Longitudinal single-bunch instabilities in the LER of KEKB

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Thanks to K. Oide, Y. Cai, Y. Suetsugu, K. Shibata, M. Tobiyama, Y. Morita, T. Agoh, H. Fukuma, J. Flanangan, K. Akai, T. Ieiri …

Accelerator physics seminar, KEK, Jul. 23, 2009

Outline

- Introduction
- Construction of a numerical impedance model
- Loss factor from numerical impedance model
- HOM power and loss factor from RF power balance
- Numerical simulations with VFP solver
- An attempt to extract impedance directly from bunch profiles
- Summary

Introduction (1)

LRC Broadband Impedance Model

For q<0, wakefield is given by

$$W(q) = -w_0[\cos(Aq) + B\sin(Aq)]\exp(xq/2Q)$$

where $A = x\sqrt{1-\frac{1}{4Q^2}}, B = \frac{1}{\sqrt{4Q^2-1}}, x = \frac{\sigma_z \omega_R}{c}$

It's integral:

$$S(q) = \int_{-\infty}^{q} W(q')dq' = -\tfrac{w_0}{A}\sin(Aq)\exp(xq/2Q)$$

Conversion of LRC parameters:

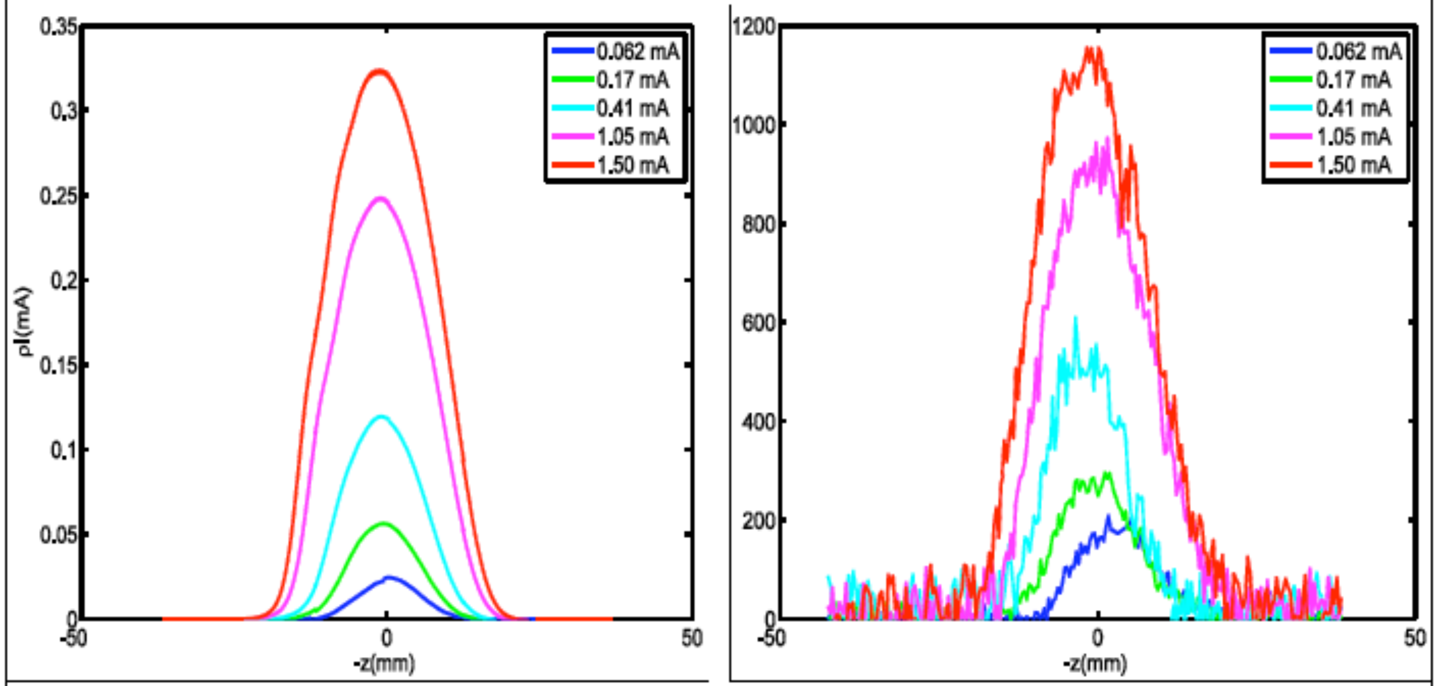
$$C = \frac{1}{w_0}, L = w_0\left(\frac{\sigma_z}{xc}\right)^2, R = Qw_0\left(\frac{\sigma_z}{xc}\right)$$

Y. Cai, KEKB meeting, Nov.20, 2008

Introduction (2)

Impedance Model and Measurement

$Q=1,\ x(\omega_R\sigma_z/c)=3,\ w_0=5\times10^5(m^{-1})$



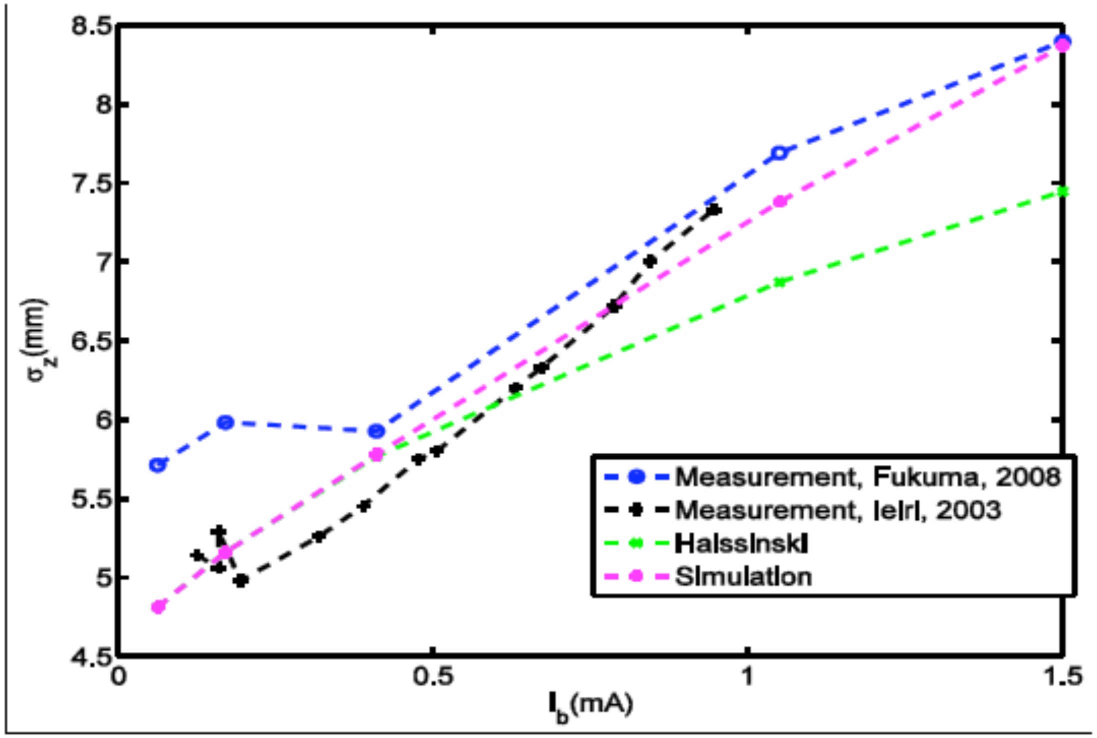
For the LER, we have L=116.8 nH, R=22.94 KΩ, C=22.1 fF

Y. Cai, KEKB meeting, Nov.20, 2008

Introduction (3)

Impedance Model and Measurement

$Q=1,\ x(\omega_R\sigma_z/c)=3,\ w_0=5\times10^5(m^{-1})$



Y. Cai, KEKB meeting, Nov.20, 2008

Introduction (4)

- Our method
  - Construct numerical impedance model (Quasi-green function)
  - Check the models with beam measurements
  - Simulate with VFP solver
- Advantages of numerical impedance model
  - More physical
  - Predict loss factor and HOM power
  - Identify effects of different impedance sources (Geometrical, Resistive wall and CSR)

Numerical impedance model (1)

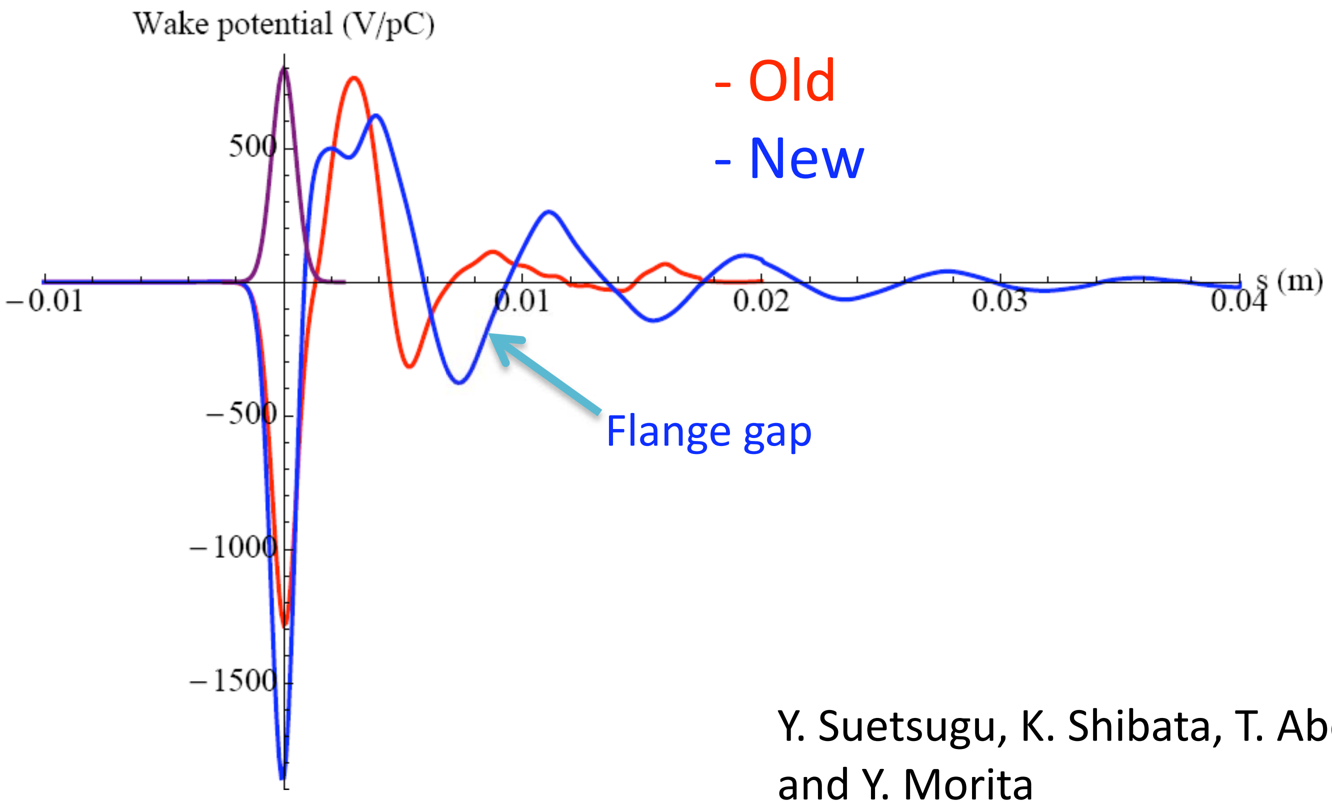
- Vacuum components: Take into account as many as possible. Crab cavity, FB, tapers, gate valves...
- Careful modeling: SR masks, flange gaps, pumping ports...

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

By Y. Suetsugu, K. Shibata, T. Abe, M. Tobiyama, Y. Morita

Numerical impedance model (2)

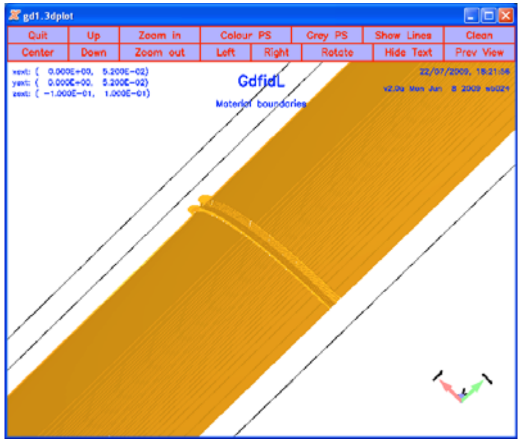
- Geometrical wake (GW) potential of 0.5mm bunch
  - Main improvements are wakes of SR masks and flange gaps
  - Contributions from crab cavity, FB, tapers and gate valves are relatively small

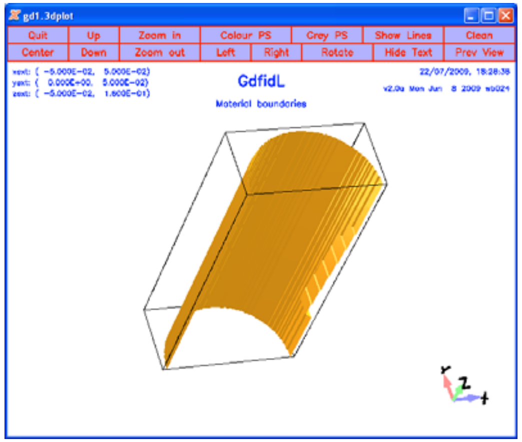


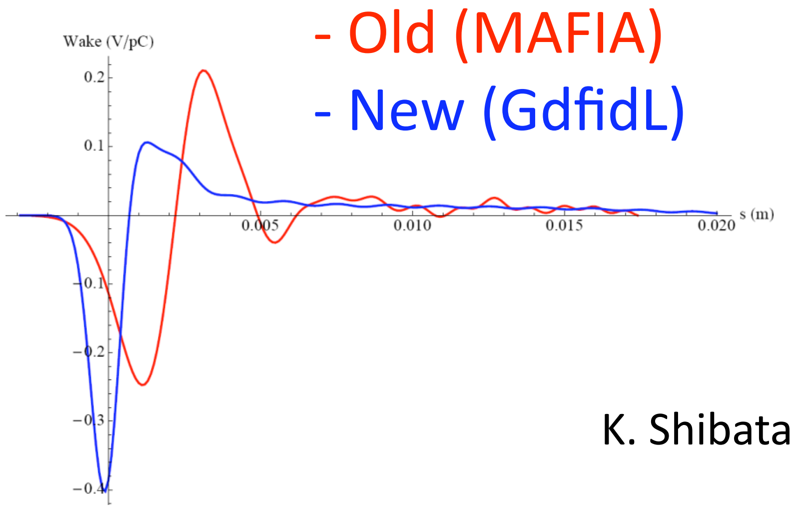
Y. Suetsugu, K. Shibata, T. Abe, M. Tobiyama, and Y. Morita

Examples of improving impedance calculation

- 0.5mm bunch drives “trapped” modes in gaps







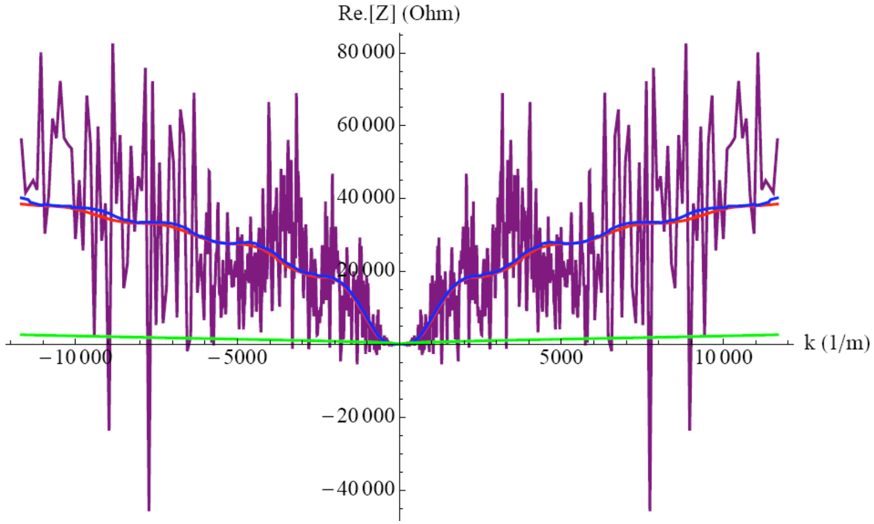
K. Shibata

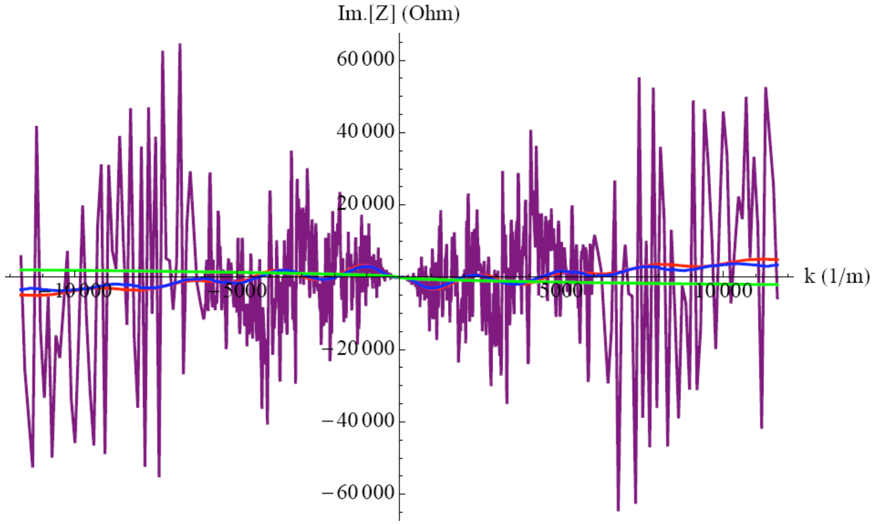
CSR impedance of dipoles by Oide's code (1)

- For dipoles, no big difference w/ and w/o antechamber
- Drifts between dipoles have large effects

Bending radius=0.89041m
Bending angle=0.0561rad

- R=47mm, single dipole with infinite drift x 112
- R=45mm, single dipole with antechamber and infinite drift x 112
- R=47mm, 4 dipoles with finite drifts x 28
- Total resistive wall impedance

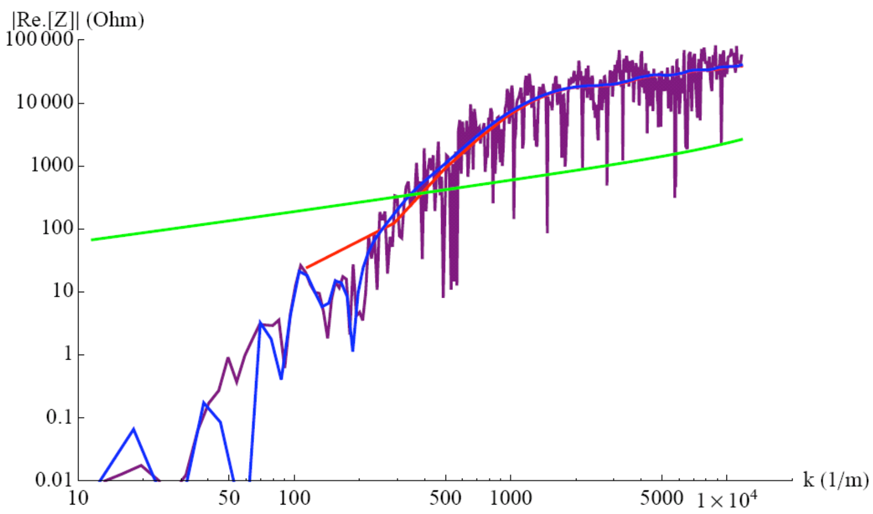


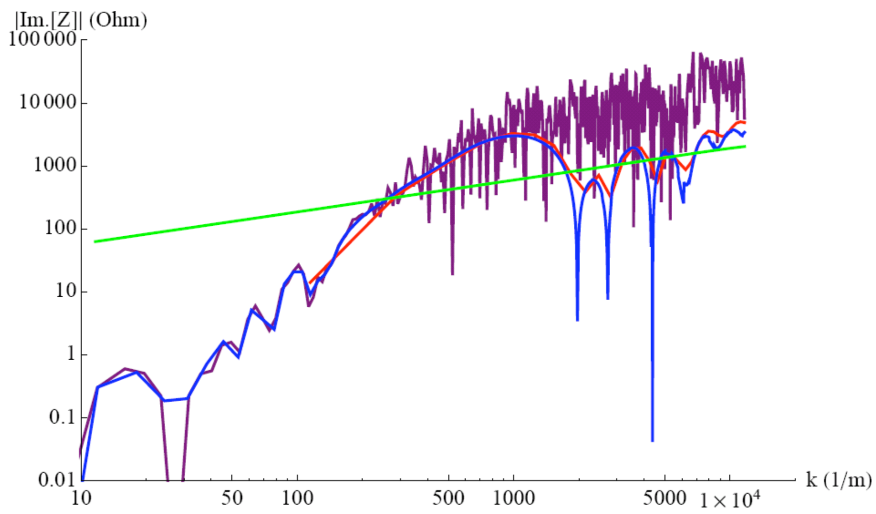


CSR impedance of dipoles by Oide's code (3)

- Log-Log plot

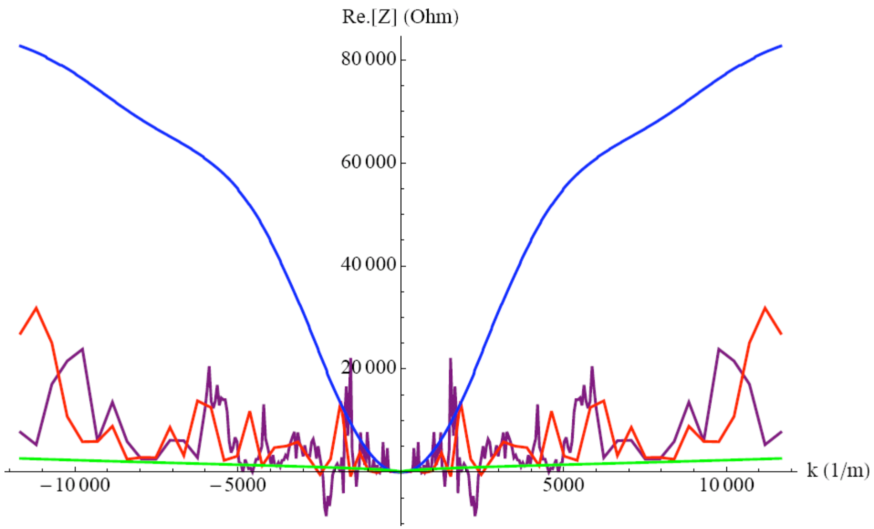
- R=47mm, single dipole with infinite drift x 112
- R=45mm, single dipole with antechamber and infinite drift x 112
- R=47mm, 4 dipoles with finite drifts x 28
- Total RW

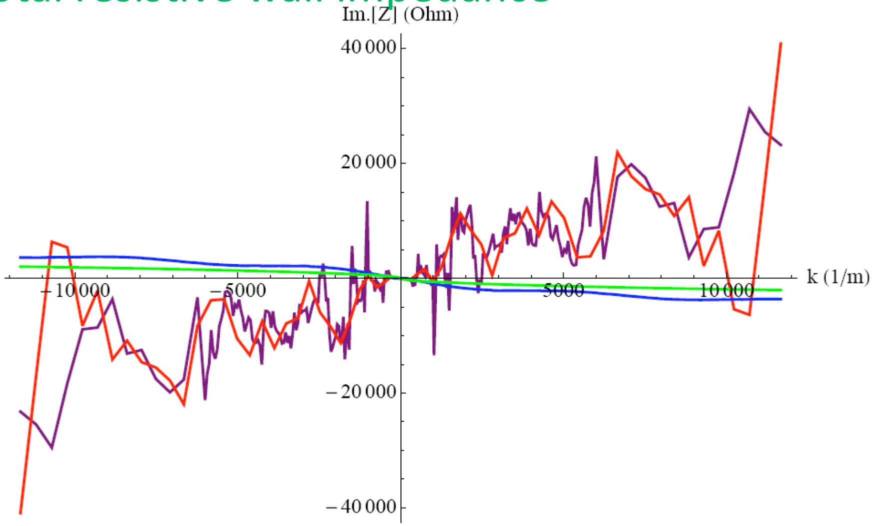




CSR impedance of wigglers by Oide's code (1)

- For wigglers, drifts have very serious effects on CSR
- Different with the case of dipoles, the sign of imaginary part change when wave number goes higher(>500)

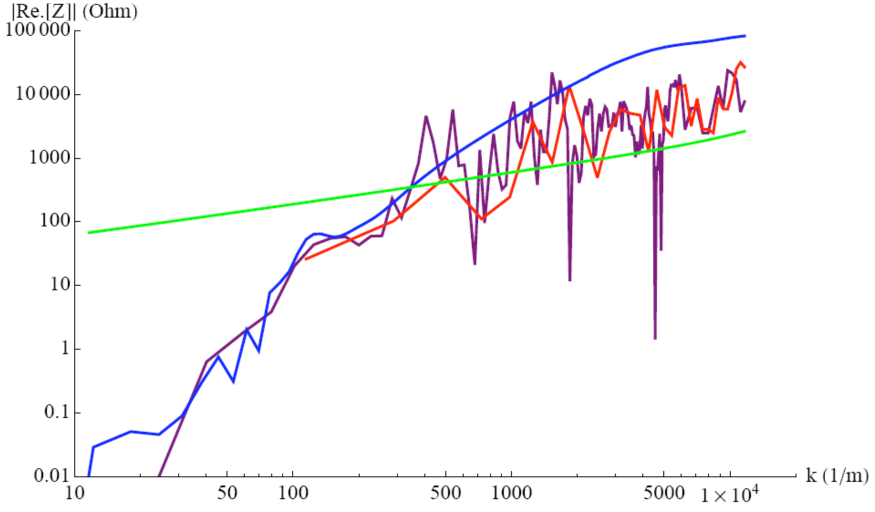


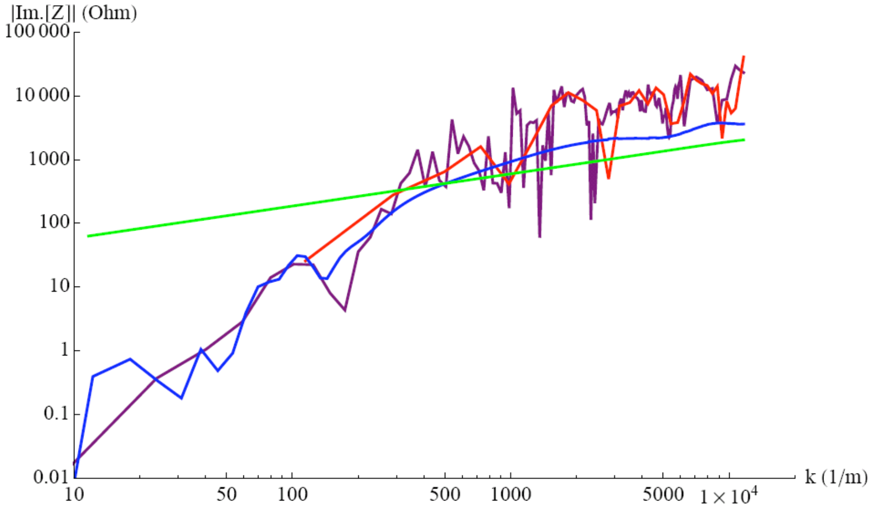


CSR impedance of wigglers by Oide's code (3)

- Log-Log plot

- R=47mm, single pole with infinite drift x 304
- R=45mm, 152 poles with antechamber and drifts (SuperKEKB) x 2
- R=47mm, 152 poles with drifts x 2
- Total RW

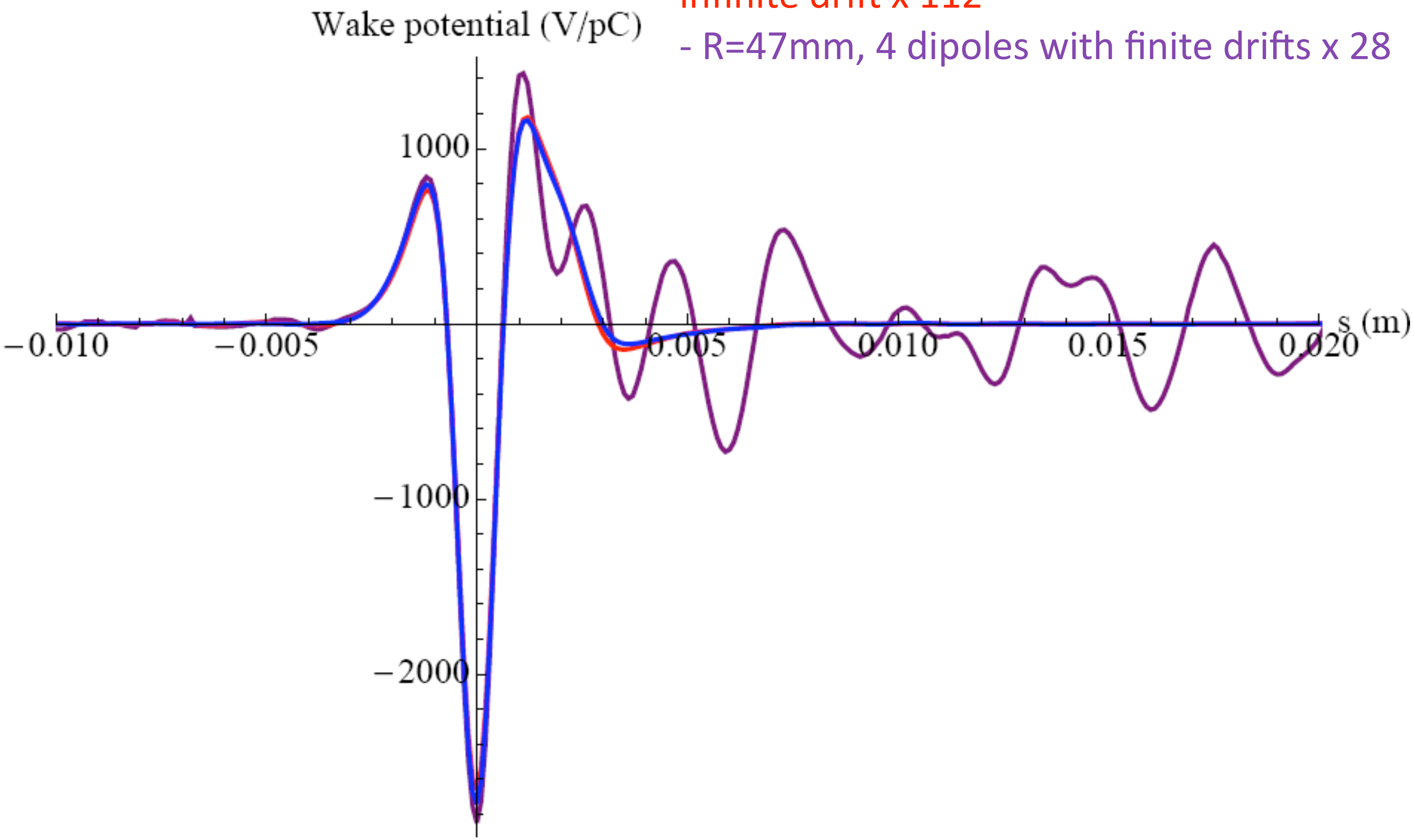




CSR wake potential of 0.5mm bunch (1)

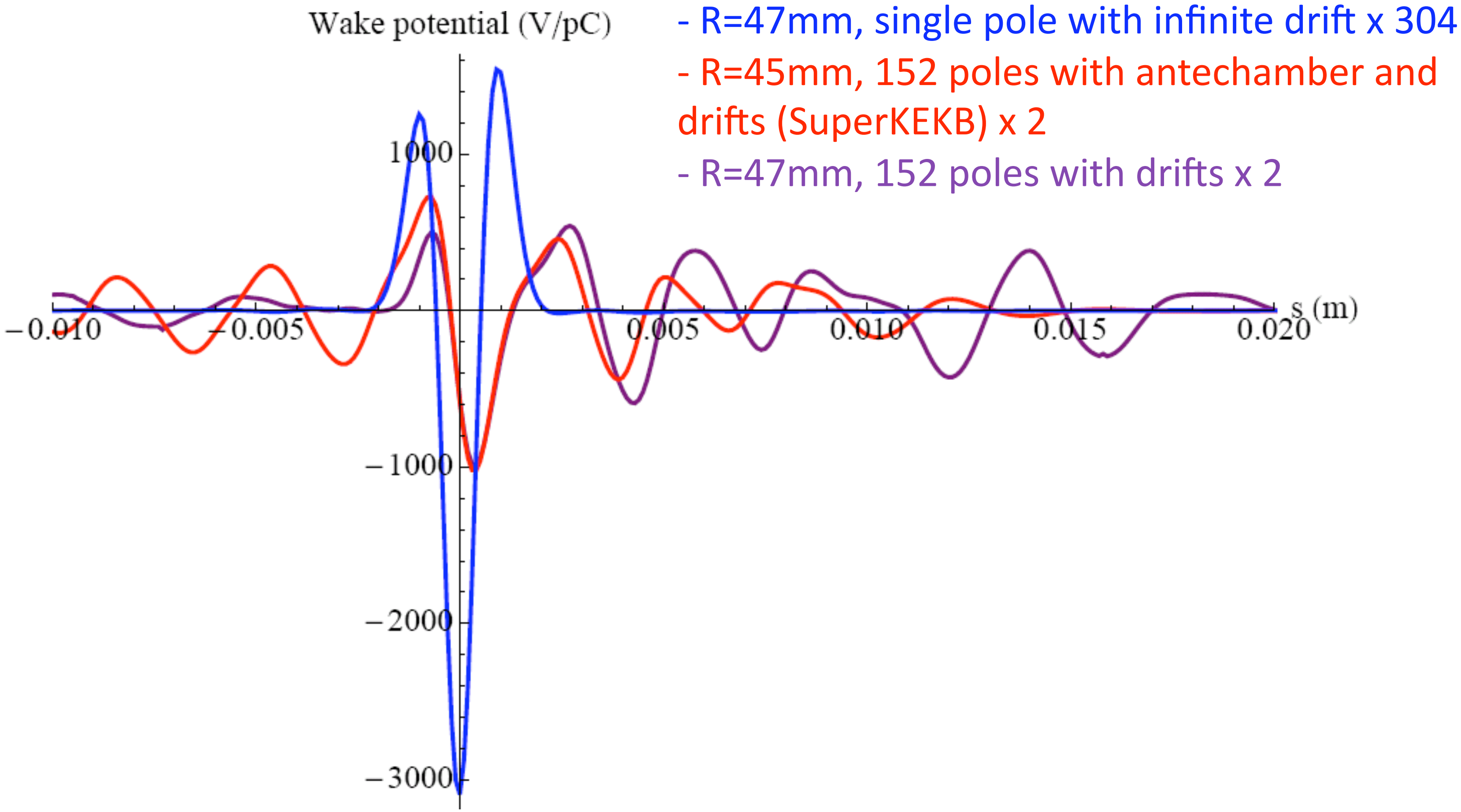
- Dipoles

- R=47mm, single dipole with infinite drift x 112
- R=45mm, single dipole with antechamber and infinite drift x 112
- R=47mm, 4 dipoles with finite drifts x 28

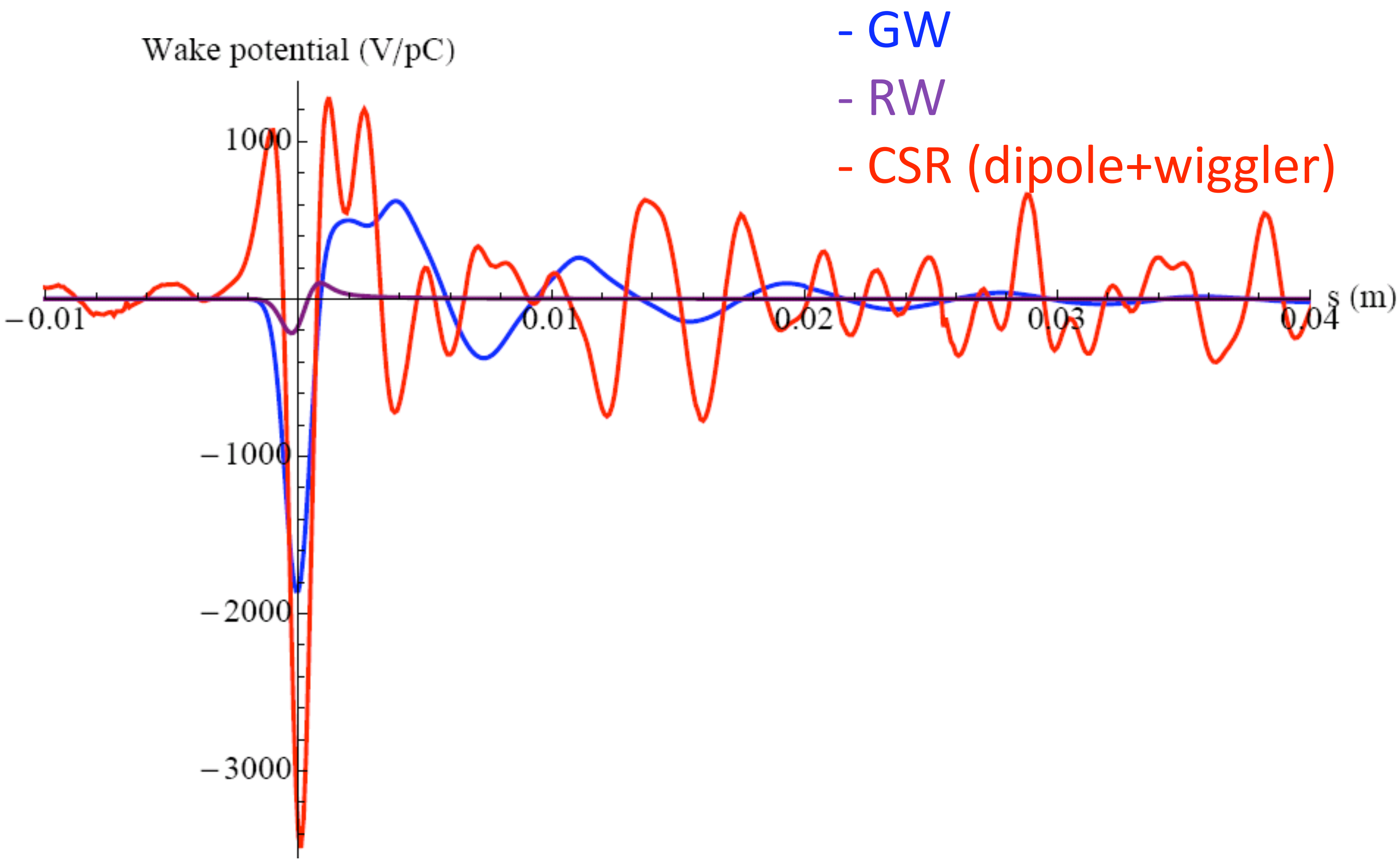


CSR wake potential of 0.5mm bunch (2)

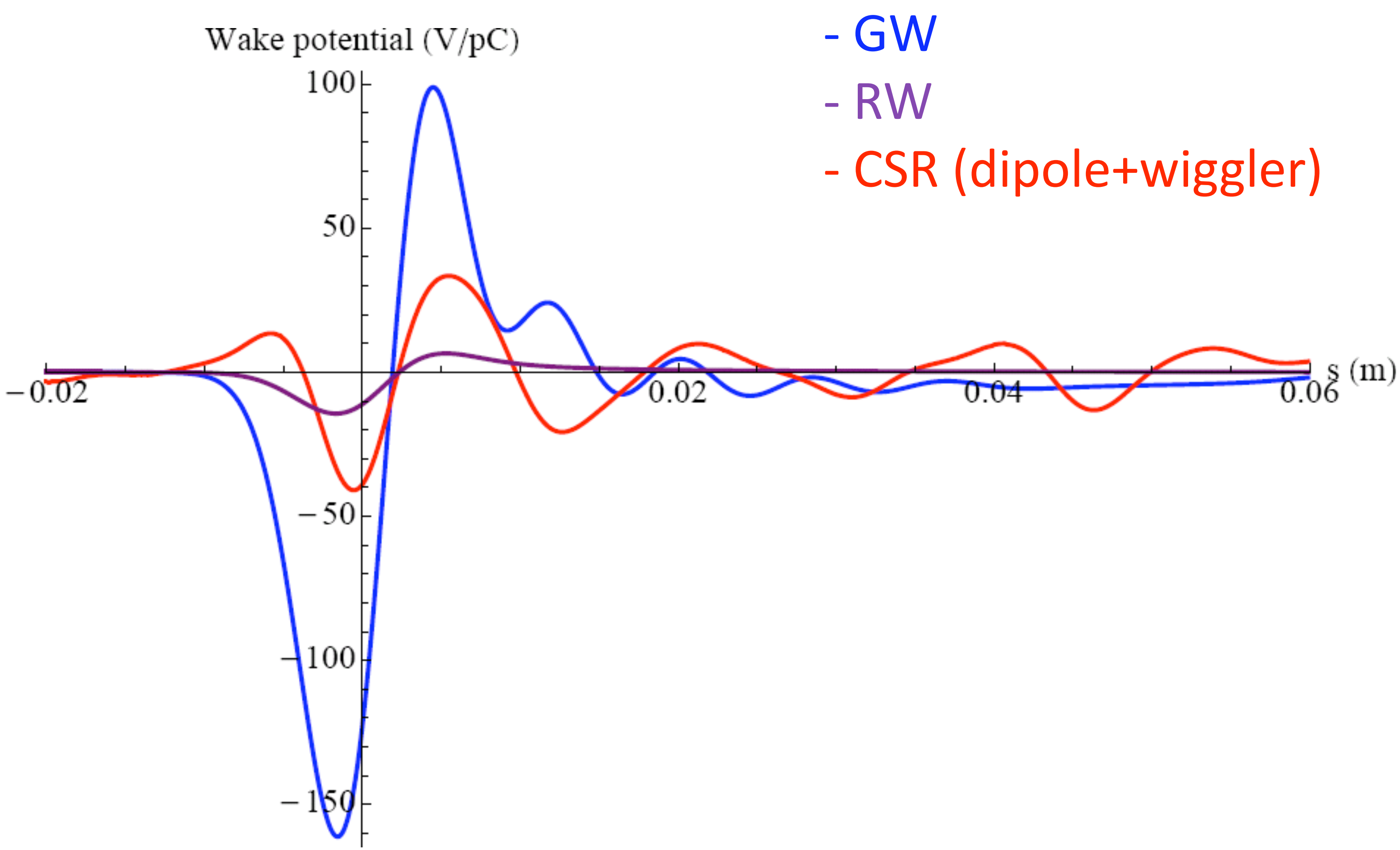
- Wigglers
  - Drifts relax CSR wake



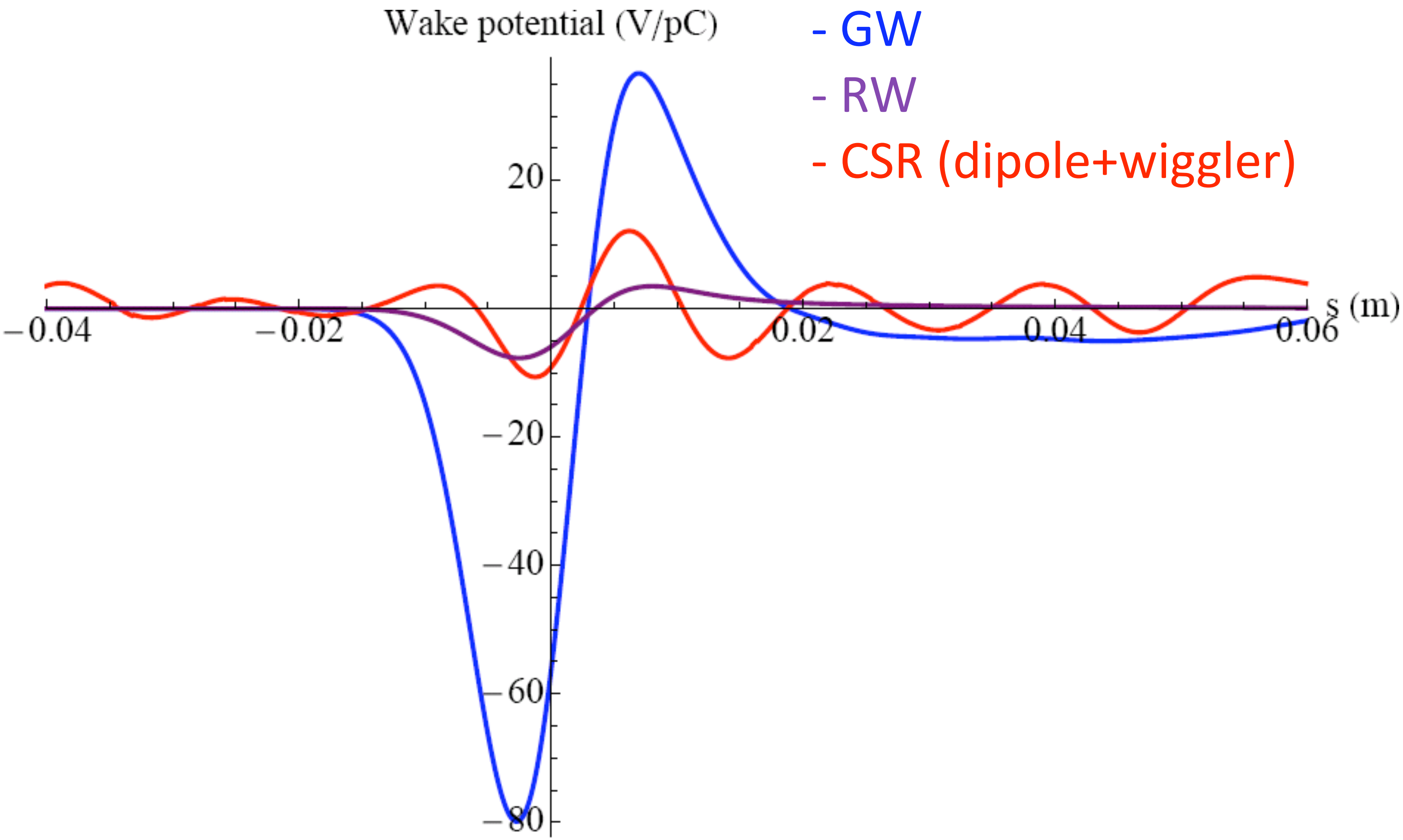
GW, RW and CSR wake potential of 0.5mm bunch



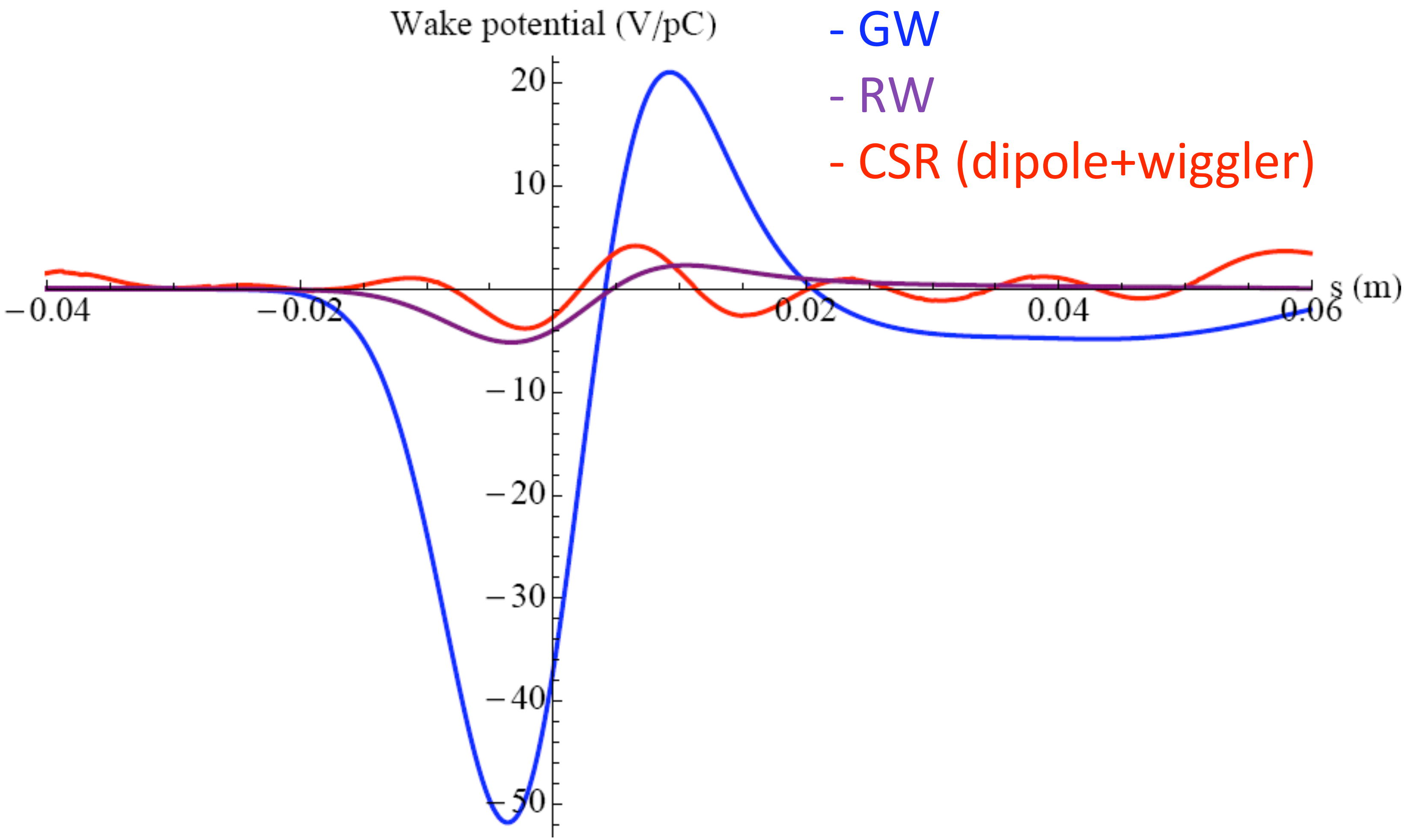
GW, RW and CSR wake potential of 3mm bunch



GW, RW and CSR wake potential of 4.58mm bunch

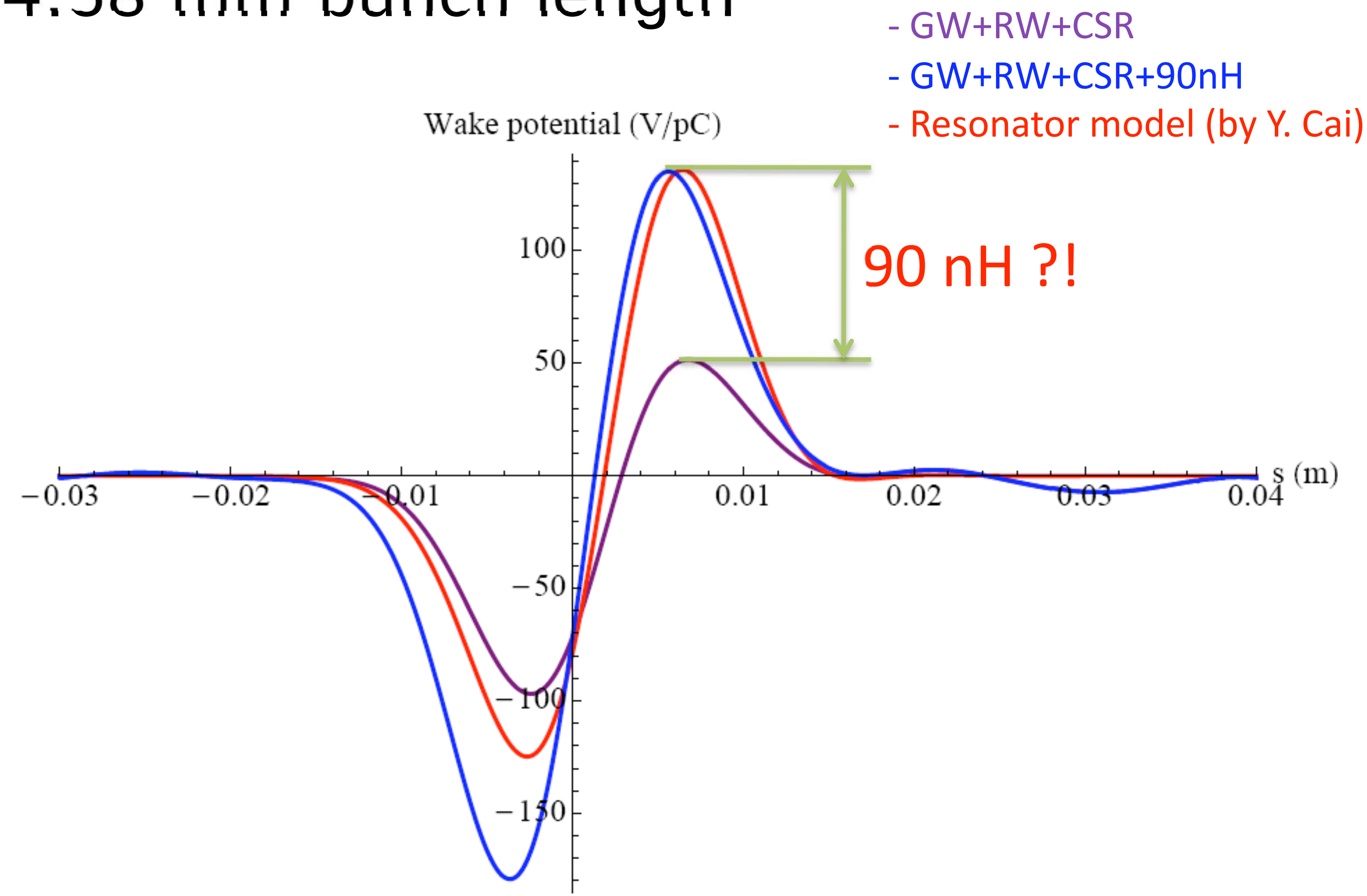


GW, RW and CSR wake potential of 6mm bunch



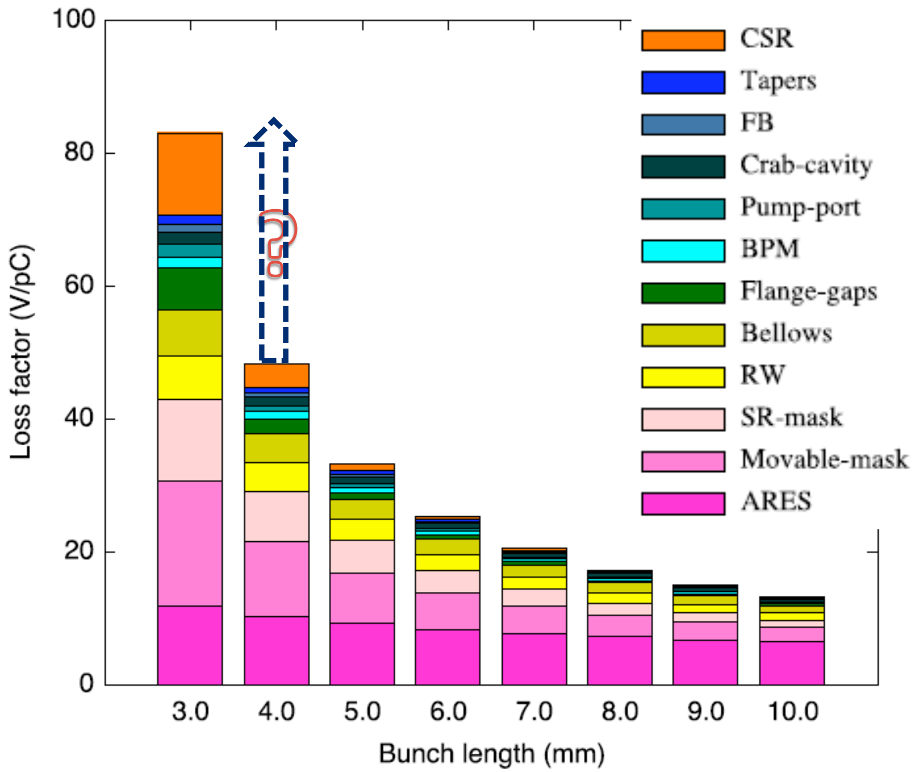
Compare with Cai's resonator model

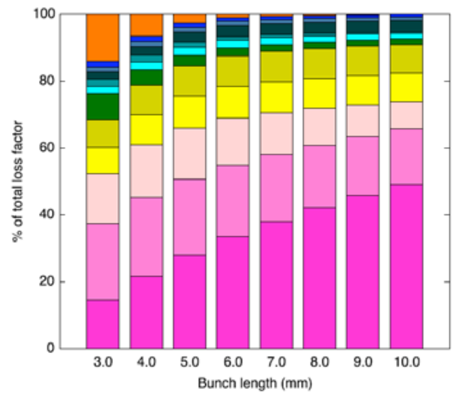
- 4.58 mm bunch length

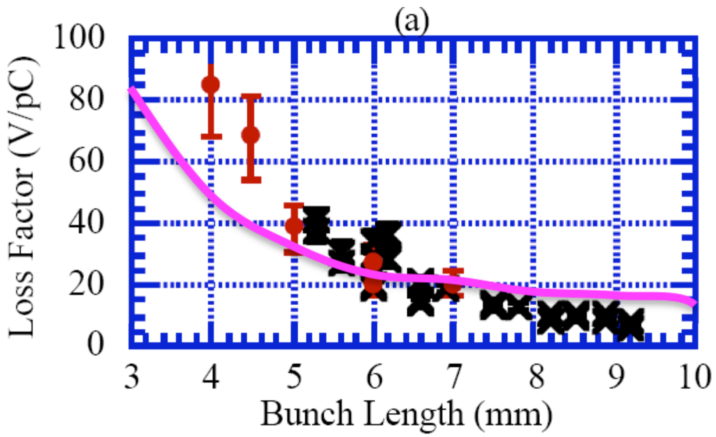


Loss factor from calculated wake potential (1)

- Calculated loss factor is much smaller than measurement when sigma<5mm, but higher when sigma>7mm
- Loss factor due to CSR decays quickly when bunch length increases



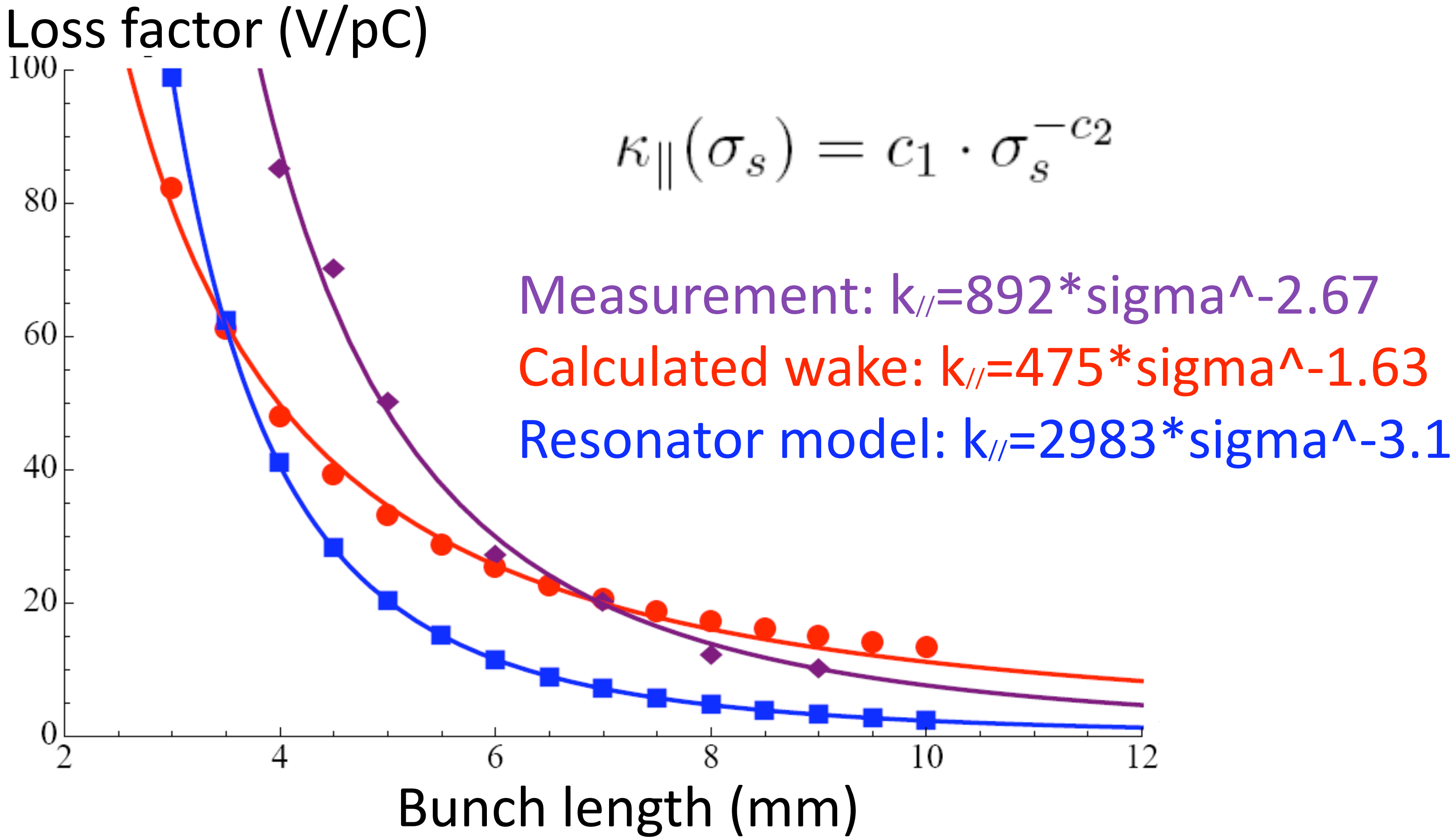




Ieiri & Koiso, 2003

Loss factor from calculated wake potential (2)

- Loss factor as function of bunch length can be well described by a simple power function



HOM power (1)

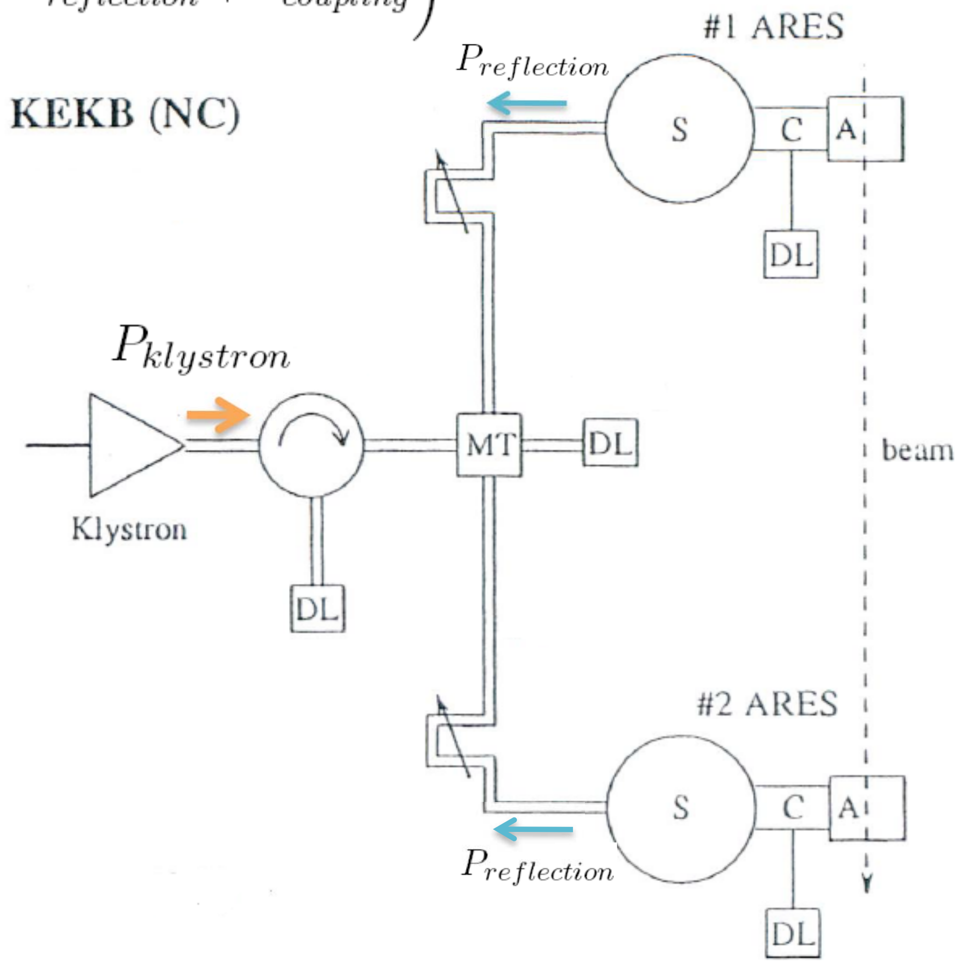
- RF power balance (originated idea from PEP-II)

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

Klystron power calibrated
(K. Akai's suggestion):

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

Power of wall loss at each cavity:
154 kW@Vc=0.5 MV



Reference: A. Novokhatski, PAC07

K. Akai, KEKB ARC 1999

HOM power (2)

- The models

$$P_{beam} = P_{SR} + P_{HOM}$$

KEKB LER:

$U_0 = 1.6369316MV \quad E_0 = 3.5GeV$

$$\begin{aligned} P_{SR}[kW] =& U(E)[MV] \cdot I_{beam}[mA] \\ =& U_0[MV] \cdot \left(\frac{E}{E_0}\right)^4 \cdot I_{beam}[mA] \end{aligned}$$

$$P_{HOM} = \kappa_{||}(\sigma_s) \cdot \frac{I_{beam}^2}{N_b} \cdot T_0$$

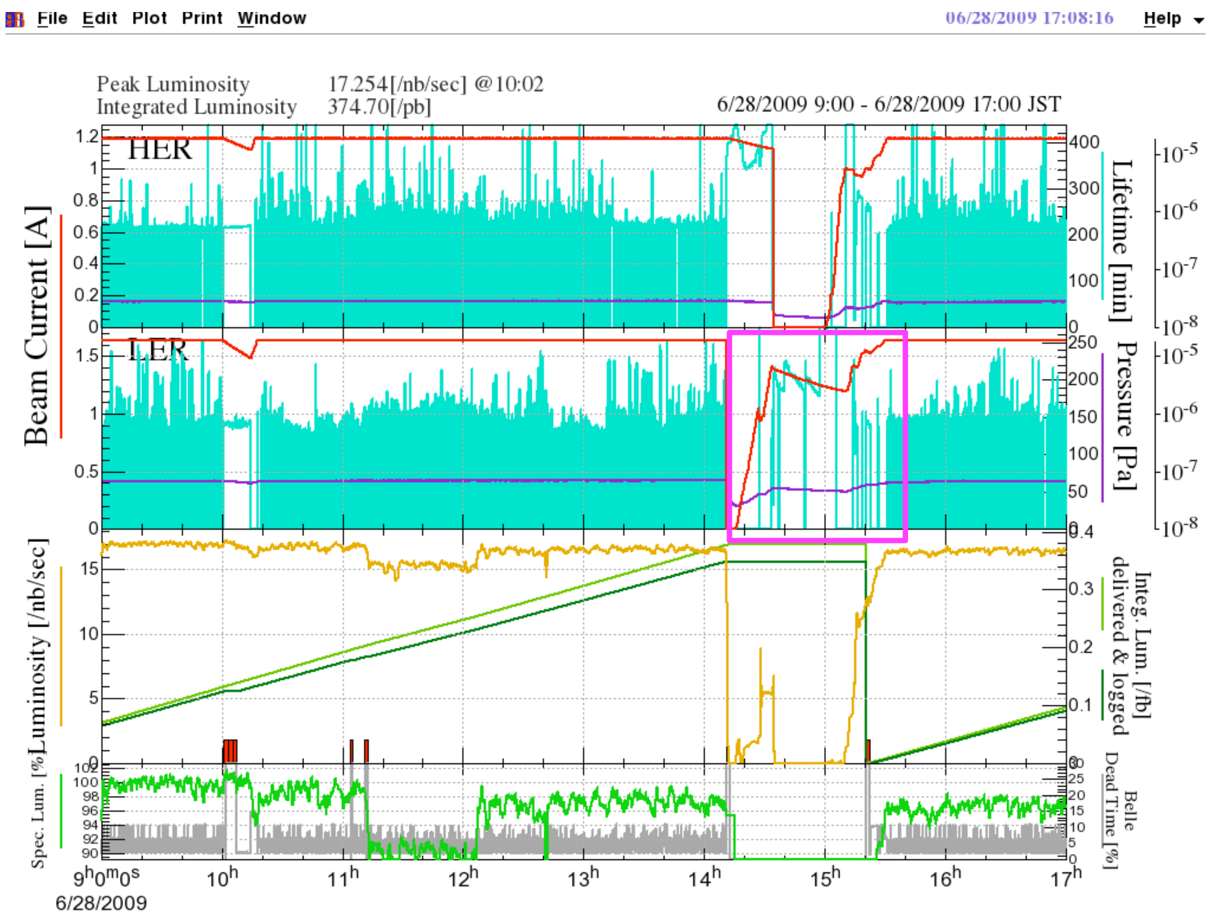
Simple models for loss factor and bunch lengthening:

$$\kappa_{||}(\sigma_s) = c_1 \cdot \sigma_s^{-c_2} \qquad \sigma_s(I_{bunch}) = \sigma_s(0)(1 + c_3 \cdot I_{bunch})$$

For simplification, we choose c_3=0.5/mA

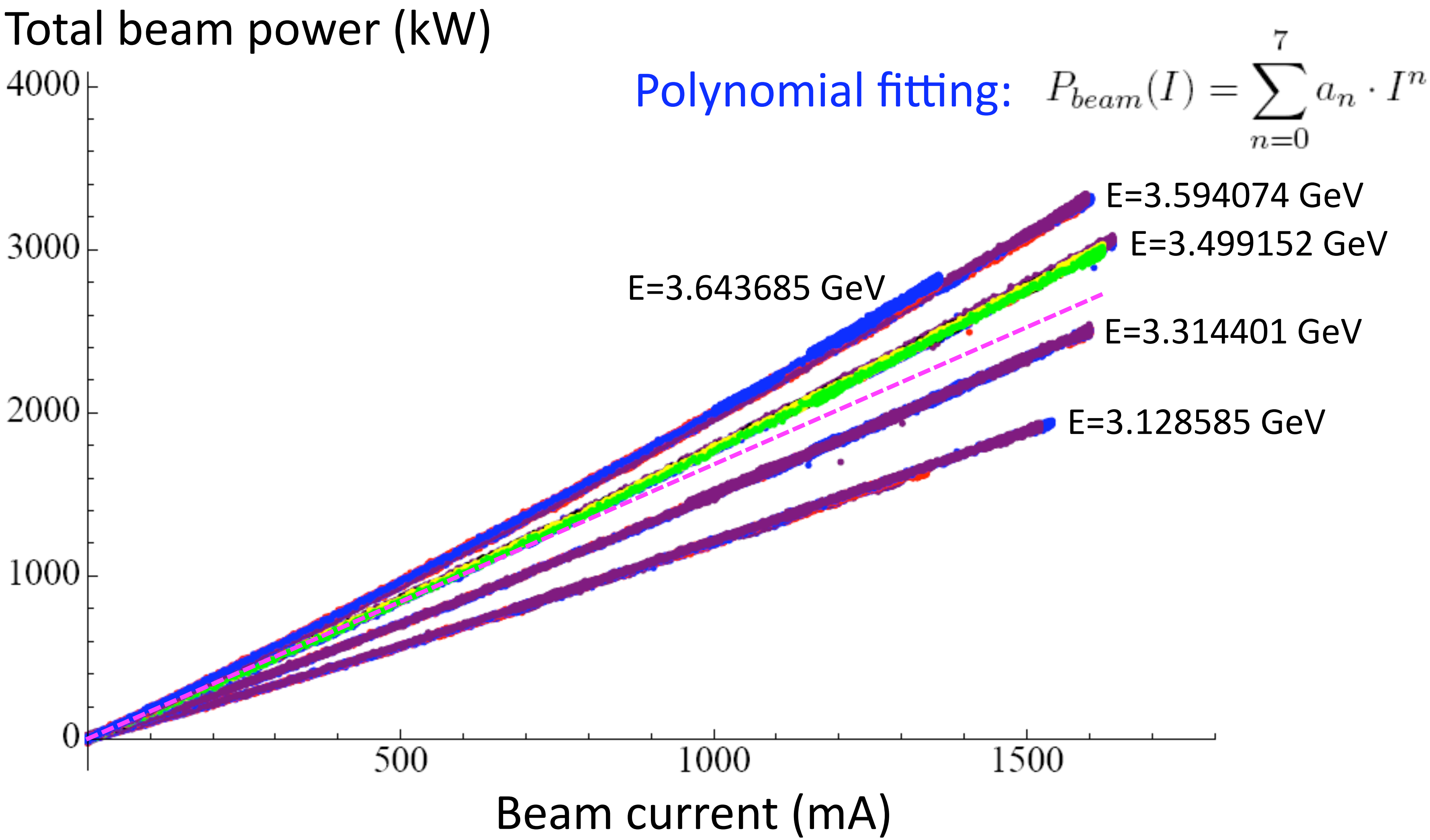
HOM power (3)

- KBlog data during injection are used to calculate current dependent beam power



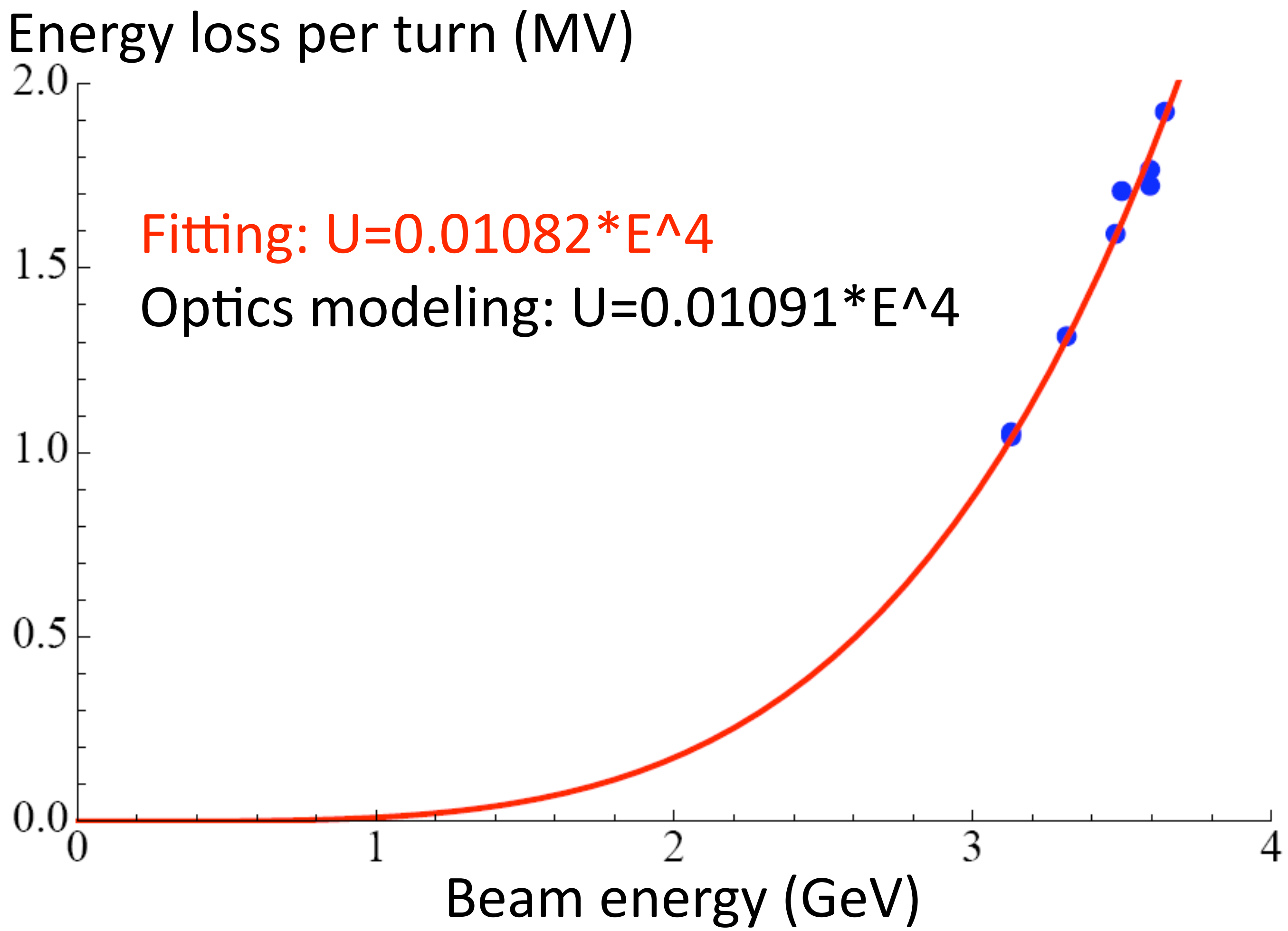
Total beam power

- Use polynomial fitting to extract linear part



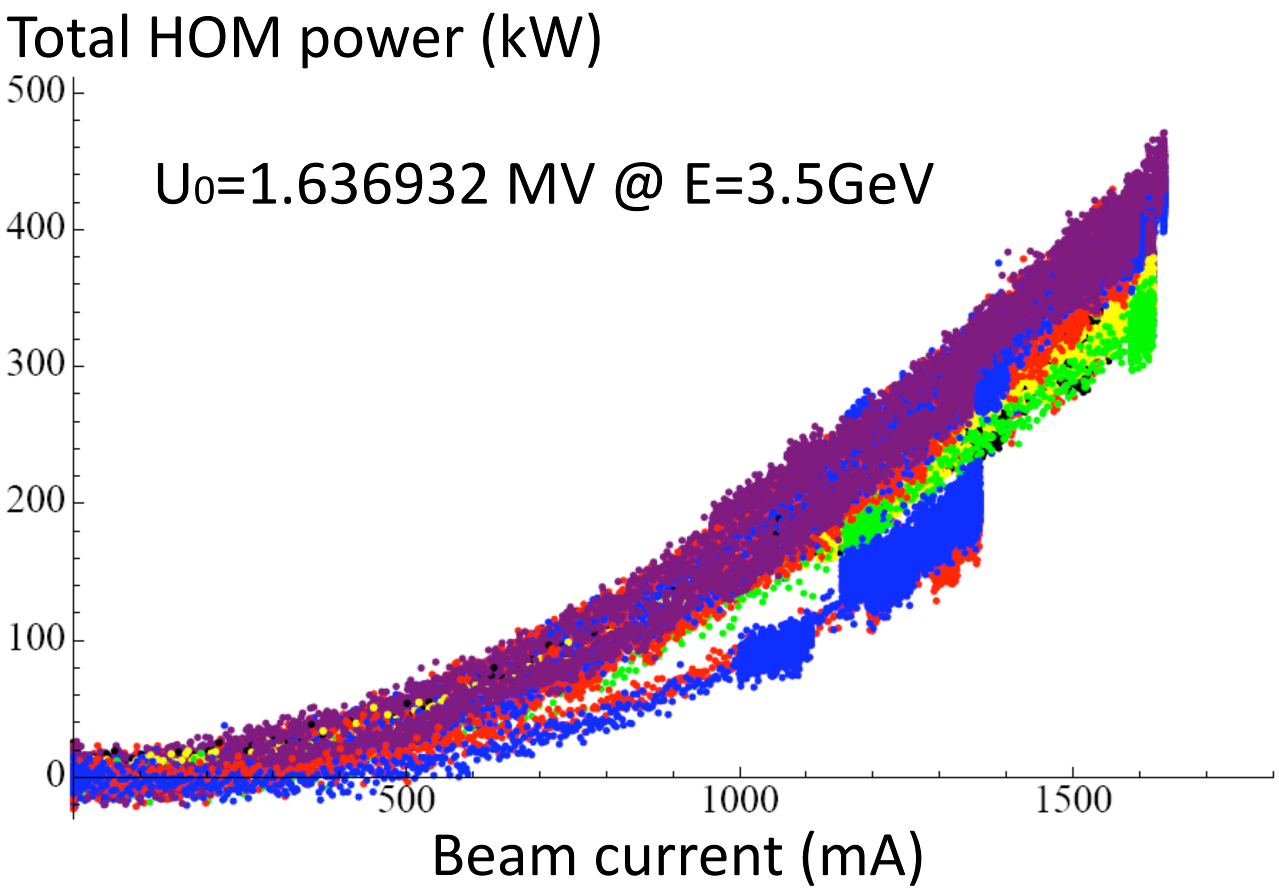
Energy loss per turn

- The fitted SR power agree with estimation by optics model



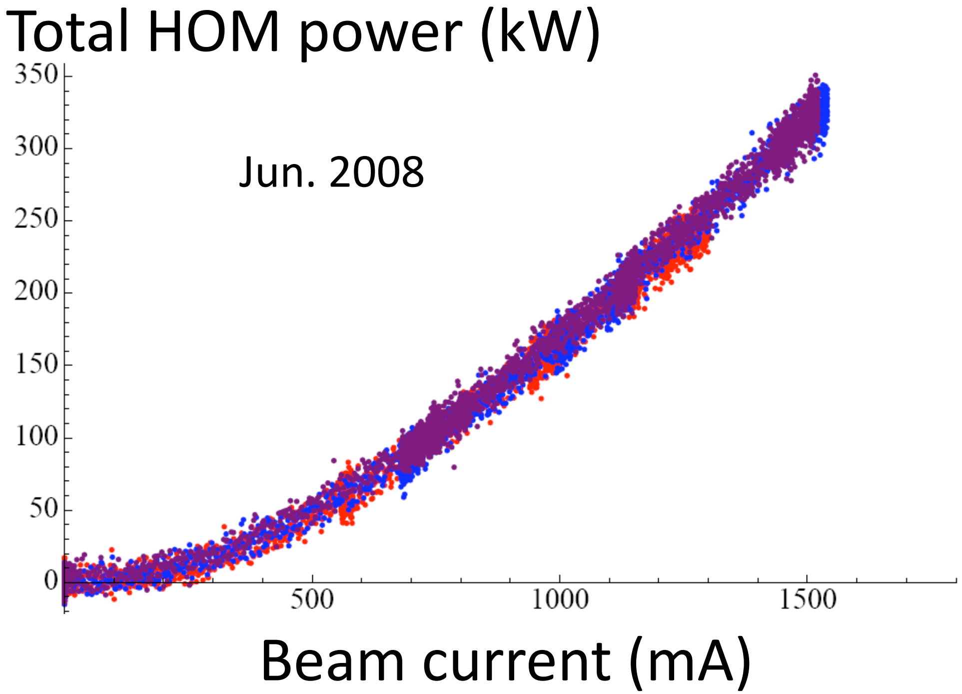
HOM power with different beam energy

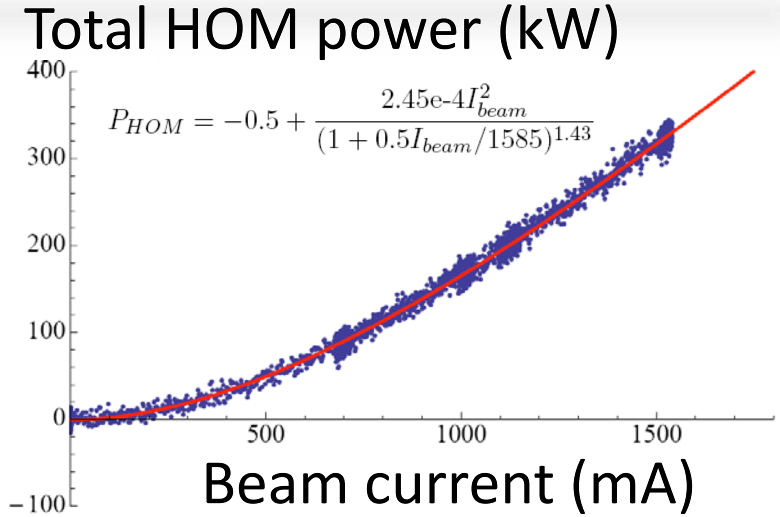
- SR power is estimated using optics model when subtracting SR power from the total beam power

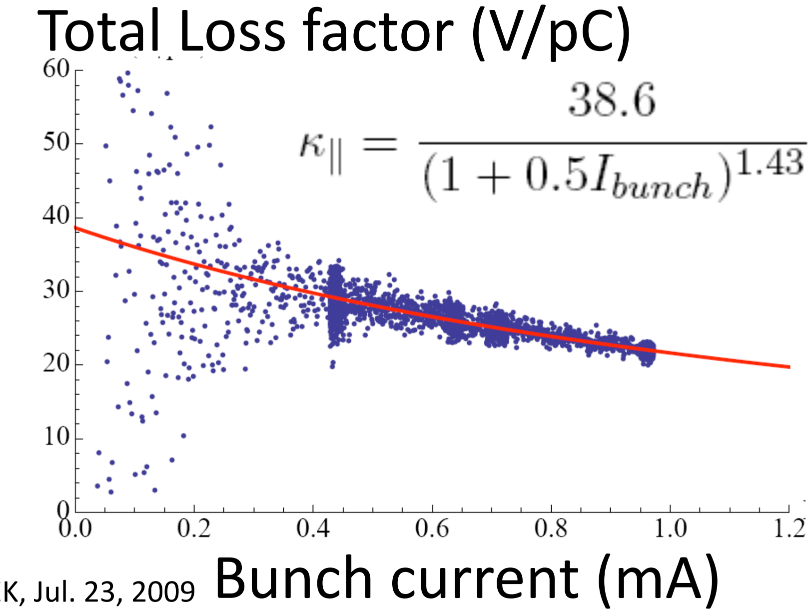


HOM power and loss factor (1)

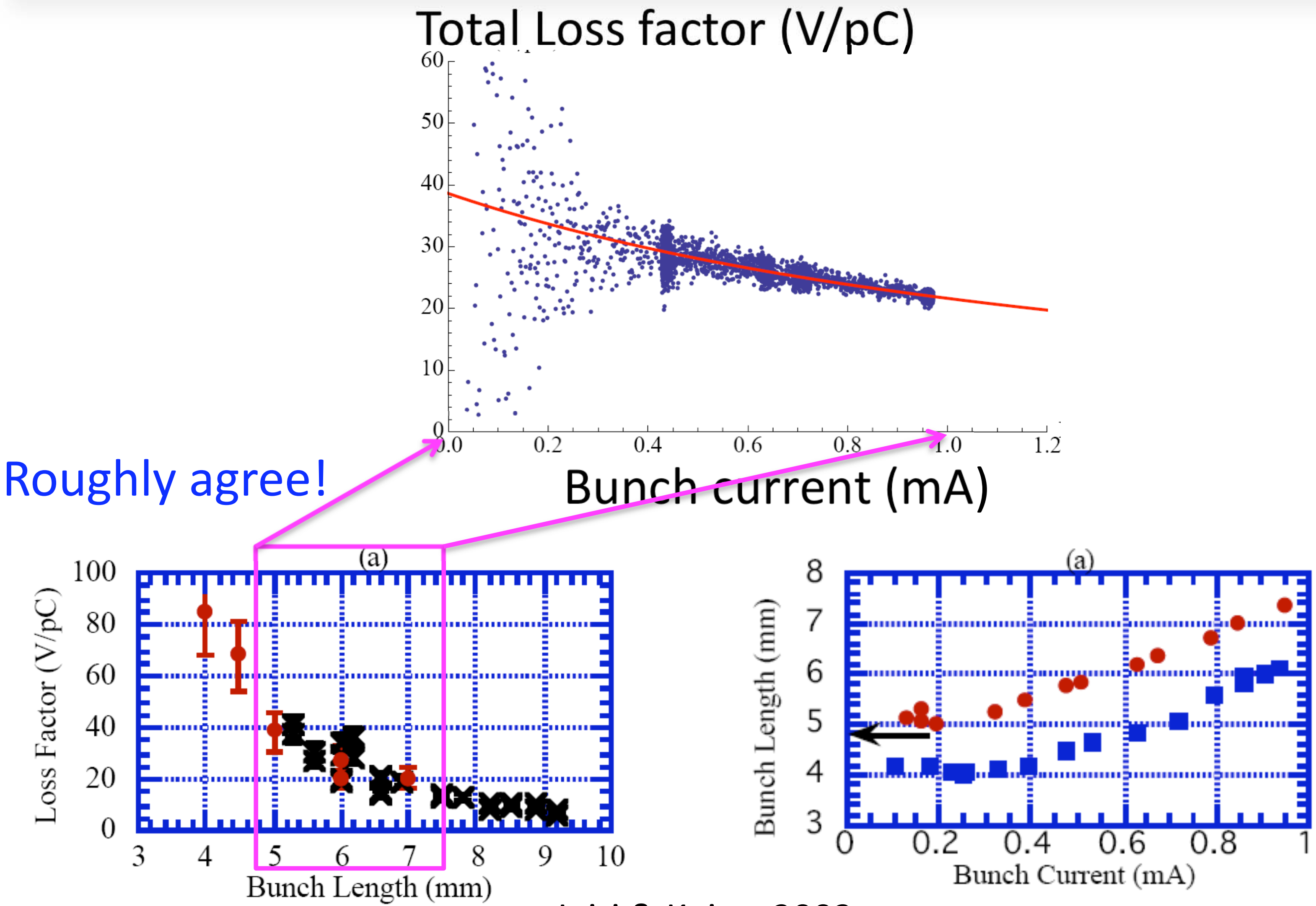
- E=3.128585 GeV







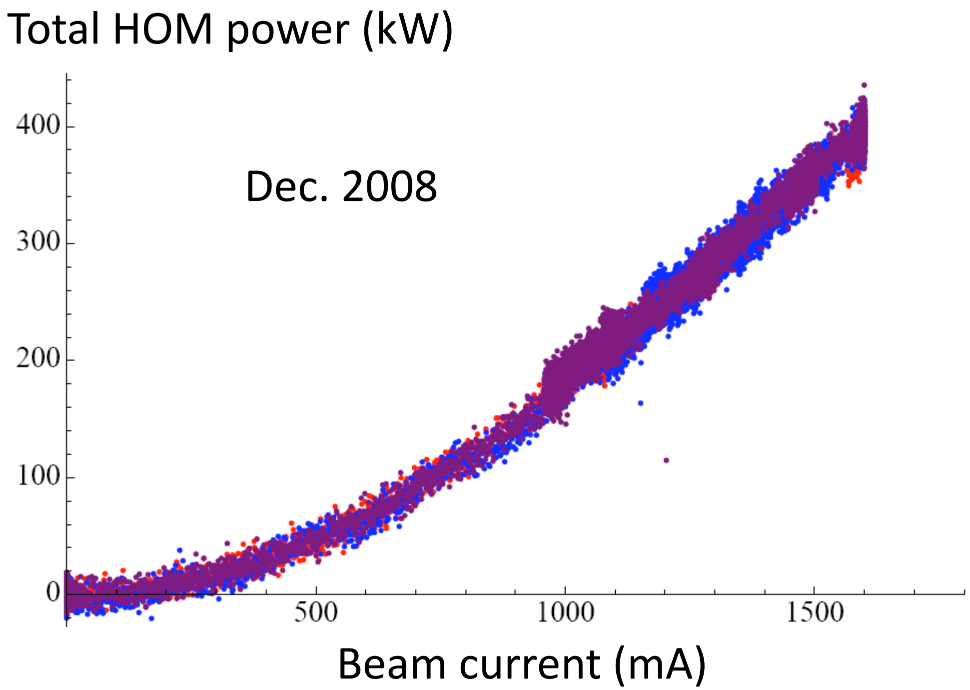
Compare with direct beam measurements

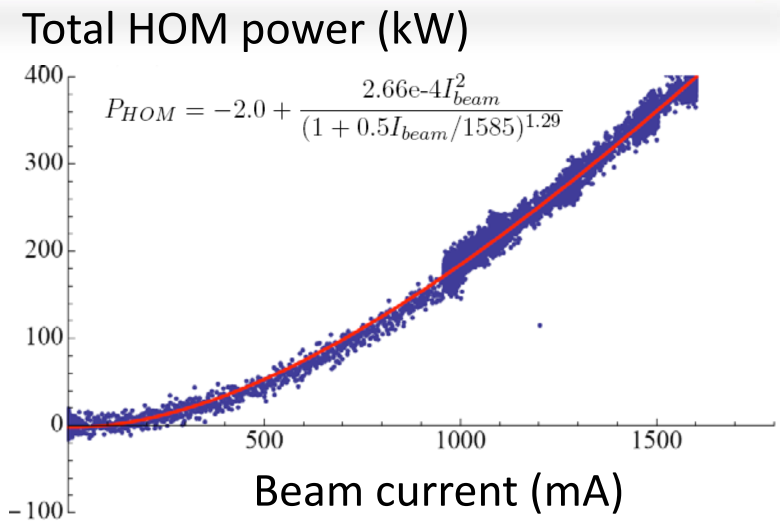


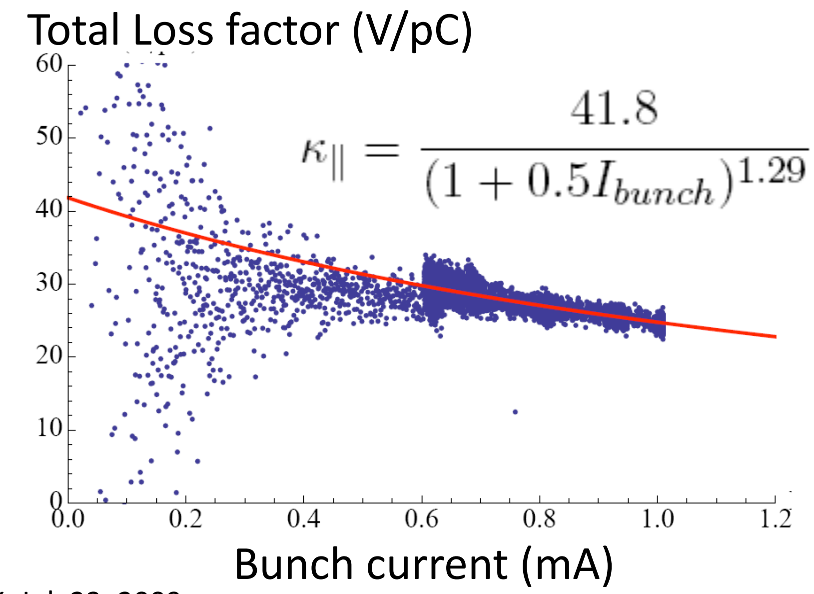
Ieiri & Koiso, 2003

HOM power and loss factor (2)

- E=3.314401 GeV



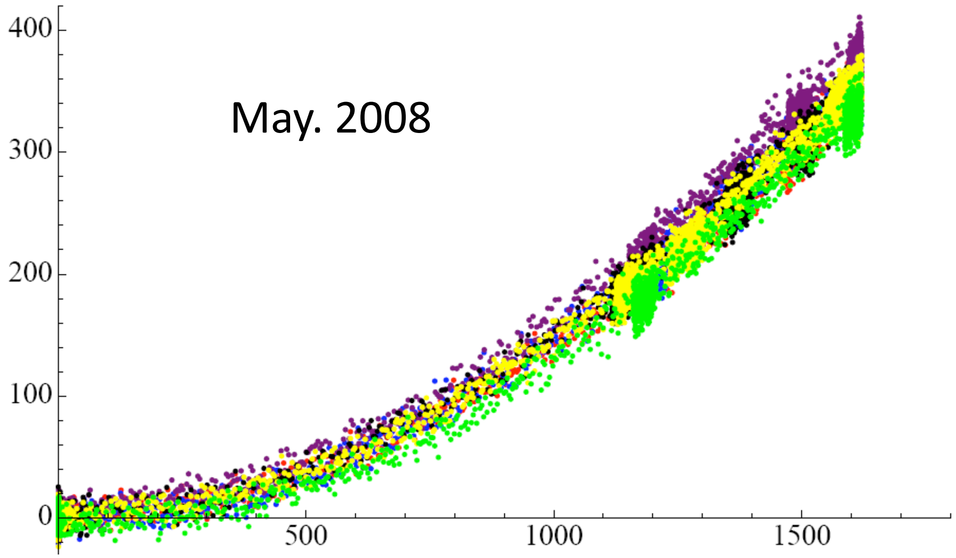




HOM power and loss factor (3)

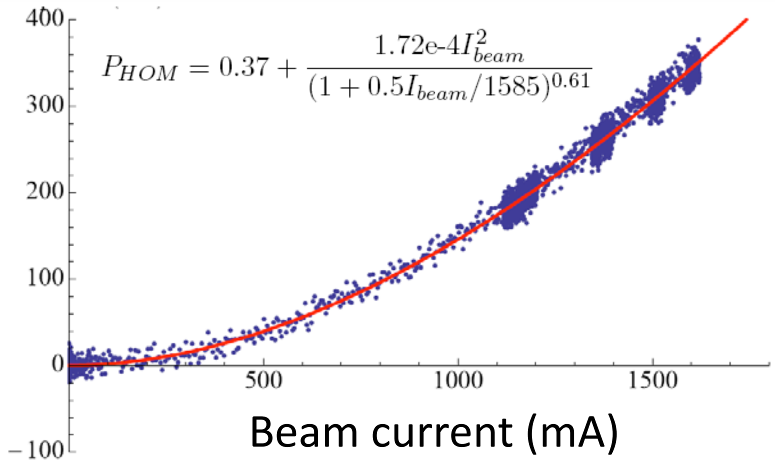
- E=3.499152 GeV

Total HOM power (kW)



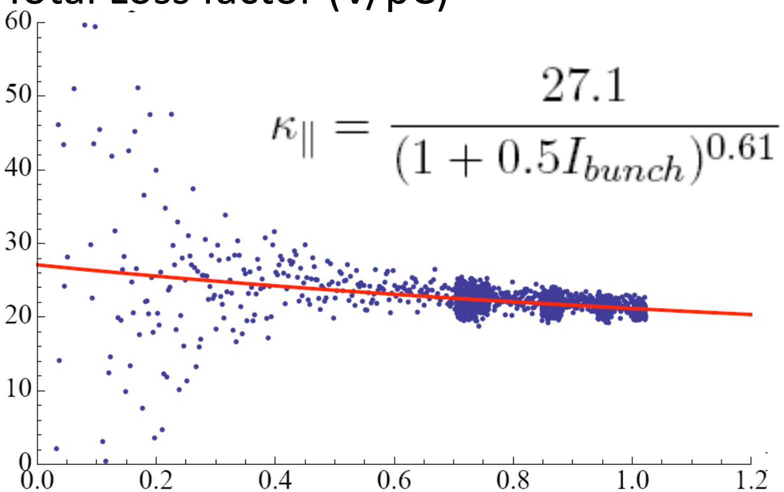
Beam current (mA)

Total HOM power (kW)



Beam current (mA)

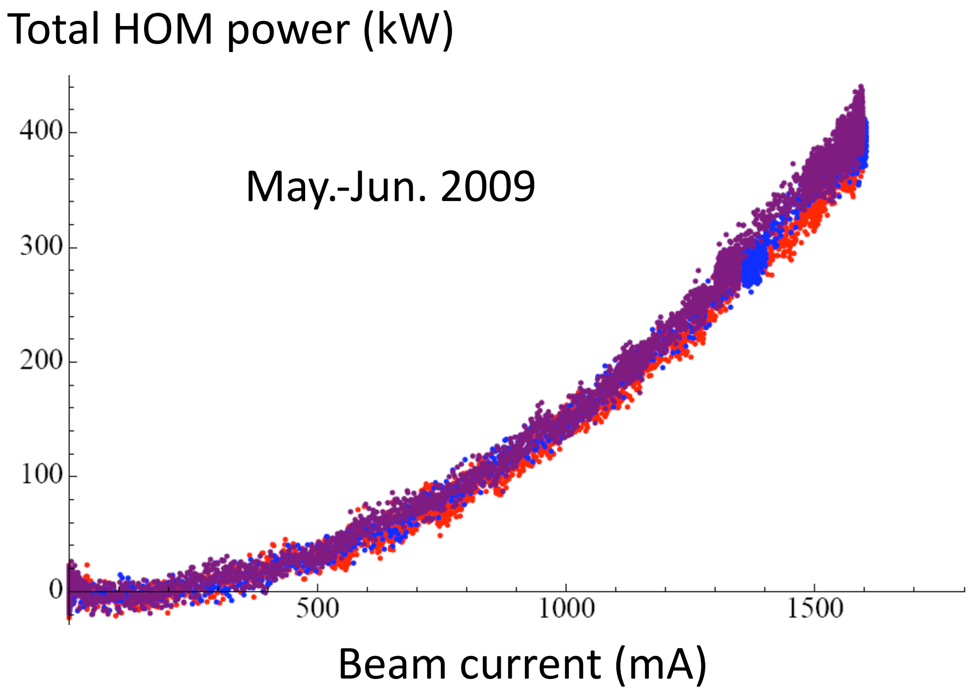
Total Loss factor (V/pC)

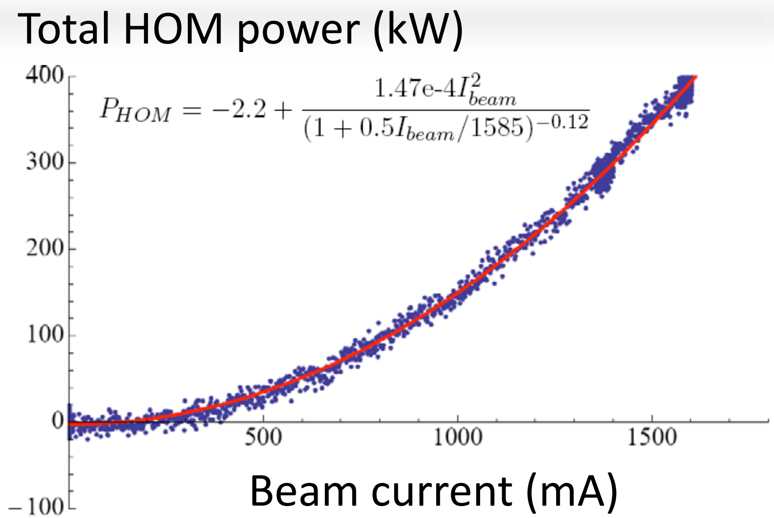


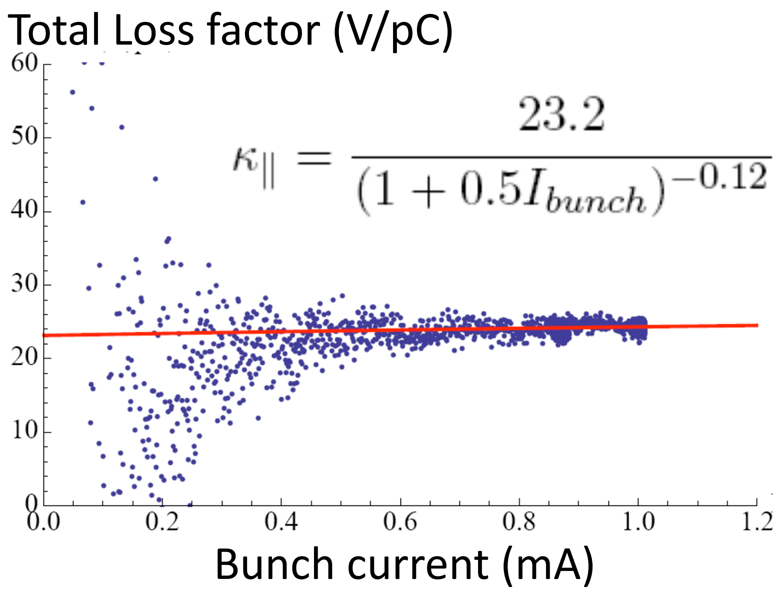
Bunch current (mA)

HOM power and loss factor (4)

- E=3.594074 GeV

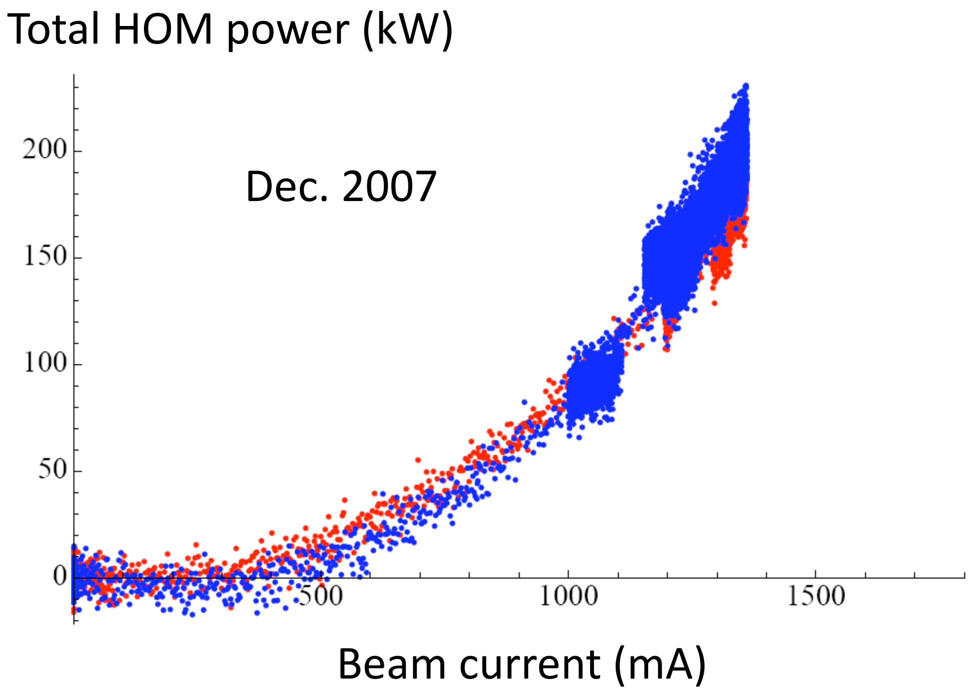


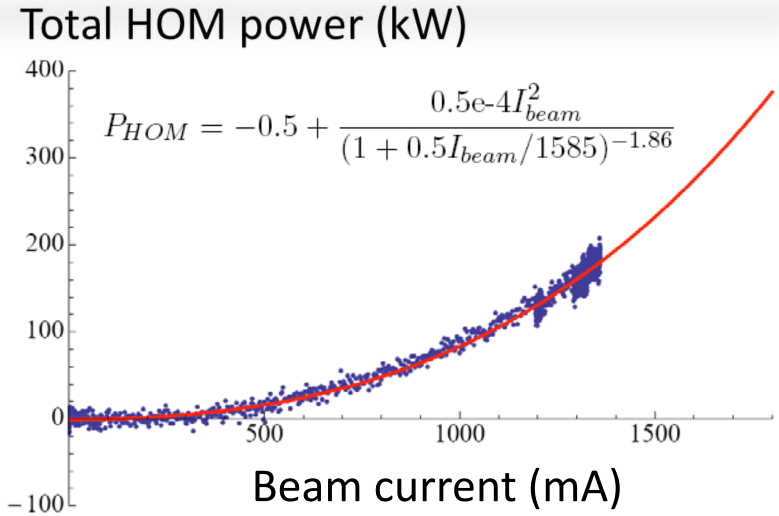


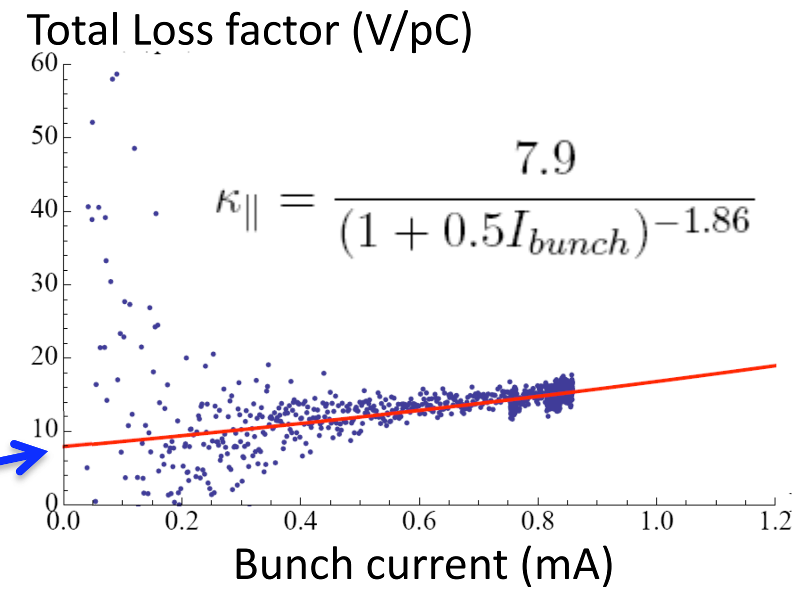


HOM power and loss factor (5)

- E=3.643685 GeV







Unphysical!
SR power overestimated ?

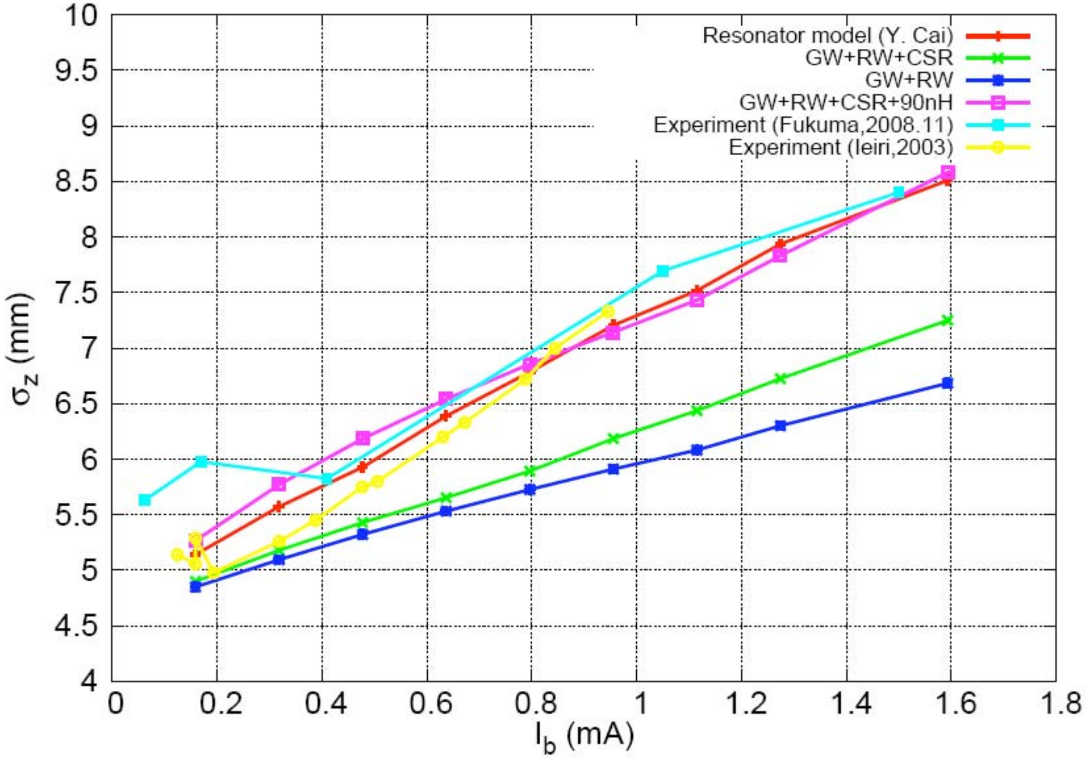
Simulations using VFP solver (2)

- Machine parameters (KEKB LER)

Parameter	Value
E (GeV)	3.5
Sigma_z (mm)	4.58/3
Sigma_p (x10^-4)	7.27
Nu_s (synchrotron tune)	0.024
Tau_s (z damping time, turn)	2000

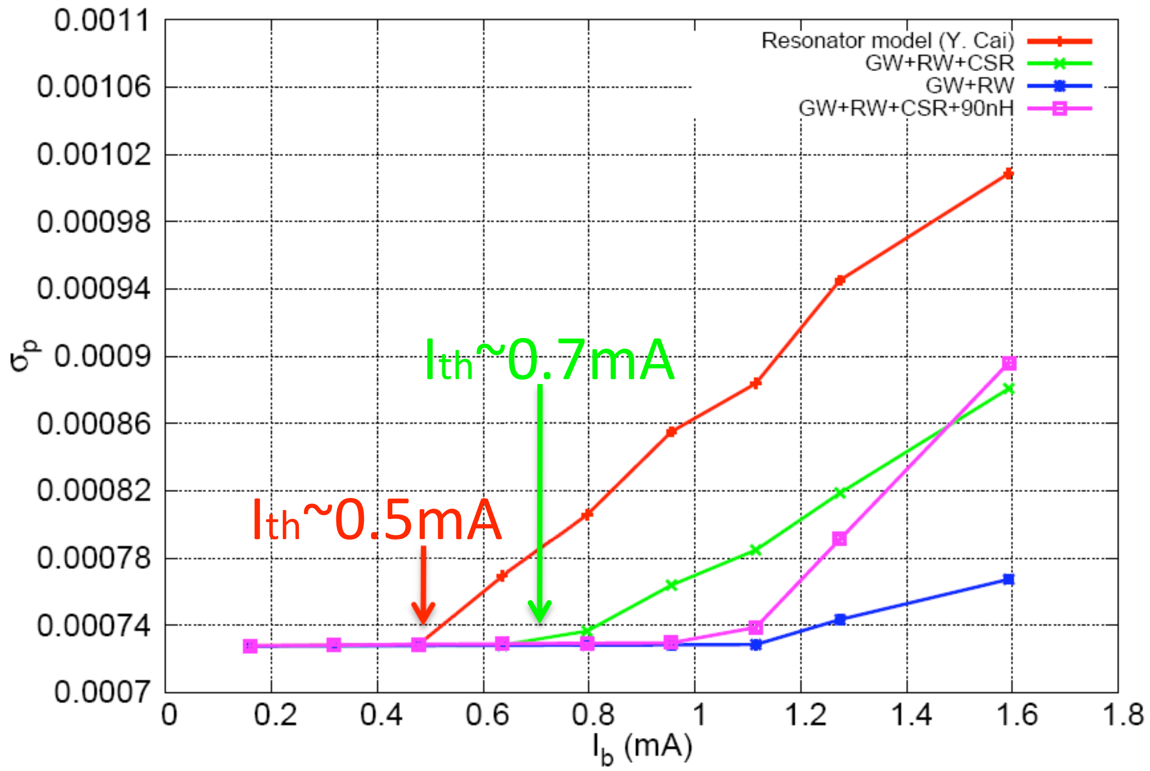
Simulations using VFP solver (2)

- Natural bunch length: 4.58mm
  - Pure inductive wake of around 90nH should be added to the numerical impedance model to get the similar bunch lengthening as measurement shows!



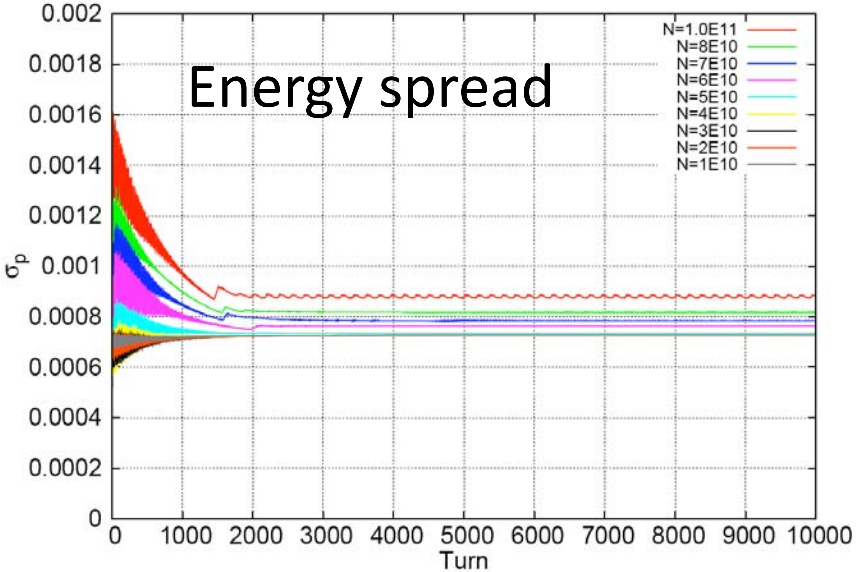
Simulations using VFP solver (3)

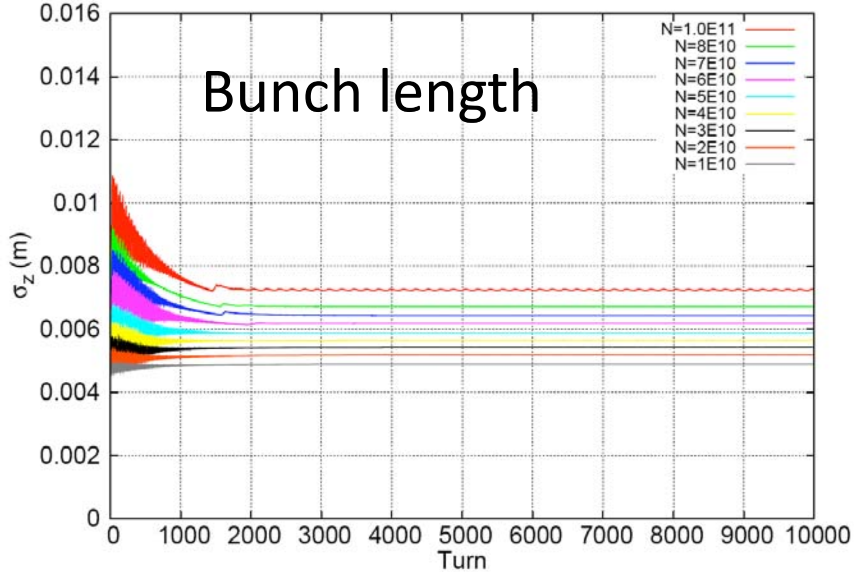
- Natural bunch length: 4.58mm
  - But when pure inductive wake is added, the Microwave instability threshold gets higher(?)
  - CSR is important for microwave instabilities



Simulations using VFP solver (4)

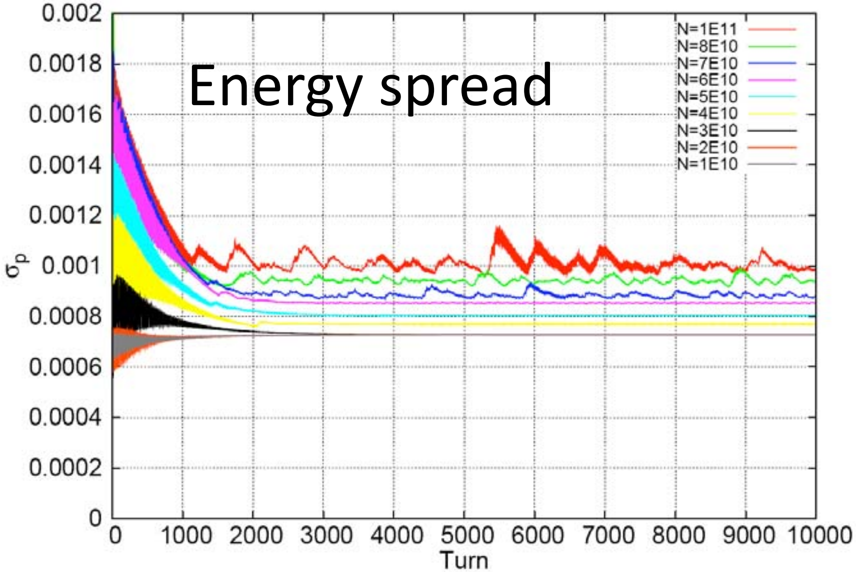
- Turn-by-turn energy spread and bunch length with numerical impedance model
  - Beam becomes unstable when bunch population reaches 10x10^10

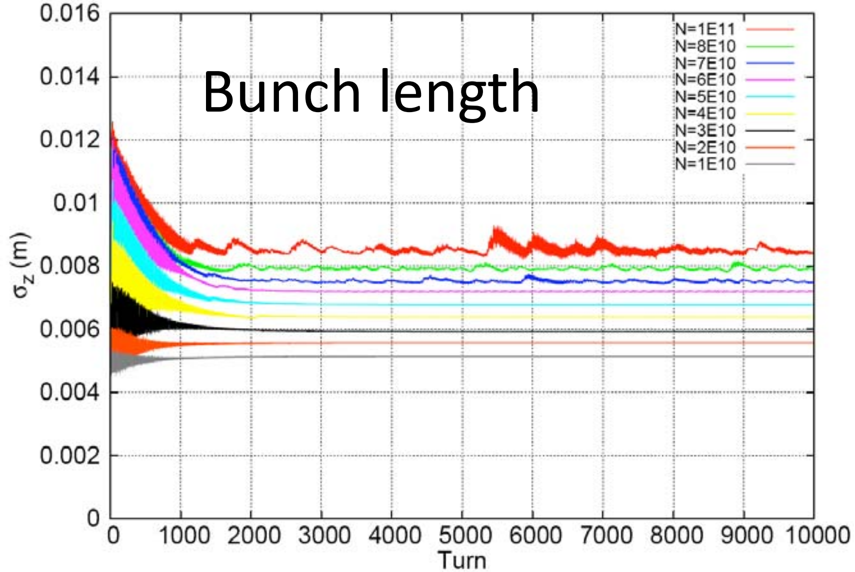




Simulations using VFP solver (5)

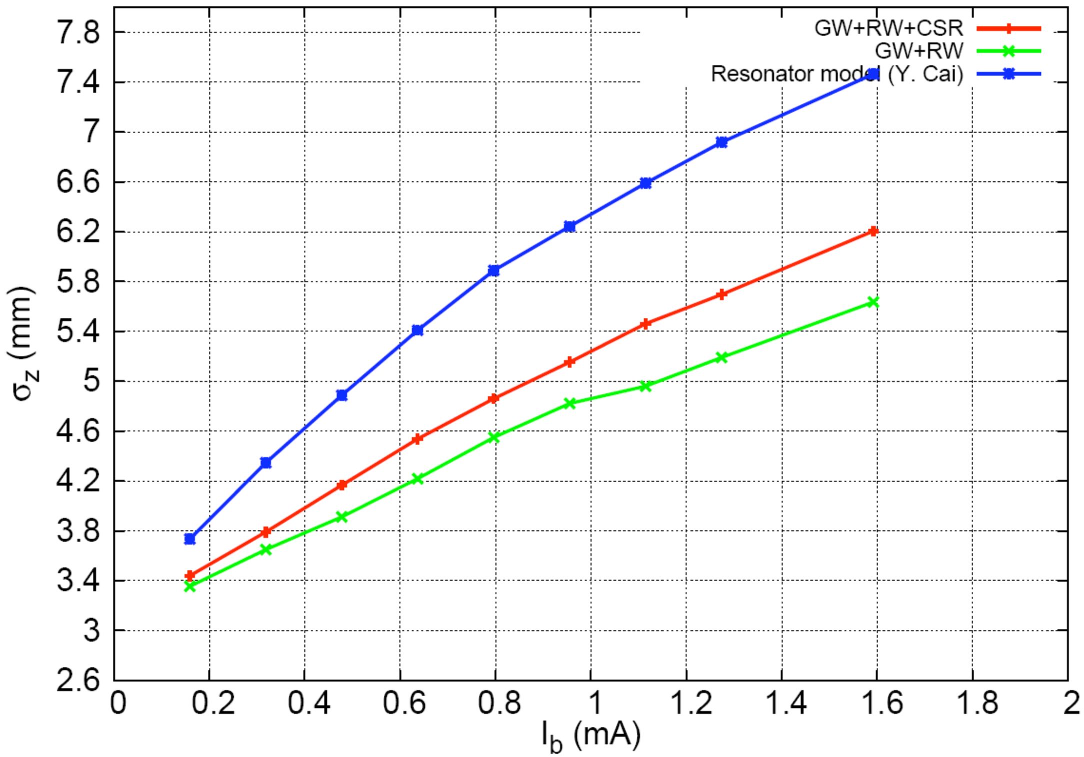
- Turn-by-turn energy spread and bunch length with resonator model
  - Beam becomes unstable when bunch population exceeds 6x10^10

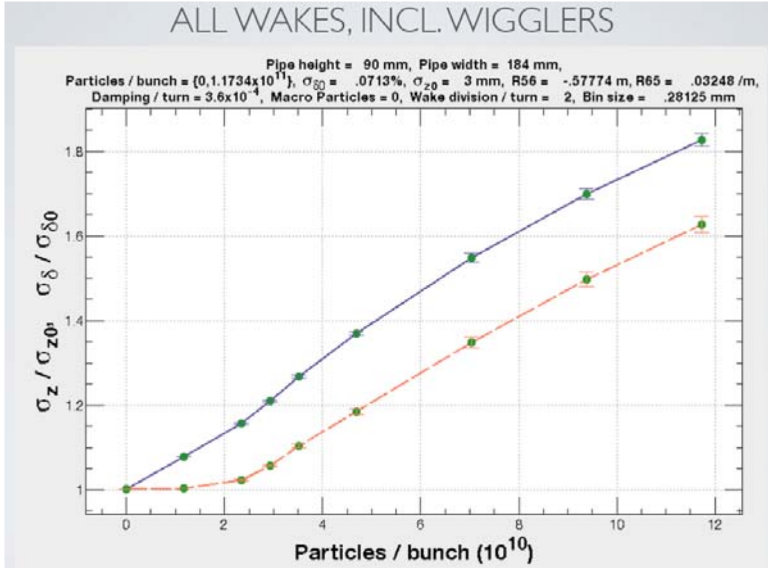




Simulations using VFP solver (6)

- Natural bunch length: 3mm
  - GW+RW dominate the bunch lengthening
  - With the numerical impedance model (GW+RW+CSR), the bunch lengthening is similar to the case of SuperKEKB (short bunch option)

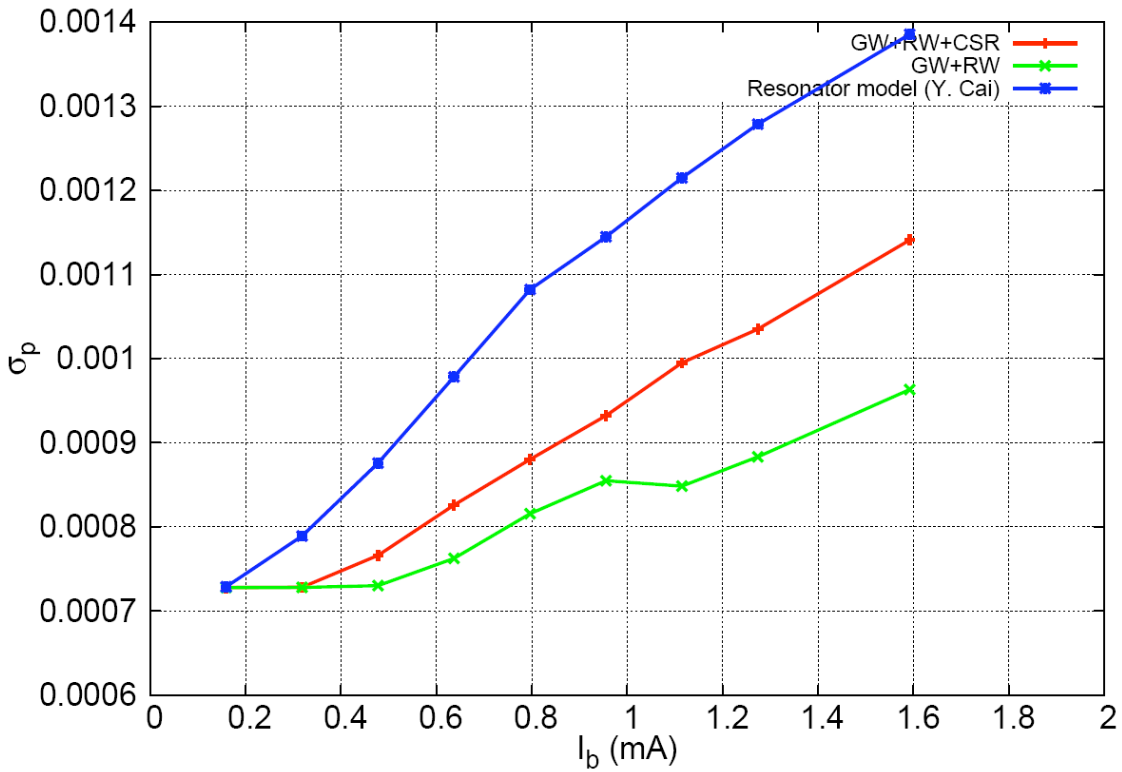


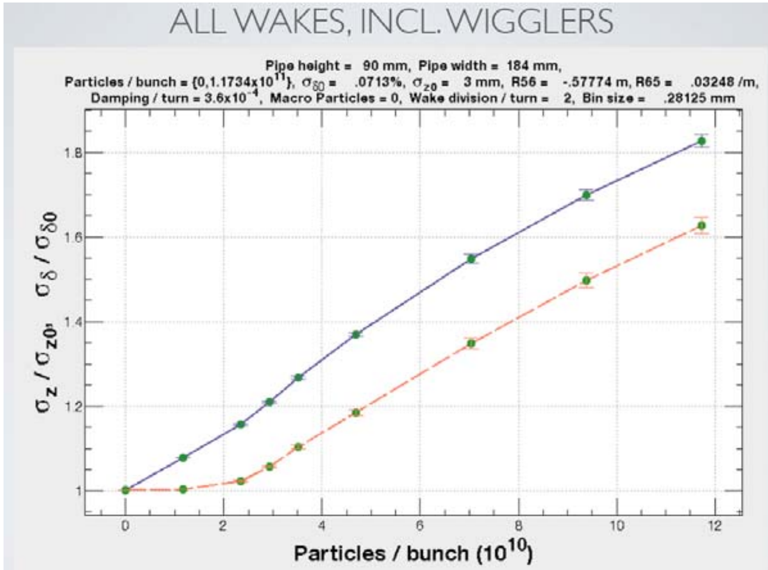


K. Oide, KEKB ARC 2009

Simulations using VFP solver (7)

- Natural bunch length: 3mm
  - With the numerical impedance model (GW+RW +CSR), the MWI is also similar to the case of SuperKEKB (short bunch option)



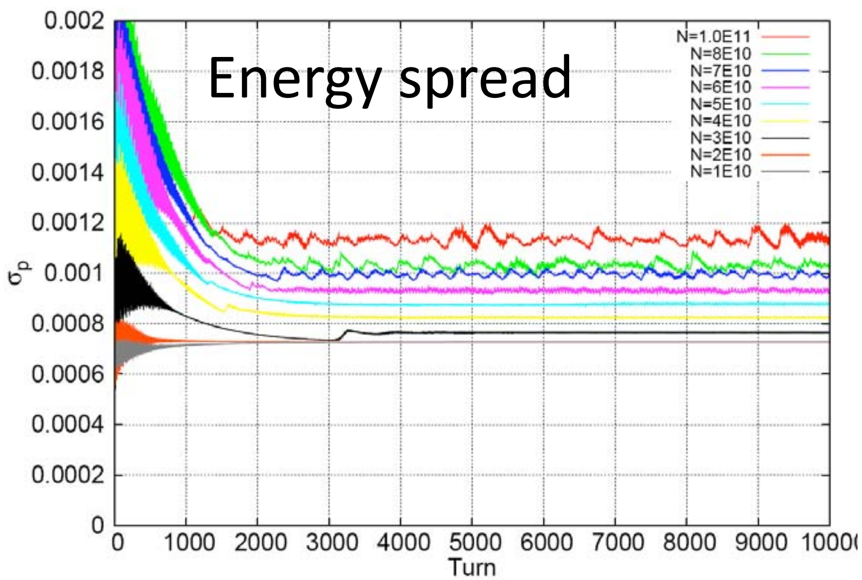


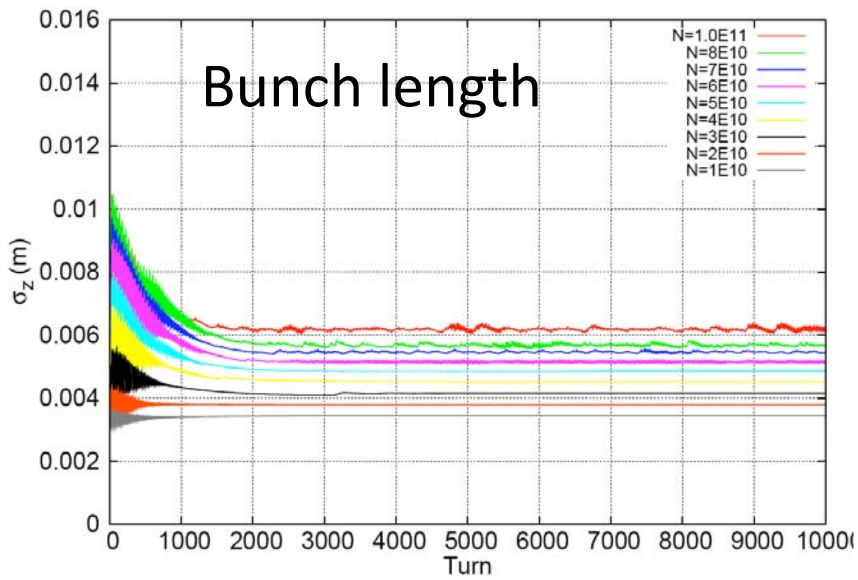
K. Oide, KEKB ARC 2009

3, 2009

Simulations using VFP solver (8)

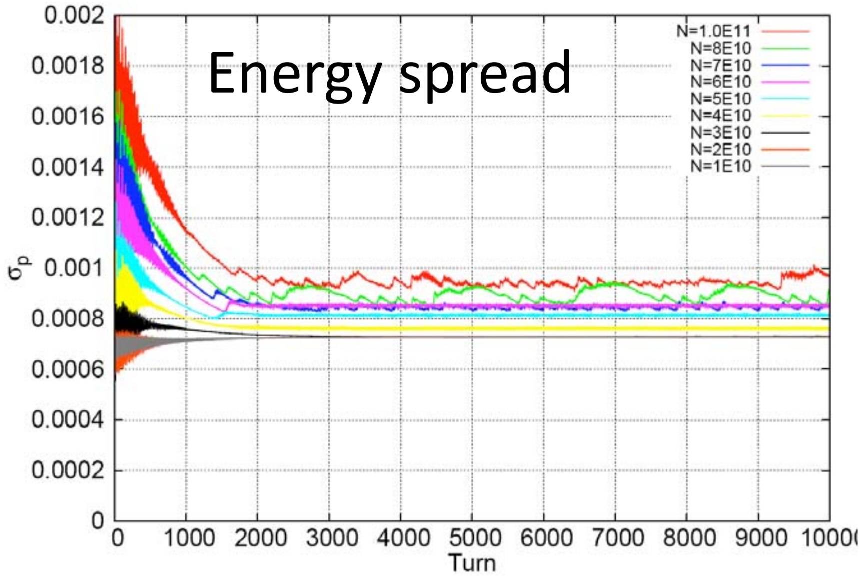
- Turn-by-turn energy spread and bunch length with GW+RW+CSR
  - Beam becomes unstable when bunch population exceeds 5x10^10

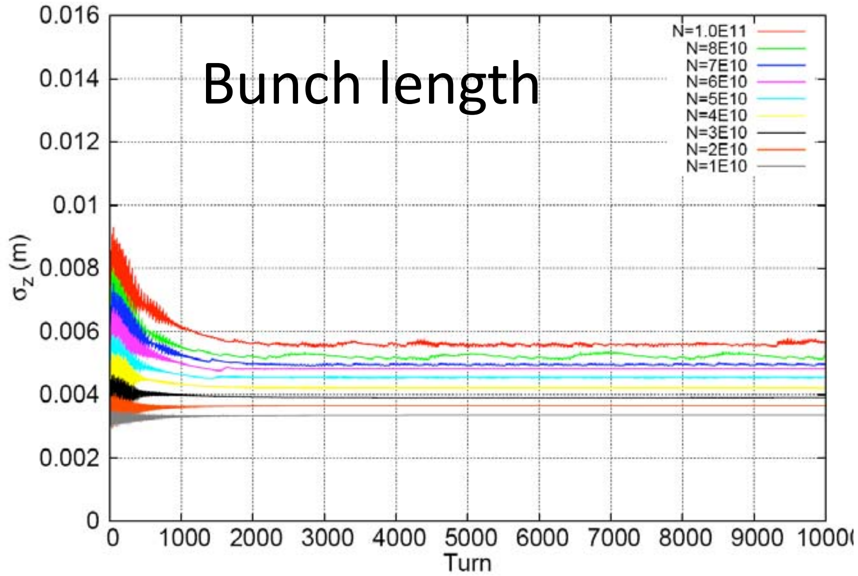




Simulations using VFP solver (9)

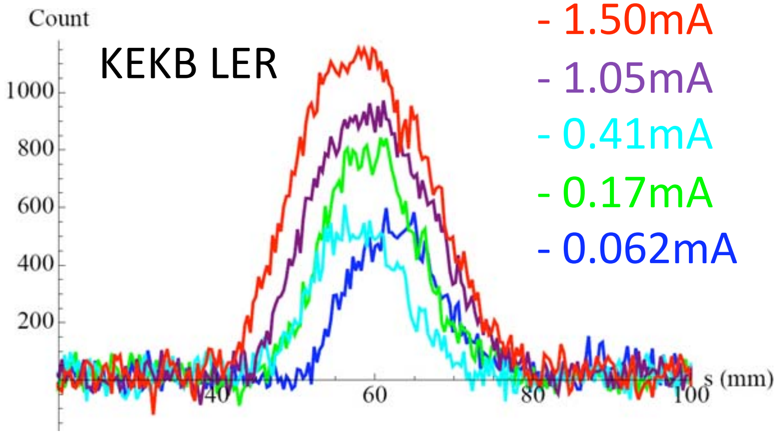
- Turn-by-turn energy spread and bunch length with GW+RW
  - Beam becomes unstable when bunch population exceeds 6x10^10





An attempt to extract impedance directly from bunch profile (with help from Y. Cai and A. Chao)

- Idea: inverse problem of Haissinski equation
- Data: Streak camera
- Challenges
  - Noise
  - Bunch center



H. Fukuma, 2008.11

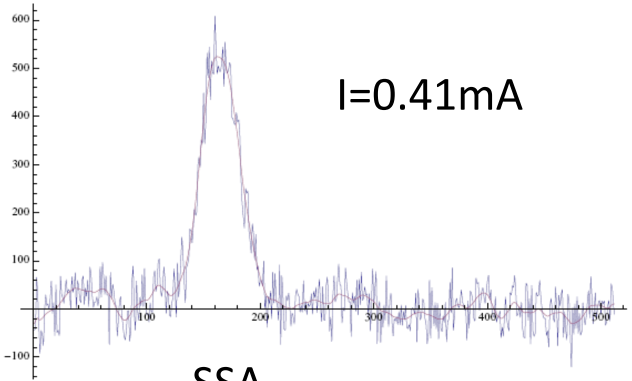
Haissinski Equation:

$$\lambda(q) = \frac{1}{K}\mathrm{Exp}[-\frac{q^2}{2} + I_n \int_{-\infty}^{q} dq'' \int_{-\infty}^{\infty} dq' \lambda(q') W(q'' - q')]$$

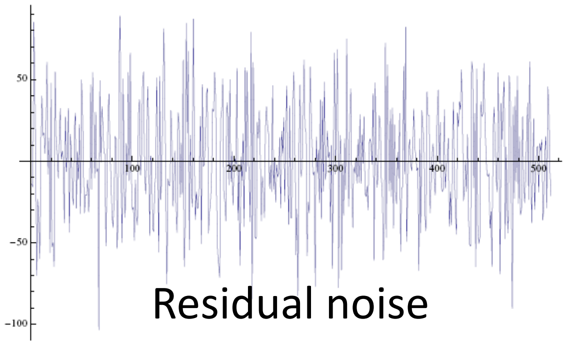
Inverse problem: $$Z(\omega) = \frac{i\omega}{I_n} \frac{\int_{-\infty}^{\infty} \{\ln[K\lambda(q)] + \frac{q^2}{2}\} e^{-i\omega q} dq}{\int_{-\infty}^{\infty} \lambda(q) e^{-i\omega q} dq}$$

An attempt to extract impedance directly from bunch profile (with help from Y. Cai and A. Chao)

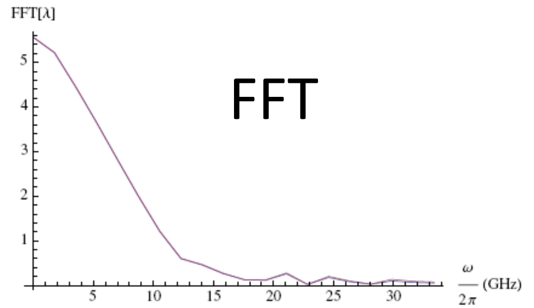
- Recent progress
  - SSA(Singular Spectrum Analysis) technique applied to remove noise
  - CZT(Chirp Z-Transform) applied to improve frequency resolution

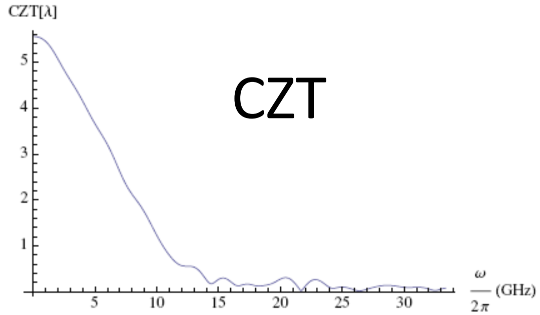


SSA



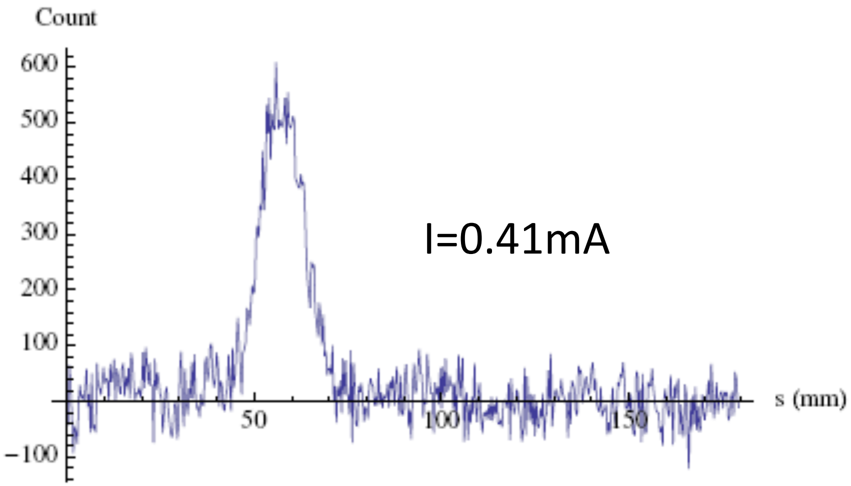
Residual noise

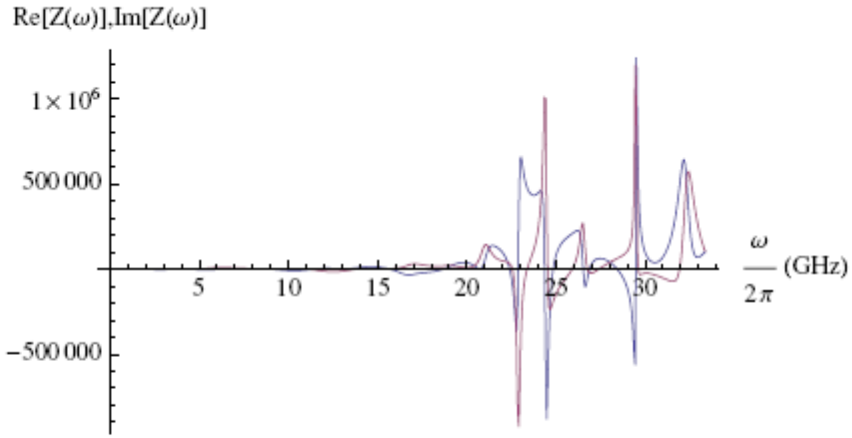


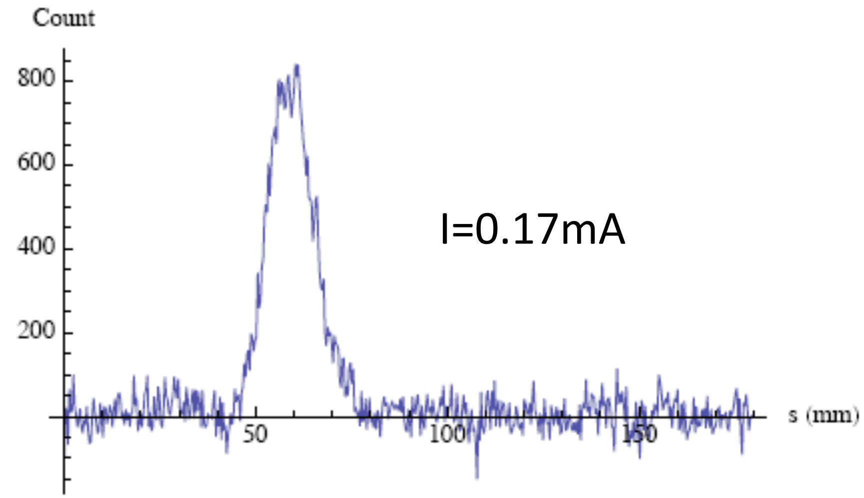


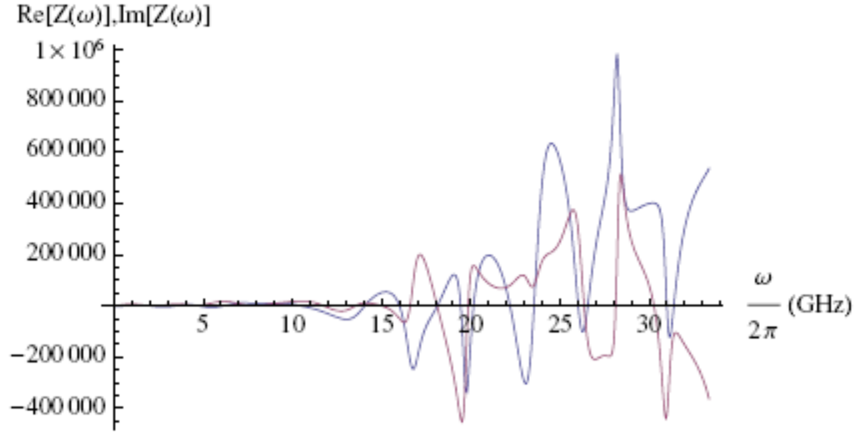
An attempt to extract impedance directly from bunch profile (with help from Y. Cai and A. Chao)

- First result









Summary (1)

- Loss factor
  - The numerical impedance model predict lower loss factor at sigma<5mm and higher loss factor at sigma>7mm (Gaussian bunch)
  - RF power balance method roughly agrees with beam phase measurements, more work need to be done
- Bunch lengthening
  - The numerical impedance model predict much weaker bunch lengthening than measurements and Y. Cai's resonator model
  - The discrepancy is around 90nH

Summary (2)

- Microwave instability
  - The bunch current threshold predicted by numerical impedance model is around 0.7mA
  - CSR can be important source of MWI
- Open questions
  - Other sources of impedance not taken into account?
  - CSR is well calculated?

Thanks for your attention!

Backup (1)

- Negative momentum compaction (sigma0=3mm)