Comparison of machine impedance calculation with beam based measurements

Karl Bane and Demin Zhou

Acknowledgements:

T. Abe, K. Akai, Y. Cai, J. Flanagan, H. Fukuma, Y. Funakoshi, T. Kobayashi, T. Ieiri, H. Ikeda, T. Ishibashi, T. Mitsuhashi, Y. Morita, K. Ohmi, K. Oide, K. Shibata, Y. Suetsugu, M. Tobiyama

International Workshop on Impedances and Beam Instabilities in Particle Accelerators

Benevento, Italy, 20 September, 2017

Motivation

Can a "bottom-up" approach to a pseudo-Green function wake calculation hope to obtain the broad-band impedance of a modern, complicated storage ring such as KEKB and SuperKEKB (SKEKB)? Or do we need to resort to e.g. a Q= 1 resonator model with the parameters obtained by machine measurements?

Earlier streak camera measurements at KEKB and SKEKB were in clear disagreement with simulations using the calculated pseudo-Green function wakes for the machines. What can we learn from a revisit to this problem, focusing in particular on measurements of RF phase vs current?

T. Ieri and H. Koiso, (*The 14th Symposium on Accelerator Science and Technology, Tsukuba, Japan,* 2003) presented beam phase vs. current measurements for KEKB LER. There were systematic errors. We present here measurements that were performed again, in 2009, on KEKB LER.

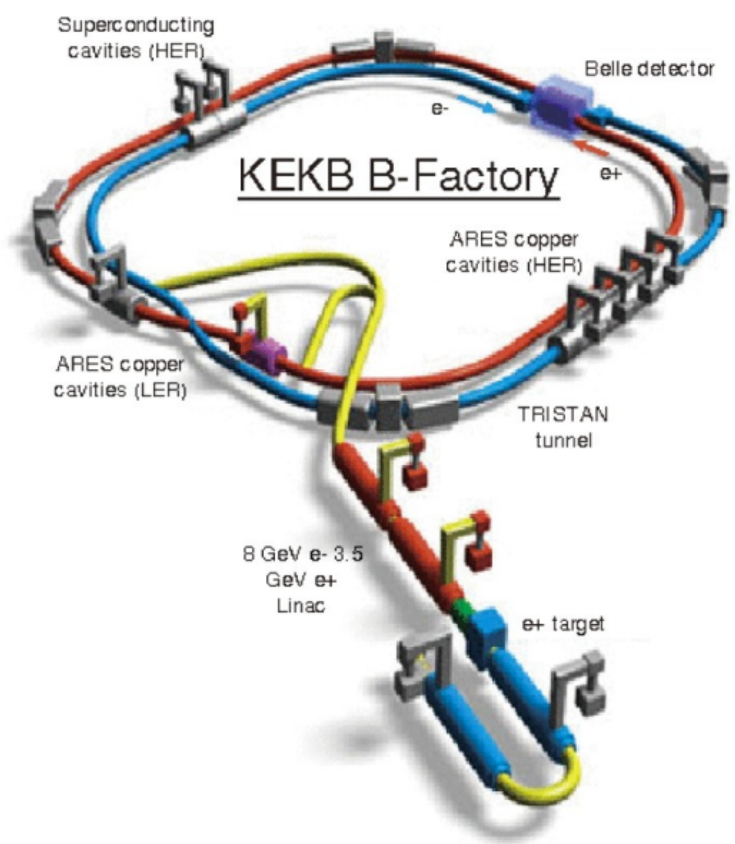
While KEKB and SKEKB are running, many RF system parameters are continually being logged. Can we extract phase vs. current data from this, particularly from the klystron power measurement?

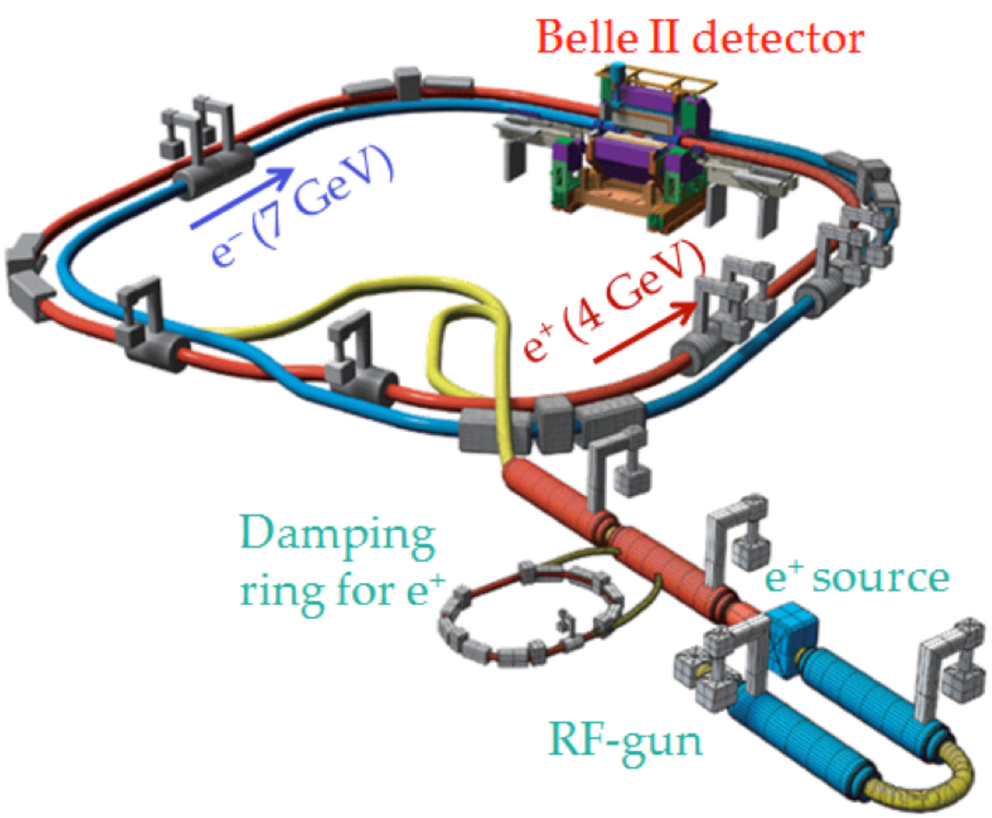
Outline

- Introduction
- 3D wakefield computations
- MWI simulation
- Beam phase measurement
- HOM power
- Summary

1. Introduction

	LER		HER	
	SKEKB	KEKB*	SKEKB	KEKB*
E (GeV)	4	3.5	7.007	8
I_{bunch} (mA)	1.44	1.03	1.04	0.75
ε_x (nm)	3.2	18	4.6	24
ε_y (pm)	8.64	180	12.9	240
α_p (10^{-4})	3.25	3.31	4.55	3.43
σ_δ (10^{-4})	8.08	7.73	6.37	6.3
σ_z (mm)	5	4.6	4.9	5.2

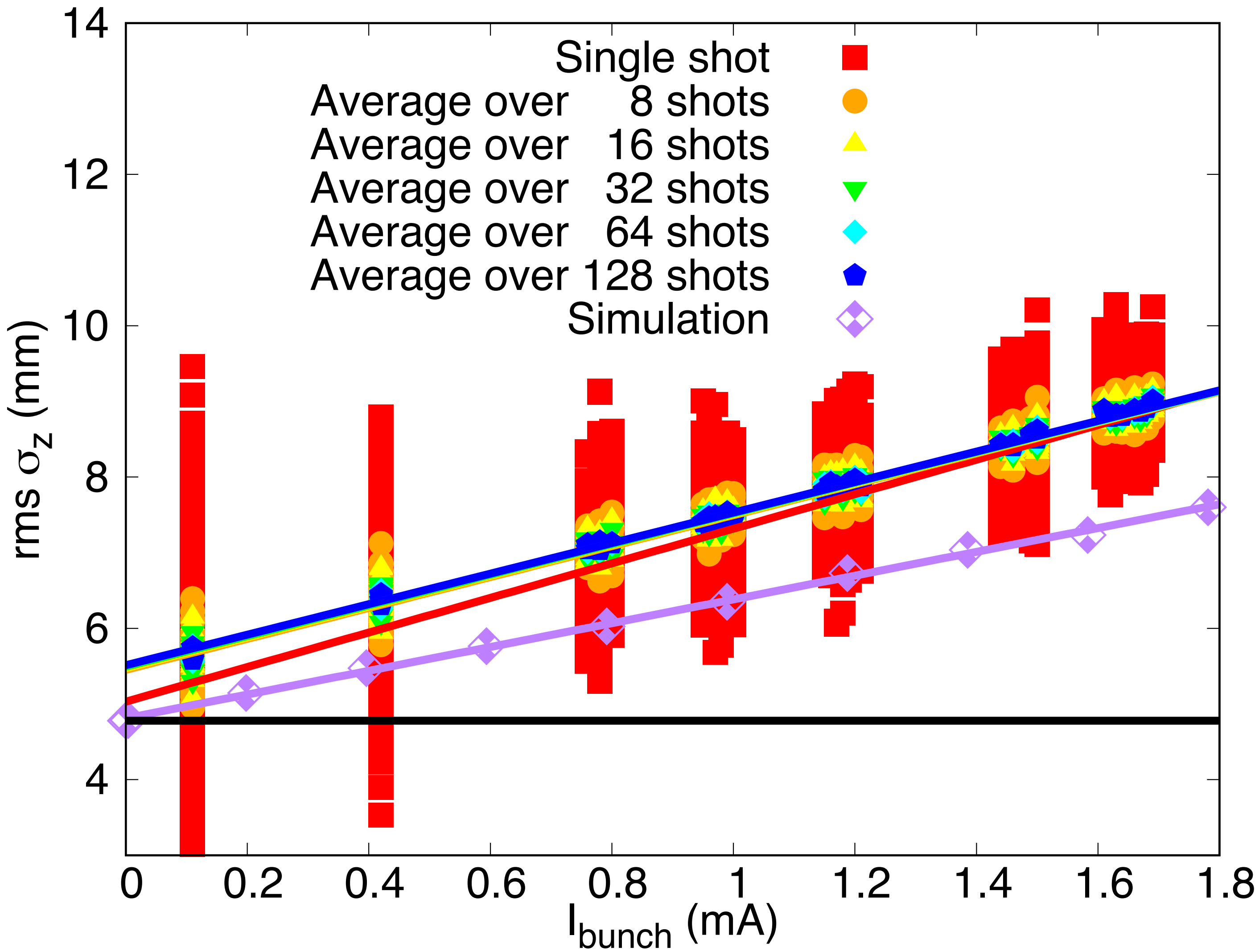




1. Introduction

➢ Motivation: Streak camera measurements in KEKB LER

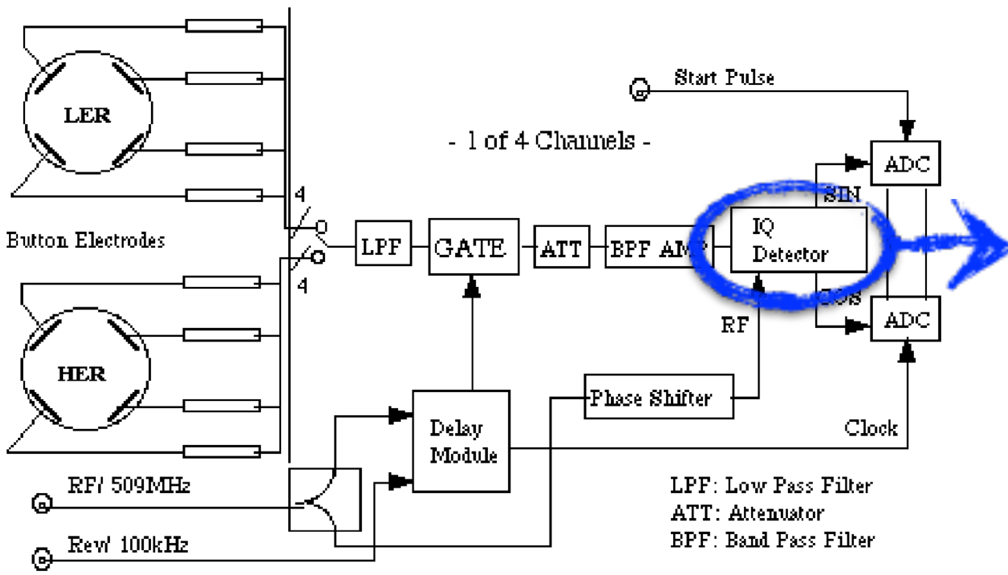
- Data taken on Oct. 26, 2009 with nominal bunch length 4.78 mm
- Single-shot measurement (128 shots per bunch current)
- Average over different number of shots: Converge to same results
- Shot noise and timing jitter expected to be small
- There were systematic errors in the SC system?



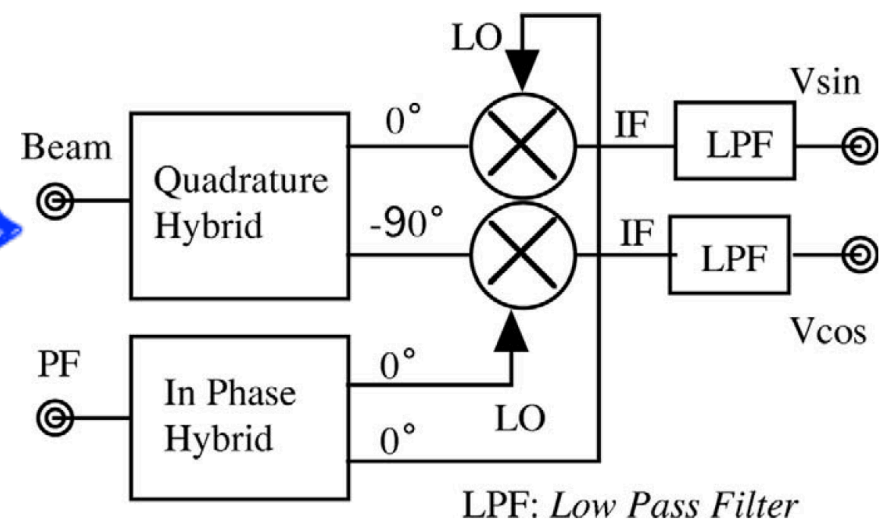
1. Introduction

➤ Beam phase measurement using gated BPM

- Refer to T. Ieiri et al., NIMA 606 (2009) 248-256



Block diagram of a GBPM



Principle of IQ detector

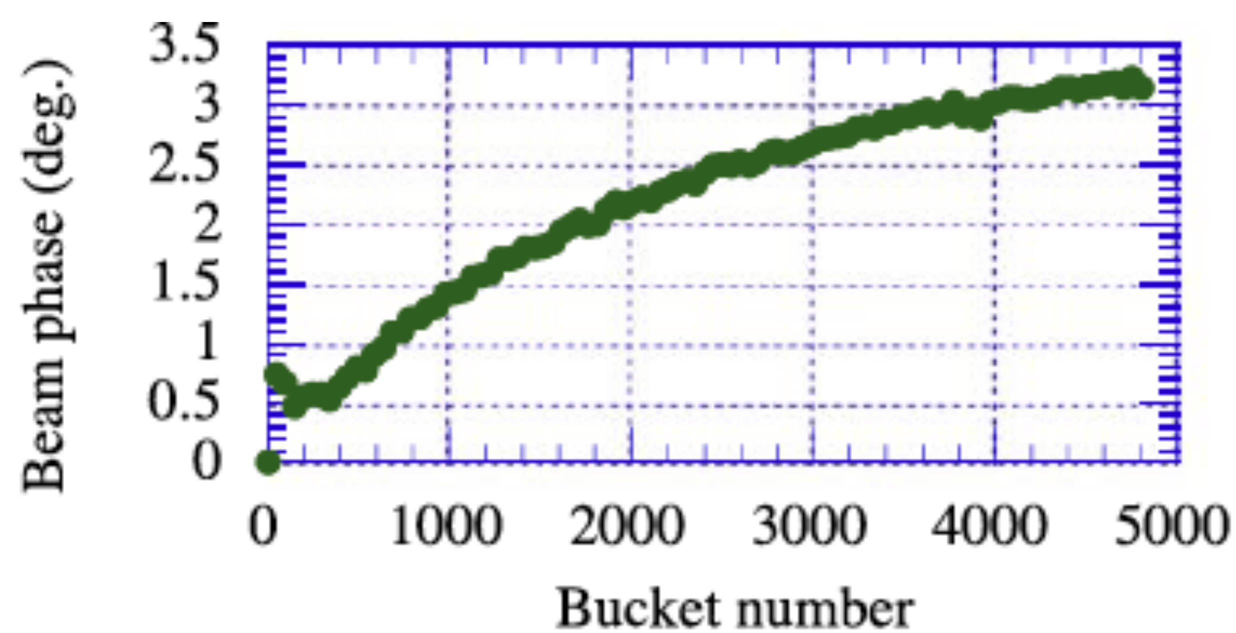
Equations:

$$V_{\sin} = \frac{1}{2} V_{\mathrm{b}} V_{\mathrm{rf}} \sin(\phi_{\mathrm{b}} - \phi_{\mathrm{rf0}})$$

$$V_{\cos} = -\frac{1}{2} V_{\mathrm{b}} V_{\mathrm{rf}} \cos(\phi_{\mathrm{b}} - \phi_{\mathrm{rf0}})$$

$$\phi_{\mathrm{b}} - \phi_{\mathrm{rf0}} = \tan^{-1}\left(-\frac{V_{\sin}}{V_{\cos}}\right)$$

Bunch signal



1. Introduction

➢ Beam power in a storage ring

- Total beam power = SR power (P_{SR}) + HOM power (P_{HOM})

  = $I_{beam} V_{rf}$ Sin[ϕ_{rf}]

- $P_{SR}=U_0 I_{beam}$ with U_0 calculated from lattice model or from measurement
- Loss factor $\kappa_{||}$ can be numerically computed or extracted from P_{HOM} or ϕ_{rf} through experiment

$$P_{\mathrm{beam}} = P_{\mathrm{SR}} + P_{\mathrm{HOM}} = I_{\mathrm{beam}}[\mathrm{mA}] V_{\mathrm{rf}} \sin[\phi_{\mathrm{rf}}]$$

$$P_{\mathrm{SR}}[\mathrm{kW}] = U_0[\mathrm{MV}] \cdot I_{\mathrm{beam}}[\mathrm{mA}]$$

$$P_{\mathrm{HOM}} = \kappa_{||}(\sigma_{\mathrm{s}}) \cdot I_{\mathrm{beam}}^2 \cdot T_0 / N_{\mathrm{bunch}}$$

1. Introduction

➤ **Scaling laws for machine parameters of a storage ring**

$$U_0 = C_\gamma \frac{E^4}{\rho} \propto E^4 \qquad U_0 = V_{\mathrm{rf}} \sin\phi_s$$

$$\sigma_s = \frac{c|\eta_c|\sigma_\delta}{2\pi\nu_s f_{\mathrm{rev}}}$$

$$\nu_s = \sqrt{\frac{heV_{\mathrm{rf}}|\eta_c \cos\phi_s|}{2\pi\beta^2 E}} \propto \sqrt{\frac{|\cos\phi_s|}{E}}$$

$$\sigma_\delta = \sqrt{C_q \gamma^2 \frac{< |\rho^{-3}| >_z}{J_\epsilon < \rho^{-2} >_z}} \propto E$$

1. Introduction

➢ Scaled machine parameters of KEKB LER

- Assume the KEKB operation followed the scaling laws over beam energy
- Assume momentum compaction is energy-independent

Beam energy [GeV]	3.594074	3.5	3.314401	3.128585
RF voltage [MV]	8	8	8	7
SR loss [MeV/turn]	1.820	1.637	1.316	1.045
Nominal bunch length [mm]	4.78	4.58	4.20	4.12
Synch. tune	0.0236	0.024	0.0248	0.0239
Energy spread [10^{-4}]	7.465	7.27	6.884	6.499
Long. damping time [ms]	20.716	21.6	25.436	30.242
Circumference [m]	3016.25	3016.25	3016.25	3016.25
RF phase [deg]	13.15	11.81	9.47	8.59

2. 3D wakefield computations for KEKB LER

T. Abe, K. Shibata,
T. Ishibashi, M. Tobiyama, et al

➤ **Impedance sources in the ring**

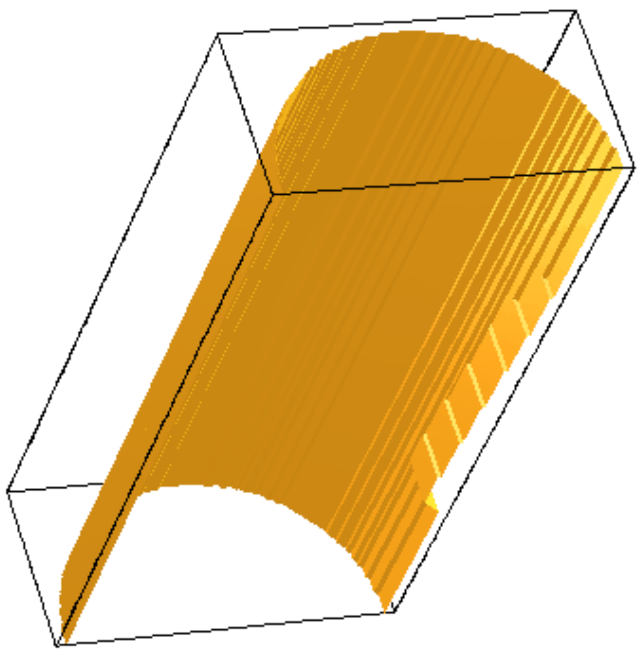
- **Geometric wakes, resistive wall, CSR, and CWR**

Component	Number	Code
ARES cavity	20	GdfidL
Movable mask	16	GdfidL
SR mask (arc/wiggler)	1000 (905/95)	GdfidL
Bellows	1000	GdfidL
Flange gap	2000	GdfidL
BPM	440	GdfidL
Pumping port	3000	GdfidL
Crab cavity	1	ABCI
FB kicker/BPM	1/40	GdfidL
Tapers ARES/Crab/Abort/Injection IR(IP/QCSL/QCSR)	4/2/2/2 6(2/2/2)	GdfidL
Gate valves f94/f150/94x150	26/13/2	GdfidL
CSR/CWR	-	CSRZ

2. 3D wakefield computations for KEKB LER

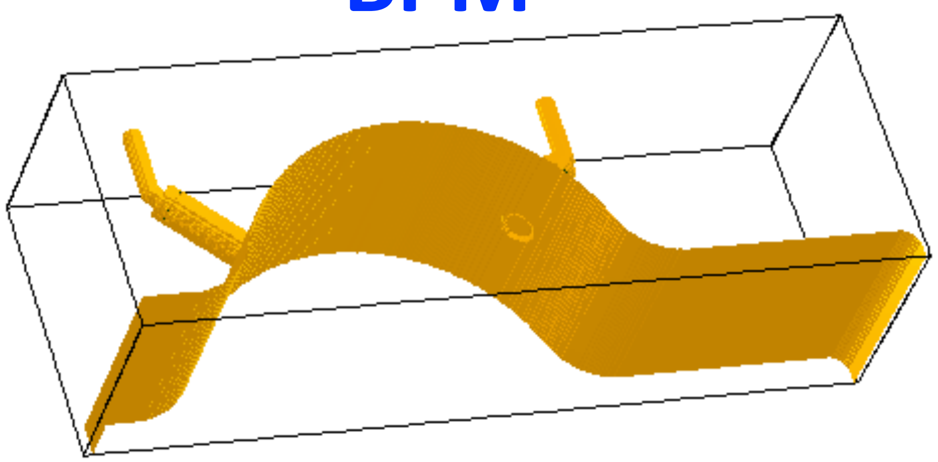
➤ **Examples of 3D components modeled by GdfidL**

Movable mask

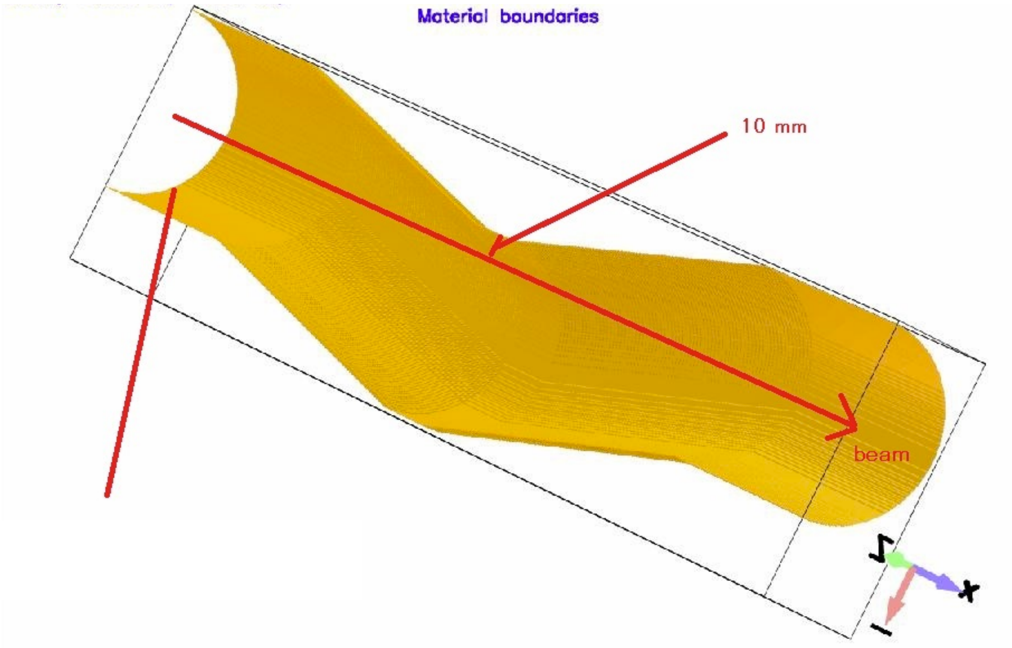


ARES RF cavity

BPM



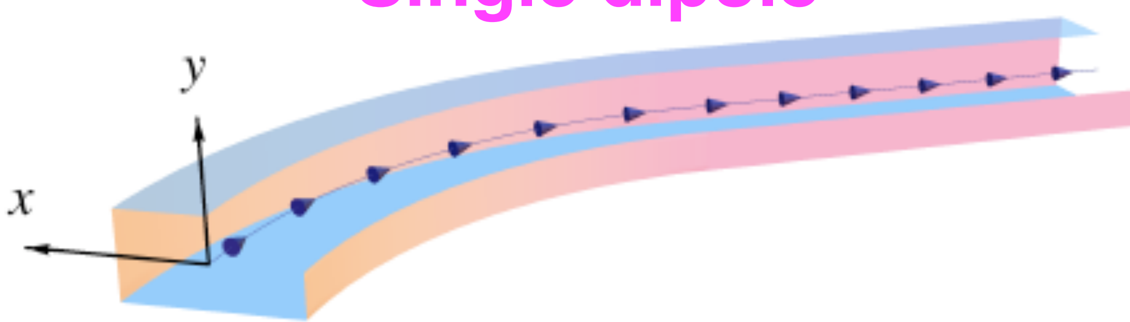
Movable mask



2. 3D wakefield computations for KEKB LER

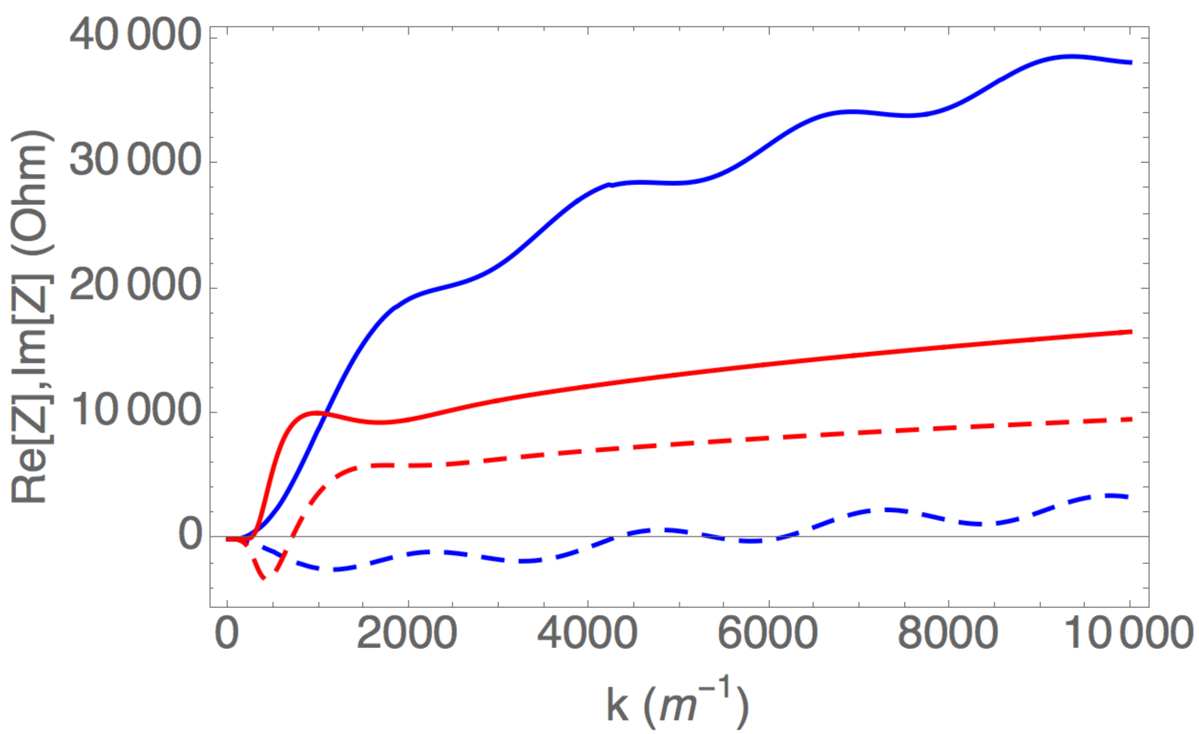
- ➤ **CSR in storage rings ➡ Chamber shielding ➡ CSRZ code**
- ➤ **Features of CSRZ: Arbitrarily curved chamber; Small numerical noise; Multi-bend interference; Treat wigglers; ...**

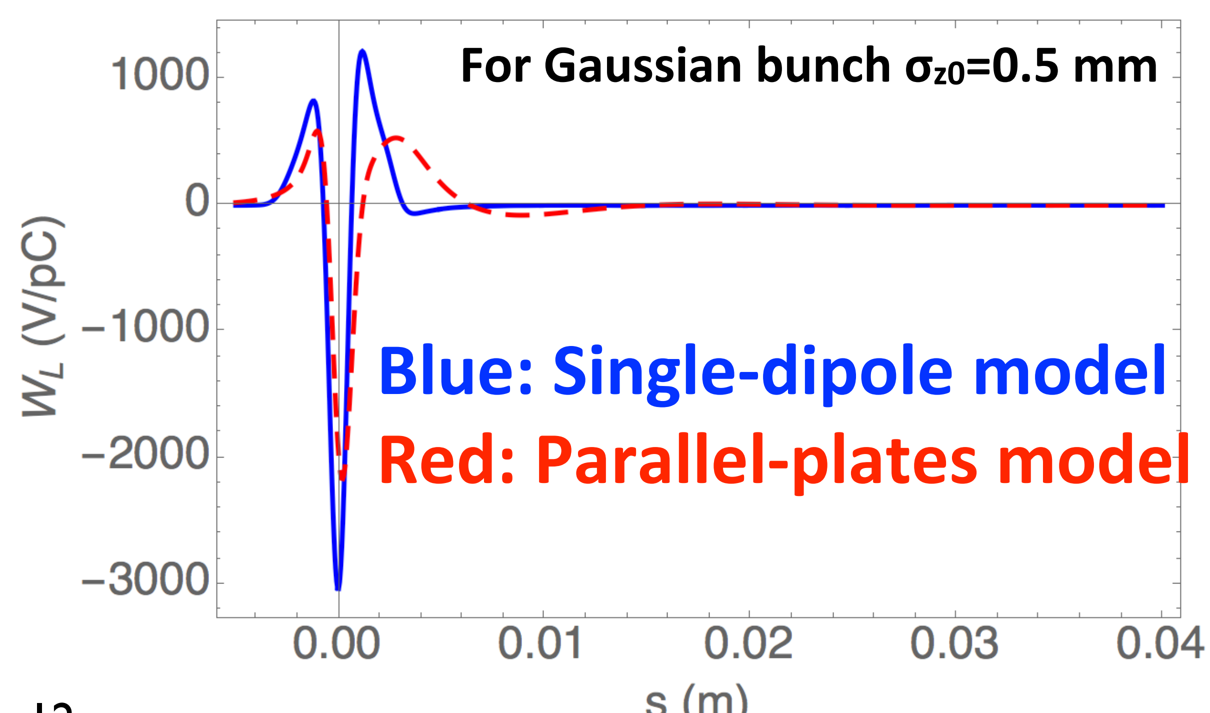
Single dipole



Wiggler - "Wiggling pipe"

CSRZ model for KEKB dipole:
L=0.89 m, R=15.87 m, Square chamber with ϕ=94 mm

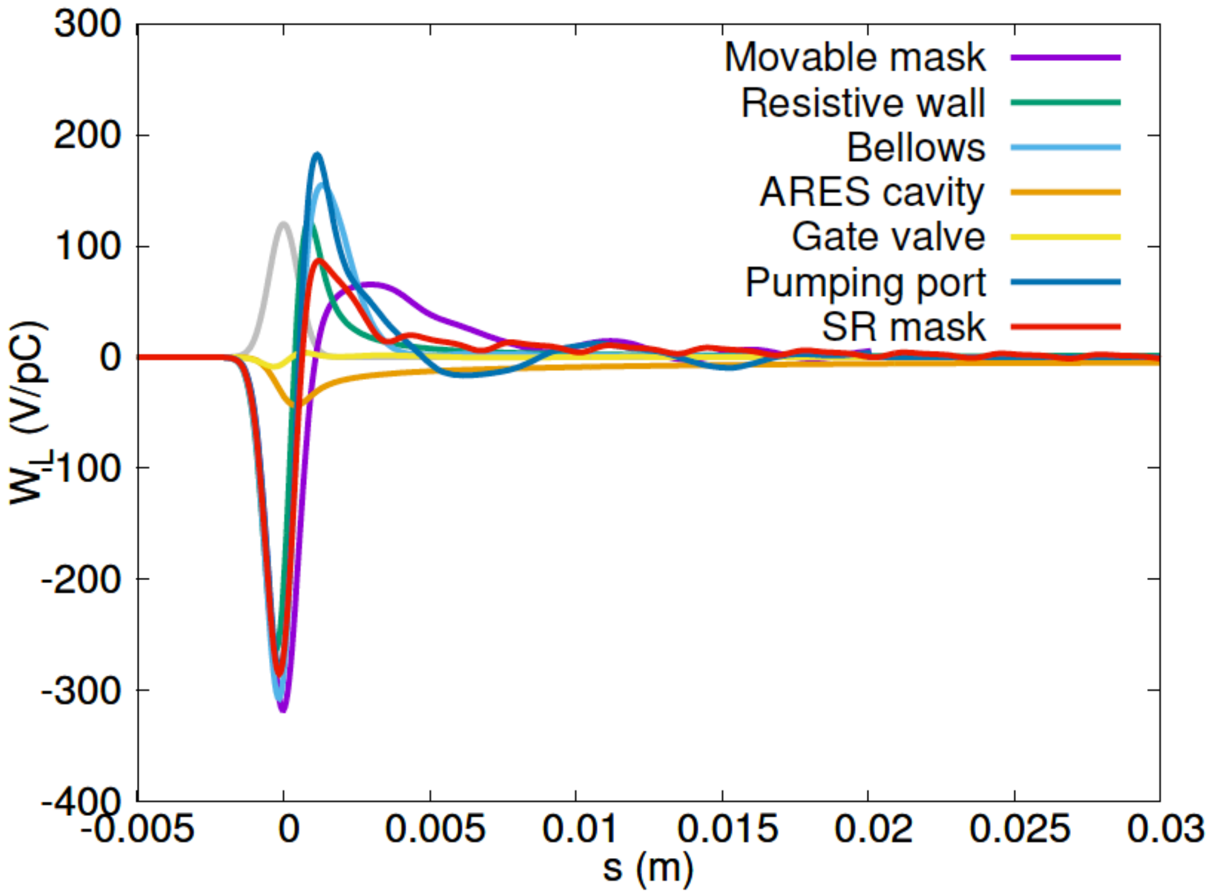


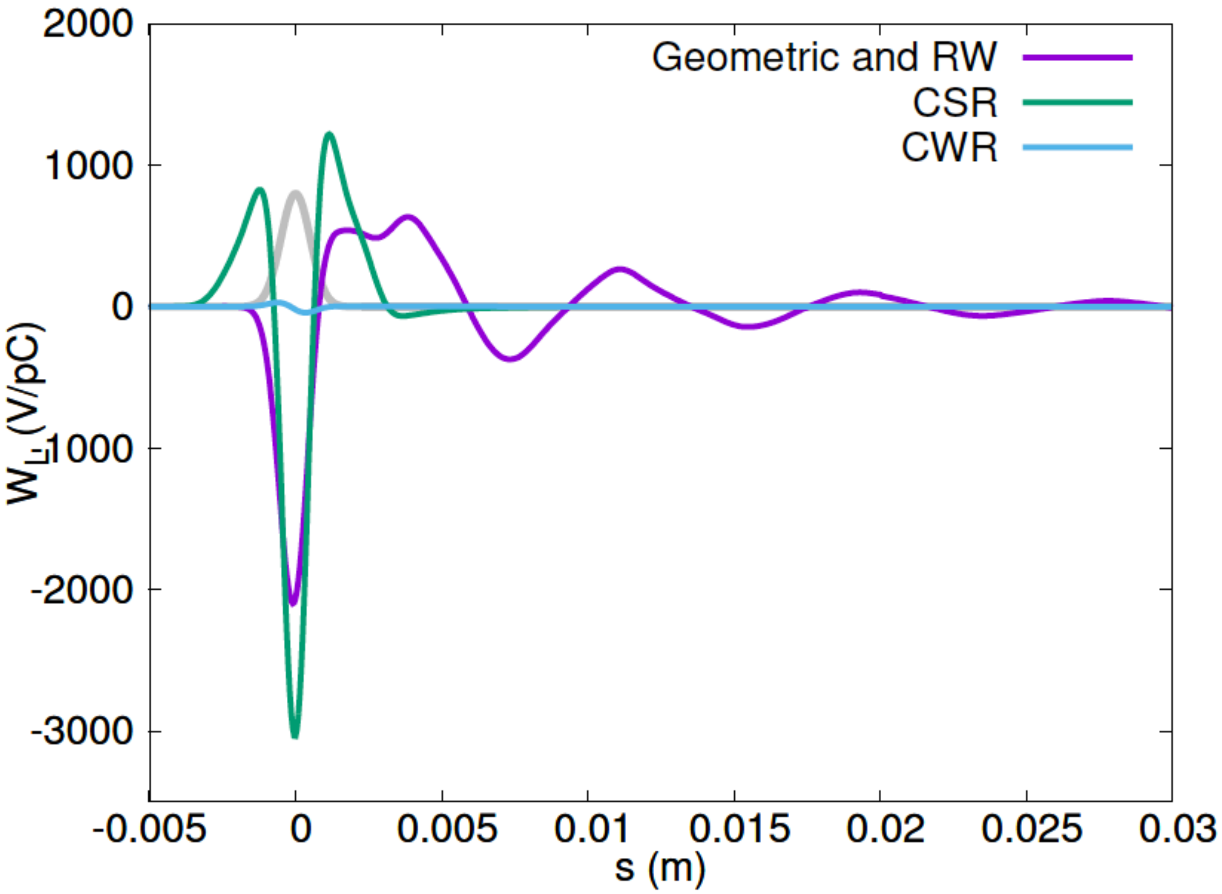


2. 3D wakefield computations for KEKB LER

➤ **Pseudo-Green wake function**

- **Gaussian bunch σ_z=0.5 mm**
- **CSR and CWR: CSRZ code with rectangular chamber**

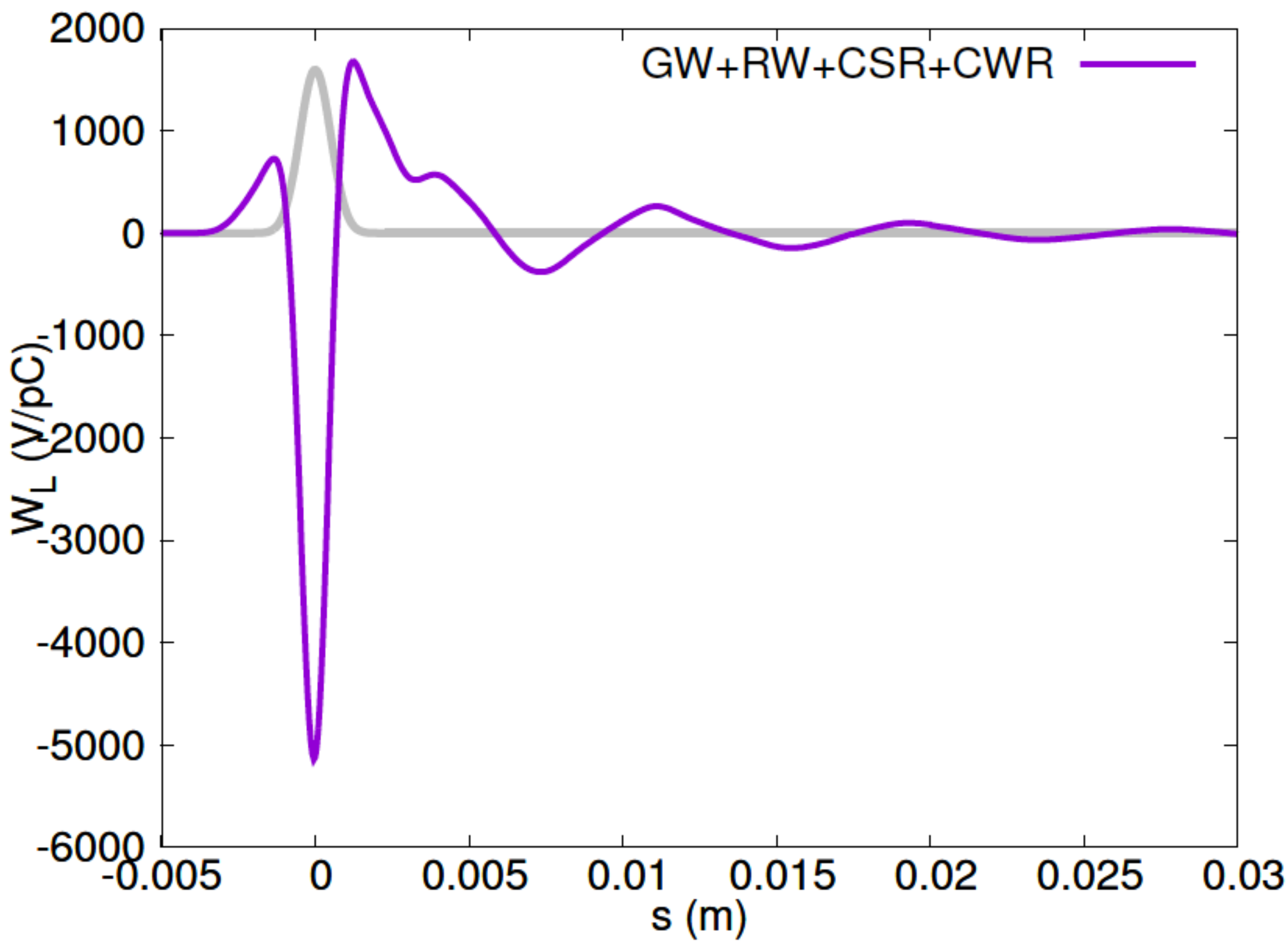




2. 3D wakefield computations for KEKB LER

➤ Pseudo-Green wake function

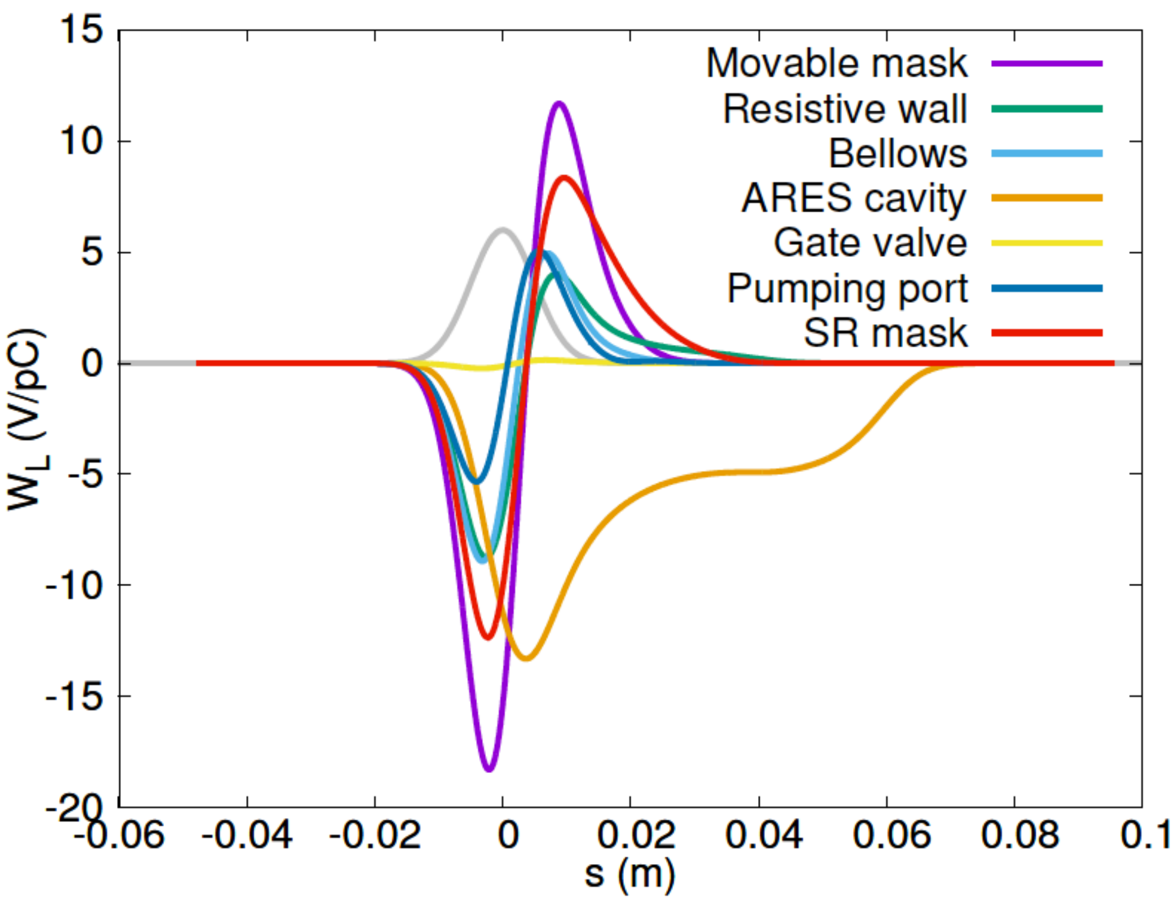
- **Total wake with Gaussian bunch σ_z=0.5 mm**

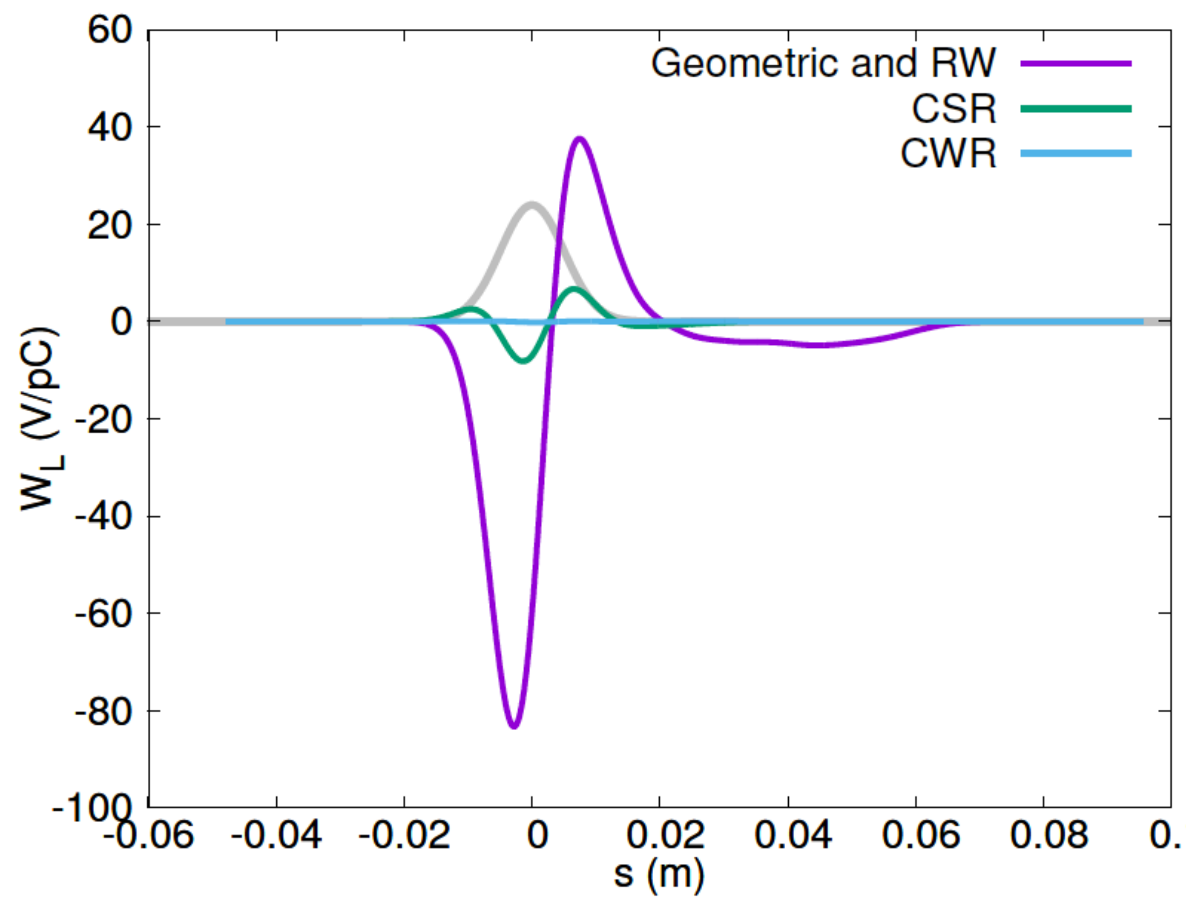


2. 3D wakefield computations for KEKB LER

➢ Pseudo-Green wake function

- **Nominal bunch length σ_{z0}=4.78mm @E=3.594 GeV, V_{rf}=8 MV**
- **CSR and CWR: CSRZ code with rectangular chamber**





2. 3D wakefield computations for KEKB LER

➤ Impedance budget for LER: Comparison of KEKB and SKEKB

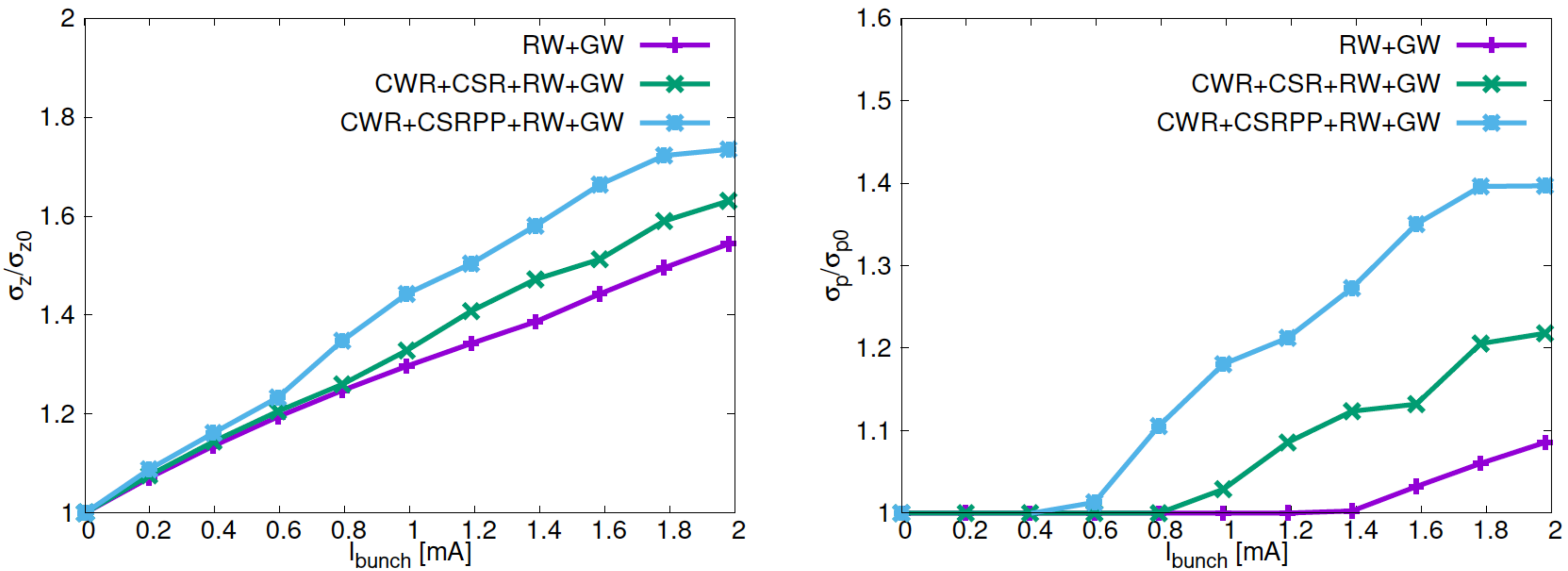
Component	Super-LER			KEKB-LER		
	$k_{\|\|}$	R	L	$k_{\|\|}$	R	L
ARES cavity	8.9	524	-	9.2	545	-
Crab cavity	-	-	-	1.0	60.1	-
Collimator	1.1	62.4	13.0	7.6	447	11.9
Res. wall	3.9	231	5.7	3.7	222	5.5
Bellows	2.7	159	5.1	3.0	178	6.6
Flange	0.2	13.7	4.1	1.1	62.1	18.5
Pump. port	0.0	0.0	0.0	0.5	28.8	5.5
SR mask	0.0	0.0	0.0	5.0	298	8.5
IR duct	0.0	2.2	0.5	0.2	9.9	0.6
BPM	0.1	8.2	0.6	0.8	46.8	0.8
FB kicker	0.4	26.3	0.0	0.2	13.2	0.0
FB BPM	0.0	1.1	0.0	0.2	13.5	0.7
Gate valve	-	-	-	0.1	4.2	0.2
Taper	0.0	0.7	0.1	0.3	16.6	1.3
Long. kicker	1.8	105	1.2	-	-	-
Groove pipe	0.1	5.7	0.9	-	-	-
Electrode	0.0	2.2	2.3	-	-	-
Total	19.2	1142	33.5	32.9	1945	60.1

Note: Antechamber is used in SKEKB LER, suppressing impedances from flanges, pumping ports and SR masks.

3. MWI simulation for KEKB LER

➤ Simulations with input of Pseudo-Green wake

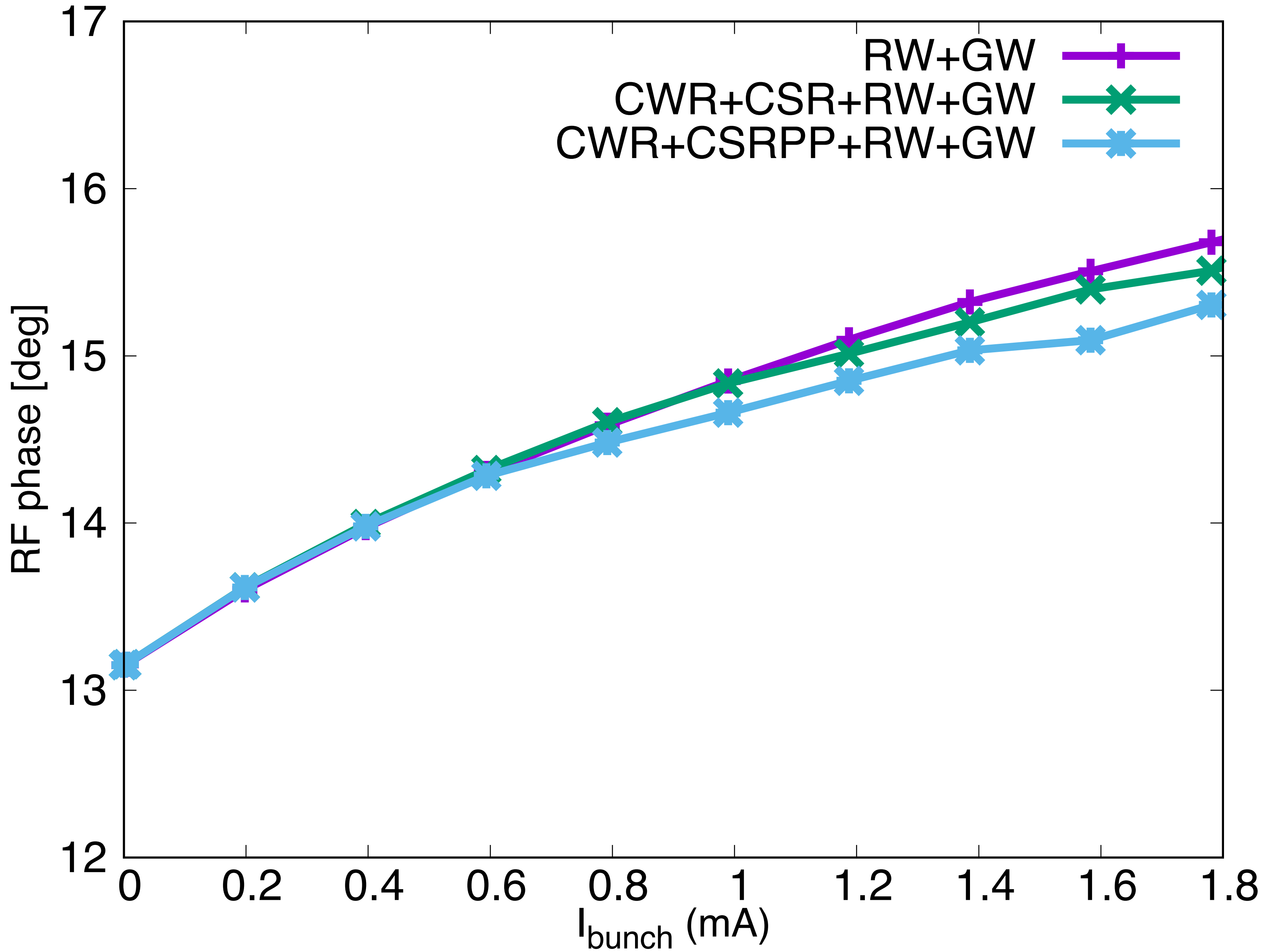
- Use Warnock-Cai's VFP solver for simulation
- Nominal bunch length σ_{z0}=4.78mm @E=3.594 GeV, V_{rf}=8 MV
- Interplay of CSR and other wakes decreases MWI threshold
- Chamber shielding is important in CSR



3. MWI simulation for KEKB LER

➤ **Simulations with input of Pseudo-Green wake**

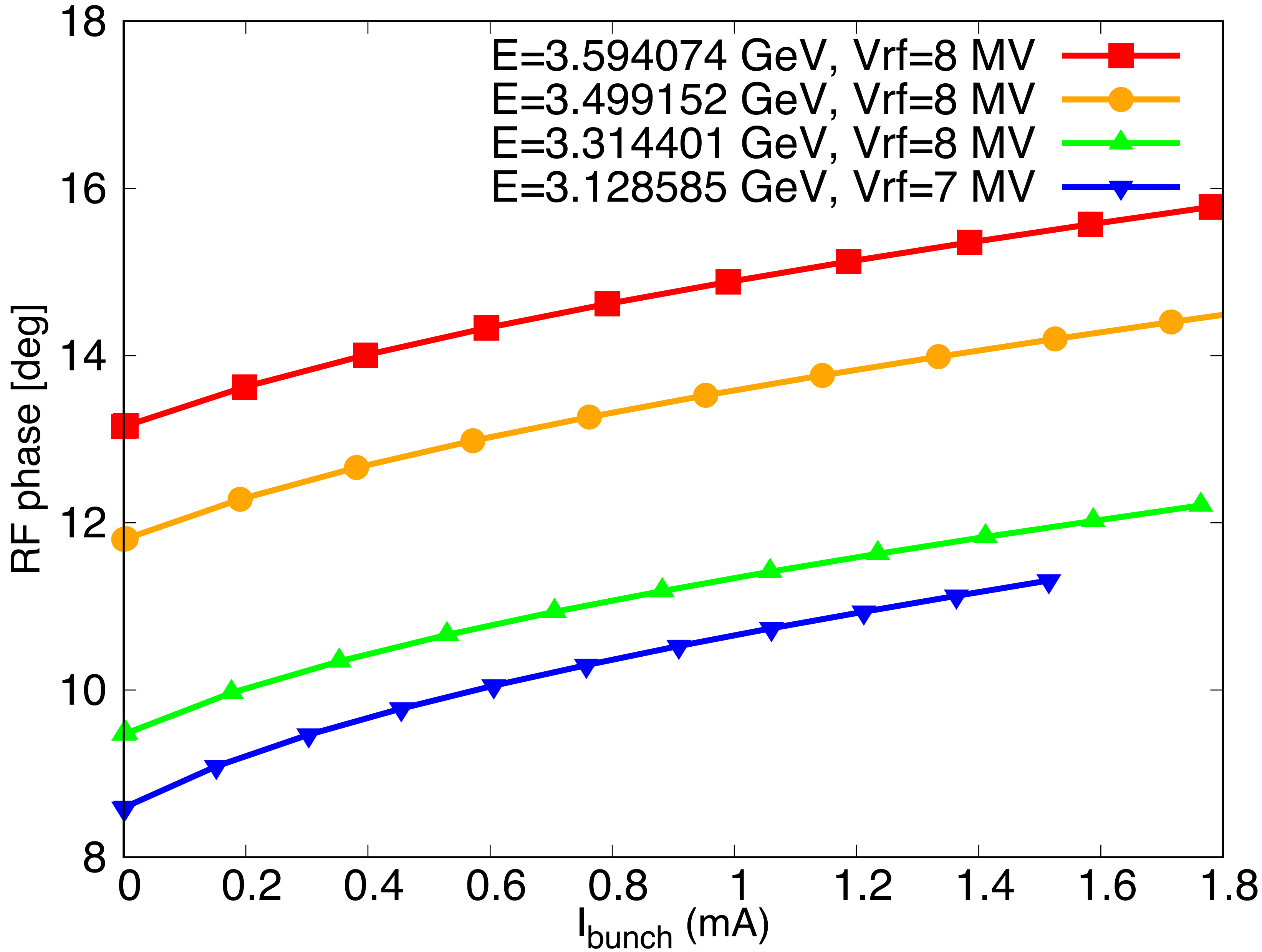
- **Use Warnock-Cai's VFP solver for simulation**
- **Nominal bunch length σ_{z0}=4.78mm @E=3.594 GeV, V_{rf}=8 MV**
- **Simulated RF phase vs. bunch current**



3. MWI simulation for KEKB LER

➢ **Expected RF phase vs. beam energy for KEKB LER**

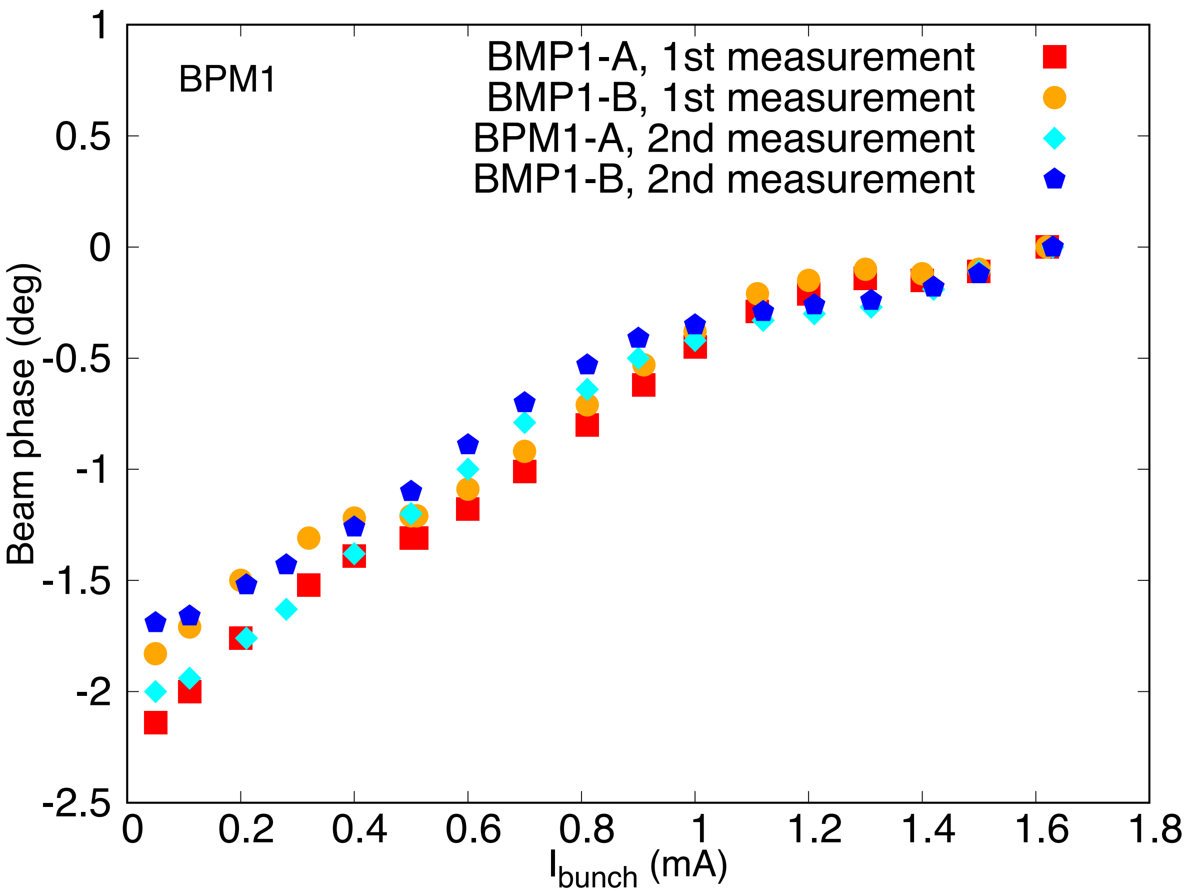
- **Use the same Pseudo-Green function wake**
- **Use Warnock-Cai's VFP solver for simulation**
- **RF phase calculated from simulated bunch profile (Haissinski solution)**

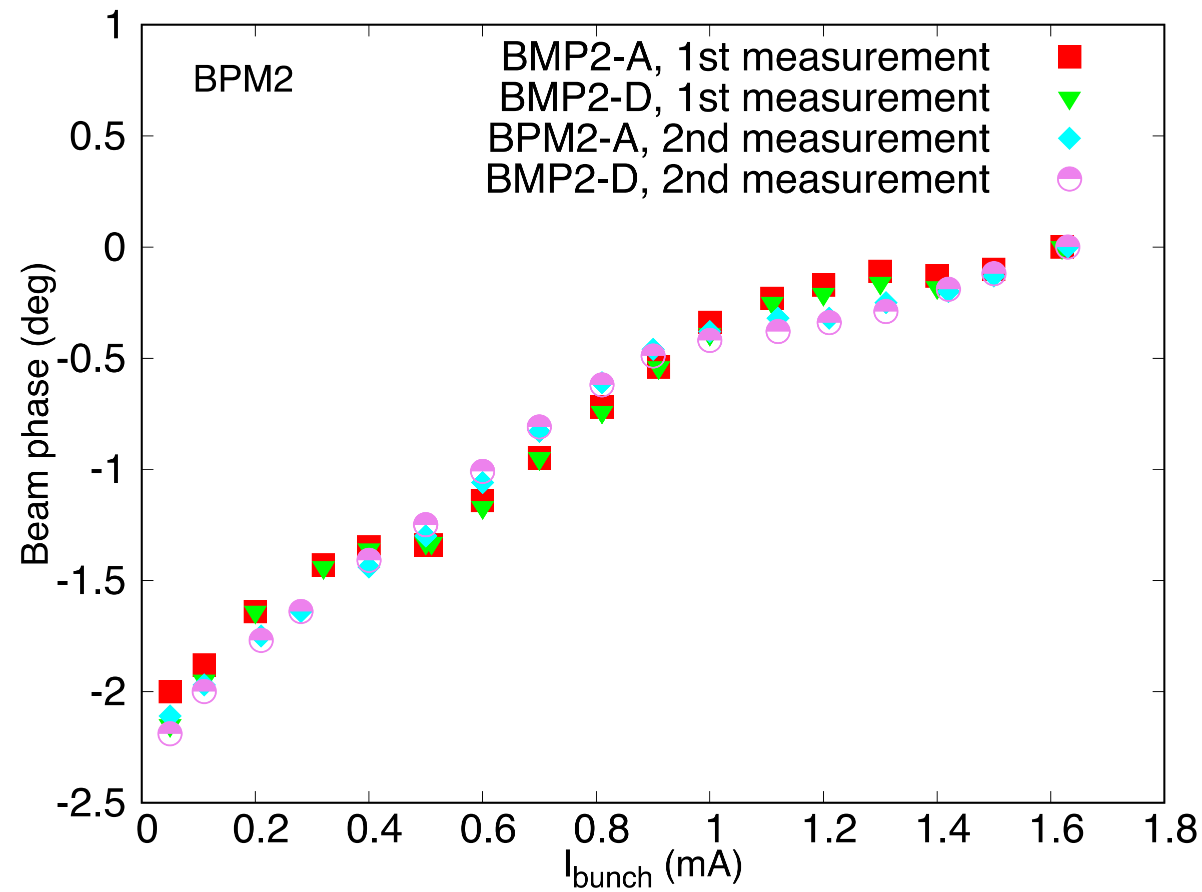


4. Beam phase measurement at KEKB LER

➤ Gated BPM measurements on beam phase

- Re-analysis on the data taken on Oct. 26, 2009
- E=3.594 GeV and V_{rf}=8 MV
- Good reproducibility in GBPM data but larger variations at lower bunch currents
- Only relative beam phase obtained, and assumed the same reference phase at highest bunch current

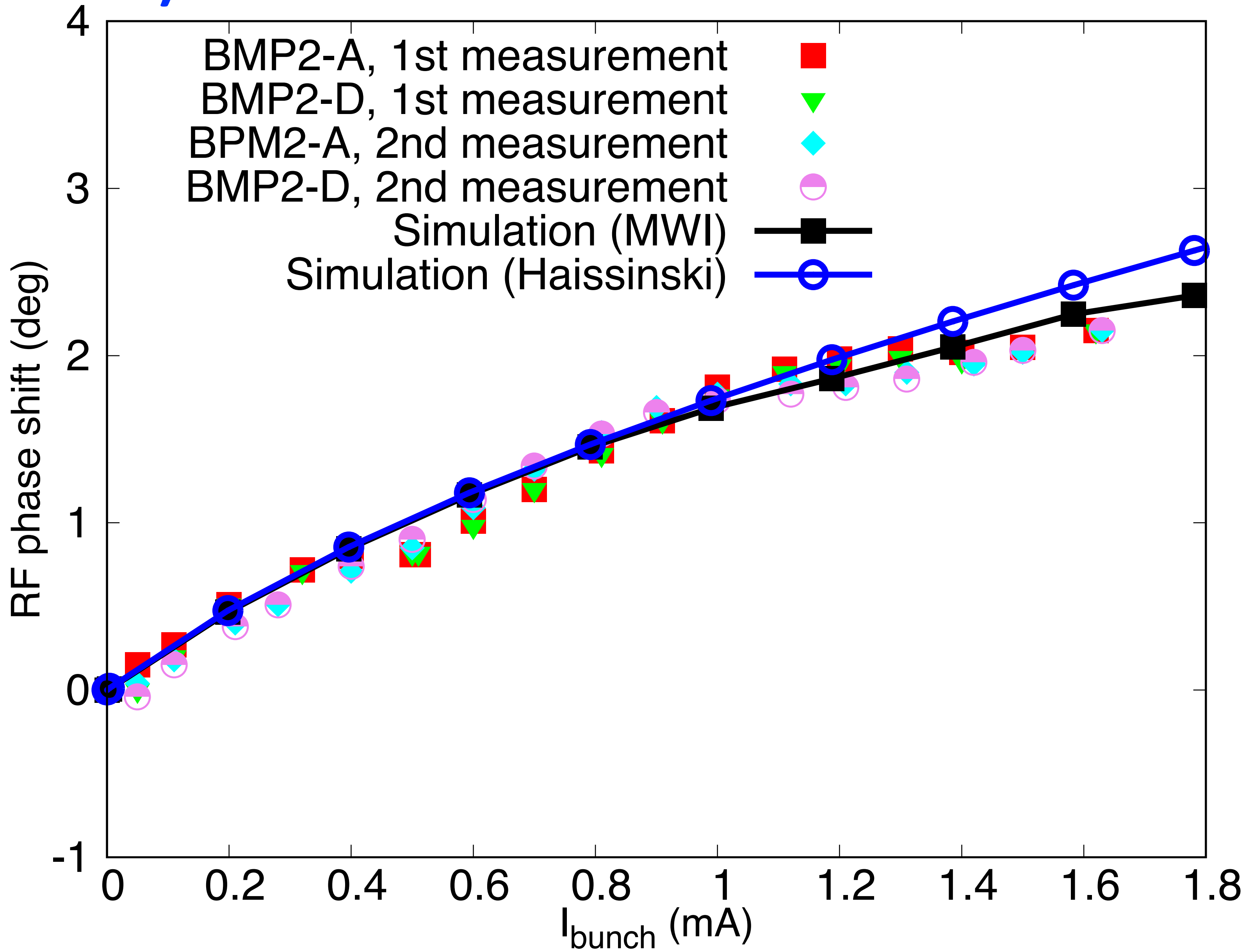




4. Beam phase measurement at KEKB LER

➤ Comparison with MWI simulations

- Use Warnock-Cai's VFP solver for simulation
- E=3.594 GeV and V_{rf}=8 MV
- Beam phase at zero current taken as -2.15 deg (extracted from experimental data)



5. HOM power in KEKB LER

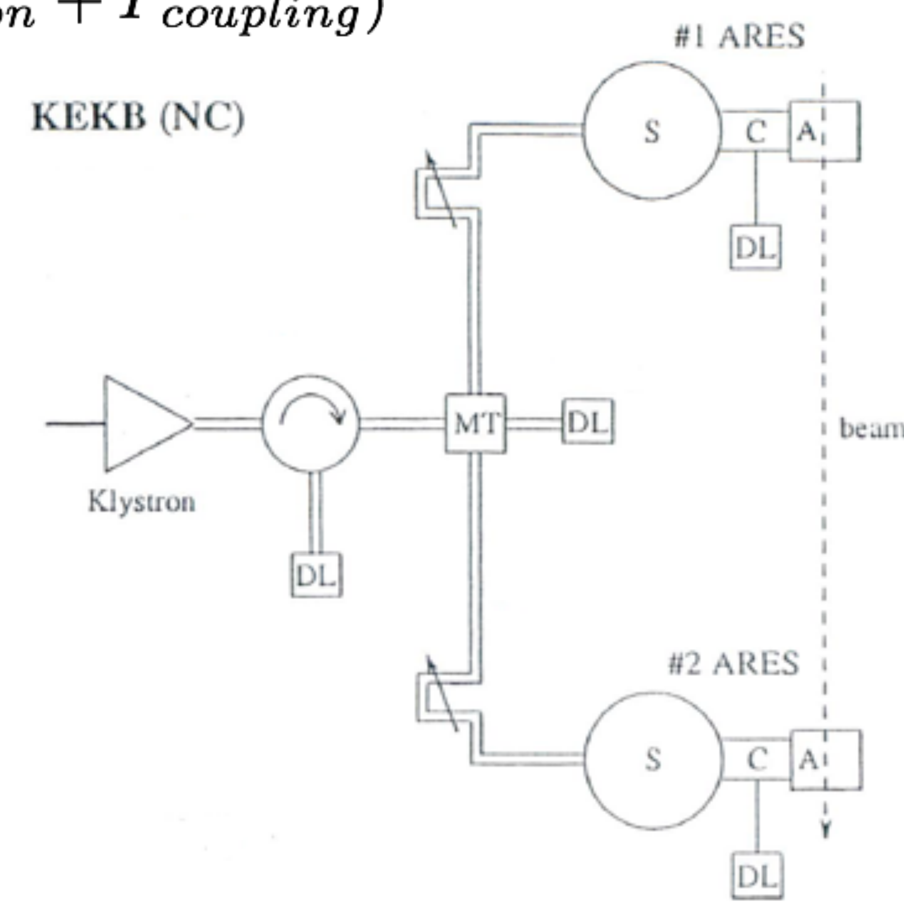
➢ The method

- Refer to A. Novokhatski's work on PEP-II (PAC'07)
- Use the log data for RF systems in KEKB
- Power of wall loss at each cavity: P_{wall}=154 kW@V_c=0.5 MV
- The calibration factor k for each klystron is determined by

$P_{beam}(I_{beam}=0)=0$

$$P_{beam}(I_{beam}) = \sum k \cdot P_{klystron} - \sum (P_{wall} + P_{reflection} + P_{coupling})$$
$$= \sum P_{RFinput} - \sum (P_{wall} + P_{reflection} + P_{coupling})$$

Note: Summation is done for all klystrons and RF cavities



Logged data in KEKB:

$P_{klystron}$: Klystron output power

$P_{reflection}$: Power reflected from RF cavity

$P_{coupling}$: Power to DL (dummy load)

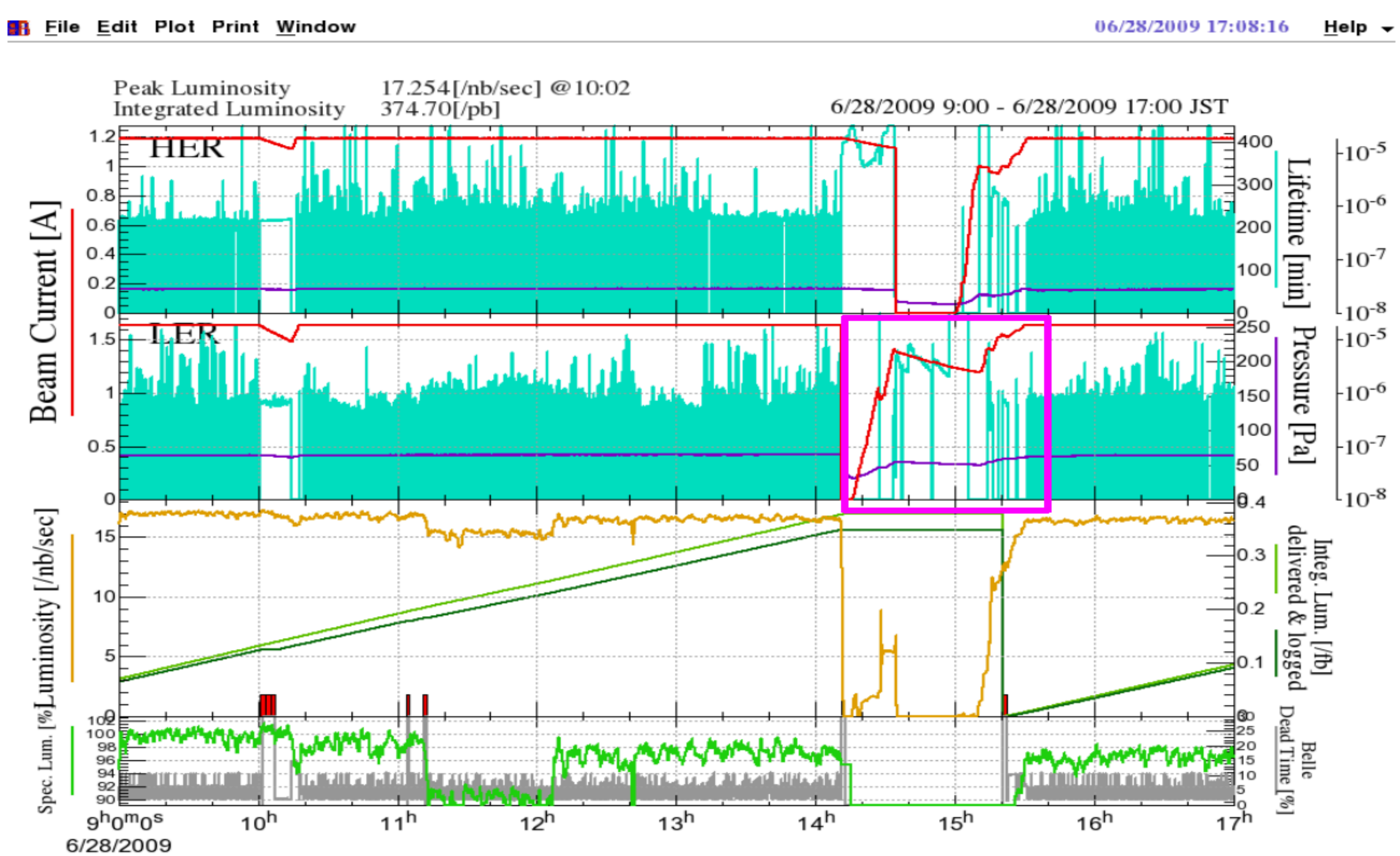
$P_{RFinput}$: Input power to RF cavity

K. Akai, KEKB ARC 1999

5. HOM power in KEKB LER

➤ The method

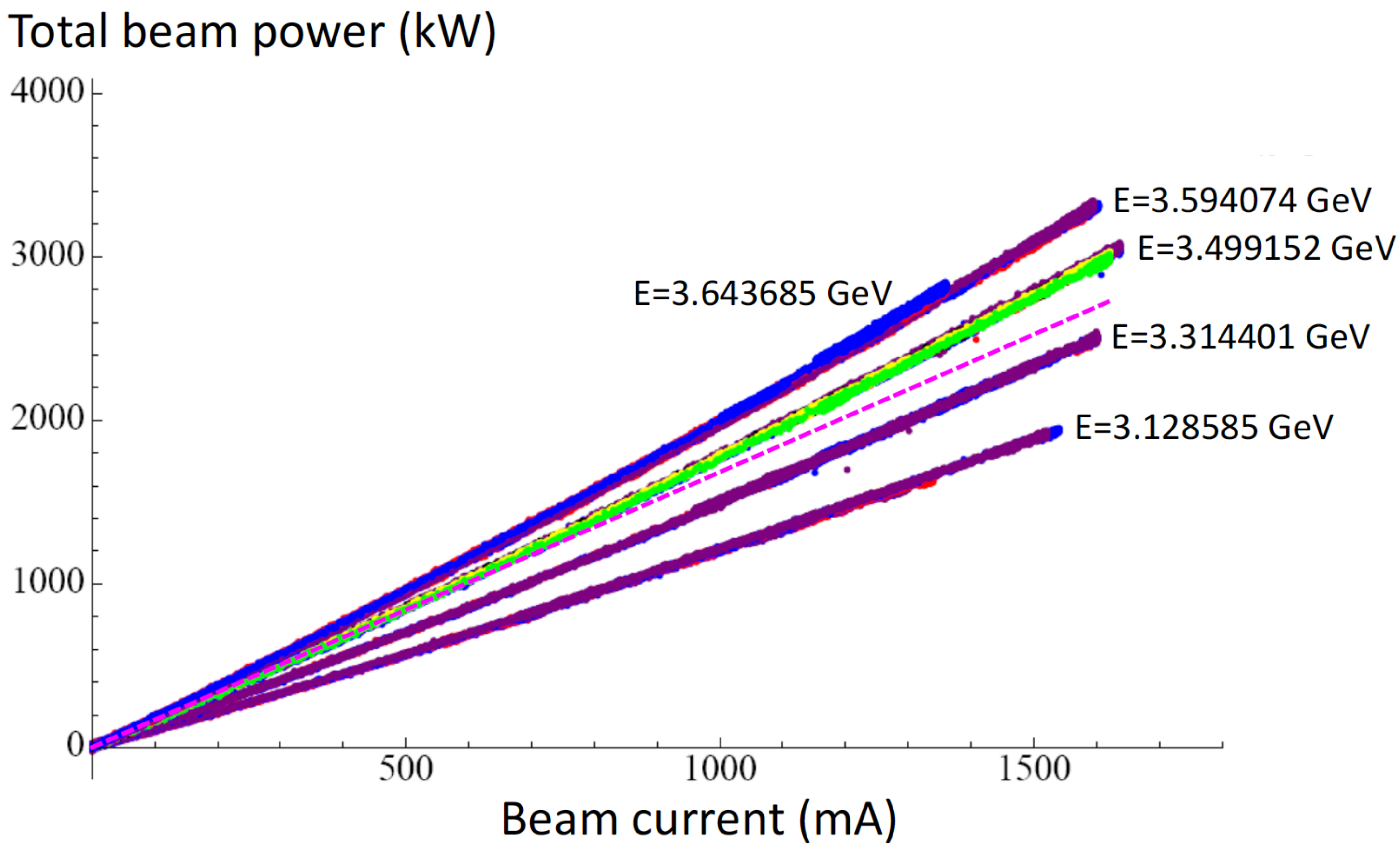
- **Beam current dependent power can be found from beam injection to the rings (after beam abort)**
- **For physics run in 2008 and 2009 the typical number of bunches is N_{bunch}=1584+1 (one pilot bunch)**
- **Assumed bunch current is uniform along the bunch train (this is true because of injection optimization**
- **Bunch spacing is ~3-4 RF bucket**



5. HOM power in KEKB LER

➤ **Beam power**

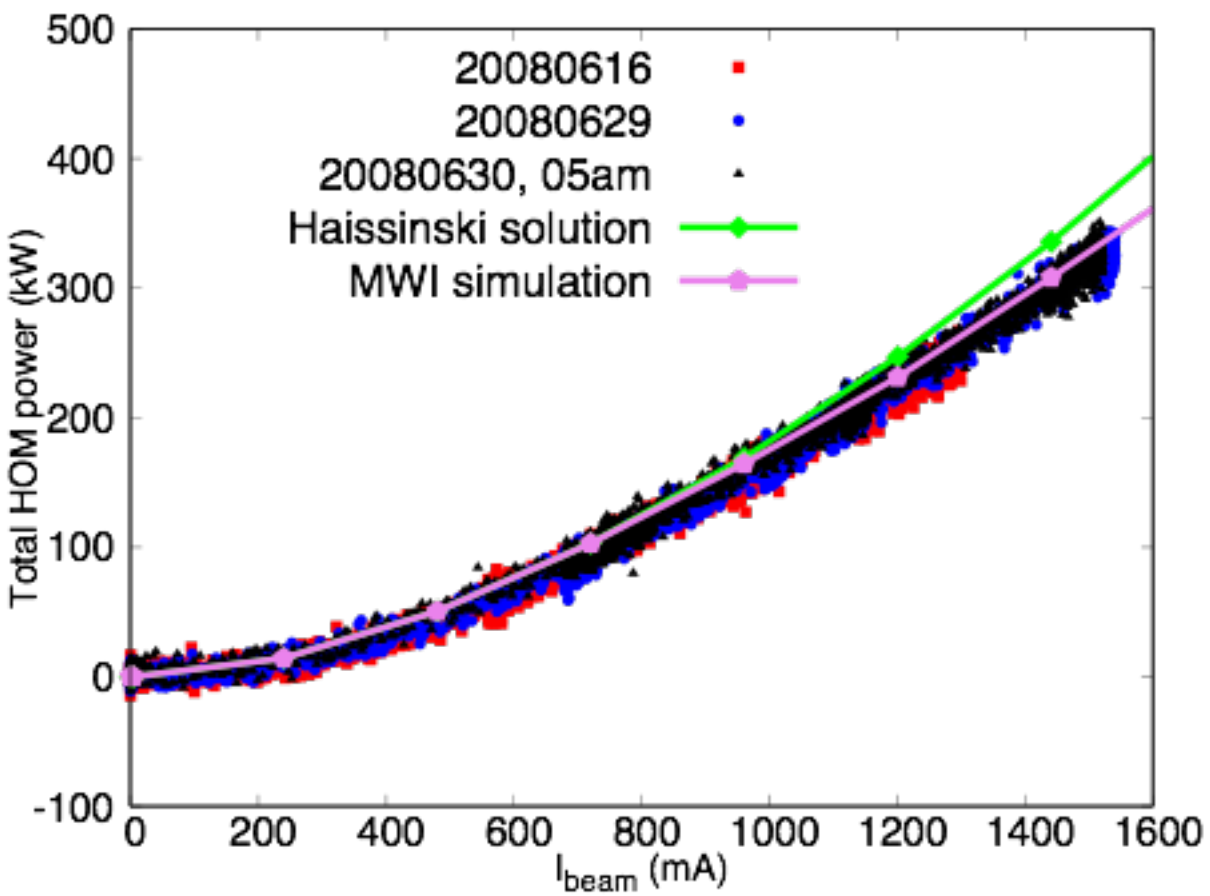
- **Beam power depends on beam energy**
- **SR power linearly depends on beam current**

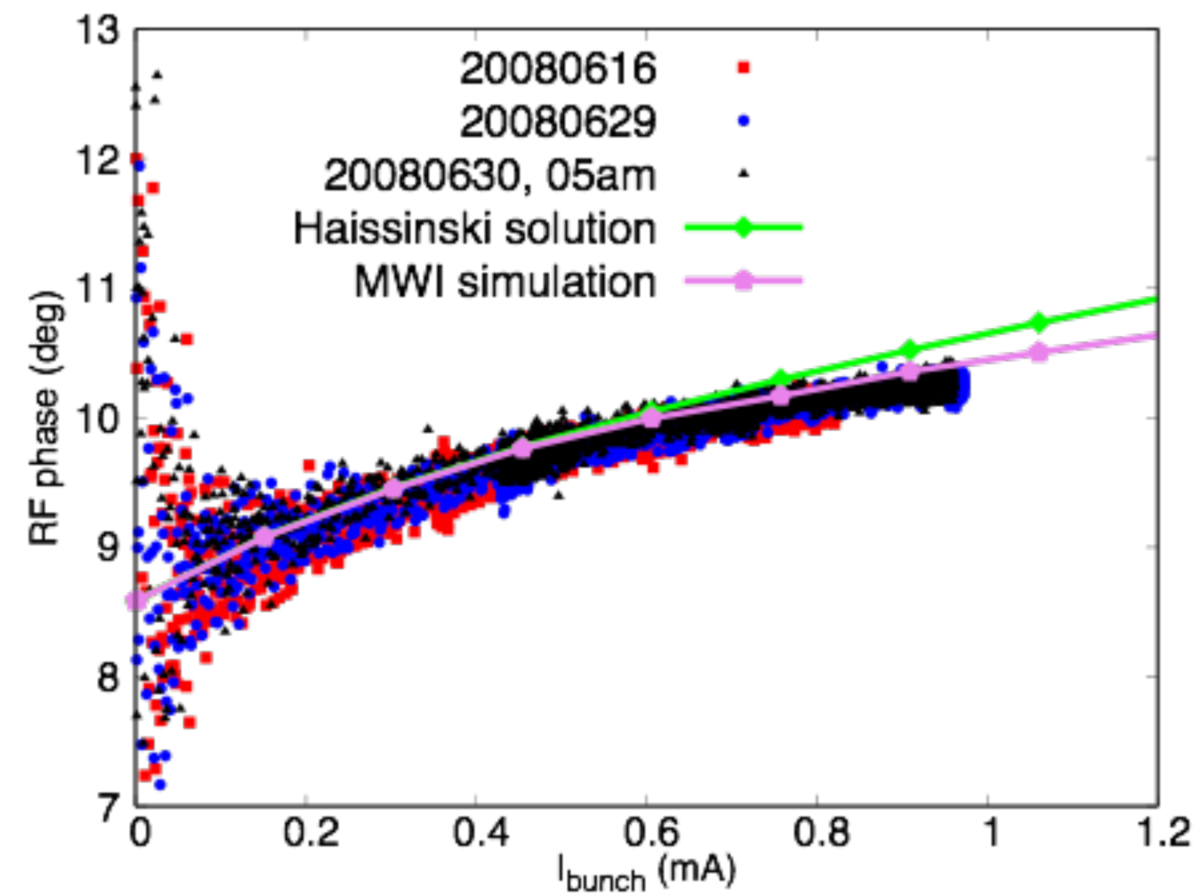


5. HOM power in KEKB LER

➤ **HOM power (E=3.128585 GeV, Vrf=7 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**

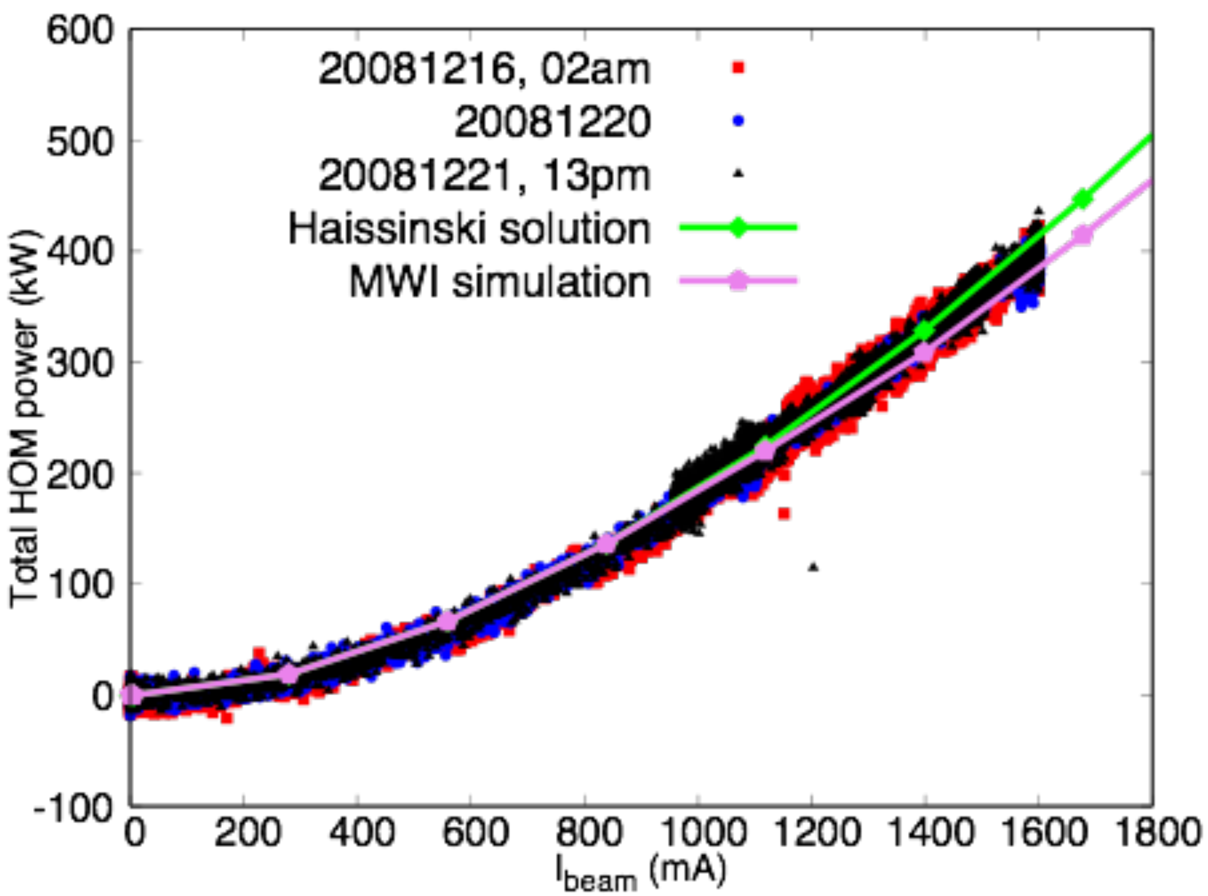


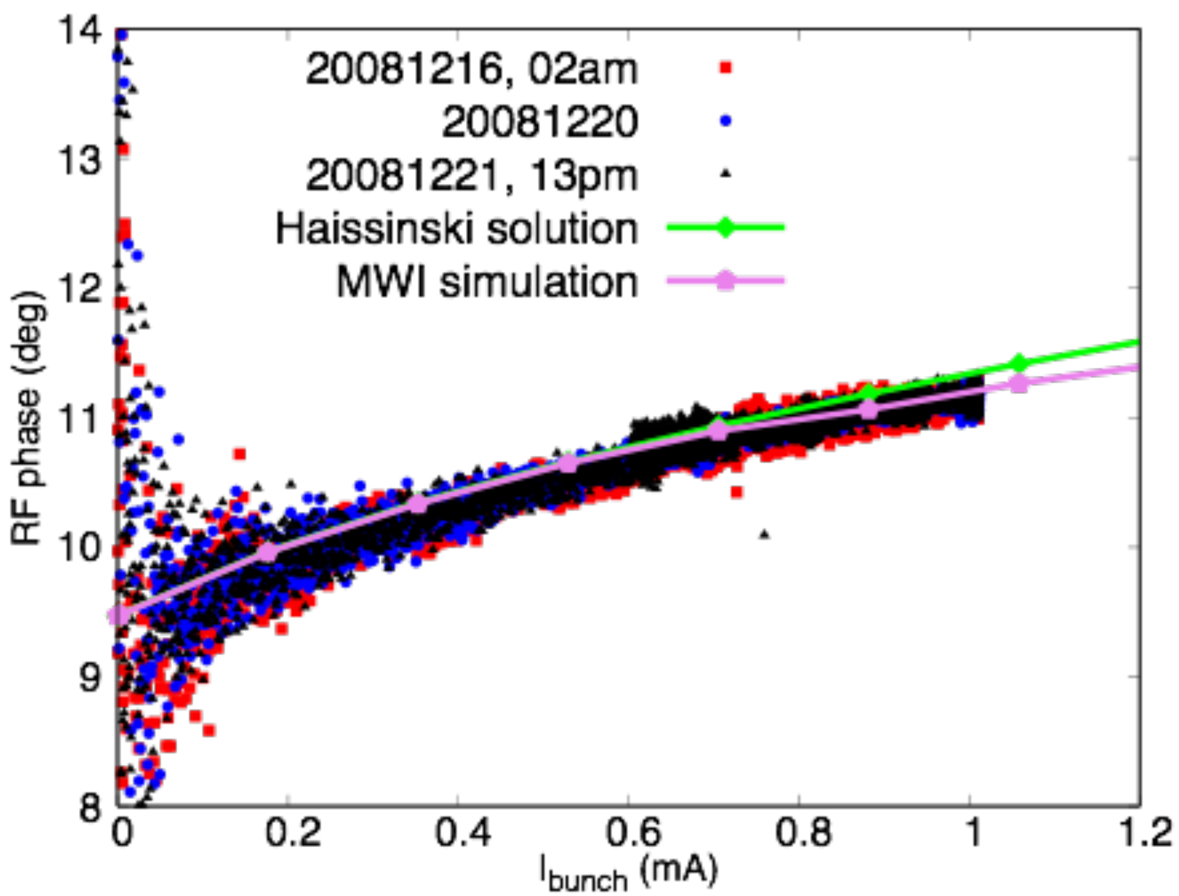


5. HOM power in KEKB LER

➢ **HOM power (E=3.314401 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**

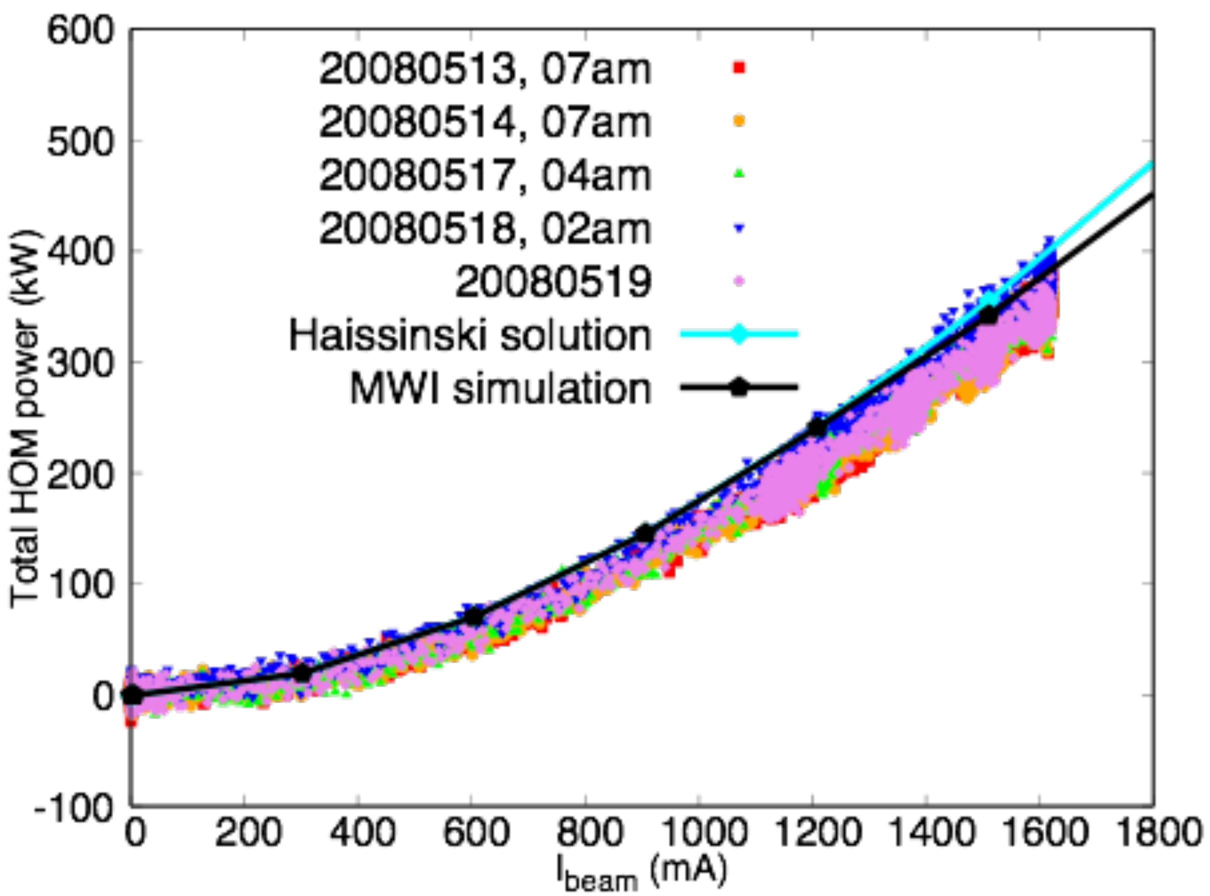


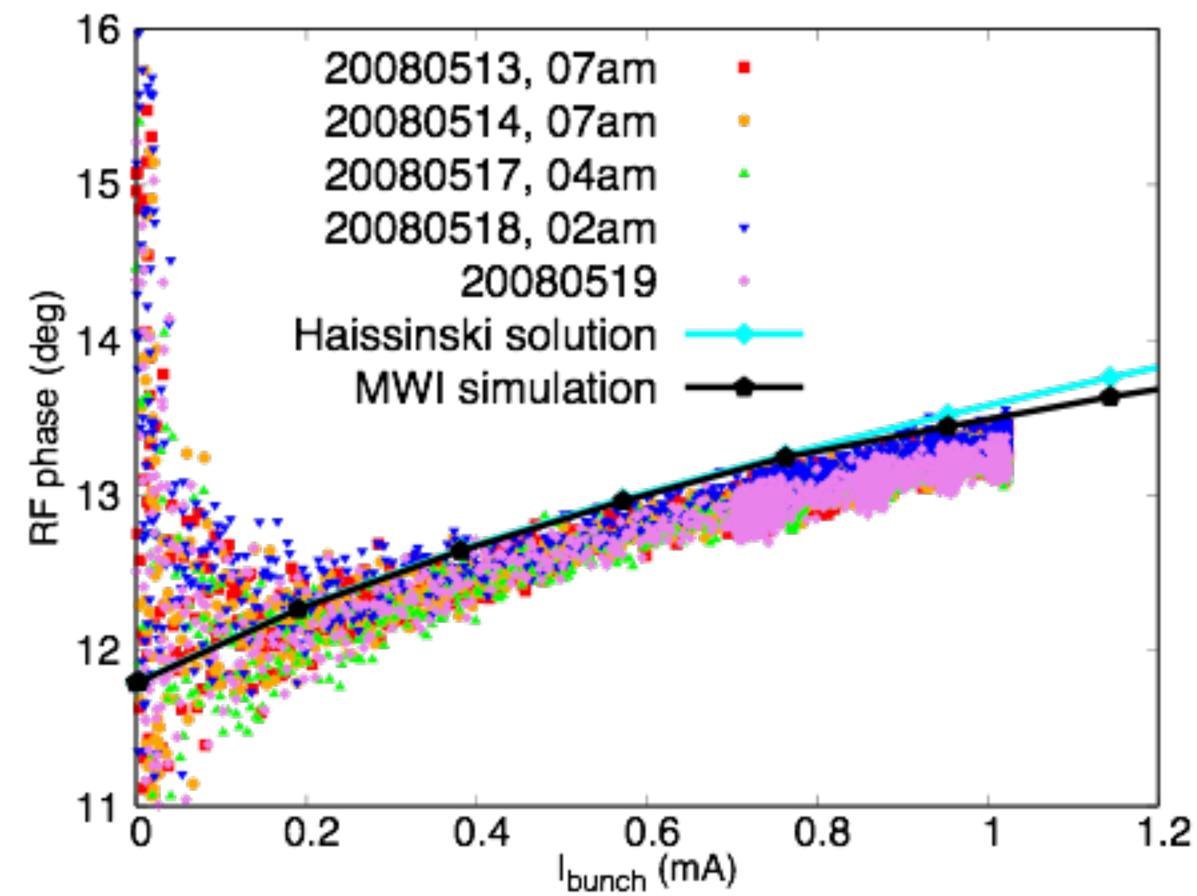


5. HOM power in KEKB LER

➤ **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?**

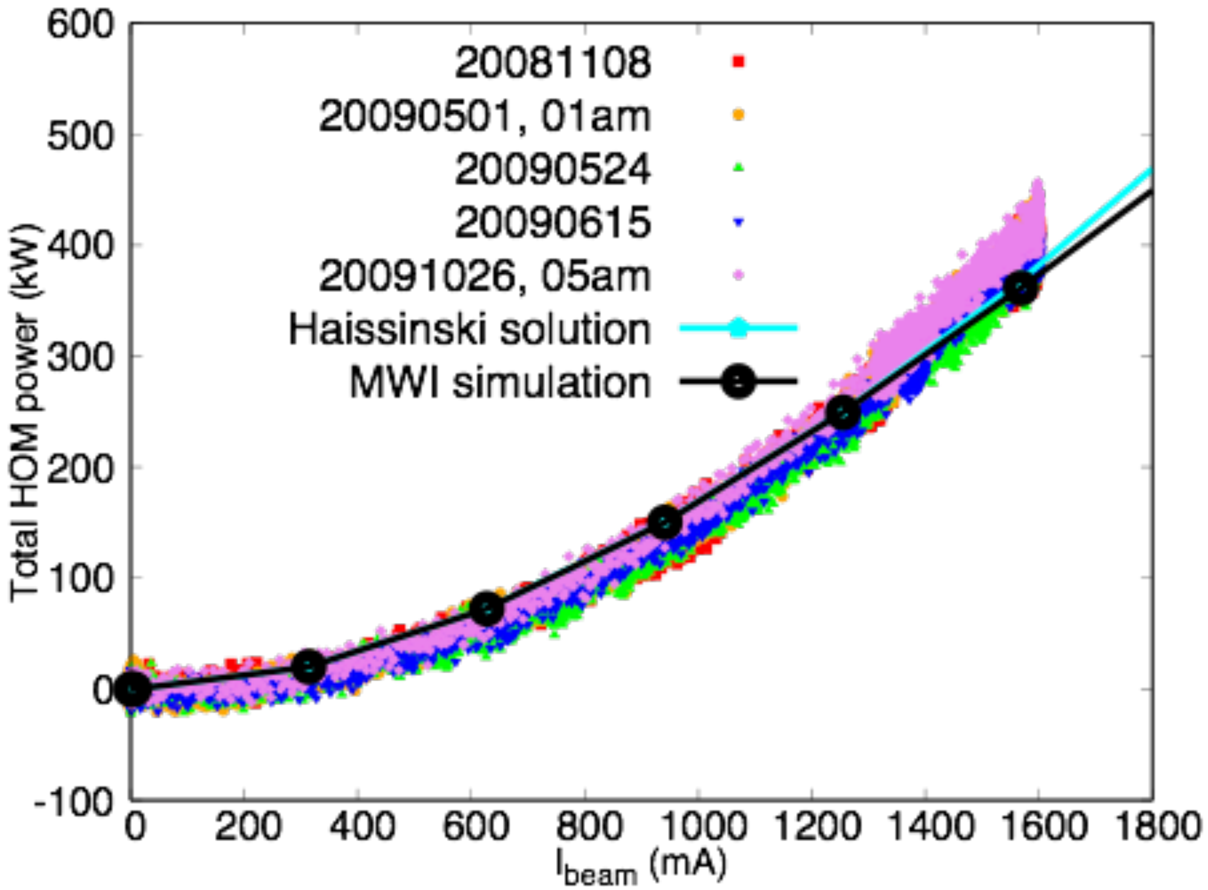


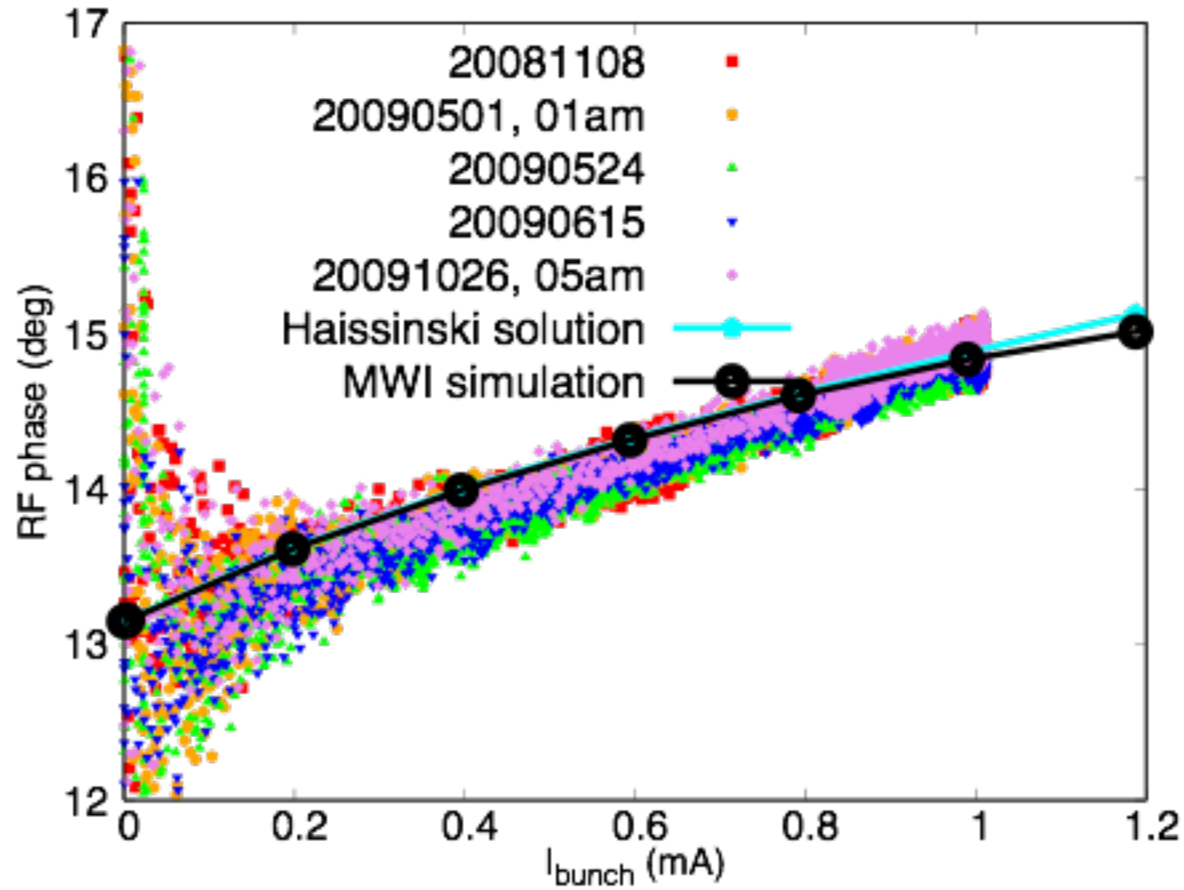


5. HOM power in KEKB LER

➤ HOM power (E=3.594074 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?





Conclusion

We have shown that for KEKB LER, beam phase vs *I* measurements of 2009 agree well with theoretical calculations

From klystron power measurements, we find good agreement to the phase measurements and the calculations, except at high beam energies—the reason is not presently understood. We believe at the moment that this is a problem of us not completely understanding the rf feedback system

The theoretical calculations were "bottom-up" wake calculations, where we numerically obtain the wakes for a short Gaussian bunch for the different vacuum chamber objects in the ring beginning with the chamber drawings, and including CSR. There are no fitting parameters.

CSR is a significant contributor to the pseudo-Green function, with the beam pipe shape being important—the parallel plate model yields a different threshold and bunch length variation with current, and the difference in the phase vs *I* curve is also significant.

The fact that there is good agreement between the phase calculations and measurements suggests that the ring broad-band impedance is well understood. This in spite of the complicated 3D nature of many objects

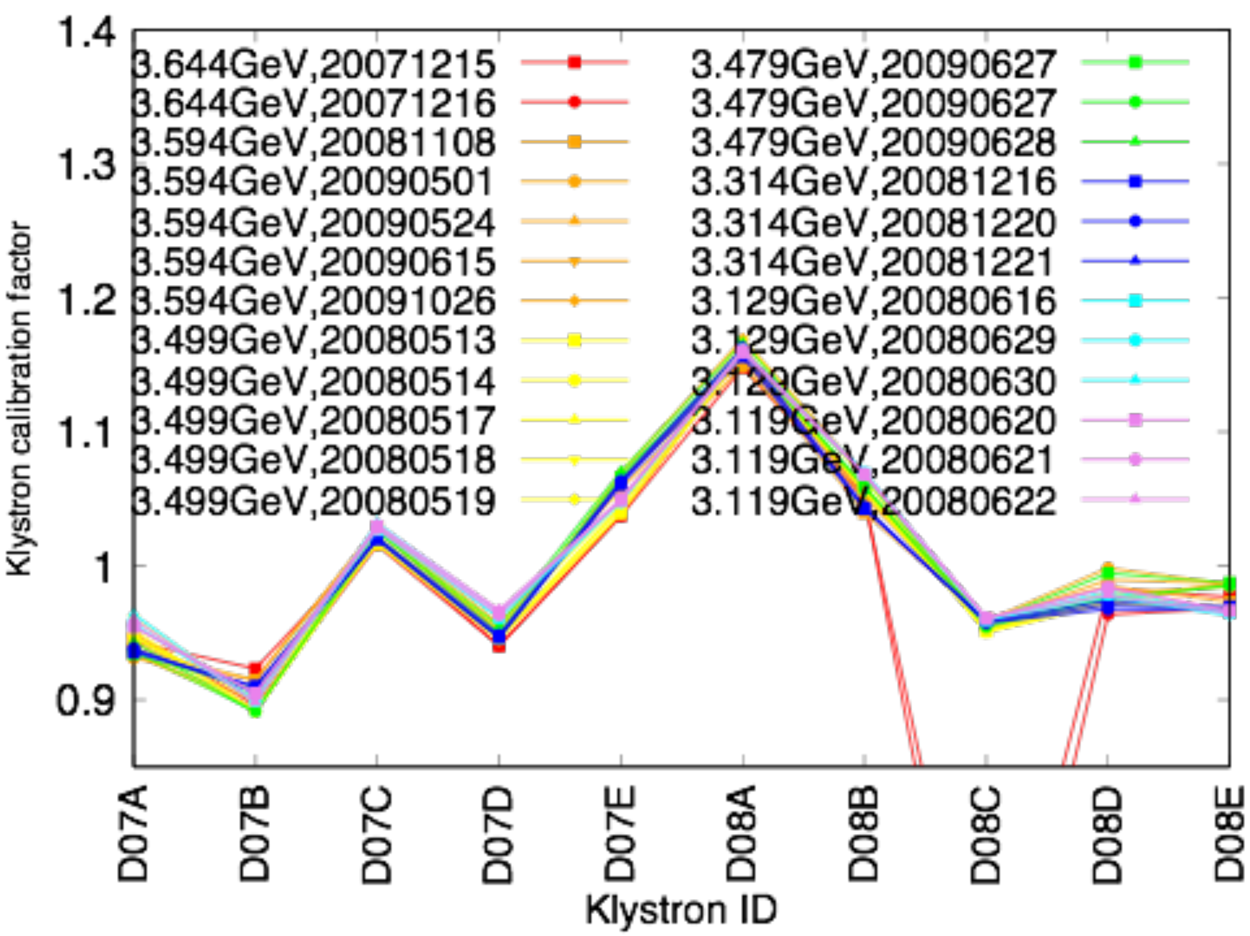
The calculated KEKB LER ring impedance is resistive in character, which is also indicated by the relative large slope in phase vs *I* measurements. These results disagree with earlier streak camera measurements that indicated a very inductive impedance (large bunch lengthening and small phase shift with *I*). We suspect that there were systematic errors in the streak camera measurements. We will try to resolve this discrepancy—which also exists for measurements on the (similar) SuperKEKB rings—once SuperKEKB restarts next year

Backup slides

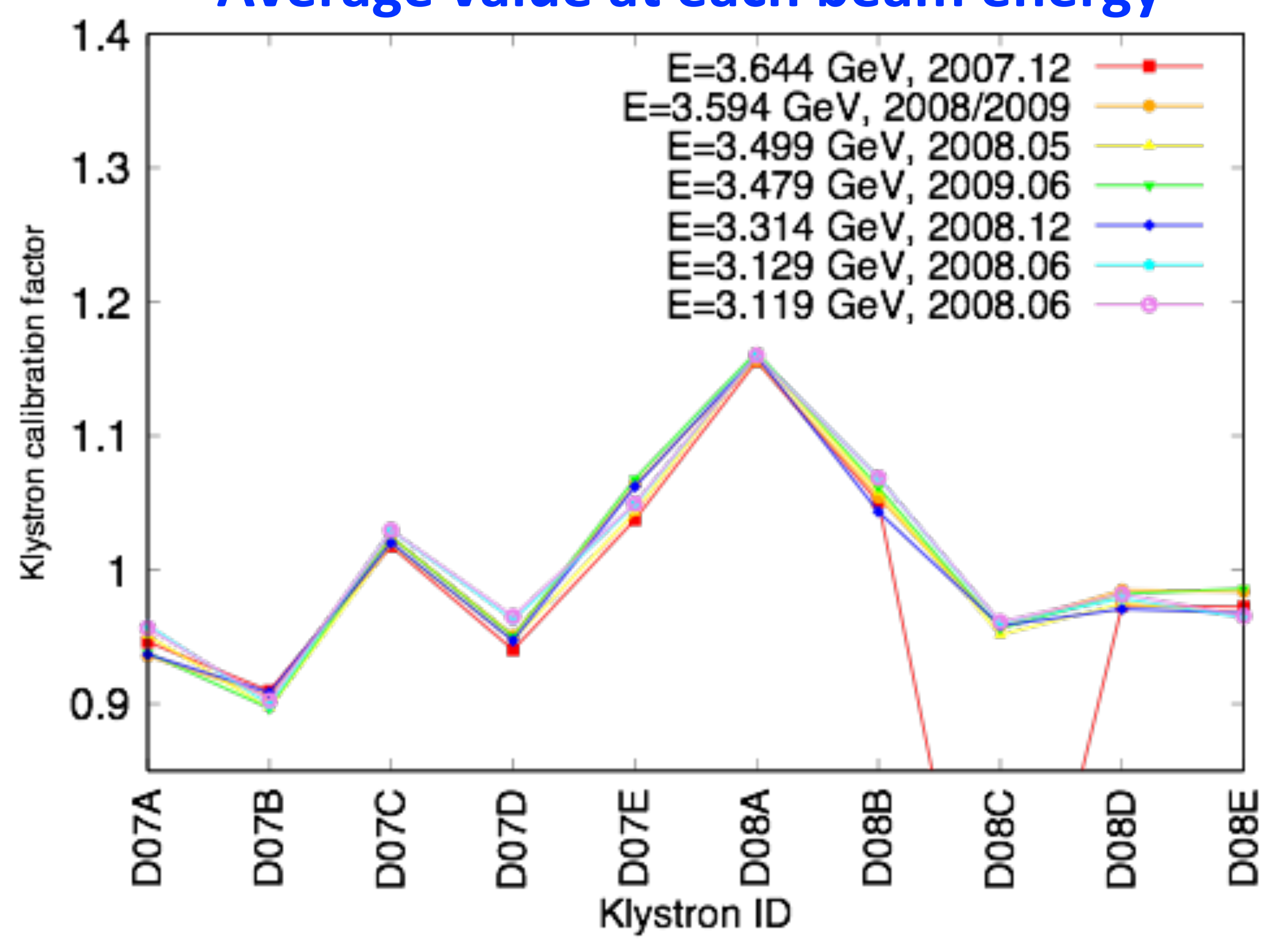
5. HOM power in KEKB LER

➤ Calibration factor for klystron output power

- Calculated from the power balance at zero beam current
- Vary by klystrons
- Larger than 1 for some klystrons
- Vary over time for each klystron?



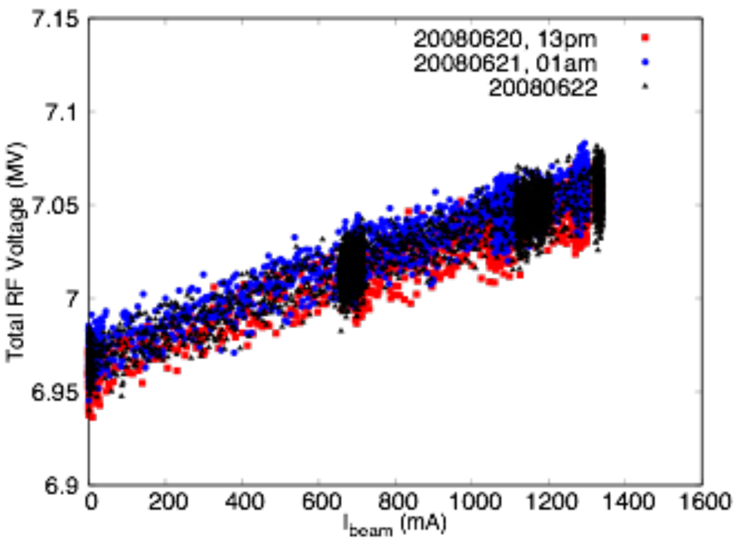
Average value at each beam energy

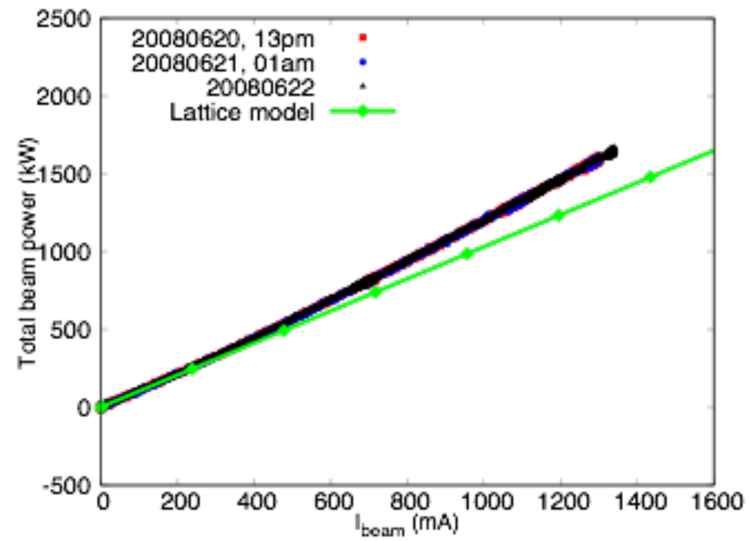


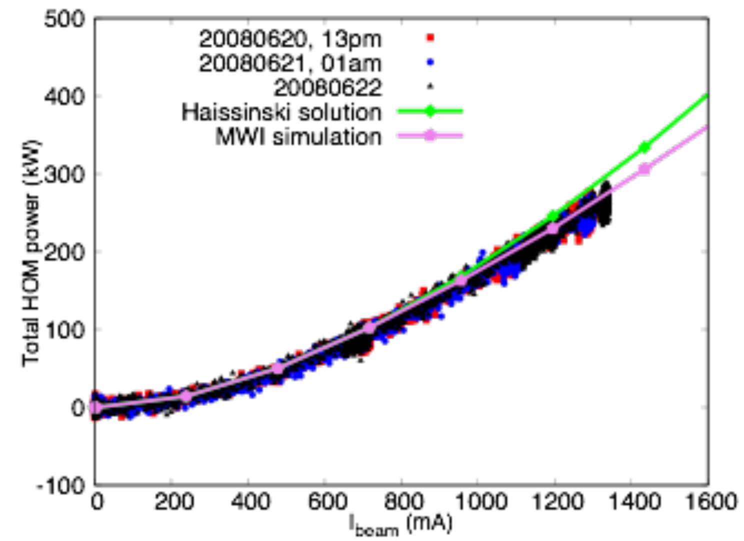
5. HOM power in KEKB LER

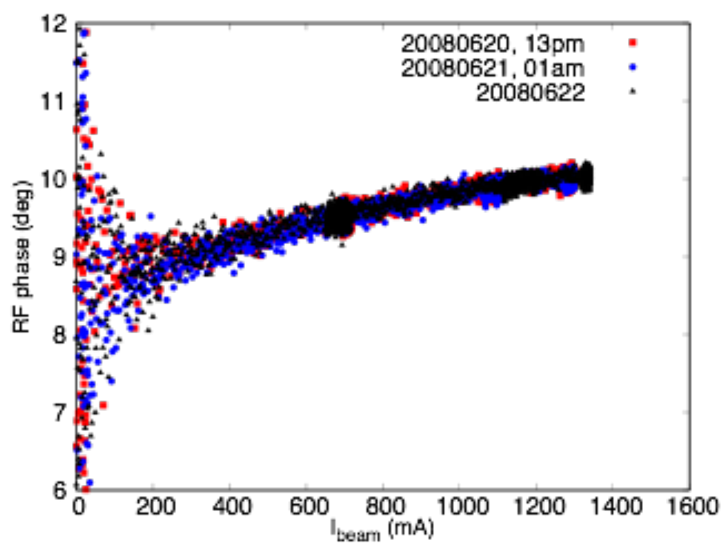
➢ HOM power (E=3.118663 GeV, Vrf=7 MV)

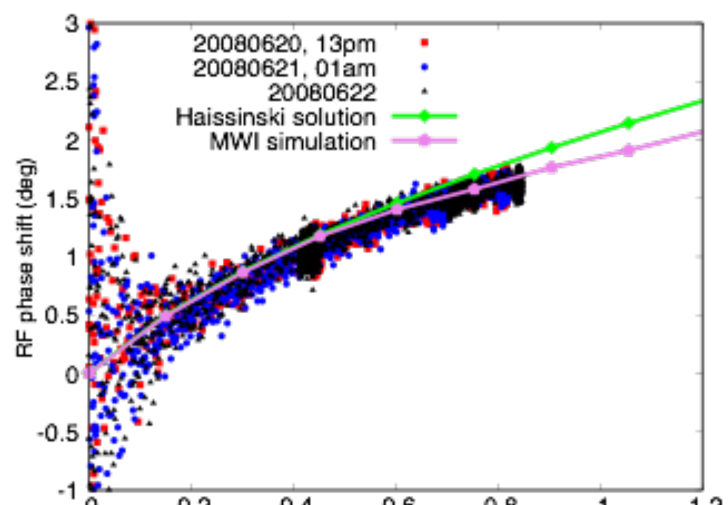
- **SR power calculated from lattice model**
- **Good reproducibility in beam power data**
- **Above MWI threshold: Additional drop in HOM power and RF phase due to energy spread increase**

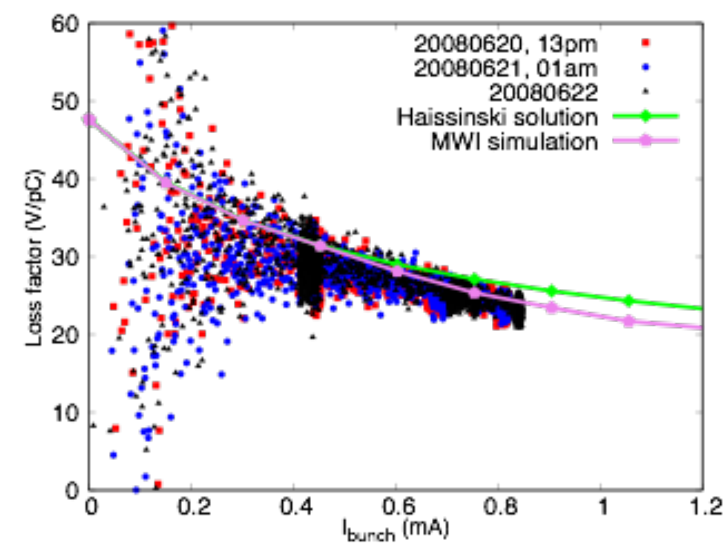












5. HOM power in KEKB LER

➤ HOM power (E=3.478613 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