Impedance issues and other collective effects

Demin Zhou

Acknowledgements:

K. Ohmi, the SKB-BD workgroup,

and the SuperKEKB team

1st SuperKEKB Beam Dynamics Mini-Workshop

Jul. 17, 2019, KEK

Outline

- **Potential-well distortion**
- **Betatron tune shift (single bunch)**
- **Beam tilt due to transverse impedance**
- **Other collective effects**

1. Potential-well distortion

➤ Three types of effects important to SuperKEKB

- Bunch lengthening => Direct luminosity loss
- Shift of center of mass => RF phase shift
- Bunch profile tilt => Optimum RF phase

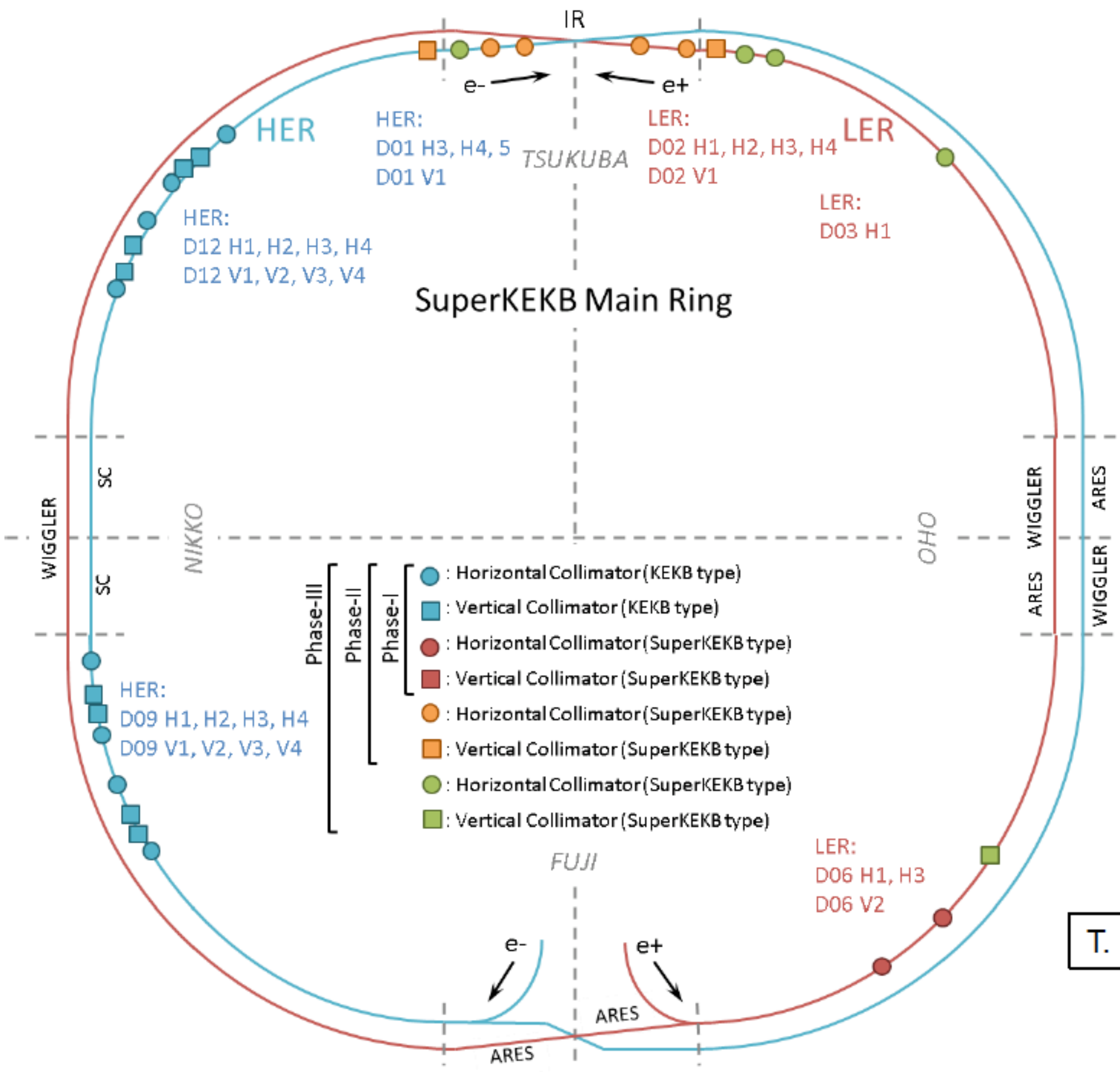
1. Potential-well distortion

➤ Impedance budget in Phase-1, Phase-2 and Phase-3

- **Installed in Phase-3 (Thanks to Y. Suetsugu):**

  HER: D01-H3

  LER: D03-H1, D02-H1, D02-H2, D06-V2

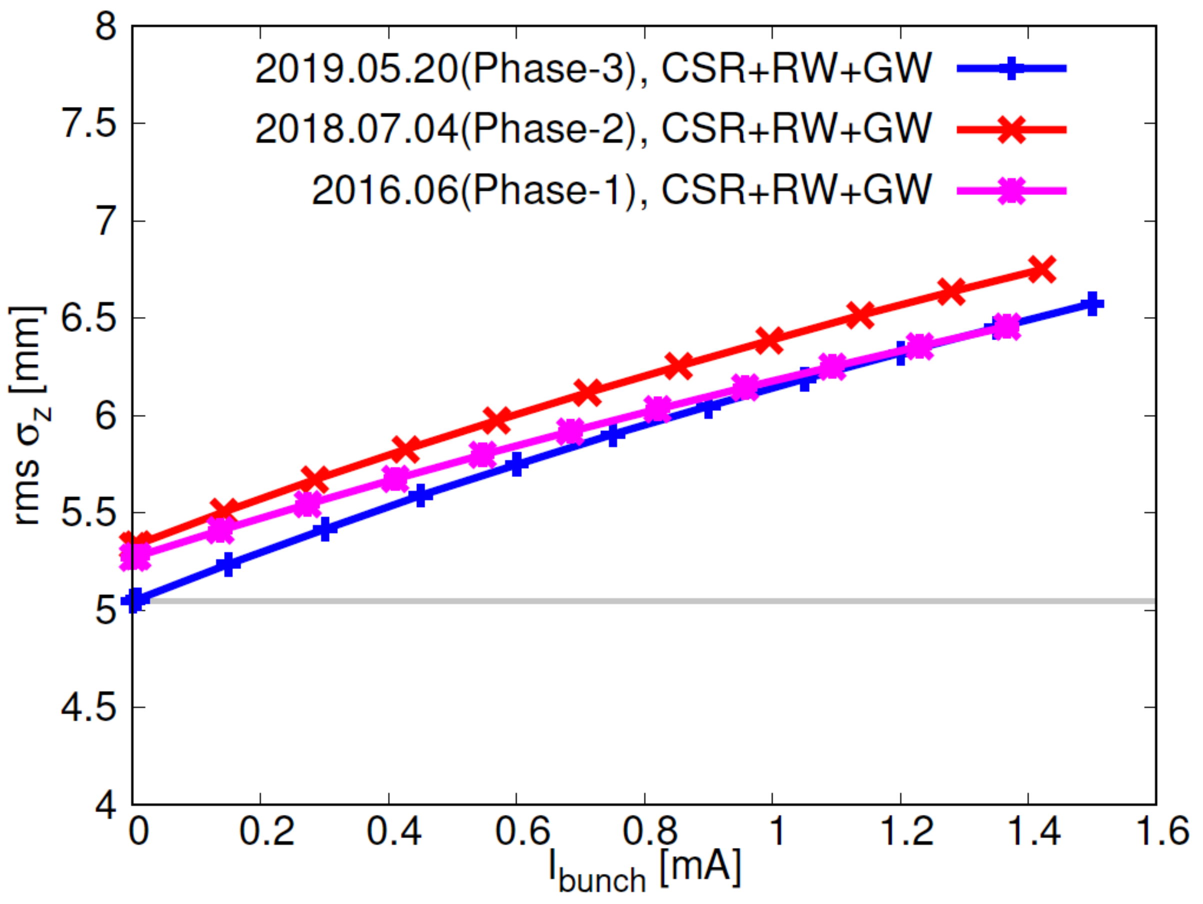


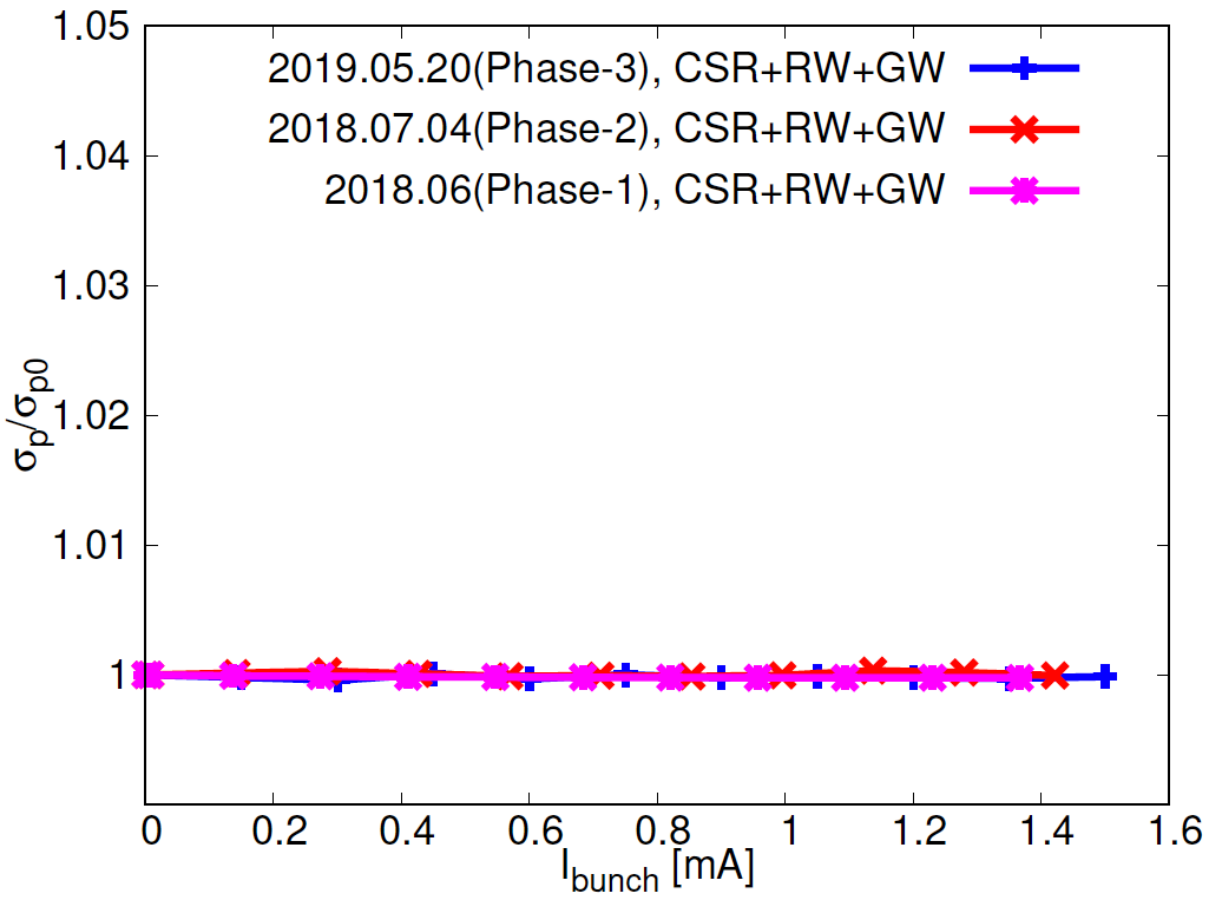
T. Ishibashi

1. Potential-well distortion

➤ Simulation results of MWI: HER

- Comparison of Phase-1, Phase-2 and Phase-3
- MWI threshold above 1.5 mA
- The main difference of impedance sources between the three phases is from collimators

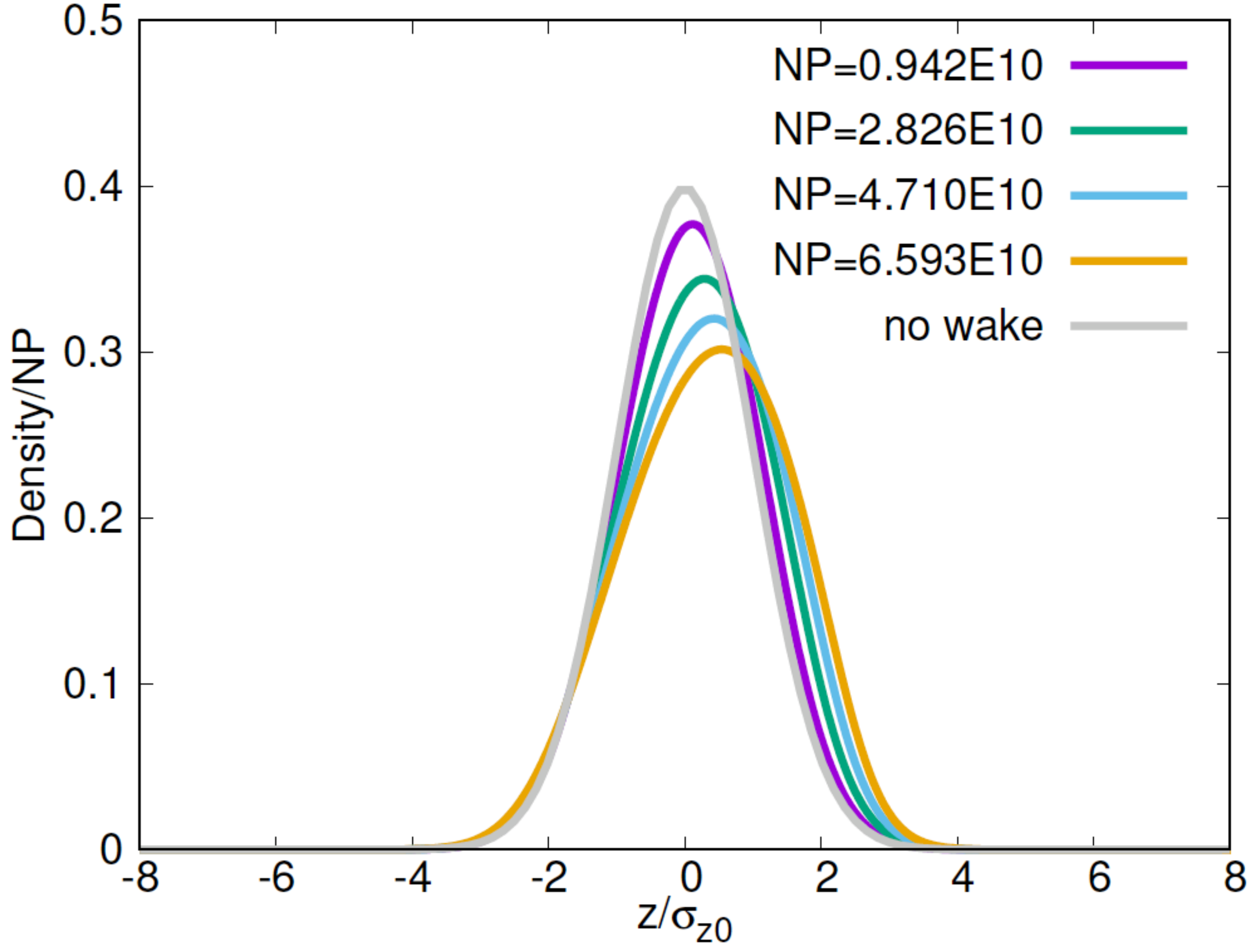




1. Potential-well distortion

➤ Simulation results of MWI: HER

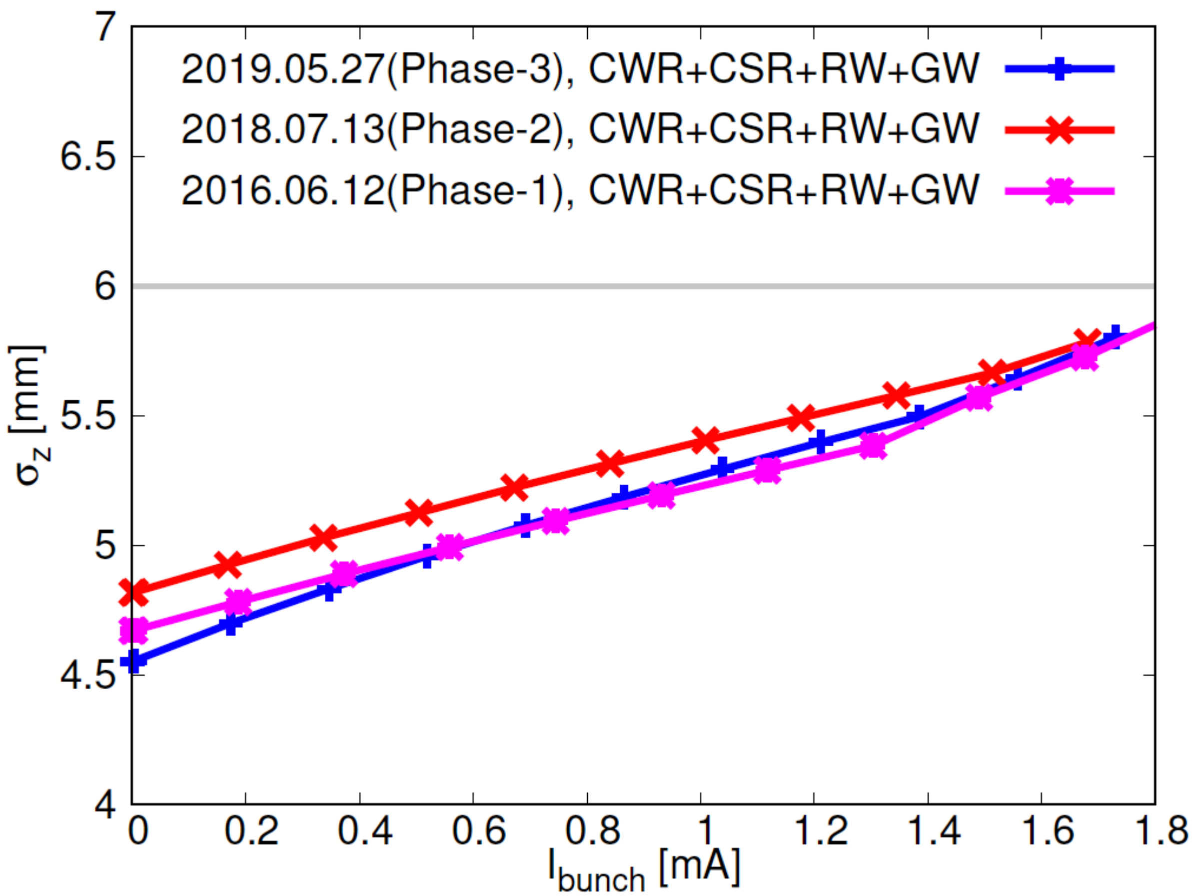
- Shift of center of mass => RF phase shift
- Bunch profile tilt => Optimum RF phase
- To be investigated: Effects on luminosity and interplay with beam-beam effects

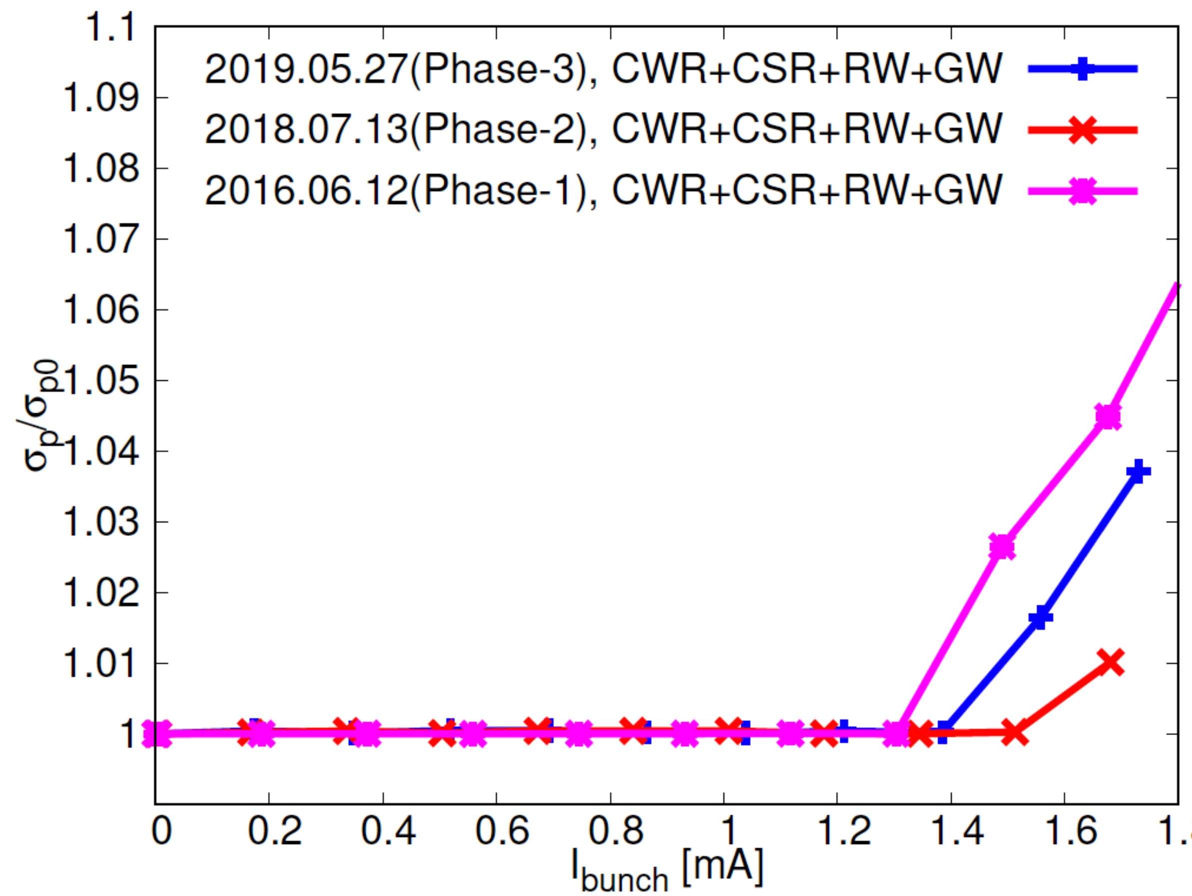


1. Potential-well distortion

➤ Simulation results of MWI: LER

- Comparison of Phase-1, Phase-2 and Phase-3
- MWI threshold above 1.4 mA for Phase-3, depending on CSR
- The main difference of impedance sources between the three phases is from collimators
- Collimator impedance is inductive => Improve the MWI threshold
- RF cavity impedance is resistive => Cause strong tilt and excite CSR

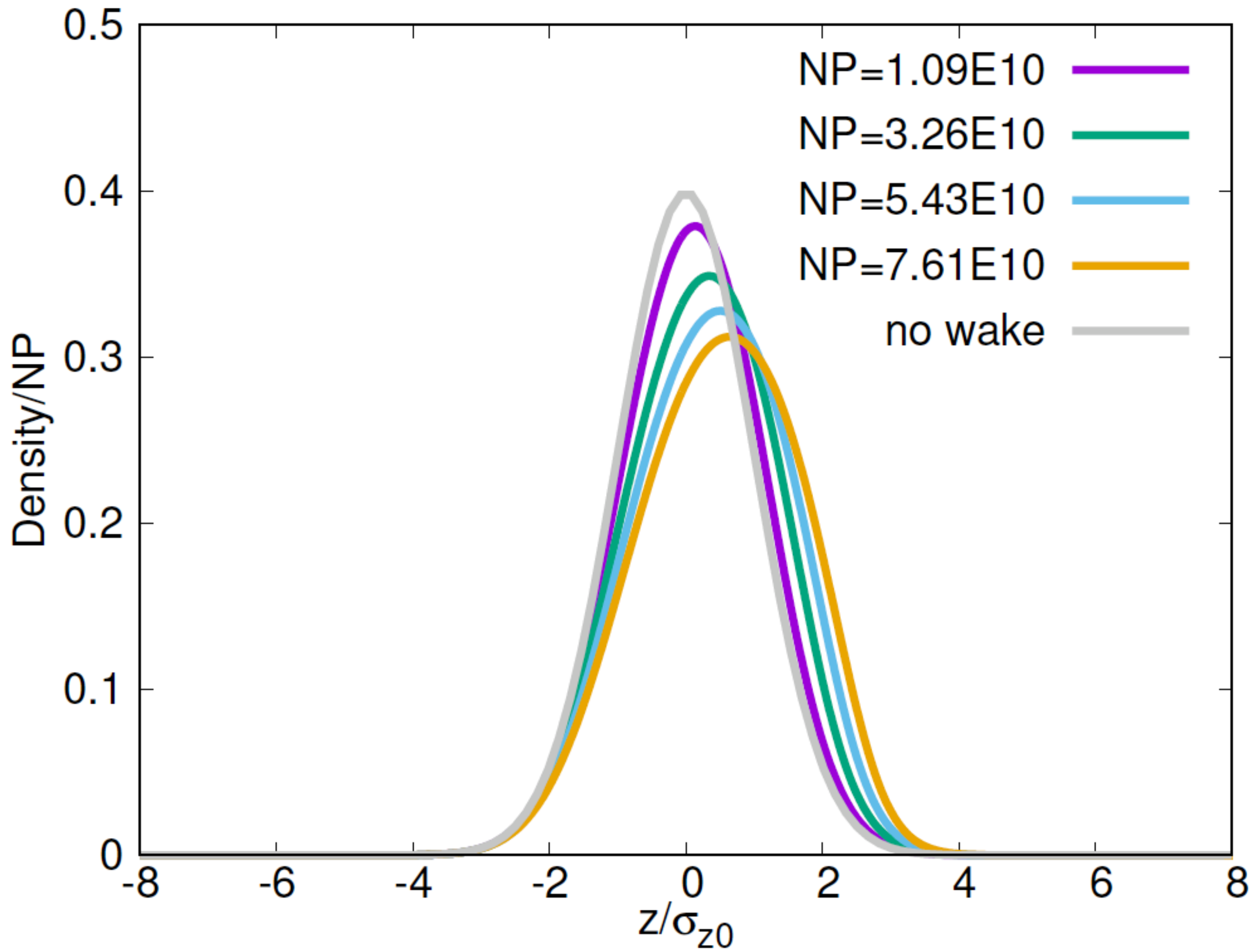




1. Potential-well distortion

➤ Simulation results of MWI: LER

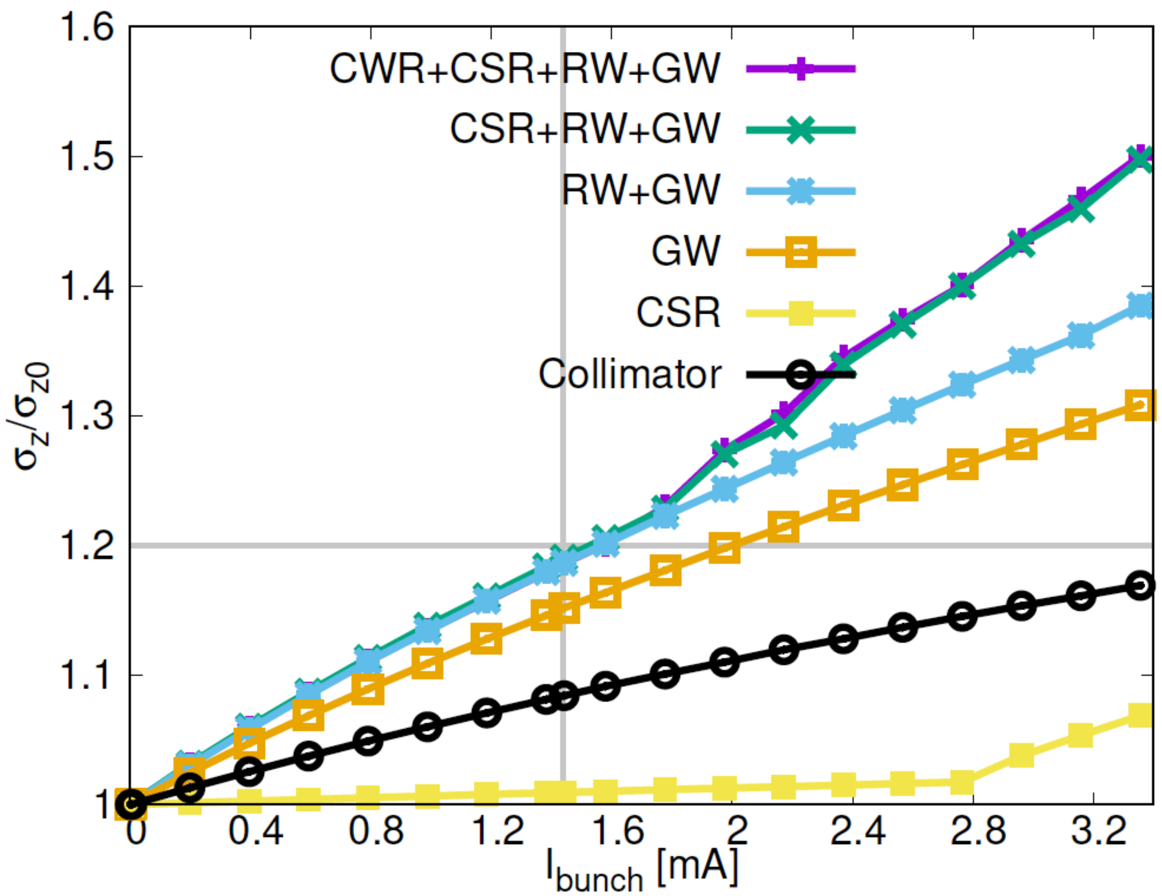
- Shift of center of mass => RF phase shift
- Bunch profile tilt => Optimum RF phase
- To be investigated: Effects on luminosity and interplay with beam-beam effects

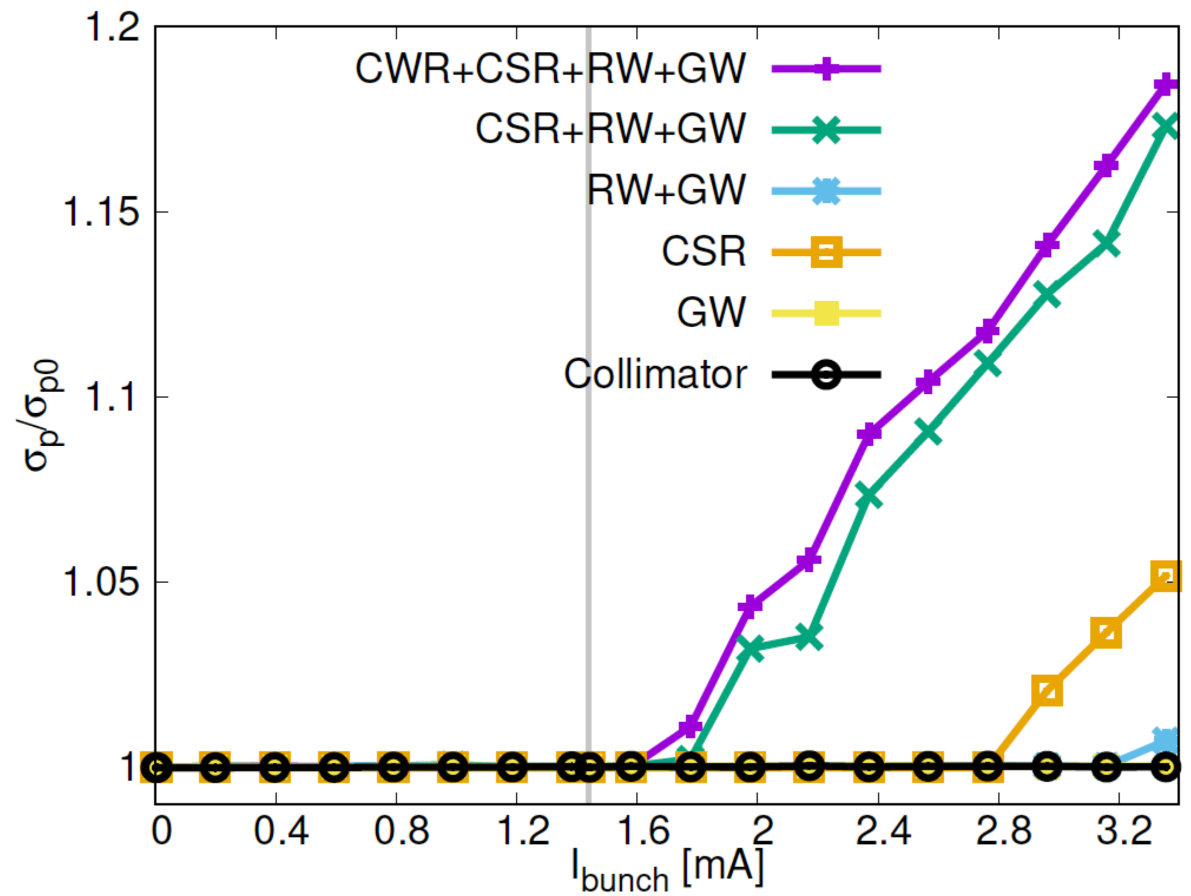


1. Potential-well distortion

➤ Simulation results of MWI: LER(Final design)

- CSR+CWR is important in determining the MWI threshold
- The final design of LER has more collimators (to be installed)
- Collimator impedance is inductive => Improve the MWI threshold
- RF cavity impedance is resistive => Cause strong tilt and excite CSR





Ref. D. Zhou, in Proceedings of IPAC'14, Dresden, Germany

1. Potential-well distortion

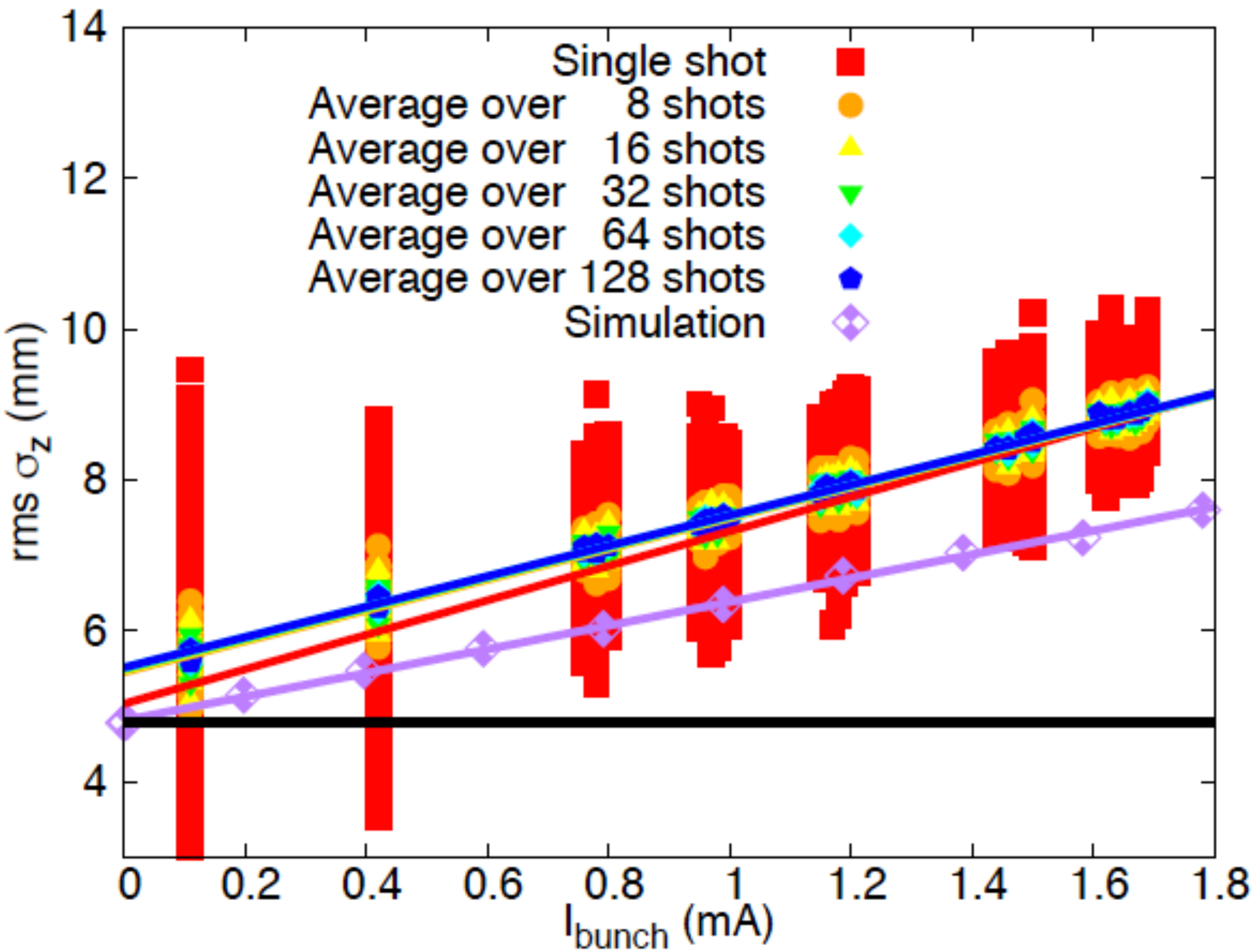
➤ Comparison of MWI simulations with streak camera

- From KEKB to SuperKEKB, huge discrepancy always seen, very hard to explain
- In KEKB LER, we compared five methods:
  ** 1) MWI simulations (D. Zhou)
  ** 2) Streak camera (H. Ikeda et al.)
  ** 3) Direct beam phase measurements (T. Ieiri)
  ** 4) RF power analysis (D. Zhou)
  ** 5) Belle hadron events (Y. Cai, Phys. Rev. ST Accel. Beams 12, 061002 (2009))
  ** We did find good agreements in 1), 3) and 4) (K. Bane and D. Zhou, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017). Also fair agreement with 5).
- We propose detailed studies should be done for SuperKEKB, especially:
  ** RF phase scan with beam-beam interaction
  ** Belle2 data (z_{IP} distribution, Ref. H. Kichimi et al 2010 JINST 5 P03011)

1. Potential-well distortion

➤ Comparison of MWI simulations with streak camera

- **The case of KEKB LER: MWI simulation vs. Streak camera**

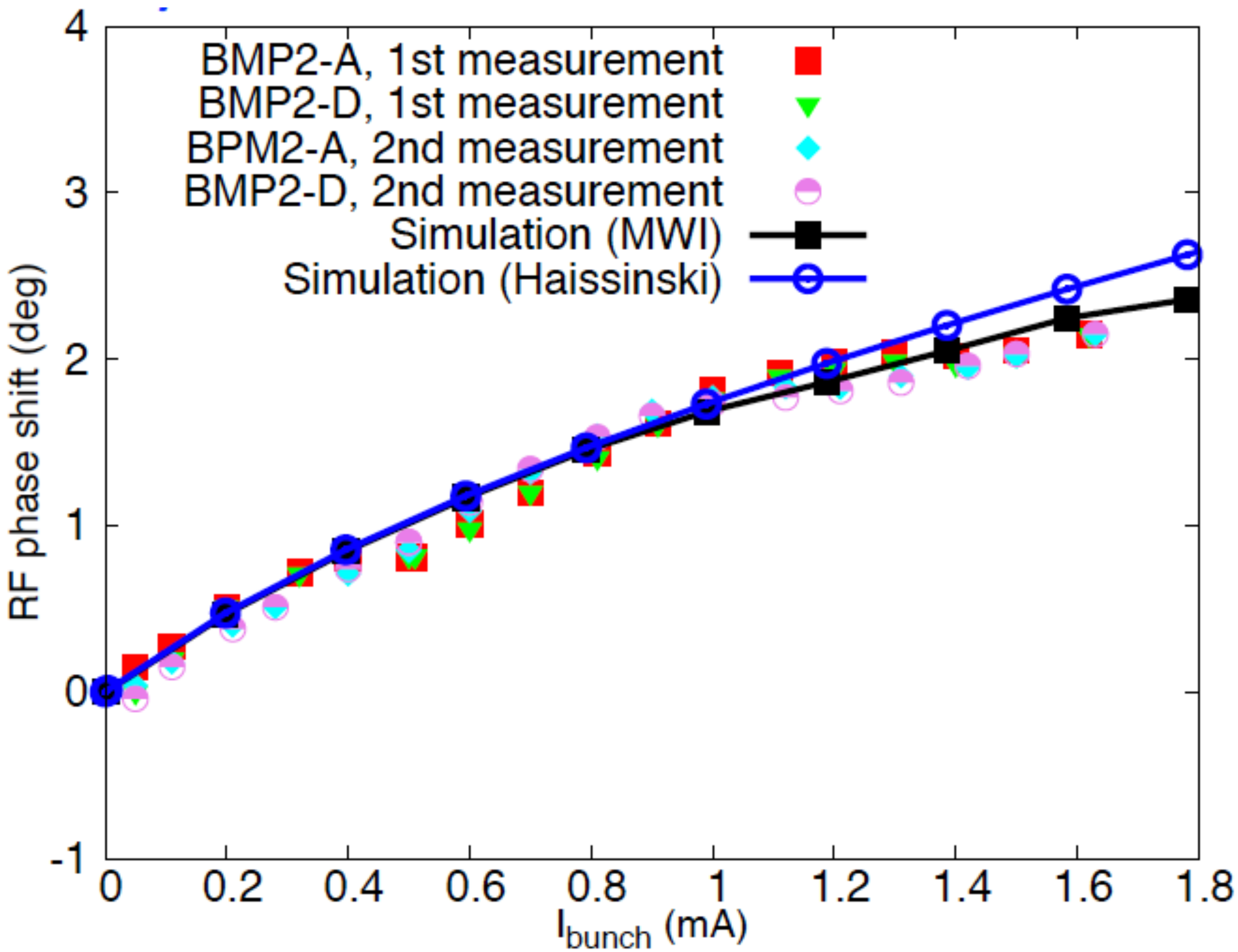


Ref. K. Bane, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017

1. Potential-well distortion

➤ Comparison of MWI simulations with streak camera

- **The case of KEKB LER: MWI simulation vs. Beam phase**
- **With beam energy 3.594 GeV and RF voltage 8 MV**

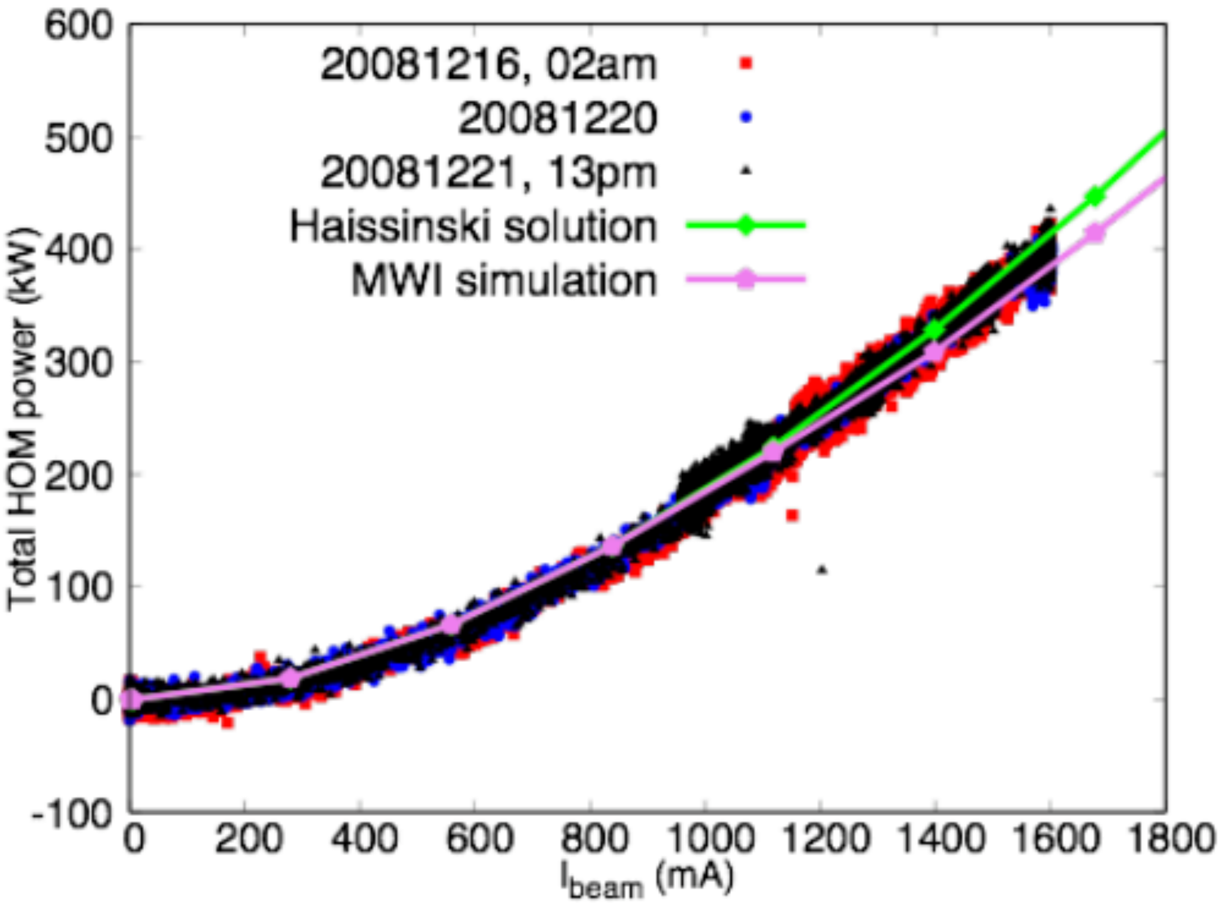


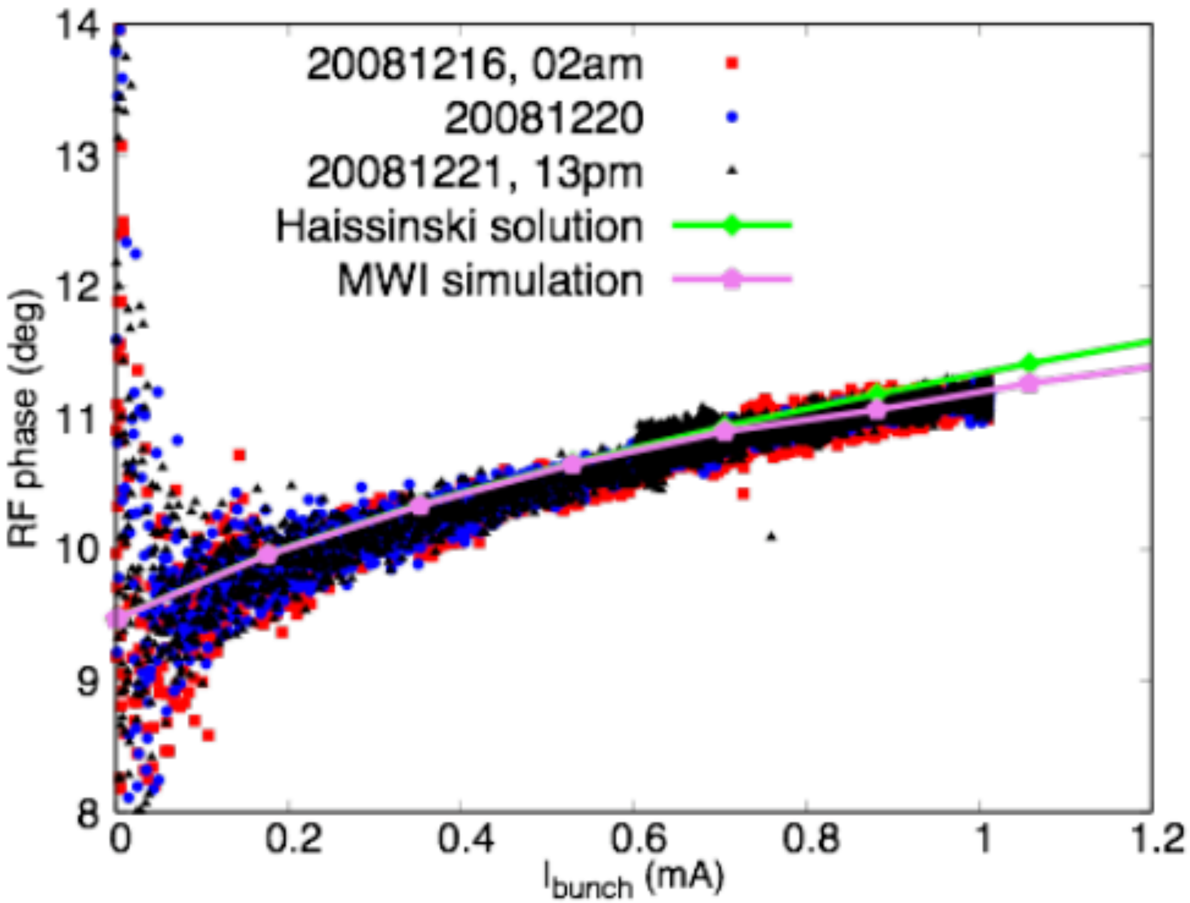
Ref. K. Bane, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017

1. Potential-well distortion

➤ Comparison of MWI simulations with streak camera

- The case of KEKB LER: MWI simulation vs. RF power analysis
- With beam energy 3.3144 GeV and RF voltage 8 MV



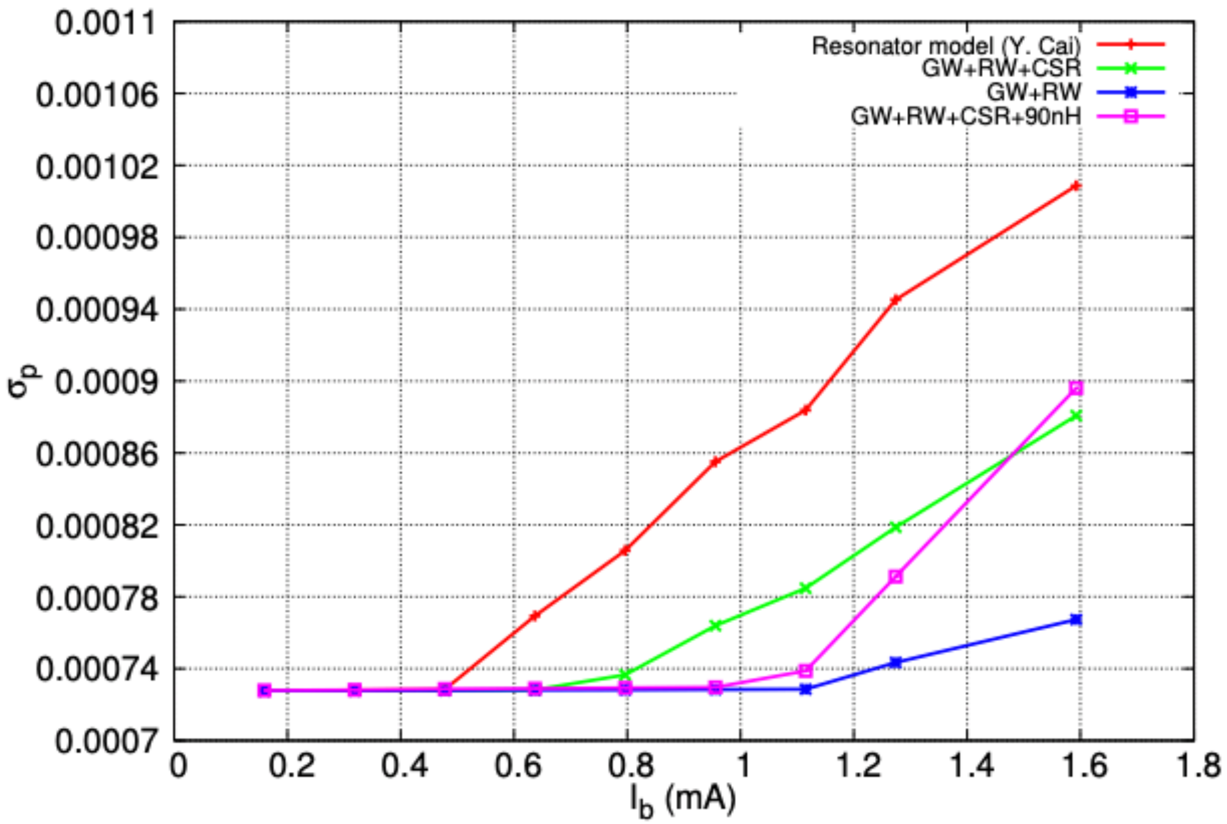


Ref. K. Bane, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017

1. Potential-well distortion

➤ Comparison of MWI simulations with streak camera

- The case of KEKB LER: MWI simulation vs. Belle hadron events
- My simulation better agree with Belle data?



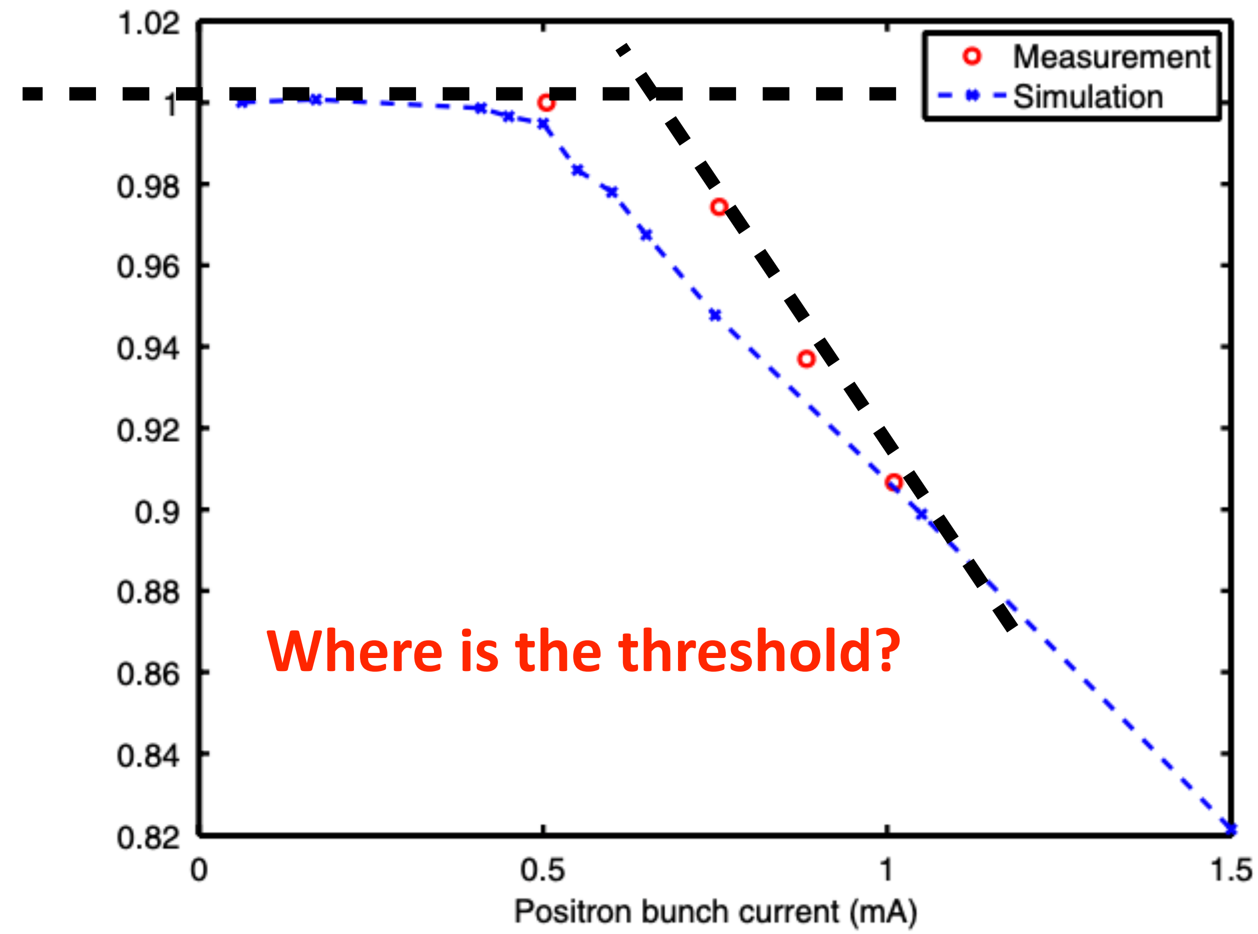


FIG. 6. (Color) Ratio of hadron events to Bhabha was measured as a function of positron bunch current using the Belle detector. The data is normalized to the measured value at 0.5 mA. The result of simulation is plotted according to Eq. (18) and the energy spreads at zero currents are used for the normalization.

Ref. K. Bane, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017

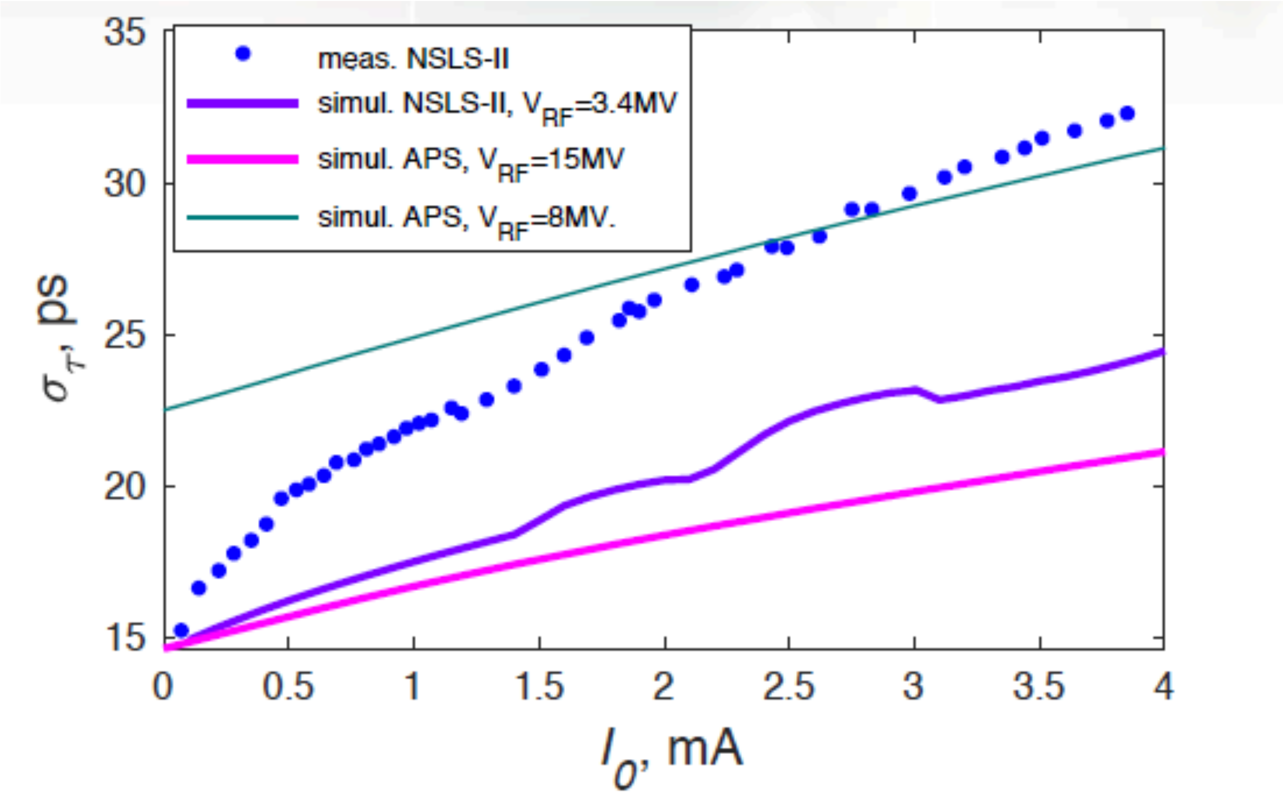
Ref. Y. Cai, Phys. Rev. ST Accel. Beams 12, 061002 (2009)

1. Potential-well distortion

➤ Comparison of MWI simulations with streak camera

- **We are not alone. The NSLS-II (also use Hamamatsu products) shares similar experiences with SuperKEKB**

Energy	$E_0(GeV)$	3		
Revolution period	$T_0(\mu s)$	2.6		
Momentum compaction	α	3.7 x 10^{-4}		
RF voltage	$V_{RF}(MV)$	3.4		
Synchrotron tune	ν_s	9.2 x 10^{-3}		
		BL	1DW	3DW
Energy loss	$U(keV)$	287	400	674
Damping time	$\tau_x, \tau_s\ (ms)$	54, 27	40, 20	23, 11.5
Energy spread	σ_δ	0.5 x 10^{-3}	0.71 x 10^{-3}	0.82 x 10^{-3}
Horizontal Emittance	$\varepsilon_x\ (nm)$	2.1	1.4	0.9
Bunch length (at low current)	$\sigma_z\ (mm)$	2.5	3.5	4



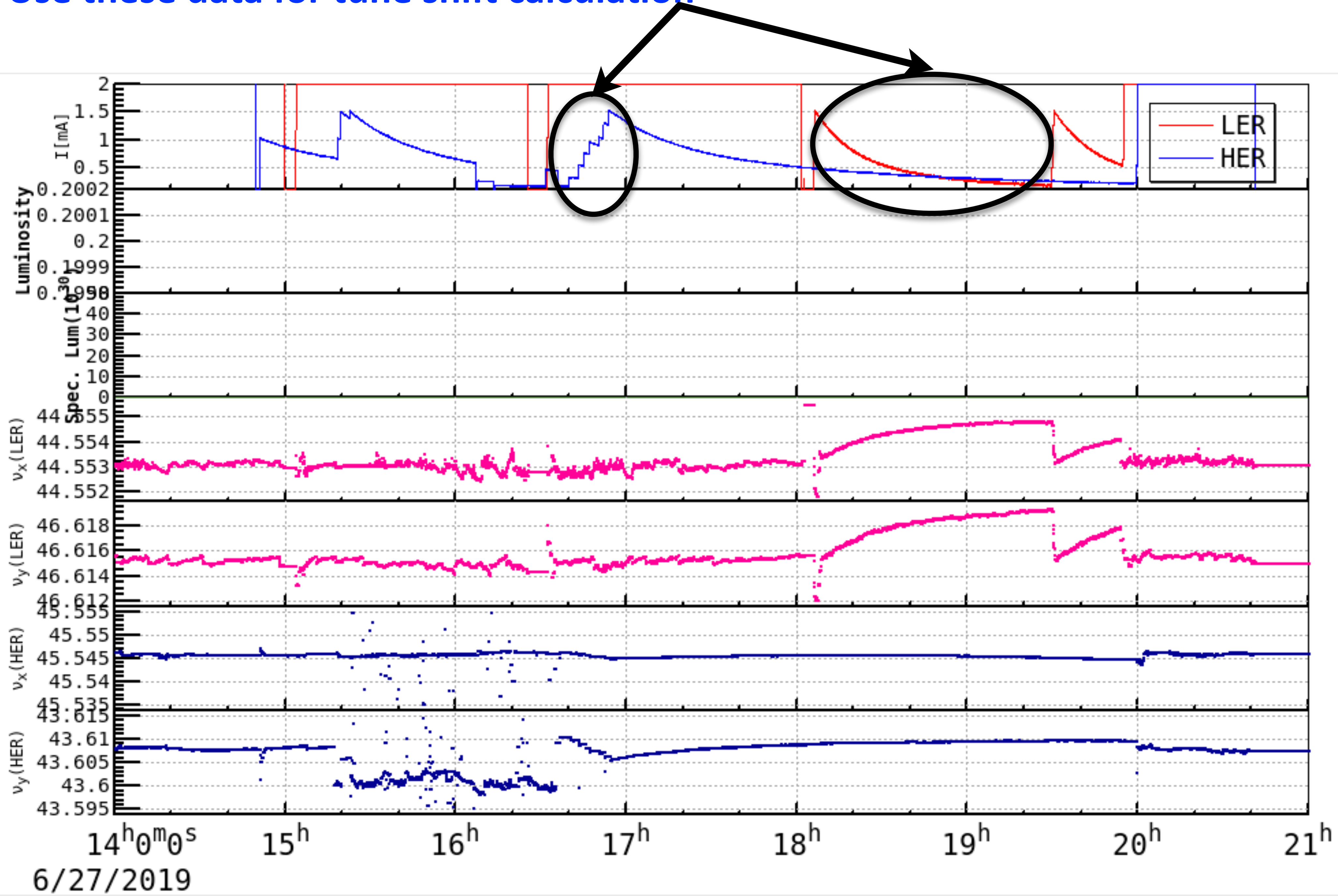
Streak camera measurements of the bunch length as a function of single-bunch current $\sigma_\tau(I_0)$ vs VFP particle tracking simulations at $V_{RF} = 3MV$

Ref. A. Blednykh, Private communication

2. Betatron tune shift (single bunch)

➤ Measurements of Phase-3

- Data recorded in the kblog system
- Use these data for tune shift calculation

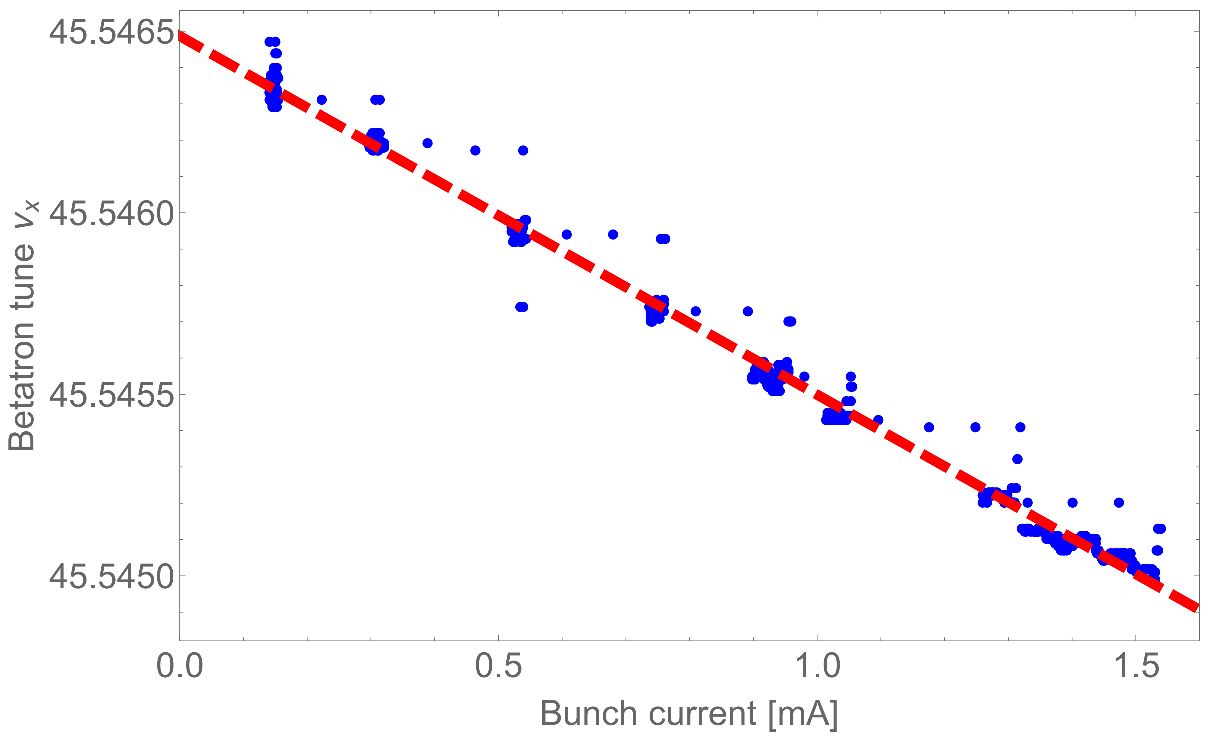


2. Betatron tune shift (single bunch)

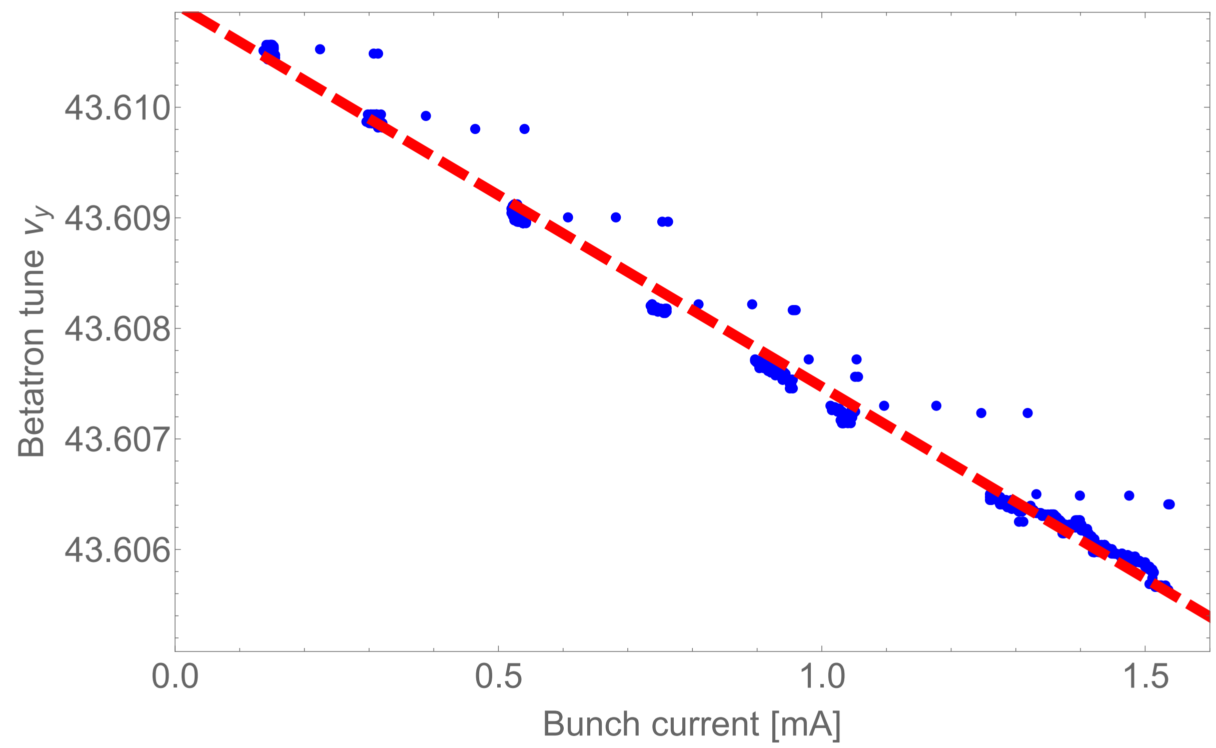
➤ Single-bunch betatron tune shift: HER (2019.06.27)

- **Linear fitting model: f(x)=a+b*x**
- **$Zeff_x$ ~48.7 kΩ/m, $Zeff_y$ ~164 kΩ/m**

Linear fitting:
f(I)=45.5465 - 0.000988*I[mA]



Linear fitting:
f(I)=43.6109 - 0.00347*I[mA]



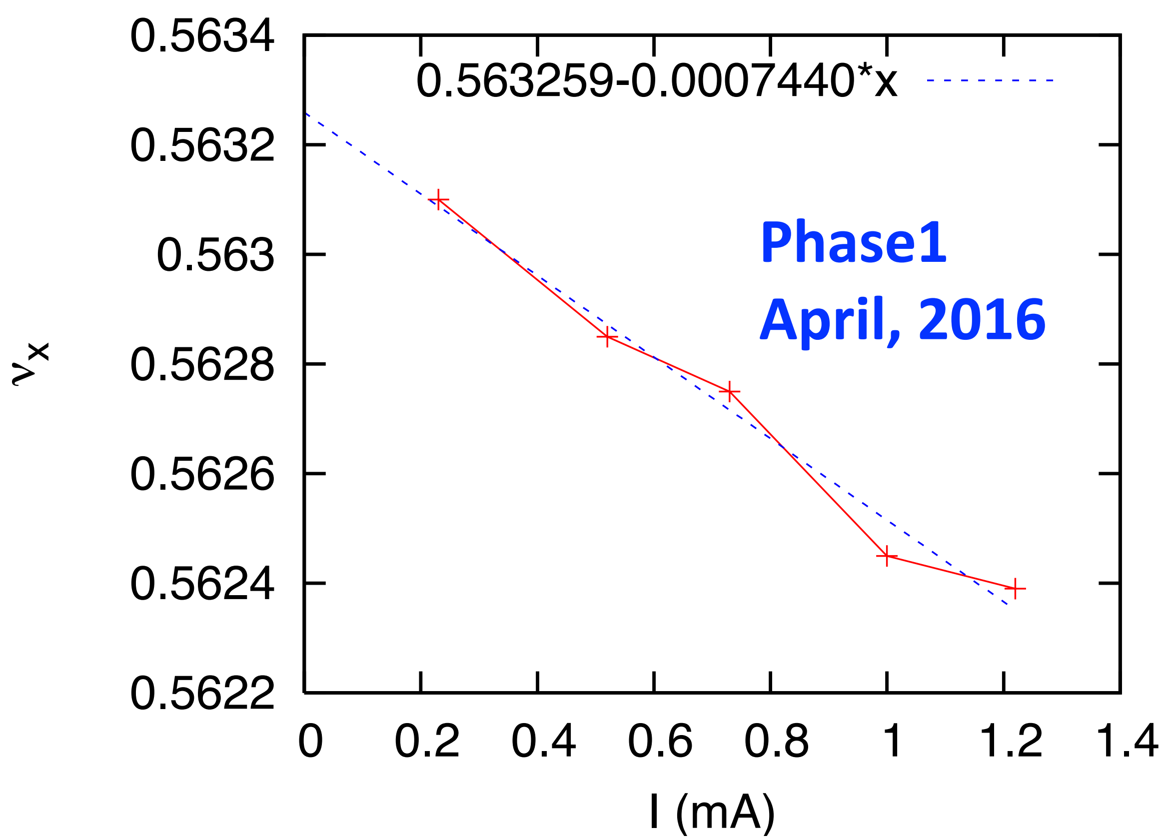
2. Betatron tune shift (single bunch)

➤ **HER: Horizontal plane**

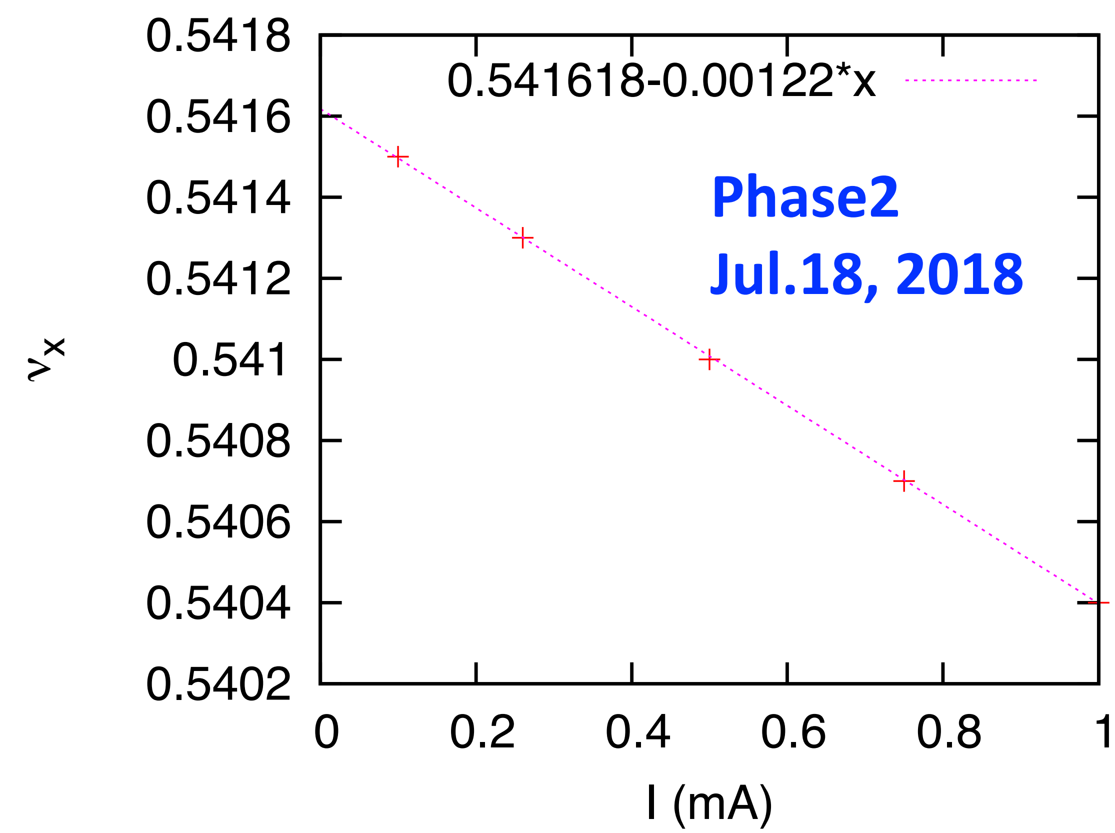
- **Left figure: Data taken in Phase 1**
- **Right figure: Data taken in Phase 2**

$$iZ_{\rm eff}({\rm k}\Omega/{\rm m}) = 58.2\frac{\Delta\nu}{I_{\rm bunch}({\rm A})}$$

$$iZ^X_{\rm eff} = 43\ {\rm k}\Omega/{\rm m}$$



$$iZ^X_{\rm eff} = 71\ {\rm k}\Omega/{\rm m}$$



From K. Ohmi

Ref. http://www-kekb.kek.jp/MAC/2018/Report/Ohmi.pdf

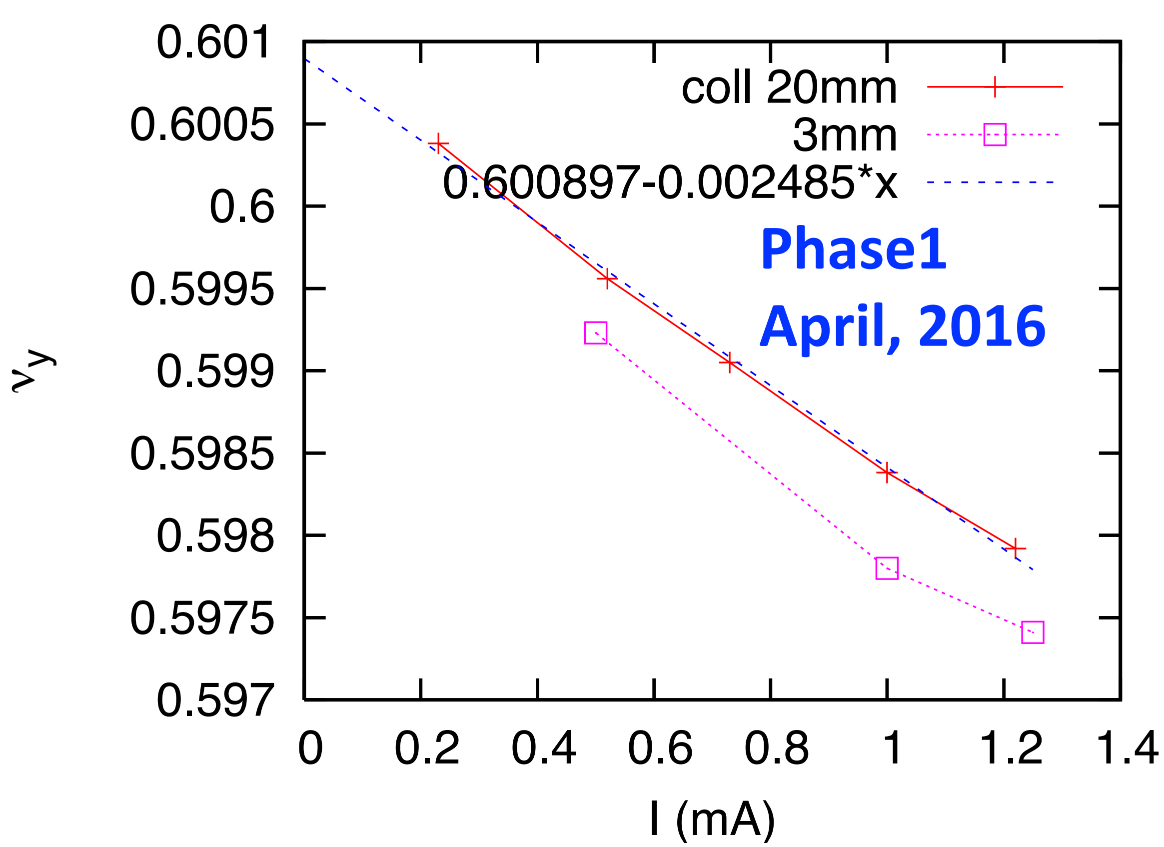
2. Betatron tune shift (single bunch)

➤ HER: Vertical plane

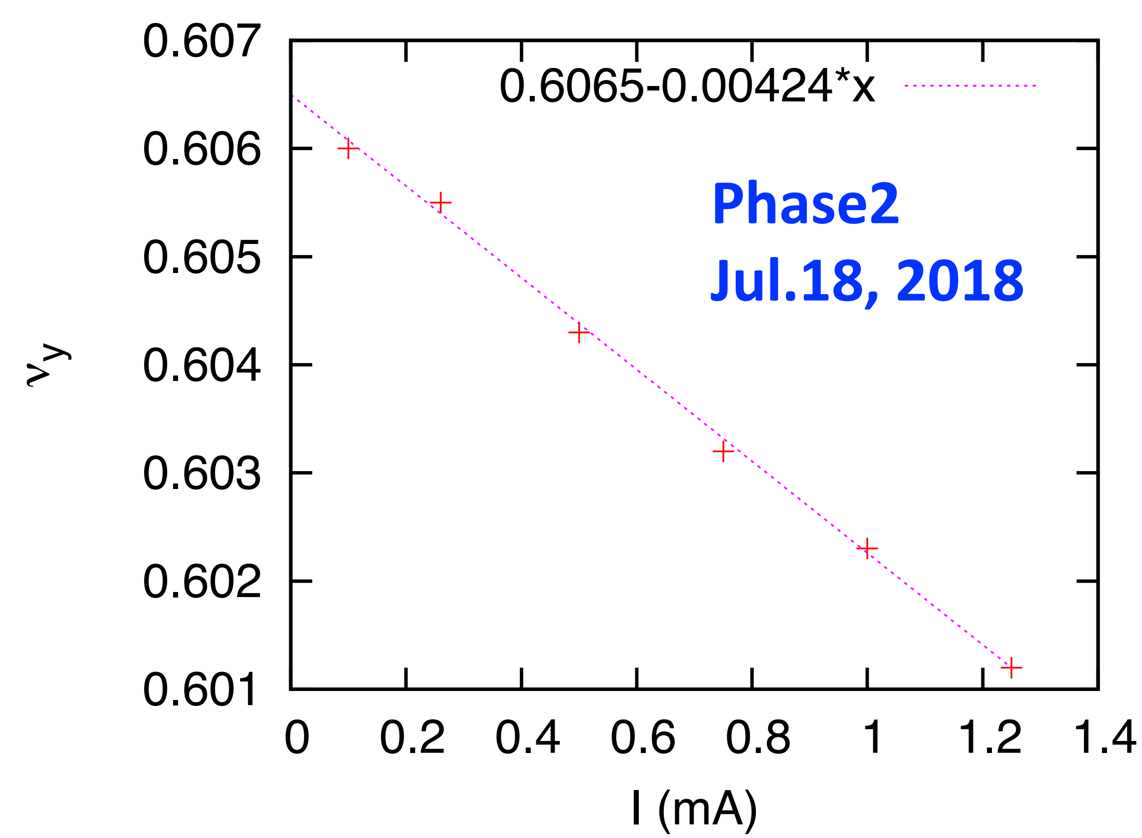
- **Left figure: Data taken in Phase 1**
- **Right figure: Data taken in Phase 2**

$$iZ_{\text{eff}}(\text{k}\Omega/\text{m}) = 58.2\frac{\Delta\nu}{I_{\text{bunch}}(\text{A})}$$

$$iZ^{Y}_{\text{eff}} = 145\ \text{k}\Omega/\text{m}$$



$$iZ^{Y}_{\text{eff}} = 247\ \text{k}\Omega/\text{m}$$



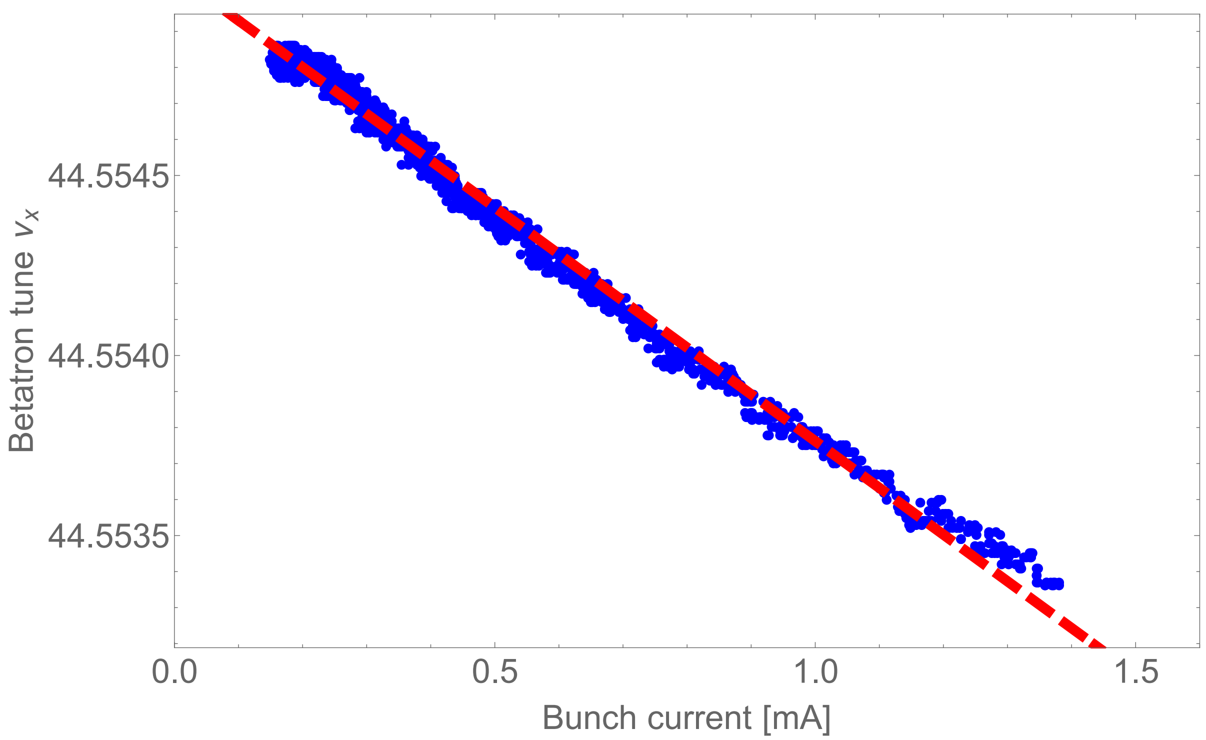
From K. Ohmi **Ref. http://www-kekb.kek.jp/MAC/2018/Report/Ohmi.pdf**

2. Betatron tune shift (single bunch)

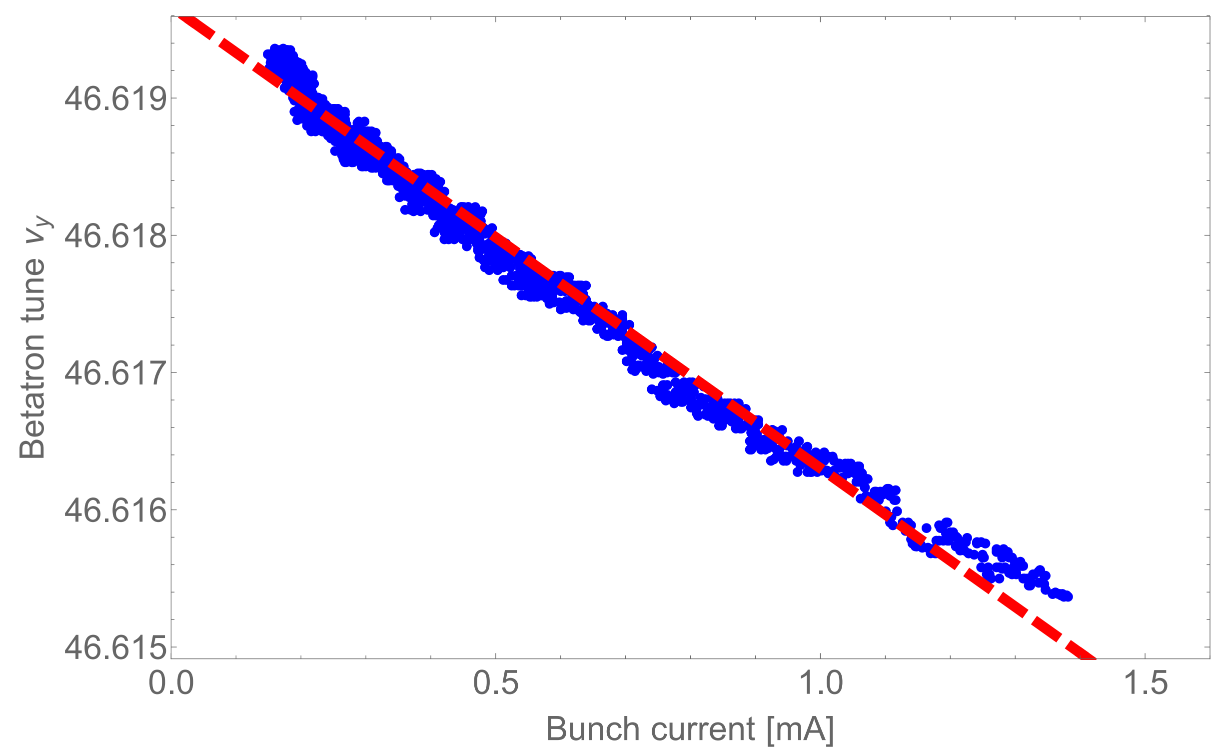
➤ Single-bunch betatron tune shift: LER (2019.06.27)

- **Linear fitting model: f(x)=a+b*x**
- **Used natural decay of bunch current: Problematic because of changing machine conditions with time**
- **$Zeff_x$ ~32.2 kΩ/m, $Zeff_y$ ~87.4 kΩ/m**

Linear fitting:
f(I)=44.5551 - 0.00130*I[mA]



Linear fitting:
f(I)=46.6197 - 0.00337*I[mA]



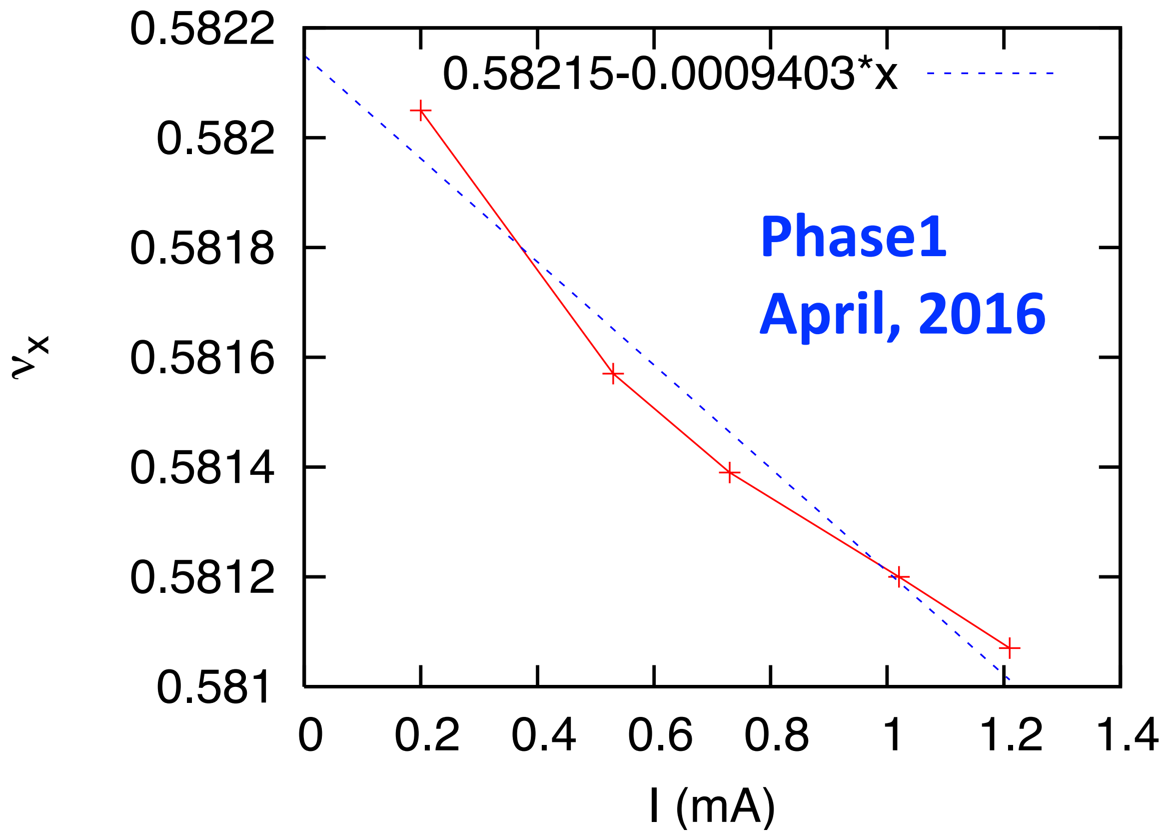
2. Betatron tune shift (single bunch)

➤ **LER: Horizontal plane**

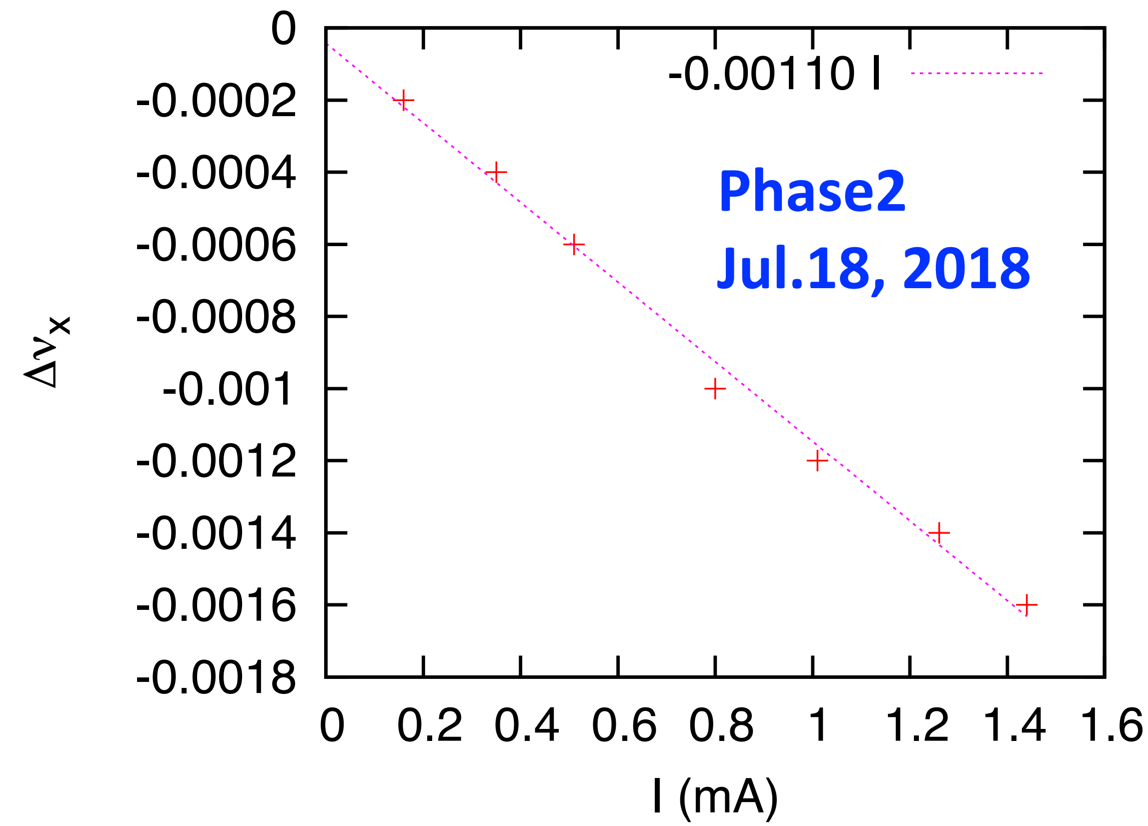
- **Left figure: Data taken in Phase 1**
- **Right figure: Data taken in Phase 2**

$$iZ_{\text{eff}}(\mathrm{k}\Omega/\mathrm{m}) = 33.3\frac{\Delta\nu}{I_{\text{bunch}}(\mathrm{A})}$$

$$iZ_{\text{eff}}^{X} = 31\ \mathrm{k}\Omega/\mathrm{m}$$



$$iZ_{\text{eff}}^{X} = 37\ \mathrm{k}\Omega/\mathrm{m}$$



From K. Ohmi

Ref. http://www-kekb.kek.jp/MAC/2018/Report/Ohmi.pdf

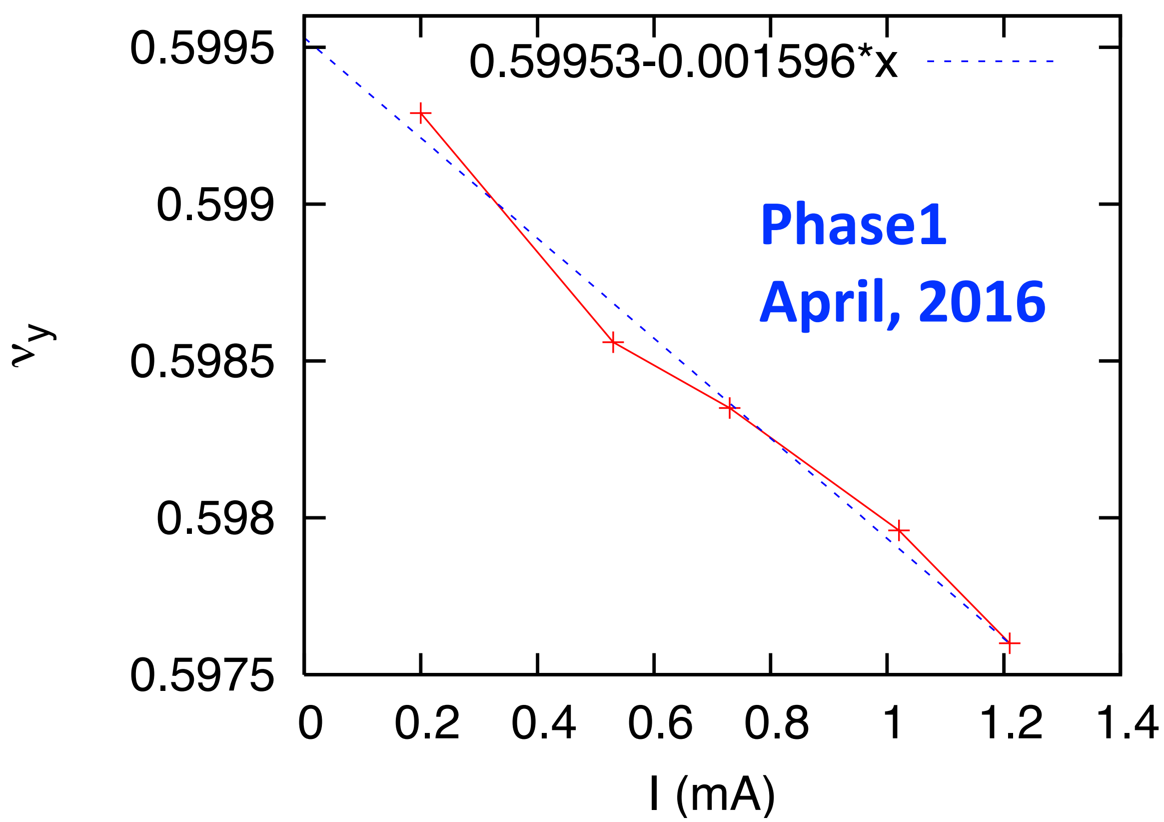
2. Betatron tune shift (single bunch)

➤ **LER: Vertical plane**

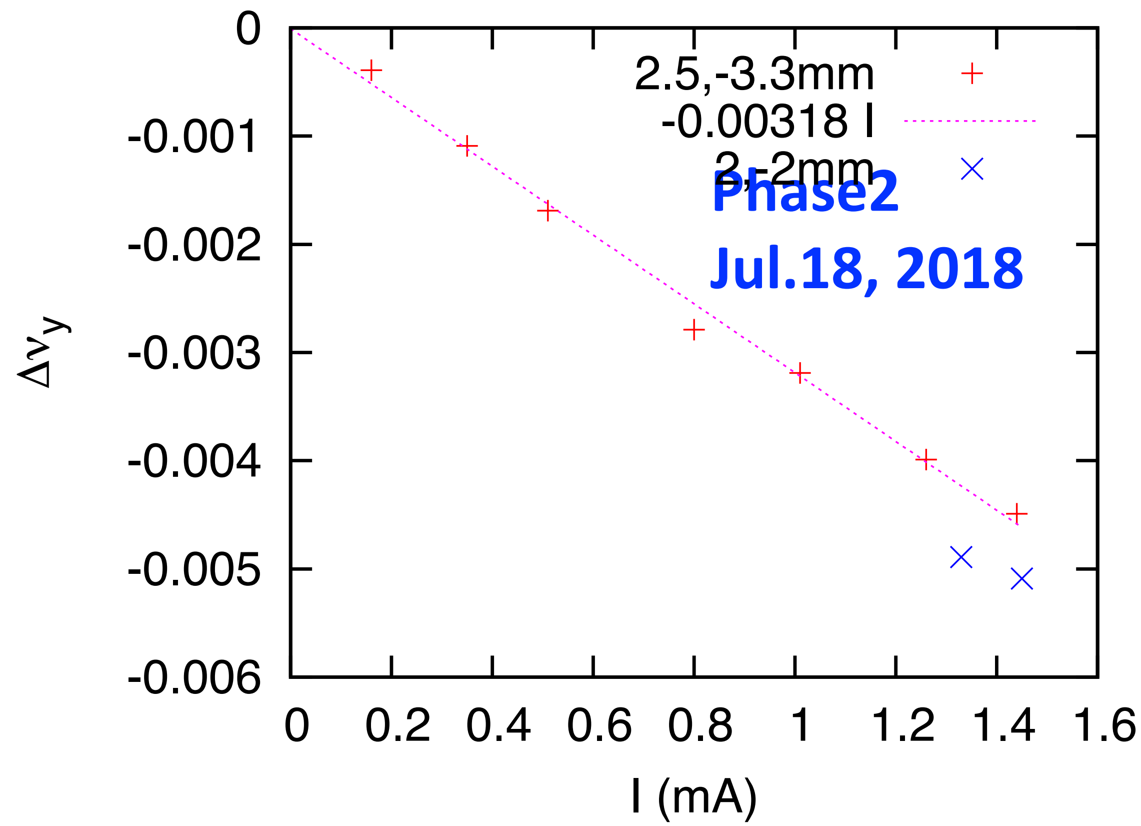
- **Left figure: Data taken in Phase 1**
- **Right figure: Data taken in Phase 2**

$$iZ_{\rm eff}({\rm k}\Omega/{\rm m}) = 33.3\frac{\Delta\nu}{I_{\rm bunch}({\rm A})}$$

$$iZ^{Y}_{\rm eff} = 53\ {\rm k}\Omega/{\rm m}$$



$$iZ^{Y}_{\rm eff} = 106\ {\rm k}\Omega/{\rm m}$$



From K. Ohmi **Ref. http://www-kekb.kek.jp/MAC/2018/Report/Ohmi.pdf**

2. Betatron tune shift (single bunch)

➤ Comparison

- **LER:**
  X: 31 (2016.04) -> 37 (2018.07.18) -> 32 (2019.06.27) kΩ/m
  Y: 53 (2016.04) -> 106 (2018.07.18) -> 87 (2019.06.27) kΩ/m
- **HER:**
  X: 43 (2016.04) -> 71 (2018.07.18) -> 49 (2019.06.27) kΩ/m
  Y: 145 (2016.04) -> 247 (2018.07.18) -> 164 (2019.06.27) kΩ/m
- **Discrepancy to be understood**

3. Beam tilt due to transverse impedance

➤ The problem realized

● **Asymmetric transerve impedances can cause transverse beam tilt to the beams [Ref. G. Stupakov and D. Zhou, Nucl. Instrum. Meth. A 764 (2014) 378–382.**

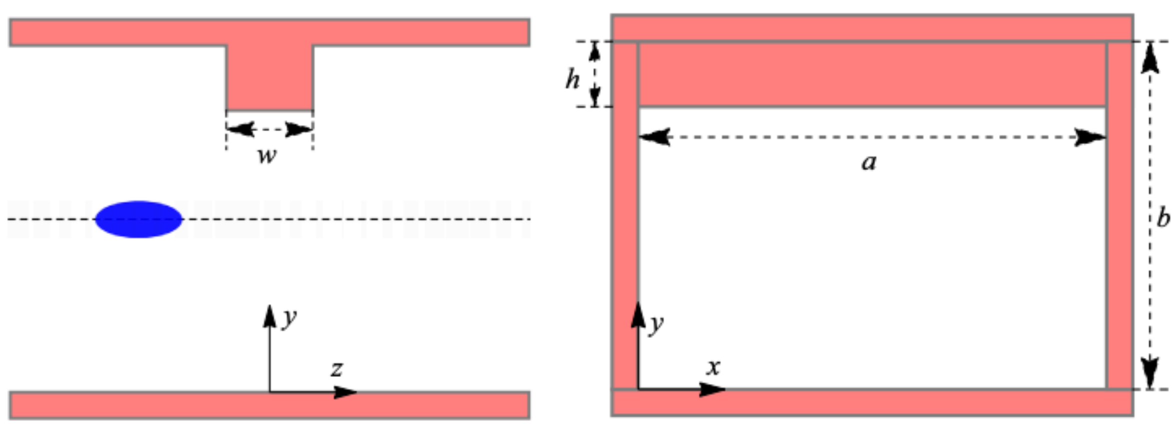


Fig. 1. Geometry of a rectangular vacuum chamber with an asymmetric protrusion. The design orbit goes through the center of the $a \times b$ cross-section.

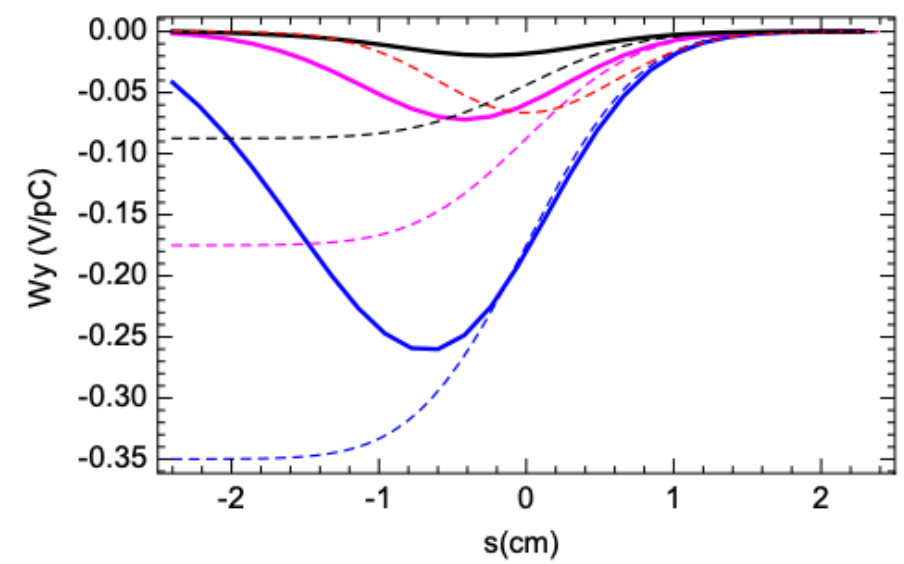


Fig. 3. Wakefield of a bunch with $\sigma_z = 6$ mm for three values of the protrusion depth h: 1 cm (blue), 0.5 cm (magenta) and 0.25 cm (black). The dashed lines of the same color show the corresponding wakes computed with the optical model. The red dashed line shows the profile of the beam. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

3. Beam tilt due to transverse impedance

➤ The problem noticed at HER

- D09-V{1234} are set on the same side
- D12-V{1234} are set not symmetrically

Current: 26.350 mA Life: 337.952 min Man1

HER ALL GO Normal

ID	HeadPos	TargetPos	Go	Pulse	1shot	BeamPosX	BeamPosY	HomePos	I O H E	GH	Stop	ErrClr		LossMonitor
D09-H1-IN	-10.51	-10.50		2147382388		0.08	0.04	-19.06					0	0.09 V
D09-H2-IN	-11.51	-11.50		2147386878		-0.09	0.11	-19.67					0	0.01 V
D09-H3-IN	-11.04	-11.00		2147386088		0.12	-0.02	-19.18					0	0.14 V
D09-H4-IN	-11.04	-11.00		2147382028		-0.27	-0.09	-19.58					0	0.12 V
D12-H1-IN	-11.05	-11.00		2147376678		0.05	0.15	-20.02					0	0.03 V
D12-H2-IN	-11.05	-11.00		2147380258		-0.15	0.08	-19.75					0	0.03 V
D12-H3-IN	-10.96	-11.00		2147376808		0.21	0.29	-20.08					0	0.03 V
D12-H4-IN	-12.49	-12.50		2147394888		0.13	0.01	-20.07					0	0.04 V
D01-H3-OUT	7	7.00		-161375	I O	-0.31	-0.12	26.05					0x0	0 V
D01-H3-IN	-6.99	-7.00		-158593	I O	-0.31	-0.12	-25.7					0x0	
D01-H4-OUT	20.02	20.00		-30233	I O	-0.07	0.75	25.99					0x0	0 V
D01-H4-IN	-20.04	-20.00		-39192	I O	-0.07	0.75	-27.75					0x0	
D01-H5-OUT	7.98	8.00		-85234	I O	0.75	0.7	24.62					0x0	0 V
D01-H5-IN	-8	-8.00		-96409	I O	0.75	0.7	-27.6					0x0	

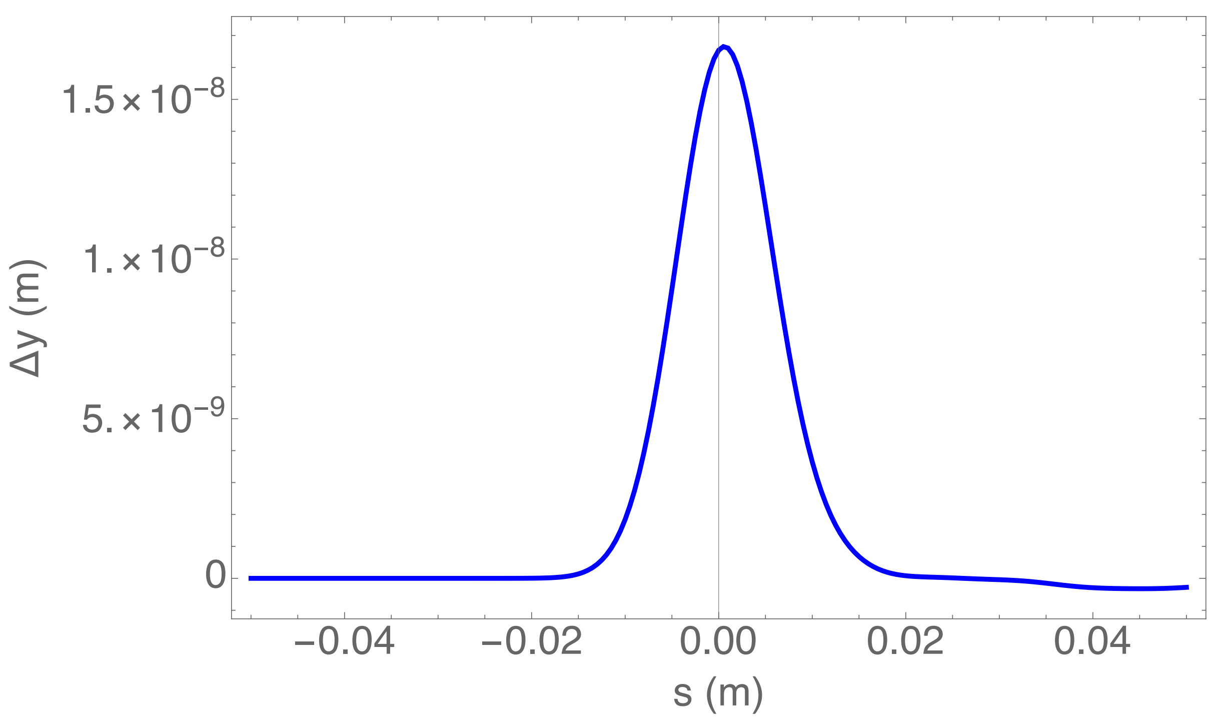
ID	HeadPos	TargetPos	Go	Pulse	1shot	BeamPosX	BeamPosY	HomePos	I O H E	GH	Stop	ErrClr		LossMonitor	
D09-V1-BTM	-2.39	-2.30		2147316048		-0.07	-0.14	-19.79					0	0.13 V	
D09-V2-BTM	-2.88	-2.90		2147327808		-0.05	-0.29	-19.26					0	0.1 V	
D09-V3-BTM	-2.37	-2.30		2147317148		0.34	0.05	-19.67					0	0.12 V	
D09-V4-BTM	-2.72	-2.70		2147325518		0.02	0.01	-19.86					0	0.15 V	
D12-V1-TOP	2.61	2.60		165410		-0.03	-0.22	20.22					0	0.06 V	
D12-V2-BTM	-2.41	-2.40		2147313838		0.07	0.14	-20.28					0	-0.05 V	
D12-V3-TOP	2.74	2.70		156270		0.32	0.73	19.28					0	0.06 V	
D12-V4-BTM	-3.17	-3.20		2147333418		-0.11	-0.26	-18.92					0	0 V	
D01-V1-TOP	2.4	2.40		-97232	I O	-0.32	0.04	21.81					0x0	0 V	0 V
D01-V1-BTM	-2.39	-2.40		-64884	I O	-0.32	0.04	-15.3					0x0		

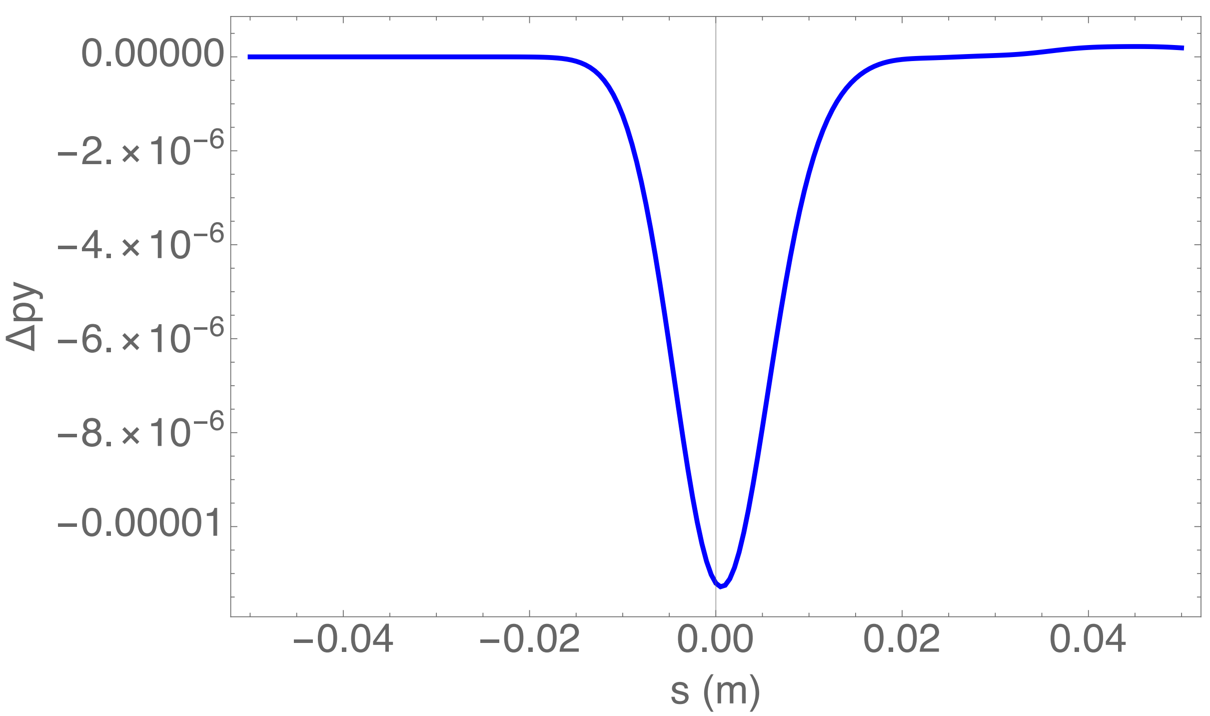
Snapshot on 2019.05.20

3. Beam tilt due to transverse impedance

➤ **The first test with collimator settings on 2019.05.20**

- **Beam current 600 mA, Bunch # 1576**
- **The phase advance between collimators is roughly Pi, this helps cancel the transverse tilt**
- **The residual tilt kick (translated to IP) is mainly from:**
  - ** Non-zero alpha functions at collimators
  - ** Asymmetric settings of the collimator heads

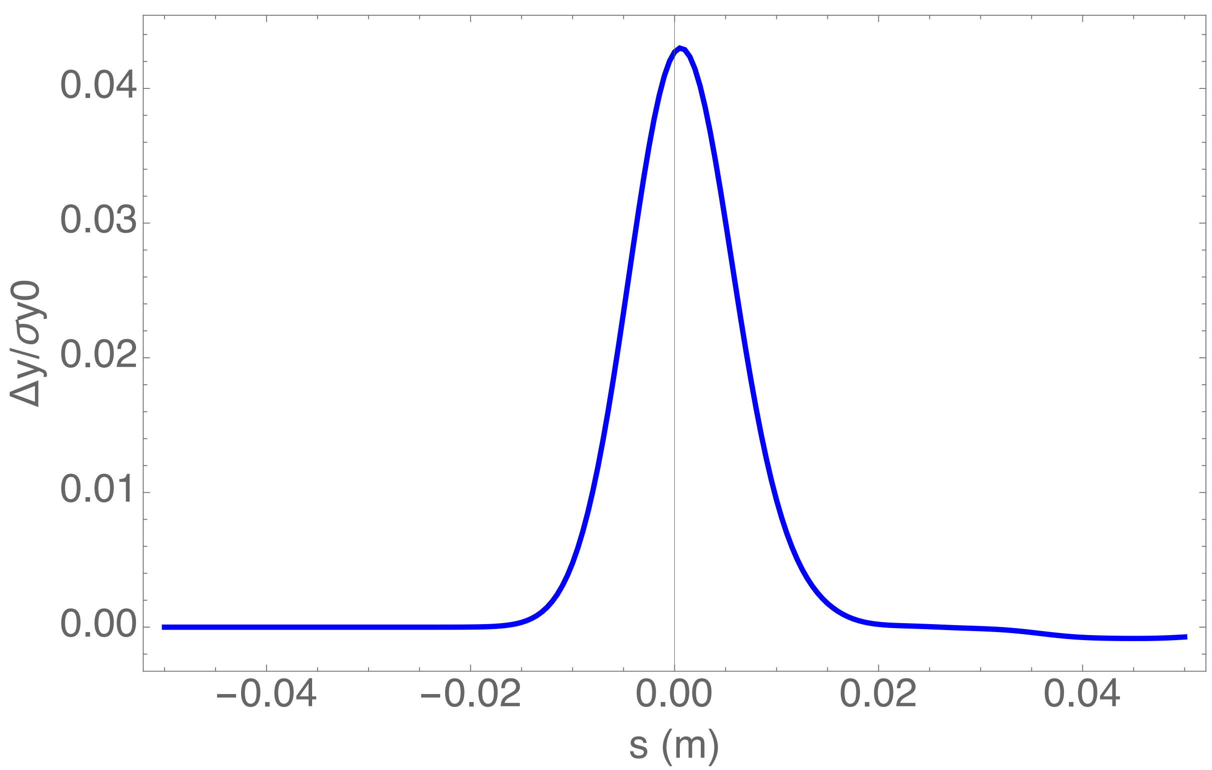


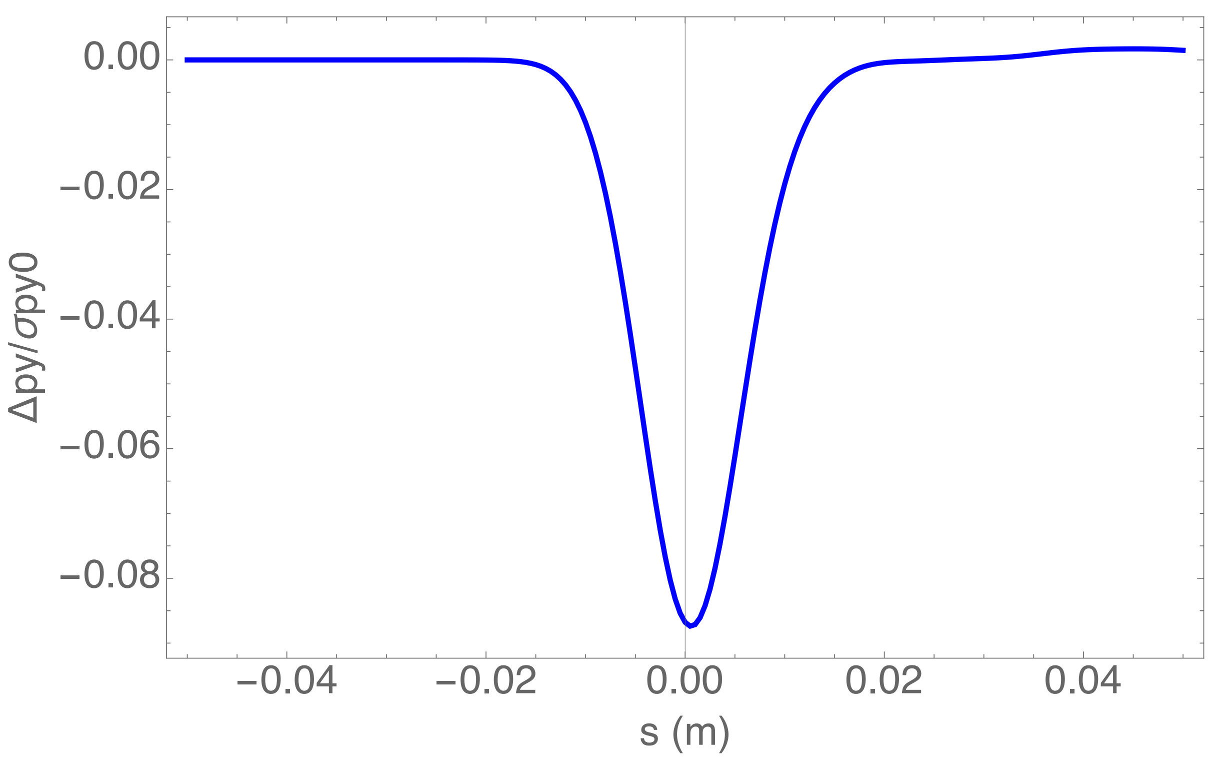


3. Beam tilt due to transverse impedance

➤ The first test with collimator settings on 2019.05.20

- The tilt was not strong enough in early Phase-3
- The countermeasures:
  ** Careful control of phase advance between collimators
  ** Control alpha functions at collimators
  ** Control COD at collimators





3. Beam tilt due to transverse impedance

➤ The first test with collimator settings on 2019.05.20

- **It can become a big problem with the final design parameters: Higher currents and smaller beam sizes at IP**

This time I included 8 collimators in total: PMD09V{1234}, PMD12V{1234}.

For HER, using parameters:

I_bunch ~ 0.4 mA [Final design: ~1 mA]

emittance_y = 50 pm [Final design: ~13 pm]

beta_y* = 3 mm [Final design: 0.3 mm]

3. Other effects

➤ Issues to be investigated

- **Space charge**

  2019.06.26: LER: Ibeam=370 mA, Nbunch=789

  Tune shift: (-0.0018, -0.026) in X/Y with emit_y=20 pm

- **Intra-beam scattering**

  LER horizontal emittance: 1.6 nm -> 1.9 nm with beam parameters on 2019.07.01

- **Dust events**

4. Response to the comment of morning talk

➤ Log data on 2019.06.20