Impedance model for SuperKEKB

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Acknowledgements

T. Abe, K. Shibata, M. Tobiyama, T. Ishibashi,
and SuperKEKB commissioning group

SuperKEKB TMCI workgroup meeting, Aug. 27, 2021, KEK

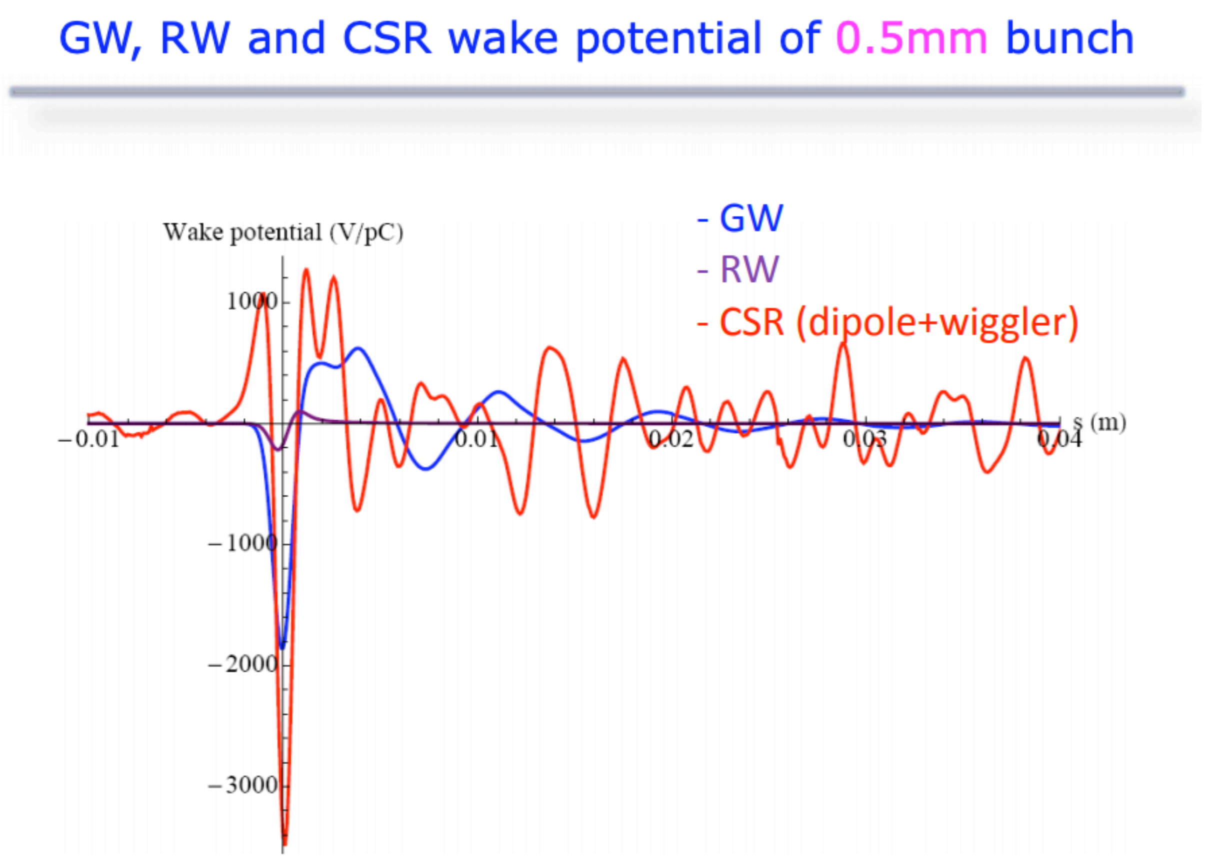
Outline

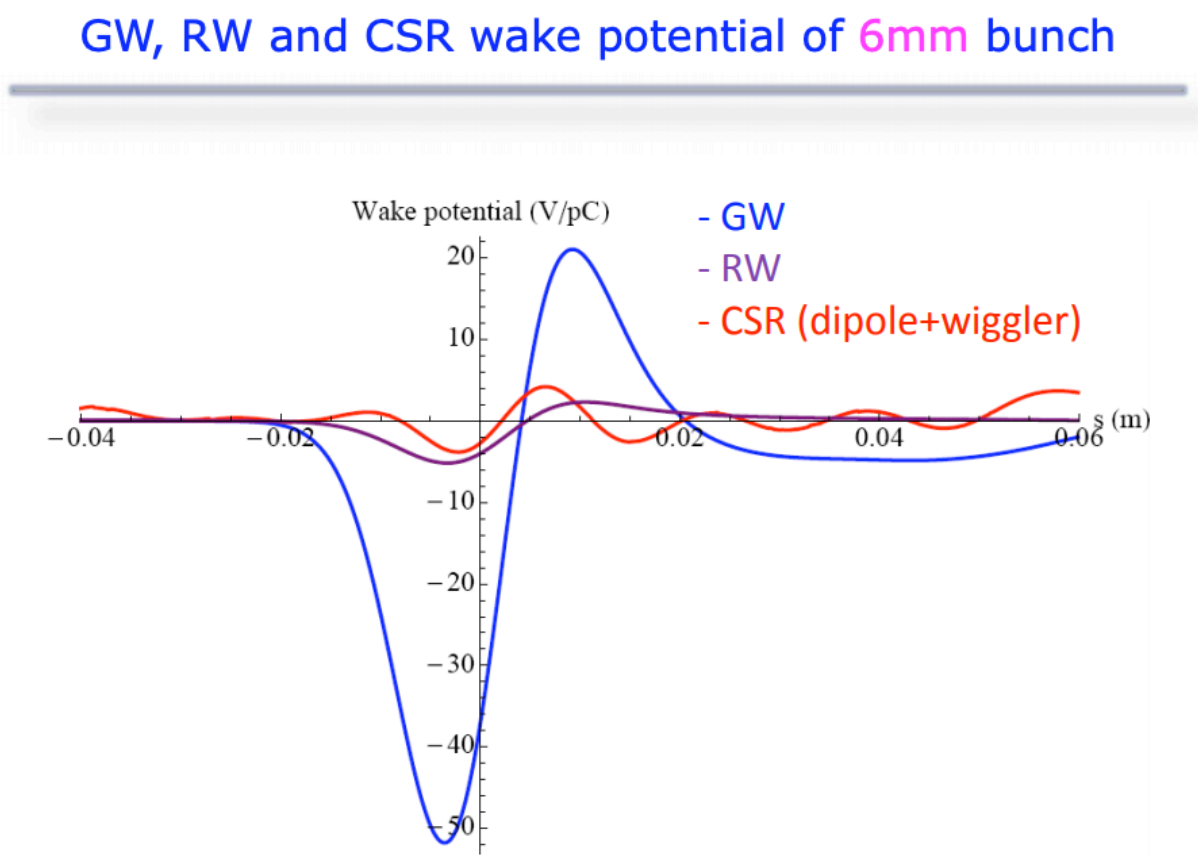
- This talk gives an overview of my work on impedance model for KEKB and SuperKEKB. The work was done together with colleagues of hardware groups.
- Lots of work were done by T. Ishibashi and others but not covered in this talk.

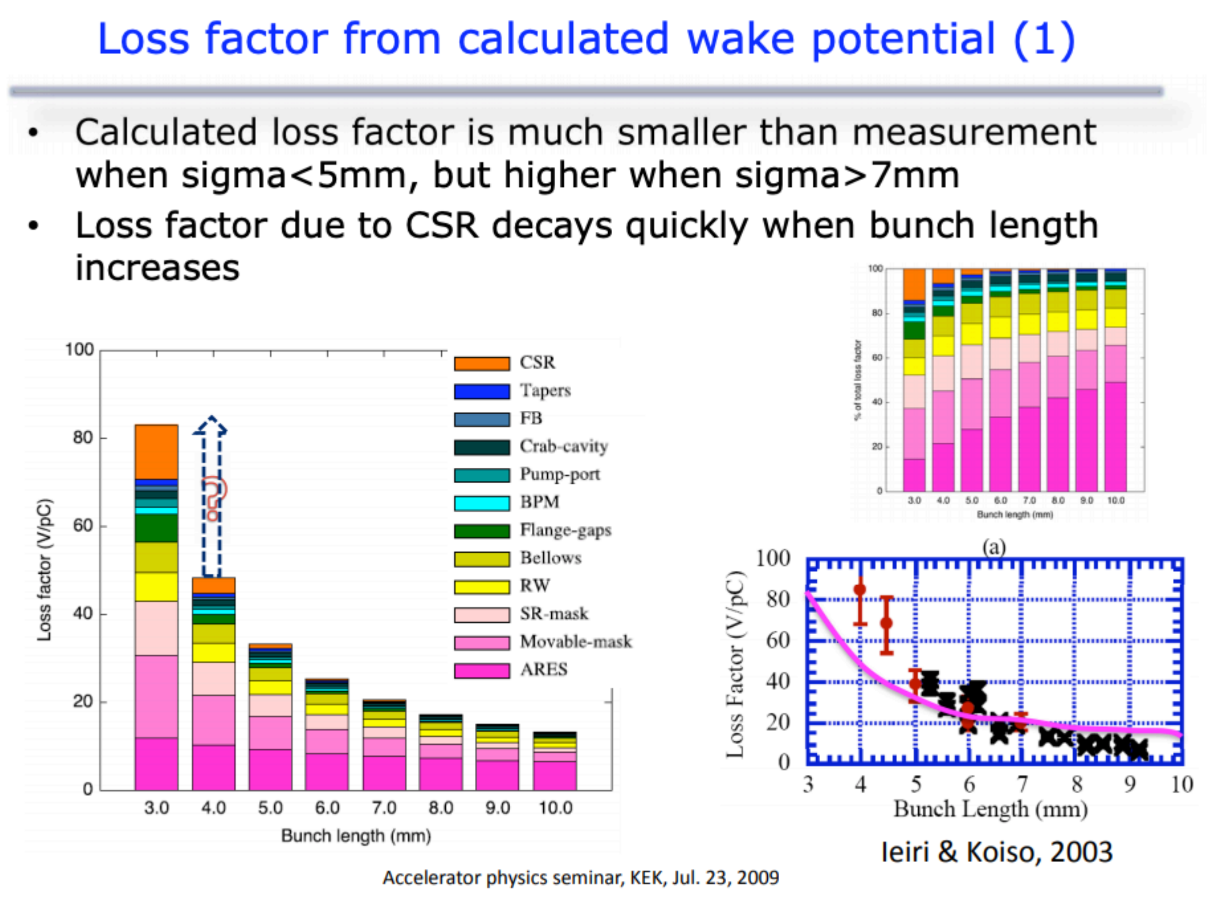
- Contents
  - Longitudinal pseudo-Green's function impedance model for KEKB LER
  - Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER
  - Transverse pseudo-Green's function impedance model for SuperKEKB LER

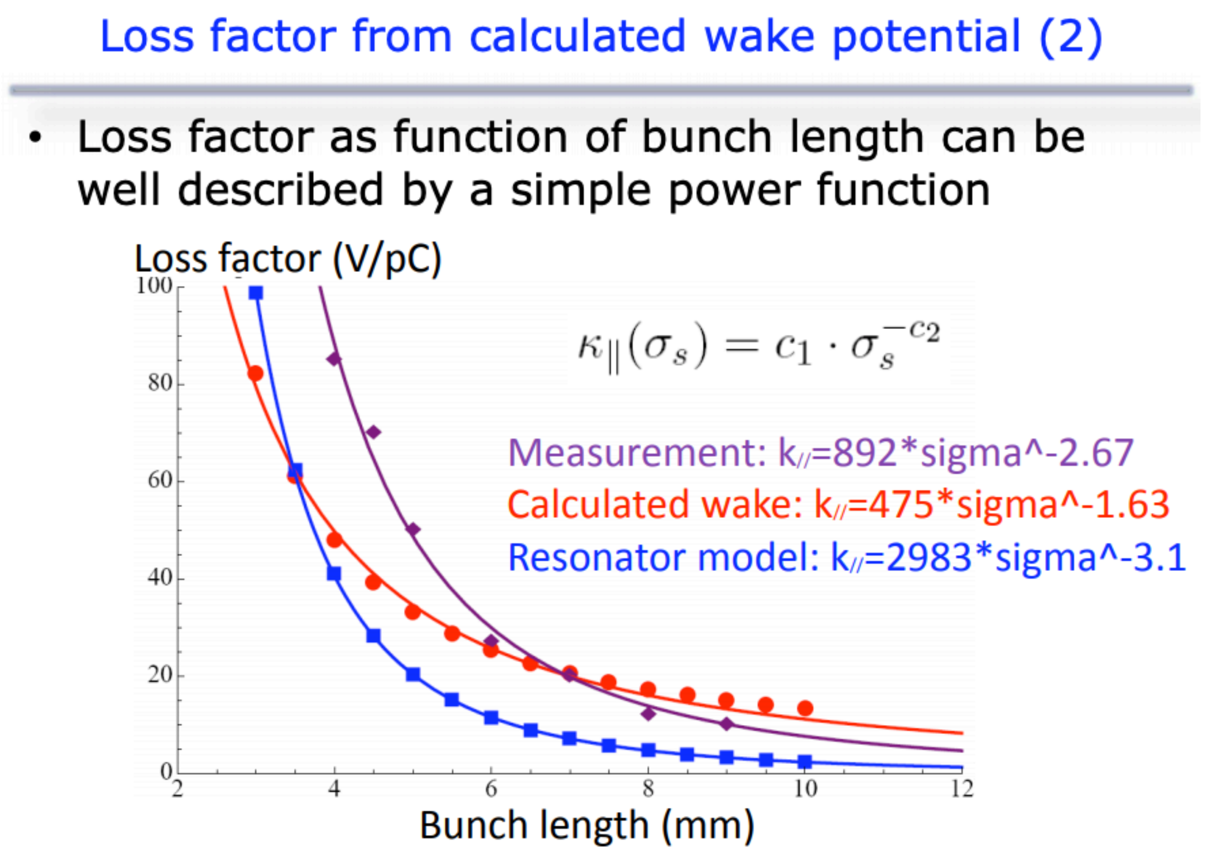
Longitudinal pseudo-Green's function impedance model for KEKB LER

- Motivation
  - As part of my thesis work, I studied the microwave instability (MWI) in KEKB LER.
  - I asked for help from colleagues to calculate wakes with Gaussian bunch length of 0.5 mm. Then I summed up the wake for MWI simulations.
- Findings
  - First results were reported in Ref. [1]. Calculations were refined later but did not change the whole picture much.
  - Calculated loss factors smaller than measurements at $\sigma_z \leq 6$ mm, but larger at $\sigma_z \geq 8$ mm.





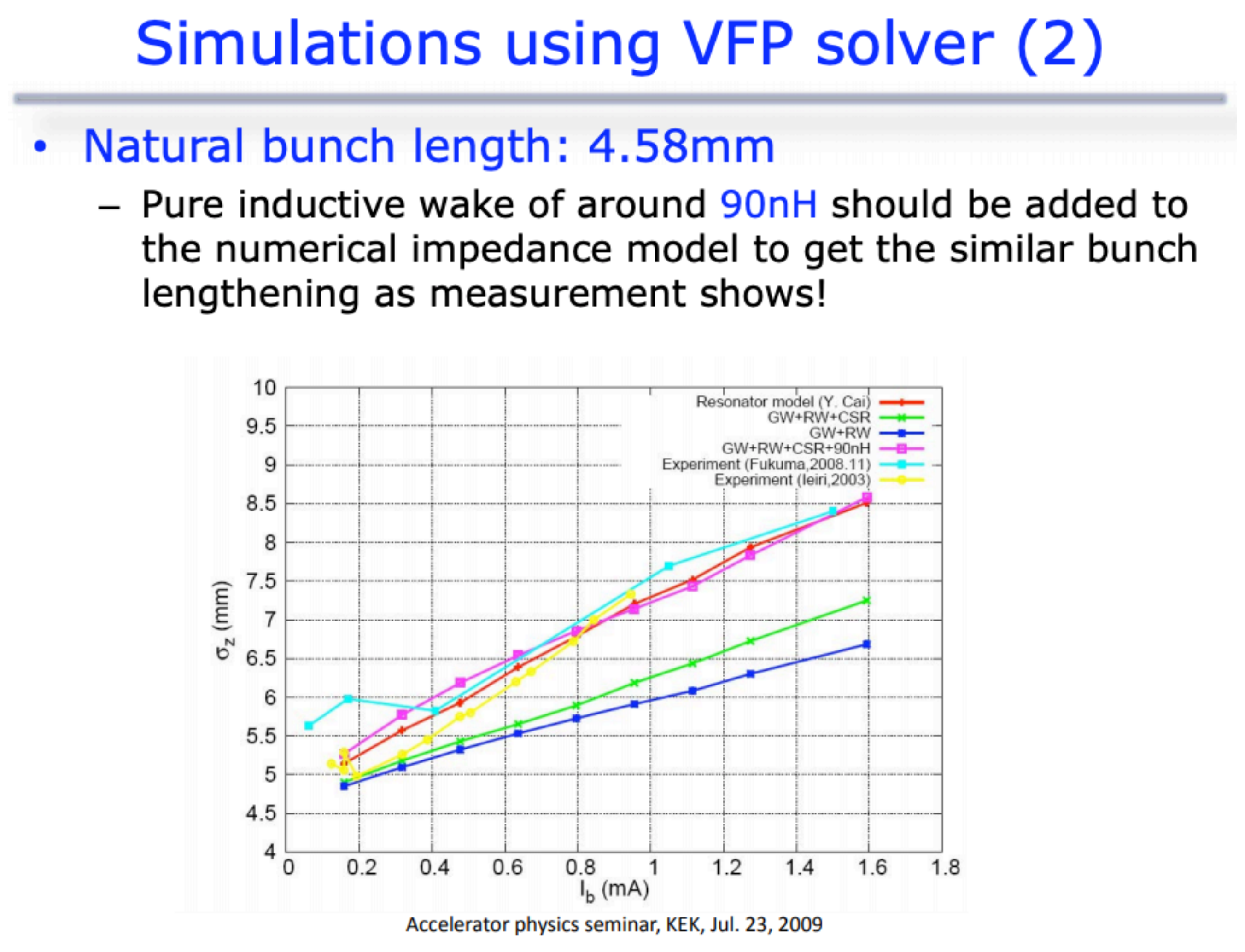


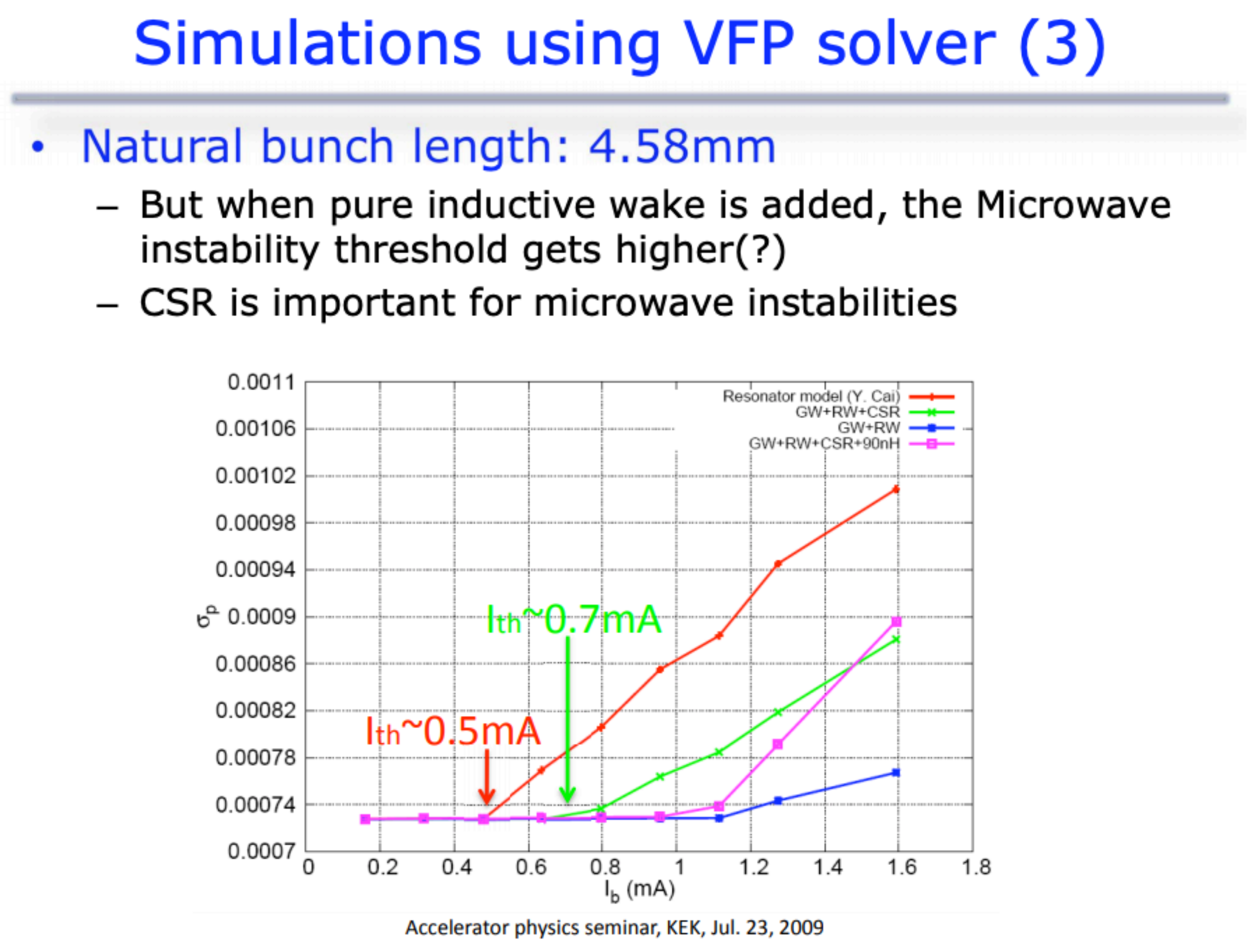


[1] D. Zhou, Longitudinal single-bunch instabilities in the LER of KEKB, Talk presented at the Accelerator Physics Seminar, KEK, Jul. 23, 2009.

Longitudinal pseudo-Green’s function impedance model for KEKB LER

- Findings (cont’d)
  - Simulated bunch lengthening was much weaker than measurements. A large inductance (~90 nH) was required to fill the gap.
  - Simulated MWI threshold was $I_{th} \approx 0.7$ mA with CSR, while Belle data gave $I_{th} \approx 0.5$ mA [1,2].



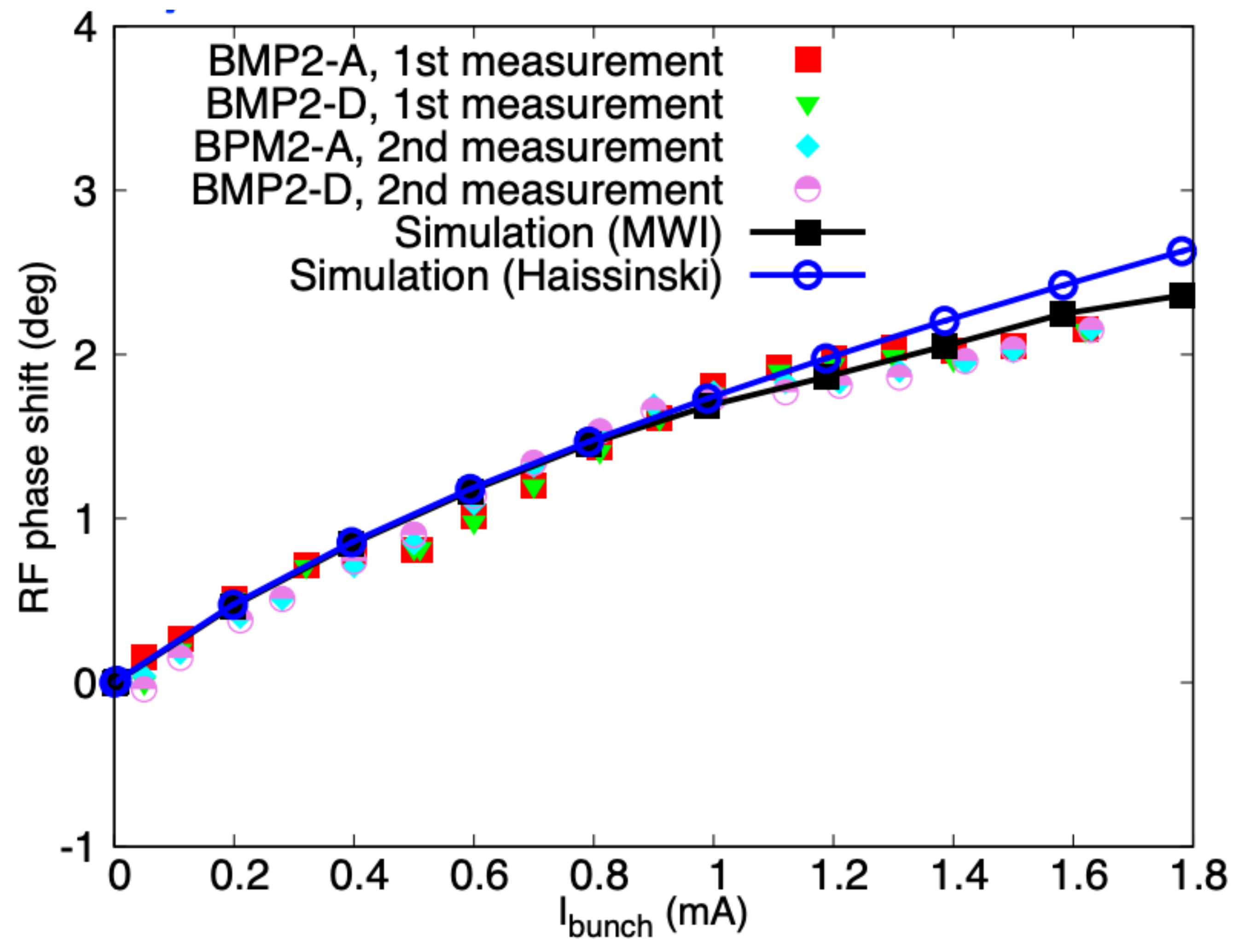


[1] D. Zhou, Longitudinal single-bunch instabilities in the LER of KEKB, Talk presented at the Accelerator Physics Seminar, KEK, Jul. 23, 2009.

[2] D. Zhou et al., Simulation of Microwave Instability in LER of KEKB And SuperKEKB, in Proceedings of ICAP09, San Francisco, CA, USA.

Longitudinal pseudo-Green's function impedance model for KEKB LER

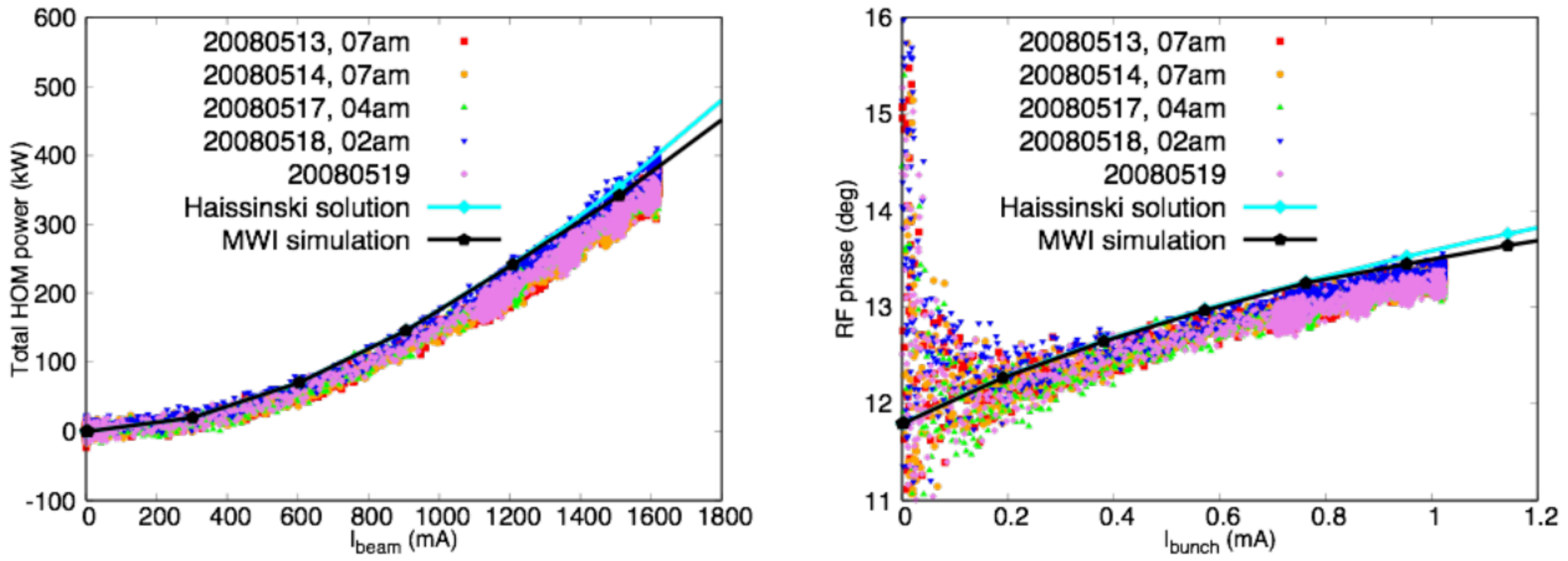
- Revisit of MWI at KEKB LER
  - In 2017, K. Bane and I revisited the problem.
  - This time we found good agreement between three methods: 1) Simulations based on pseudo-Green's function wake; 2) HOM power extracted from logged data of RF system; 3) Beam-phase measurements (see Ref. [3] for an overview).
  - But poor agreement with streak camera data remained.
- I repeated my studies of impedance and MWI for KEKB LER to SuperKEKB.



5. HOM power in KEKB LER

➤ **HOM power (E=3.499152 GeV, Vrf=8 MV)**

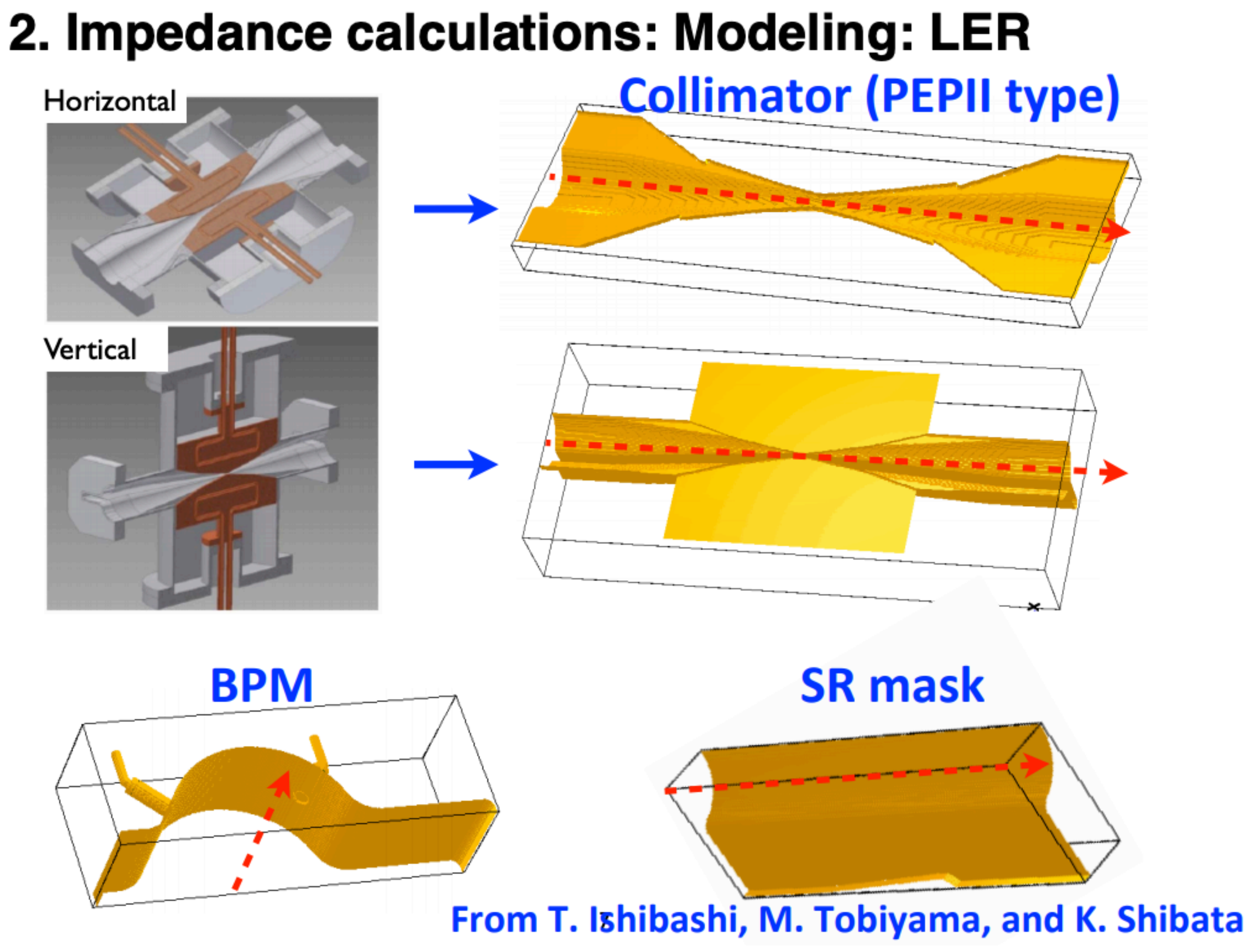
- **SR power calculated from lattice model**
- **Good reproducibility in beam power data**
- **Above MWI threshold: Additional drop in HOM power and RF phase due to energy spread increase**
- **As beam energy increase, the MWI threshold moves higher**
- **Overestimate on SR power?**

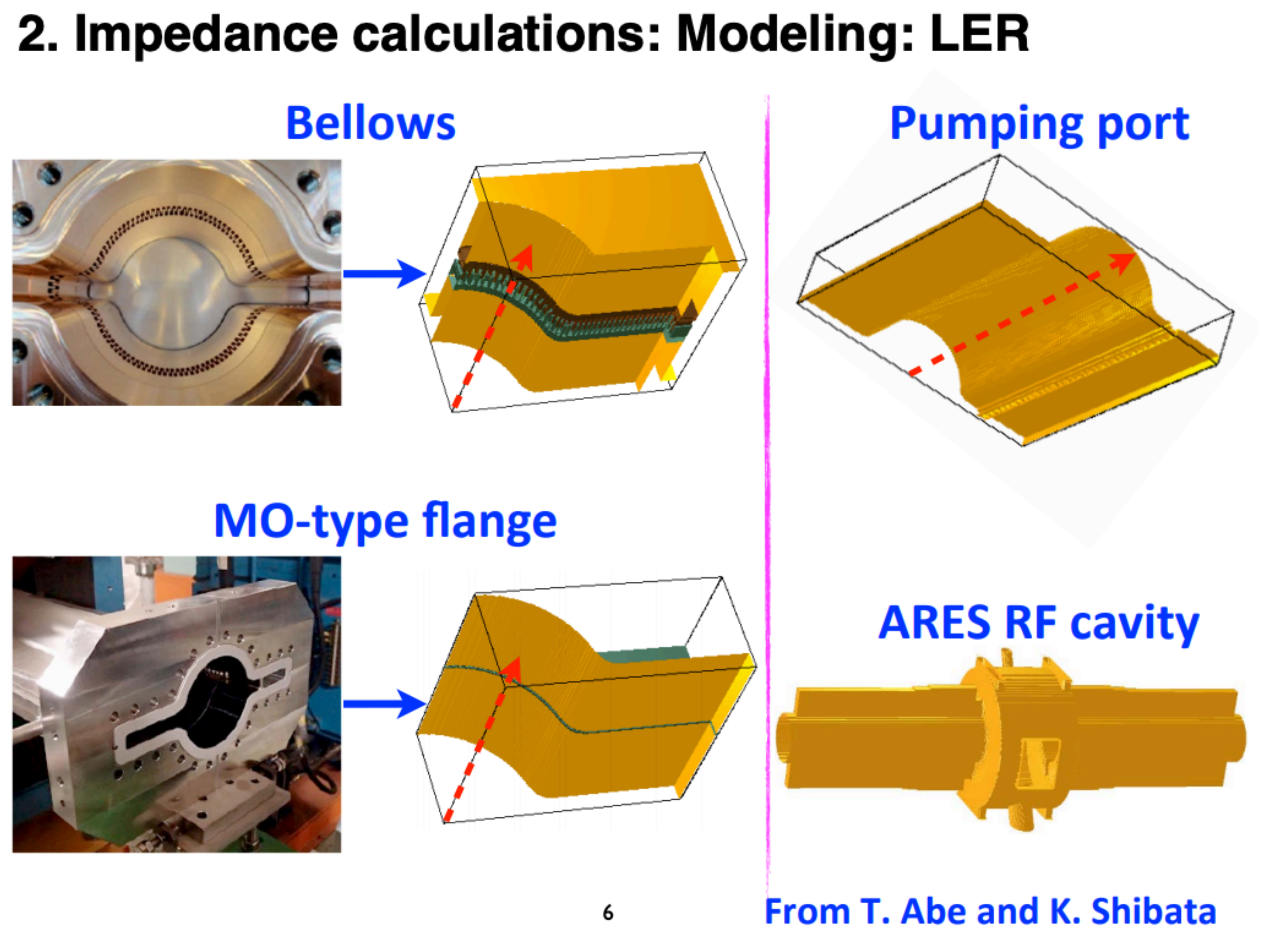


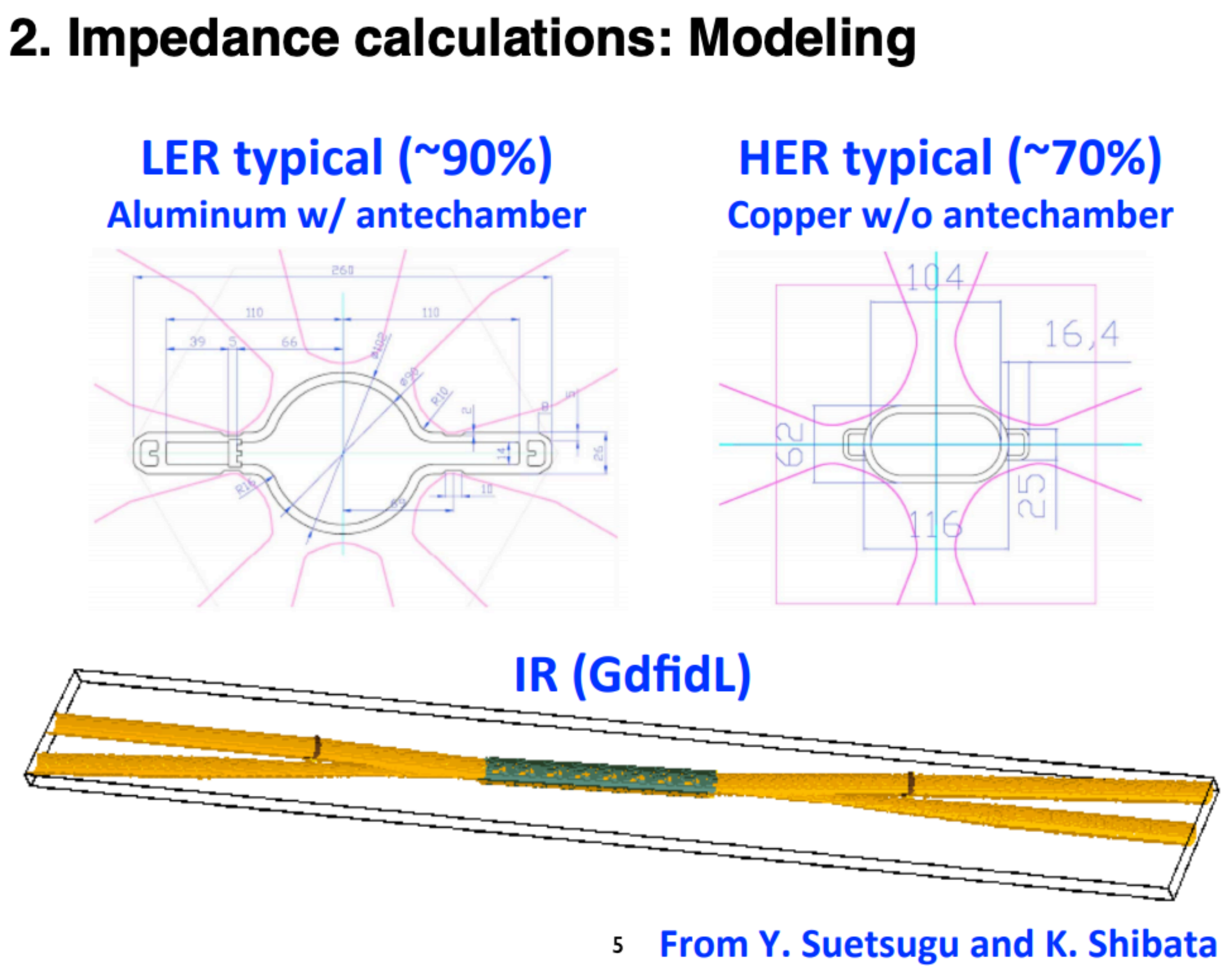
[3] K. Bane and D. Zhou, Comparison of machine impedance calculation with beam based measurements, Talk presented at the International Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 20 September, 2017.

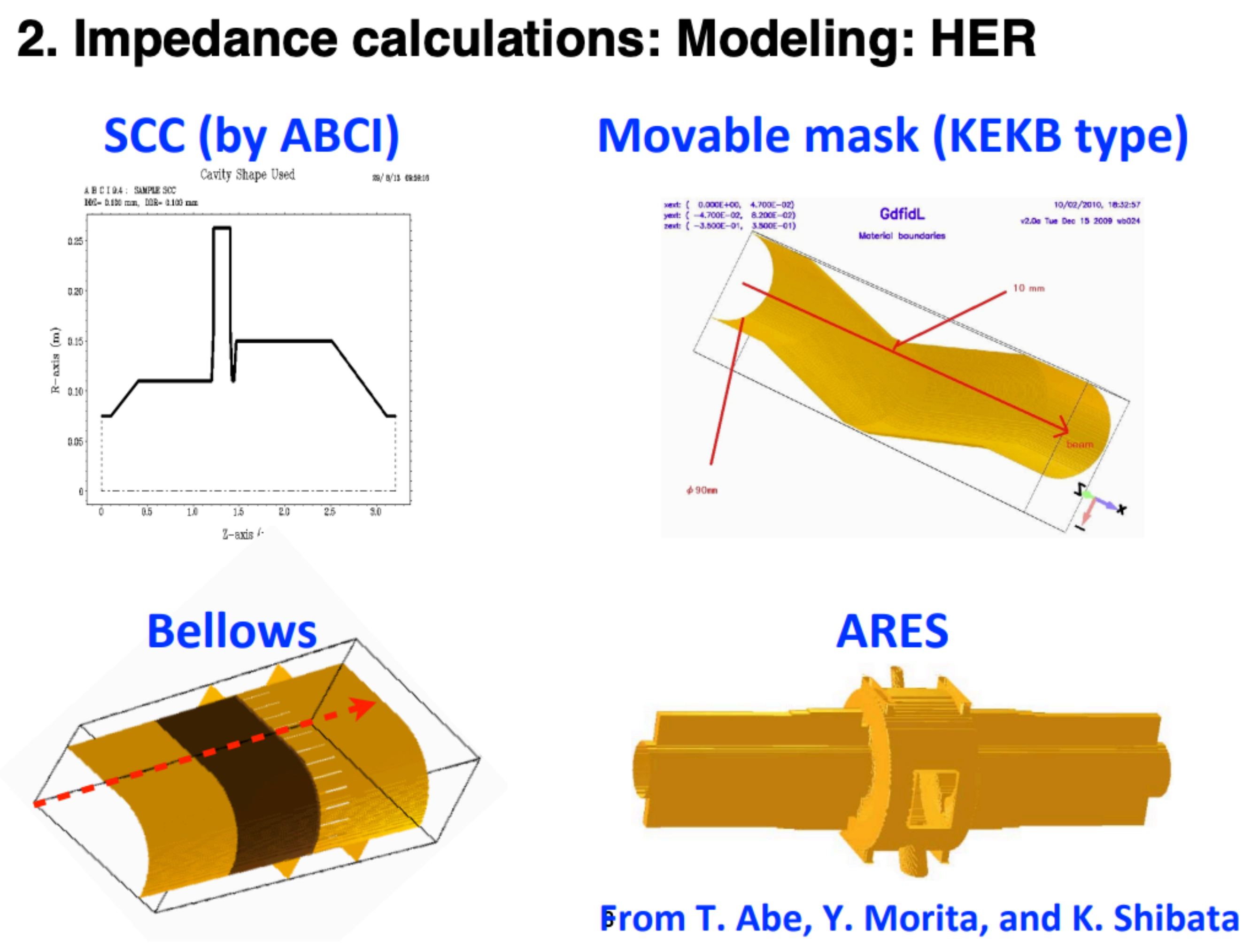
Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

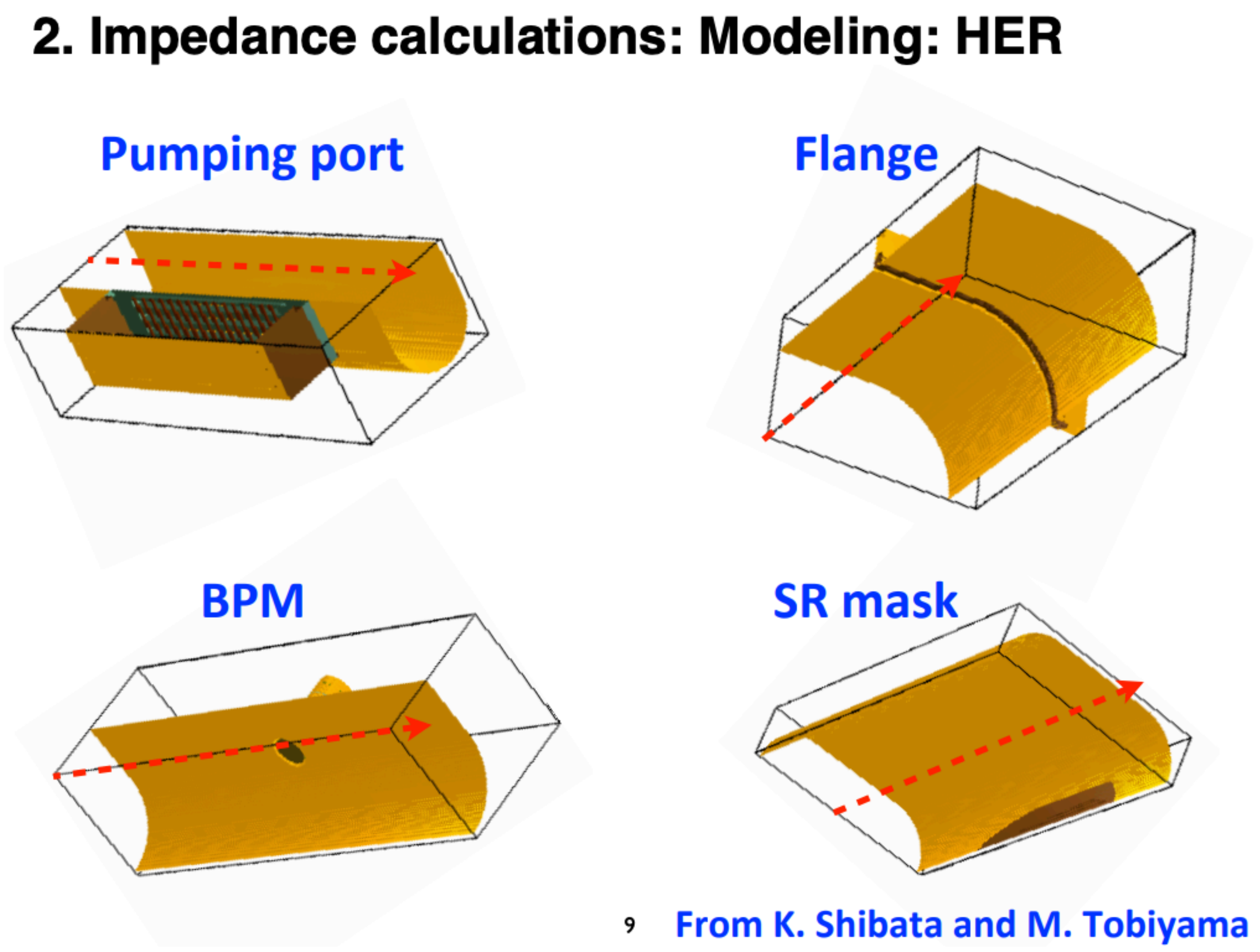
- Long. wakes for SuperKEKB
  - T. Abe, T. Ishibashi, M. Tobiyama, and others calculated the wakes with 0.5 mm Gaussian bunch.I collected wake data for MWI simulations using VFP solver.
  - Most of the wake calculations were done using GdfidL.
  - Compare with KEKB: Most of LER chambers were new; most of HER chambers were reused.











[4] D. Zhou, Impedance Issues in SuperKEKB, Talk presented at the 19th KEKB Accelerator Review Committee, KEK, Mar. 3, 2014.

Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

- Long. wakes for SuperKEKB (cont'd)
  - Impedance budget was constructed with design configurations.

Table 1: Impedance budget for the SuperKEKB main rings. Summarised are the contributions to the loss factor $k_{||}$ [V/pC], the fitted resistance R [Ω] and inductance L [nH] for each type of components. The resistances and inductances are calculated at the nominal bunch lengths of σ_z=5 and 4.9 mm for LER and HER, respectively.

Component	LER			HER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	3.3	190	-
SC cavity	-	-	-	7.8	454	-
Collimator	1.1	62.4	13.0	5.3	309	10.8
Res. wall	3.9	231	5.7	5.9	340	8.2
Bellows	2.7	159	5.1	4.6	265	16.0
Flange	0.2	13.7	4.1	0.6	34.1	19.3
Pump. port	0.0	0.0	0.0	0.6	34.1	6.6
SR mask	0.0	0.0	0.0	0.4	21.4	0.7
IR duct	0.0	2.2	0.5	0.0	2.2	0.5
BPM	0.1	8.2	0.6	0.0	0.0	0.0
FB kicker	0.4	26.3	0.0	0.5	26.2	0.0
FB BPM	0.0	1.1	0.0	0.0	1.1	0.0
Long. kicker	1.8	105	1.2	-	-	-
Groove pipe	0.1	3.8	0.5	-	-	-
Electrode	0.0	0.7	5.7	-	-	-
Total	19.2	1137	36.4	29.0	1677	62.1

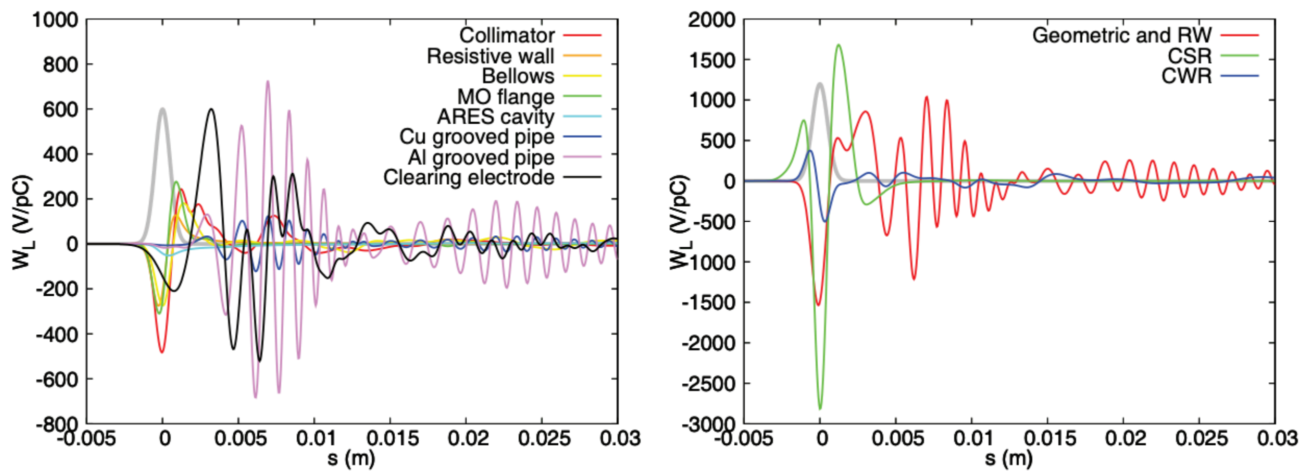


Figure 2: The wakes for important impedance sources with driving Gaussian bunch of σ_z=0.5 mm in LER. The grey line indicates the bunch profile. Left: Wakes of various components. Right: The total geometric and resistive wall wakes compared with CSR and CWR wakes.

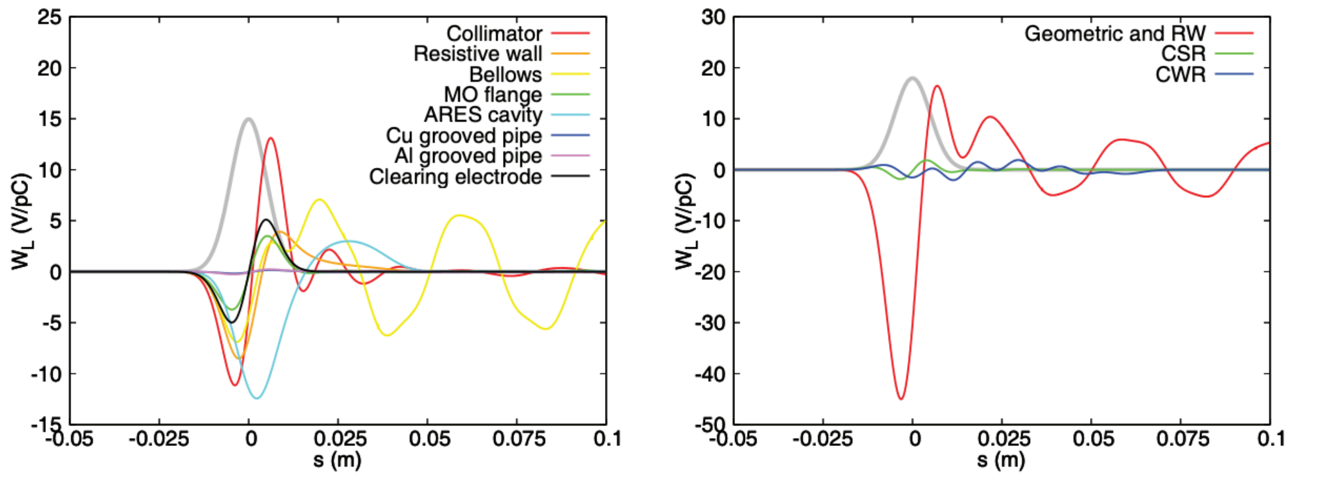


Figure 3: The wakes for important impedance sources with nominal Gaussian bunch of σ_z=5 mm in LER. Left: Wakes of various components. Right: The total geometric and resistive wall wakes compared with CSR and CWR wakes.

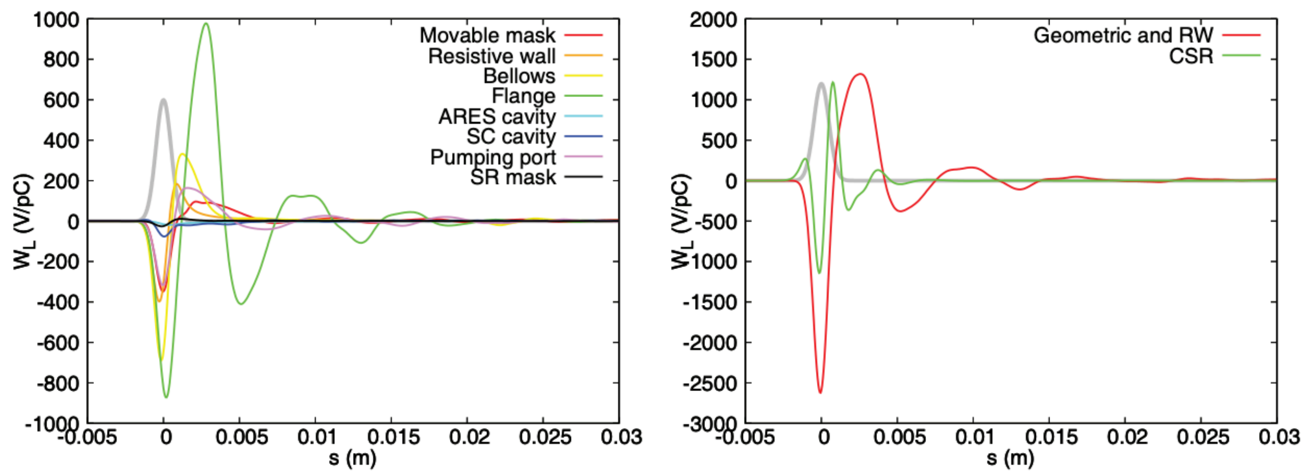


Figure 4: The wakes for important impedance sources with driving Gaussian bunch of σ_z=0.5 mm in HER. Left: Wakes of various components. Right: The total geometric and resistive wall wakes compared with CSR wake.

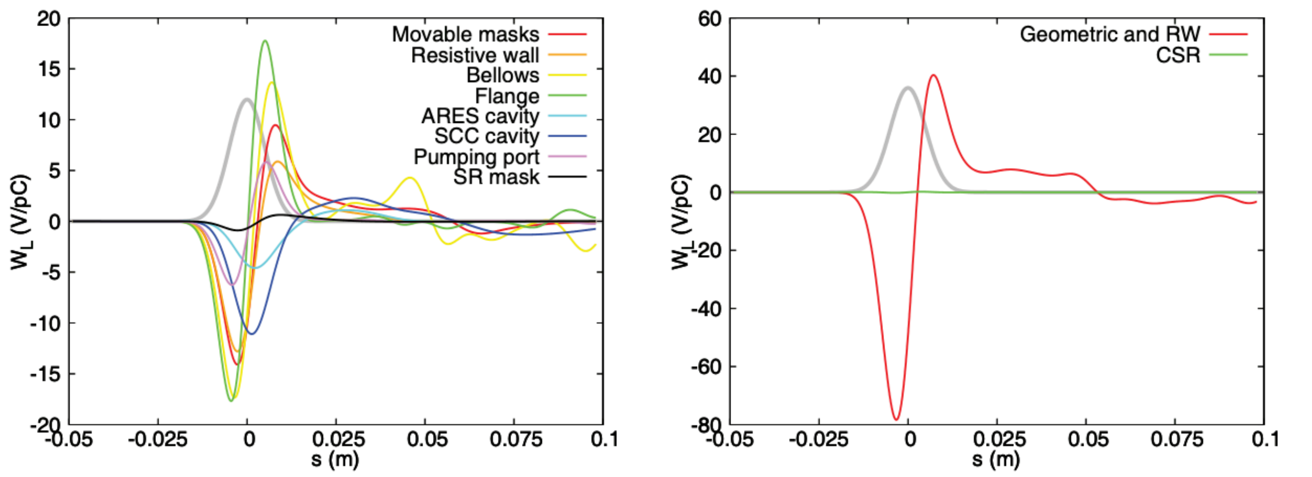


Figure 5: The wakes for important impedance sources with nominal Gaussian bunch of σ_z=4.9 mm in HER. Left: Wakes of various components. Right: The total geometric and resistive wall wakes compared with CSR wake.

This is due to the facts of longer bending radius and stronger chamber shielding. The wakes of movable masks, bellows, flanges, pumping ports and SR masks are mainly inductive.

[5] D. Zhou et al., Impedance calculation and simulation of microwave instability for the main rings of SuperKEKB, in Proceedings of IPAC'14, Dresden, Germany.

Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

- MWI simulations for SuperKEKB
  - MWI simulations were done with design configurations.
  - For LER, CSR is important in defining the MWI threshold.
  - For HER, CSR effect is negligible.

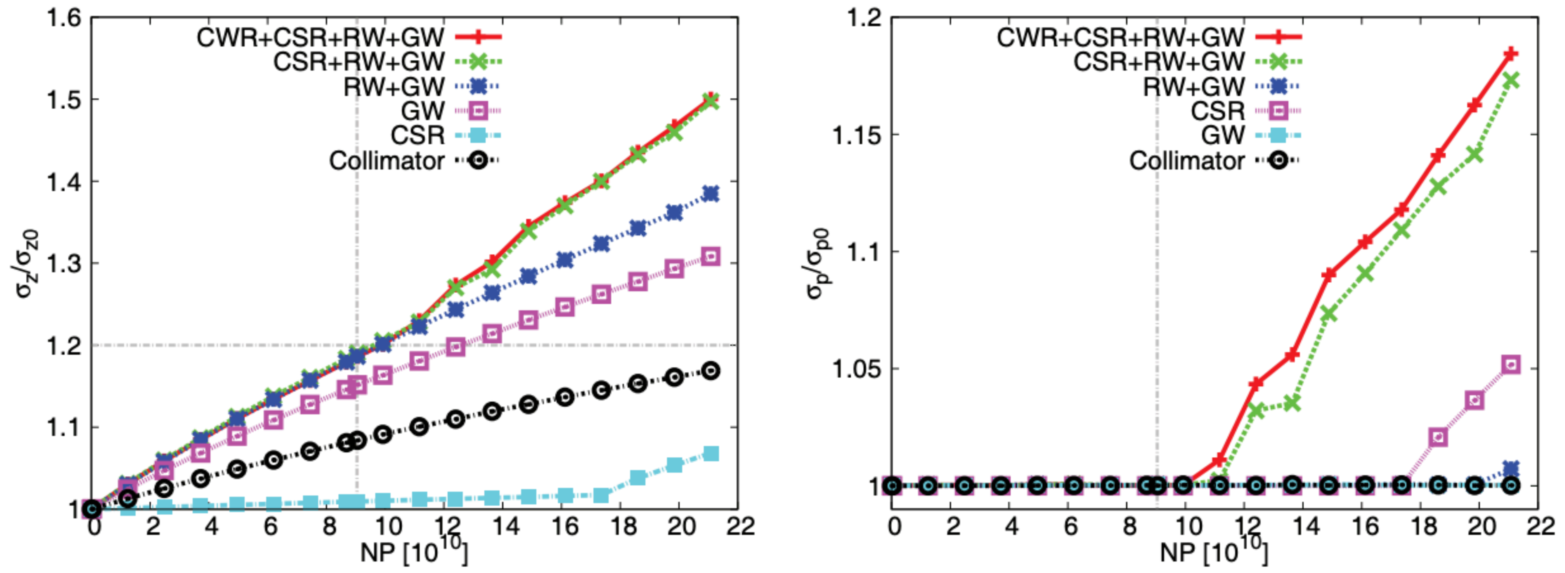


Figure 6: Normalised bunch length and energy spread as a function of the bunch population in LER. The vertical and horizontal dashed grey lines indicate the nominal bunch population and bunch length, respectively. Simulations are performed by using VFP solver with various impedance sources. Left: Bunch length. Right: Energy spread.

Table 2: Key Parameters of SuperKEKB Main Rings for MWI Simulations

Parameter	LER	HER
Circumference (m)	3016.25	3016.25
Beam energy (GeV)	4	7.007
Bunch population (10^{10})	9.04	6.53
Nominal bunch length (mm)	5	4.9
Synchrotron tune	0.0244	0.028
Long. damping time (ms)	21.6	29.0
Energy spread (10^{-4})	8.1	6.37

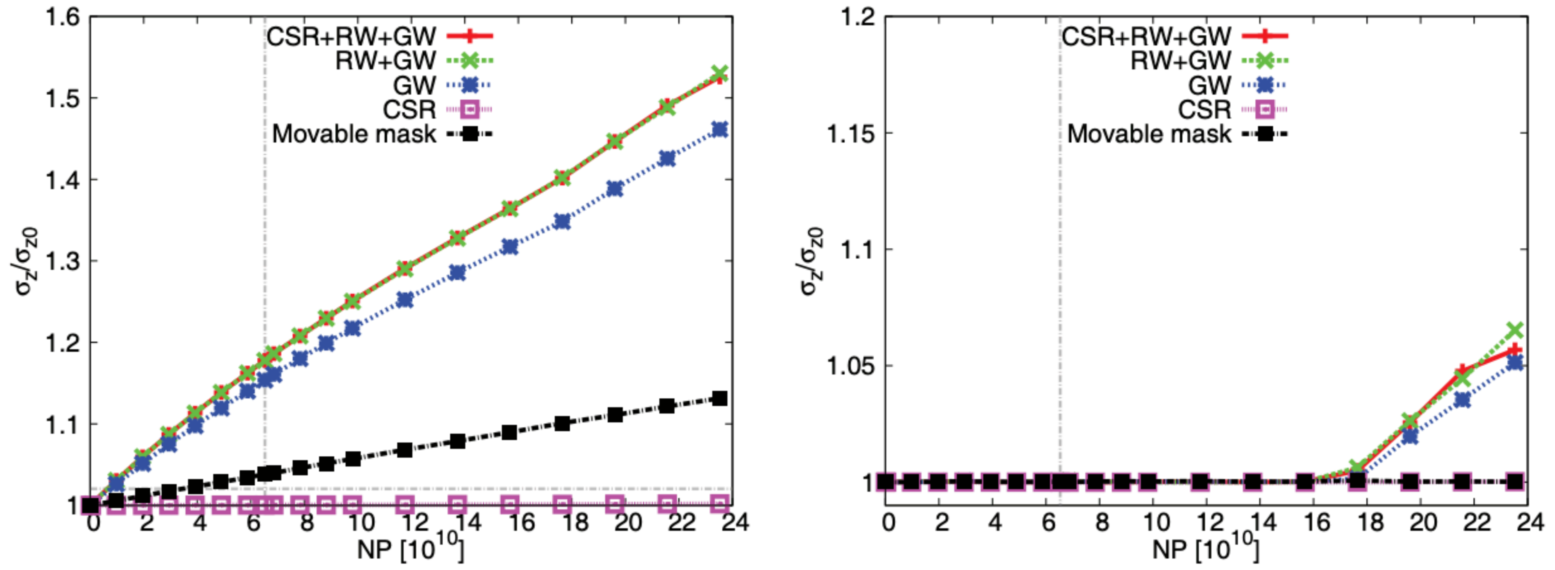
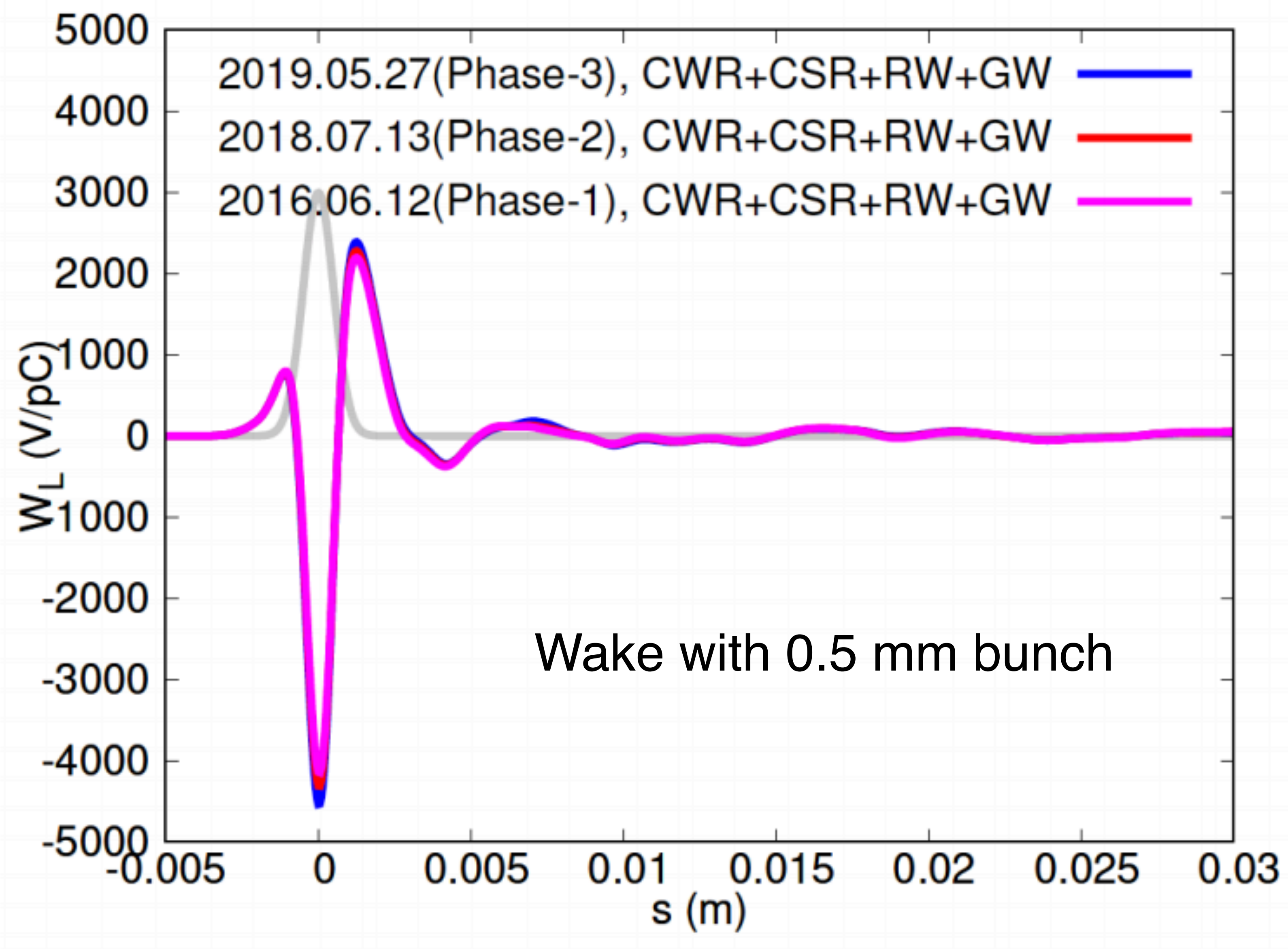


Figure 7: Normalised bunch length and energy spread as a function of the bunch population in HER. The vertical and horizontal dashed grey lines indicate the nominal bunch population and bunch length, respectively. Left: Bunch length. Right: Energy spread.

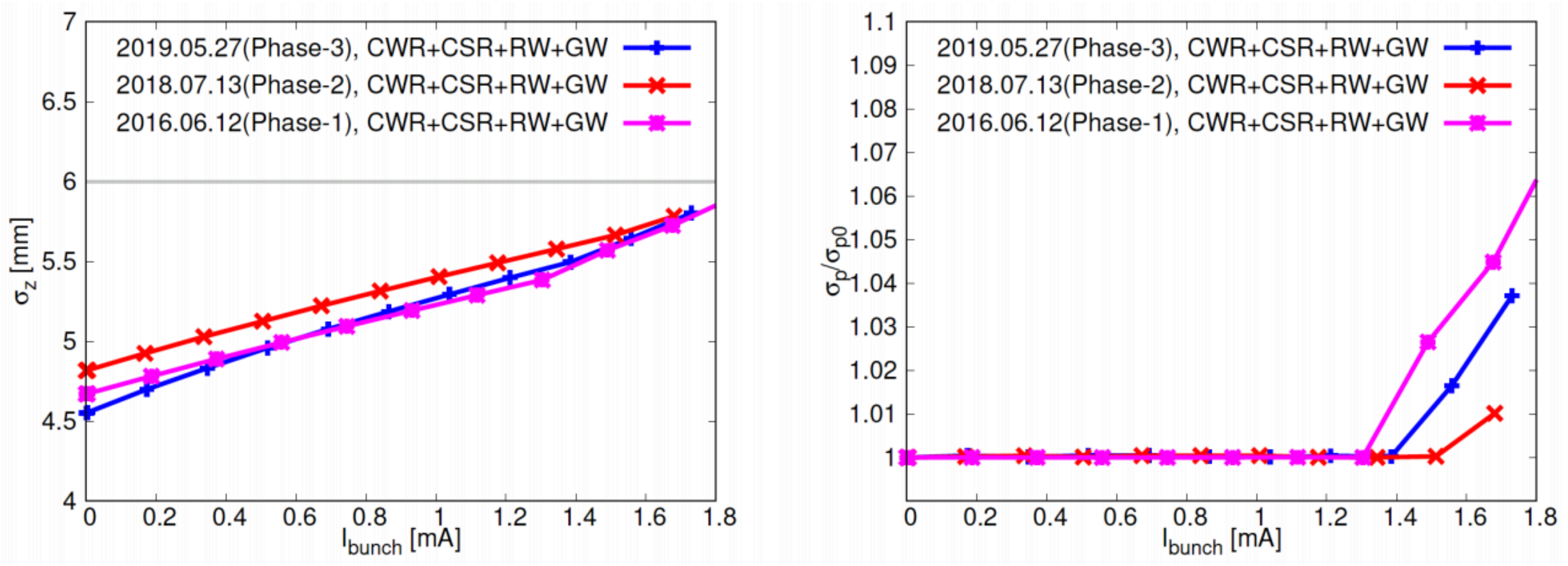
[5] D. Zhou et al., Impedance calculation and simulation of microwave instability for the main rings of SuperKEKB, in Proceedings of IPAC'14, Dresden, Germany.

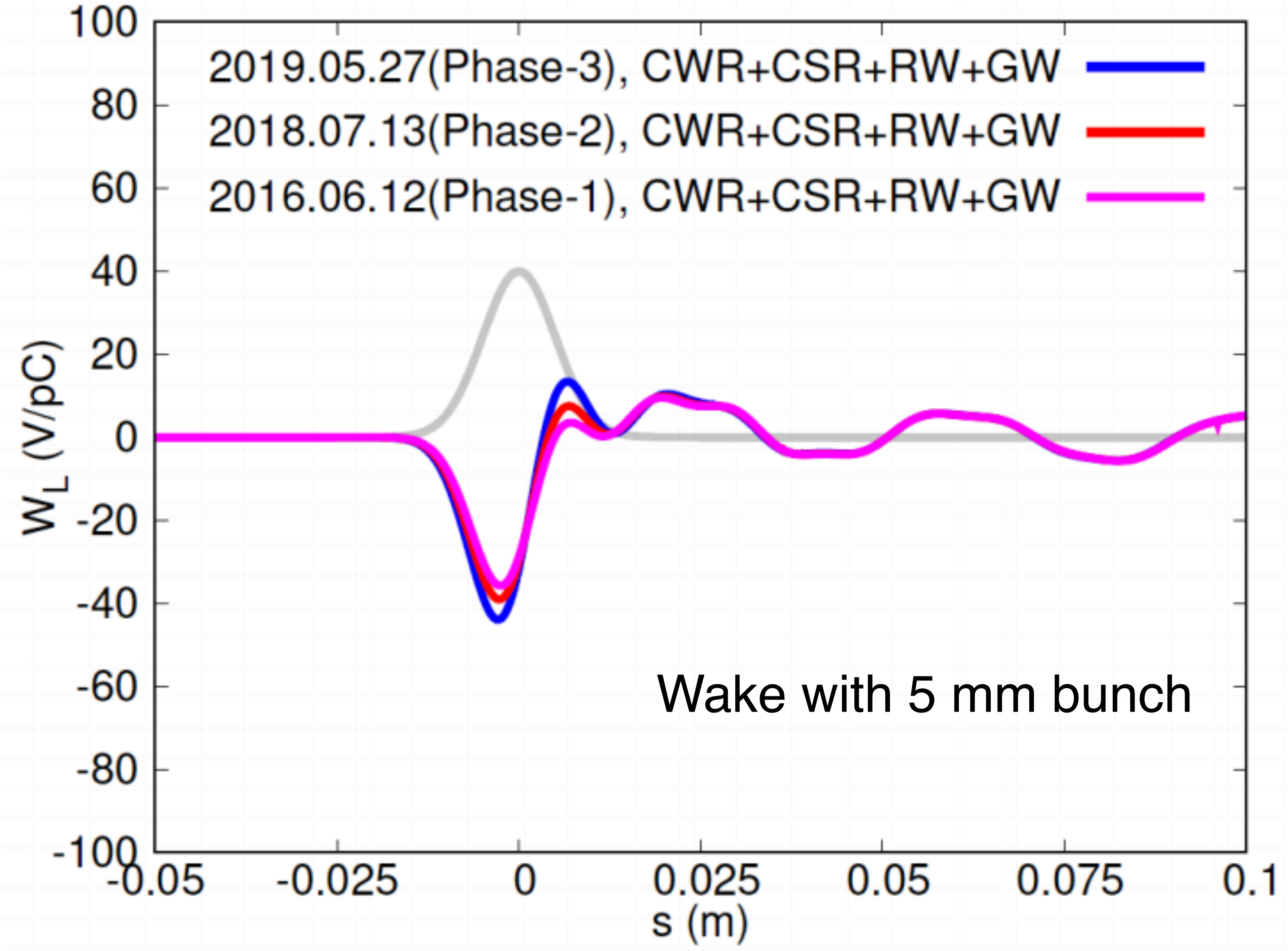
Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

- Wake models and MWI simulations for different phases of SuperKEKB LER
  - From phase-1 to phase-3, the main changes on impedance models were from collimator configurations.
  - Simulated bunch lengthening was always much weaker than measurements by streak camera.



MWI simulations using VFP solver





[6] D. Zhou, Impedance issues and other collective effects, Supplementary, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019.

Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

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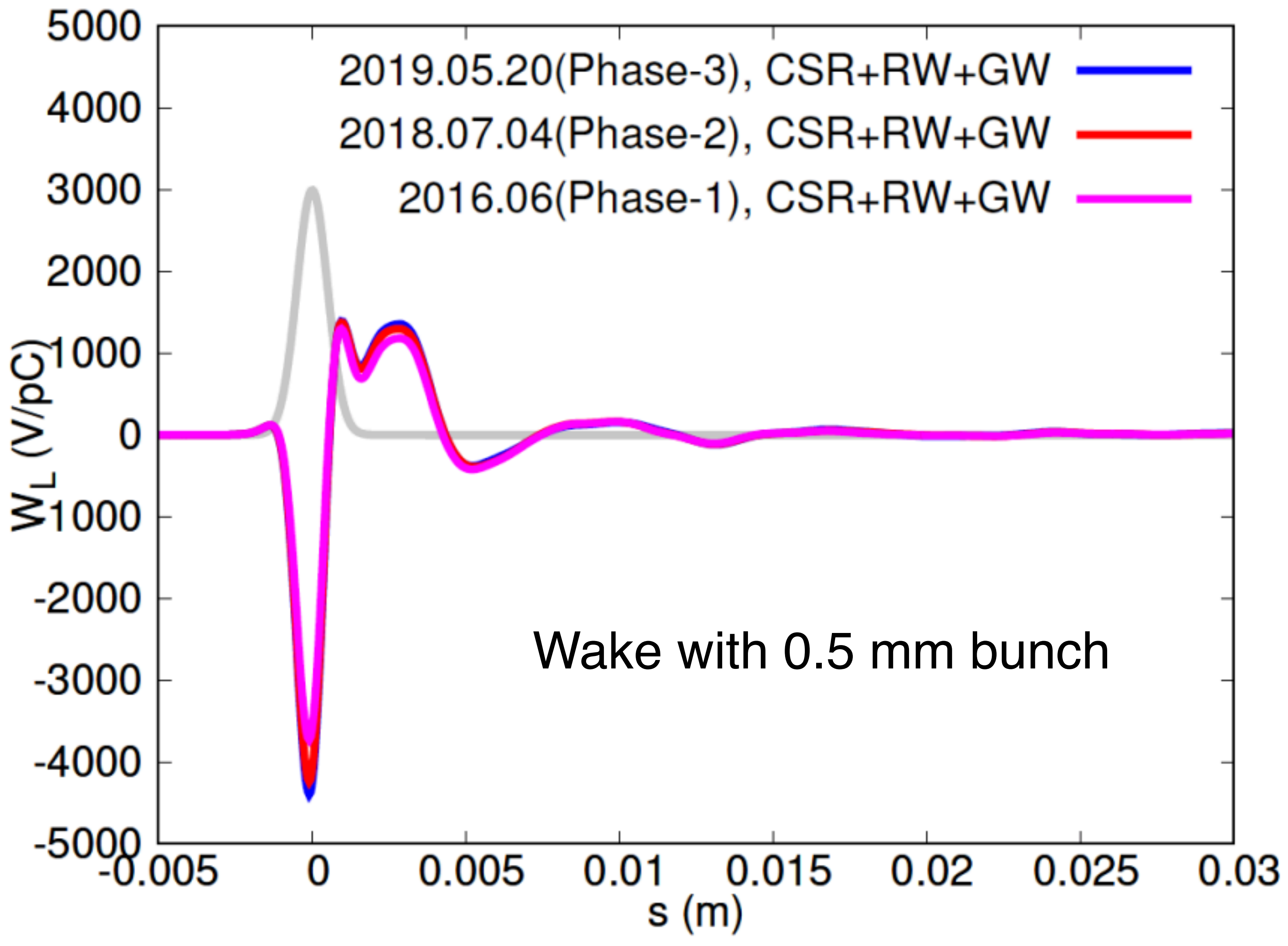
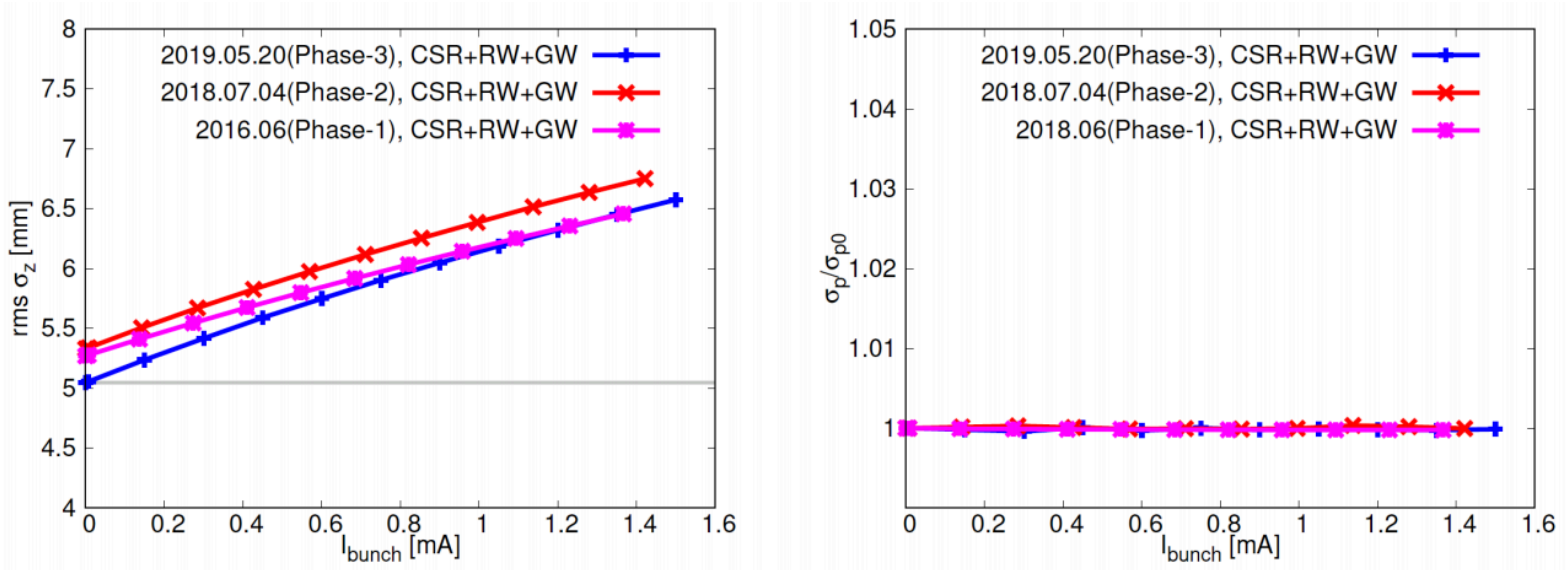
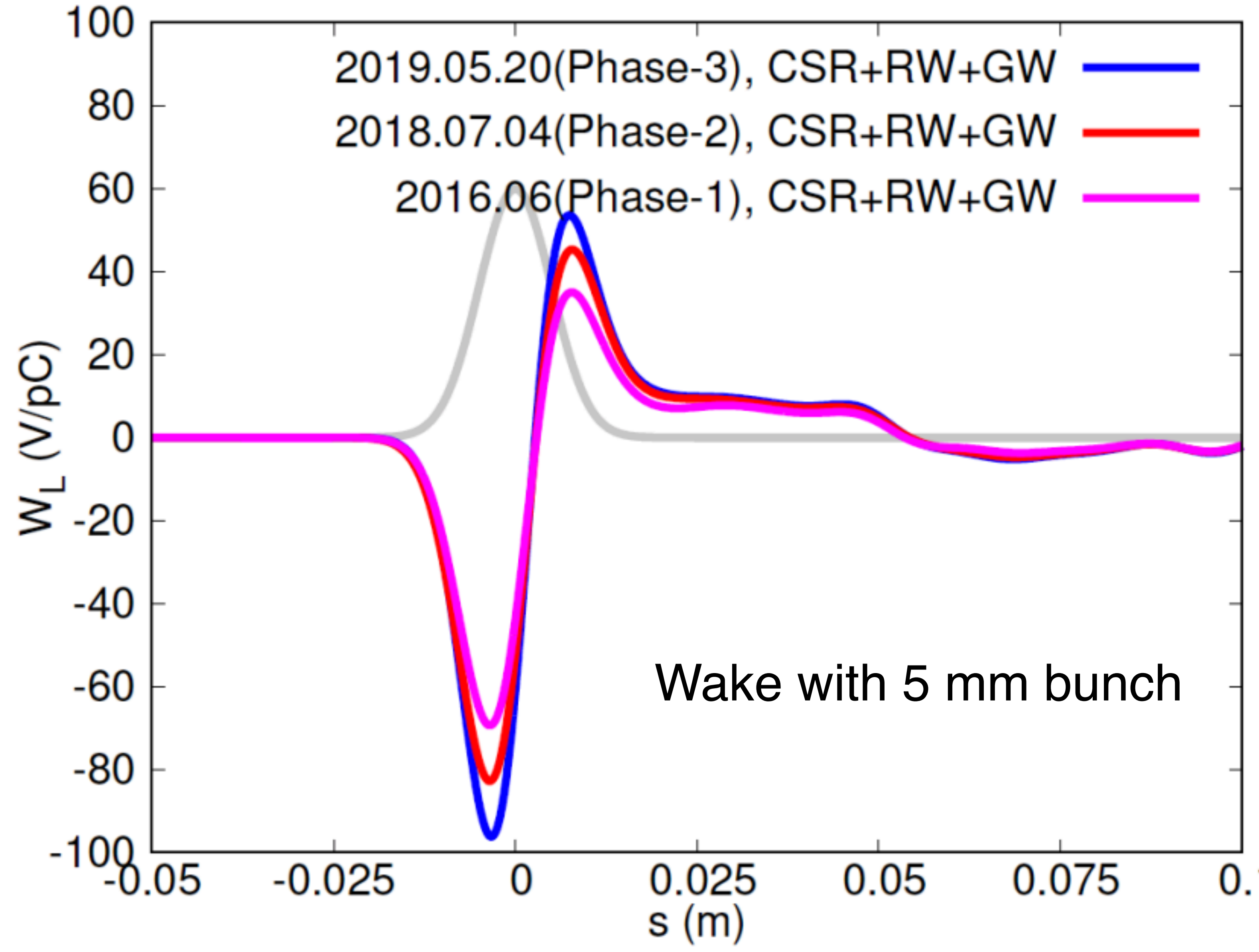


MWI simulations using VFP solver





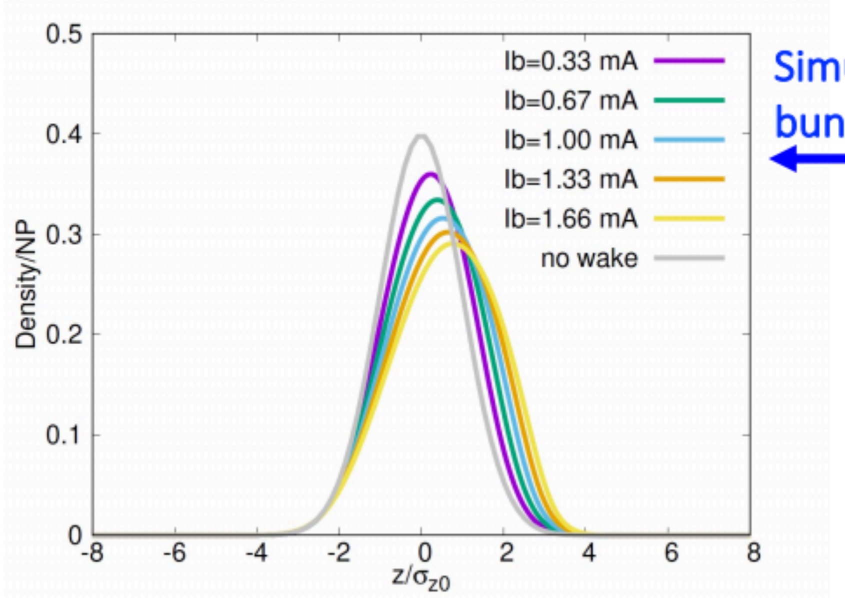
[6] D. Zhou, Impedance issues and other collective effects, Supplementary, Talk presented at the 1st SuperKEKB Beam Dynamics Mini-Workshop, KEK, Jul. 17, 2019.

Longitudinal pseudo-Green's function impedance model for SuperKEKB LER and HER

- MWI simulations compared with beam phase measurement in SuperKEKB LER
  - Recent measurement of beam phase in LER seemed to agree with MWI simulations. More studies are necessary, such as repeating the comparison in HER.

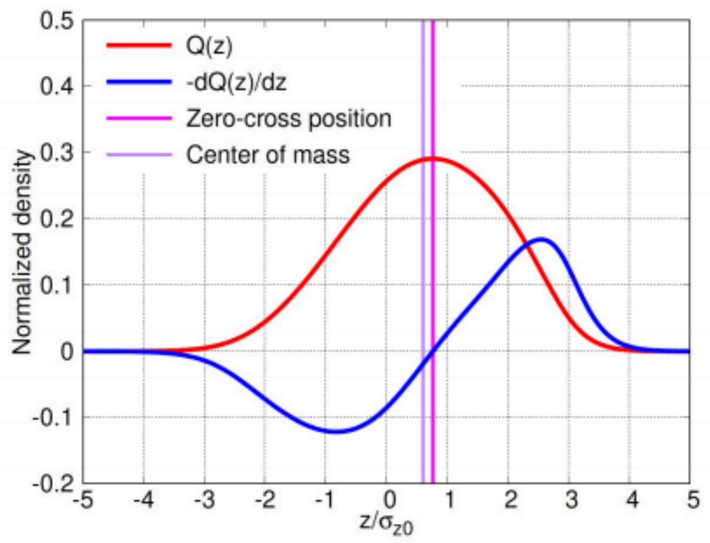
2. LER synchronous phase measurement

- Zero-cross of BPM signal (Tobiyama-san's method)
- LER measurement done in Jun. 30, 2021
- VFP solver simulations with impedance model (short-bunch wakes calculated mostly by GdfidL)



Simulated bunch profiles

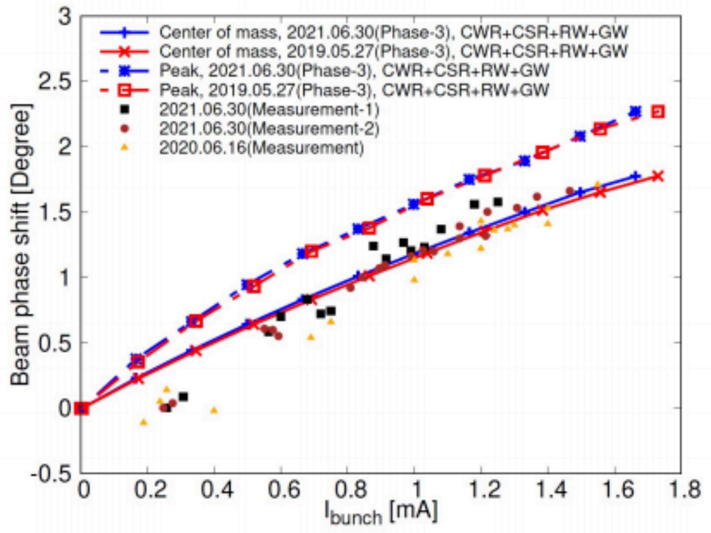
BPM signal



Simulated bunch profiles have tilt and shift in center-of-mass.
BPM signal: $i(t) = -dQ(t)/dt$
-> Zero-cross point of BPM signal is more relevant to peak of bunch profile

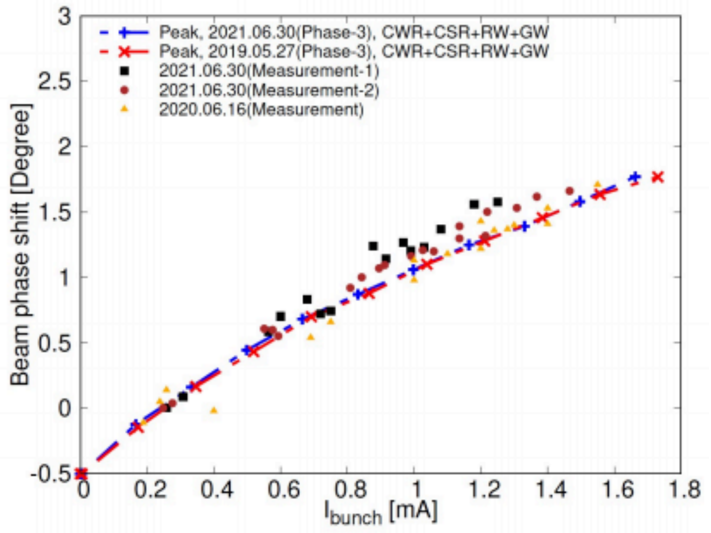
2. LER synchronous phase measurement

- Center-of-mass (=centroid) is usually used to describe the beam phase shift by accelerator physicists
- Beam phase shift depends on loss factor. And loss factor is a function of bunch length
- The drop of slope at higher bunch current is related to bunch lengthening



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.

[7] D. Zhou, Beam dynamics issues: Comparisons of theories, simulations and experiments, Talk presented at the SuperKEKB 2021ab summary meeting, KEK, Jul. 29, 2021.

Transverse pseudo-Green's function impedance model for SuperKEKB LER

- Impedance model for TMCI
  - TMCI was not of great concern in the design stage and Phase-1.
  - In vertical direction, collimators dominate the impedance driving TMCI.
  - In collimator designs, impedances were calculated and TMCI threshold was estimated. For example, see Ref. [8].

Transverse Mode Coupling

- We estimated the threshold of the TMC using actual β value at each collimator (σ_z = 6 mm).
- When the collimator's apertures are all closed to the minimum (H: 5 mm, V: 2 mm), the bunch current would exceed the threshold.
- However, there would be no problem when we operate them within the designed aperture values.

$$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i \kappa_{\perp i}(\sigma_z)}$$

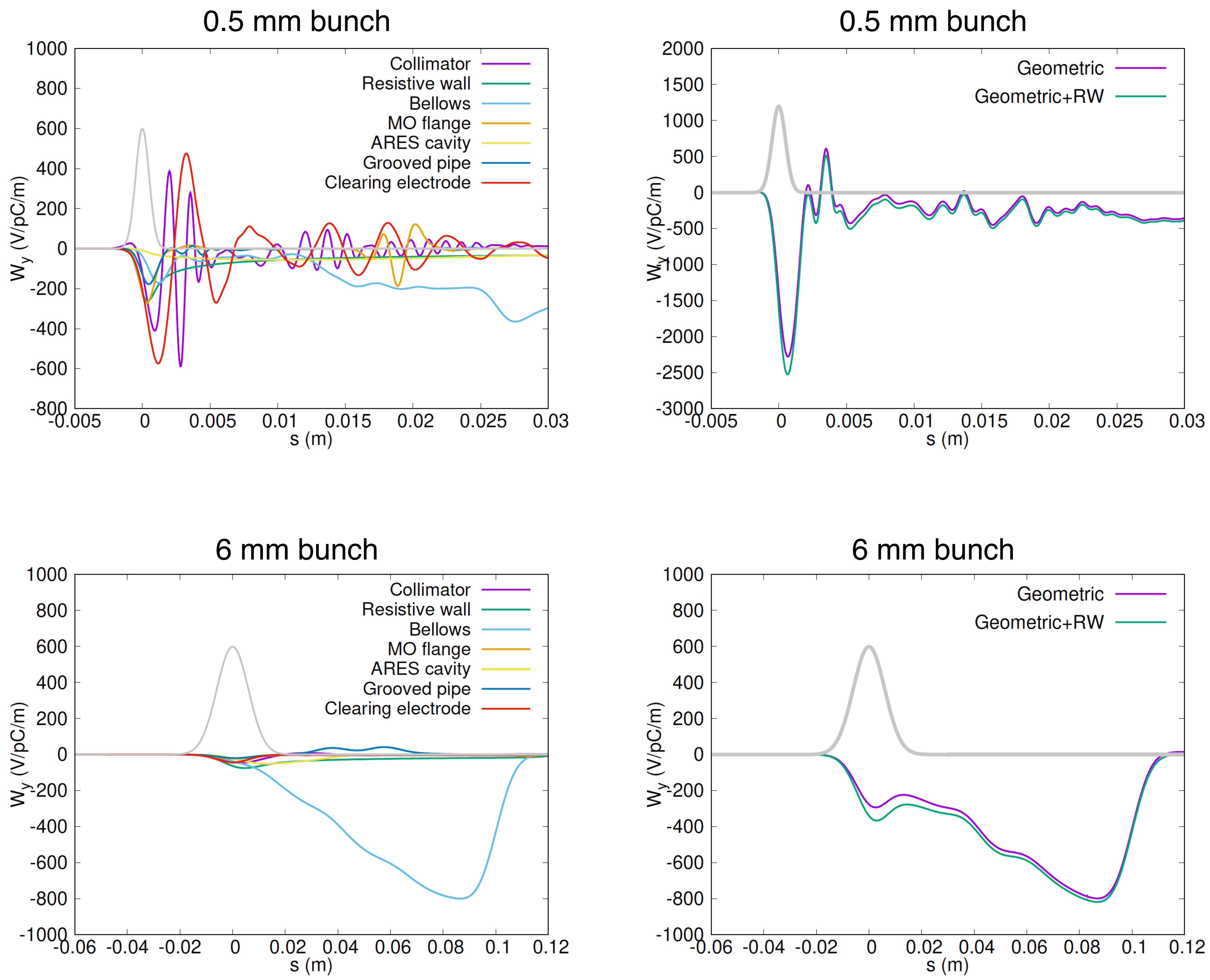
		TMC Threshold (mA/bunch)		Bunch Current
		All Closed	Realistic Apertures	(mA/bunch)
LER	Horizontal	1.41	13.15	1.44
	Vertical	0.96	5.10	

Courtesy of T. Ishibashi

[8] T. Ishibashi, Talk presented in the 2013 ARC meeting, https://www-kekb.kek.jp/MAC/2013/Report/Ishibashi.pdf.

Transverse pseudo-Green's function impedance model for SuperKEKB LER

- Impedance model for TMCI
  - The Pseudo-Green's function wakes were also calculated but not well studied.
  - One problem was that we did not separate the dipolar and quadrupolar wakes in impedance calculations.
  - I tried construction of transverse impedance model for LER in Phase-1. In Phase-1, the collimators were not dominant.



Transverse pseudo-Green's function impedance model for SuperKEKB LER

- Current situation
  - The longitudinal impedance model was studied intensively. But there is still large discrepancy between simulated and measured bunch lengthening.
  - In Phase-3, TMCI was found to be a strong limit at SuperKEKB. And collimators were found to be the dominant source of vertical impedance.
  - Ishibashi-san updated the longitudinal and transverse impedance calculations for SuperKEKB. New calculations separate the dipolar and quadrupolar wakes.
- Plan
  - Pseudo-Green's wakes are under processing and to be transformed to usable impedance model.
  - Studies on impedance theory and wake calculations for collimators with nonlinear tapering [9] are ongoing. Geometry optimization of collimators should be useful to increase TMCI threshold.

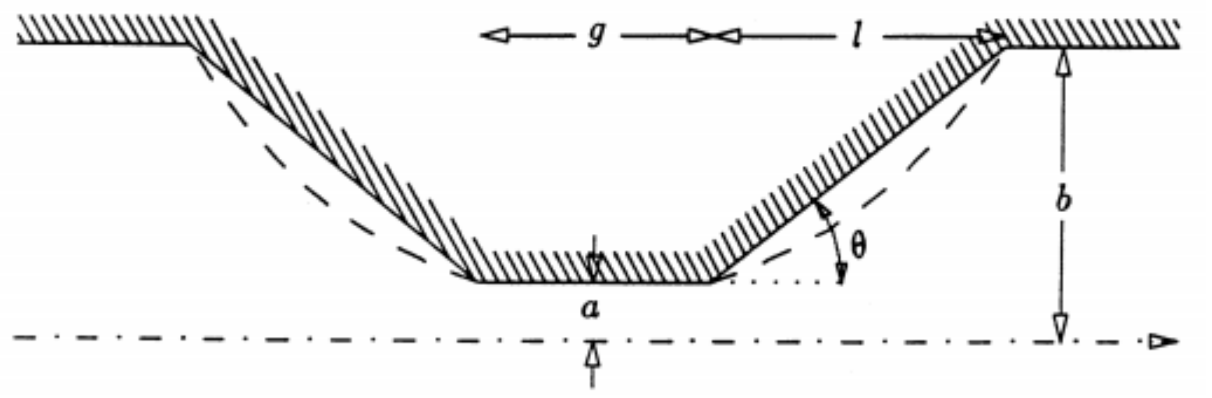


Fig.2. Linearly and exponentially tapered scrapers.

[9] K. Yokoya, CERN SL/90-88 (AP).