Impedance modeling and single-bunch collective instability simulation in the SuperKEKB main ring

The 2023 international workshop on the Circular Electron Positron Collider (CEPC)

2023-07-04

T. Ishibashi

Acknowledgements:

M. Migliorati, D. Zhou, S. Terui, K. Ohmi, K. Shibata, T. Abe, M. Tobiyama, Y. Suetsugu, T. Nakamura, A. Blednykh, I. Zagorodnov, W. Bruns

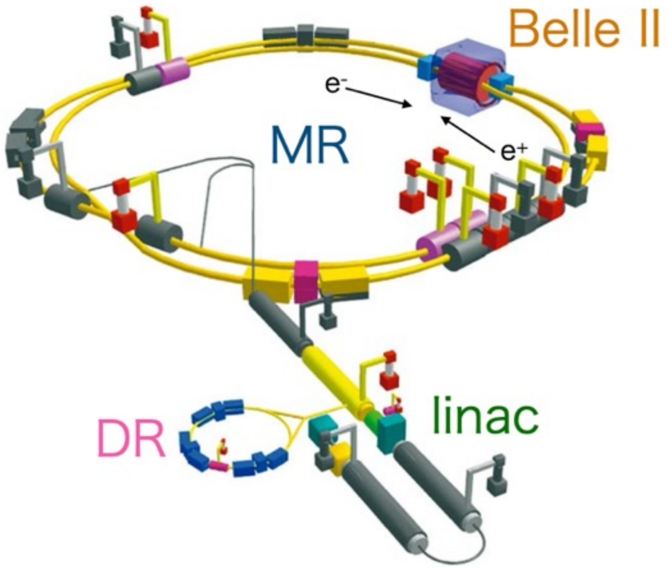
Introduction - SuperKEKB

Main facilities of SuperKEKB

- Linac
  - Length: ~700 m
  - Provide electron or positron beams to 4-ring
    - SuperKEKB HER, LER
    - PF (Photon Factory): 2.5 GeV
    - PF-AR (Photon Factory Advanced Ring): 6.5/5 GeV
- DR (Damping Ring, positron)
  - Circumferential length: ~136 m
  - Energy: 1.1 GeV, 71 mA (design)
- MR (Main Ring)
  - Circumferential length: ~3016 m
  - HER (High Energy Ring, electron): 7 GeV, 2.6 A, σ_z=5 mm (design)
  - LER (Low Energy Ring, positron): 4 GeV, 3.6 A , σ_z=6 mm (design)
- Belle II (particle detector complex)
- The achieved peak luminosity is ~4.7×10^{34} cm^{-2} s^{-1} with 1.4 A in LER and 1.1 A in HER when the stored bunch number is 2249 during 2022 spring run, and this is the world record.

Aerial photo of KEK Tsukuba Campus

Schematic drawing of SuperKEKB

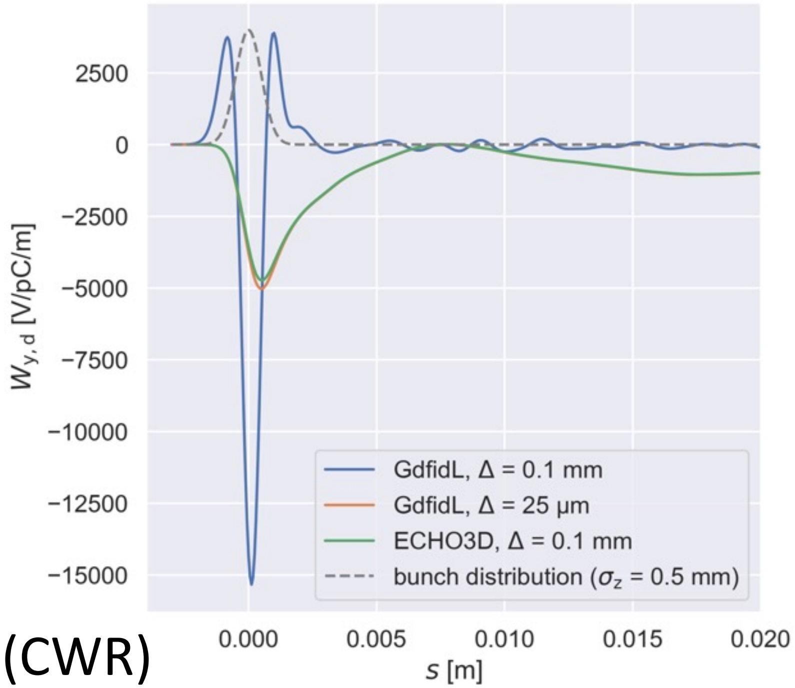


Introduction

- Impedance modeling for the SuperKEKB main ring (MR) was already performed during the construction phase [D. Zhou *et al.*, in Proc. of IPAC2014, TUPRI021].
- In the LER, beam size blow-ups were observed in the vertical direction at approximately 1 mA/bunch for a single beam operation (no collision).
- A TMCI working group was formed as part of International Task Force to study this instability and explore countermeasures.
  - contact person: Mauro Migliorati, sub-contact person: Takuya Ishibashi.
  - Indico
    - ITF: https://kds.kek.jp/category/2322/
    - TMCI group: https://kds.kek.jp/category/2247/
- We've called this instability "-1 mode instability" in this group, because a -1 mode (ν_y-ν_s) signal has been observed in the tune spectrum when the instability occurs.
  - This instability could be caused by an interplay between the vertical impedance and the bunch-by-bunch feedback system [K. Ohmi *et al.*, in Proc. of eeFACT2022, WEXAT0102].
- In the activities of this group, we have built the impedance model in LER and HER. Here, we'll present the models and some results from PyHEADTAIL simulations.

Simulation Codes

Vertical dipolar wake potential in a vertical collimator with a half aperture of 1 mm obtained with GdfidL or ECHO3D.



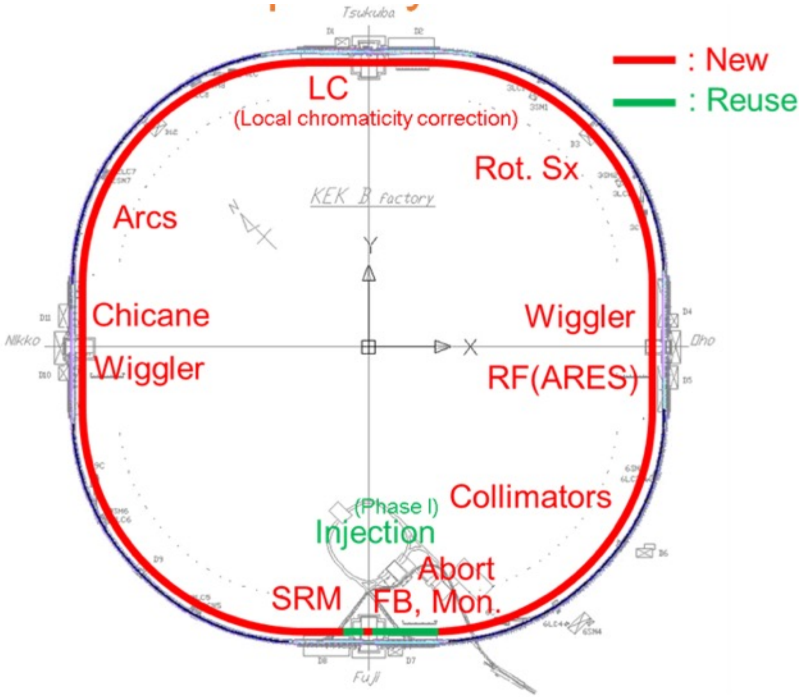
- Resistive wall impedance
  - ImpedanceWake2D [N.Mounet, https://gitlab.cern.ch/IRIS/IW2D]
  - GdfidL [W. Bruns, http://www.gdfidl.de]
- Geometrical impedance
  - GdfidL
  - ECHO3D [I. Zagorodnov, https://echo4d.de]
  - CST Studio Suite (wake field solver)
- Coherent Synchrotron Radiation (CSR) and Coherent Wiggler Radiation (CWR)
  - CSRZ [D. Zhou *et al*., Jpn. J. Appl. Phys. 51 (2012) 016401]

- In ECHO3D, the results converge even with a coarse mesh (saving computational resources).
- CST and GdfidL can simultaneously calculate the geometric and resistive wall (including coatings) impedance.

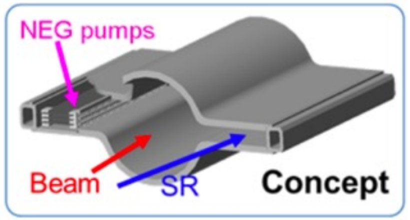
- 3D Modeling
  - Autodesk Inventor (+ Macro in CST to export the geometry and material property for GdfidL)
  - Macro in GdfidL (written during the construction phase of SuperKEKB)

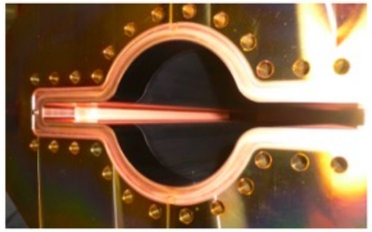
LER

- In LER, ~93% of the beam pipes and bellows chambers in length, and pumps were upgraded from KEKB to SuperKEKB.
- Various newly developed components have been introduced in order to reduce the impedance and mitigate the electron cloud effect and so on.
    - TiN-coated beam-pipe with antechambers, step-less flange (MO-flange), comb-type RF-shield, clearing electrode, grooved beam pipe, new movable collimator and so on.

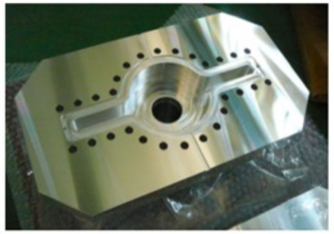


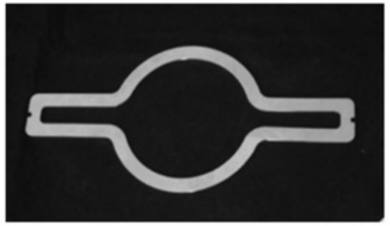
TiN coated beam-pipe with antechambers



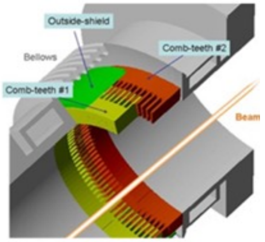


MO flange

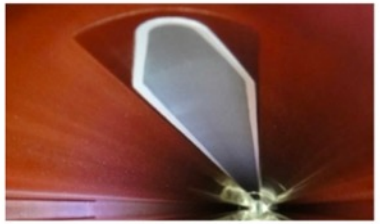




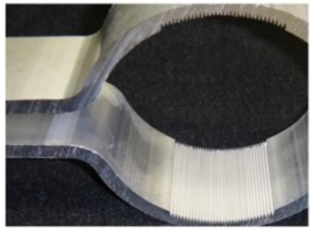
Comb-type RF-shield



Clearing electrode



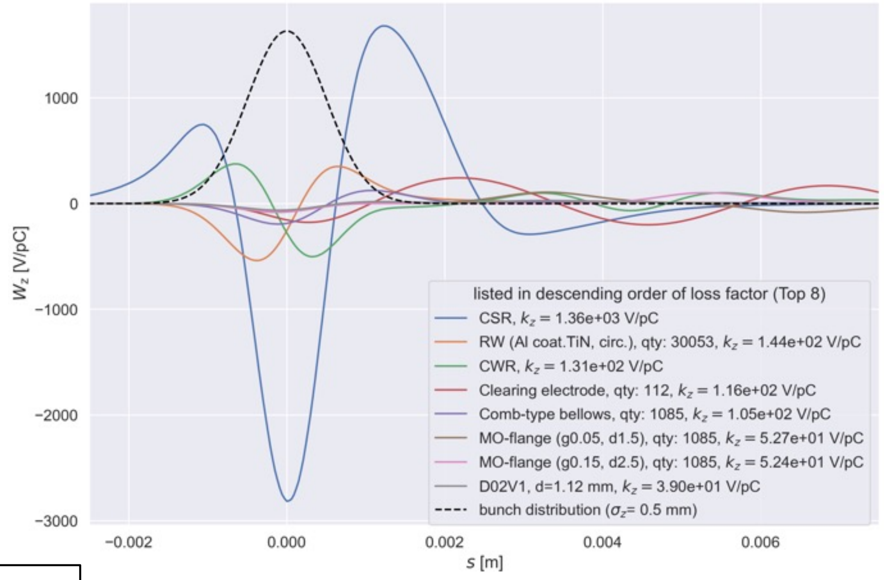
Grooved beam-pipe

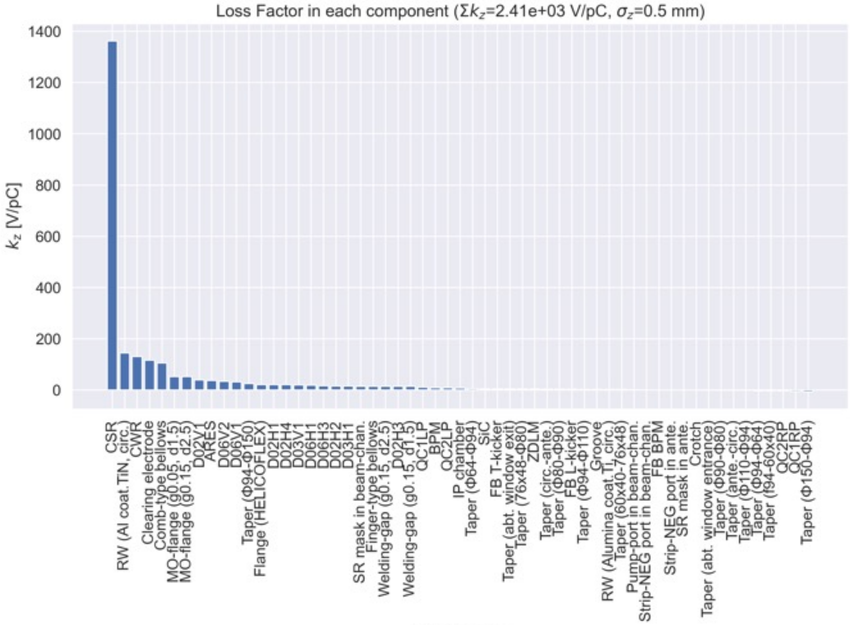


LER - longitudinal

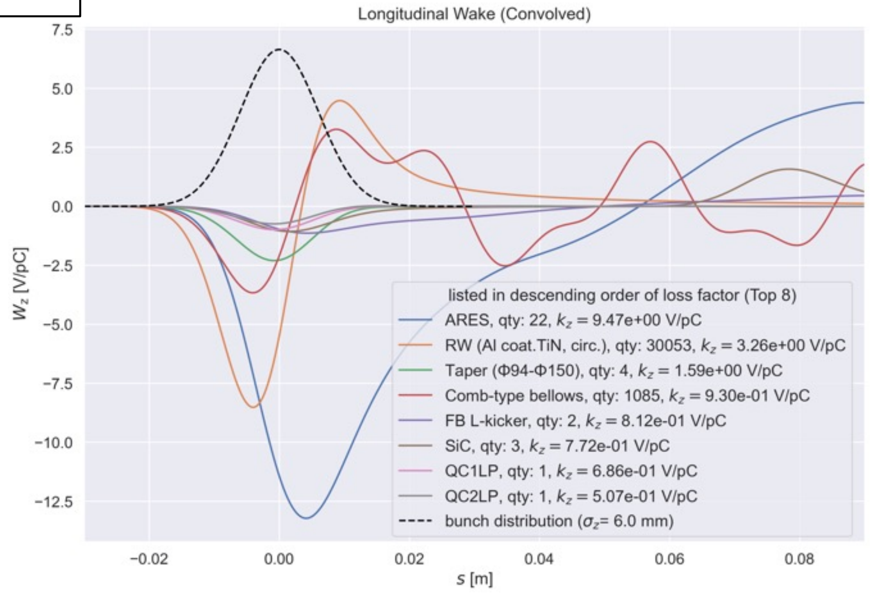
$$W(s,\sigma_z) = \int_0^\infty ds' W(s',\sigma_{z0})\lambda(s-s')$$

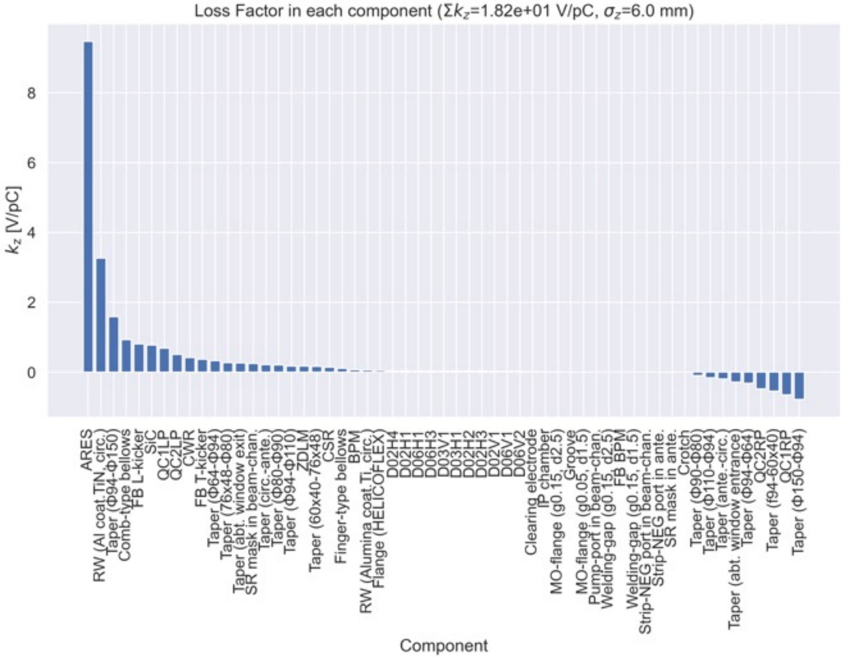
σ_{z0}=0.5 mm



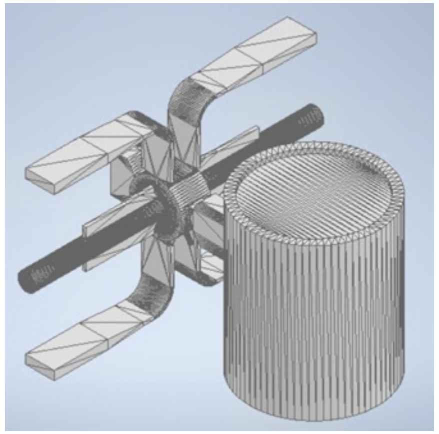


σ_z=6.0 mm

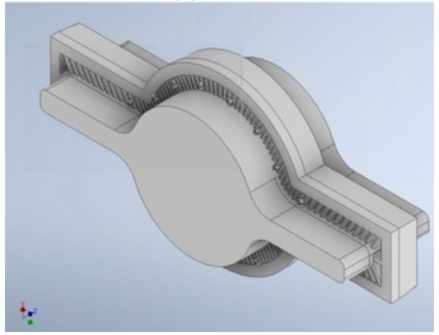




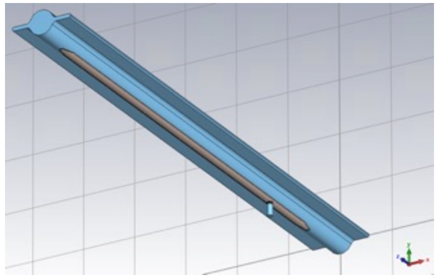
RF-cavity (ARES)



Comb-type RF-shield

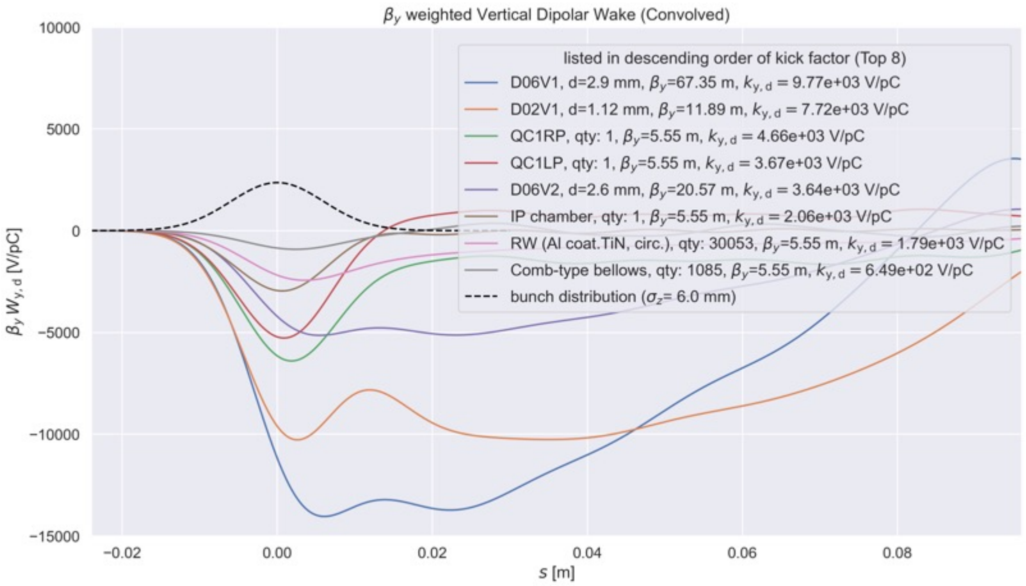


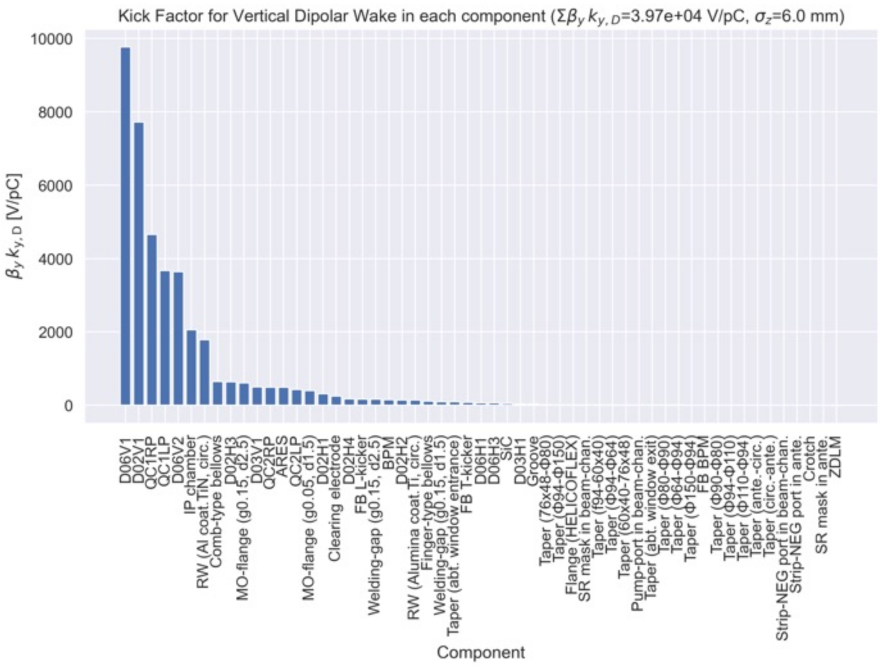
Clearing electrode



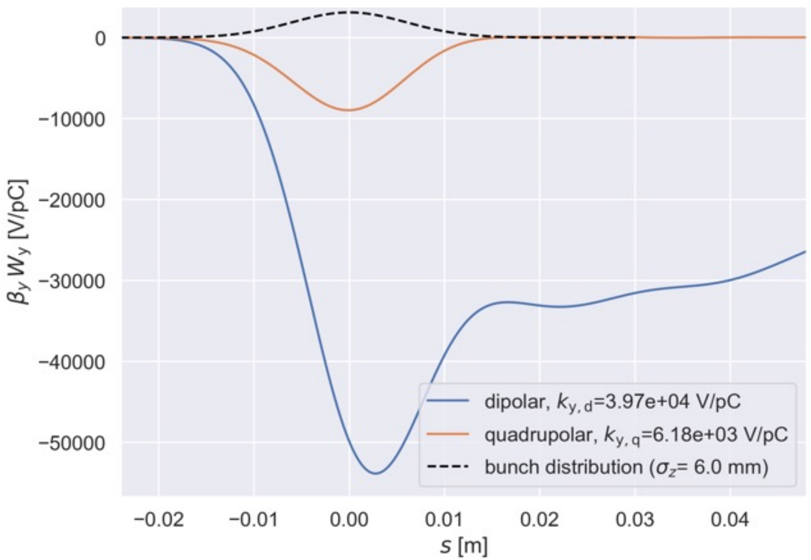
LER – vertical

σ_z=6.0 mm

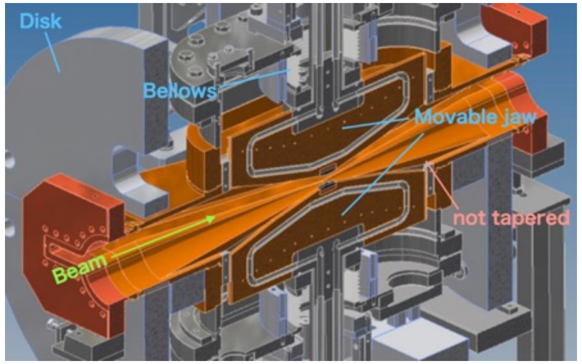




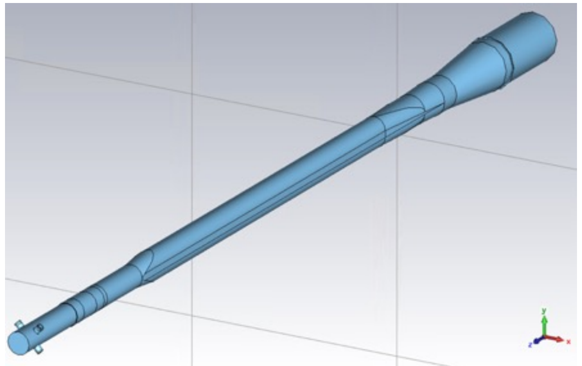
Total dipolar and quadrupolar wake potential



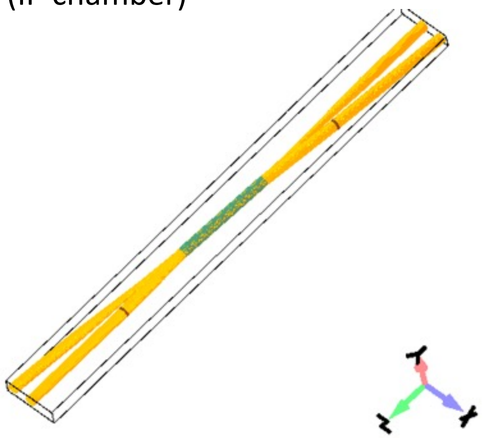
Vertical collimator



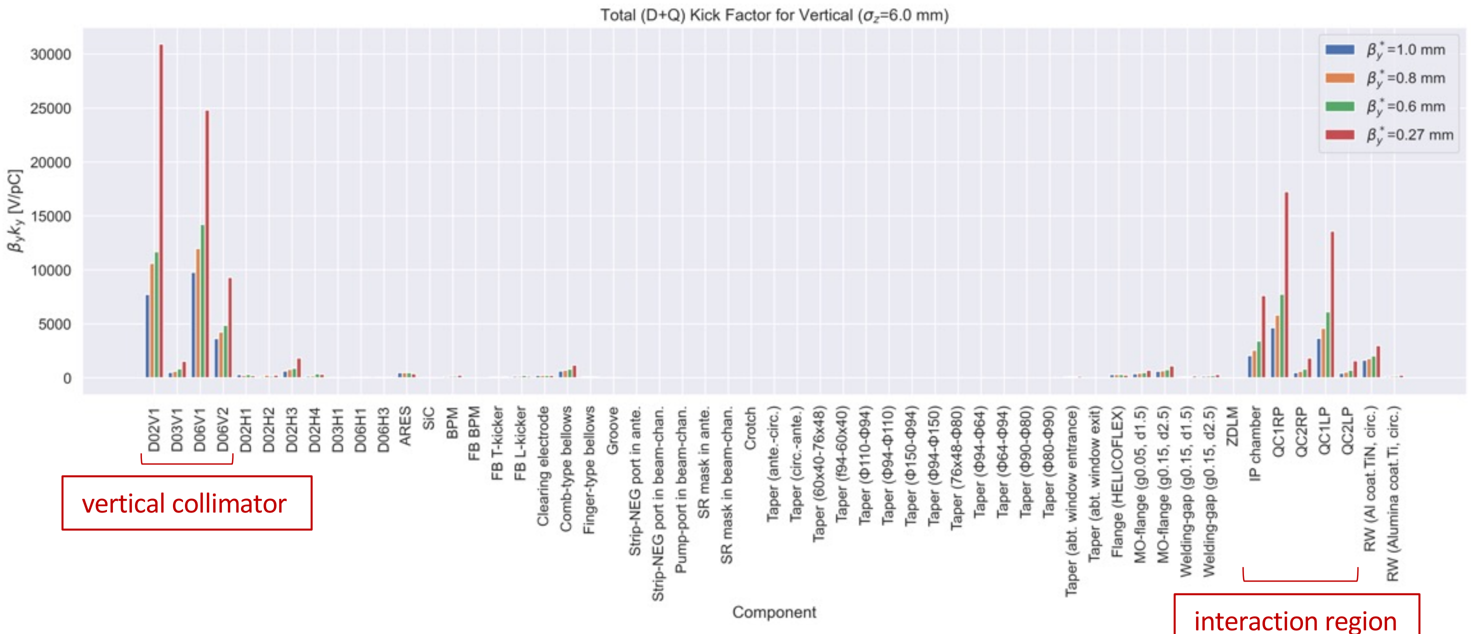
Tapered beam-pipe with BPM in final focusing magnet (QC1)



Beam-pipe around interaction point (IP chamber)

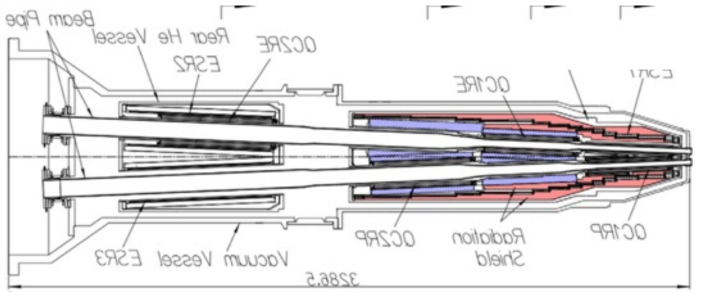


LER - vertical Kick-factor (β_y^* dependence)

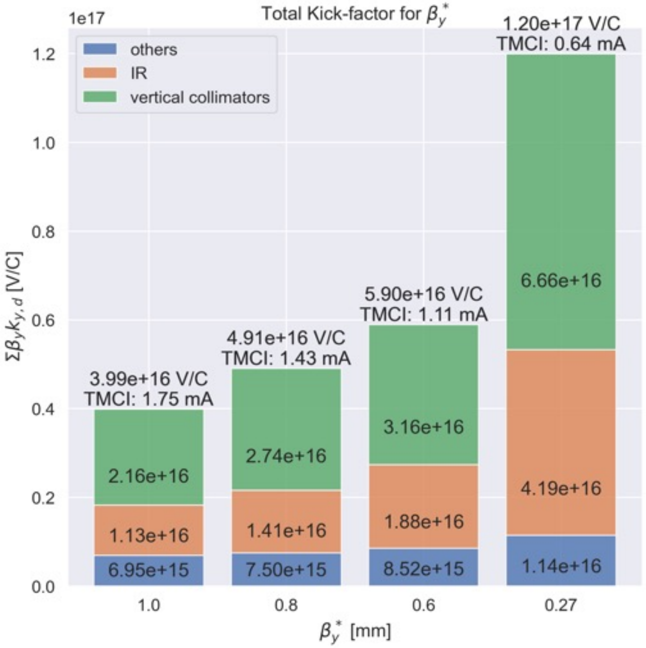


- The collimator setting is based on that in the 2021c physics run with β_y^* = 1.0 mm.
    - β_y^*: vertical beta function at the interaction point,
    - QCS: final focusing superconducting magnets
- The main vertical impedance sources are the vertical collimators.
- The reason why the kick factor in IR increases with squeezing β_y^* is that β_y gets bigger and bigger with the squeezing.

Schematic drawing of QCSR cryostat



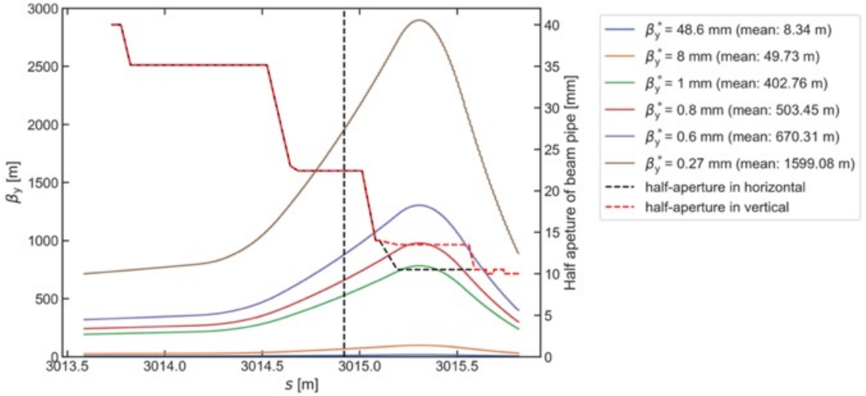
[N. Ohuchi *et al*., Nucl. Instrum. Methods Phys. Res.A, 1021, 165930 (2022)]



- The instability threshold is below the design value (1.44 mA) even in the β_y^* = 0.8 mm optics.

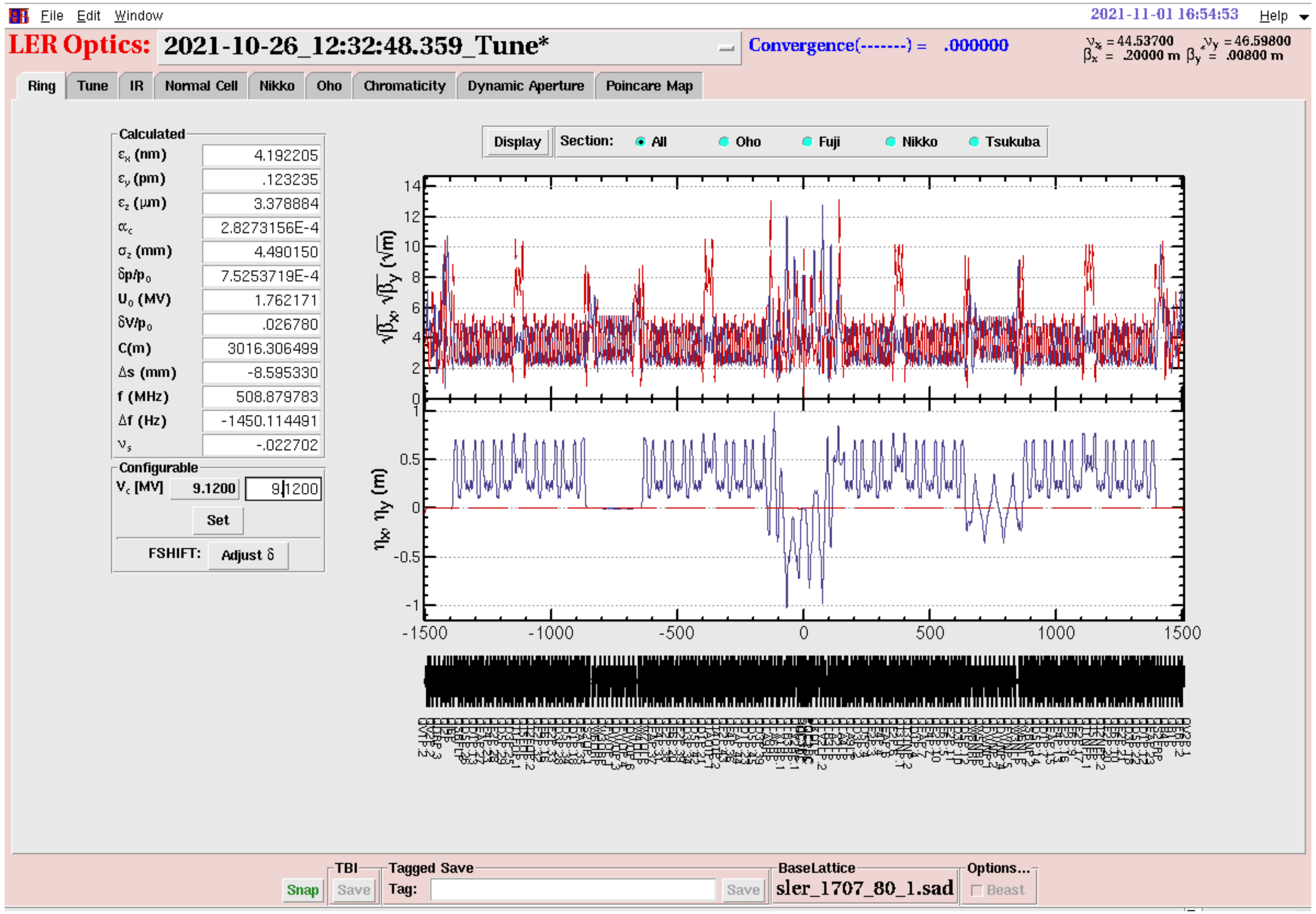
Total β_y weighted vertical dipolar kick factor for each β_y^* with σ_z = 6 mm and the bunch current threshold of TMCI simulated with PyHEADTAIL (transverse damper is not activated).

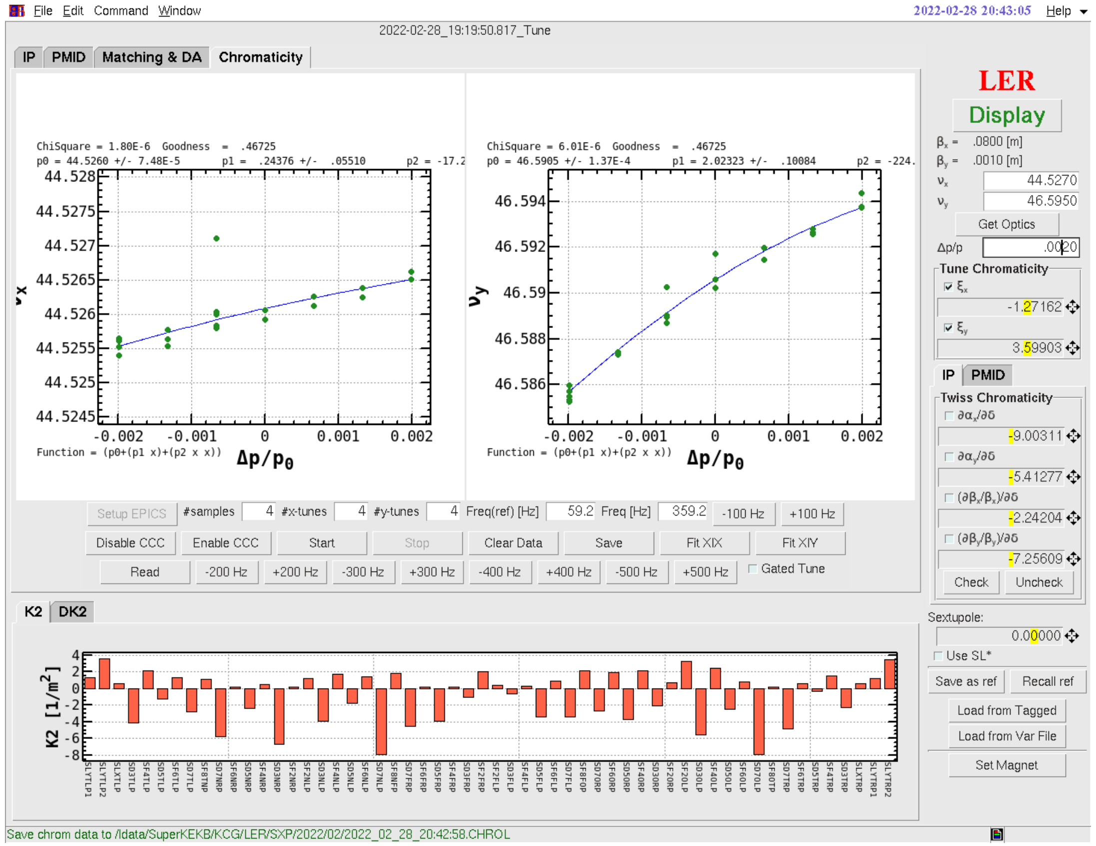
Half aperture of a QCSR beam-pipe and vertical beta-function with each vertical beta-function at the interaction point as a function of the longitudinal location.



LER - PyHEADTAIL simulation

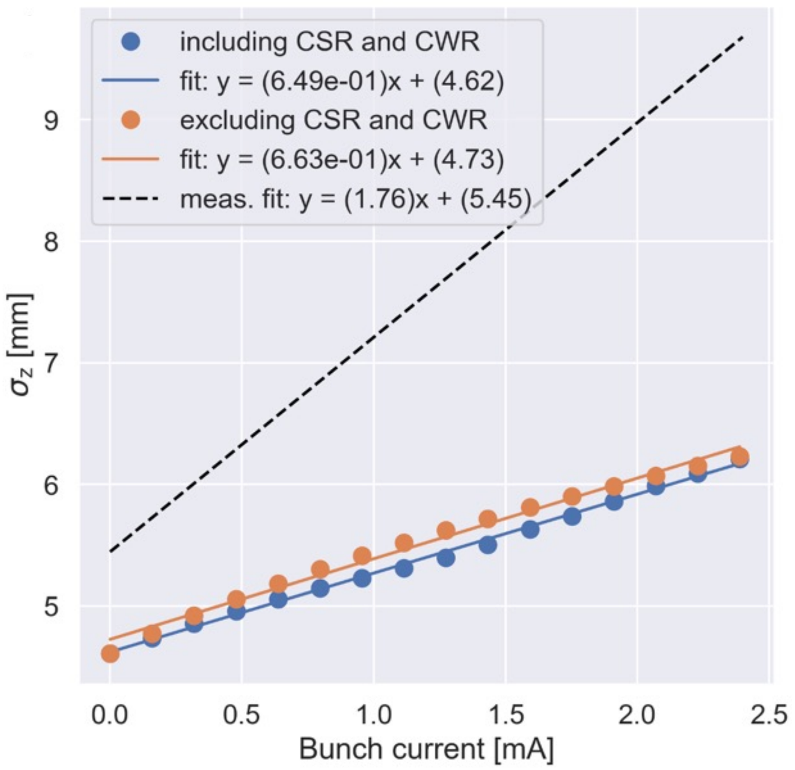
- The parameters that used are based on those of a machine study dated Oct.26th, 2021.
- The chromaticity measured on Feb. 28, 2022 is used.

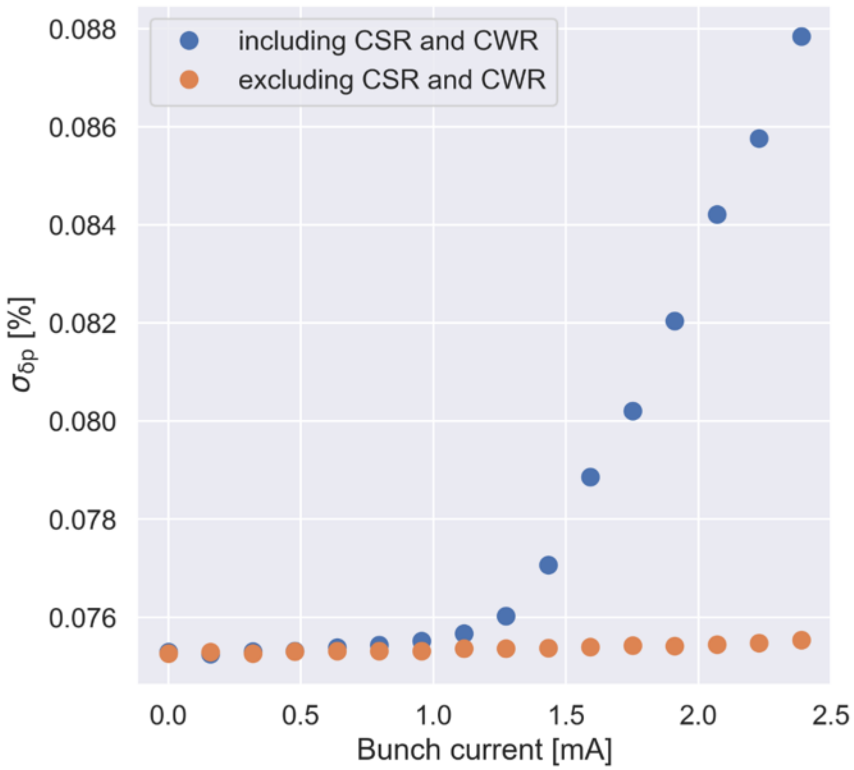




LER - longitudinal with/without CSR and CWR

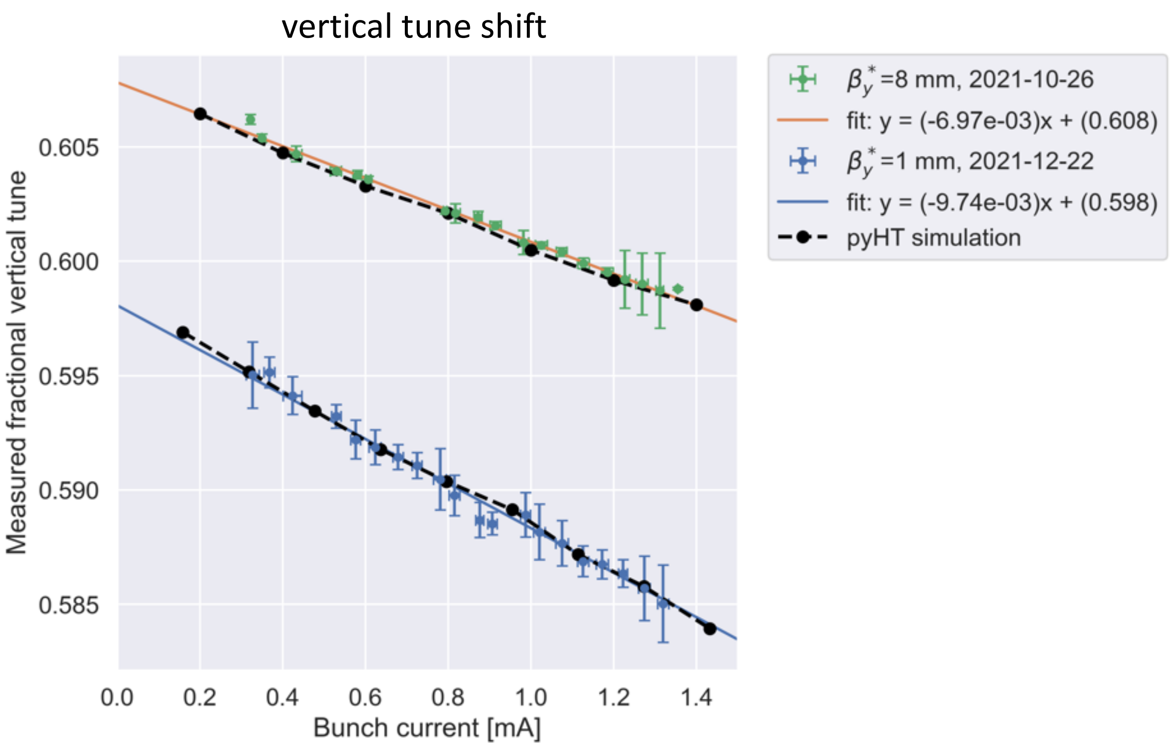
- The difference between w/wo CSR and CWR is only large for the energy spread.
  - Microwave instability (MWI) threshold:
    - ~1.3 mA with CSR and CWR
    - > 2.5 mA without CSR and CWR
- The simulated bunch length using the impedance model is shorter than the measured values.

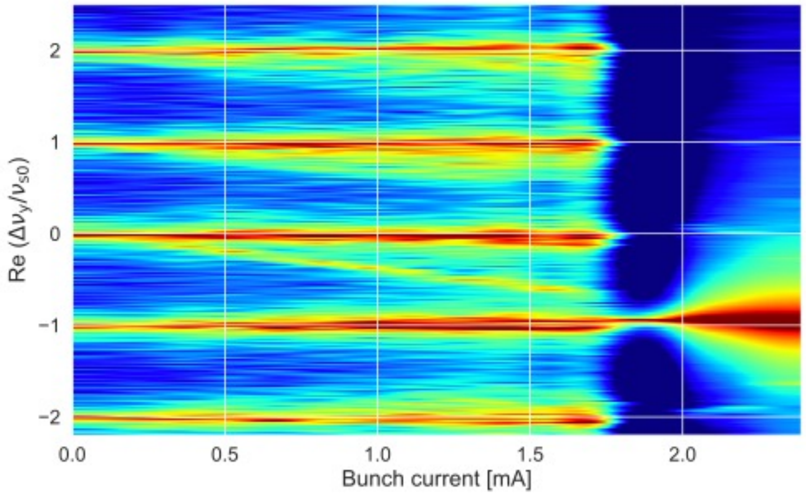




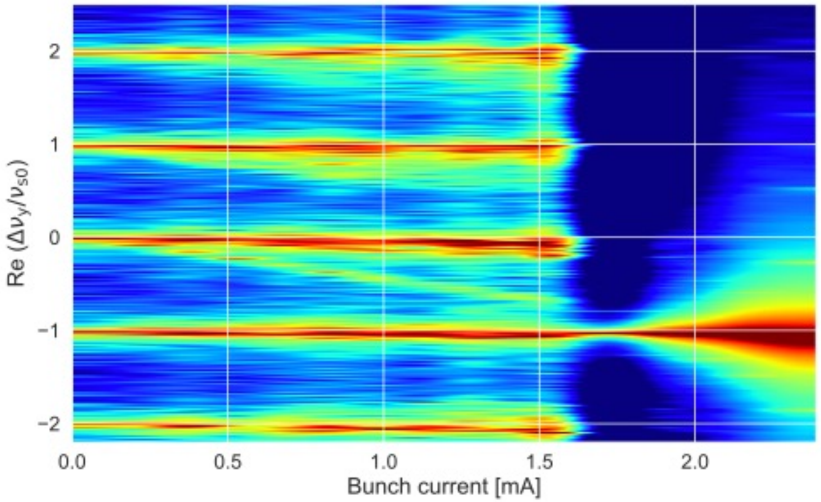
LER – vertical direction

- Vertical tune shifts in PyHT simulations using the impedance model are almost consistent with those in the measurements.
- Instability threshold:
    - ~1.91 mA/bunch with only dipolar wake
    - ~1.75 mA/bunch with dipolar and quadrupolar wake





dipolar wake
(incl. long. wake)



dipolar + quadrupolar wake
(incl. long. wake)

LER – vertical direction (transverse damper)

- A tune shift caused by the kick of the damper (bunch-by-bunch feedback system) is written by

$$\Delta\nu_{\mathrm{FB}} = \frac{e^{i\varphi}}{2\pi d}$$

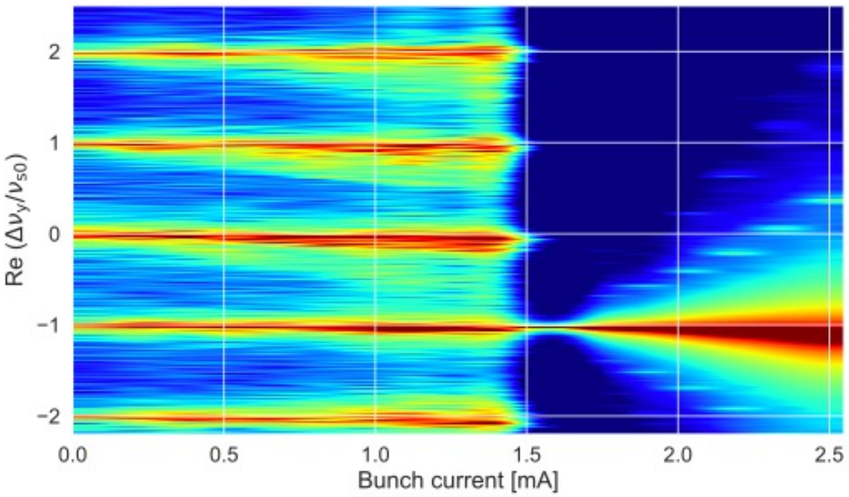
i: imaginary unit
φ: betatron phase advance between the pick-up and the kicker
d: damping time in turns

- $\varphi = 90°$ and $0°$ are called (pure) resistive and reactive damper, respectively.
  - The resistive one dampens the center-of-charge motion of the bunch.
  - The reactive one shifts the 0 mode up.
- The instability threshold:
  - ~1.75 mA/bunch with dipolar and quadrupolar wake
  - ~1.59 mA/bunch with dipolar and quadrupolar wake, and the damper (d =100, $\varphi = 90°$) is activated.

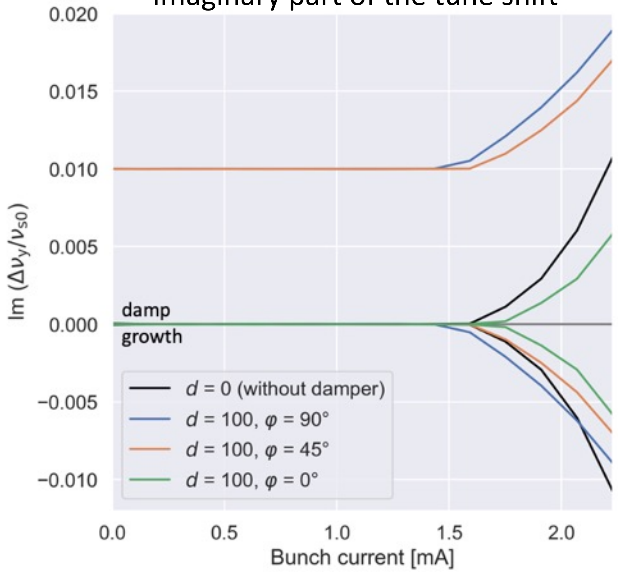
d =100 turns corresponds to ~1 ms

- The pure resistive damper lowers the instability threshold, and this could be caused by imaginary tune split and repulsion (ITSR) [E. Métral, Phys. Rev. Accel. Beams 24 (2021) 041003].

dipolar+quadrupolar (incl. long.) wake with the damper (d =100,$\varphi = 90°$)

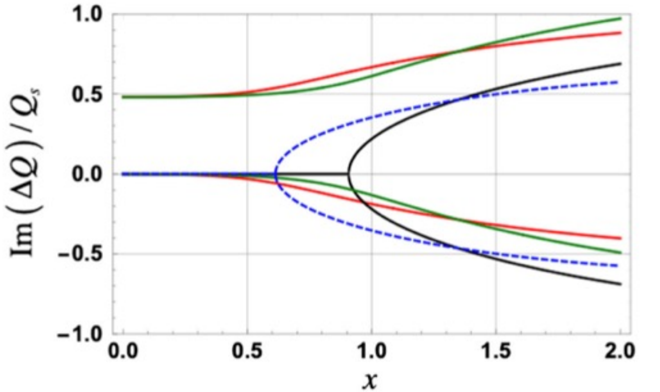


Imaginary part of the tune shift



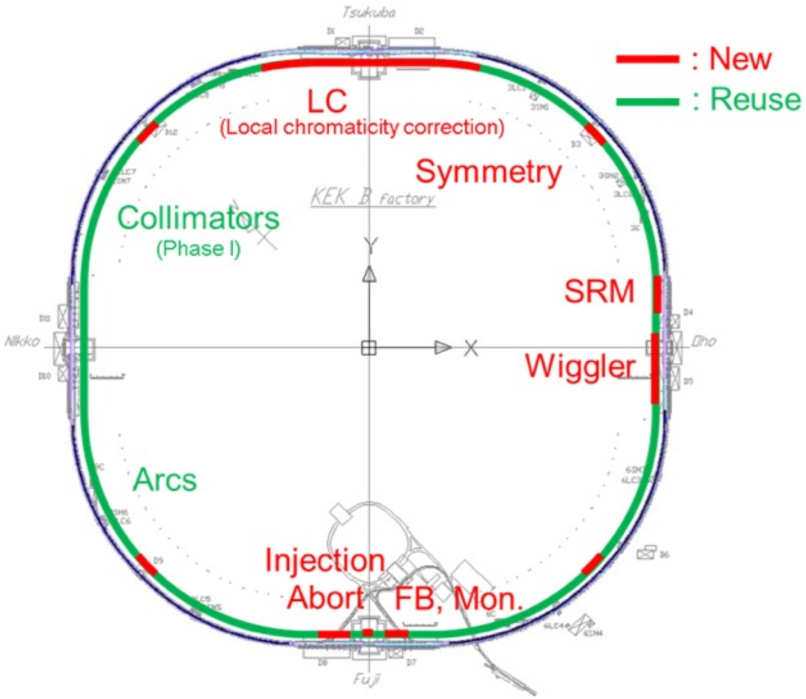
[E. Métral, PRAB 24 (2021) 041003]

FIG. 7. Solutions of the diagonalization of the 2 by 2 matrix of Eq. (2) vs x a normalized parameter proportional to the bunch intensity [4]: without TD (dotted blue line); with a resistive TD for which $\Delta Q_{TD}/Q_s = 0.48j$ (red line); with a reactive TD for which $\Delta Q_{TD}/Q_s = 0.48$ (black line); and with both a resistive and reactive TD for which $\Delta Q_{TD}/Q_s = 0.48(1+j)$ (green line). The first two pictures describe the real and imaginary parts of the complex tune shift whereas the third one is a zoom of the imaginary part in the unstable region.

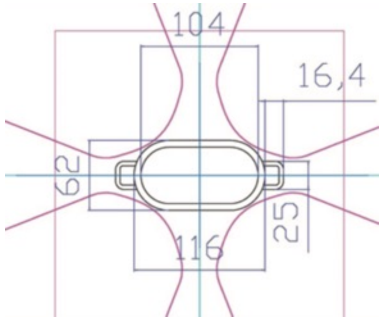


HER

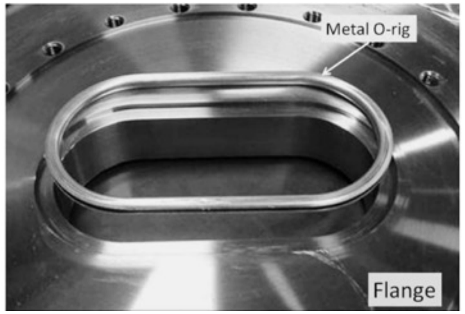
- In HER, ~82% of beam pipes and bellows chambers in length, and pumps have been reused.
  - Finger-type RF-shield, conventional flange with metal O-ring and so on.

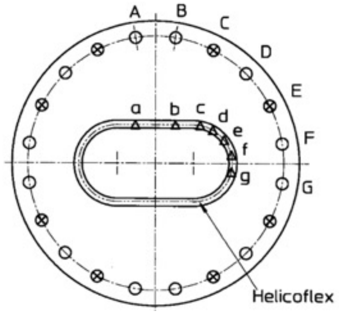


Race-track shaped beam-pipe

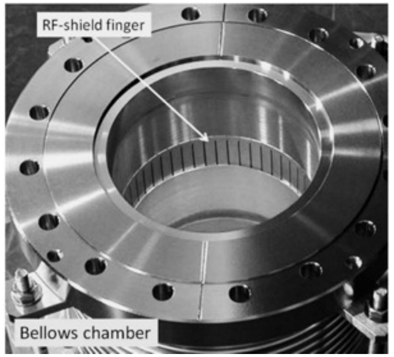


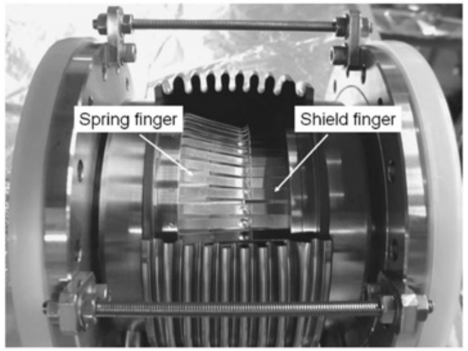
Flange with metal O-ring (HELICOFLEX)



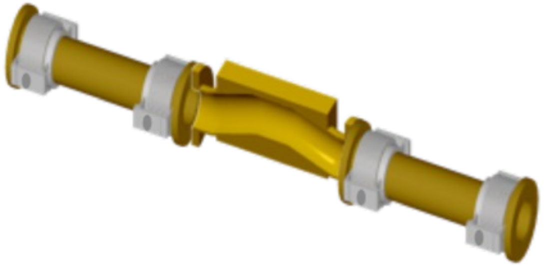


Finger type RF-shield



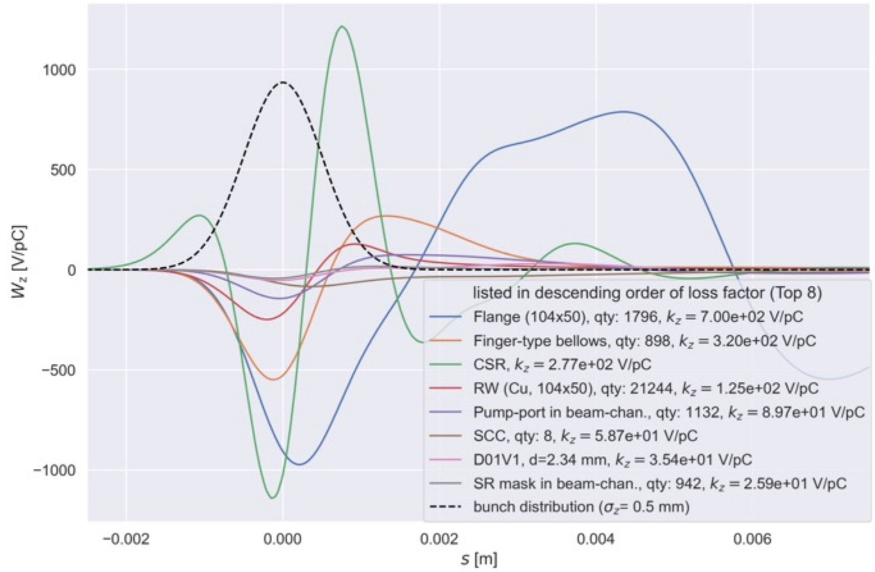


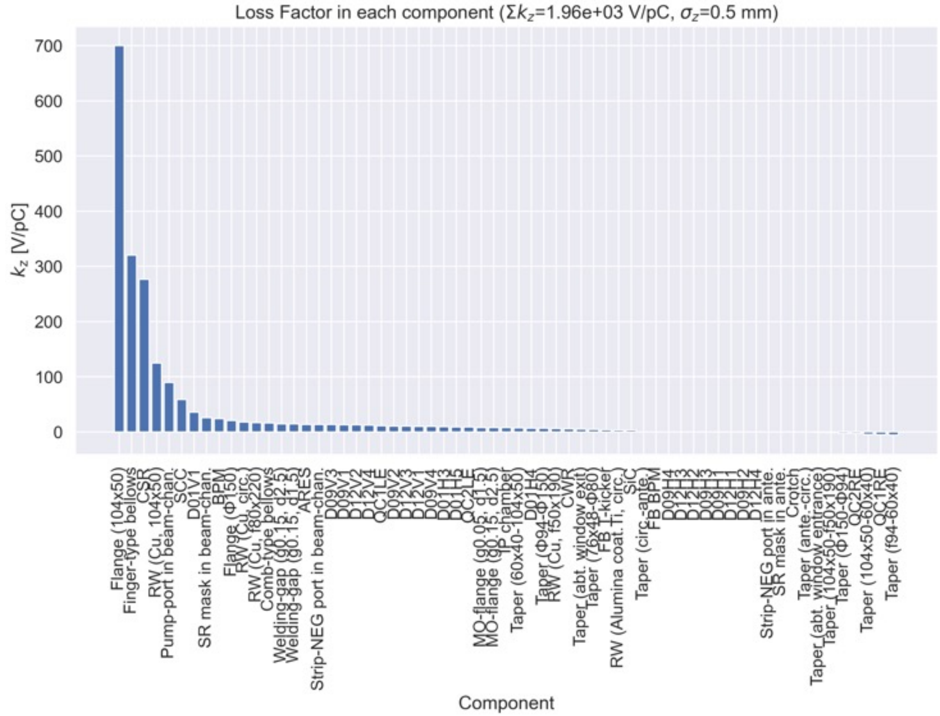
KEKB type collimator in the arc-sections



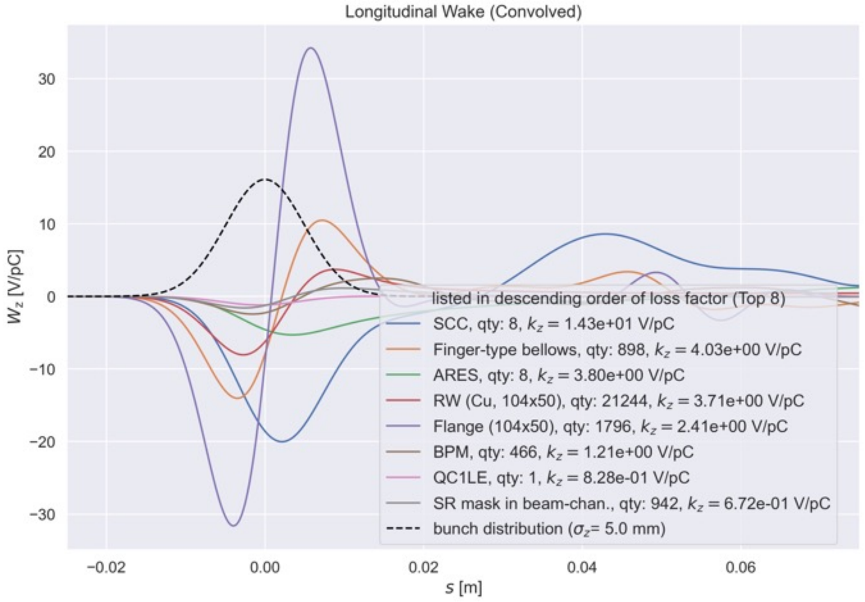
HER - longitudinal

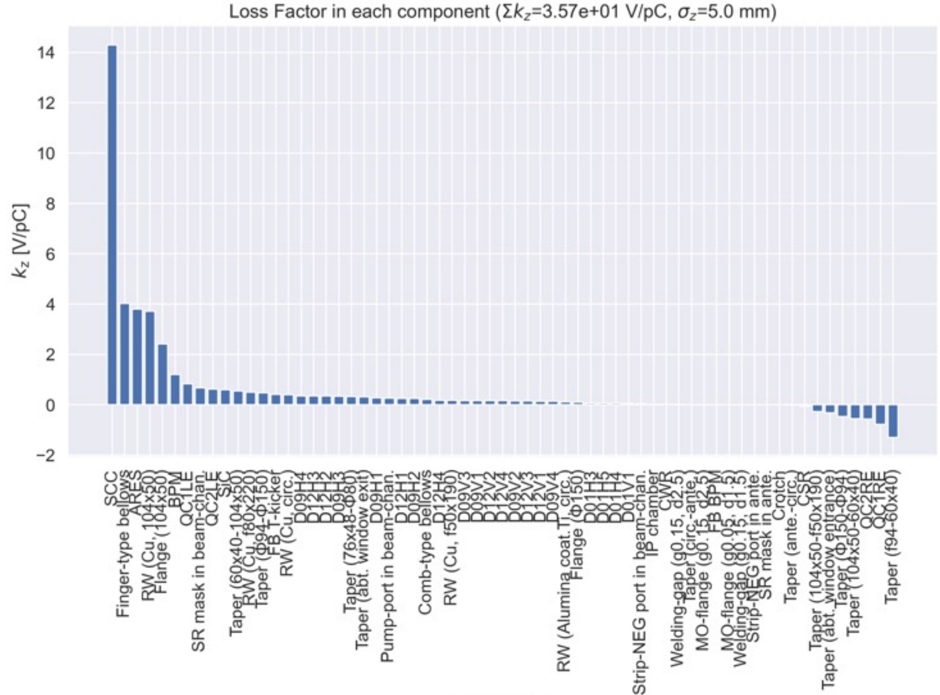
σ_{z0}=0.5 mm



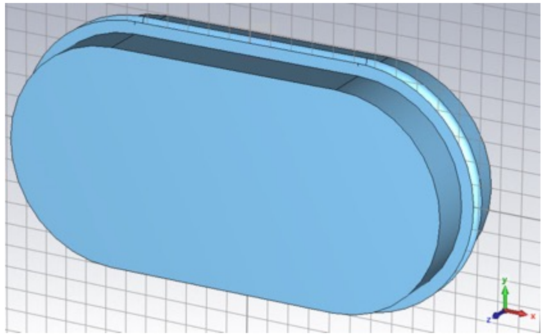


σ_z=5.0 mm

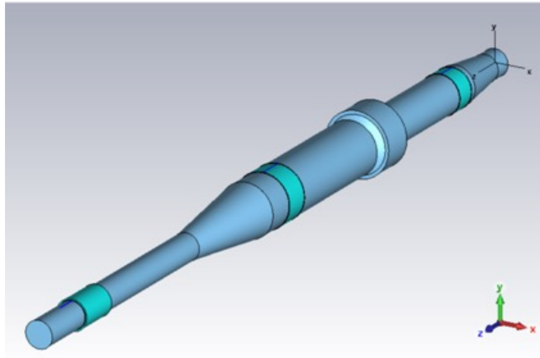




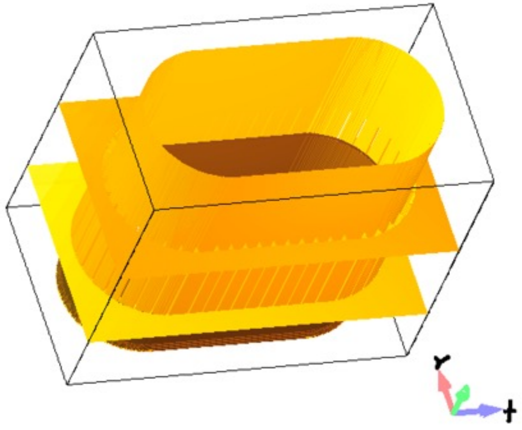
Flange (104x50)



Superconducting cavity (SCC)

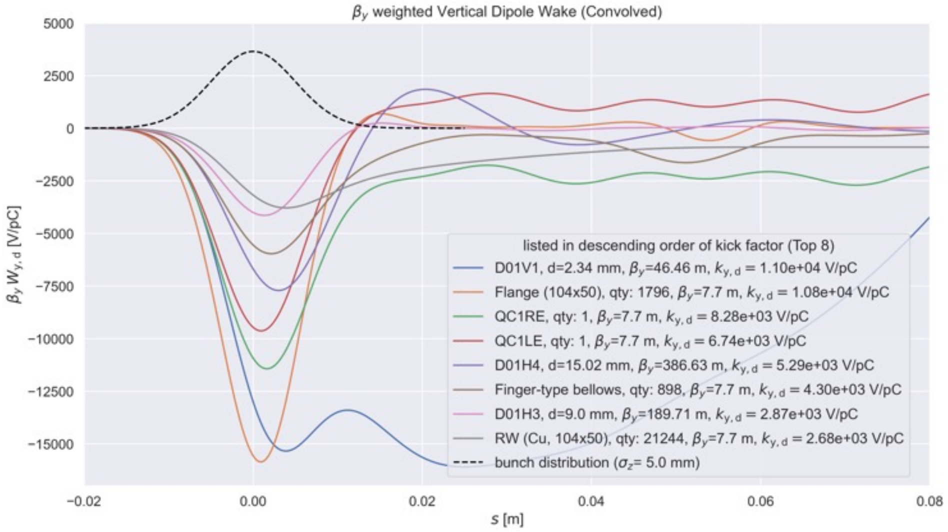


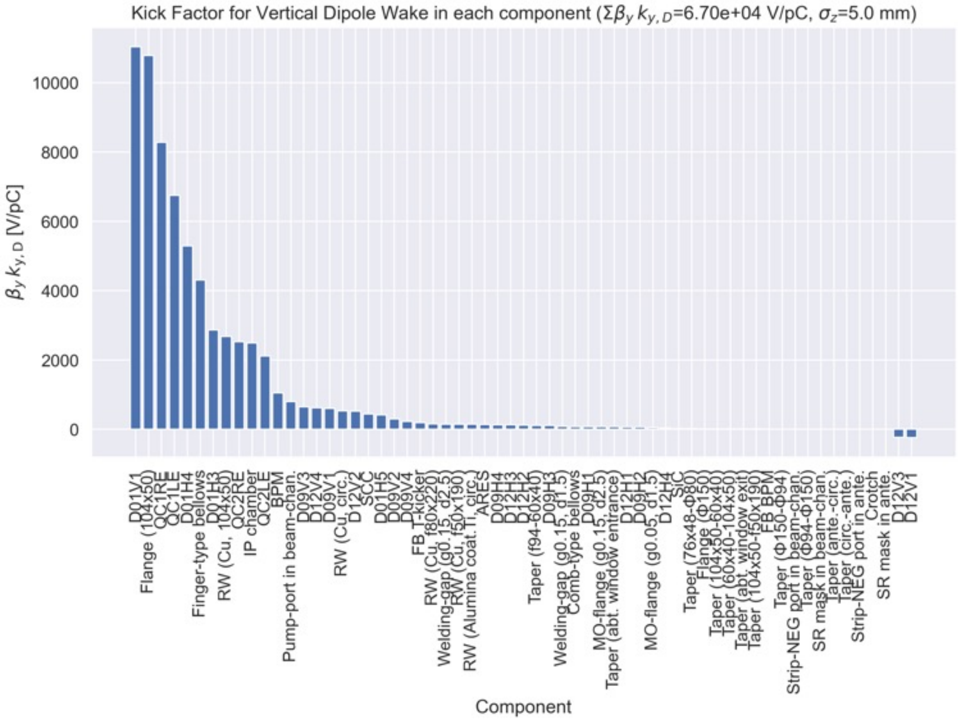
Finger-type RF-shield

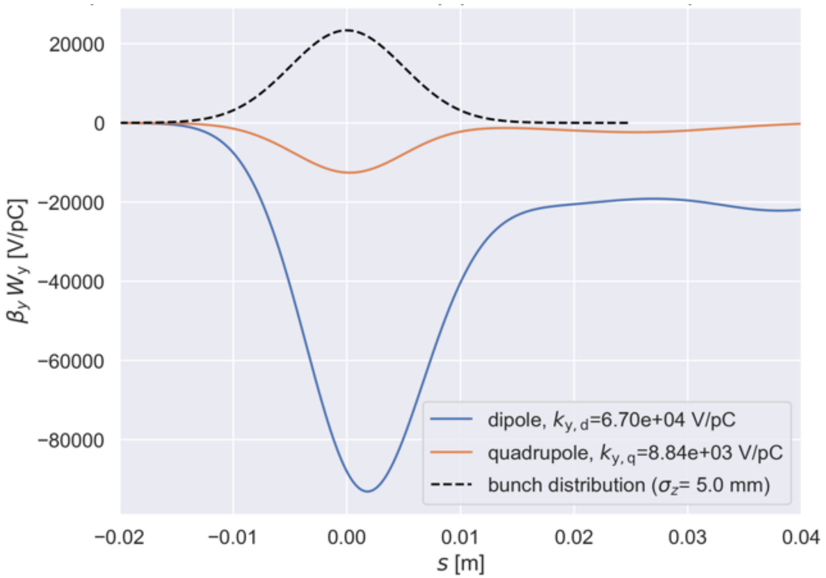


HER – vertical

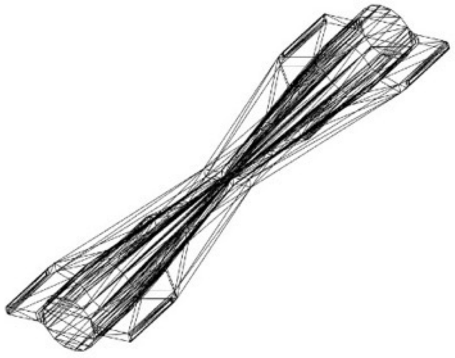
σ_z=5.0 mm



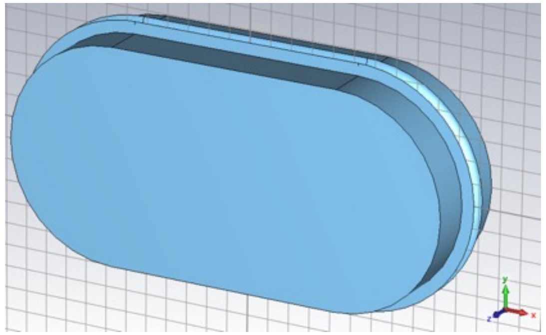




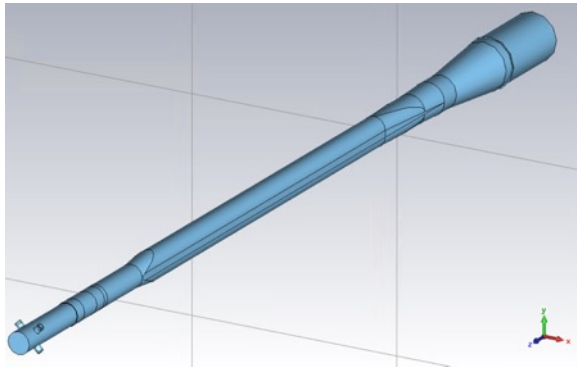
Vertical collimator



Flange (104x50)



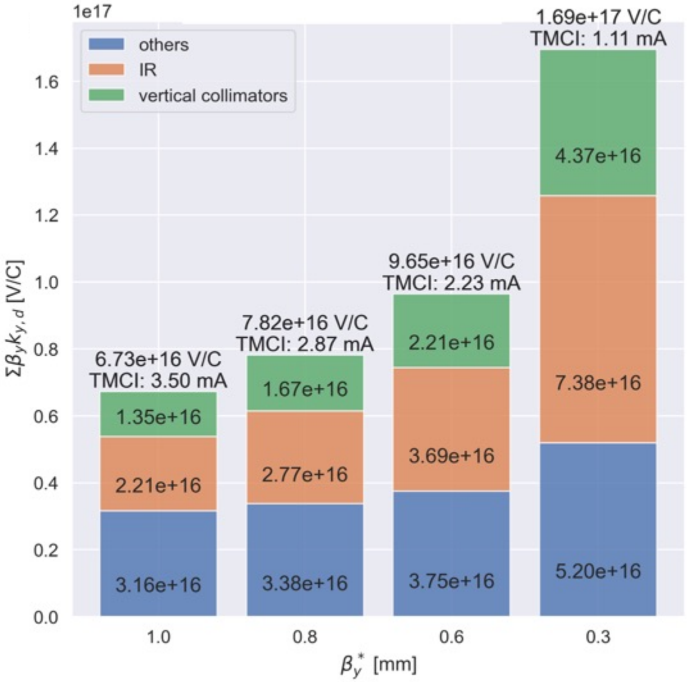
Tapered beam-pipe with BPM in final focusing magnet (QC1)



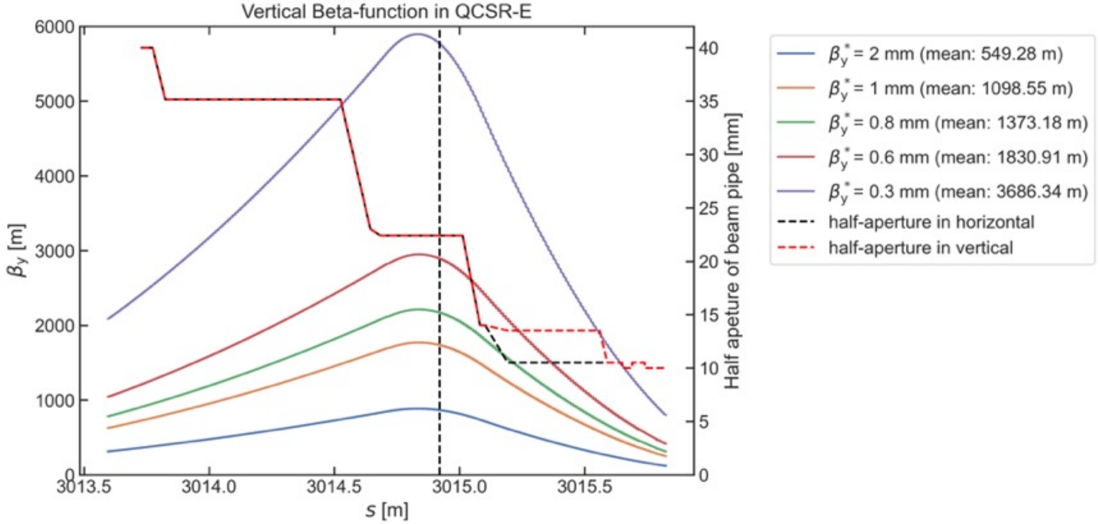
HER - vertical kick-factor (β_y^* dependence)

- Here, the collimator setting is based on that in the 2021c physics run during with β_y^* = 1.0 mm.
- Similar to the LER, I've divided two sections in QCS and used the averaged β_y when weighting the wake here.
- Compared to the LER, the instability threshold for the design value is more generous (1.04 mA/bunch).

Total β_y weighted vertical dipolar kick factor for each β_y^* with $\sigma_z = 5$ mm and the bunch current threshold of TMCI simulated with PyHEADTAIL (transverse damper is not activated).

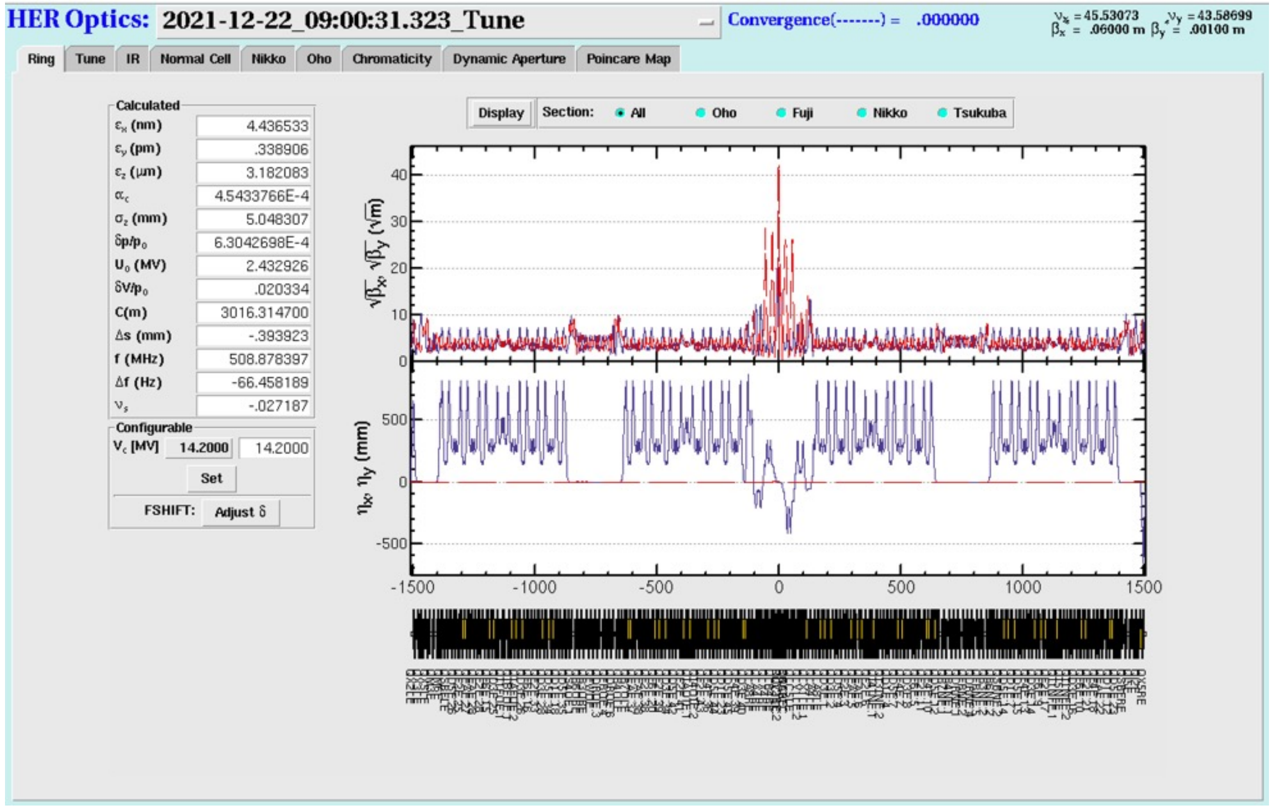


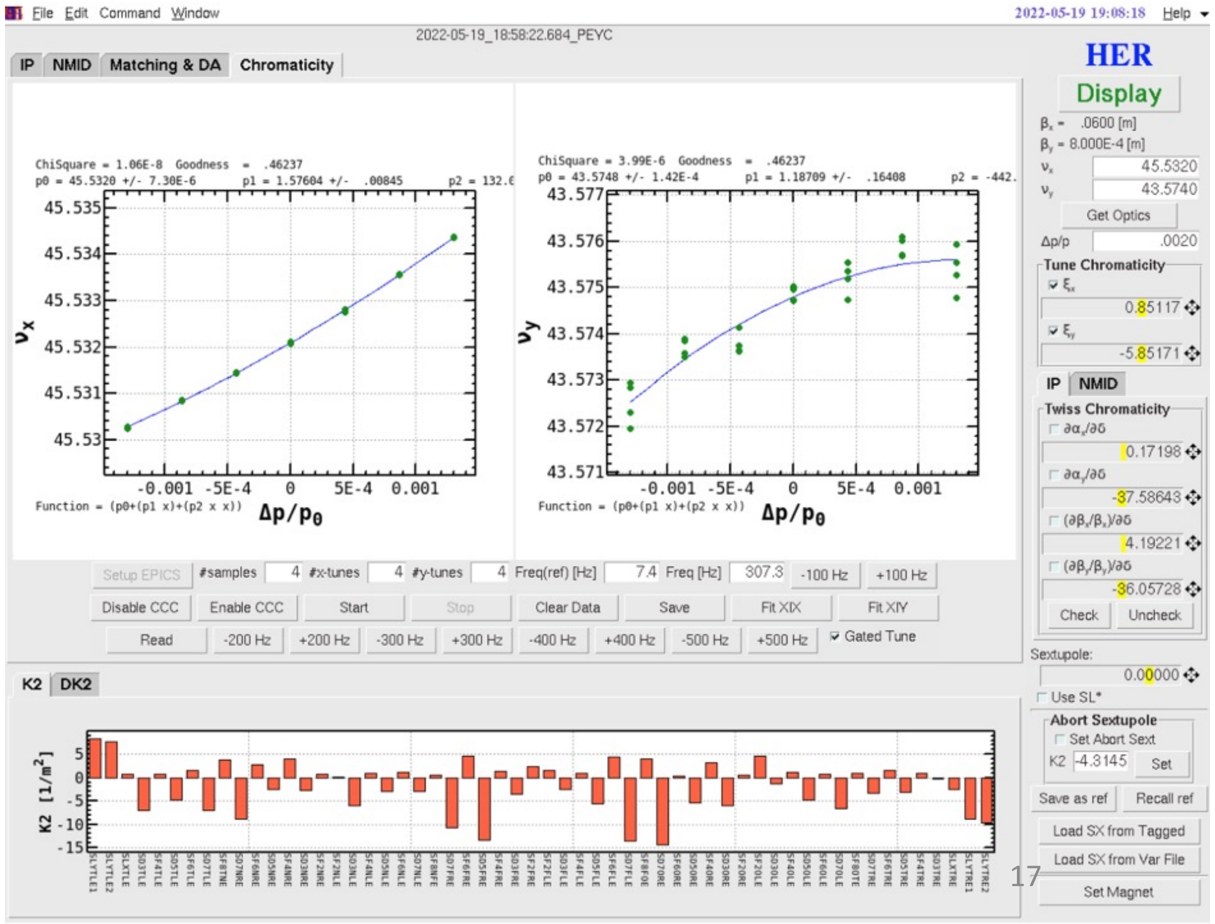
Half aperture of a QCSR beam-pipe and vertical beta-function with each vertical beta-function at the interaction point as a function of the longitudinal location.



HER - PyHEADTAIL simulation

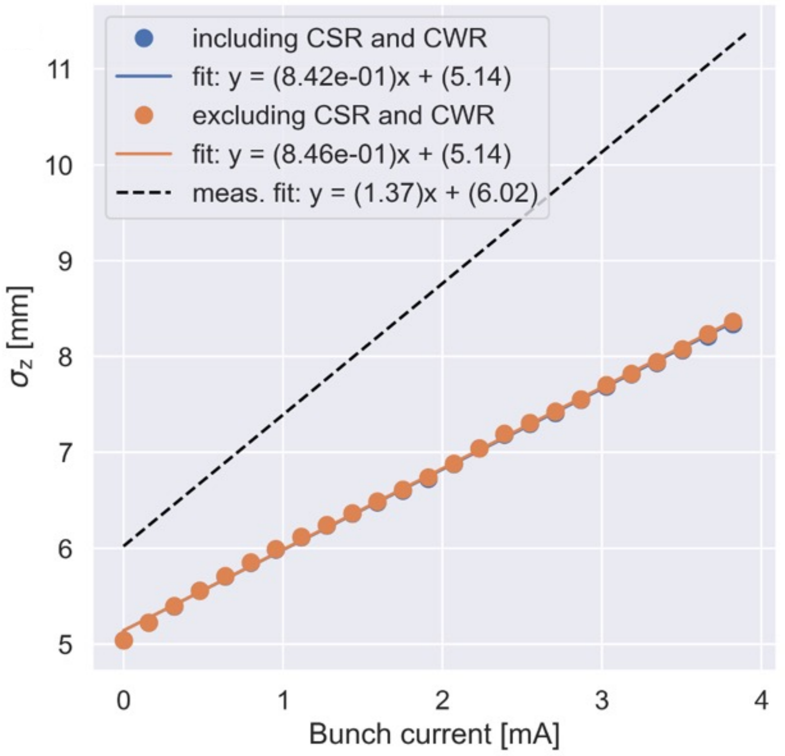
- The parameters that used are based on those of the physics run on Dec.22nd, 2021.
- The chromaticity measured on May 19, 2022 is used.

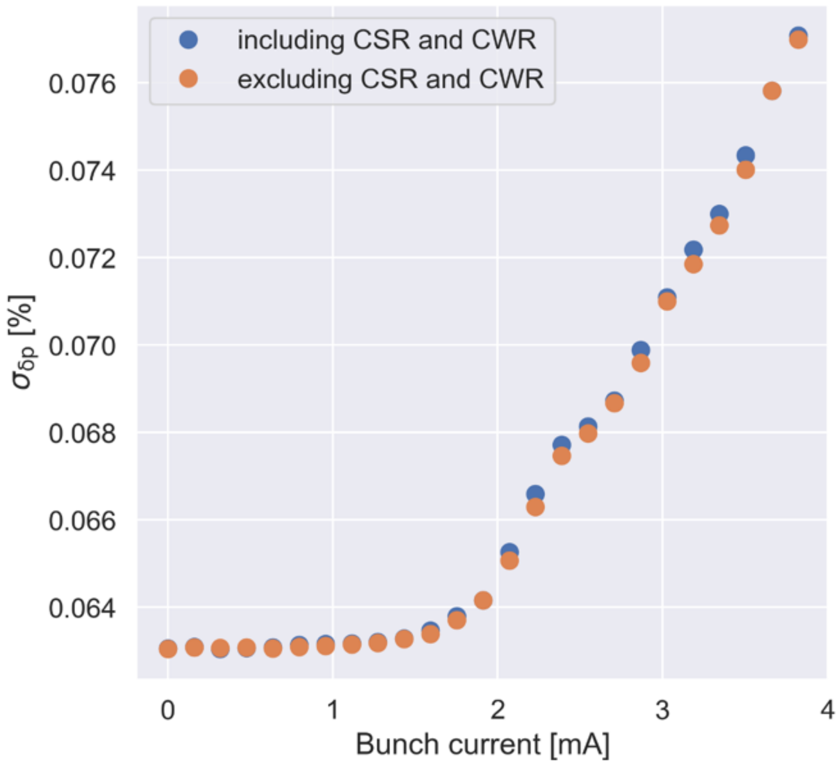




HER – bunch length between simulations and measurements

- There is not much difference with or without CSR and CWR.
- The simulated bunch length using the impedance model is shorter than the measured values, similar to the LER.
- MWI threshold is ~2 mA.

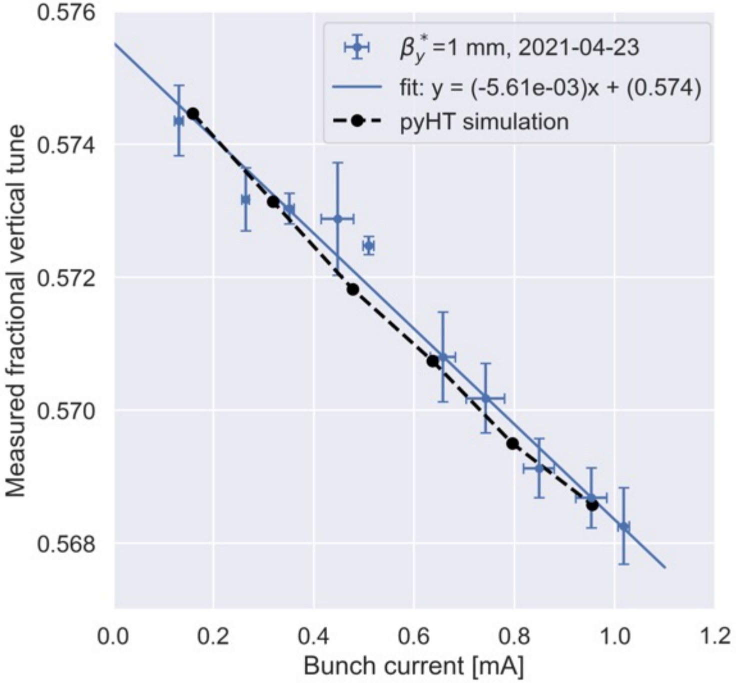




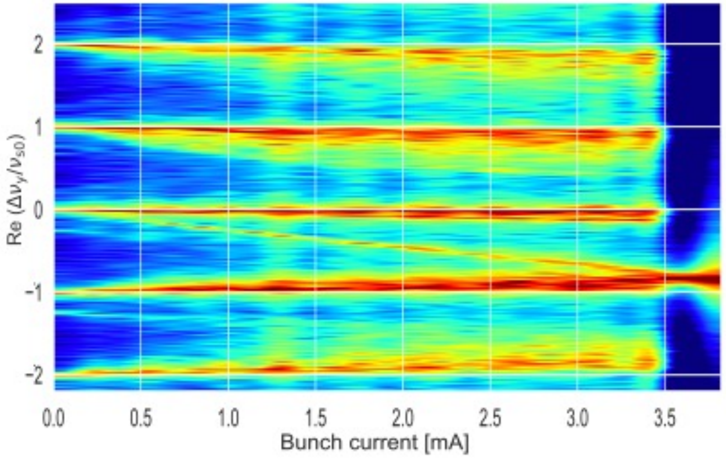
HER - vertical direction

- Simulation and measurement of the tune shift are in good agreement.
- Instability threshold:
  - ~3.66 mA/bunch with only dipolar wake
  - ~3.50 mA/bunch with dipolar and quadrupolar wake
  - ~3.18 mA/bunch with dipolar and quadrupolar wake, and the damper (d =100, $\varphi = 90°$) is activated.

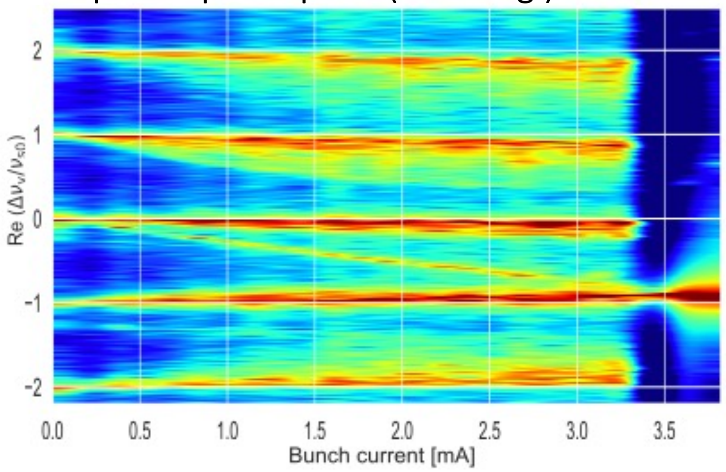
vertical tune shift



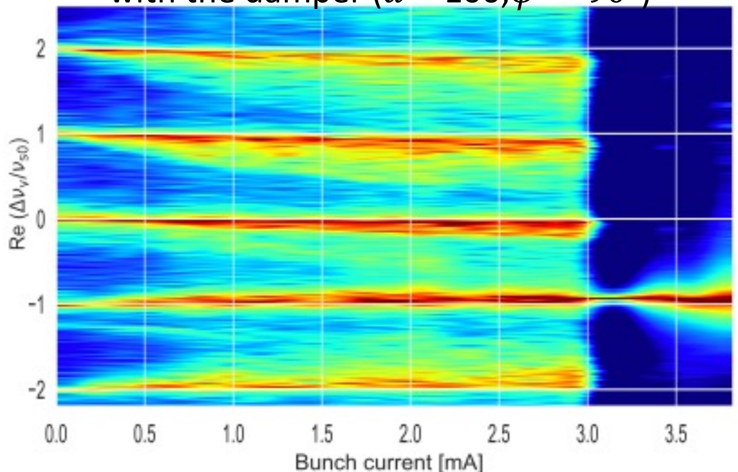
dipolar (incl. long.) wake



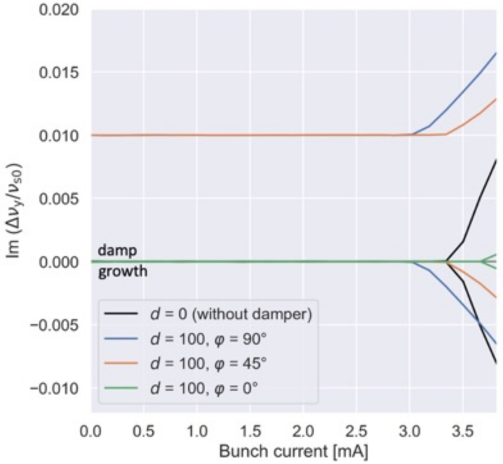
dipolar+quadrupolar (incl. long.) wake



dipolar&quadrupolar (incl. long.) wake
with the damper (d =100,$\varphi = 90°$)

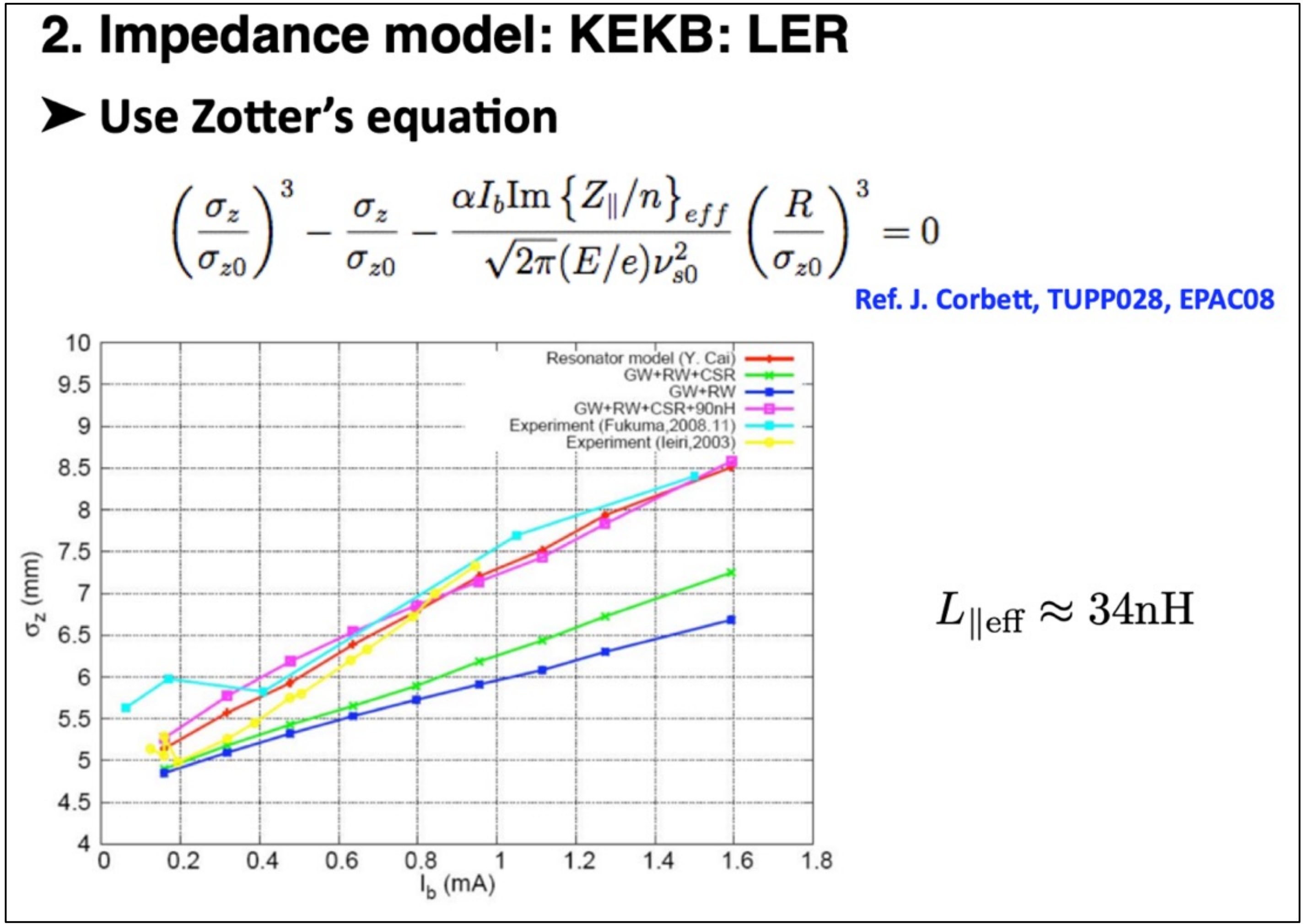


Imaginary part of the tune shift



Bunch length (simulation and measurement)

- How was the KEKB era?
  - ➢The discrepancy between measurements and simulations has existed not only in SuperKEKB, but also since the KEKB era.
  - ➢The cause of the difference is still unknown.



[D. Zhou, TWIICE 2 workshop]

Nonlinear collimation system

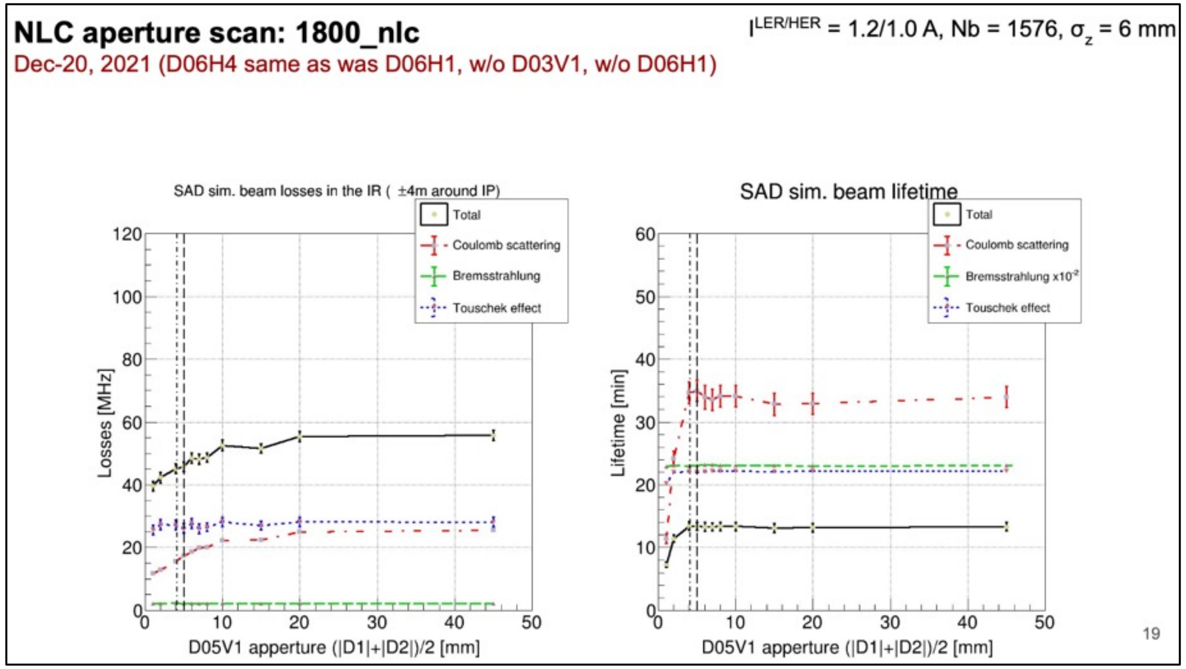
[A. Natochii]

[example] collimator setting and $\beta_y k_y$ for βy^*=1 mm optics.

Collimator	β_y [m]	Half-aperture [mm] a)	$\beta_y k_y$ [×10^{15}, V/C]
D06V1	67.35	2.9	9.77
D06V2	20.57	2.6	3.64
D03V1	16.96	8.0	0.50
D02V1	11.89	1.1	7.72
D05V1	4.05 b)	5	0.28

a) Averaged value of top and bottom half-aperture at 2021-12-22

b) Optics file: sler_1800_80_1.sad



Bunch current threshold of TMCI

$$I_{th} = \frac{4\pi\nu_s(E/e)}{T_0 \sum_i \beta_{y,i} k_{y,i}}$$

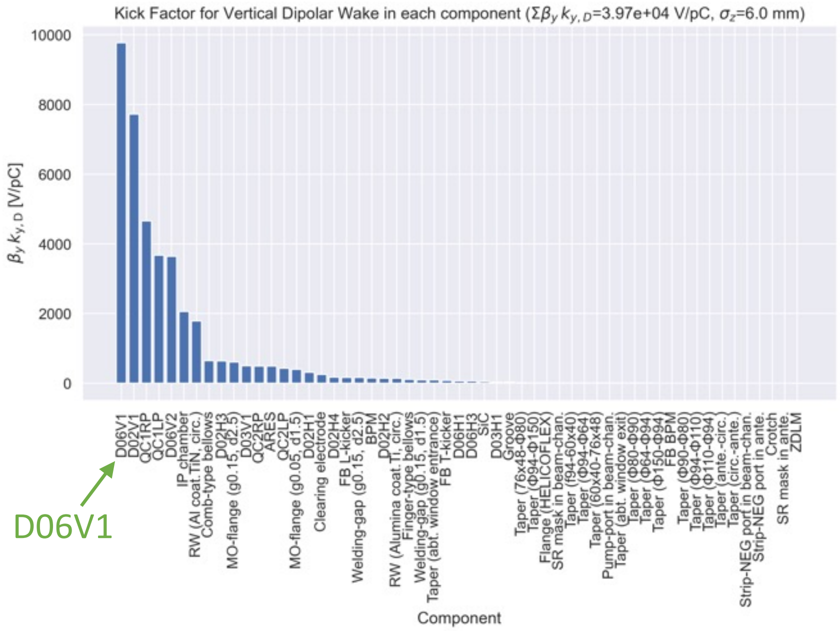
A. Morita *et al*. reported the details in the latest KEKB review.
https://superkekb.kek.jp/event/133/

- The nonlinear collimation system uses a kick from a skew sextupole magnet, and the kick makes a vertical displacement at the collimator (the optics is special, and the collimator structure itself remains the same).
- The β_y of the skew sextupole is made large to help this (β_y=378.5 m).
- D05V1 is a vertical collimator is a movable collimator in this system.
- D06V1 has been used to suppress the injection backgrounds (primary collimator) and has a large $\beta_y k_y$ because the β_y is large, and the aperture is narrow.
- D05V1 can have a small β_y and almost the same background reduction performance as D06V1 with the wider aperture.

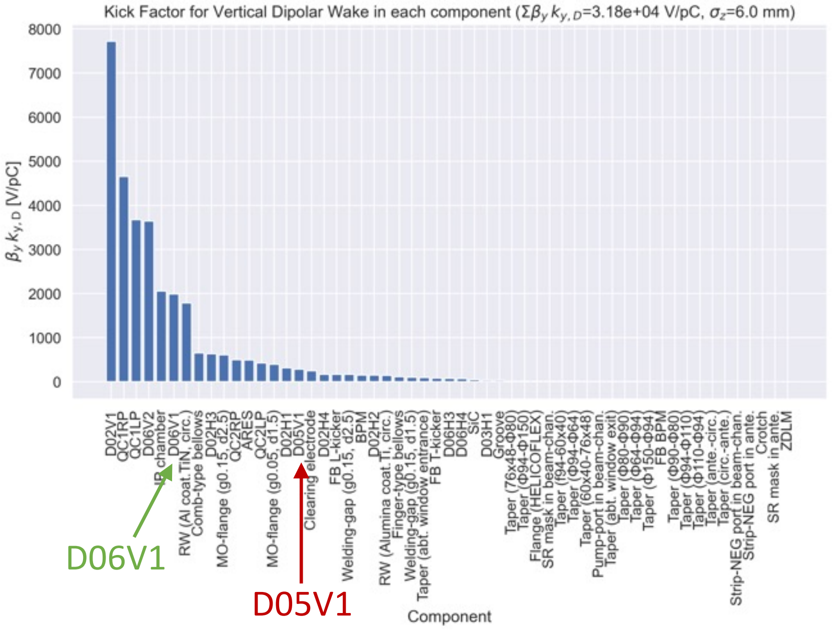
→ It can decrease the $\beta_y k_y$ if we can use D05V1 instead of D06V1.

$$\Delta p_y = \frac{B_x L}{B\rho} = \frac{K_s}{2}(y^2 - x^2)$$

2021c physics run



After LS1



β_y^*=1 mm
β_x^*=80 mm

dipolar+quadrupolar(incl. long.) wake

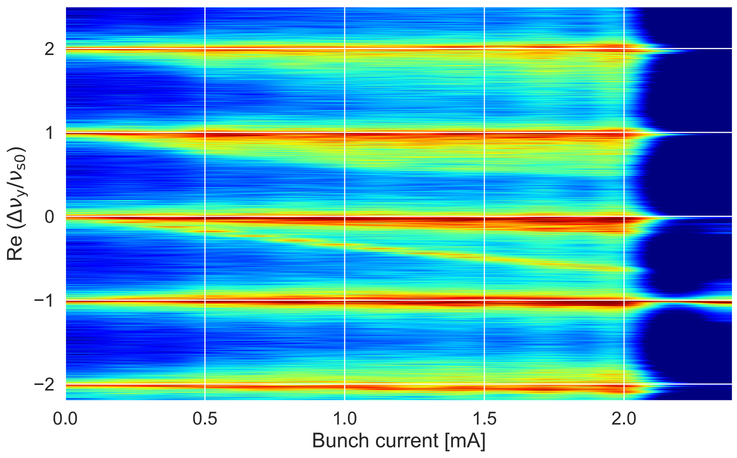
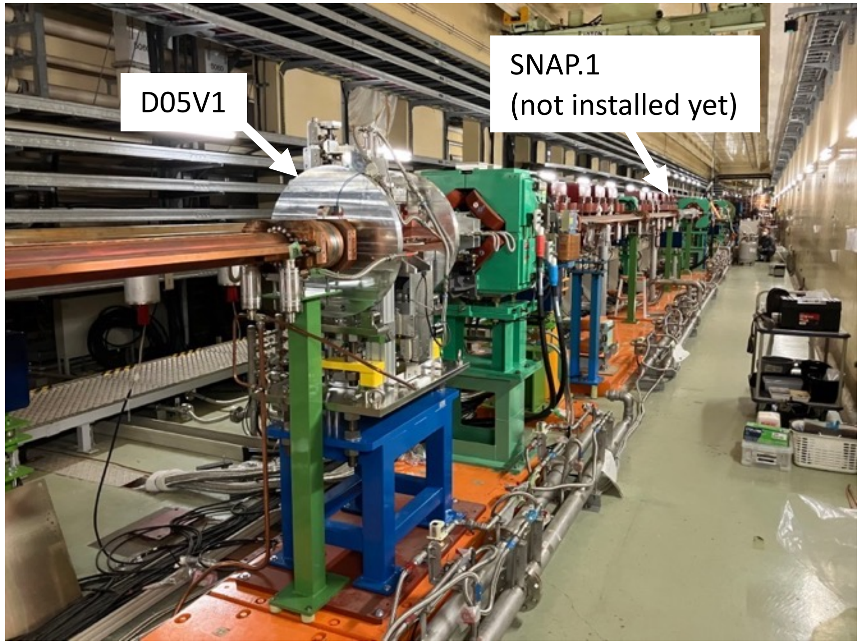


Photo of the non-linear collimator section (2023-05-26)



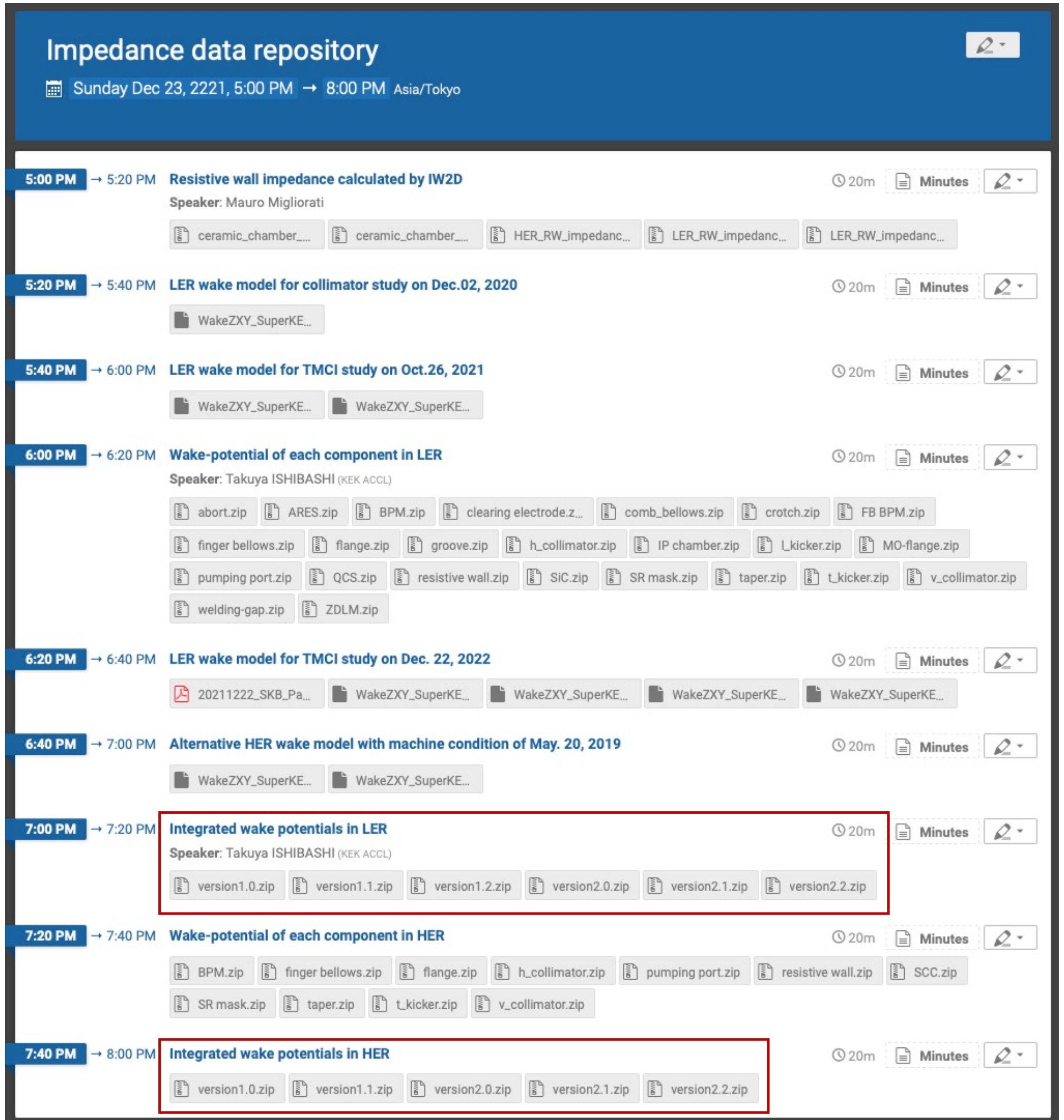
- The sum of the $\beta_y k_y$ decreases from 3.97e4 V/pC to 3.18e4 V/pC.
- The simulated TMCI threshold increases from ~1.75 mA to ~2.07 mA.
- Construction of the nonlinear collimation system is progressing well during this long shutdown (LS1).
- In the next commissioning period after LS1, we plan to use D06V1 without removing it as a buck-up of D05V1 in LER. If D05V1 turns out to be a replacement for D06V1, we can remove the D06V1 probably.

Summary

- We have rebuilt impedance models of the SuperKEKB main ring and simulated single-bunch collective instabilities using the wake obtained from this model.
- According to this model, the TMCI threshold decreases significantly with squeezing β_y^*.
    - The LER has no enough margin of the design bunch current for the threshold.
- The PyHEADTAIL simulations using the impedance model successfully predict the vertical tune shifts, but not the bunch lengthening, so we need to further investigate the differences between the measurements and simulations.
- We also ran simulations with $d =$ 10-100 turns, $\varphi =$ 0-90°, and vertical tune at 0 mA/bunch from 0.565 to 0.595, however these could not reproduce the "-1 mode instability" observed in the actual machine.
    - When we ran simulations considering a bunch-by-bunch feedback system using a multi-tap scheme with a finite impulse response (FIR) filter, which is used in the actual accelerator, this instability could be reproduced [K. Ohmi *et al.*, Proc of eeFACT2022, WEXAT0102].
    - However, this point remains questionable as instability occurs when applying higher feedback gains in the model (damping time: 10 turns) than in actual operation (damping time: 100–200 turns).
- A nonlinear collimation system in LER can reduce the vertical impedance and increase the TMCI threshold. Construction is progressing well and will be implemented in the next commissioning.
- An ITF TMCI group was closed last year and a new collective effect group has been launched.
    - contact person: Gaku Mitsuka
    - Indico: https://kds.kek.jp/category/2521/

Other

- We have prepared a repository of the wake data.
- You can download the data below.
  - https://kds.kek.jp/event/40318/
  - “Integrated wake potentials in LER/HER”



back-up

$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)$$

LER

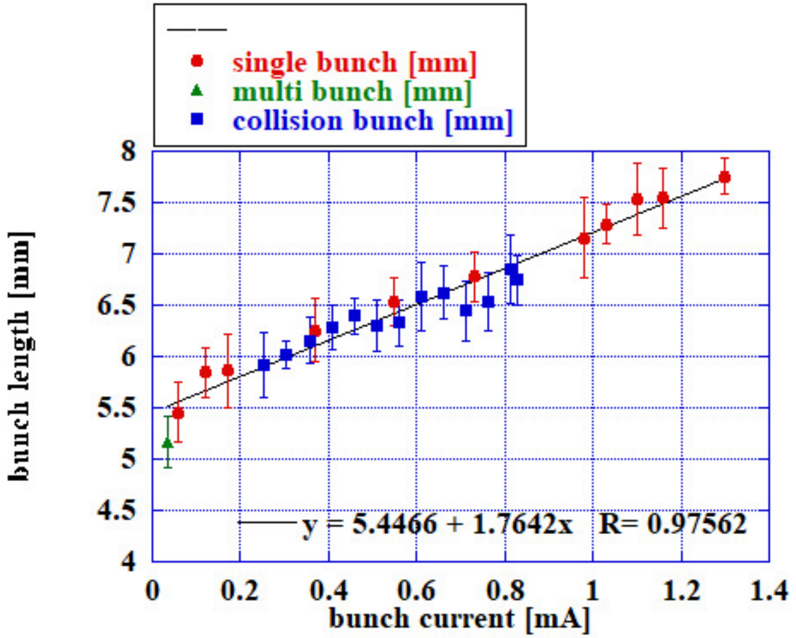
Component	k_z [V/pC]	R [Ω]	L [nH]
ARES cavities	9.5	671.9	–
Resistive-wall	3.0	213.1	9.1
Flanges (φ150, HELICOFLEX)	0.1	3.5	1.2
MO-flanges	0.0	1.4	5.2
Welding-gaps	0.0	0.3	1.4
Comb-type bellows	0.9	66.3	5.3
Longitudinal feedback kicker	0.8	57.6	−0.8
Transverse feedback kicker	0.4	26.1	0.0
Clearing electrodes [4]	0.0	1.7	2.4
Vertical collimators	0.1	8.2	5.9
Horizontal collimators	0.3	17.6	5.6
Tapered beam-pipes	0.9	61.0	1.4
QCS beam-pipes	0.1	5.1	0.6
Others	1.8	137.4	3.4
Total	17.9	1271.2	40.5

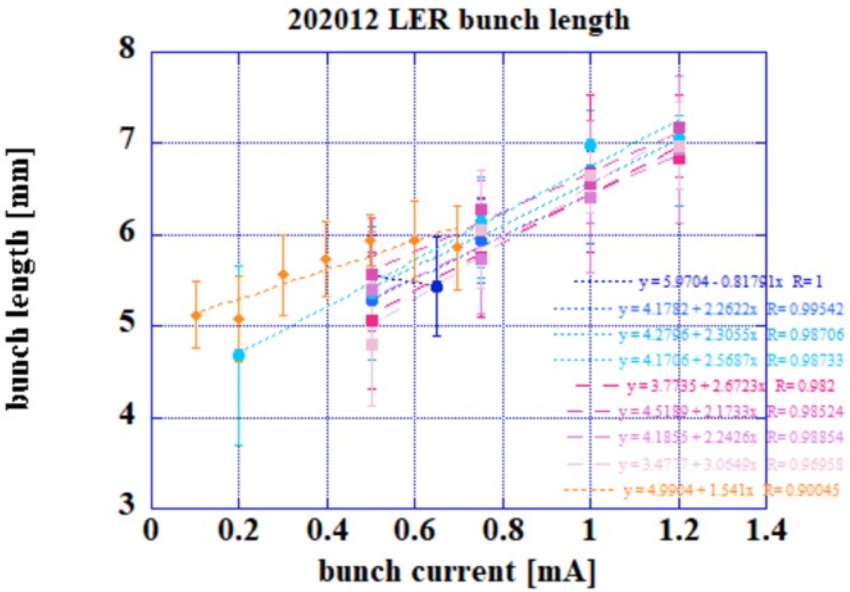
HER

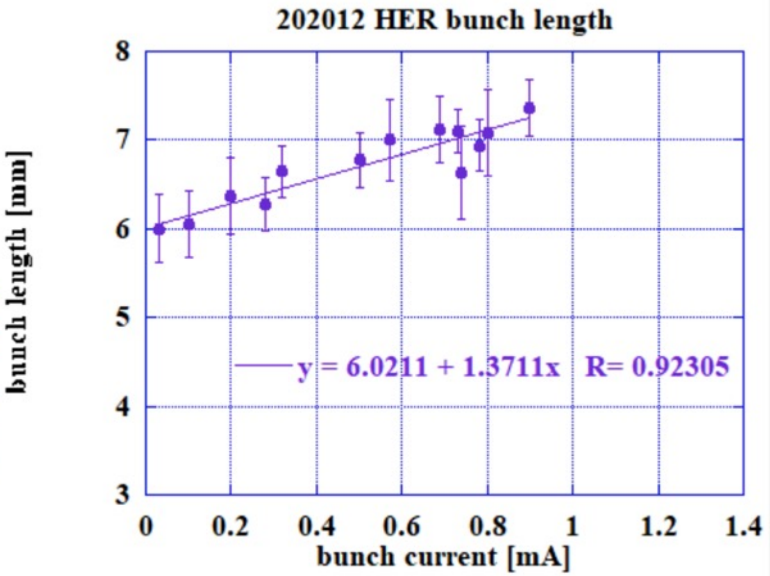
Component	k_z [V/pC]	R [Ω]	L [nH]
Superconducting cavity	14.3	845.1	–
ARES cavities	3.8	225.0	–
Resistive-wall	4.9	289.5	7.4
Flanges (φ150, HELICOFLEX)	0.1	6.1	1.2
Flanges (racetrack, HELICOFLEX)	2.4	142.6	36.4
MO-flange	0.0	0.5	0.8
Welding-gaps	0.0	0.8	1.6
Comb-type bellows	0.2	12.9	0.7
Contact-finger-type bellows	4.0	238.1	13.0
Transverse feedback kicker	0.4	24.5	0.0
BPM	1.2	71.5	1.5
Vertical collimators	1.3	76.2	4.0
Horizontal collimators	2.6	150.6	7.2
QCS beam-pipes	0.1	6.8	0.5
Pumping-screen	0.3	15.8	3.0
Others	0.1	5.7	3.0
Total	35.7	2111.7	80.3

[H. Ikeda *et al.*]

2021(?) LER bunch length





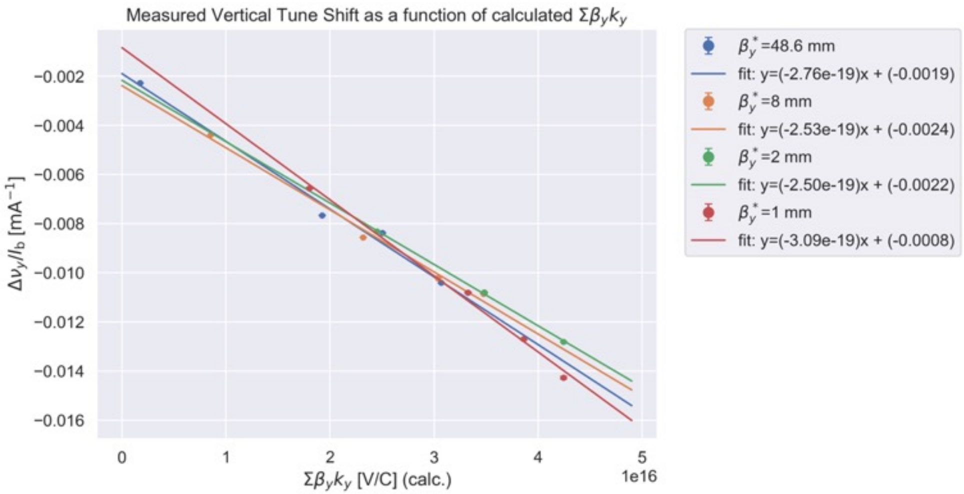


Impedance Model and Tune Shift Measurements

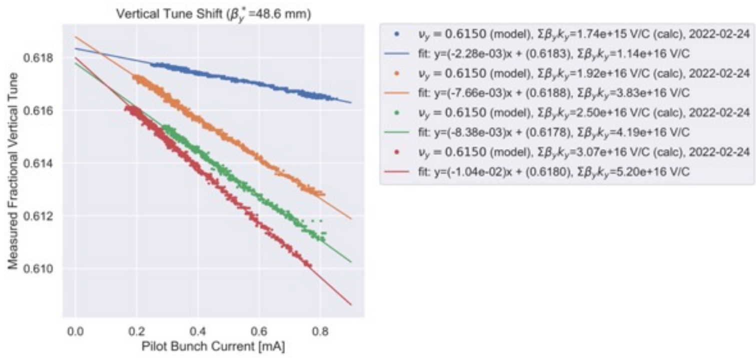
$$\Delta\nu_{x/y} = \frac{I_b T_0}{4\pi(E/e)}\Sigma\beta_{x/y}k_{x/y}$$

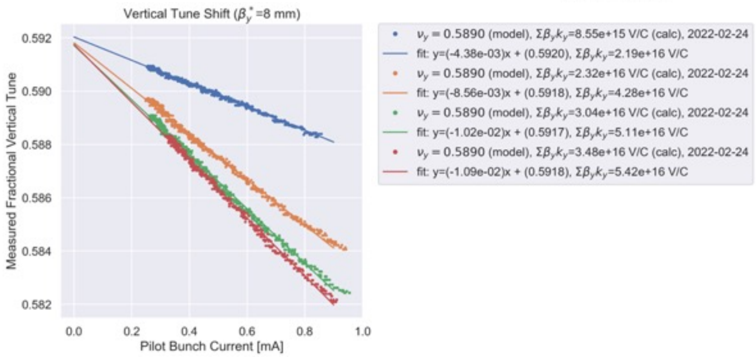
T_0 = circ./c ~1e-5 s

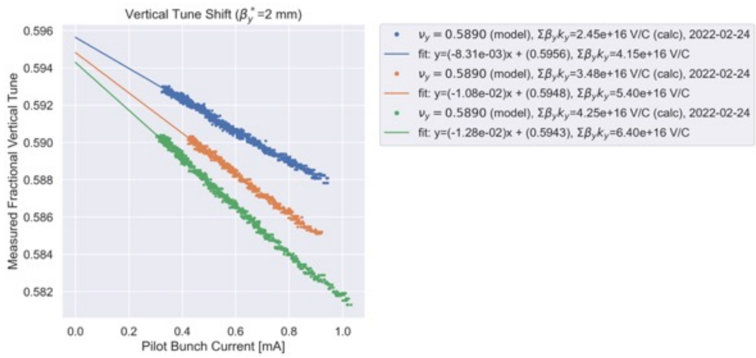
E/e = 4 GV

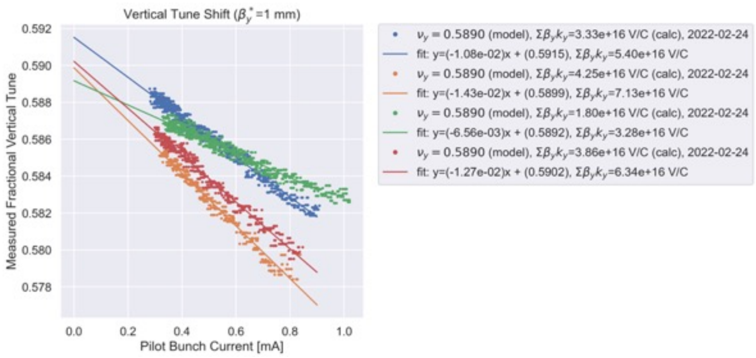


(same plot as a plot shown by Y. Ohnishi in another meetings)



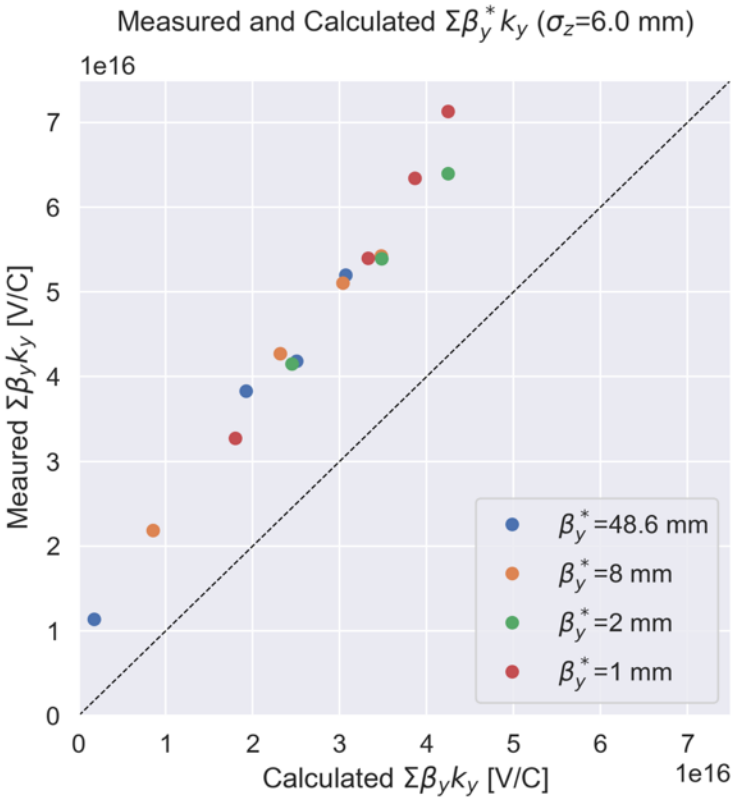


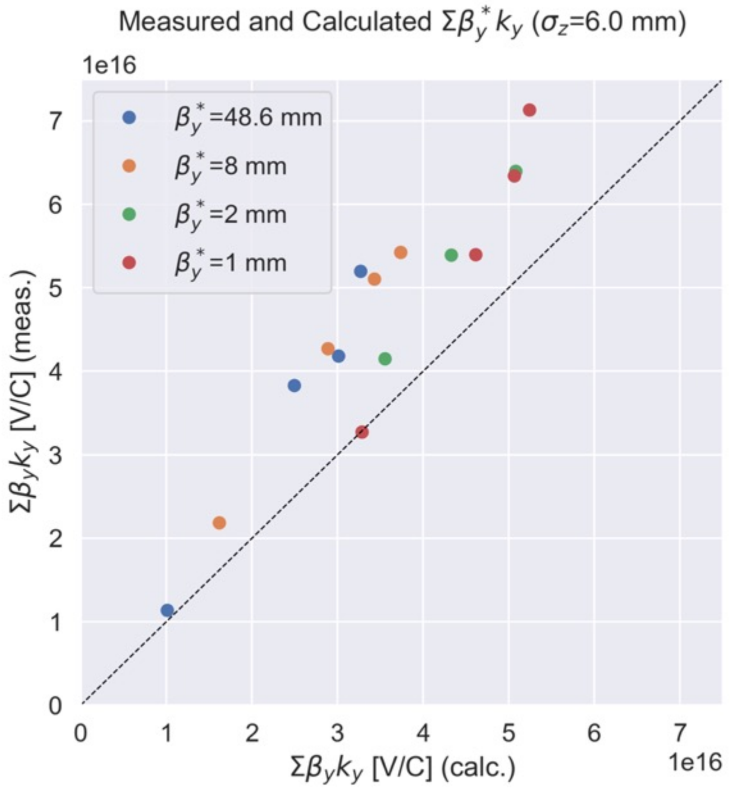




- D. Zhou will talk about same topic later in this meeting.
- Note that the $\Sigma\beta_y k_y$ in the x-axis is calculated values for only vertical collimators using results from GdfidL for σ_z=6 mm and βy in optics models.

Impedance Model and Tune Shift Measurements





✓ Note that the $\Sigma\beta_y k_y$ in the x-axis is calculated values for only vertical collimators using results from GdfidL for σ_z=6 mm and βy in optics models.

✓ Here, $\Sigma\beta_y k_y$ in the x-axis is calculated values using a current impedance model for all of the components in LER for σ_z=6 mm and βy in optics models (impedance of the collimators is calculated using ECHO3D).

- Generally speaking, the measured $\Sigma\beta_y k_y$ looks larger than the calculations.
- The discrepancy between the measurements and the model become large in the higher $\Sigma\beta_y k_y$.
  - When we increased the $\Sigma\beta_y k_y$, we mainly close an aperture of D06V1 because its βy is large (> 60 m). Something is wrong with D06V1?
  - or does the resistive-wall contribute to it? (I've not been able to calculate the impedance including the resistive-wall for collimators because of a limitation of the computation resources.)
- Note that I assumed the constant bunch length, but it's variable depending on the bunch current in actuality.

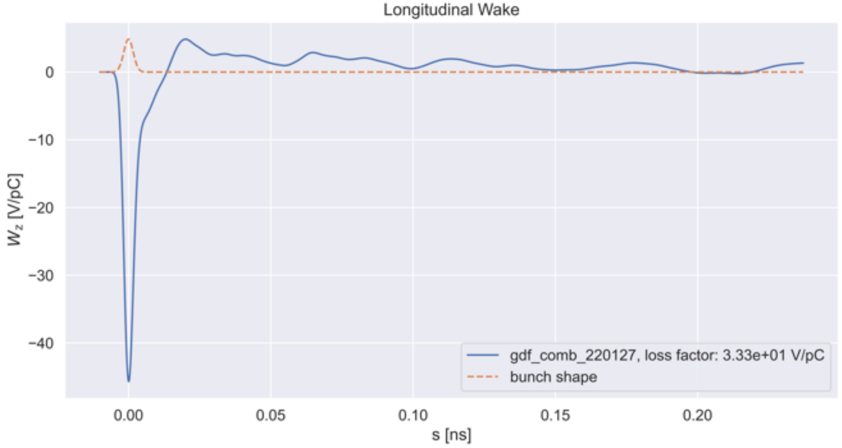
Concerns

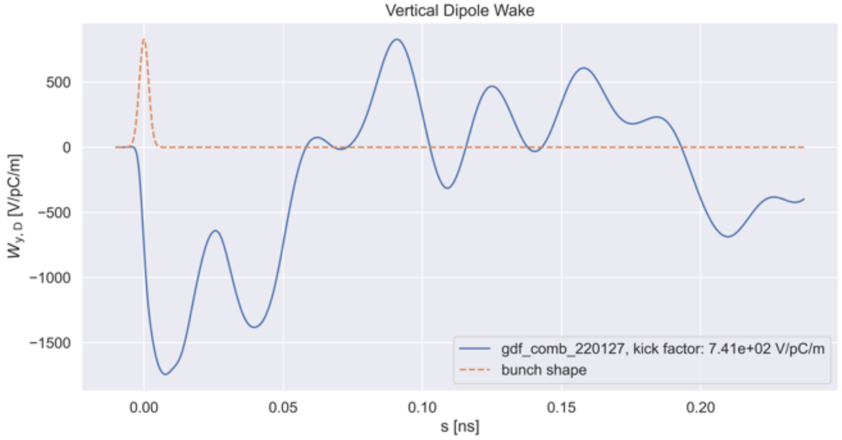
- In this model, for components such as QCS beam-pipes, where β_y changessignificantly with the longitudinal position, the impedance is calculated for several divided sections, and the vertical wake potential is calculated for these and weighted by the average value of β_y in each section. The reliability of this method is unknown.
- When calculating the impedance, we basically consider the different components installed in the ring one by one. There could be an interference effect between each component, especially if the components are placed close to each other [V. Smaluk, Nucl. Instrum. Methods Phys. Res. A 888 (2018) 22]. This interference effect is hardly considered in our model and may contribute to the impedance budget.
- The resistive-wall in LER is calculated for a circular beam-pipe, but in practice a beam-pipe with antechambers is used. There are other beam-pipes with different cross-sections in the ring too, and their resistive-wall impedance is omitted in this model.

Concerns

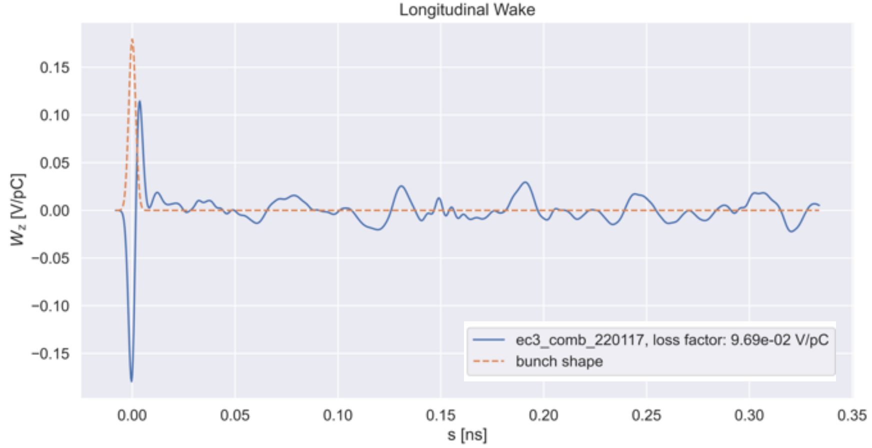
- The calculated impedances in special vacuum components used in the main ring, such as the beam-pipes with the clearing-electrodes and the comb-type RF-shields, give non-physical results depending on the simulation code. In this case, we have modeled the impedance from a simulation code that produces more realistic results, but the impedances are not cross-checked between codes, and so they are less reliable.

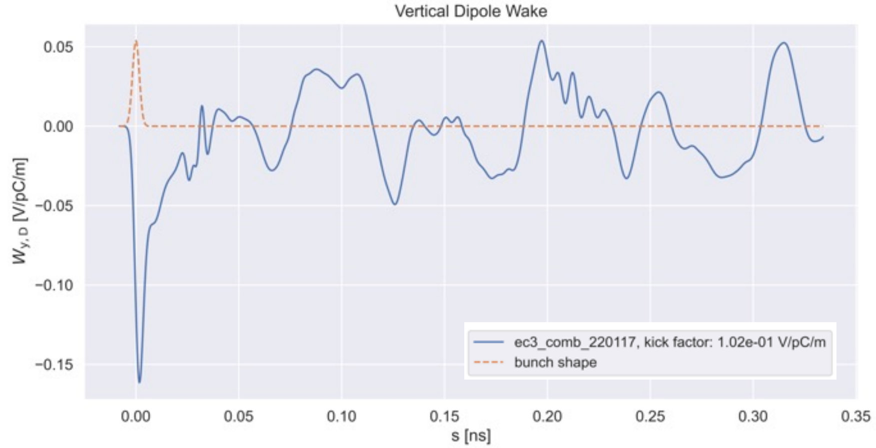
GdfidL



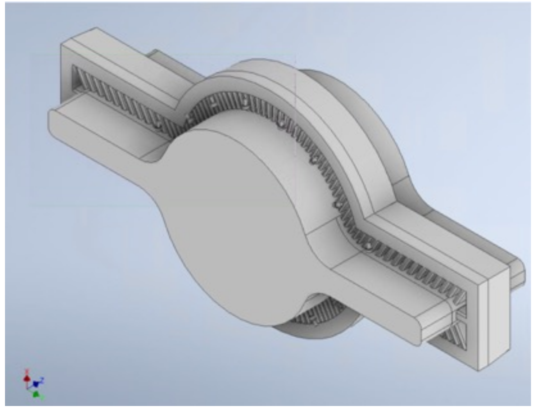


ECHO3D





Example: comb-type RF-shield



Concerns

- The measured surface conductivity of the TiN coating applied almost all-around LER is about 5.0×10^4 S/m. The surface conductivity of TiN coatings depends strongly on the coating method, but the measured values for coatings used at KEK are at least 10 times lower than for other coatings [S. Chowdhury *et al.*, Mater. Chem. Phys. 267 (2021) 124648]. When the skin depth of the coating is larger than its thickness as in our case, the value of the conductivity has almost no effect on the impedance both longitudinal and transverse, and the coating gives only an imaginary contribution to the impedance proportional to its thickness [M. Migliorati et al., Phys. Rev. Accel. Beams 21 (2018) 041001]. We will study the surface electrical conductivity of the TiN coating.

Concerns (bunch lengthening with/without CSR and CWR)

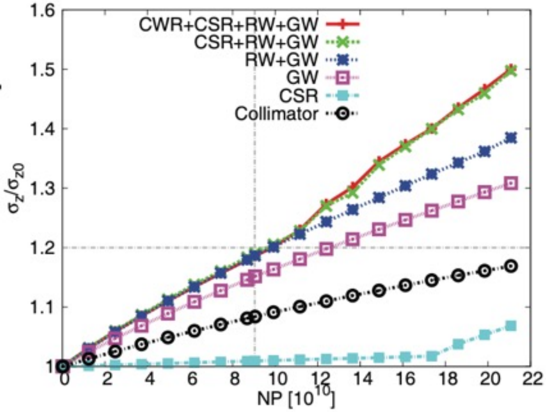
VFP solver

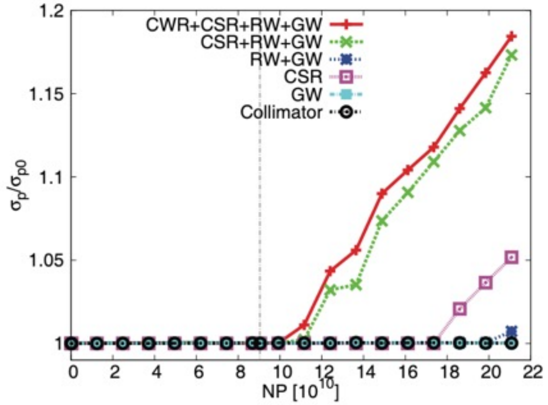
- The bunch lengthening with/without CSR and CWR is the same till the MWI threshold. Above than the threshold, the bunch length with CSR and CWR becomes longer than that without them. This behavior is independent of the “old” or “new” wake data.

PyHT and SBSC

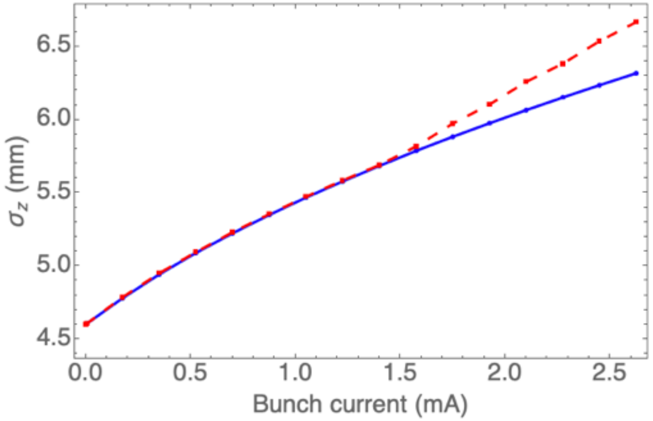
- The results of the two codes are almost same.
- The behavior of the bunch lengthening from the codes is the same as that from the VFP solver when we use the “old” wake data.
- The behavior of the bunch lengthening from the codes is different from that of the VFP solver when we use the “new” wake data.

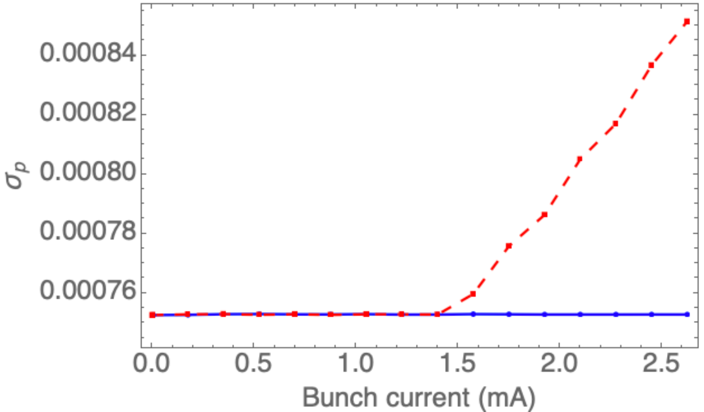
Results from the VFP solver by D. Zhou using the old wake [D. Zhou *et al.*, in Proc. of IPAC2014, TUPRI021]



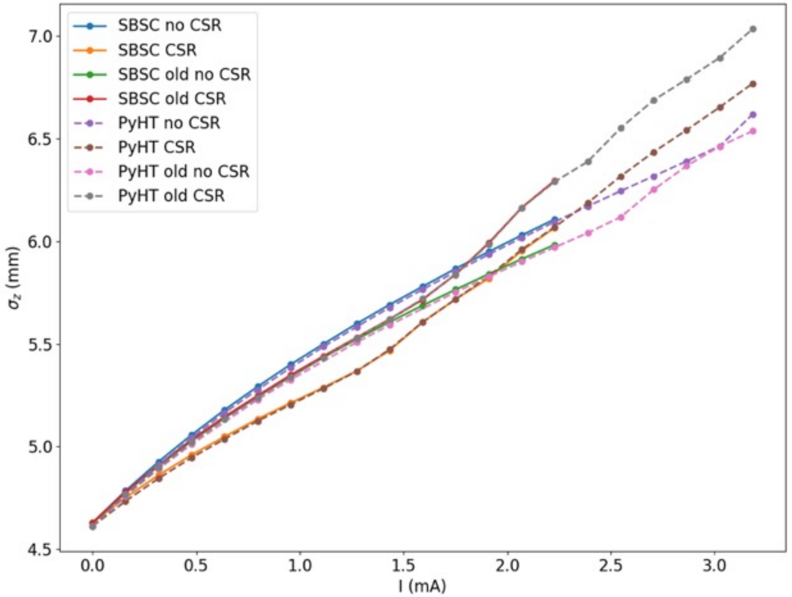


Results from the VFP solver by D. Zhou using the new wake





[M. Migliorati]



File name of the wake
old CSR: WakeZXY_SuperKEKB_LERGeometricRWCSRCWR_sigmaz_0_5mm_20211026_TMCI_Study.dat
old no CSR: WakeZXY_SuperKEKB_LERGeometricRW_sigmaz_0_5mm_20211026_TMCI_Study.dat
CSR: version2.1/wakeLT_2021c_physics.txt
no CSR: version2.1/wakeLT_2021c_physics_woCSR.txt