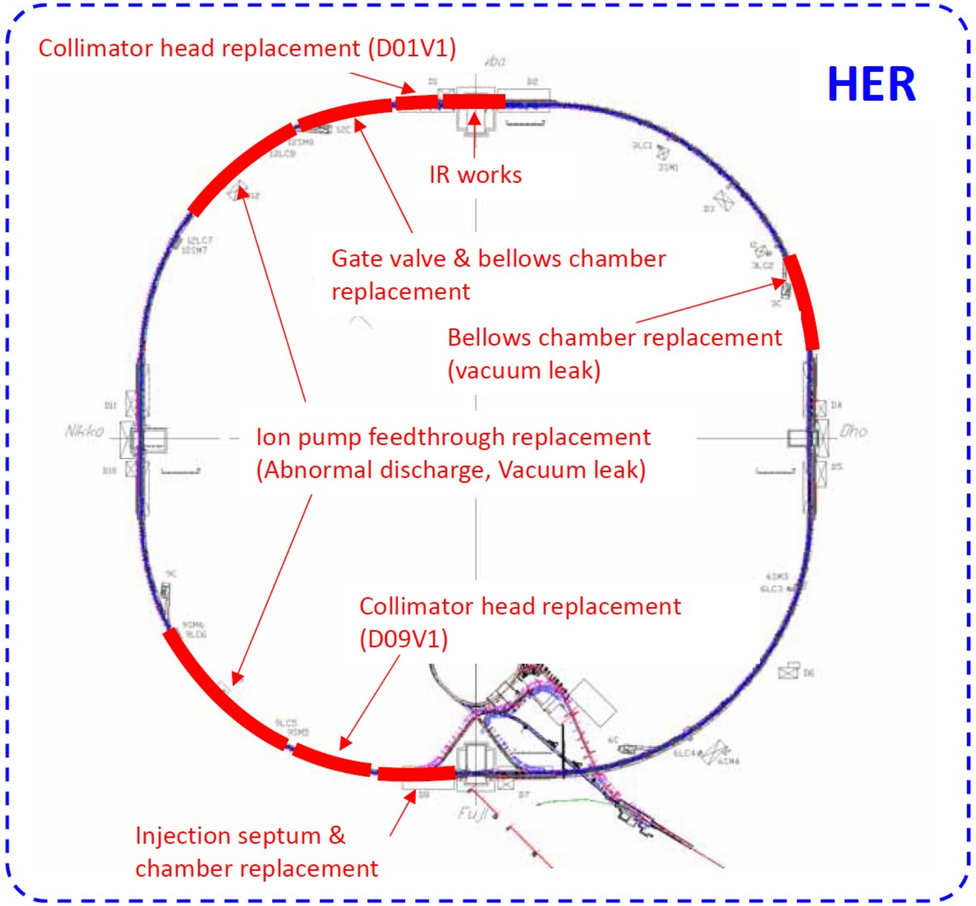
Replacement of collimator head
Monitors added, acoustic sensors around the collimators (SBL)

Coating collimator heads by cupper(SBL)

2. Status: LS1 work

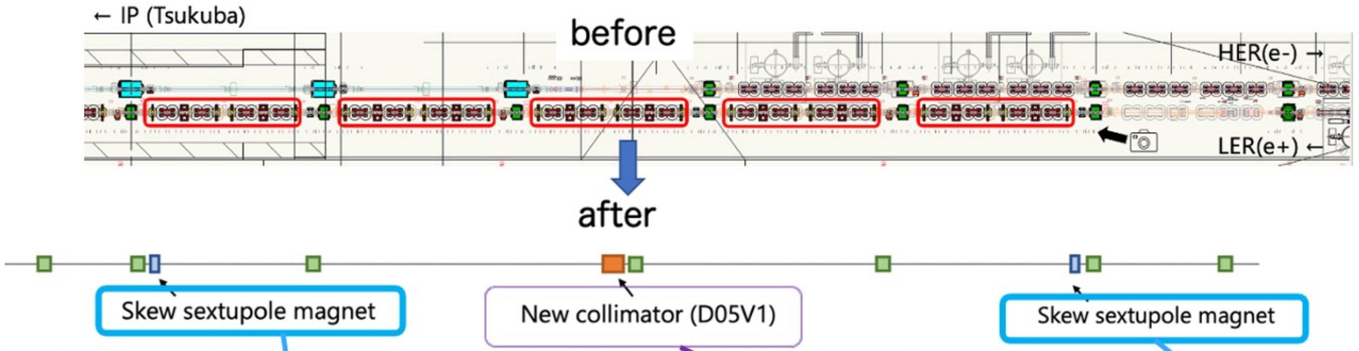
Vacuum work area, open to dry nitrogen or atmosphere, LER > HER

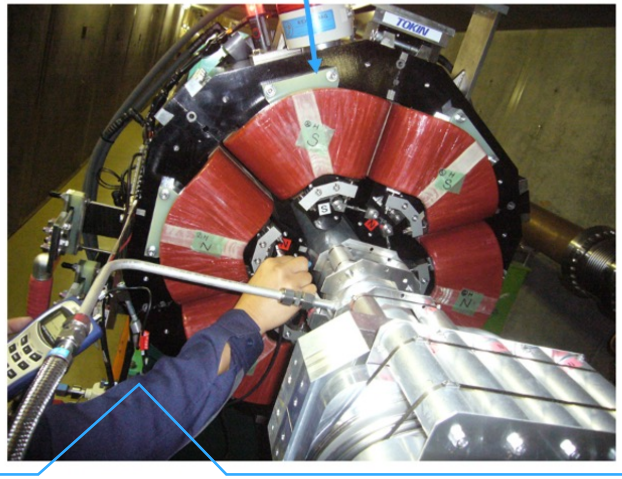


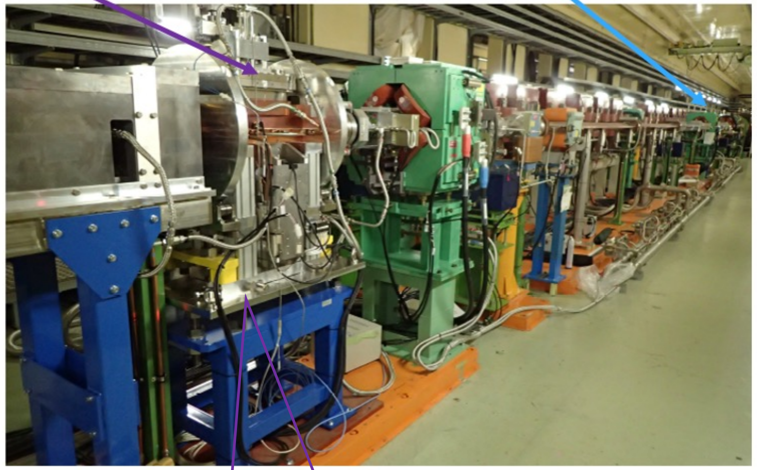


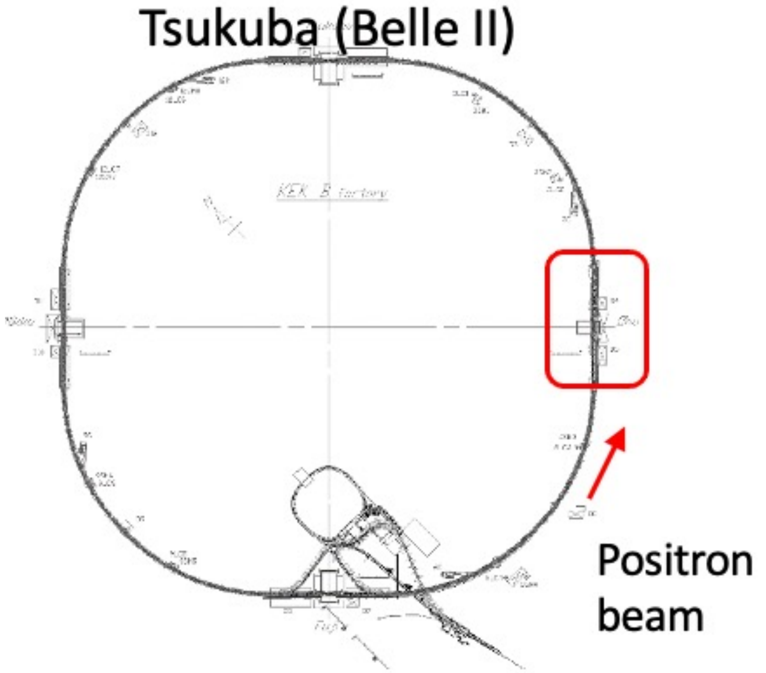
2. Status: LS1 work

Non-linear collimation system implemented for the first time in the world.









Skew sextupole magnets for generating non-linear kick to the beam

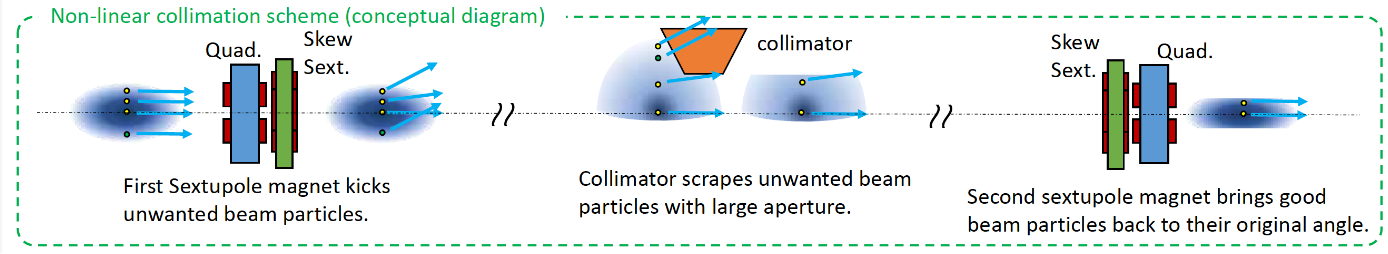
Vertical collimator

2. Status: LS1 work

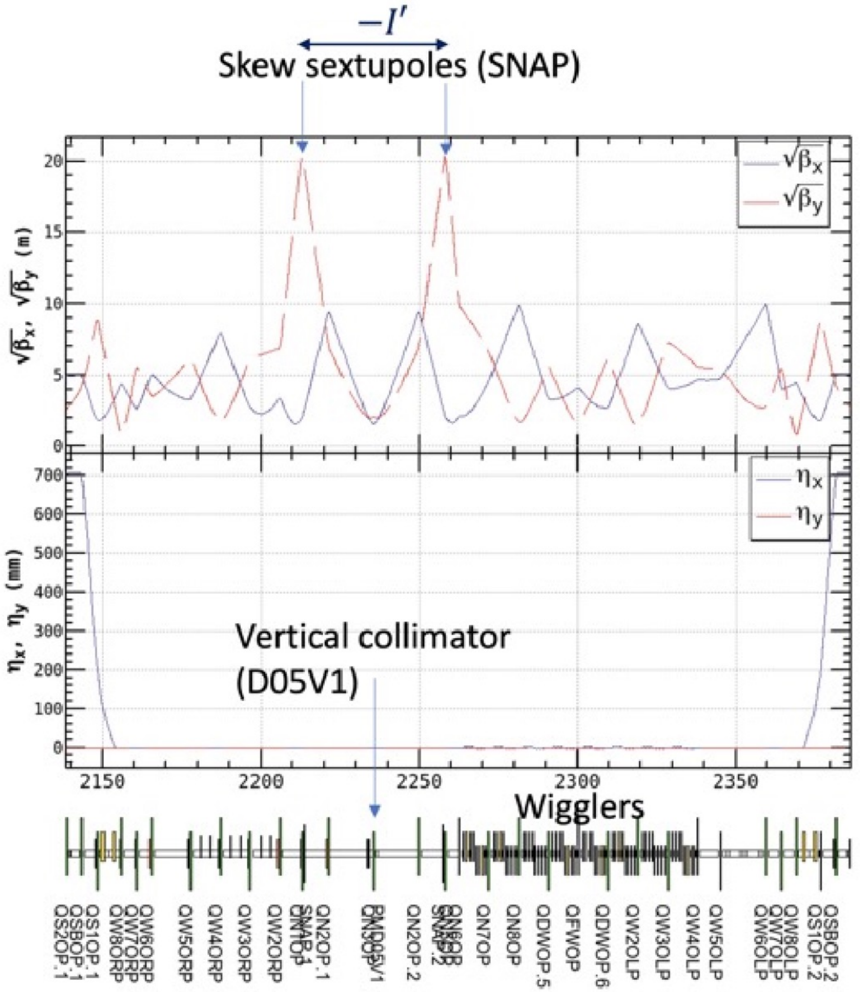
Non-linear collimation system implemented for the first time in the world.

We observed

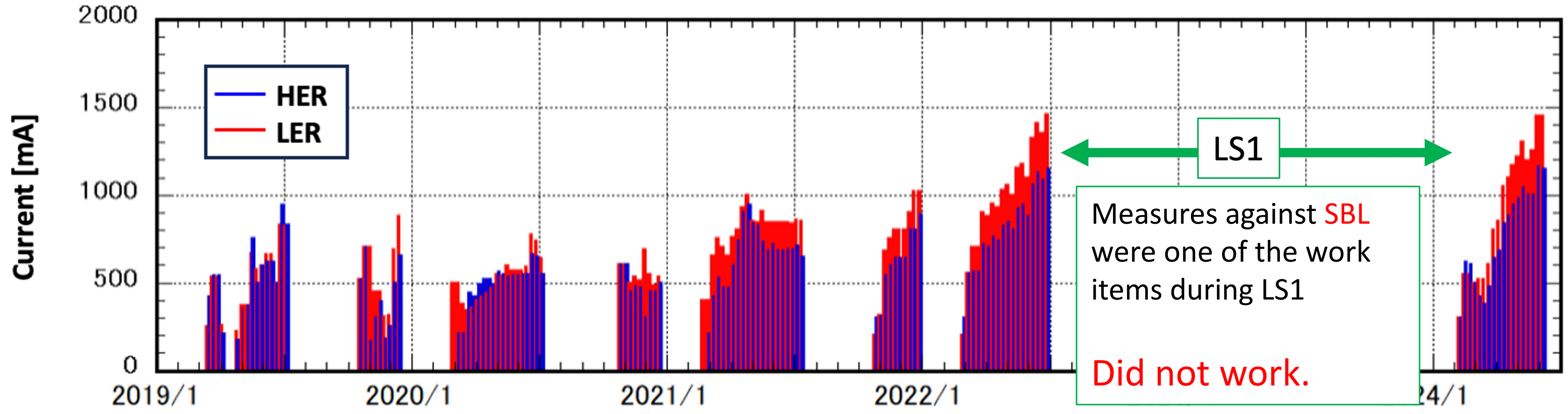
- Effective collimation obtained while keeping the D05V1 gap wider (as was expected).
- Tuning of β_x at the skew sextupole magnets may be tired to reduce the background coming from injection beam.
- Radiation shield will be added.



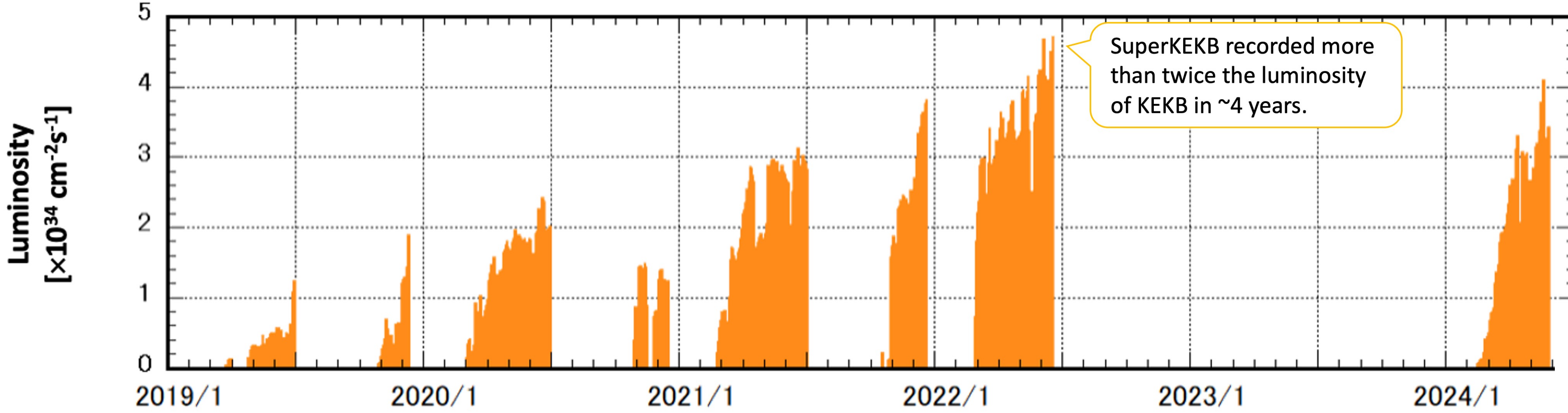
$$\Delta p_x = K_s xy$$
$$\Delta p_y = \frac{K_s}{2}(y^2 - x^2)$$



2. Status: After LS1



~100% of the max. current before LS1



~87% of the peak luminosity before LS1

HER crab waist 40%→60% on 6/5/2024

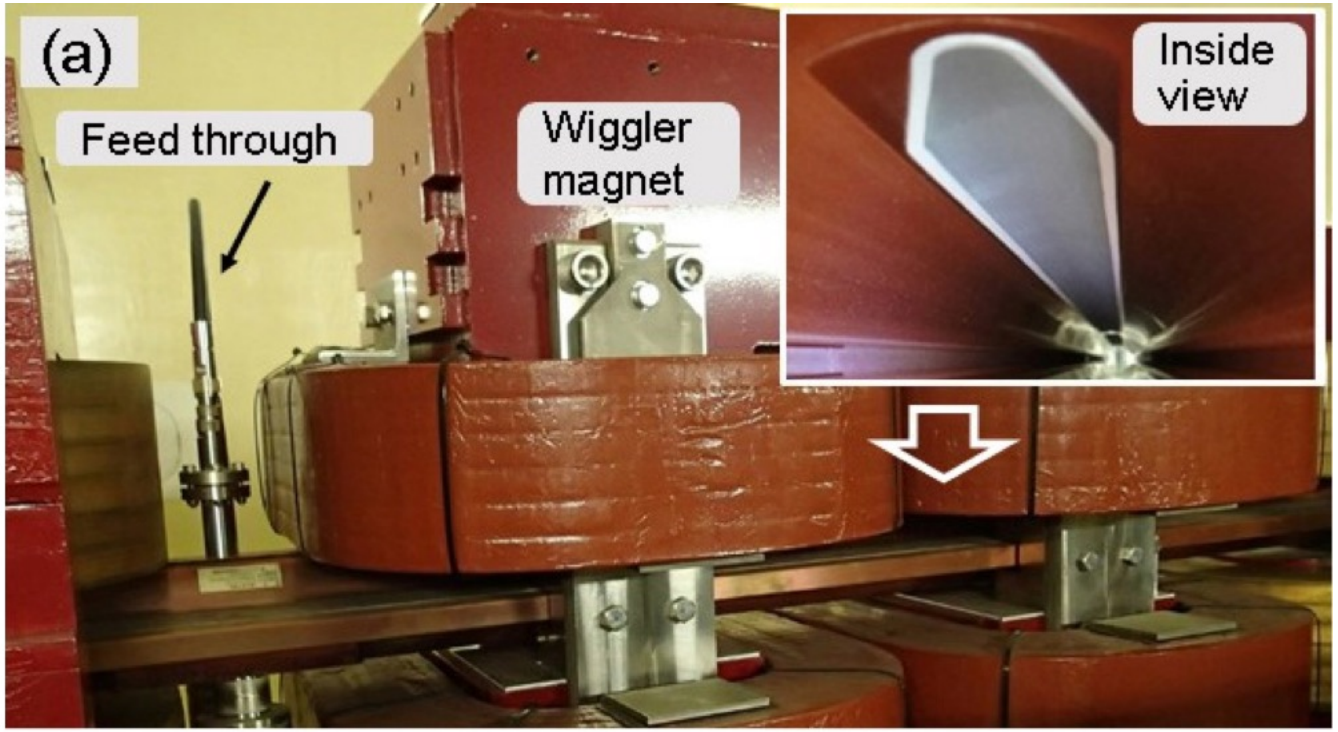
2. Status: After LS1

SBL Findings, from 2024ab run

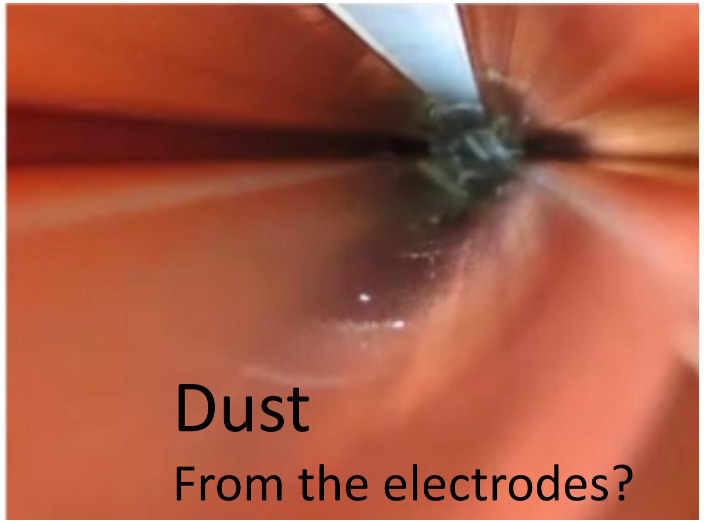
H. Ikeda's talk on Thursday

- More frequent in the LER than the HER.
- Happens with a single beam as well as in collision.
- Happens even at lower bunch currents.
- Happened when $\beta_y^* = 3\ mm$, as well (not only at $\beta_y^* = 1\ mm$).
- Higher total currents result in more frequent SBL.
- No data showing discharge at LER collimator.
- In most cases where SBL has occurred, the vacuum in a particular location has temporarily worsened.
- Hitting the beam pipe at a specific location with a "knocker" can cause SBL.

2. Status: After LS1

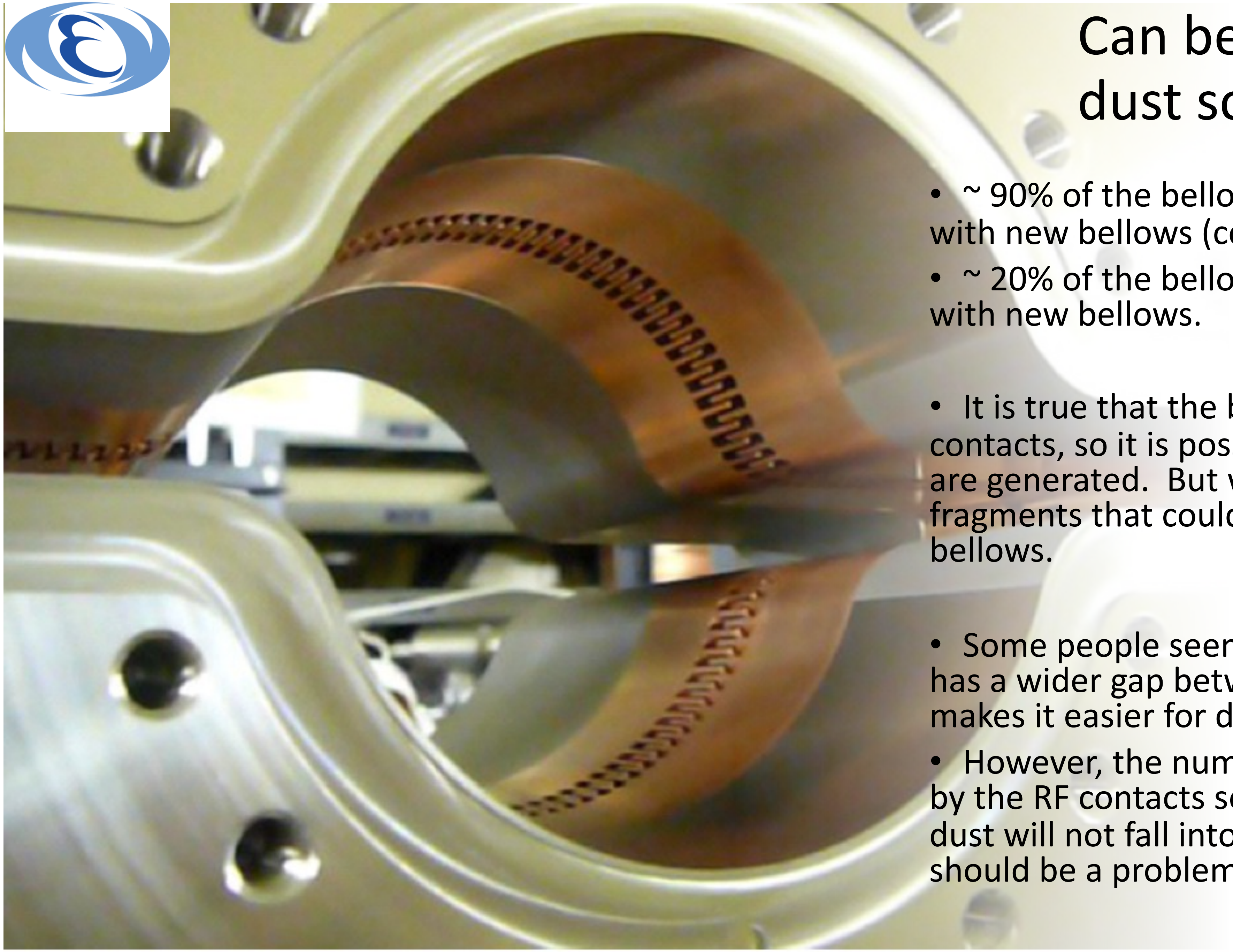


H. Ikeda's talk on Thursday



Clearing electrodes: countermeasure against the electron cloud effects

- Attract electrons by electrostatic field.
- Thin electrode (0.1 mm tungsten on 0.2 mm Al_2O_3 Aluminium oxide)
- Small impedance and effective heat transfer, tested at KEKB.



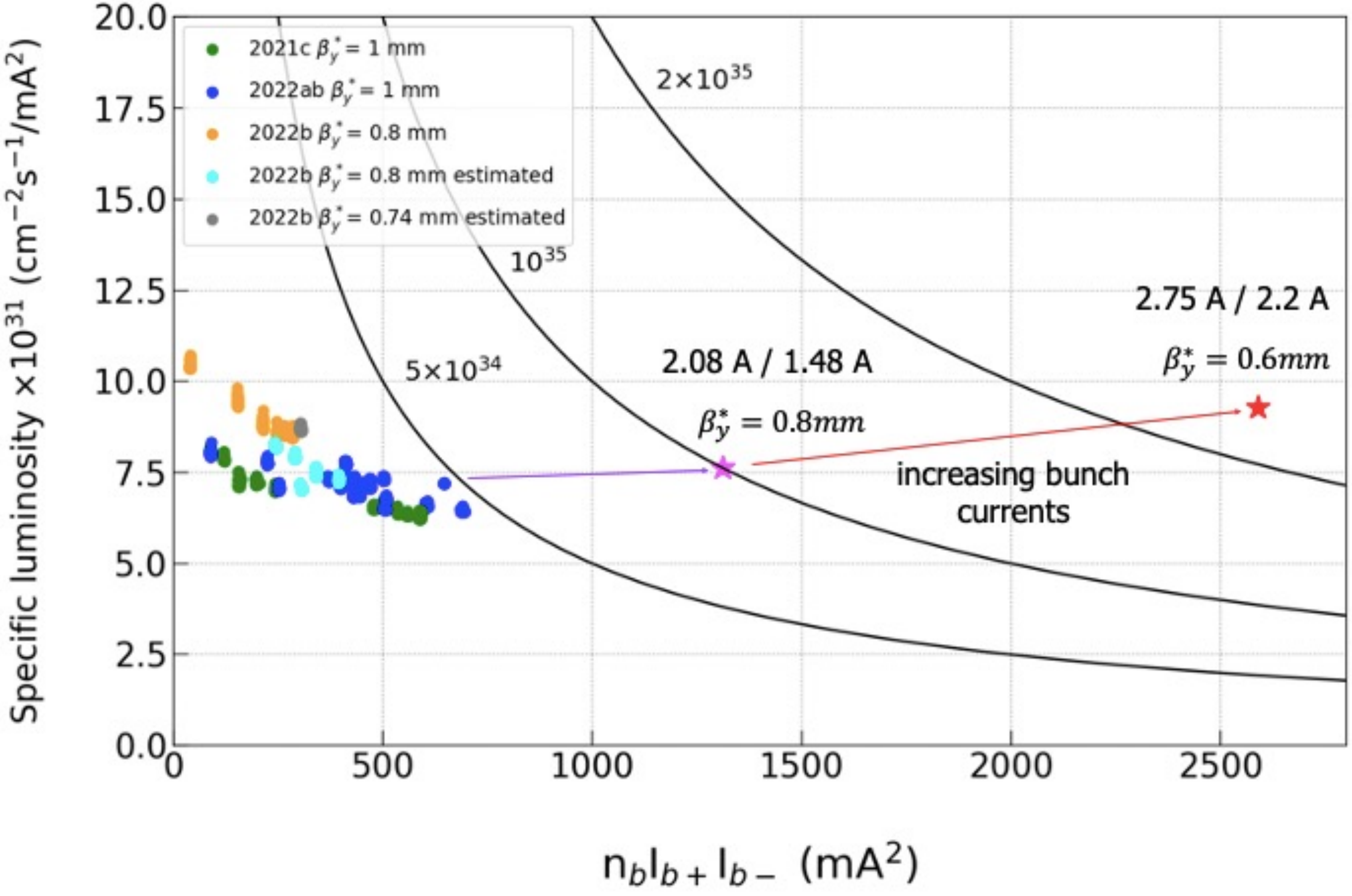
Can bellows be (also) dust source?

- ~ 90% of the bellows in the LER were replaced with new bellows (comb-tooth type).
- ~ 20% of the bellows in the HER were replaced with new bellows.

- It is true that the bellows rub against the RF contacts, so it is possible that small metal fragments are generated. But we have not seen any metallic fragments that could have been generated from the bellows.

- Some people seem to think that the newer model has a wider gap between the comb teeth, which makes it easier for dust to fall into the beam channel.
- However, the number of dust particles generated by the RF contacts seems to be small to begin with, dust will not fall into the beam channel as much as it should be a problem.

2. Strategy: After LS1:beyond 10^{35}

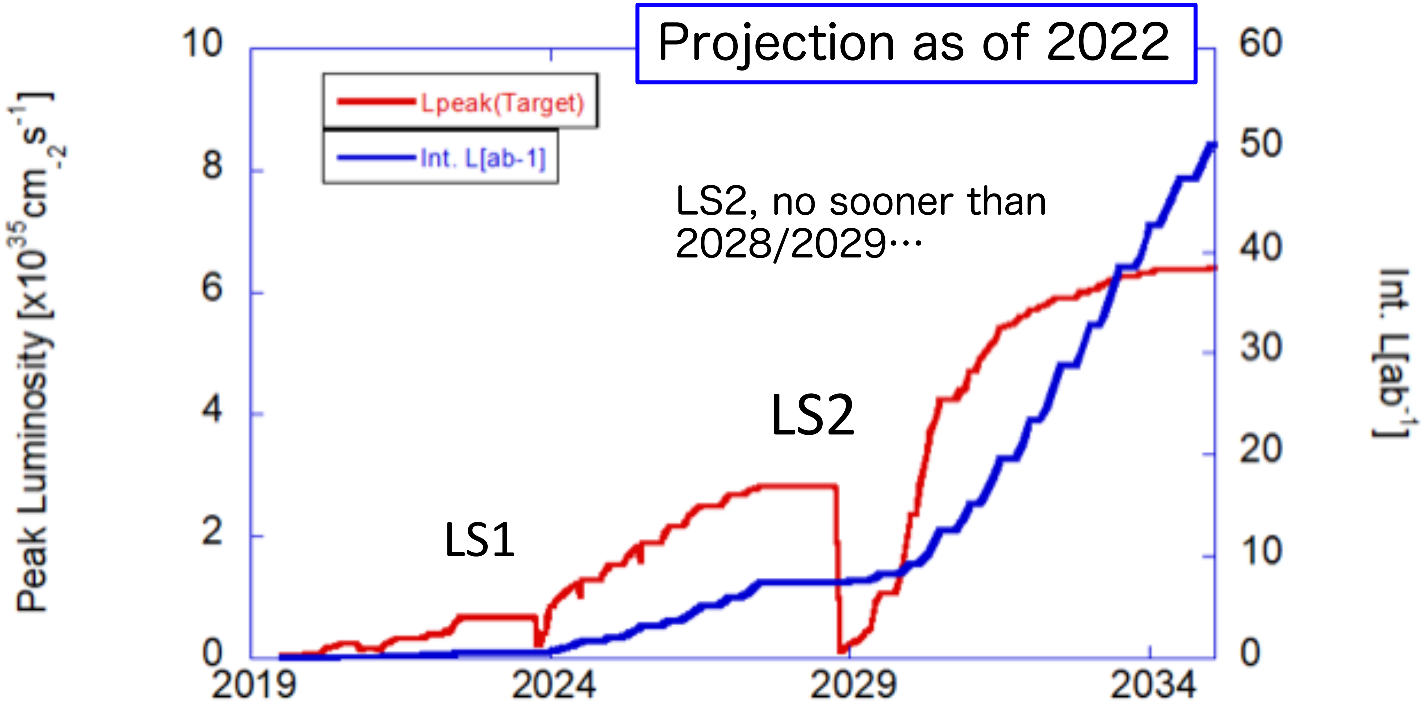


2×10^{35}

1×10^{35}

3. Upgrade ideas

3. Upgrade ideas



https://www-superkekb.kek.jp/Luminosity_projection/

LS2 Upgrade items under consideration (some can be done before LS2)

- IR (+ around) ← Today's talk
- RF system (for beam current increase)
- Beam transport line
- Injector system
- Vacuum
- Others

- Measures to address aging facilities and equipment
- Renewal of equipment for higher energy efficiency

3. Upgrade ideas

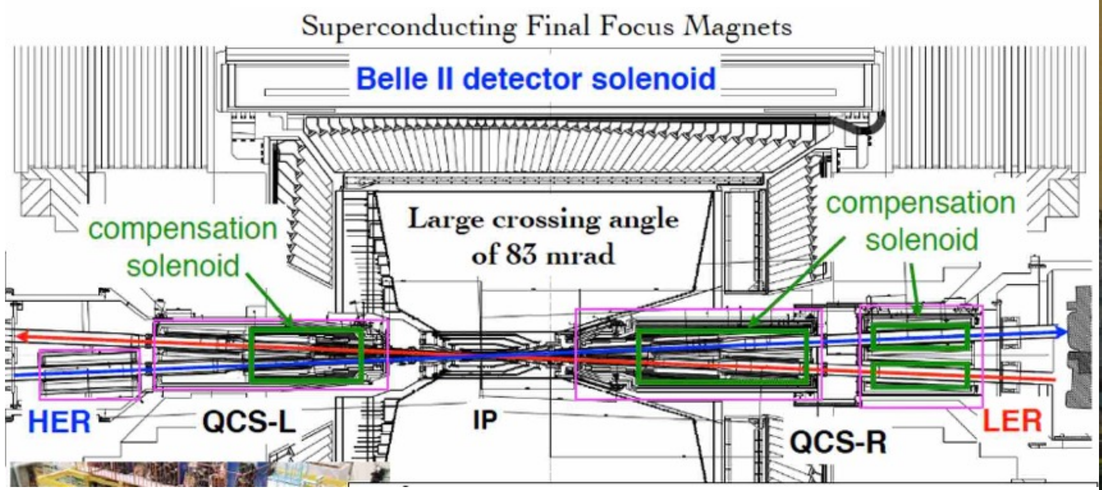
IR upgrade idea was presented at ARC (Mar. 25-27, 2024)

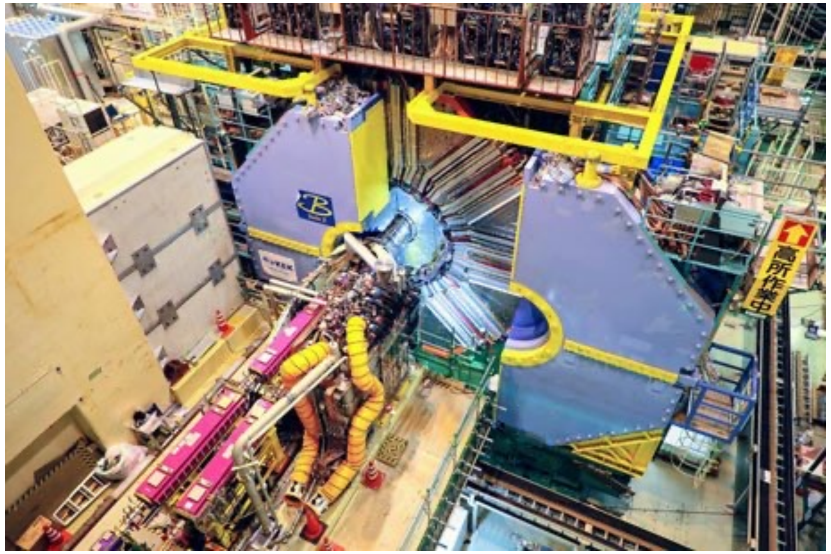
KEKB Accelerator Review Members

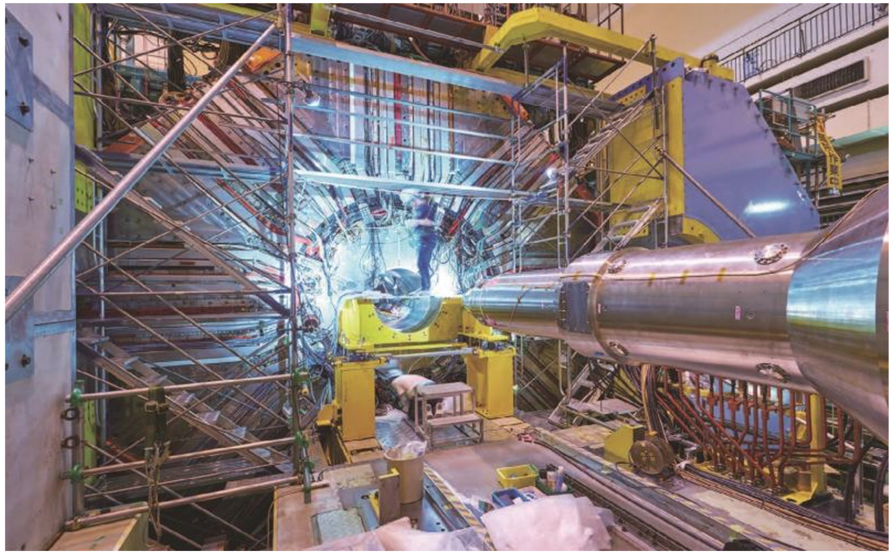
•Frank Zimmermann	CERN, Chair
•Ralph Assmann	DESY
•Vincent Baglin	CERN
•Paolo Craievich	PSI
•John Fox	Stanford University
•Andrew Hutton	JLab (excused)
•Catia Milardi	INFN-LNF
•Evgeny Perevedentsev	BINP
•Katsunobu Oide	UNIGE/CERN and KEK (ret.)
•Qing Qin	ESRF
•Bob Rimmer	JLab.
•John Seeman	SLAC
•Michael Sullivan	SLAC
•Tom Taylor	CERN (ret.)
•Rogelio Tomas	CERN

3. Upgrade ideas

The present QCS configuration

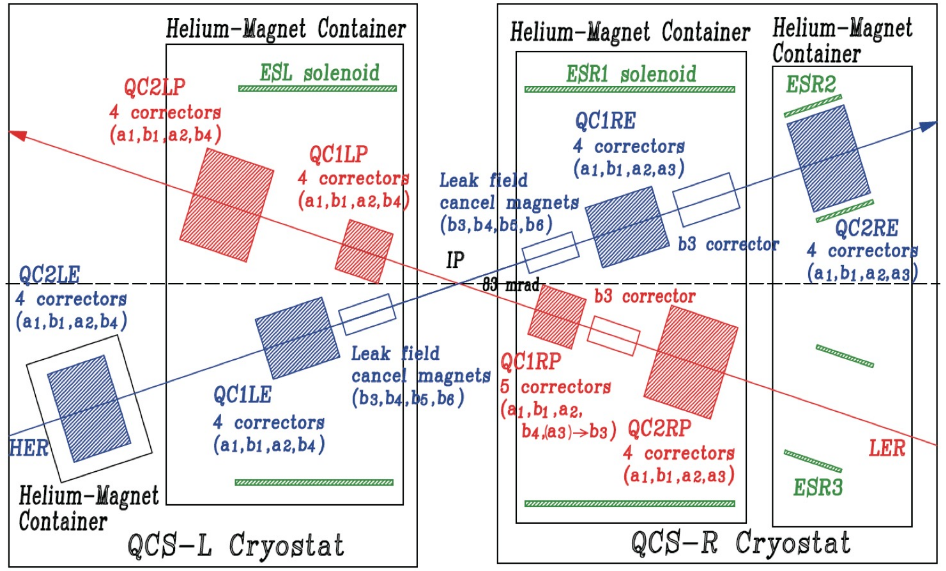


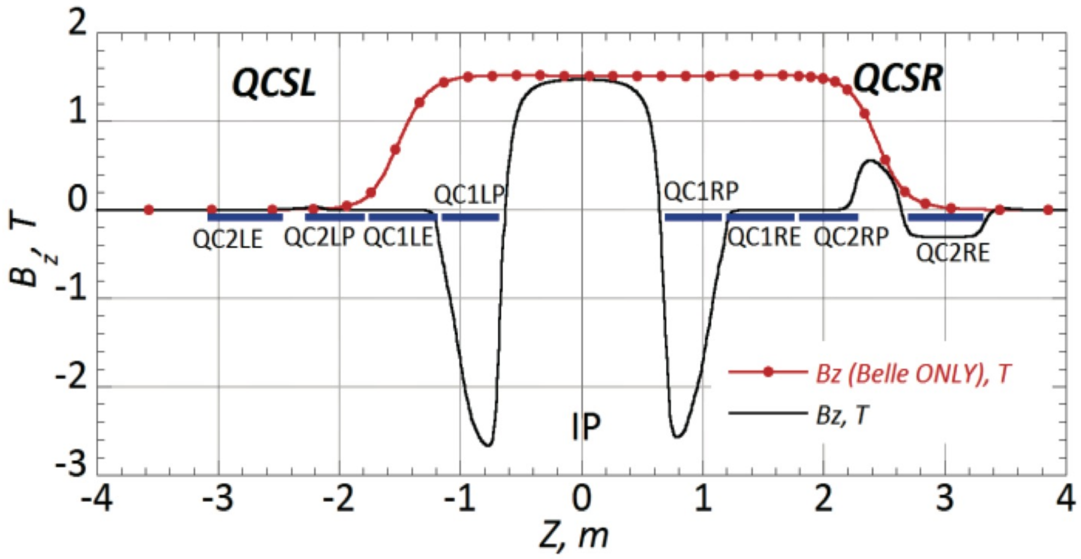




Superconducting final focusing magnet system (QCS) provides strong focusing to the HER/LER beams.

The present QCS configuration





Multipole components of leakage fields from QC1LP and QC1RP that have no yokes are canceled by other corrector magnets on the HER beam line.

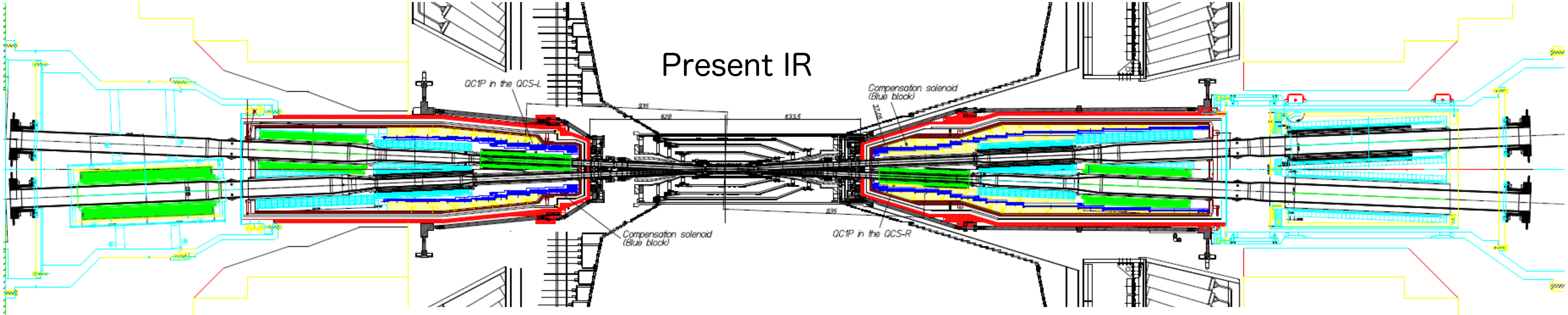
To accommodate the local orbit plane rotation caused by the solenoid magnetic field, QCs(LER) is rotated.

The magnets are placed with deliberate offsets.

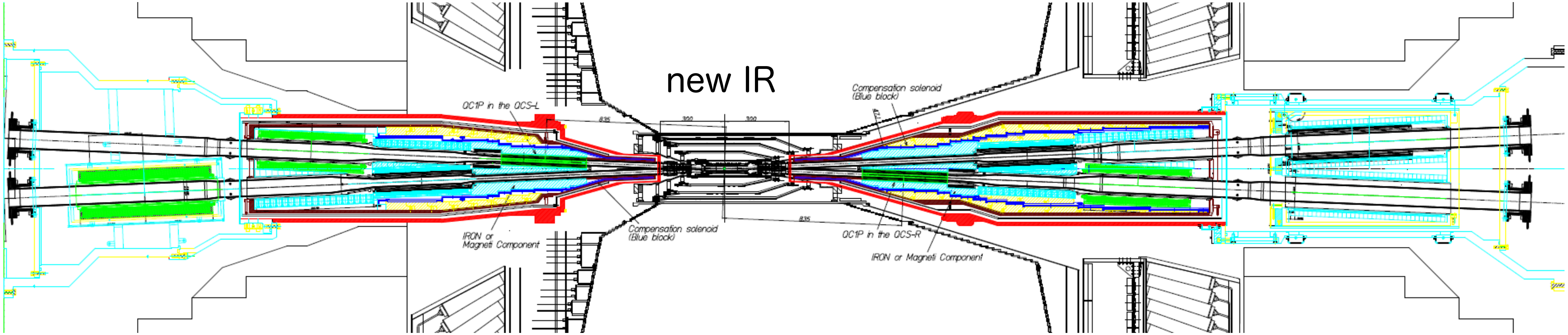
Magnet	Int. field T	Z m	Δx mm	Δy mm	Δθ mrad
QC1LP	22.96	−935	0.0	−1.5	−13.35
QC1RP	22.96	935	0.0	−1.0	7.204
QC2LP	11.48	−1925	0.0	−1.5	−3.725
QC2RP	11.54	1925	0.0	−1.0	−2.114
QC1LE	26.94	−1410	0.7	0.0	0.0
QC1RE	25.39	1410	−0.7	0.0	0.0
QC2LE	15.27	−2700	0.7	0.0	0.0
QC2RE	13.04	2925	−0.7	0.0	0.0

A very complicated system

3. Upgrade ideas



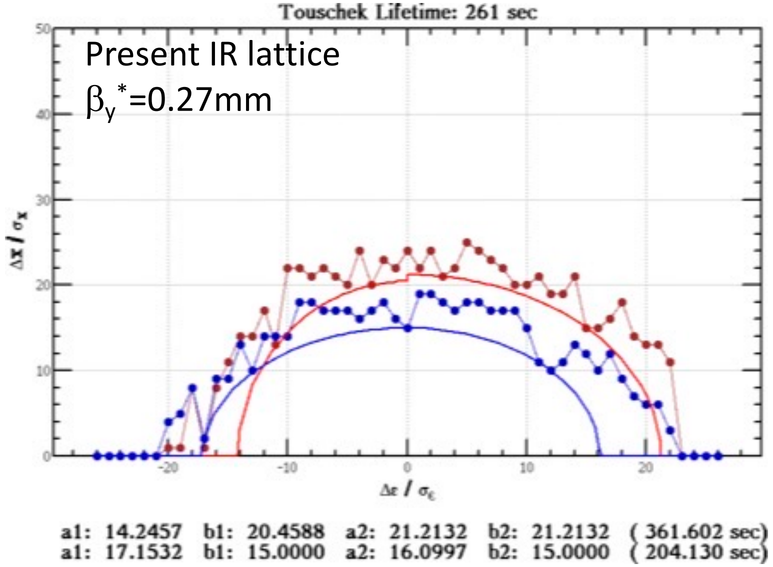
- QC1Ps from L^*=935mm to 835mm
- Cover QC1Ps with the magnetic yoke
- Install new compensation solenoid coils between IP and QC1Ps



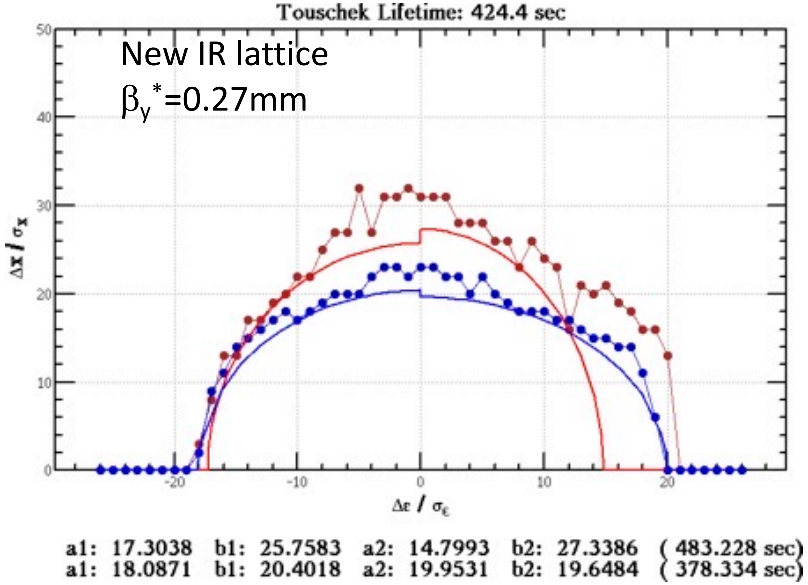
3. Upgrade ideas

By A. Morita

1. LER DA



Touschek lifetime from ~260 s to ~420 s.



2. Chromatic coupling improves significantly

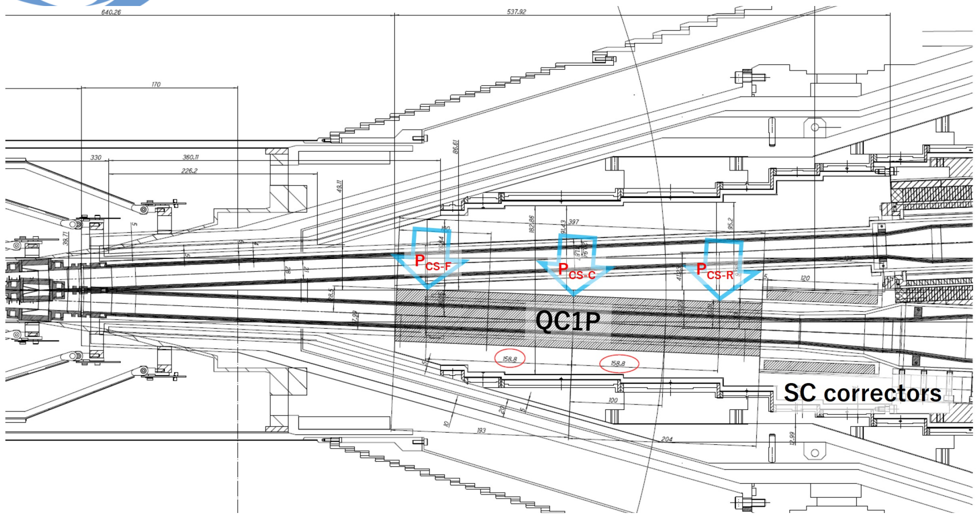
L*(mm)	$\partial R1/\partial\delta$	$\partial R2/\partial\delta$	$\partial R3/\partial\delta$	$\partial R4/\partial\delta$
935	-8.9×10^{-3}	$+4.0\times10^{-3}$	$-5.0\times10^{+1}$	$+2.9\times10^{+1}$
835	$+2.3\times10^{-5}$	-6.0×10^{-6}	-4.4×10^{-2}	$+5.5\times10^{-3}$

3. Emittance growth arises from IR is reduced to several tens of femtometer.

Beam-beam simulation, next step.

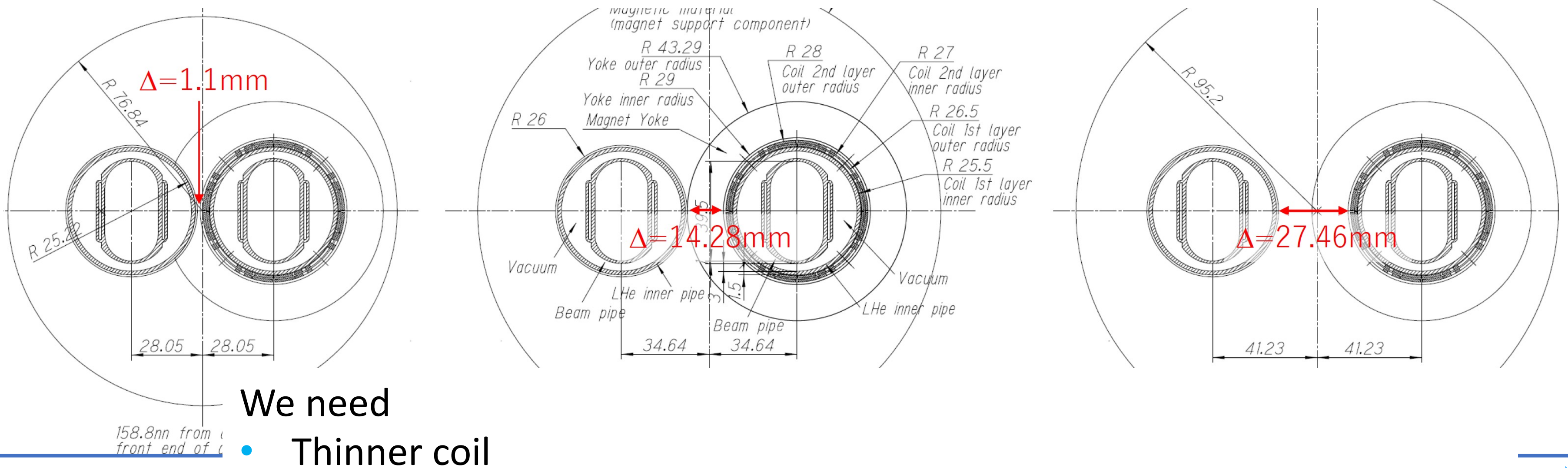
3. Upgrade ideas

By N. Ohuchi



Parameter	Current IR optics	New IR optics
L* (mm)	935	835
Distance between the coil & HER helium vessel (mm)	10.8	1.1
Required integrated field GL_{eff} (T)	23	25.75
Required field gradient G(T/m)	67.88	76.01

Cross sectional view along the LER beam line, if we scale the current NbTi QC1P



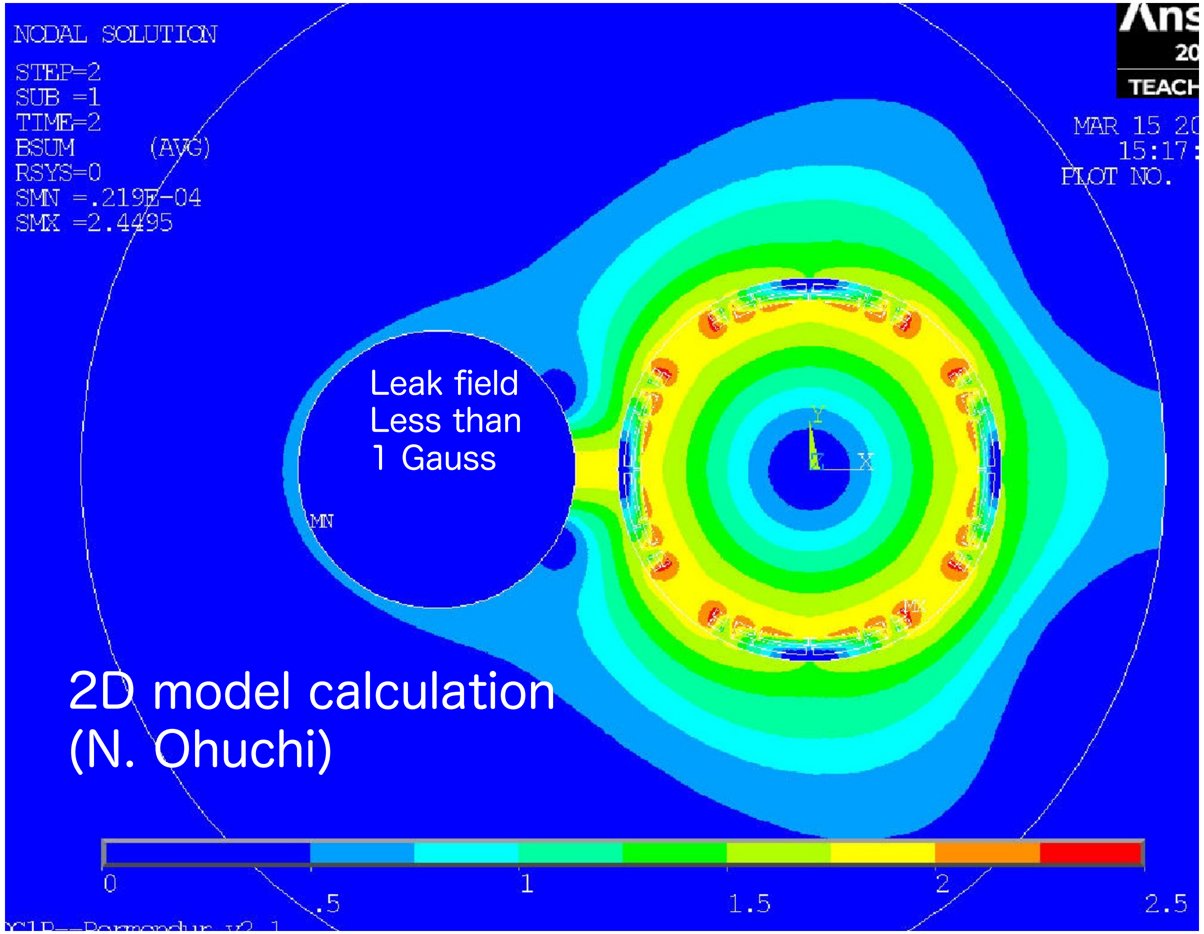
We need

- Thinner coil
- Superconducting wire that can withstand higher current density (from 1630A/mm² to >3000A/mm², beyond NbTi)

→ Nb_3Sn magnet

3. Upgrade ideas

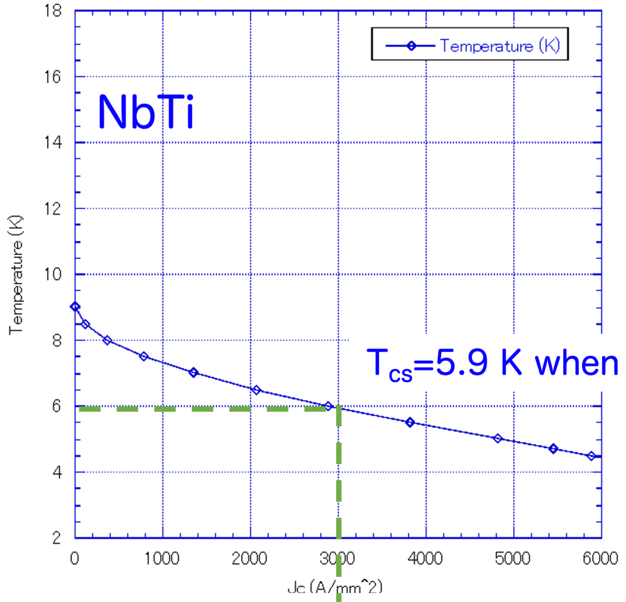
Conceptual design of the IR magnet

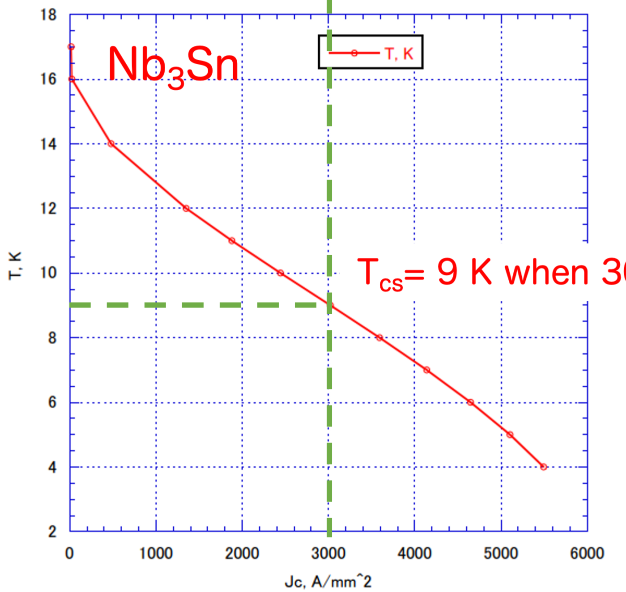


Field gradient = 80T/m, Current density in Nb_3Sn is 3112 A/mm^2

B_{max} in the coil ~ <u>2.5 T</u>

Current sharing temperature @<u>2.5T</u>

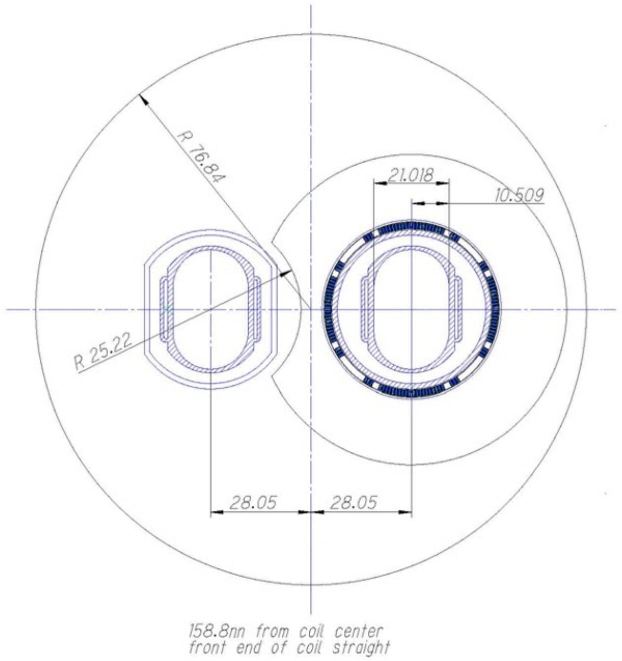




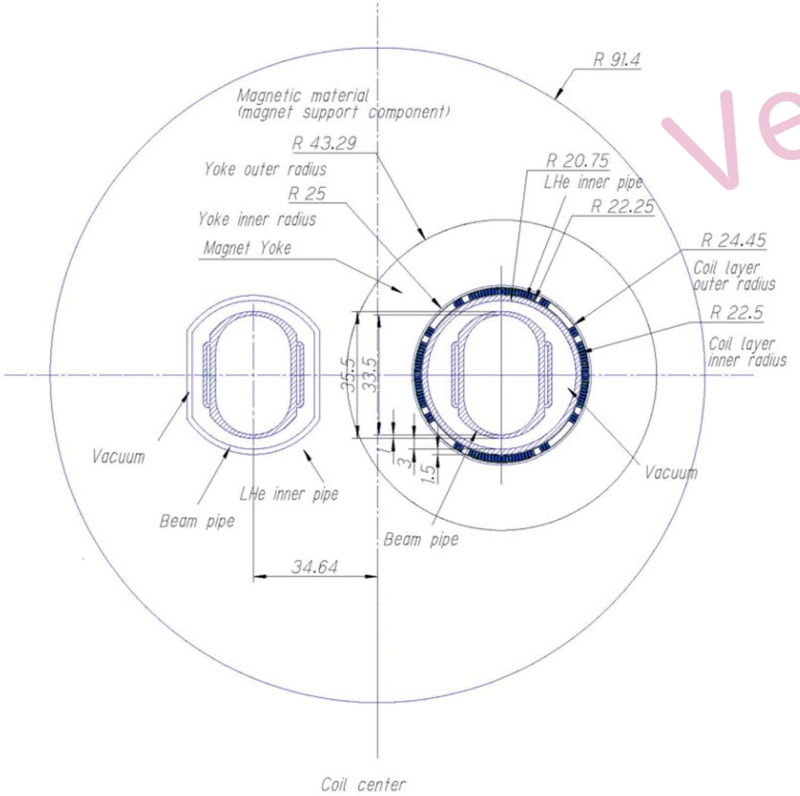
3. Upgrade ideas

Single layer magnet with Nb_3Sn cable

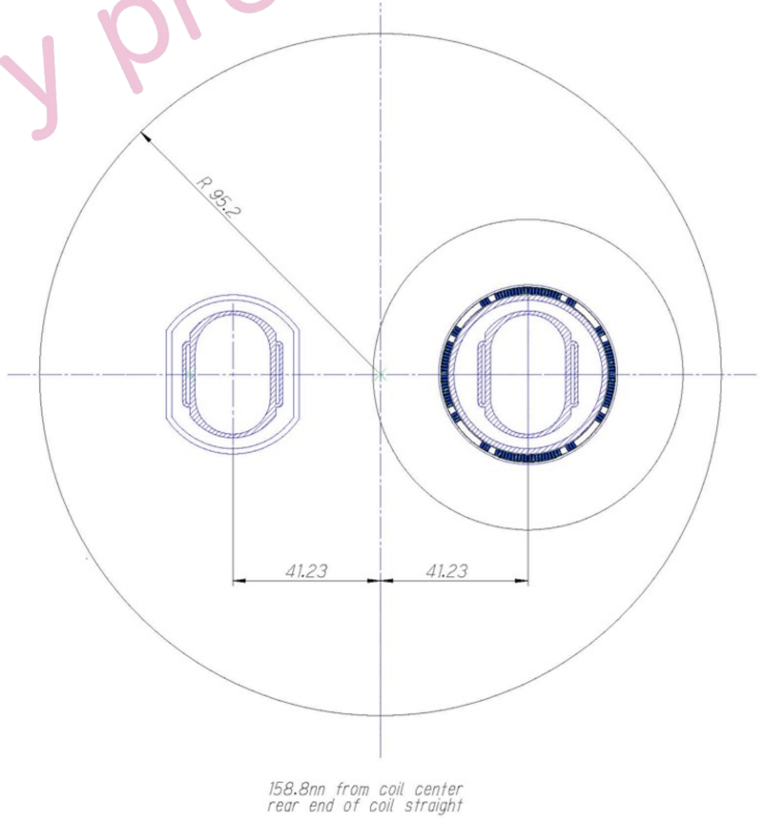
Very preliminary



Cross section at the front side
(the IP side)

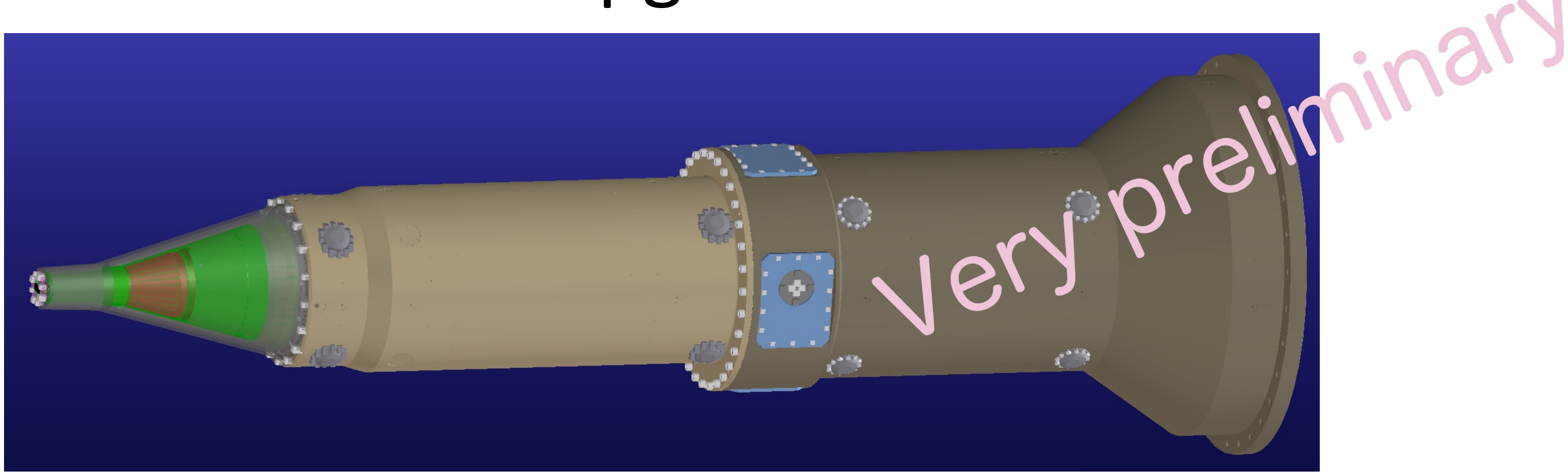


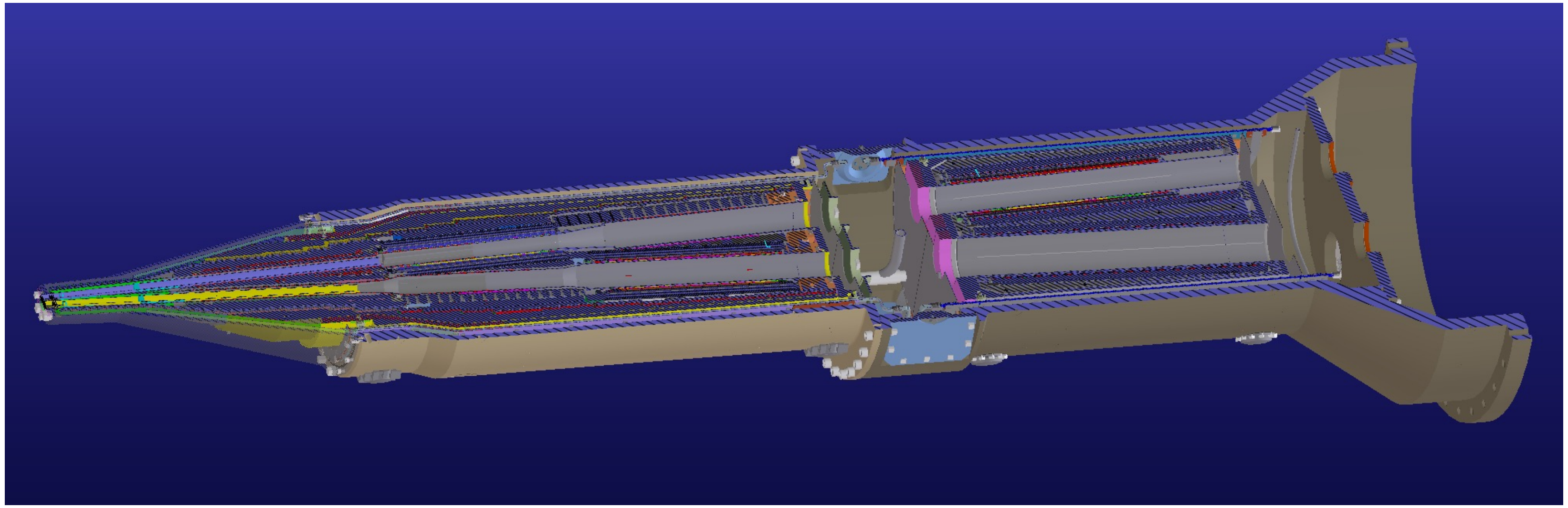
Cross section at QC1 center



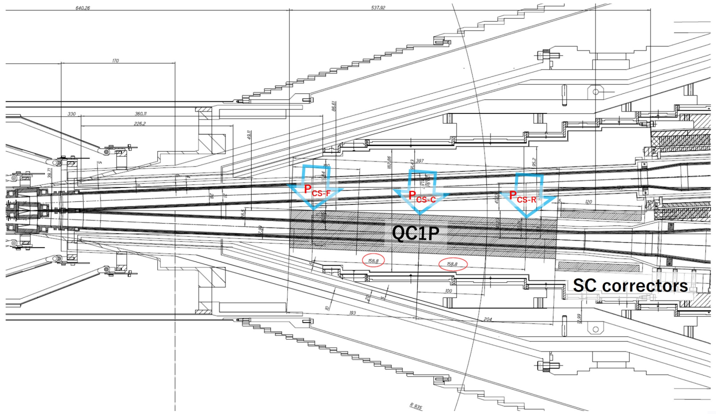
Cross section at the far side

3. Upgrade ideas



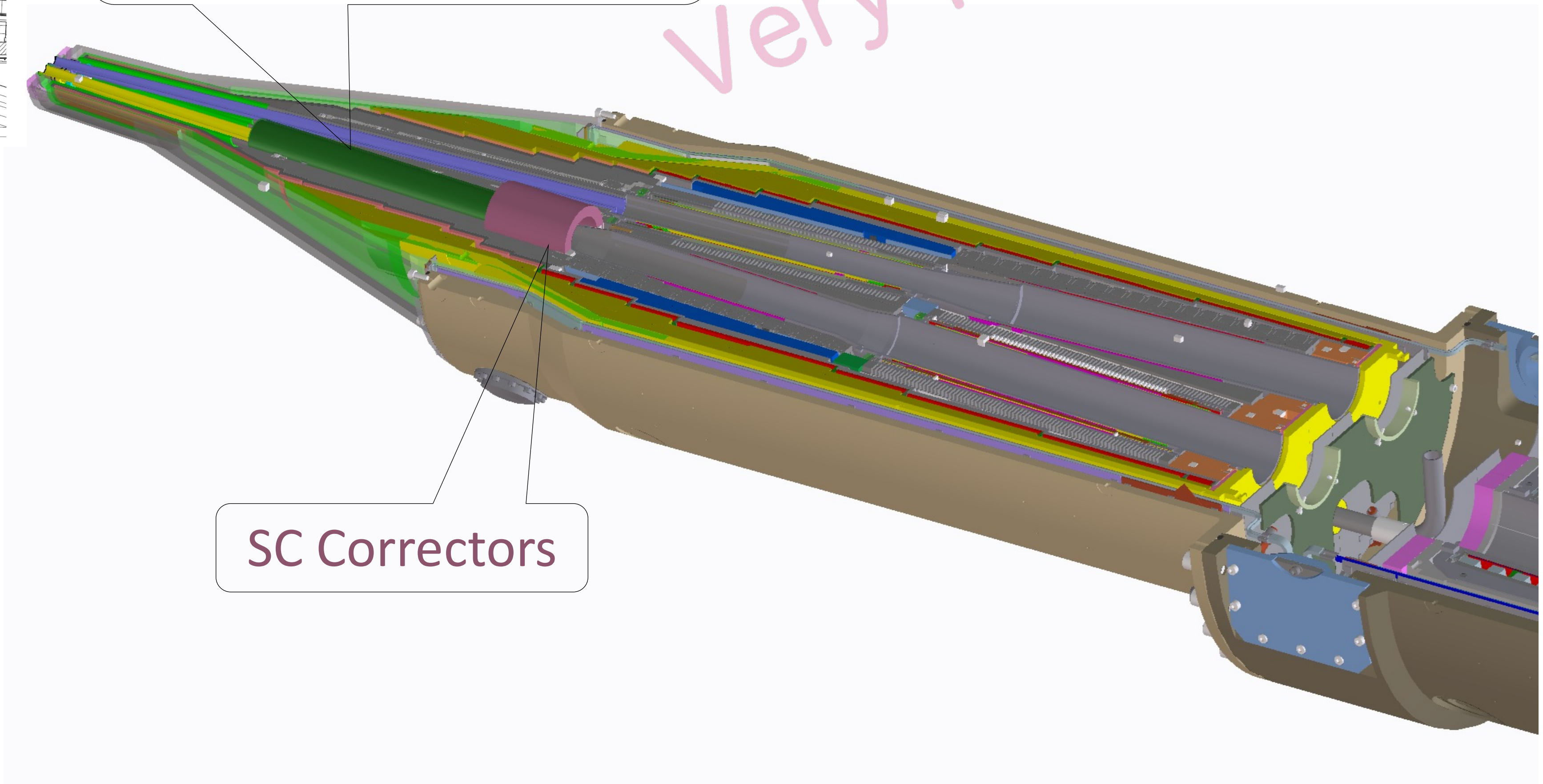


3. Upgrade ideas



QC1P:
r_{in} 22.5 mm, $l_{str} = 300$ mm

Very preliminary



SC Correctors

IR upgrade idea presented at ARC, 2024

- The new IR optics idea was evaluated using a 3D magnetic field profile.
  - Longer lifetime is expected.
  - Beams go straight through the IP, through the center of the quads.
  - Chromatic x-y coupling becomes a lot smaller.
    - Luminosity degradation, which arises from IR nonlinearity and beam-beam effects, may be recovered. Further simulation work is necessary.
  - Emittance growth from the new IR is expected to become much smaller.
  - Very simple IR

  - Nb_3Sn magnets are essential.
  - Simulation work is necessary.

- We believe that establishing the technology to make compact magnets using the Nb_3Sn superconducting wire will be useful not only for SuperKEKB IR upgrade but also for future accelerators and accelerator application.

3. Upgrade ideas

Nb_3Sn accelerator magnets

HiLumi News: 7.2-m-long niobium–tin quadrupole magnet manufactured at CERN reaches nominal current for the first time

The 7.2-metre-long version of this vital HL-LHC component reached nominal current plus an operational margin corresponding to a coil peak field of 11.5 T at 1.9 K during a test in SM18

25 JANUARY, 2023

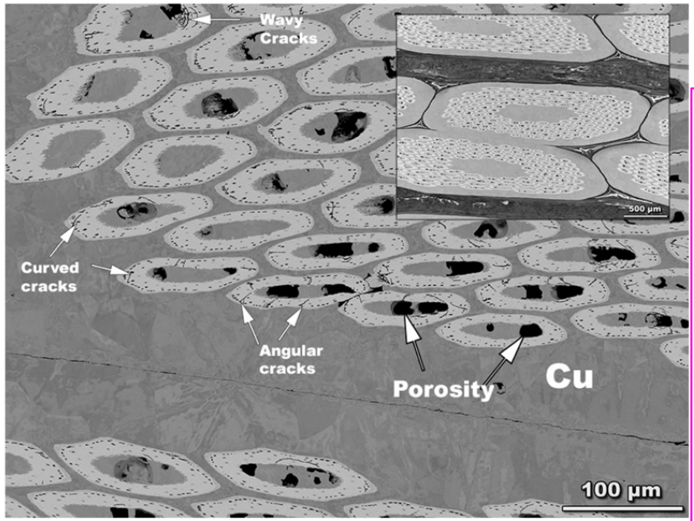
Another success for the HL-LHC magnet programme: after the successful endurance test of a 4.2-metre-long niobium–tin quadrupole magnet in the United States in spring 2022, the HL-LHC quadrupole's longer version proved its worth later in the year. "MQXFBP3", the third full-length quadrupole prototype to be tested at SM18, reached nominal current plus an operational margin in September–October 2022, confirming the success of the niobium–tin technology for superconducting magnets.

HL-LHC magnet endurance test further confirms niobium–tin's resilience

A full-size, US-produced HL-LHC quadrupole magnet based on niobium–tin technology has passed a critical endurance test, another step towards confirming the technology's viability inside accelerators

The MQXFBP3 magnet after the test, during assembly with the nested dipole orbit corrector. (Image: CERN)

https://home.cern/news/news/accelerators/hilumi-news-72-m-long-niobium-tin-quadrupole-magnet-manufactured-cern



Metallographic analysis of 11 T dipole coils for High Luminosity-Large Hadron Collider (HL-LHC)

To cite this article: Shreyas Balachandran *et al* 2021 *Supercond. Sci. Technol.* **34** 025001

Our QC1P face similar challenges and, on the other hand, quite different challenges.

- Much smaller any other Nb3Sn accelerator magnets in the world.
- Handling of such brittle wire, operating in the lower magnetic field environment than LHC.
- QC1P filament size < 5 μm , much smaller than LHC filament (~50 μm).
  - To prevent quenches from flux jump and to reduce long-term drift.

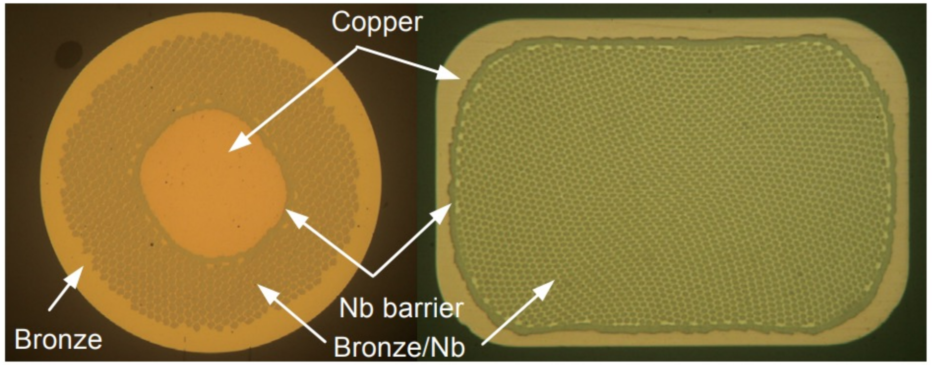
R&D

CERN, FNAL, BNL, LBL,,,

3. Upgrade ideas

Research collaboration with FNAL and Furukawa Electric Co., Ltd. and KEK has started.

Nb_3Sn Rectangular wire with S-2 Glass insulation being tested and will be purchased.



(a) NSN-100 (b) NSS-Rec[4)]

Fig. 1 Cross-sections of the typical wires.

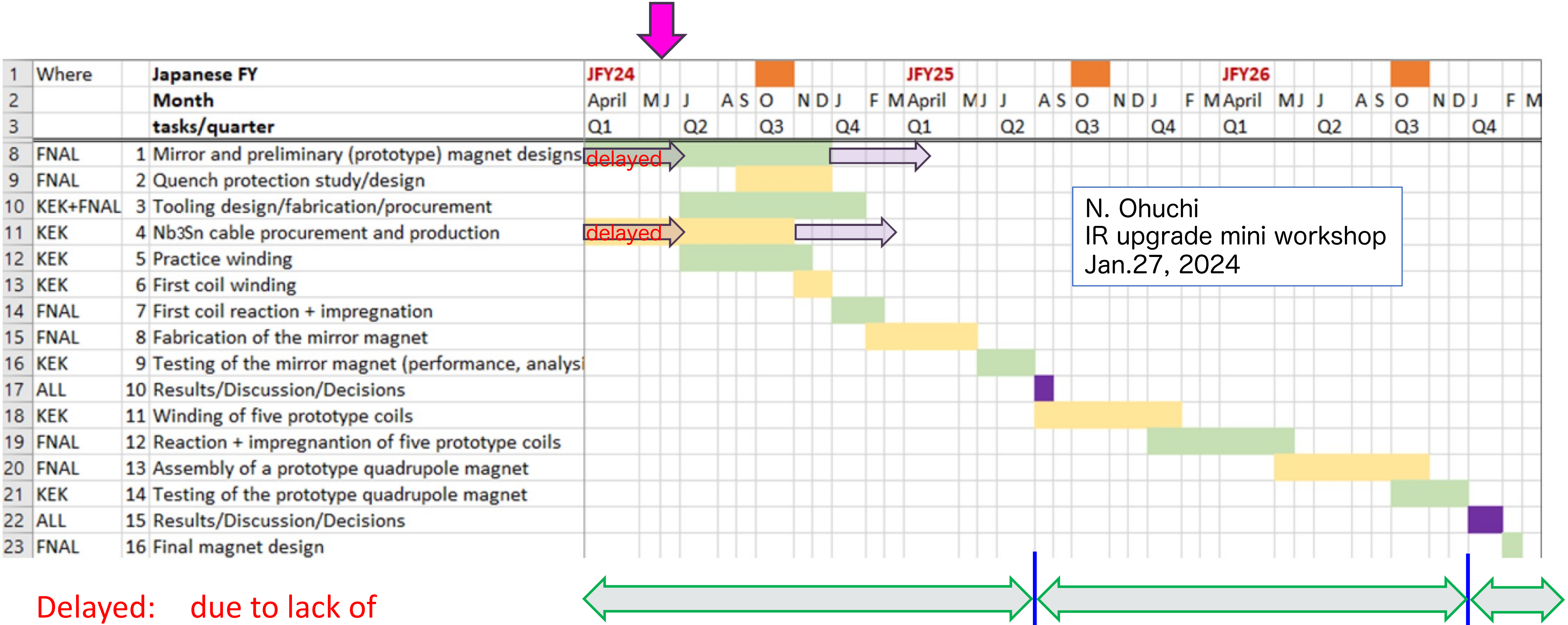
Rectangular wire modified specifically for QC1 (filament size < 5 μm)

Low field instability
Magnetization (Hysteresis) $J_c \times d(filament\ size)$

M. Sugimoto, H. Tsubouchi, et al., "Recent activity in development of Bronze-processed Nb3Sn wires-Improvement in strand performance and cabling", TEION KOGAKU (J. Cryo. Super. Soc. Jpn.) Vol 47 No. 8 (2012), pp479-485, (in Japanese).

We continue R&D on crucial technologies for Nb_3Sn QC1

Prospect of Nb_3Sn QC1P development



Delayed: due to lack of financial resources in April. KEK will support R&D costs.

- Mirror and prototype magnet design.
- Making the Nb3Sn cable specification and production.
- Construction of the mirror magnet.
- Excitation test of the magnet.

- Construction of the prototype magnet.
- Excitation test of the magnet.
- Magnetic field measurements of the magnet.

- Final magnet design.

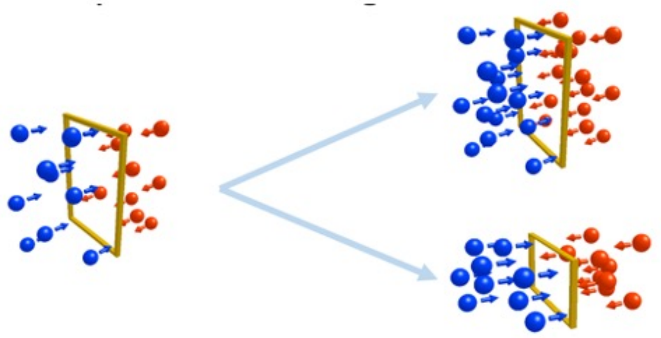
4. Summary

Nano-beam scheme SuperKEKB

- achieved more than twice the peak luminosity of KEKB in ~4 years.
- provides higher luminosity with lower beam currents than KEKB, luminosity efficient, sustainable.

As a luminosity frontier machine, SuperKEKB faces challenges

Much larger beam currents



Much smaller beam size

Difficulty in increasing beam currents → Sudden Beam Loss

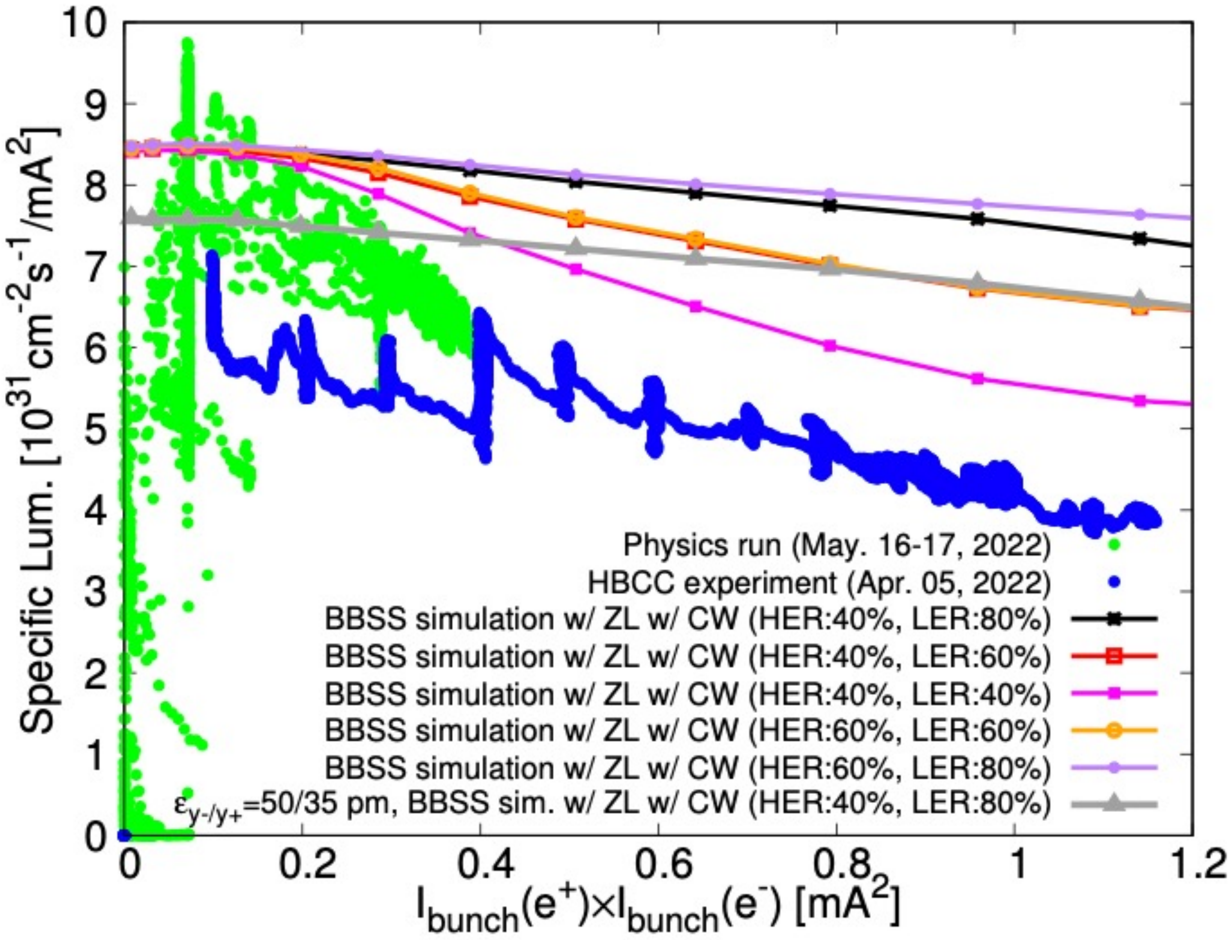
Balance among injection charge, injection efficiency, beam quality (emittance) of the injected beam, MR beam lifetime and detector background.

Continue machine study to understand and solve various problems.

4. Summary

- Upgrade items are also being considered for improving the machine performance further.
- Upgrade idea for IR (one of the upgrade items) is introduced.
  - R&D on Nb_3Sn magnet, the crucial technology, has started.

Collaboration with FCC is very important and beneficial for both.



Machine imperfections:

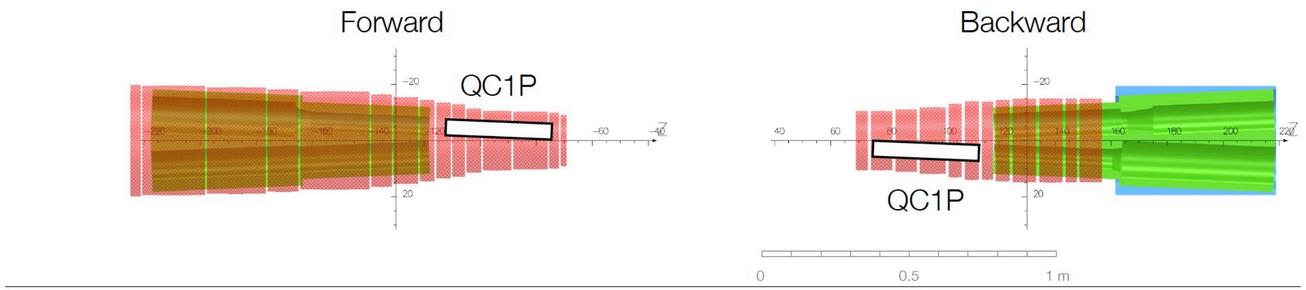
- Non-zero linear and chromatic coupling and dispersions at IP
- beam-current dependent optics distortion due to orbit change at QCS* and SLY*, etc.

•Imperfect crab waist scheme; Interplay of beam-beam interaction and beam coupling impedance.

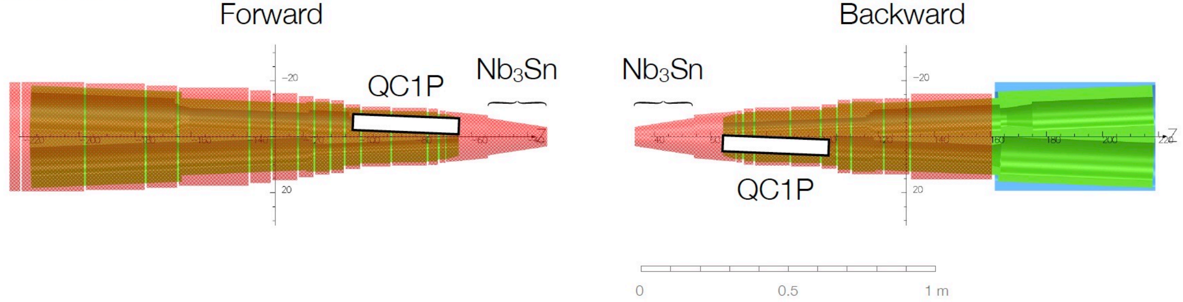
•Beam oscillation excited by injection kickers at LER causes luminosity loss by ~10%.

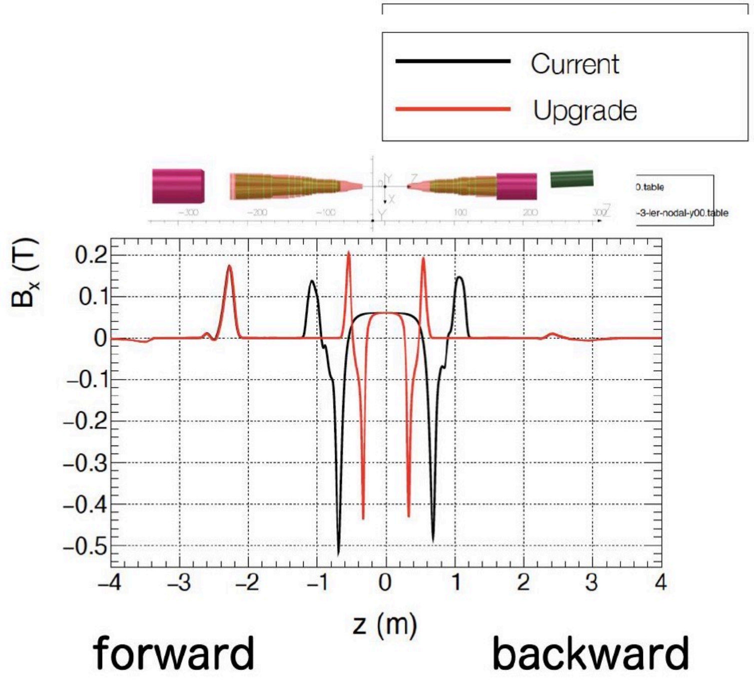
BB simulation with the new IR

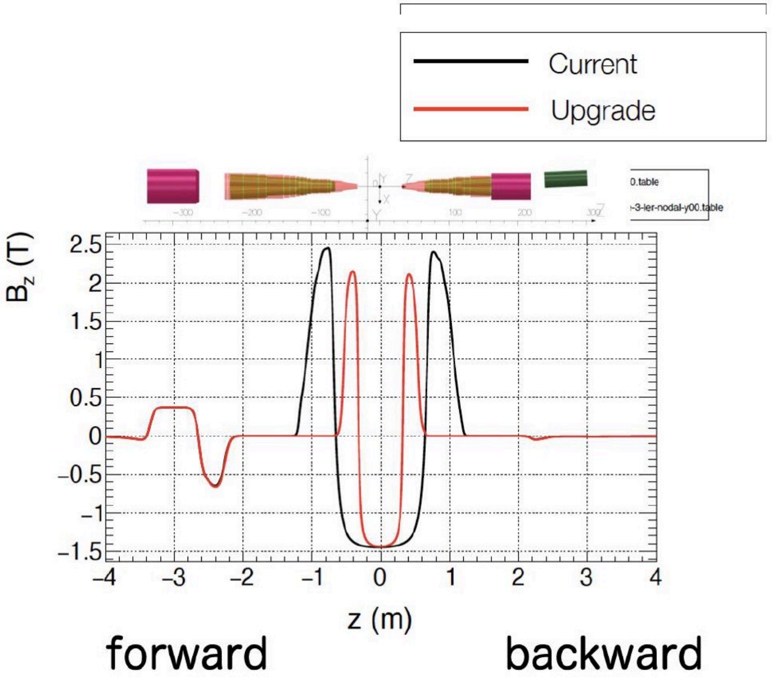
D. Zhou et.al
https://doi.org/10.18429/JACoW-IPAC2022-WEPOPT064



Upgraded ver.







SuperKEKB Design concepts, strategy

Comparison with KEKB

- Low β_y^* of $\sim 300\ \mu m$
- Low β_x^* of $\sim 30\ mm$, which is roughly one-tenth of the design value of KEKB (330 mm, although a
- larger β_x^* was used in operation with the crab crossing of KEKB).
- Low emittances and flat beams: $2 \sim 5\ nm$ (horizontal) and : $9 \sim 12\ pm$ (vertical).
- Large Piwinski angles of ~ 20.
- Modest bunch lengths of $5 \sim 6\ mm$.
- Modest (?) vertical beam-beam parameters of 0.09.
- Short beam lifetimes of 360 sec.
- Low β_y^* and β_x^* decrease the dynamic aperture, resulting in short beam lifetimes and strict requirements for injection beams.
- Thus, a powerful injector that can deliver low-emittance beams is necessary.

SuperKEKB Collider K.Akai, K. Furukawa, H. Koiso
arXiv:1809.01958v2 [physics.acc-ph] 10 Sep 2018