Transverse coupled-bunch instability driven by resistive wall impedance

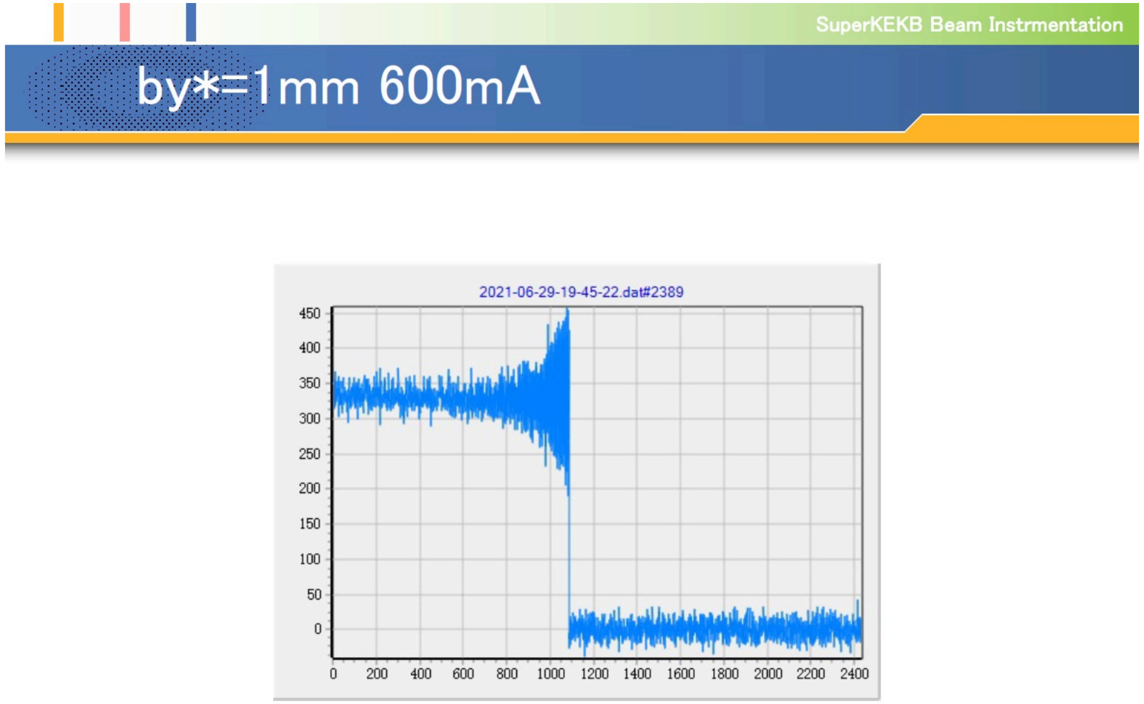
- TCBI observed in HER (during growth time study)
- TCBI theory with RW impedance
- TCBI by RW in LER

- D. Zhou, M. Tobiyama

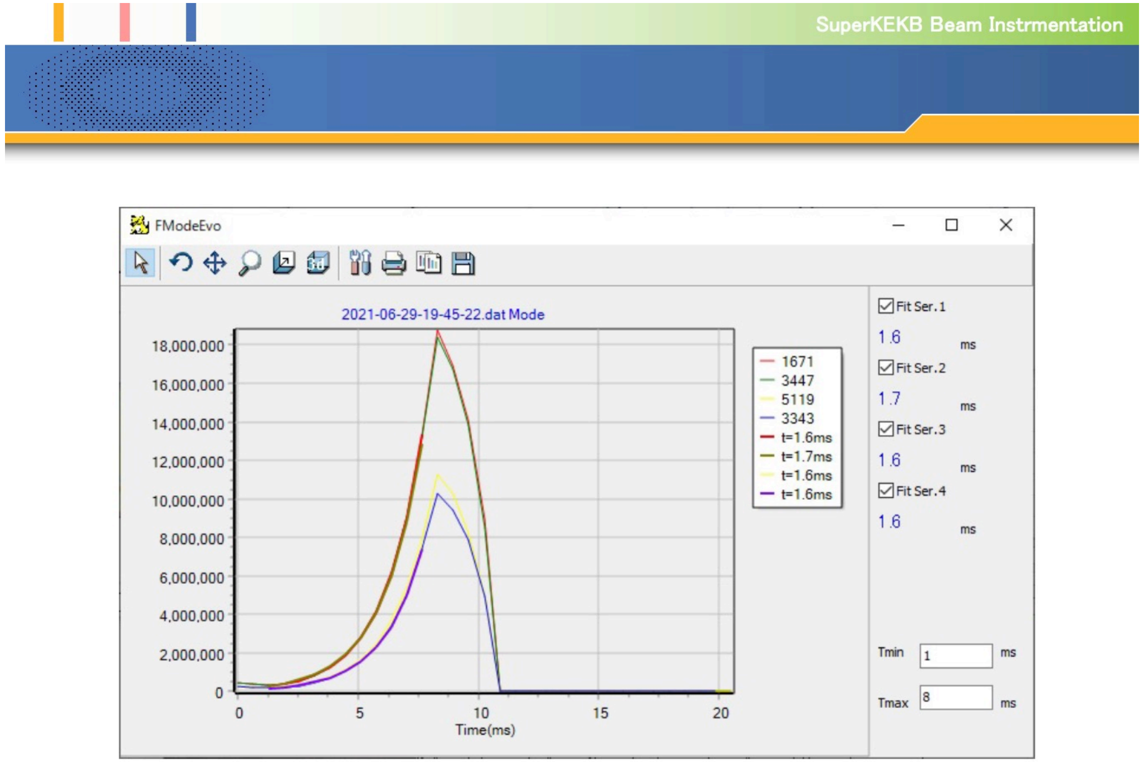
- SuperKEKB MDI meeting, KEK, Aug. 05, 2021

1. HER growth time study

- HER growth time study (2021/06/29 19:45:07)
- 599+496 mA 1272 bunch (no Belle HV)
- Coupled-bunch instability observed in vertical direction with FB off
- Fasted modes {1671,3447,5119}; Growth time ~1.6 ms with I_0=600 mA



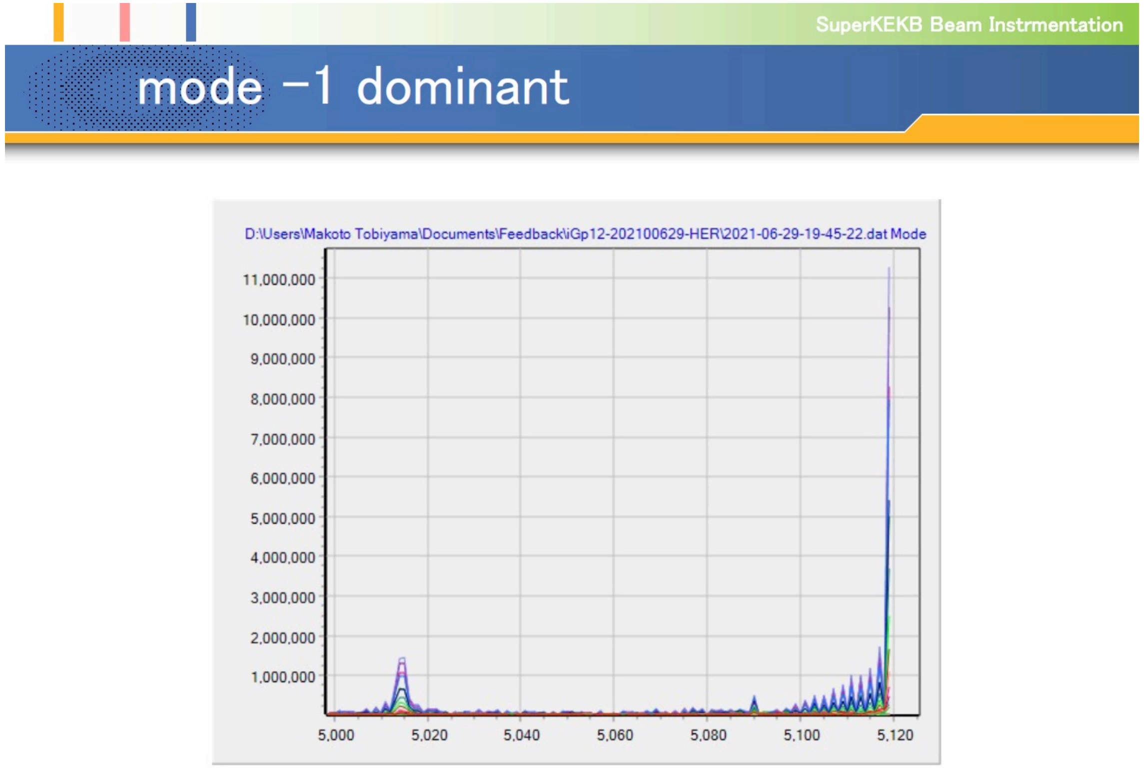
Unable to recapture (CLAWS,VXD)

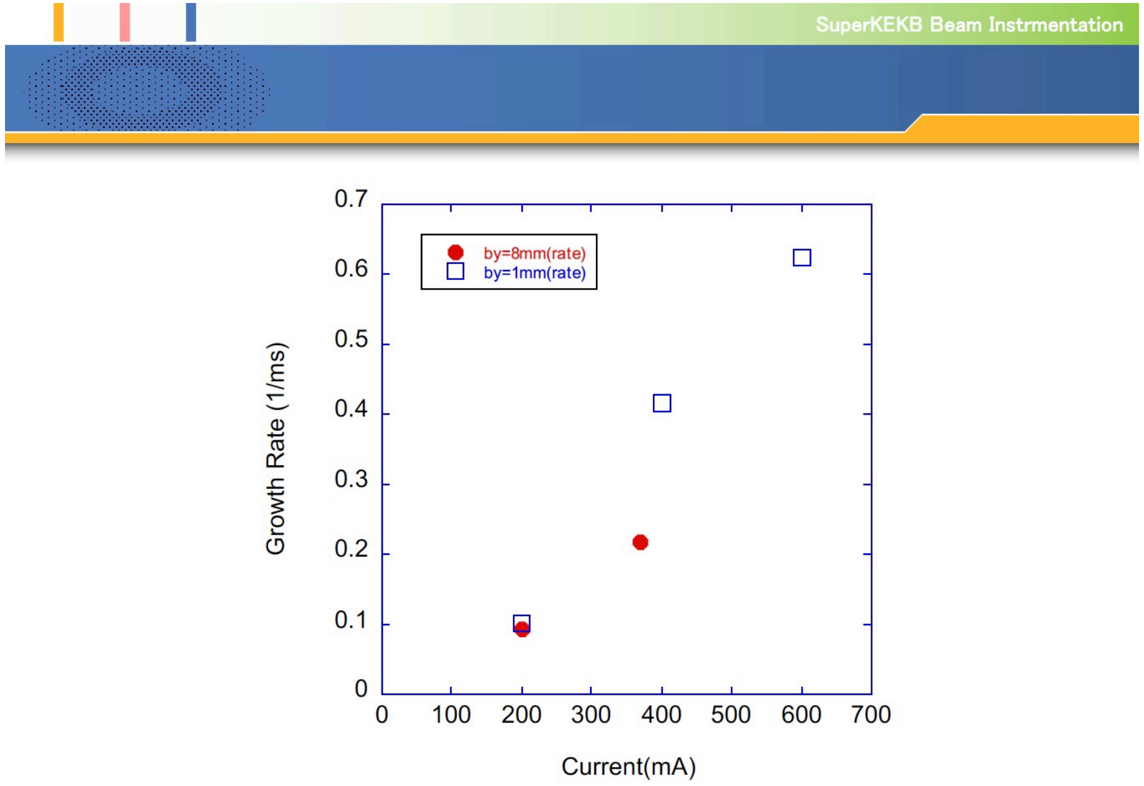


Courtesy of M. Tobiyama, SuperKEKB MDI meeting, Jul. 1, 2021

1. HER growth time study

- **HER growth time study (2021/06/29 19:45:07)**
- **599+496 mA 1272 bunch (no Belle HV)**
- **“mode -1 dominant”**
- **Growth time almost linearly proportional to total beam current**





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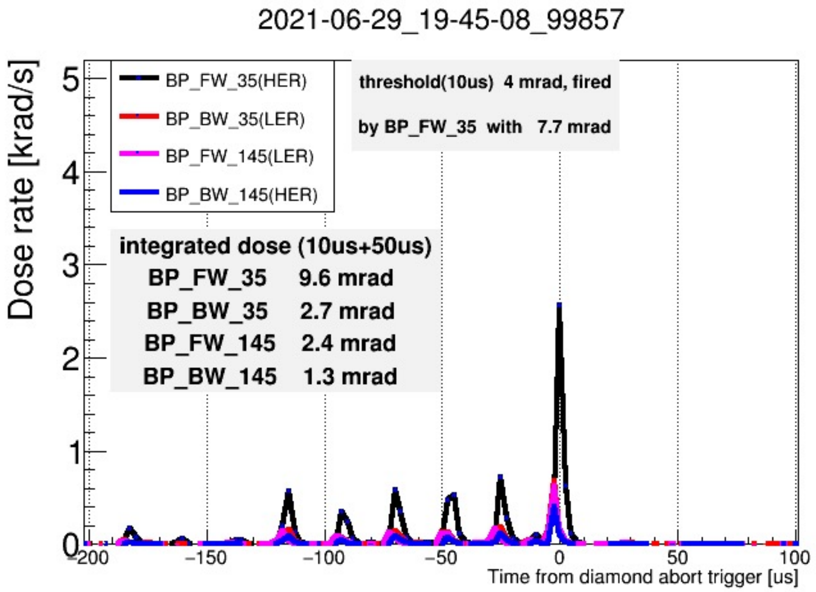
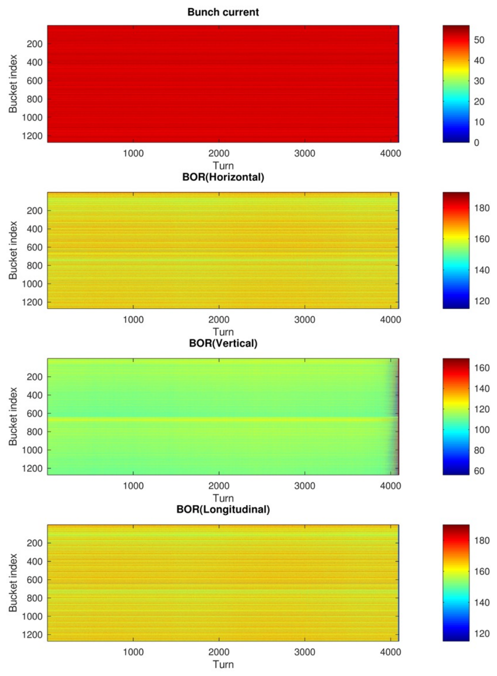
2. BOR/BCM data

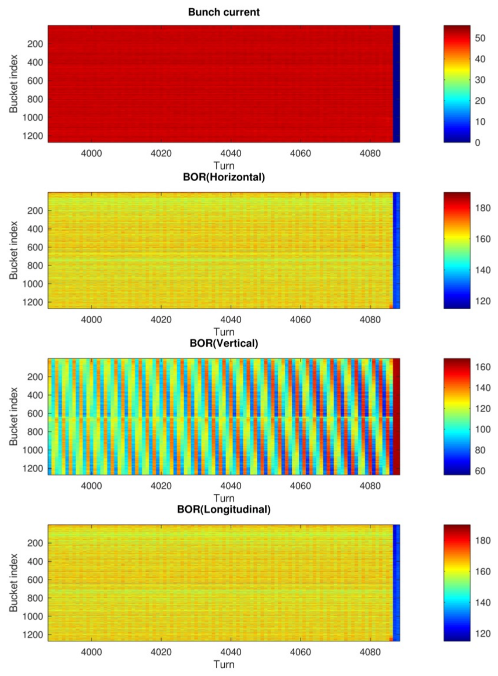
- HER growth time study (2021/06/29 19:45:07)
- **599+496 mA 1272 bunch (no Belle HV)**
- **Coupled-bunch instability observed in vertical direction with FB off**
- **CBI cuased abort and logged by BOR/BCM**



4096 turns (HER)



100 turns before abort (HER)



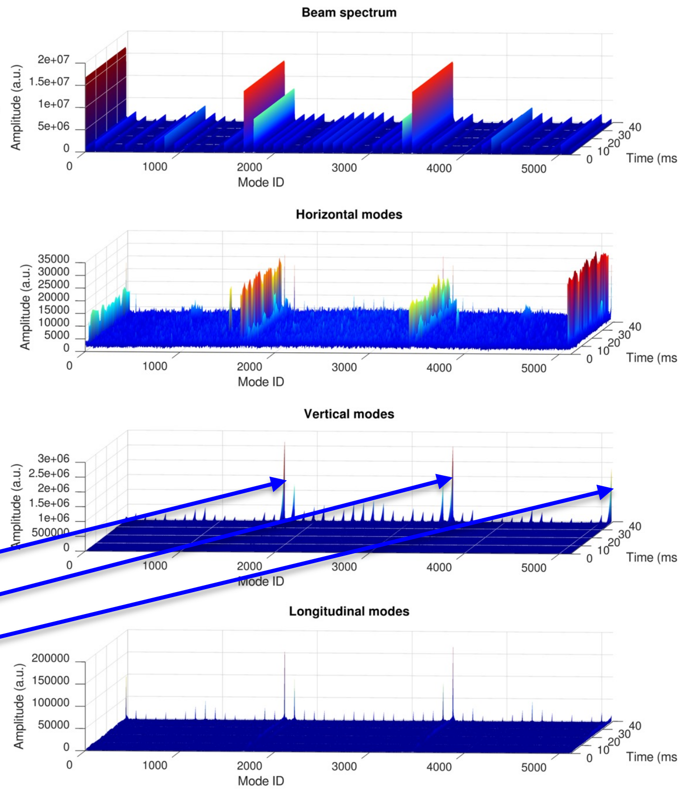
Coupled-bunch instability in vertical direction

2. BOR/BCM data

- HER growth time study (2021/06/29 19:45:07)
- 3.06 filling pattern: beam modes of {0, 1672, 3448, …}
- Vertical unstable "-1 modes": CBI modes of {5119, 1671, 3447, …}
- The "-1 modes" correspond to "beam modes minus 1"

The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{5086, 1638, 3414, 37, 3485}
The first 5 modes of vertical motion:
{1671, 3447, 5119, 3343, 1775}
The first 5 modes of longitudinal motion:
{5119, 3447, 1671, 1672, 3448}

In vertical direction, the "-1 mode" was found to be dominant. This is consistent with Tobiyama-san's analysis of iGp12 data.
-> The "-1 mode" can be explained by resistive-wall instability
-> See next page



* Beam spectrum: FFT of BxB data with 5120(buckets)x256(turns)
* Use moving window per 64 turns
* Find sideband at $m*f_{rev}+f_{\beta}$ [Ref. M. Tobiyama, PRST-AB 9, 012801 (2006)]
* The horizontal modes do not grow after FB turned off -> The modes are from noise?
* The vertical modes grow fast after FB turned off -> Coupled-bunch instability

3. TCBI theory w/ RW applied to HER

- The classic theory (uniform filling pattern) of RW instability is applied
- Simple impedance model (round chamber) for RW is used. This might be not good for the asymmetric KEKB collimators.
- Note that definition of CBI modes are different between BOR analysis and CBI theory.
- For nonuniform filling pattern, fastest modes appear at “beam modes -1” -> “-1 modes”

Fastest growth rate of RW modes (classic theory):

$$\frac{1}{\tau_y} \approx \frac{cI_0 e}{4\pi E\nu_y} \frac{1}{\sqrt{1-Q_y}} \mathrm{Re.} Z_y^{RW}(\omega_0)$$

Simple estimate with Copper chamber (Radius 25 mm): τ_y~5.6 ms

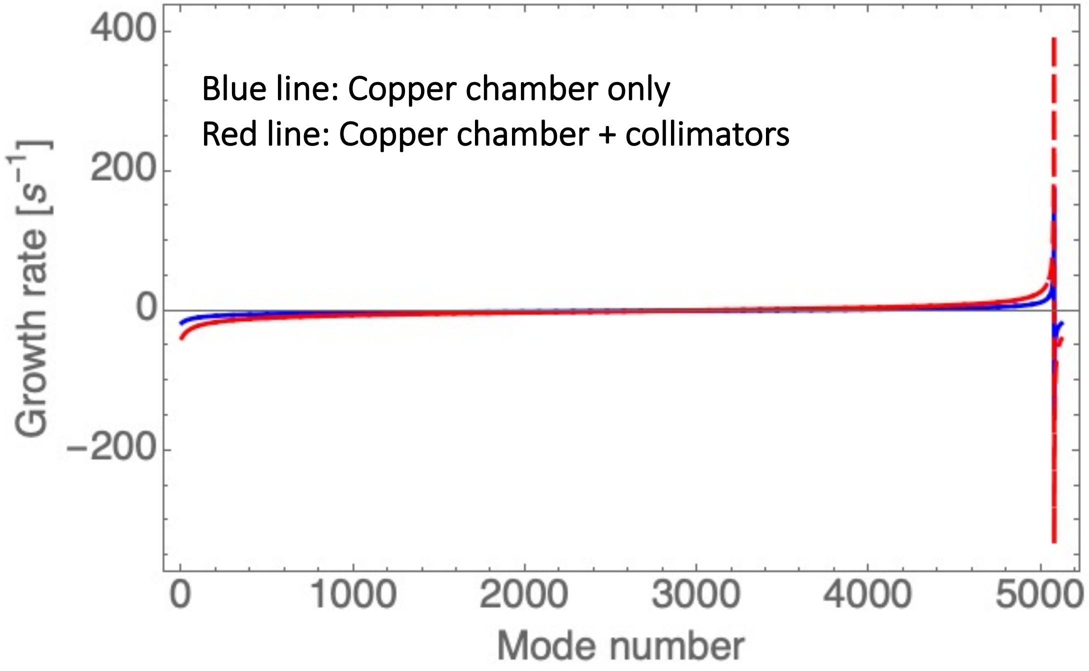
Consider RW of collimators (important): τ_y~2.5 ms

With parameters:

I_0=600 mA, ν_y=43.582, Q_y=0.582

-> Seems close to measurement: 1.6 ms [measured by M. Tobiyama]?

$$\frac{Z_\perp(\omega)}{L} \approx \frac{c}{\omega} \frac{1-\mathrm{sgn}(\omega)i}{\pi b^3 \delta_{skin}\sigma} \qquad \delta_{skin} = \sqrt{\frac{4\pi}{Z_0 c} \frac{c^2}{2\pi\sigma|\omega|}}$$



Estimate of growth rates vs mode number:

$$\frac{1}{\tau_y(\mu)} \approx -\frac{cI_0 e}{4\pi E\nu_y} \Sigma_{p=-\infty}^{+\infty} \mathrm{Re}\left[Z_y^{RW}((pM+\mu+\nu_y)\omega_0)\right]$$

3. TCBI theory w/ RW applied to LER

- **The classic theory (uniform filling pattern) of RW instability is applied**
- **Simple impedance model (round chamber) for RW is used. This might be not good for the SuperKEKB collimators.**

Fastest growth rate of RW modes (classic theory):

$$\frac{1}{\tau_y} \approx \frac{cI_0 e}{4\pi E\nu_y}\frac{1}{\sqrt{1-Q_y}}\mathrm{Re}.Z_y^{RW}(\omega_0)$$

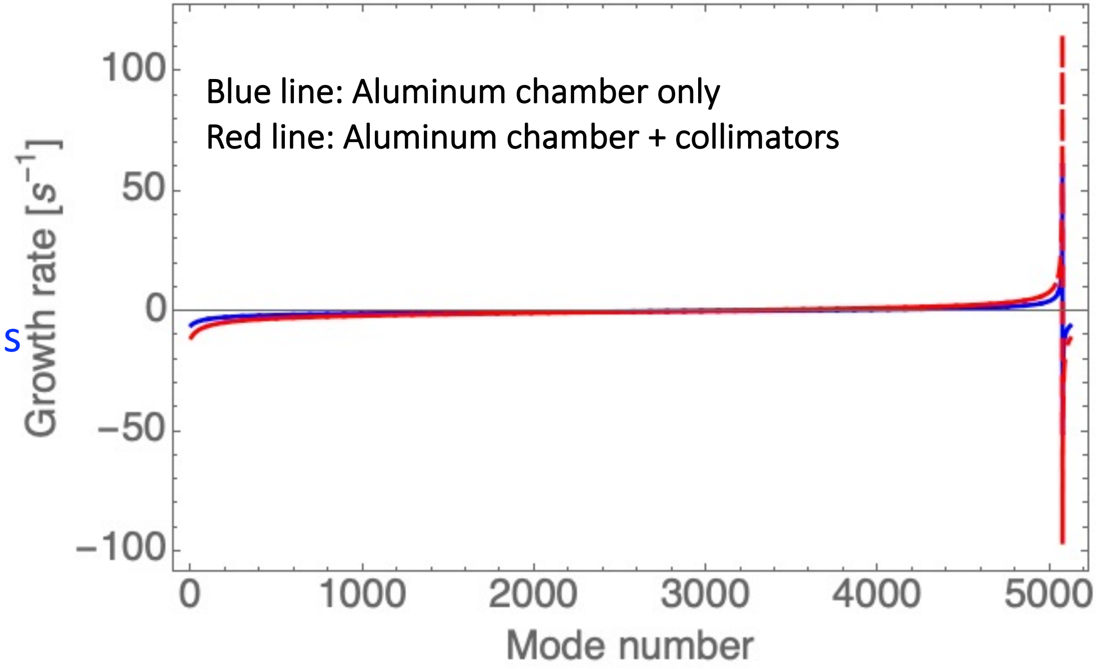
Simple estimate with aluminum chamber (Radius 45 mm): τ_y~16.2 ms

Consider RW of collimators: τ_y~8.6 ms

With parameters:

I_0=600 mA, ν_y=46.593, Q_y=0.593

-> Can be suppressed by FB system



$$\frac{Z_\perp(\omega)}{L} \approx \frac{c}{\omega}\frac{1-\mathrm{sgn}(\omega)i}{\pi b^3 \delta_{skin}\sigma} \qquad \delta_{skin} = \sqrt{\frac{4\pi}{Z_0 c}\frac{c^2}{2\pi\sigma|\omega|}}$$

Estimate of growth rates vs mode number:

$$\frac{1}{\tau_y(\mu)} \approx -\frac{cI_0 e}{4\pi E\nu_y}\sum_{p=-\infty}^{+\infty}\mathrm{Re}\left[Z_y^{RW}((pM+\mu+\nu_y)\omega_0)\right]$$

3. TCBI theory w/ RW applied to LER

- **The classic theory (uniform filling pattern) of RW instability is applied**
- **Simple impedance model (round chamber) for RW is used. This might be not good for the SuperKEKB collimators.**

Fastest growth rate of RW modes (classic theory):

$$\frac{1}{\tau_y} \approx \frac{cI_0e}{4\pi E\nu_y}\frac{1}{\sqrt{1-Q_y}}\mathrm{Re}.Z_y^{RW}(\omega_0)$$

Simple estimate with aluminum chamber (Radius 45 mm): τ_y~16.2 ms

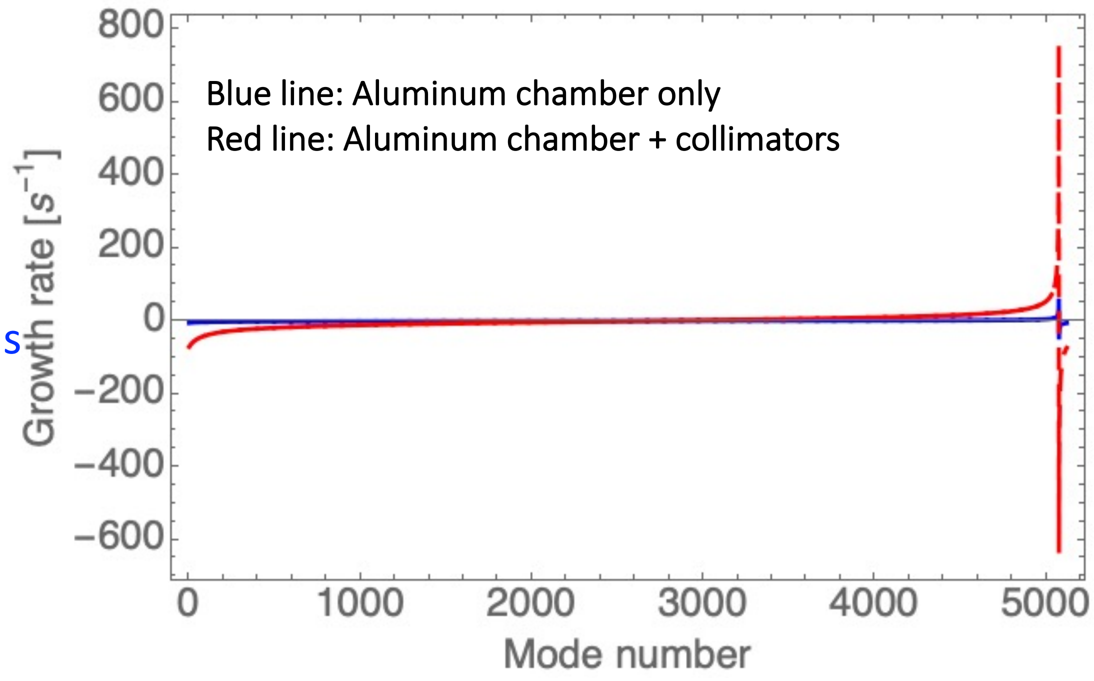
Consider RW of collimators: τ_y~8.6 ms

Consider D02V1 as carbon collimator (Conductivity 3.e5 S/m, Jaw length 60 mm): τ_y~1.3 ms

-> Carbon collimator contributes most of RW impedance

With parameters:

I_0=600 mA, ν_y=46.593, Q_y=0.593



Estimate of growth rates vs mode number:

$$\frac{1}{\tau_y(\mu)} \approx -\frac{cI_0e}{4\pi E\nu_y}\Sigma_{p=-\infty}^{+\infty}\mathrm{Re}\left[Z_y^{RW}((pM+\mu+\nu_y)\omega_0)\right]$$

Summary

- Consistency between measurement and theory
  - "-1 modes" are "beam modes minus 1" (The beam modes are determined by filling pattern)
  - Growth rate of TCBI by RW is linearly proportional to total beam current
  - Meaured growth time roughly agrees with analytic estimate

- Outlook
  - TCBI by RW is suppressed by BxB FB system -> Should not be a concern for luminosity and beamm loss?