Impedance and Instability Issues in SuperKEKB

Demin Zhou

With contributions from

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SLAC: **Y. Cai, G. Stupakov, L. Wang, R. Warnock**

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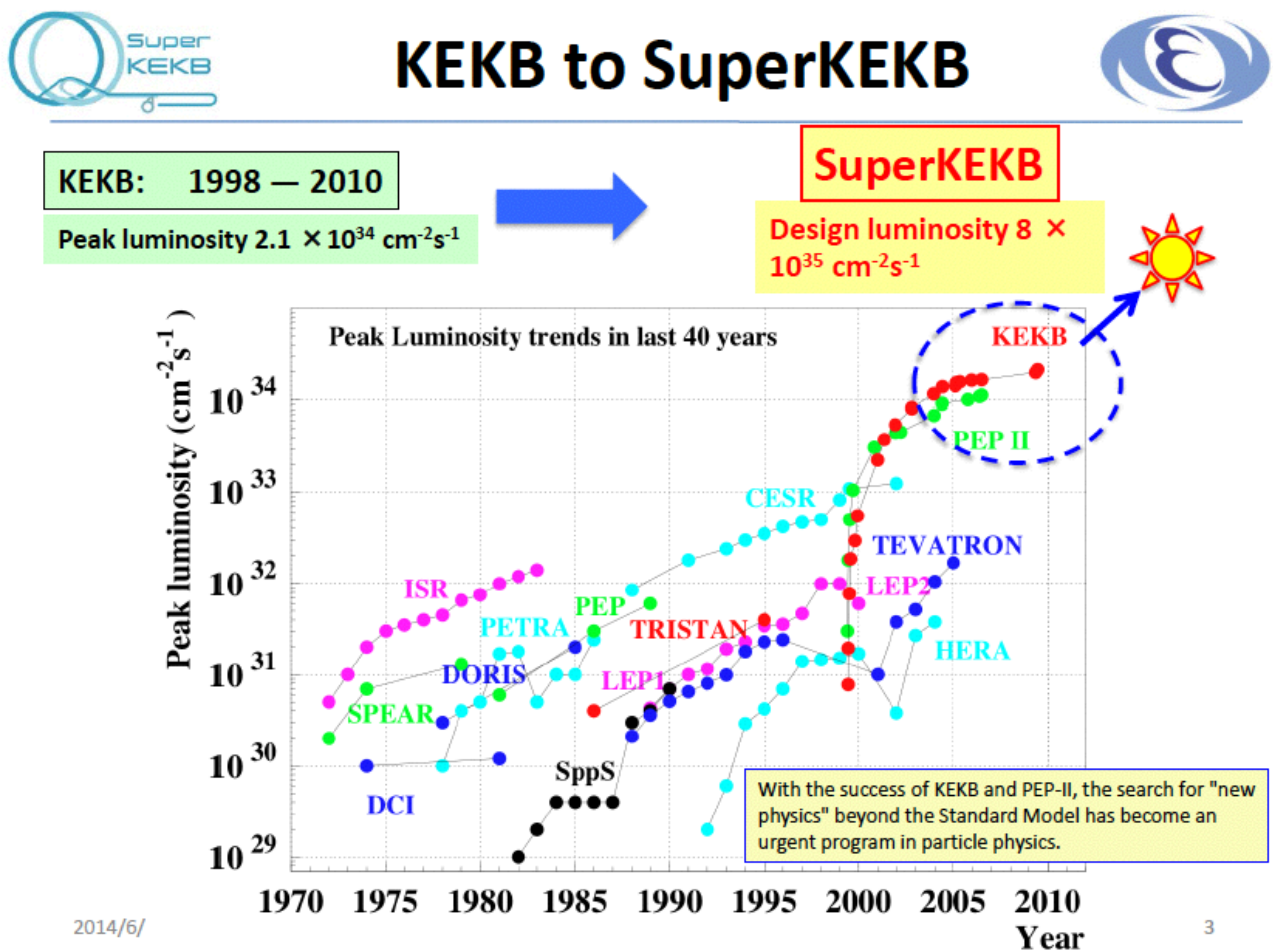
Theory club, FEL & Beam Physics Department, SLAC

Aug. 01, 2014

Outline

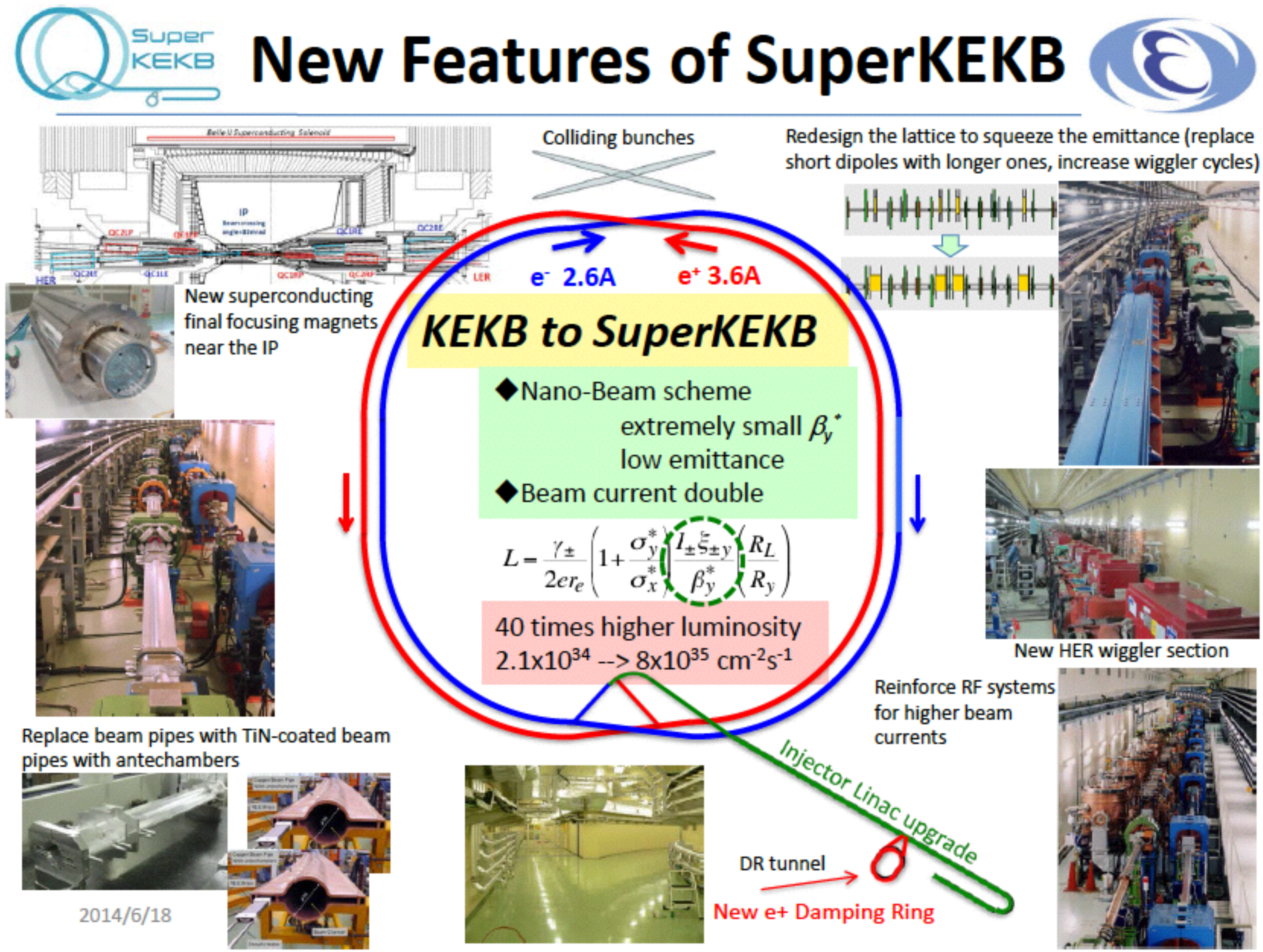
- Introduction
  - Luminosity target, Features of SuperKEKB, ...
- Impedance calculations
  - Modelling, Pseudo-Green wake function, ...
  - Impedance budget
- Single-bunch effects
  - Longitudinal: Bunch lengthening, MWI, ...
  - Transverse: Beam tilt, TMCI, ...
- Coherent synchrotron radiation (CSR)
  - CSR effects in SuperKEKB, PE and numerical calculations, Field dynamics, Experiments
- Coherent wiggler/undulator radiation (CWR/CUR)
  - Numerical and analytical calculations
- Summary

1. Introduction: Lum. trends



From N. Ohuchi, IPAC14, WEOCA01

1. Introduction: Features of SuperKEKB



From N. Ohuchi, IPAC14, WEOCA01

1. Introduction: Expected lum. gain

SuperKEKB

- Increase the luminosity by 40 times based on "Nano-Beam" scheme

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$$

	KEKB → SuperKEKB	Luminosity Gain
Vertical β function at IP :	5.9 → 0.27/0.30 mm	(× 20)
Beam current :	1.7/1.4 → 3.6/2.6 A	(× 2)
Vertical beam−beam parameter :	0.09 → 0.09	(× 1)
Beam energy:	3.5/8.0 → 4.0/7.0 GeV	

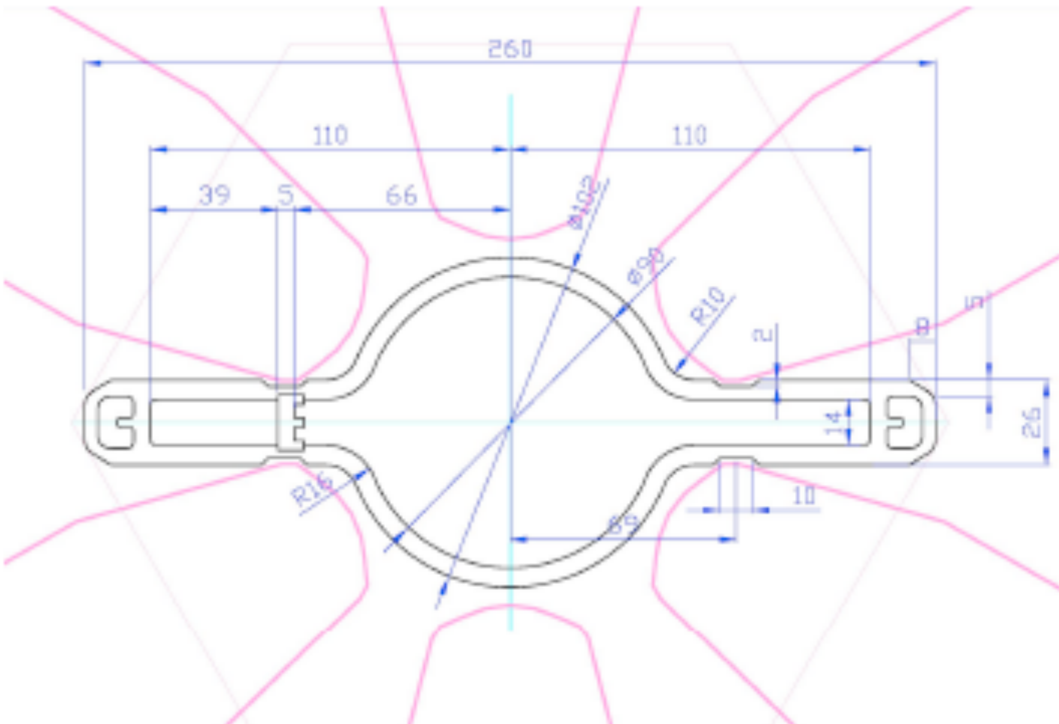
LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra−beam scattering

HER : Lower emittance and lower SR power

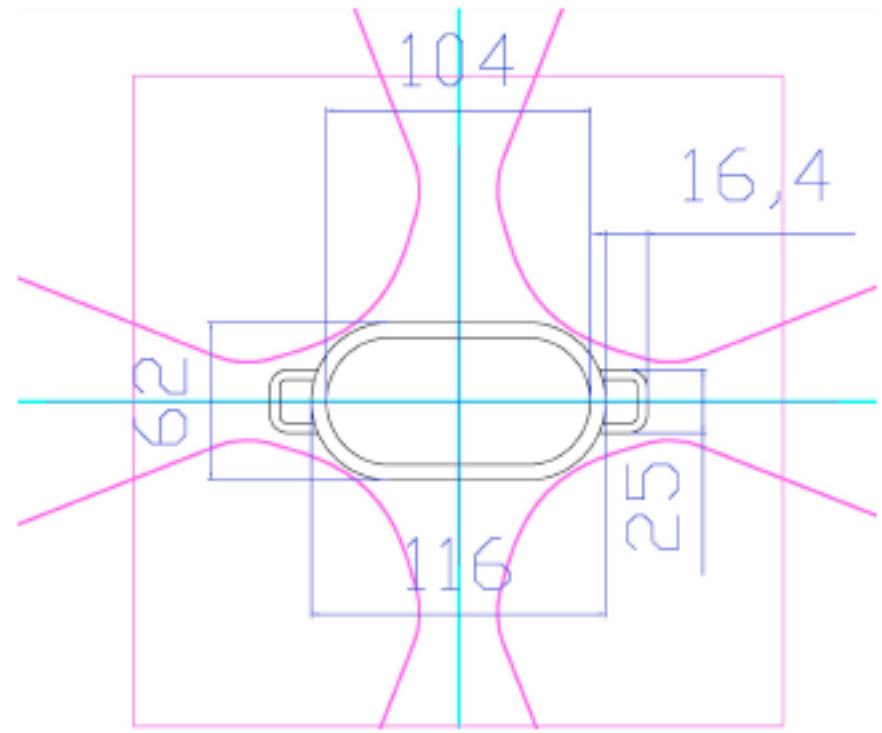
From N. Ohuchi, IPAC14, WEOCA01

2. Impedance calculations: Modelling

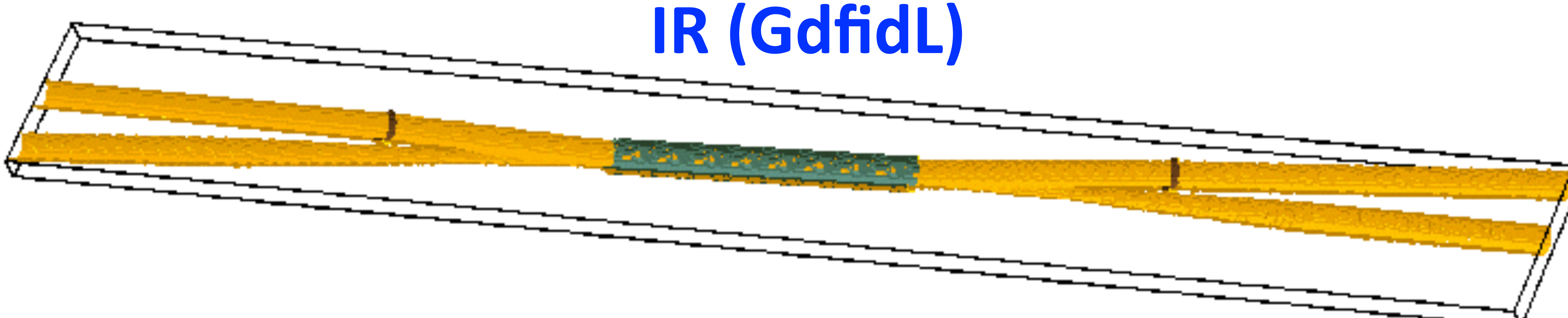
LER typical (~90%)
Aluminum w/ antechamber



HER typical (~70%)
Copper w/o antechamber



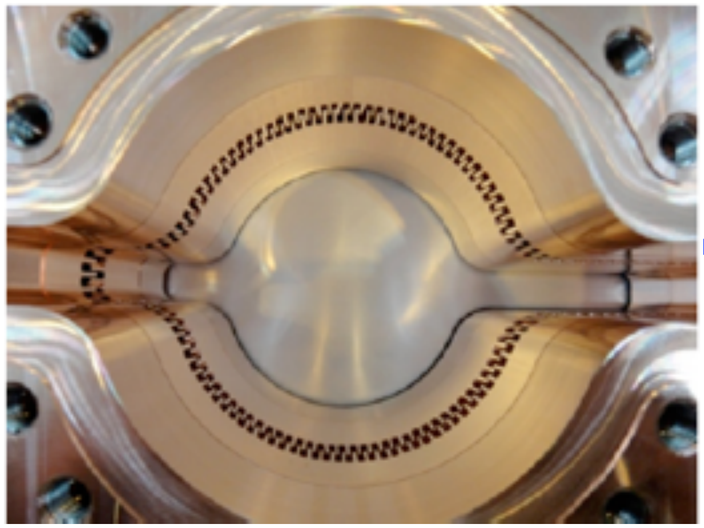
IR (GdfidL)

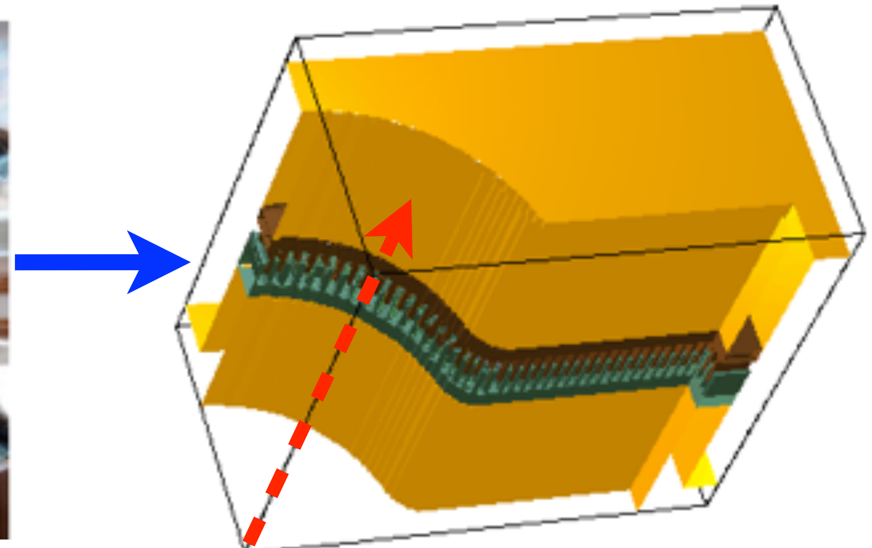


From Y. Suetsugu and K. Shibata

2. Impedance calculations: Modelling: LER

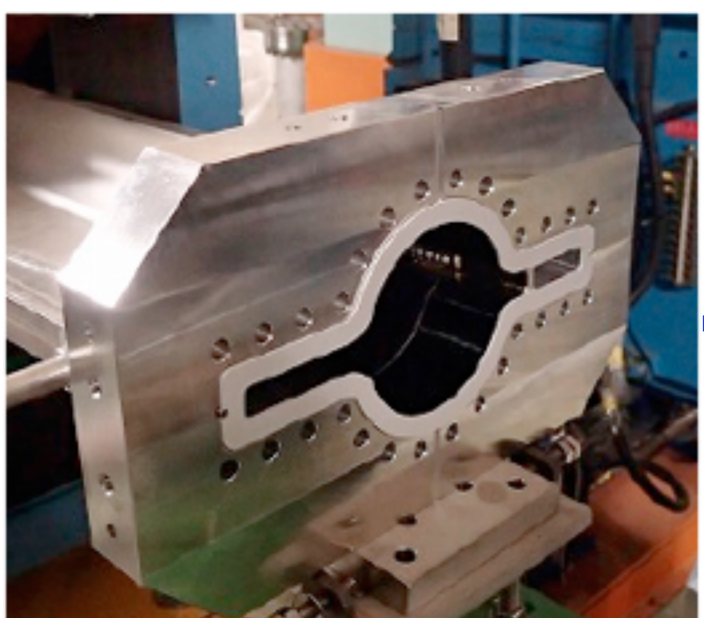
Bellows

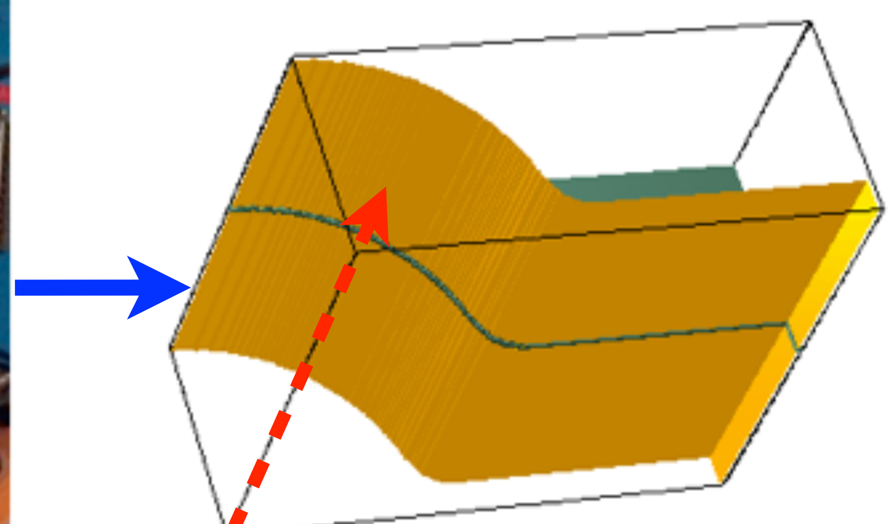




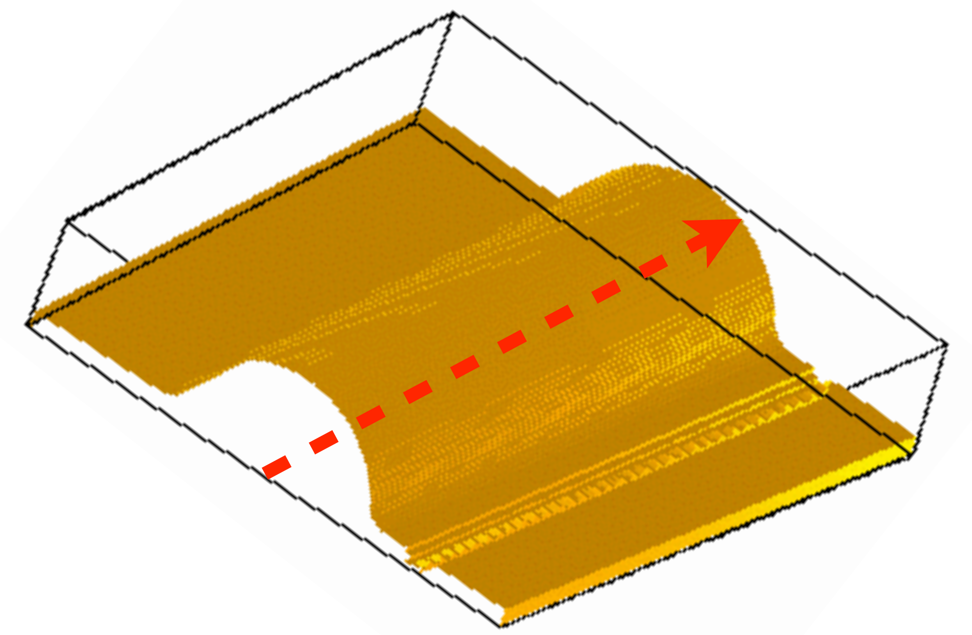
Comb-type: Unique for SuperKEKB

MO-type flange





Pumping port

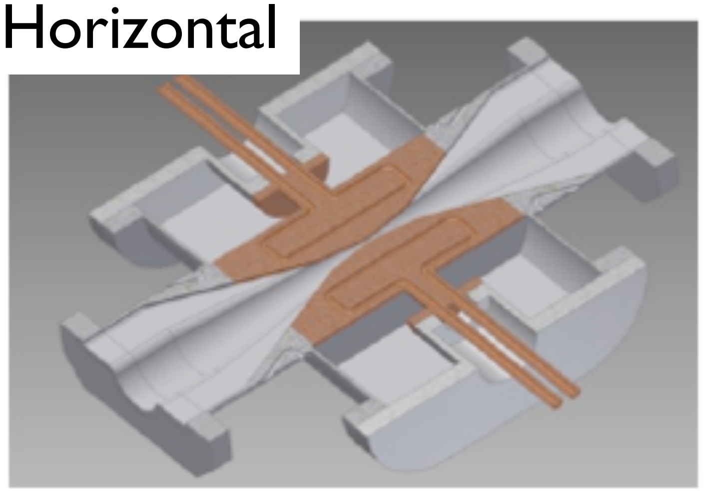


ARES RF cavity

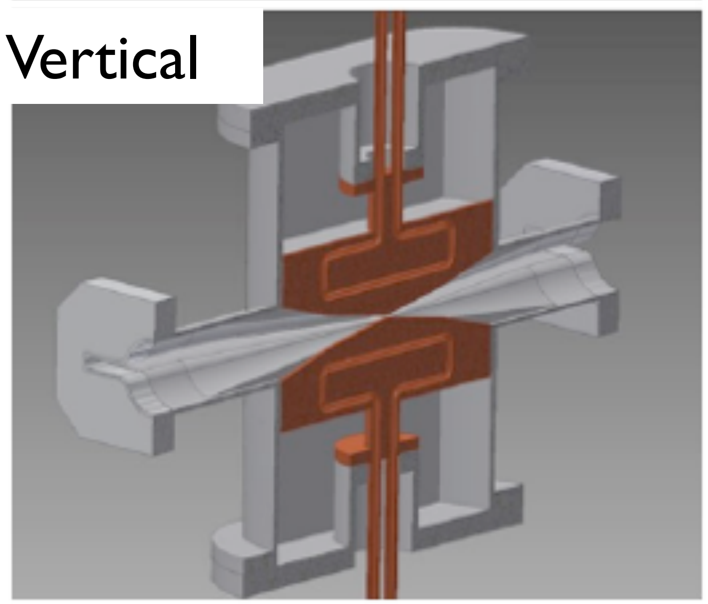
From T. Abe and K. Shibata

2. Impedance calculations: Modelling: LER

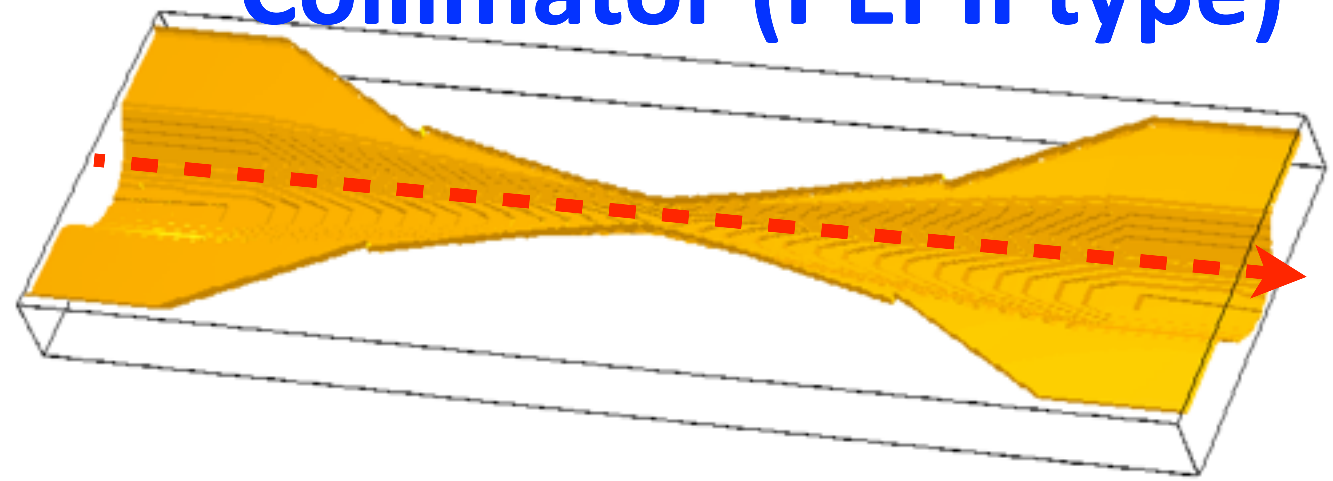
Horizontal

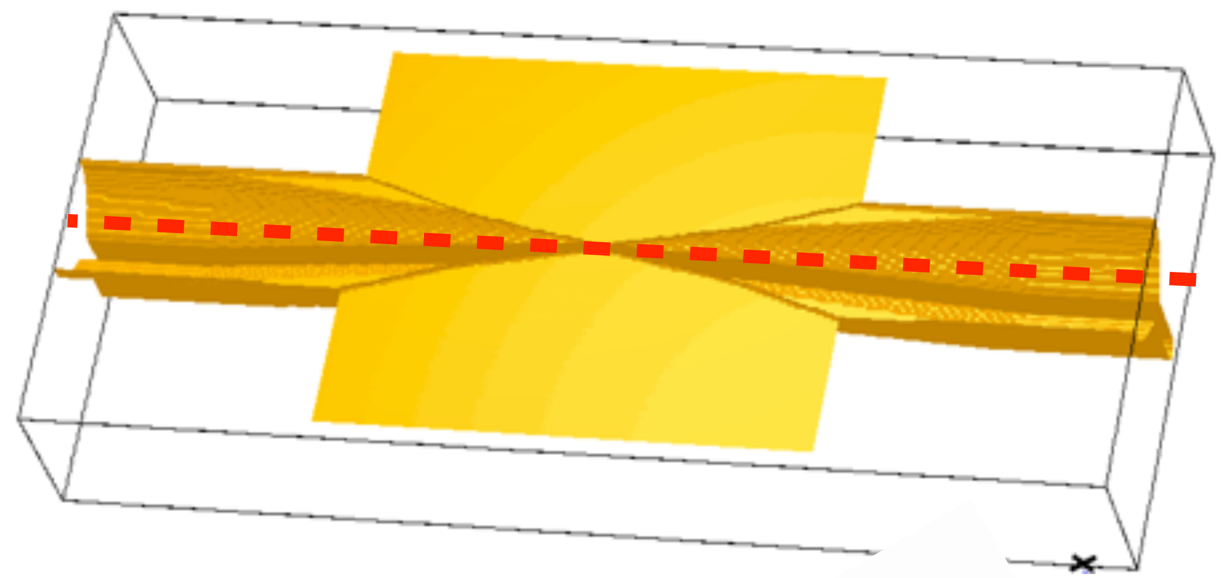


Vertical

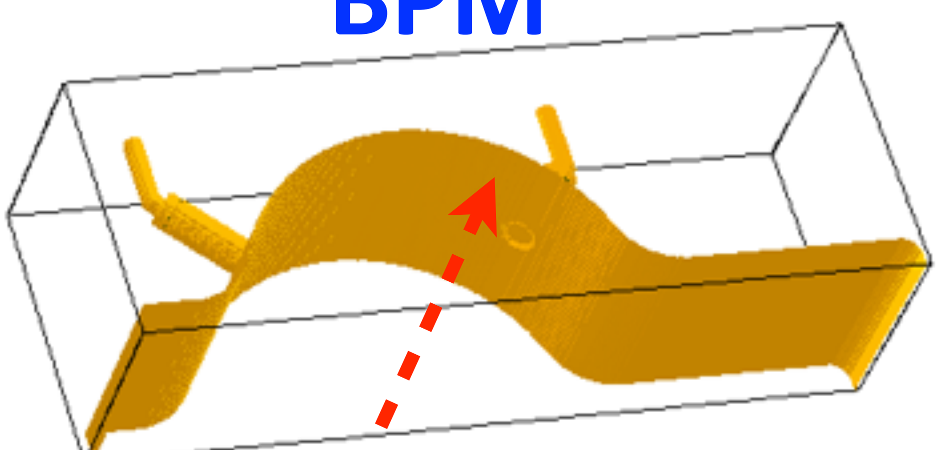


Collimator (PEPII type)

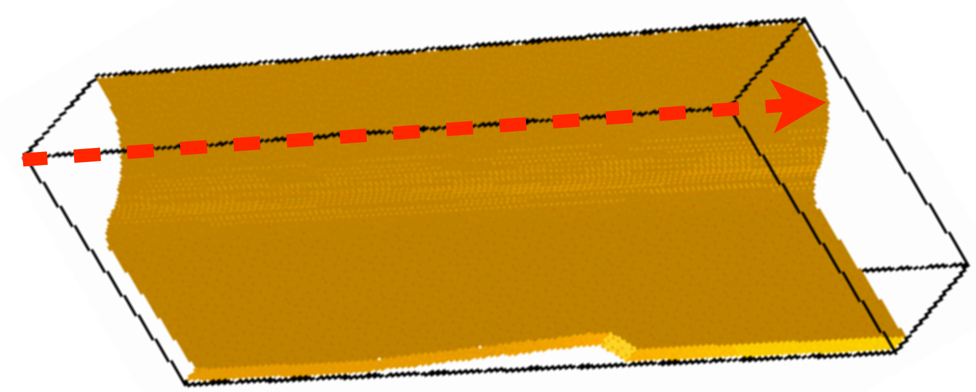




BPM



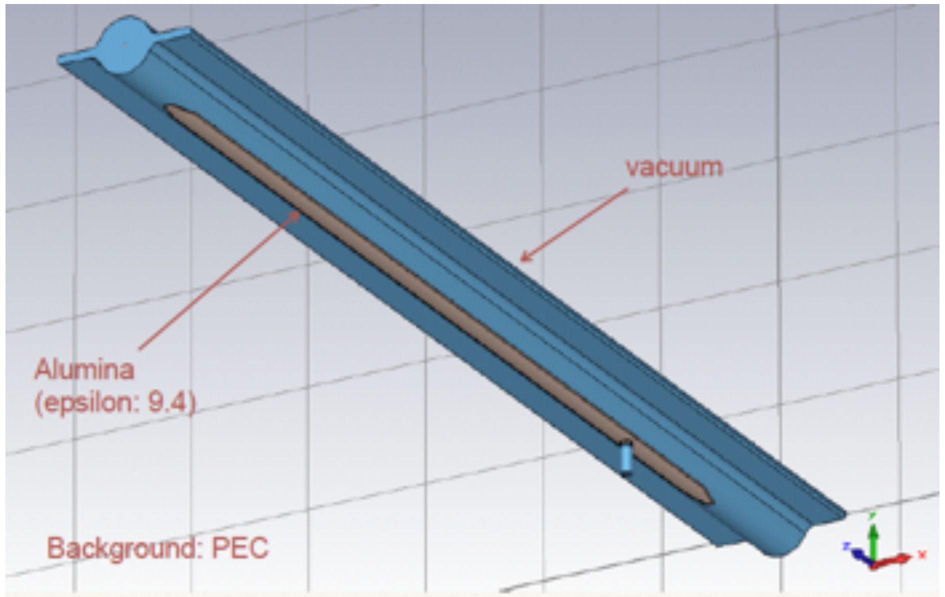
SR mask



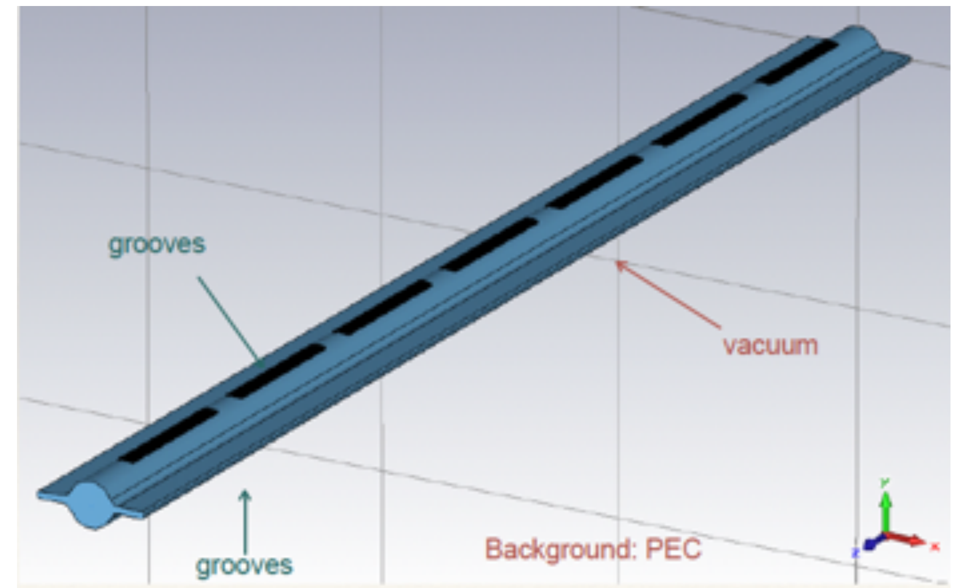
From T. Ishibashi, M. Tobiyama, and K. Shibata

2. Impedance calculations: Modelling: LER

Clearing electrode



Grooved surfaces



From T. Ishibashi

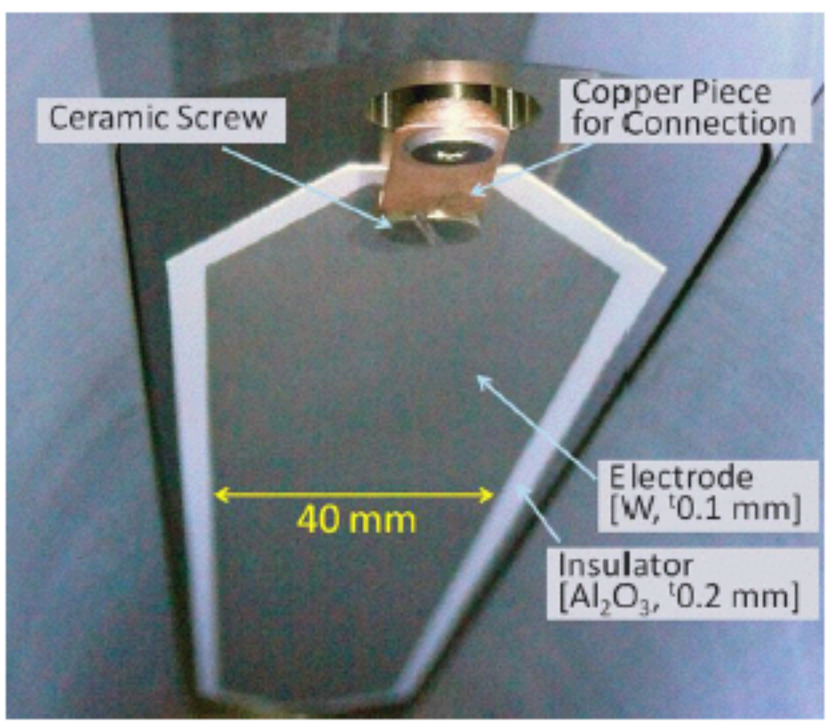


Fig. 2. Clearing electrode installed in test chamber. The electrode and the feed-through are connected by small piece of copper.

Tested in KEKB

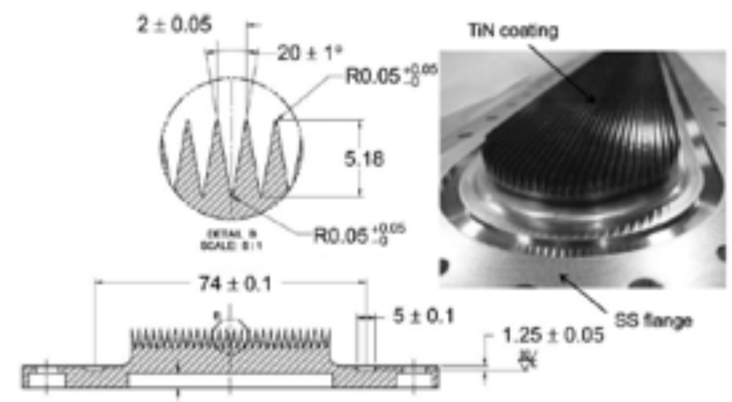


Fig. 1. Insertion with TiN-coated groove surface.

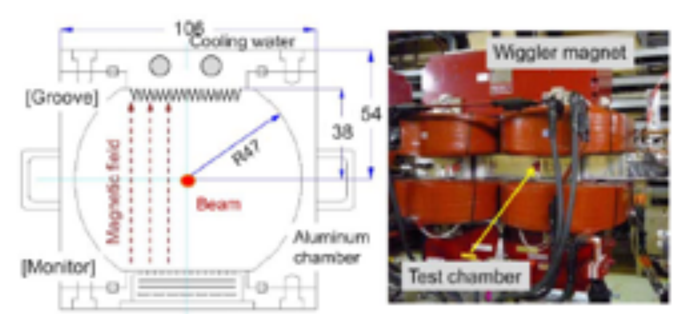


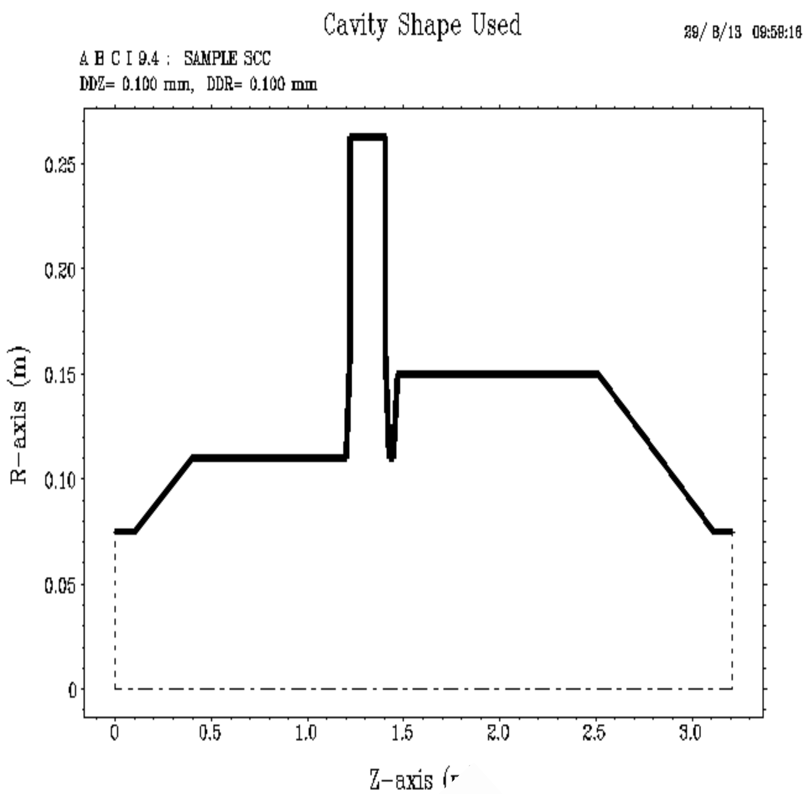
Fig. 2. Cross-section of the test chamber and the experimental setup in a wiggler magnet section in the KEKB positron ring.

Ref. Y. Suetsugu et al., NIMA 598 (2009)

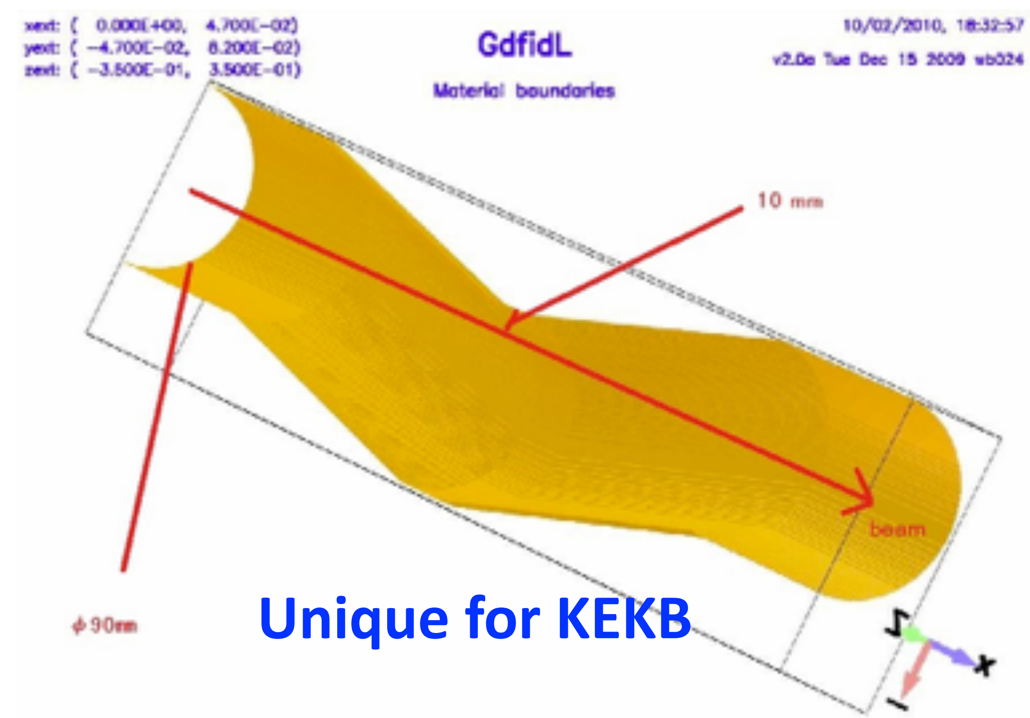
Ref. Y. Suetsugu et al., NIMA 604 (2009)

2. Impedance calculations: Modelling: HER

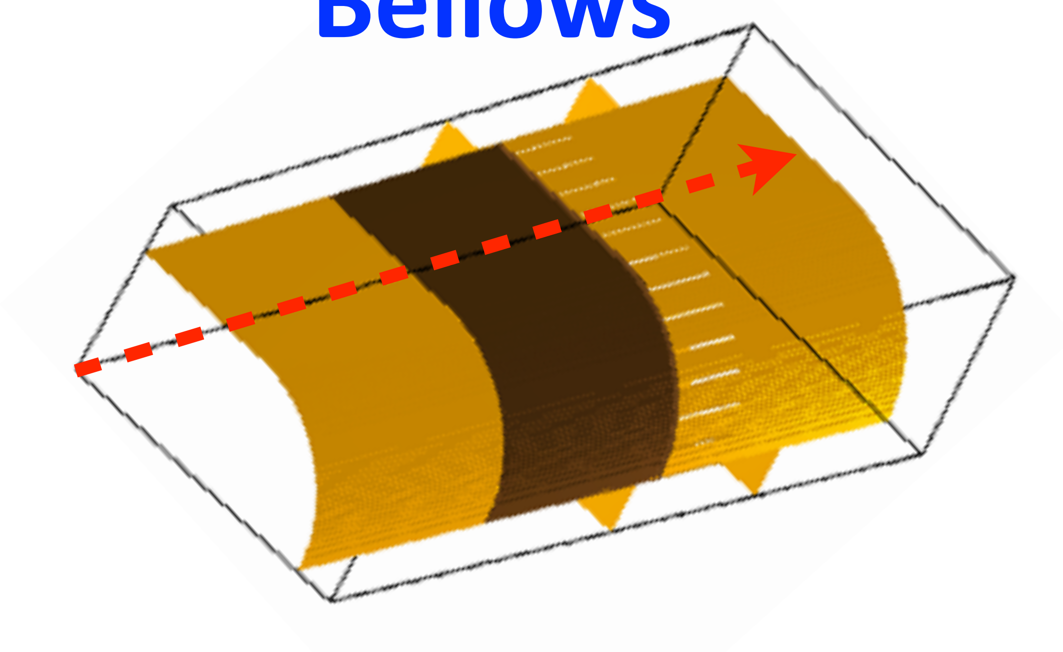
SCC (by ABCI)



Movable mask (KEKB type)



Bellows

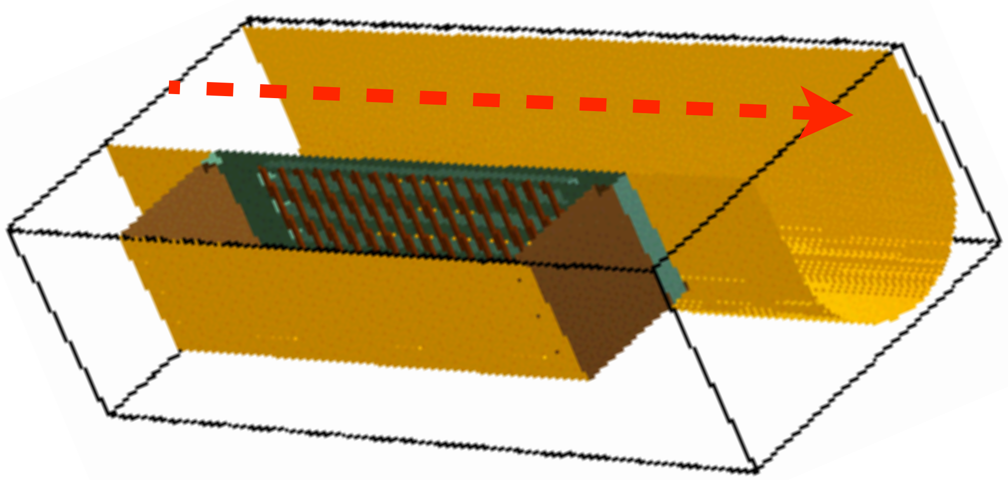


ARES

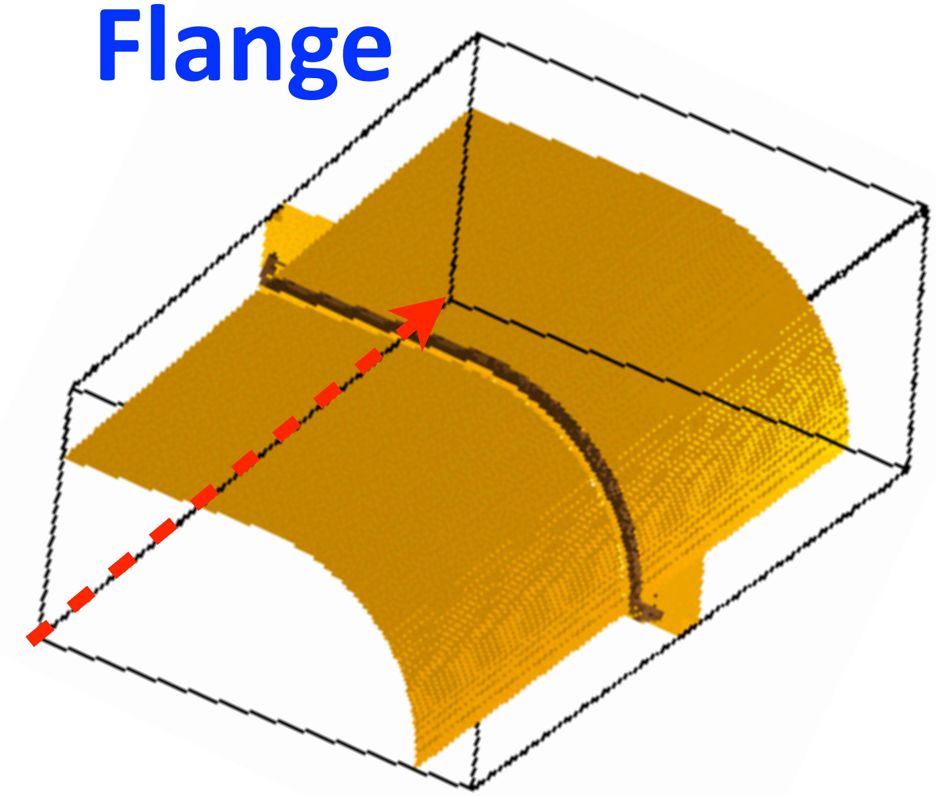
From T. Abe, Y. Morita, and K. Shibata

2. Impedance calculations: Modelling: HER

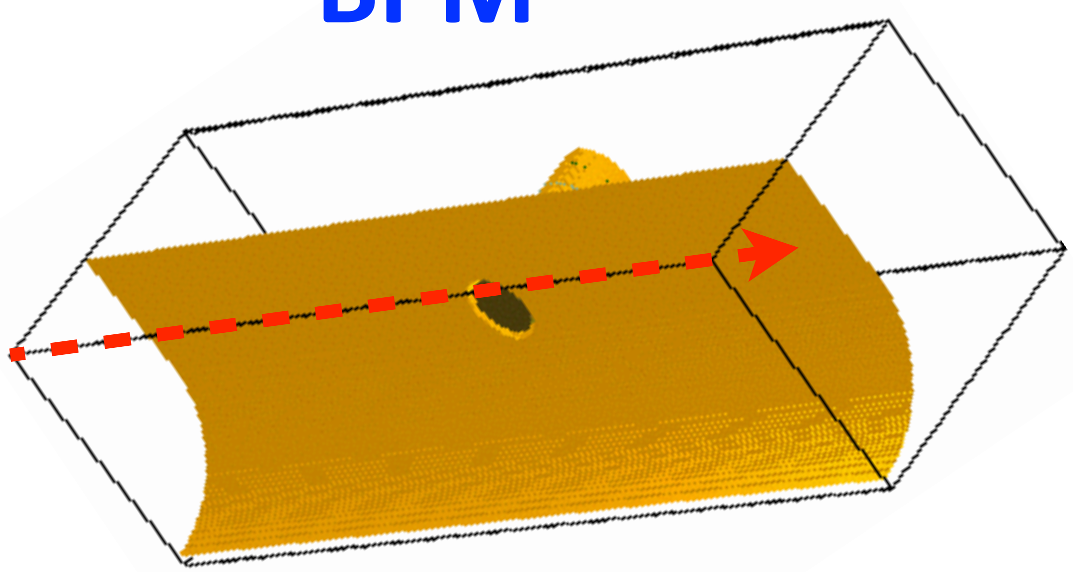
Pumping port



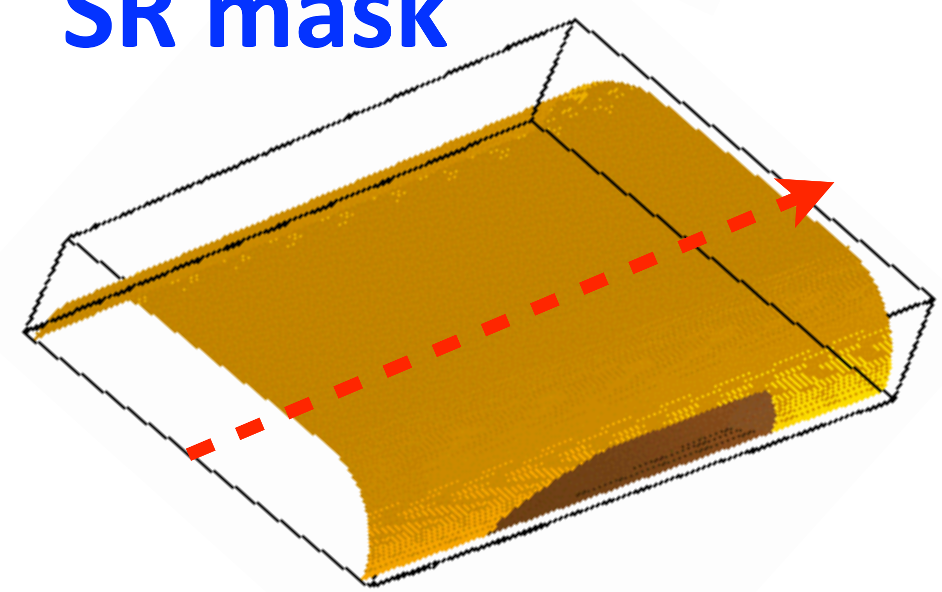
Flange



BPM



SR mask

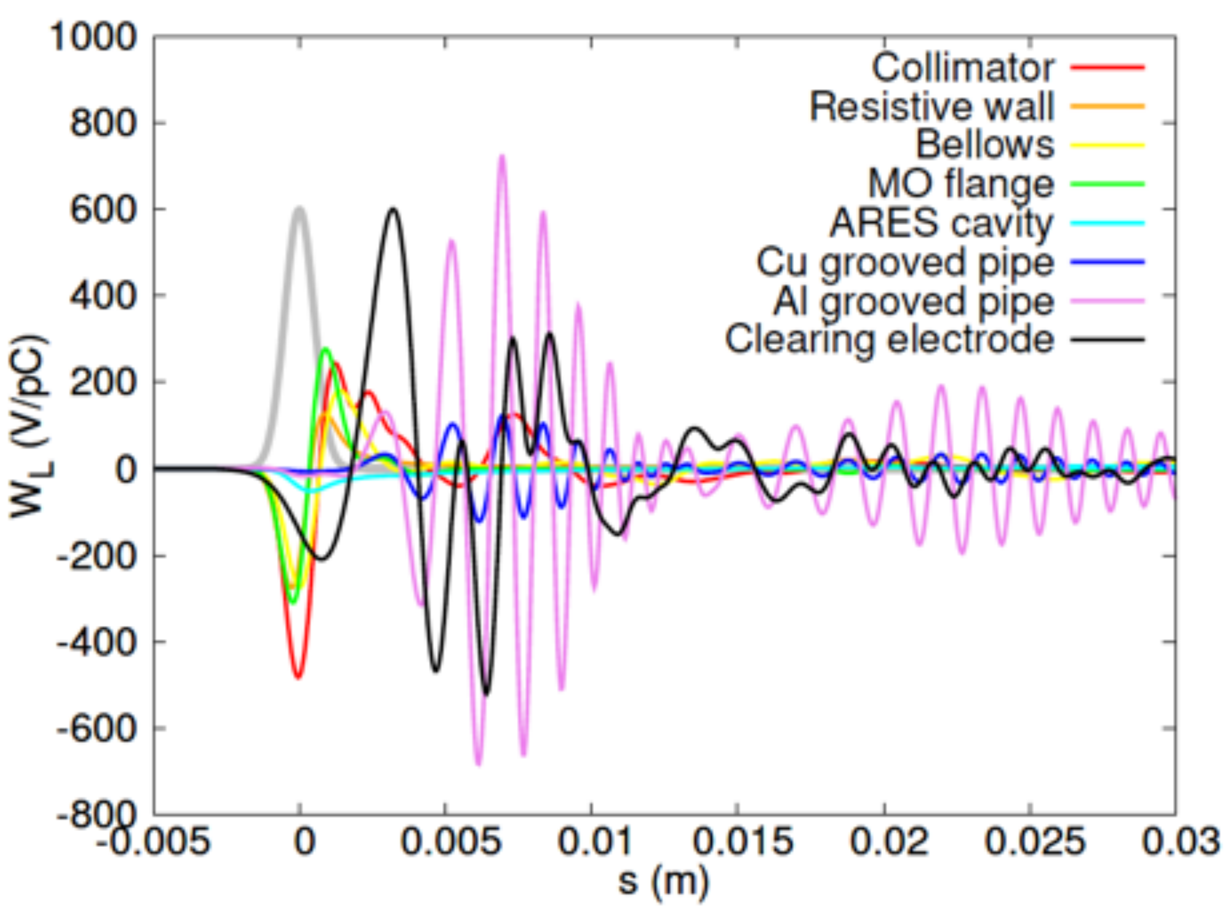


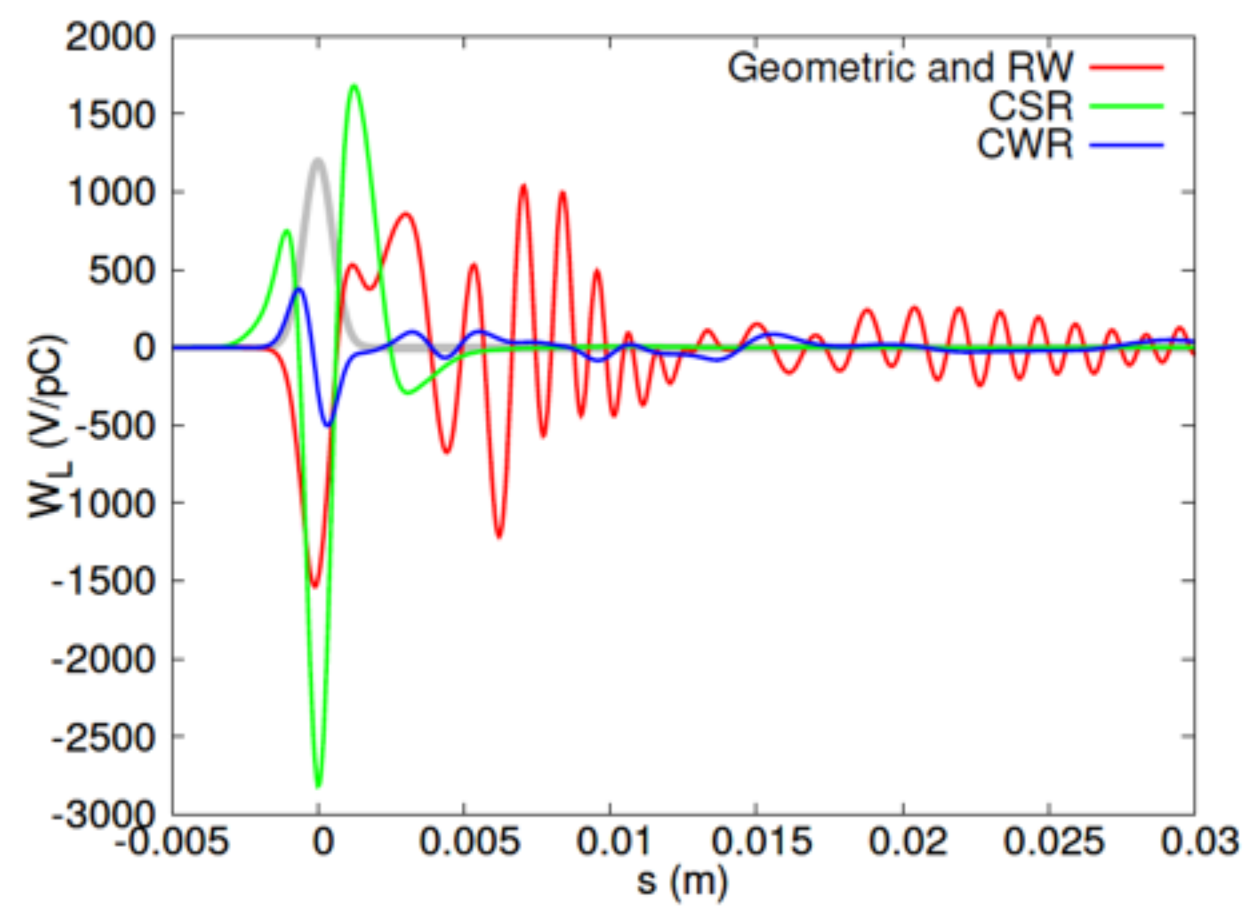
From K. Shibata and M. Tobiyama

2. Impedance calculations: Results: LER

➤ **Pseudo-Green wake function**

- **σ_z=0.5mm**
- **Pumping ports and SR masks are negligible sources because of antechamber**
- **CSR and CWR (Wiggler radiation): CSRZ code with rectangular chamber**

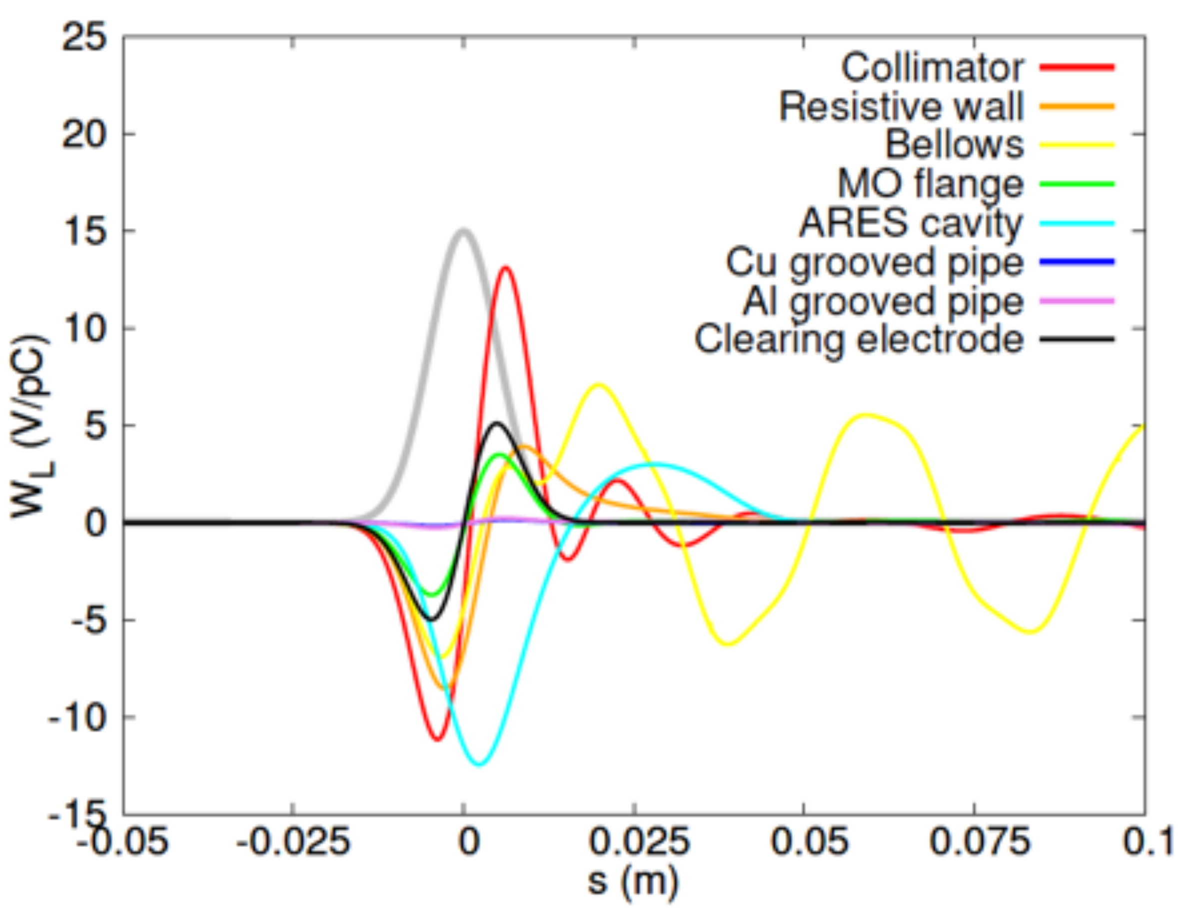


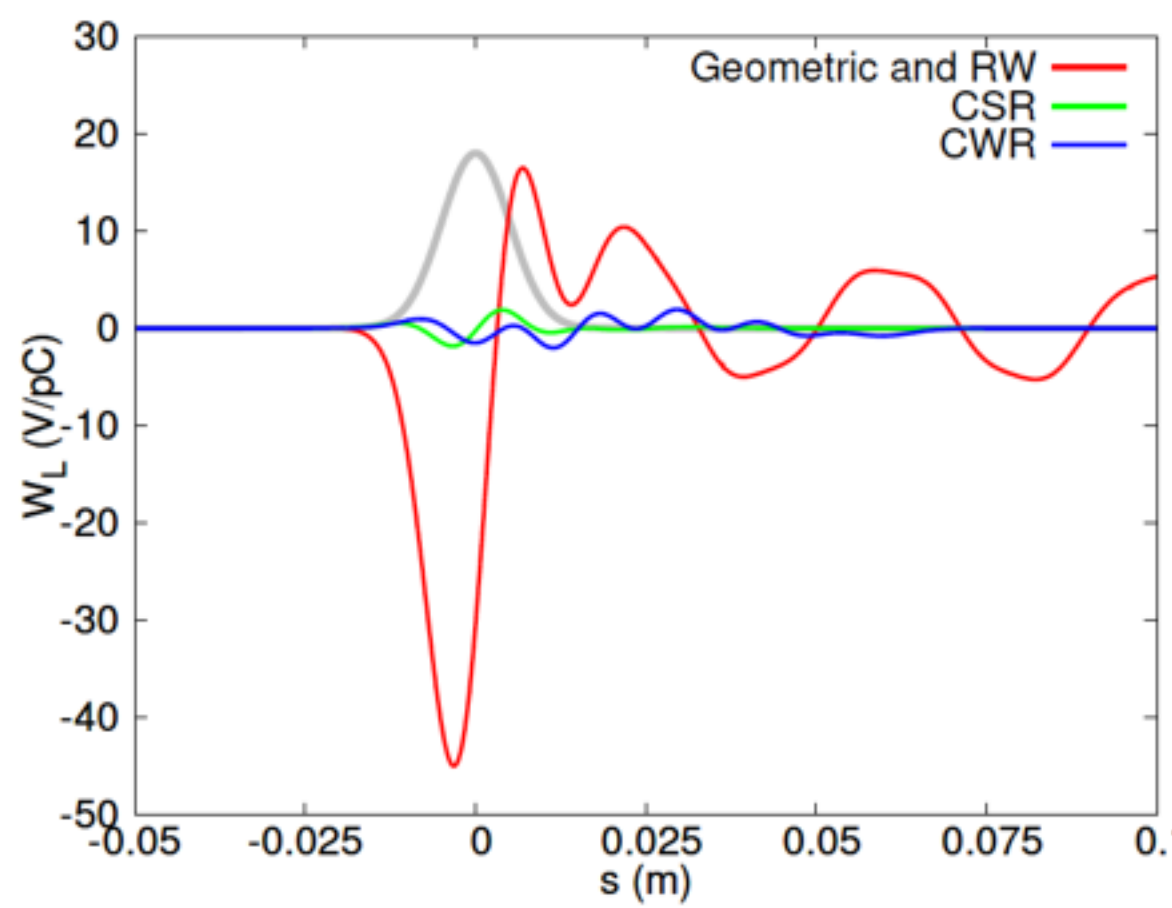


2. Impedance calculations: Results: LER

➤ **Wake potential with nominal bunch length**

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

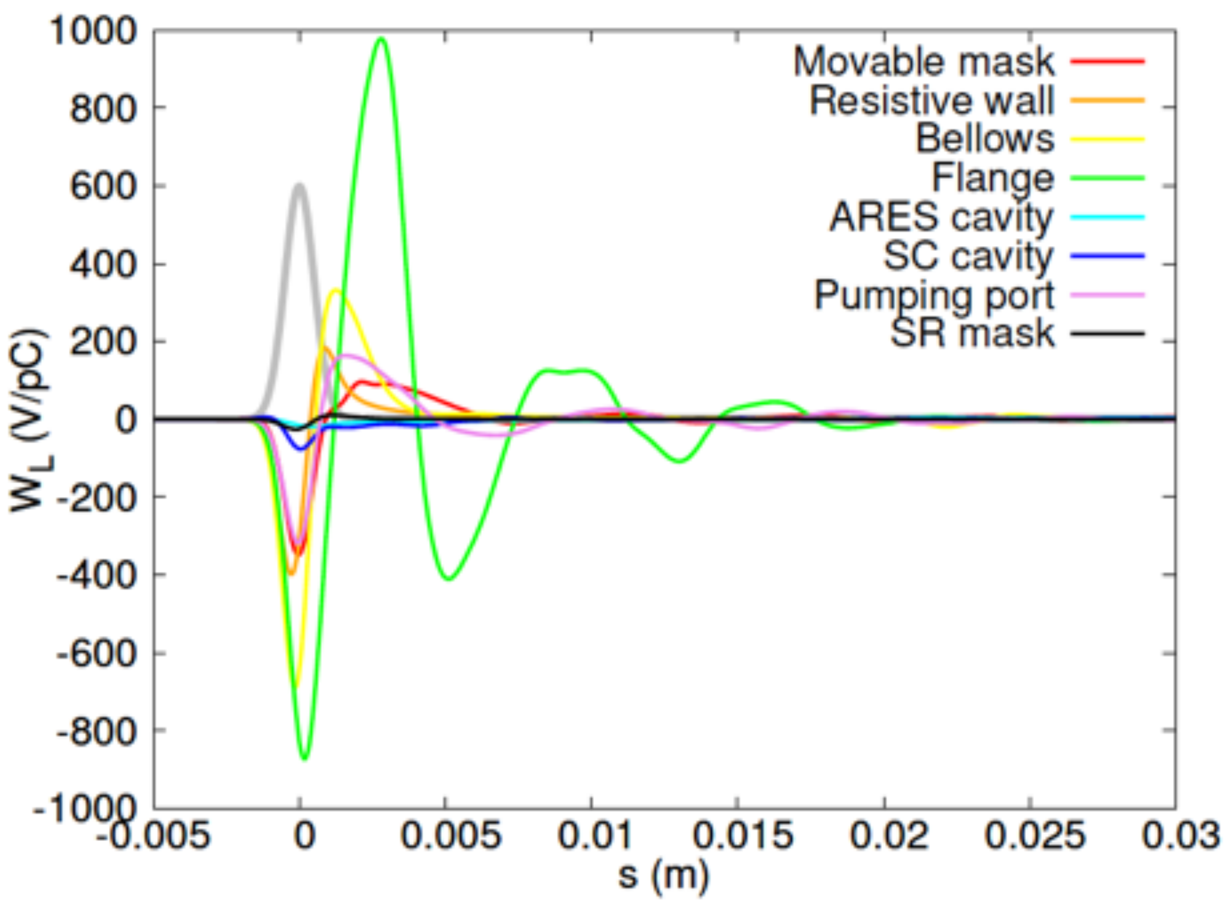


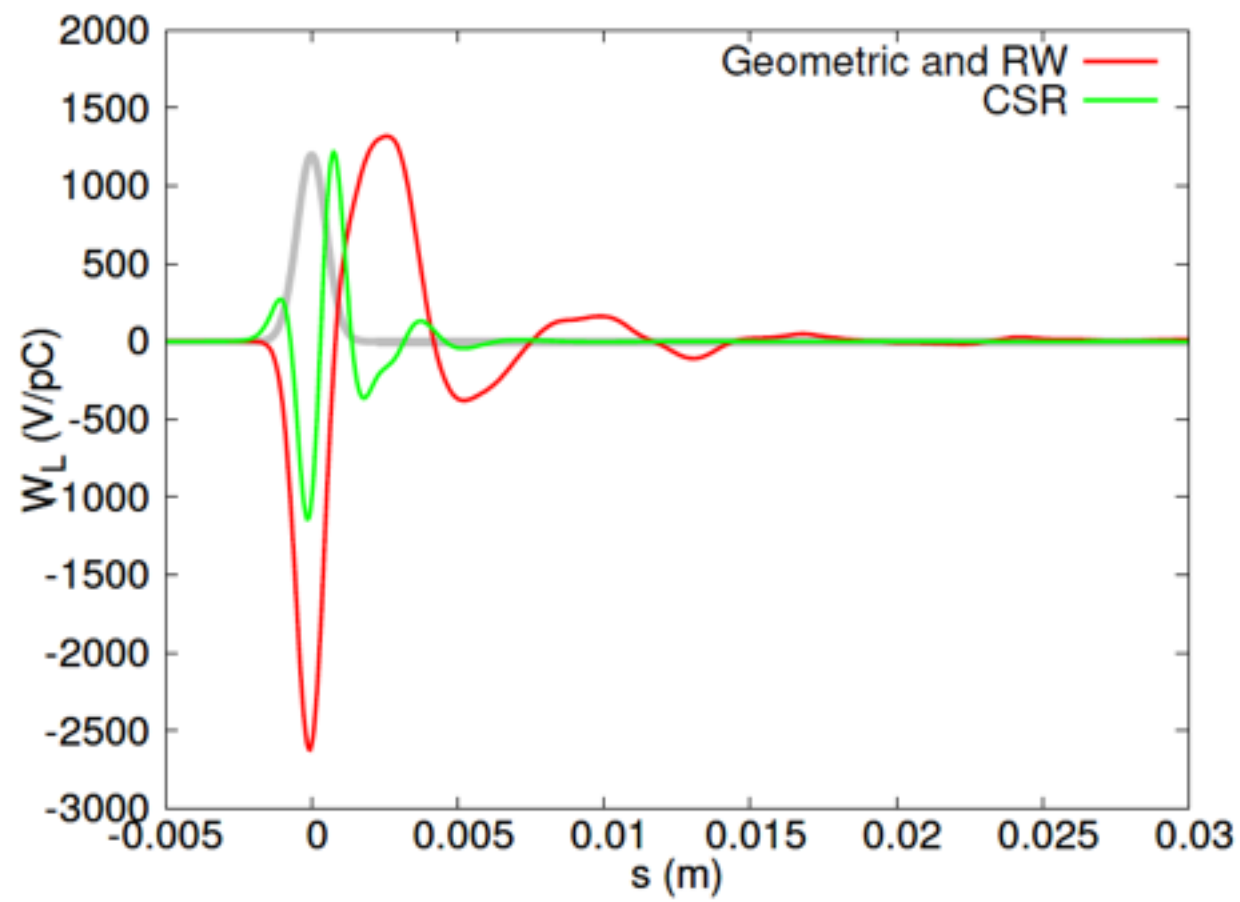


2. Impedance calculations: Results: HER

➤ **Pseudo-Green wake function**

- σ_z=0.5mm
- CSR: CSRZ code with rectangular chamber
- CWR (Wiggler radiation) not considered yet

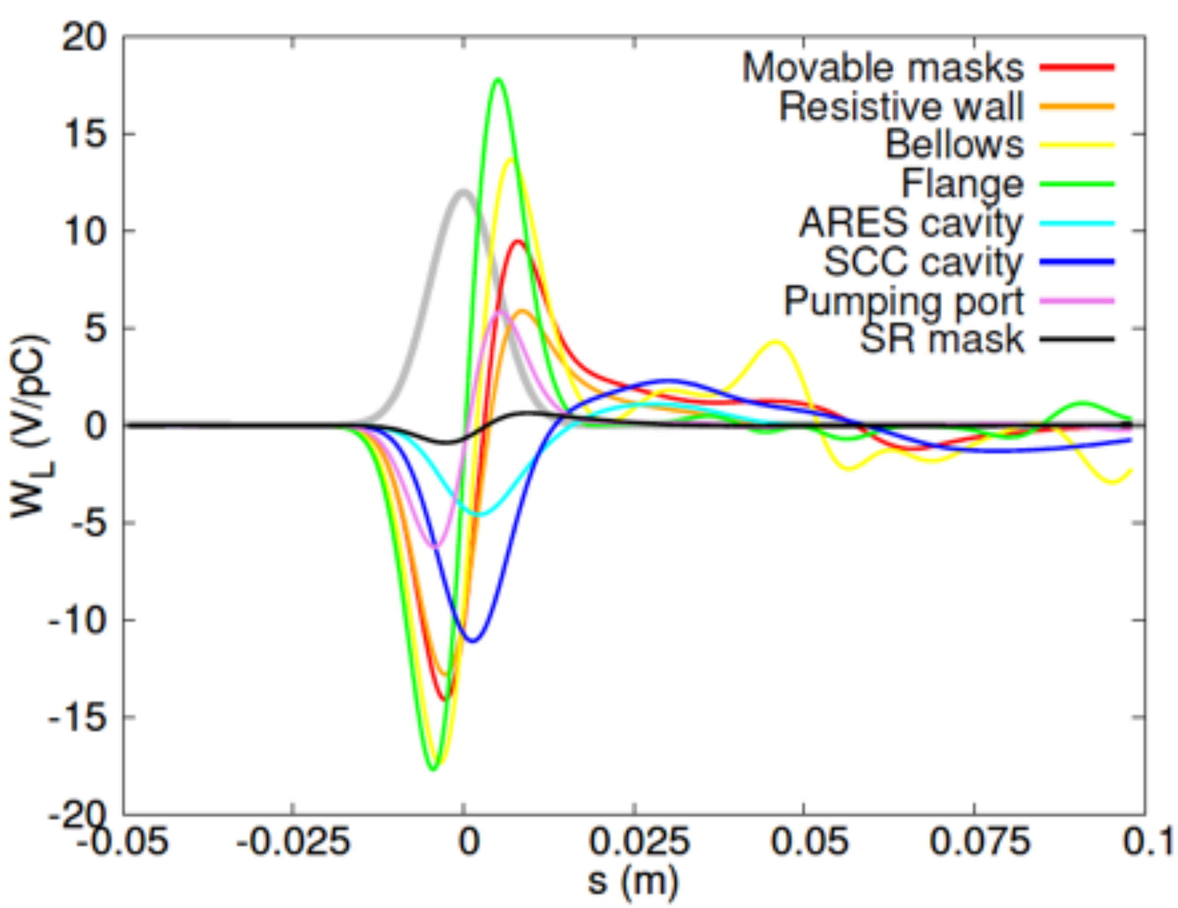


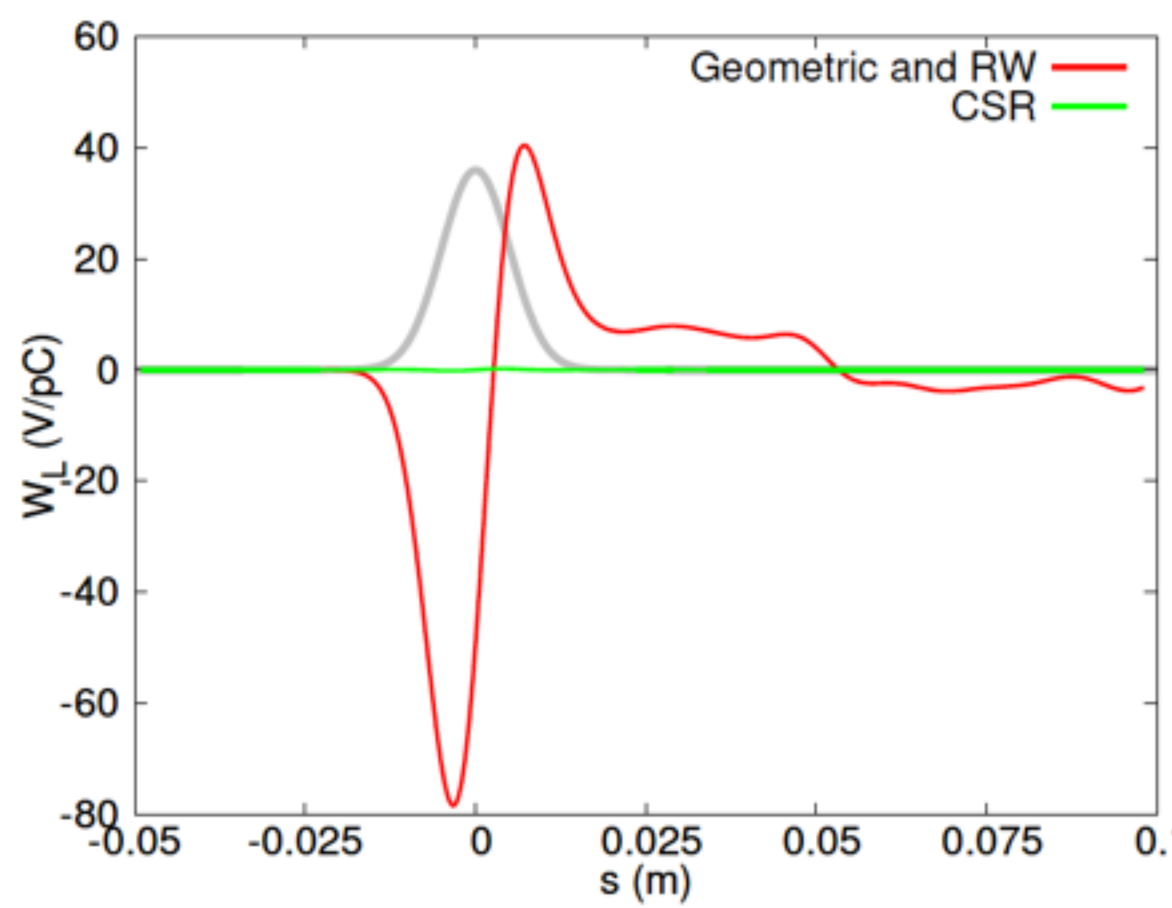


2. Impedance calculations: Results: HER

➤ **Wake potential with nominal bunch length**

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





2. Impedance calculations: Impedance budget

➤ **Impedance budget with σ_z=5/4.9mm:**

- **Loss factors, resistance and inductance are calculated at nominal bunch lengths**
- **Bellows, flanges and pumping ports contribute more impedance in HER than in LER**

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

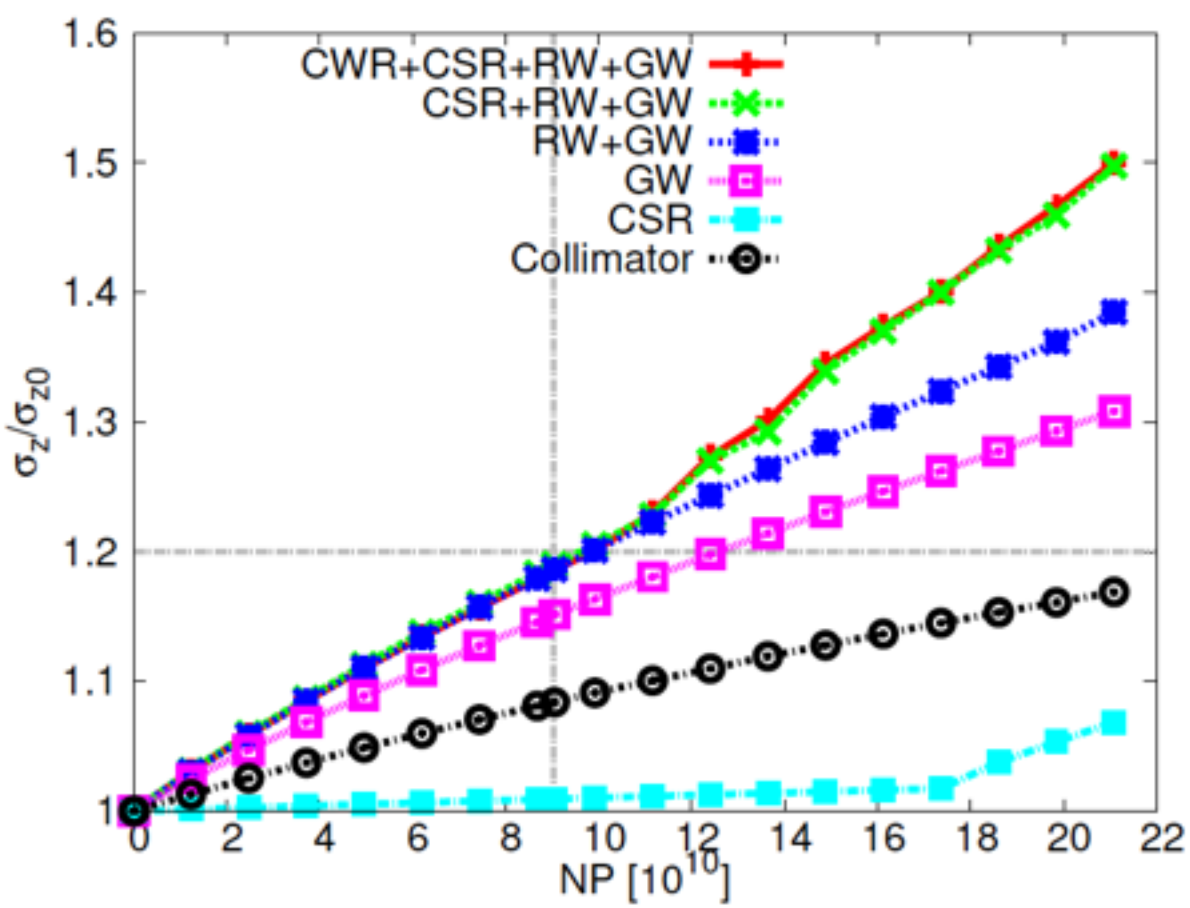
Table 2: Key parameters of SuperKEKB main rings for MWI simulations.

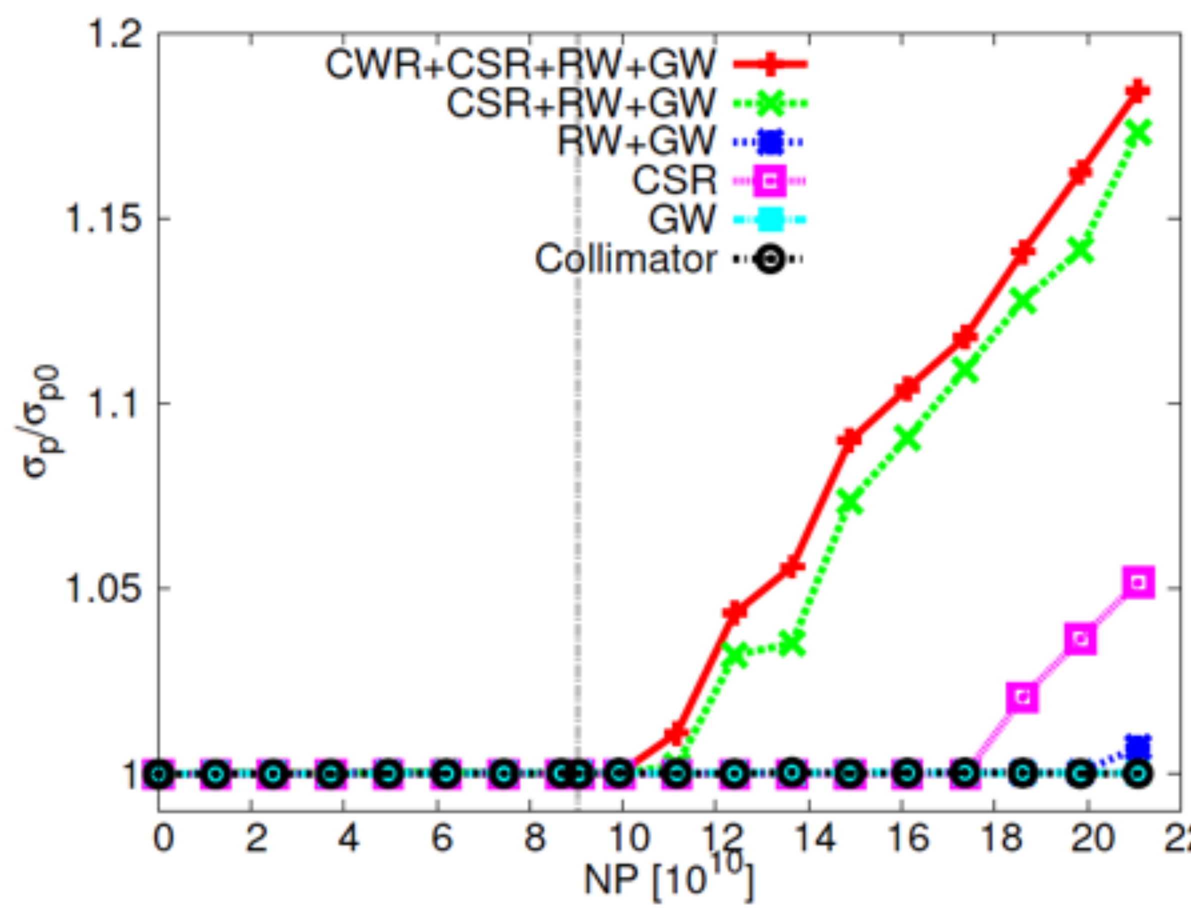
Parameter	LER	HER
Circumference (m)	3016.25	3016.25
Beam energy (GeV)	4	7.007
Bunch population (10^{10})	9.04	6.53
Nominal bunch length (mm)	5	4.9
Synchrotron tune	0.0244	0.028
Long. damping time (ms)	21.6	29.0
Energy spread (10^{-4})	8.1	6.37

Ref. D. Zhou, IPAC14, TUPRI021

3. Single-bunch effects: Longitudinal: LER

- **Simulations with input of Pseudo-Green wake:**
  - **Use Warnock-Cai's VFP solver**
  - **Collimators are important sources in bunch lengthening**
  - **Simulated $\sigma_z \approx 5.9$mm @Design bunch current**
  - **Simulated MWI threshold is around $NP_{th}=1.05E11$**
  - **Interplay between CSR and conventional wakes?**

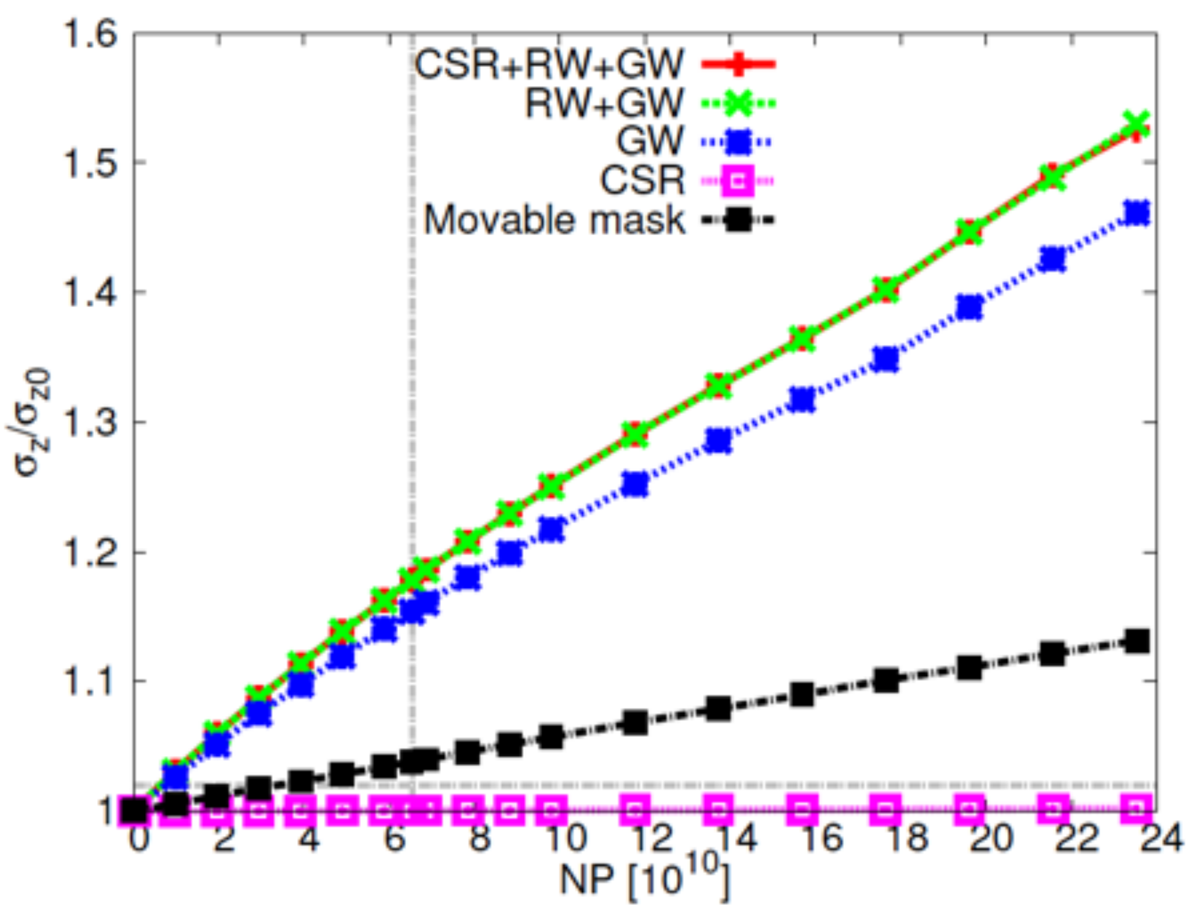


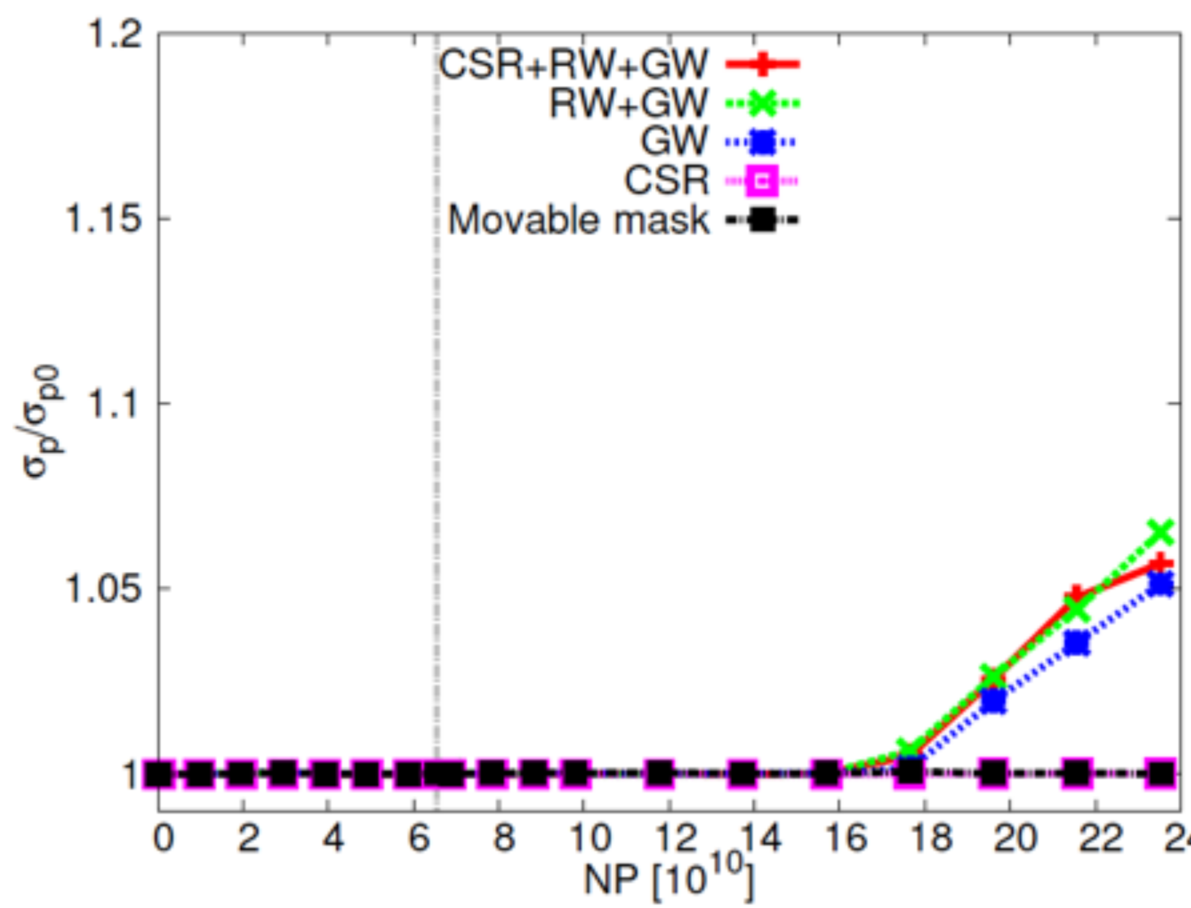


3. Single-bunch effects: Longitudinal: HER

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

- **Use Warnock-Cai's VFP solver**
- **Simulated $\sigma_z \approx 5.8$mm @Design bunch current**
- **Simulated MWI threshold is around NP_{th}=1.7E11**
- **CSR and CWR are likely to be not important.**





3. 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:

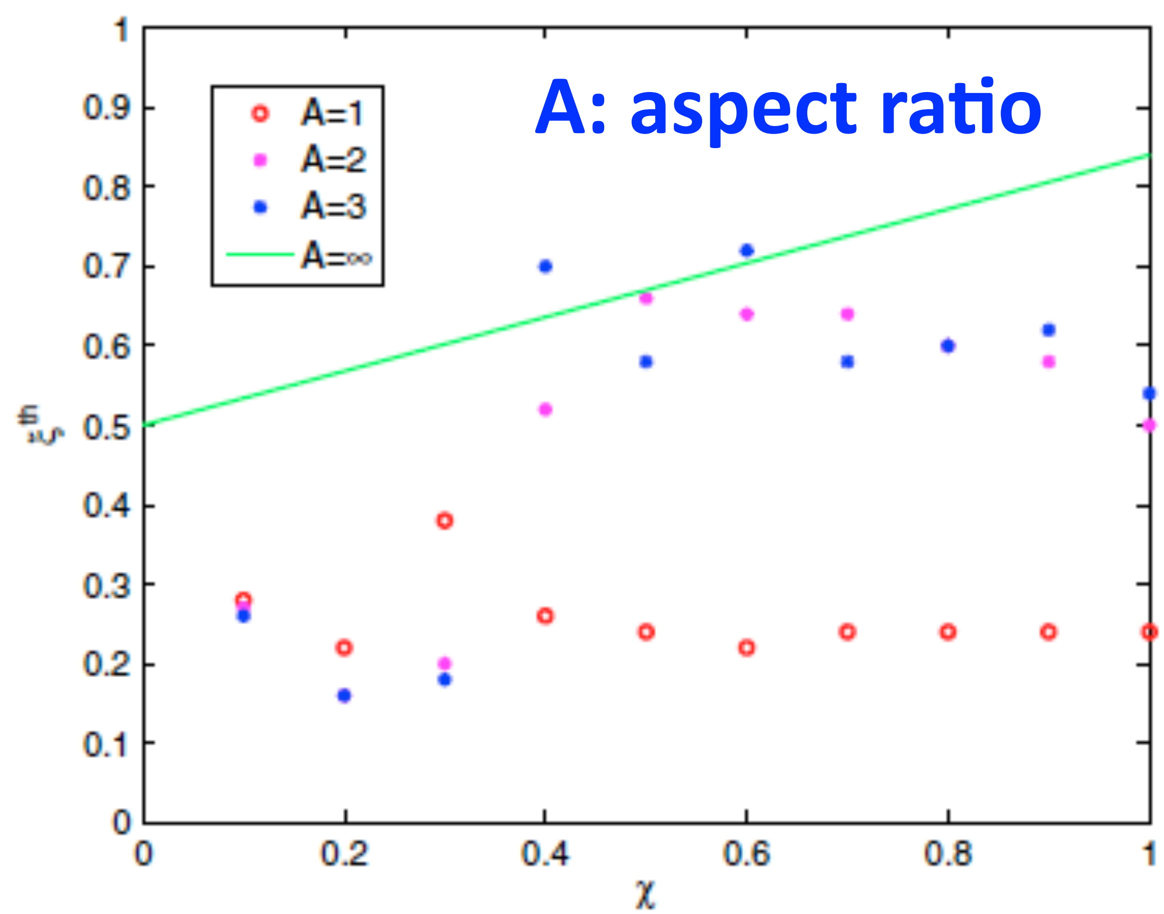
$$\xi = \xi_{th}(\chi, A = \frac{a}{b}, \frac{1}{\omega_s \tau_d})$$

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)

3. Single-bunch effects: Longitudinal: CSR

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

	DR			LER	HER
E(GeV)	1.1			4	7.007
NP(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	141			3.25	4.55
σ	5.5			8.08	6.37
σ	6.6	7.8	11	6	5
ξ	1.49	1.67	2.16	1.15	2.1
N	4.4	5.2	7.6	8.8	20.2
ξ	0.5(?)	0.5(?)	0.5(?)	0.25	0.5(?)
N	1.5	1.6	1.8	1.9	4.9

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

3. Single-bunch effects: Transverse: Beam tilt

- **G. Stupakov's theory on transverse beam tilt:**
  - **To be a concern in low emittance rings**
  - **Asymmetric protrusion (if exists)**

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

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

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

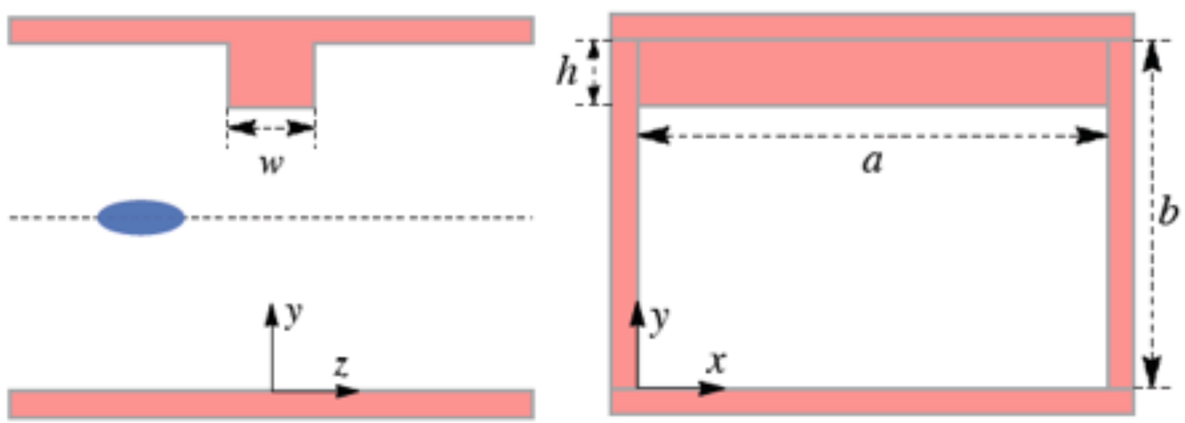
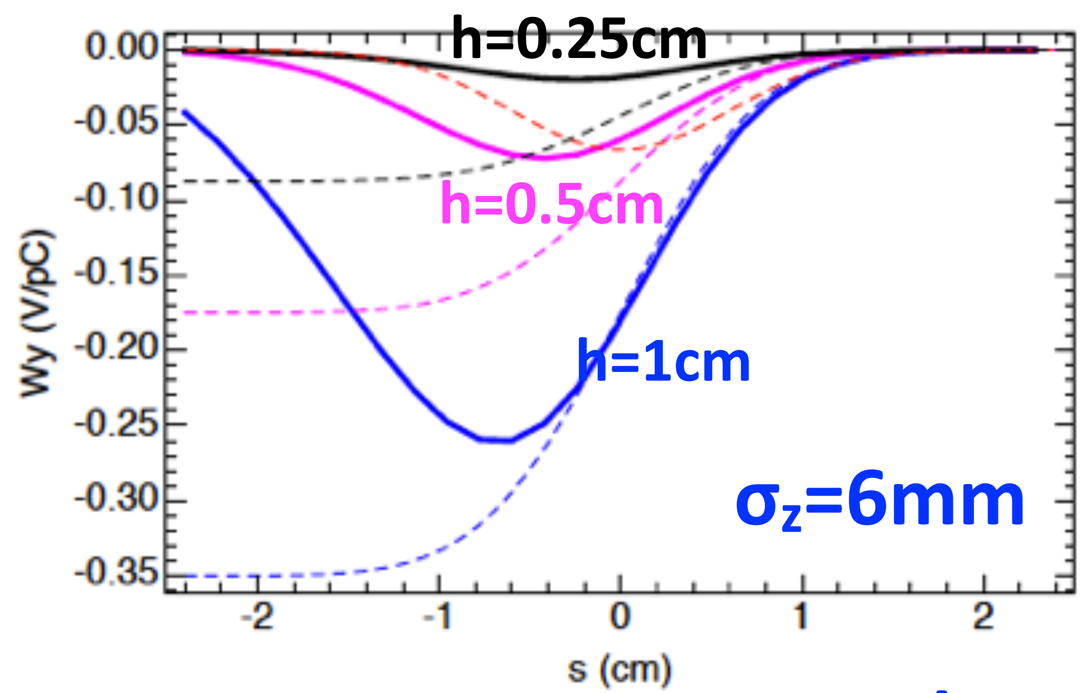


TABLE II. Emittance increase in LER of SUPERKEKB

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

Submitted to NIMA



From G. Stupakov

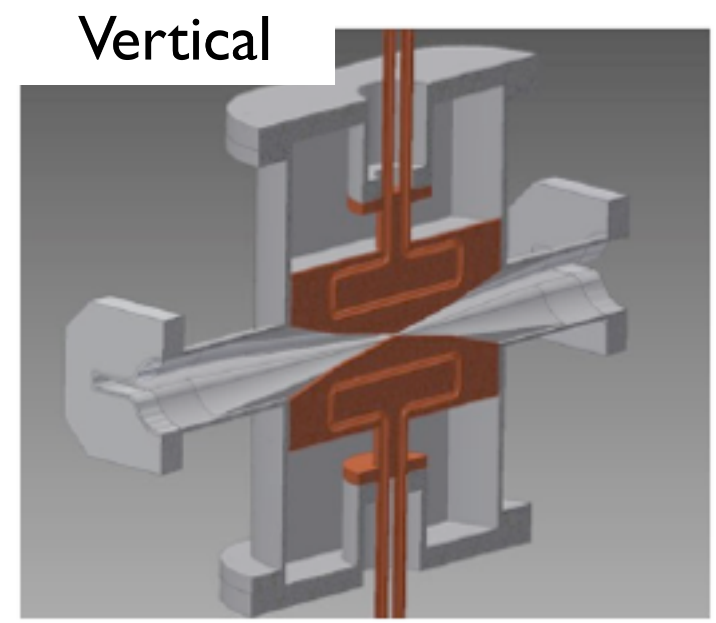
3. Single-bunch effects: Transverse: Beam tilt

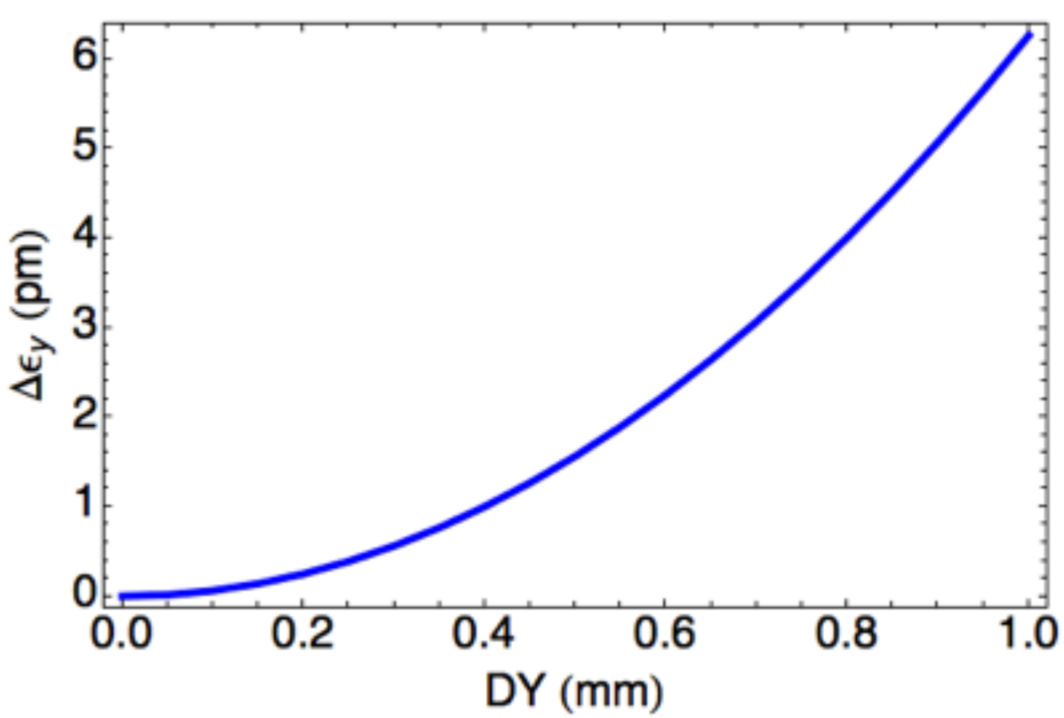
➤ **G. Stupakov's theory on transverse beam tilt:**

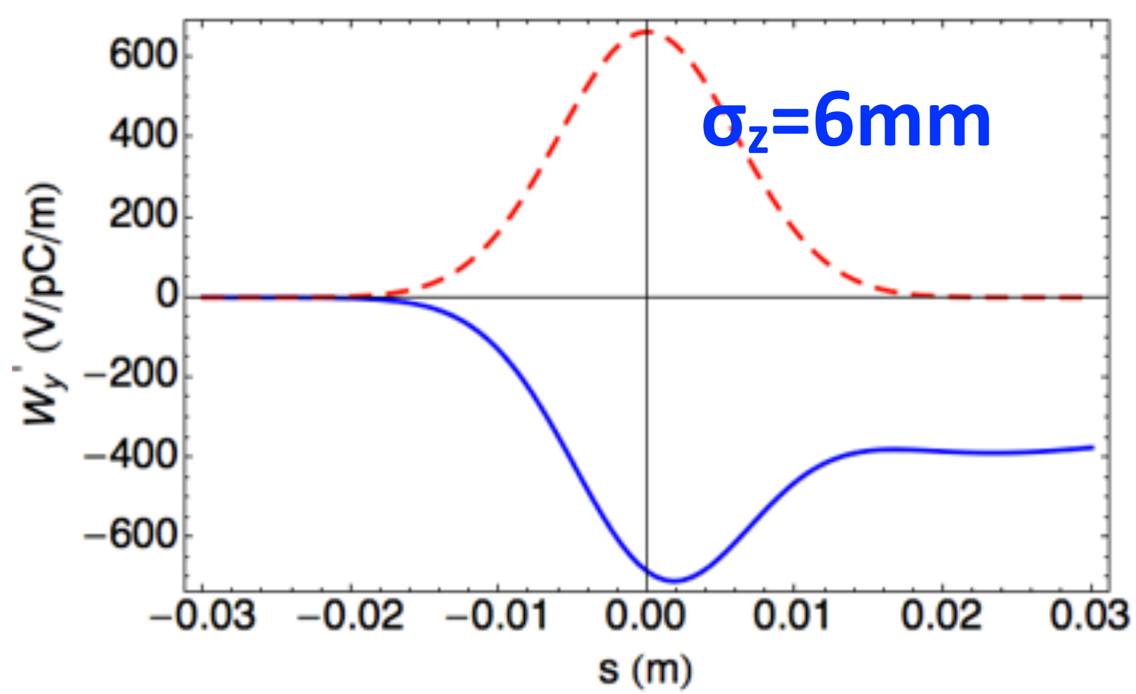
- **Symmetric 3D structure (like collimator) with orbit offset**
- **D02V1 in LER as an example: d=-2/2mm, βy=104.6m**
- **COD DY < 0.2 mm required?**

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

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







3. 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

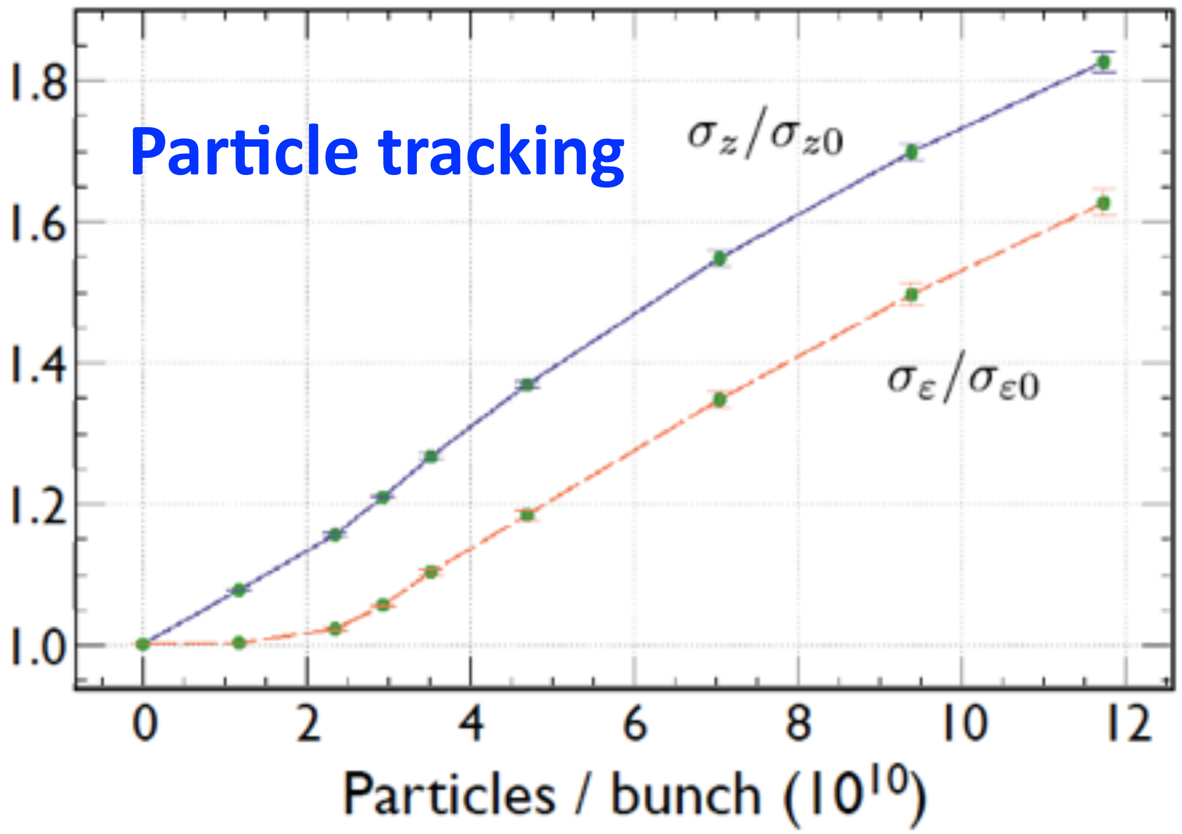
From T. Ishibashi and Y. Suetsugu

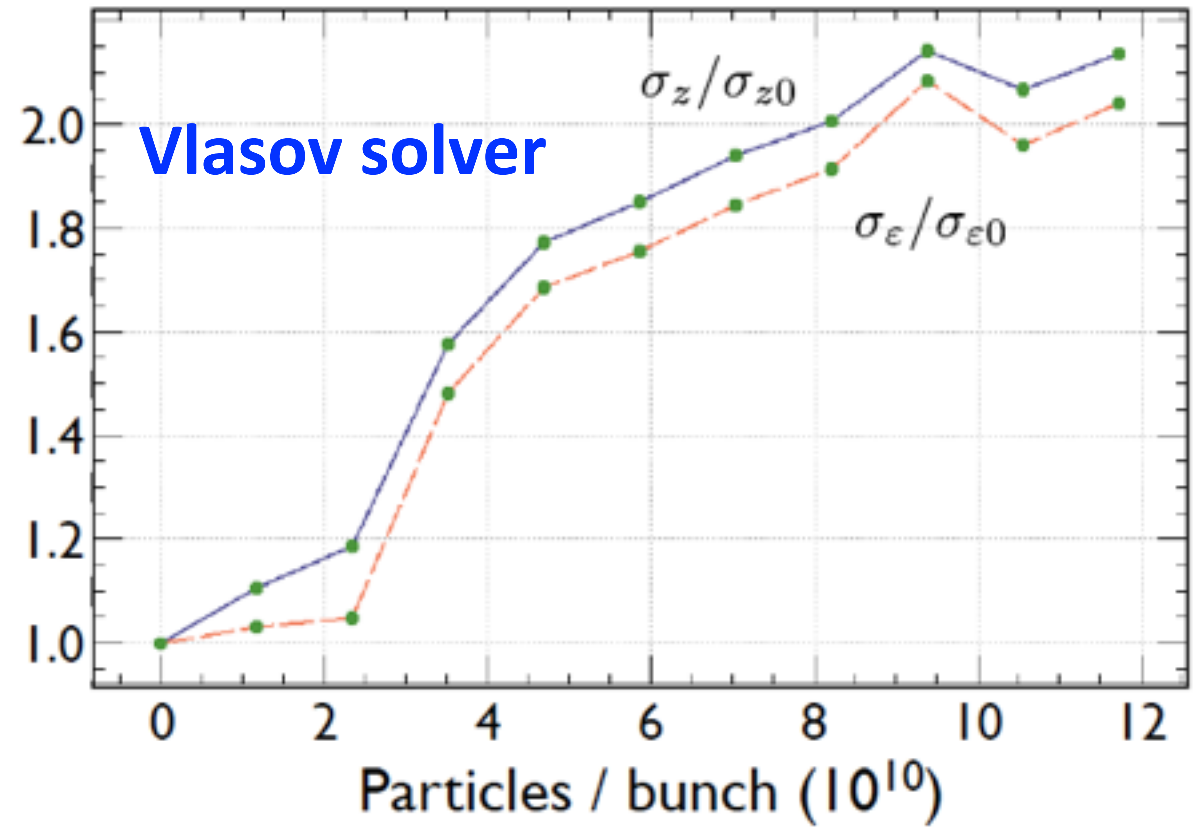
4. CSR: SuperKEKB design

- **CSR strongly changed the design of SuperKEKB**
  - **One of the bottlenecks for the "high-current" scheme**
  - **Showstopper for the low-α_p design of the damping ring**
  - **Potentially dangerous for the present "nano-beam" scheme [P.21 of this talk]**
- **Efforts of dedicated researches**
  - **T. Agoh, PhD thesis, 1999-2004**
  - **K. Oide, CSR code integrated into SAD, 2008**
  - **D. Zhou, PhD thesis, 2008-2011**

4. CSR: SuperKEKB: High-current scheme

➤ **Microwave instability due to CSR in LER was very serious.**





N (design)	11.7	10^{10}
σ_{z0}	3	mm
$\sigma_{\varepsilon 0}$	7.1	10^{-4}
ν_z	-0.022	

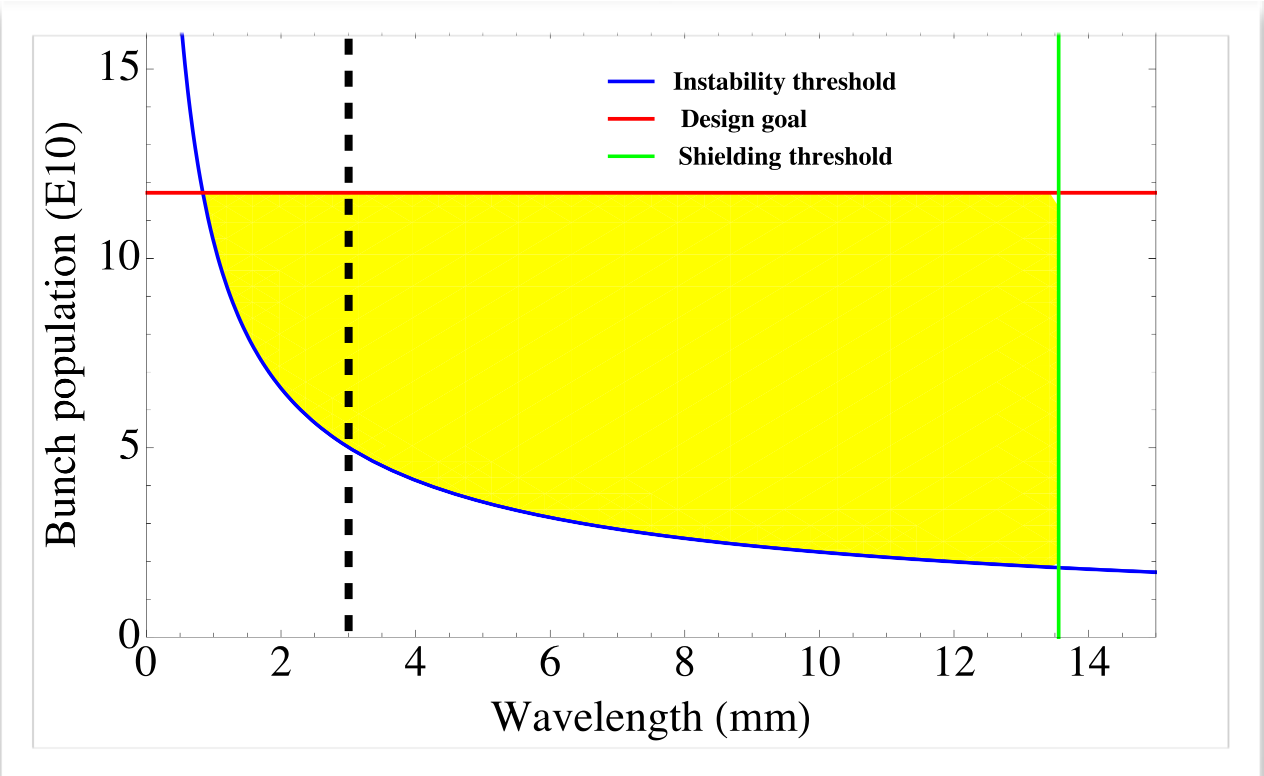
K. Oide, et al., MO3RAI01, PAC'09 (2009)
T. Agoh, PhD thesis (2004)

4. CSR: SuperKEKB: High-current scheme

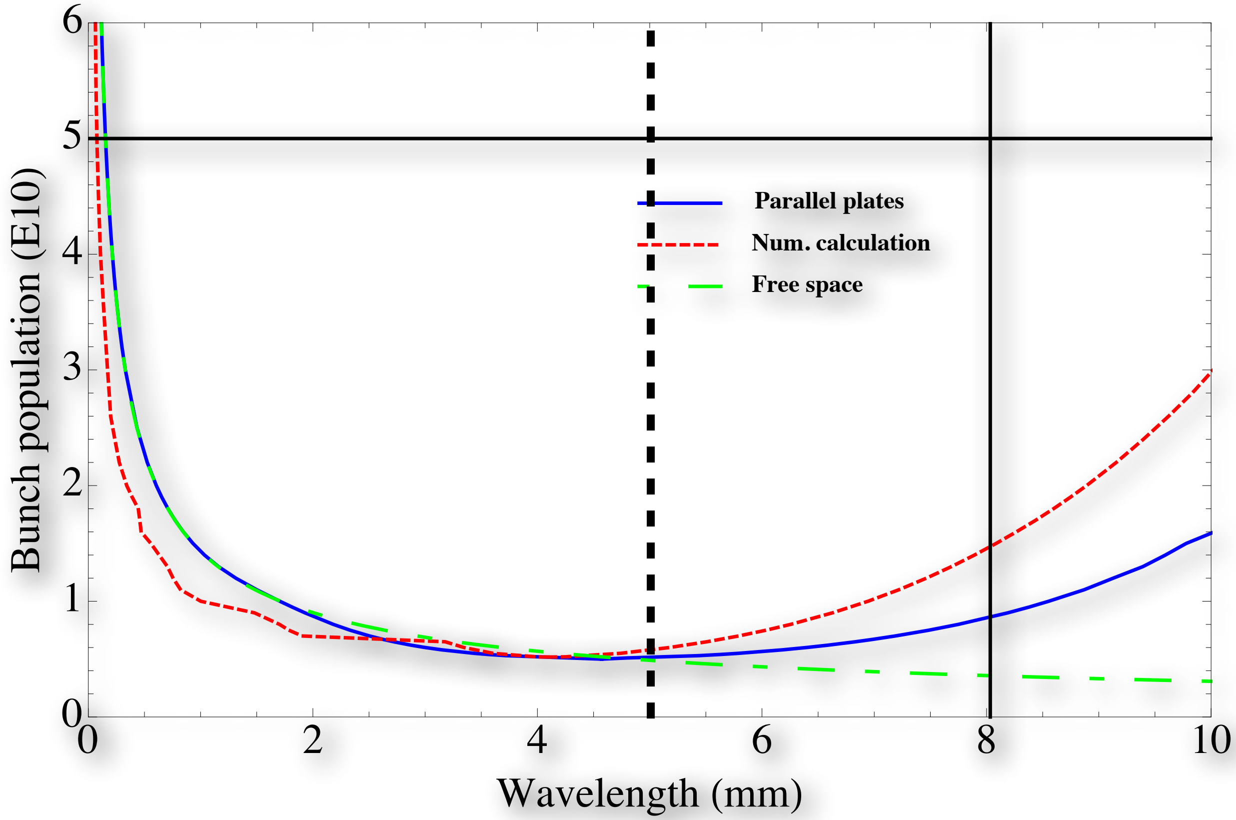
Simple estimation of CSR instability threshold [Stupakov and Heifets (2002)] **...**

$$I_b > \frac{\pi^{1/6}}{\sqrt{2}} \frac{ec}{r_0} \frac{\gamma}{\rho^{1/3}} \alpha_p \delta_0^2 \sigma_z \frac{1}{\lambda^{2/3}}$$

SuperKEKB LER (High-current scheme)



SuperKEKB DR (Version 1.140)



Shielding threshold:

$$\lambda_c = 2\sqrt{b^3/R}$$

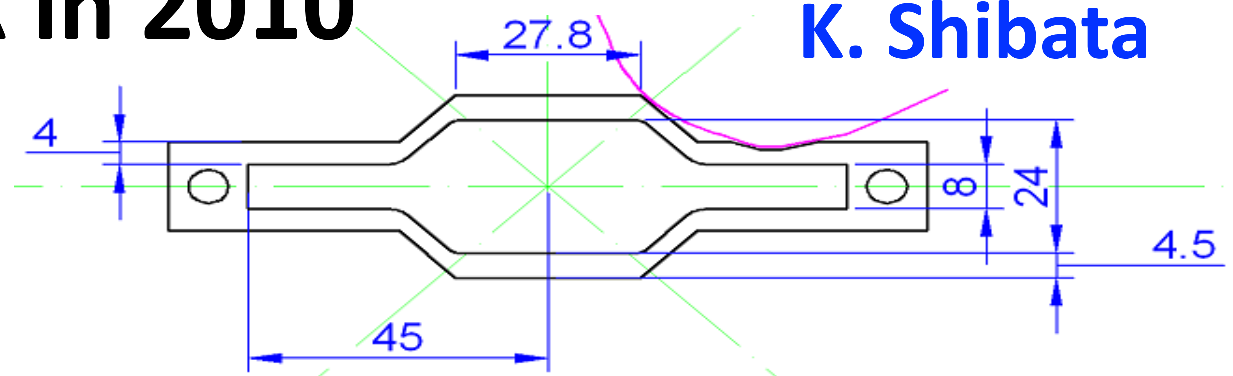
G. Stupakov and S. Heifets, PRST-AB 5, 054402 (2002)
J. Byrd, et al., PRL 89, 22, Nov. 2002
D. Zhou, et al., IPAC'10, p. 1554 (2010)

4. CSR: SuperKEKB: Damping ring

➤ Found to be important in DR in 2010

- Optics: CSR-optimized
- Vacuum chamber and RF system

K. Shibata



➤ Collaboration

- KEK: T. Agoh, H. Ikeda, M. Kikuchi, K. Ohmi, K. Oide, K. Shibata, K. Yokoya, D. Zhou
- SLAC: Y. Cai, G. Stupakov, L. Wang
- CERN: F. Zimmermann

➤ Intensive CSR impedance calculations

- Benchmark: 5 codes (Agoh, Oide, Zhou, Stupakov, L. Wang)
- Single-bend and multi-bend
- Rectangular and arbitrary cross-section of chamber

➤ Intensive simulations of MWI

- Macro-particle tracking: SAD
- Vlasov solver: SAD, Warnock-Cai's code

4. CSR: Field dynamics

Parabolic equation (PE) in Frenet-Serret coordinate system:

$$\frac{\partial \vec{E}_\perp}{\partial s} = \frac{i}{2k}\left[\nabla_\perp^2 \vec{E}_\perp - \frac{1}{\epsilon_0}\nabla_\perp \rho_0 + 2k^2\left(\frac{x}{R(s)} - \frac{1}{2\gamma^2}\right)\vec{E}_\perp\right]$$

T. Agoh, PRST-AB 7, 054403 (2004).

Longitudinal field and impedance:

$$E_s = \frac{i}{k}\left(\nabla_\perp \cdot \vec{E}_\perp - \mu_0 c J_s\right) \qquad Z(k) = -\frac{1}{q}\int_0^\infty E_s(x_c, y_c)\,ds$$

Contributors:

- G. Stupakov and I.A. Kotelnikov (Mode expansion, PRST-AB 2003, 2009)
- T. Agoh & K. Yokoya (Mesh and Eigenfunction expansion, PRST-AB 2004, 2009)
- D.R. Gillingham and T.M. Antonsen (Time-domain PE, PRST-AB 2007)
- K. Oide (Mesh + Eigen solver, PAC 2009)
- D. Zhou (Mesh + Finite difference, JJAP 2012)
- L. Wang (Mesh + Finite element, 2012)
- D.A. Bizzozero (Mesh + Discontinuous Galerkin method, 2013)
- R. Warnock (?)

4. CSR: Field dynamics

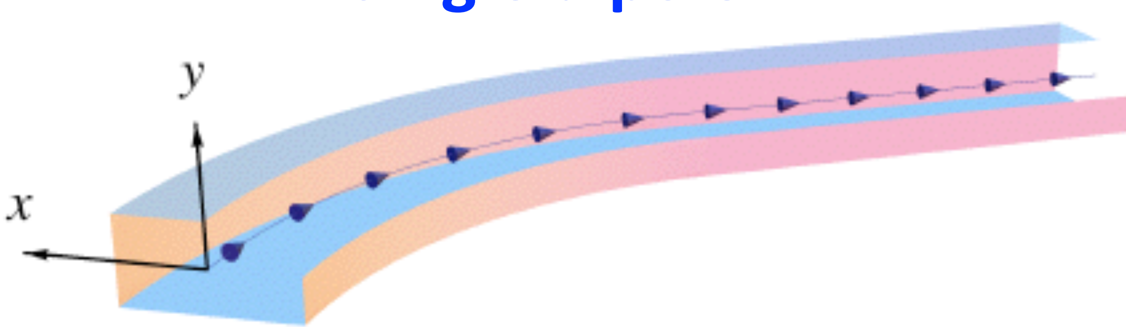
CSRZ code (D. Zhou): Uniform rectangular cross-section

Field separation:

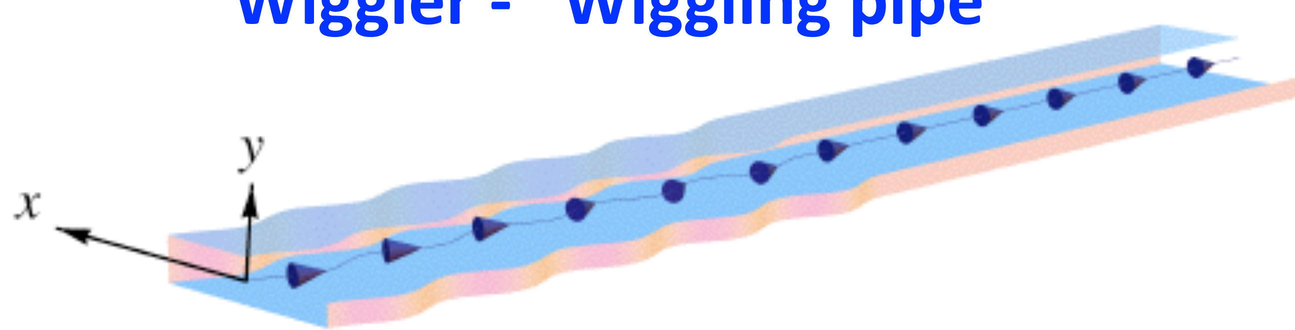
$$\vec{E}_\perp = \vec{E}^r_\perp + \vec{E}^b_\perp \quad \rightarrow \quad \frac{\partial \vec{E}^r_\perp}{\partial s} = \frac{i}{2k}\left[\nabla^2_\perp \vec{E}^r_\perp + 2k^2\left(\frac{x}{R(s)} - \frac{1}{2\gamma^2}\right)\left(\vec{E}^r_\perp + \vec{E}^b_\perp\right)\right]$$

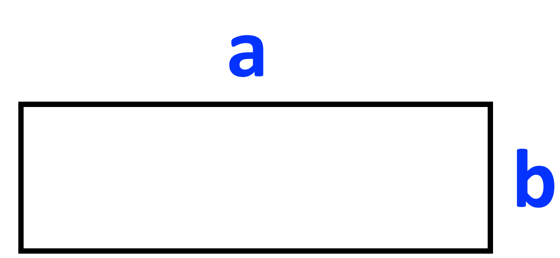
The curvature is variable (Single dipole, soft fringe, a series of dipoles, wiggler, etc.):

Single dipole



Wiggler - "Wiggling pipe"

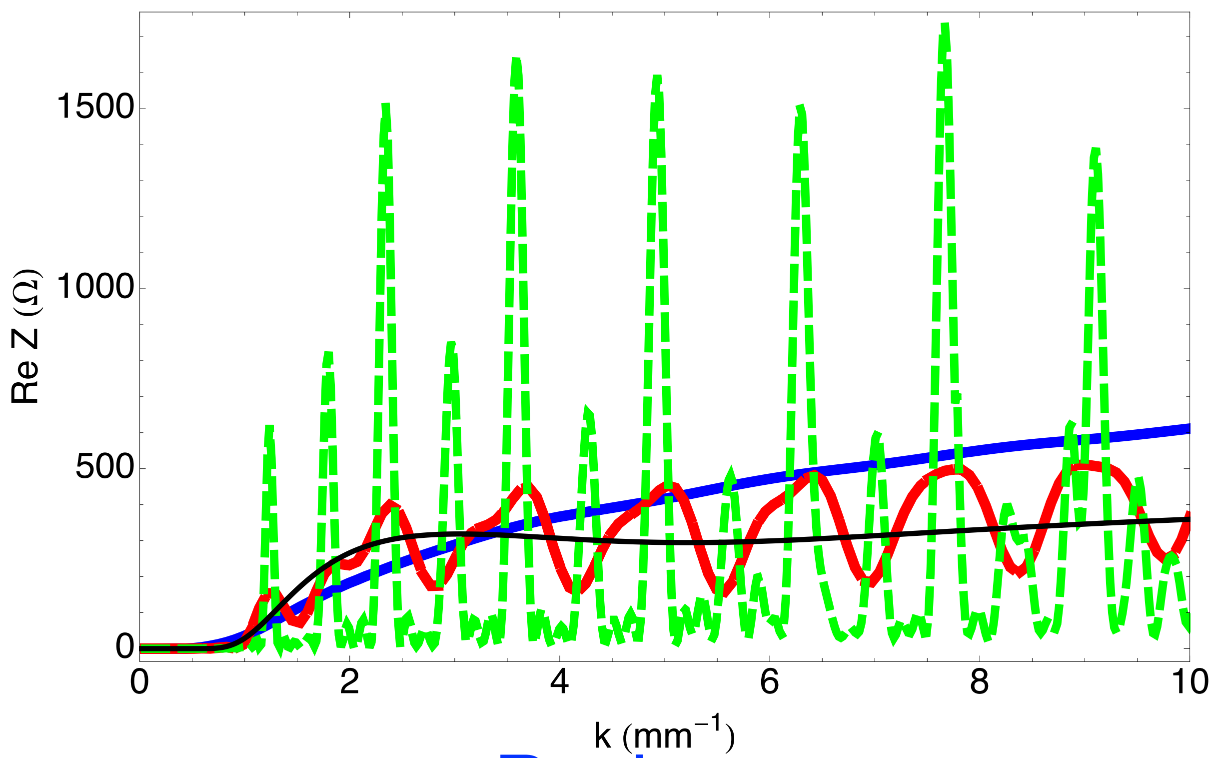




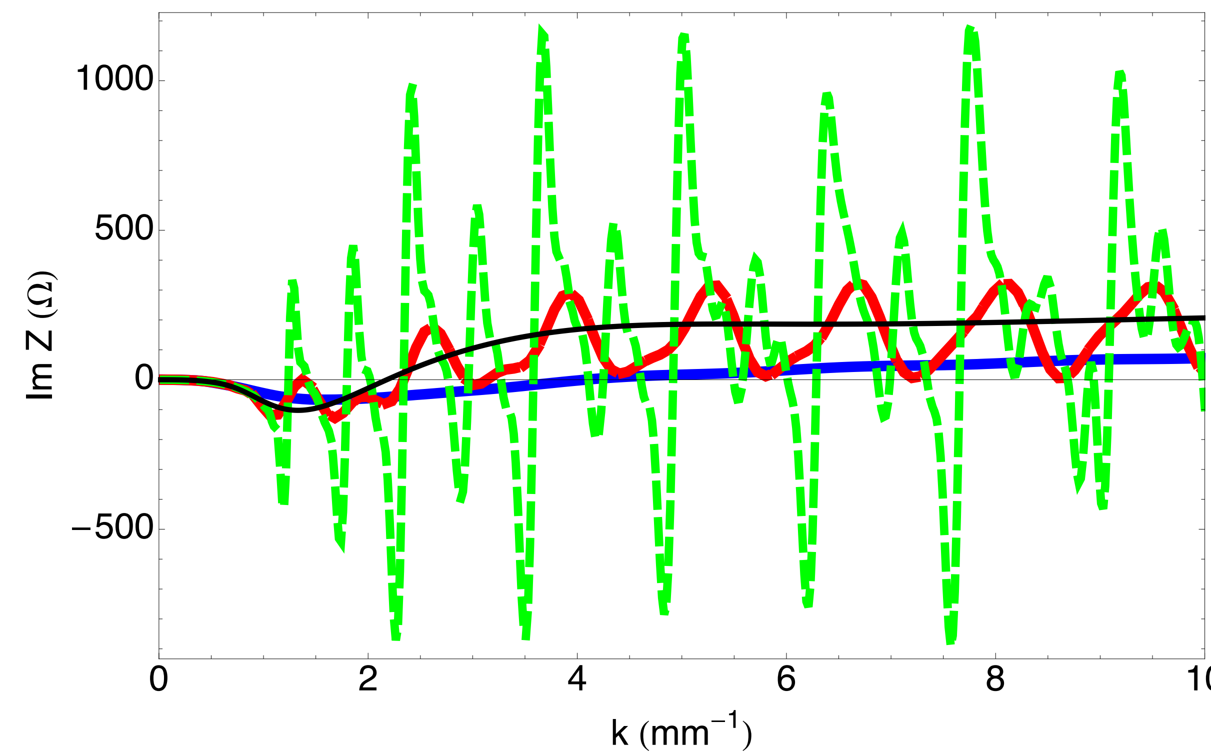
4. CSR: Field dynamics: Eigenmodes

A single bend: excited modes of toroidal chamber

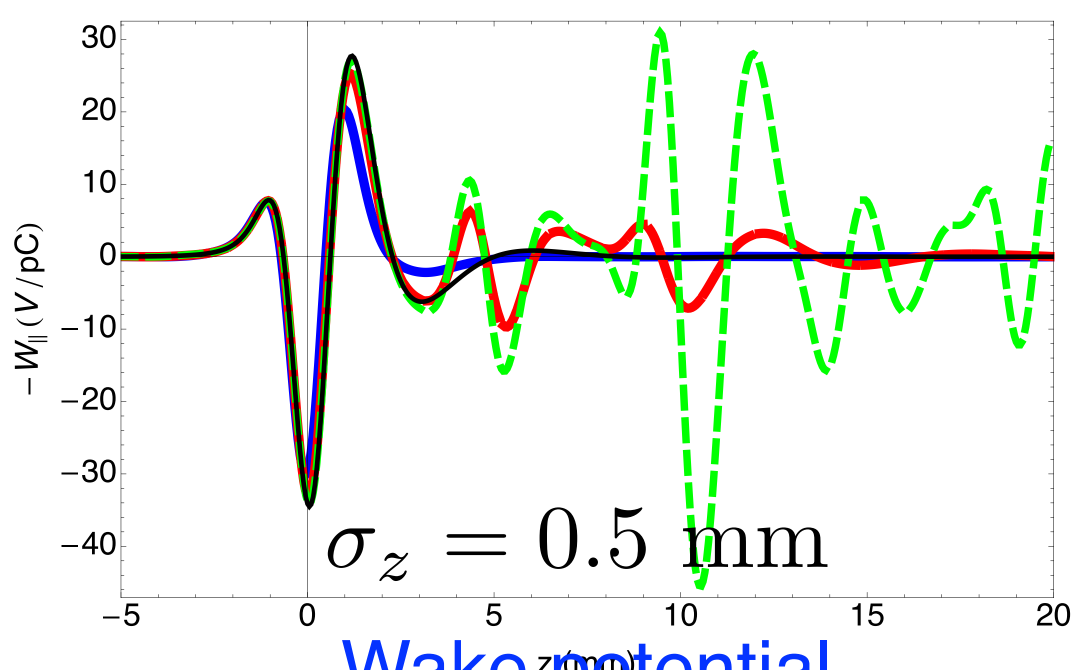
a/b=60/30 mm, R=5 m, L_{bend}=0.5/2/8 m



Real part



Imaginary part



Wake potential

$$L_c \approx 2\sqrt{2Rx_b}$$

Blue solid: L_{bend}=0.5 m

Red dashed: L_{bend}=2 m

Green dotted: L_{bend}=8 m

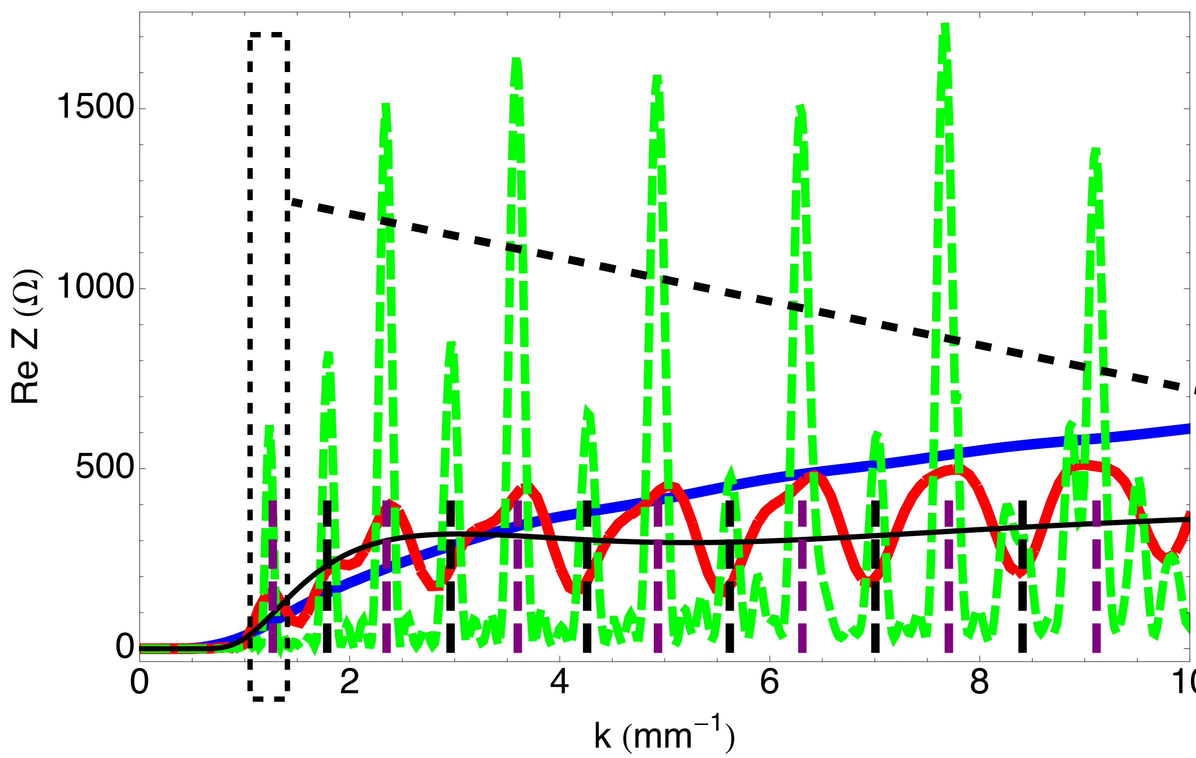
Black solid: Parallel-plates model

D. Zhou et al., Jpn. J. Appl. Phys. 51 (2012) 016401.

4. CSR: Field dynamics: Eigenmodes

Resonance poles = Eigen modes

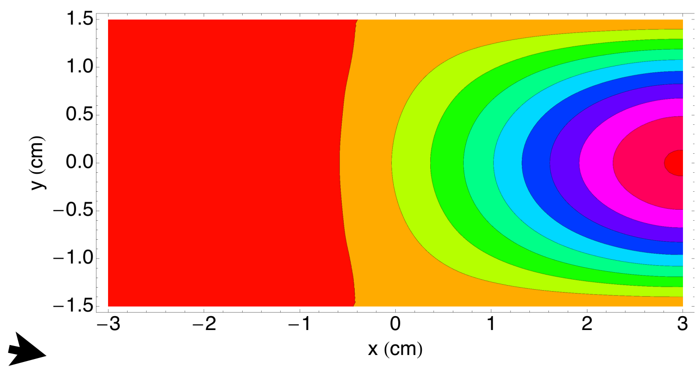
a/b=60/30 mm, L_{bend}=8 m, R=5 m



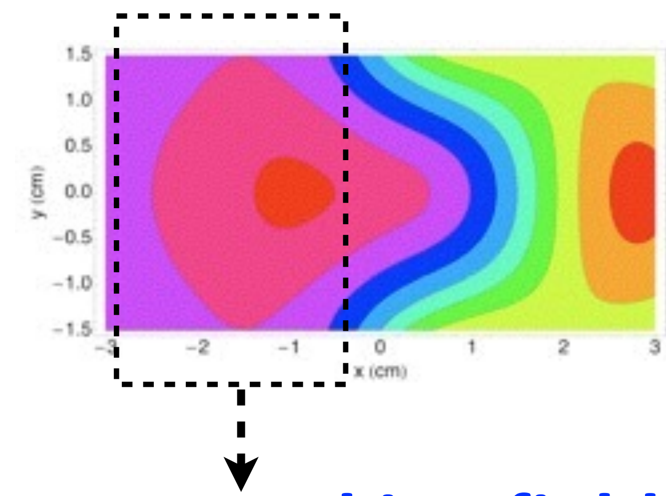
Freq. & index

$$k = 1230 \text{ m}^{-1}$$
$$(m, p) = (0, 1)$$

Im. E_x^r:

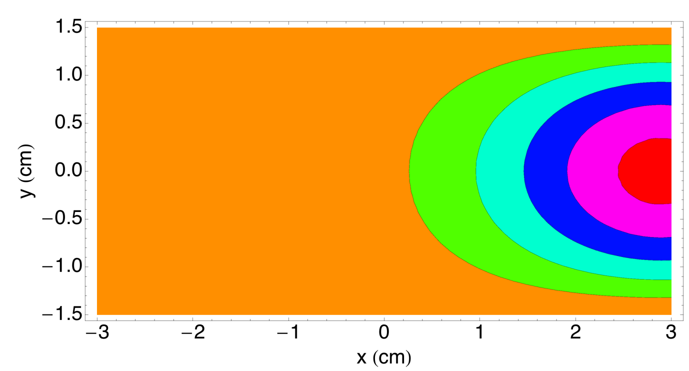


Re. E_x^r:



Overtaking fields

Mode pattern:



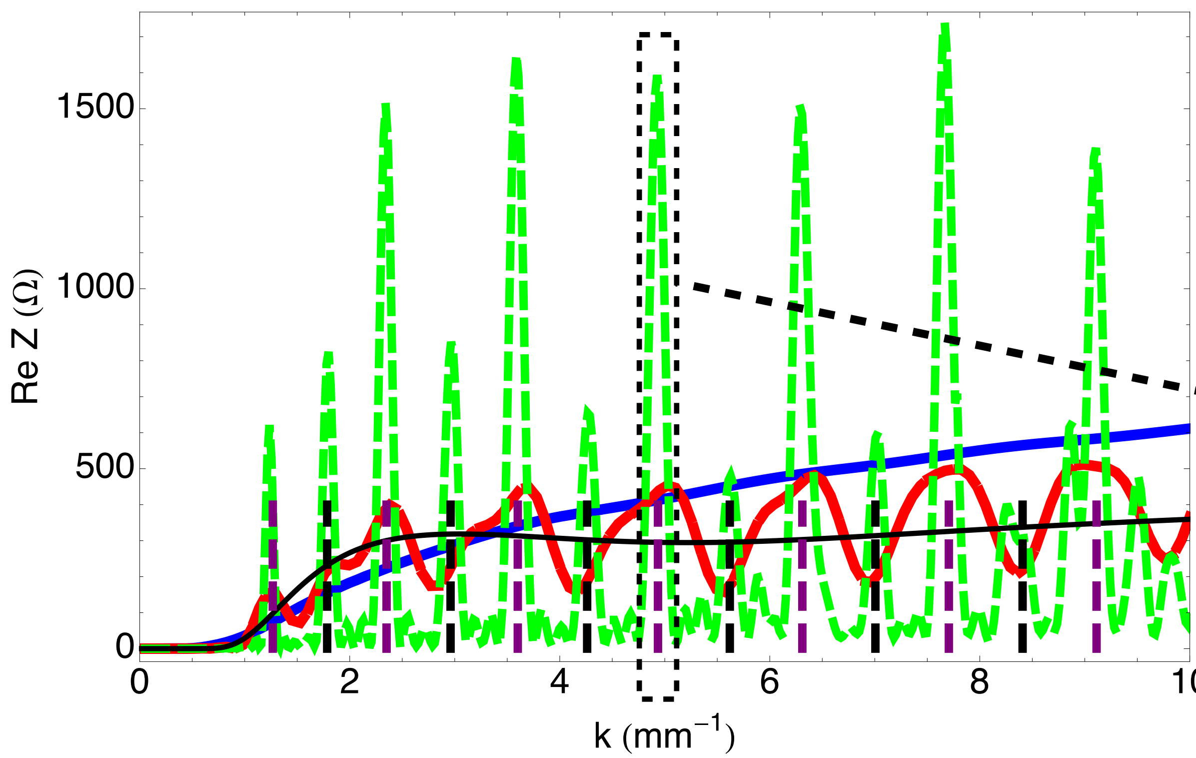
E_x mode: $$E_x(x, y) = E_{x0} \text{Ai}\left(k_y^2 \kappa^2 - x/\kappa\right) \sin\left[k_y(y + b/2)\right]$$

 G. Stupakov and I. Kotelnikov, PRST-AB 6, 034401 (2003).

4. CSR: Field dynamics: Eigenmodes

Resonance poles = Eigen modes

a/b=60/30 mm, L_{bend}=8 m, R=5 m

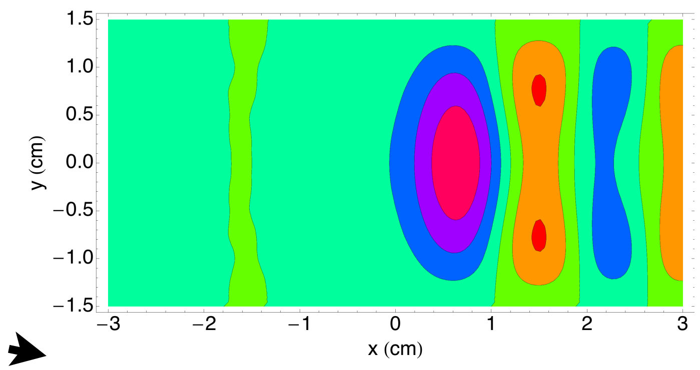


Freq. & index

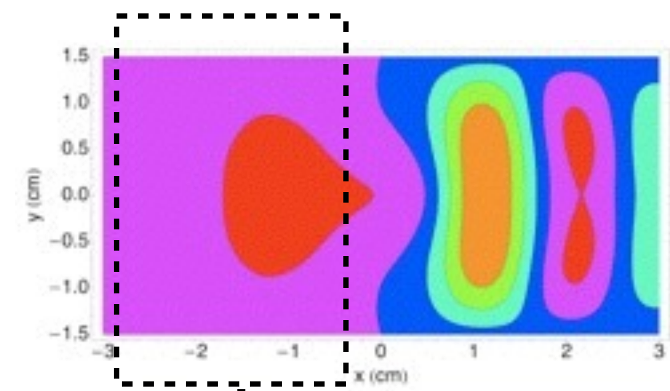
$$k = 4930\ \mathrm{m}^{-1}$$

$$(m, p) = (3, 1)$$

Im. E_x^r:

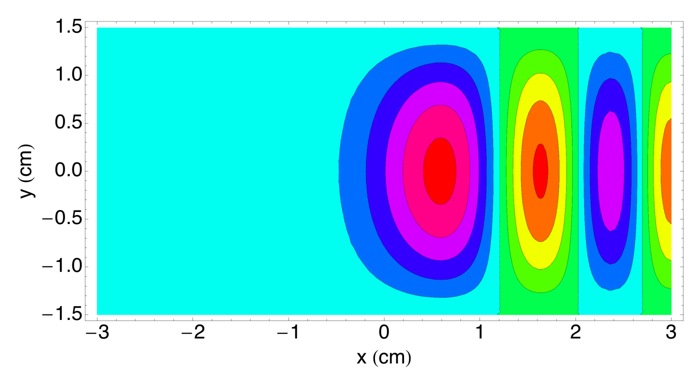


Re. E_x^r:



Overtaking fields

Mode pattern:



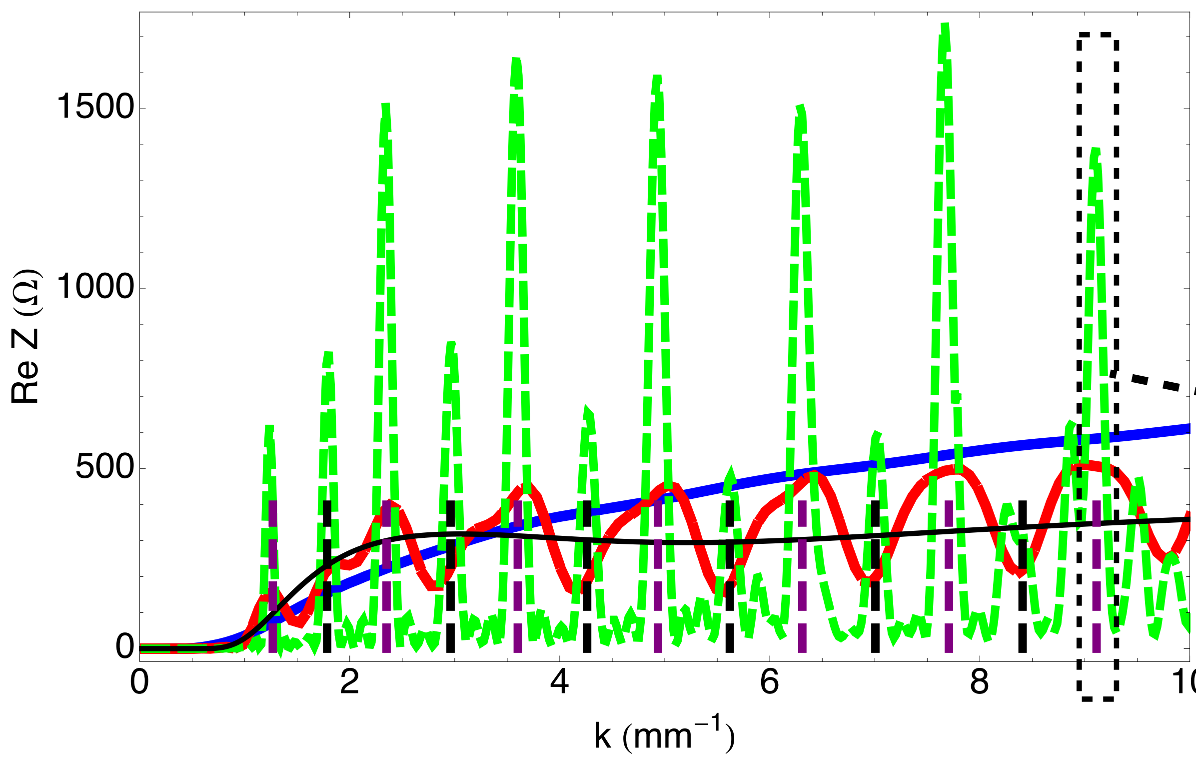
E_x mode: $$E_x(x, y) = E_{x0}\mathrm{Ai}\left(k_y^2\kappa^2 - x/\kappa\right)\sin\left[k_y(y + b/2)\right]$$

 G. Stupakov and I. Kotelnikov, PRST-AB 6, 034401 (2003).

4. CSR: Field dynamics: Eigenmodes

Resonance poles = Eigen modes

a/b=60/30 mm, L_{bend}=8 m, R=5 m

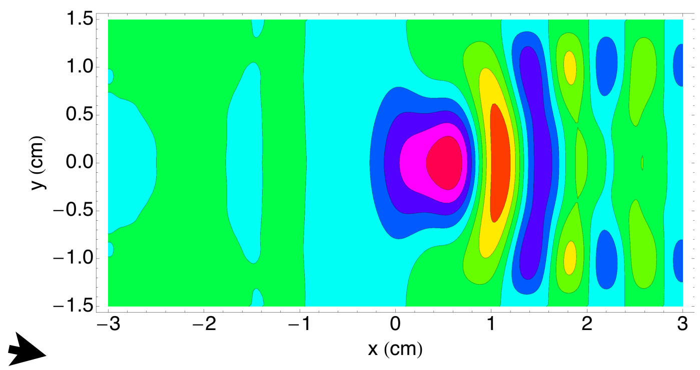


Freq. & index

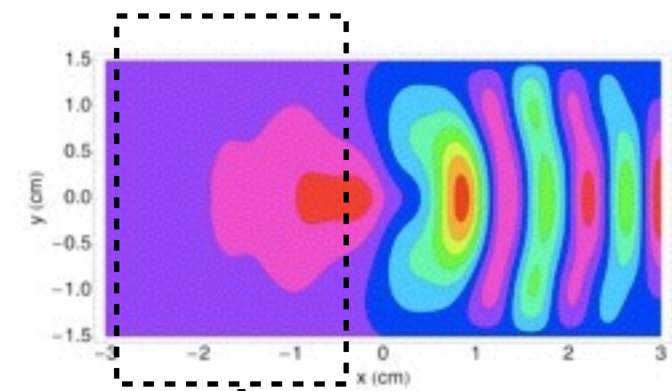
$$k = 9100\ \mathrm{m}^{-1}$$

$$(m,p) = (6,1)$$

Im. E_x^r:

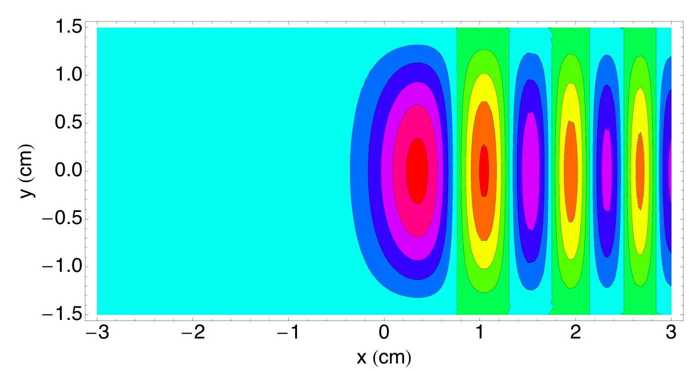


Re. E_x^r:



Overtaking fields

Mode pattern:

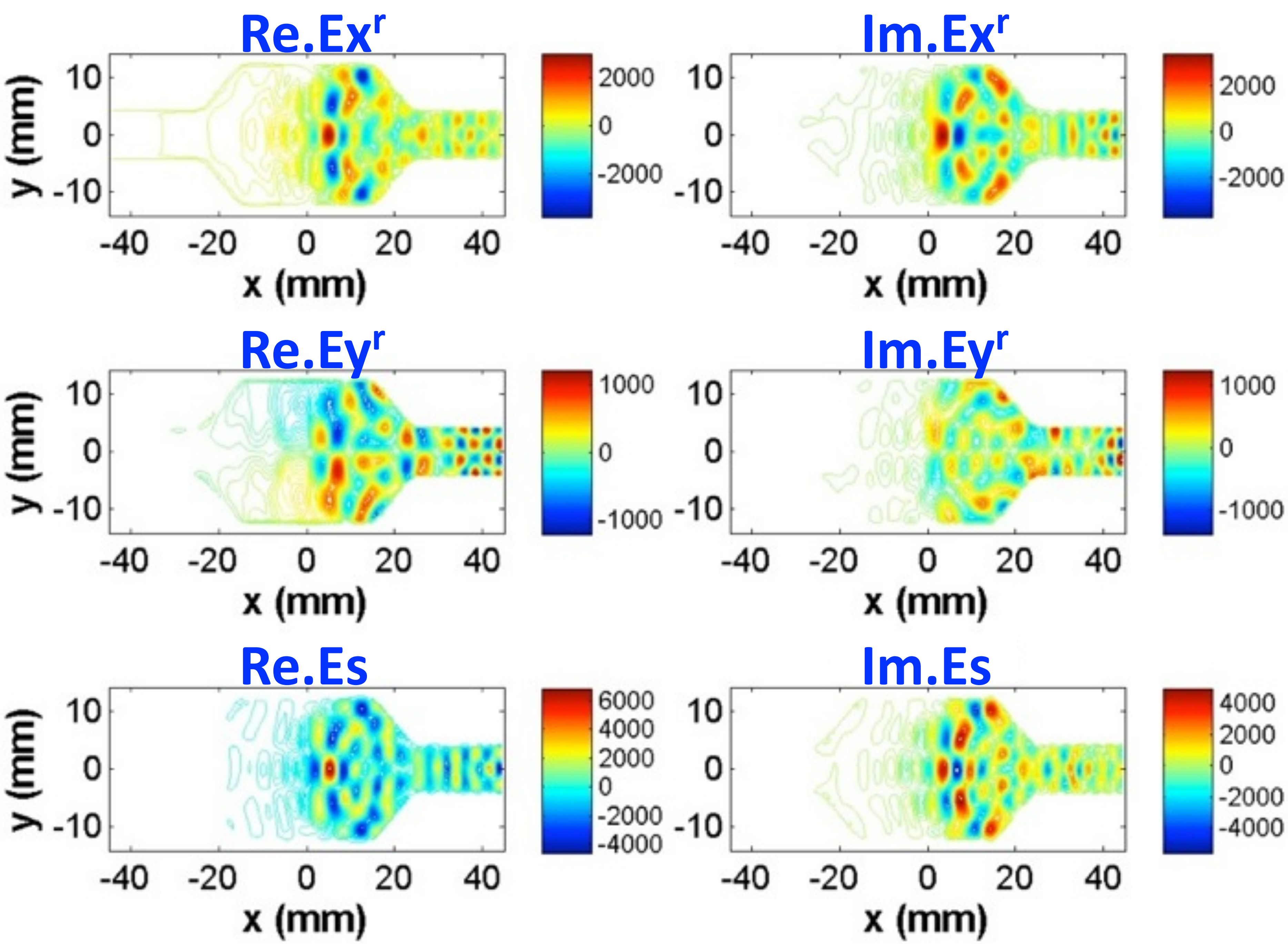


E_x mode: $$E_x(x,y) = E_{x0}\mathrm{Ai}\left(k_y^2\kappa^2 - x/\kappa\right)\sin\left[k_y(y+b/2)\right]$$

G. Stupakov and I. Kotelnikov, PRST-AB 6, 034401 (2003).

4. CSR: Field dynamics: Eigenmodes

Arbitrary cross-section: Finite element technique + parabolic equation (L. Wang)



Courtesy of L. Wang

4. CSR: Field dynamics: Eigenmodes

Rectangular cross-section: Discontinuous Galerkin method + parabolic equation (D.A. Bizzozero)

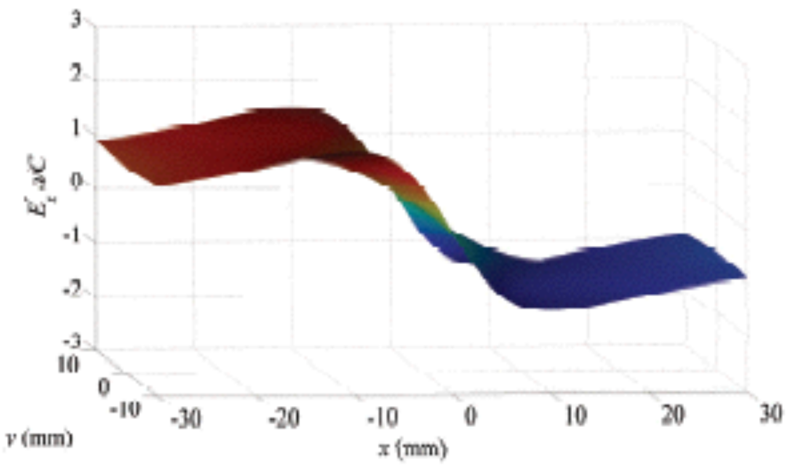


Figure 2: Initial condition for E_x^r.

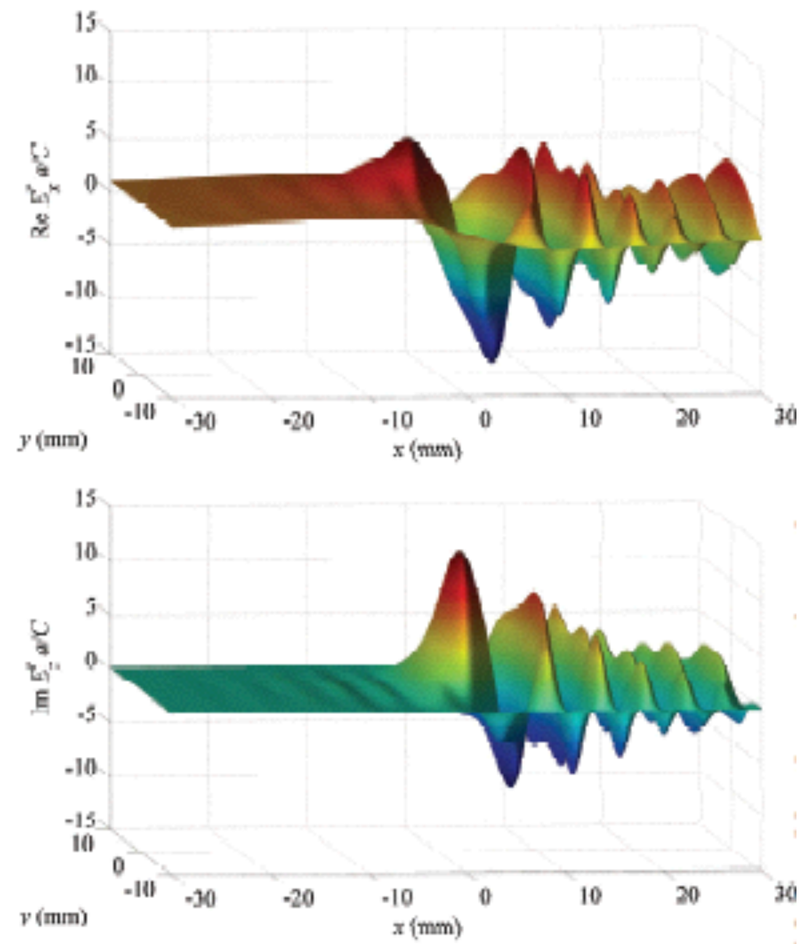
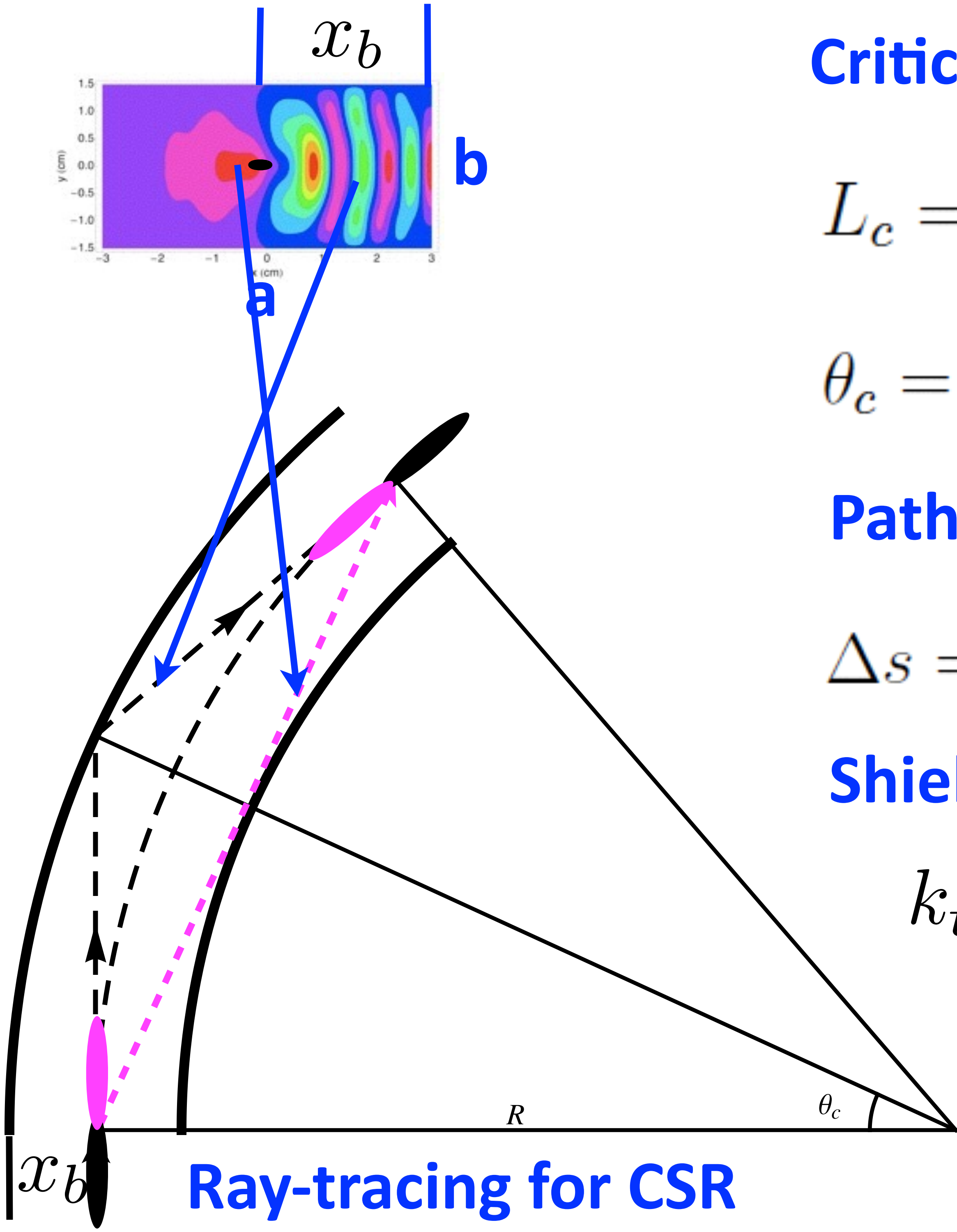


Figure 3: Real (top) and Imaginary (bottom) parts of E_x^r for $\rho = 1$ m, $L = 200$ mm, $a = 30$ mm, $b = 10$ mm, $k = 8\,\mathrm{mm}^{-1}$.

Courtesy of D.A. Bizzozero

4. CSR: Field dynamics: Optical model

Outer-wall reflection can be well approximated by optical model [Derbenev (1995), Carr (2001), Sagan (2009), Oide (2010)]



Ray-tracing for CSR

Critical length (Catch-up distance):

$$L_c = 2R\theta_c \approx 2\sqrt{2Rx_b} \qquad x_b \ll R$$

$$\theta_c = \mathrm{ArcCos}\left(R/(R+x_b)\right) \approx \sqrt{2x_b/R}$$

Path difference:

$$\Delta s = 2R(\mathrm{Tan}(\theta_c) - \theta_c) \approx \frac{4}{3}\sqrt{\frac{2x_b^3}{R}}$$

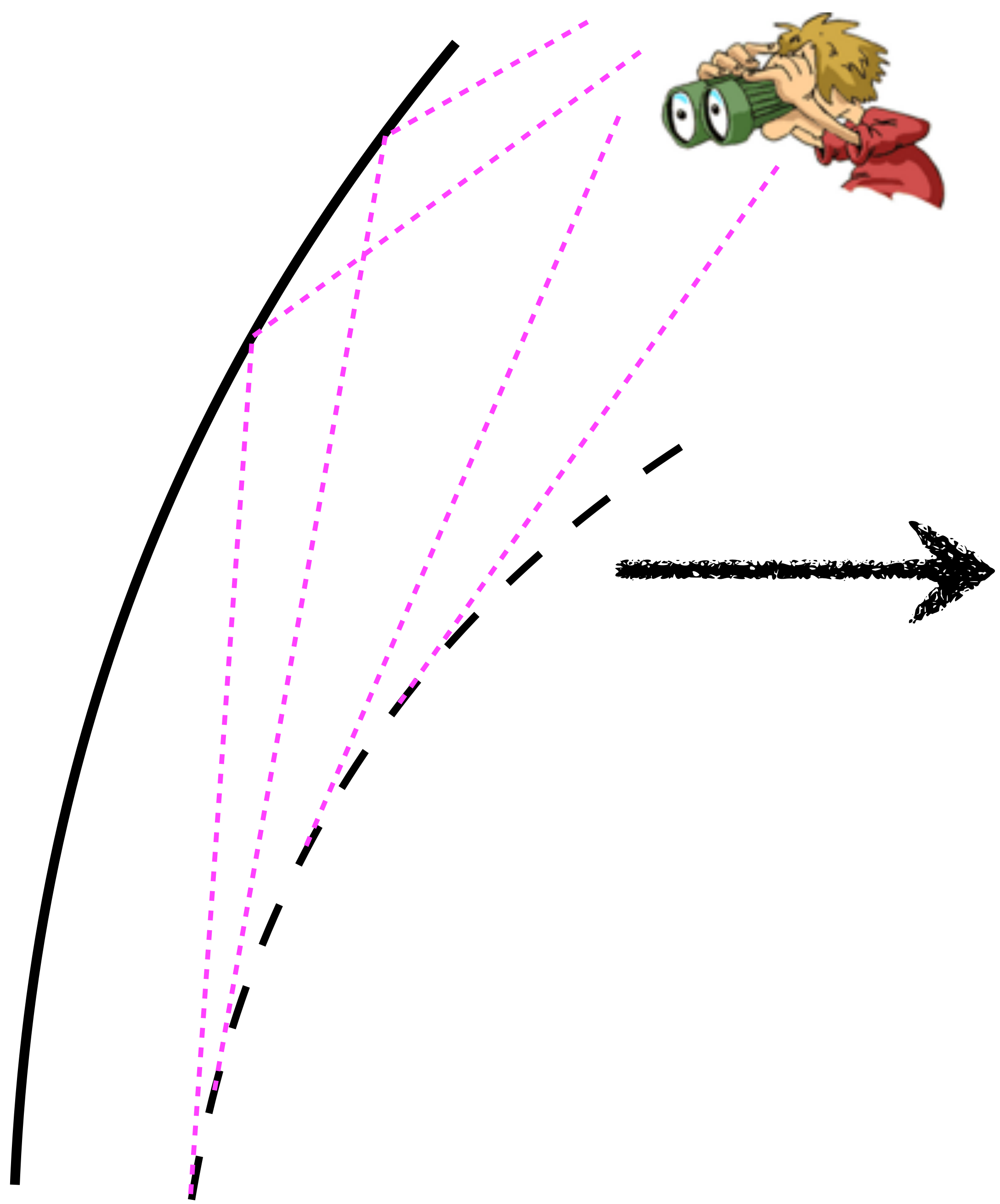
Shielding threshold:

$$k_{th} = \pi\sqrt{R/b^3}$$

Y. S. Derbenev et al., TESLA FEL-Report 1995-05 (1995).
G. L. Carr et al., PAC'01, p. 377 (2001).
D. Sagan et al., PRST-AB 12, 040703 (2009).
K. Oide, Talk at CSR mini-workshop, Nov. 08, 2010.
D. Zhou et al., Jpn. J. Appl. Phys. 51 (2012) 016401.

4. CSR: Field dynamics: Optical model

Since the interesting wavelength of CSR is much smaller than the chamber geometry (λ << b), we can safely do ray-tracing for even complicated geometry.



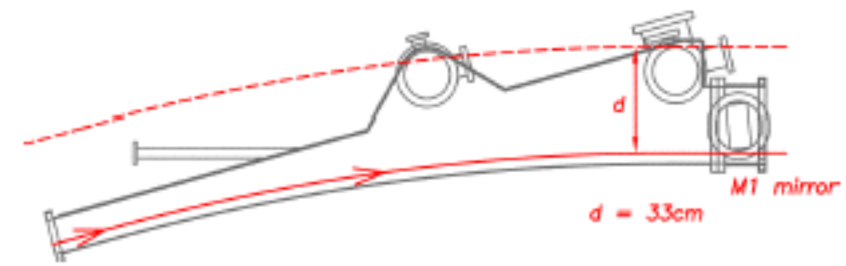


Figure 10: Vacuum chamber of CLS at dipole where IR is extracted

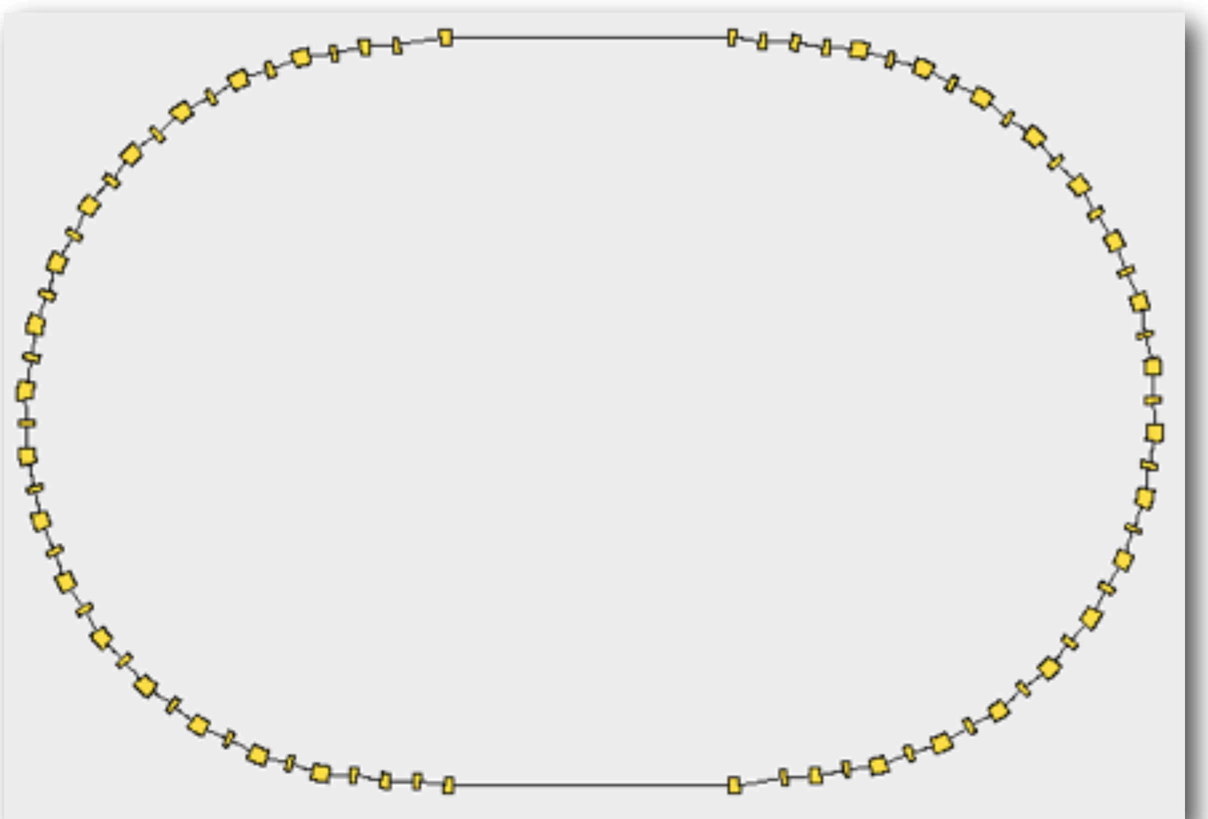
From R. Warnock

4. CSR: Field dynamics: Multi-bend interference

SuperKEKB damping ring:

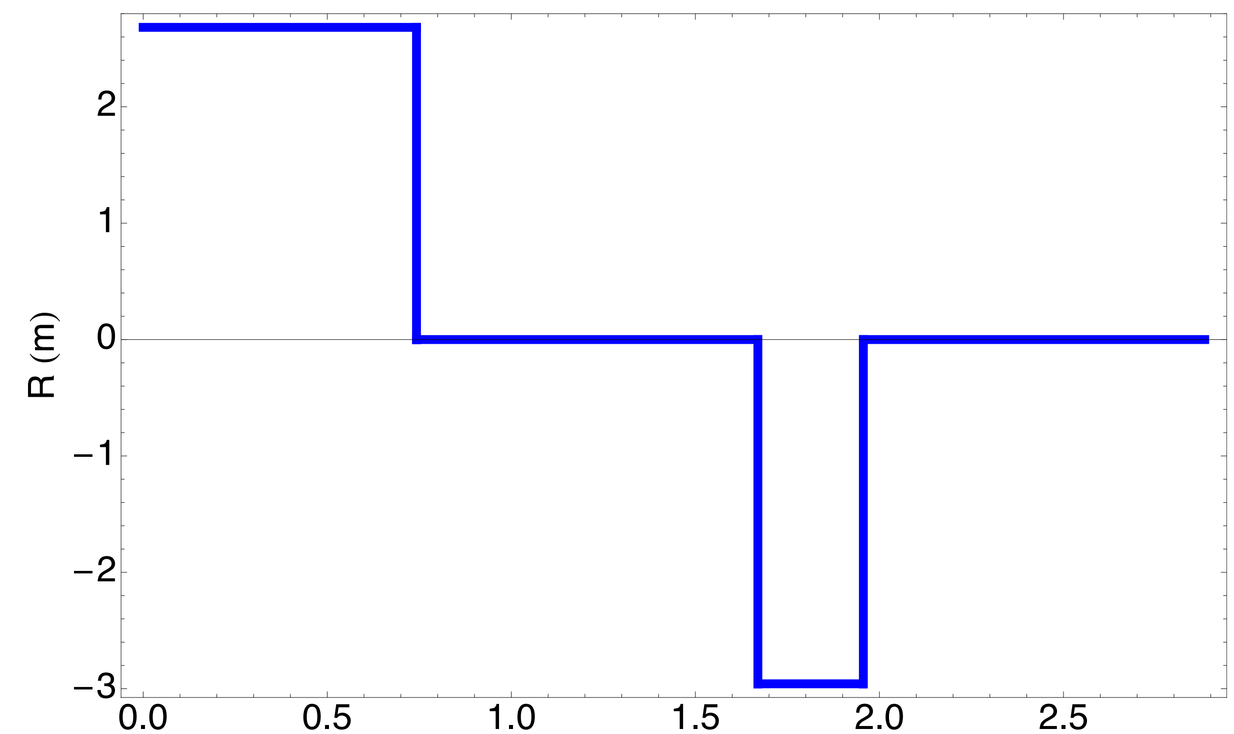
a/b=34/34 mm, L_{bend}=0.74/0.29 m, ρ=2.7/-3 m (reverse bends)
L_{drift}=0.9 m, N_{cell}=32

The vacuum chamber is curved along the beam orbit



Layout

Bend 1



Bend 2

Reverse bends (1 cell)

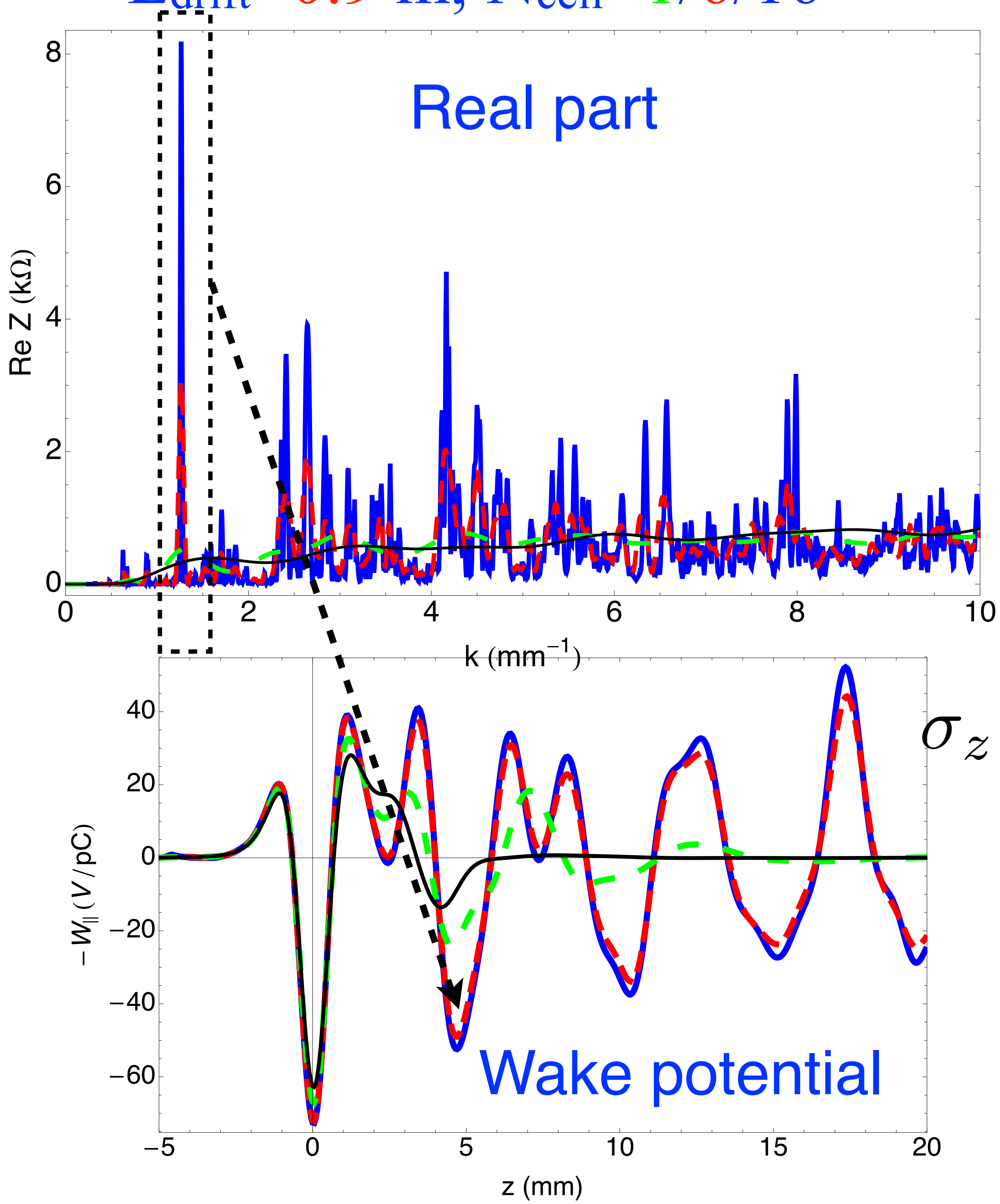
M. Kikuchi, et al., IPAC'10, p. 1641 (2010)

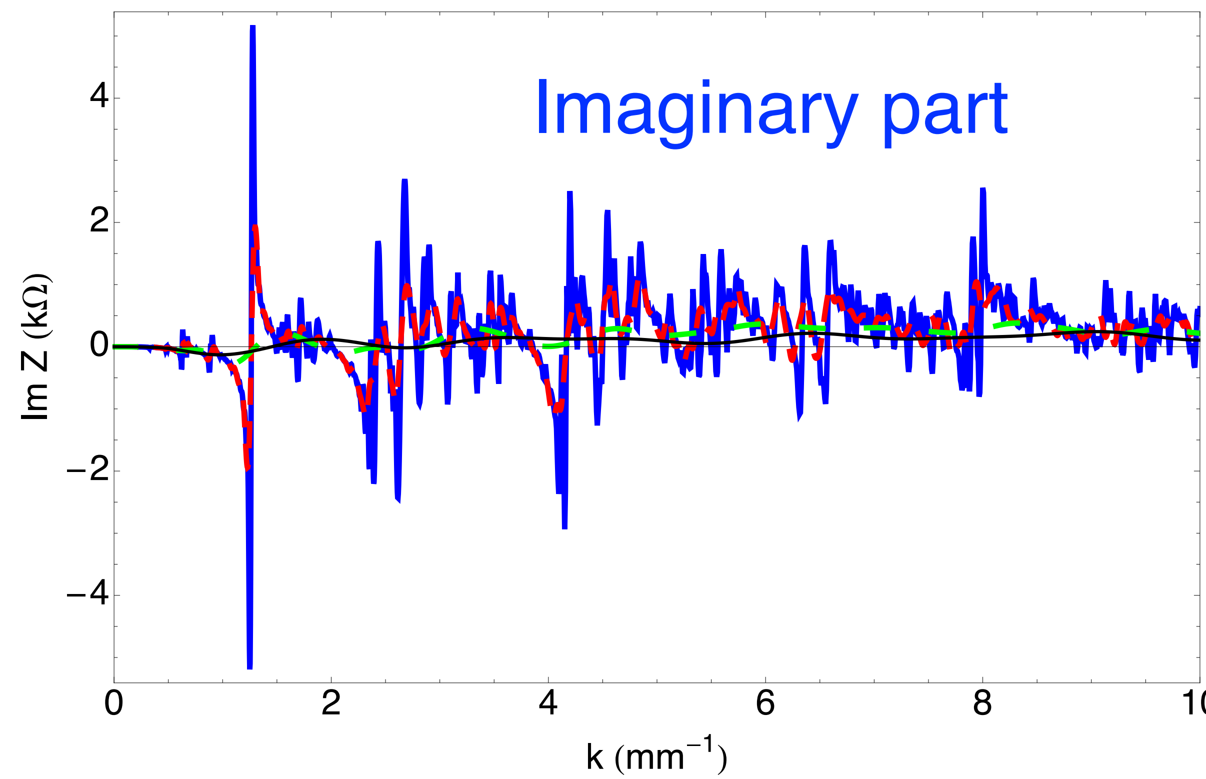
4. CSR: Field dynamics: Multi-bend interference

SuperKEKB damping ring (one arc section) (Perfect conducting wall)

a/b=34/34 mm, L_{bend}=0.74/0.29 m, ρ=2.7/-3 m (reverse bends)

L_{drift}=0.9 m, N_{cell}=1/6/16





$$\sigma_z = 0.5 \text{ mm}$$

Blue solid lines: 16 cells

Red dashed lines: 6 cells

Green dotted lines: 1 cell

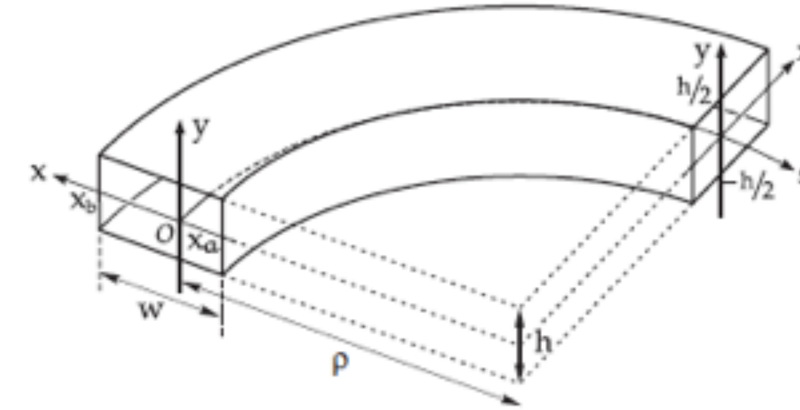
Black solid lines: single-bend

D. Zhou et al., Jpn. J. Appl. Phys. 51 (2012) 016401.

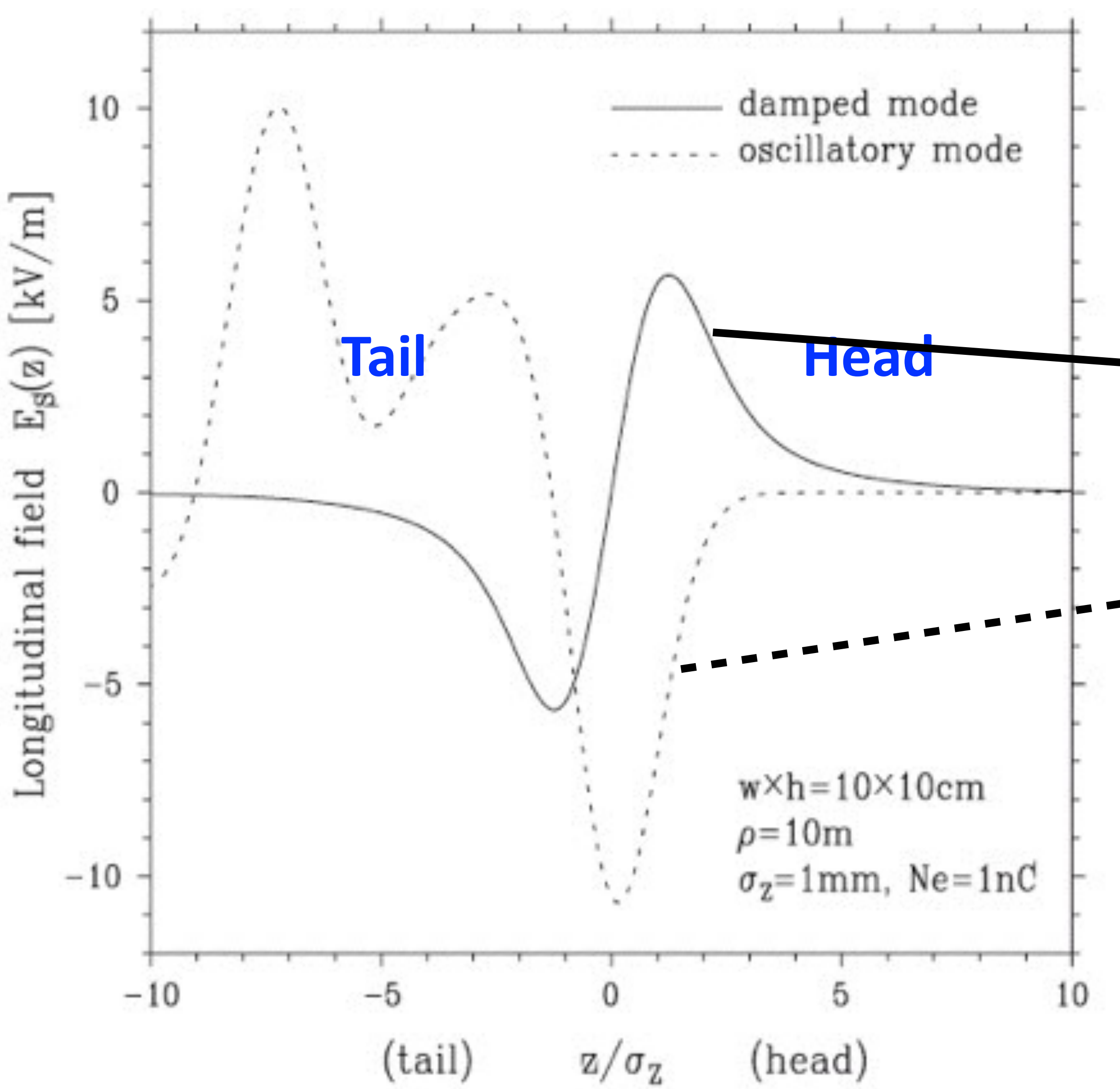
4. CSR: Field dynamics: Steady-state

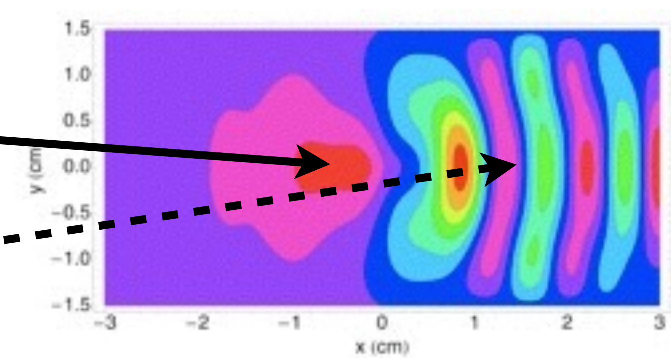
CSR fields can be decomposed to a sum of propagating (oscillatory and trailing) and decaying (damped and overtaking) waves in a toroidal waveguide [Agoh (2009)].

Geometry



Long. wakefields for a Gaussian bunch





T. Agoh, PRST-AB 12, 094402 (2009).

4. CSR: Field dynamics: Experiments

CSR measurements at NSLS VUV ring

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 463 (2001) 387–392

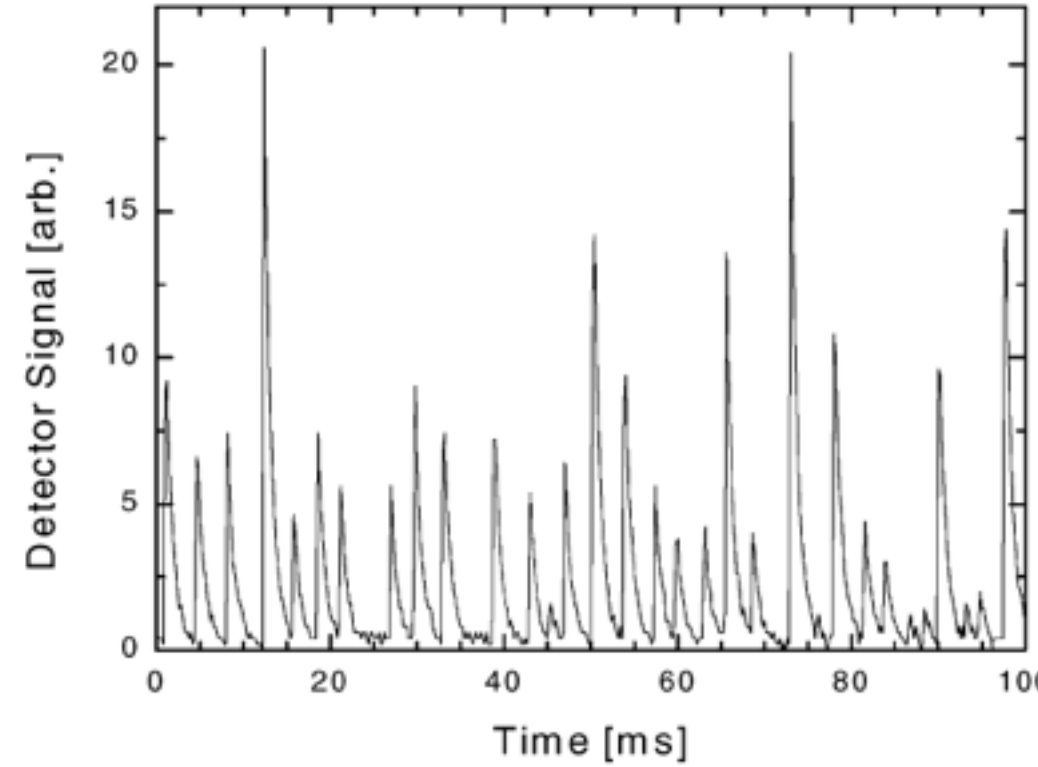
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.nl/locate/nima

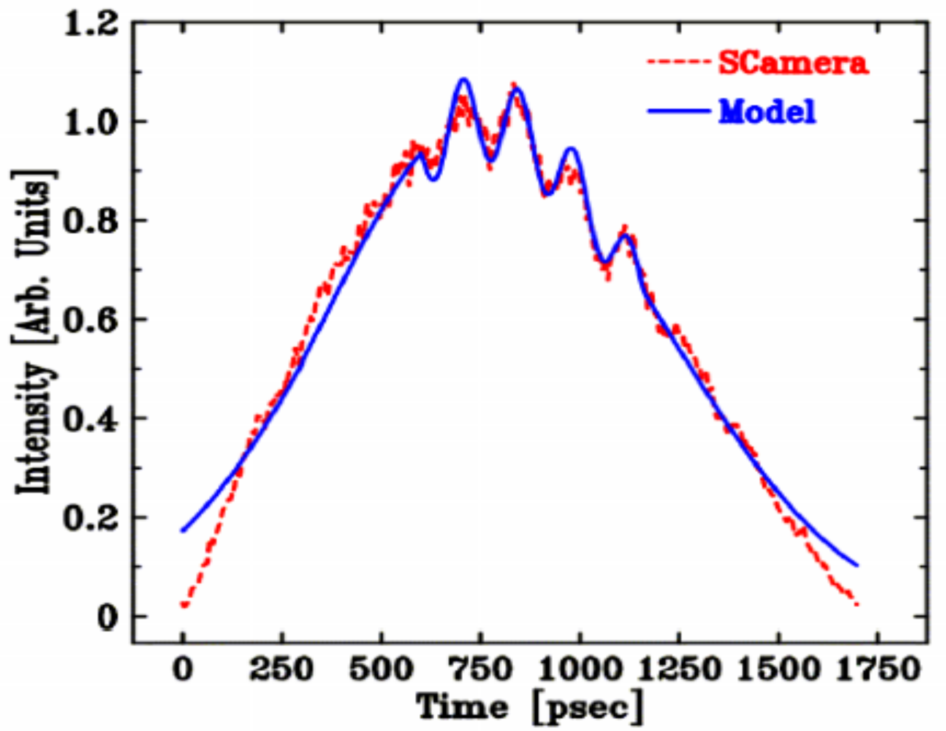
Observation of coherent synchrotron radiation from the NSLS VUV ring

G.L. Carr[a,*], S.L. Kramer[a], J.B. Murphy[a], R.P.S.M. Lobo[b], D.B. Tanner[b]

FIR signal

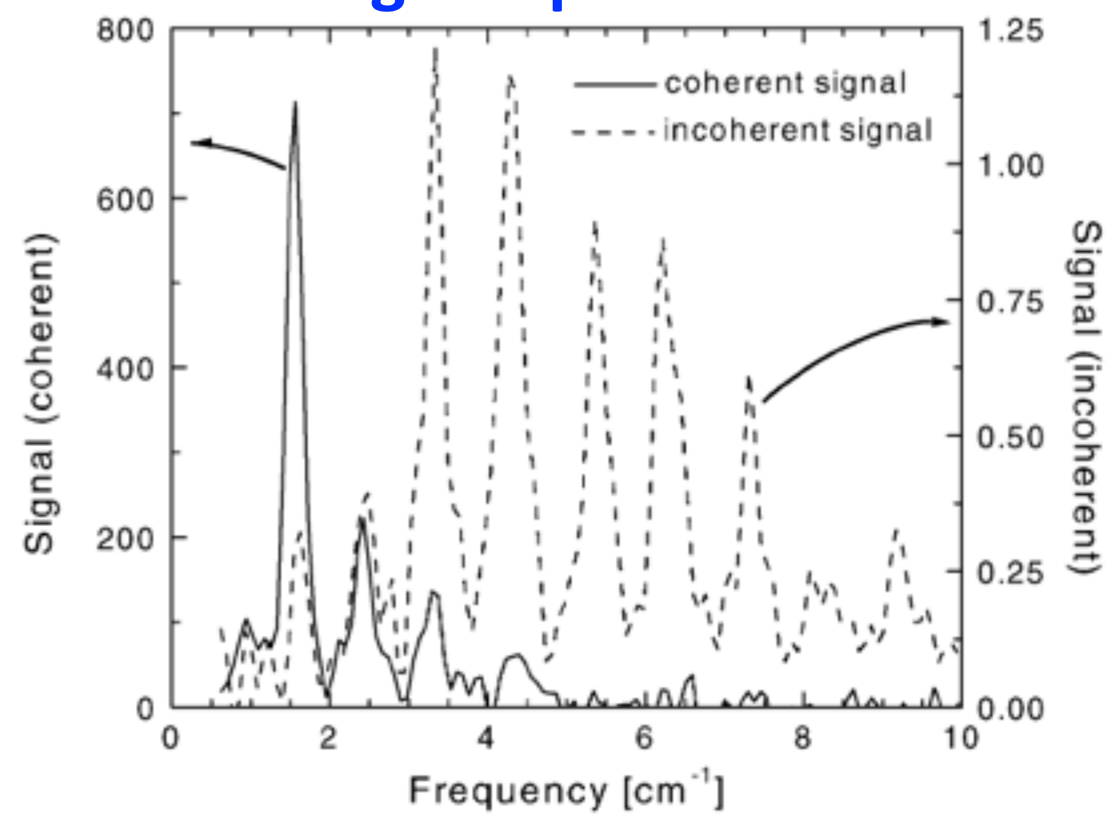


Microbunching@Streak Camera



S. Kramer, EPAC 2002

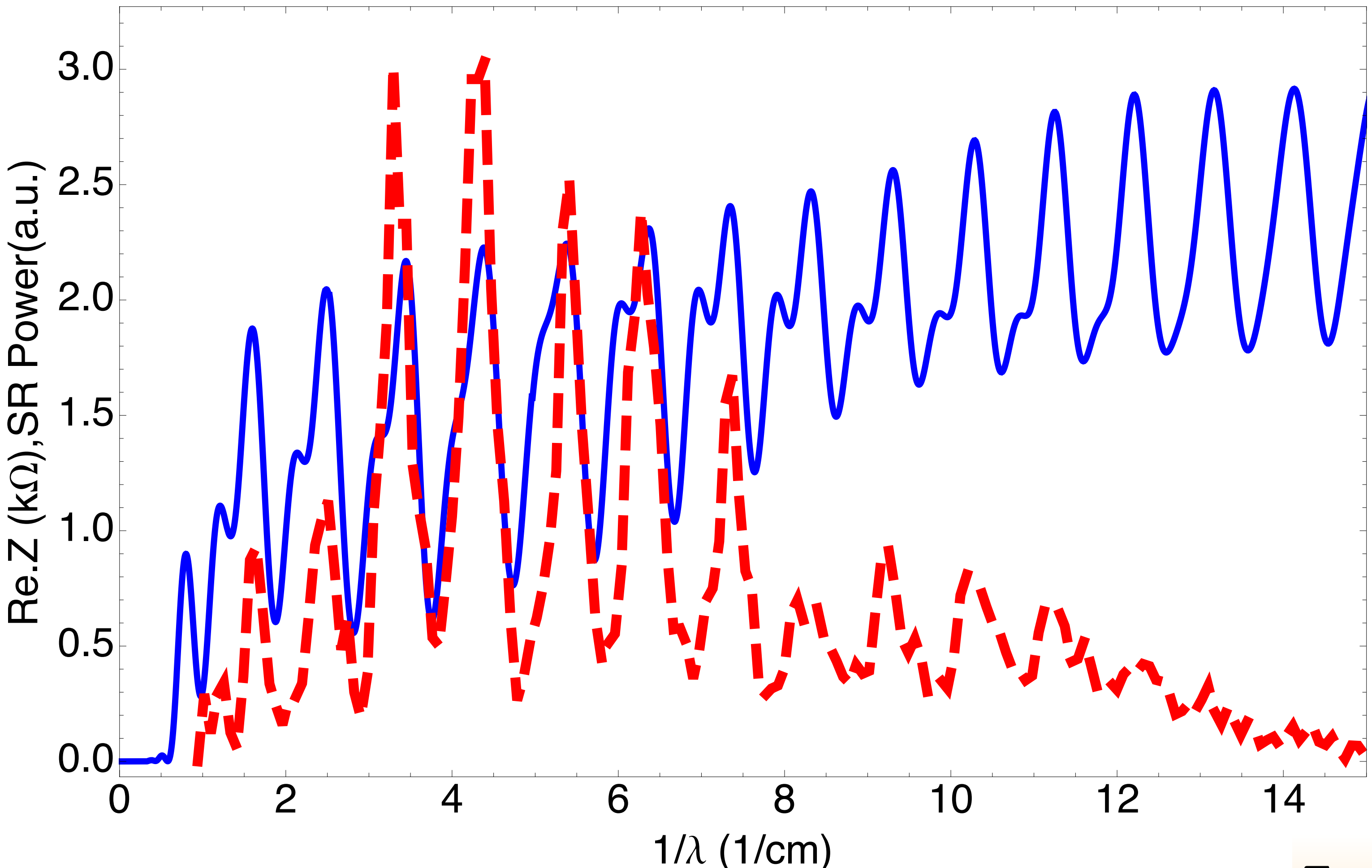
Signal spectrum



4. CSR: Field dynamics: Experiments

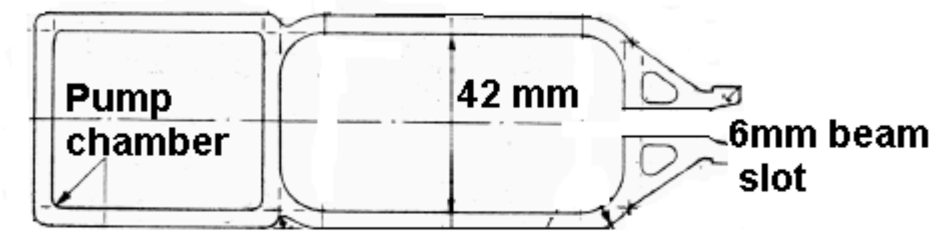
CSR measurements at NSLS VUV ring

$a/b=80/42$ mm, $L_{bend}=1.5$ m, $R=1.91$ m

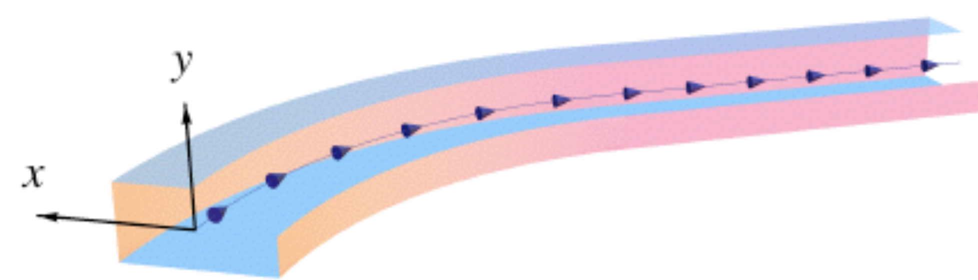


$L_{bend} > L_c=0.8$ m

Chamber cross section



Model for calculation



Blue solid: SR impedance
Red dashed: Measured ISR spectrum
(Data provided by S.L. Kramer)

Excellent agreements in peak positions and widths.
The discrepancy in amplitude at low- and high-frequency parts is attributed to the transfer function of the detection system.

4. CSR: Field dynamics: Experiments

R. Warnock's idea: Similarity of steady-state CSR and whispering gallery modes

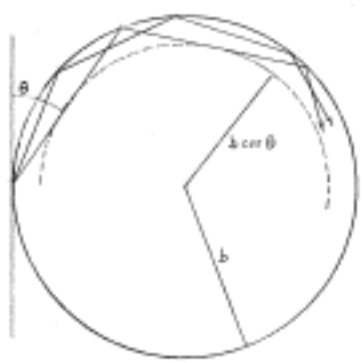
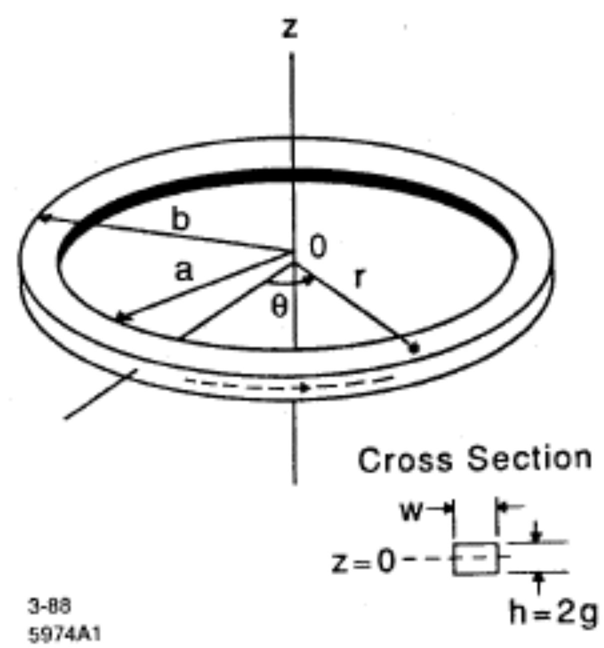


Figure 3: Rayleigh's ray picture



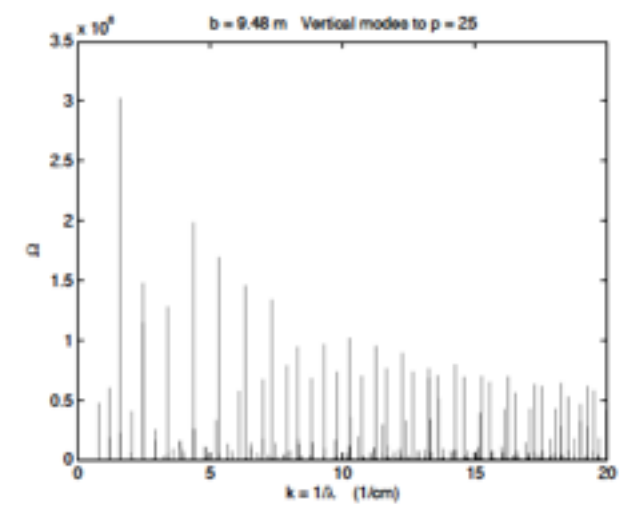


Figure 7: Re $Z(n, n\omega_0)$ for parameters of VUV light source, vs. wave number $1/\lambda$ in units of cm^{-1}.

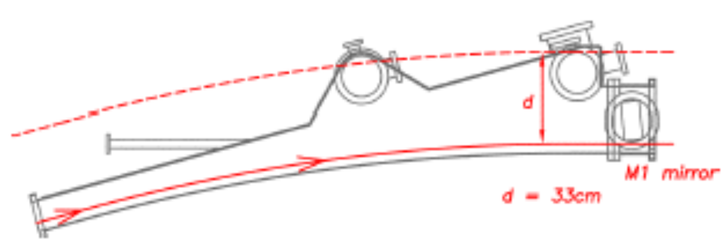


Figure 10: Vacuum chamber of CLS at dipole where IR is extracted

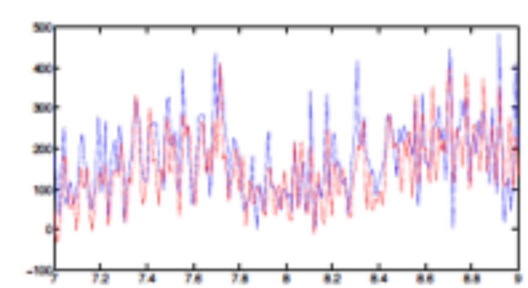


Figure 11: CLS spectra from two very different runs, power (a.u.) vs. k in cm^{-1}.

From R. Warnock

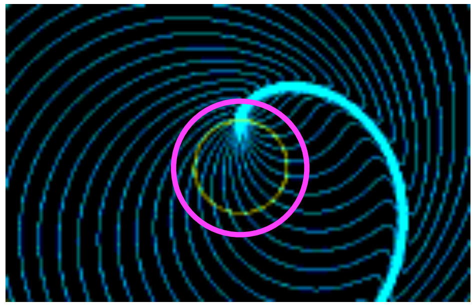
Q: A code to handle 3D chamber is necessary?

Ref. R. Warnock, in ICFA beam dynamics Newsletter 63 (2014)

4. CSR: Field dynamics: Short summary

➤ **We can view CSR from various aspects:**

- **Take CSR as light and apply optical theory**
- **Take the vacuum chamber as a curved waveguide and search for eigenmodes, and take the beam as exciting source**
- **Impedance theory: Think about the properties of CSR impedance => Causality, Kramers-Kronig relation, and Hilbert transform, … => Compare with space charge, wiggler/undulator ration, Chenrenkov radiation, …**
- **Whispering gallery modes in acoustics (R. Warnock)**
- **To well understand observations in accelerators, we may need to develop 3D frequency-domain code for ring? 3D time-domain code for linac (chicane)?**
- **Far-/near-field => Radiation/Instability**
- **Paraxial approximation works well**



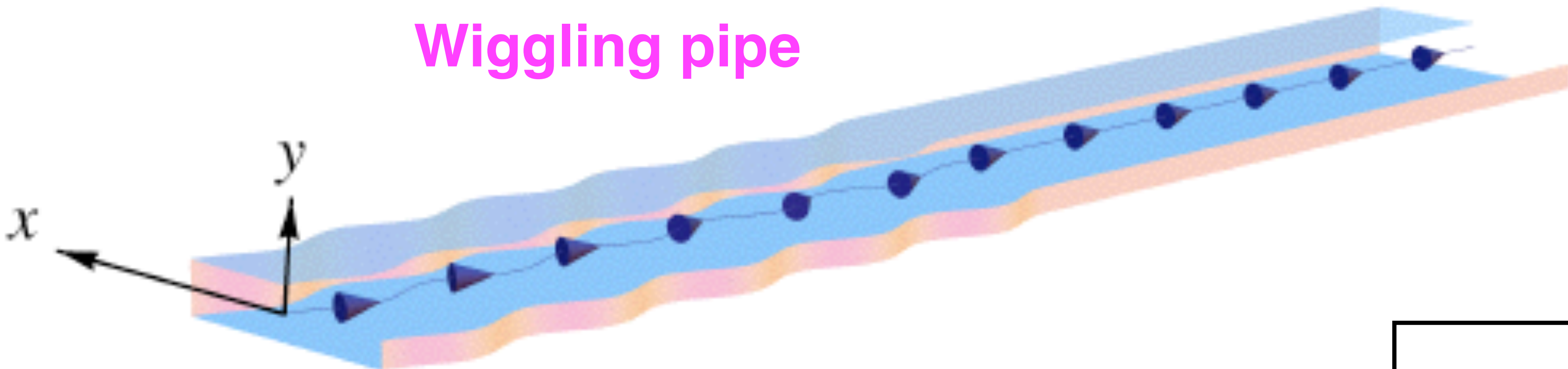
From http://www.shintakelab.com/

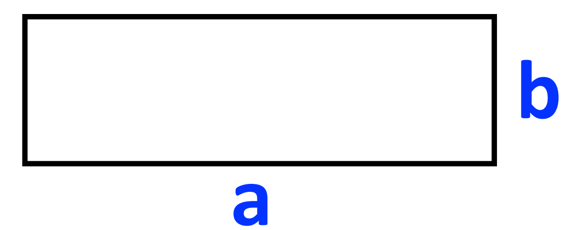
5. CWR/CUR: Problem definition

[1959] Motz/Nakamura => [1990] Y. Chin => [1998] Saldin et al. => [2003] Wu et al. => [2010] Stupakov/Zhou

The model for numerical calculation:

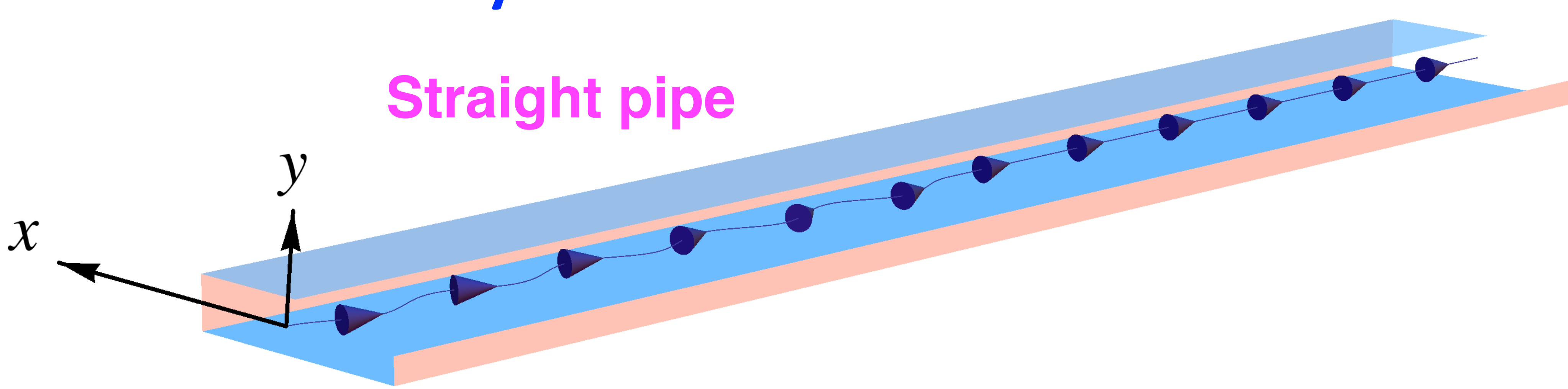
Wiggling pipe





The model for analytical calculation:

Straight pipe



G. Stupakov and D. Zhou, SLAC-PUB-14332 (2010).

5. CWR/CUR: Mode expansion method

We found a satisfying solution for the real part for CWR/CUR impedance for a finite-length wiggler [Stupakov (2010)]**:**

$$\mathrm{Re}\ Z(k) = \frac{4Z_0}{abR_0^2}\sum_{m=0}^{\infty}\sum_{p=1}^{\infty}\frac{k}{(1+\delta_{m0})k_z}\frac{\sin^2\left((k-k_z-k_w)L_w/2\right)}{(k-k_z)^2-k_w^2}$$

With presumed condition (small-angle orbit approximation):

$$K/\gamma \ll 1$$

Very good agreement with simulation:

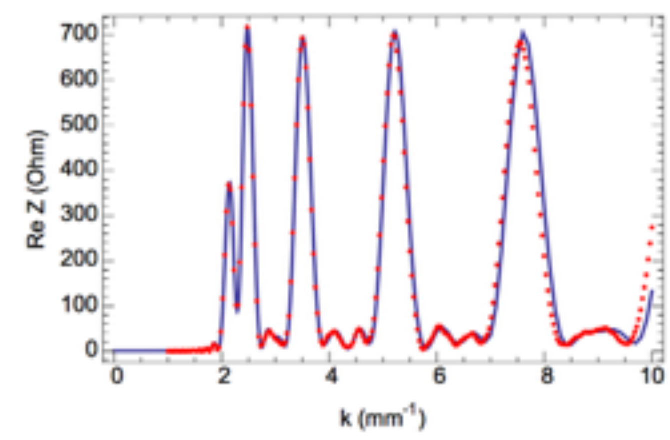


FIG. 3: Re Z as a function of the wavenumber k for a rectangular cross-section of the beam pipe with the aspect ratio 5. The thick blue line is the theory, and the red dots are the simulation result.

G. Stupakov and D. Zhou, SLAC-PUB-14332 (2010).

5. CWR/CUR: Mode expansion method

Apply to the SuperKEKB wiggler section: Many sharp peaks in the impedance spectrum.

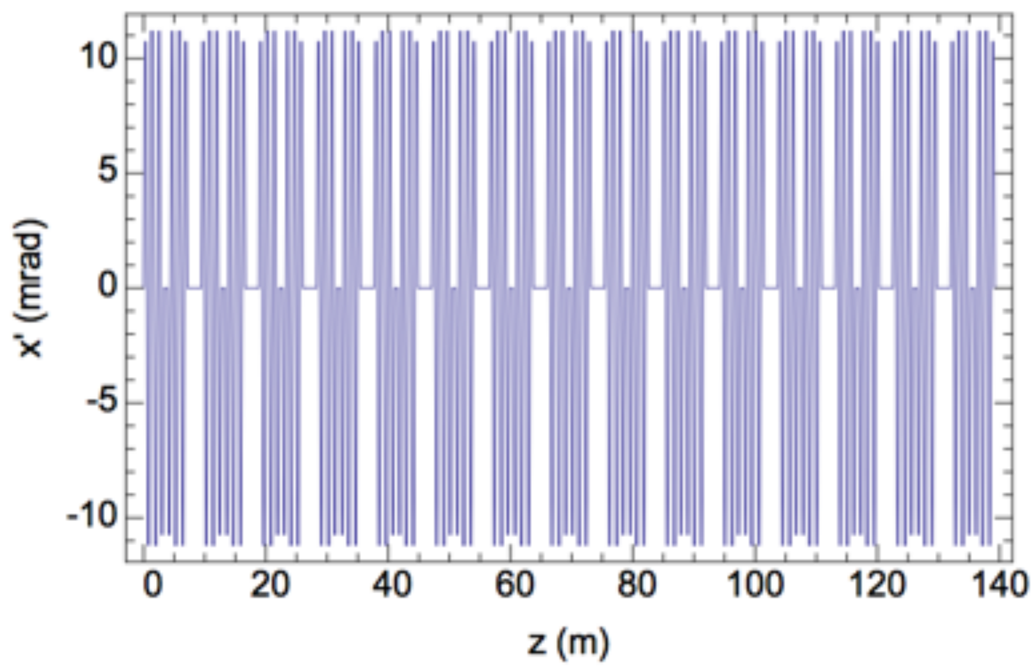


FIG. 4: The derivative dx_0/dz for particle's orbit in the wiggler.

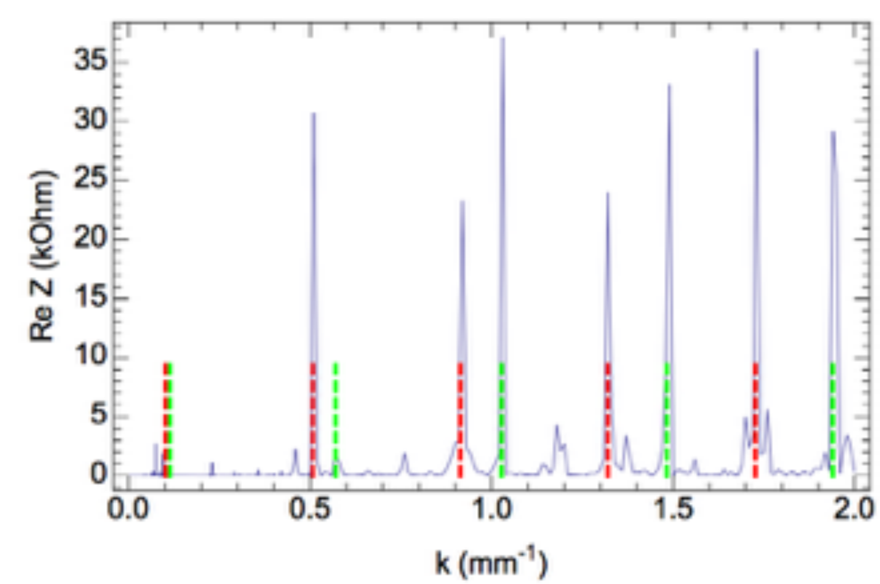


FIG. 6: Re Z as a function of the wavenumber k for the low energy SuperKEKB wiggler.

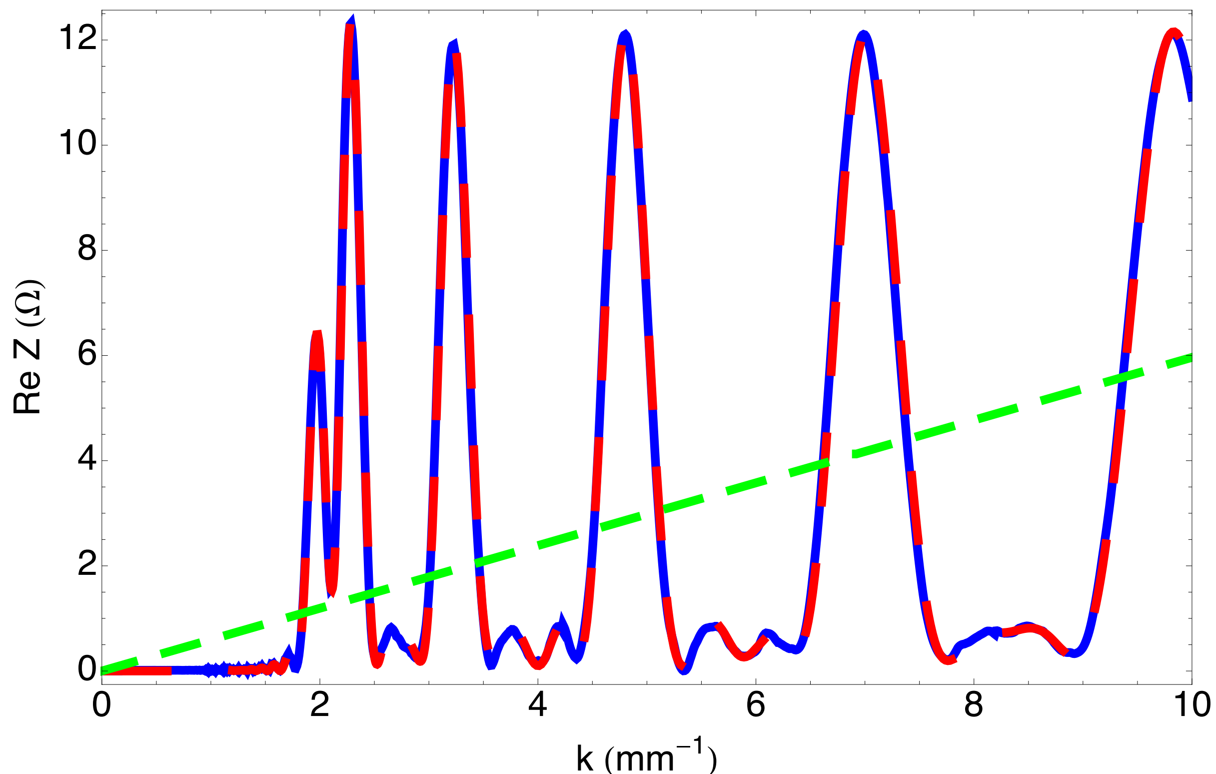
BUT: The imaginary part of CWR/CUR impedance is very hard to tackle, far beyond your expectations!

G. Stupakov and D. Zhou, SLAC-PUB-14332 (2010).

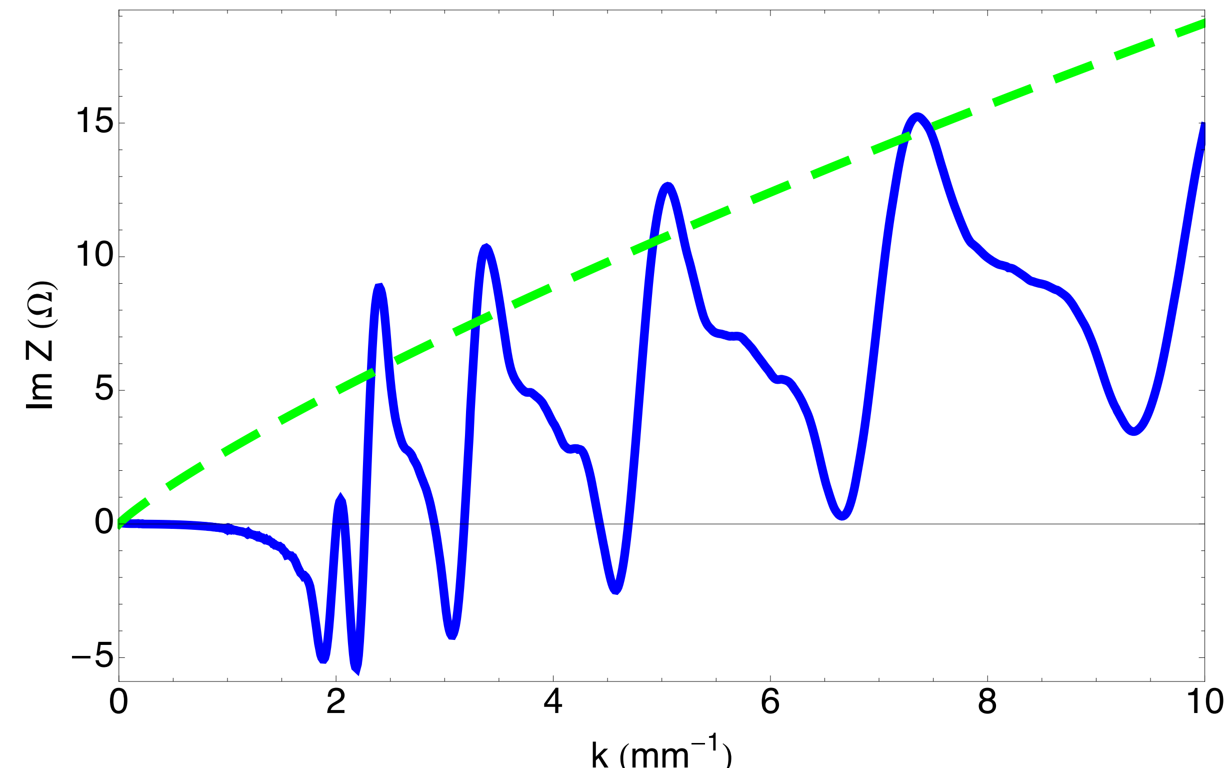
5. CWR/CUR: Numerical calculation

A weak wiggler: a test

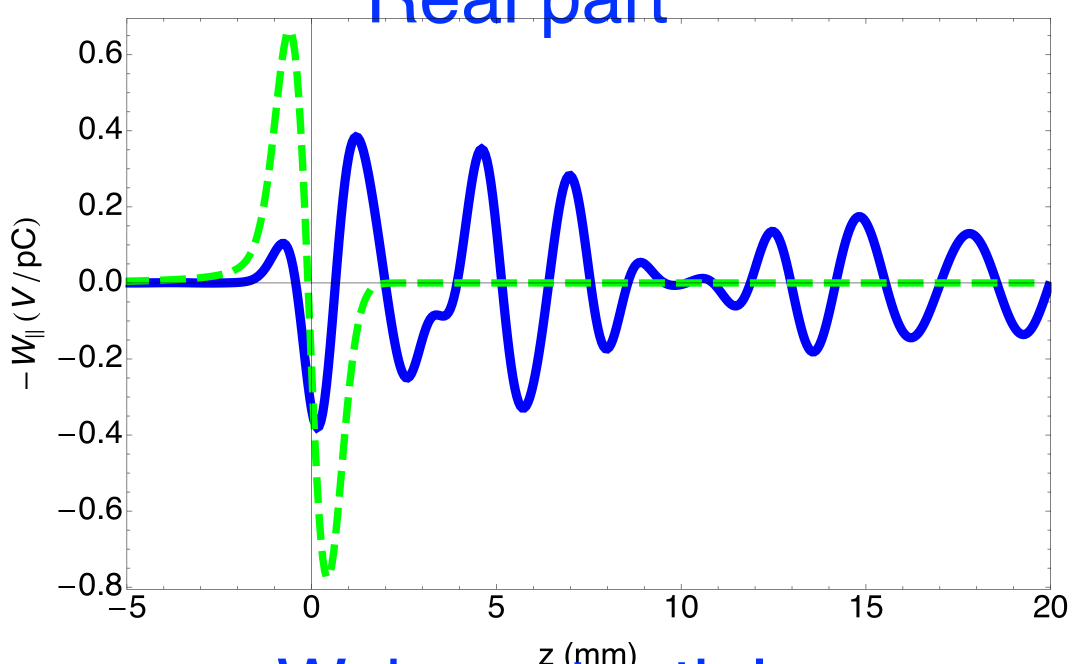
a/b=100/20 mm, λ_w=1 m, R_0=100 m, N_w=10



Real part



Imaginary part



Wake potential

Blue solid lines: numerical

Red dashed lines: analytic model w/ waveguide

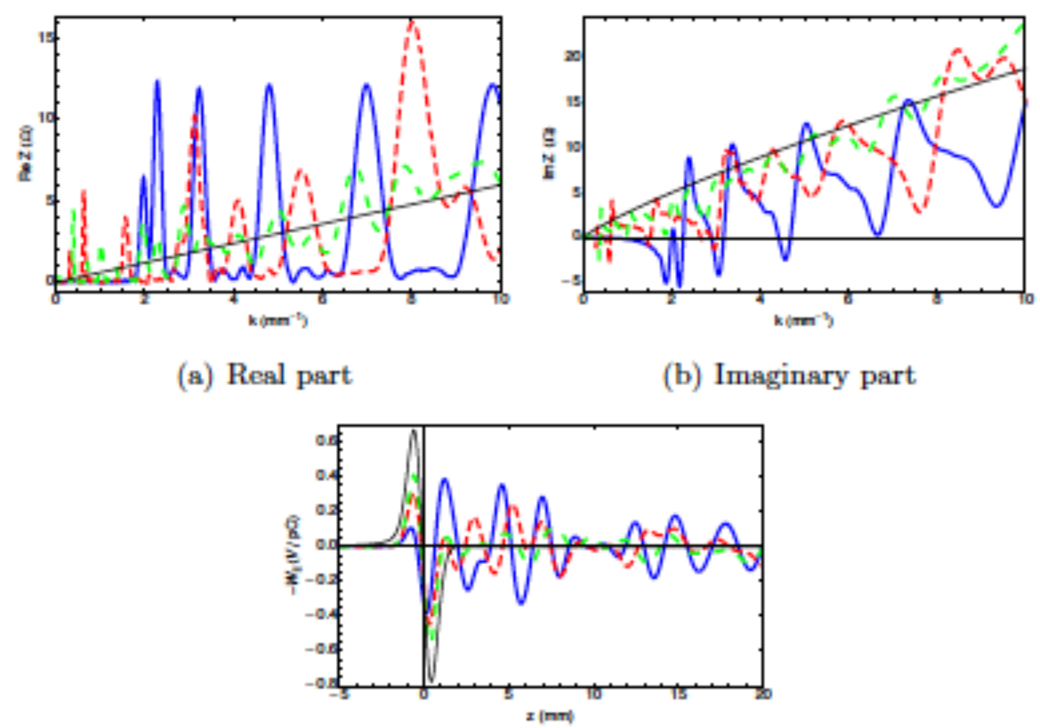
Green dashed line: analytic model in free space

G. Stupakov and D. Zhou, SLAC-PUB-14332 (2010).

J. Wu, et al., PRST-AB 6, 040701 (2003).

5. CWR/CUR: Numerical calculation

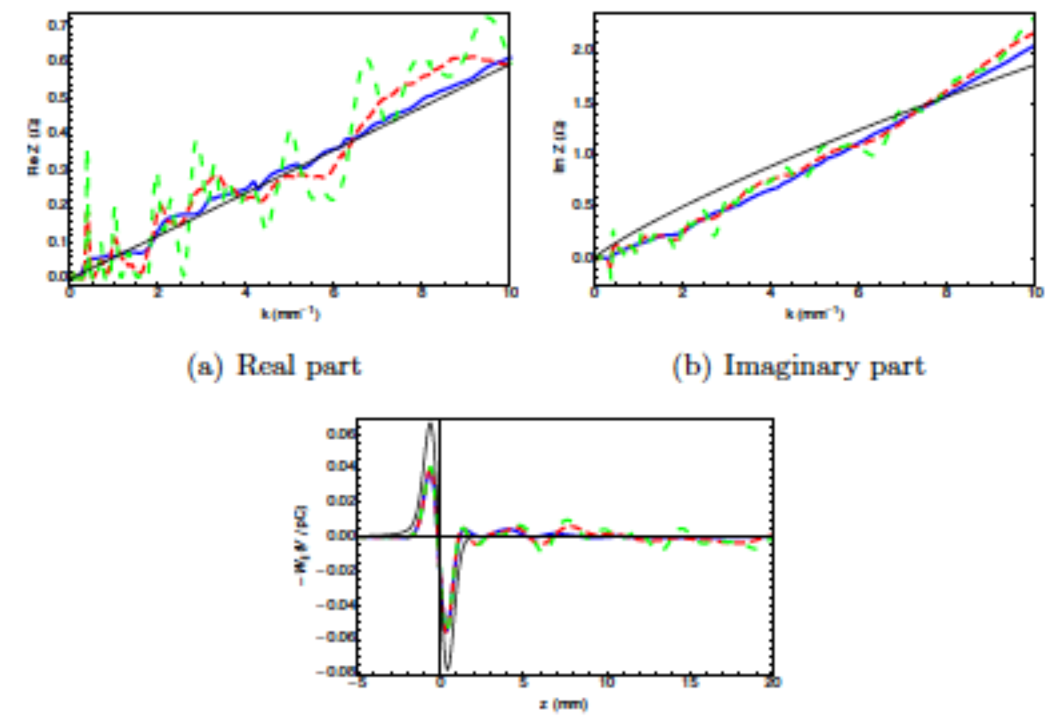
Varying chamber dimensions and wiggler length



(a) Real part (b) Imaginary part

(c) Wake potential

Figure 2.23: CSR impedance and wake potential of a wiggler with $b = 2, 5, 10$ cm. The gaussian bunch length $\sigma_z = 0.5$ mm with bunch head to the left side. Blue solid lines: $b = 2$ cm; red dashed lines: $b = 5$ cm; green dashed lines: $b = 10$ cm; black solid lines: free-space model.



(a) Real part (b) Imaginary part

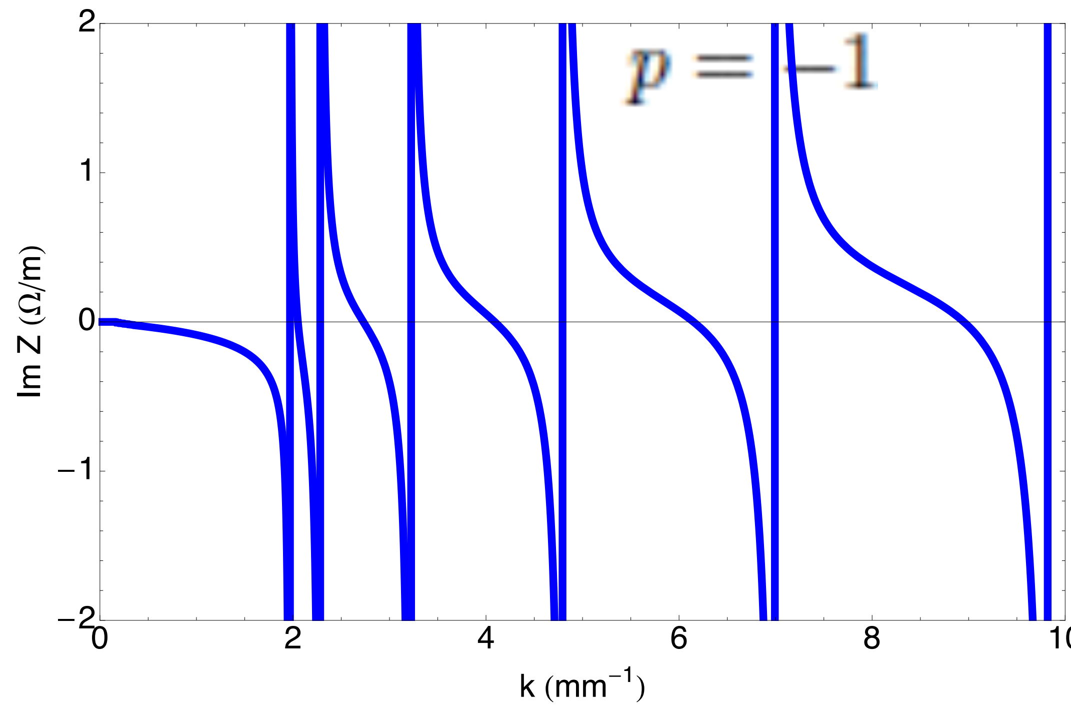
(c) Wake potential

Figure 2.24: CSR impedance and wake potential of a wiggler with the total length varied by setting $N_u = 1, 4, 8$. The impedances and wake potentials have been normalized by the number of period for convenience of comparison. The gaussian bunch length $\sigma_z = 0.5$ mm with bunch head to the left side. Blue solid lines: $N_u = 1$; red dashed lines: $N_u = 4$; green dashed lines: $N_u = 8$; black solid lines: free-space model.

5. CWR/CUR: Steady-state

An infinitely long wiggler:

w/h=100/20 mm, λ_w=1 m, R_0=100 m



p: harmonic number of beam motion

Steady-state CSR [Agoh (2009)]

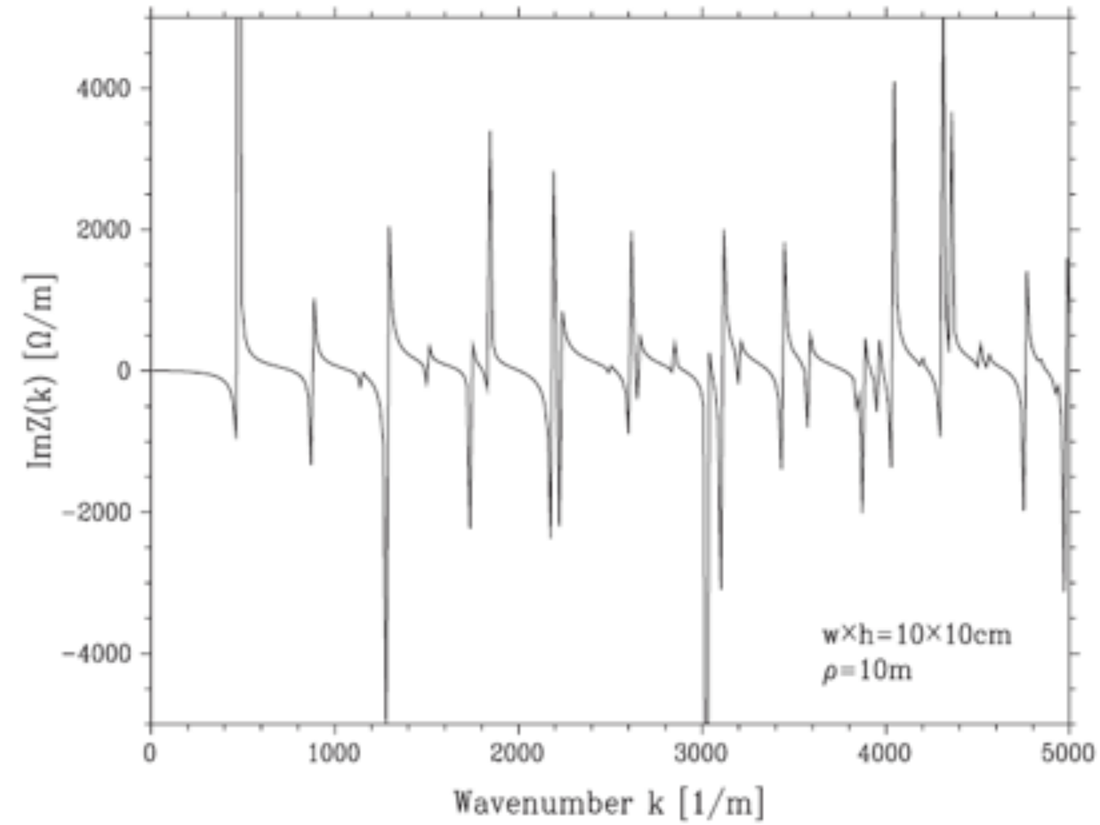


FIG. 2. CSR impedance of a square pipe. The pipe width and the height are $w \times h = 10$ cm $\times$ 10 cm, the bending radius is $\rho = 10$ m. We put $\gamma = \infty$ and $\Lambda_p = 1$ in Eq. (69).

T. Agoh, PRST-AB 12, 094402 (2009).

Steady-state CSR and CWR impedances have similar features.
The physics is contained in the real and imaginary singular poles.

6. Summary

➤ **Impedance and single-bunch instability in SuperKEKB**

- **Pseudo-Green function wakes are available**
- **CSR is becoming a concern once again**
- **Pseudo-Green function wakes for CSR ($Z \sim k^{1/3}$) and resistive wall ($Z \sim k^{1/2}$) might not be proper**
- **Beam tilt and TMCI are potential important**

➤ **CSR**

- **Here or there, it shows mysterious properties**
- **The power of PE is far from fully investigated**
- **CSR remains to be a concern in SuperKEKB**
- **BUT, definitely useful from another side: THz sources**

➤ **CWR/CUR**

- **Chamber shielding makes difference**
- **A not fully solved problem**
- **BUT, definitely CUR is important for FEL**

Acknowledgements

Special thanks to Y. Cai, G. Stupakov, and L. Wang for their constant support to SuperKEKB project!

Thanks to all of you for your hospitality!

Thanks for your attention!

AND

Welcome to KEK!

Backup

1. Introduction: Scaling SuperKEKB/KEKB

	LER			HER		
	SKEKB	KEKB	Factor	SKEKB	KEKB	Factor
E(GeV)	4	3.5	1.14	7.007	8	0.876
I	1.44	1.03	1.4	1.04	0.75	1.4
ε	3.2	18	0.18	4.6	24	0.19
ε	8.64	180	0.048	11.5	240	0.048
β	0.032	1.2	0.027	0.025	1.2	0.021
β	0.27	5.9	0.046	0.3	5.9	0.051
α	3.25	3.31	0.98	4.55	3.43	1.33
σ	8.08	7.73	1.11	6.37	6.3	0.96
σ	5	4.6		4.9	5.2	

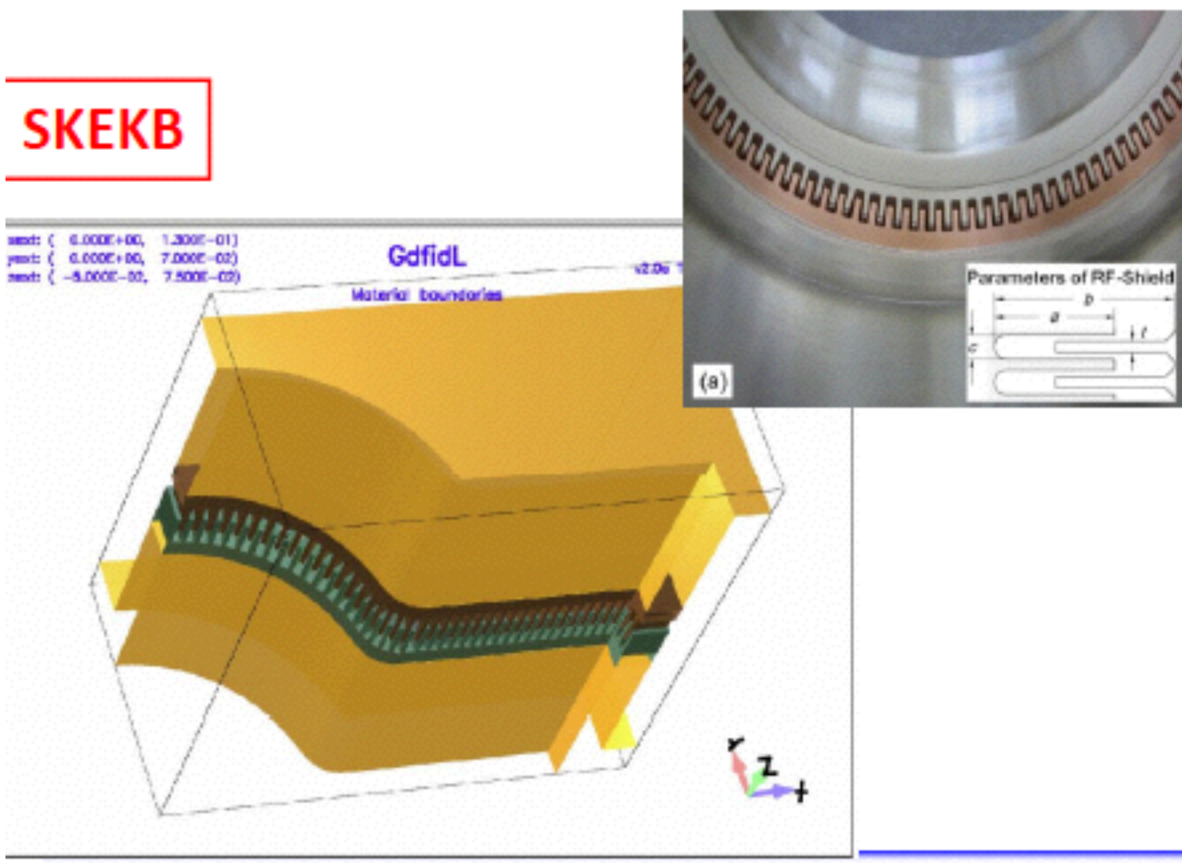
*Machine parameters on Jun.17, 2009

See http://www-superkekb.kek.jp/index.html for details

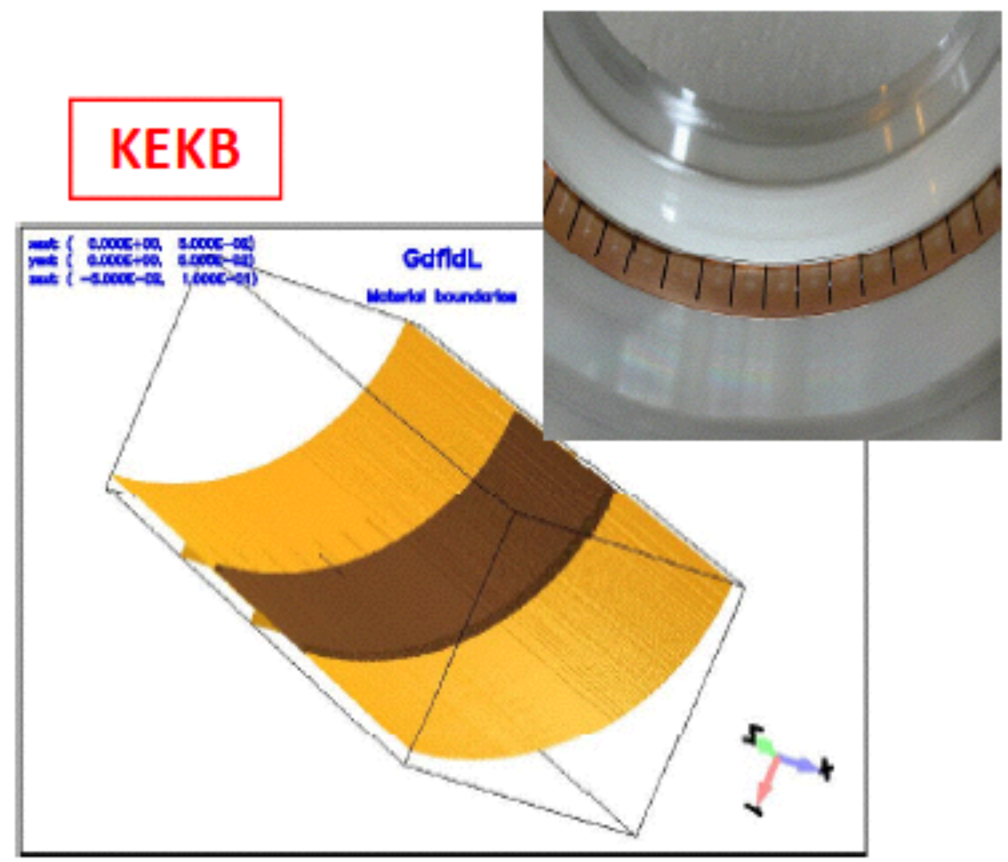
Bellows

- Bellows chamber with comb-type RF shield will be used in SKEKB.
  - There is no radial step on the inner surface.
    (There is a small step (~1 mm) in a conventional bellows chamber.)
  - RF is shielded by nested comb teeth.
    length : 10 mm
    radial thickness : 10 mm

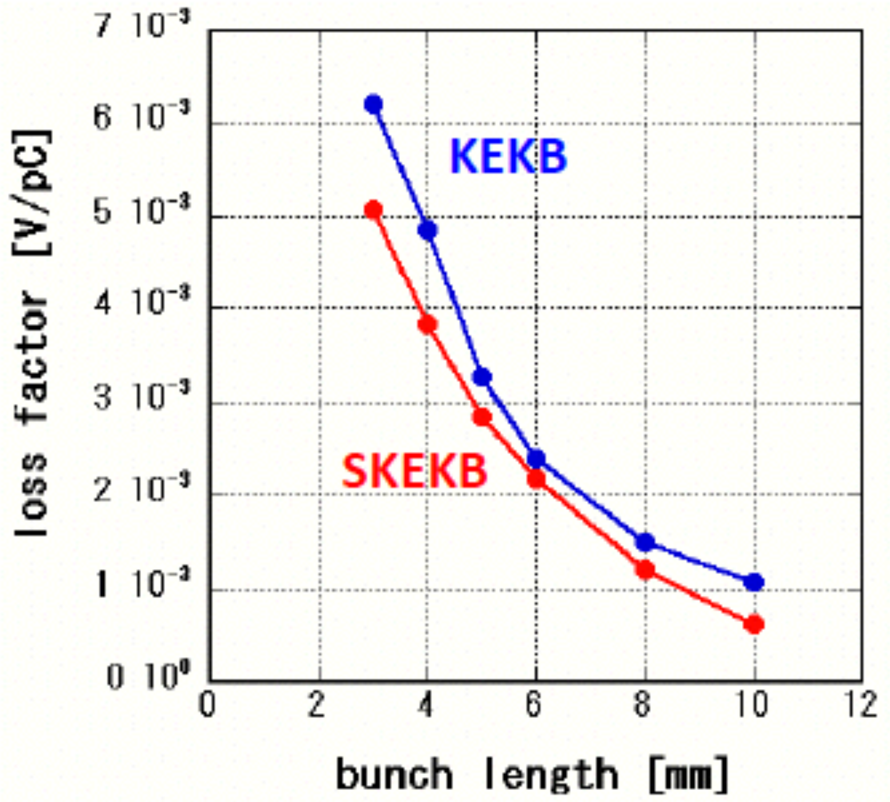
SKEKB

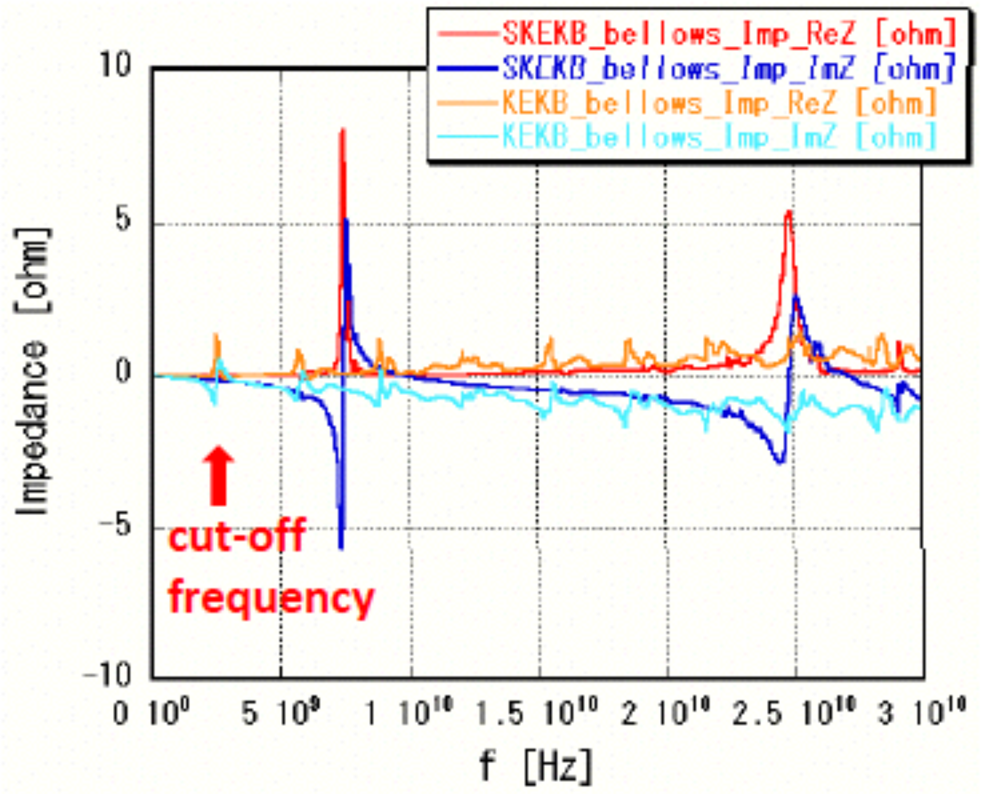


KEKB



Bellows





- Loss factor (σ_z = 6 mm)

  $k = 2.2\times10^{-3}$ V/pC

  ⇩ 1000 pieces in one ring

  k_total = 2.2 V/pC

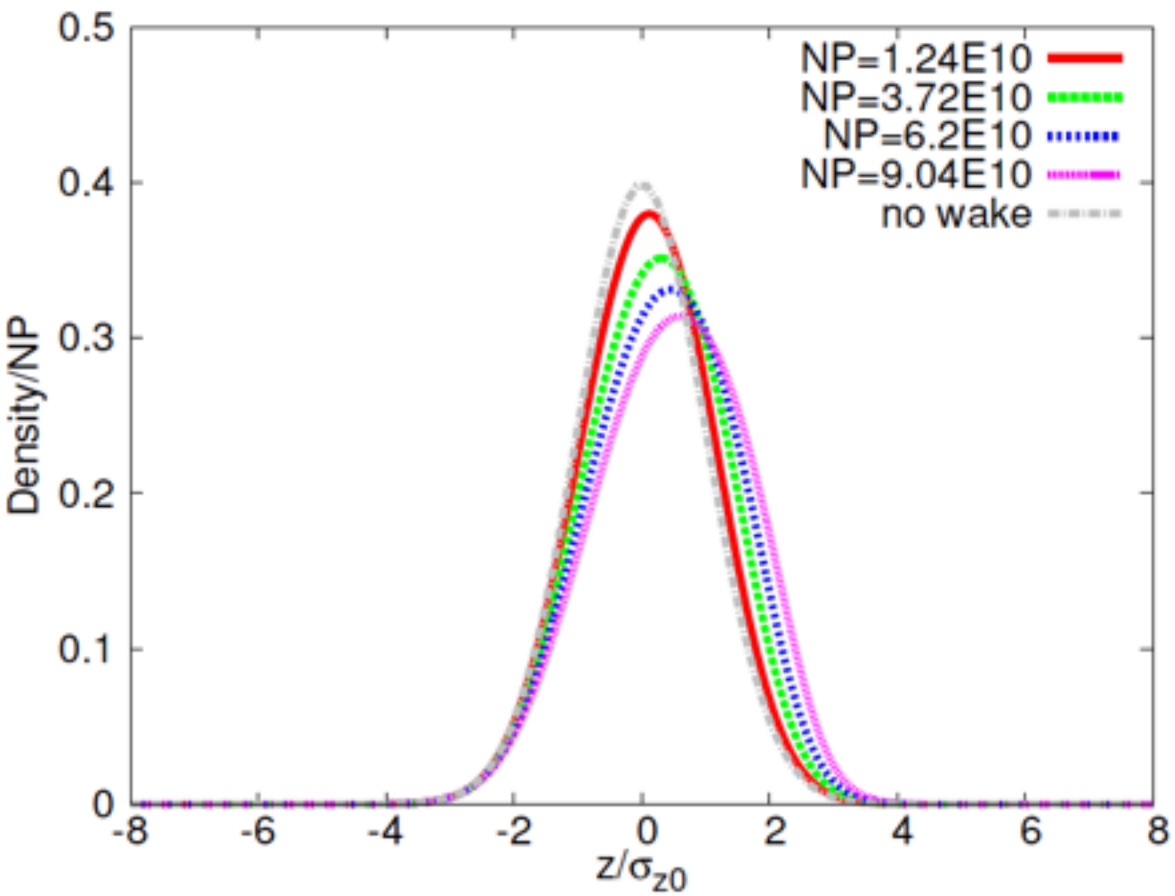
- Impedance

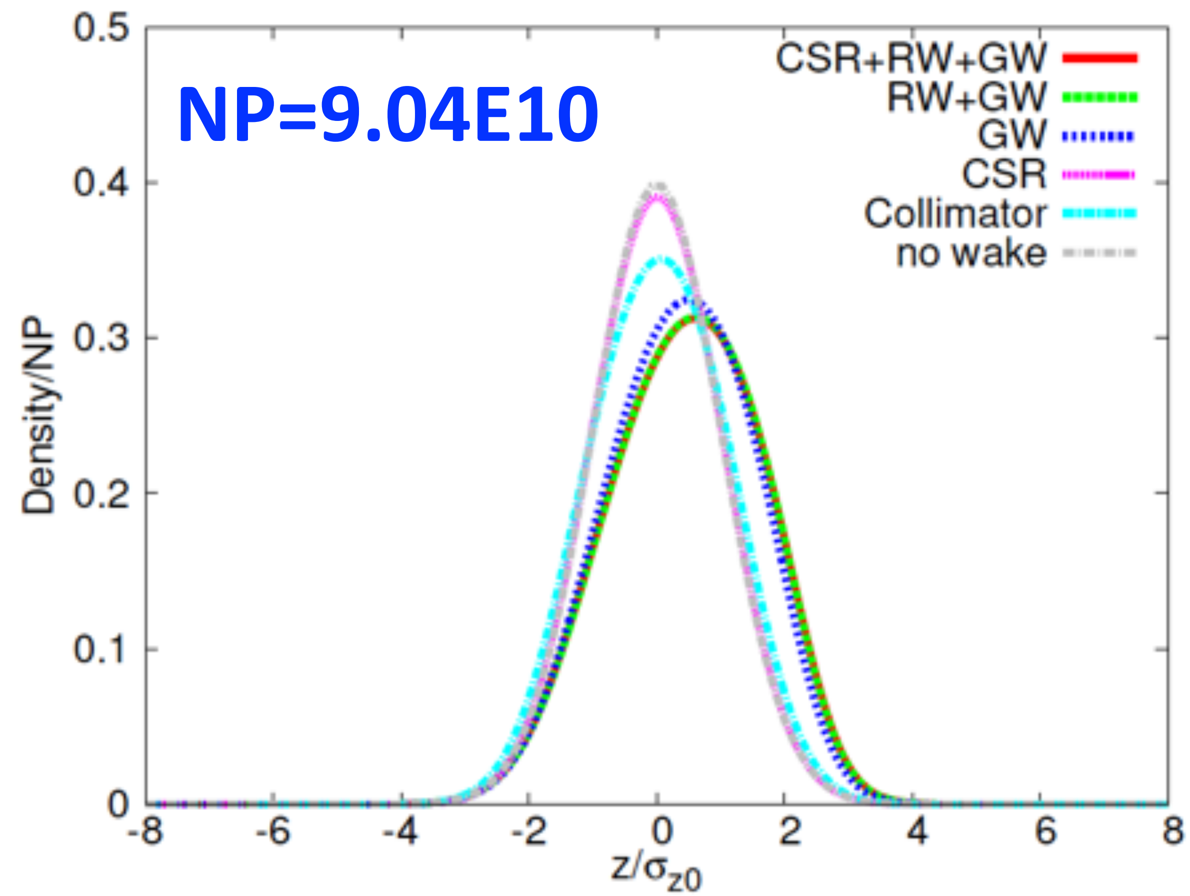
  It was found that there are trapped modes at 7.5 GHz and 25 GHz (over cut-off frequency (2.5GHz)). Effects of these trapped modes on the beams will be investigated.

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**

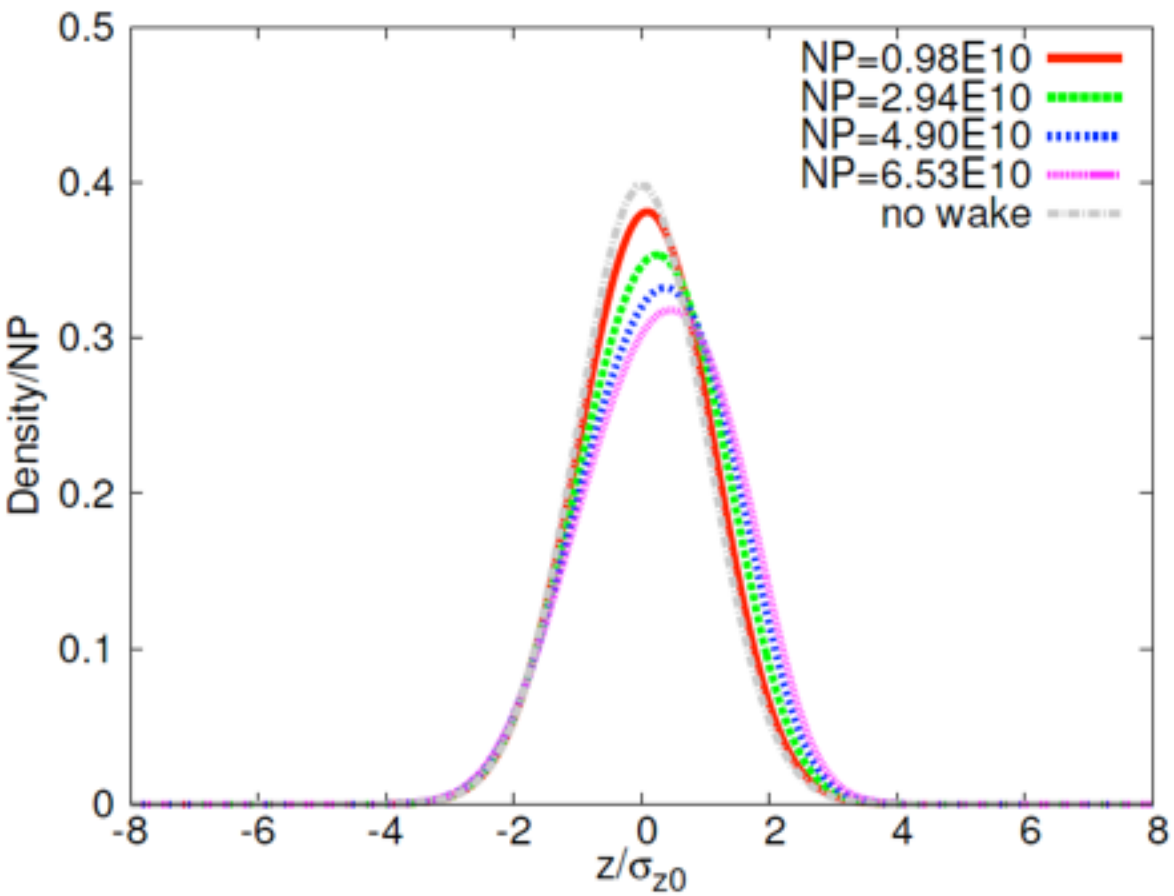


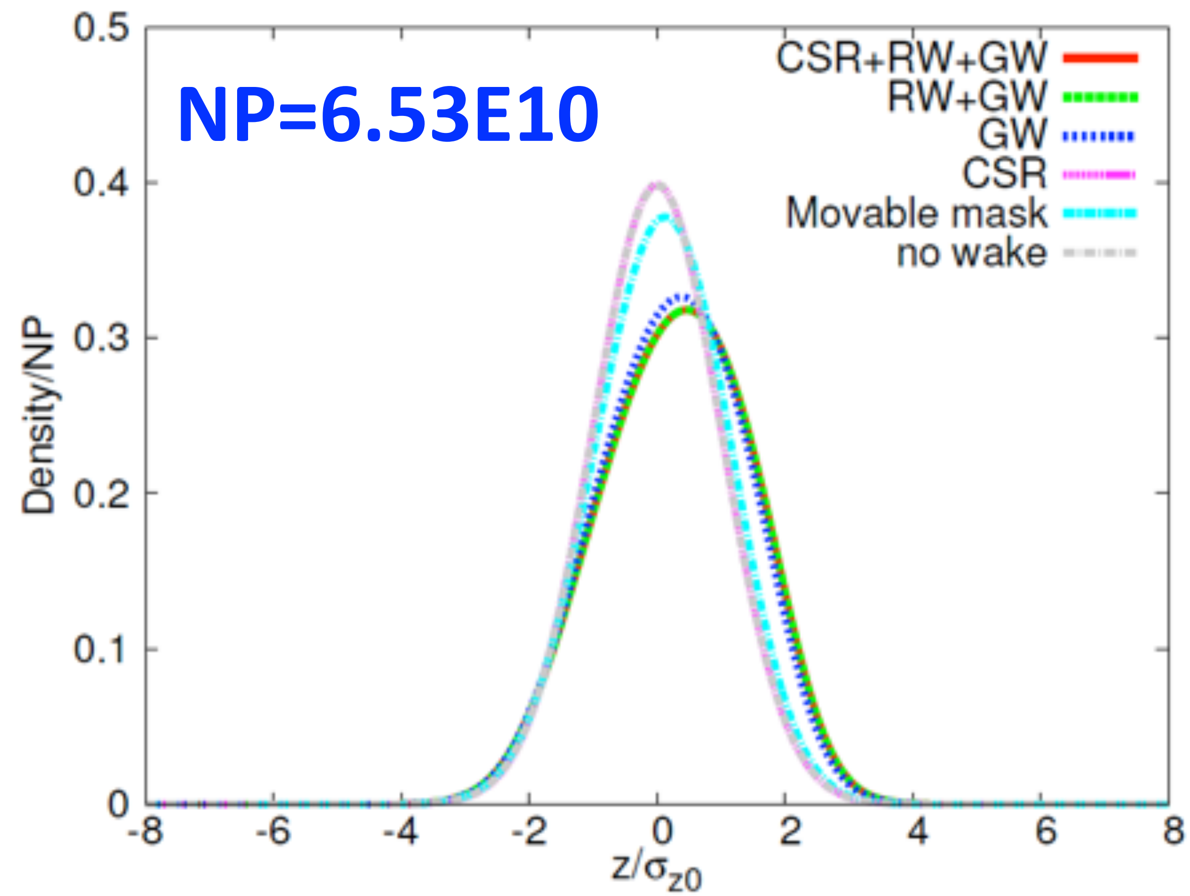


4. Single-bunch effects: Longitudinal: HER

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

- **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**



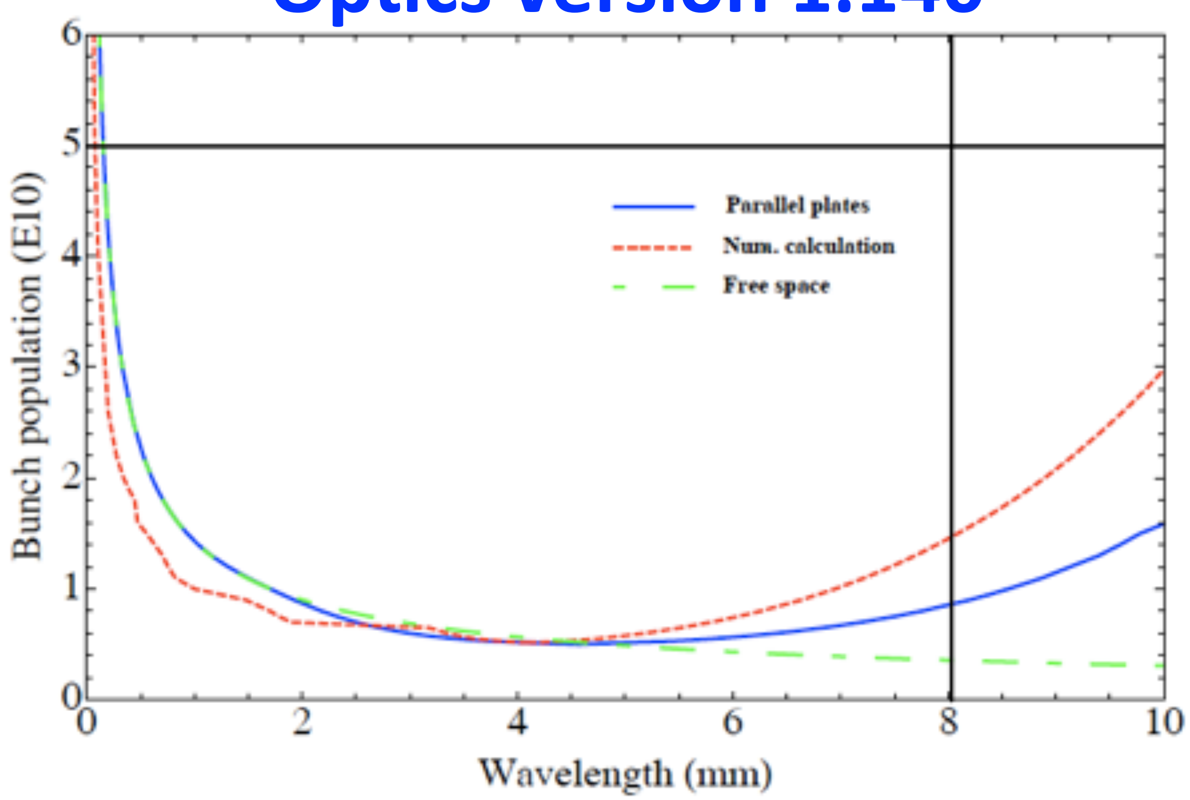


4. CSR: SuperKEKB: Damping ring

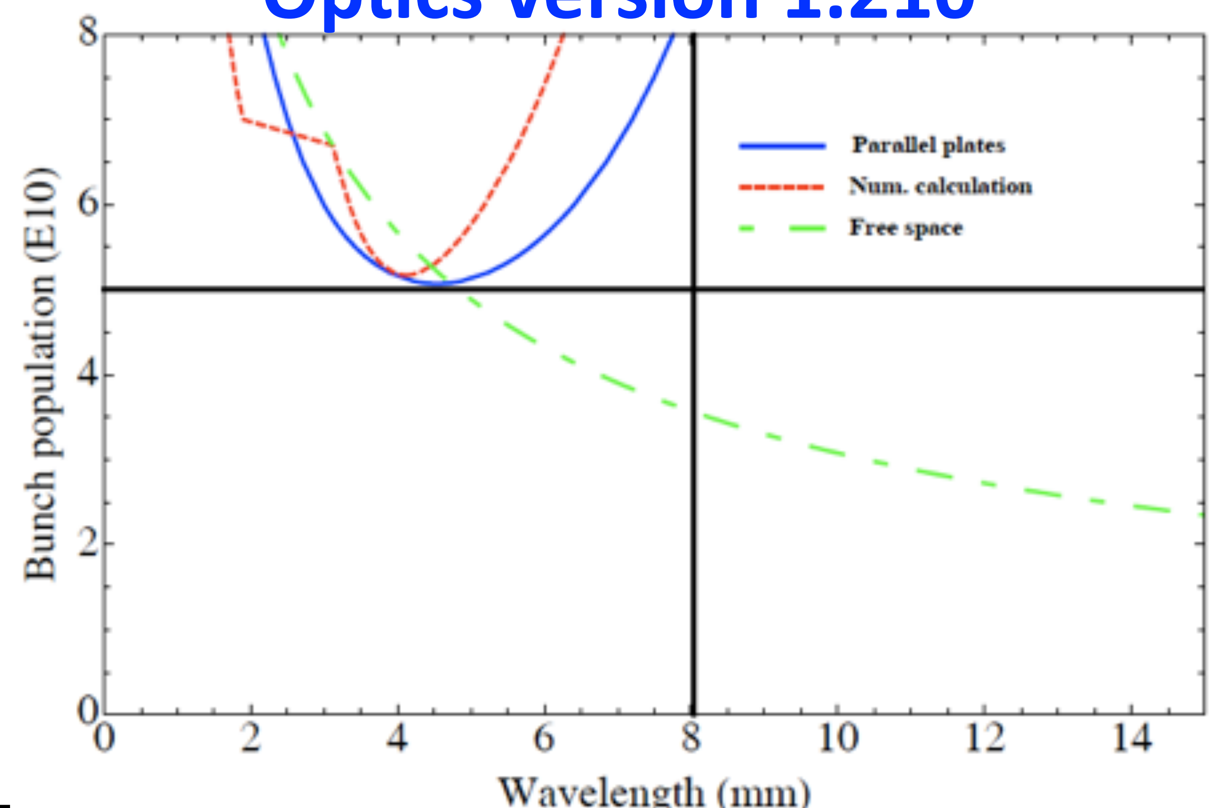
➤ Findings: General

- CSR: High-frequency impedance in the mm wave regime; Overtaking self-fields
- Numerical noise in impedance calculation: Low/high in rectangular/arbitrary chamber cross-section
- Instability analysis(Stupakov-Heifets theory): a simple, but robust method for estimate of CSR effect

Optics version 1.140



Optics version 1.210

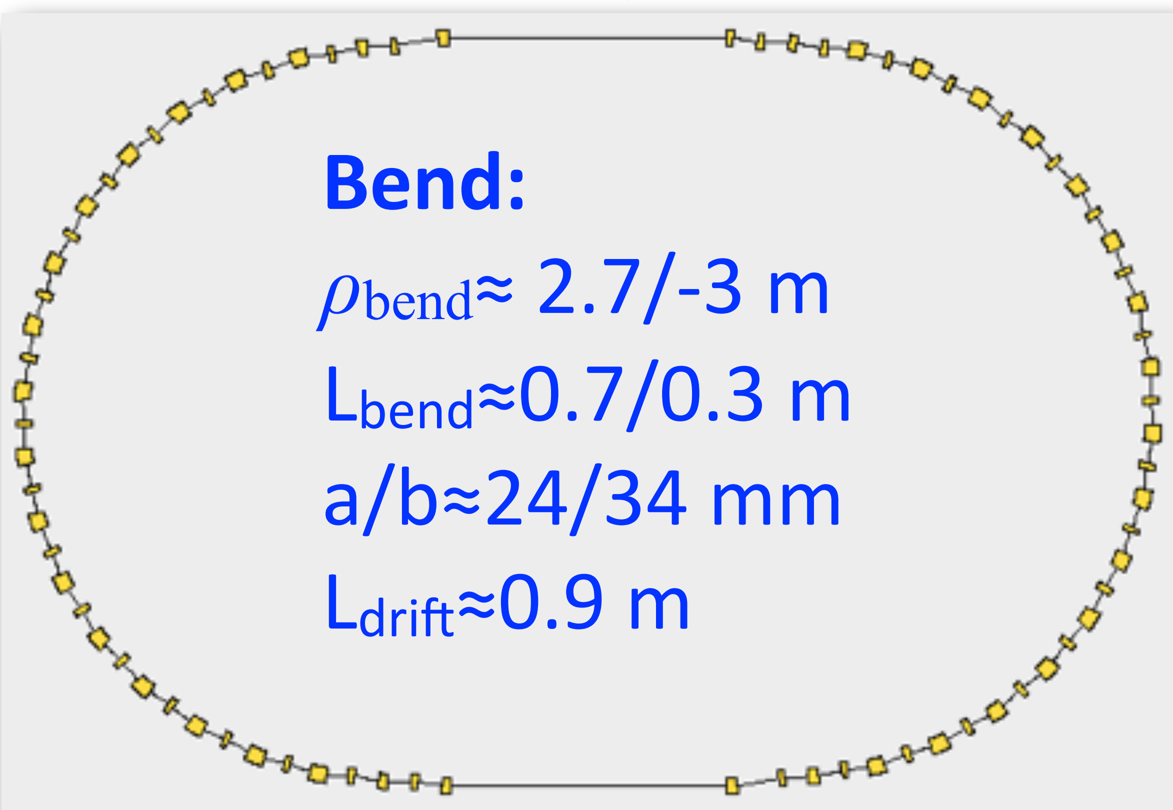


4. CSR: SuperKEKB: Damping ring

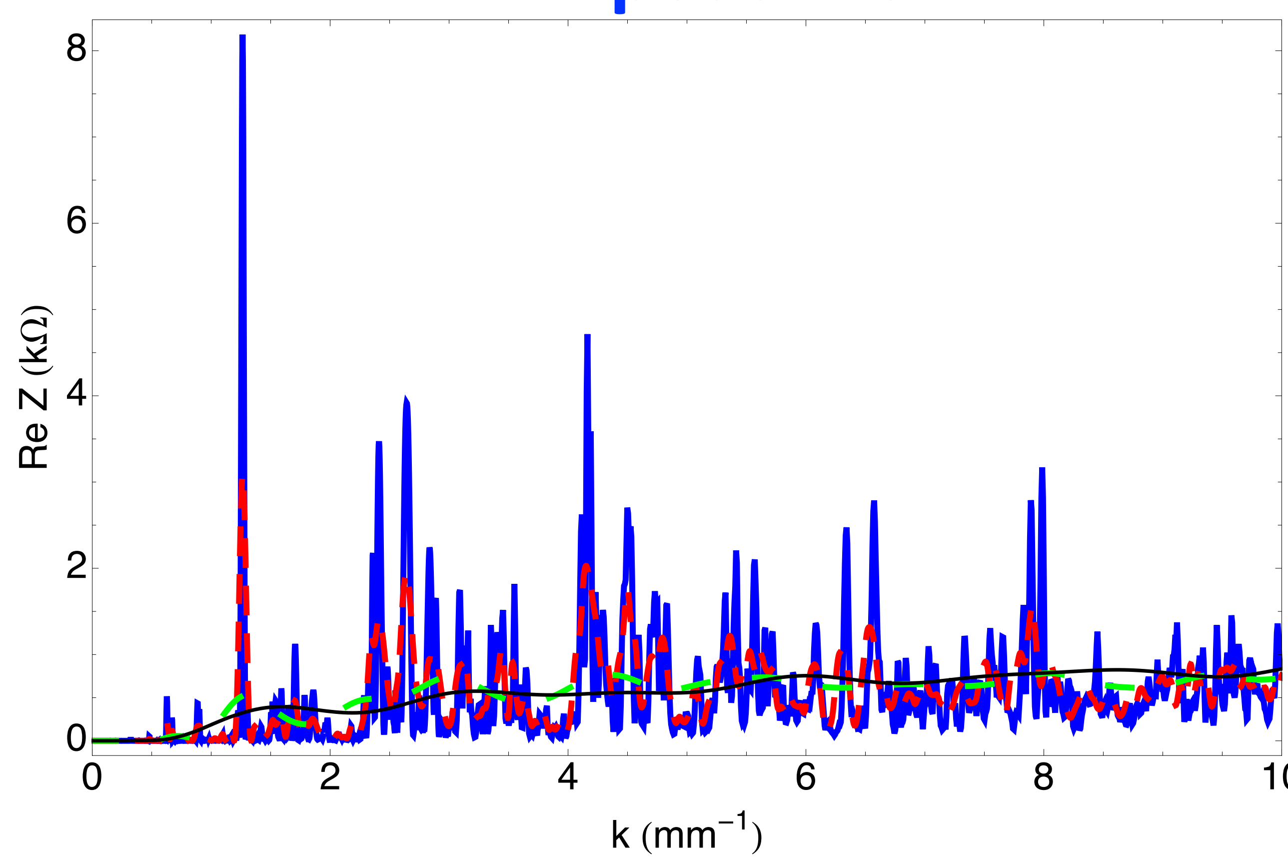
➤ Findings: Impedance

- **CSR impedance: Forest of "narrow-band" spikes**
- **Multi-bend interference in CSR: Interesting but likely not important for both single- and multi-bunch instability**

DR layout



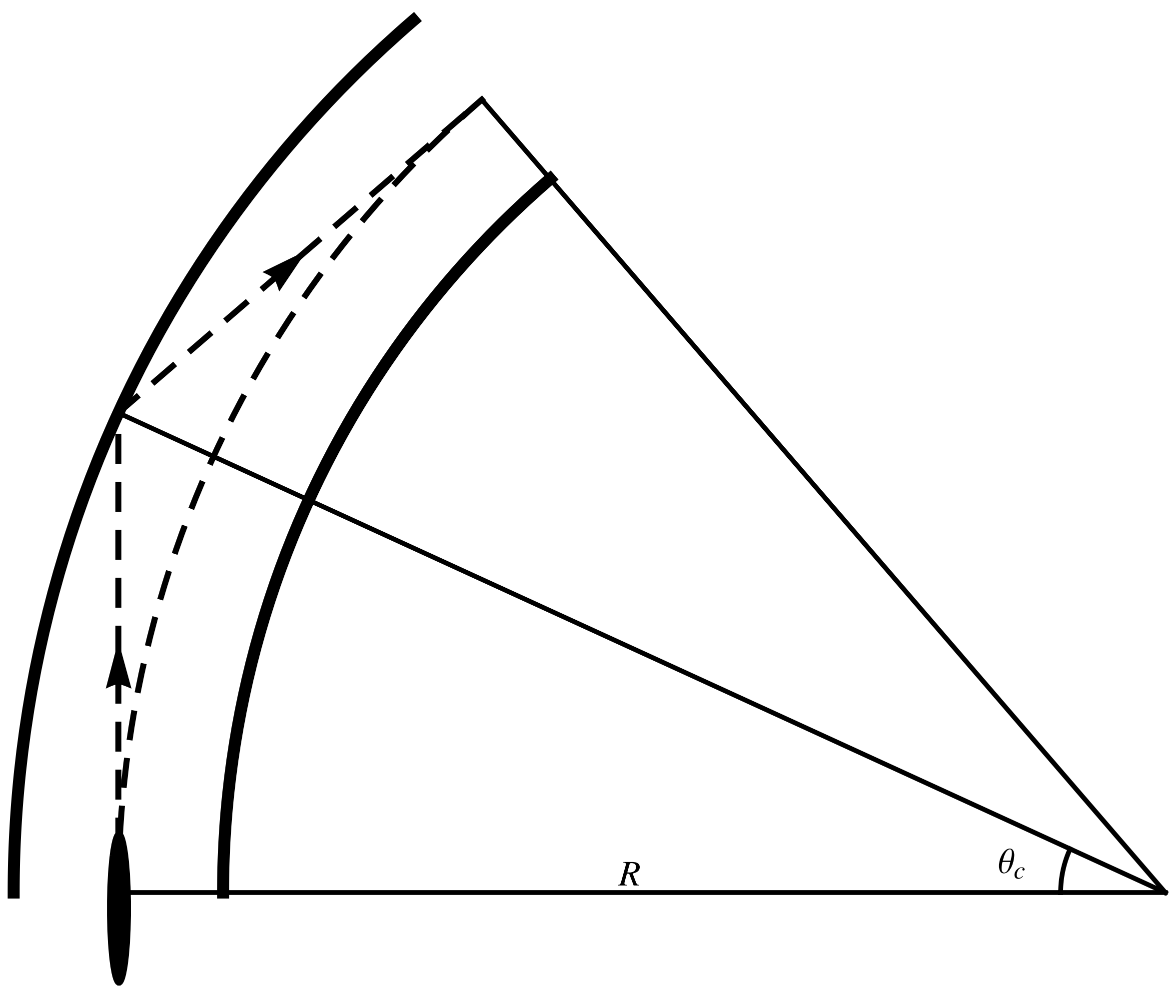
Impedance

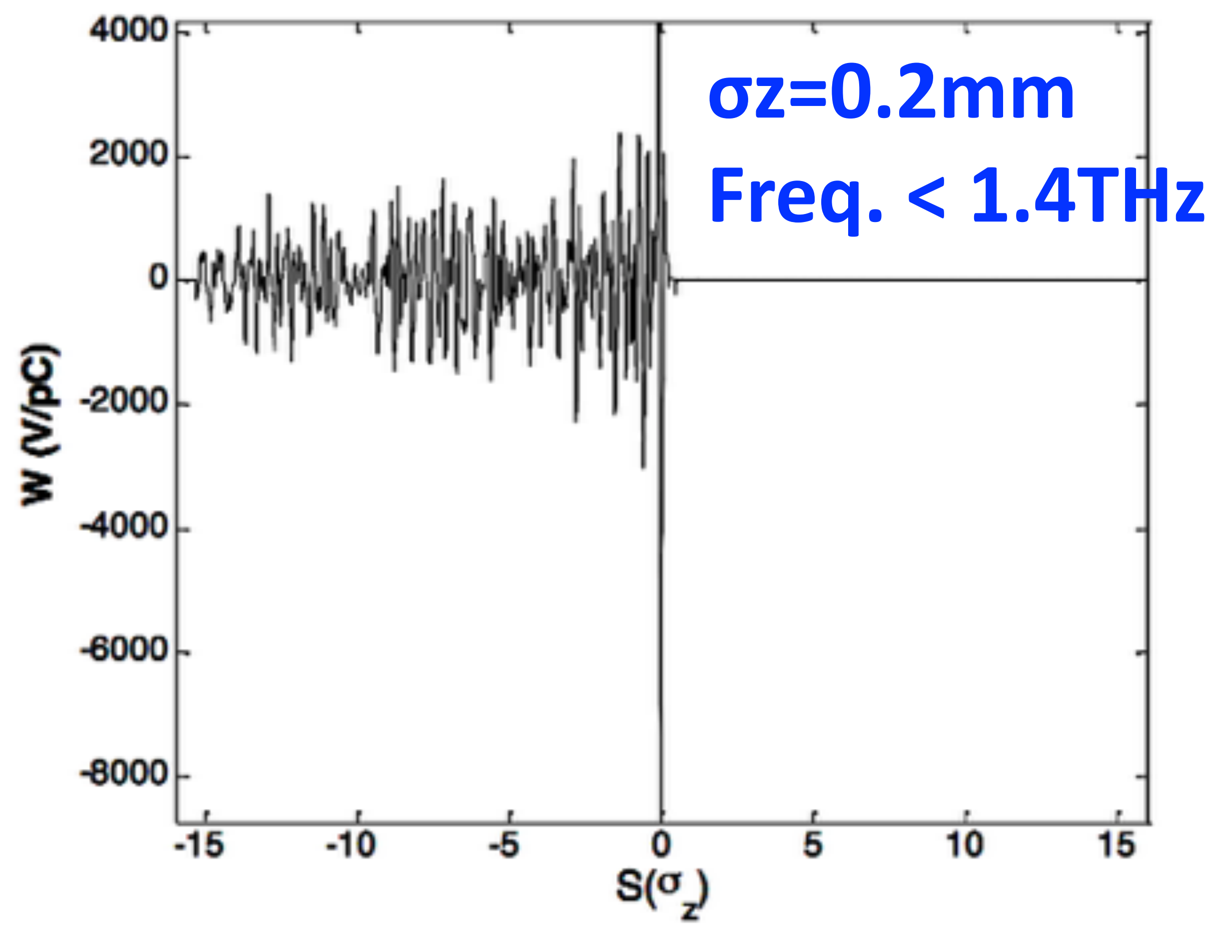


4. CSR: SuperKEKB: Damping ring

➤ **Findings: Multi-bunch instability**

- **Long-range CSR wake extend to distance of ~0.1 m**
- **Not considered in CSR impedance calculation: Resistive wall and chamber discontinuities**
- **No multi-bunch CSR instability(?)**



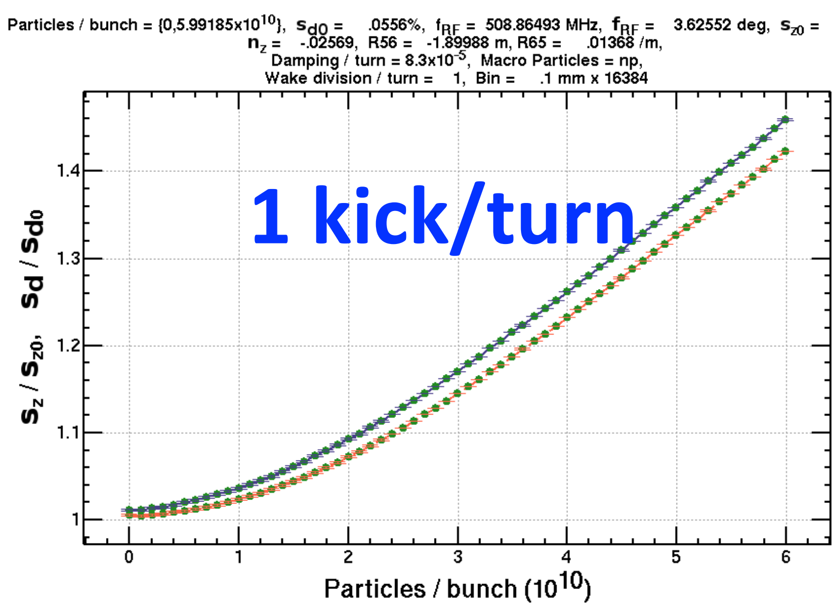


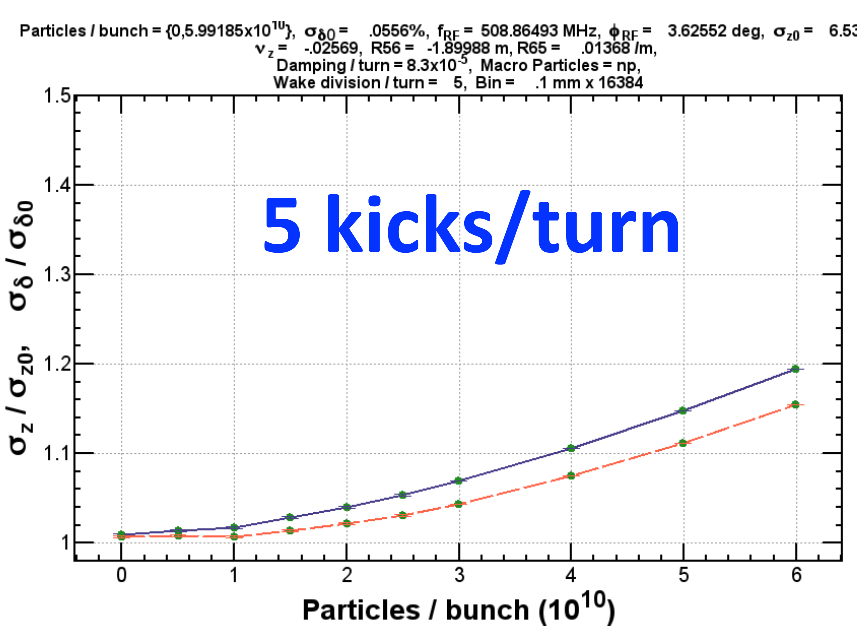
L. Wang and D. Zhou

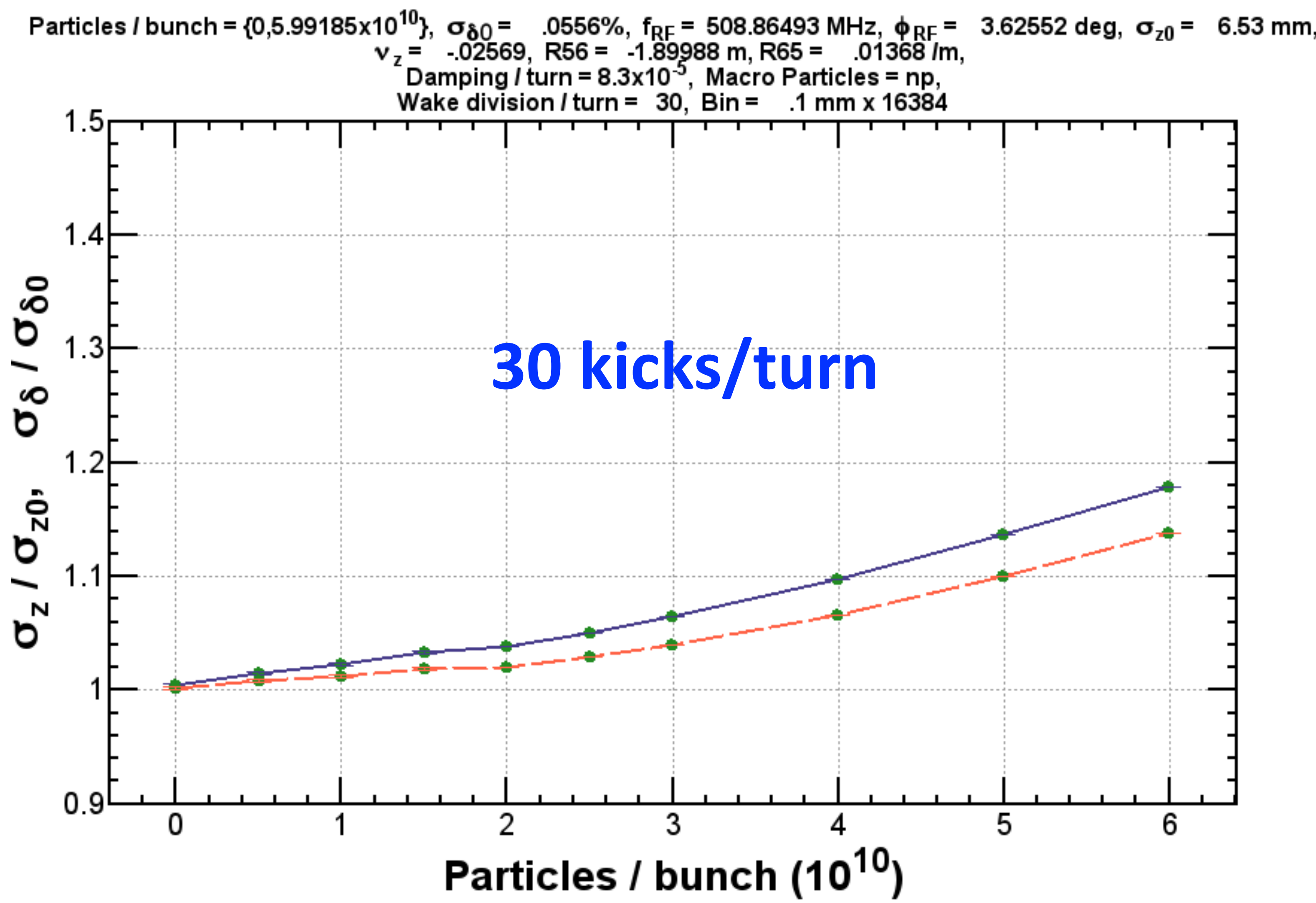
4. CSR: SuperKEKB: Damping ring

➤ Findings: PIC tracking

- CSR instability is sensitive to number of kicks per turn
- Mesh size contribute to numerical noise
- Tracking always suffers from numerical noise







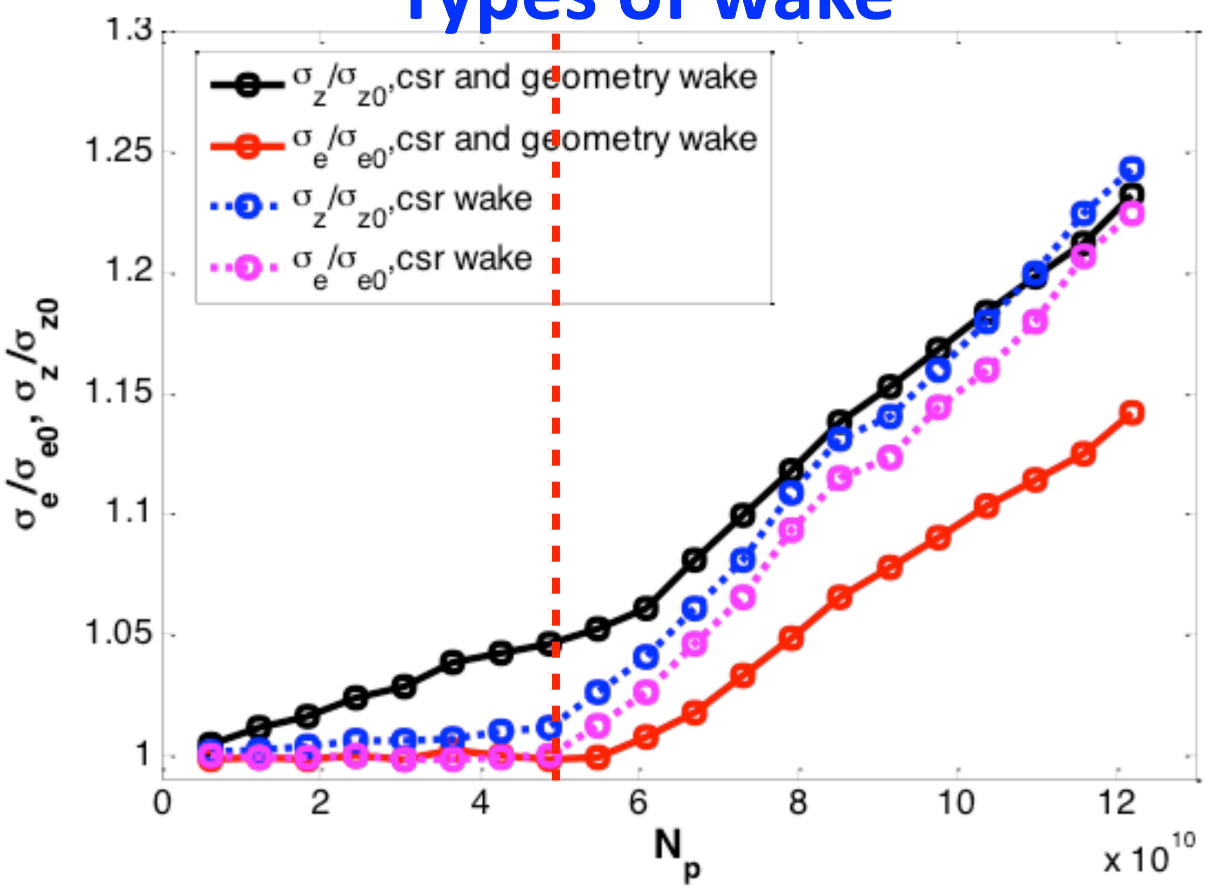
Courtesy of H. Ikeda

4. CSR: SuperKEKB: Damping ring

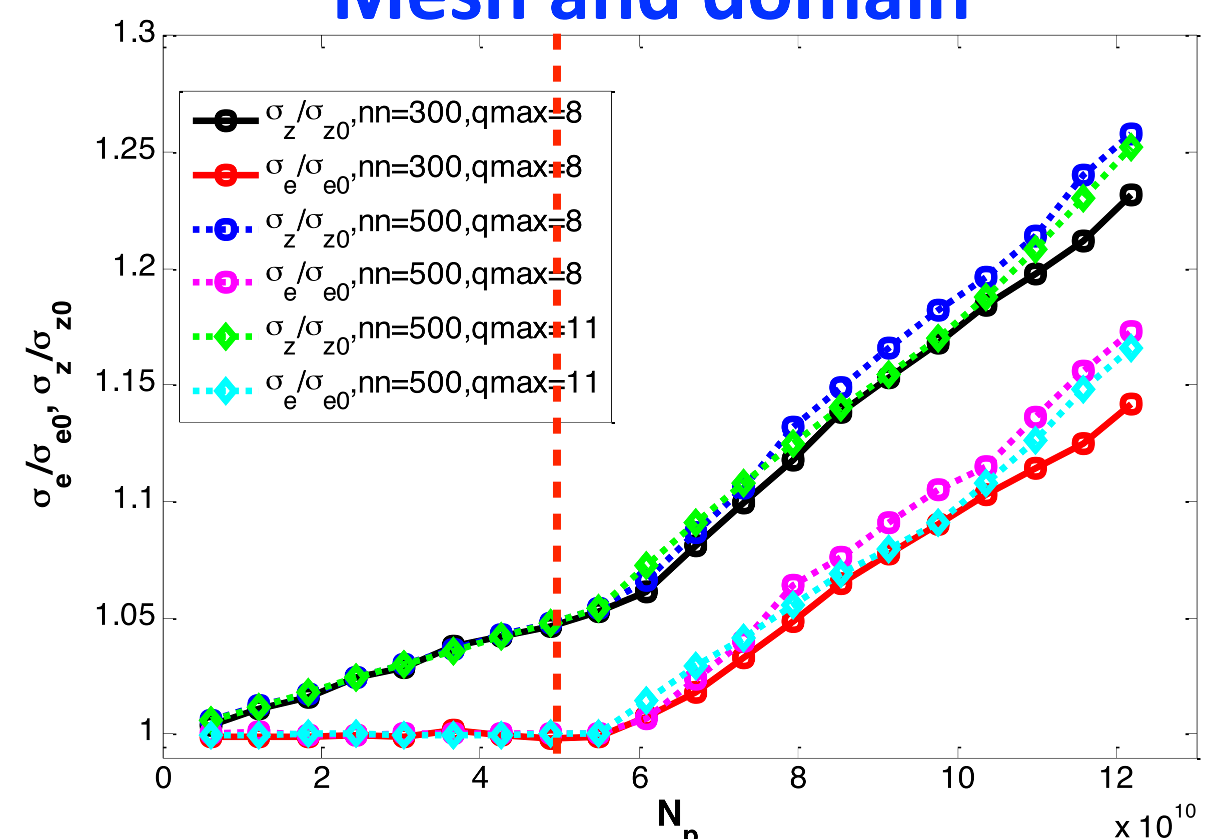
➤ Findings: Vlasov solver

- CSR instability is sensitive to number of kicks per turn
- Sizes of mesh and domain contribute to numerical noise
- Numerical noise significantly suppressed
- Typical: 1024 kicks per synch. period
- Almost no CSR instability below design bunch current
- Threshold(CSR) close to Stupakov-Heifets-Cai theory

Types of wake



Mesh and domain



L. Wang and D. Zhou