Beam dynamics issues: Comparisons of theories, simulations and experiments

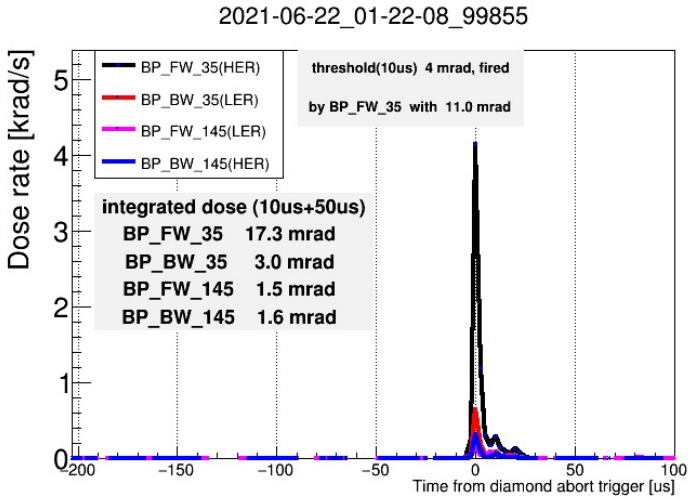
- D. Zhou, M. Tobiyama, K. Ohmi

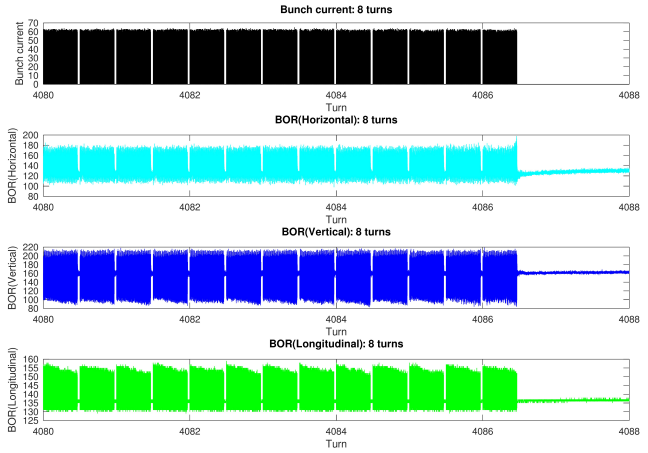
- Thanks to H. Nakamaya, S. Terui, KCG and BCG groups

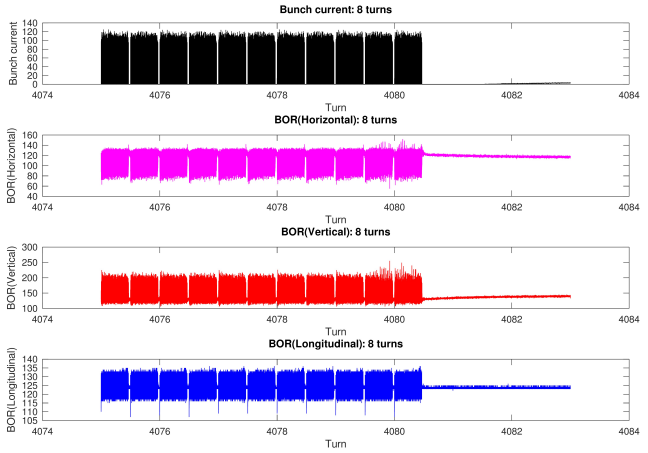
- SuperKEKB mini-optics meeting, KEK, JuL. 20, 2021

1. BOR/BCM data 2021/06/22 01:22:07

- **Abort both**
- **Belle2 CLAWS +diamond +D10-3**
- **638+787mA 1174 bunch**
- **113+34mRad/s**



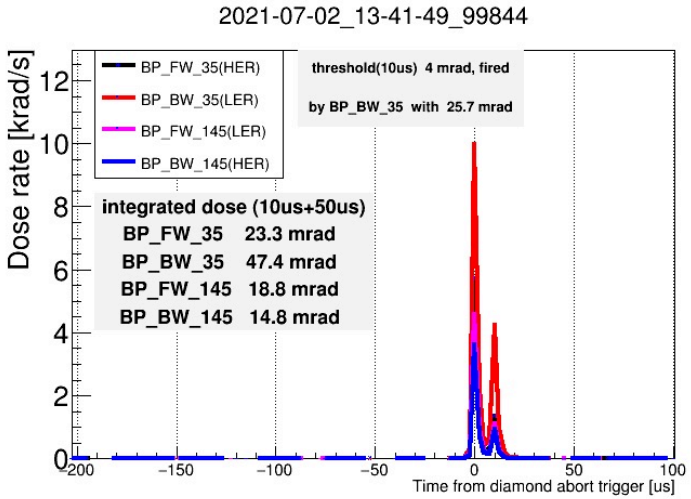


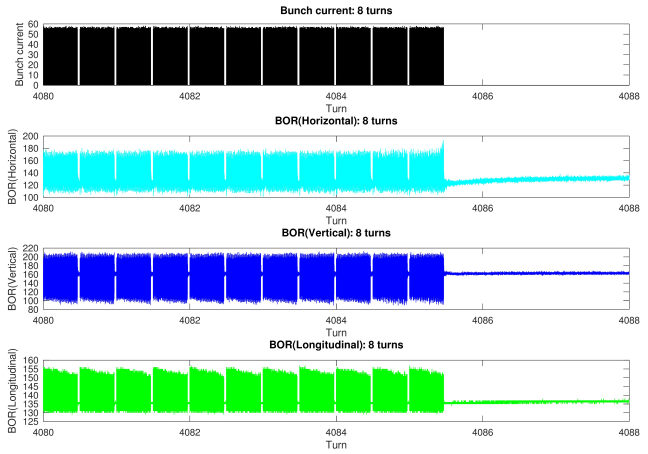


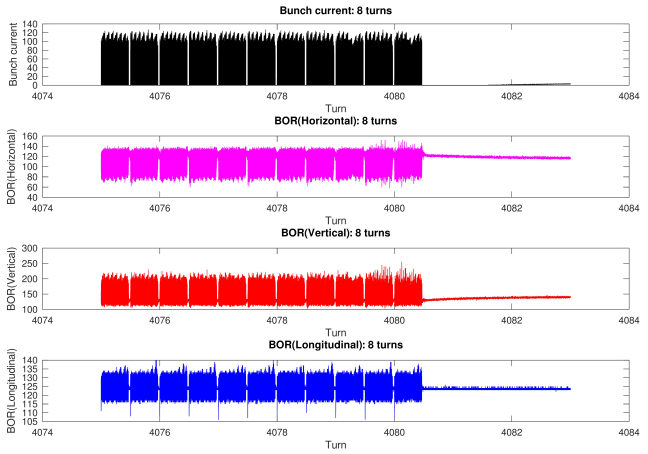
Ref. http://kekb-co-web.kek.jp/doc/Image/BELLE/abort_summary/web/abortlist.html

1. BOR/BCM data 2021/07/02 13:41:48

- **Abort both**
- **Belle2 CLAWS +diamond**
- **637+841 mA 1272 bunch**
- **4+162mRad/s**





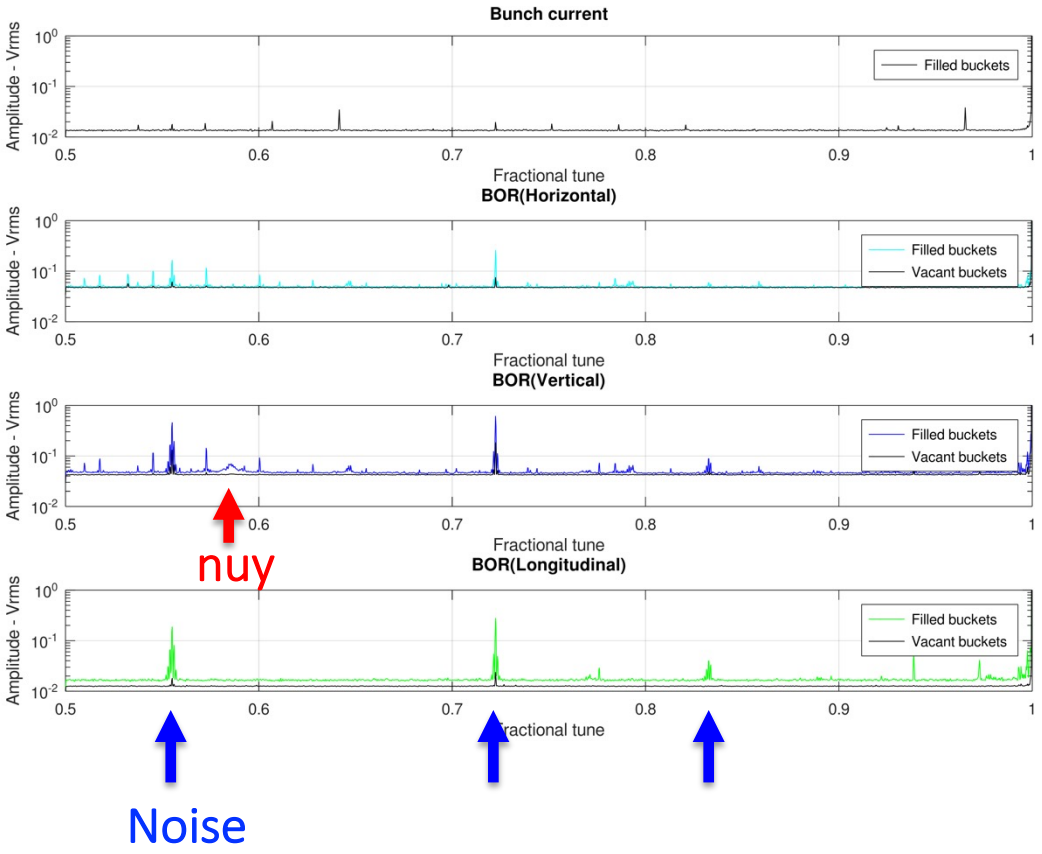


Ref. http://kekb-co-web.kek.jp/doc/Image/BELLE/abort_summary/web/abortlist.html

BCM/BOR data: HER

Beam spectrum: FFT of TbT data for each bucket
Average over all filled and vacant buckets separately

2021/06/22 01:22:07



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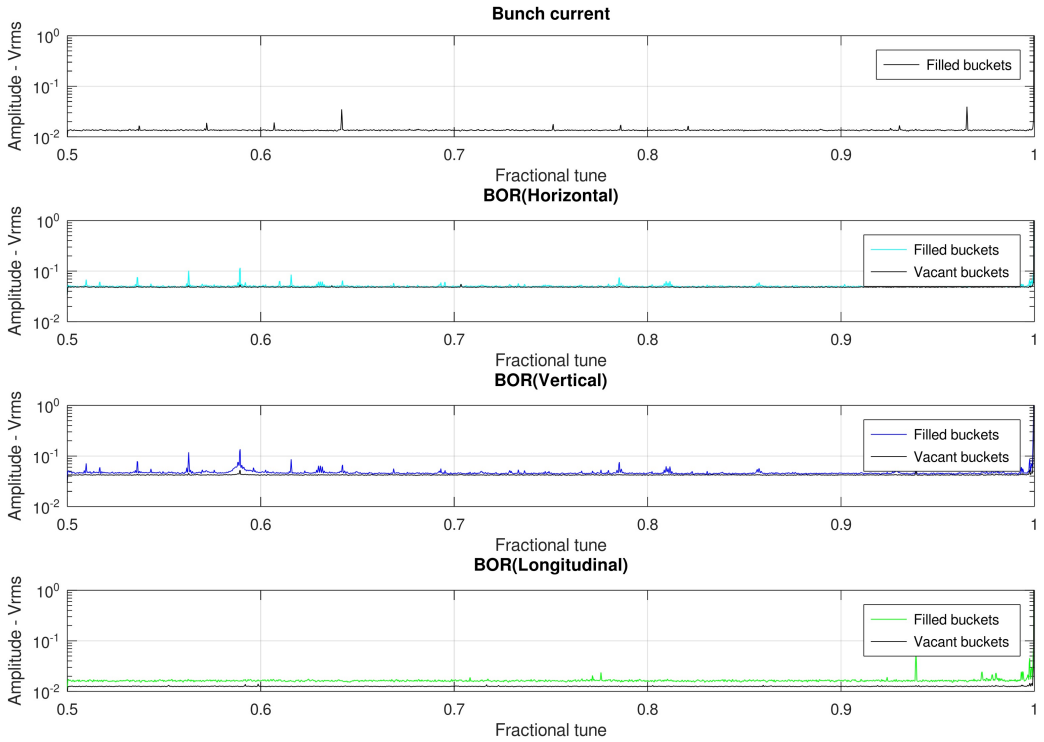

Noise much suppressed after Jun.29, 2021

BCM/BOR data: HER

* Preliminary results of CBI modes
* Sideband searching is not good and may pick up noises

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)]

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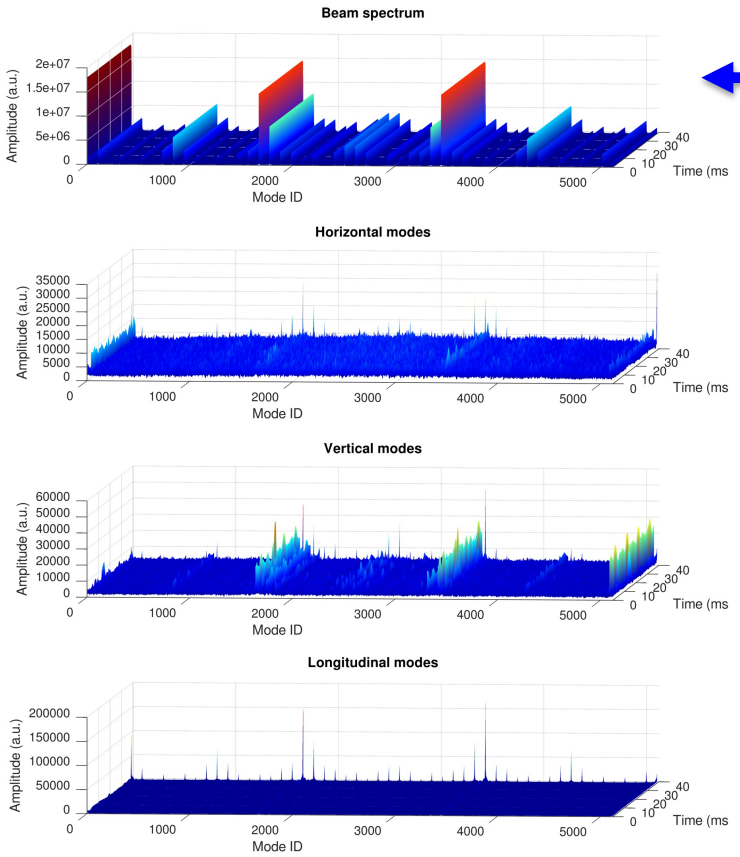

The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{39, 3487, 5086, 1711, 5084}
The first 5 modes of vertical motion:
{5088, 3416, 1640, 3312, 1744}
The first 5 modes of longitudinal motion:
{3448, 1672, 5119, 1671, 3447}

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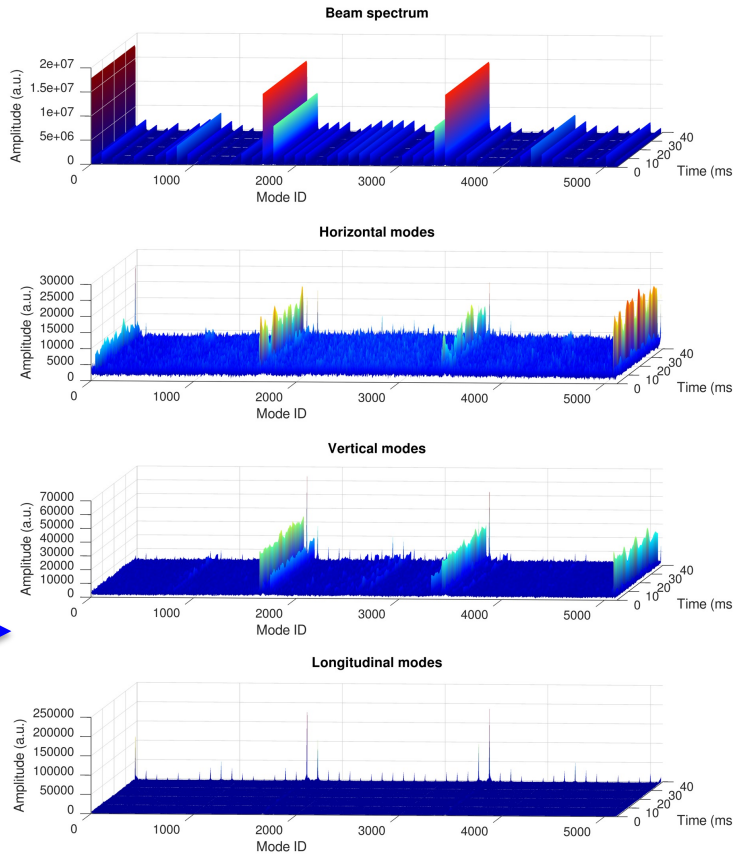
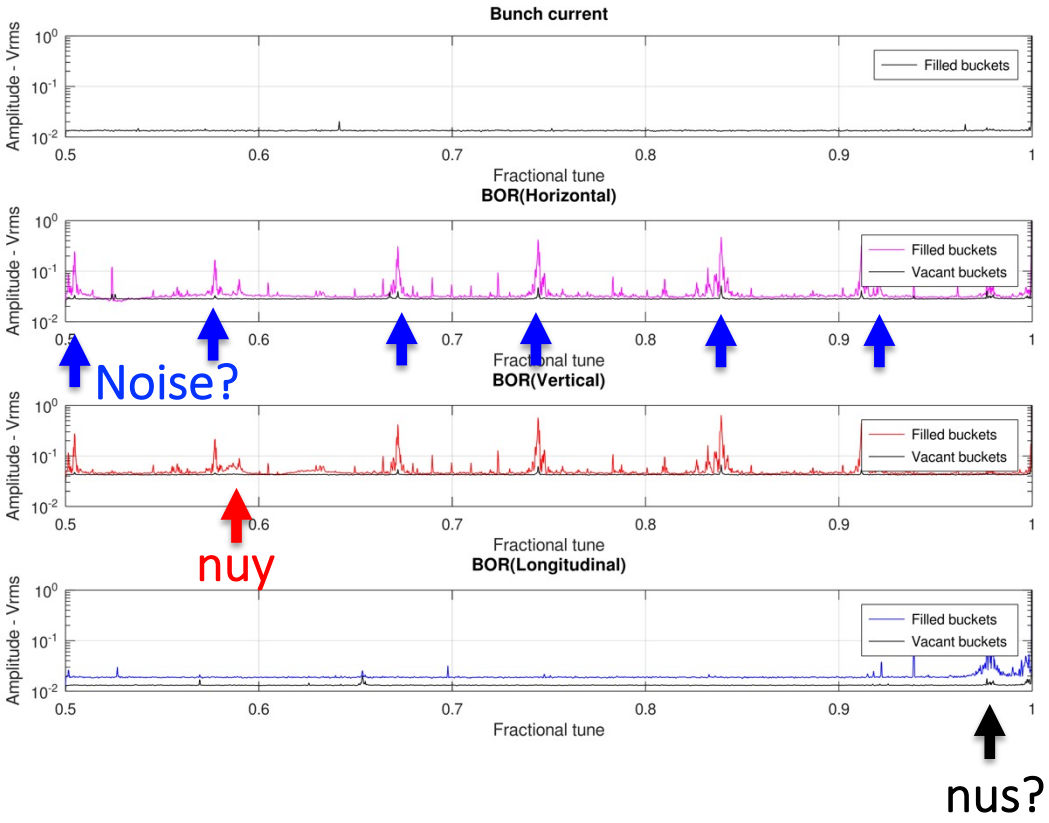


The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{5084, 1636, 3412, 41, 3489}
The first 5 modes of vertical motion:
{1640, 5088, 3416, 1744, 3312}
The first 5 modes of longitudinal motion:
{1672, 3448, 5119, 0, 3447}

BCM/BOR data: LER

Beam spectrum: FFT of TbT data for each bucket
Average over all filled and vacant buckets separately

2021/06/22 01:22:07



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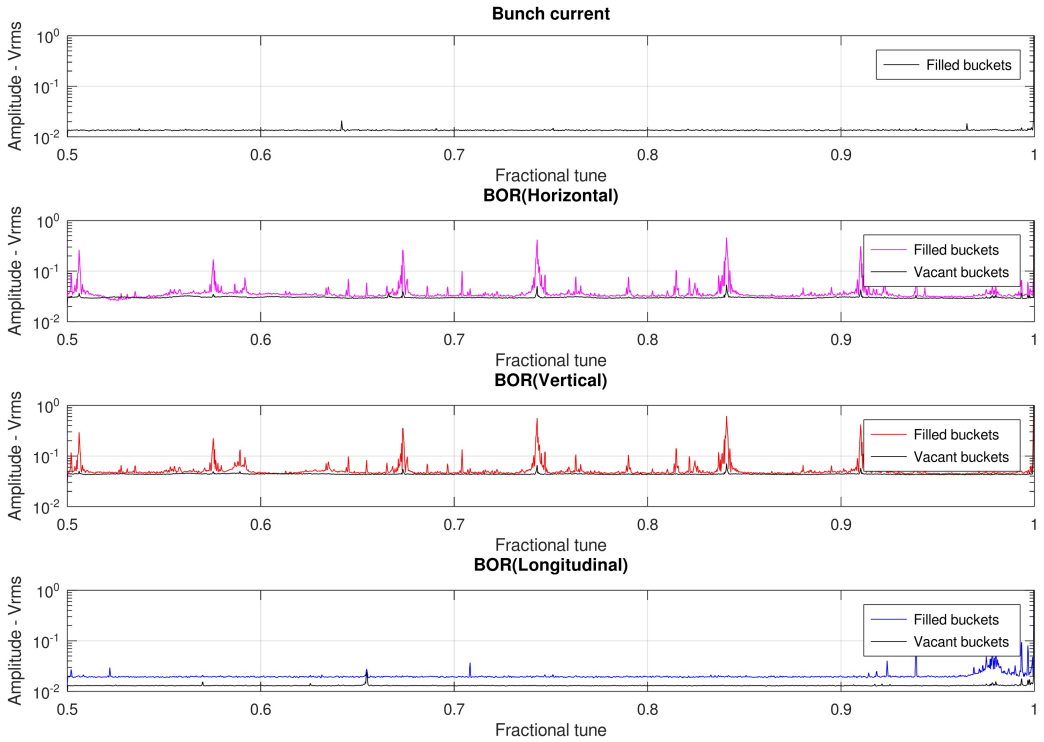

BCM/BOR data: LER

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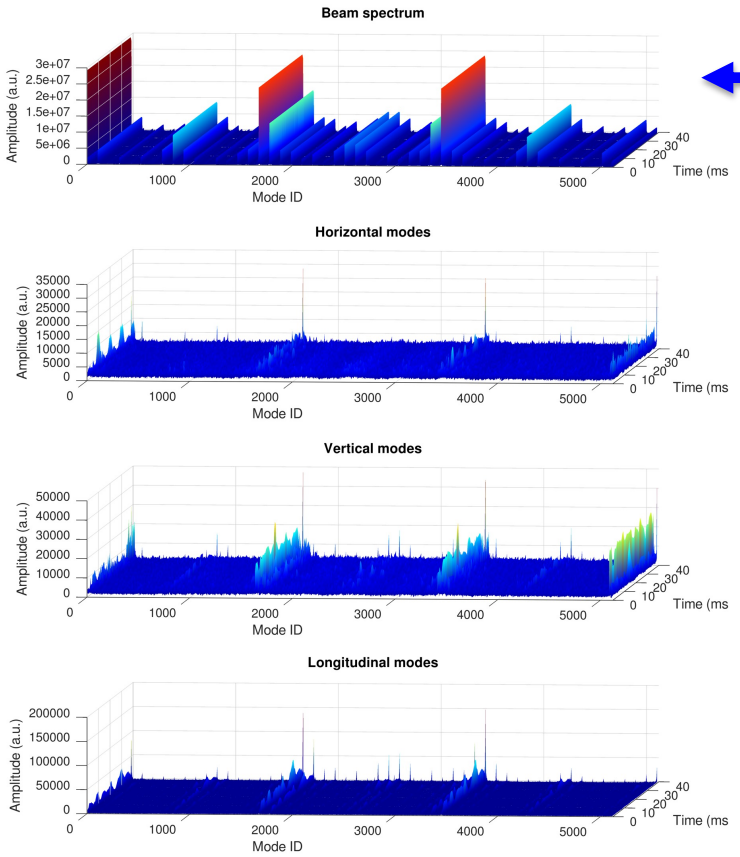

The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{29, 5093, 5094, 5092, 1645}
The first 5 modes of vertical motion:
{5084, 1636, 3412, 32, 1671}
The first 5 modes of longitudinal motion:
{3448, 1672, 0, 1776, 3344}

The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{5094, 27, 1361, 29, 1646}
The first 5 modes of vertical motion:
{32, 3480, 1704, 3376, 1808}
The first 5 modes of longitudinal motion:
{3448, 1672, 0, 3344, 1776}

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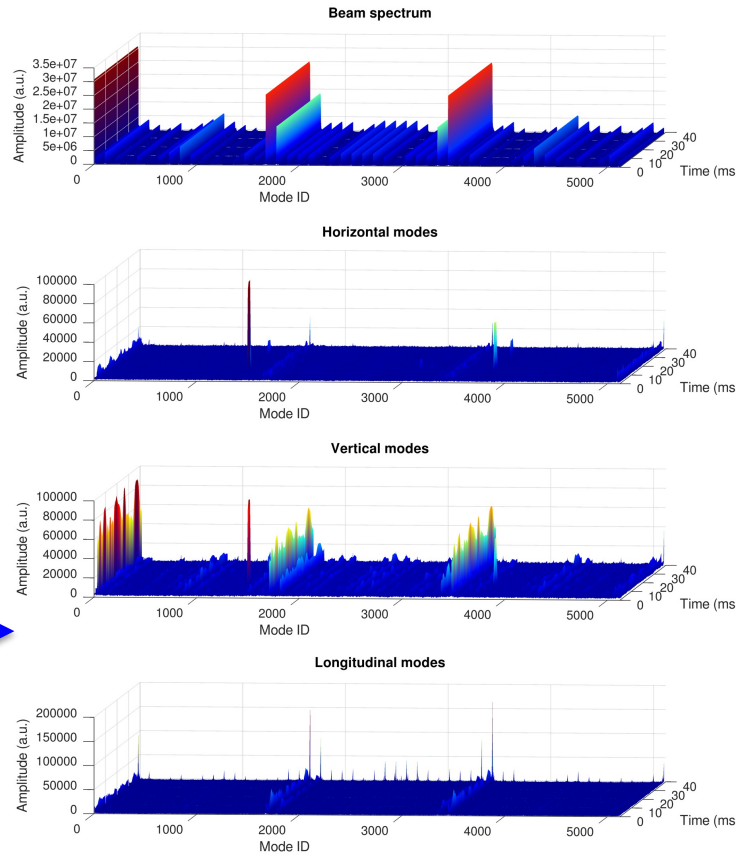

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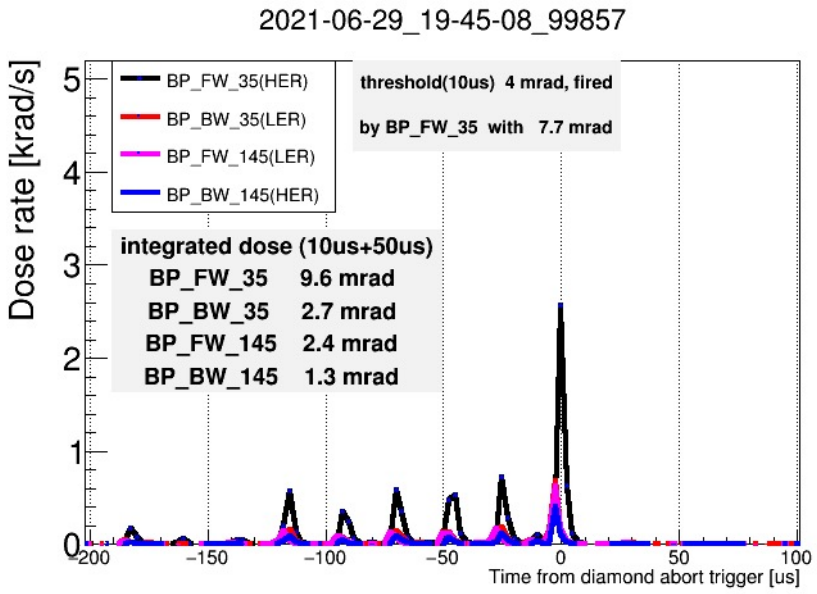
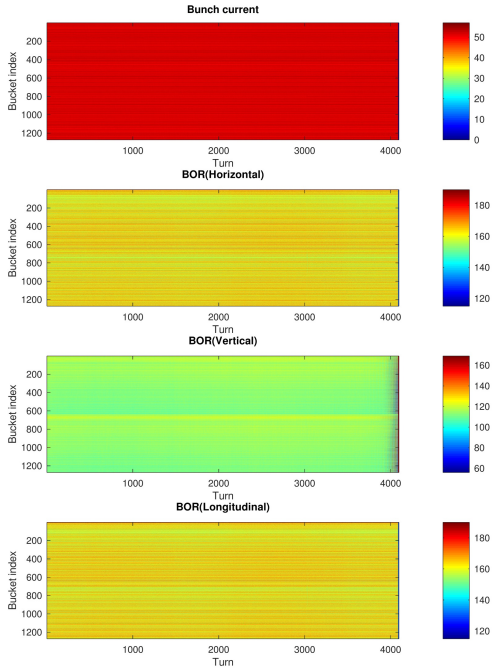
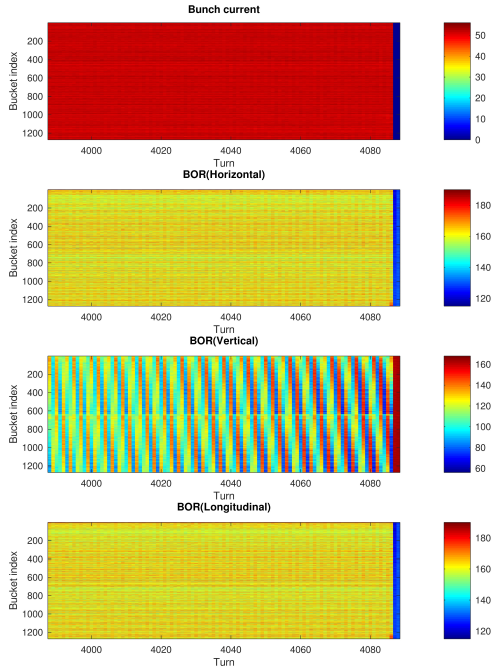
- **Abort both**
- **Loss Monitor D10-2 +diamond +D10-3**
- **599+496 mA 1272 bunch (no Belle HV)**
- **HER growth time study**



4096 turns (HER)



100 turns before abort (HER)



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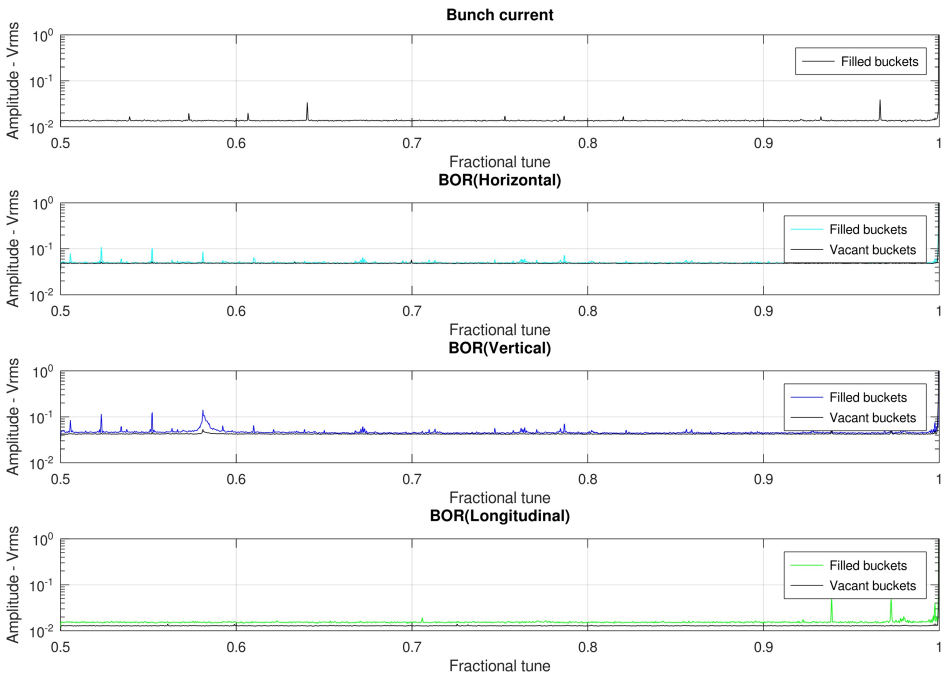
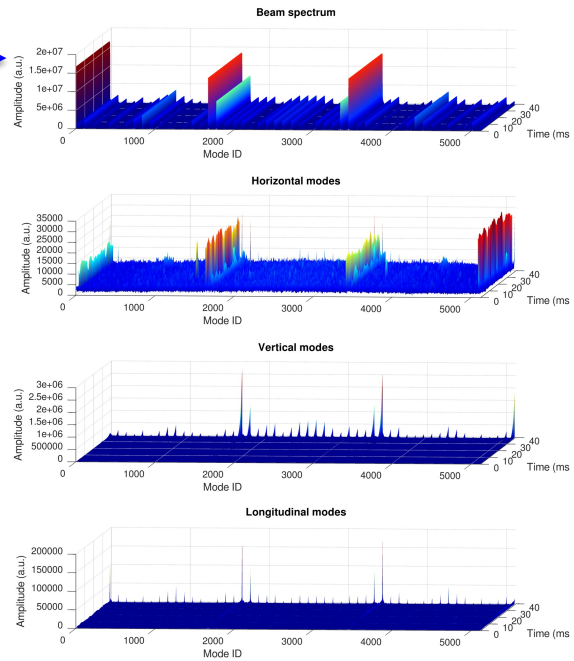


The first 5 modes of beam current:
{0, 1672, 3448, 1776, 3344}
The first 5 modes of horizontal motion:
{5086, 1638, 3414, 37, 3485}
The first 5 modes of vertical motion:
{1671, 3447, 5119, 3343, 1775}
The first 5 modes of longitudinal motion:
{5119, 3447, 1671, 1672, 3448}



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

2021/06/29 19:45:07

- **Abort both**
- **Loss Monitor D10-2 +diamond +D10-3**
- **599+496 mA 1272 bunch (no Belle HV)**
- **HER growth time study**

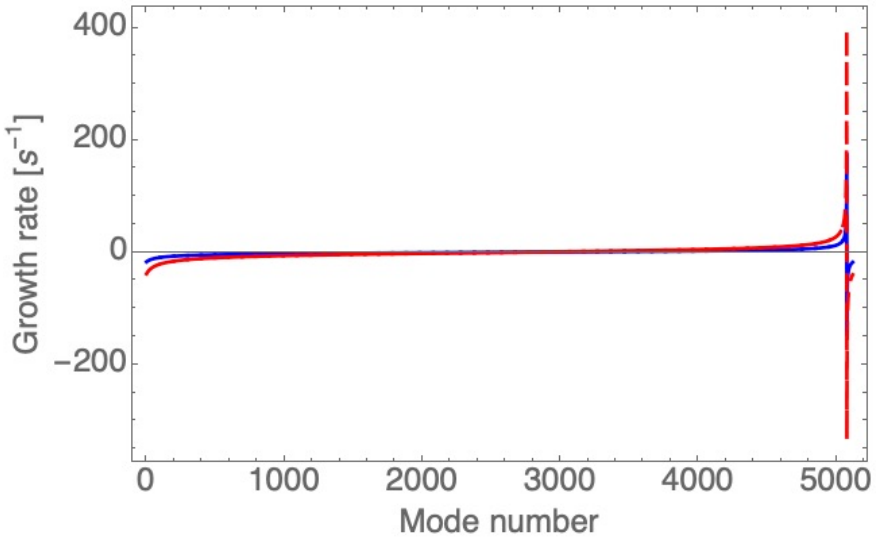
Fastest growth rate of RW modes:

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

Simple estimate with Copper chamber (Radius 25 mm):
τ_y~5.6 ms
Consider RW of collimators: τ_y~2.5 ms

-> Close to measurement: 1.6 ms [M. Tobiyama]

Other parameters:
I_0=600 mA, ν_y=43.582, Q_y=0.582

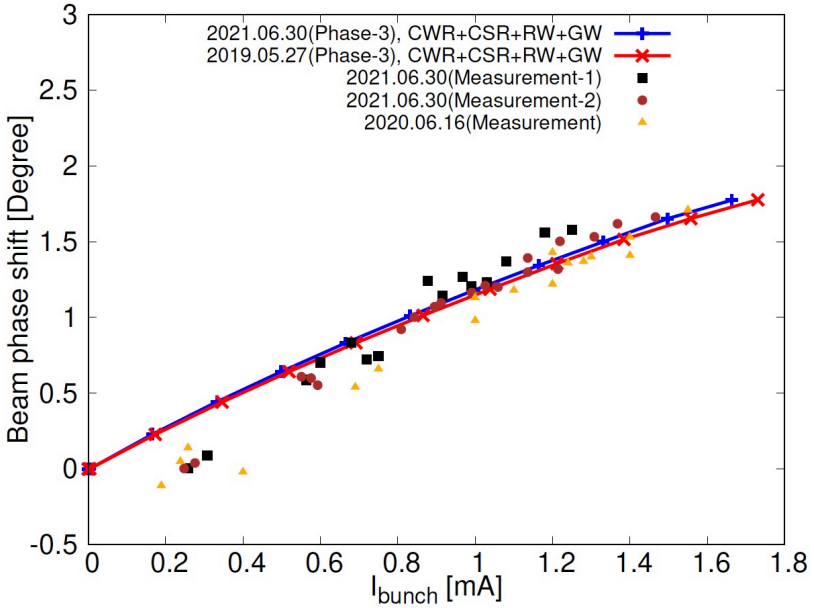


Estimate of growth rates vs mode number:

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

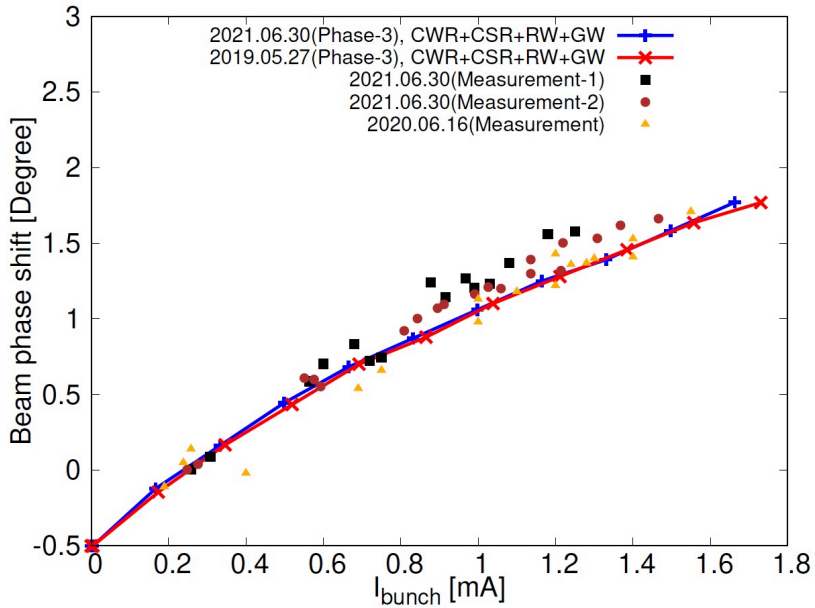
2. LER synchronous phase measurement

- **Zero-cross of BPM signal (Tobiyama-san's method)**
- **LER measurement done in Jun. 30, 2021**
- **Vlasov solver simulation with impedance model**



Comparison of center-of-mass shift with synch. Phase shift, the agreement is not good at low bunch currents.

Simulation data shifted by -0.5 deg.



Comparison of peak shift with synch. Phase shift, the agreement at low bunch currents seems to be better.

2. LER synchronous phase measurement

- **Zero-cross of BPM signal (Tobiyama-san's method)**
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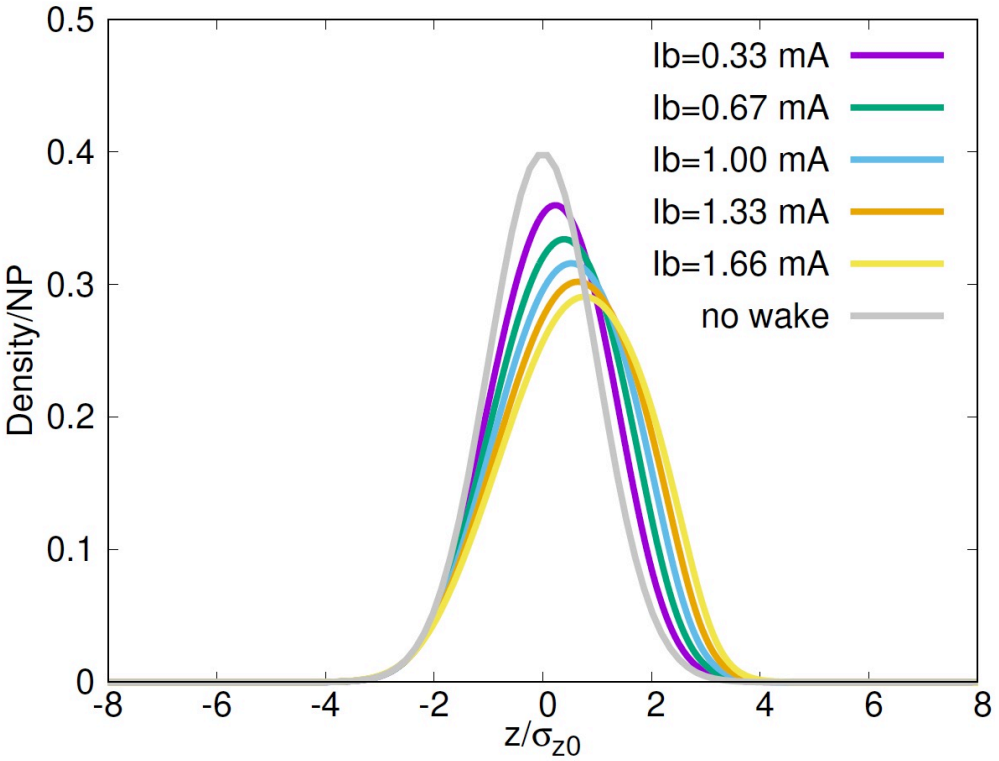
- **Vlasov solver simulation with impedance model**



Simulated bunch profiles have tilt and shift in center-of-mass.

BPM signal: $\boldsymbol{i(t) = -dQ(t)/dt}$

-> Zero-cross point of BPM signal is more relevant to peak of bunch profile

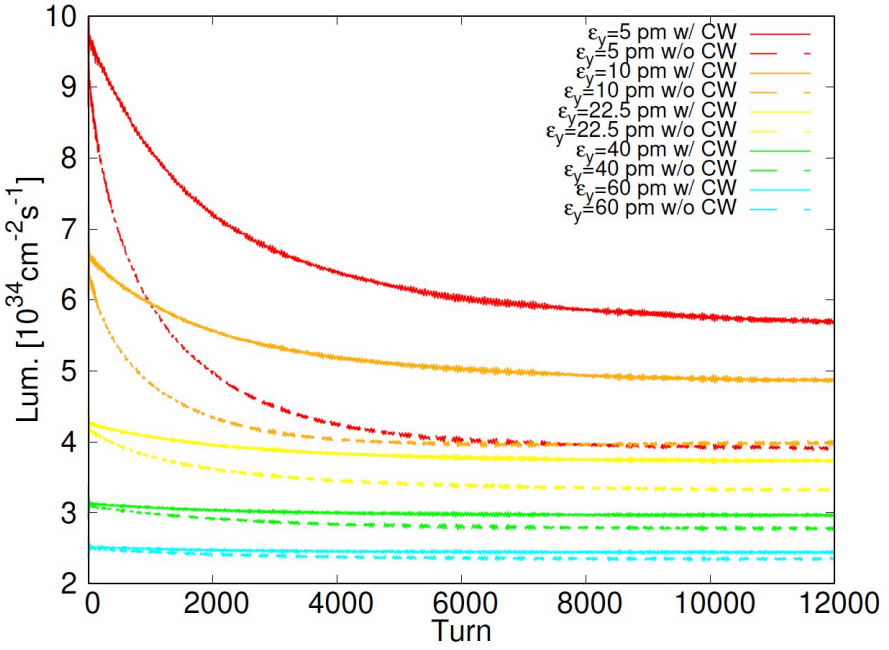
3. Luminosity performance

- **Luminosity from strong-strong beam-beam simulations**
- **Observed luminosity performance**
- **High bunch-current collision study (Jul. 1, 2021)**
- **Slope of specific luminosity**

	2021.05.14		Comments
	HER	LER	
I_b (A)	0.68	0.84	
# bunch	1174		
ε_x (nm)	4.6	4.24	w/ IBS
ε_y (pm)	22.5	22.5	Estimated from XRM data
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	6	6	w/ bunch lengthening by impedance
σ_y (μm)	0.15	0.15	Observed from XRM
ν_x	45.52989	44.5247	Measured tune of pilot bunch
ν_y	43.59055	46.57279	Measured tune of pilot bunch
ν_s	0.02719	0.02212	Calculated from lattice
Crab waist	40%	80%	Lattice design

Beam parameters in May. 14, 2021

Solid yellow line corresponds to parameter table



Achieved luminosity in 2021ab: ~3.0e34 $cm^{-1}s^{-1}$
This is about ~80% of simulated value (BBSS)

3. Luminosity performance

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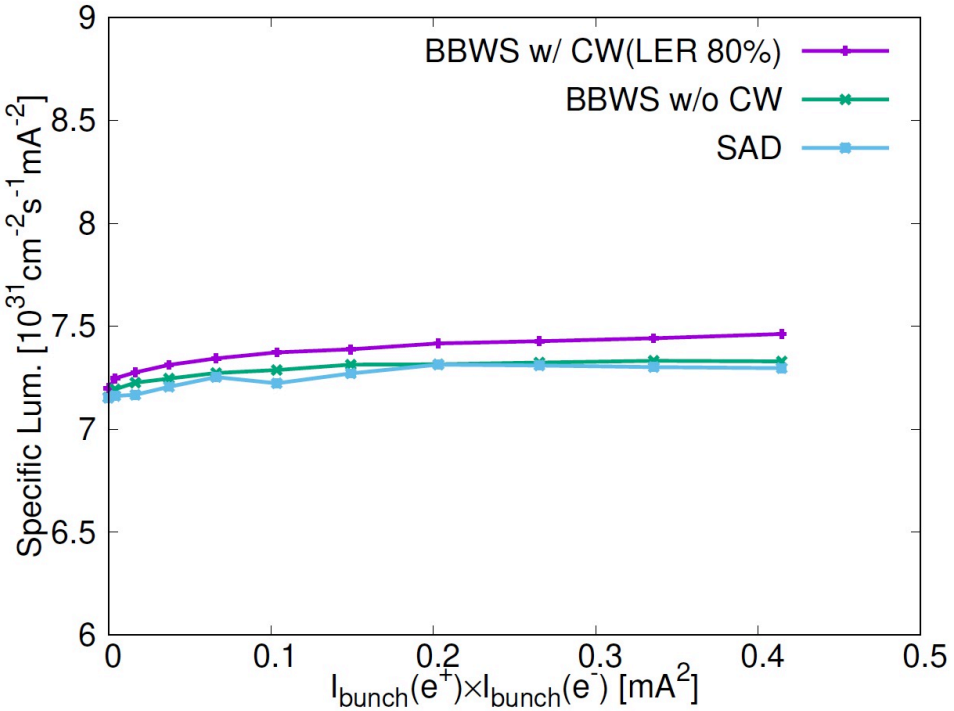
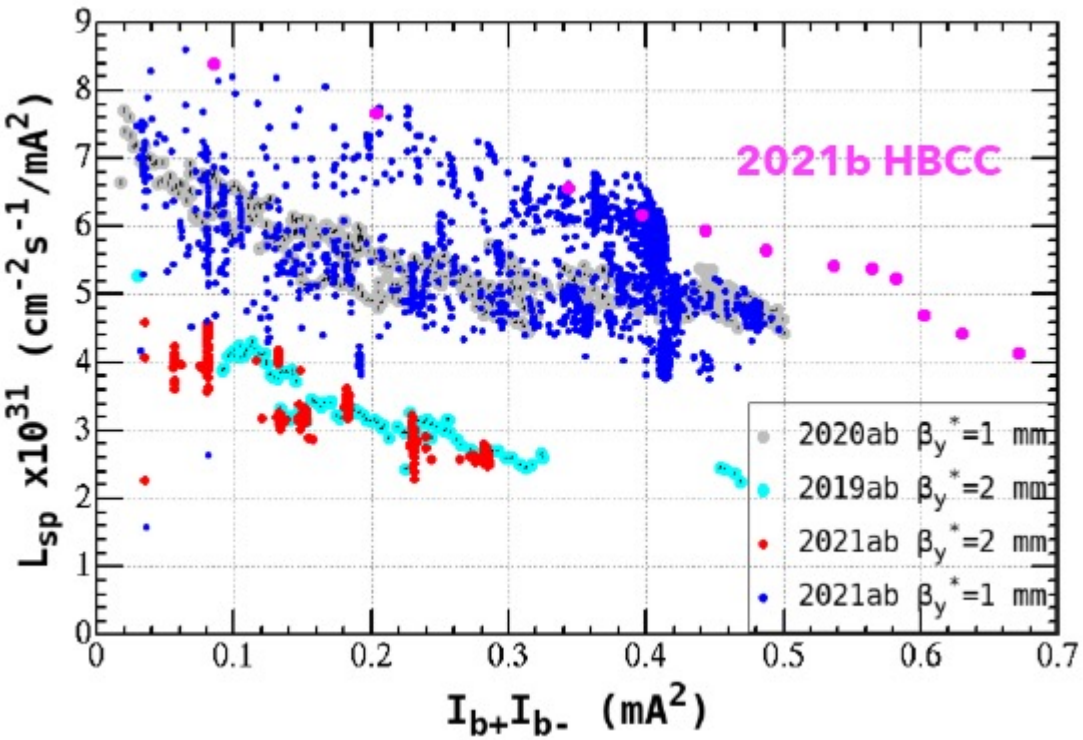
- **Slope of specific luminosity**



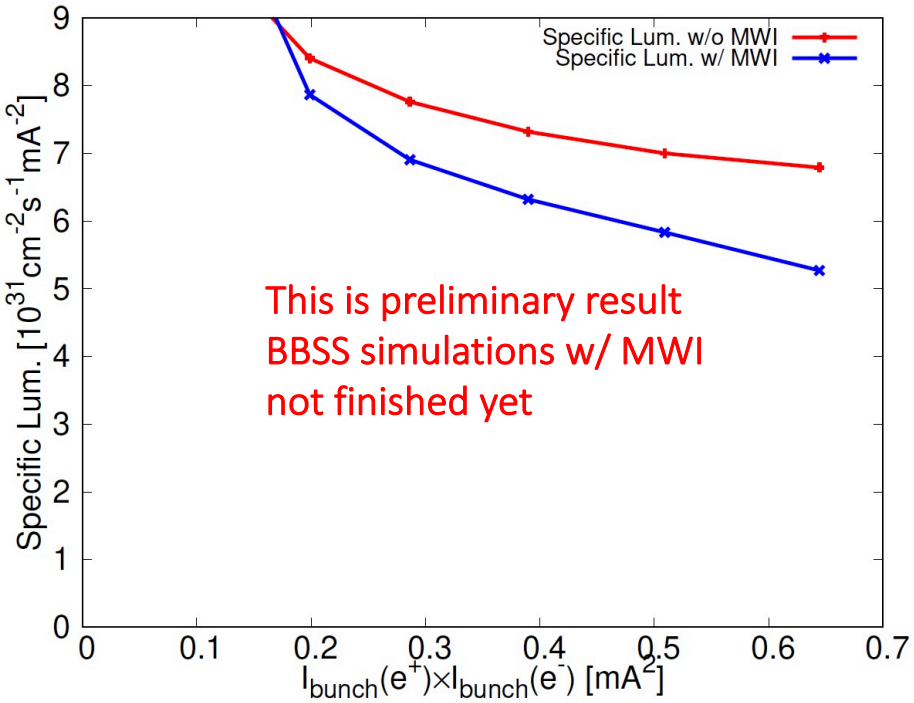
Simulation with lattice (Use beam parameters in May. 14, 2021):
* No clear evidence of lum. loss from interplay of beam-beam interaction and lattice nonlinearity
* Note that in BBWS simulations crab waist cannot be applied to the strong beam

3. Luminosity performance

- **Luminosity from strong-strong beam-beam simulations**
- **Observed luminosity performance**
- **High bunch-current collision study (Jul. 1, 2021)**
- **Slope of specific luminosity**



High bunch-current collision experiments
Courtesy of Y. Ohnishi



Consider bunch lengthening from MWI simulations:
HER: σ_z(mm)=5.05+1.07*I_{bunch}(mA)
HER: σ_z(mm)=4.84+0.83*I_{bunch}(mA)

3. Luminosity performance

- **Luminosity from strong-strong beam-beam simulations**
- **Observed luminosity performance**
- **High bunch-current collision study (Jul. 1, 2021)**
- **Slope of specific luminosity**

$$\mathcal{L} = \mathcal{L}_0 \cdot R_\theta$$

$$\mathcal{L}_0 = \frac{N_\mathrm{p} N_\mathrm{e} f N_\mathrm{b}}{2\pi\sqrt{\sigma_\mathrm{xp}^{*2}+\sigma_\mathrm{xe}^{*2}}\sqrt{\sigma_\mathrm{yp}^{*2}+\sigma_\mathrm{ye}^{*2}}}$$

$$R_\theta \approx \frac{1}{\sqrt{1+\frac{\sigma_\mathrm{zp}^{*2}+\sigma_\mathrm{ze}^{*2}}{\sigma_\mathrm{xp}^{*2}+\sigma_\mathrm{xe}^{*2}}\tan^2\frac{\theta}{2}}}$$

$$\theta_\mathrm{PW} = \sqrt{\frac{\sigma_\mathrm{zp}^{*2}+\sigma_\mathrm{ze}^{*2}}{\sigma_\mathrm{xp}^{*2}+\sigma_\mathrm{xe}^{*2}}}\tan\frac{\theta}{2}$$

$$\theta_\mathrm{PW} \gg 1 \longrightarrow$$

$$\mathcal{L} \approx \frac{N_\mathrm{p} N_\mathrm{e} f N_\mathrm{b}}{2\pi\sqrt{\sigma_\mathrm{yp}^{*2}+\sigma_\mathrm{ye}^{*2}}\sqrt{\sigma_\mathrm{zp}^{*2}+\sigma_\mathrm{ze}^{*2}}\tan\frac{\theta}{2}}$$

With nano-beam scheme, the luminonisity is inversely proportional to bunch length.

-> It seems that bunch lengthening can partially contribute to drop of specific lum.

3. Luminosity performance

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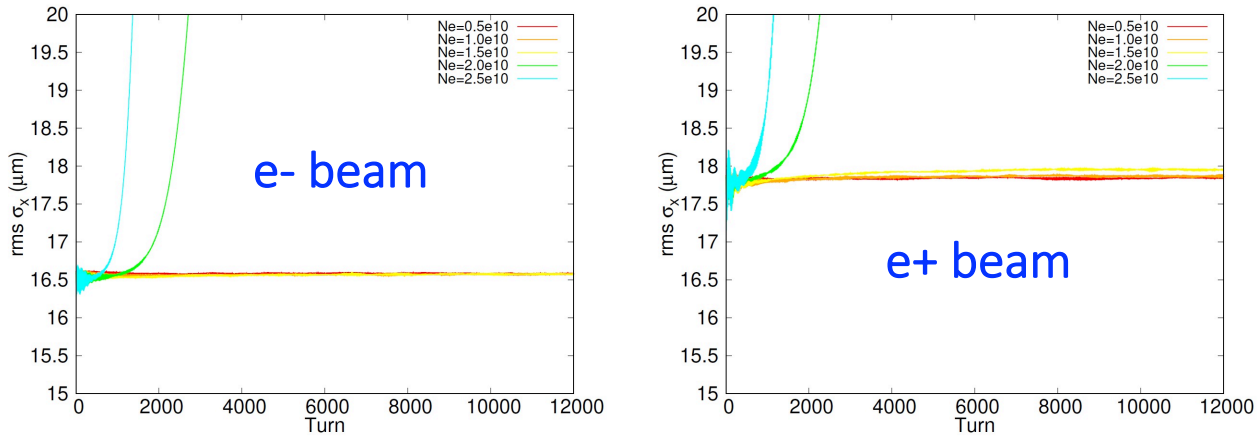
- **Slope of specific luminosity**

	2021.07.01		Comments
	HER	LER	
I_b (A)	Ie	1.255*Ie	
# bunch	393		
ε_x (nm)	4.6	4.0	w/ IBS
ε_y (pm)	18	18	Single beam (Estimated from XRM data)
β_x (mm)	60	80	Calculated from lattice
β_y (mm)	1	1	Calculated from lattice
σ_z (mm)	5.05	4.84	Natural bunch length (w/o MWI)
ν_x	45.532	44.525	Measured tune of pilot bunch
ν_y	43.582	46.593	Measured tune of pilot bunch
ν_s	0.0272	0.0221	Calculated from lattice
Crab waist	40%	80%	Lattice design



Beam parameters in Jul. 01, 2021, for high bunch-current collision

BBSS simulations show coherent x-z instability. Consistent with experiment?

Summary

- BOR/BMC data
  - No clear evidence of aborts caused by coupled-bunch instability?
  - HER “-1 mode” can be explained by resistive-wall instability?
- LER synchronous phase shift
  - Good agreement with MWI simulations using calculated imepdance model?
- Luminosity performance
  - Luminosity with beam parameters of May. 14, 2021: ~80% of simulated luminosity was achieved?
  - Bunch lengthening can partially explain the drop of specific luminosity?