Coupled-bunch instability driven by resistive wall impedance at SuperKEKB main rings

Demin Zhou

Accelerator theory group, Accelerator laboratory, KEK

Acknowledgments

M. Tobiyama, T. Ishibashi, M. Migliorati, G. Bassi, A. Blednykh

Mini-workshop on impedance modeling and impedance effects at SuperKEKB and future colliders, KEK, Dec. 15, 2022

Outline

- Vacuum chambers
- Optics
- Measurements of TCBI at SuperKEKB
- TCBI theory and predictions of TCBI growth time

Vacuum chambers

- Normal chambers at SuperKEKB rings [1]
  - LER: Round chamber with ante-chambers ~90%, radius 45 mm, aluminum with TiN 0.2 μm coating.
  - HER: Race-track chamber ~70%, copper.

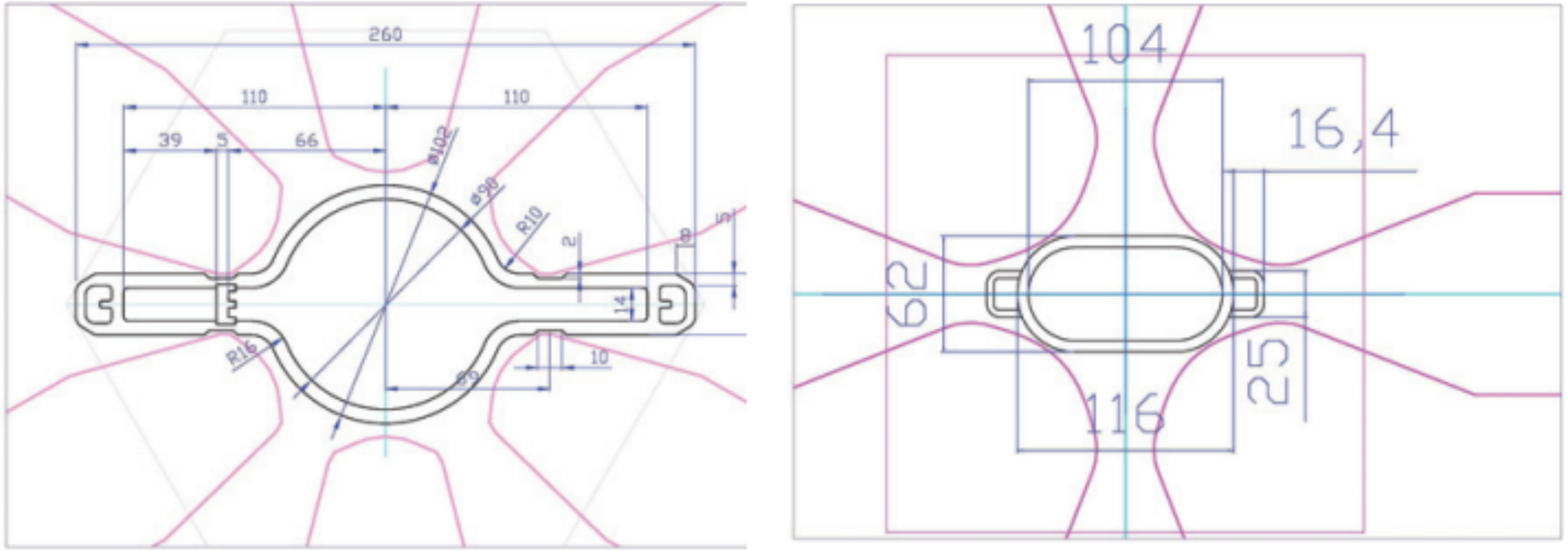


Figure 1: Typical cross-section of beam pipes in SuperKEKB. Left: LER with antechamber at arc sections in a sextuple magnet. Right: HER with race-track shape at the arc sections in a quadrupole magnet.

[1] D. Zhou et al., IPAC’14.

Vacuum chambers

Do analytic theories of RW impedance apply to SuperKEKB IR chamber?

$$Z_1^{\perp}(\omega) = \frac{f_Y L(\mathbf{sgn}(\omega) - i)}{\pi b^3}\sqrt{\frac{Z_0 c}{2|\omega|\sigma_c}}$$

- IR chamber [1]
  - Chamber radius from 40 to 10 mm from ±2.5 m from IP.
  - Local beta functions vary very fast around IP.

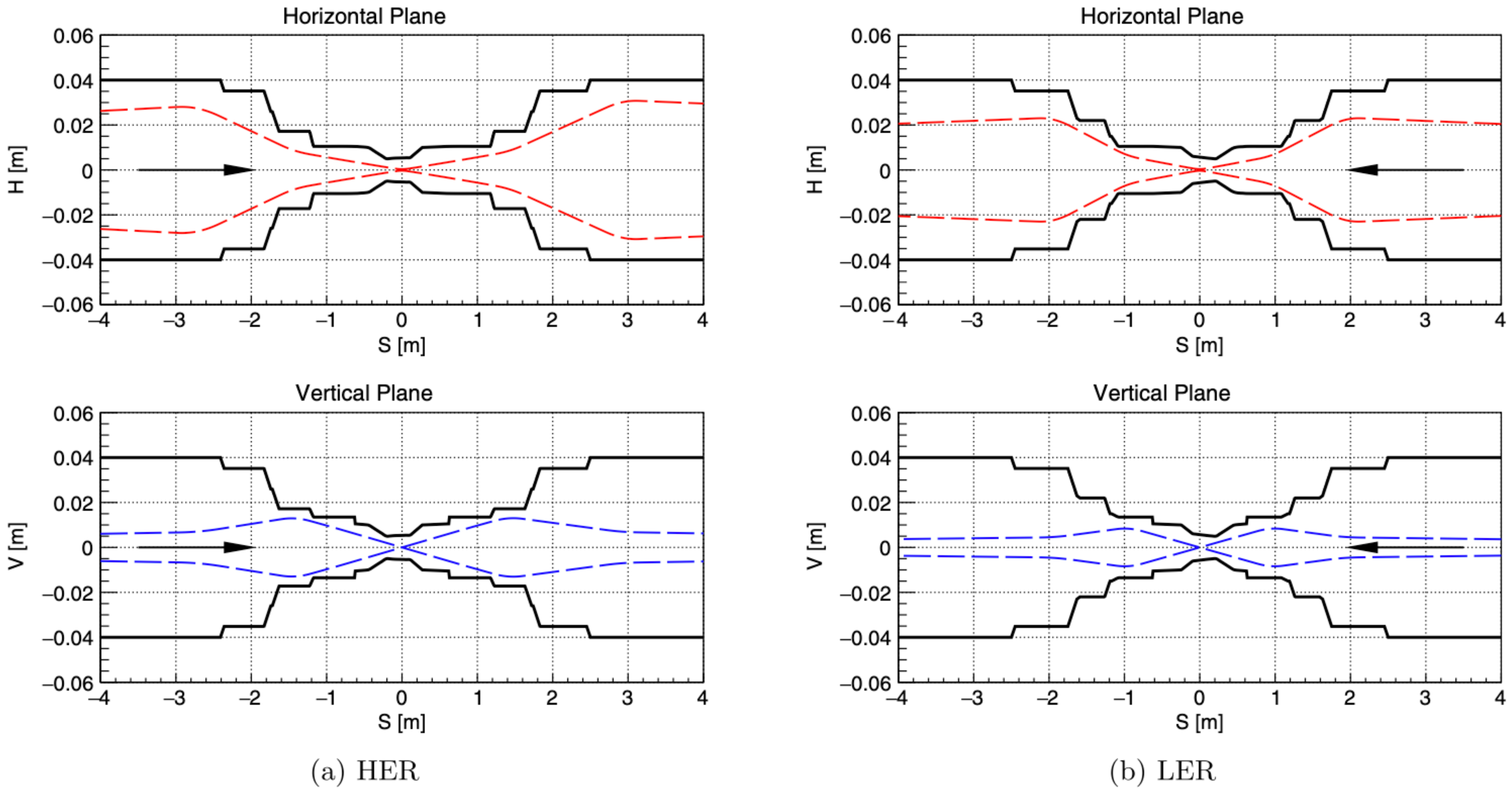


FIG. 7. Physical aperture of the HER (a) and LER (b) beam pipes in the IR, as implemented in SAD. Colored lines represent the beam envelope, which is limited by collimators. Arrows indicate the beam direction. The beam optics simulated are those of June 2020: a beta function at the IP of $\beta^*_{\mathrm{H/V}} = 60/0.8$ mm and crab sextupoles turned on for a so-called Crab Waist collision scheme [27].

Courtesy of A. Natochii

[1] A. Natochii et al., PRAB 24, 081001 (2021).

Vacuum chambers

Do analytic theories of RW impedance apply to SuperKEKB collimators?

$$Z_1^{\perp}(\omega) = \frac{f_Y L(\mathbf{sgn}(\omega) - i)}{\pi b^3} \sqrt{\frac{Z_0 c}{2|\omega|\sigma_c}}$$

- Collimators [1]
  - KEKB-type collimators are mainly used in HER.
  - SuperKEKB-type collimators are mainly used in LER (ante-chambers limit the use of KEKB-type collimators in LER).

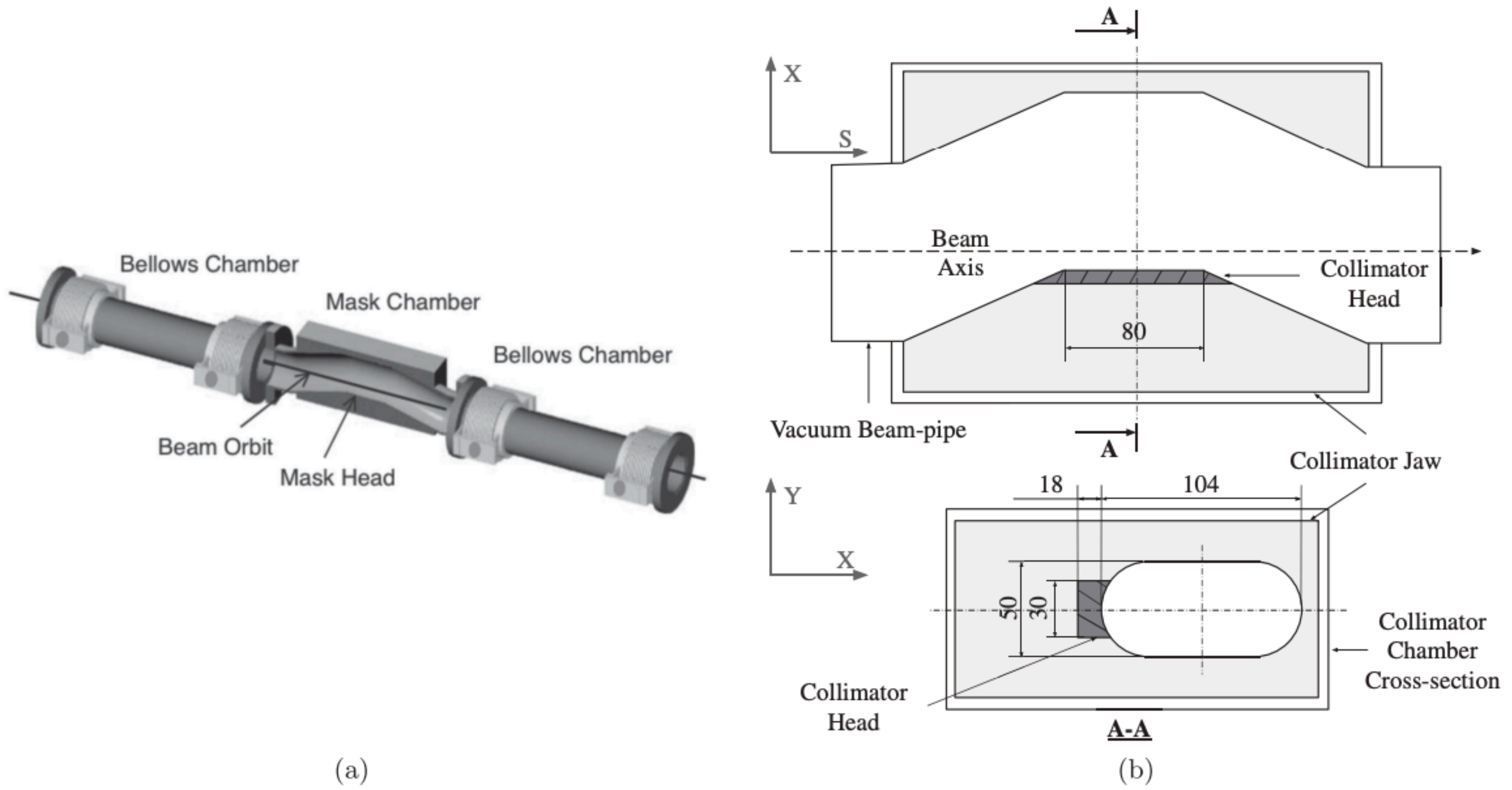


FIG. 5. *KEKB-type* collimators have a single jaw, on only one side of the beam. All dimensions are in mm. (a) Conceptual drawing of the collimator assembly [16]. (b) Schematic drawing of the horizontal collimator chamber.

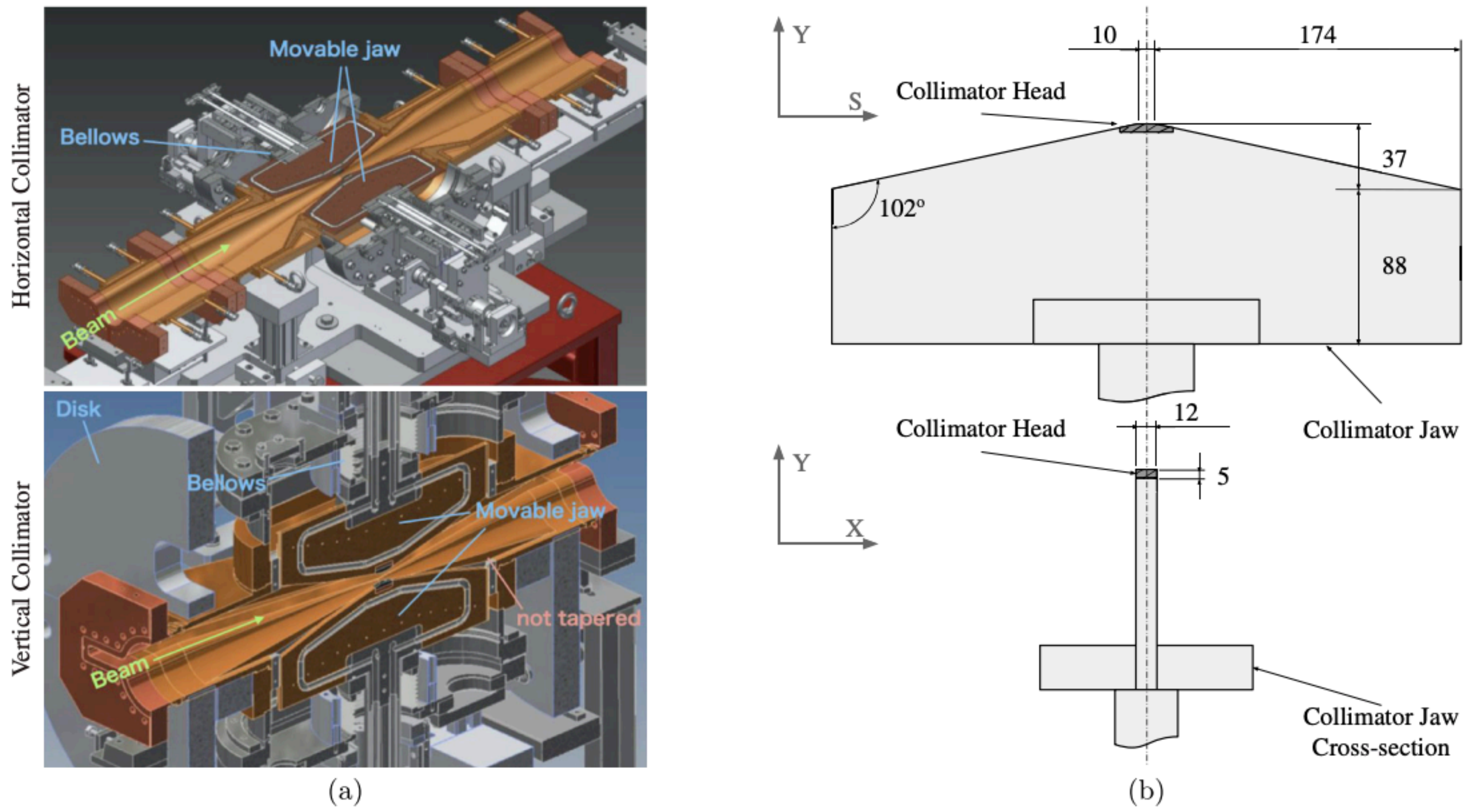


FIG. 6. *SuperKEKB-type* collimators have two jaws, one on each side of the beam. All dimensions are in mm. (a) Conceptual drawings of the collimator assembly [17]. (b) Schematic drawing of the collimator jaw.

Courtesy of A. Natochii

[1] A. Natochii et al., PRAB 24, 081001 (2021).

Optics

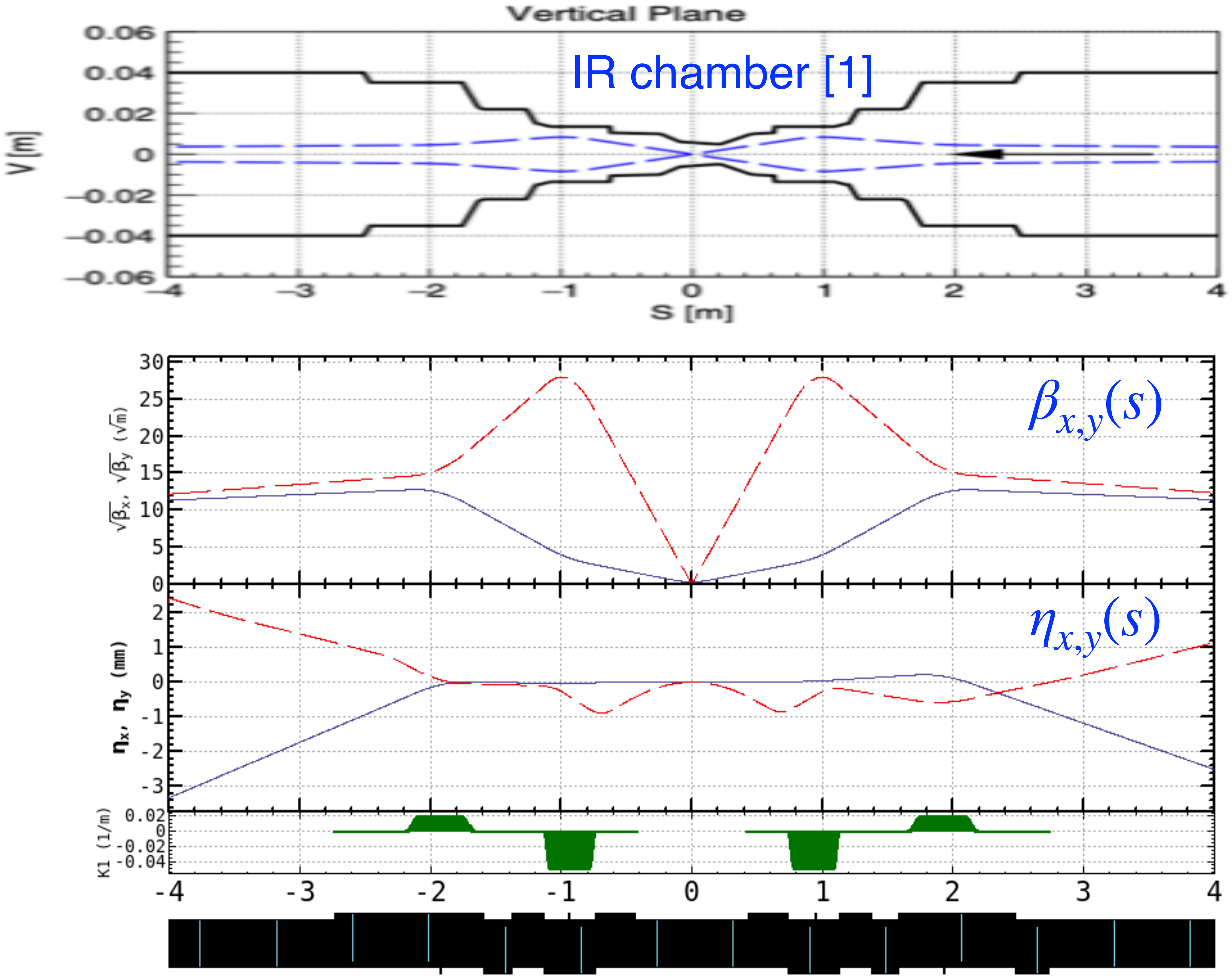
See talks by G. Bassi and T. Ishibashi

- IR optics
  - TCBI theory depend on beta functions

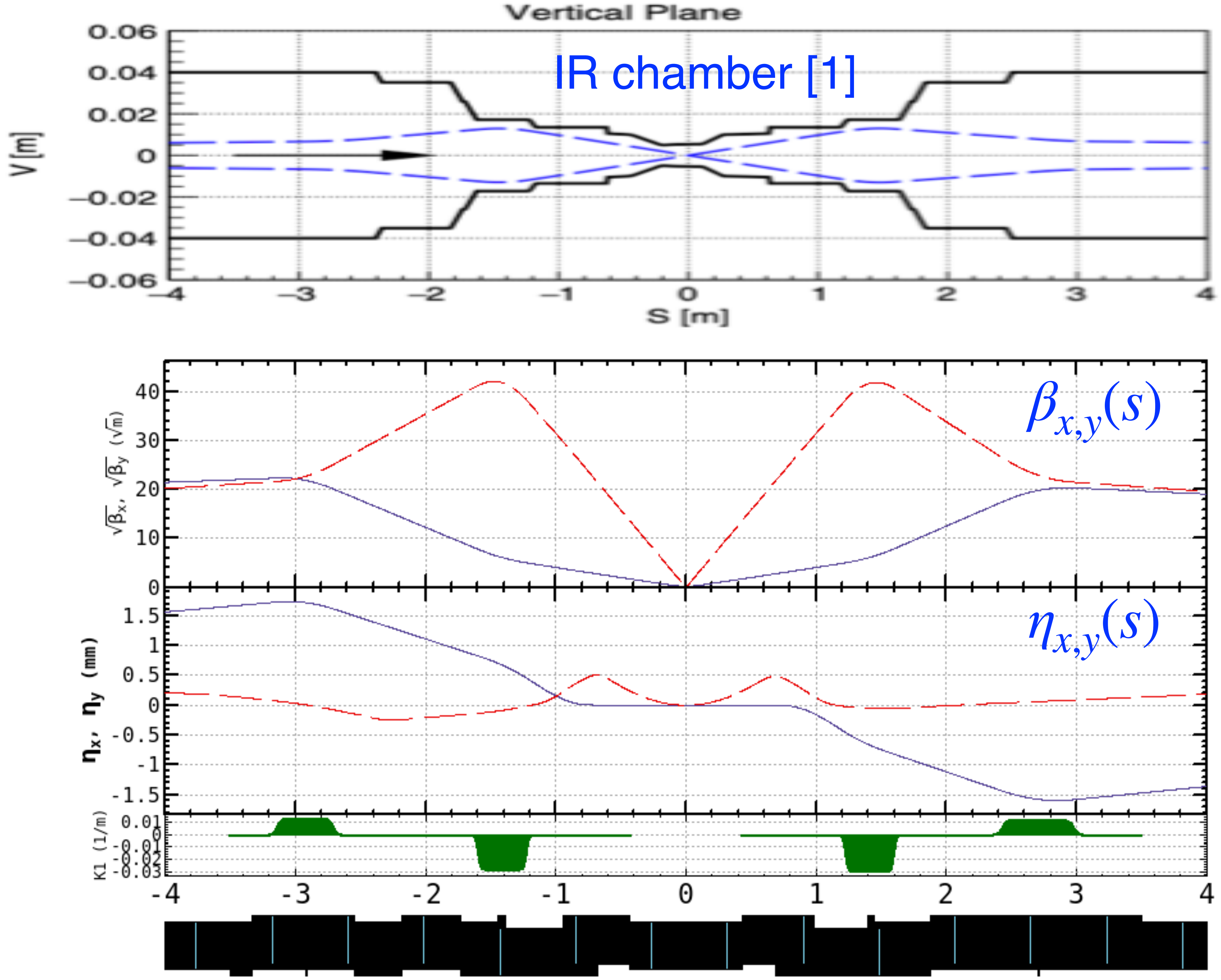
$$\bar{Z}_1^{\perp}(\omega) = \sum_i \beta_{yi} Z_{1i}^{\perp}(\omega)$$

Does "smooth approximation" apply to SuperKEKB IR?

LER



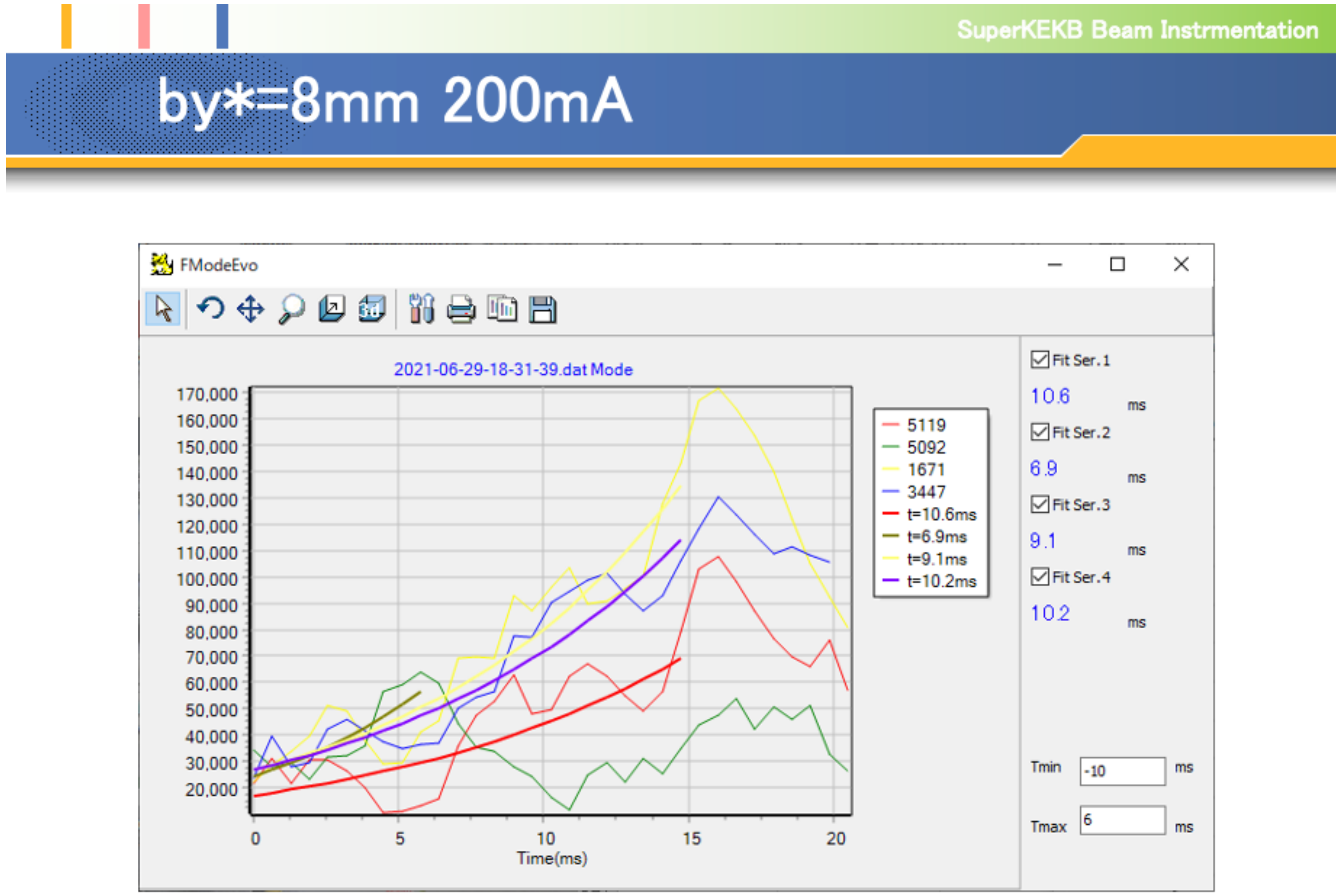
HER

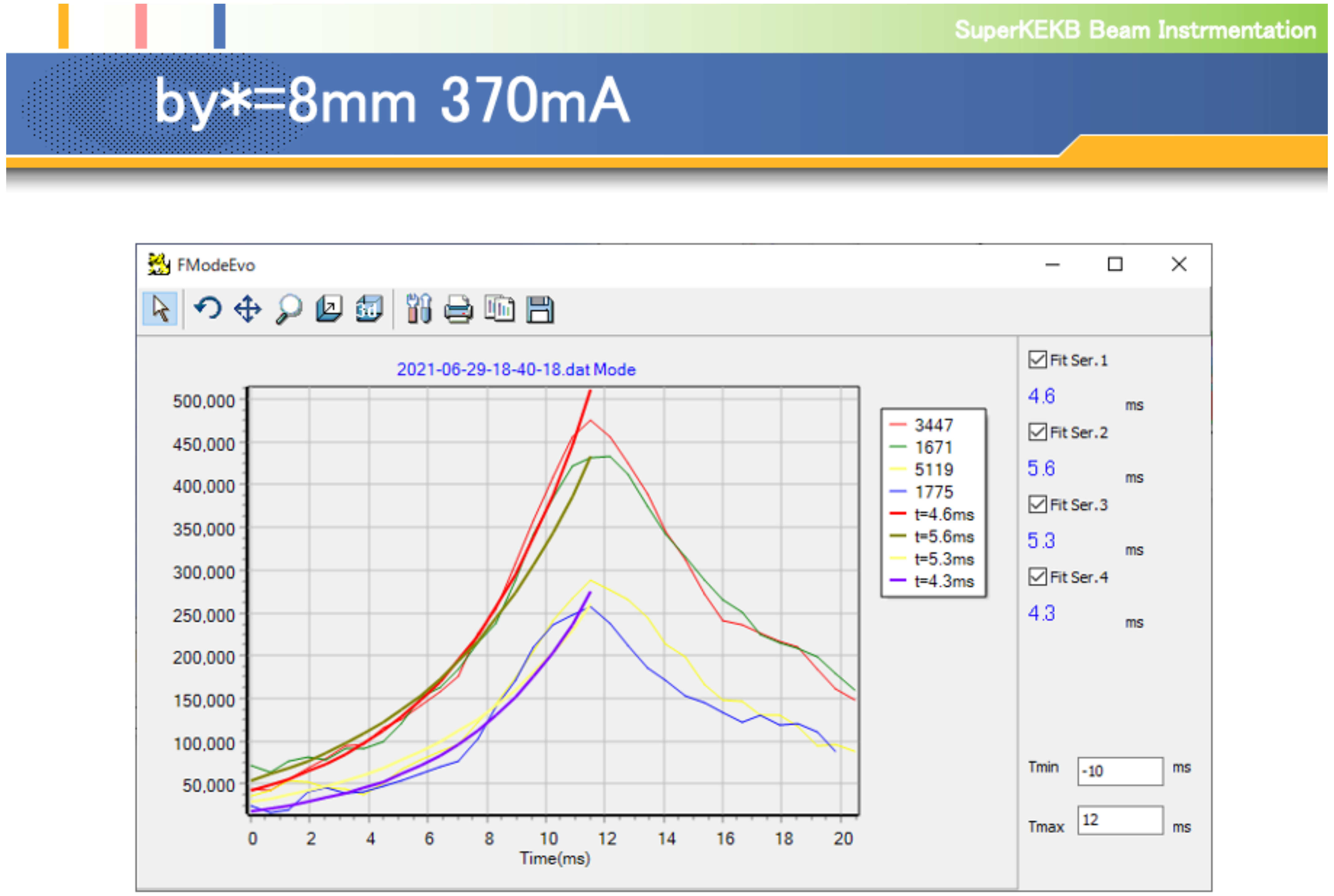


[1] A. Natochii et al., PRAB 24, 081001 (2021).

TCBI at HER

- Grow-damp study at HER (2021.06.29, M. Tobiyama)
  - Mode -1 dominates the instability.
  - This instability should be attributed to resistive wall (RW) impedance.





Courtesy of M. Tobiyama

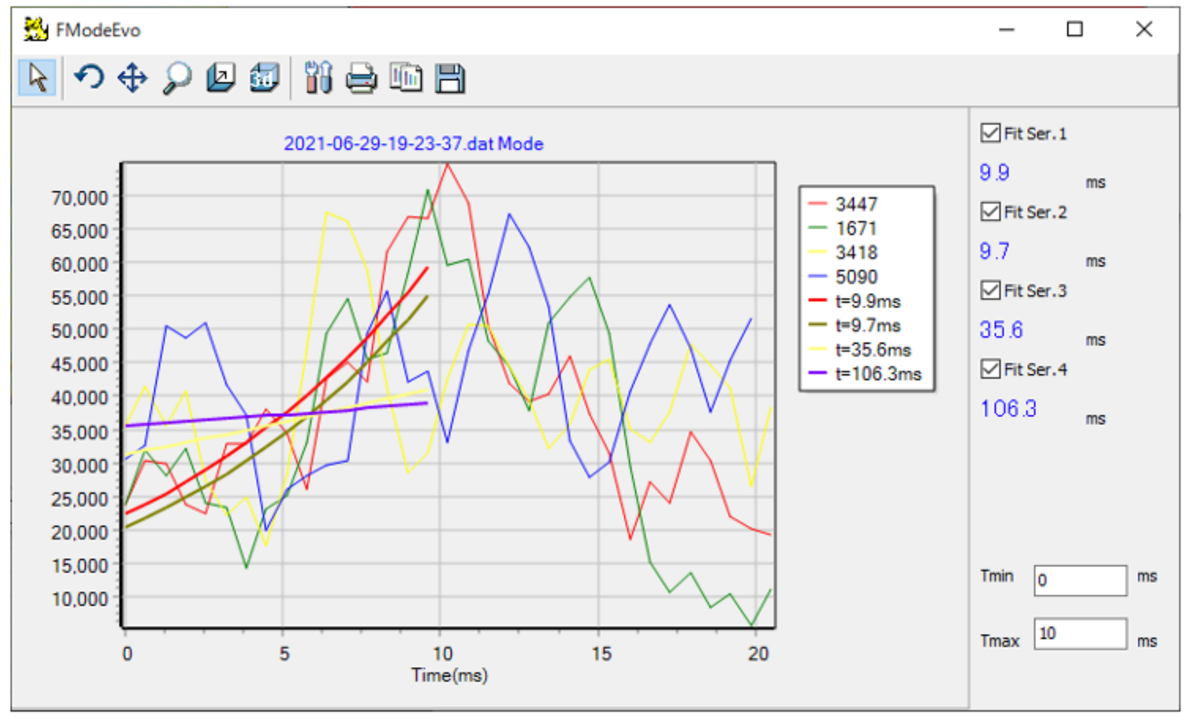
TCBI at HER

- Grow-damp study at HER (2021.06.29, M. Tobiyama)
  - Mode -1 dominates the instability.

Question:
Does the growth rate depend on β_y^*?

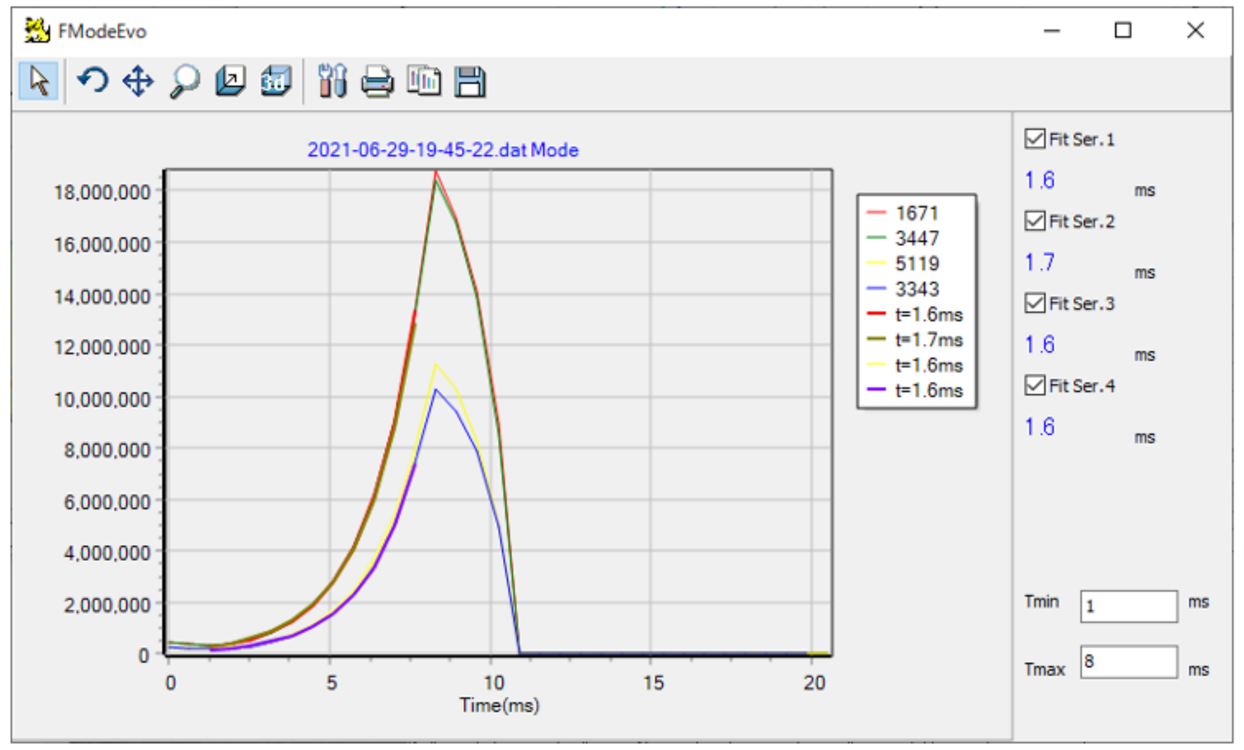
SuperKEKB Beam Instrmentation

by*=1mm 200mA



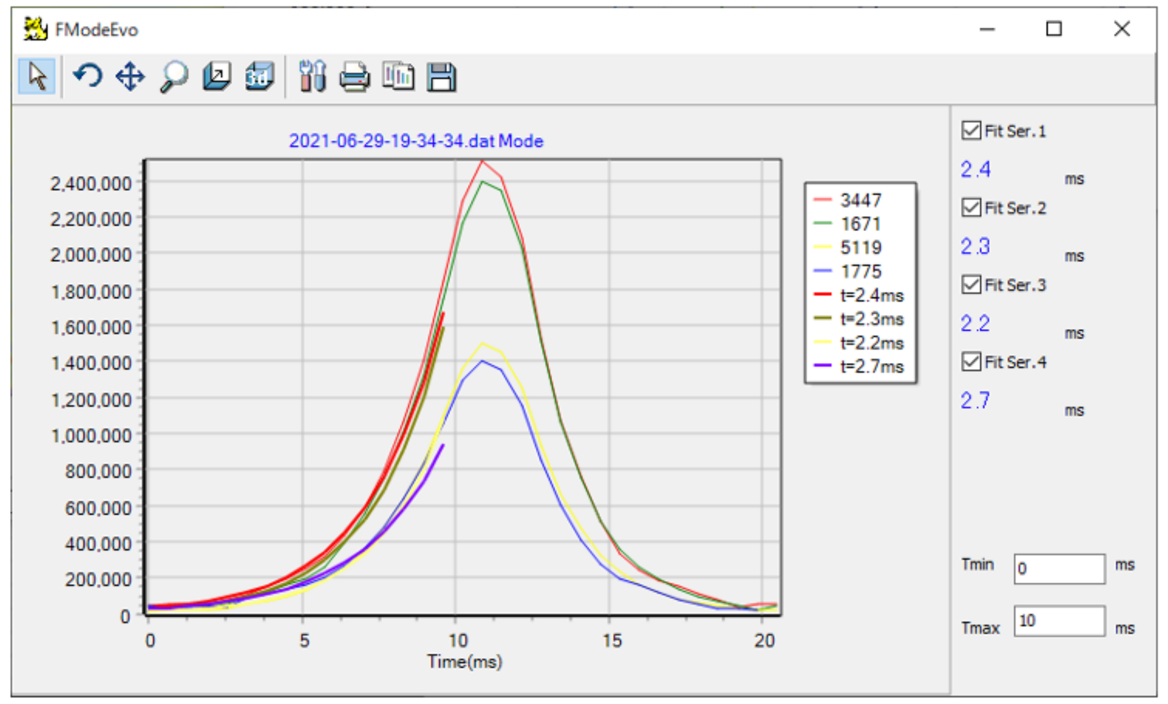
SuperKEKB Beam Instrmentation

by*=1mm 600mA



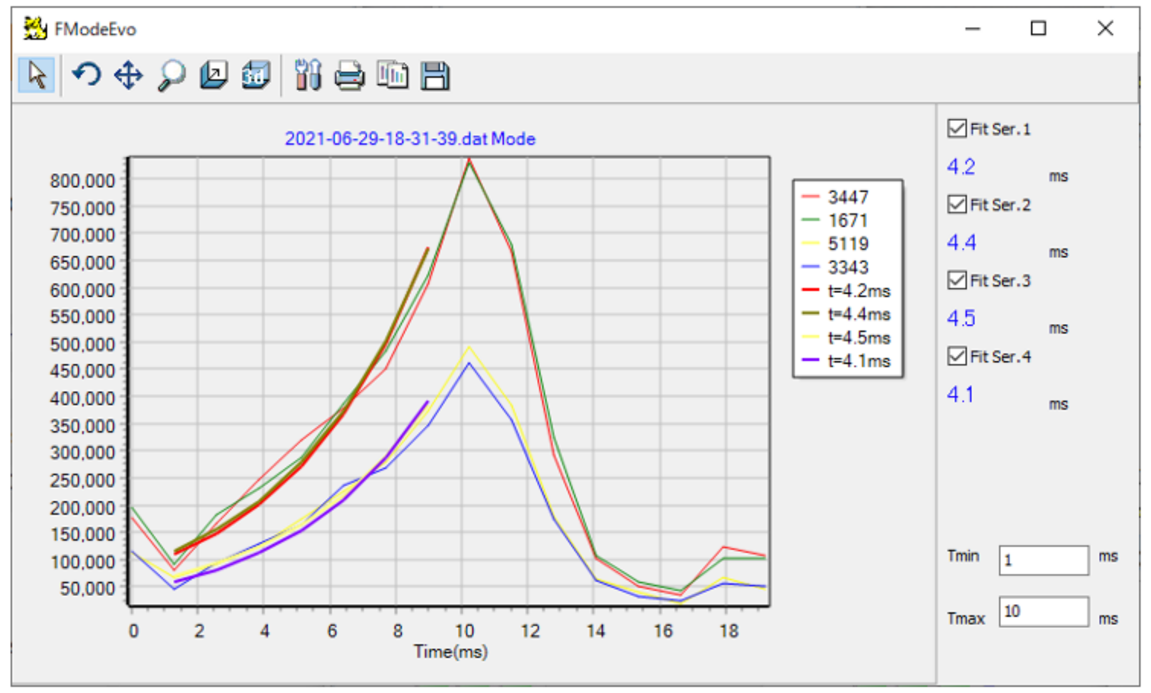
SuperKEKB Beam Instrmentation

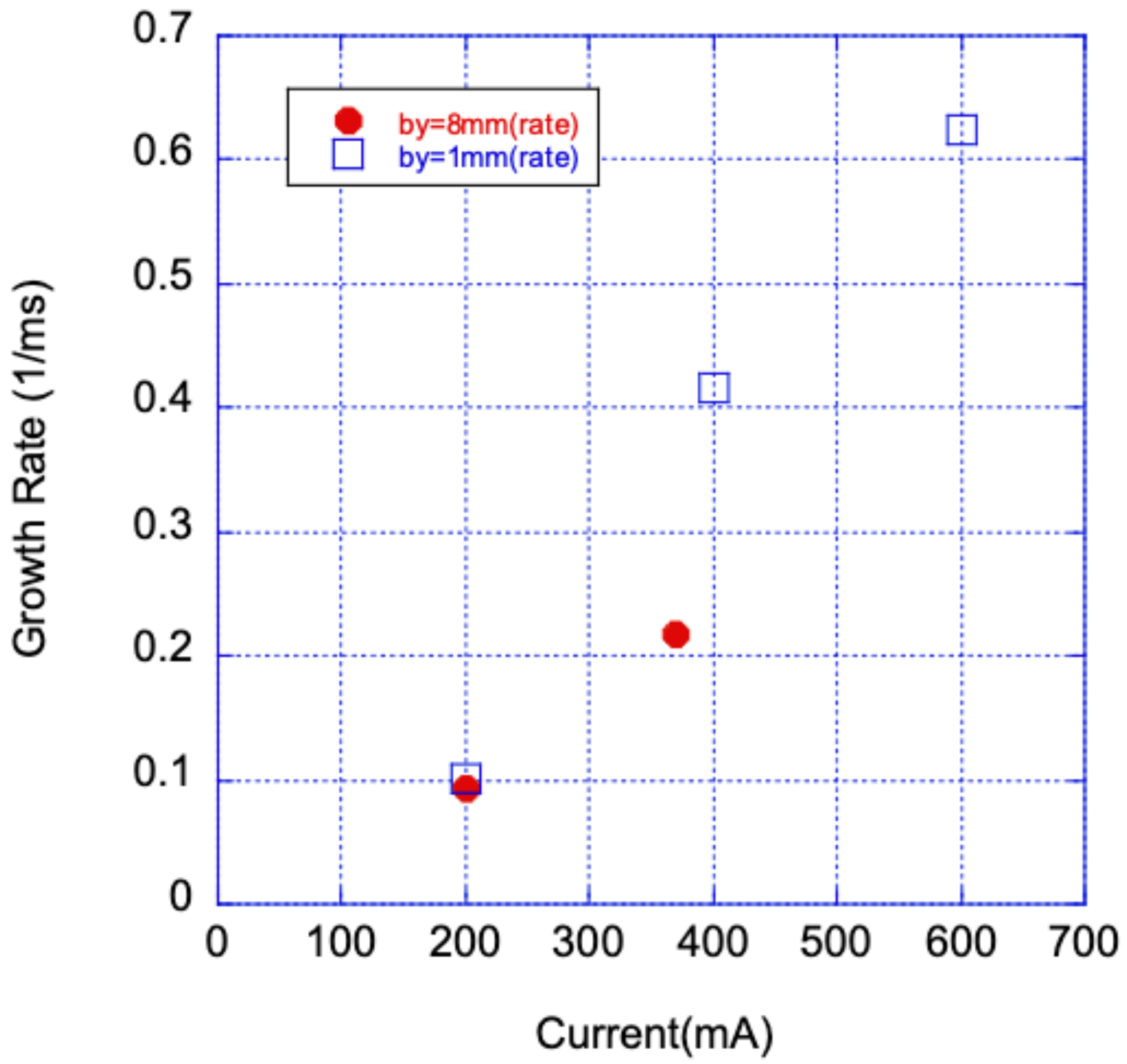
by*=1mm 400mA



SuperKEKB Beam Instrmentation

During collision (by*=1mm, 670mA)

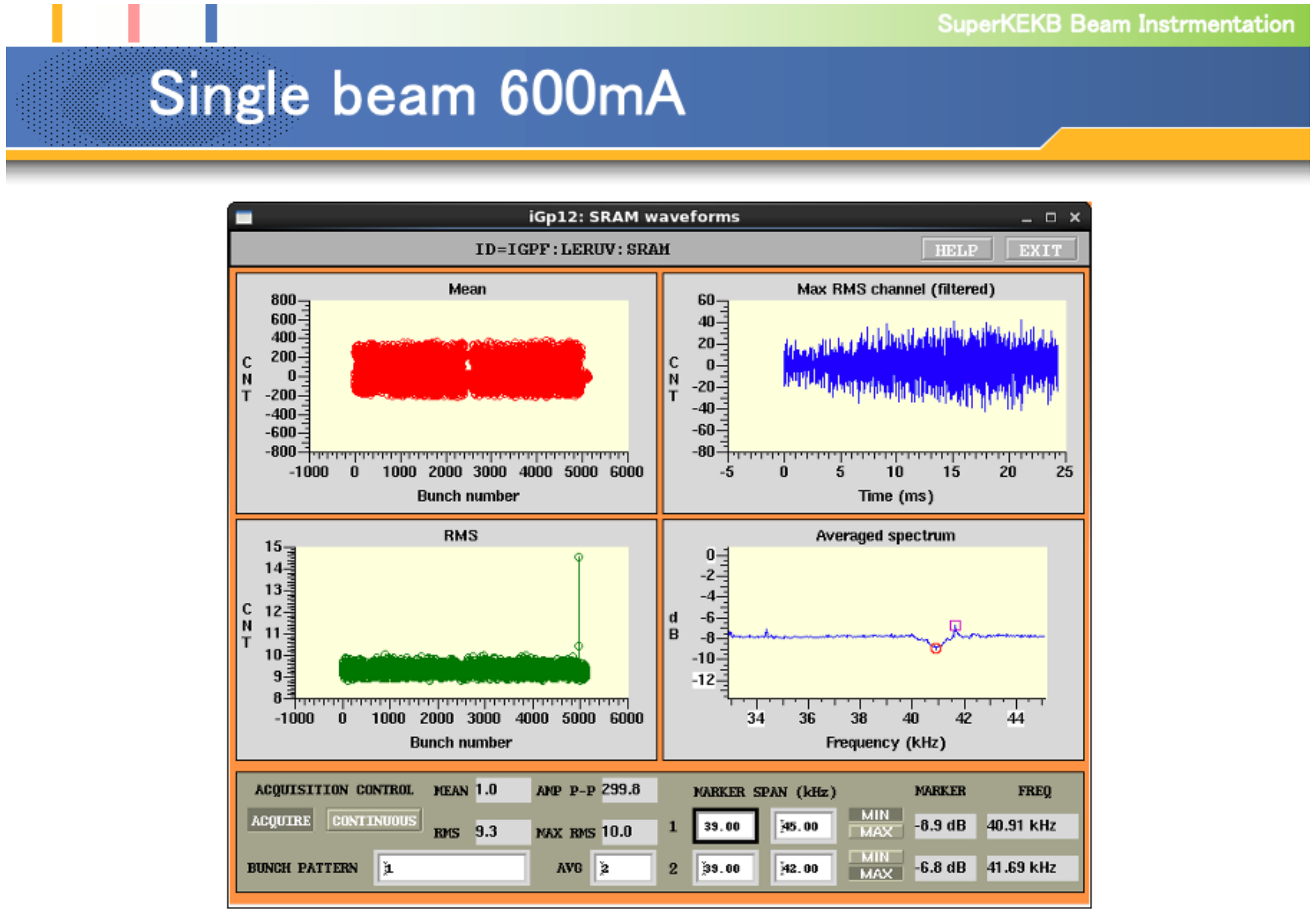


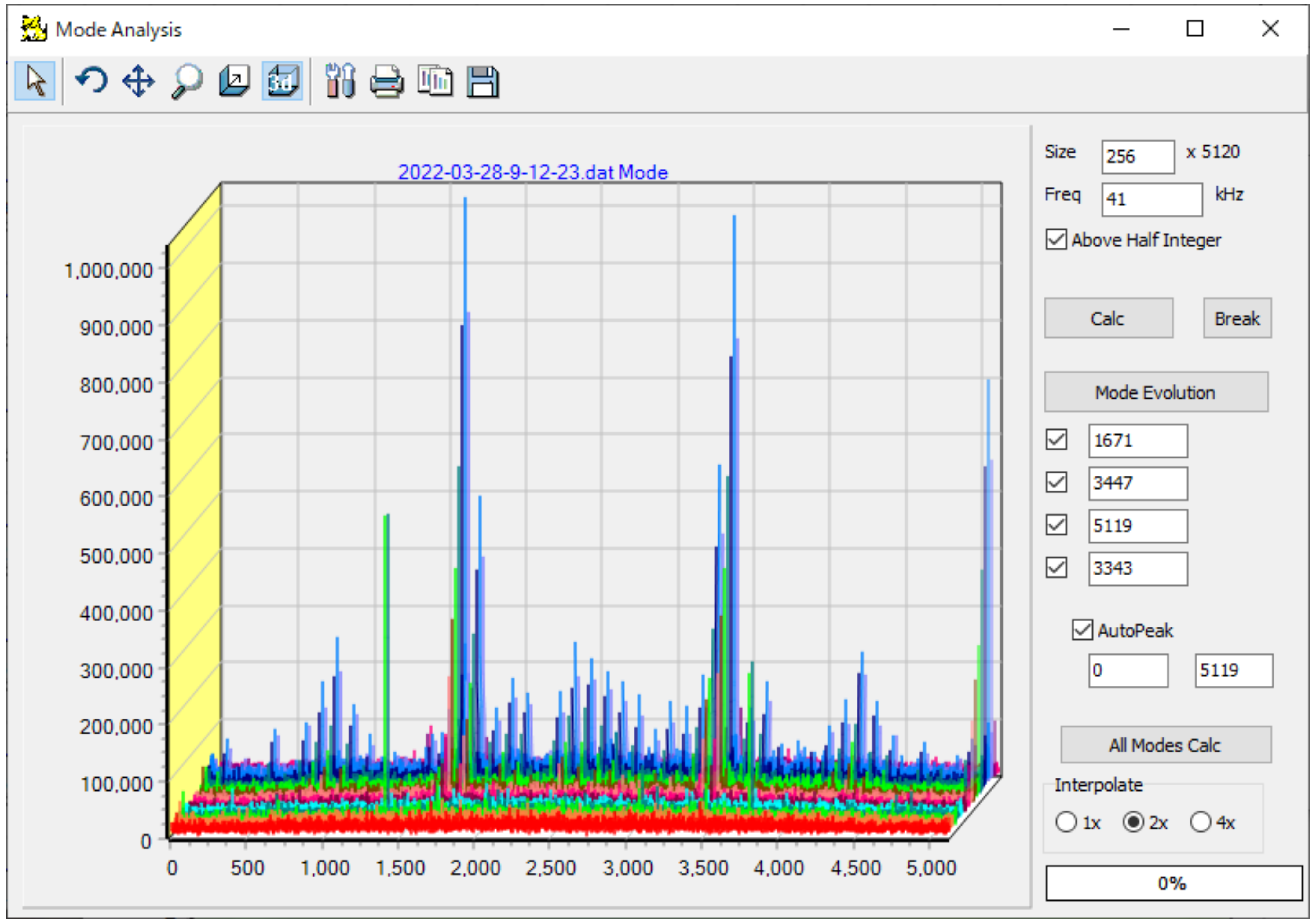


Courtesy of M. Tobiyama

TCBI at LER

- Grow-damp study at LER (2022.03.28, M. Tobiyama)
  - Mode -1 dominates the instability.
  - This instability should be attributed to resistive wall (RW) impedance.

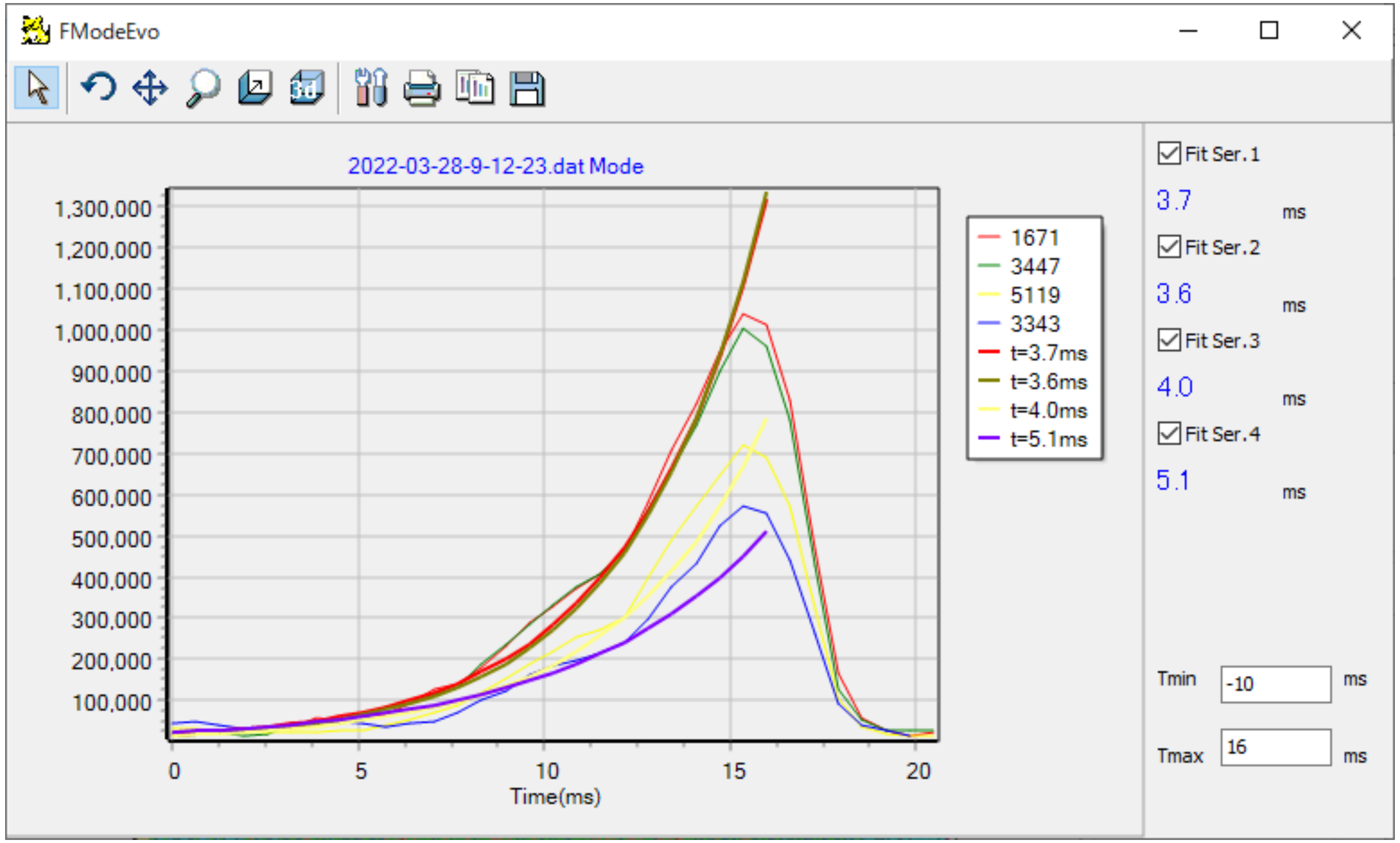




Courtesy of M. Tobiyama

TCBI at LER

- Grow-damp study at LER (2022.03.28, M. Tobiyama)
  - Mode -1 dominates the instability.
  - Growth time around 3.6 ms with Ibeam=600 mA.
  - This instability should be attributed to resistive wall (RW) impedance.



Courtesy of M. Tobiyama

TCBI theory

- Assume a uniform filling pattern. The n-th bunch takes the motion of [1]

$$y_n^{\mu}(t) = Ae^{2\pi i \frac{\mu n}{M}} e^{-i\Omega_\mu^U t} \quad \textbf{(1)}$$

- M=5120 for SuperKEKB. The eigenvalues Ω_μ^U are given by [2]

$$\Omega_\mu^U = -i\frac{I_0}{2T_0(E/e)} \sum_{p=-\infty}^{+\infty} |\tilde{\lambda(p')}|^2 \bar{Z}_1^{\perp}(p') \quad \textbf{(2)}$$

- $p' = (pM + \mu + \nu_y)\omega_0$, $\omega_0 = 2\pi f_0 = 2\pi/T_0 = 2\pi/(C/c)$ with $C = 3016.315$ m for SuperKEKB. I_0 is the total beam current. E is the beam energy. The imaginary part of Ω_μ^U determines the growth rate

$$\frac{1}{\tau_\mu^U} = -\frac{I_0}{2T_0(E/e)} \sum_{p=-\infty}^{+\infty} |\tilde{\lambda(p')}|^2 \textbf{Re}[\bar{Z}_1^{\perp}(p')] \quad \textbf{(3)}$$

[1] A. Wolski, “Beam dynamics in high energy particle accelerators”, Imperial College Press, 2014.

[2] G. Bassi et al, PRAB 25, 014402 (2022).

TCBI theory

- The transverse average impedance $\bar{Z}_1^{\perp}(\omega)$ (weighted by local beta functions) is

$$\bar{Z}_1^{\perp}(\omega) = \sum_i \beta_{yi} Z_{1i}^{\perp}(\omega) \quad \textbf{(4)}$$

- The major contribution to the TCBI is from low-frequency resistive wall impedance [1]

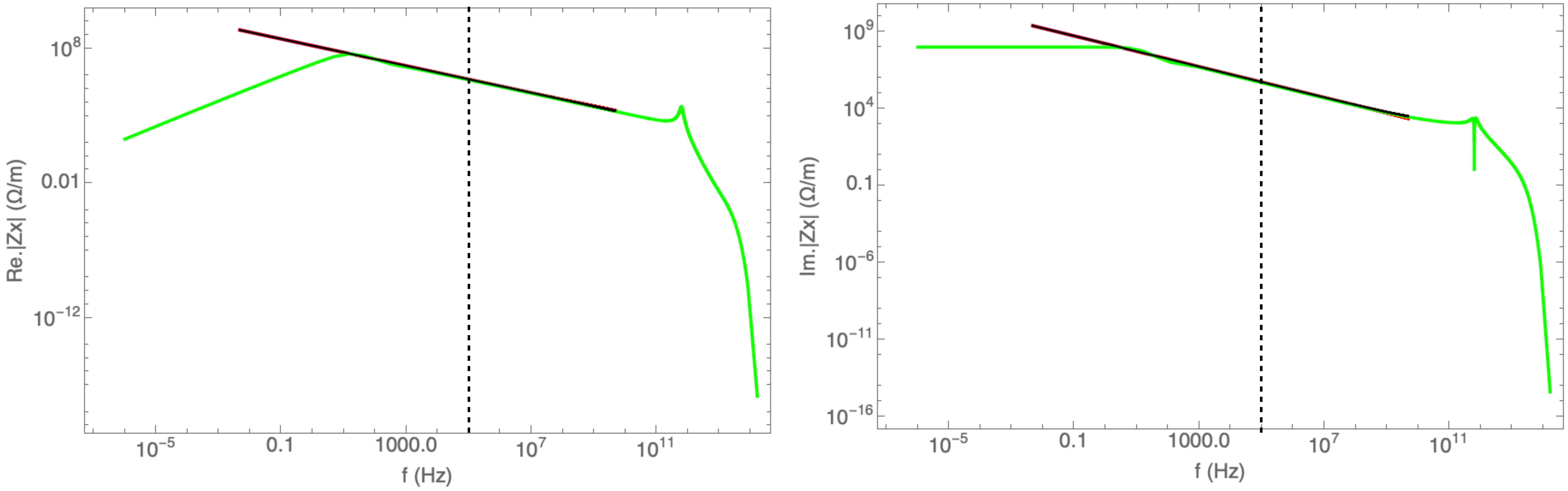
$$Z_1^{\perp}(\omega) = \frac{f_Y L(\mathbf{sgn}(\omega) - i)}{\pi b^3} \sqrt{\frac{Z_0 c}{2|\omega|\sigma_c}} \quad \textbf{(5)}$$

- f_Y is the geometric factor (Yokoya factor): For components with round geometry, f_Y=1; For components with parallel-plates geometry, $f_Y = \pi^2/12$. L is the length of the component. b is the half aperture (chamber radius). σ_c is the electrical conductivity. Since only impedance at low frequency $\omega \approx \omega_0$ is important for TCBI, coating (such as TiN) is negligible in the evaluation of TCBI.

[1] A. Chao et al. “Handbook of Accelerator Physics and Engineering”, World Scientific, 2013.

TCBI theory

- Benchmark of impedance formulae with IW2D (Green lines, by M. Migliorati) for LER
- Good agreement was seen in the frequency range ($f_0 \approx 100$ kHz) of interest for TCBI analysis.
- Analytic theory for RW: Simple model (Eq.(5)) and two-layer model [1]



[1] M. Ivanyan and V. Tsakanov, PRST-AB 7, 114402 (2004).

TCBI theory

- The growth rate of RW driven TCBI scale as

$$\frac{1}{\tau_\mu^U} \propto \frac{I_0 L \beta_y}{b^3 \sqrt{\sigma_c}} \quad \textbf{(6)}$$

Question:
Does Eq.(6) imply the collimators (small b) and IR (large β_y) can be important for TCBI?

- The fasted growth rate of RW driven TCBI modes is given by

$$\frac{1}{\tau_y} = \frac{I_0}{2T_0(E/e)} \mathbf{Re}[\bar{Z}_1^\perp(-(1-Q_y)\omega_0)] = \frac{I_0}{2T_0(E/e)} \frac{1}{\sqrt{1-Q_y}} \mathbf{Re}[\bar{Z}_1^\perp(\omega_0)] \quad \textbf{(7)}$$

- Q_y is the fractional part of ν_y: $Q_y = \nu_y - \text{Int}[\nu_y]$. The above equation is determined by [1]

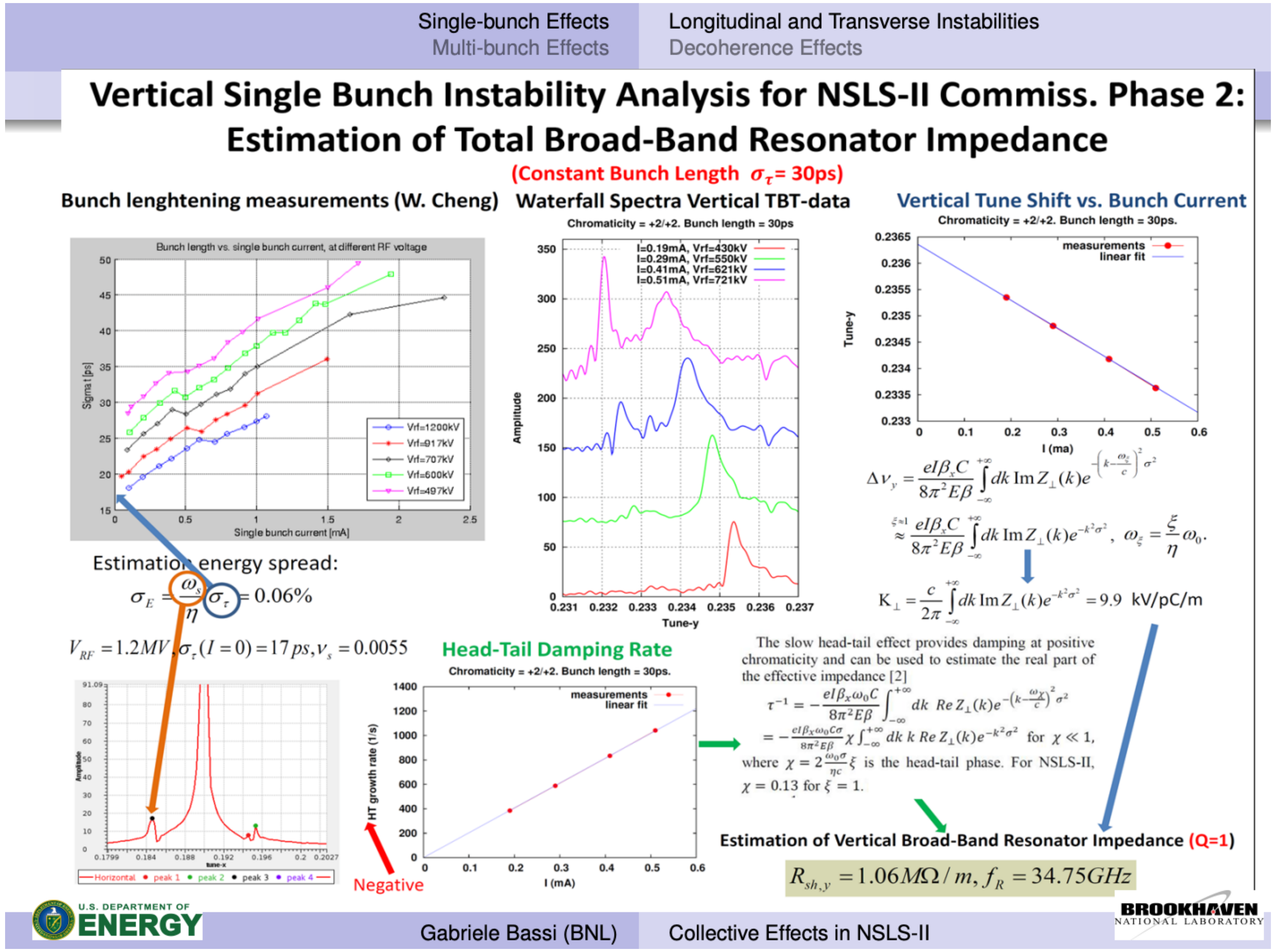
$$p' = (pM + \mu + \nu_y)\omega_0 = -(1-Q_y)\omega_0 \quad \textbf{(8)}$$

- It gives p=-1, $\mu_m = M - (\nu_y + 1 - Q_y) = M - \text{Int}(\nu_y) - 1$, assuming $0 \leq \mu < M$. The fast mode μ_m corresponds to the "-1 mode" in measurement.

[1] A. Wolski, "Beam dynamics in high energy particle accelerators", Imperial College Press, 2014.

Effect of slow head-tail effect

- Positive chromaticity generates head-tail damping [1,2]



[1] G. Bassi, Talk to TWIICE, 2016.

[2] G. Bassi et al., NIMA 810 (2016) 151-163.

Effect of uneven filling pattern

- With a gap ratio w<0.3, the simple theory with an even filling pattern seems to work well [1]

Multi-bunch instability with uneven fills

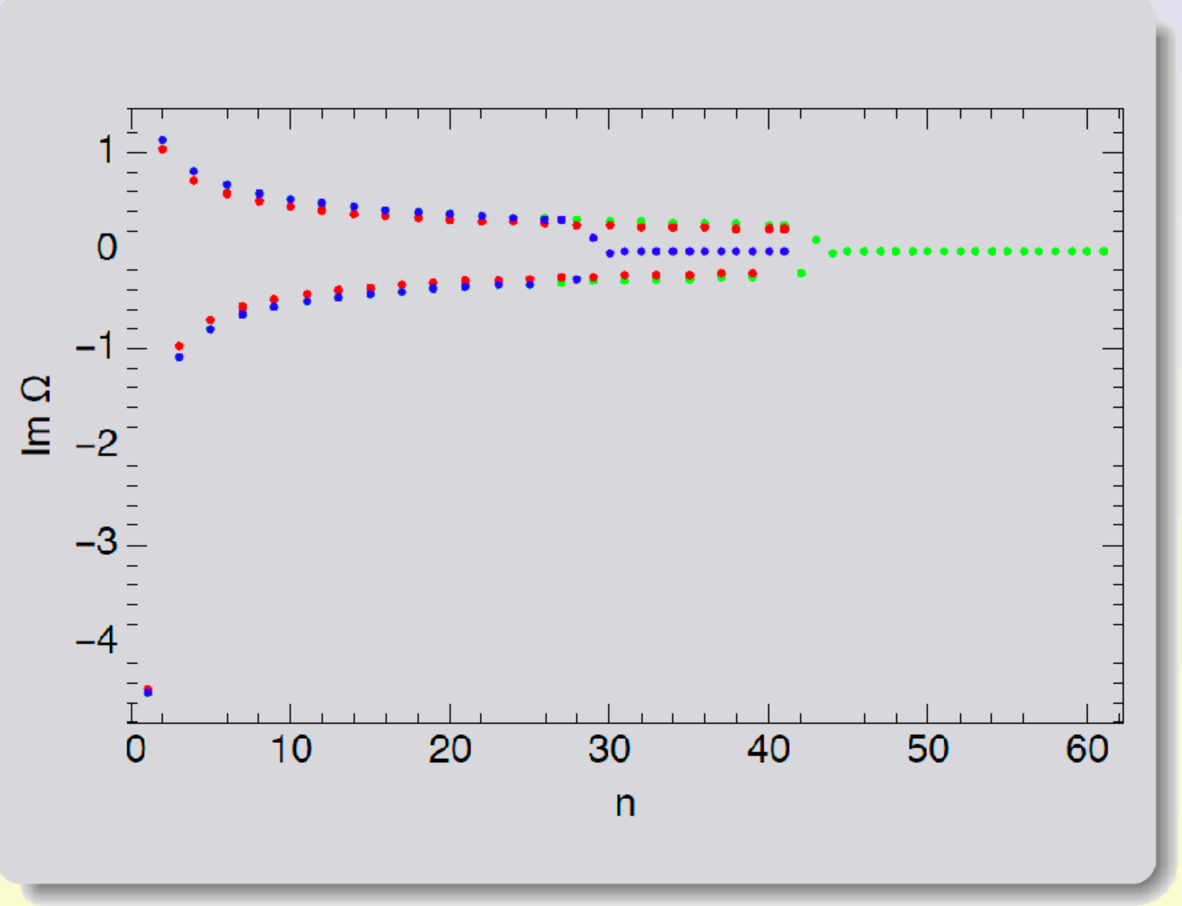
Gennady Stupakov
SLAC National Accelerator Laboratory, Menlo Park, CA 94025

CERN, April 18, 2016

Gap $w = 0.3$ in the bunch train

$[\nu_\beta] = 0.05$, gap $w = 0.3$ with the same beam current $\bar{I}$ as in a uniform fill.

Red—uniform fill, blue—a fill with 0.3 gap, 41 modes, green—a fill with 0.3 gap, 61 modes.



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Summary

- With the number of bunches in the collider $M \gg 1$ one can use a continuous approximation to calculate the transverse MBI with non-uniform fills. An integral equation is derived for the coherent frequency shift of the beam oscillations in fluid approximation. For a given fill pattern, this equation can be easily solved using the Fourier expansion.
- For the RW MBI, gaps up to $w = 0.3$ do not noticeably change the growth rate of the most unstable mode (assuming the same averaged current of the beam)

I am interested in finding other applications for this technique and making comparison with computer simulations.

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[1] G. Stupakov, "Multi-bunch instability with uneven fills", presented at HSC meeting, CERN, Apr. 18, 2016.

TCBI at LER (Machine conditions of 2022.03.28)

- For SuperKEKB LER, the main sources of RW impedance are: 1) Normal chambers with b=45 mm; 2) IR chambers with large β_y and $b \approx$ 10 mm; 3) Small-gap collimators with b ~1 mm.
- For normal chambers, we take b=45 mm, L=3011 m, σ_c=3.8e7 S/m for aluminum, $\bar{\beta}_y$=25.3 m for the arc and straight sections. The growth time of the fast mode is τ_{y1}=6.65 ms with I_0=600 mA.
- For IR chambers, τ_{y2}=1.14 ms with I_0=600 mA and β_y^*=1 mm.
- For collimators, τ_{y3}=23.1 ms with I_0=600 mA.
- SR radiation damping time τ_{ySR}=-45.7 ms.
- Head-tail damping time with ξ_y=+1.5, τ_{yHT}=-17.9 ms. (This value seems to be consistent with the findings of Refs.[1,2] (to be confirmed))
- In total, we obtain a growth time of τ_y^{Theory}=1 ms. This cannot explain the experimental data of τ_y^{Exp}=3.6 ms (see page.11).

$$\frac{1}{\tau_y^{Theory}} = \frac{1}{\tau_{y1}} + \frac{1}{\tau_{y2}} + \frac{1}{\tau_{y3}} + \frac{1}{\tau_{ySR}} + \frac{1}{\tau_{yHT}}$$

[1] J. Keintzel et al., IPAC2021, TUPAB010.
[2] N. Kuroo et al., IPAC2017, THPVA012.

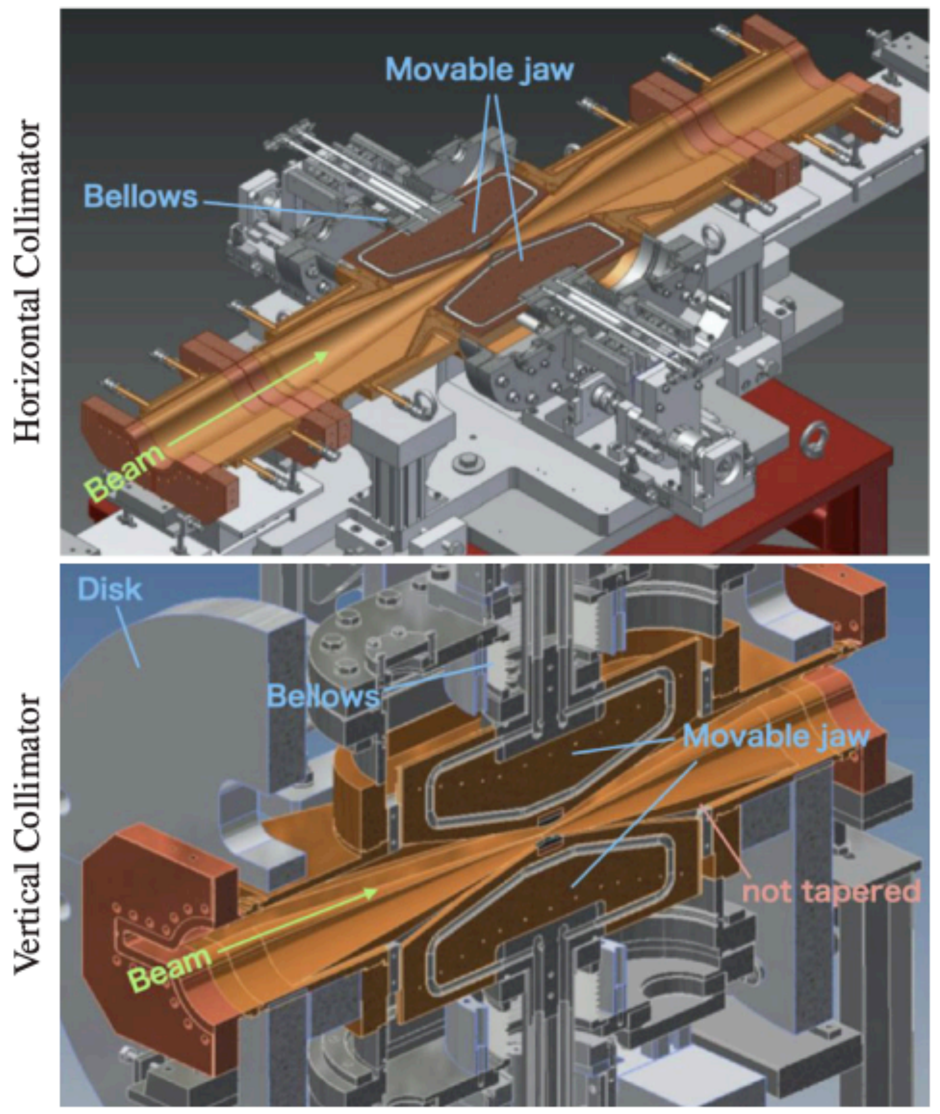
TCBI at HER (Machine conditions of 2021.06.29)

- For SuperKEKB LER, the main sources of RW impedance are: 1) Normal chambers with b=25 mm, considering Yokoya factor; 2) IR chambers with large β_y and $b \approx$ 10 mm; 3) Small-gap collimators with b ~1.4 - 4.0 mm.
- For normal chambers, we take b=25 mm, L=3011 m, σ_c=5.8e7 S/m for copper, $\bar{\beta}_y$=25.8 m for the arc and straight sections. The growth time of the fast mode is τ_{y1}=1.68 ms with I_0=600 mA.
- For IR chambers, τ_{y2}=0.82 ms with I_0=600 mA and β_y^*=1 mm.
- For collimators, τ_{y3}=5.25 ms with I_0=600 mA (Total jaw length is longer than that of LER).
- SR radiation damping time τ_{ySR}=-58 ms.
- Head-tail damping time with ξ_y=+1.5, τ_{yHT}=? ms (Not estimated yet).
- In total, we obtain a growth time of τ_y^{Theory}=0.5 ms. This cannot explain the experimental data of τ_y^{Exp}=1.6 ms.

$$\frac{1}{\tau_y^{Theory}} = \frac{1}{\tau_{y1}} + \frac{1}{\tau_{y2}} + \frac{1}{\tau_{y3}} + \frac{1}{\tau_{ySR}} + \frac{1}{\tau_{yHT}}$$

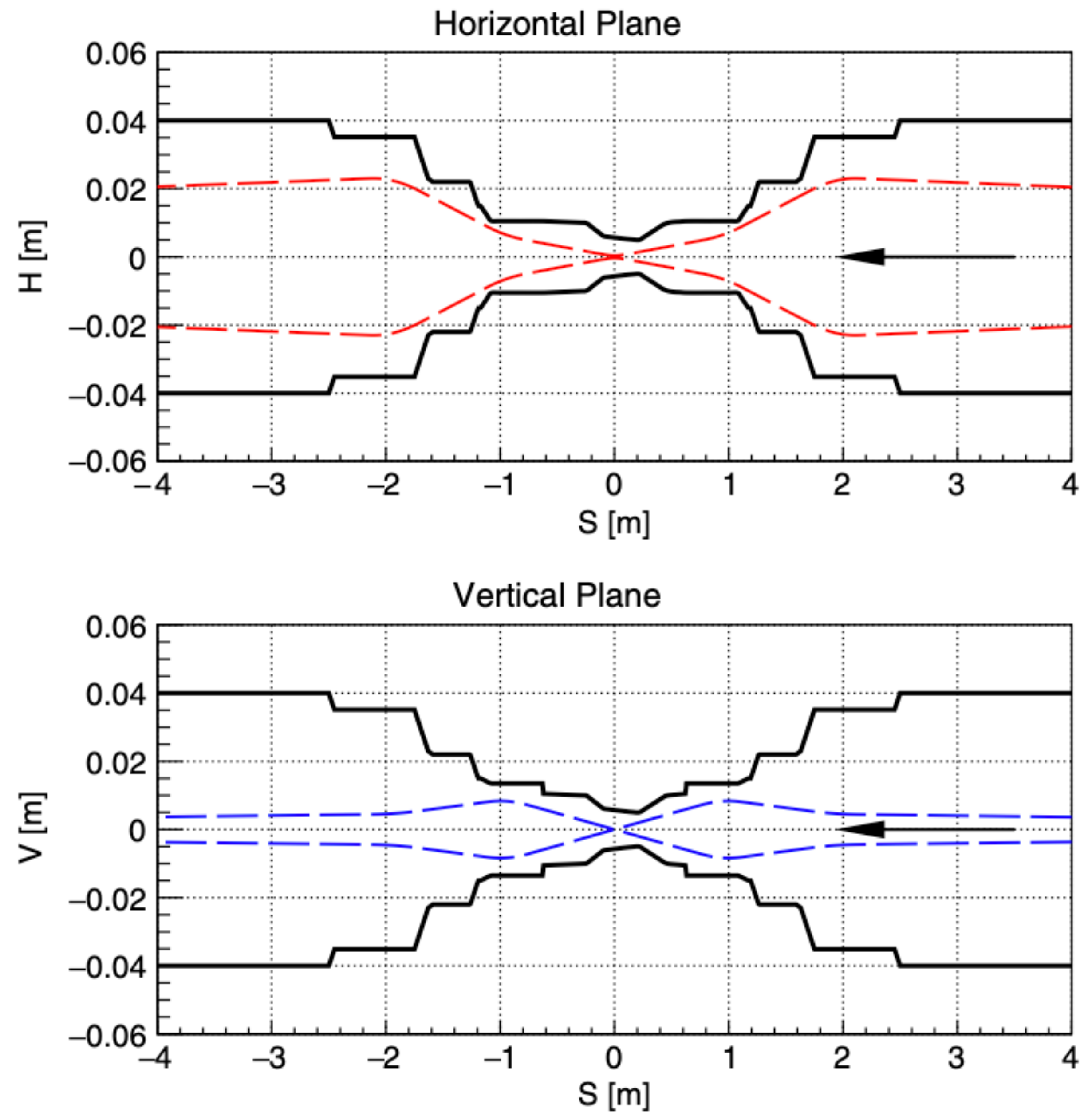
Open questions

Courtesy of A. Natochii



(a)

Courtesy of A. Natochii



(b) LER

Do Eqs. (4-5) with $\omega_0 = 2\pi f_0$ apply to the SuperKEKB-type collimator (L and b are simultaneously very small)?

$$\bar{Z}_1^{\perp}(\omega) = \sum_i \beta_{yi} Z_{1i}^{\perp}(\omega) \quad \textbf{(4)}$$

$$Z_1^{\perp}(\omega) = \frac{f_Y L(\mathbf{sgn}(\omega) - i)}{\pi b^3} \sqrt{\frac{Z_0 c}{2|\omega|\sigma_c}} \quad \textbf{(5)}$$

Do Eqs. (4-5) with $\omega_0 = 2\pi f_0$ apply to the SuperKEKB IR (tapered structure with fast variation in beta functions)?

Summary

- The TCBI observed in SuperKEKB cannot be well explained by the simple CBI model (uniform filling pattern) with a simple resistive wall model.
- Questions
  - The theories of RW impedance assume a smooth chamber in the s-direction. Are these theories applicable to the cases of 3D structures like IR chambers and collimators (where chamber lengths are small)?
  - Are there any missing factors affecting TCBI growth time?
- Squeezing β_y^* may cause more contributions to TCBI from the interaction region (due to larger β_y) and vertical collimators (due to smaller gaps).

TCBI at HER

- Grow-damp study at HER (2021.06.29, M. Tobiyama)
  - Mode -1 dominates the instability.
  - This instability should be attributed to resistive wall (RW) impedance.

Courtesy of M. Tobiyama

SuperKEKB Beam Instrmentation

HER vertical CBI

- **Measurement of instability growth rate and feedback damping rate using transient domain analysis with iGp12 digital filters.**
  - turn off FB (10ms – 15ms) and turn-on again, record 12MB data
- **by*=8mm (200mA, 370mA), by*=1mm (200mA, 400mA, 600mA) with normal filling pattern of current runs.**

SuperKEKB Beam Instrmentation

by*=8mm 200mA