Impedance and collective effects for CEPC double ring

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Outline

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

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Main parameters of CEPC

Parameter	Symbol, unit	H-High lumi.	H-low power	Z
Beam energy	E, GeV	120	120	45.5
Circumference	C, km	54	54	54
Beam current	I_0, mA	16.9	10.5	45.4
Bunch number	n_b	67	44	1100
Bunch Population	N_e	2.85×10^{11}	2.67×10^{11}	0.46×10^{11}
Natural bunch length	σ_{l0}, mm	4.1	4.0	4.0
Emittance (horz./vert.)	$\varepsilon_x/\varepsilon_y$, nm	2.45/0.0074	2.06/0.0062	0.62/0.002
RF frequency	f_{rf}, GHz	0.65	0.65	0.65
Harmonic number	h	117081	117081	117081
Natural energy spread	σ_{e0}	1.3E-3	1.3E-3	5.0E-4
Momentum compaction factor	α_p	2.5E-5	2.2E-5	3.5E-5
Betatron tune	ν_x/ν_y	319.21/318.42	319.21/318.42	?
Synchrotron tune	ν_s	0.08	0.08	0.04
Damping time (H/V/s)	$\tau_x/\tau_y/\tau_z$, ms	14/14/7?	?	?

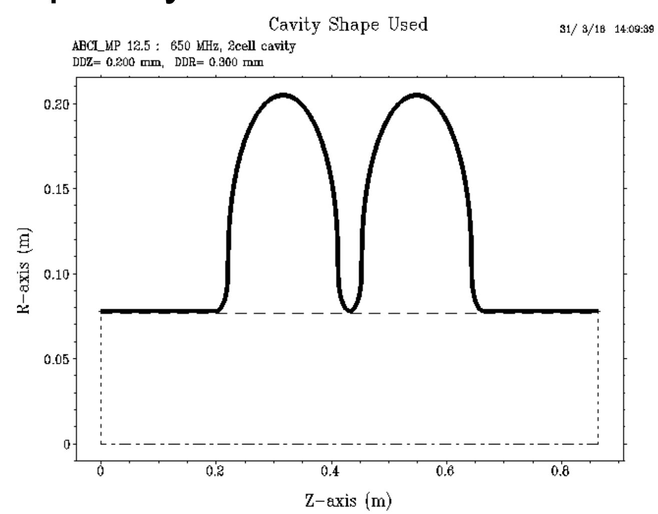
1. Impedance budget

- Resistive wall
  - Copper beam pipe with NEG coating will be used. The beam pipe has an elliptical cross section with half height of a_x/a_y=52/28 mm.
  - Resistive wall impedance in a two layer cylindrical beam pipe

$$Z_{\parallel}^{RW}(\omega)=\frac{iZ_0ck_r}{2\pi\omega a_2}\frac{I_0(k_ra_1)I_0(k_rr)}{I_0(k_ra_2)}\left[\frac{\kappa M}{\kappa MI_1(k_ra_2)+I_0(k_ra_2)}\right]$$

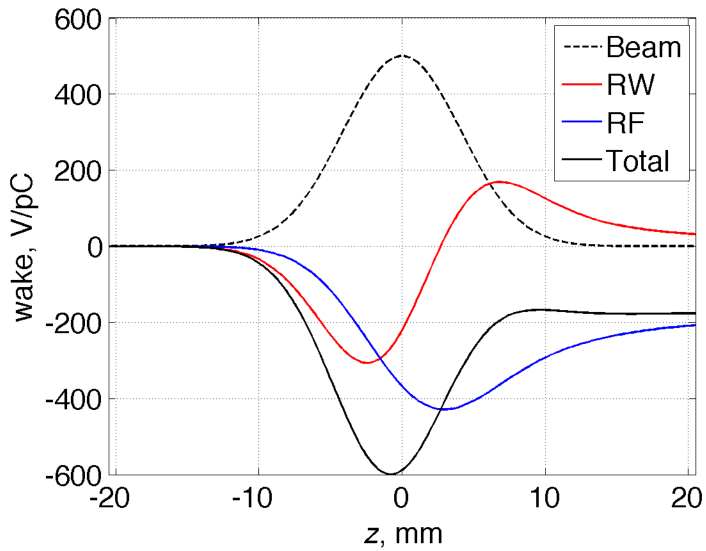
where $I_n(x)$ are the modified Bessel functions, κ and M are determined by the parameters of the beam pipe.

- RF cavities
  - A five cell SC RF cavity structure with RF frequency of 650 MHz will be used.
  - Given a design accelerating gradient of ~20MV/m, 384 cavities are needed.
  - The wake of the RF cavities is calculated with ABCI.



- CEPC ring wake and impedance budget

Object	Contributions			
	R [kΩ]	L [nH]	k_{loss} [V/pC]	$\|Z_{//}/n\|_{eff}$ [Ω]
Resistive wall	6.1	154.7	146.8	0.017
RF cavities (N=384)	14.9	-132.7	307.5	0.005
Total	21.0	22.0	454.3	0.022



Longitudinal wake at nominal bunch length (σ_z=4.1mm)

- The loss factor is dominated by the RF cavities.
- 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 $|Z_{//}/n| < 0.024\ \Omega$.
  - LEP:

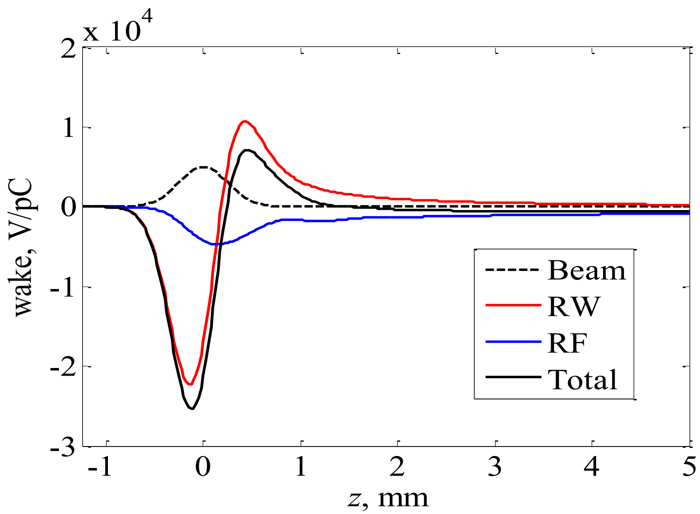
    Threshold current for turbulent bunch lengthening was measured. And the stability criterion gives effective longitudinal impedance of about 30 mΩ. (B. Zotter, EPAC'92, p.273)

Old!!!

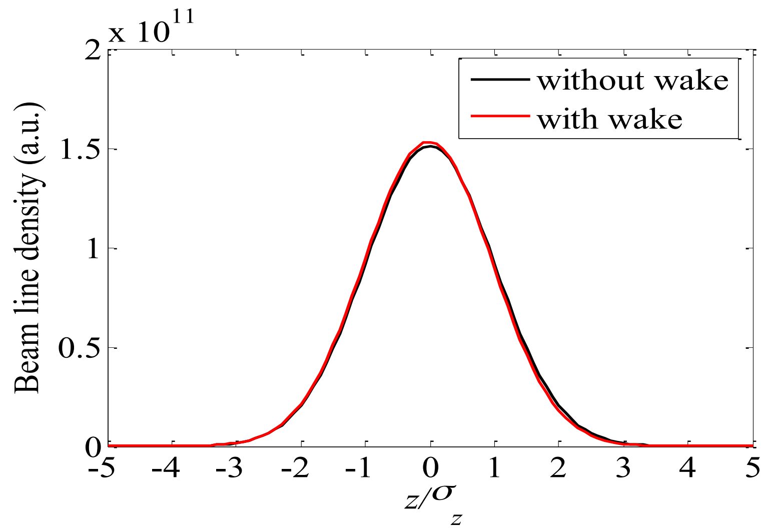
- Bunch lengthening
  - Steady-state bunch shape is obtained by numerically solving the Haissinski equation.

$$\rho(z) = \rho(0)\exp\left[-\frac{1}{2}\left(\frac{\omega_s z}{\eta c \sigma_\delta}\right)^2 + \frac{r_0}{\eta \sigma_\delta^2 \gamma C}\int_0^z dz'' \int_{z''}^{\infty} dz' \rho(z') W_0'(z''-z')\right]$$

  - The Pseudo-Green function wake with bunch length of 0.25mm 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=0.25mm)

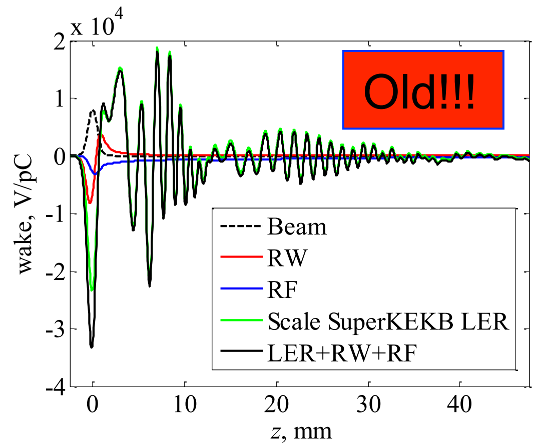


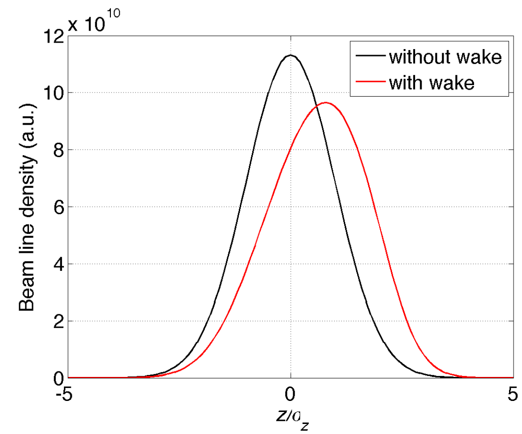
Steady-state bunch distribution

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

– Scaled LER wake+RW

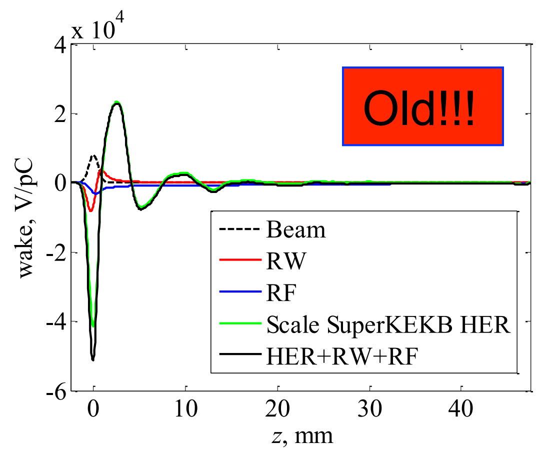
– Bunch is lengthened by 17.8%

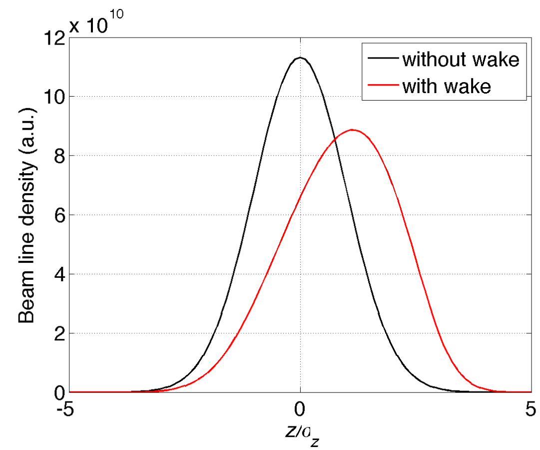




– Scaled HER wake+RW

– Bunch is lengthened by 29.0%





- 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.

- 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

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

  - For CEPC, $\sigma_z\rho^{1/2}/h^{3/2}$=68.9 (=> CSR shielded)
  - The CSR threshold in CEPC is $N_{b,Th} = 1.7\times10^{13} >> N_b = 2.85\times10^{11}$.

- Space charge tune shift

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

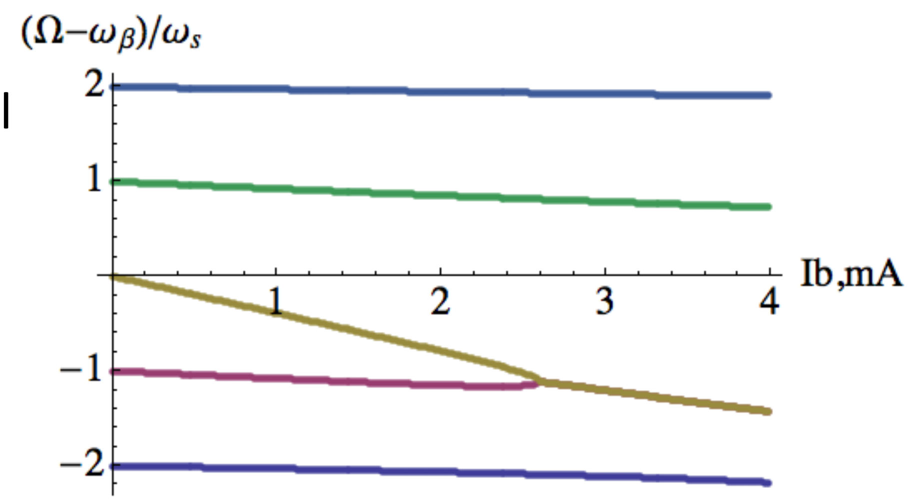
$\Delta\nu_y = -3.6e-4$, $\Delta\nu_x = -2.0e-5$

- Transverse mode coupling instability (TMCI)
  - For Gaussian bunch, the threshold of the instability can be expressed with the transverse loss factor:

$$I_0^{th} = \frac{2Q_s\omega_0 E / e}{\sum_j \beta_{\perp,j}\kappa_{y,j}}\Theta$$

  - The total kick factor is 10.2kV/pC/m, which gives the threshold bunch current is 1.7 mA ($N_b^{th} = 1.9\times10^{12}$)

- Eigen mode analysis
  - Considering only resistive wall impedance
  - Beam current threshold: I_b^{th}=2.6mA (I_0^{th}=115mA)



- Tune shift due to transverse impedance
  - With transverse tune of (319.21, 318.42), beam could become unstable at lower current than that for transverse mode coupling instability.

$$\Delta\nu_\beta = -i\,\frac{N_e r_e}{4\pi^{3/2}\gamma}\frac{L}{\nu_\beta\sigma_z}\frac{Z_{\mathrm{eff}}}{Z_0}$$

  - The tune shift is given by

$$\Delta\nu_\beta = -2.22\times\frac{N_e}{3.77\times10^{11}}Z_{eff}\left(\frac{\mathrm{M\Omega}}{\mathrm{m}}\right)$$

  - When the tune approaches to integer, the tune variation is larger than that given by the above equation.
  - The effective impedance for $\Delta\nu_\beta$=0.21 is Z_{eff}=12.5MΩ/m
  - Effective impedance:

    Z_{eff}= 468 kΩ/m (CEPC resistive wall)

    Z_{eff}= 26 kΩ/m (CEPC RF cavities)

    Z_{eff}=895 kΩ/m (KEKB, bunch shape taken into account)

    Z_{eff}=409 kΩ/m (LEP, bunch shape taken into account)

- 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

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

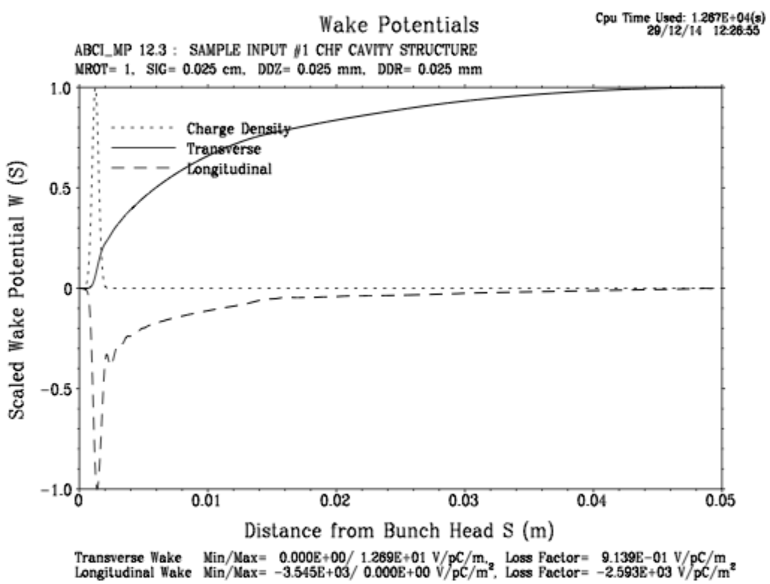
  - This will lead to a transverse displacement of the bunch tail at IP

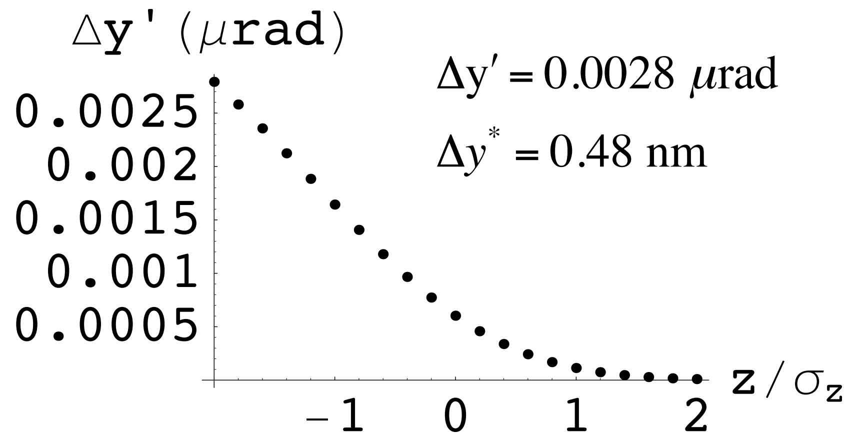
$$\Delta y = \sqrt{0.5\beta_y^*\beta_y}\,\Delta y'$$

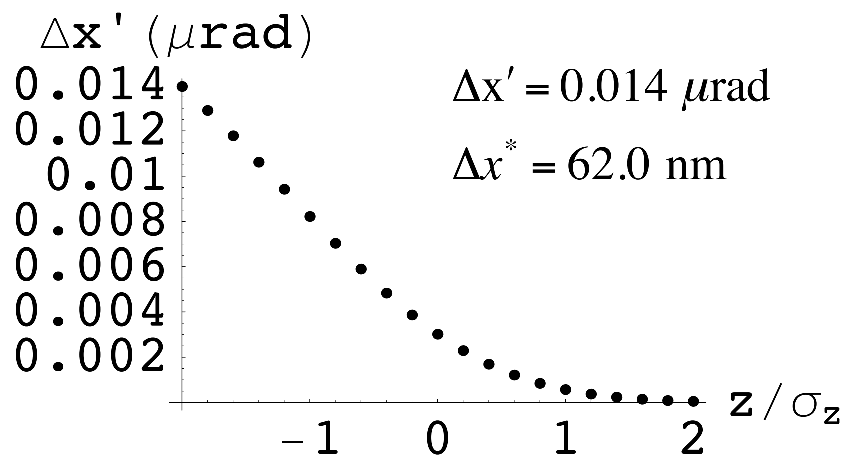
  - CEPC case:
    - Closed orbit of 1mm in vertical

Beam tilt due to the RF cavity wake

- Transverse wake for one RF cavity with σ_z=0.25mm







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

$\Delta x^*=48\sqrt{8}*62.0\text{nm}=8.3\mu\text{m}$

$\Delta y^*=48\sqrt{8}*0.48\text{nm}=0.065\mu\text{m}$

(beam size at IP: σ_x^*/σ_y^*=69.97/0.15μm)

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

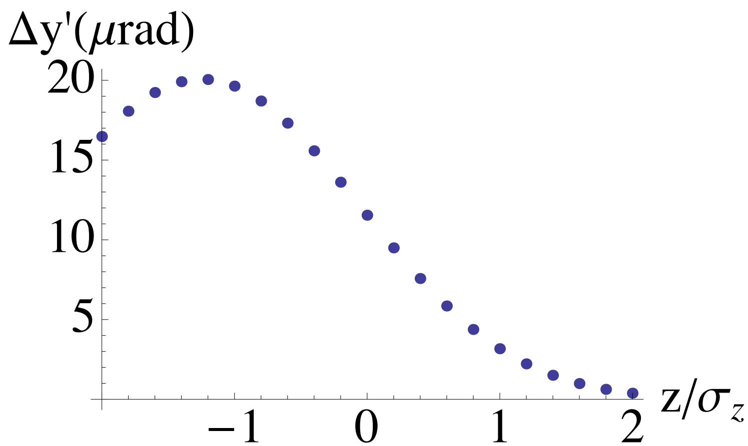
$$\frac{\omega_r}{c} = 400\mathrm{m}^{-1}$$

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

$$Q = 1$$

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

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



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

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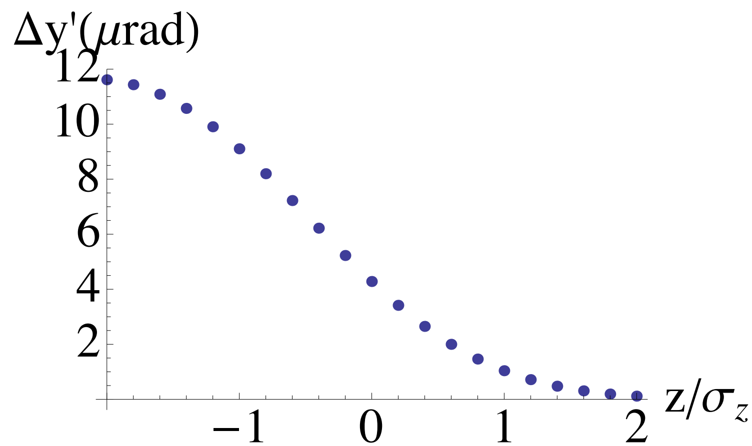
$$\frac{\omega_{r1}}{c} = 42\mathrm{m}^{-1} \qquad \frac{\omega_{r2}}{c} = 252\mathrm{m}^{-1}$$

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

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

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

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



- 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.

Old!!!

3. Multi-bunch effects

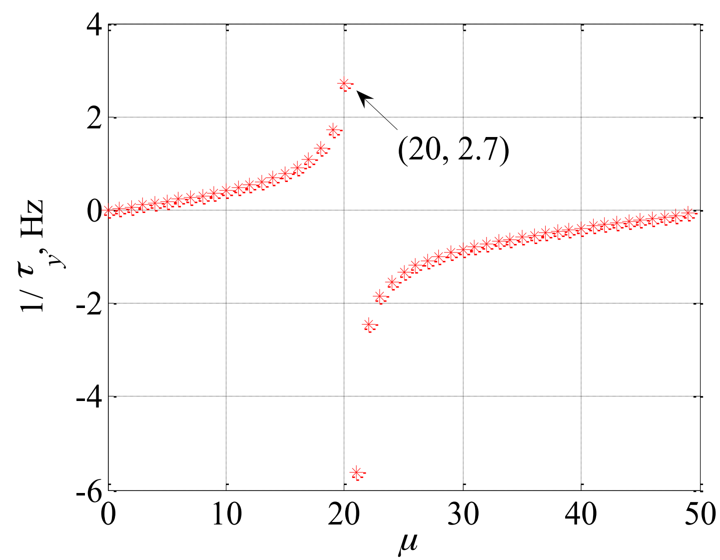
- Transverse resistive wall instability

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

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

➢ With bunch space of 159.3ns, the growth rate for the most dangerous instability mode is 2.7 Hz (τ=0.4s) 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

Old!!!

- Coupled bunch instability induced by the RF HOM's

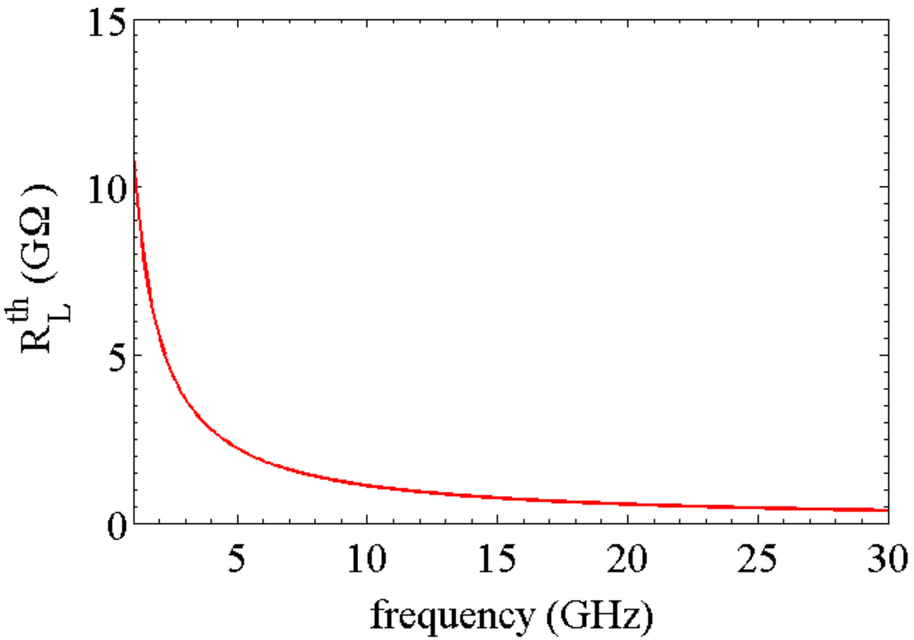
Monopole Mode	f **(GHz)**	$R/Q(\Omega)$ *
TM011	1.173	84.8
TM020	1.427	54.15
Dipole Mode	f **(GHz)**	$R/Q(\Omega/m)$ **
TE111	0.824	832.23
TM110	0.930	681.15
TE122	1.232	544.5
TM112	1.440	101.53

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

Old!!!

- 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

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



Longitudinal impedance threshold

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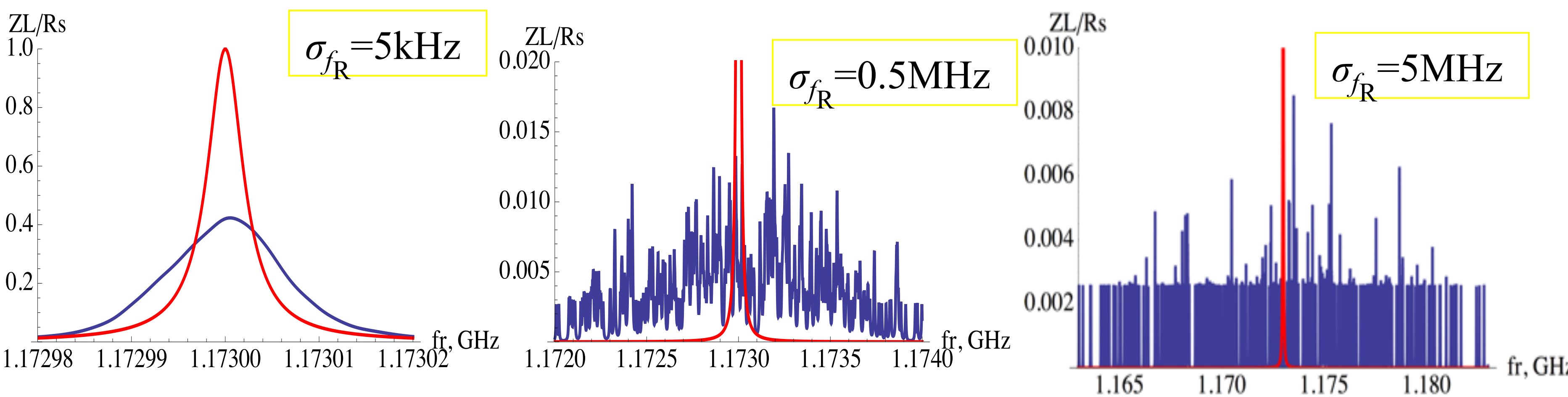
- Considering the whole RF system, there will be finite tolerances in the cavity construction.
- To find the total effects of all the RF cavities, we need to take into account the spread in the resonance frequencies of different cavities.
- For small frequency spread, this will result in an "effective"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



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

Old!!!

Monopole Mode	f (GHz)	$R/Q(\Omega)$ *	Q_{limit} σ_{f_R}=0.5MHz	Q_{limit} σ_{f_R}=5MHz
TM011	1.173	84.8	2.9×10^7	5.8×10^7
TM020	1.427	54.15	3.7×10^7	7.5×10^7
Dipole Mode	**f (GHz)**	**$R/Q(\Omega/m)$** **		
TE111	0.824	832.23	1.2×10^6	2.4×10^6
TM110	0.930	681.15	1.5×10^6	3.0×10^6
TE122	1.232	544.5	1.9×10^6	3.7×10^6
TM112	1.440	101.53	1.0×10^7	2.0×10^7

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

- The threshold value of Q largely depends on the actual tolerance of the cavity construction.

4. Electron cloud instability

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

$$\rho_{e,th} = \frac{2\gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L}$$

$K = \omega_e \sigma_z / c$
$Q = \min(Q_{nl}, \omega_e \sigma_z / c)$
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 7.5×10^{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 $\omega_G L_{SP}/c$ = 5.9, which means the electrons are not supposed to accumulate and the multipacting effects are 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	287
Phase angle $\omega_e\sigma_z/c$	2.94	18.8	28.5	24.7
Threshold density $\rho_{e,th}$, 10^{12}m^{-3}	**0.7**	**0.27**	**0.4**	**0.75**
Multi-bunch effect				
p-e per meter n_γ, p/(m)	5.0E8	1.5E9	3.6E9	8.2E9
Characteristic freq. ω_G, MHz	62.8	87.2	69.6	36.7
Phase angle $\omega_G L_{sp}/c$	**0.13**	**0.35**	**0.28**	**5.9**

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

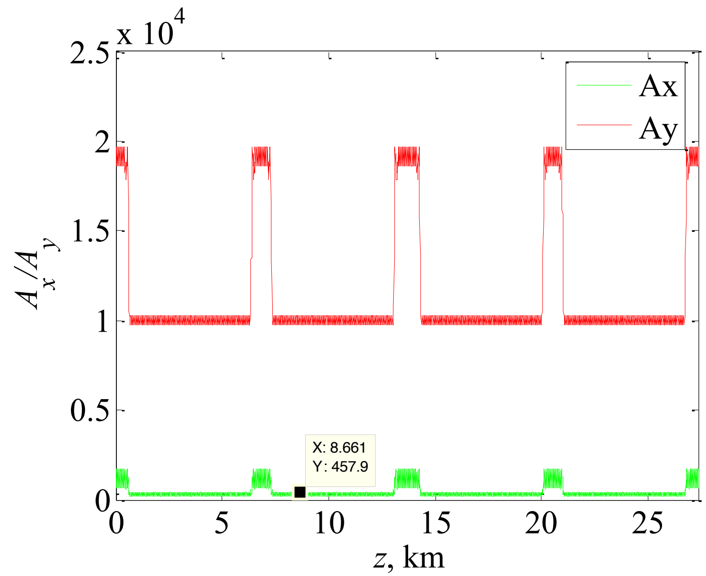
Old!!!

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.

Summary

Beam instability	H-High lumi.	H-low power	Z
Microwave instability, $\|Z_{\|\|}/n\|_{th}$ [mΩ]	24		
Bunch lengthening	10~20%		
CSR threshold N_{bth} [E11]	170		
Space charge tune shift $\Delta v_{x,y}$	-2E-5/-4E-4		
Transverse impedance tune shift $\Delta v_{x,y}$	-8E-3/-8E-3		
Transverse Mode Coupling, N_{bth} [E11]	19		
Beam tilt	?		
Transverse resistive wall instability, t [ms]	?		
Coupled bunch instability of HOM	?		
Electron cloud instability, N_{bth} [E11]	7.5		
Fast beam ion instability, t [ms]	?		