Impedance Issues in SuperKEKB

D. Zhou

With contributions from

KEK: T. Abe, T. Ishibashi, Y. Morita, K. Shibata, Y. Suetsugu, M. Tobiyama, M. Yoshida, ...

SLAC: Y. Cai, G. Stupakov

The 19th KEKB Accelerator Review Committee, Mar. 03, 2014

Outline

- ➤ **Introduction**
  - **Machine parameters, Tasks definition, ...**
- ➤ **Impedance calculations**
  - **Modeling, Pseudo-Green wake function, ...**
- ➤ **Loss factors and HOM power**
- ➤ **Single-bunch effects**
  - **Longitudinal: Bunch lengthening, Potential-well distortion, MWI, ...**
  - **Transverse: Beam tilt, TMCI, ...**
- ➤ **Summary and Future plan**

1. Introduction: Machine parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.18×10^{-4}	4.53×10^{-4}		
σ_δ	$8.10(7.73)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

From http://www-superkekb.kek.jp/index.html

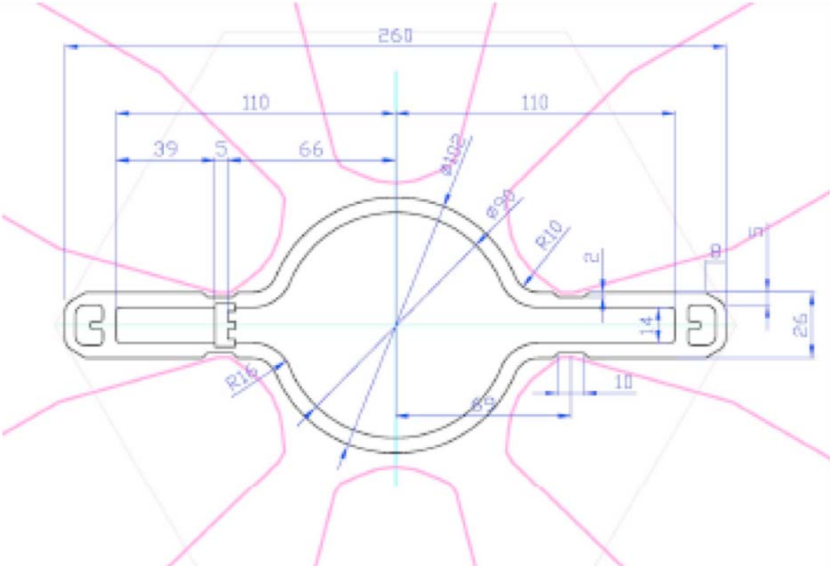
1. Introduction: Tasks on impedance issues

- **Impedance calculations**
  - **Tools: Analytical, GdfidL, CST particle studio, ABCI, ...**
  - **Pseudo-Green wake function: σ_z=0.5mm**
- **HOM heating**
  - **Loss factors and HOM power**
  - **Heating load and its impact on vacuum components**
- **Single-bunch collective effects**
  - **Longitudinal: Bunch lengthening, potential-well distortion, MWI**
  - **Transverse: Beam tilt, TMCI (mainly y-direction)**
- **Multi-bunch collective effects**
  - **Multi-bunch transverse instability (mainly due to resistive wall impedance)**

2. Impedance calculations: Modeling

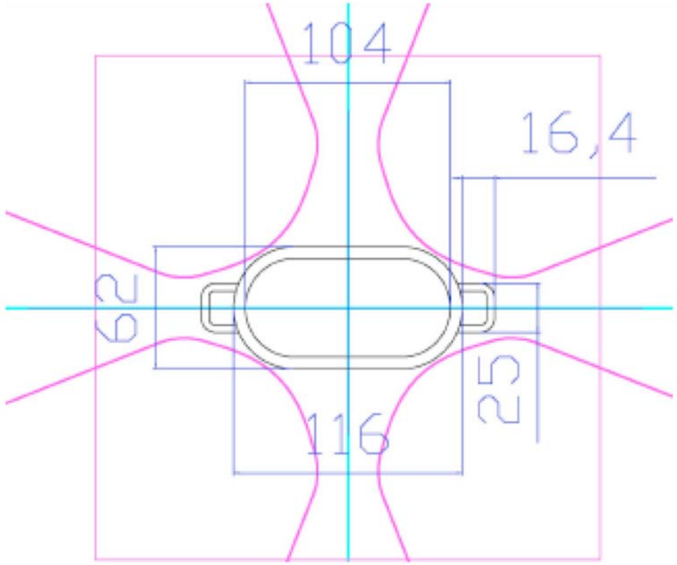
LER typical (~90%)

Aluminum w/ antechamber

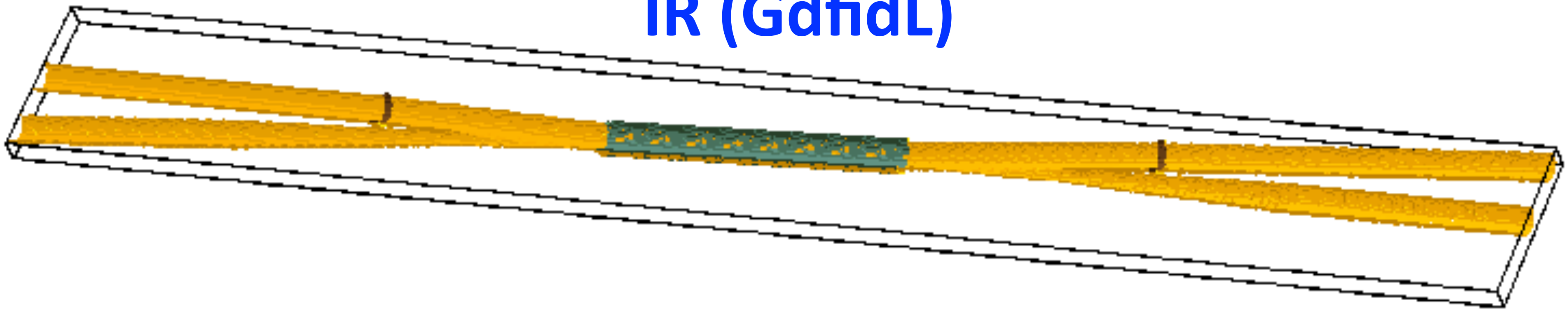


HER typical (~70%)

Copper w/o antechamber



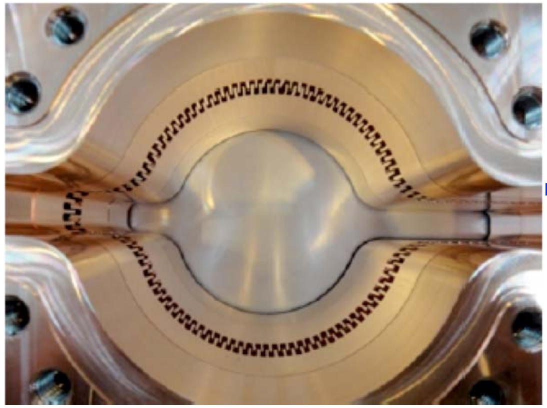
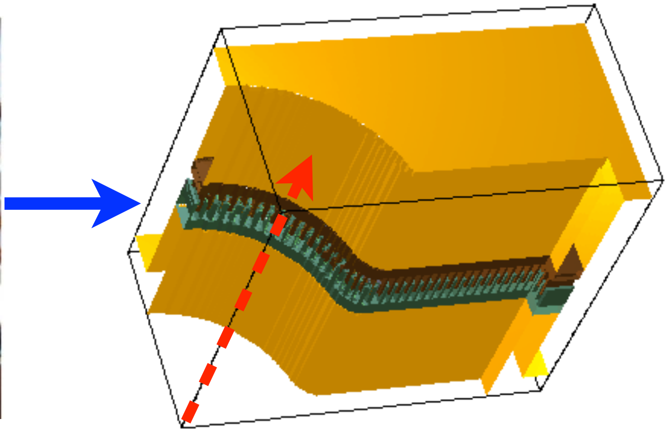
IR (GdfidL)



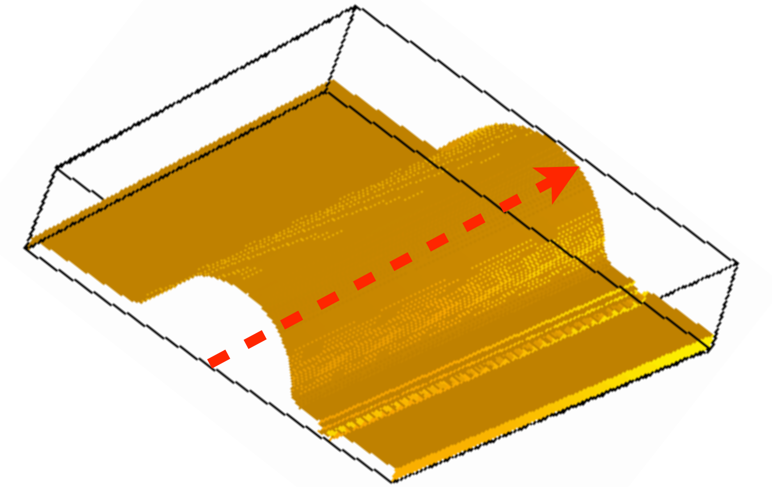
From Y. Suetsugu and K. Shibata

2. Impedance calculations: Modeling: LER

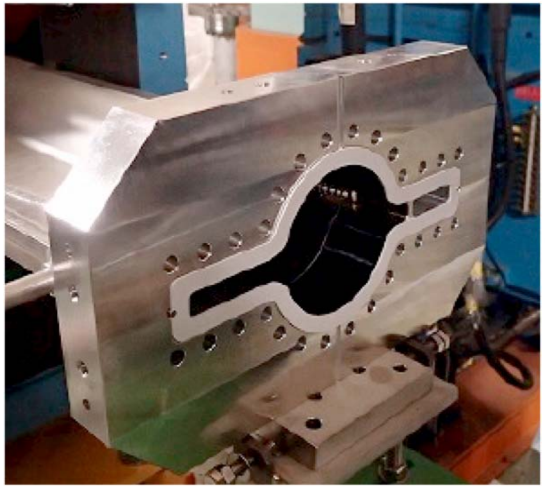
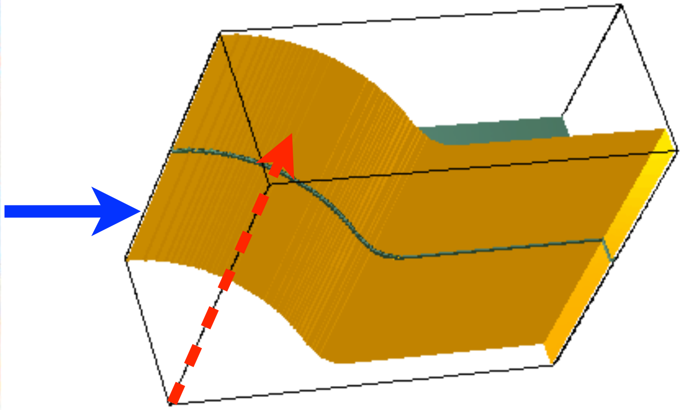
Bellows

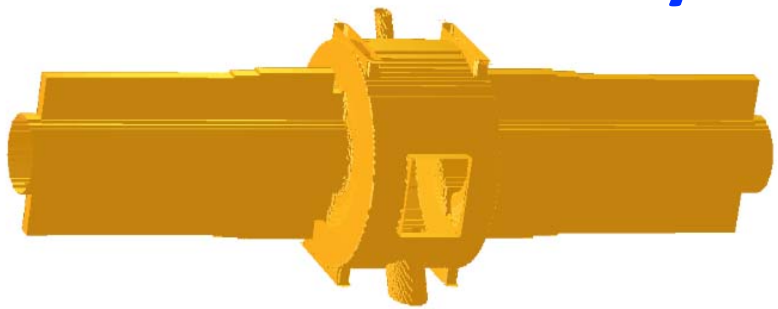
Pumping port



MO-type flange

ARES RF cavity

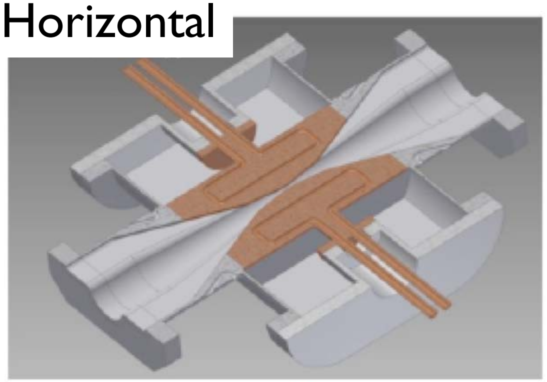


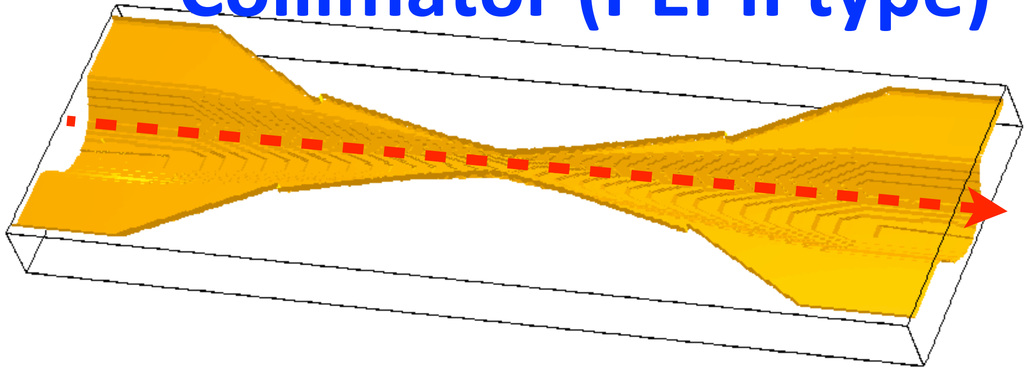
From T. Abe and K. Shibata

2. Impedance calculations: Modeling: LER

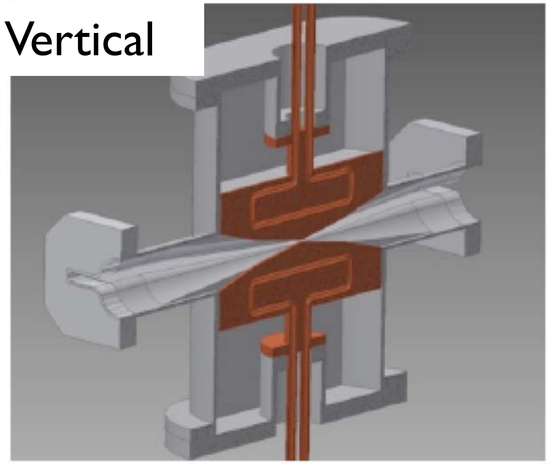
Collimator (PEPII type)

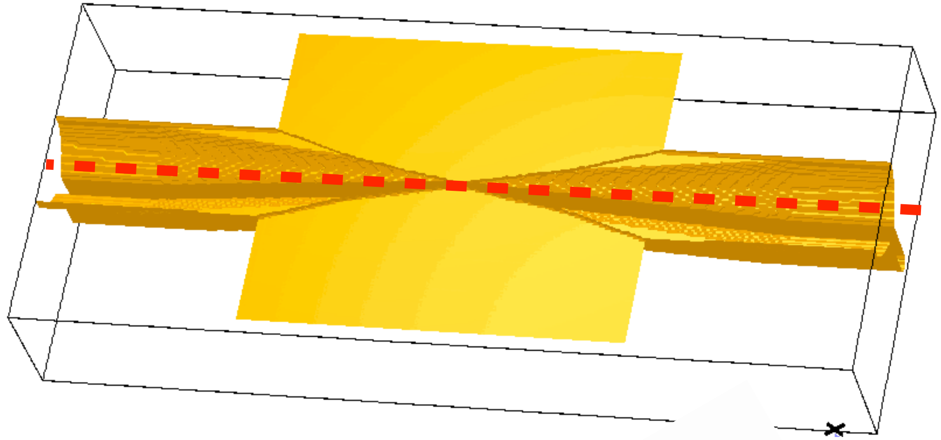
Horizontal



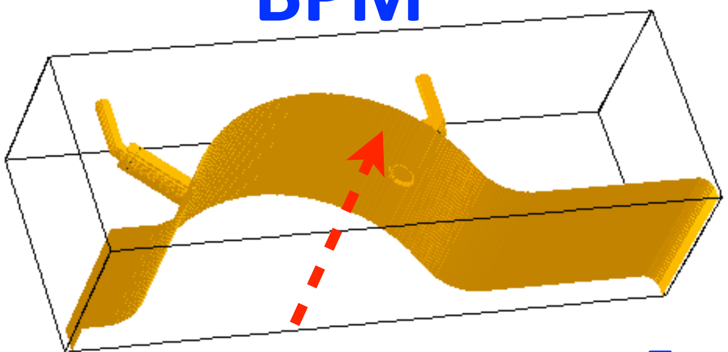


Vertical

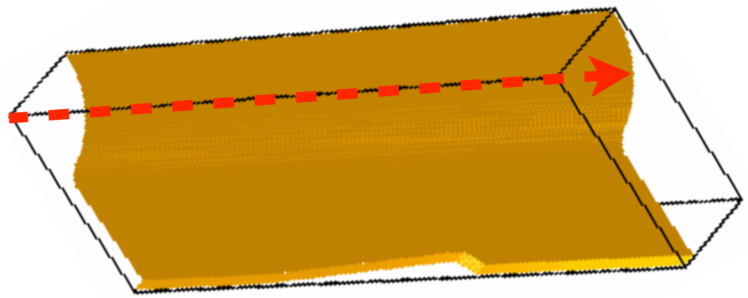




BPM



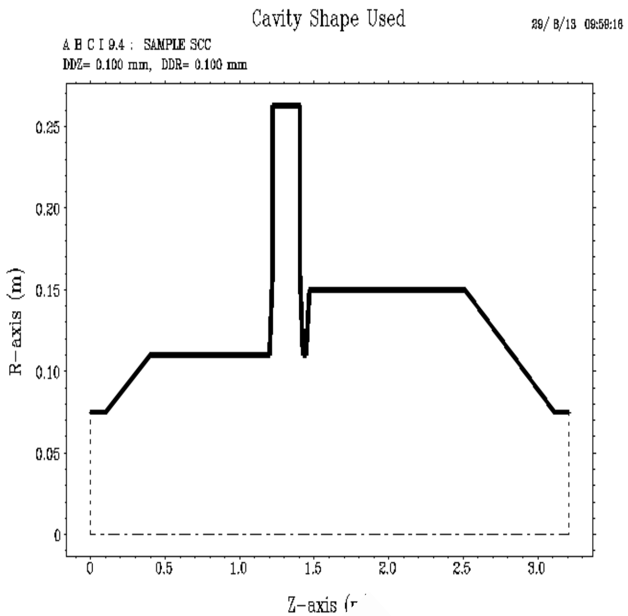
SR mask



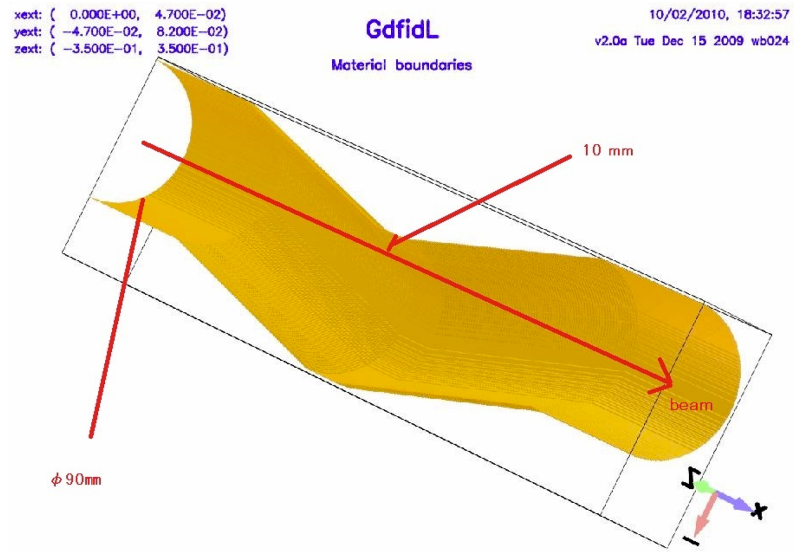
From T. Ishibashi, M. Tobiyama, and K. Shibata

2. Impedance calculations: Modeling: HER

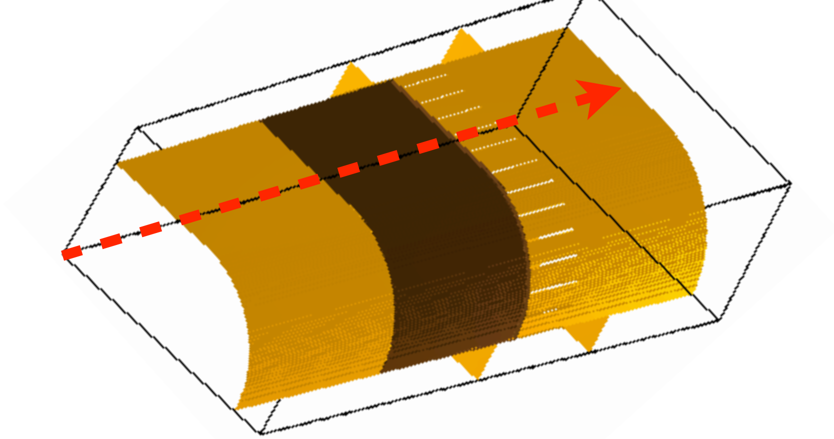
SCC (by ABCI)



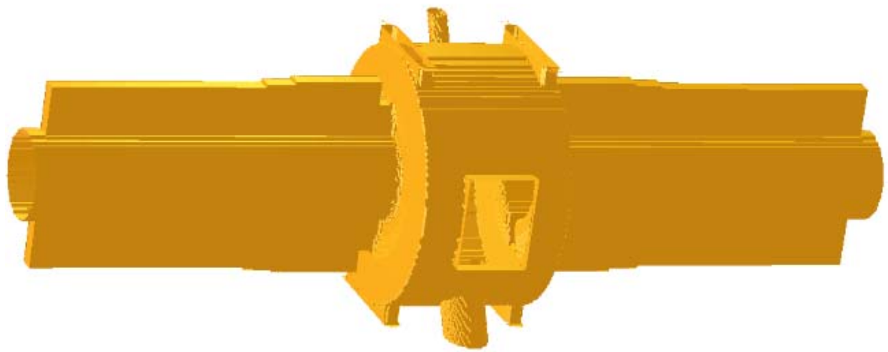
Movable mask (KEKB type)



Bellows



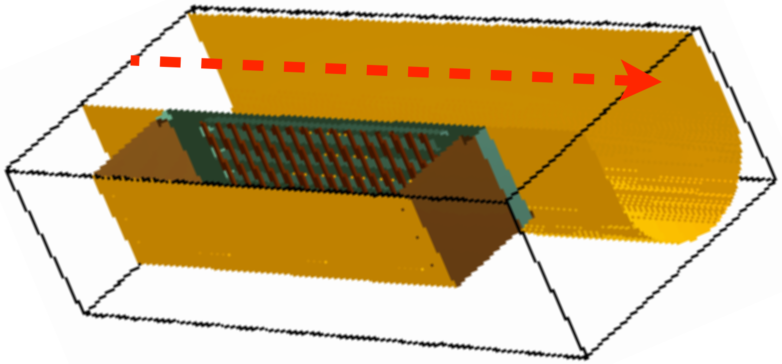
ARES



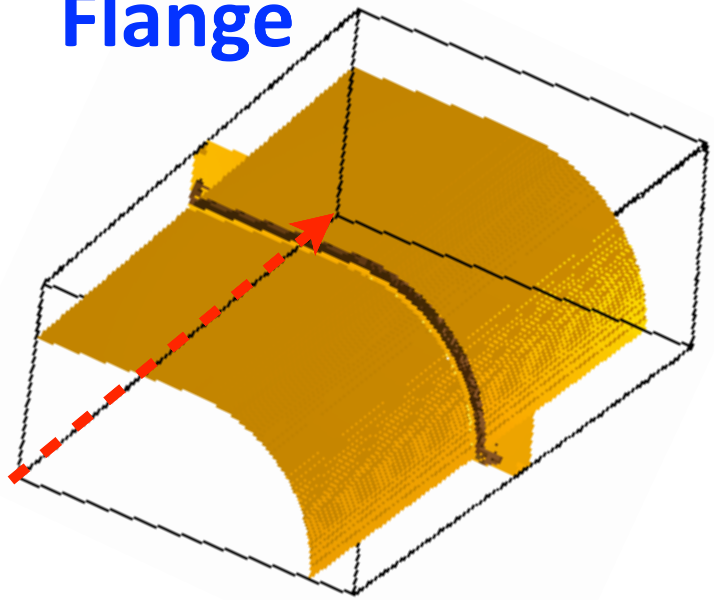
From T. Abe, Y. Morita, and K. Shibata

2. Impedance calculations: Modeling: HER

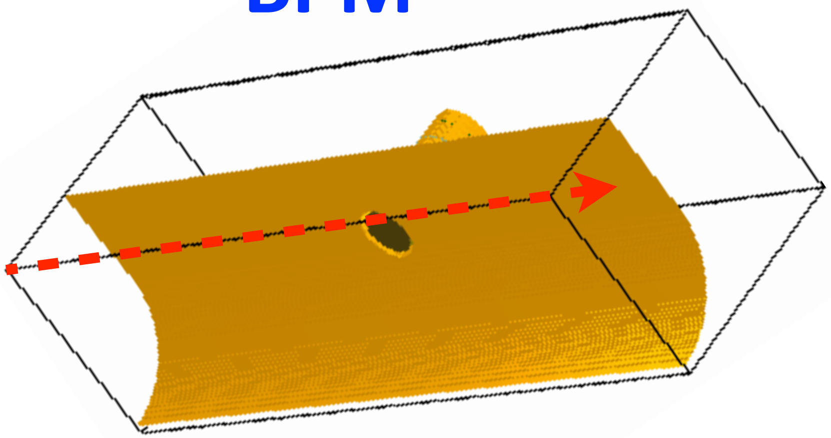
Pumping port



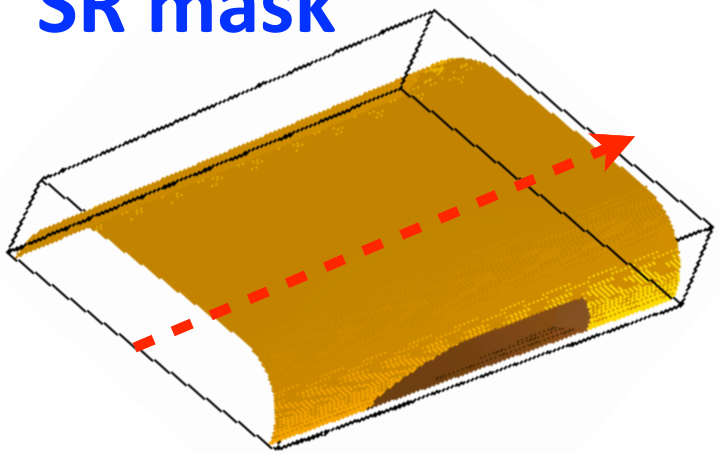
Flange



BPM



SR mask

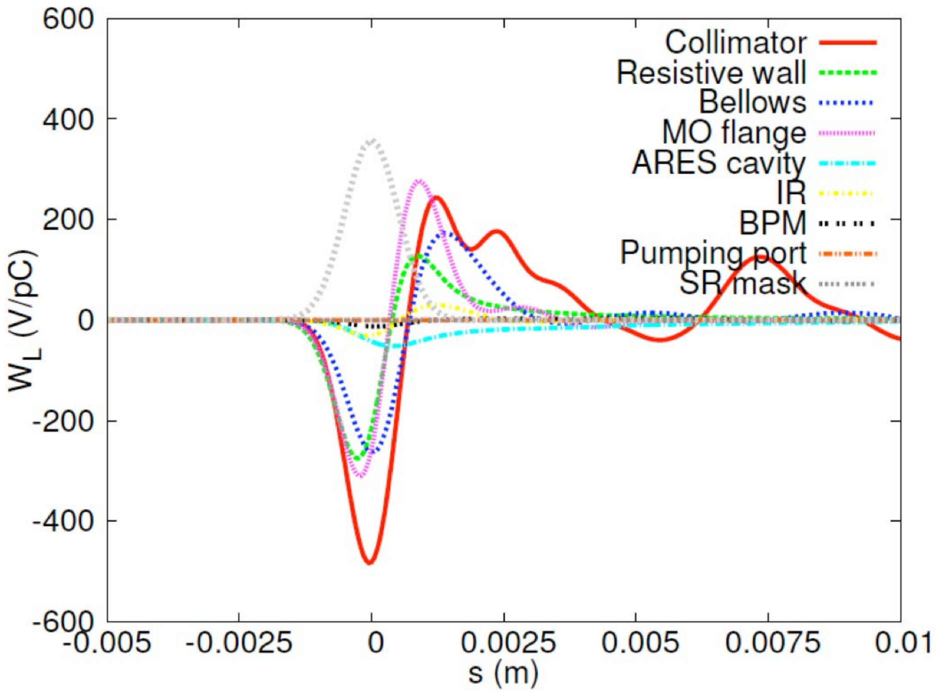


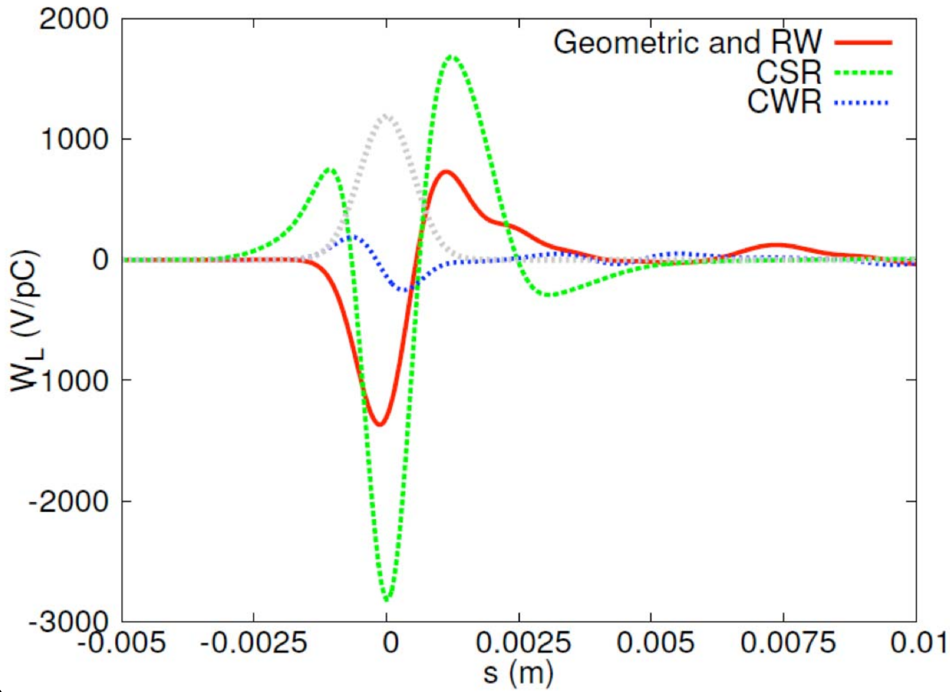
From K. Shibata and M. Tobiyama

2. Impedance calculations: Results: LER

➤ Pseudo-Green wake function

- σ_z=0.5mm
- Pumping ports and SR masks are negligible sources
- CSR and CWR (Wiggler radiation): CSRZ code with rectangular chamber
- Not considered yet: Gate valves, BxB FB BPMs, Grooves surface, Clearing electrodes

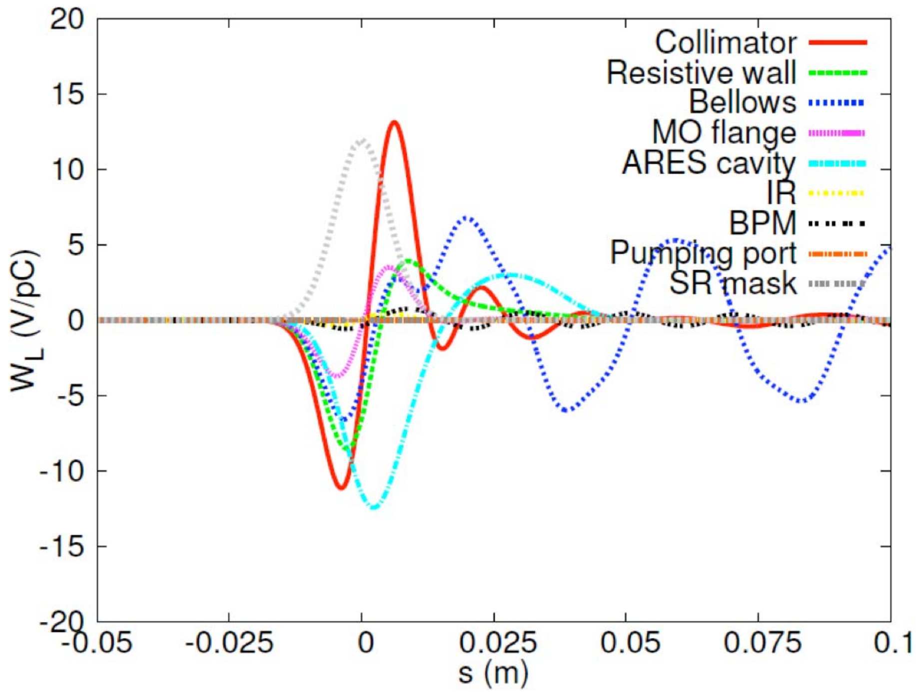


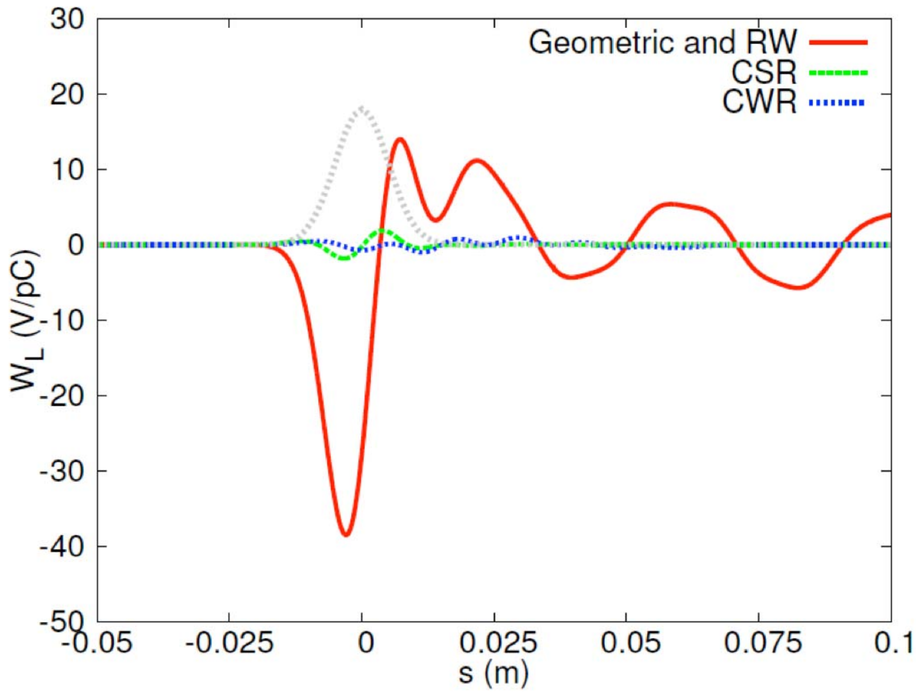


2. Impedance calculations: Results: LER

➤ **Wake potential with nominal bunch length**

- **σ_z=5mm**
- **Main sources: Collimators, Resistive wall, ARES cavity, Bellows, MO flanges**
- **CSR and CWR are not strong if no microbunching happens**

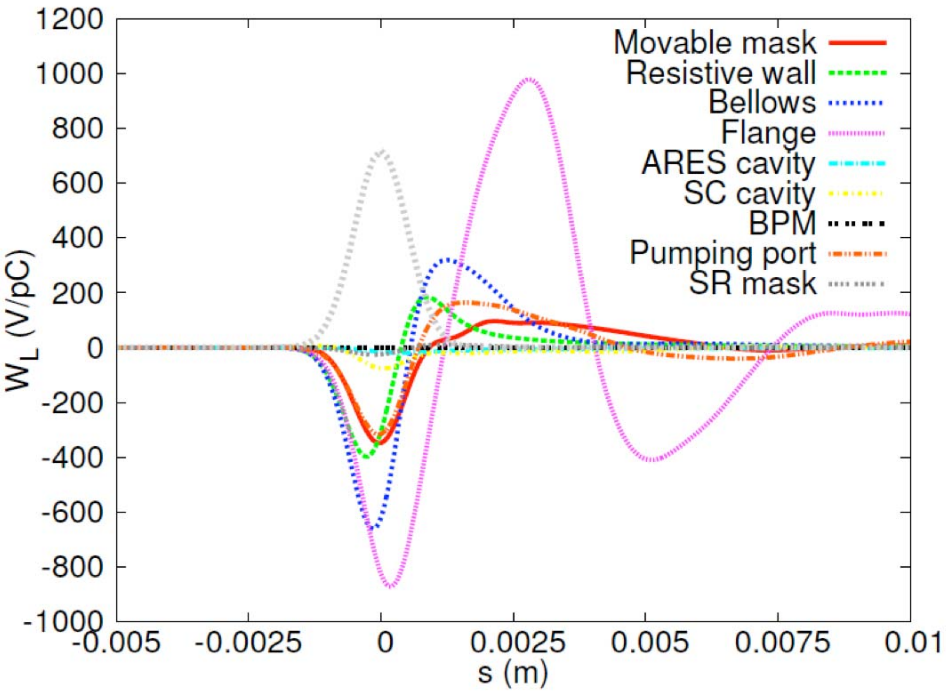


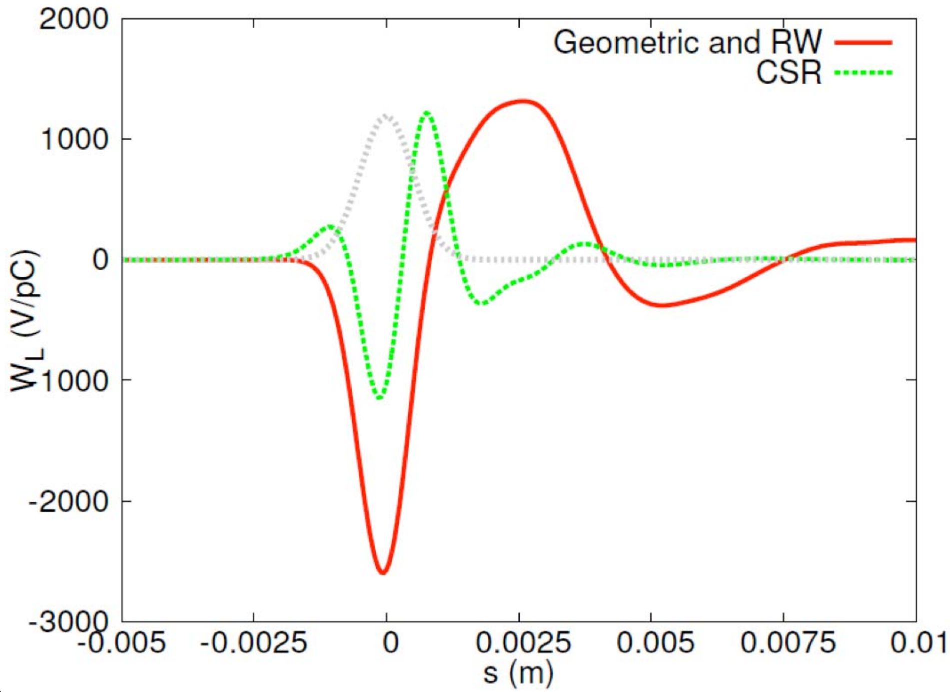


2. Impedance calculations: Results: HER

➤ **Pseudo-Green wake function**

- σ_z=0.5mm
- CSR: CSRZ code with rectangular chamber
- CWR (Wiggler radiation) not considered yet
- Not considered yet: Gate valves, Tapers, BxB FB BPMs

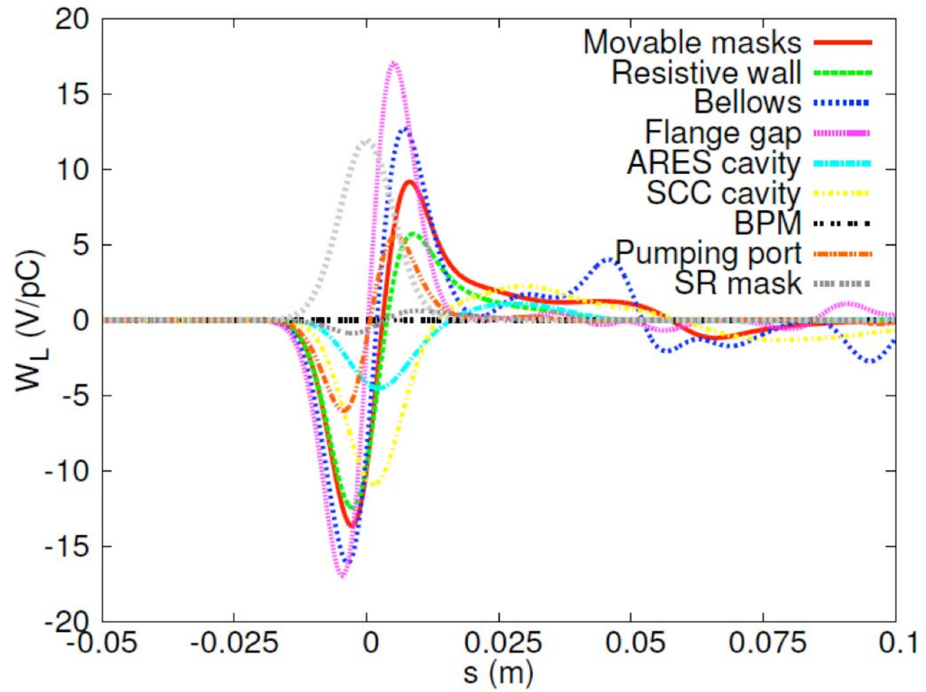


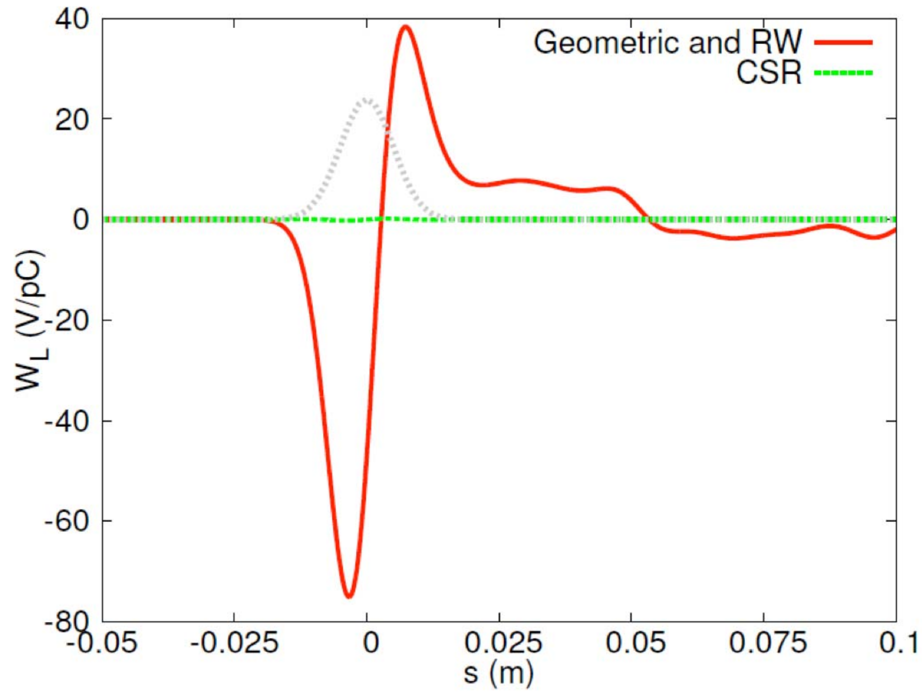


2. Impedance calculations: Results: HER

➤ **Wake potential with nominal bunch length**

- σ_z=5mm
- Important sources: Movable masks, Resistive wall, Flange gaps, Bellows, SCC cavities, ARES cavities, Pumping port
- CSR is weak if no microbunching happens





3. Loss factors and HOM power: LER

- Main results with σ_z=6mm for LER:
  - Total loss factor: ~20 V/pC
  - Total HOM power at full current: ~1000 kW

Component	k^{*1} [V C^{-1}] (per 1 m)	Number of Items	Total k [V C^{-1}]	P_1 [kW]
Resistive Wall*2	1.1×10^9	3000 m	3.3×10^{12}	170
Pumping Holes	4.3×10^2	2400 m	1.0×10^6	5.2×10^{-5}
Flange	1.5×10^7	2000	3.0×10^{10}	1.6
Bellows chamber	3.0×10^9	1000	3.0×10^{12}	160
SR Mask*3	1.8×10^{-3}	1000	1.8×10^3	9.3×10^{-8}
Gate Valves	3.0×10^9	47	1.4×10^{11}	7.3
Collimators*	$4.0\times10^{10*}$	13	5.0×10^{11}	26
Taper	3.8×10^8	50	1.9×10^{10}	0.99
BPM	1.6×10^8	450	7.2×10^{10}	3.7
B×B FB BPM	5.9×10^8	10	5.9×10^9	0.31
FB kicker	5.0×10^{11}	1	5.0×10^{11}	26
Grooved surface	2.6×10^8	520 m	1.4×10^{11}	7.2
Clearing electrode	1.1×10^9	150 m	1.7×10^{11}	8.8
IR Chamber	8.0×10^8	1	8.0×10^8	0.041
Cavity (ARES)	4.4×10^{11}	22	9.7×10^{12}	500
Total			$\sim20\times10^{12}$	~1000

From Y. Suetsugu

3. Loss factors and HOM power: HER

- **Main results with σ_z=6mm for HER:**
  - **Total loss factor: ~30 V/pC**
  - **Total HOM power at full current: ~800 kW**

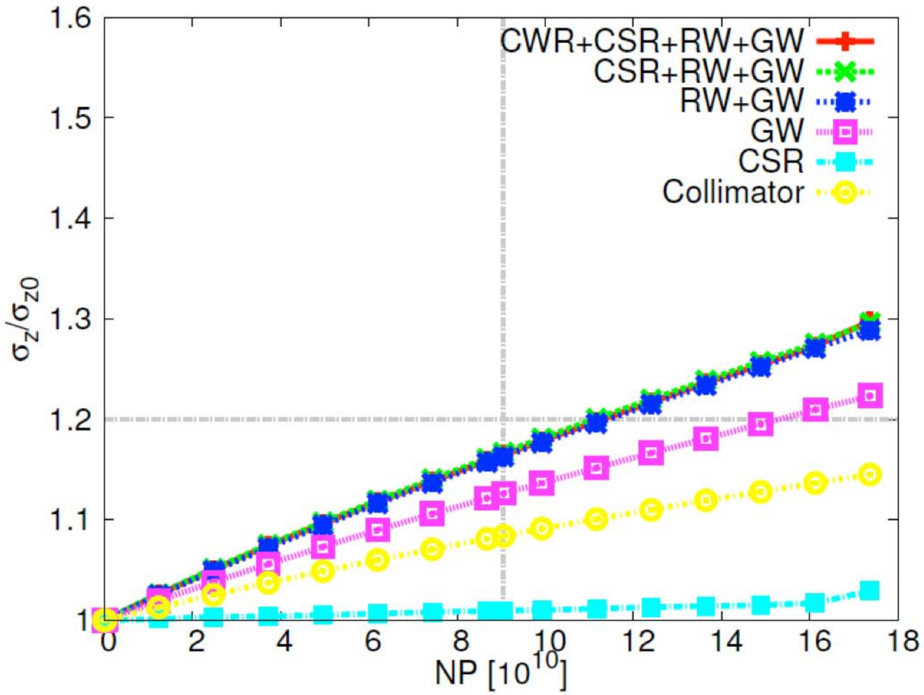
Component	k[*1] [V C^{-1}] (per 1 m)	Number of Items	Total k [V C^{-1}]	P_l [kW]
Resistive Wall [*]	1.4×10^{9}	3000 m	4.2×10^{12}	110
Pumping Holes	7.0×10^{7}	1000	7.0×10^{10}	1.9
Flange	3.0×10^{8}	2000	6.0×10^{11}	16
Bellows chamber	3.0×10^{9}	1000	3.0×10^{12}	81
SR Mask[*3]	2.5×10^{8}	1000	2.5×10^{11}	6.8
Gate Valves	3.0×10^{9}	41	1.2×10^{11}	3.2
Collimators[*4]	2.3×10^{11}	16	3.7×10^{12}	100
Taper	3.8×10^{8}	20	7.6×10^{9}	0.21
BPM	1.6×10^{8}	450	7.2×10^{10}	1.9
B×B FB BPM	5.9×10^{8}	10	5.9×10^{9}	0.16
FB kicker	5.0×10^{11}	1	5.0×10^{11}	14
IR Chamber	8.0×10^{8}	1	8.0×10^{8}	0.022
Cavity (ARES)	4.4×10^{11}	8	3.5×10^{12}	95
Cavity (SCC)	1.4×10^{12}	8	1.1×10^{13}	300
Total			$\sim30\times10^{12}$	~800

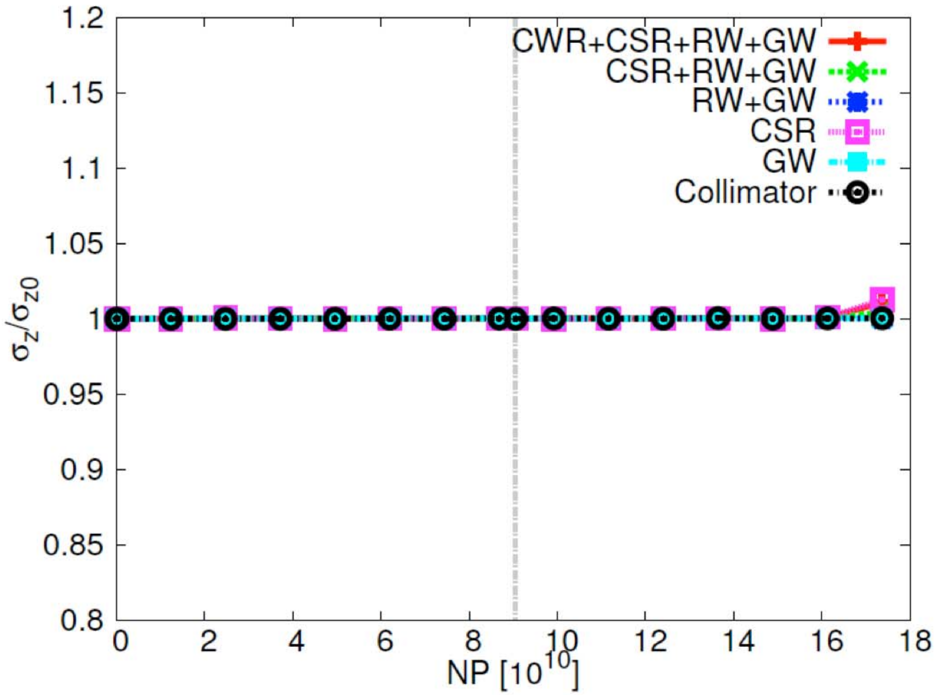
From Y. Suetsugu

4. Single-bunch effects: Longitudinal: LER

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

- **Use Cai-Warnock's VFP solver**
- **Collimators are important sources in bunch lengthening**
- **Simulated $\sigma_z \approx 5.8$mm @Design bunch current**
- **Simulated MWI threshold is around NP_{th}=17.E10**
- **CSR and CWR are likely to be not important. BUT ...**

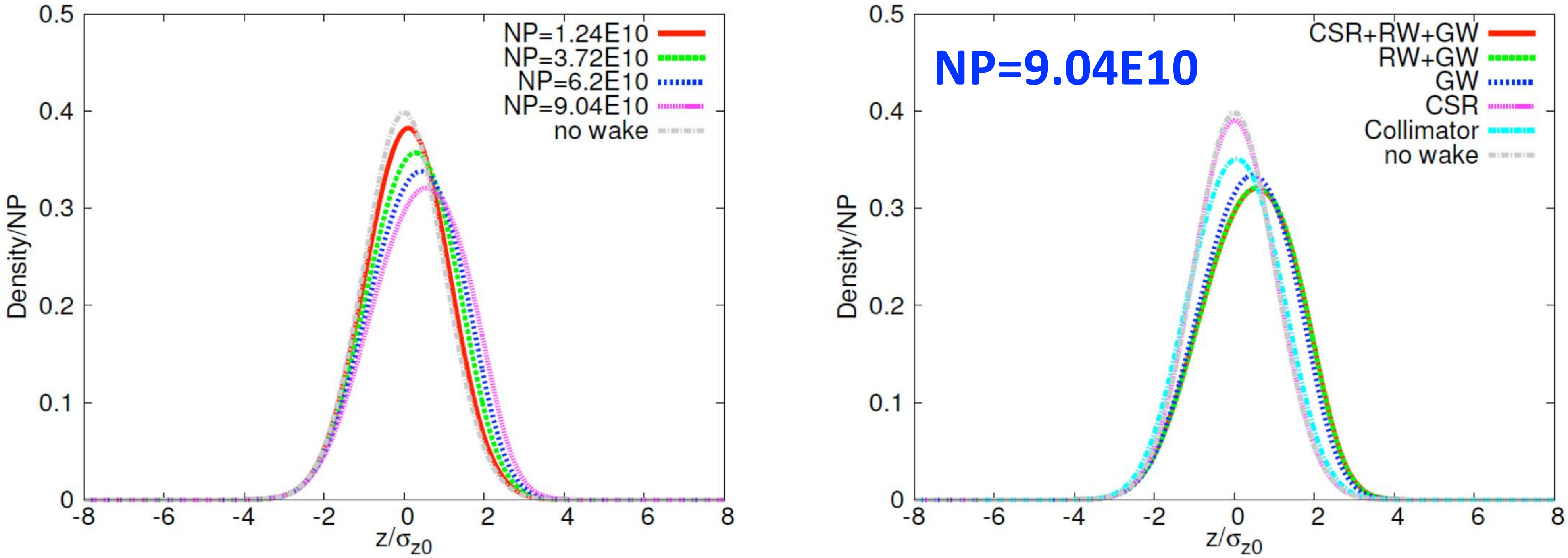




4. Single-bunch effects: Longitudinal: LER

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

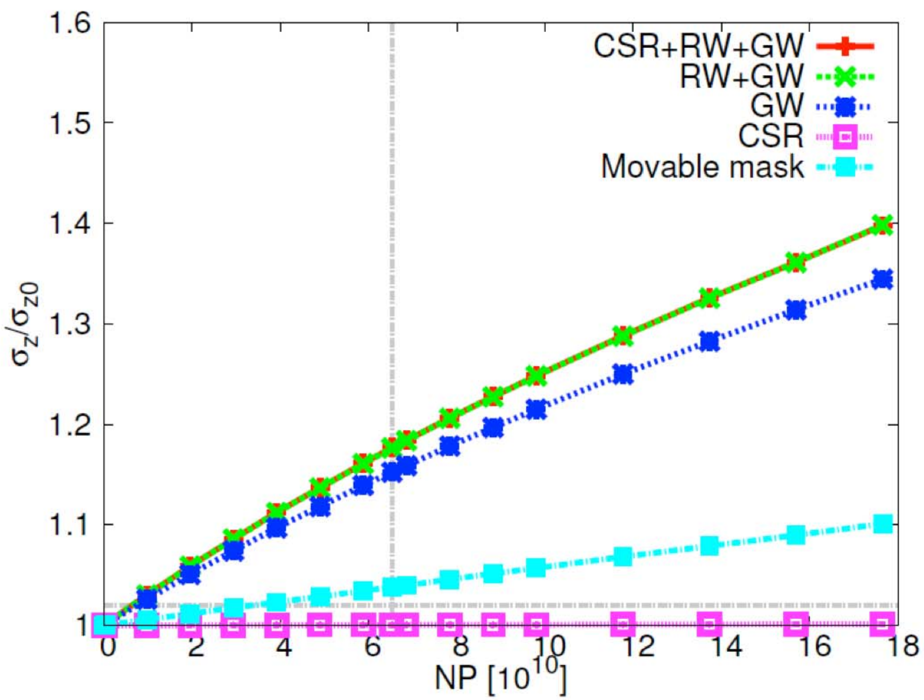
- **BUT, pseudo-Green wakes for CSR, CWR and RW are not good choices. => To be improved.**
- **Potential-well distortion => Longitudinal beam tilt => Impact on luminosity to be evaluated**

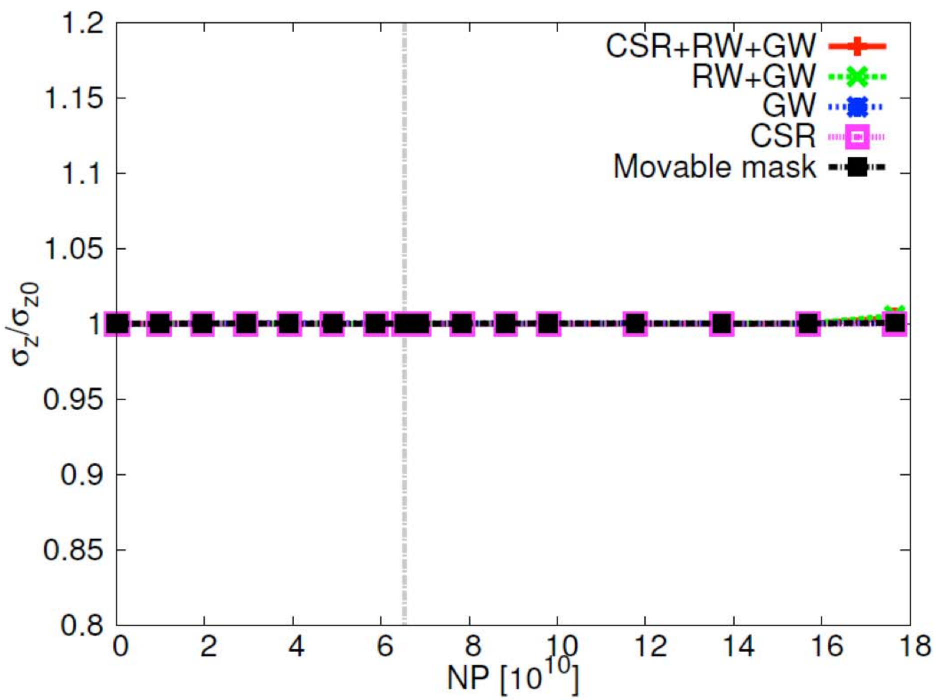


4. Single-bunch effects: Longitudinal: HER

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

- **Use Cai-Warnock's VFP solver**
- **Movable mask: KEKB-type model used => To be improved**
- **Simulated $\sigma_z \approx 5.8$mm @Design bunch current**
- **Simulated MWI threshold is around NP_{th}=17.E10**
- **CSR and CWR are likely to be not important.**





4. Single-bunch effects: Longitudinal: HER

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

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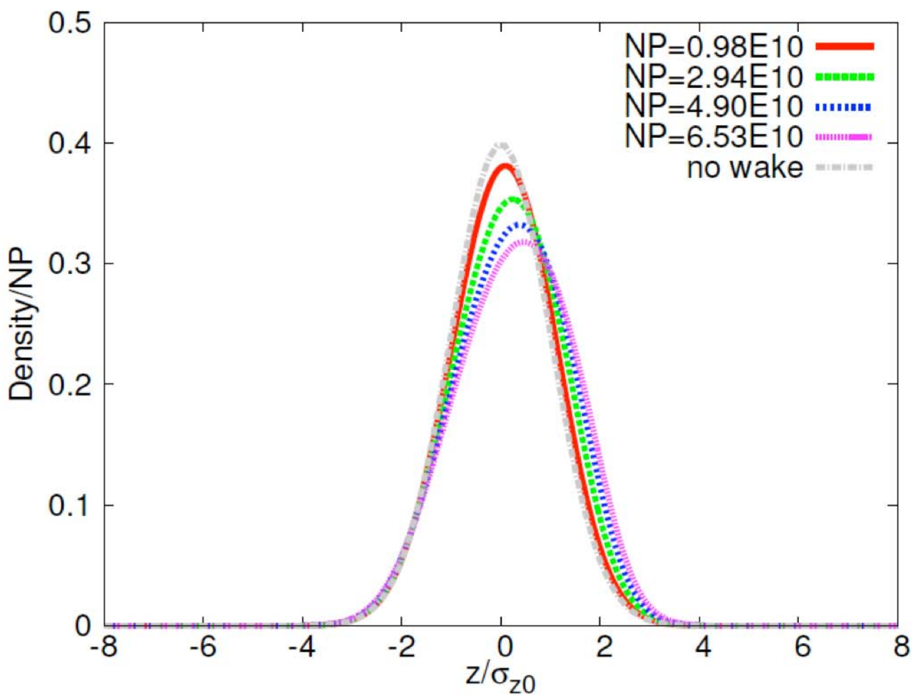
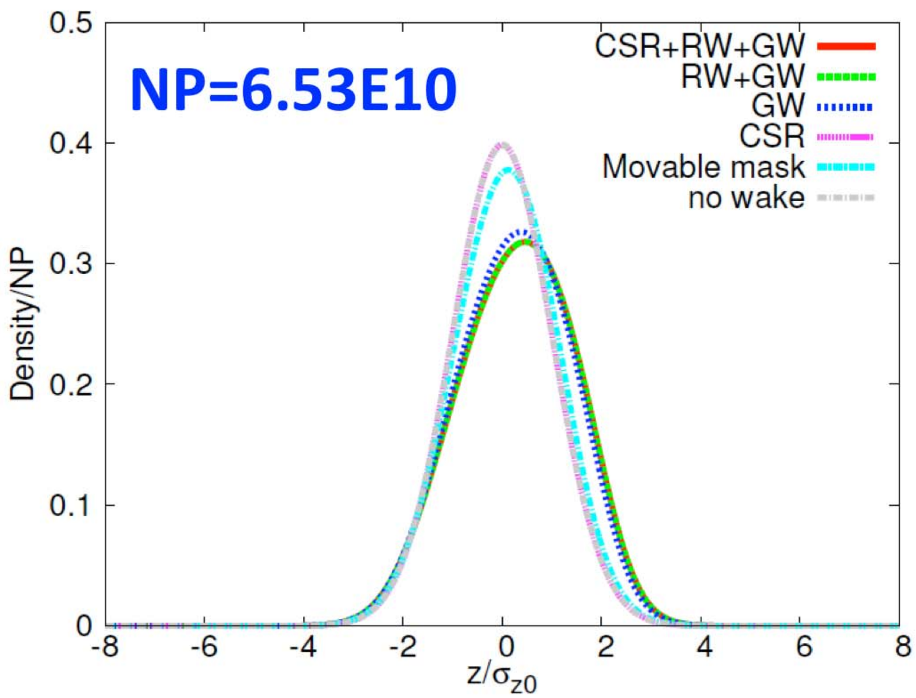




4. Single-bunch effects: Longitudinal: CSR

➤ **Y. Cai's theory on CSR effects in rectangular chamber:**

- **Steady-state CSR model**
- **Square chamber lowers MWI threshold ...**
- **Chamber aspect ratio >2 preferred**

$$N_{th} = \frac{CI_A}{ce}\frac{\alpha_p \gamma \sigma_\delta^2}{\sigma_z}\frac{\sigma_z^{4/3}}{R^{1/3}}\xi_{th}$$

$$I_A = 4\pi\epsilon_0 \frac{m_e c^3}{e} \qquad \chi = \sigma_z\sqrt{\frac{R}{b^3}}$$

Parallel plates:

$$\xi_{th} = 0.5 + 0.34\chi$$

Rectangular chamber:

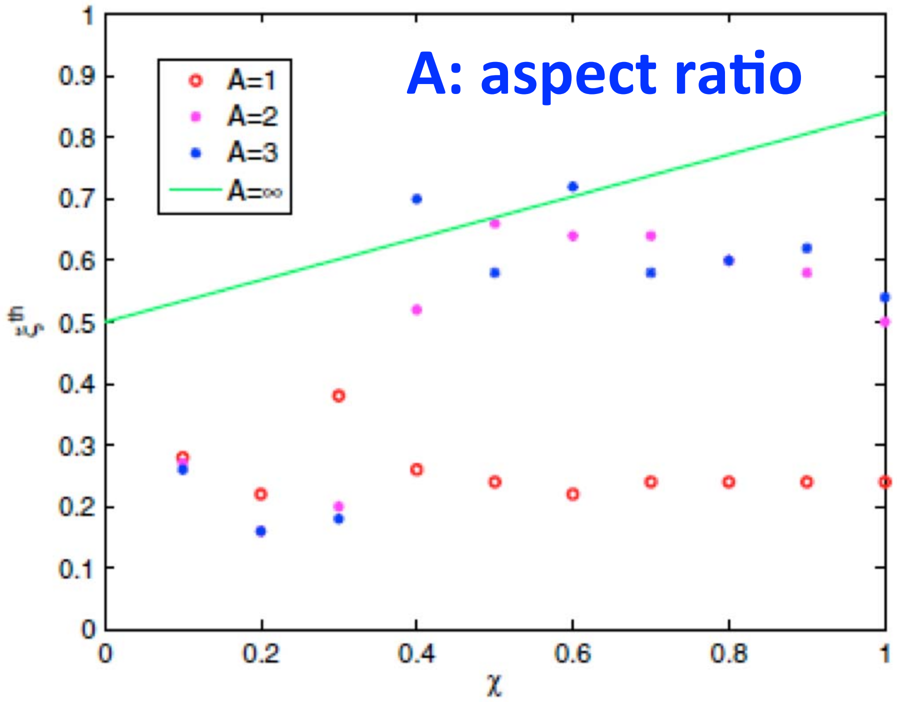
$$\xi = \xi_{th}(\chi, A = \frac{a}{b}, \frac{1}{\omega_s \tau_d})$$

Scaling law of coherent synchrotron radiation in a rectangular chamber

Yunhai Cai

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

(Received 21 October 2013; published 12 February 2014)



Ref. Y. Cai, PRST-AB 17, 020702 (2014)

4. Single-bunch effects: Longitudinal: CSR

- **Y. Cai's theory on CSR effects in rectangular chamber:**
  - **Applicable conditions to be validated for SuperKEKB**

	DR			LER	HER
E(GeV)	1.1			4.0	7.007
NP(10^{10})	5			9.04	6.53
b(mm)	24			90	50
a(mm)	34			90	104
R(m)	2.7/3			74.7	106
χ	1.49	1.67	2.16	1.15	1.98
α_p(10^{-4})	141			3.25	4.55
σ_δ(10^{-4})	5.5			8.08	6.37
σ_z(mm)	6.6	7.8	11	6	5
ξ_{th}^{old}	1.49	1.67	2.16	1.15	2.1
N_{th}^{old}(10^{10})	4.4	5.2	7.6	8.8	20.2
ξ_{th}^{new}	0.5(?)	0.5(?)	0.5(?)	0.25	0.5
N_{th}^{new}(10^{10})	1.5(?)	1.6(?)	1.8(?)	1.9	4.9

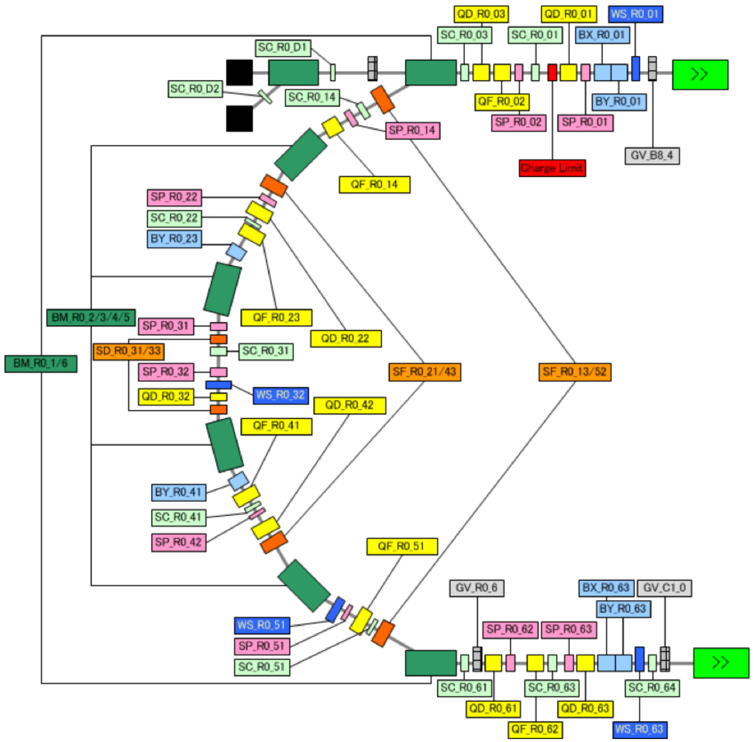
Ref. Y. Cai, PRST-AB 17, 020702 (2014)

4. Single-bunch effects: Longitudinal: CSR

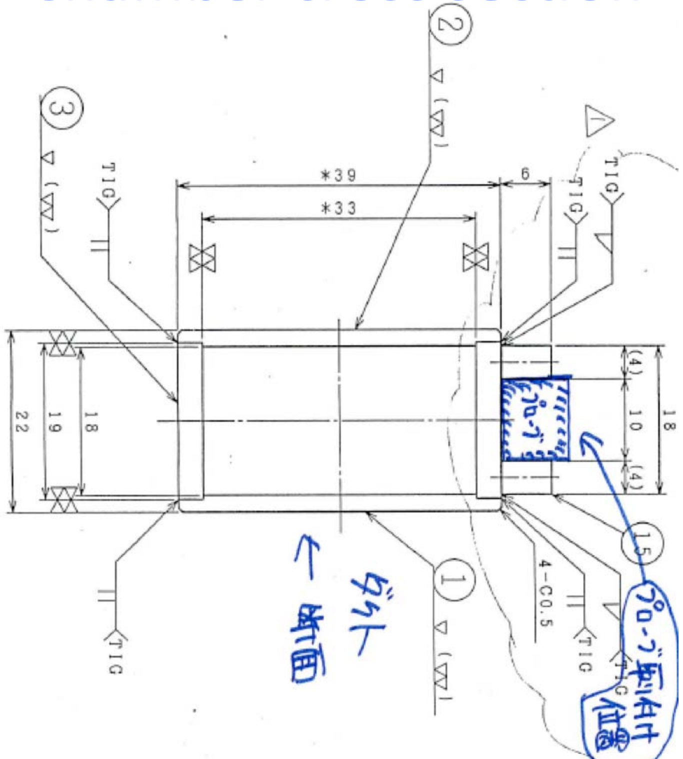
➤ CSR at J-ARC of SuperKEKB linac:

- Impedance calculated by CSRZ
- Chamber: a=33mm, b=18mm, R=3.643m
- Bunch full length: 10 ps - 4 ps
- Maximum bunch charge: 5nC

J-ARC layout



Chamber cross section



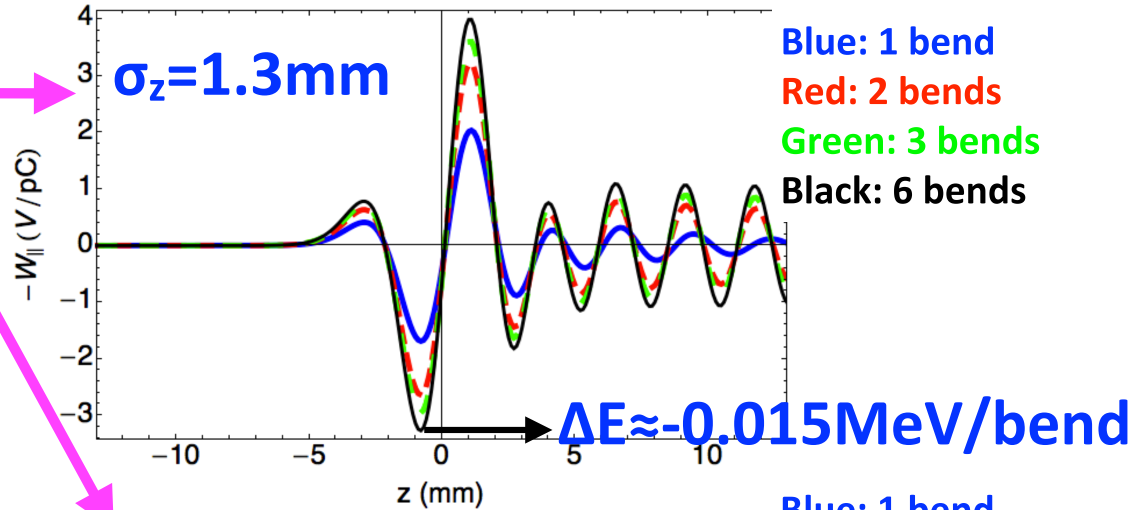
From M. Yoshida

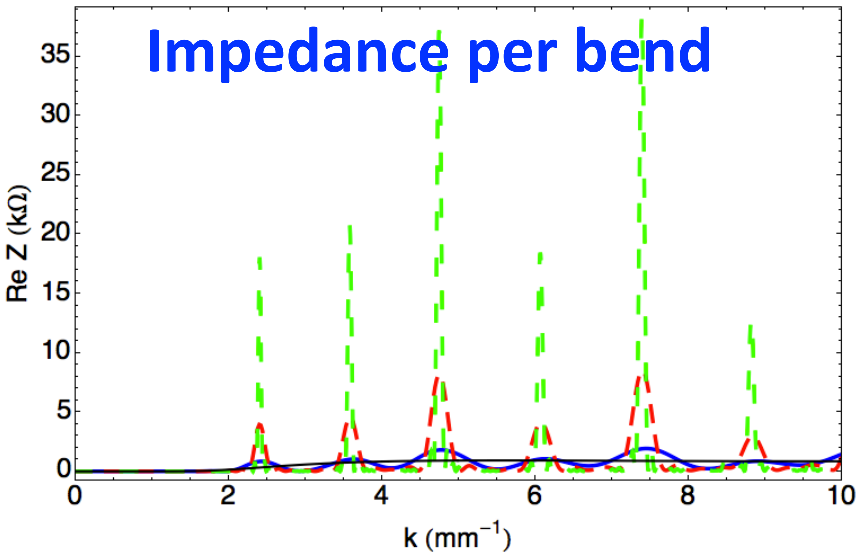
4. Single-bunch effects: Longitudinal: CSR

➤ CSR at J-ARC of SuperKEKB linac:

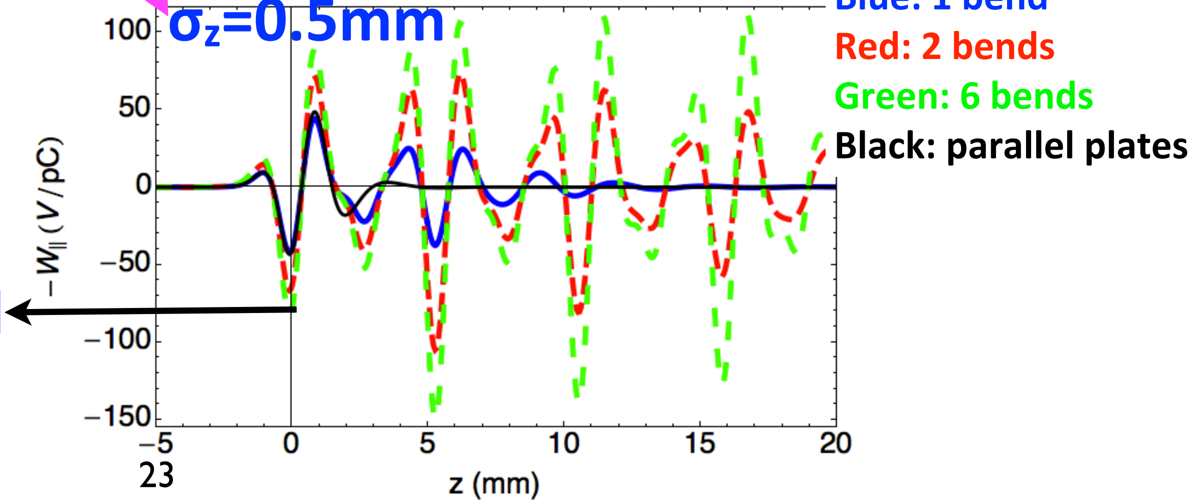
- Sharp peaks correspond to multi-bend CSR interference
- Bunch full width 10-4ps: Strong chamber shielding
- Tracking simulations to be done

Assume Gaussian bunch





ΔE≈-0.4MeV/bend



4. Single-bunch effects: Transverse: Beam tilt

➤ **G. Stupakov's theory on transverse beam tilt:**

- **To be a concern in small emittance rings**
- **Asymmetric protrusion (if exists)**

$$\Delta\epsilon_y = \frac{1}{4\sin^2(\pi\nu_y)}\beta_y\theta^2_{\rm rms}$$

$$\theta_{\rm rms} = \frac{Ne^2}{\gamma m_0 c^2}\sqrt{\langle(W_y - \langle W_y\rangle)^2\rangle}$$

$$\langle W_y\rangle = \int_{-\infty}^{\infty} W_y(s)\lambda(s)ds$$

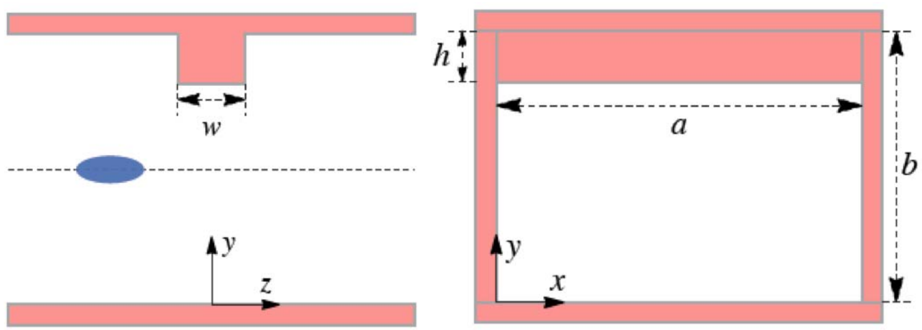
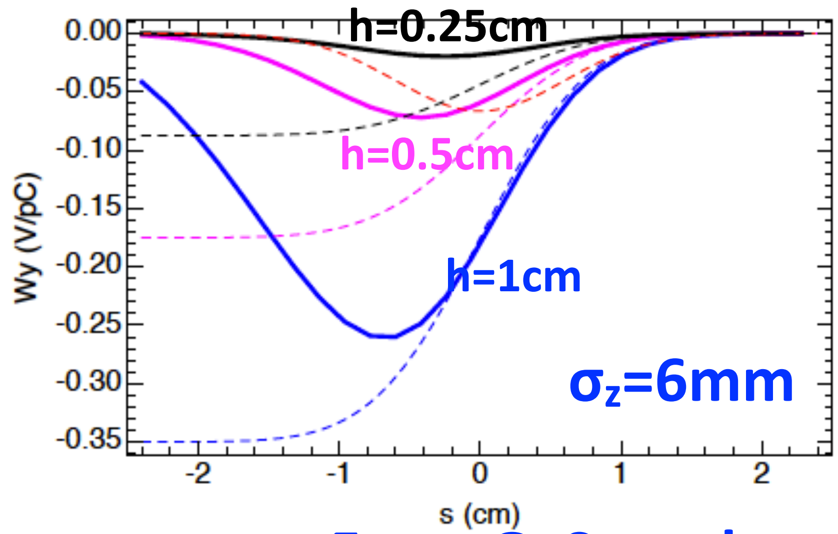


TABLE II. Emittance increase in LER of SUPERKEKB

Corrugation depth h (cm)	1	0.5	0.25
$\theta_{\rm rms}$ (nrad)	290	77	20
$\Delta\epsilon$ (pm)	0.45	0.03	0.002



From G. Stupakov

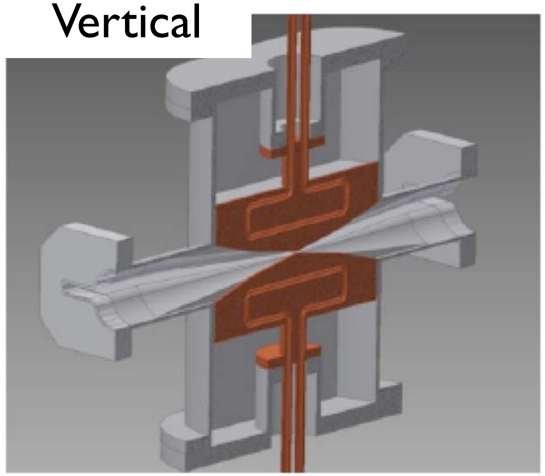
4. Single-bunch effects: Transverse: Beam tilt

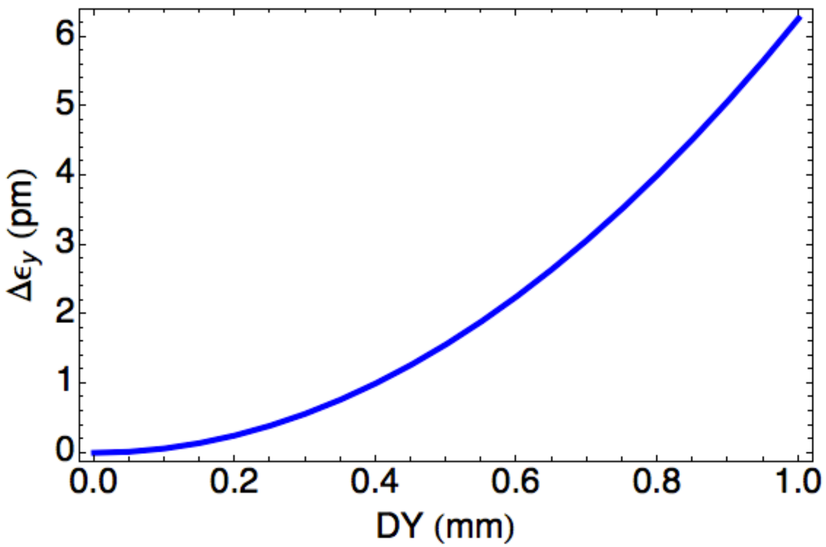
➤ G. Stupakov's theory on transverse beam tilt:

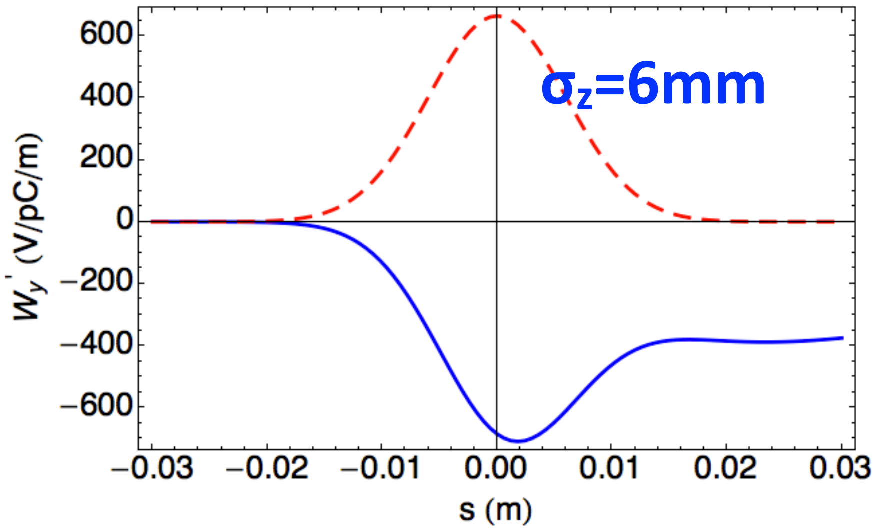
- Symmetric 3D structure (like collimator) with orbit offset
- D02V1 in LER as an example: d=-2/2mm, βy=104.6m
- COD DY < 0.2 mm required?

$$\Delta\epsilon_y = \frac{1}{4\sin^2(\pi\nu_y)}\beta_y\theta_{\rm rms}^2$$

$$\theta_{\rm rms} = \frac{Ne^2\Delta y}{\gamma m_0 c^2}\sqrt{\langle (W_y' - \langle W_y'\rangle)^2\rangle}$$







4. Single-bunch effects: TMCI: LER

- We estimated the threshold of the Transverse Mode Coupling Instability using actual β value at each collimator with σ_z = 6 mm.
- The bunch current of the design value in LER is 1.44 mA/bunch.
- A kick factor in D02V1 is quite large because of the narrow aperture (±2 mm), and it limits the bunch current.
- We may need an another structure, such as long heads with gradual slope, for D02V1.

	TMC Threshold (mA/bunch)	
	All Closed	Actual Apertures
Horizontal	1.41	13.15
Vertical	0.96	1.25

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

Collimator No.	d [mm]	k [V pC^{-1}]	$k_\perp$ [V pC^{-1}m^{-1}]	β_x [m]	β_y [m]
D06 H1	-16.0 / +17.0	0.036	8	24.28	5.5043
D06 H2	-16.0 / +16.0	0.036	8	24.28	5.5042
D06 H3	-16.0 / +15.0	0.036	9	24.28	5.5043
D06 H4	-13.0 / +13.0	0.037	15	24.28	5.5042
D03 H1	-21.0 / +20.0	0.036	6	28.97	3.021
D03 H2	-18.0 / +20.0	0.036	7	28.97	3.021
D03 V1	-9.0 / +9.0	0.058	40	10.38	17.05
D03 V2	-9.0 / +9.0	0.058	40	10.38	17.05
D02 H1	-10.6 / + 12.0	0.038	25	33.20	19.06
D02 H2	-16.0 / +20.0	0.036	8	81.01	22.01
D02 H3	-18.0 / +21.0	0.036	7	31.09	173.3
D02 H4	-13.0 / +9.0	0.04	40	45.63	6.236
D02 V1	-2.0 / 2.0	0.098	600	21.79	104.6

Lattice version: sler_1689

From T. Ishibashi and Y. Suetsugu

5. Summary

- **Impedance calculations**
  - **Impedance calculations with σ_z=6mm => Loss factors and HOM power estimation**
  - **Longitudinal impedance calculations with σ_z=0.5mm => Pseudo-Green wake => Simulations of MWI**
  - **Transverse impedance calculations with σ_z=0.5mm => Catalogued but need COD for further instability analysis**
- **Longitudinal single-bunch effects**
  - **$\sigma_z \approx$5.8mm @Design bunch current for both LER and HER**
  - **CSR remains to be a concern**
  - **MWI threshold: Need more (very) careful simulations**
- **Transverse single-bunch effects**
  - **Beam tilt due to transverse impedance examined**
  - **TMCI due to collimators remains to be a concern**

6. Future plan

➤ **Refining pseudo-Green wake function**

- Consider all impedance sources
- Update impedance calculations while hardware designs change
- Double-check finished impedance calculations
- Proper models of CSR, CWR, and RW: Point-charge wake function

➤ **Numerical simulations**

- Careful simulations of MWI via Vlasov solver (Very tricky and request high computing power, especially with CSR!)
- Tracking simulations of beam tilt and TMCI
- Impact of single-bunch effects on luminosity performance

➤ **Collaborations**

- Y. Cai: CSR, MWI, ...
- G. Stupakov: Impedance calculations, beam instabilities, ...

➤ **Prepare beam measurements in 2015**

- Bunch lengthening, impedance, space charge, ecloud, fast ion, ...

Thanks for your attention!