SKB Limitations and upgrade path

Mika Masuzawa
KEK Accelerator Laboratory

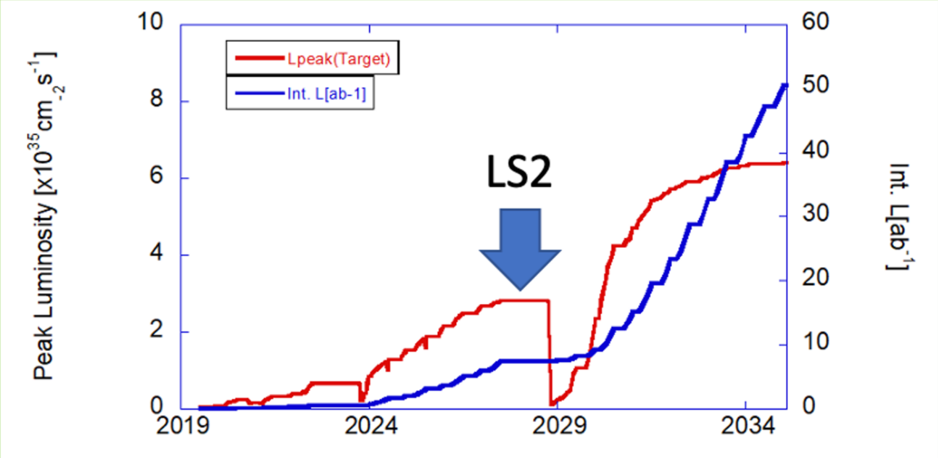
Contents

1. BPAC 2023

1. Introduction

- We need another long shutdown (LS2) to improve the machine performance beyond $\sim 2\times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ and toward the target peak luminosity of $6\times 10^{35}\mathrm{cm^{-2}s^{-1}}$.

- It probably requires
  a. modifications of the IR
  b. an upgrade of the injection complex.



- The modifications must be effective enough that there is a gain of a factor of ~2 at least (depending on the length of the shutdown) in peak luminosity.

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1. BPAC 2023

2. Main Ring (IR)

Three scenarios are under consideration.

1. Moderate scale modification around 2027 (more than 1 year shutdown):
   - New QC1 with larger physical aperture, installed closer to the IP for larger dynamic aperture, keeping the boundary as is.
     - R&D work on Nb_3Sn quadrupole magnet is necessary.
     - Evaluate the impact of modifications on machine performance by 2025 at the latest.
2. Larger scale modification, in addition to 1:
   - New anti-solenoid configuration, which probably requires detector modifications.
     - Optical evaluation of the anti-solenoid field profile and coil design needed.
     - R&D work on Nb_3Sn thin solenoid is necessary.
     - New cryostats and a cryogenic system for anti-solenoid coils need to be designed and fabricated.
3. Much Larger scale modification sometime later (~203x)
   - New ideas to be sought for, by the ITF, for example.

➢ **SuperKEKB-wide effort needs to be made to establish a reliable model through extensive machine studies after LS1.**

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2. Progress since

2. Main Ring (IR)

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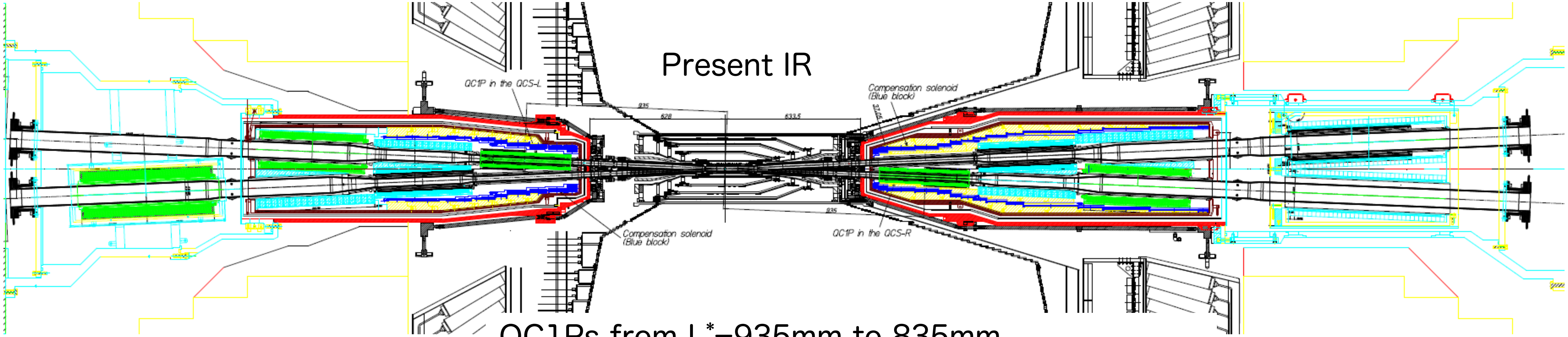
- Magnet configuration

⇅

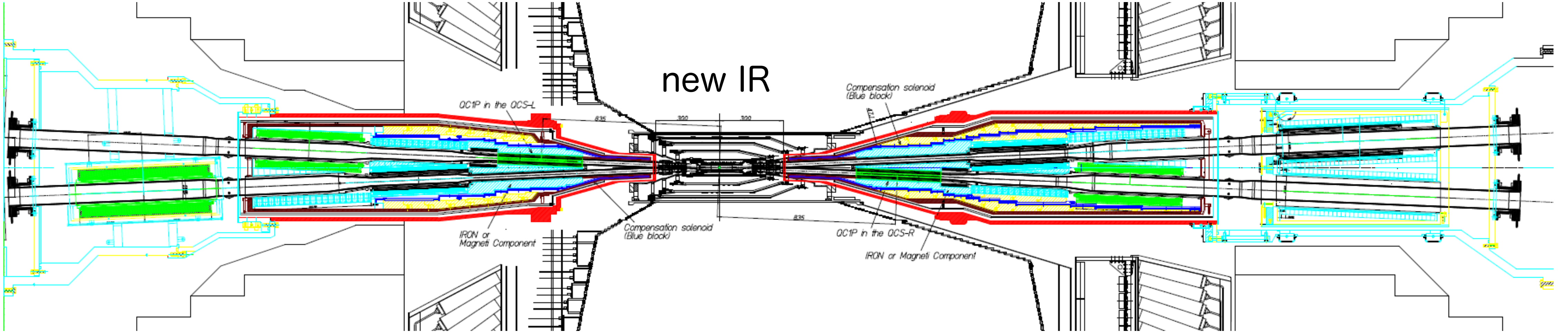
- Optics evaluation using 3D magnetic field profile

2. Progress since

- Magnet configuration



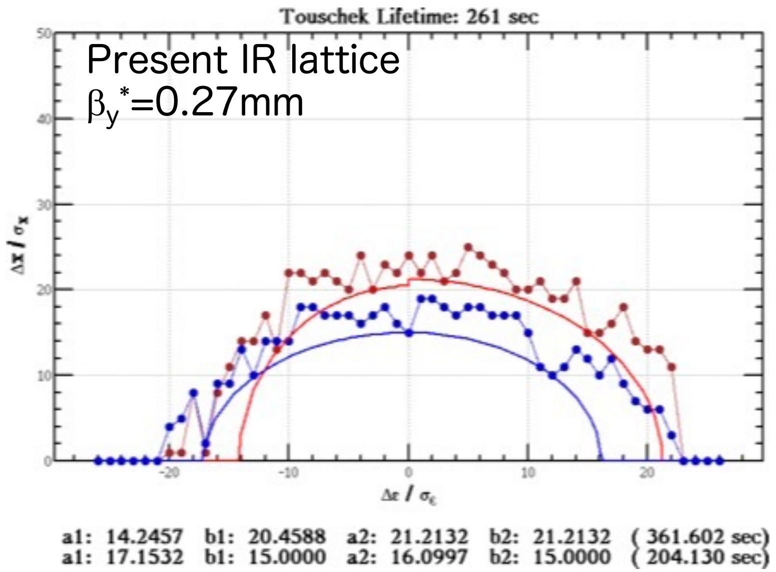
QC1Ps from L^*=935mm to 835mm
Cover QC1Ps with the magnetic yoke
Install new solenoid coils between IP and QC1Ps



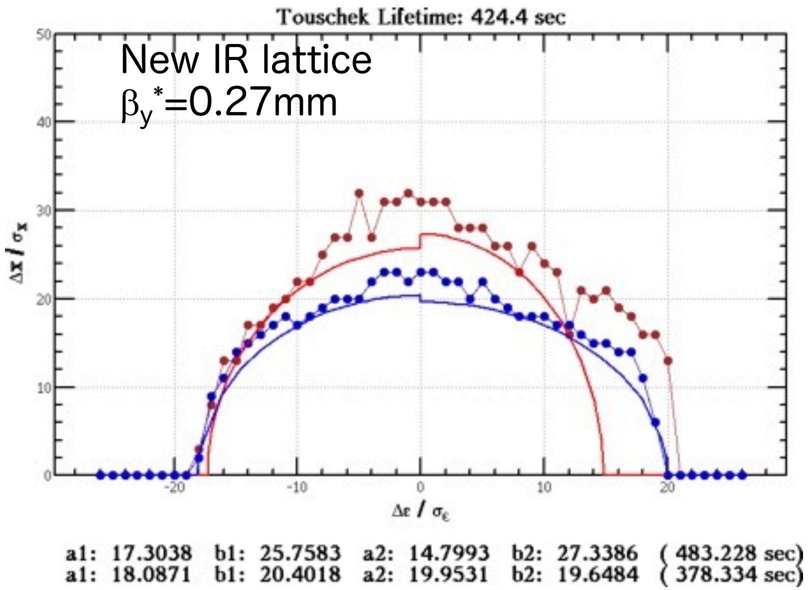
2. Progress since

- Optics evaluation using 3D magnetic field profile

1. LER DA



Touschek lifetime from ~260 s to ~420 s.

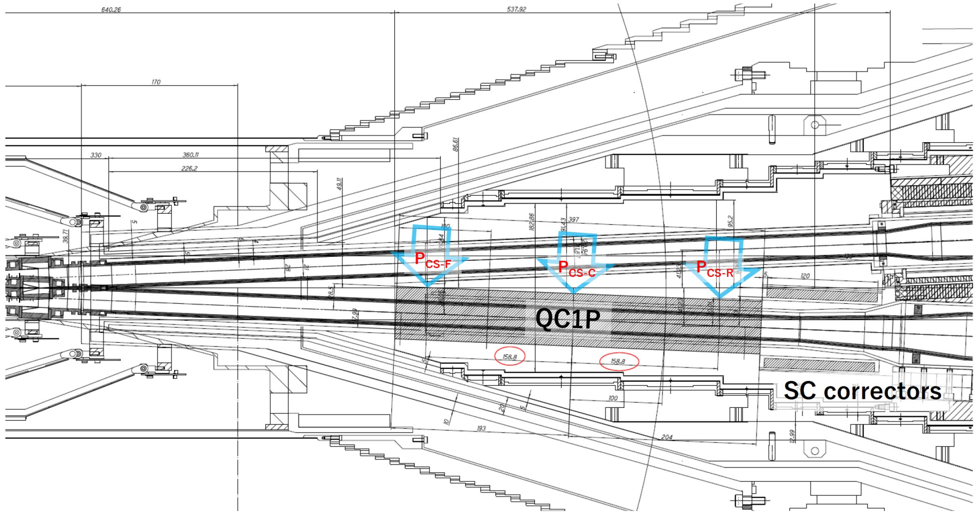


2. Chromatic coupling improves significantly,

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}	$+5.5\times10^{-3}$

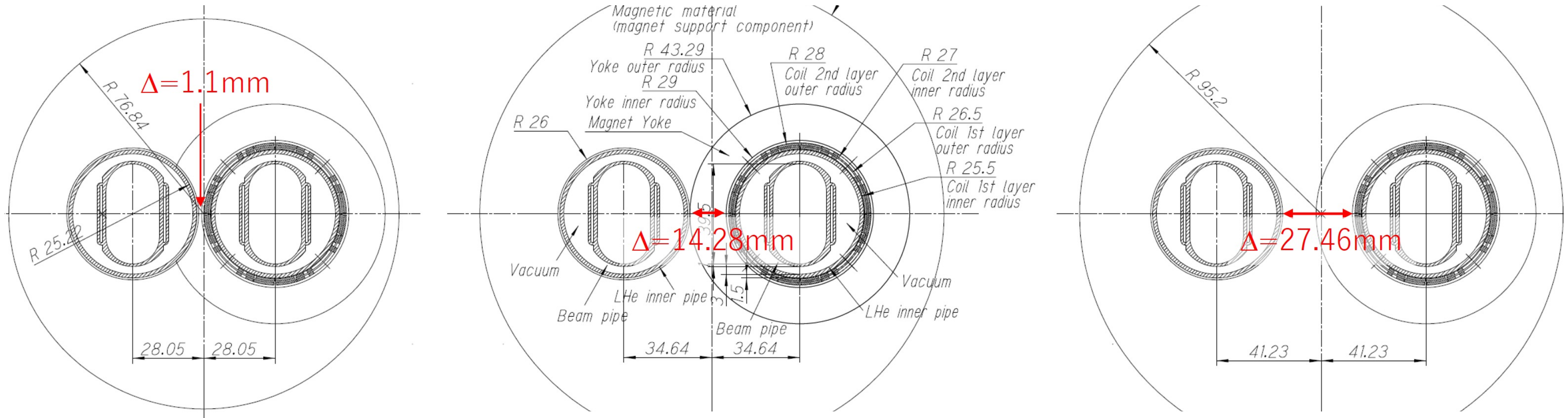
3. Emittance growth is reduced to several tens of femtometer.

3. Conceptual design of the magnet



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, when we scale the current NbTi QC1P

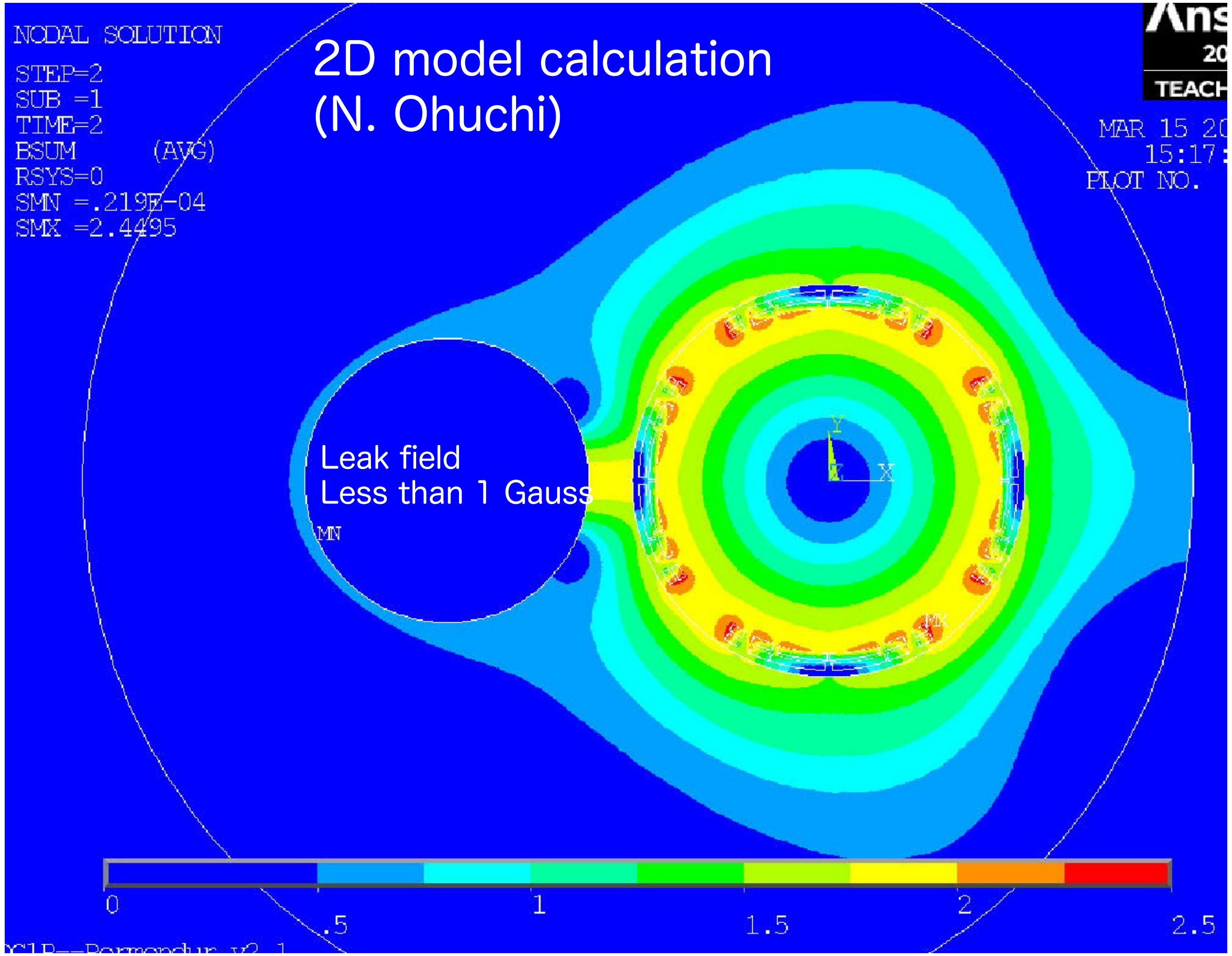


We need

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

➡ Nb_3Sn magnet

3. Conceptual design of the magnet

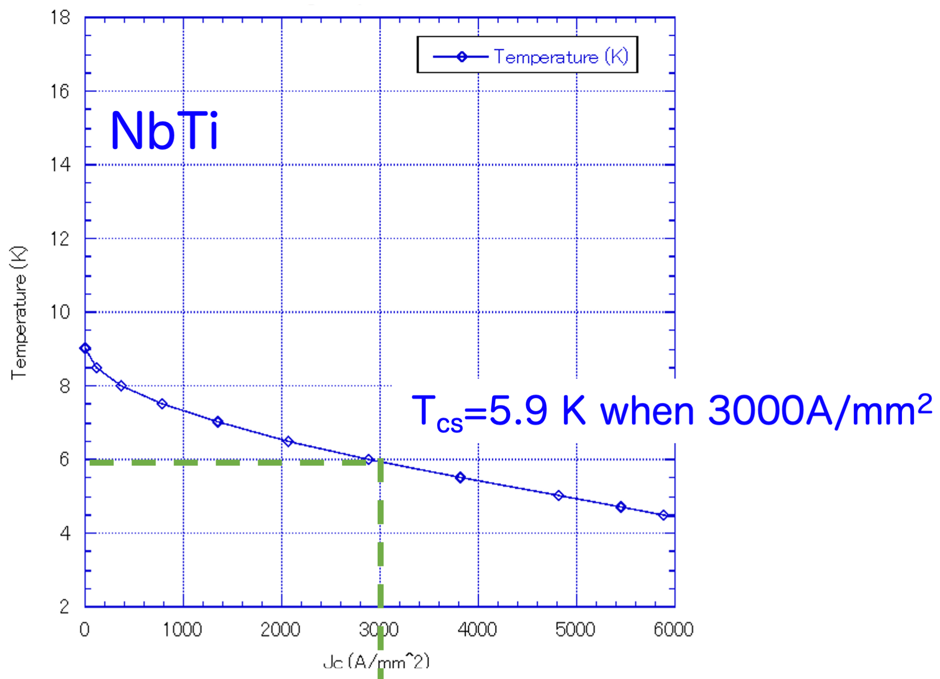


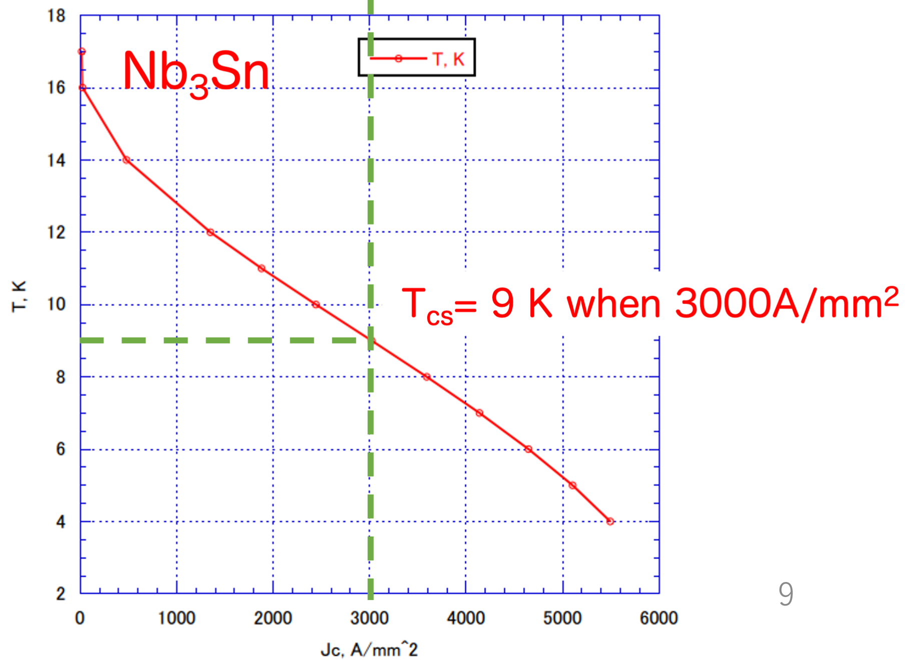
Field gradient = 80T/m

Current density in Nb_3Sn is 3112 A/mm^2

B_{max} in the coil ~ 2.5 T

Current sharing temperature @2.5T





3. Conceptual design of the magnet

Nb_3Sn accelerator magnets at CERN

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

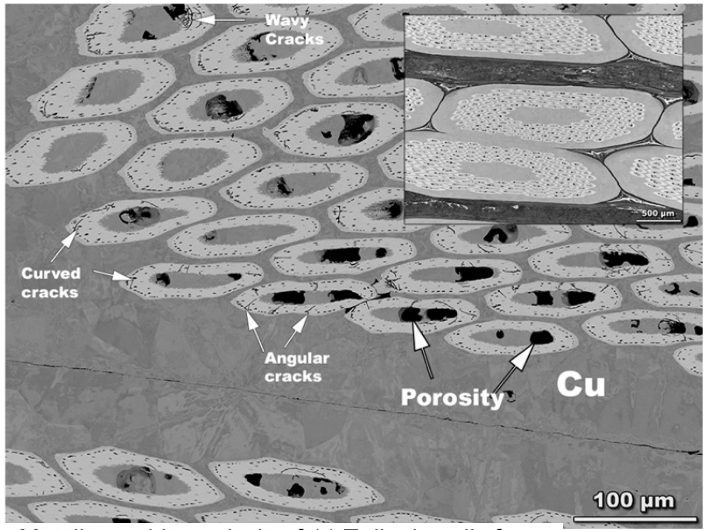
The 7.2-metre-long version of this vital HL-LHC component reached nominal current plus an operational margin corresponding to a coil peak field of 11.5 T at 1.9 K during a test in SM18

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.

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 required

3. Conceptual design of the magnet

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

Some Furukawa technologies are subject to Non-Disclosure Agreement (NDA)

3. Conceptual design of the magnet

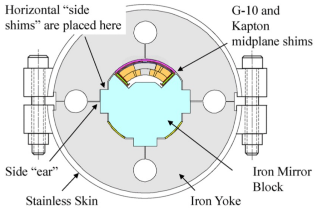
Presented by N. Ohuchi
@IR upgrade mini workshop Jan.27, 2024

1	Where	Japanese FY	JFY24	JFY25	JFY26
2		Month	April M J J A S O N D J F M	April M J J A S O N D J F M	April M J J A S O N D J F M
3		tasks/quarter	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
8	FNAL	1 Mirror and preliminary (prototype) magnet designs			
9	FNAL	2 Quench protection study/design			
10	KEK+FNAL	3 Tooling design/fabrication/procurement			
11	KEK	4 Nb3Sn cable procurement and production			
12	KEK	5 Practice winding			
13	KEK	6 First coil winding			
14	FNAL	7 First coil reaction + impregnation			
15	FNAL	8 Fabrication of the mirror magnet			
16	KEK	9 Testing of the mirror magnet (performance, analysi			
17	ALL	10 Results/Discussion/Decisions			
18	KEK	11 Winding of five prototype coils			
19	FNAL	12 Reaction + impregnantion of five prototype coils			
20	FNAL	13 Assembly of a prototype quadrupole magnet			
21	KEK	14 Testing of the prototype quadrupole magnet			
22	ALL	15 Results/Discussion/Decisions			
23	FNAL	16 Final magnet design			

- 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.

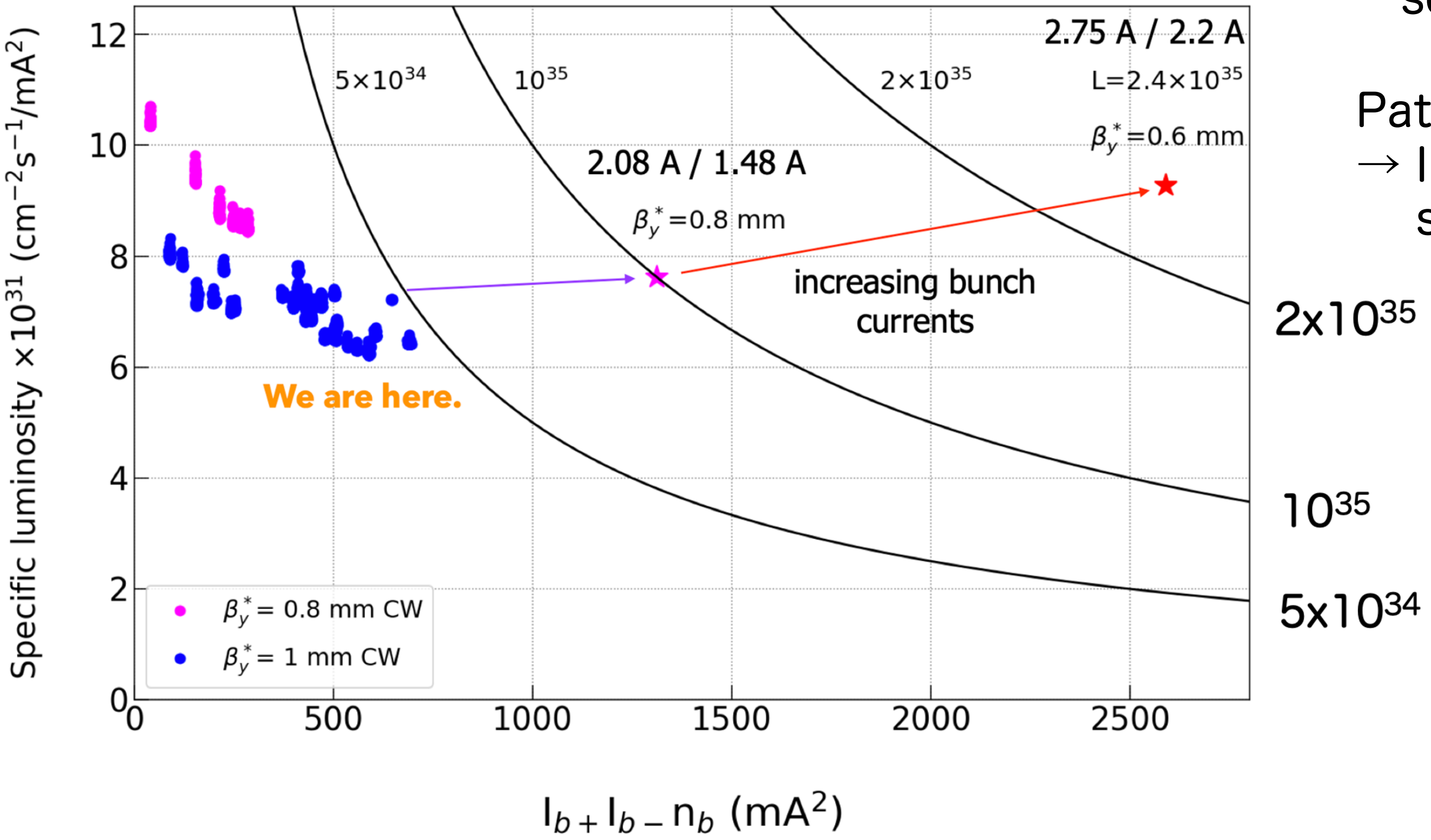


"mirror" HQM (Nb_3Sn) for LHC upgrade

4. Luminosity

$$L_{sp} = \frac{L}{I_{b+} I_{b-} n_b}$$

The first milestone after LS1 is 10^{35} cm^{-2}s^{-1}.



Path toward 10^{35}
→Increasing I_b and squeezing β_y^* to 0.8 mm

Path toward 2×10^{35}
→ Increasing I_b more and squeezing β_y^* to 0.6 mm

Specific luminosity improvement at higher I_b

4. Luminosity

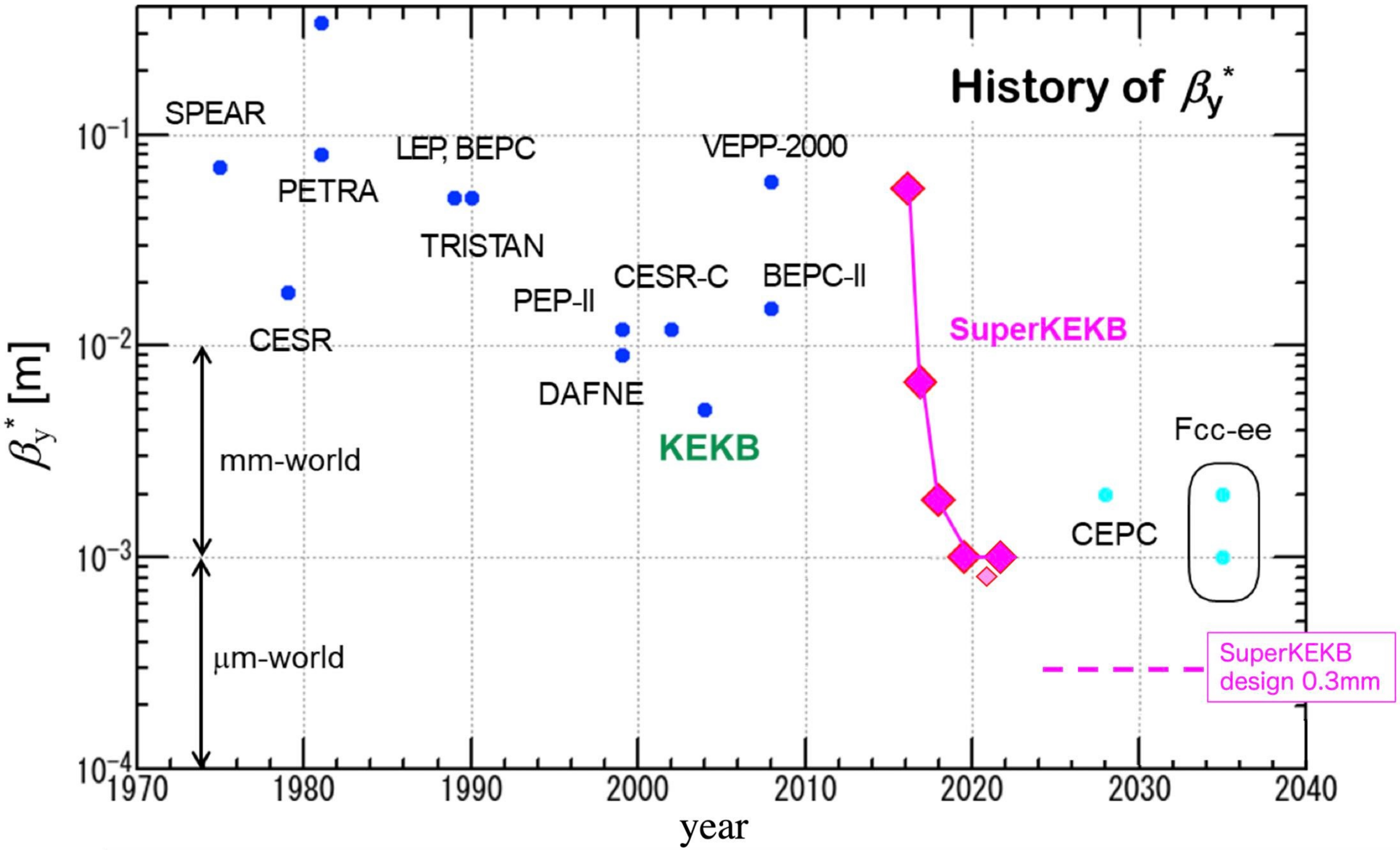
Machine Parameters

( )design

Parameter set examples by Y.Funakoshi

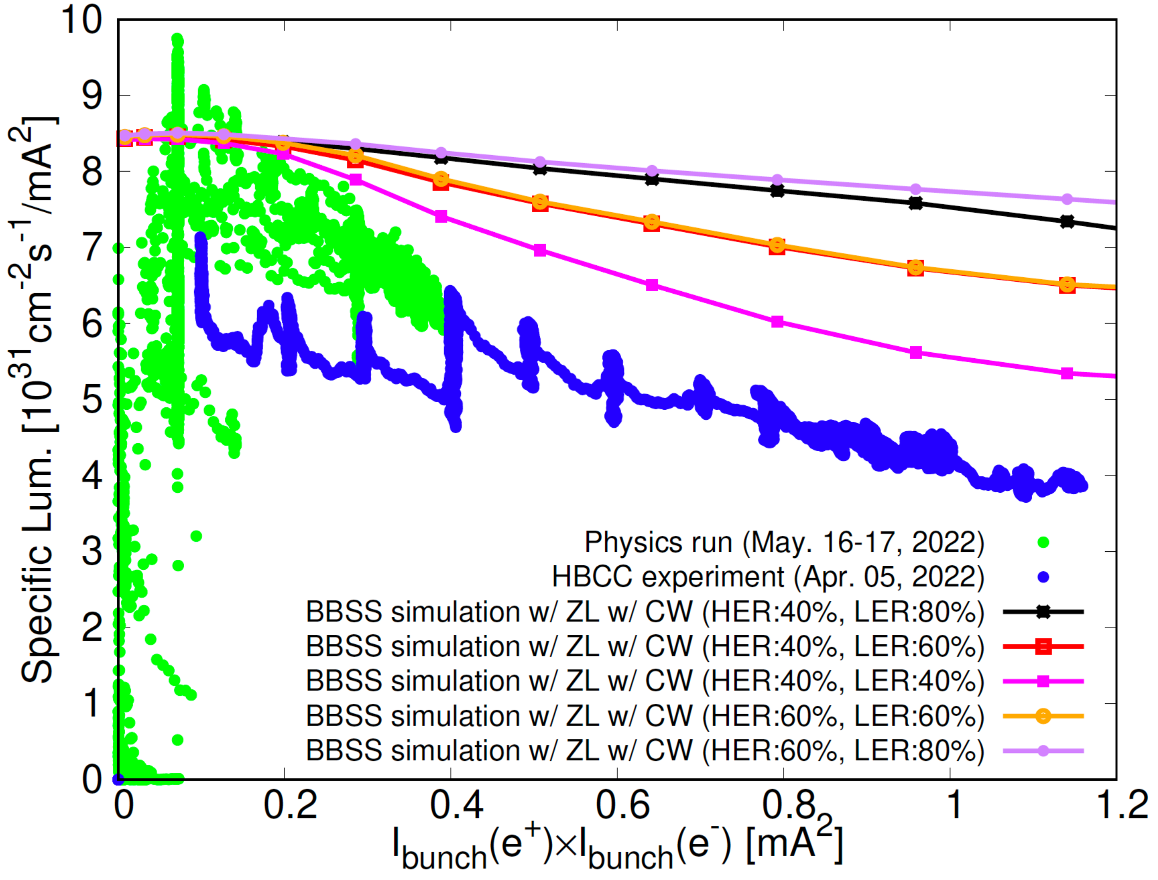
	June 8, 2022		Target at post-LS1 (1)		Target at post-LS1 (2)		Unit
Ring	LER	HER	LER	HER	LER	HER	
Emittance	4.0	4.6	4.0	4.6	4.0	4.6	nm
Beam Current	1321	1099	2080	1480	2750 (3600)	2200 (2600)	mA
Number of bunches	2249		2346		2346 (2500)		
Bunch current	0.587	0.489	0.89	0.63	1.17 (1.44)	0.94 (1.04)	mA
Horizontal size σ_x*	17.9	16.6	17.9	16.6	17.9	16.6	μm
Vertical cap sigma Σ_y*	0.303		0.217		0.178		μm
Vertical size σ_y*	0.215		0.154		0.126		μm
Betatron tunes ν_x / ν_y	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	44.525 / 46.589	45.532 / 43.573	
β_x* / β_y*	80 / 1.0	60 / 1.0	80 / 0.8	60 / 0.8	80 / 0.6	60 / 0.6	mm
σ_z	4.6	5.1	6.5	6.4	6.5	6.4	mm
Piwinski angle	10.7	12.7	10.7	12.7	10.7	12.7	
Crab waist ratio	80	40	80	80	80	80	%
Beam-Beam ξ_y	0.0407	0.0279	0.0444	0.0356	0.0604	0.0431	
Specific luminosity	7.21×10^{31}		7.62×10^{31}		9.31×10^{31}		$cm^{-2}s^{-1}/mA^2$
Luminosity	4.65×10^{34}		1×10^{35}		2.4×10^{35}		$cm^{-2}s^{-1}$

4. Luminosity



4. Luminosity

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



- 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
  - The nonlinear optics and optics distortion (machine errors, current-dependent orbit drift, etc.) around the IR might reduce the effectiveness of CW in suppressing BB resonances.
- Better working point in the tune space?
- Increasing the HER crab waist strength might help.

We will check them during the 2024ab run

4. Luminosity

- Injection is another very important factor for luminosity performance.
- →LINAC talk by H. Ego.

- New HER BT line (presented at BPAC2023)

- Installation of additional high-power klystrons for storing higher beam current.

- Renewal and maintenance of aging components.

- If new breakthrough found during the 2024 run, then will be considered.

5. Summary

The new IR optics idea was evaluated using the 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 needed.
  - We have started collaboration with FNAL and Furukawa Electric Co., Ltd. .

Luminosity strategy

- Operate the machine at higher I_b, smaller β_y^*
- Improve the specific luminosity at higher I_b
- Aim at peak luminosity $1{\times}10^{35}\ cm^{-2}s^{-1}$ and beyond.

- Efforts will be made to establish a reliable model through extensive machine studies during 2024 run to understand the discrepancies between the simulation and the machine.
  - The path to higher luminosity will become clearer.