Impedance estimation of SuperKEKB components

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KEKB Accelerator review 2003/02/11

KEKB

Due to high design currents (2.6A LER, 1.1A HER), effects of beam interactions with its surroundings were an important concern already in the design of KEKB collider (KEK Report 95-7). Resulting effects include:

- Coupled-bunch instabilities due to high-Q resonant structures (i.e. RF cavities)
- Power deposition generated by the beam in the form of HOM losses
  - short bunches, needed to achieve high luminosity, can pick up impedance at very high frequency → enormous heat deposition
  - Heat likely to be localized where wake fields can be trapped (IR beampipe, masks, fingers, etc.)

Goal

- Reduce impedance of various beam-line components

- Eliminate structures which can trap higher order modes (HOM) of the generated wake fields

Due to complex geometries of beam-line components, the problem was mostly approached at by numerical computation of wakes and loss factors using ABCI and MAFIA simulation codes

- ABCI is a 2D code exploiting rotational symmetry in ϕ (r,ϕ,z) to reduce number of mesh points

- MAFIA is a 3D code, can use mirror symmetries over (x,y,z) to reduce number of mesh points – slow, needed for asymmetric problems

Impedance estimation for KEKB

KEKB LER σ=4mm	No. of items	Loss factor [V/pC]
ARES cavity	20	10.6
SC cavity	-	-
Resistive wall	3016m	4.0
Masks at arc	1000	4.6
Pumping slots (arc)	10×1800	0.37
Pumping slots (straight)	800	+
BPMs	4×400	0.79
Masks at IP	1	0.08
IP chamber	1	0.29
Recomb. chambers	2	1.6
Bellows	1000	2.5
Flange gap	2000	+
Trans. to antechamber	-	-
Gate valve	40	+
Feedback kicker	1	+
Inj./abort kickers	4	+
Septum	1	+
Movable masks	16	+
HOM absorbers (RF end)	4	+
Tapers (RF end)	4	+
Total		25.7+

Many items not yet estimated

Estimate of the Loss Factor of LER (94ϕduct), as in the KEKB design report

Major remaining problems

- Measured longitudinal loss factor of the KEKB storage ring differs from the one obtained from numerical calculation for a factor of 2-3

- IR chamber within Belle (version for SVD1.x detector) is resonant to HOM generated at certain bunch patterns (5 bucket spacing) and due to overheating poses a constraint on KEKB operation

Total loss factor measurement

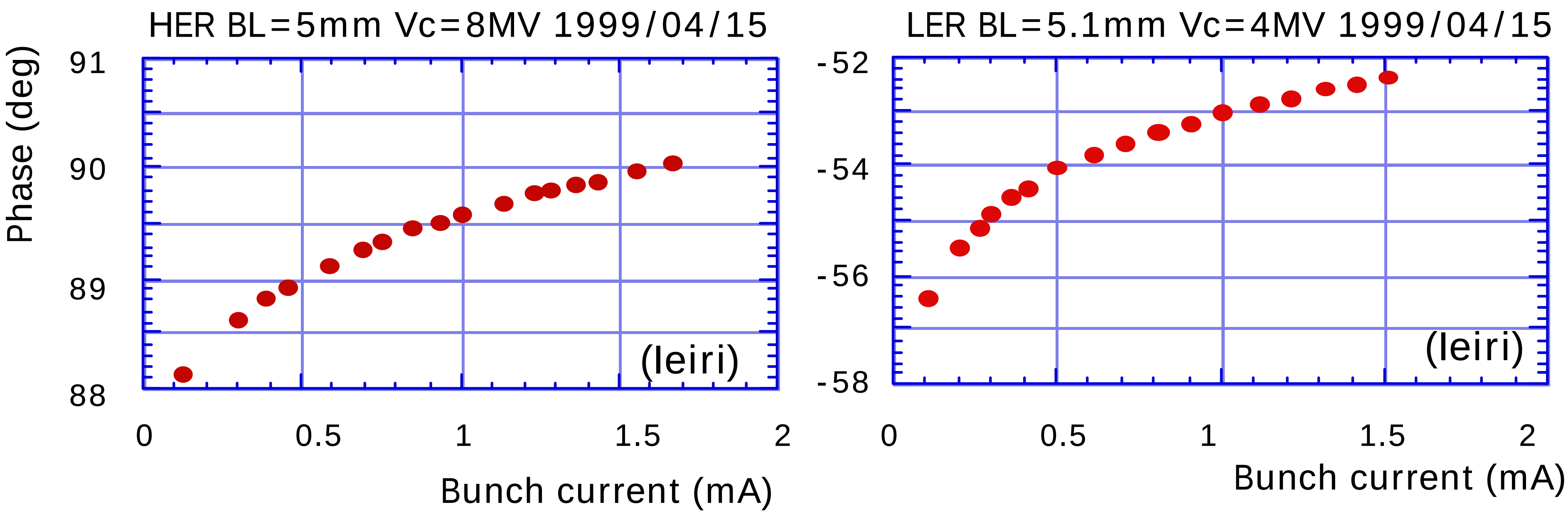
Total loss factor of the ring

$$k(\sigma) = \frac{1}{\pi}\int_0^\infty Z_r(\omega)e^{-\omega\sigma)^2}d\omega$$

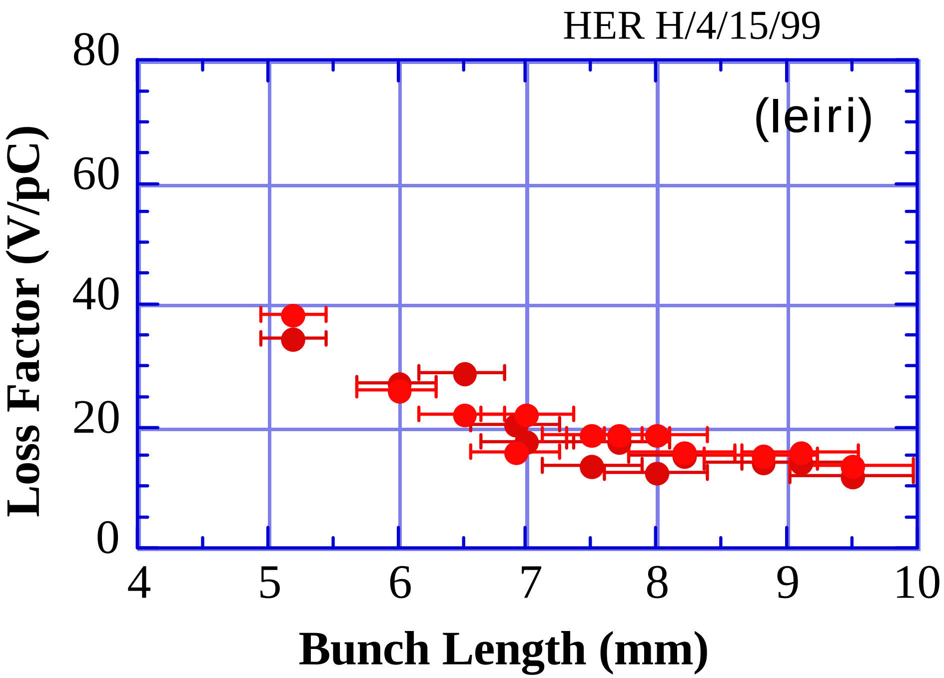
can be related to a shift in synchronous phase:

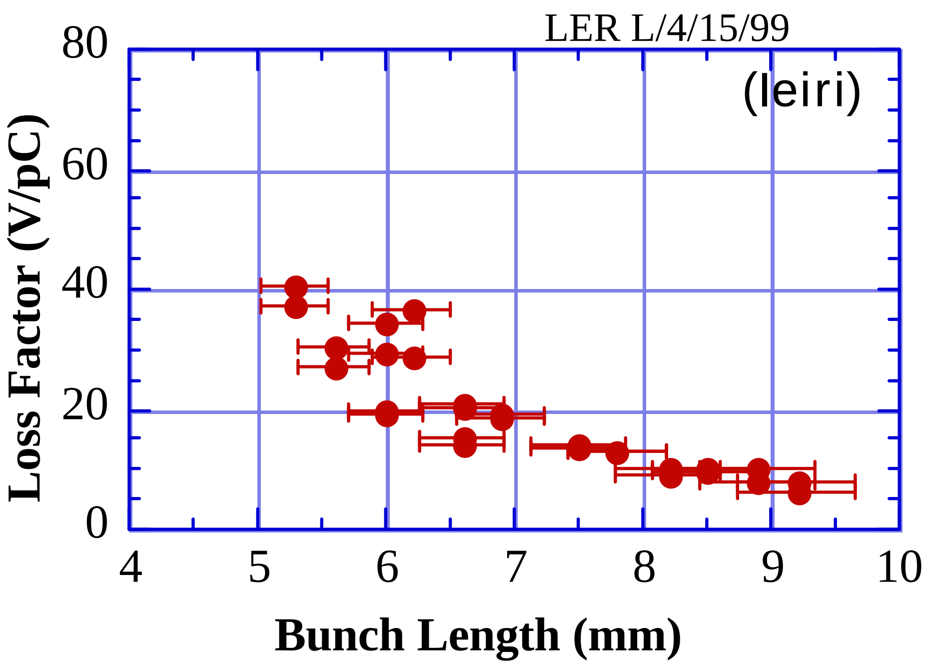
$$k(\sigma) = \frac{V_c \cos\Phi_{s0}}{T_0}\frac{\Delta\Phi_s}{I_b}$$

Which can be measured as a function of bunch current:



Results

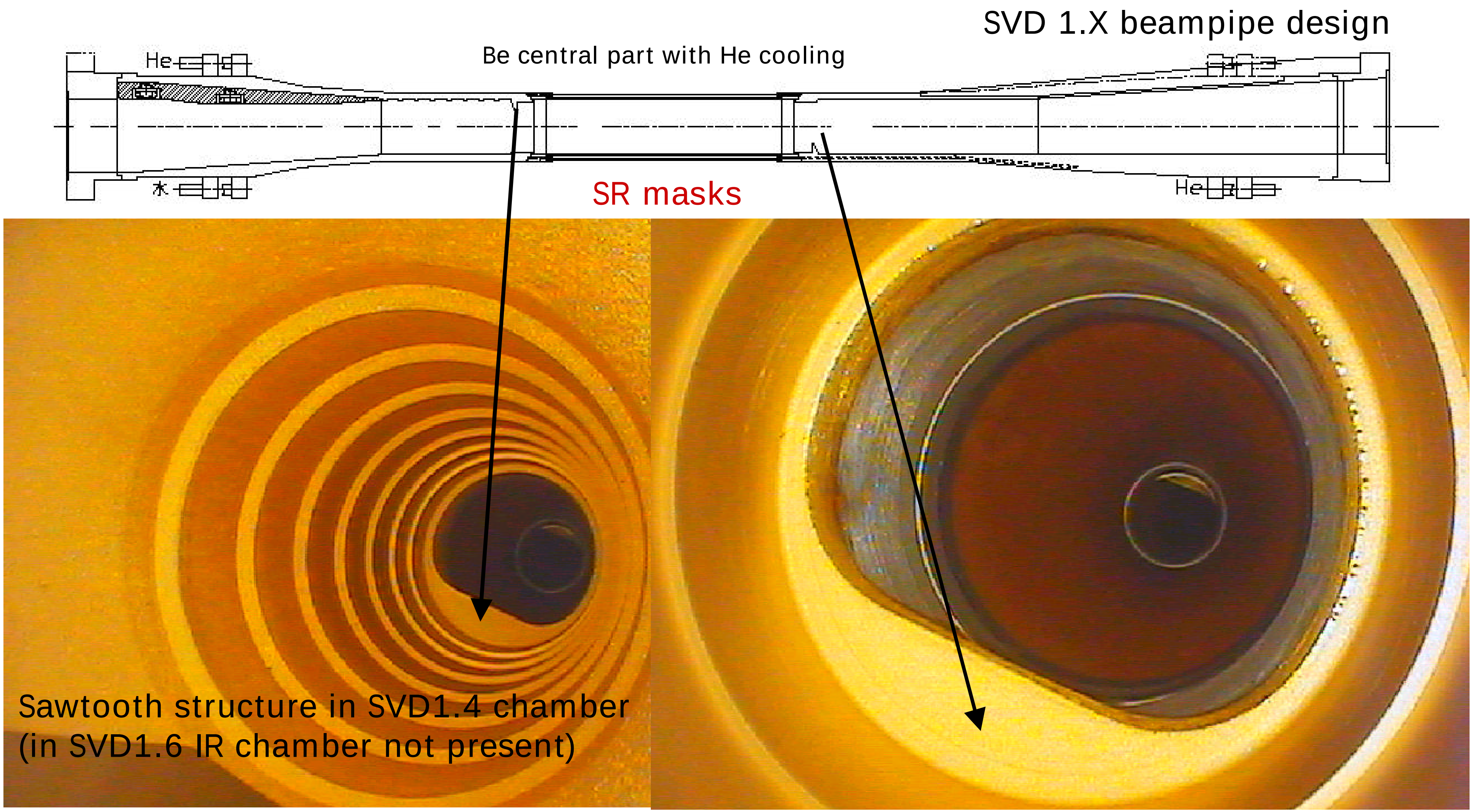




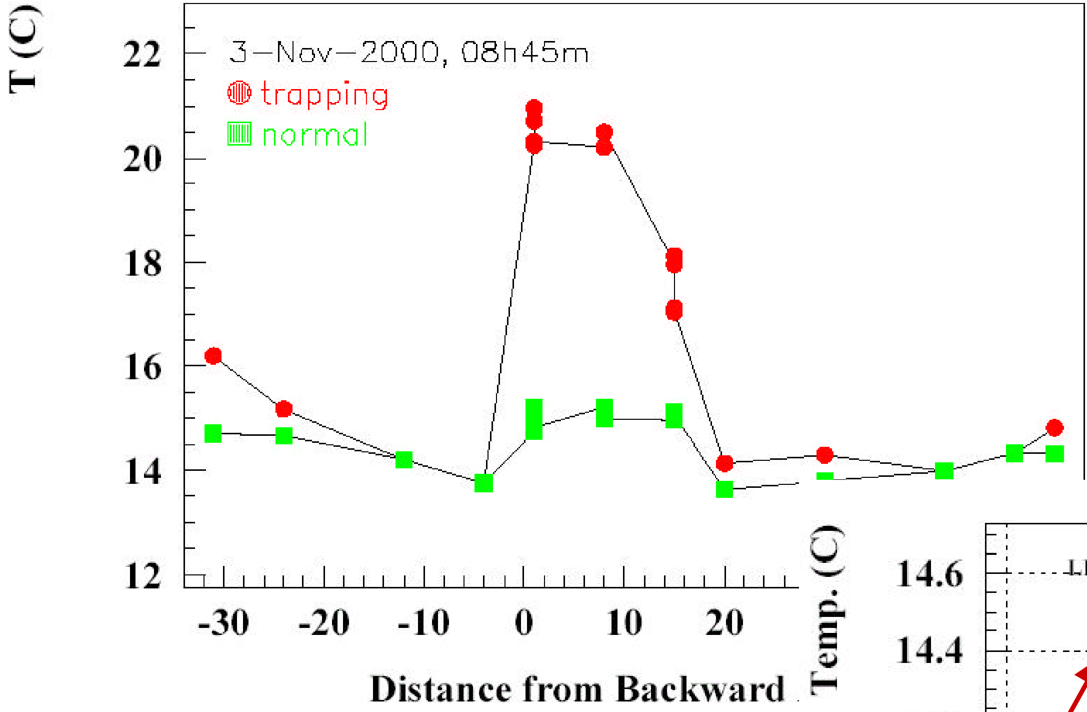
- In both rings loss factor is 20-30 V/pC for 6-7mm long bunches
- Hard to estimate for 4mm or 3mm, exponential extrapolation gives much more than the estimated values!

New experiment is scheduled where we will be able to measure the loss factor dependence down to 3mm (SuperKEKB design) by changing the beam optics

Present IP chamber was found to be resonant to HOM generated in 5 bucket spacing operation



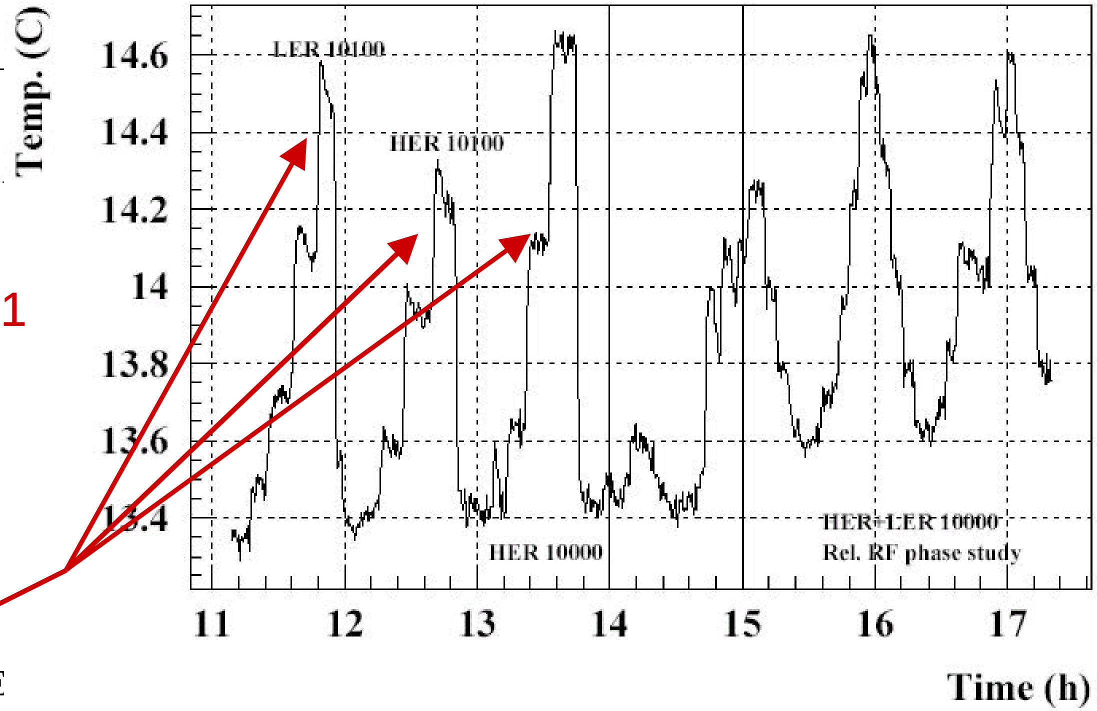
Resonant mode identified



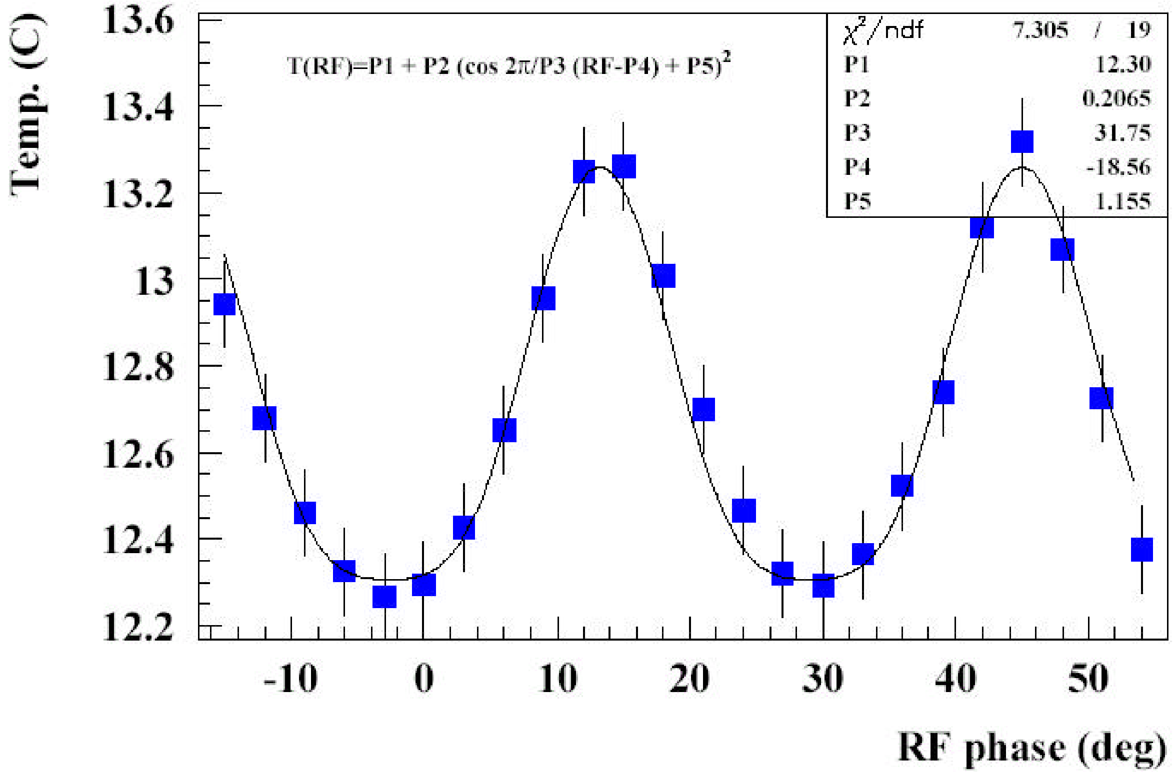
Multi-bunch resonance occurred since the eigen-frequency of the IR chamber was integer multiple of KEKB bunch frequency

$$f = N \times f_{RF}/n_b$$

Observed resonance was predicted to be due to TM-01 mode by multi-bunch simulation, with f=5.81GHz, and was seen for 5 bucket spacing for both beams, as well as HER and LER alone



And experimentally confirmed

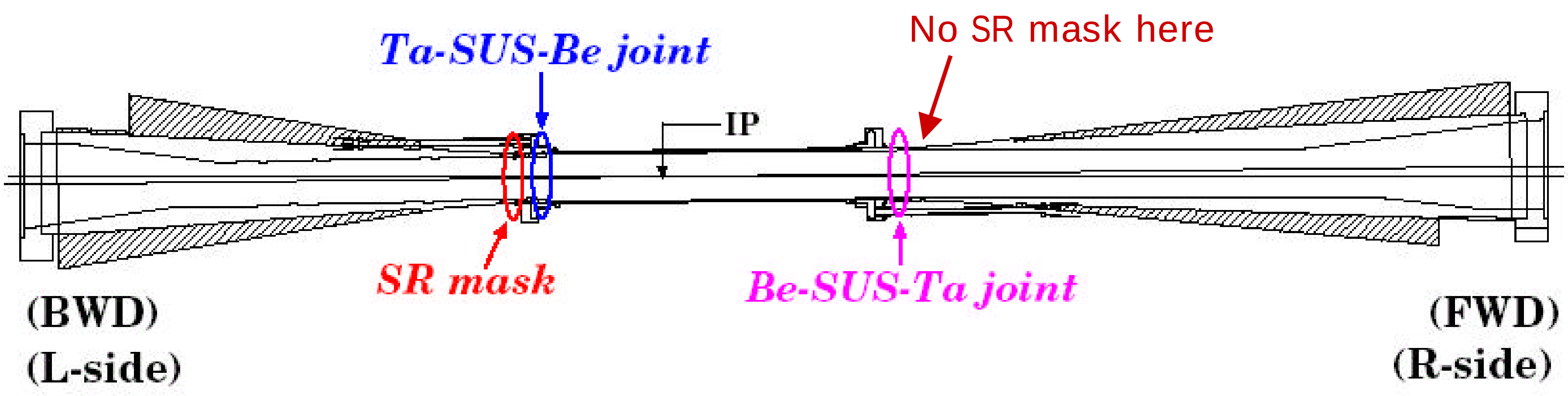


By tuning the RF phase difference between HER and LER it was possible to achieve destructive interference between HOMs from the two beams, where temperature rise dissapears

Measured phase shift of 31.75 deg agrees nicely with the predicted 31.54 deg

Remedy

The problem will be solved in the upgraded version of IR chamber (for SVD2.0), by removing one of the SR masks and thus prevent HOM trapping



SuperKEKB

Physics processes of interest require further increase of luminosity and vertex precision:

- Smaller radius of IR chamber (1-1.5cm)
- Shorther beam bunches (design KEKB 4mm, current 6mm → design SuperKEKB 3mm!)
- Resonance free design of beamline components for all (or at least most) bunch patterns, especially design of the IP

All KEKB HOM considerations remain, plus a necessity to increase the number of RF stations to compensate for larger beam energy loss.

Estimate of required no. of RF stations in LER

Total RF power needed
To compensate for energy loss:

$$\begin{aligned} P_{b\,tot} &= P_{rad} + P_{HOM} \\ &= U_0 I_b + k_{tot} \times \left[\frac{T_0}{N_b}\right] I_b^2 \end{aligned}$$

$$P_{b\,tot} = N_{cav} P_{b\,0}$$

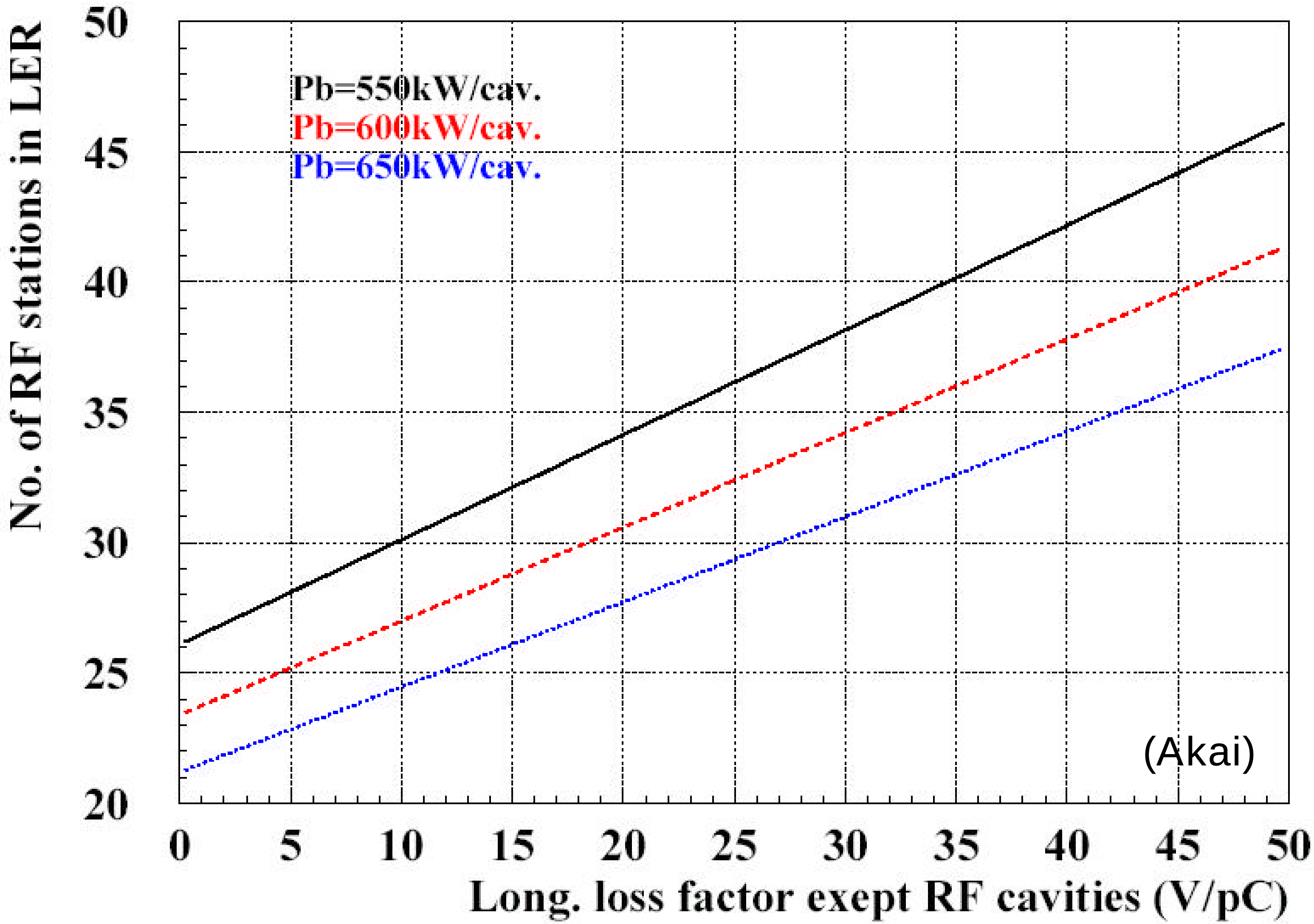
Contrib. to the loss factor from RF cavities separated from those for rest of the ring:

$$k_{tot} = N_{cav} k_{cav} + k_{other}$$

No. of RF cavities as a function of k_{other}:

$$N_{cav} = \frac{U_0 I_b + \left(\frac{T_0}{N_b}\right) I_b^2 \times k_{other}}{P_{b\,0} - \left(\frac{T_0}{N_b}\right) I_b^2 \times k_{cav}}$$

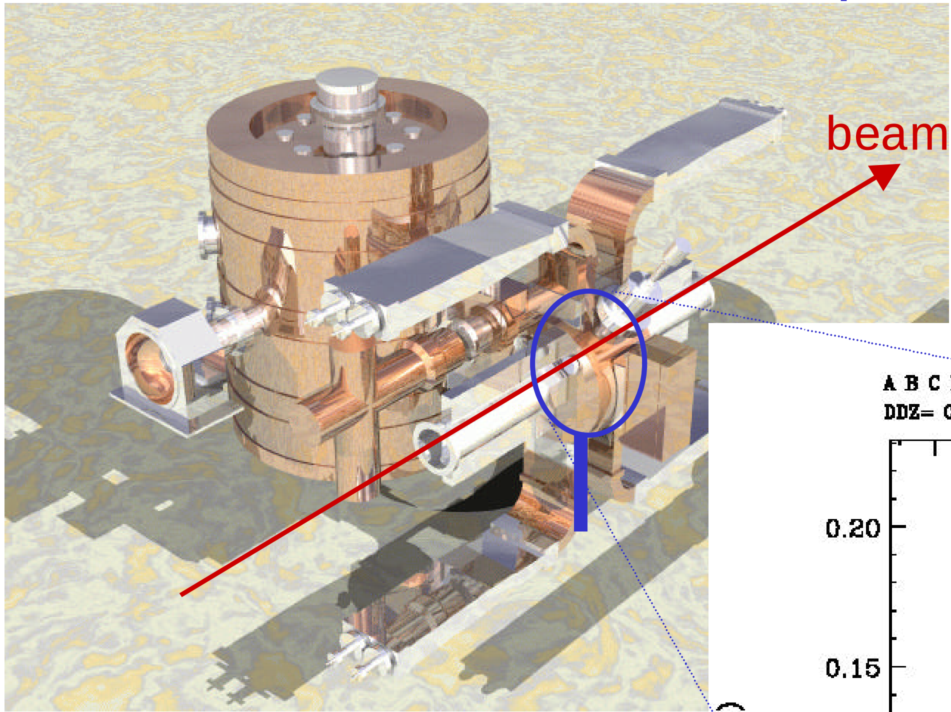
Required No. of RF stations in LER

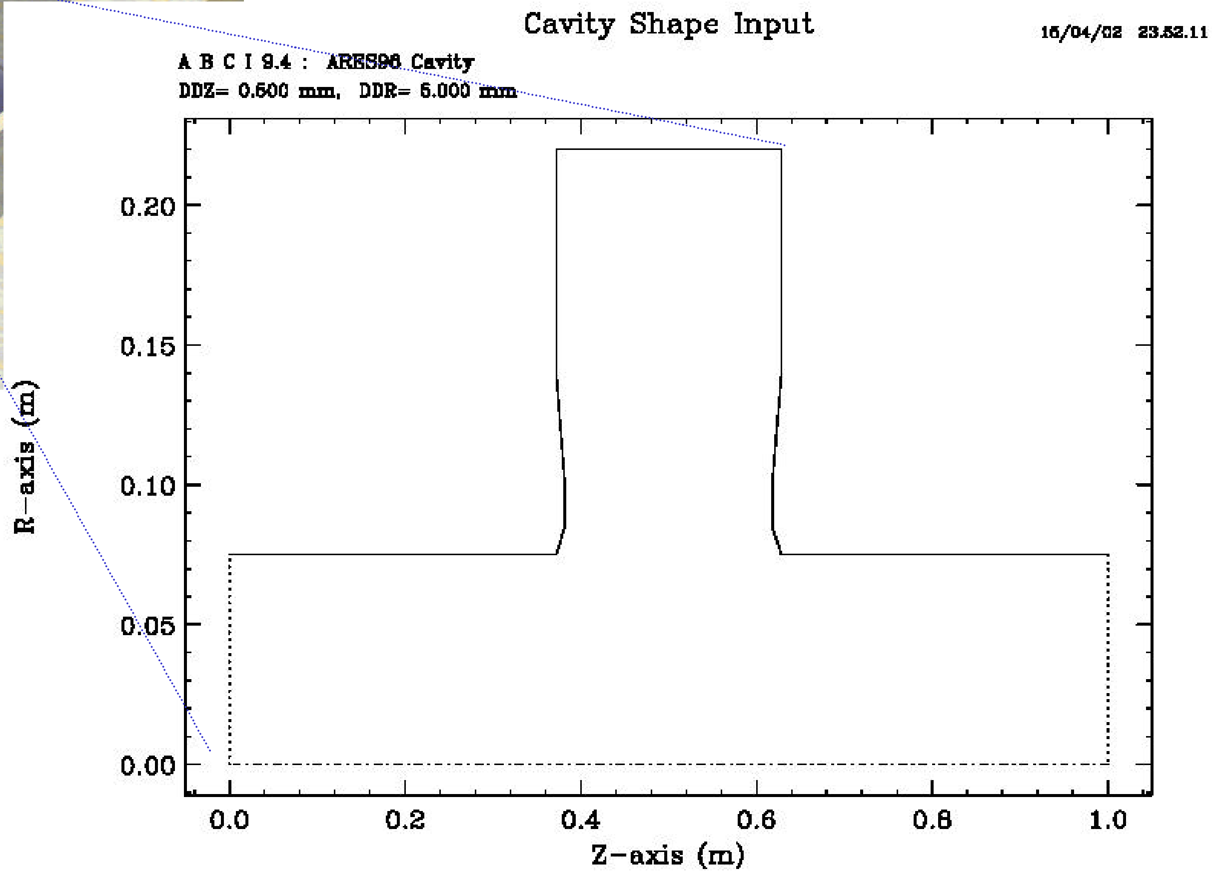


Smaller number of RF stations highly desired

- Due to limited available space in the KEKB tunnel for cavity installation
- Larger number of cavities present a larger threat for beam instabilities
- Due to limited funding we wish to minimize construction (200MYen/ARES station) and running costs (1.2MW/ARES station)

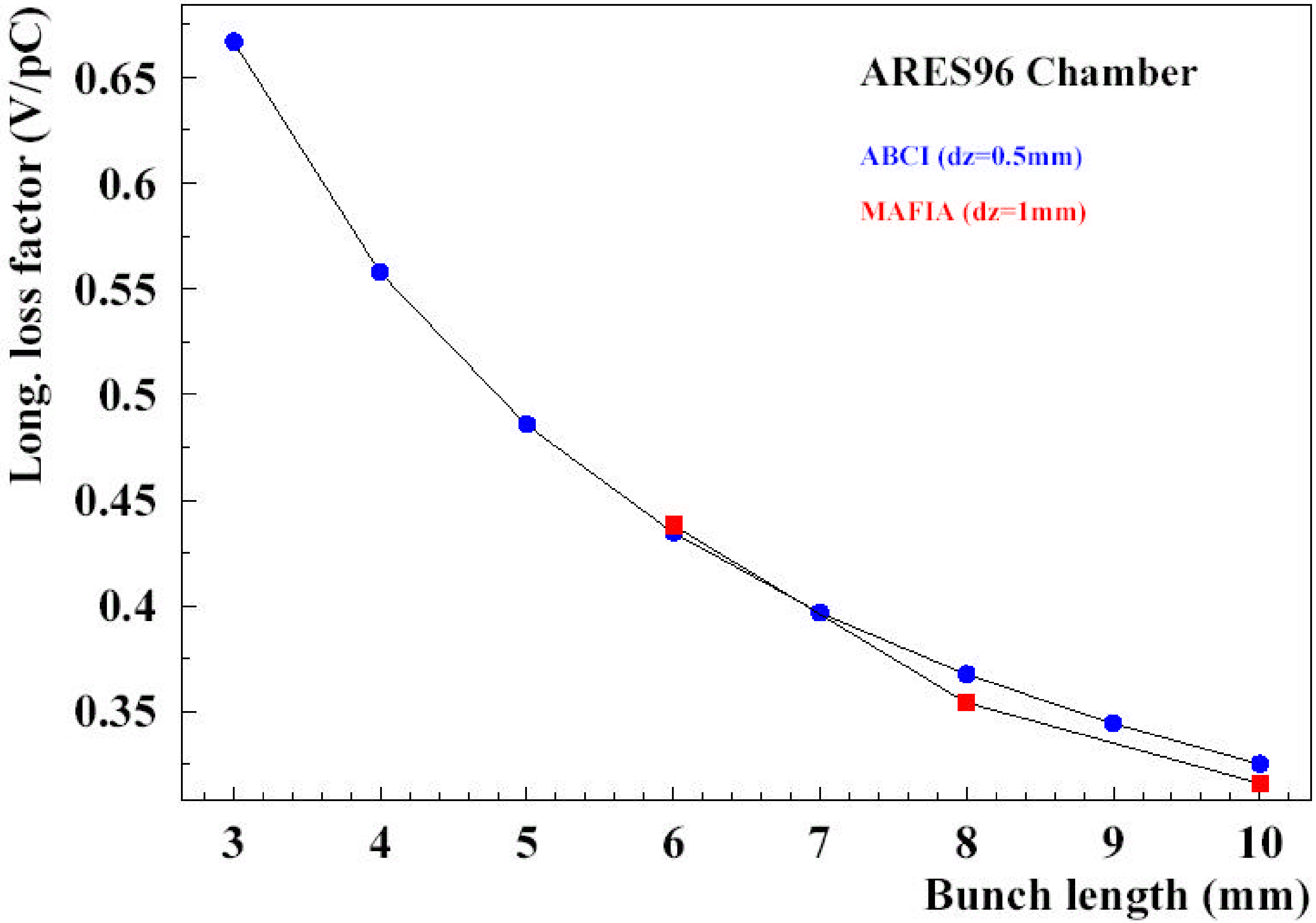
ABCI vs. MAFIA comparison at NC RF (ARES) cavity





Shape of the accelerating part of ARES cavity as used by the ABCI code

Long. Loss factor of ARES

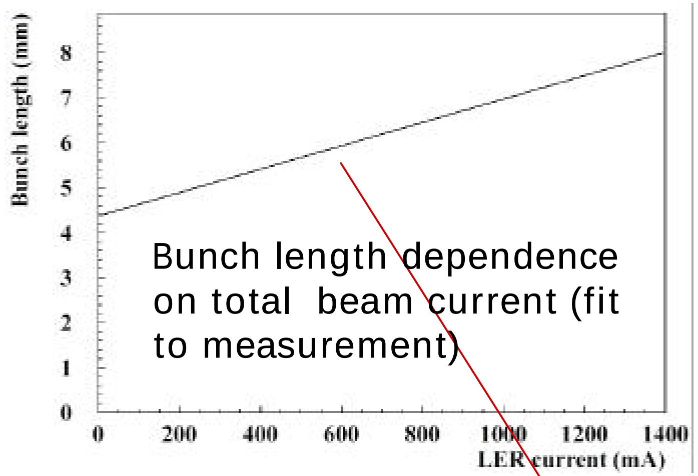


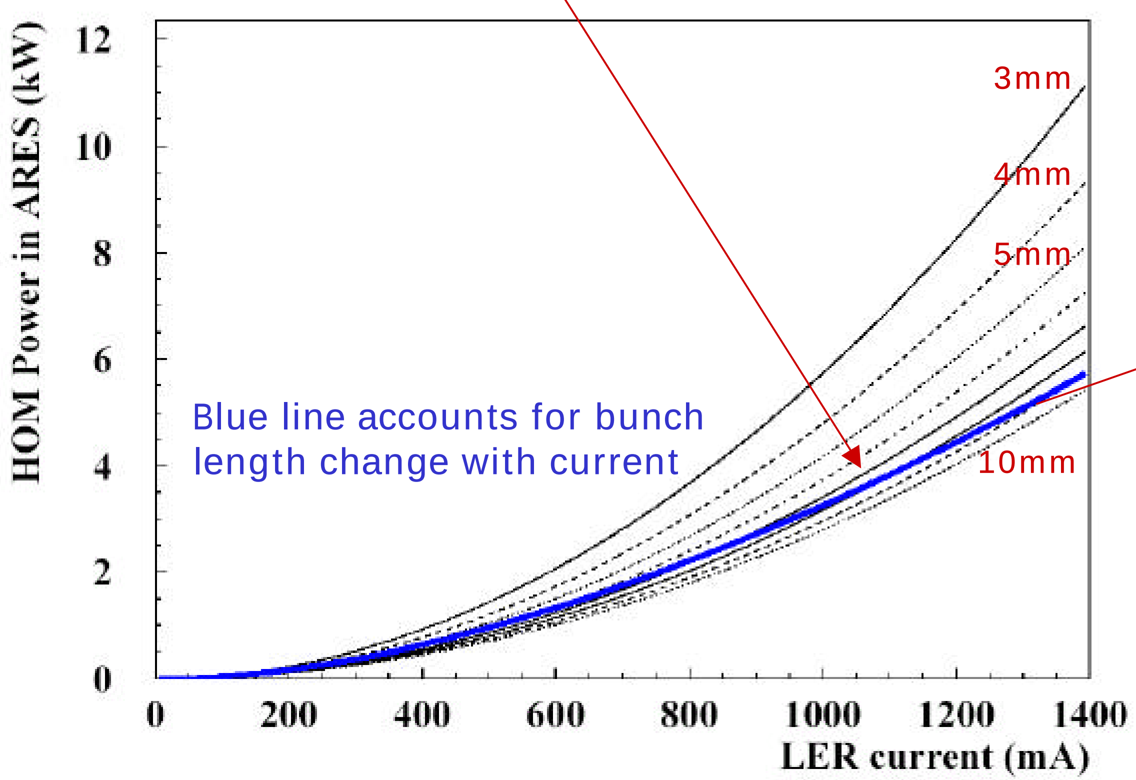
Good agreement between ABCI and MAFIA simulation

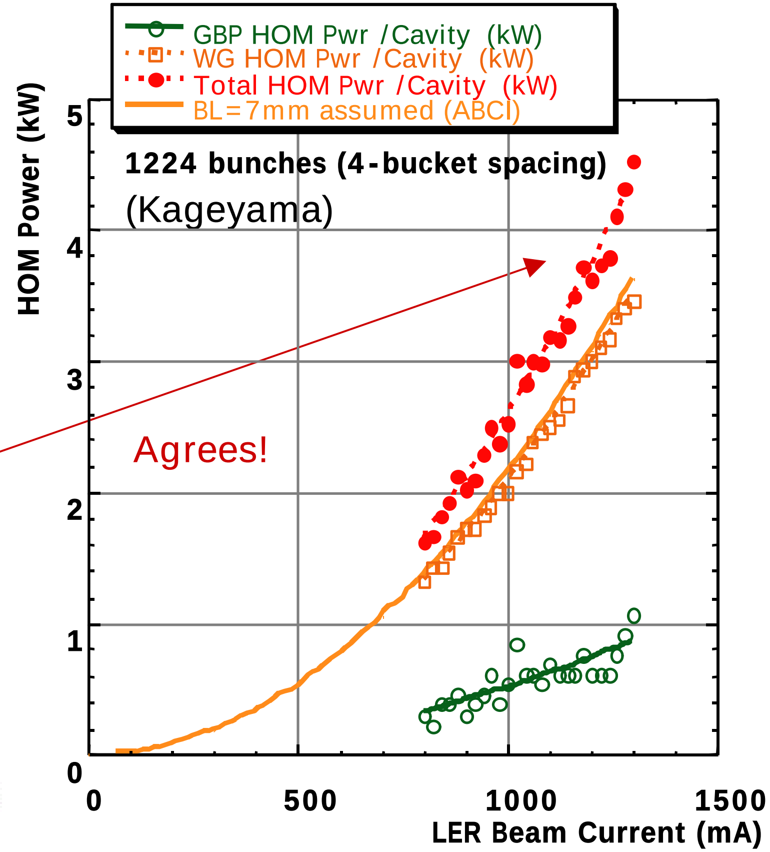
HOM power estimation in ARES

HOM power in ARES as a function of beam current:

$$P_{HOM} = k_{\|} \frac{I_0^2}{f_0 \, n_b}$$







Reducing the impedance beam-line components using small-angle tapers

- Long. loss factor at locations where beampipe radius changes can be reduced using tapered structure

- Change in radius contributes a log(R/r) term – comparing to step, taper can reduce the loss factor for up to 50 %

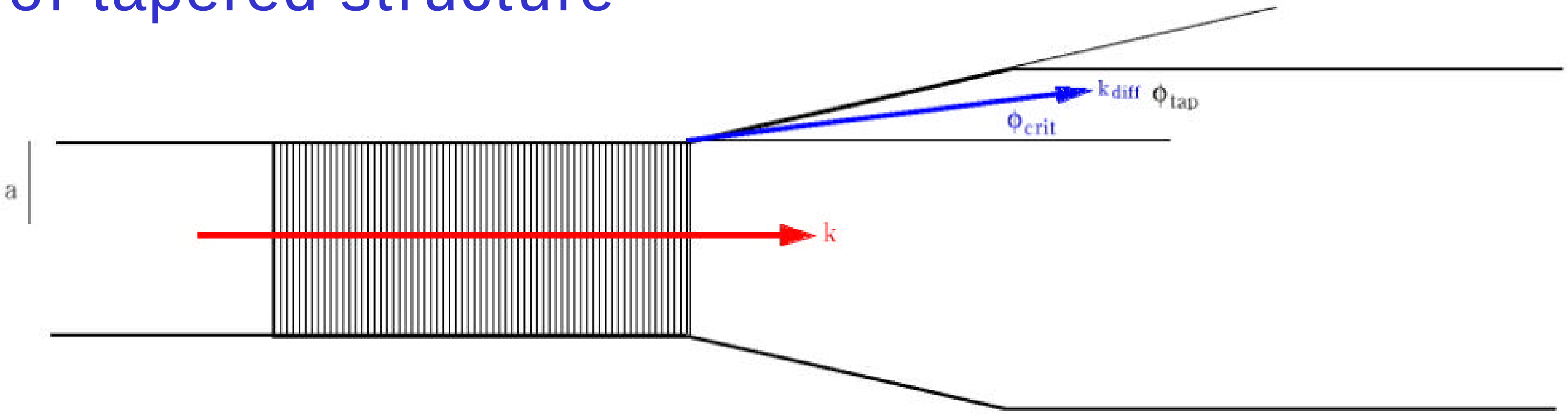
$$k_l(\sigma) = \frac{\ln(R_{large}/R_{small})}{2\pi\epsilon_0\sigma\sqrt{\pi}}\left[1 - \frac{\tilde{\eta}}{2}\right]$$

$$\tilde{\eta} = \min(1, \eta) \qquad \eta = \frac{l_{taper}\sigma}{(R_{large} - R_{small})^2}$$

- Reasonable taper length is

$$l_{taper}^{max}(\sigma) = \frac{(R_{large} - R_{small})^2}{\sigma}$$

Accuracy criterion for a numerical mesh computation of tapered structure



Field surrounding beam almost plane wave, diffracted at edge with

$\lambda_{dif} \ll a$ and diffraction angle $\phi_{dif} \simeq \frac{1}{k_z a} = \frac{\lambda_{dif}}{2\pi a}$

In a mesh with given dz largest wave number that can be seen is

$$k_{max} = \frac{\pi}{\Delta z}$$

Smallest taper that can be calculated is $1/k_{max}\,a$, limited by the given mesh size dz.

For convergence we must require: $1 \ll k_{max} a\phi_{tap} = \frac{\pi}{\Delta z} a\phi_{tap}$

$$k_{crit} = \frac{1}{a\phi_{tap}}$$

Critical wave number – here the difraction angle equals the taper angle

$$\xi = \frac{k_{max}}{1/\sigma_z} = \frac{\pi\sigma_z}{\Delta z}$$

"frequency range" a mesh can represent, in units of σ_z

$$\eta = \frac{k_{max}}{k_{crit}} = \frac{\pi a\phi_{tap}}{\Delta z}$$

Optimization parameter, guaranteeing convergence above certain η_{min}

Ansatz gives

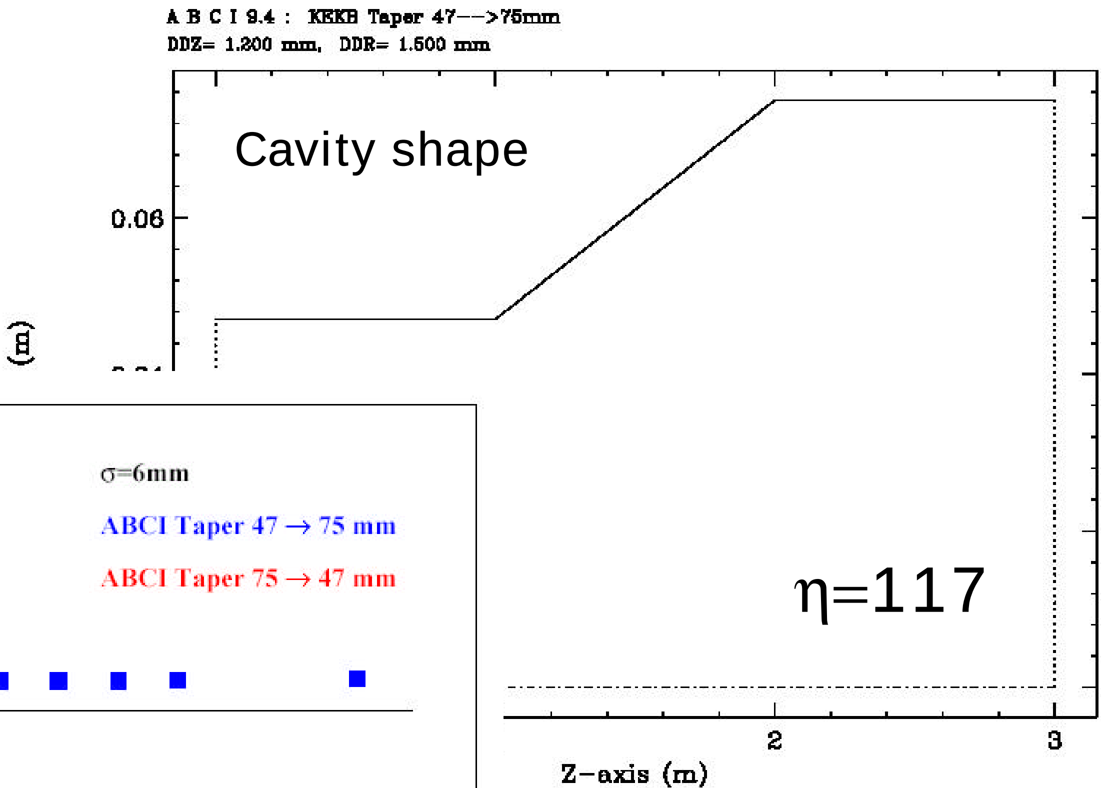
$$\eta_{min} \simeq \frac{b}{\xi} \Rightarrow \frac{b\eta_{min}}{\pi^2} \leq \frac{a\phi_{tap}}{\Delta z}\frac{\sigma_z}{\Delta z}$$

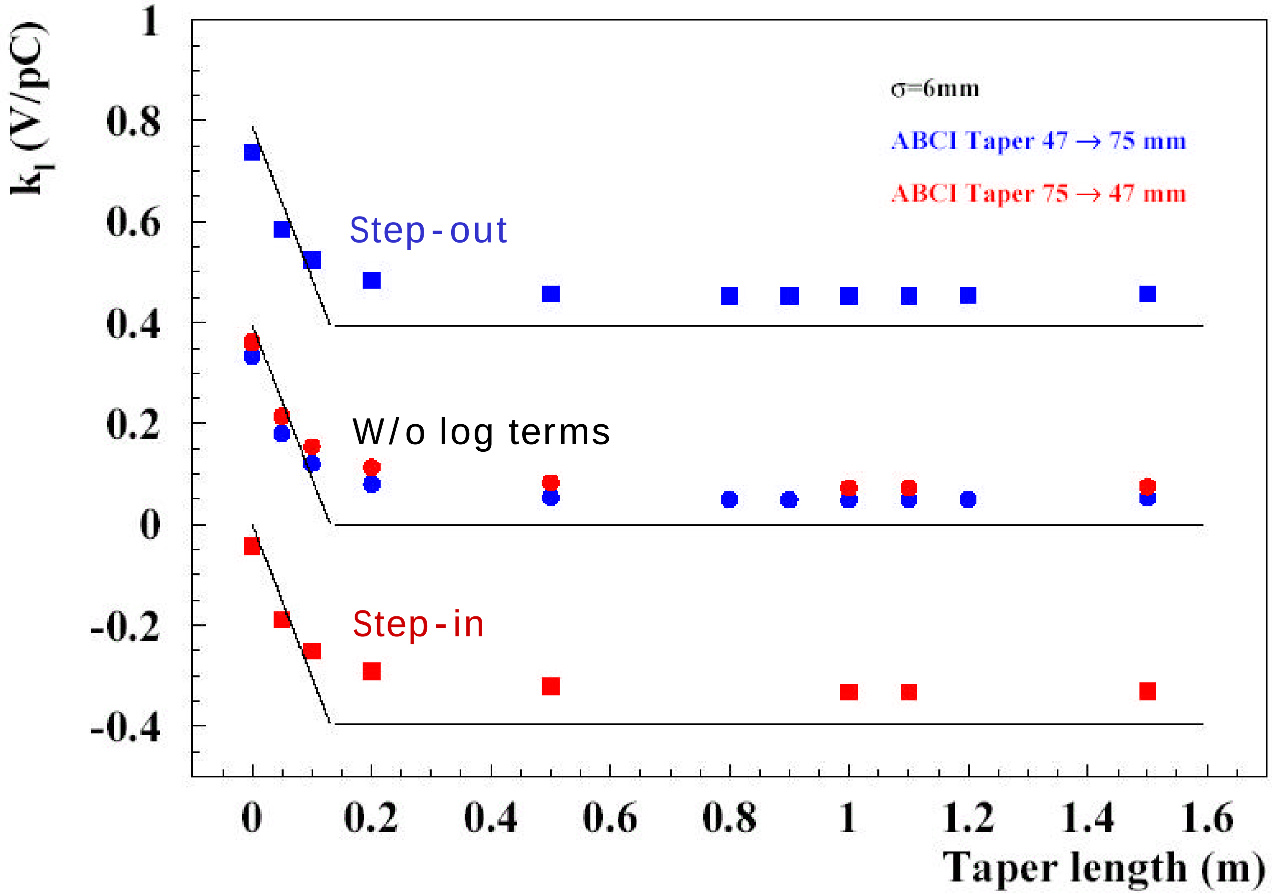
Empyrically

$$\frac{b\eta_{min}}{\pi^2} \simeq 100$$

For shallow tapers and short bunches we need a very fine mesh dz!

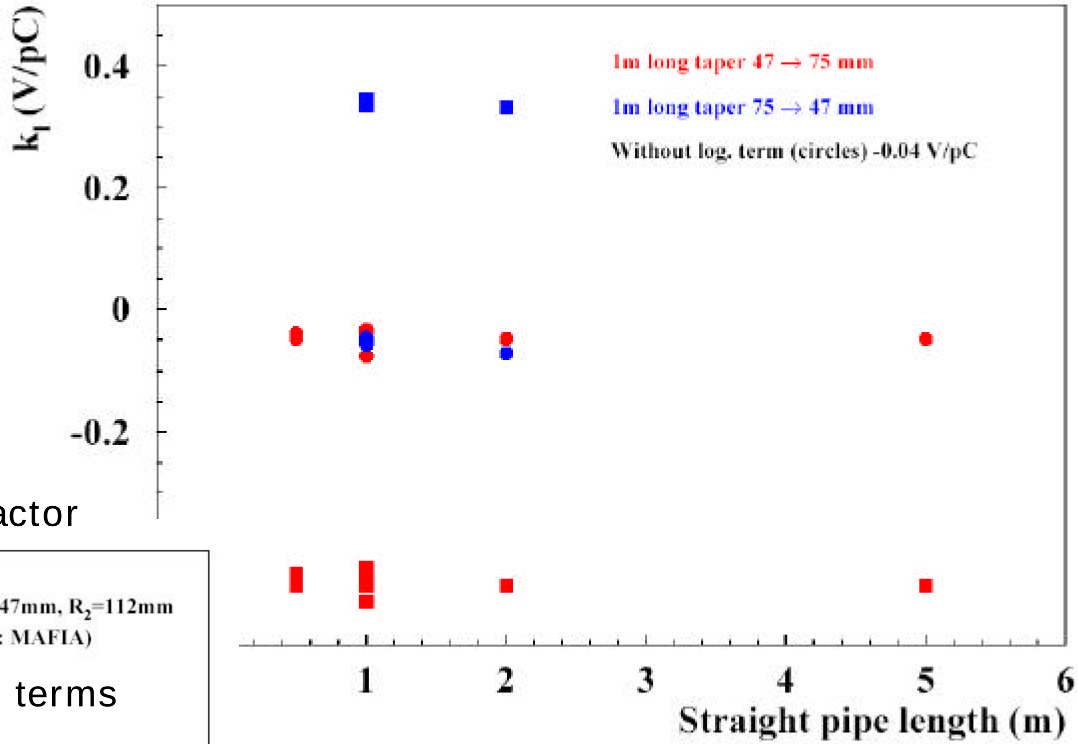
Example: Symmetric tapered structure (ABC



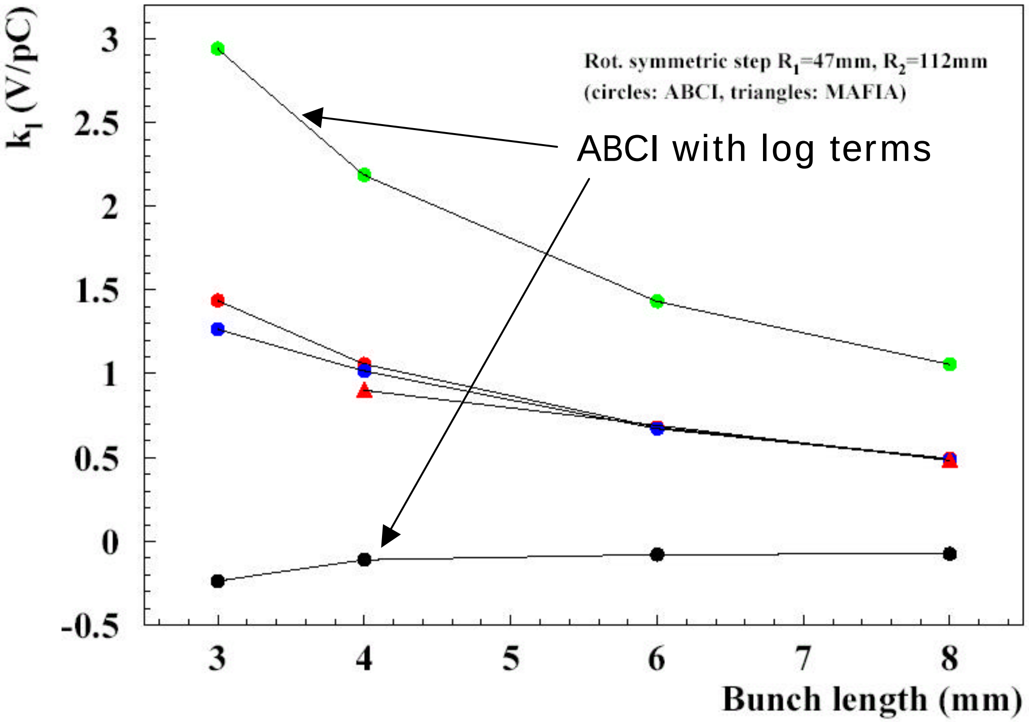


Taper length dependence of loss factor. Squares: log terms for step-in and step-out included

Example:
Result stability w.r.t. calculation parameters

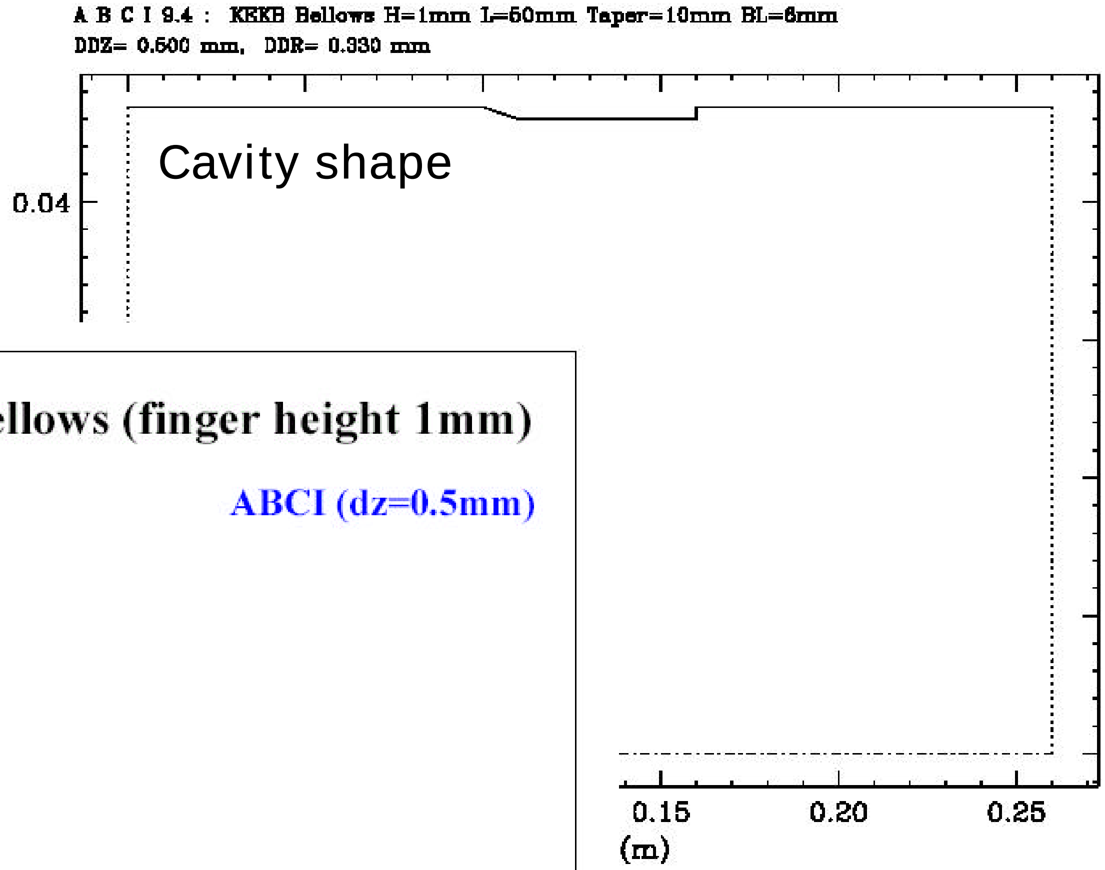


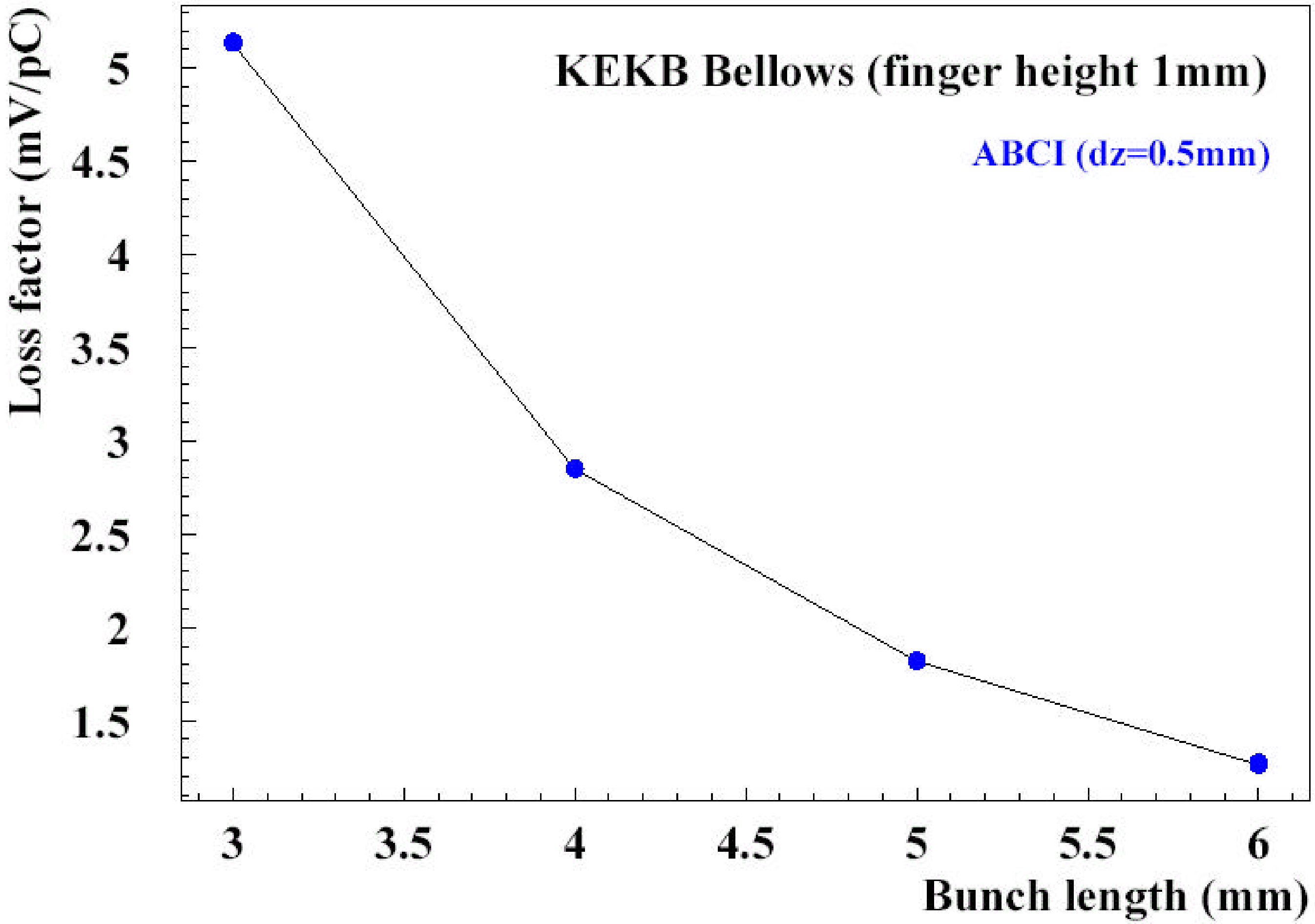
Bunch length dependence of long. Loss factor



ABCI vs. MAFIA comparison for rot. symmetric step

Example: Finger in bellows (ABCI)

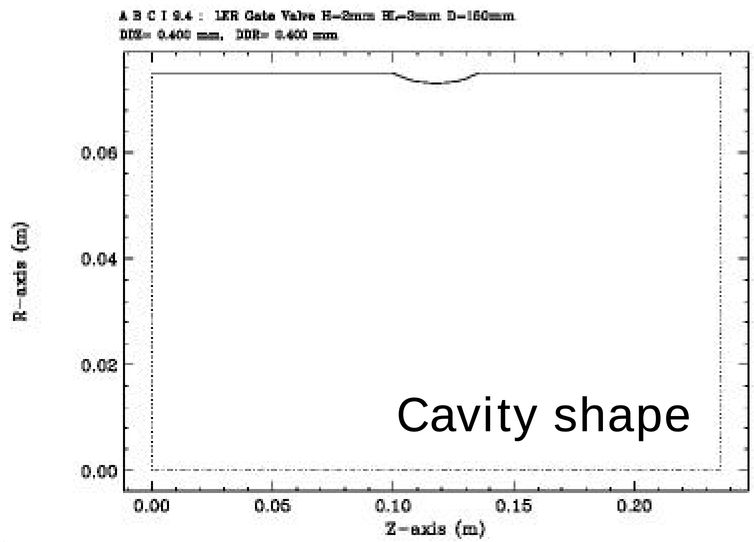


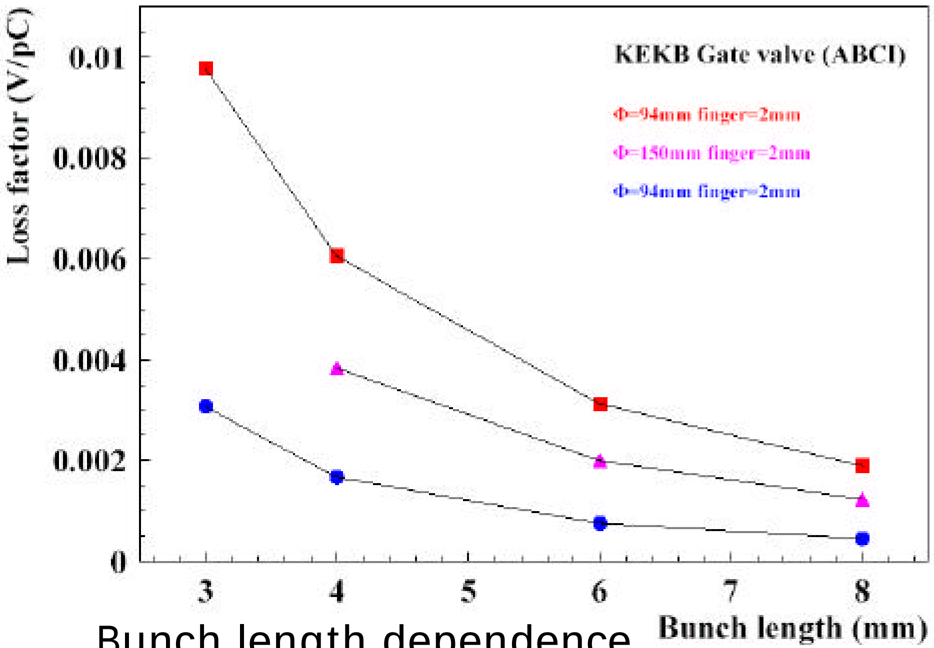


Bunch length dependence of long. Loss factor

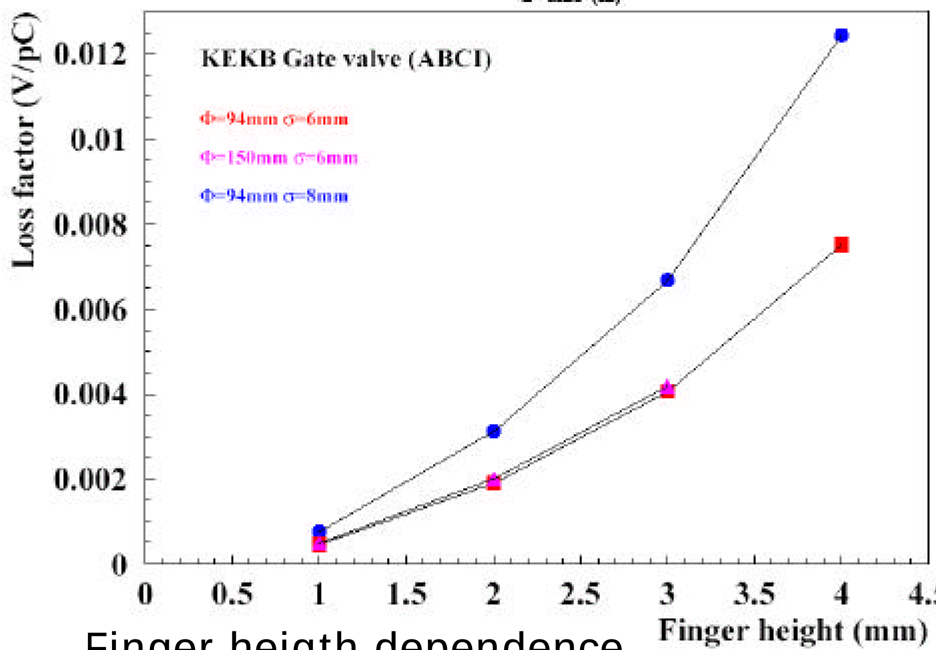
Example:
Gate valve (ABCI)

(RF shield that covers the valve entrance enters into the duct)





Bunch length dependence for various finger heights



Finger heigth dependence for various configurations

Impedance estimation for SuperKEKB

SuperKEKB σ=3mm	No. of items	Loss factor [V/pC]
ARES cavity	20	20
SC cavity (HER)	12	20.3
Resistive wall	3016m	6.5
Masks at arc	-	-
Pumping slots (arc)	-	-
Pumping slots (straight)	800	+
BPMs	4×400	+
Masks at IP	1	+
IP chamber	1	+
Recomb. chambers	2	+
Bellows	1000	5.2
Flange gap	2000	1-3
Gate valve	40	0.12
Trans. to antechamber	40	+
Feedback kicker	1	+
Inj./abort kickers	4	+
Septum	1	+
Movable masks	16	1.6-3.2
HOM absorbers (RF end)	4	2
Tapers (RF end)	4	0.16
Total (tentative)		36.6-40.2+

More work needed!

Preliminary estimate of the Loss Factor of LER (94ϕduct) for SuperKEKB

Summary

• Combining computer simulation and experiment we are striving to reduce discrepancy between estimated and measured loss factor of KEKB rings

• "Tuning" the design parameters of various beam-line components we are trying to decrease the overall loss factor of the rings and to avoid dangerous resonances, especially in the IR

• Success of these endeavors is of particular interest for SuperKEKB, where from the viewpoint of RF systems smaller loss factor means less problems and smaller financial burden