Impedance and collective effects of CEPC

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Outline

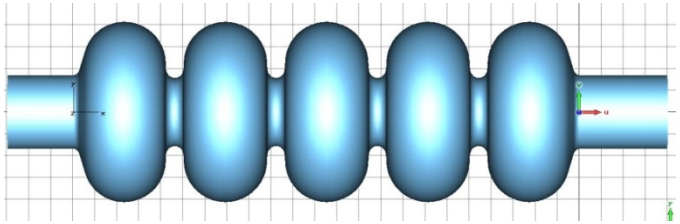
- Impedance budget
- Single-bunch effects
- Multi-bunch effects
- Electron cloud instability
- Beam ion instability

Main parameters of CEPC

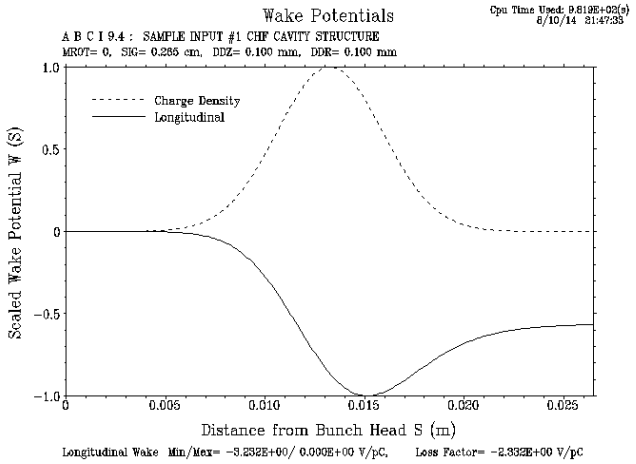
Parameter	Symbol, unit	Value
Beam energy	E, GeV	120
Circumference	C, m	54752
Beam current	I_0, mA	16.6
Bunch number	n_b	50
Bunch Population	N_e	3.79×10^{11}
Natural bunch length	σ_{l0}, mm	2.65
Emittance (horz./vert.)	$\varepsilon_x/\varepsilon_y$, nm	6.12/0.018
RF frequency	f_{rf}, GHz	0.65
Harmonic number	h	118800
Natural energy spread	σ_{e0}	1.63E-3
Momentum compaction factor	α_p	3.36E-5
Betatron tune	ν_x/ν_y	179.08/179.22
Synchrotron tune	ν_s	0.18
Damping time (H/V/s)	$\tau_x/\tau_y/\tau_z$, ms	14/14/7

1. Impedance budget

- RF cavities
  - A five cell SC RF cavity structure with RF frequency of 650 MHz will be used.



  - Given a design accelerating gradient of 15.6 MV/m, 384 cavities are needed.
  - The wake of the RF cavities is calculated with ABCI.



Short range wake at nominal bunch length

  - Loss factor for one RF cavity is k_l=2.332 V/pC.
  - We fit the bunch wake with the analytical model

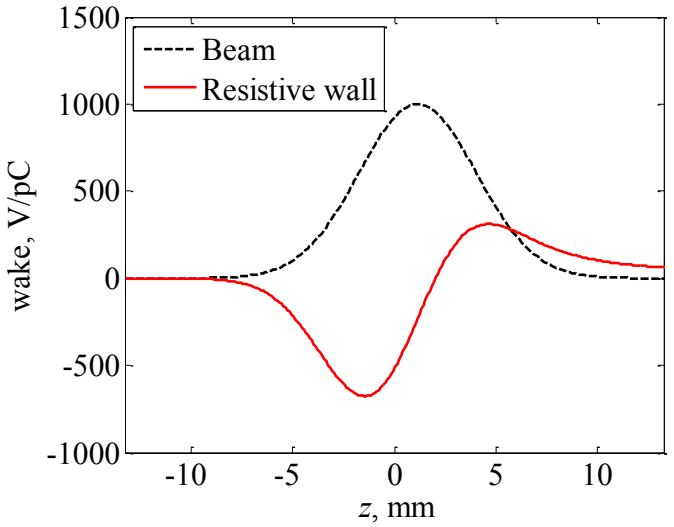
$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)$$

L and *R* are effective inductance and resistance, respectively.

- Resistive wall
  - Aluminum beam pipe is assumed. The beam pipe has an elliptical cross section with half height of a_x/a_y=52/28 mm.
  - Resistive wall wake for a Gaussian bunch in a cylindrical beam pipe is calculated analytically

$$W(s) = \frac{cl}{8\sqrt{2}\pi a}\frac{1}{\sigma_z^{3/2}}\sqrt{\frac{Z_0}{\sigma_c}}f(s/c)$$

where $f(x) = \sqrt{|x|^3}e^{-x^2/4}\left(I_{1/4} - I_{-3/4} \pm I_{-1/4} \mp I_{3/4}\right)\Big|_{x^2/4}$, and $I_n(x)$ are the modified Bessel functions.

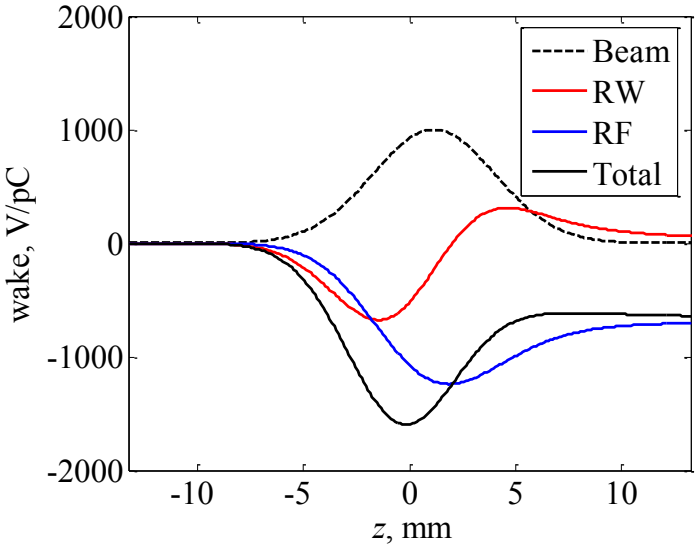


  - Loss factor: k_l=309.6 V/pC.
  - Fitted parameter:

    R=9.7kΩ, L=126.8nH

- CEPC ring wake and impedance budget

Object	Contributions			
	R [kΩ]	L [nH]	k_{loss} [V/pC]	$\lvert Z_{//}/n \rvert_{eff}$ [Ω]
Resistive wall (Al)	9.7	126.8	309.6	0.0044
RF cavities (N=384)	28.1	--	895.5	---
Total	37.8	126.8	1205.1	0.0044



Longitudinal wake at nominal bunch length (σ_z=2.65mm)

- The loss factor is dominated by the RF cavities.
- The imaginary part of the RF cavities is capacitive, the fitted *L* has no physical meaning.
- A more complete impedance budget will be obtained as the vacuum components are designed.

2. Single-bunch effects

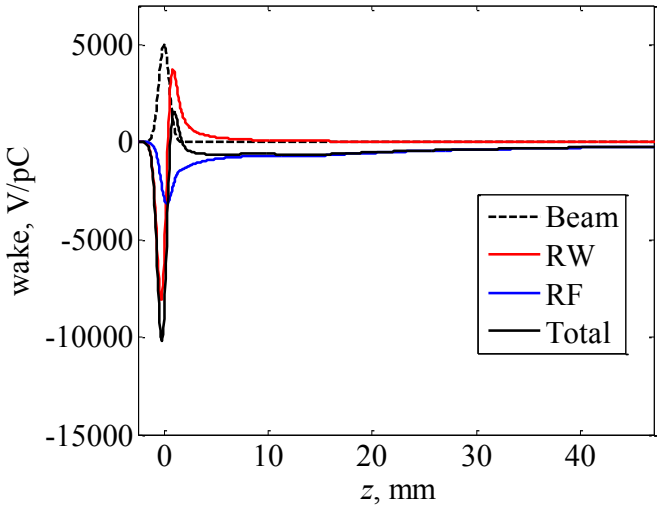
- Longitudinal microwave instability
  - The longitudinal microwave instability is estimated according to the Boussard or Keil-Schnell criterion:

$$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_{e0}{}^2 \sigma_l}{R \left| \frac{Z}{n} \right|_{eff}}$$

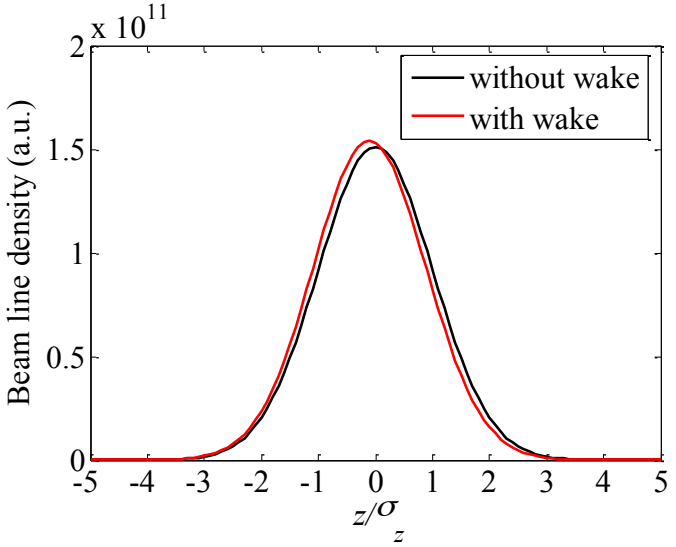
  - The threshold of the longitudinal impedance is $|Z_{//}/n| < 0.025\ \Omega$.
  - LEP:

    Measurement: $|Z_{//}/n|_{th} = 0.03\Omega$ (B. Zotter, EPAC'92, p.273)

- Bunch lengthening
  - Steady-state bunch shape is obtained by numerically solving the Haissinski equation.
  - The Pseudo-Green function wake with bunch length of 0.5mm is used in the calculation.
  - Bunch is shortened due to the capacitive property of the RF cavities (Here, only resistive wall and RF cavities are considered)



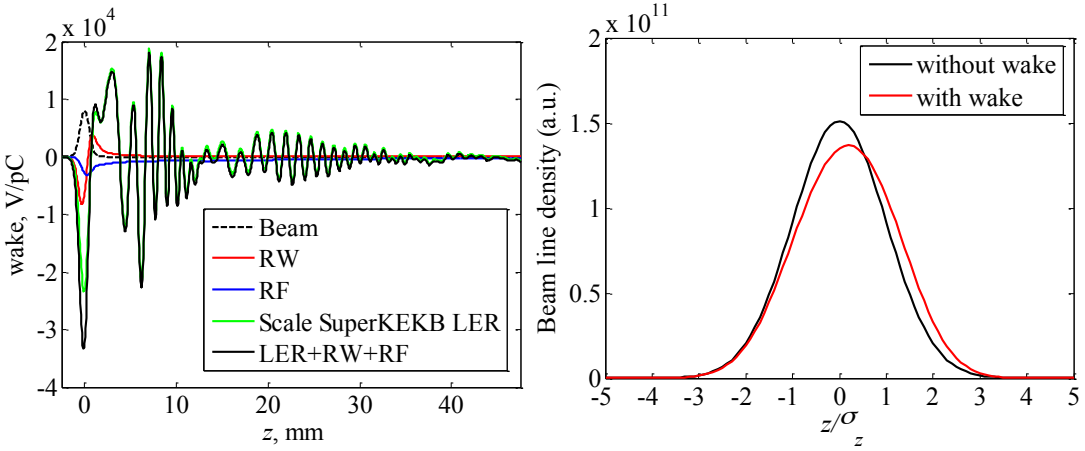
Pseudo-Green function wake (σ_z=0.5mm)



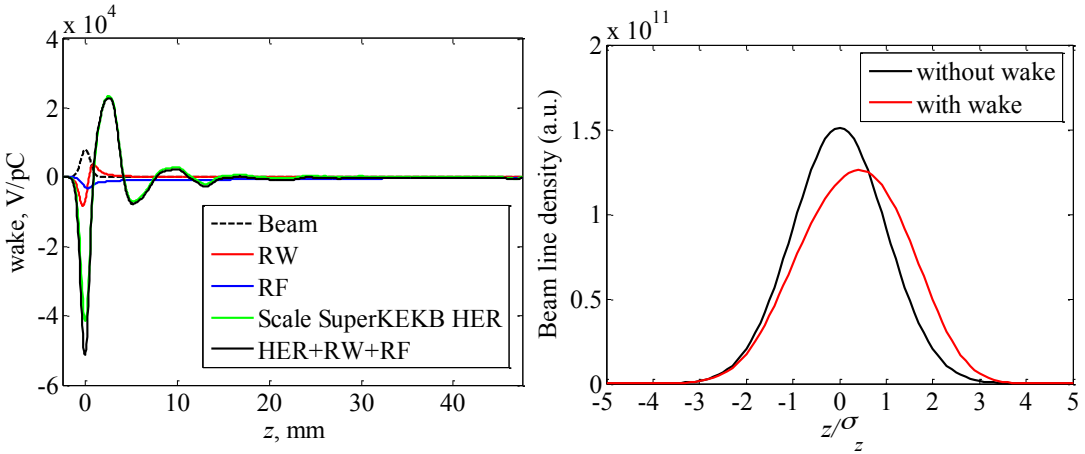
Steady-state bunch distribution

- Bunch lengthening with scaled SuperKEKB's geometry wake
  - The scaling factor is Cir (CEPC)/Cir(SuperKEKB)

– Scaled LER wake+RW+RF
– Bunch is lengthened by 10.6%

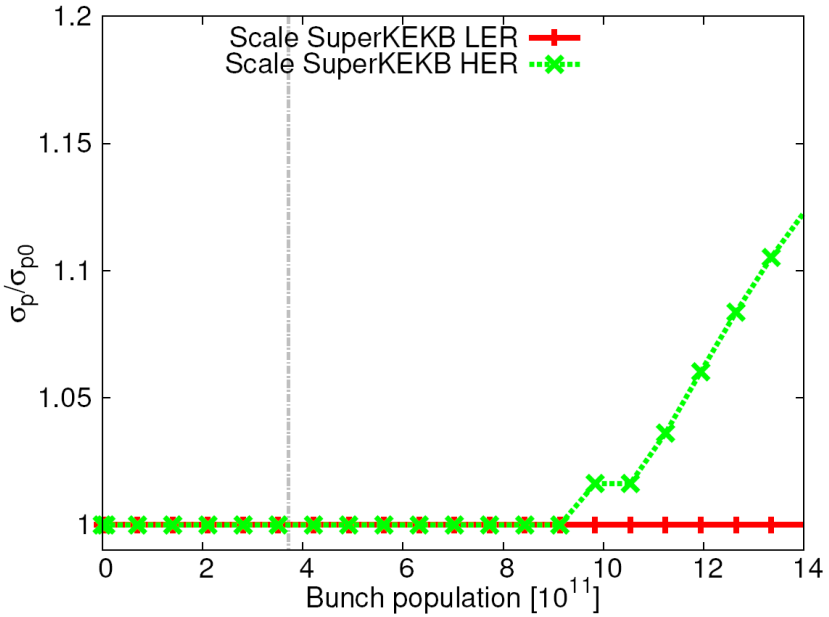


– Scaled HER wake+RW+RF
– Bunch is lengthened by 20.9%

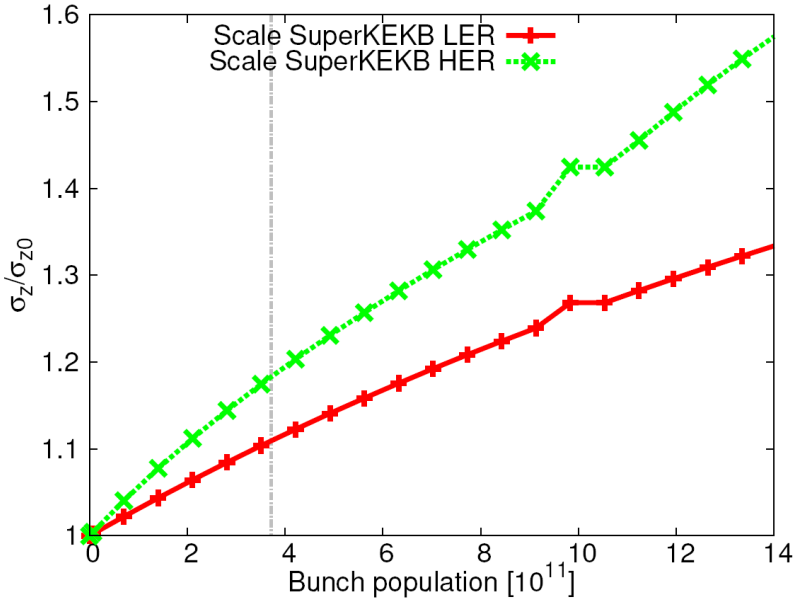


- Difference of the impedance models between SuperKEKB LER and HER:
  - There is ante-chamber in the LER, but not in the HER. Without ante-chamber, the SR masks, pumping ports, and bellows contribute more impedances.

- Simulation results with scaled wake of SuperKEKB LER/HER



Energy spread with bunch current



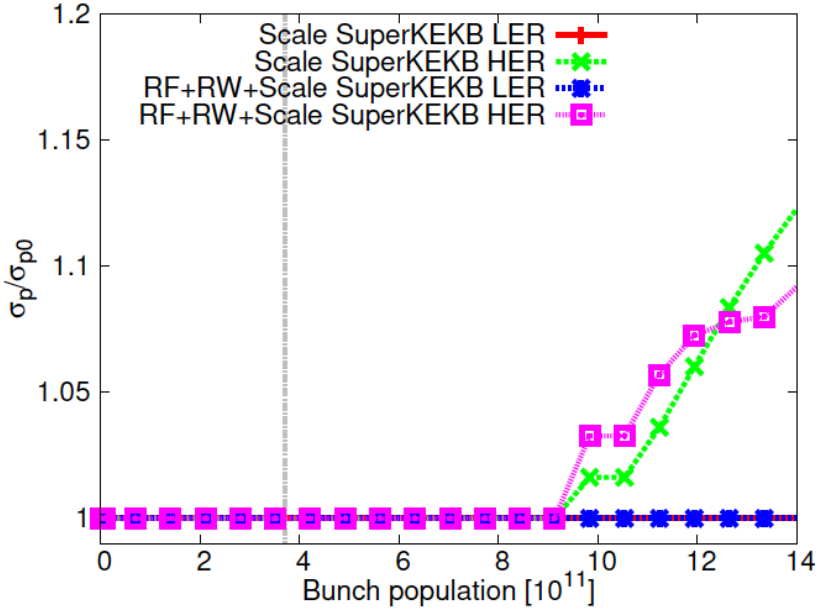
Bunch length with bunch current

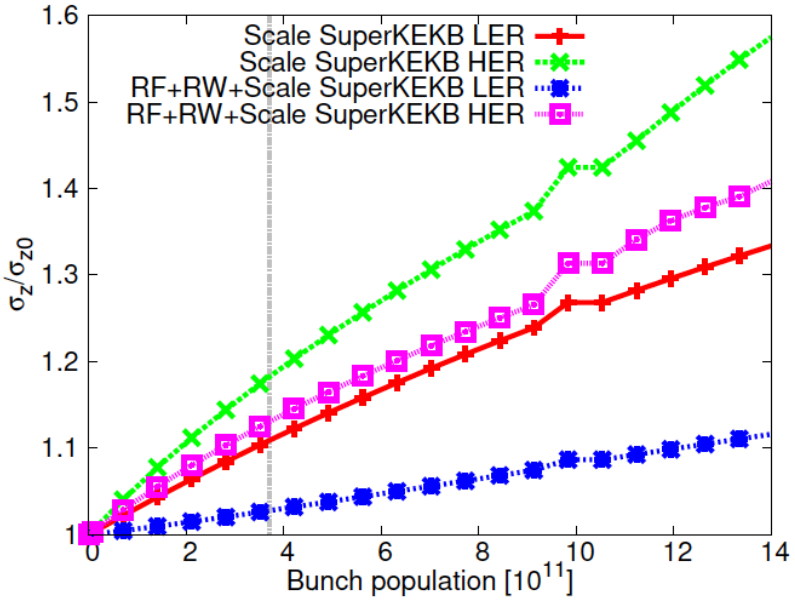
- Scale SuperKEKB LER/HER:

  (Geometric+RW impedance of SuperKEKB LER/HER) * Cir(CEPC)/Cir(SuperKEKB)

- The threshold for the longitudinal microwave instability is much higher than the design bunch population.
- The bunch lengthening at nominal bunch current are 10.9% (LER) and 18.5 (HER)

- Simulation with more careful scaling





- RF+RW+Scale SuperKEKB LER/HER:
  - Impedance data of CEPC RF+RW
  - Multiply Cir(CEPC)/Cir(SKEKB):bellows, flanges, pumping ports, SR masks, BPMs
  - No scaling: Feedback kicker, Longitudinal kicker
  - Scale by number of IP: collimators, IR duct
- The bunch lengthening are 2.9% (LER) and 13.3% (HER)
- CEPC should be safe from the microwave instability.

- Coherent synchrotron radiation (K. Bane, Y. Cai, G. Stupakov, PRST-AB, 2010)
  - The beam is assumed to be moving in a circle of radius ρ between two parallel plates at locations $y = \pm h$.
  - The threshold of bunch population for CSR is given by

$$S^{\mathrm{th}} = 0.50 + 0.12\Pi \qquad S = \frac{r_e N_b \rho^{1/3}}{2\pi \nu_s \gamma \sigma_\delta \sigma_z^{4/3}}, \qquad \Pi = \frac{\sigma_z \rho^{1/2}}{h^{3/2}}$$

  - For CEPC, $\sigma_z\rho^{1/2}/h^{3/2}$=15.6 (=> CSR shielded)
  - The CSR threshold in CEPC is $N_{b,Th} = 7.3\times10^{12} >> N_b = 3.79\times10^{11}$.

- Space charge tune shift

$$\Delta\nu_{x,y} = -\frac{r_e N_b}{(2\pi)^{3/2}\gamma^3\sigma_z}\oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)(\sigma_x(s)+\sigma_y(s))}ds$$

$\Delta\nu_y$ = -1.9e-4, $\Delta\nu_x$ = -5.8e-6

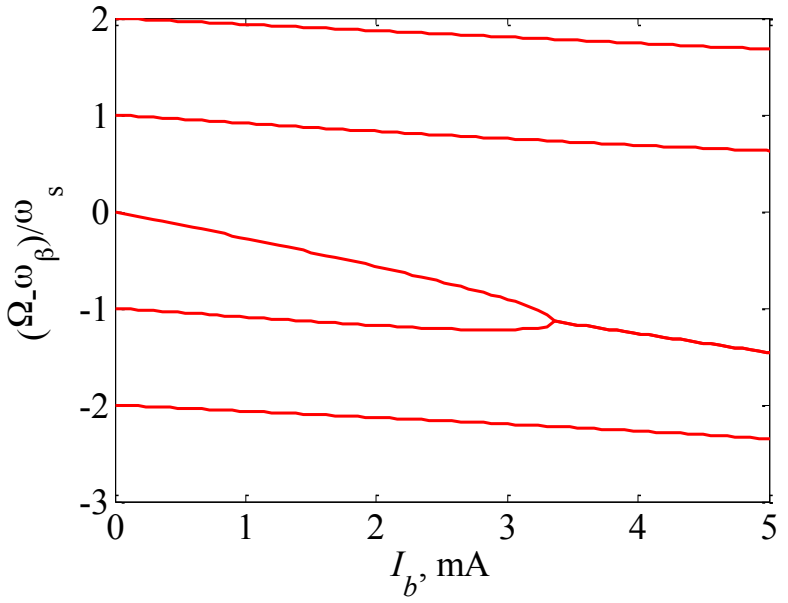
- Transverse mode coupling instability (TMCI)

$$|Z_\perp| \le \frac{4\nu_s Eb}{eI_b R < \beta_\perp >}$$

  - The threshold of transverse impedance is $|Z_\perp| < 17.2\ \mathrm{M\Omega/m}$.
  - The equivalent longitudinal impedance is 0.8 Ω, which is much higher than that of the longitudinal instability.

- Eigen mode analysis
  - Considering only resistive wall impedance
  - Beam current threshold:

    I_b^{th}=3.4mA (I_0^{th}=168mA)



- Beam tilt due to the transverse wake fields
  - When a beam passes through a impedance with a transverse offset, the tail particles will receive transverse kicks

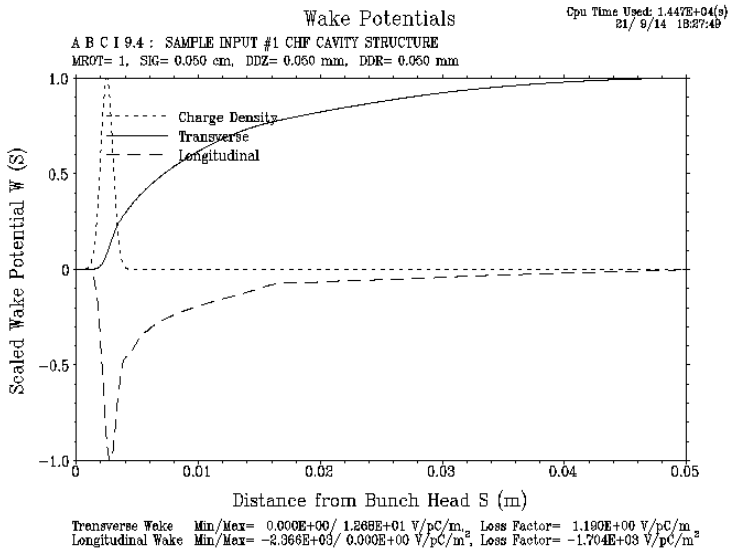
$$\Delta y'(z) = \frac{Ne^2}{E}\int_0^\infty dz'\rho(z'+z)W_\perp(y_b, z')$$

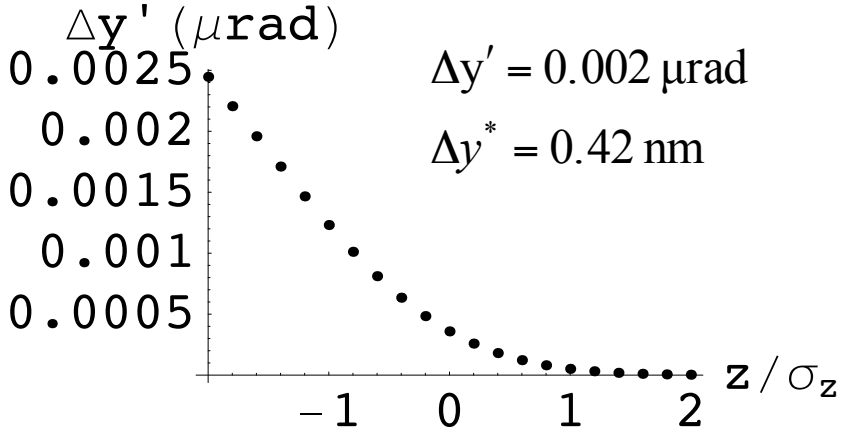
  - This will lead to a transverse displacement of the bunch tail at IP

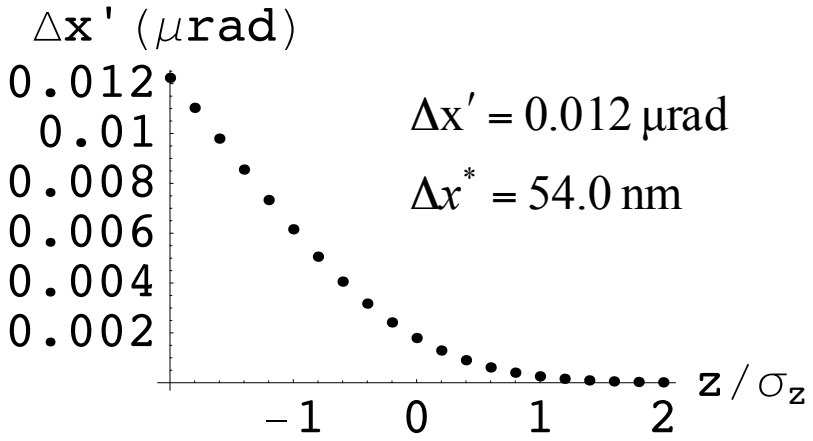
$$\Delta y = \sqrt{0.5\beta_y^*\beta_y}\,\Delta y'$$

  - CEPC case:
    - Pretzel orbit of 5mm in horizontal
    - Closed orbit of 1mm in vertical

- Beam tilt due to the RF cavity wake
  - Transverse wake for one RF cavity with σ_z=0.5mm







As there are 384 cavities located in 8 positions in the ring, the displacements at IP are

$\Delta x^* = 48\sqrt{8} * 54.0\text{nm} = 7.3\mu\text{m}$

$\Delta y^* = 48\sqrt{8} * 0.42\text{nm} = 0.057\mu\text{m}$

(beam size at IP: $\sigma_x^*/\sigma_y^* = 69.97/0.15\mu\text{m}$)

KEKB's impedance model (D. Zhou, K. Ohmi, A. Chao, IPAC2011, p.601)

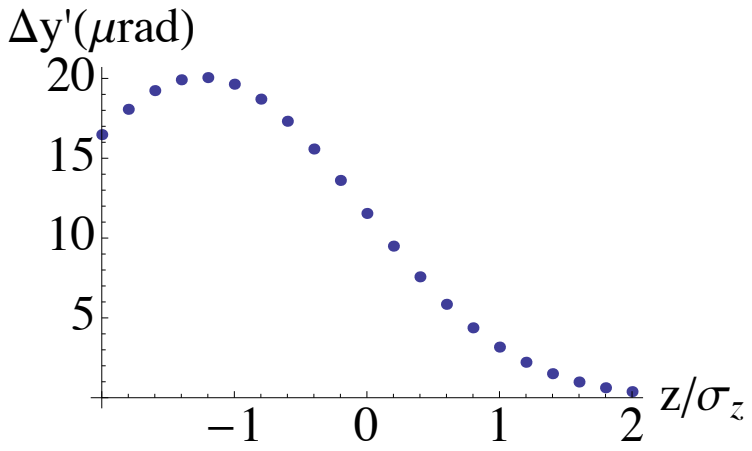
$\frac{\omega_r}{c} = 400\mathrm{m}^{-1}$

$R_s^1 = 4\times10^8\,\Omega/\mathrm{m}^2$

$Q = 1$

$\Delta x' = 100.3\,\mu\mathrm{rad}, \quad \Delta x^* = 442.3\,\mu\mathrm{m}$

$\Delta y' = 20.1\,\mu\mathrm{rad}, \quad \Delta y^* = 3.4\,\mu\mathrm{m}$



LEP's impedance model (B. Zotter, EPAC1992, p.273)

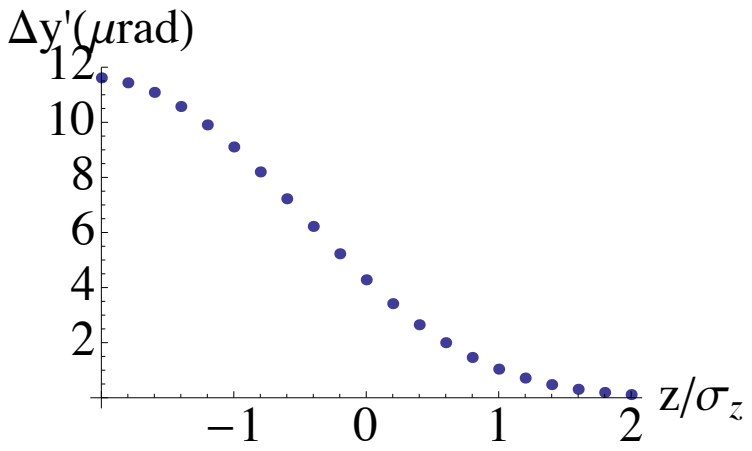
$\frac{\omega_{r1}}{c} = 42\mathrm{m}^{-1}$ $\qquad$ $\frac{\omega_{r2}}{c} = 252\mathrm{m}^{-1}$

$R_s^1 = 5.9\times10^7\,\Omega/\mathrm{m}^2$ $\qquad$ $R_s^2 = 1.5\times10^8\,\Omega/\mathrm{m}^2$

$Q = 1$ $\qquad$ $Q = 1$

$\Delta x' = 58.1\,\mu\mathrm{rad}, \quad \Delta x^* = 256.2\,\mu\mathrm{m}$

$\Delta y' = 11.6\,\mu\mathrm{rad}, \quad \Delta y^* = 2.0\mu\mathrm{m}$



- The impedance is assumed to be localized at one point in the ring → Distributed impedance will reduce this effect.
- Average beta function is used instead of that at the location of impedance → Smaller beta function can reduce this effect.
- Transverse impedance should be carefully studied and well controlled.

3. Multi-bunch effects

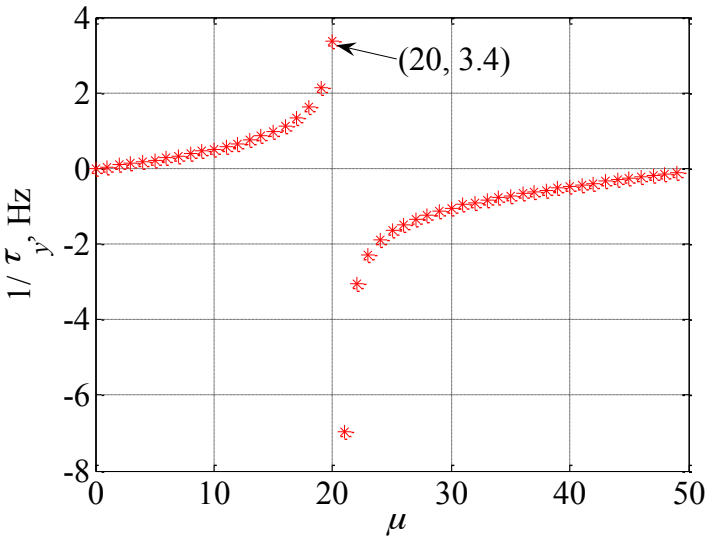
- Transverse resistive wall instability

$$\frac{1}{\tau_\perp} = -\frac{n_b I_b c}{4\pi (E/e)\nu_{x,y}} \sum_{p=-\infty}^{\infty} e^{-(\omega_{pn}-\xi\omega_0/\alpha_p)^2\sigma_\tau^2} \operatorname{Re} Z_\perp(\omega_{pn})$$

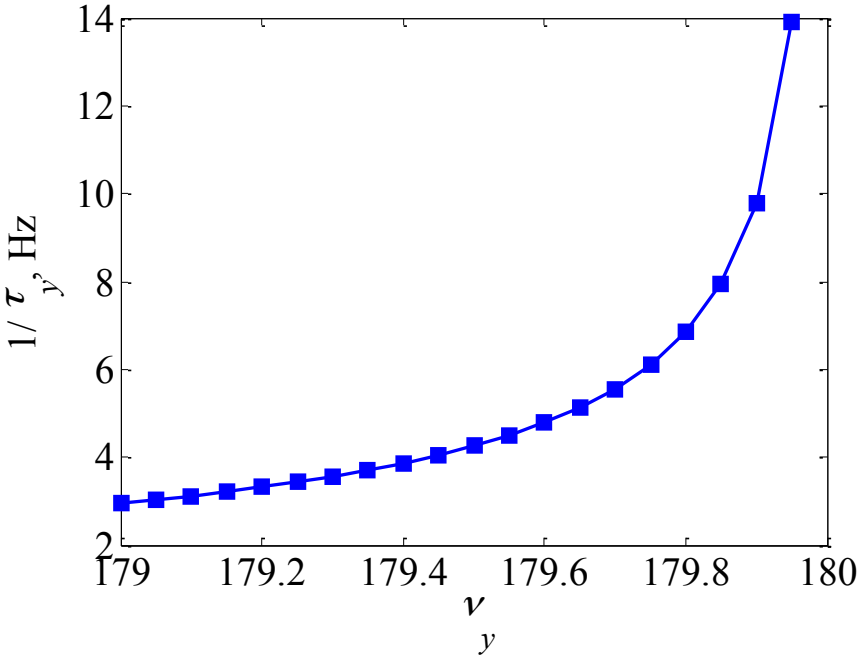
$$\text{with } \omega_{pn} = 2\pi f_{rev} \times (pn_b + n + \nu_{x,y})$$

➢ The growth rate for the most dangerous instability mode is 3.4 Hz (τ=0.3s) in the vertical plane with mode number of μ = 20.

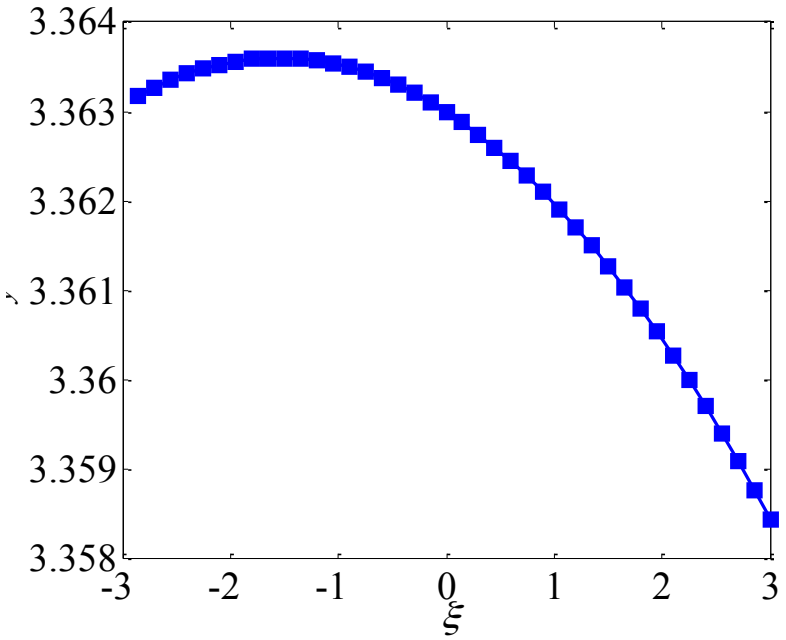
➢ The growth time is much higher than the transverse radiation damping time.



Growth rate vs. mode number in the vertical plane



Instability growth rate vs. vertical tune



Instability growth rate vs. chromaticity

- Smaller decimal tune is preferred to alleviate the transverse resistive wall instability.
- The growth rate is not quite sensitive to the chromaticity.

- Coupled bunch instability induced by the RF HOM's

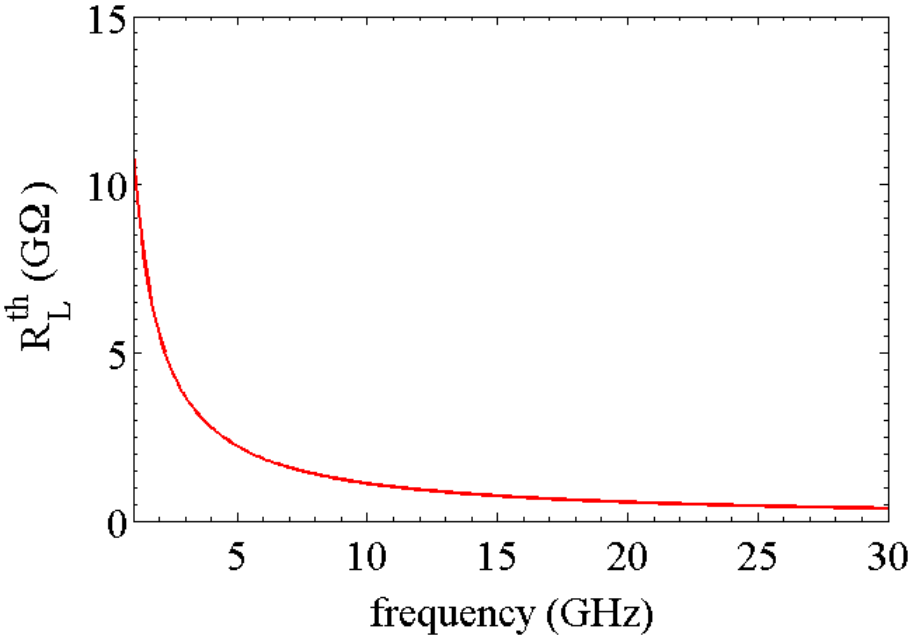
Monopole Mode	***f* (GHz)**	***R*/*Q*(Ω)** *
TM011	1.173	84.8
TM020	1.427	54.15
Dipole Mode	***f* (GHz)**	***R*/*Q*(Ω/m)****
TE111	0.824	832.23
TM110	0.930	681.15
TE122	1.232	544.5
TM112	1.440	101.53

* $k_{//\,\mathrm{mode}} = 2\pi f \cdot (R/Q)/4$ [V/pC]

** $k_{\perp\,\mathrm{mode}} = 2\pi f \cdot (R/Q)/4$ [V/(pC·m)]

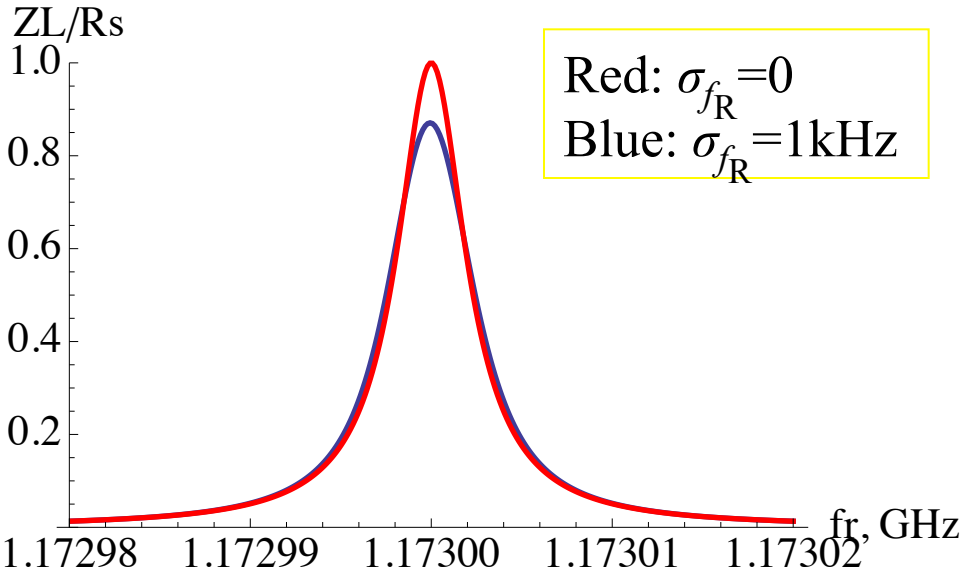
- To keep the beam stable, the radiation damping time should be less than the rise time of any of the oscillation modes.
- In the resonant condition, the threshold shunt impedances are

$$R_L^{th} = \frac{2(E_0/e)\nu_s}{f_L I_0 \alpha_p \tau_z} = \frac{11.1(\mathrm{G\Omega \cdot GHz})}{f_L(\mathrm{GHz})} \qquad R_T^{th} = \frac{2(E_0/e)}{f_{rev} I_0 \beta_{x,y} \tau_{x,y}} = 3.9(\mathrm{G\Omega/m})$$

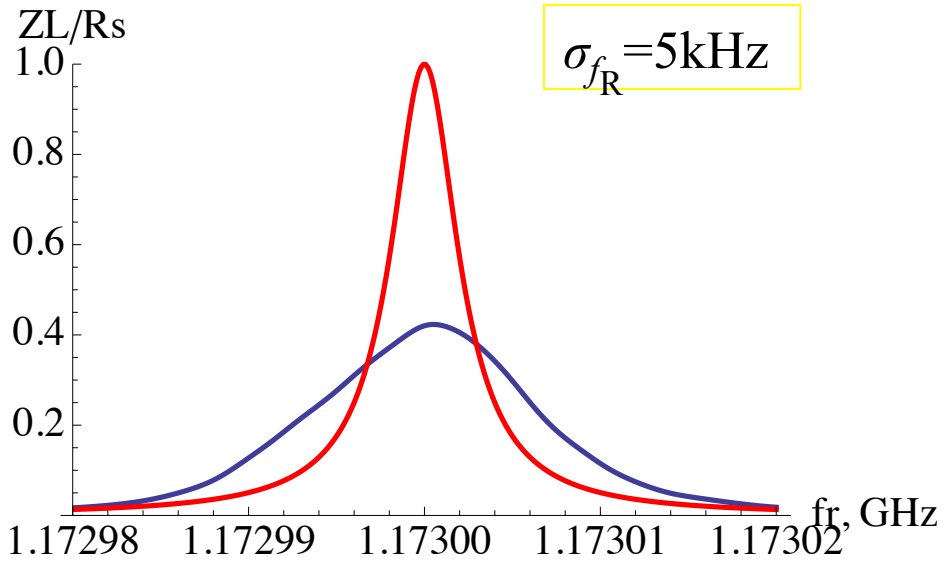


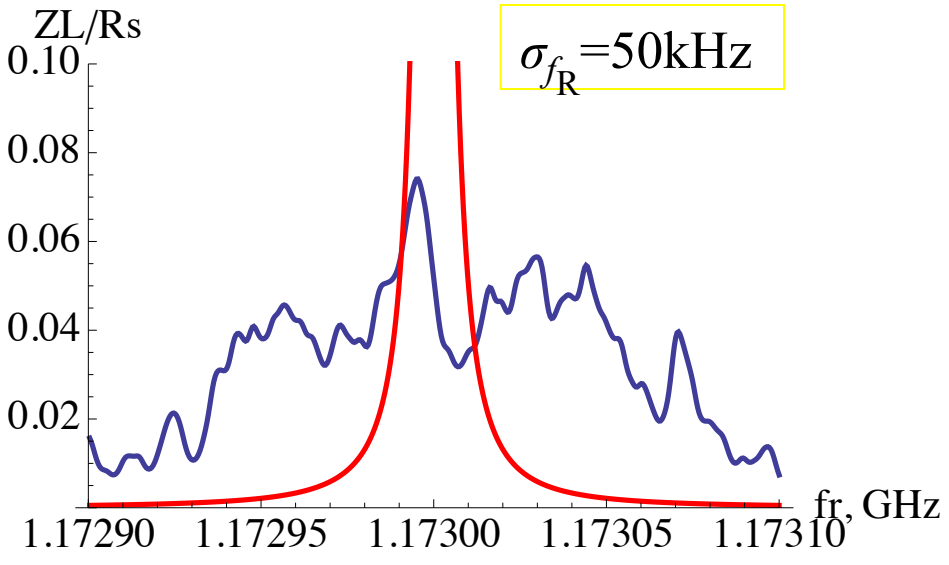
Longitudinal impedance threshold

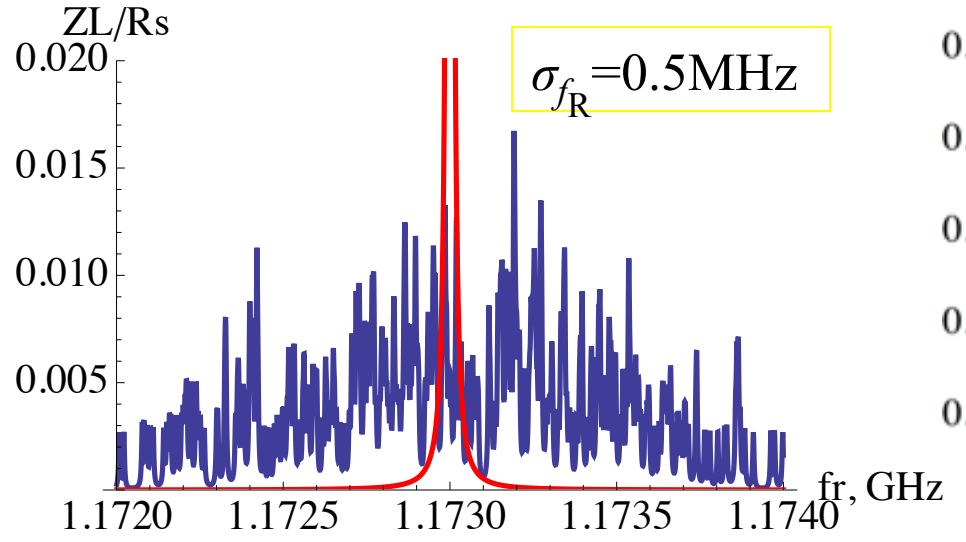
- Considering the whole RF system, there will be finite tolerances in the cavity construction.
- To find the total effects of all the RF cavities, we need to take into account the spread in the resonance frequencies of different cavities.
- For small frequency spread, this will result in an "effective" quality factor Q of the whole RF system.

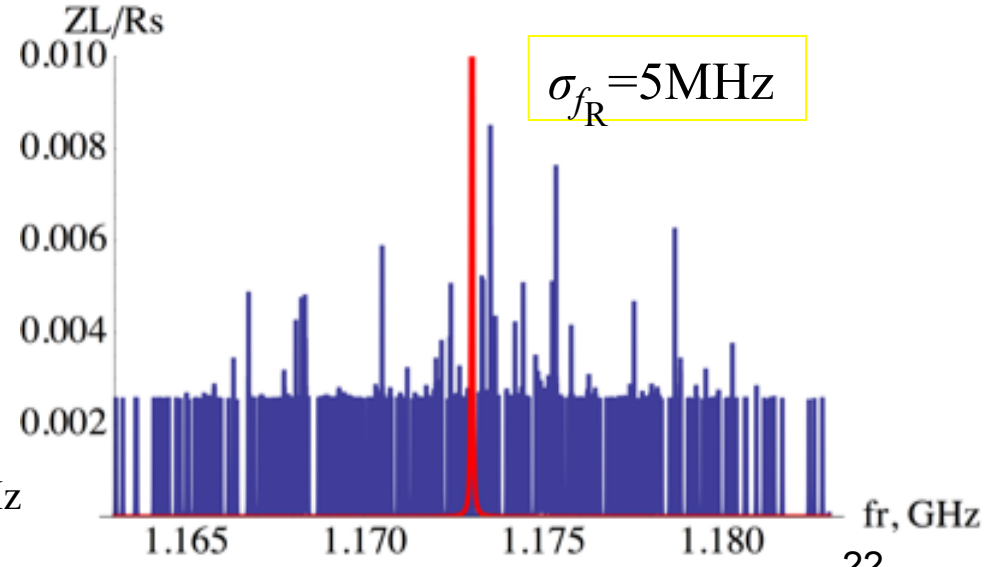


f_R=1.173GHz, Q=2.54×10^5, 384 RF cavities


ZL/Rs
1.0
0.8
0.6
0.4
0.2
σ_{f_R}=5kHz
fr, GHz
1.17298
1.17299
1.17300
1.17301
1.17302


ZL/Rs
0.10
0.08
0.06
0.04
0.02
σ_{f_R}=50kHz
fr, GHz
1.17290
1.17295
1.17300
1.17305
1.17310


ZL/Rs
0.020
0.015
0.010
0.005
σ_{f_R}=0.5MHz
fr, GHz
1.1720
1.1725
1.1730
1.1735
1.1740


ZL/Rs
0.010
0.008
0.006
0.004
0.002
σ_{f_R}=5MHz
fr, GHz
1.165
1.170
1.175
1.180

4. Electron cloud instability

- The threshold value of the volume density of the electron cloud for the head-tail instability

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z / c}{\sqrt{3}KQr_0\beta L}$$

$K = \omega_e\sigma_z/c$
$Q = \min(Q_{nl}, \omega_e\sigma_z/c)$
Q_{nl} depends on the nonlinear interaction

  - We take Q_{nl} = 7 for analytical estimation, and get the threshold density for the single bunch instability is 9.3×10^{11} m^{-3}

- For the multi-bunch instability, the electron cloud is considered as a rigid Gaussian with the chamber size. The characteristic frequency is

$$\omega_{G,y}^2 = \frac{2\lambda_b r_e c^2}{(\sum_x + \sum_y)\sum_y}$$

  - The phase angle between adjacent bunches is $\omega_G L_{SP}/c$ = 32.3, which means the electrons are not supposed to accumulate and the multipacting effects is low.

	KEKB	SuperKEKB	SuperB	CEPC
Beam energy E, GeV	3.5	4.0	6.7	120
Circumference L, m	3016	3016	1370	54752
Number of e^+/bunch, 10^{10}	3.3	9	5.74	37.9
Emittance H/V $\varepsilon_x/\varepsilon_y$, nm	18/0.36	3.2/0.01	1.6/0.004	6.12/0.018
Bunch length σ_z, mm	4	6	5	2.88
Bunch space Lsp, ns	2	4	4	3653
Single bunch effect				
Electron freq. $\omega_e/2\pi$, GHz	35.1	150	272	187.3
Phase angle $\omega_e\sigma_z/c$	2.94	18.8	28.5	10.6
Threshold density $\rho_{e,th}$, $10^{12}m^{-3}$	**0.7**	**0.27**	**0.4**	**0.9**
Multi-bunch effect				
p-e per meter n_γ, p/(m)	5.0E8	1.5E9	3.6E9	1.1E10
Characteristic freq. ω_G, MHz	62.8	87.2	69.6	8.8
Phase angle $\omega_G L_{sp}/c$	**0.13**	**0.35**	**0.28**	**32.3**

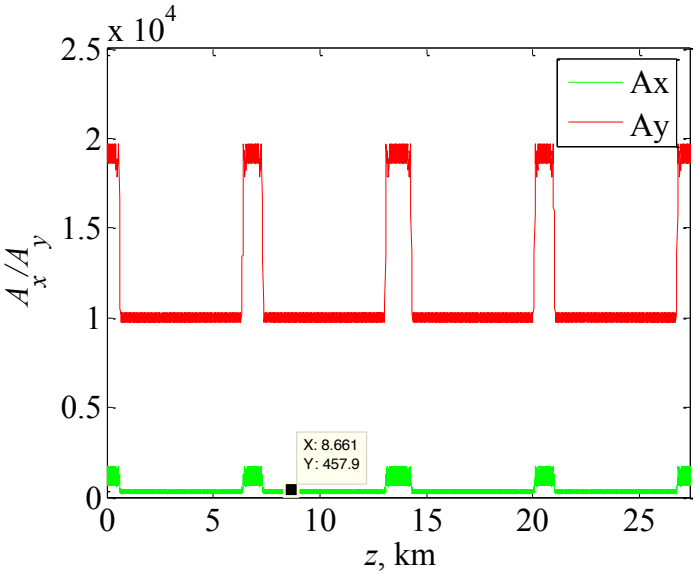
- Threshold density for the single bunch effect is considerable high.
- The phase angle for the multi-bunch effect is about two orders higher.

5. Beam ion instability

- Ion trapping
  - With uniform filling pattern, the ions with a relative molecular mass larger than $A_{x,y}$ will be trapped.

$$A_{x,y} = \frac{N_b r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x,y}}$$

The critical mass number is quite high, so the ions will not be trapped by the beam.



Critical mass number along half of the ring

- Fast beam ion instability
  - The phase angle between adjacent bunches is $\omega_i L_{sep}/c$=42. So the ions will not accumulate due to the overfocus inside the bunch train.

The effect of pretzel on the instability

- In the pretzel scheme, there are two beams hosted in the same beam pipe.
- When a beam cross a resonator (eg. RF cavity), the wake field excited by the beam will affect the other beam, i.e. the two beams will talk to each other.
- For the electron cloud instability, the electron beam will disturb the electron cloud accumulation. For the beam ion instability, the positron beam will affect the distribution of the ions in the beam pipe. In some point of view, both effects will be suppressed by the other counter rotating beam. (Discussion with K. Ohmi and G. Stupakov)

Summary

- With the impedance of resistive wall and RF cavities, the bunch length is reduced due to the capacitive property of the RF cavity. Analysis based on KEKB's geometry impedance shows that bunch lengthening of 10% is expected.
- Bunch shape distortion due to the transverse wake is another potential restriction to the high luminosity. More detail analysis take into account impedance localization are needed.
- CEPC should be safe from microwave instability and transverse mode coupling instability.
- Coupled bunch instabilities are less important compare to the single bunch effects since the bunch spacing is large.
- Electron cloud and ion instability should not be a problem due to the overfocus inside the bunch train.
- The effect of pretzel on the beam instability will be studied in the future.

Thank you for your attention!