Chromatic aberrations and Coherent Synchrotron Radiation in the KEKB and SuperKEKB

Demin Zhou

Acknowledgements: G. Stupakov, K. Oide, Y. Cai, K. Ohmi, T. Agoh, K. Yokoya, Y. Funakoshi, Y. Ohnishi, Y. Seimiya and all KEKB group members

IHEP, Dec. 22, 2010

Outline - Chromatic aberrations

1. Introduction

2. Chromatic aberrations (momentum-dependent nonlinearities)

2.1 Theory (Y. Seimiya, K. Ohmi, et al.)

2.2 Measurements (Y. Ohnishi, K. Ohmi, et al.)

2.3 Simulations (D. Zhou, K.Ohmi, et al.)

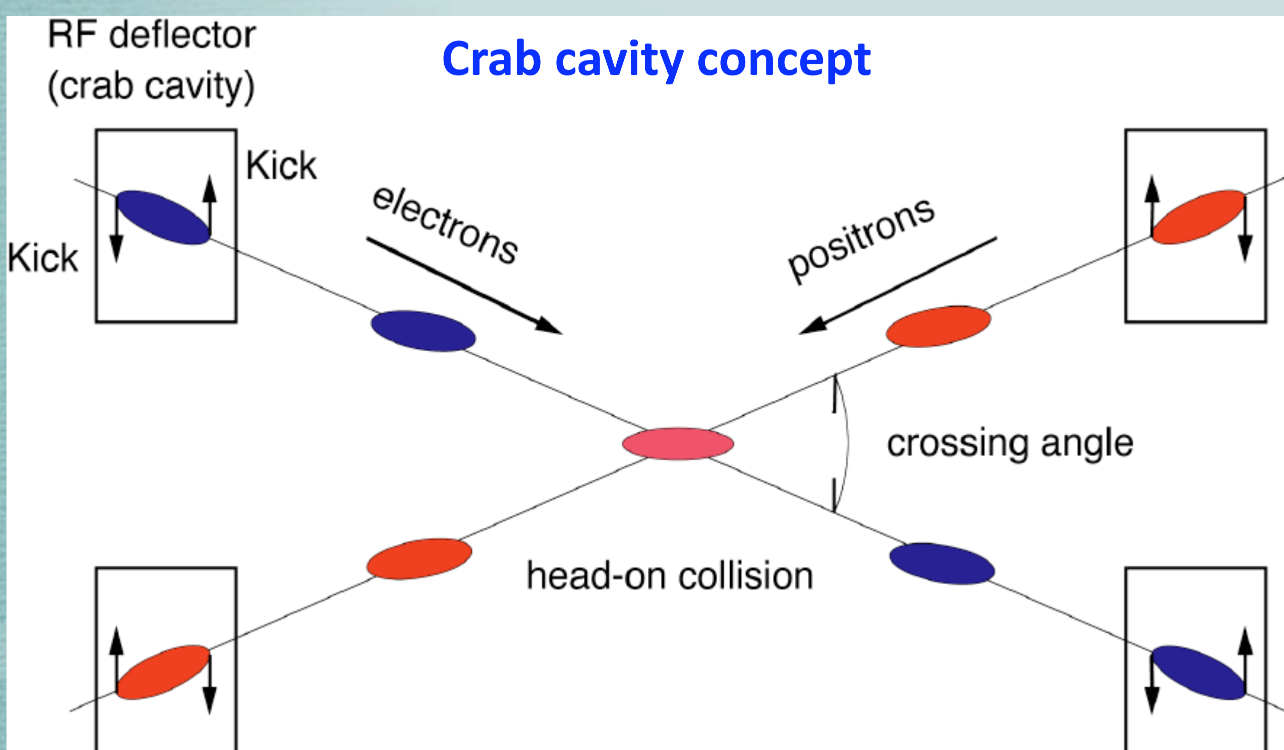
2.4 Observed luminosity performance

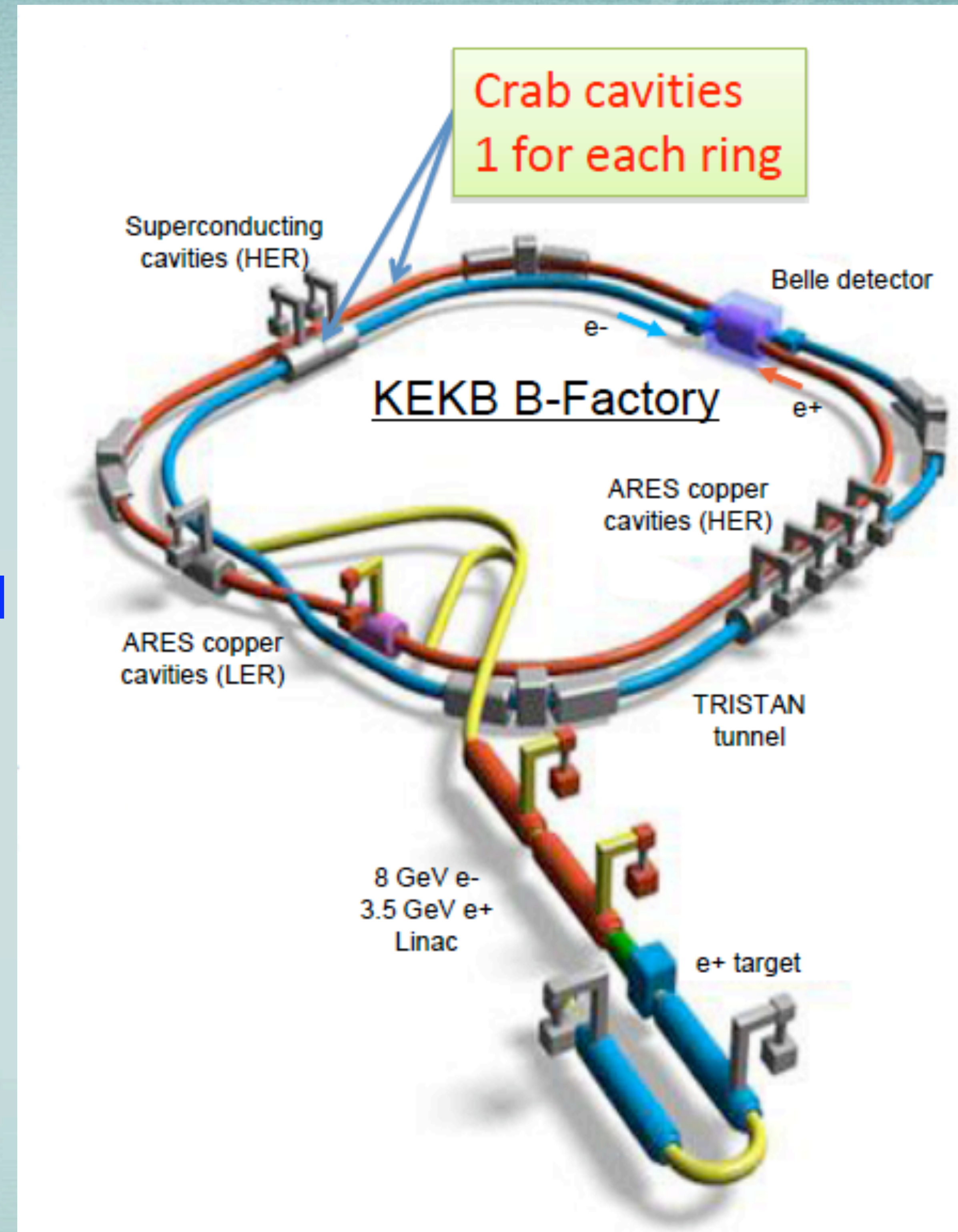
3. Summary

KEKB B-Factory

Milestones since 2007

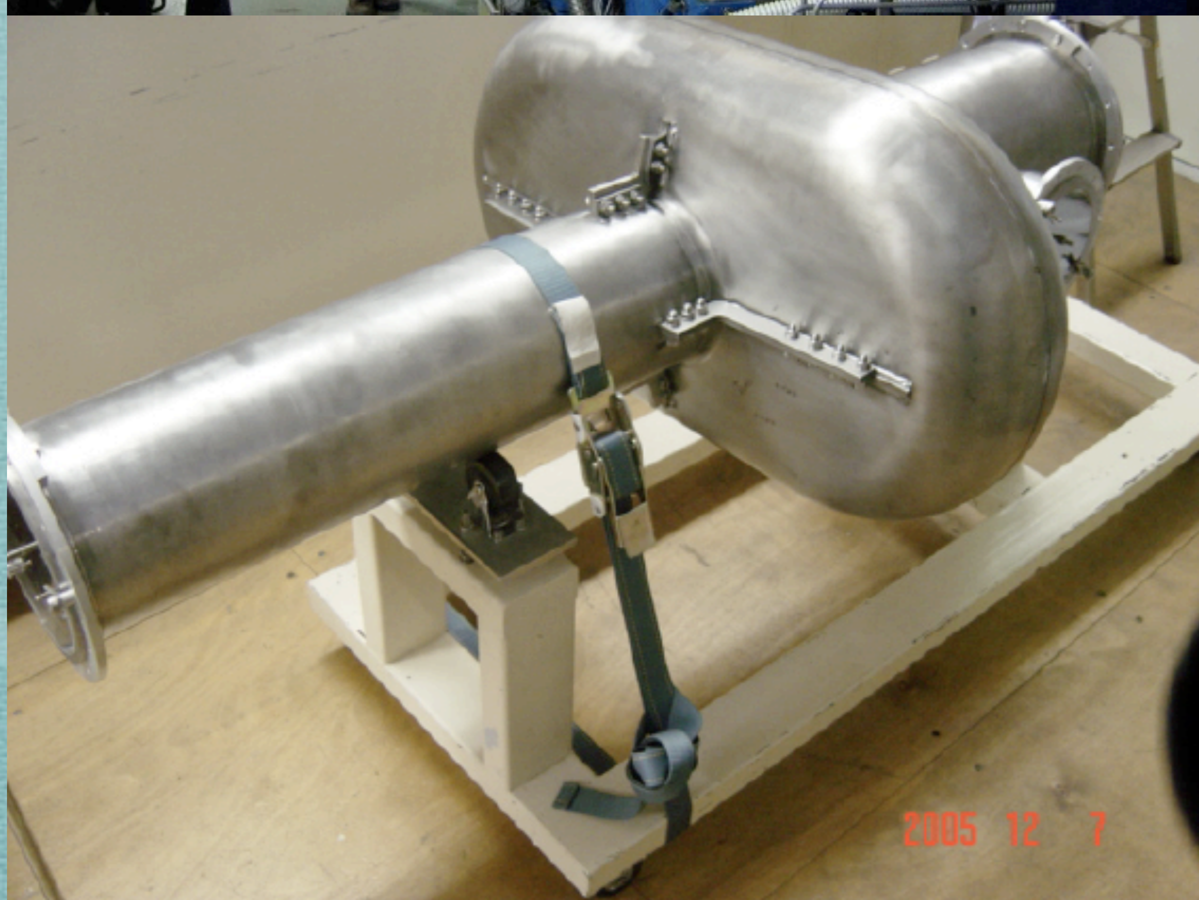
2007 Jan. Crab cavities installed
2007 Mar. Crab tuning started
2009 Apr. Skew-sext. installed
2009 Jun. Lum. ➽ $2.11 \times 10^{34} cm^{-2} s^{-1}$
2009 Nov. ∫Lum. ➽ $1000 fb^{-1}$
2010 Jun. KEKB shut down
2010 Jun. SuperKEKB officially approved

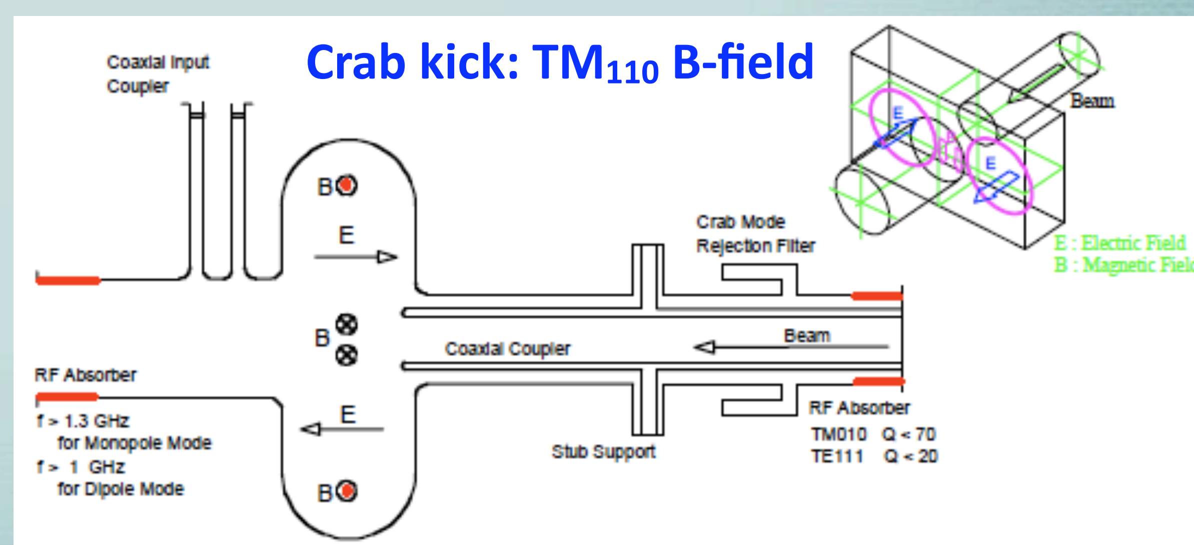




Ref. Y. Funakoshi, IPAC10

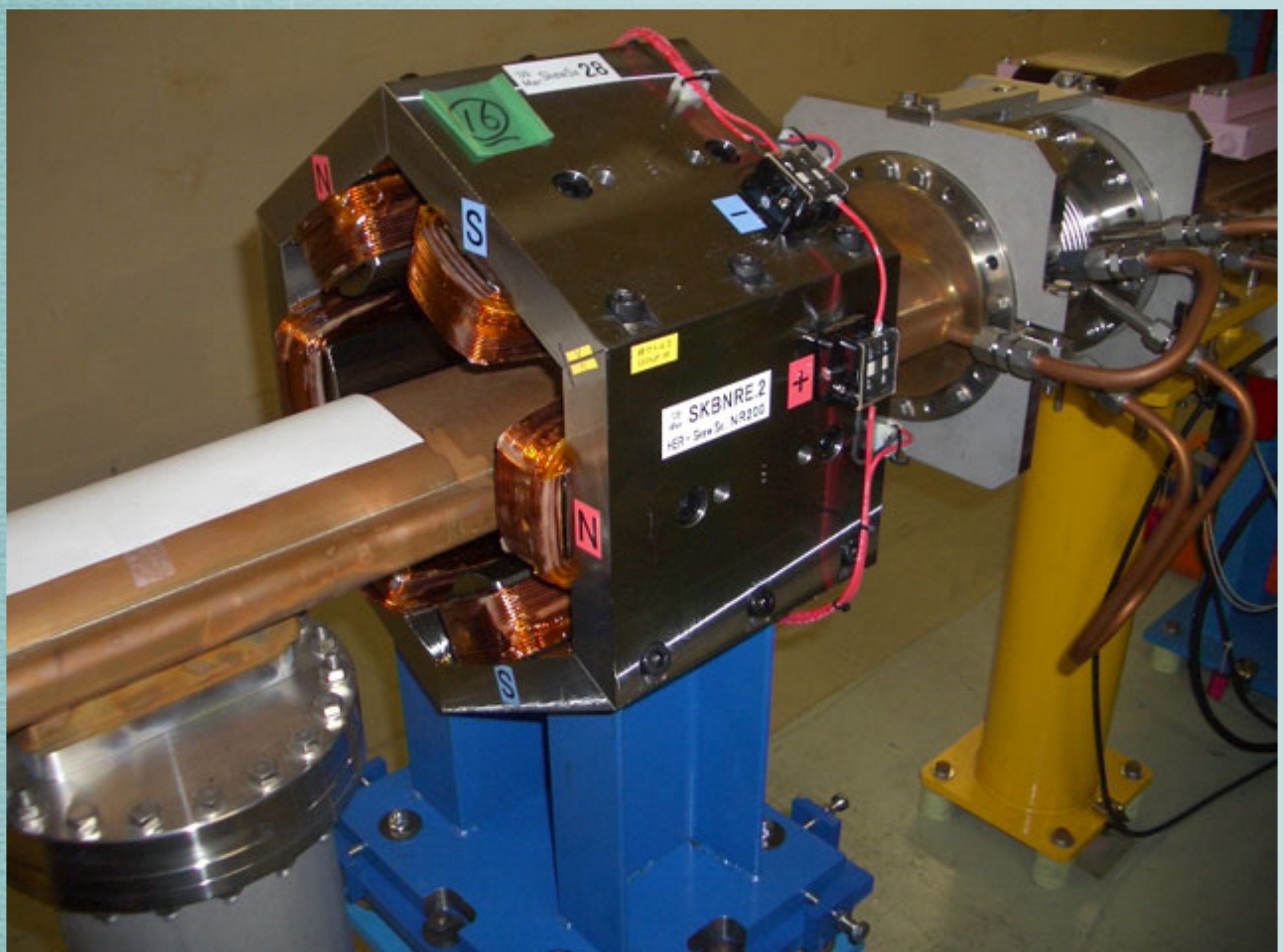
Crab cavity

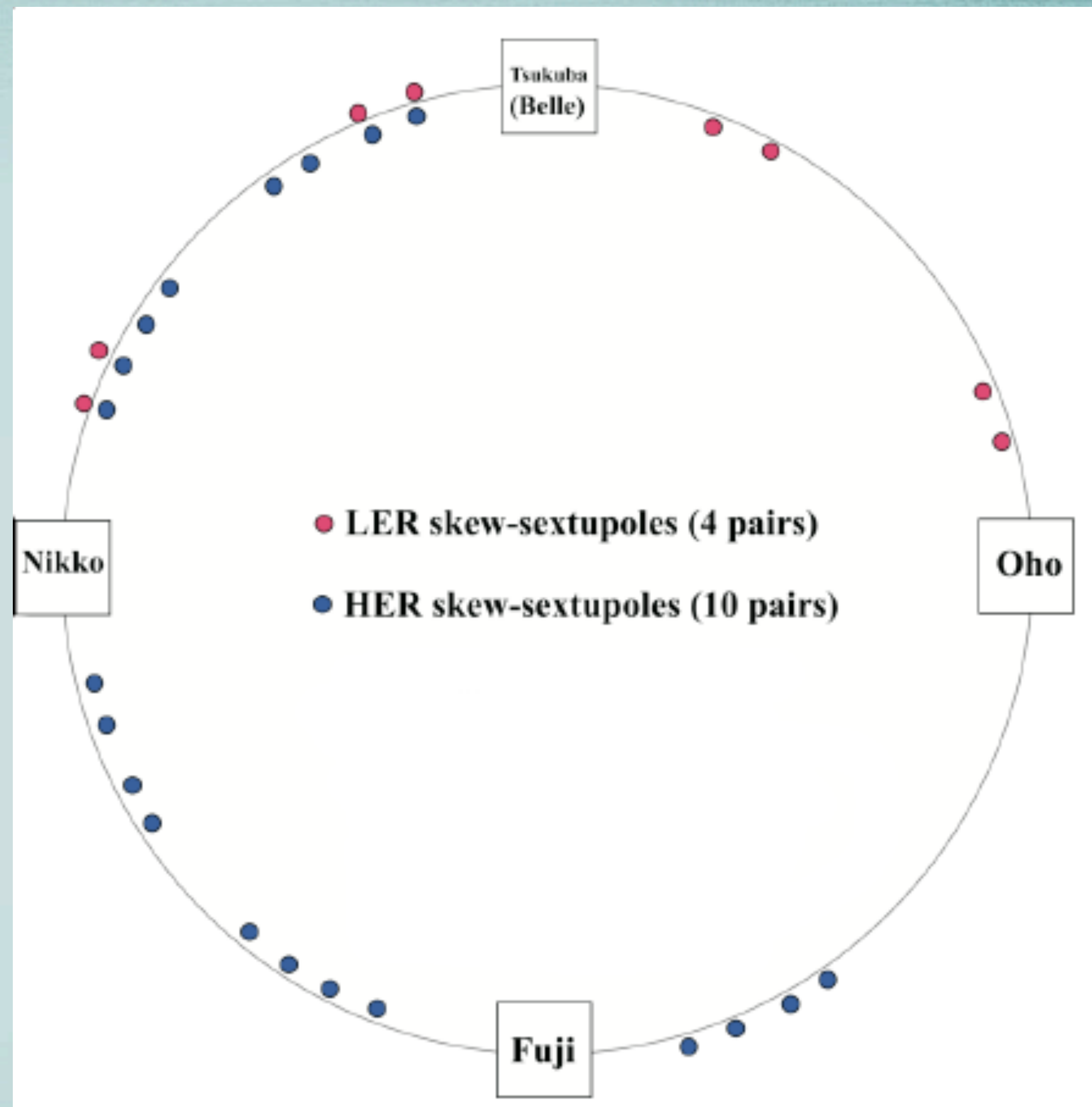




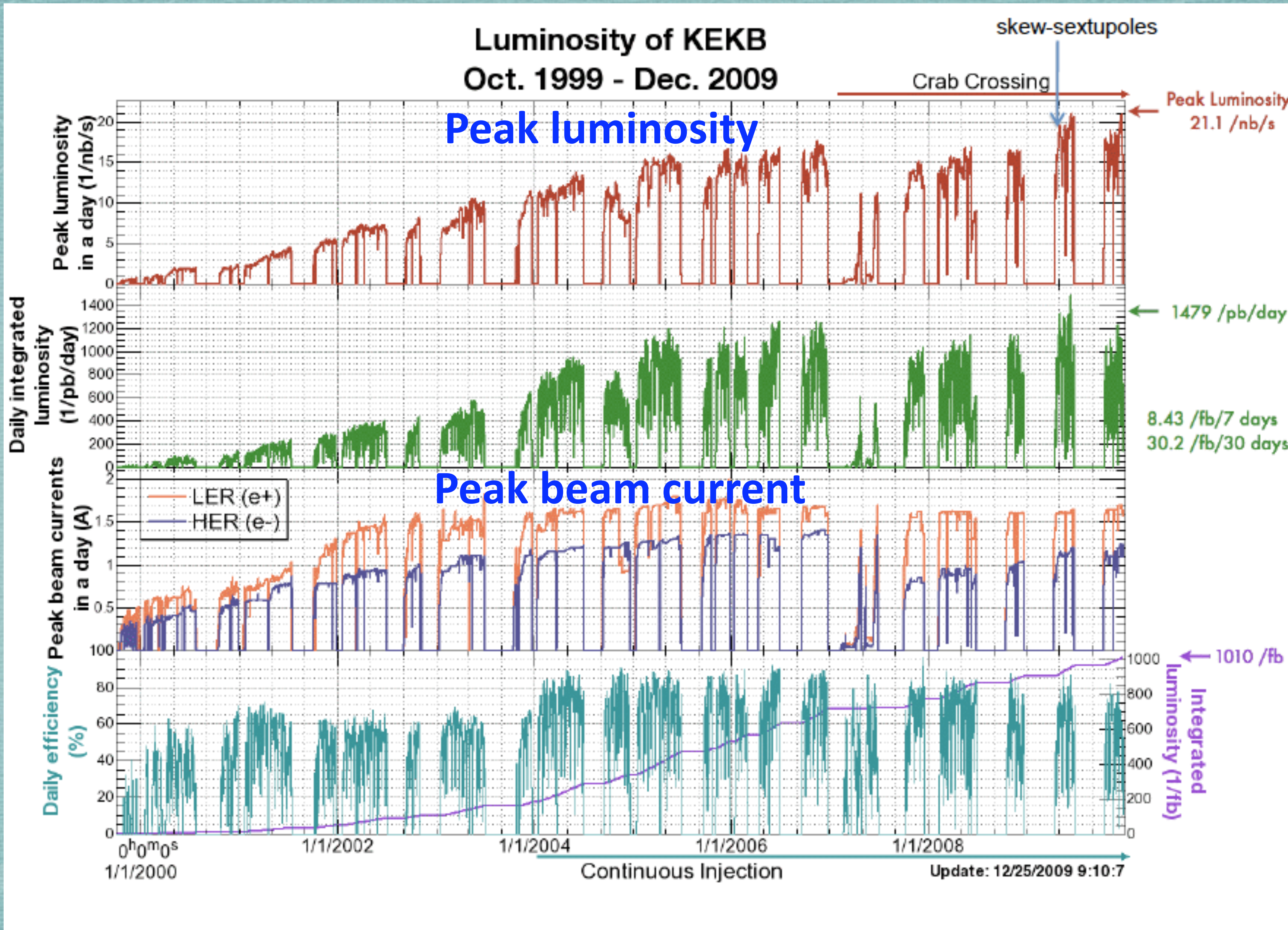
Ref. Y. Funakoshi, IPAC10
K. Hosoyama, EPAC08

Skew-sextupole





Ref. Y. Funakoshi, IPAC10



Ref. Y. Funakoshi, IPAC10

Sunday, December 26, 2010

Machine parameters

Date	Nov.15 2006 before crab		Jun. 17 2009 with crab		
	LER	HER	LER	HER	
Current	1.65	1.33	1.64	1.19	A
Bunches	1389		1584		
Bunch current	1.19	0.96	1.03	0.750	mA
spacing	2.10		1.84		mA
emittance ε_x	18	24	18	24	nm
β_x^*	59	56	120	120	cm
β_y^*	6.5	5.9	5.9	5.9	mm
σ_x @IP	103	107	147	170	µm
σ_y @IP	1.8	1.8	0.94	0.94	µm
ν_x	45.505	43.534	45.506	44.511	
ν_y	44.509	41.565	43.561	41.585	
ν_s	-0.0246	-0.0226	-0.0246	-0.0209	
beam-beam ξ_x	0.117	0.070	0.127	0.102	
beam-beam ξ_y	0.108	0.058	0.129	0.090	
Luminosity	17.6		21.08		$10^{33}cm^{-2}s^{-1}$

NOTE:
With crab cavities installed, β_x^* could not be small enough due to poor beam lifetime.

Ref. Y. Funakoshi, IPAC10

Chromatic aberration - Theory

The ideas:

✓ All machine parameters depend on momentum deviation.
✓ Extend Courant-Snyder formalism to off-momentum particles.
✓ Re-construct the symplectic map in 6-D phase space to include the crosstalk between betatron and synchrotron motion.
✓ Implement the map for chromatic aberrations in beam-beam simulations.
✓ Evaluate the luminosity loss using simulations.

Chromatic aberrations (definition):

$$\alpha_u(\delta) = \sum_{i=0}^{\infty} \alpha_{ui}\delta^i \qquad \beta_u(\delta) = \sum_{i=0}^{\infty} \beta_{ui}\delta^i$$

$$\nu_u(\delta) = \sum_{i=0}^{\infty} \nu_{ui}\delta^i \qquad r_j(\delta) = \sum_{i=0}^{\infty} r_{ji}\delta^i$$

$$u = x, y \quad \text{and} \quad j = 1, 2, 3, 4,$$

$$\delta = (p - p_0)/p_0$$

NOTE:
Chromatic aberrations can be estimated using optics codes or measured using beam.

Y. Seimiya, et al., to be published.
D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Luminosity loss due to all chromatic aberrations:

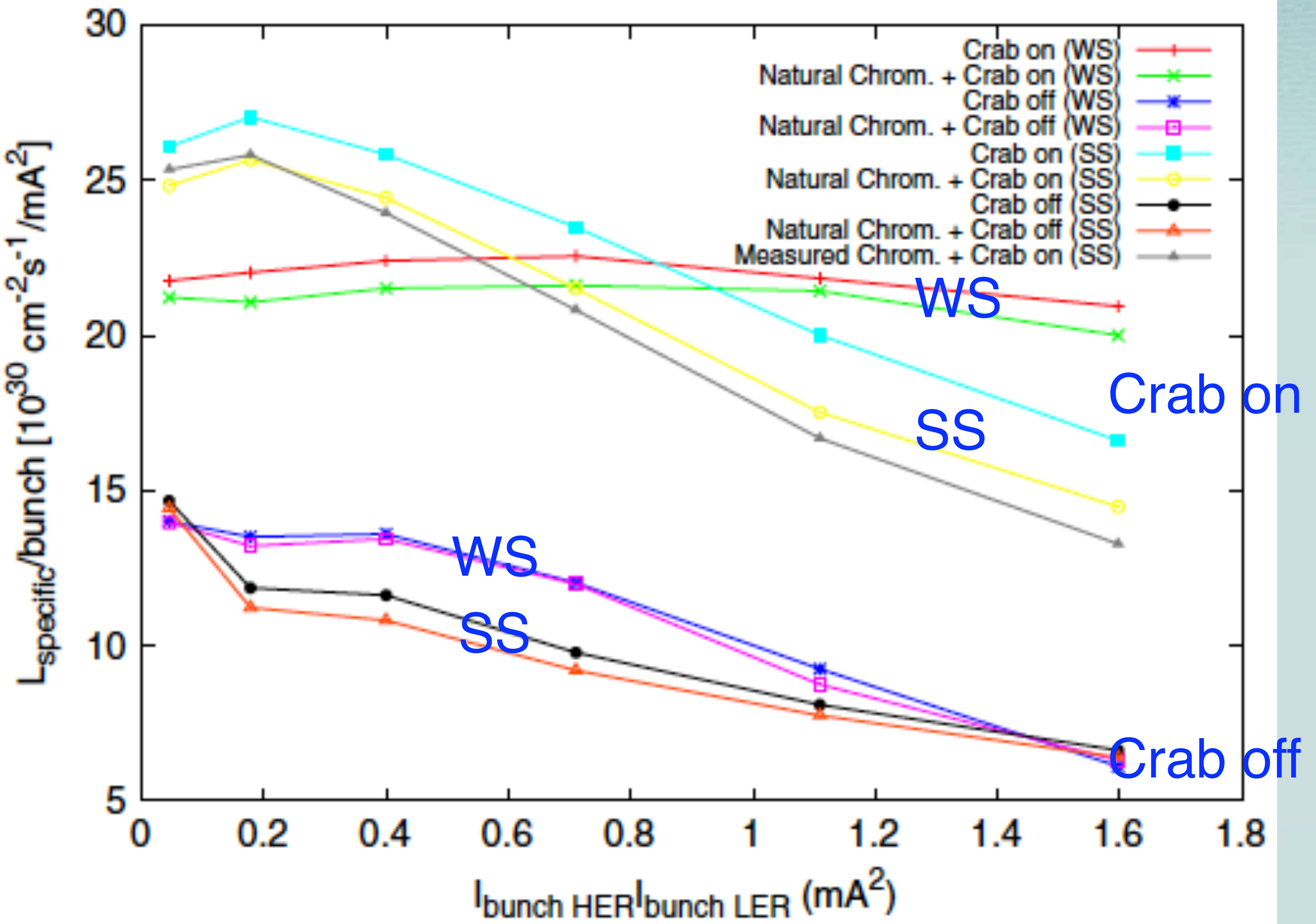


FIG. 5. (Color) Specific luminosity as a function of current product for KEKB. The natural chrom. and measured chrom. indicate natural chromaticity and measured chromaticity calculated from ideal optics and measurement data at KEKB HER, respectively. The WS and SS represent weak-strong and strong-strong simulations, respectively.

WS: weak-strong
SS: strong-strong

$\beta_x^* = 0.9m \quad \beta_y^* = 6mm$

$\nu_x = 44.515 \quad \nu_y = 41.606$

$\kappa = 1\%$

NOTE:
Luminosity loss:
WS: ~5%
SS: ~10%

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

Scan with first-order chromaticity of X-Y couplings (WS, Crab on):

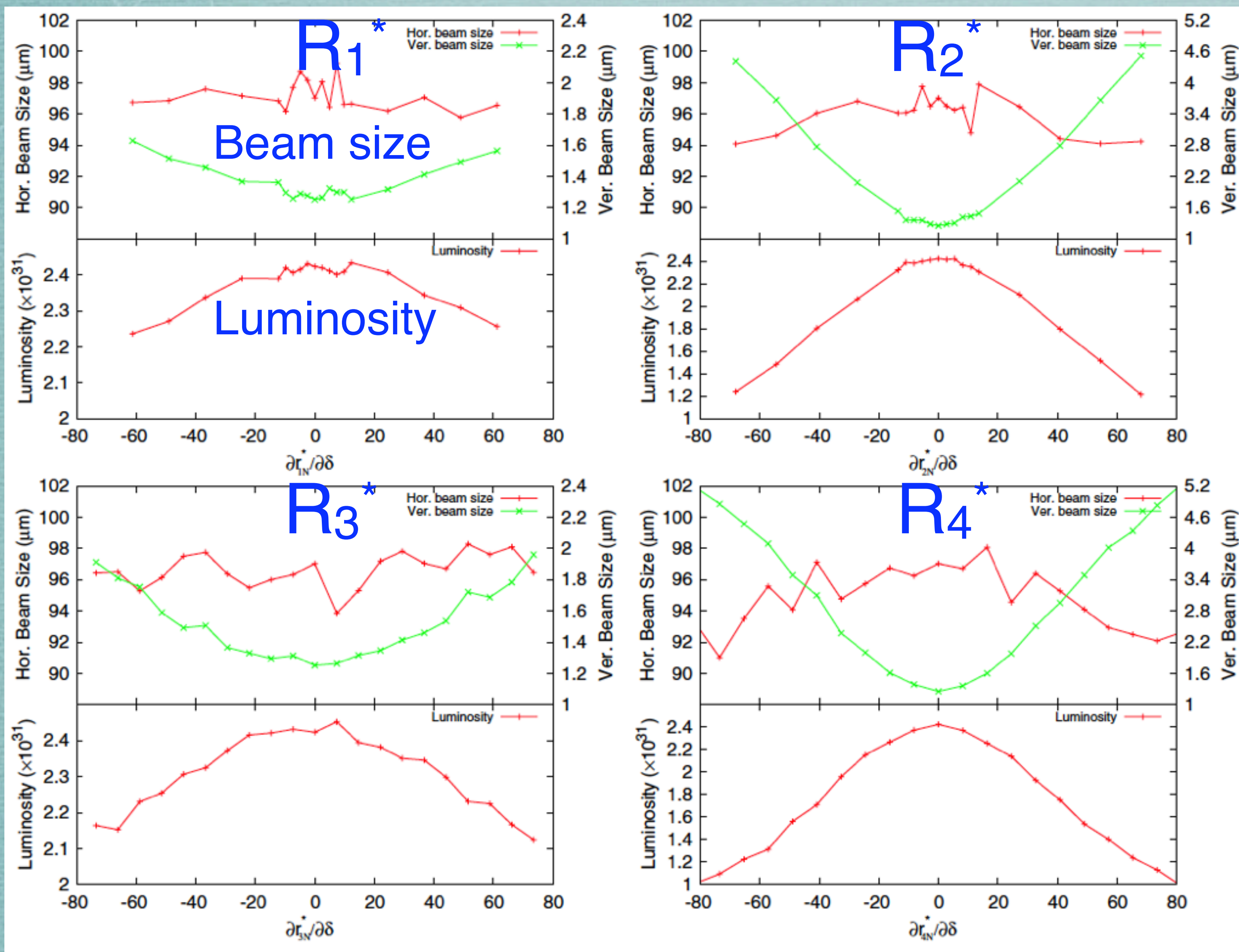


FIG. 8. (Color) Scan of first-order chromaticity of *X*-*Y* couplings at the IP.

$$\begin{pmatrix} r_{1N}^* & r_{2N}^* \\ r_{3N}^* & r_{4N}^* \end{pmatrix} = \begin{pmatrix} r_1^*\sqrt{\beta_x^*/\beta_y^*} & r_2^*/\sqrt{\beta_x^*\beta_y^*} \\ r_3^*\sqrt{\beta_x^*\beta_y^*} & r_4^*\sqrt{\beta_y^*/\beta_x^*} \end{pmatrix}$$

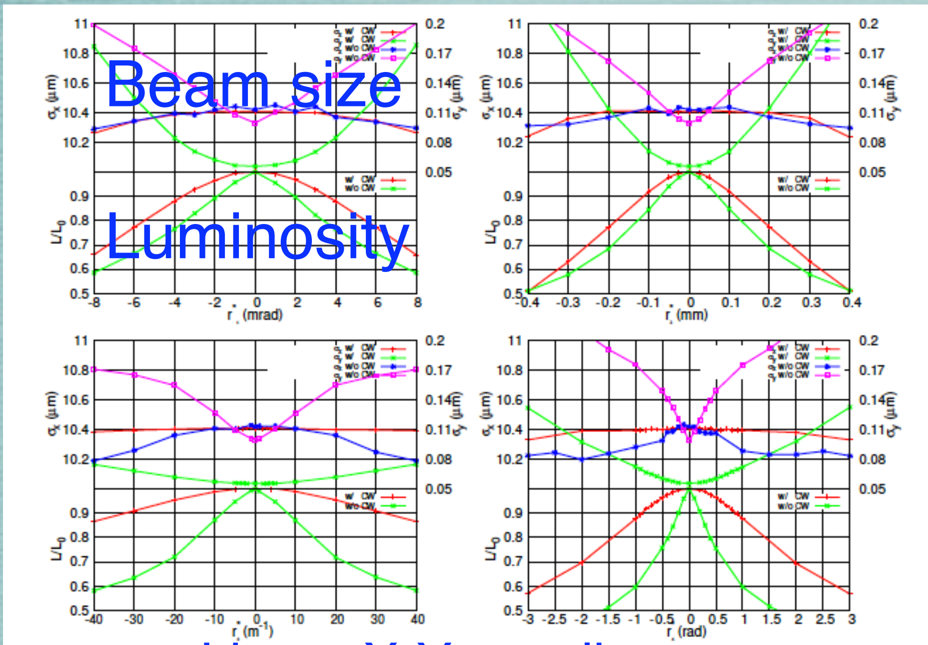
NOTE:
Simulations predicted significant luminosity loss. No particle loss was observed.

D. Zhou, et al., PRST-AB 13, 021001 (2010).

Chromatic aberration - Simulations

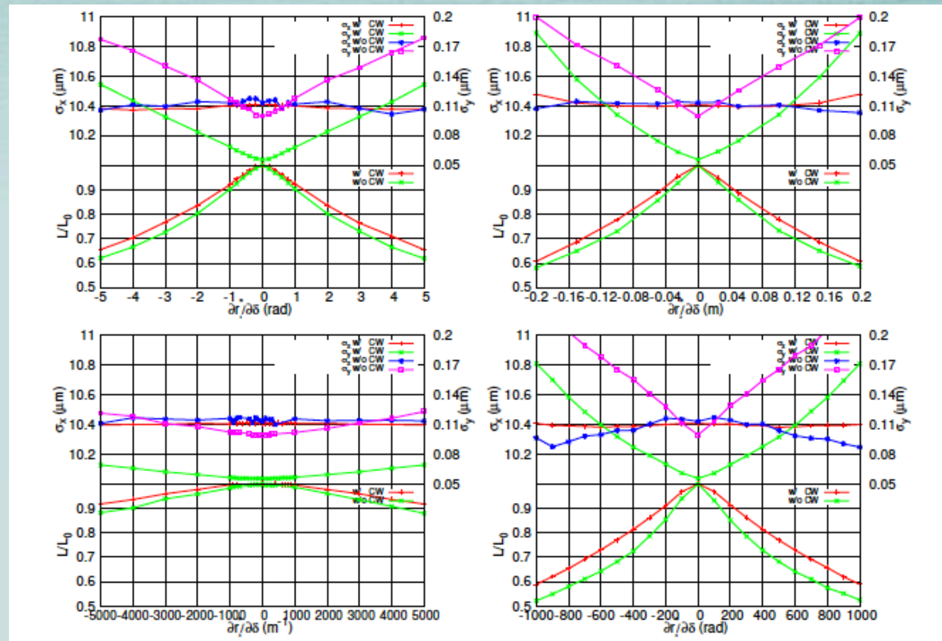
Linear and chromatic X-Y couplings at the SuperKEKB:

Set the tolerances for the reference of optics design and optics corrections



Linear X-Y couplings

Figure 1: Beam sizes and relative luminosity as function of the linear X-Y couplings at the IP with and without crab waist.



Chromatic X-Y couplings

Figure 2: Beam sizes and relative luminosity as function of the chromatic X-Y couplings at the IP with and without crab waist.

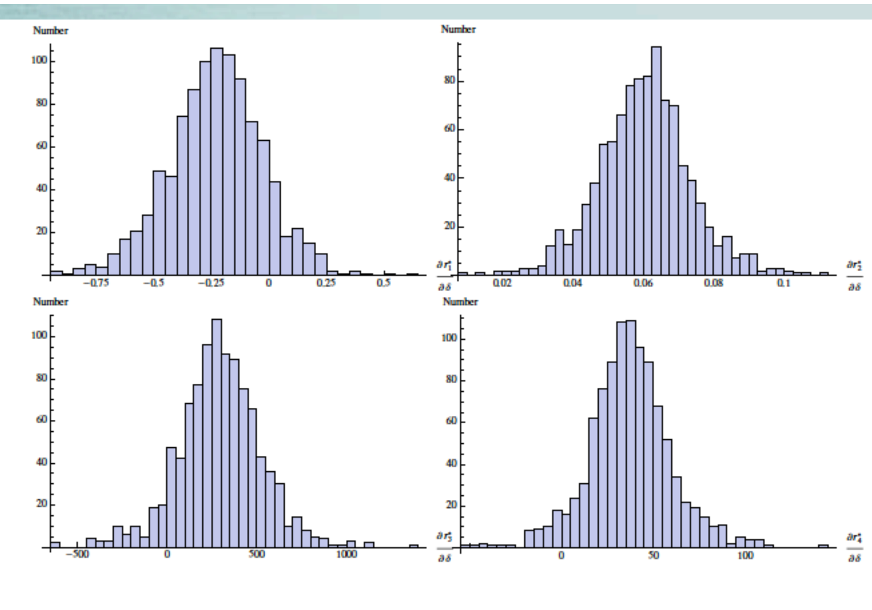


Figure 3: Distributions of the chromatic X-Y couplings with 1000 error seeds for the SuperKEKB LER.

Table 3: Tolerances for the linear and chromatic X-Y couplings at the IP of the SuperKEKB LER, assuming a rate of 20% luminosity degradation.

Parameter	w/ crab waist	w/o crab waist
r_1^* $(mrad)$	±5.3	±3.5
r_2^* (mm)	±0.18	±0.13
r_3^* (m^{-1})	±55	±15
r_4^* (rad)	±1.4	±0.4
r_{11} (rad)	±2.3	±2.0
r_{21} (m)	±0.09	±0.07
r_{31} (m^{-1})	±11000	±9400
r_{41} (rad)	±430	±280

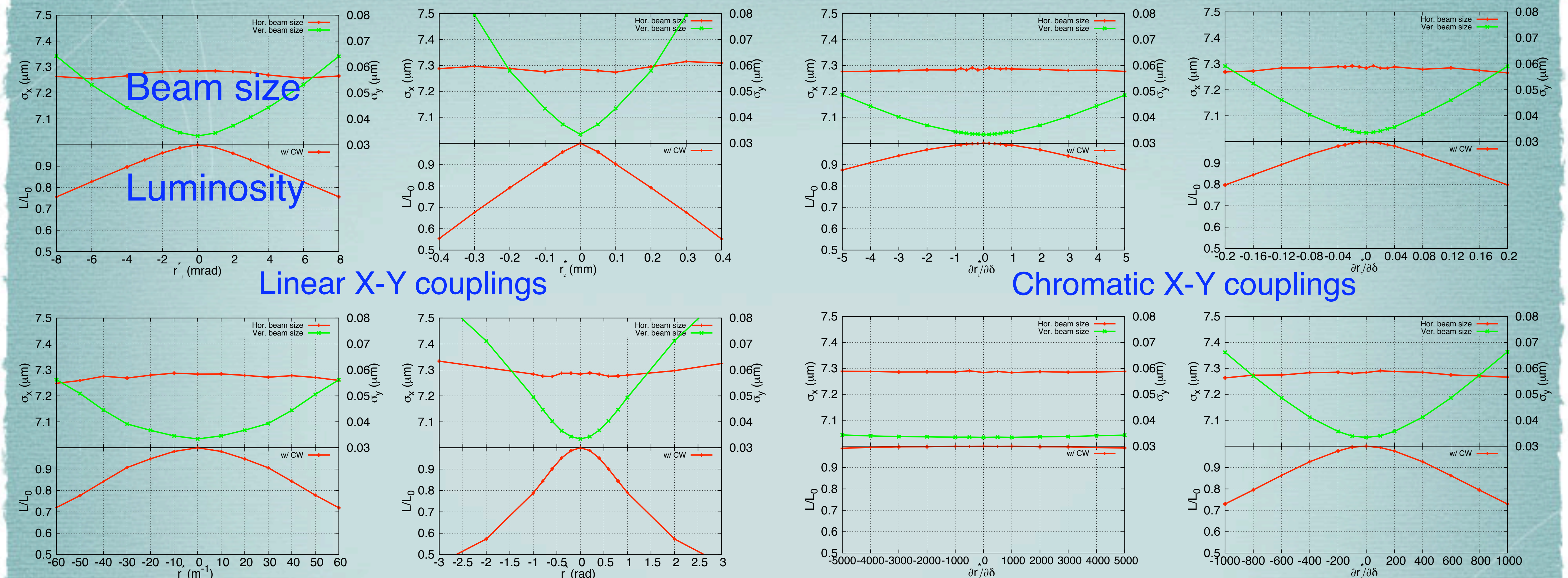
Tolerances

D. Zhou, et al., IPAC10

Chromatic aberration - Simulations

Linear and chromatic X-Y couplings at the SuperB (w/ CW):

Set the tolerances for the reference of optics design and optics corrections



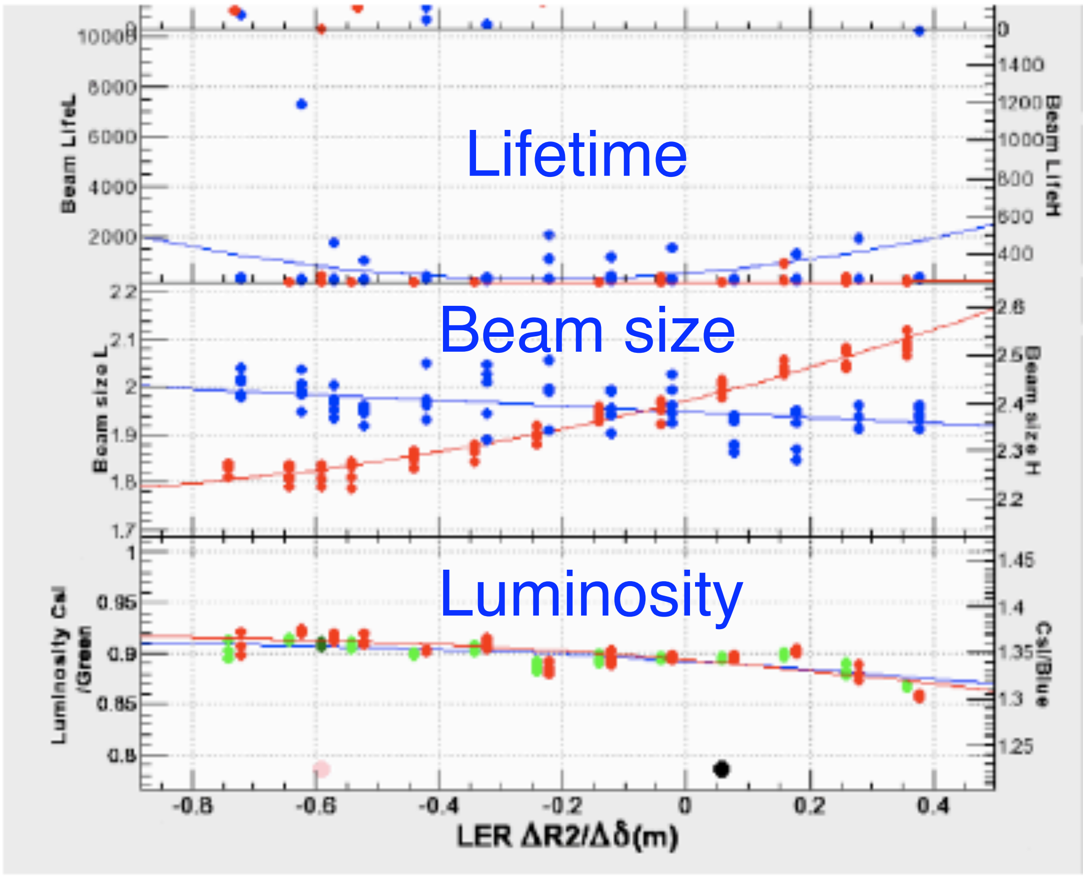
Tolerances

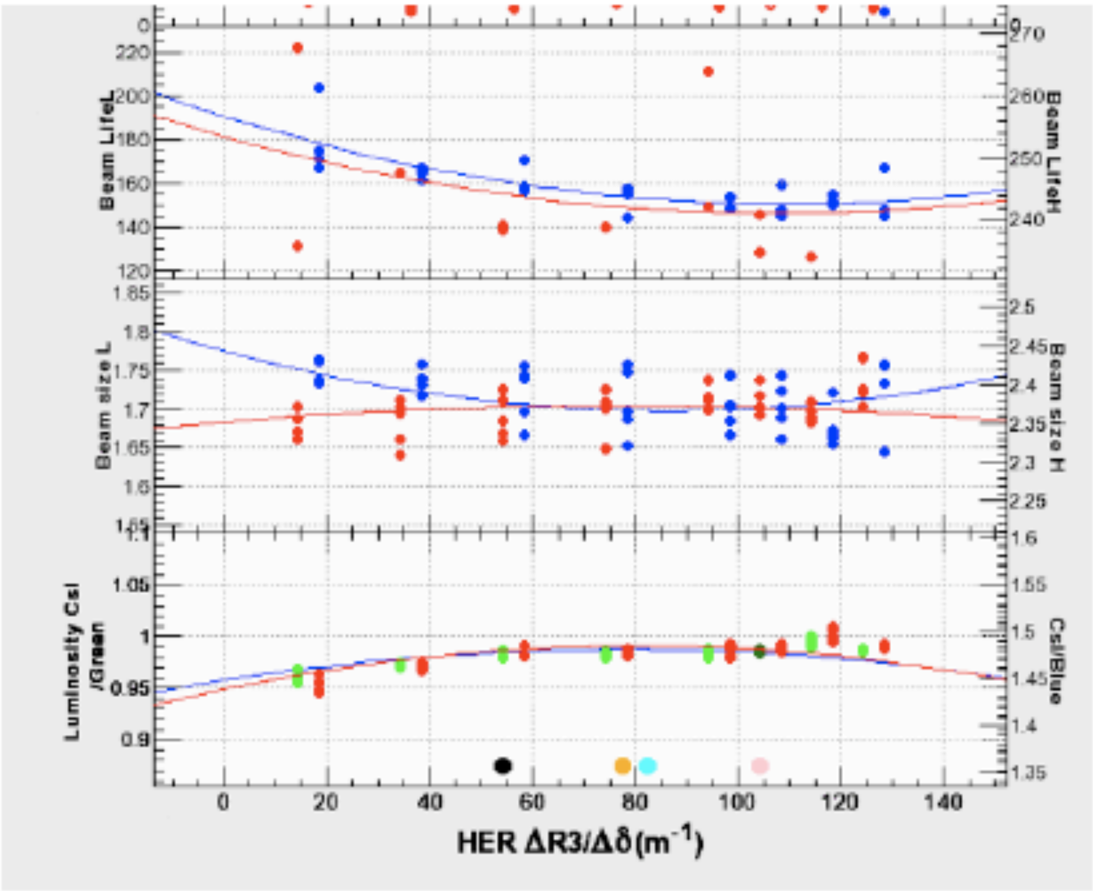
Parameter	Tolerance
r_1^* (mrad)	±6.7
r_2^* (mm)	±0.19
r_3^* (m^{-1})	±46
r_4^* (rad)	±0.96
$\partial r_1^*/\partial\delta$ (rad)	±7
$\partial r_2^*/\partial\delta$ (m)	±0.19
$\partial r_3^*/\partial\delta$ (m^{-1})	>5000 or <-5000
$\partial r_4^*/\partial\delta$ (rad)	±770

Collaborate with M. Zobov (INFN)

Observed luminosity performance

Typical examples of scanning chromatic X-Y couplings at IP during the KEKB operation:

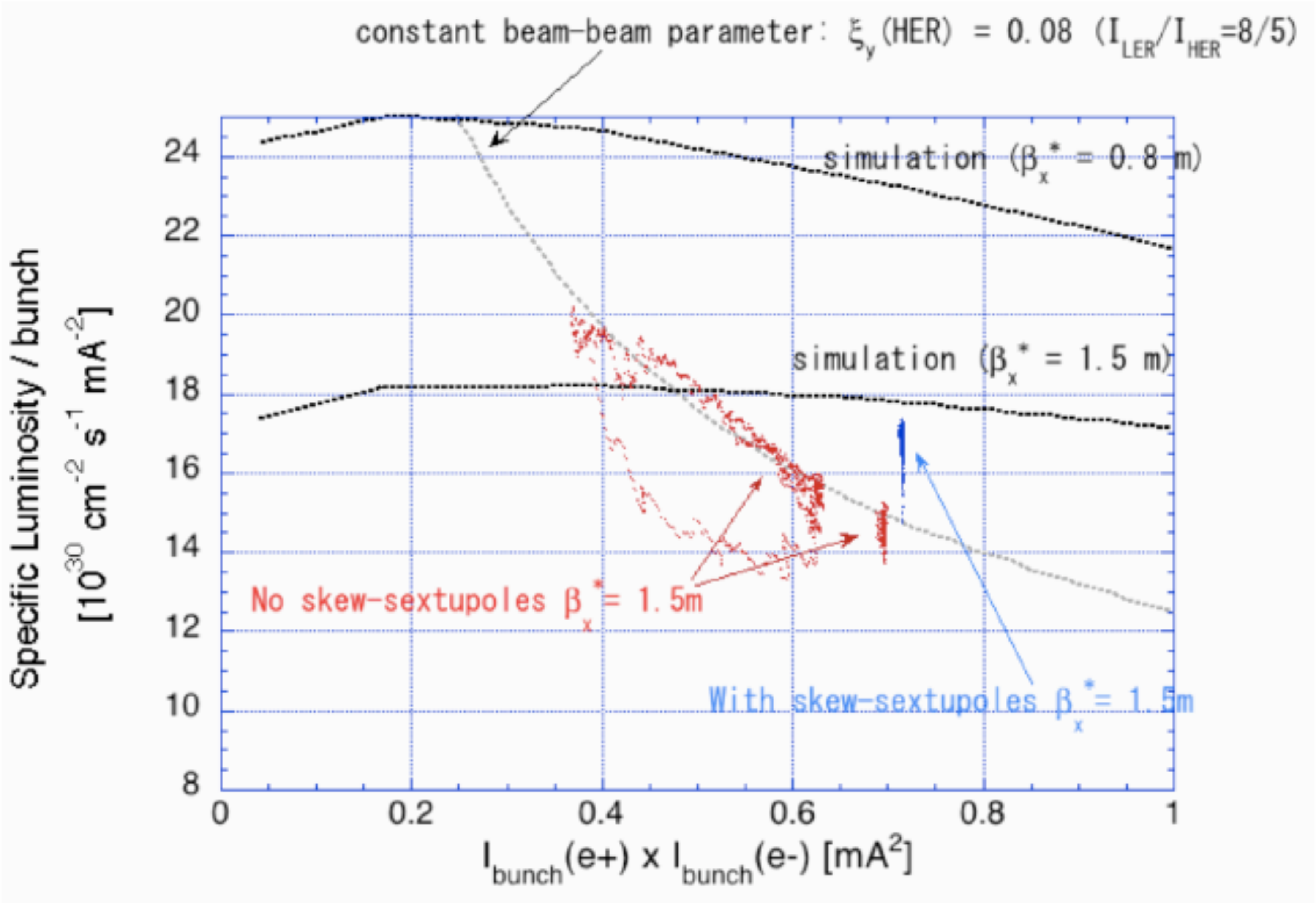




Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

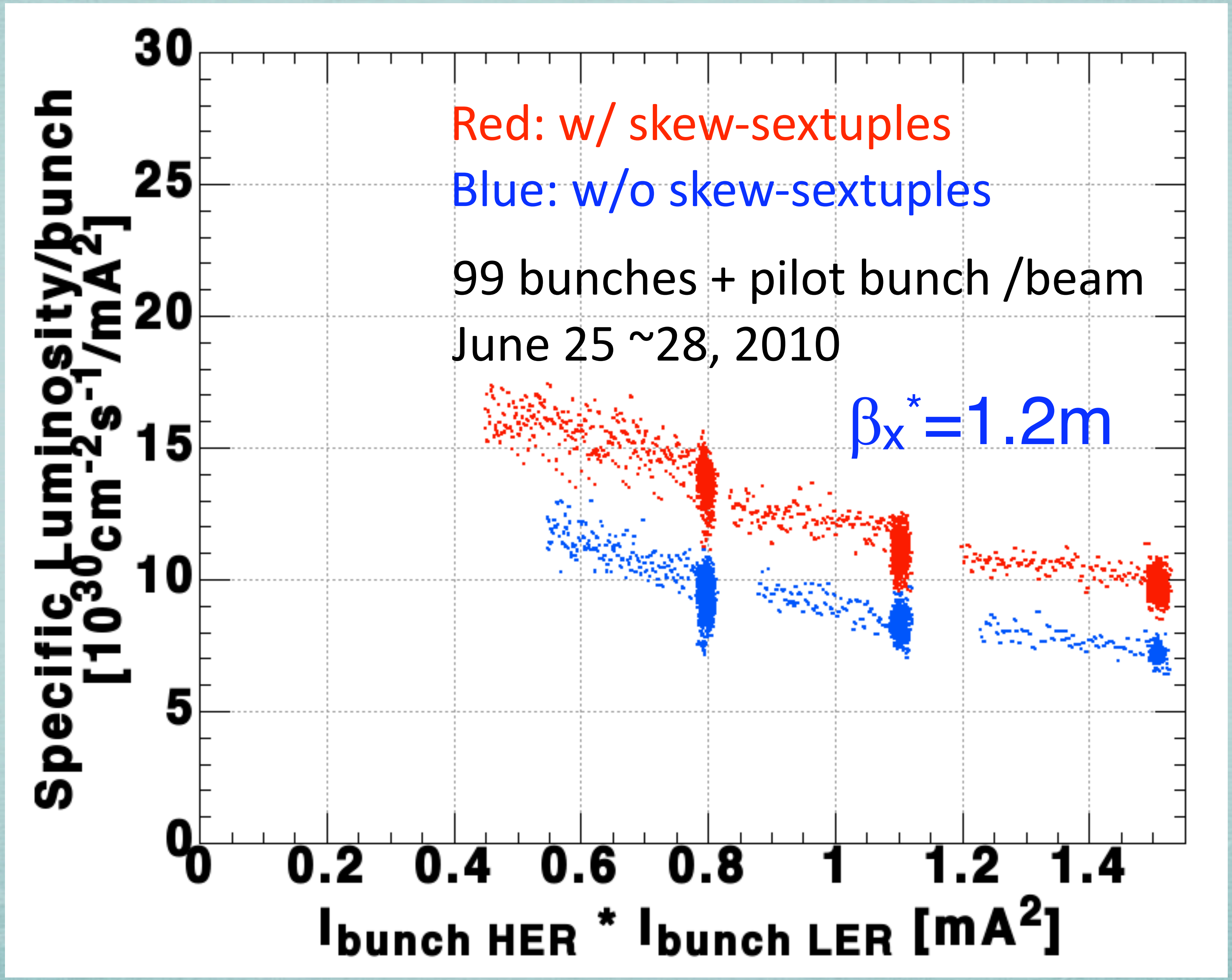
Effectiveness of skew-sextupole magnets (crab on)



Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

Effectiveness of skew-sextupoles (Crab off)

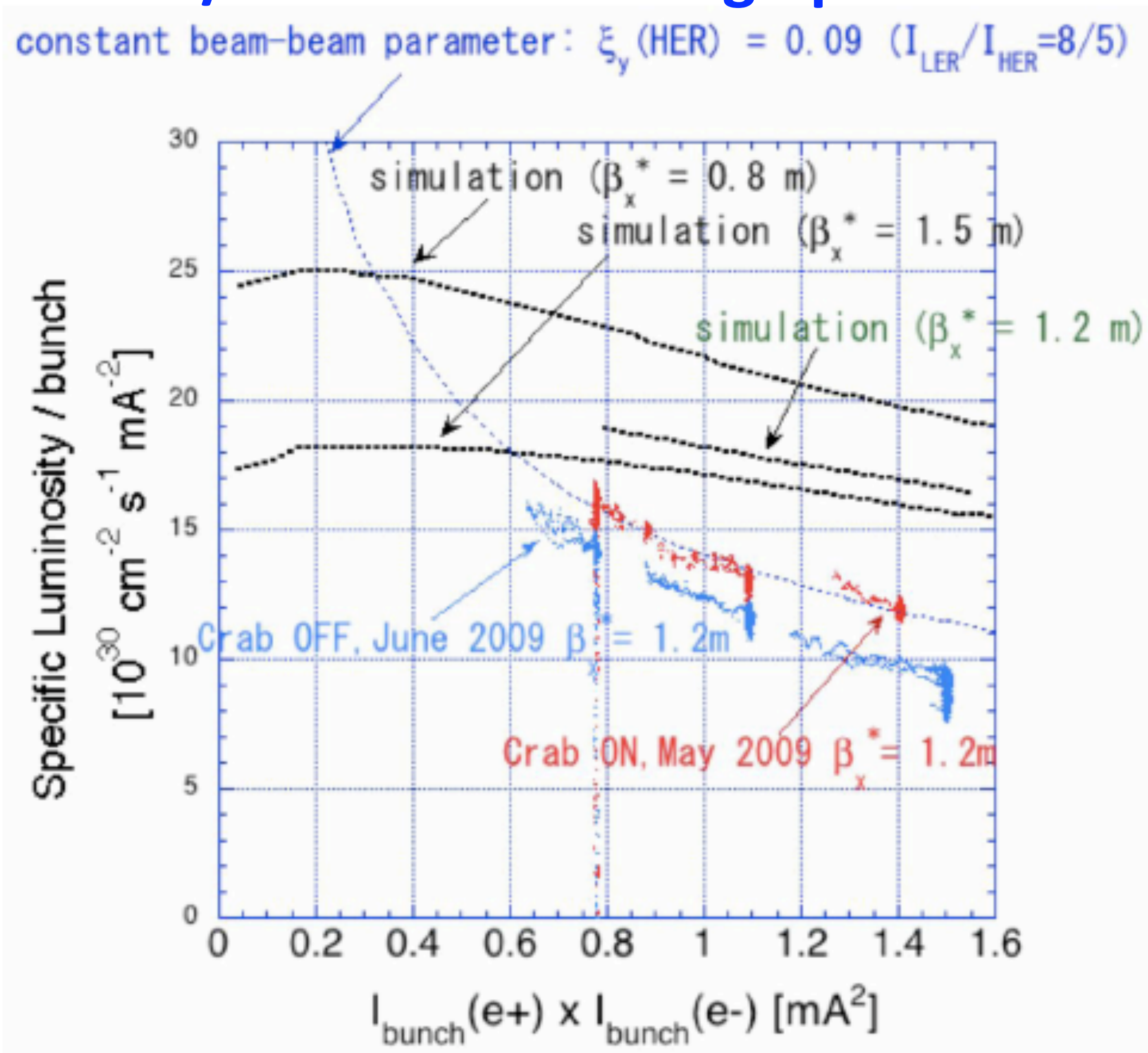


Courtesy of Y. Funakoshi

Observed luminosity performance

Specific luminosity (crab on/off)

W/ skew-sext. tuning optimized

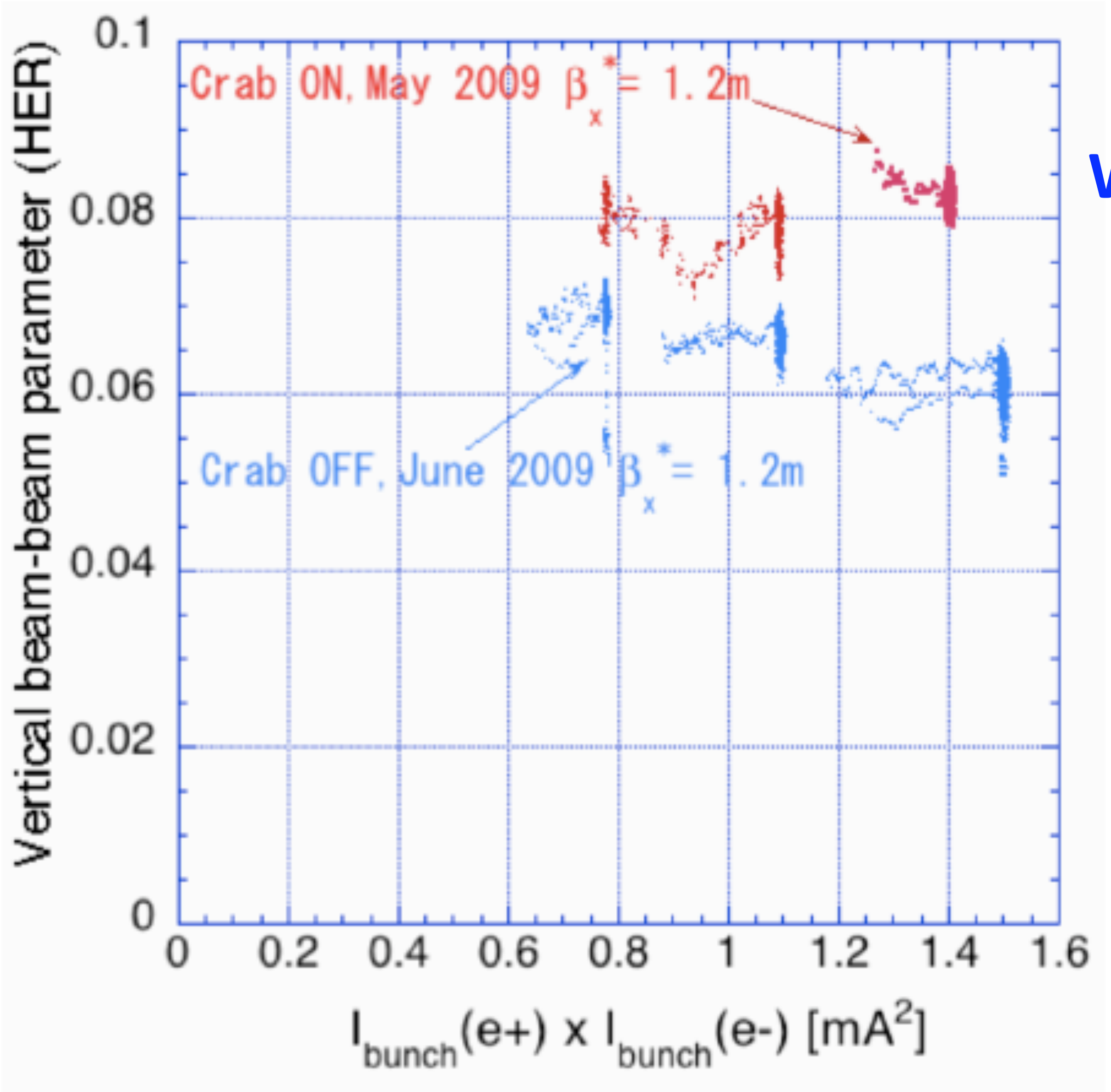


Luminosity improvement by crab cavities is about 20%.
Geometrical loss due to the crossing angle is about 11%.

Ref. Y. Funakoshi, IPAC10

Observed luminosity performance

Beam-beam parameter (crab on/off)



W/ skew-sext. tuning optimized

	Crab on	Crab off
R_L	0.828	0.763
$R_{\xi y}$(HER)	1.15	0.993

Ref. Y. Funakoshi, IPAC10

Summary - Chromatic aberrations

❖ The theory of chromatic aberrations looks pretty good.
❖ The simulations were quite reliable and did lead to the remarkable achievements in KEKB.
❖ The beam tuning in the KEKB revealed that chromatic X-Y couplings are very important in the KEKB.
❖ The crab cavities did contribute to luminosity gain (~20%).
❖ The skew-sextupoles contributed additional luminosity gain (~15%).
❖ But the strong-strong simulations predicted the luminosity gain in a factor of 2(@β_x^*=0.8m). There is still big discrepancy.

Outline - CSR

1. Introduction

2. Algorithms

3. Benchmark results

3.1 Single dipole

3.2 Wiggler/undulator

4. CSR in wigglers

4.1 KEKB LER

4.2 SuperKEKB LER

5. Fringe field and interference

5.1 KEKB LER

5.2 SuperKEKB DR

6. Summary

Introduction

Motivations:

1. To find out the unknown source of longitudinal impedance which drive the microwave instability (MWI) in the KEKB LER
2. To work out a reliable impedance model for SuperKEKB DR
3. CSR in wigglers, with interference, or with resistive wall

Existing publications on numerical calculations of CSR impedance:

1. T. Agoh and K. Yokoya, PRST-AB 7, 054403 (2004) and T. Agoh, PhD. Thesis (2004)
2. K. Oide, Presentation at KEKB ARC 2009 and PAC09
3. G. Stupakov and I. Kotelnikov, PRST-AB 12, 104401 (2009)

Algorithms - Fundamental equations

Parabolic equation in curvilinear coordinate system:

$$\frac{\partial \vec{E}_\perp}{\partial s} = \frac{i}{2k}\left(\nabla_\perp^2 \vec{E}_\perp - \mu_0 c^2 \nabla_\perp \rho_0 + \frac{2k^2 x}{\rho(s)}\vec{E}_\perp\right)$$

β=1

Field separation:

$$\vec{E}_\perp = \vec{E}_\perp^r + \vec{E}_\perp^b$$

$$\frac{\partial \vec{E}_\perp^r}{\partial s} = \frac{i}{2k}\left[\nabla_\perp^2 \vec{E}_\perp^r + \frac{2k^2 x}{\rho}(\vec{E}_\perp^r + \vec{E}_\perp^b)\right]$$

Beam field in free space (independent of s):

$$\frac{\partial^2 E_x^b}{\partial x^2} + \frac{\partial^2 E_x^b}{\partial y^2} = \mu_0 c^2 \frac{\partial \rho_0}{\partial x}$$

$$\frac{\partial^2 E_y^b}{\partial x^2} + \frac{\partial^2 E_y^b}{\partial y^2} = \mu_0 c^2 \frac{\partial \rho_0}{\partial y}$$

Ref. T. Agoh and K. Yokoya, PRST-AB 7, 054403 (2004)

Algorithms - Beam field

Beam field in free space with finite beam sizes

Typical beam size: σ_x=0.5mm, σ_y=0.01mm (bi-gaussian)

$$E_x(x,y) = \frac{\lambda(k)}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\mathrm{Im}[F(x,y)]$$

$$E_y(x,y) = \frac{\lambda(k)}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\mathrm{Re}[F(x,y)]$$

$$F(x,y) = w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}} w\left(\frac{\frac{\sigma_y}{\sigma_x}x + i\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)$$

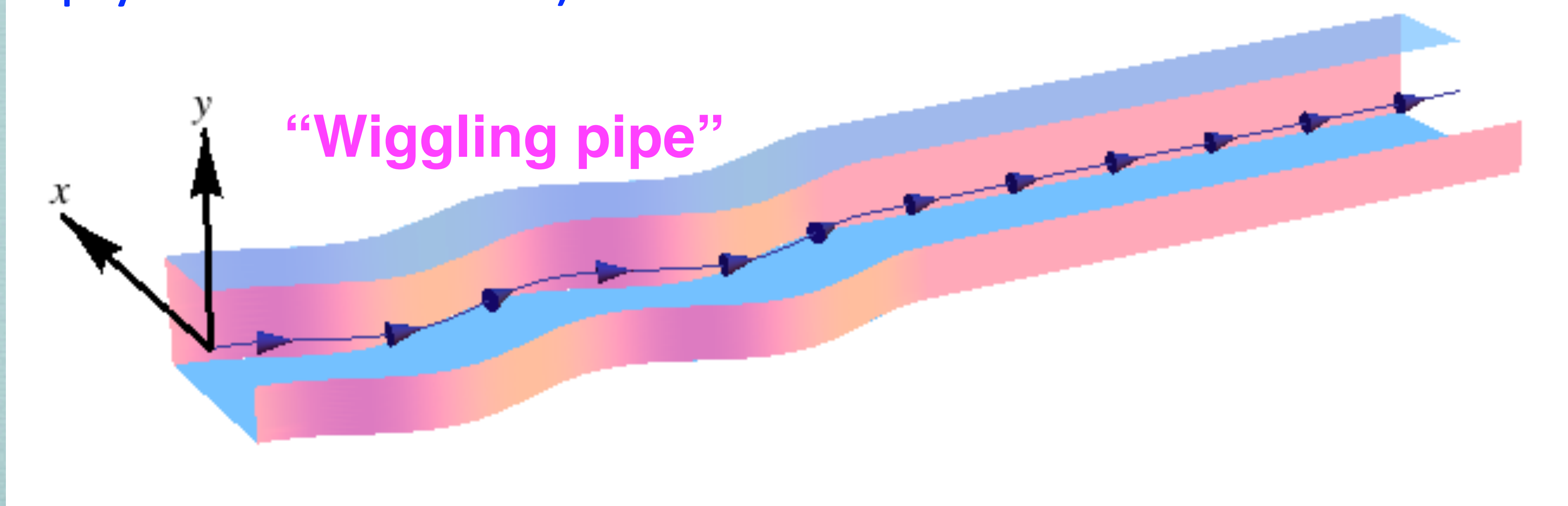
$$w(z) = e^{-z^2}\left(1 + \frac{2i}{\sqrt{\pi}}\int_0^z e^{t^2}dt\right)$$

Ref. T. Agoh, Ph.D. Thesis (2004)

Algorithms - Beam pipe

Model of the beam pipe:

1. The bending radius can be arbitrarily s-dependent, which allows for treating fringe field, wigglers or a series of dipole magnets
2. Uniform rectangular cross section along the beam orbit (simply the calculation)



Field integration along s:

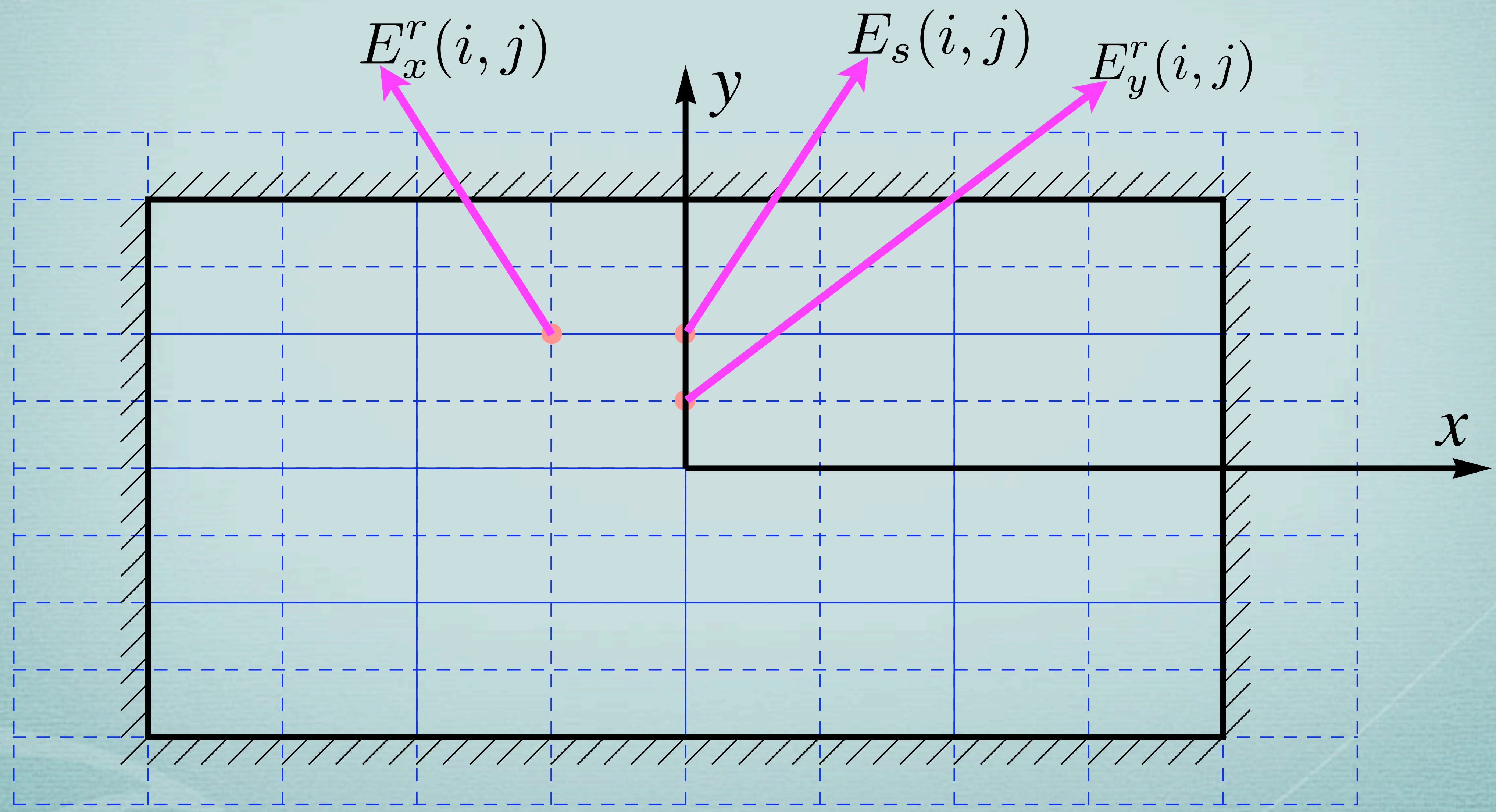
1. Toroidal part: Numerical integration
2. Straight pipe: mode expansion

Ref. T. Agoh, Ph.D. Thesis (2004)
G. Stupakov and I. Kotelnikov, PRST-AB 12, 104401 (2009)

Algorithms - Mesh

Finite-difference discretization:

1. Staggered grid: Central difference
2. Ghost point: Boundary conditions with perfect wall

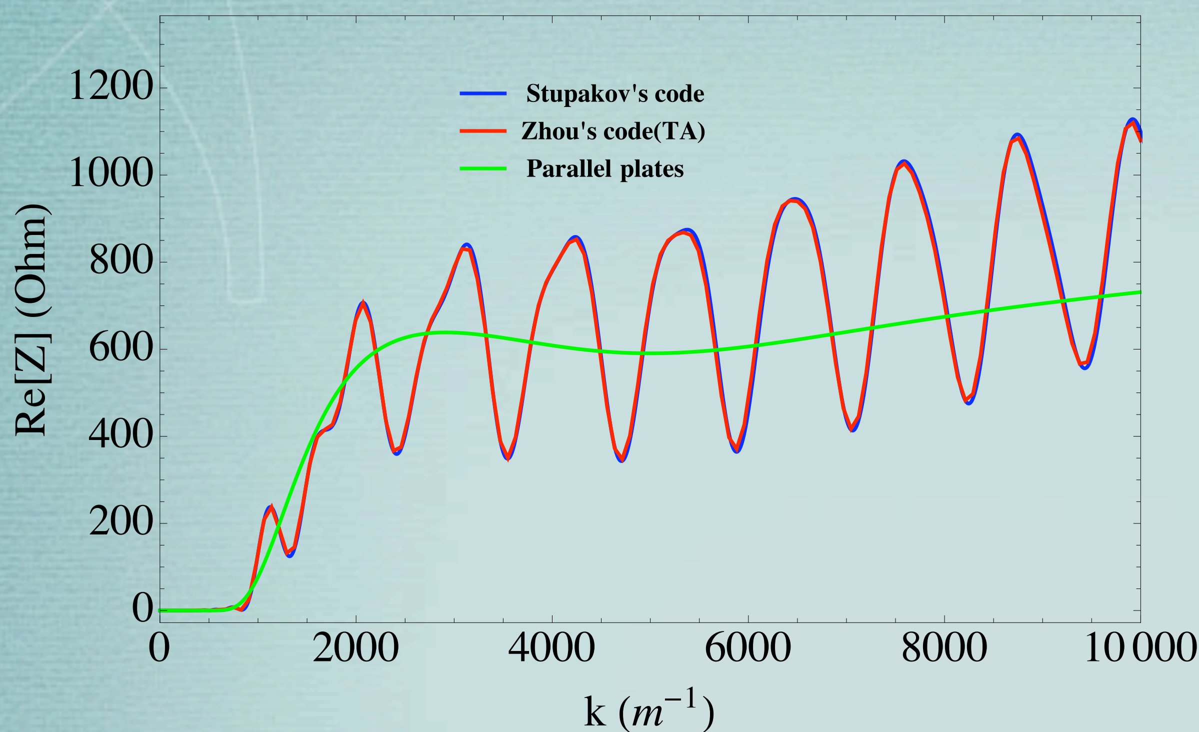


Ref. T. Agoh, Ph.D. Thesis (2004)

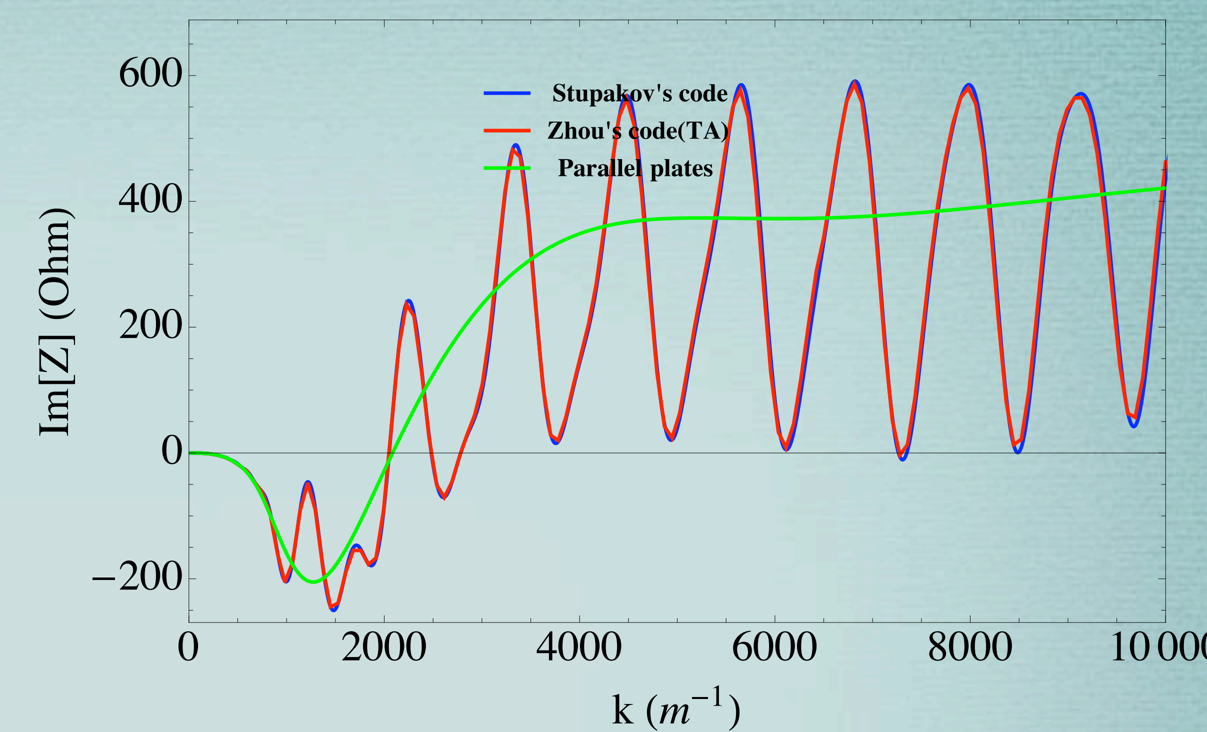
Benchmark results - Single dipole

Collaborate with K. Marit

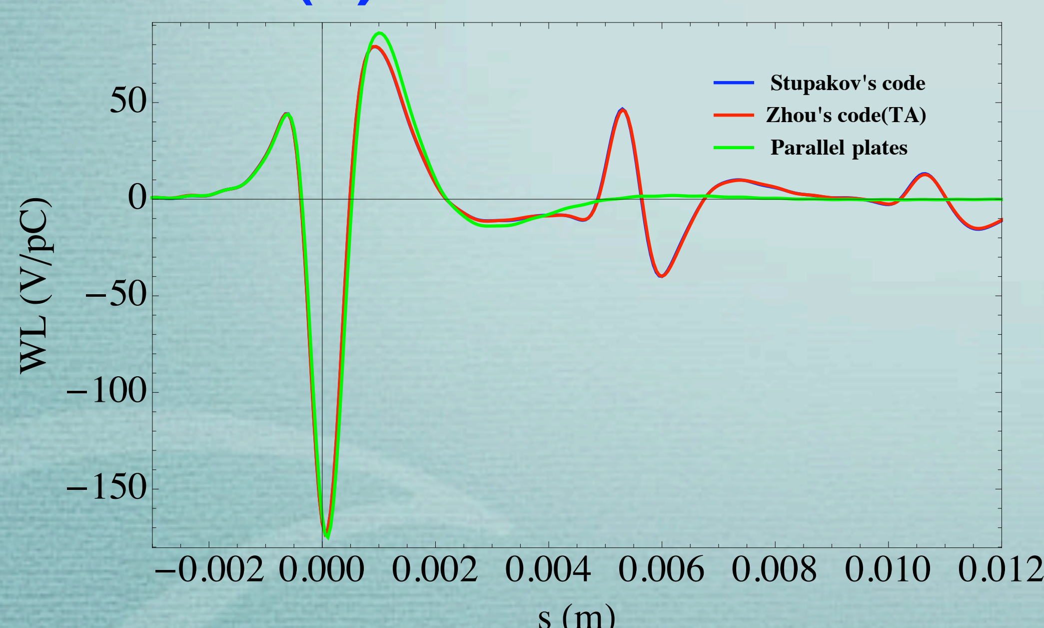
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



Fluctuation in impedance is due to reflections of side walls (see Oide's talk)

ANKA

w/h=70/32mm

L_{bend}=2.183m

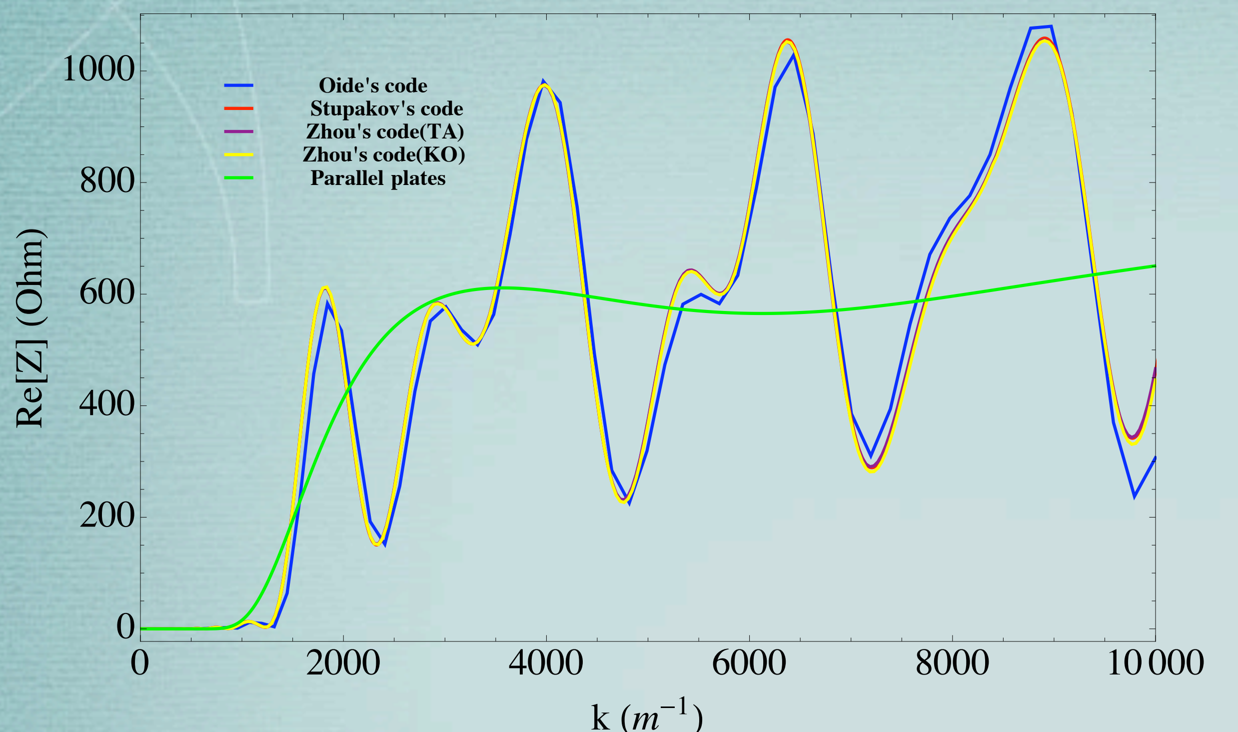
ρ=5.559m

L_{exit}=Infinity (pipe after exit)

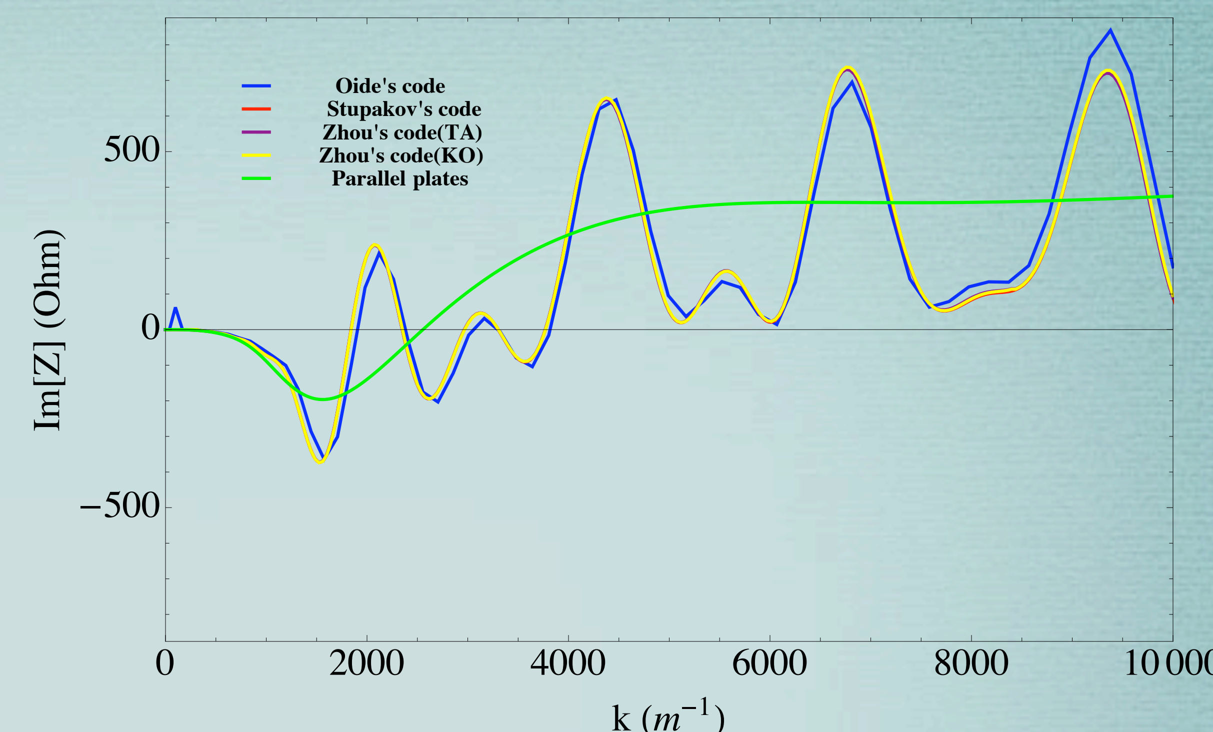
X_{offset}=0mm

Benchmark results - Single dipole

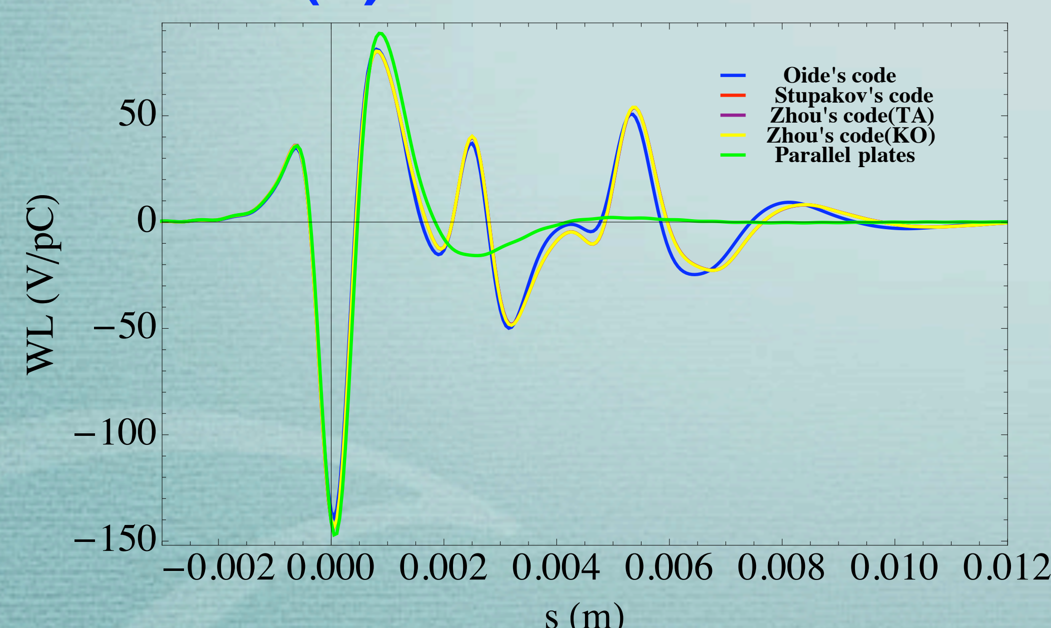
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



TA: Agoh's algorithm
KO: Oide's algorithm

w/h=60/40mm

L_{bend}=4m

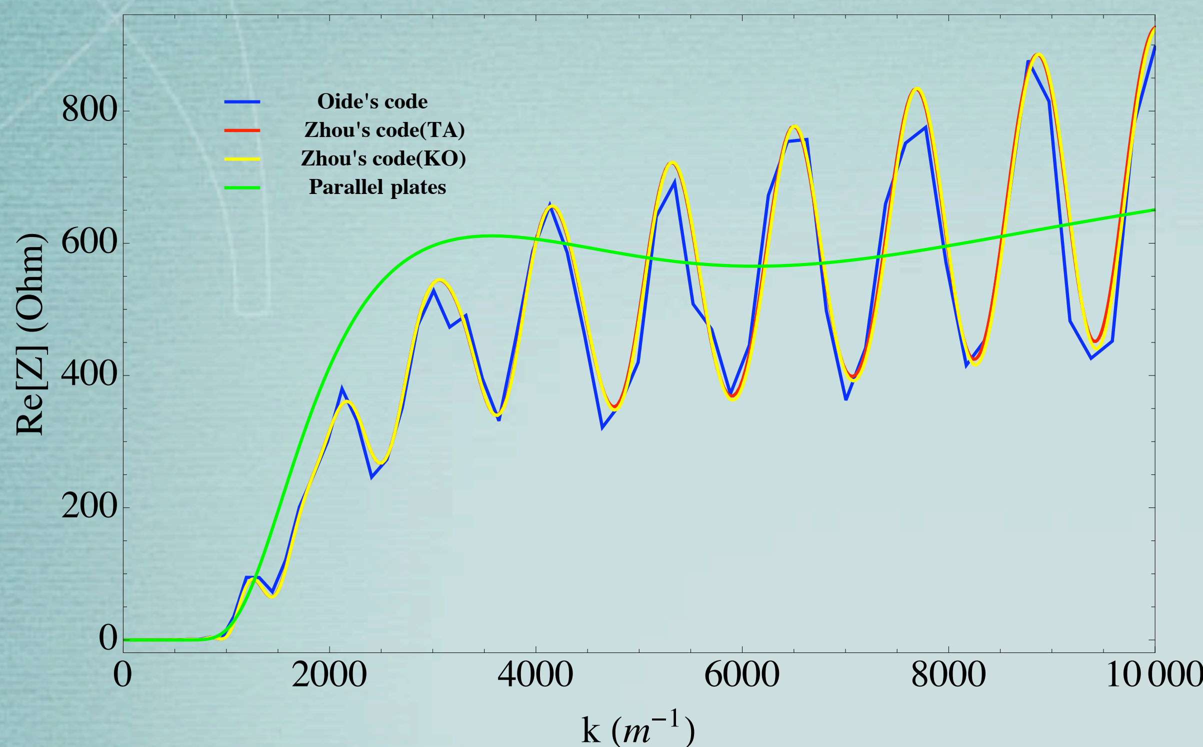
ρ=16.3m

L_{exit}=Infinity (pipe after exit)

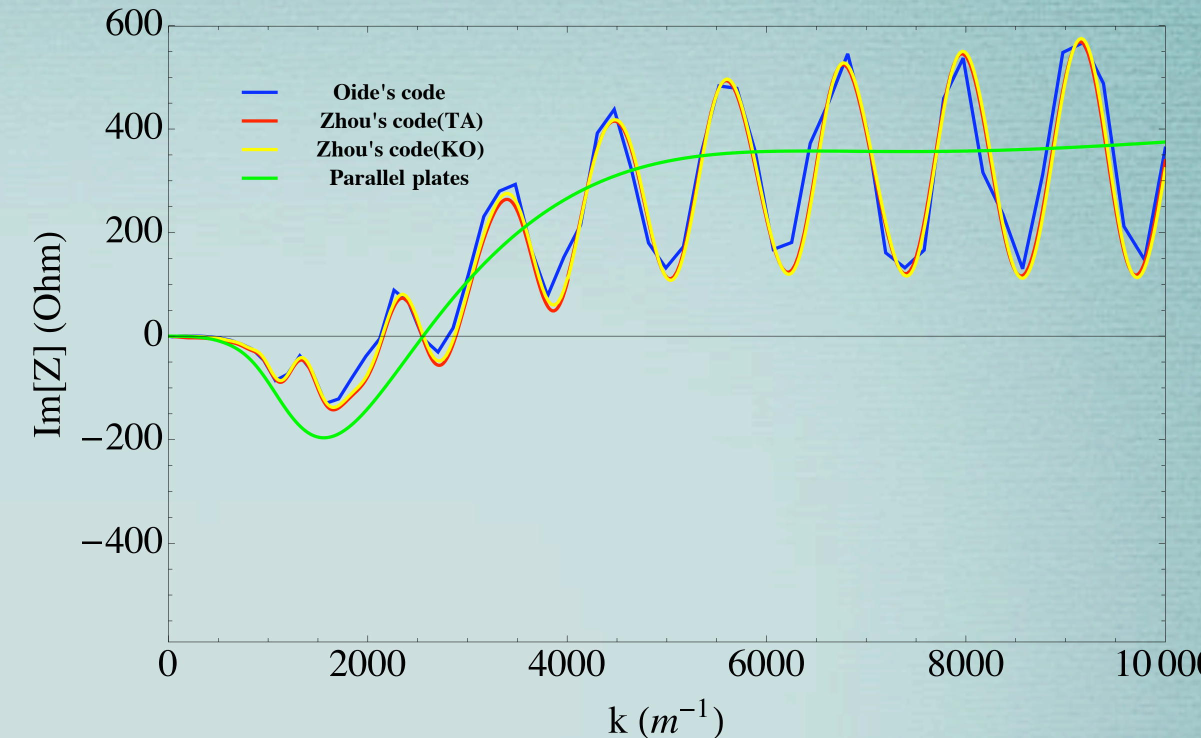
X_{offset}=0mm

Benchmark results - Single dipole

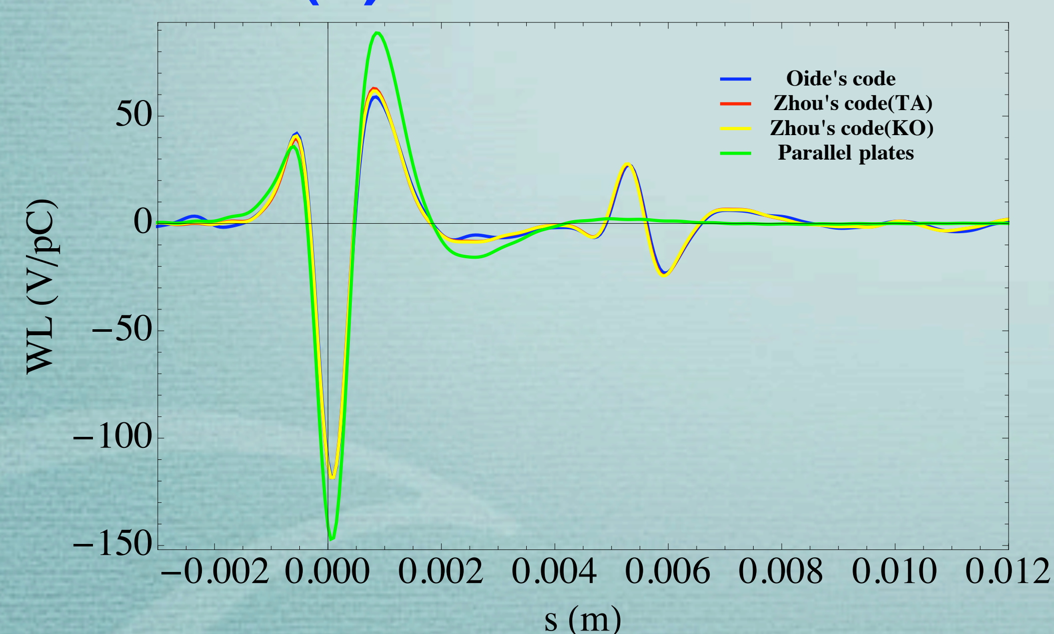
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm

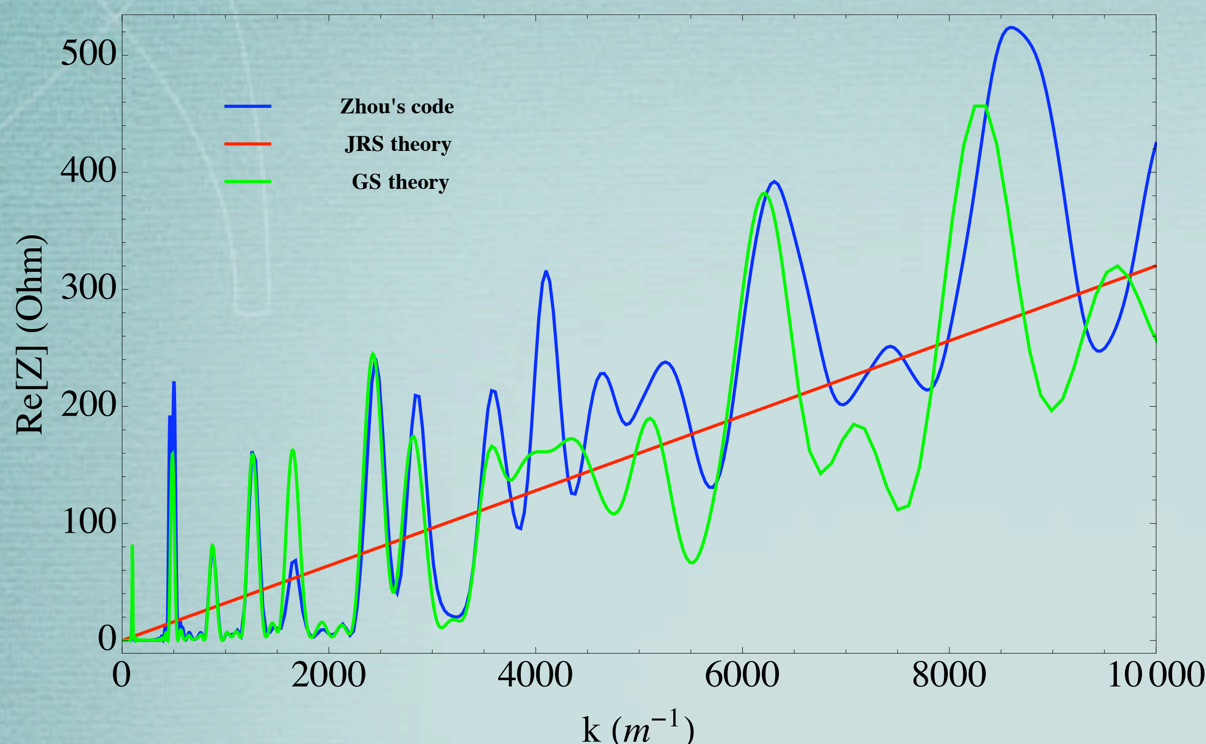


TA: Agoh's algorithm
KO: Oide's algorithm

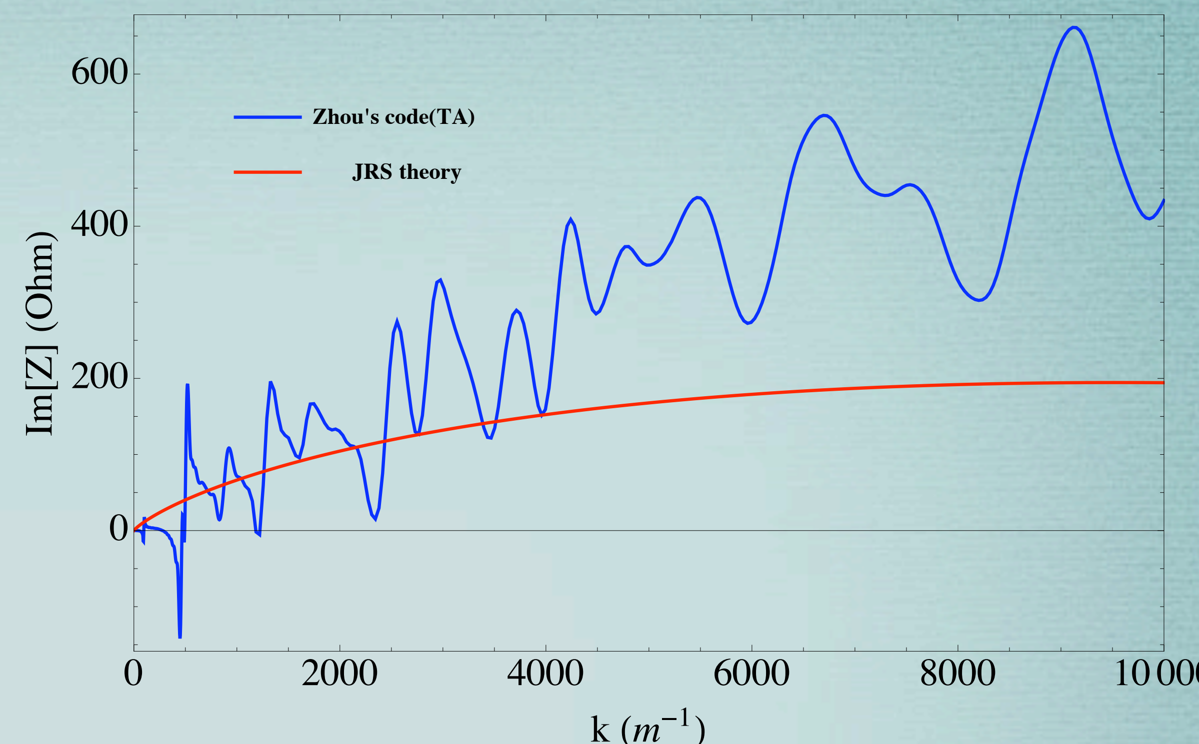
w/h=60/40mm
L_{bend}=4m
ρ=16.3m
L_{exit}=Infinity (pipe after exit)
X_{offset}=-20mm (To inner wall)

Benchmark results - Wiggler

Re.Z_L(k)

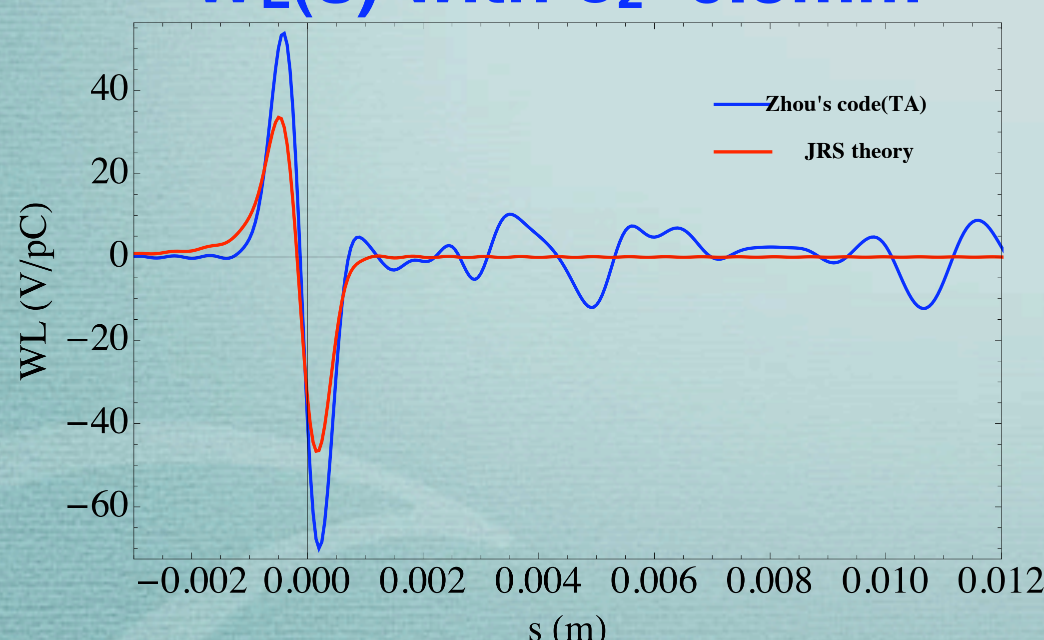


Im.Z_L(k)



JRS: Wu-Stupakov-Raubenheimer theory
J. Wu et al., PRST-AB 6, 040701 (2003)

W_L(s) with σ_z=0.3mm

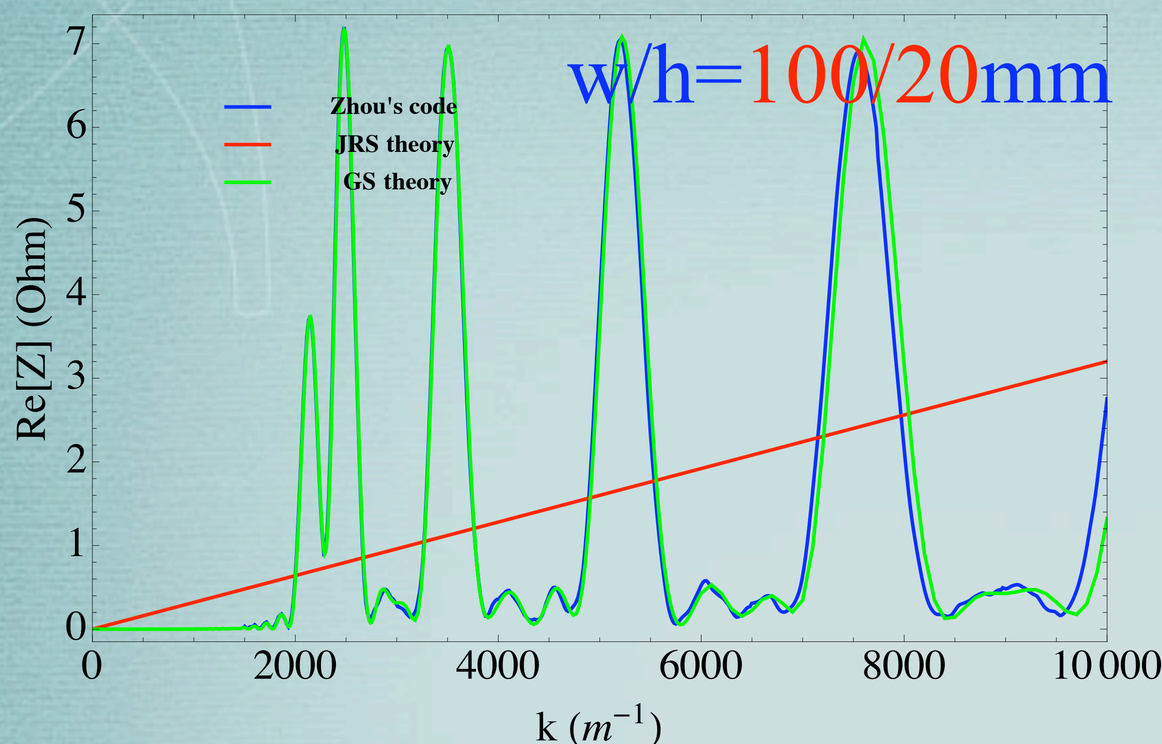


N_{period}=10
w/h=94/94mm
λ_w=1.088m
ρ=15.483m
L_{exit}=Infinity (pipe after exit)
Xoffset=0mm

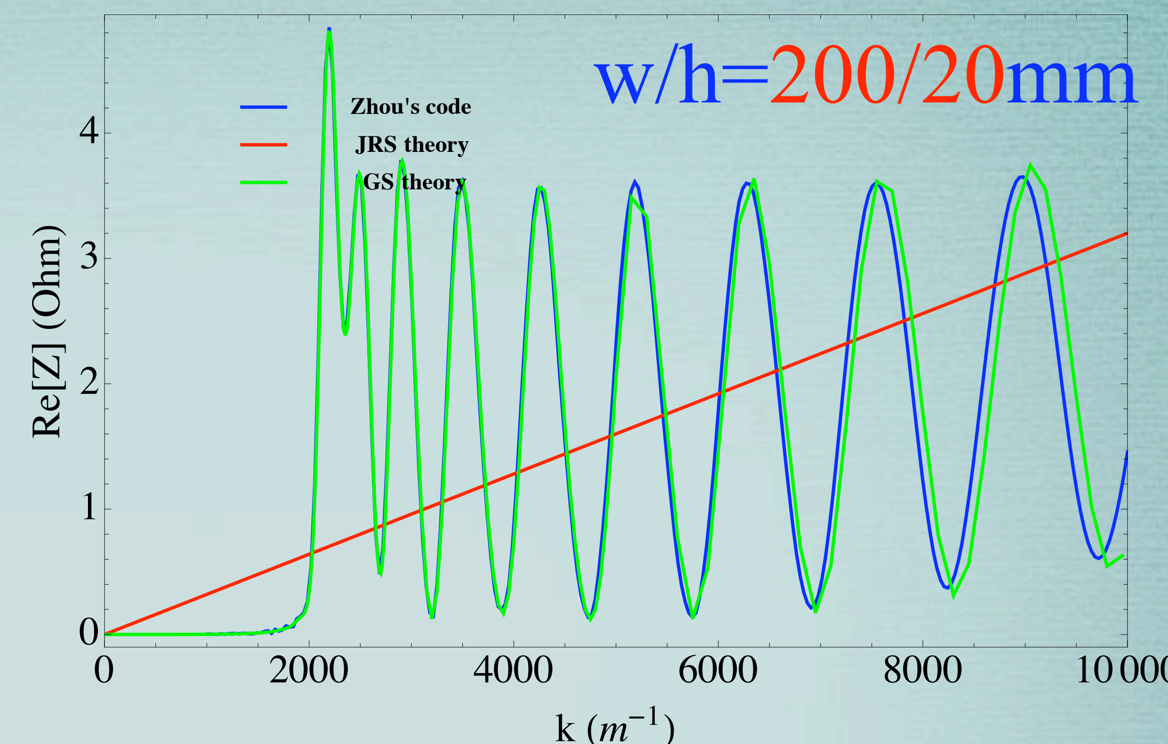
KEKB-LER type

Benchmark results - Wiggler

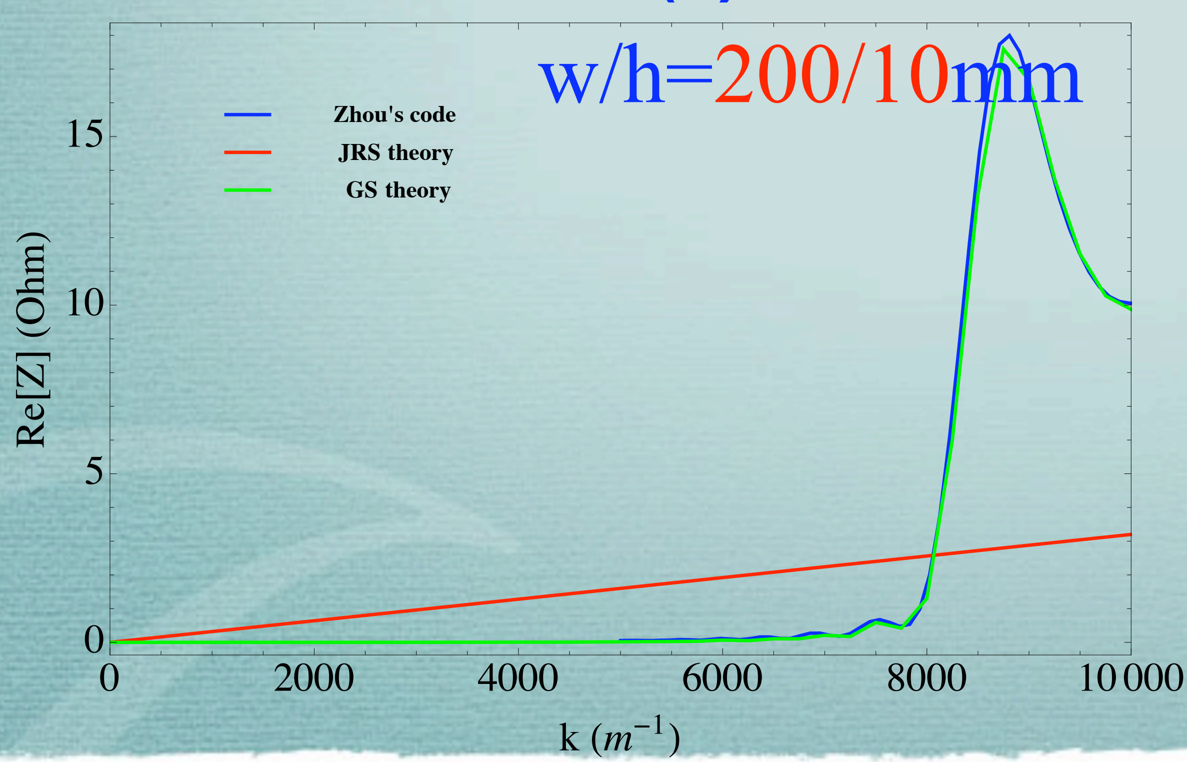
Re.Z_L(k)



Re.Z_L(k)



Re.Z_L(k)



Note: "Wiggling pipe" is not good enough!

N_{period}=10

λ_w=1.088m

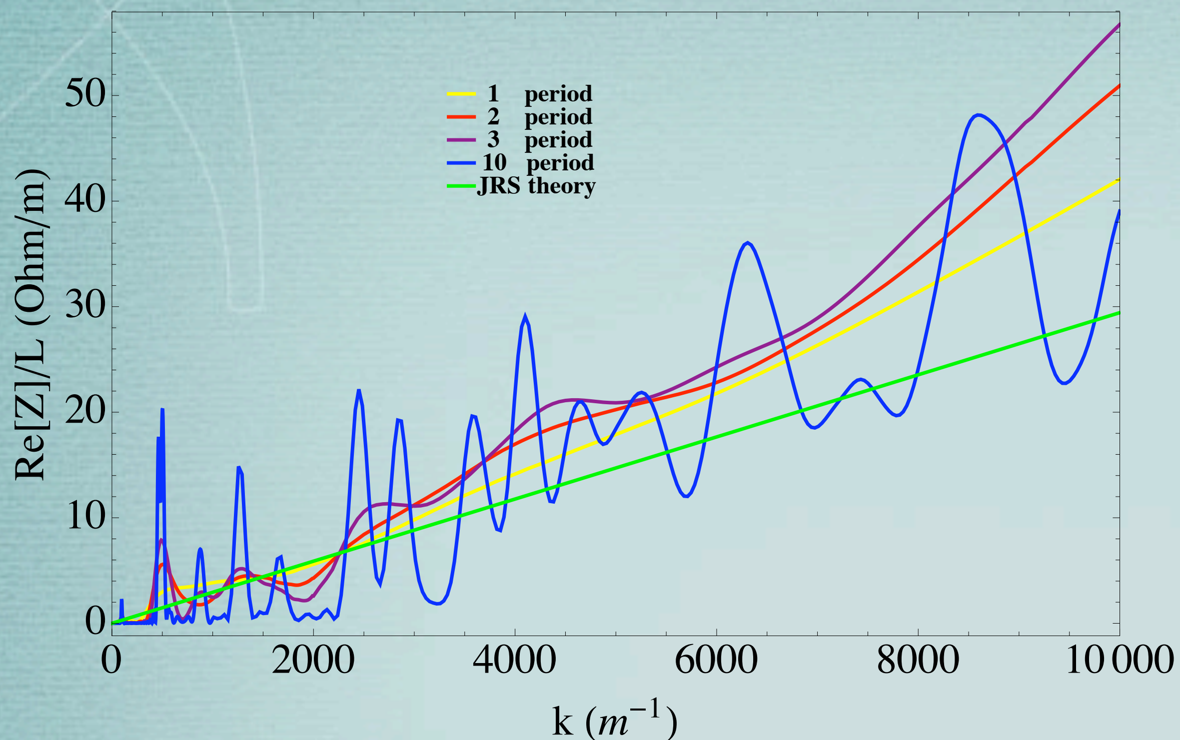
ρ=154.83m

L_{exit}=Infinity (pipe after exit)

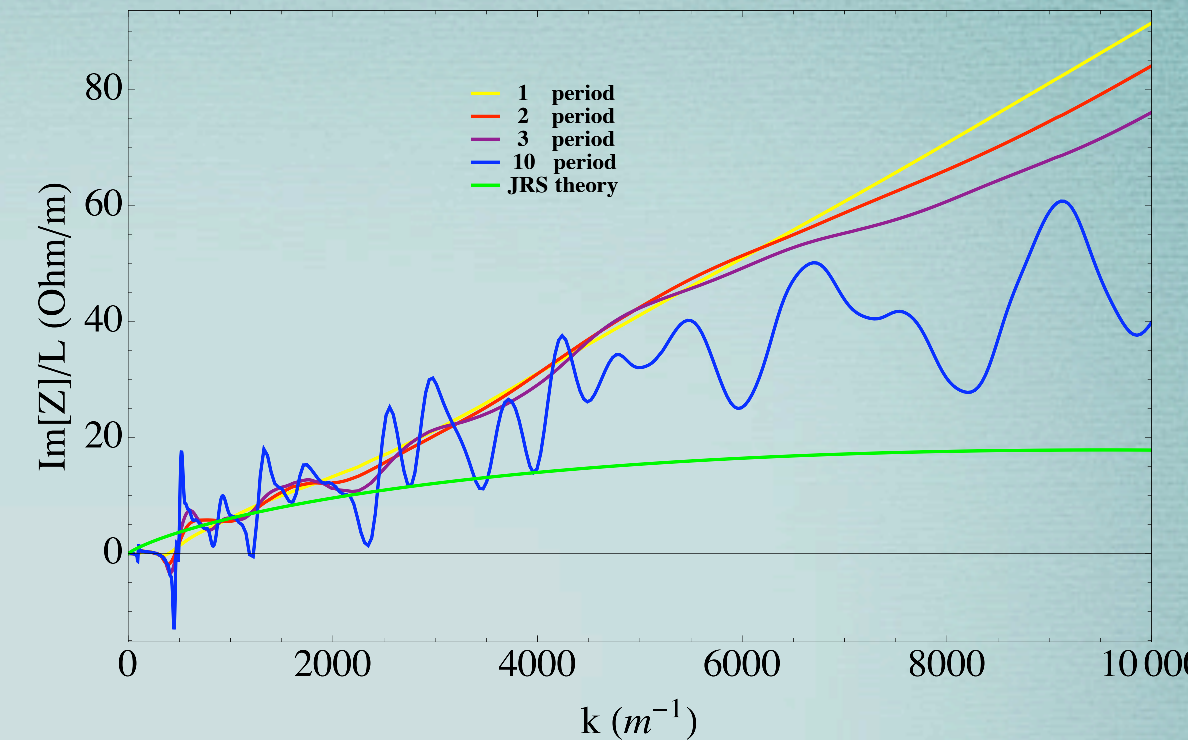
Xoffset=0mm

CSR in wigglers - KEKB LER

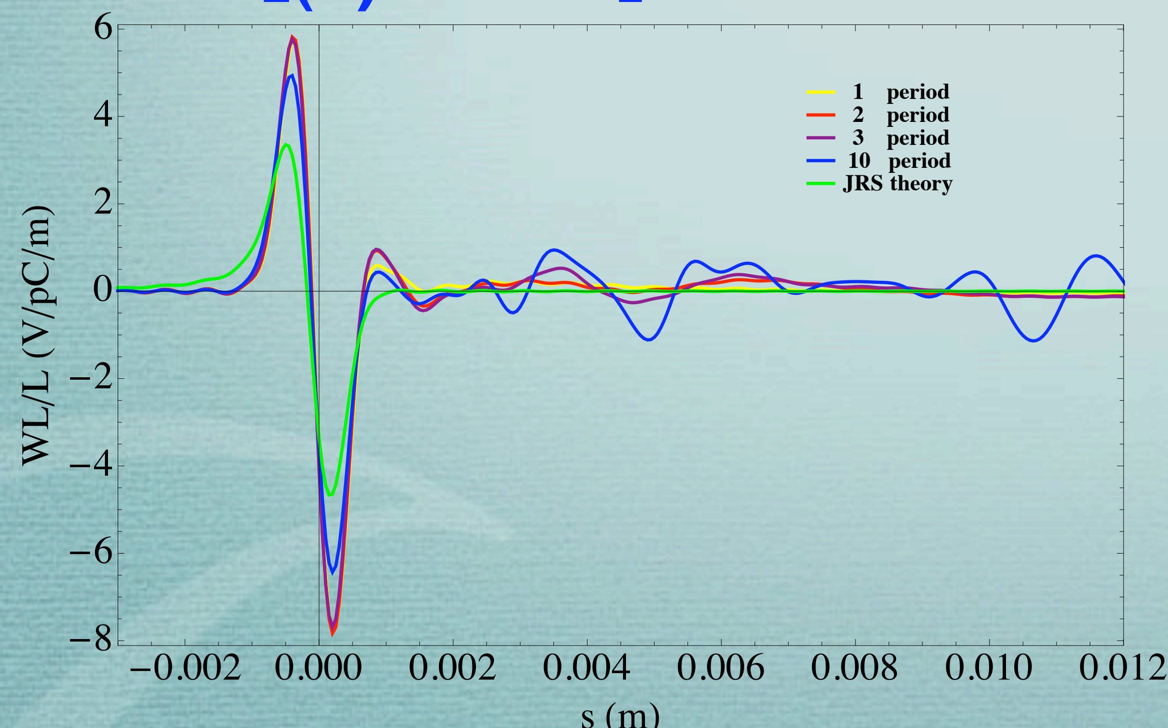
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



N_{period}=1/2/3/10

w/h=94/94mm

λ_w=1.088m

ρ=15.483m

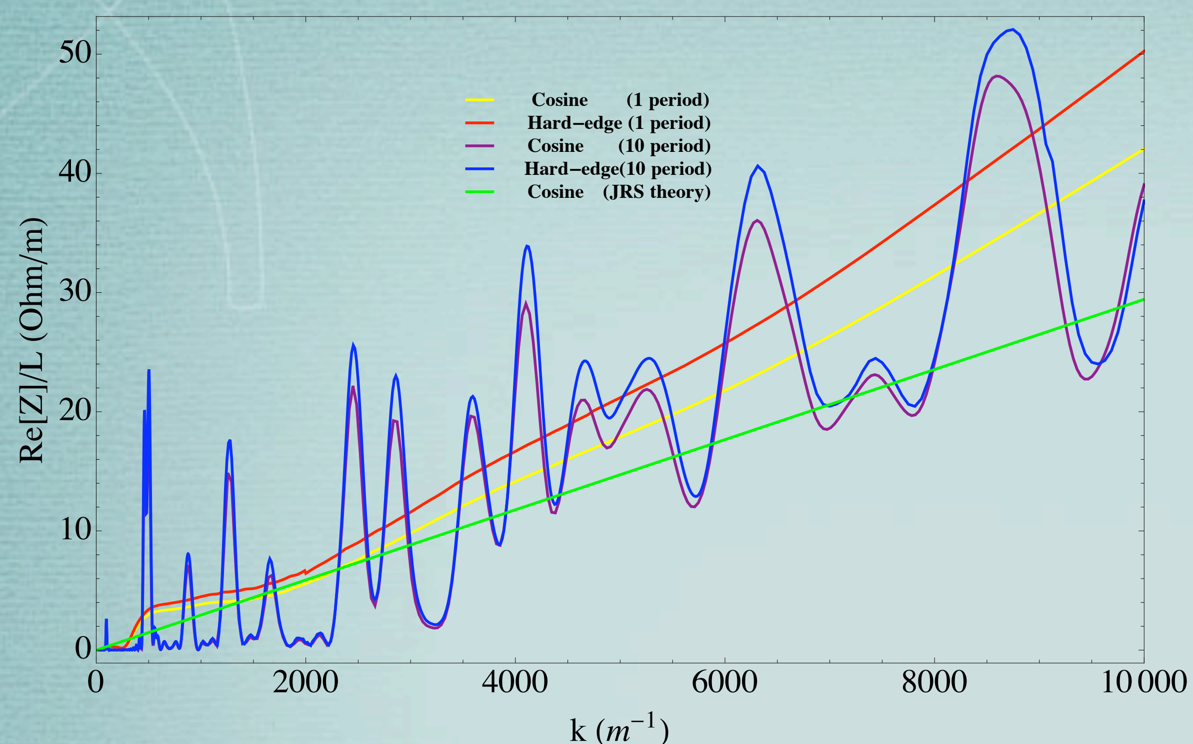
L_{exit}=Infinity (pipe after exit)

Xoffset=0mm

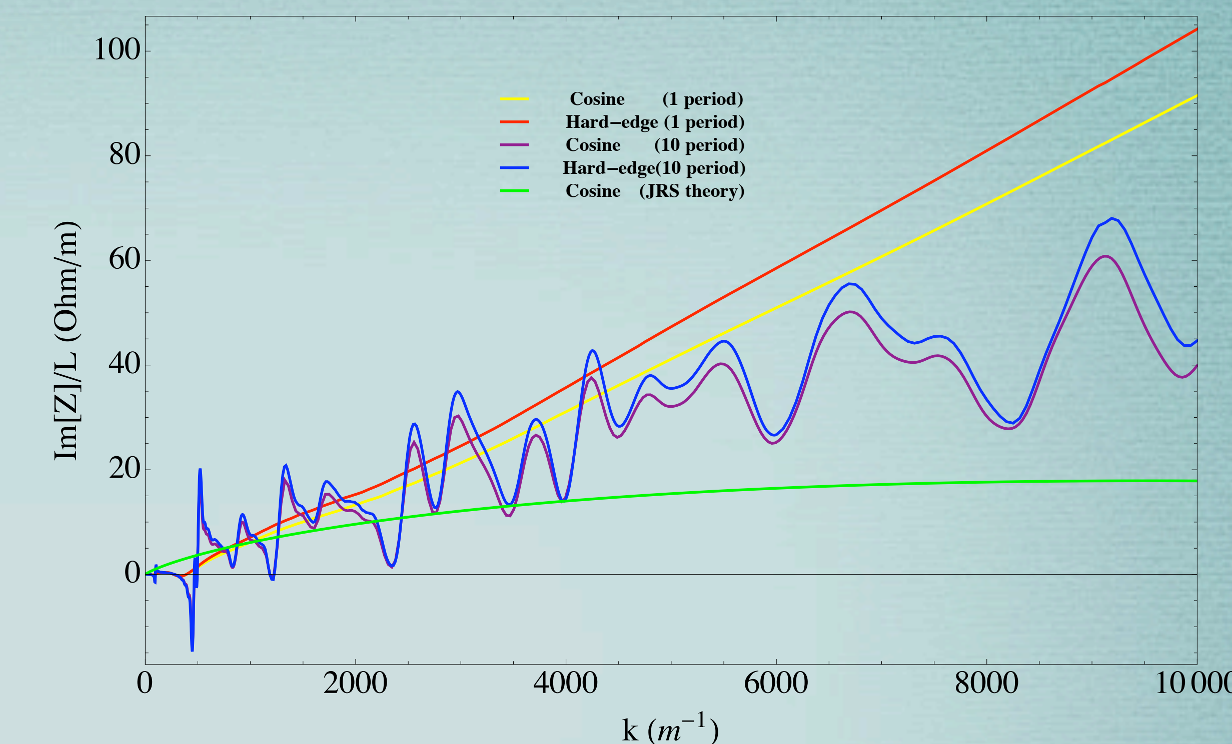
Field distribution: Cosine

CSR in wigglers - Hard-edge approximation

Re.Z_L(k)

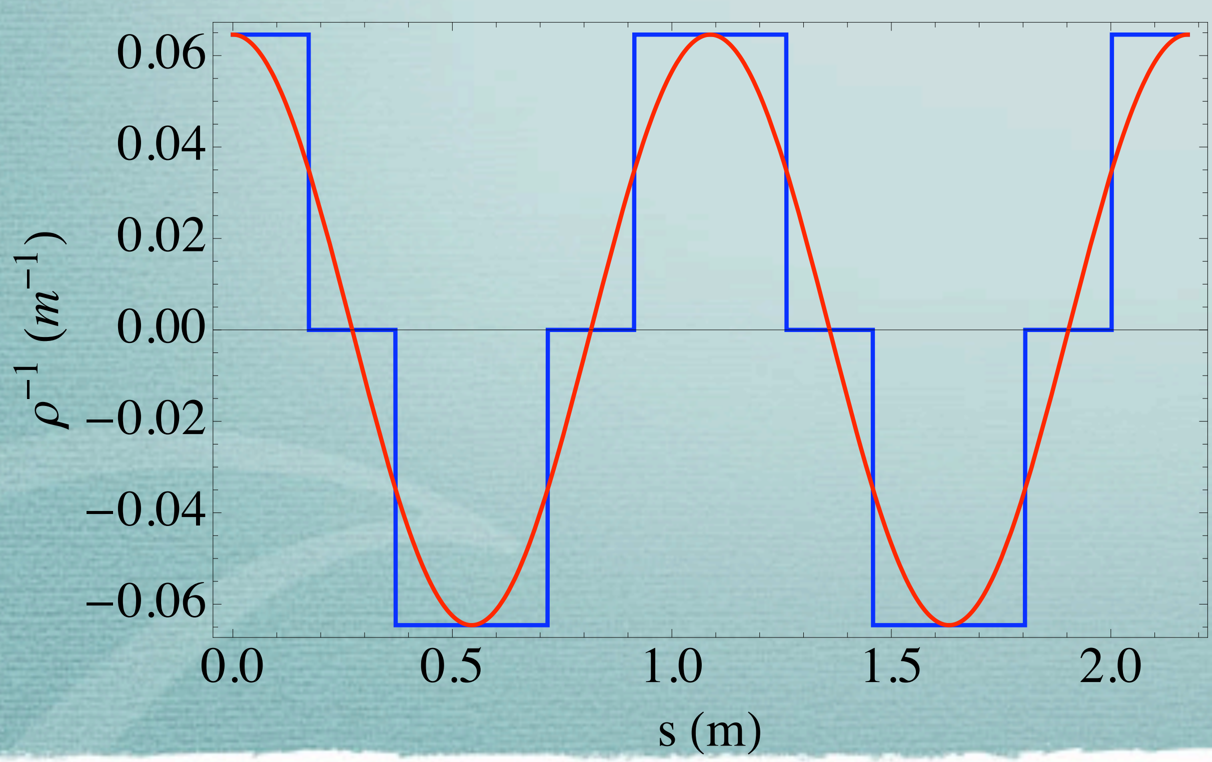


Im.Z_L(k)



H.E. model looks to be good?

Field distribution



N_{period}=1/10

w/h=94/94mm

λ_w=1.088m

ρ=15.483m

L_{exit}=Infinity (pipe after exit)

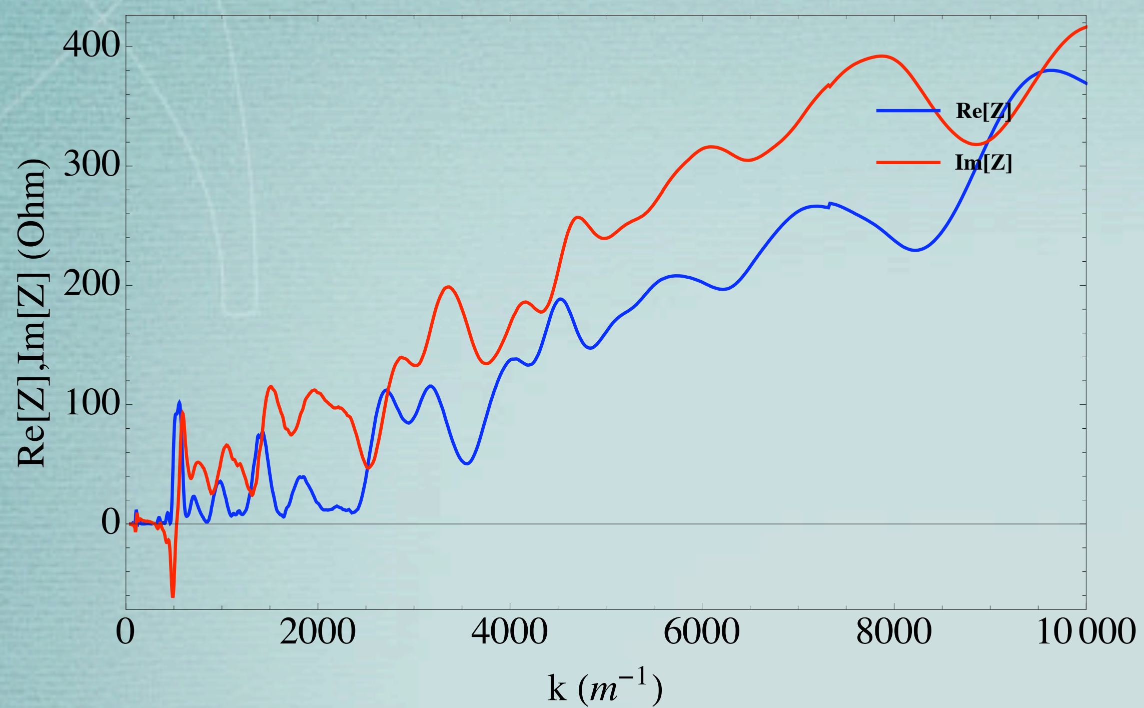
Xoffset=0mm (To inner wall)

Field distribution: Cosine/H.E.

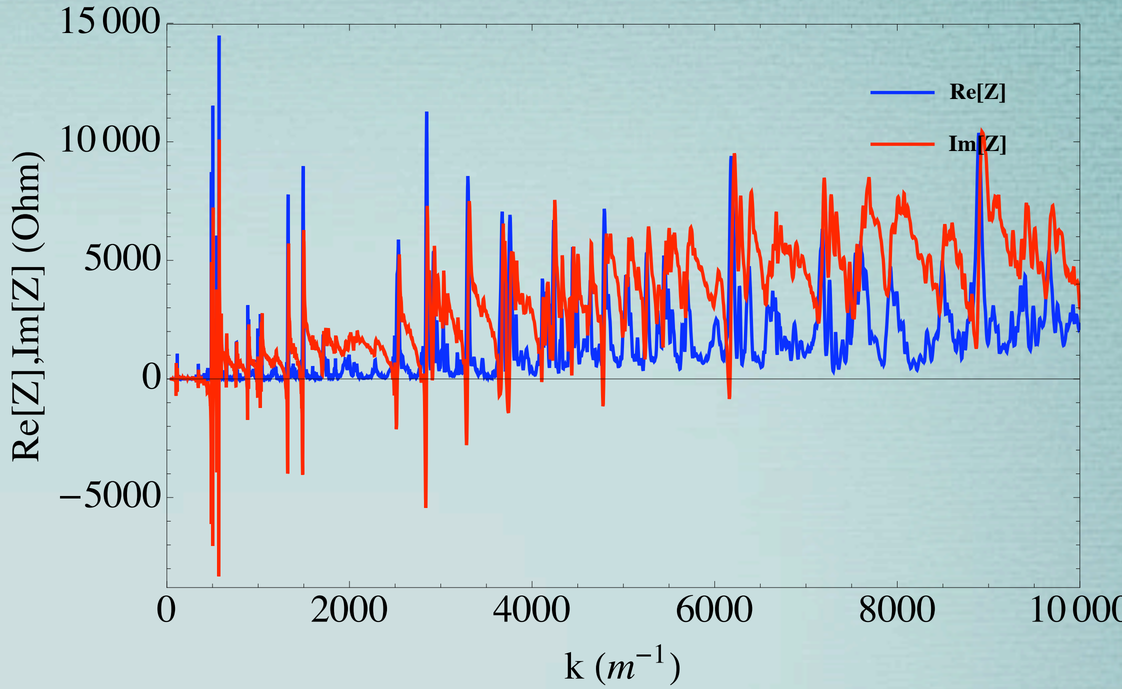
KEKB-LER

CSR in wigglers - SuperKEKB LER

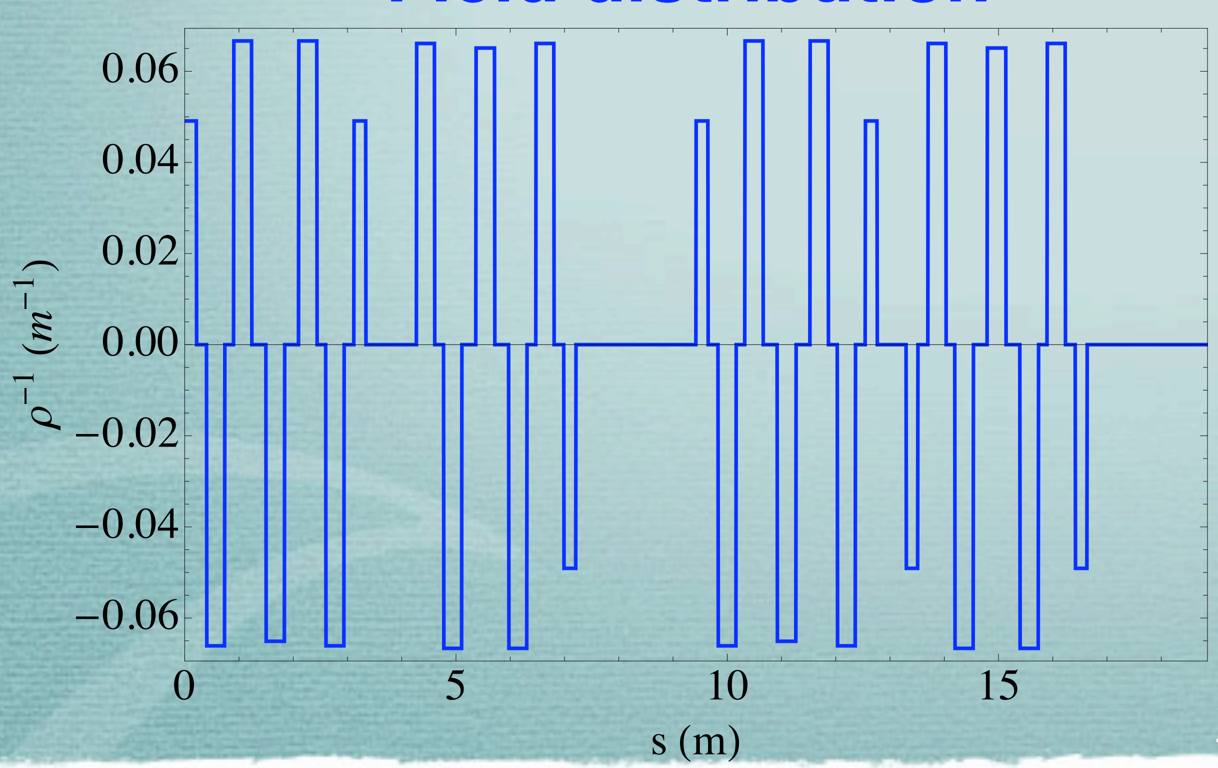
Z_L(k) ,1 Super-period



Z_L(k) ,15 Super-periods



Field distribution



$N_{super\text{-}period}$=1/15

w/h=90/90mm

L_w=140m

ρ≅15m

L_{exit}=Infinity (pipe after exit)

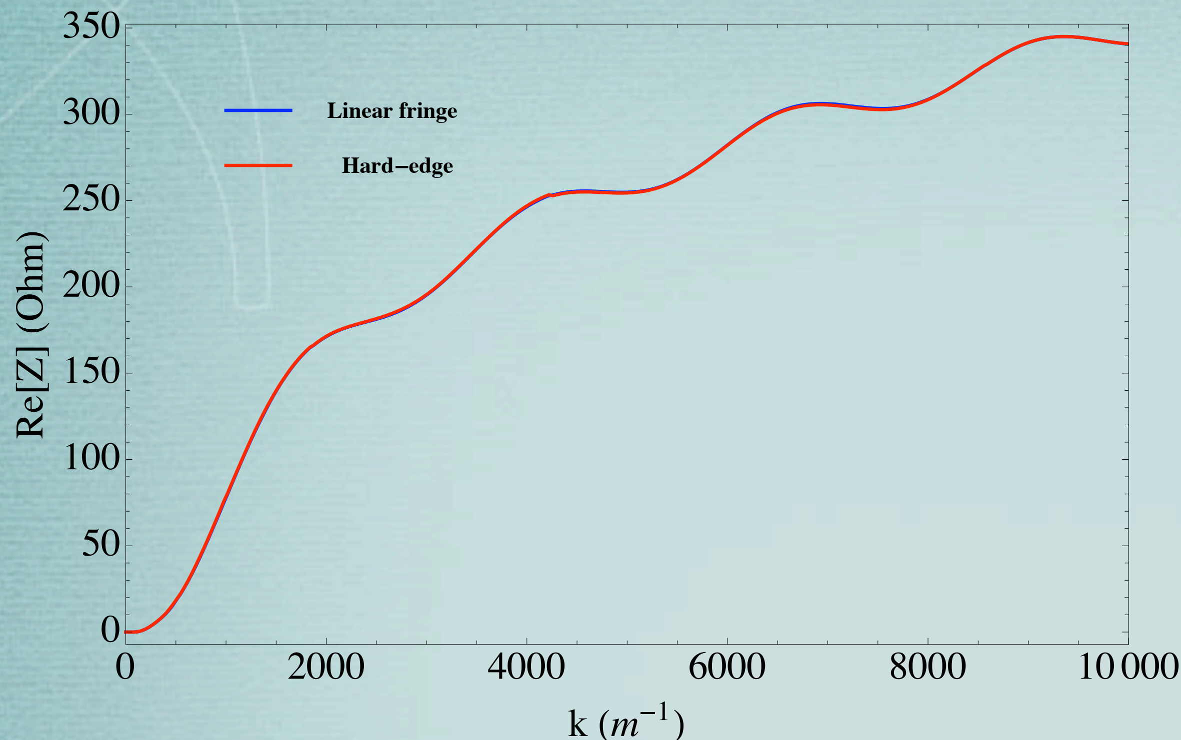
Xoffset=0mm

Field distribution: Hard-edge

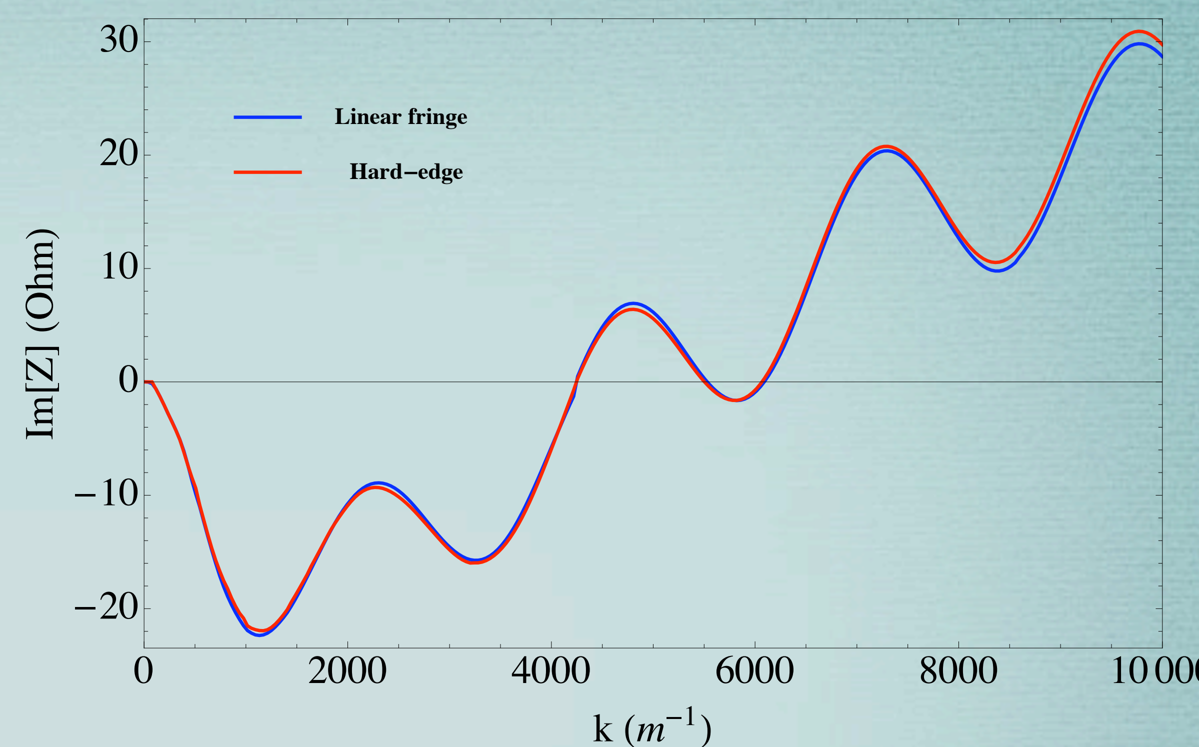
Sunday, December 26, 2010

Fringe field - KEKB LER

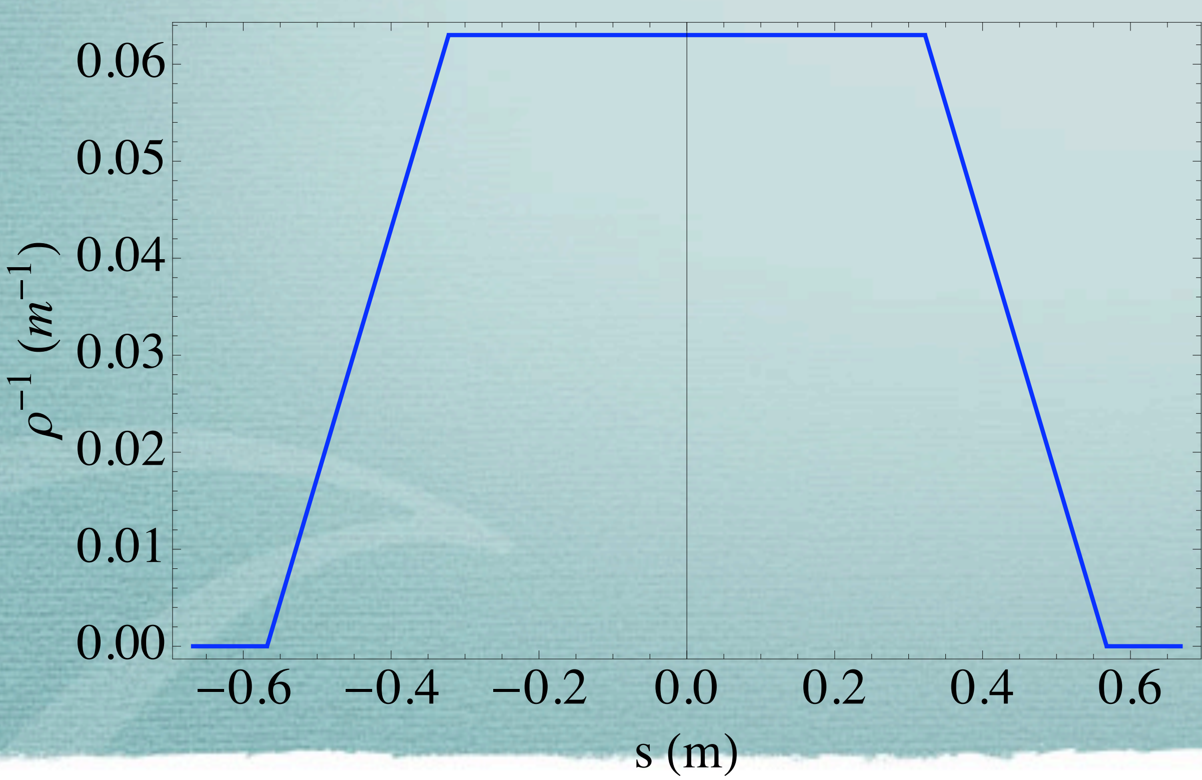
Re.Z_L(k)



Im.Z_L(k)



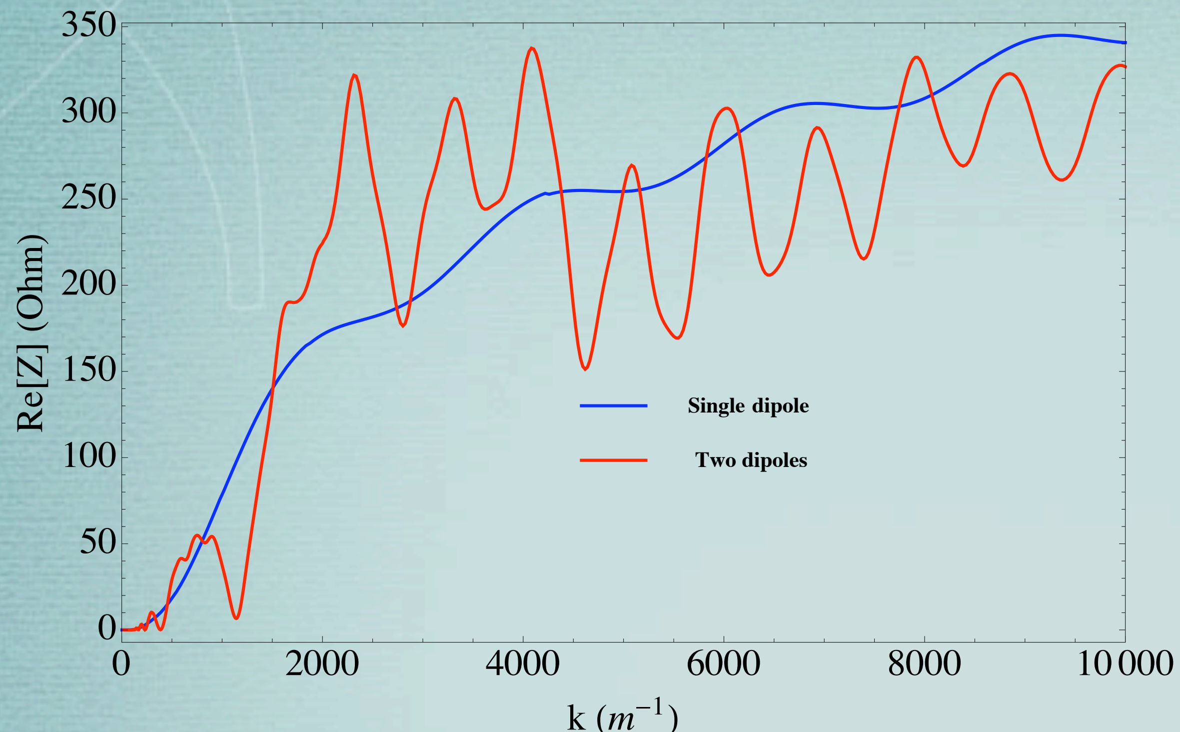
Field distribution



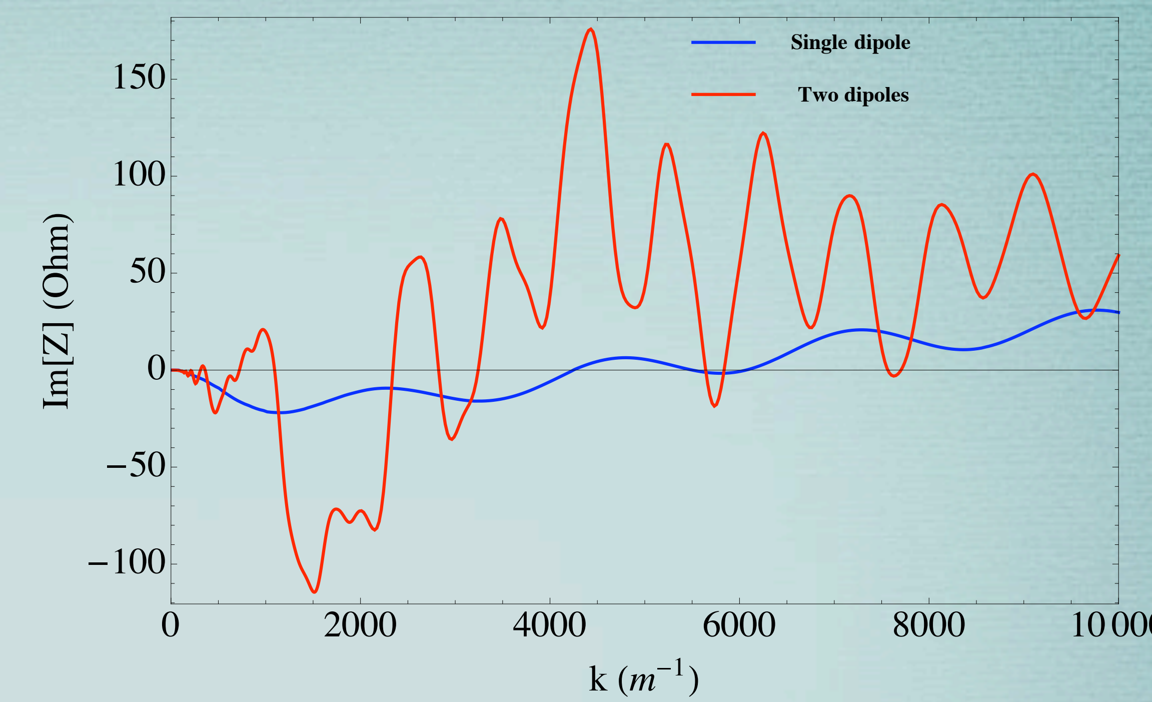
"Fringe effect" is negligible?

Interference - KEKB LER

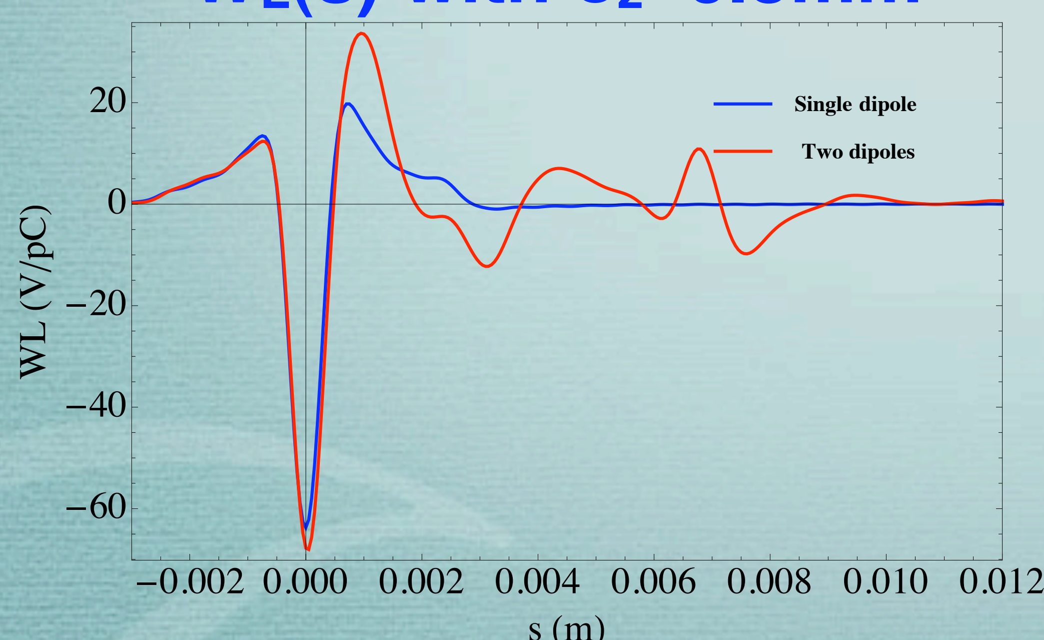
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



Two dipoles

w/h=94/94mm

L_{bend}=0.89m

L_{drift}=5.65m

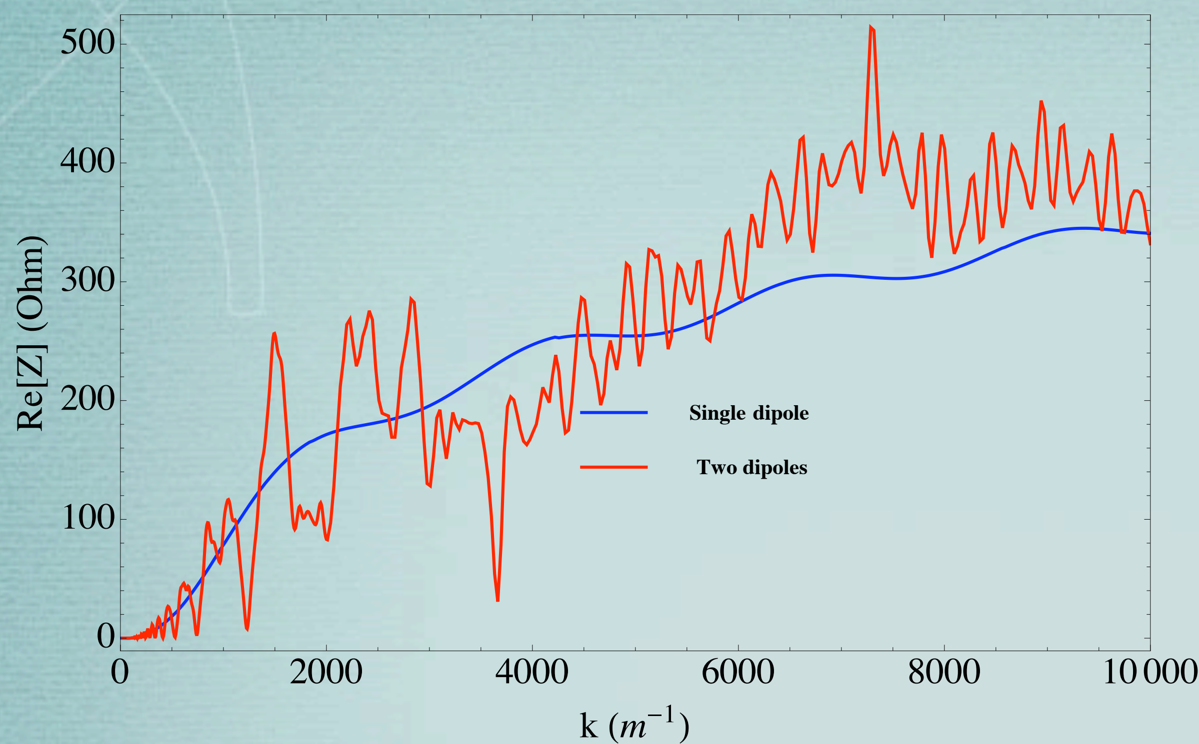
ρ=15.872m

L_{exit}=Infinity (pipe after exit)

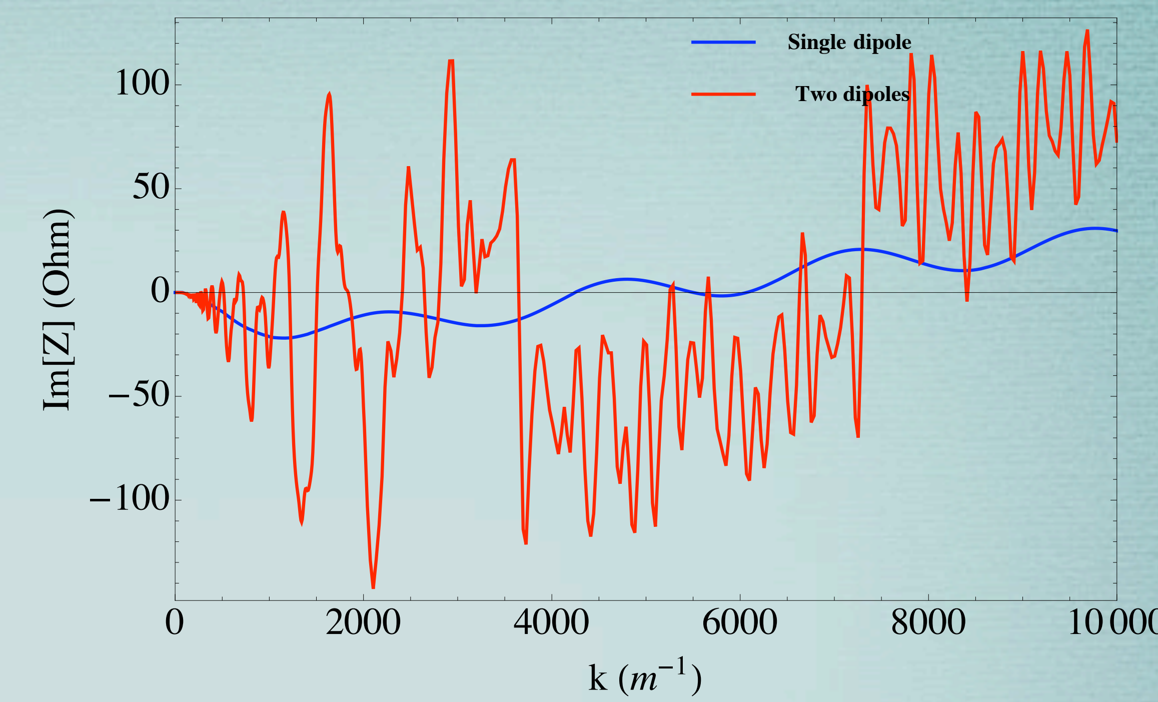
Xoffset=0mm

Interference - KEKB LER

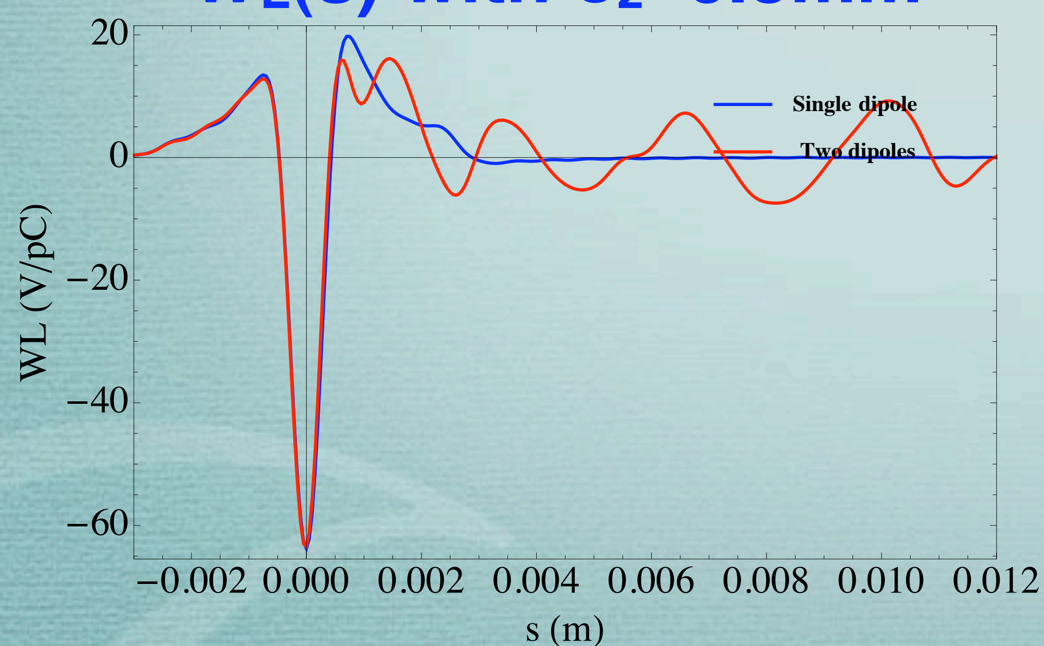
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



Two dipoles

w/h=94/94mm

L_{bend}=0.89m

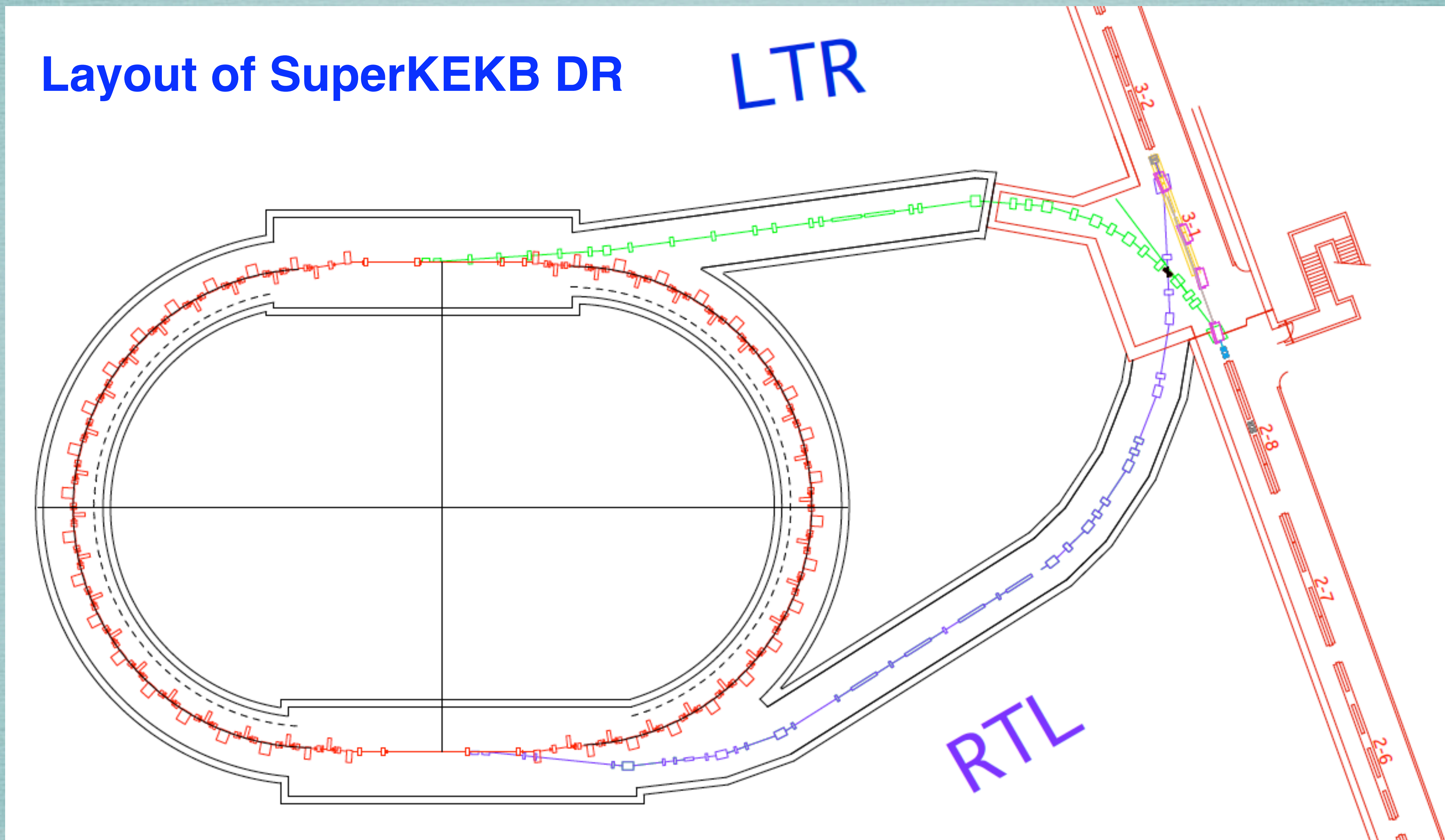
L_{drift}=20m

ρ=15.872m

L_{exit}=Infinity (pipe after exit)

Xoffset=0mm

Interference - SuperKEKB DR



M. Kikuchi

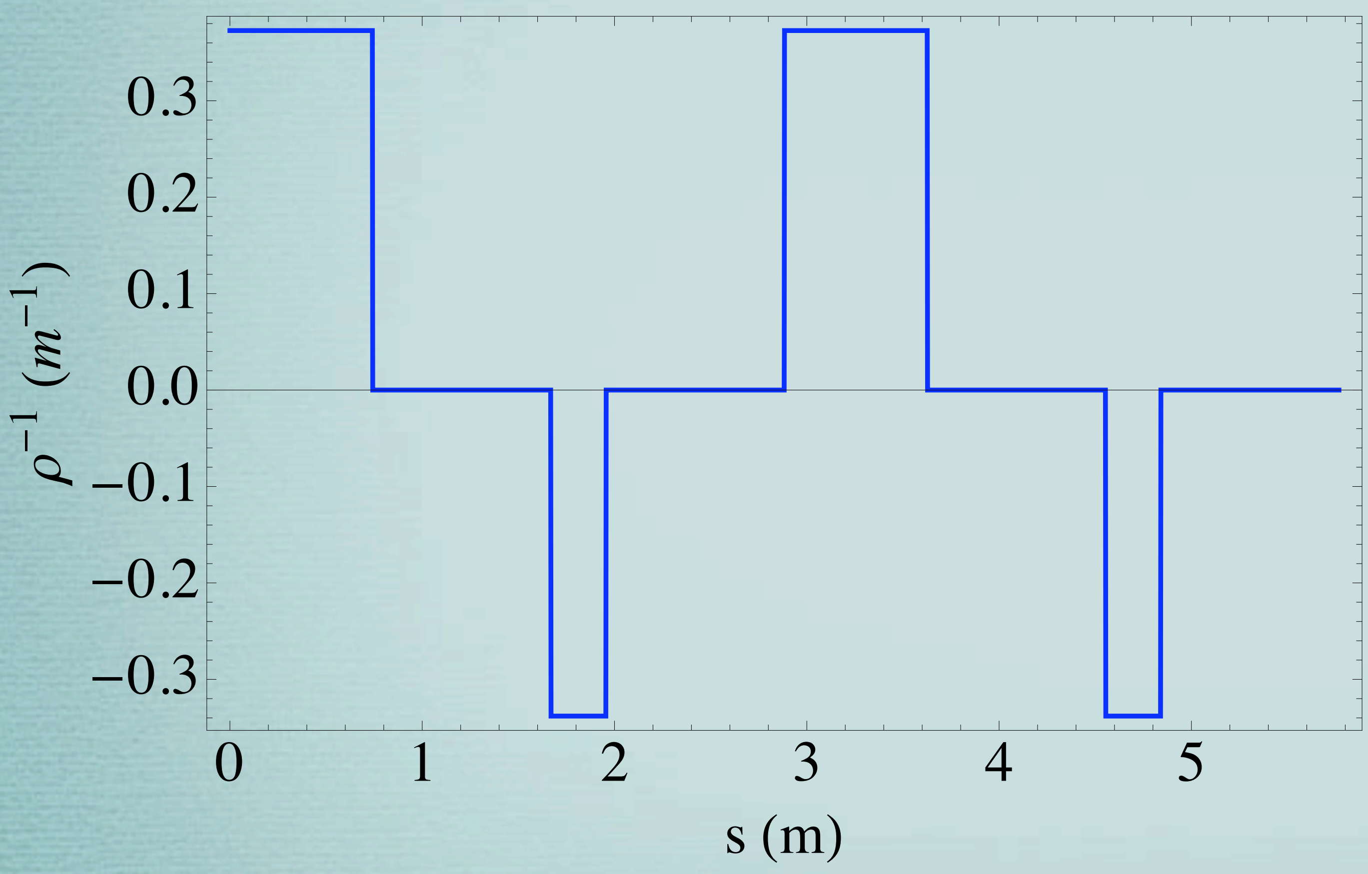
Interference - SuperKEKB DR

SuperKEKB DR parameters

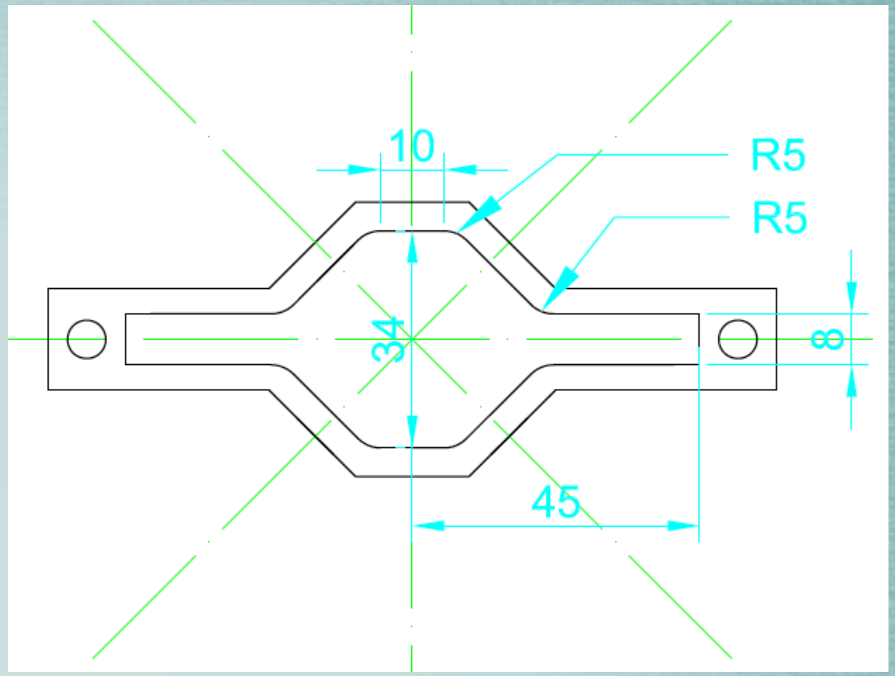
parameter	Value
Beam energy (GeV)	1.1
Circumference (m)	135.502
Bunch Length (mm)	11.1
Rel. Energy spread (10^{-4})	5.53
Beam pipe height in bends (mm)	34
Beam pipe width in bends w/o antechamber (mm)	34
Effective Length of bends (B1/B2/B3/B4)	0.74248/0.28654/0.39208/.47935
Number of bends (B1/B2/B3/B4)	32/38/4/4
Bending radius (m) (B1/B2/B3/B4)	2.68/2.96/3.15/3.15

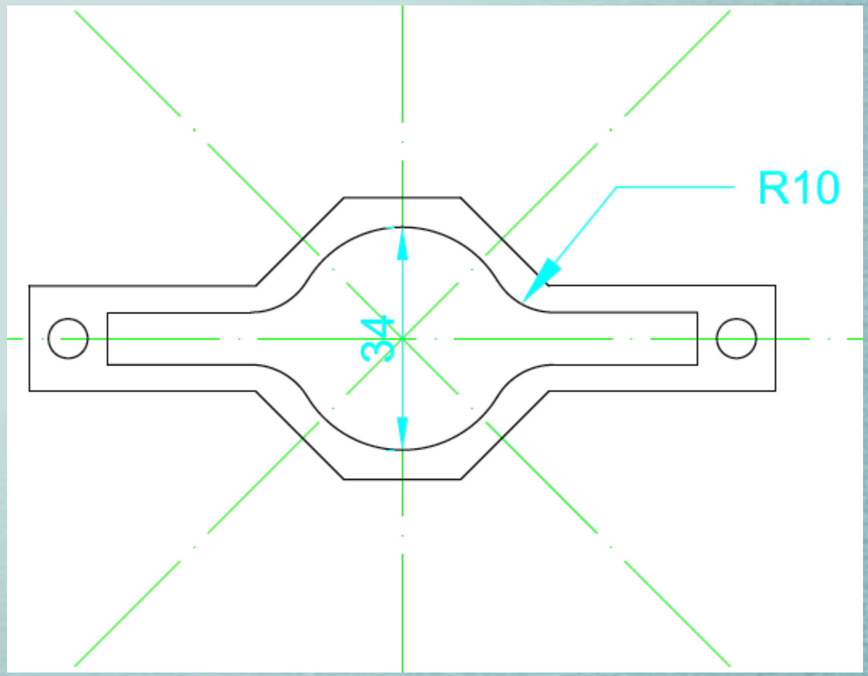
Interference - SuperKEKB DR

Field distribution (2 cells)



Vacuum chamber (candidates)

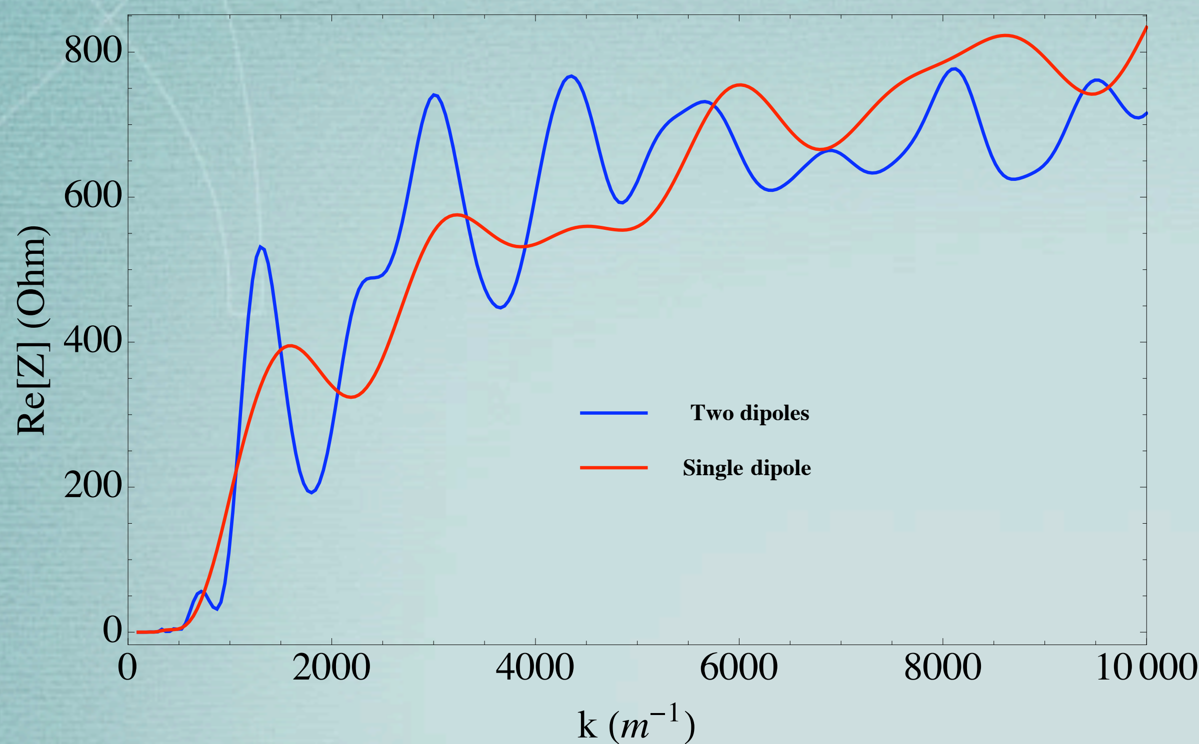




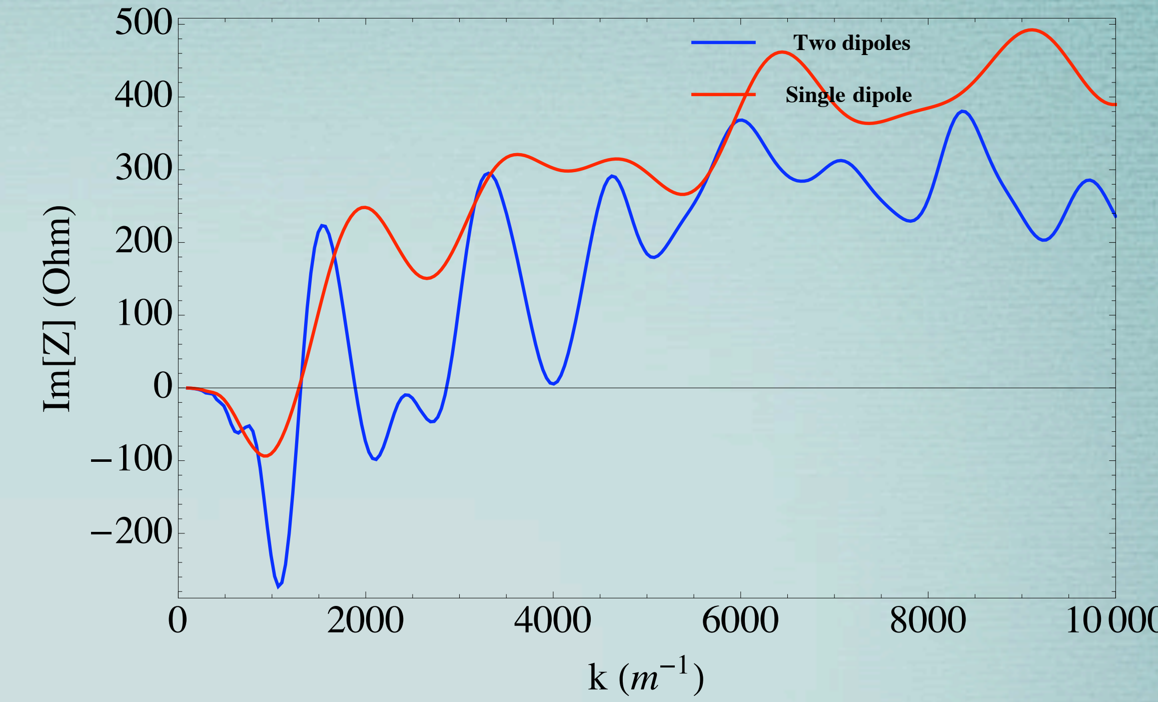
K. Shibata

Interference - SuperKEKB DR

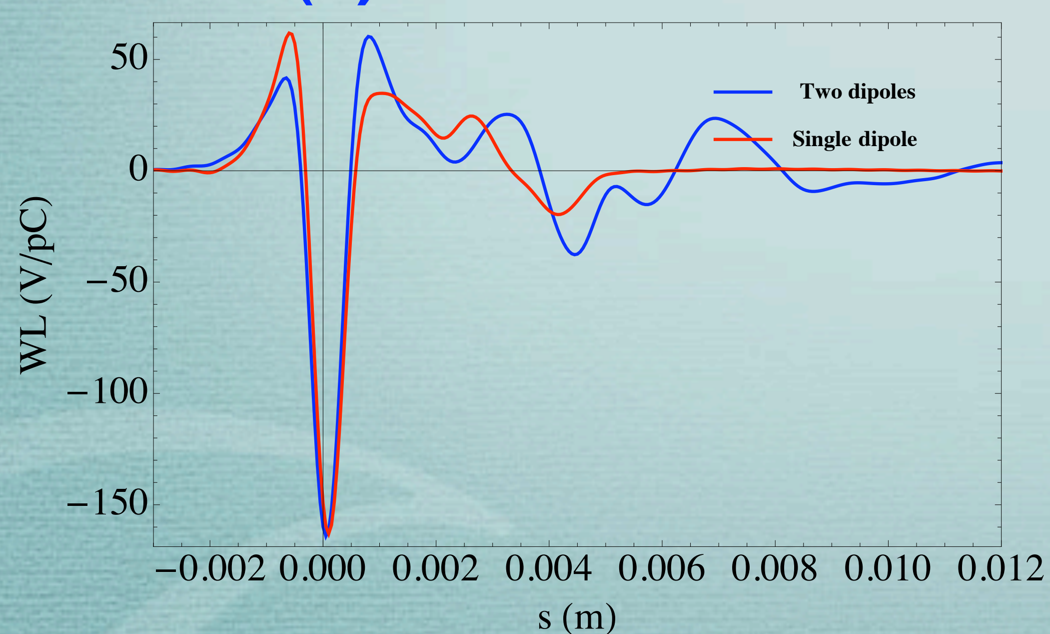
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



1 cell

w/h=34/34mm

B1+B2

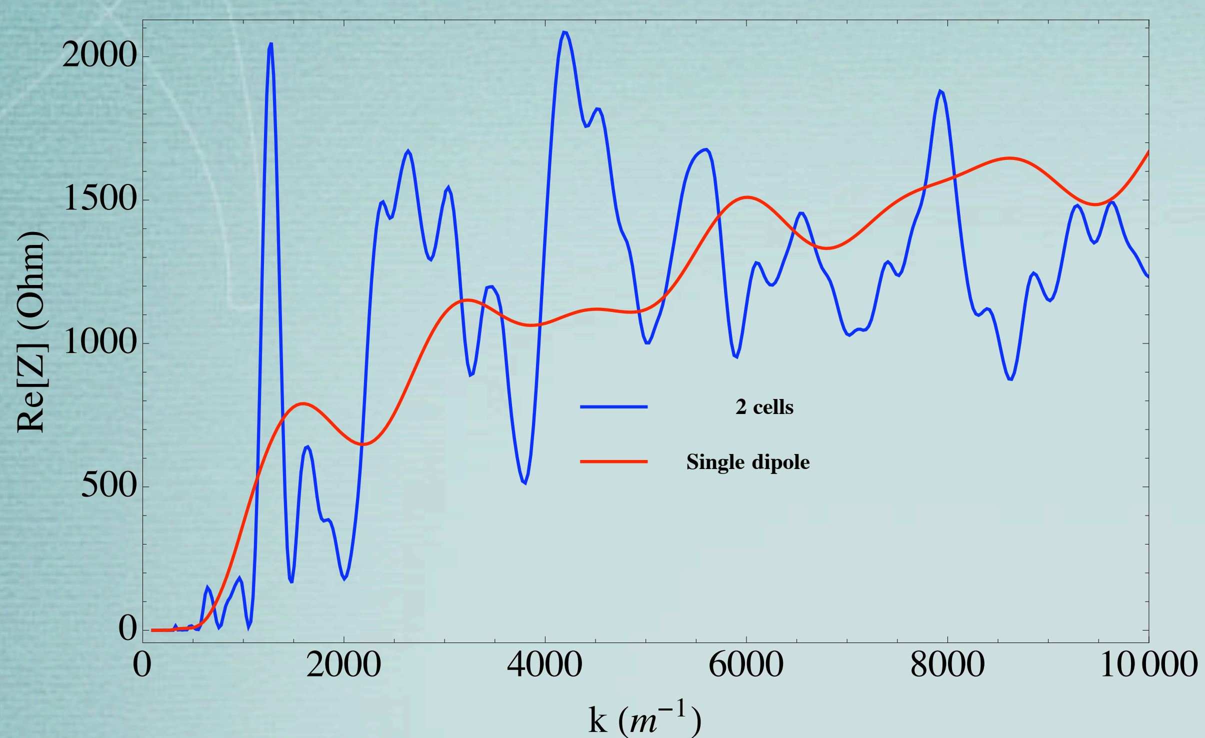
L_{drift}=0.93m

L_{exit}=Infinity (pipe after exit)

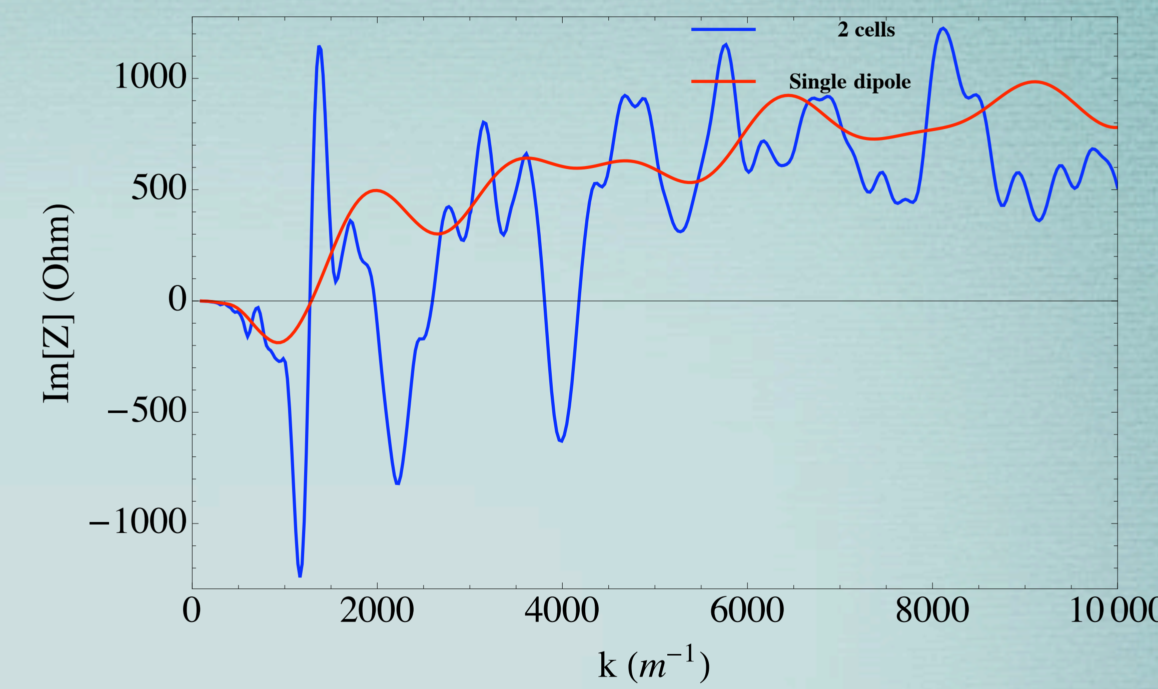
Xoffset=0mm

Interference - SuperKEKB DR

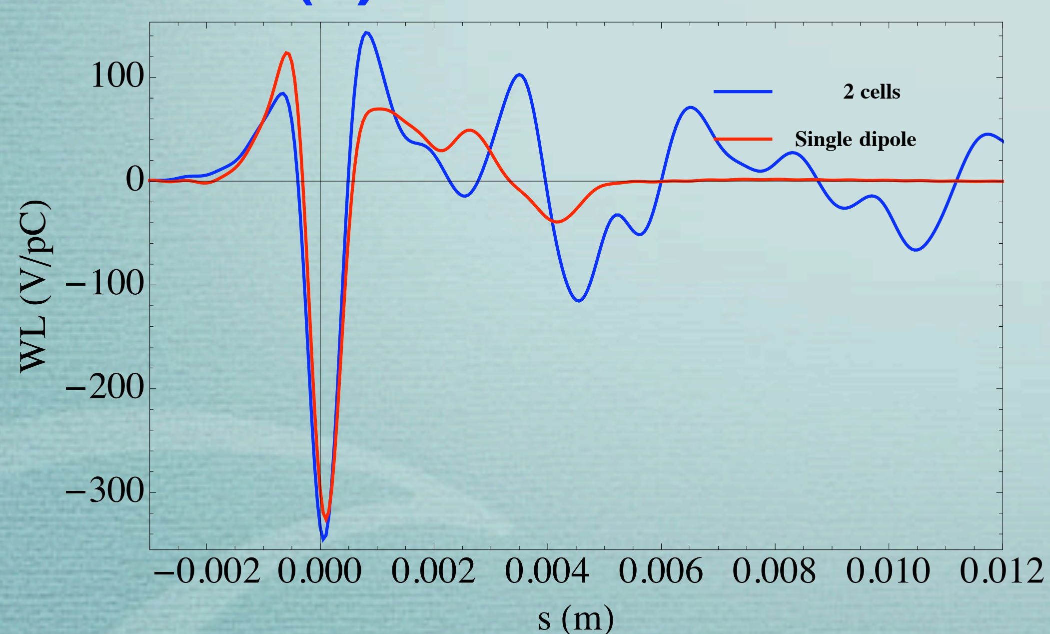
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



2 cells

w/h=34/34mm

2×(B1+B2)

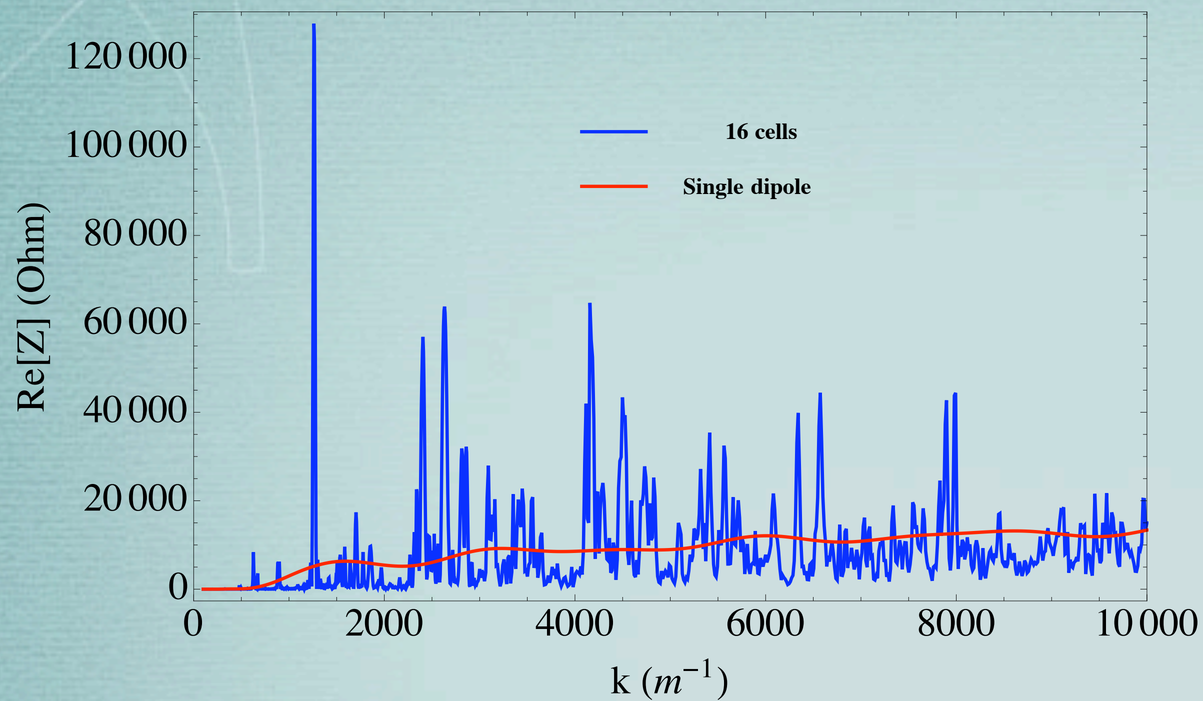
L_{drift}=0.93m

L_{exit}=Infinity (pipe after exit)

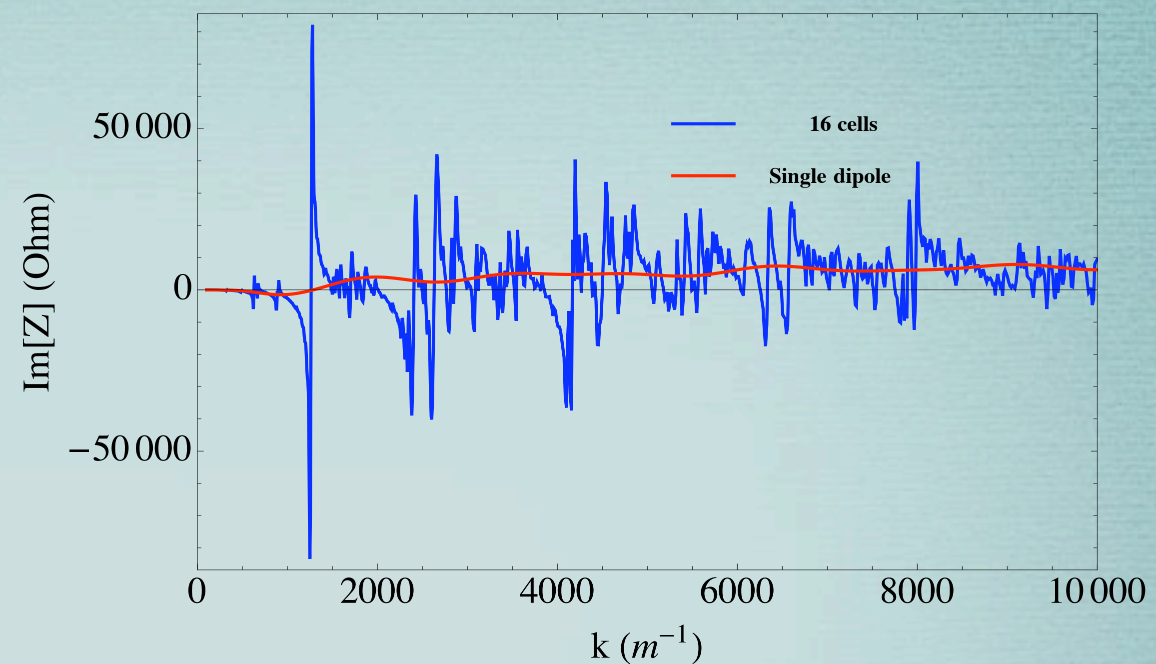
Xoffset=0mm

Interference - SuperKEKB DR

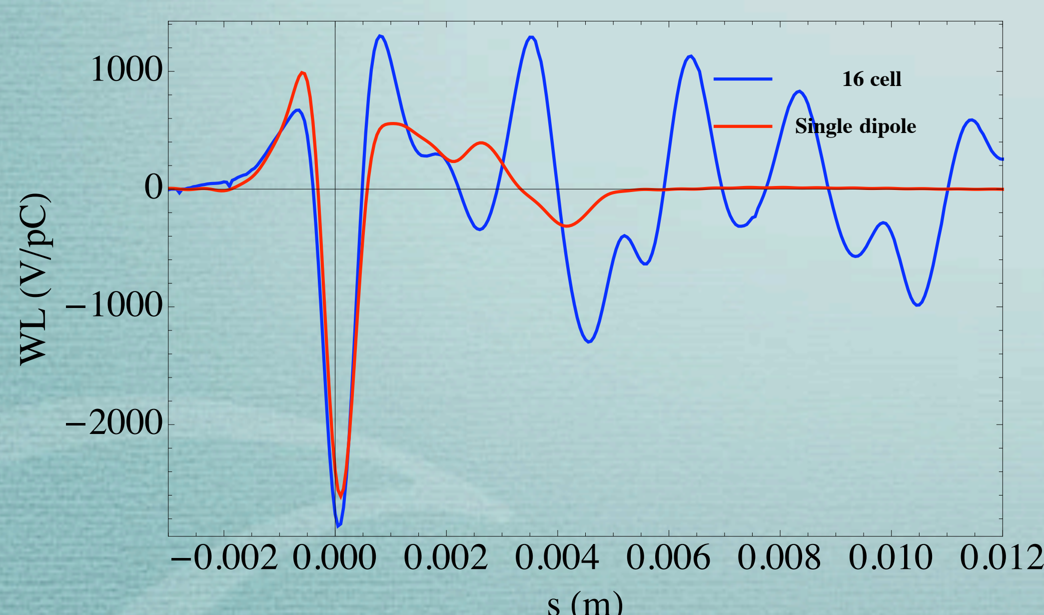
Re.Z_L(k)



Im.Z_L(k)



W_L(s) with σ_z=0.3mm



16 cells

w/h=34/34mm

16×(B1+B2)

L_{drift}=0.93m

L_{exit}=Infinity (pipe after exit)

Xoffset=0mm

Summary - CSR

1. Features of the new CSR code (CSRZ):

1.1 Low noise level

1.2 Allow for s-dependent bending radius (fringe field, wigglers, interference between consecutive dipoles)

1.3 Allow for resistive wall (not discussed in this talk and to be benchmarked)

2. Achievements

2.1 Limitations in all three codes (GS, KO, DZ) improved after careful benchmark work

2.2 Narrow-band impedances (spikes) due to CSR of wigglers were observed which are unexpected according to traditional theories

2.3 Interference between consecutive dipoles can be significant and leads to narrow-band CSR impedances (with perfect wall)

2.4 CSR calculation for SuperKEKB project

3. Challenges

3.1 Computing time is not quite acceptable at high freq. or very long components which require refinements in meshes or huge integration steps

3.2 “Wiggling pipe” is not good approximation

3.3 Treating pipe with arbitrary cross section is unavailable