The broad-band impedance budget in the accumulator ring of ALS-U project

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Acknowledgment

AR Impedance Collaboration:

- Physics group: Marco Venturin, Stefano De Santis, Derun Li, Tianhuan Luo (LBNL)
- Engineering group: Michael Mardenfeld, Tom Miller (LBNL)
- Karl Bane (consultant) and Robert Warnock from SLAC
- Rui Li from Jlab

Outline

1. Motivation of the study on broad-band (BB) impedance at ALS-U

2. Methods we are using

3. Broad band Impedance modeling
   - Resistive wall
   - Geometric

4. Total budget: longitudinal & transverse

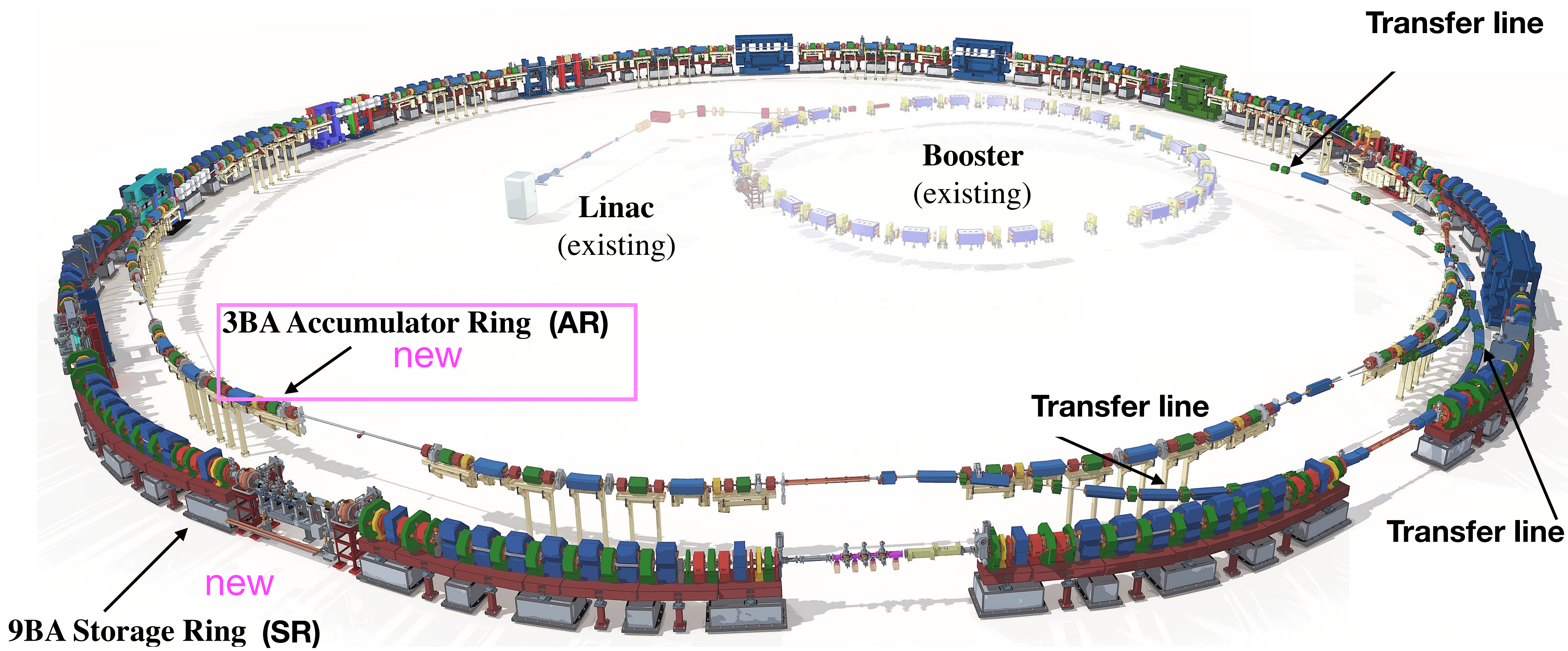
5. Beam instability study due to broad band impedance
   - Longitudinal threshold
   - Transverse threshold

6. Discussion and Summary

Motivation and method

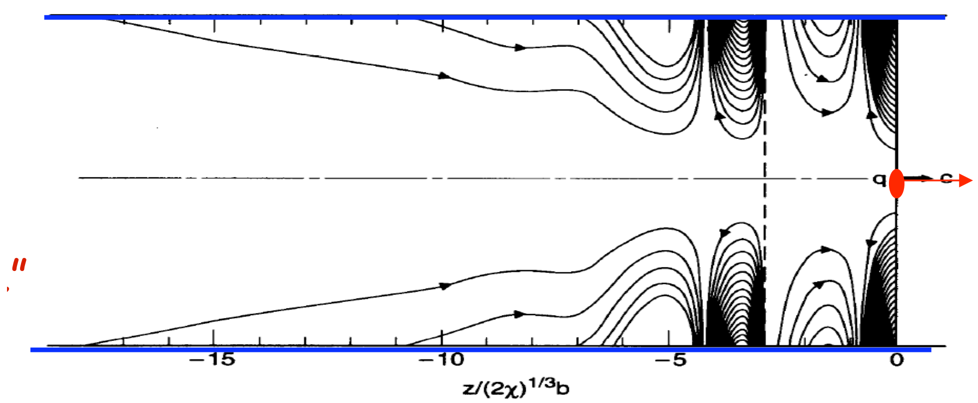
Introduction of the ALS-U project

- Update of the Advanced Light Source (ALS-U) to a multi-bend-achromat lattice as a 4th generation LS
- Provide a soft x-ray source that is up to 100–1,000 times brighter than today's ALS

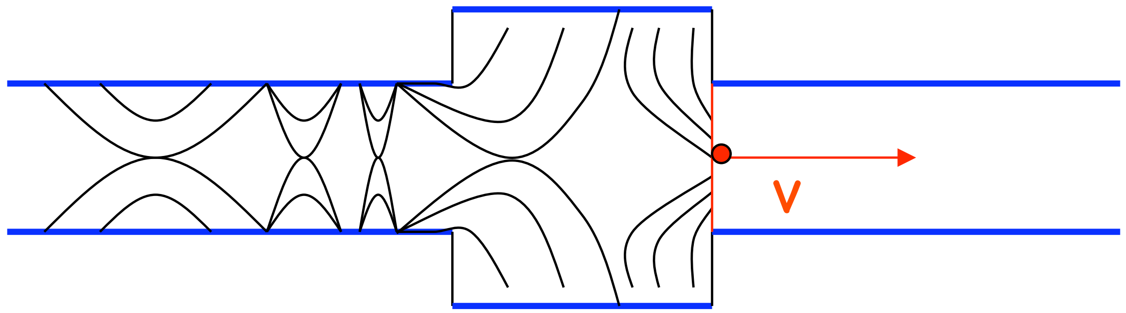


Short-range wakefield/BB impedance in the ring

- Source: resistive wall // geometric elements



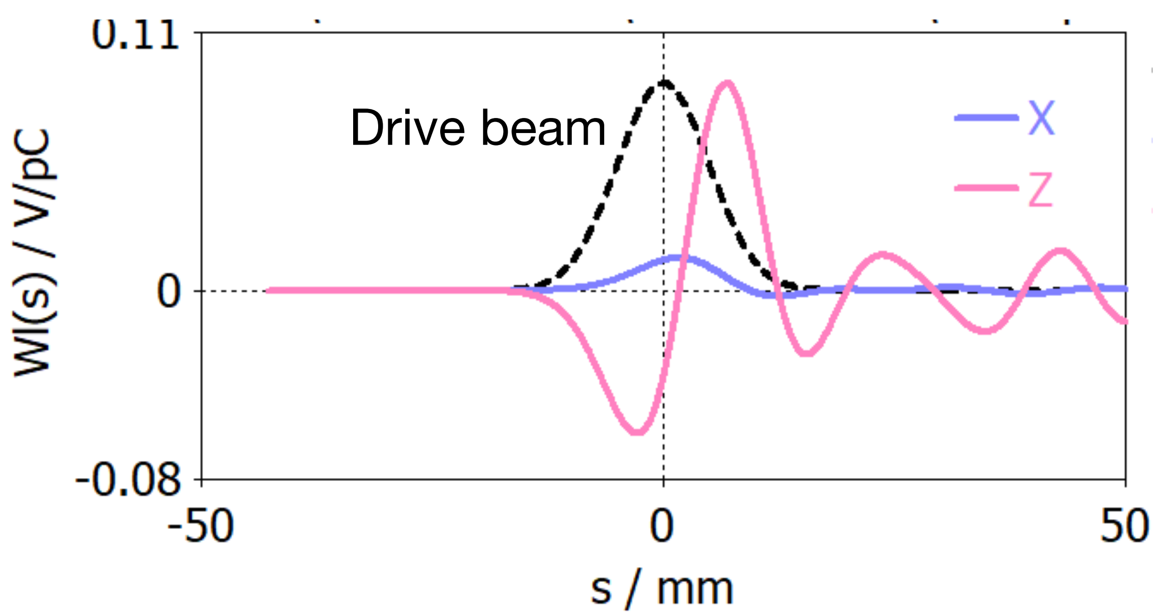
Wakefield in smooth pipe with finite resistance



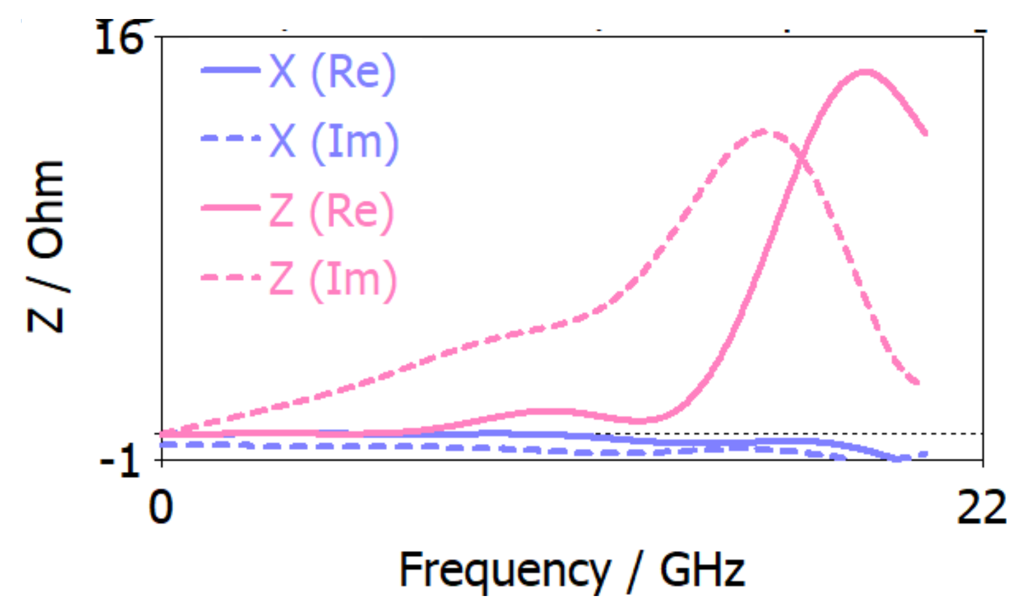
Wakefield in intersection of a geometry change

FFT

Short range wakefield

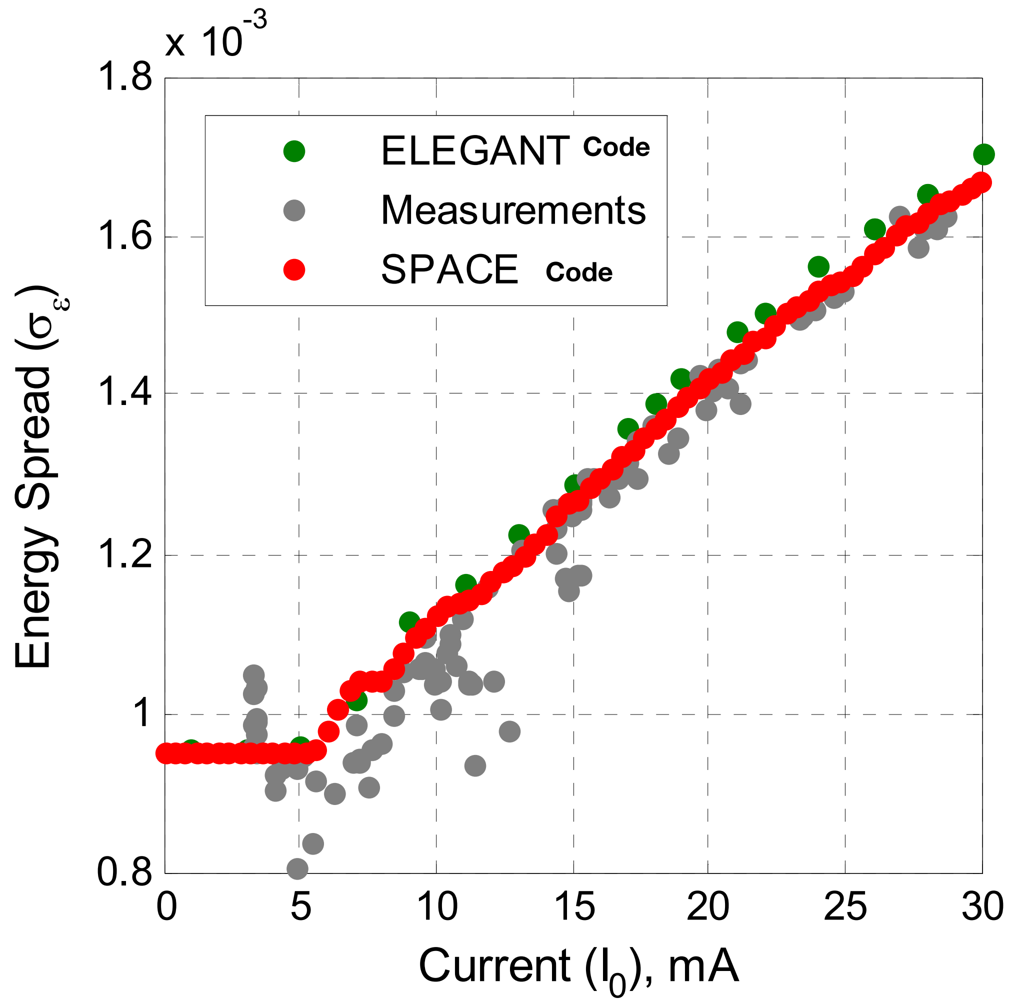


Broad-band Impedance

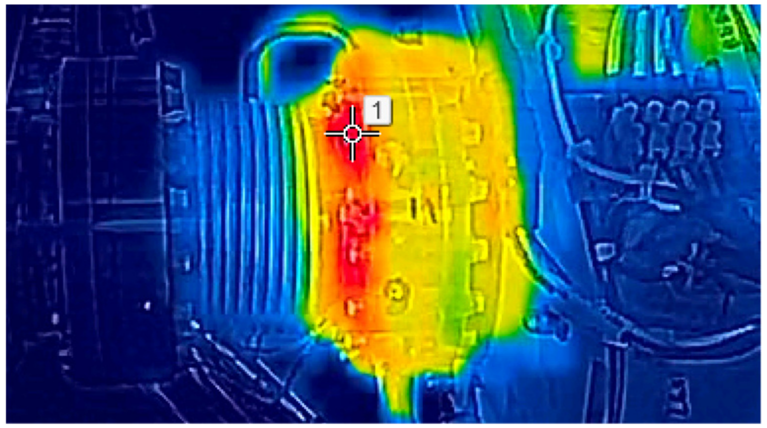


Short-range wakefield/BB impedance in the ring

- Effect: deterioration of beam quality (bunch lengthening, tune shift, instability…) // overheat the vacuum chamber
- limitation of beam intensity ☹



[1] Energy spread increase when charge goes high due to BB impedance @ APS
A. Blednykh, et., al., NAPAC2016, TUPOB51



[2] Local overheating image of flange joint at NSLS-II A. Blednykh, et., al., IPAC2019, TUPGW082

[3] Spring deformed and brazed to RF fingers @ LHC

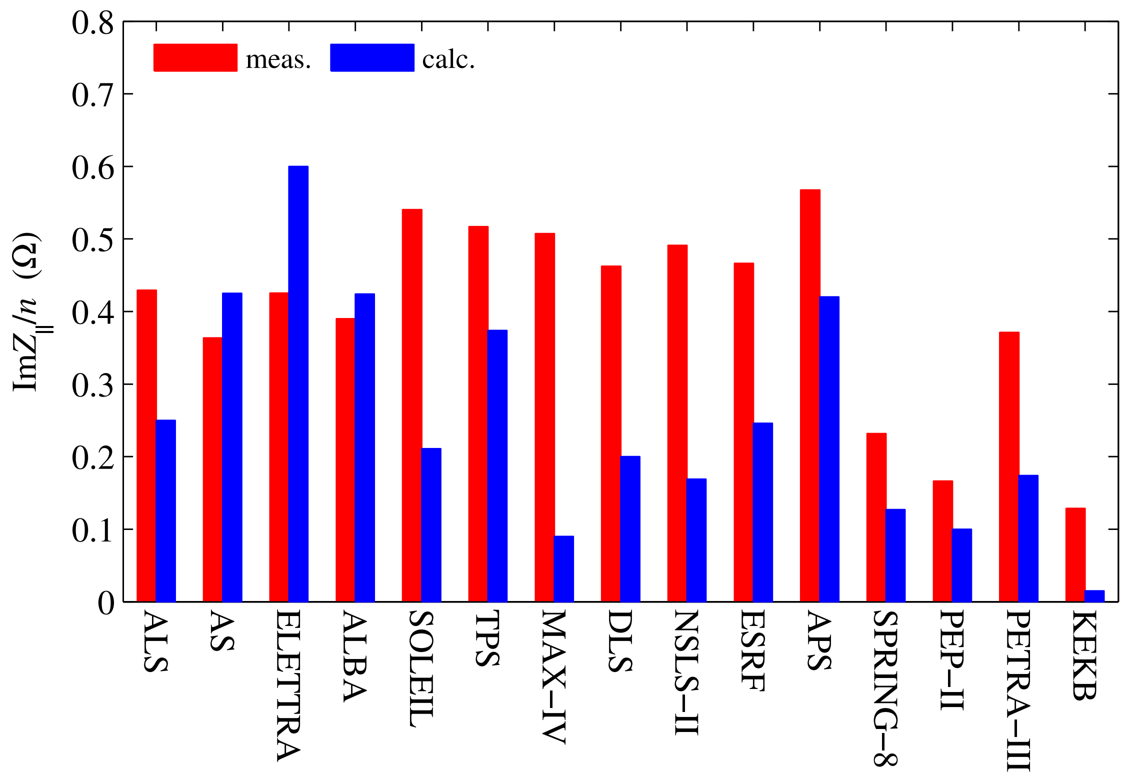
E. Métral, et., al., IPAC2013, TUPWA042

Overview of the BB impedance study

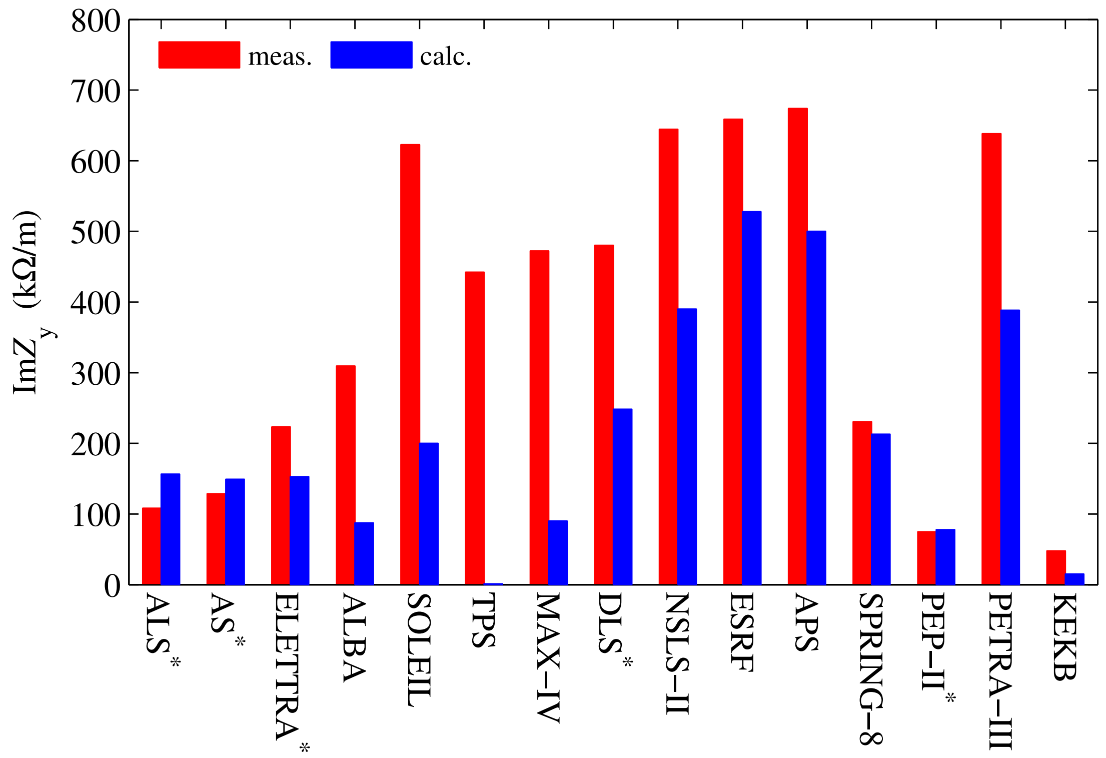
- Essential part of accelerator design
- Similar oder of the impedance value for different facilities
- Discrepancy between measurement and calculation…

Measurements and calculated BB impedance budgets for different rings

V. Smaluk., to be published in NIMA, 2018



Longitudinal normalized impedance



Vertical low-frequency impedance

Workflow/method in the study

- Close collaboration with vacuum engineers

Optimize for low impedance

Vacuum design → Impedance modeling → Impedance budget → Beam dynamics

Vacuum design	Impedance modeling	Impedance budget	Beam dynamics
Excel List; track	**3D CST particle studio*** CAD model—> W(s) & Z(w) **Analytical** prediction; cross-check	**Matlab** Data post-processing	**Elegant** Macro-particle simul. **VPF solver** Numerical solver **Analytical** Instability threshold**

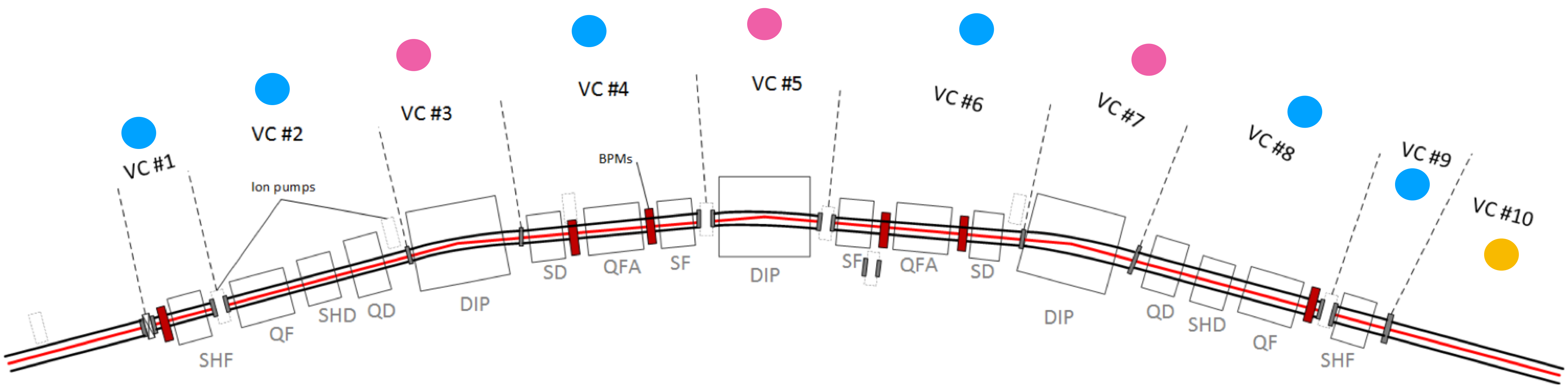
*In the modeling we use both 5mm (nominal bunch length of designed beam) and 1mm drive beam (correspondent to impedance up to 100 GHz, to get the Pseudo-Green function in beam dynamics study)

**The designed beam at ALS-U AR is 1.15nC

Impedance modeling

Identify the impedance source_1: resistive wall

- Resistive wall impedance is determined by the beam pipe dimensions, shape and materials



1 normal sector in the AR, 12 sectors in total

chamber type	VC	chamber ID	chamber profile across	total length	material
dipole chamber	3,5,7	14×40 mm	ellipse	3m	aluminum
arc section	1,2,4,6,8,9	28 mm	circular	7.8m	stainless steel
straight section	10	47 mm	circular	4.2m	stainless steel

Identify the impedance source_1: resistive wall

- Resistive wall impedance is calculated with theoretical formulas with infinite thickness wall and DC conductivity [1-3]

RW impedance:

$$Z_{||}(\omega) = \frac{Z_0 \delta \omega}{4\pi bc}(\textbf{sign}(\omega) - i) \times F_{YOKOYA}$$

$$Z_{\perp}(\omega) = \frac{Z_0 \delta}{2\pi b^3}(\textbf{sign}(\omega) - i) \times F_{YOKAYA}$$

Chamber radius: b

Skin depth: $\delta = \sqrt{2/\mu_0 \sigma_c |\omega|}$

F_{YOKOYA} : geometric factor, Fy=0.83 and Fx = 0.43 for AR elliptical dipole chamber

RW wakefield:

$$W_{||} = \frac{Z_0 c}{4\pi} \frac{1}{2b\sqrt{2Z_0 \mu_r \sigma_c}} \frac{1}{\sigma_z^{3/2}} f_z(s/\sigma_z)$$

$$W_{\perp} = \frac{1}{b^2} \cdot \frac{Z_0 c}{4\pi} \frac{1}{2b\sqrt{2Z_0 \mu_r \sigma_c}} \frac{1}{\sigma_z^{1/2}} f_x(s/\sigma_z)$$

Drive beam bunch length: σ_z

Drive beam bunch distribution: λ

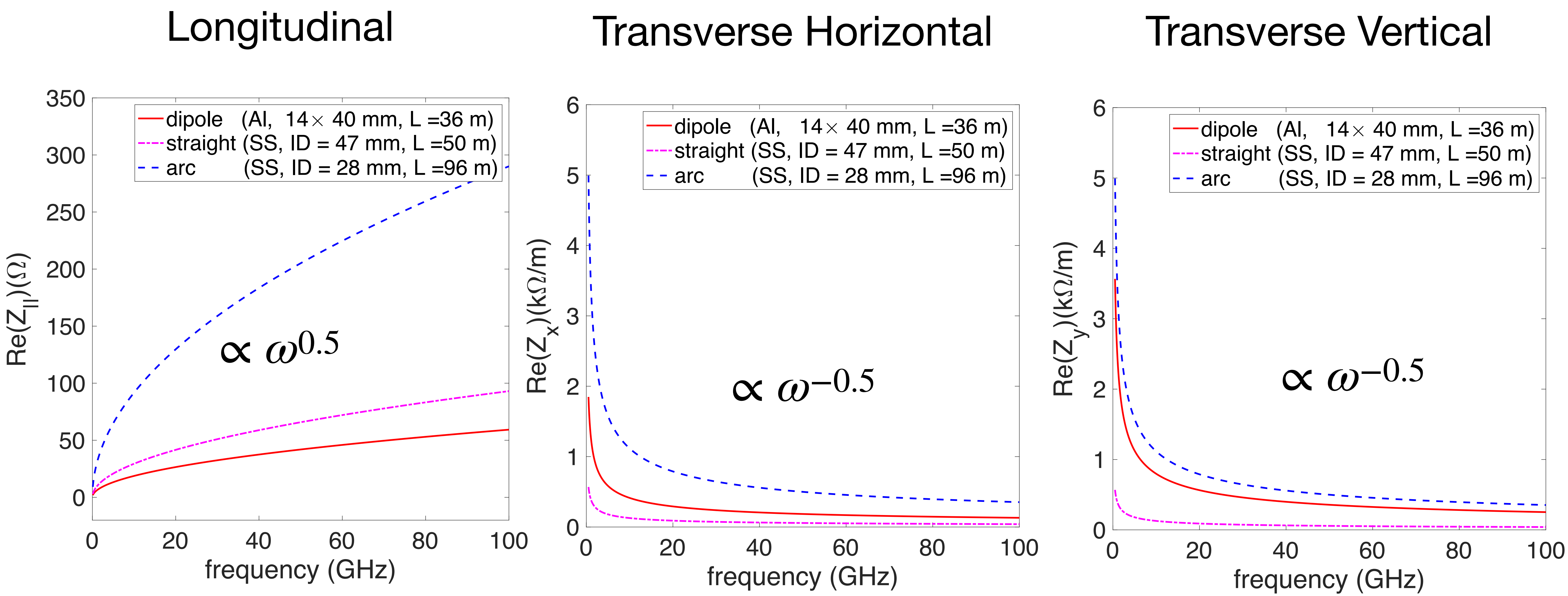
Loss factor and kick factor:

$$\kappa_l = \int_{-\infty}^{\infty} ds \lambda(s) W_{||}(s) \qquad \kappa_{\perp} = \int_{-\infty}^{\infty} ds \lambda(s) W_{\perp}(s)$$

1. A.Piwinski, Wakefield and ohmic losses in round vacuum chambers, 1992
2. K. Bane, The short range resistive wall wakefield, 1996
3. K. Yokoya, in Proceedings of International Conference on Particle Accelerators (IEEE, 1993), pp. 3441–3443

Identify the impedance source_1: resistive wall

- Resistive wall impedance results, by vacuum chamber type:



For nominal bunch length: σ_z = 5mm:

Loss factor: 1.6 V/pC H-kick factor: 58.6 V/pC/m V-kick factor: 72.2 V/pC/m

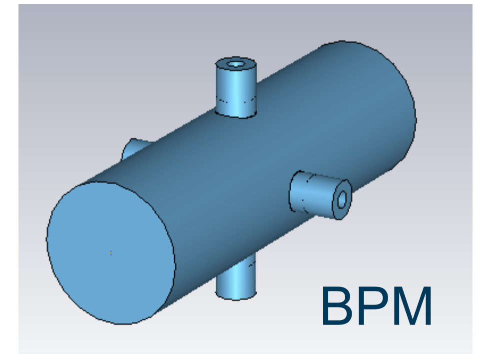
Identify the impedance source_2: geometric ones

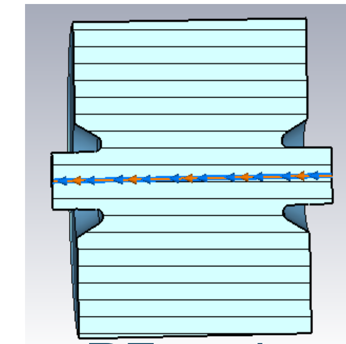
Majority has been simulated

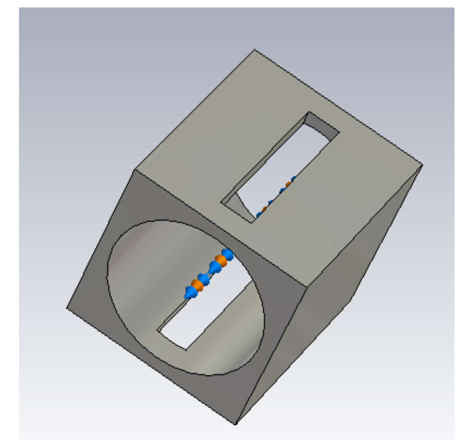
Per sector (12 sectors in AR)		In the ring	
Component	**Quantity**	**Component**	**Quantity**
Flange	20	RF cavity	2
Pump screen	4	Cavity transition	2
Transition_DA	3	LFB kicker	1
Transition_SA	1	LFB transition	1
BPM	6	Stripline kicker	1
Inline pump	4		
Bellow	7		

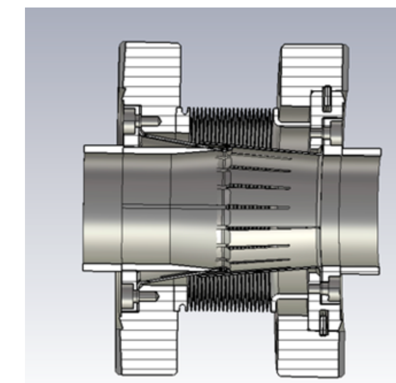
To be studied

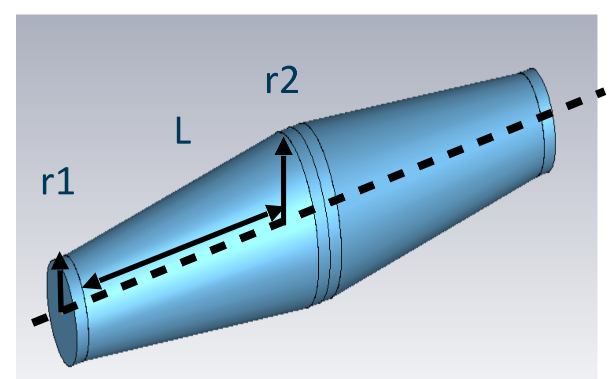
Component	Quantity
Scraper	1
Injection kicker	2
Gate valve	4
TBD	TBD


BPM

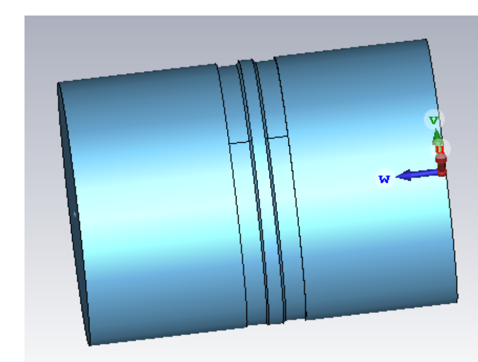

RF cavity


Pump screen


Bellows with RF finger shielding

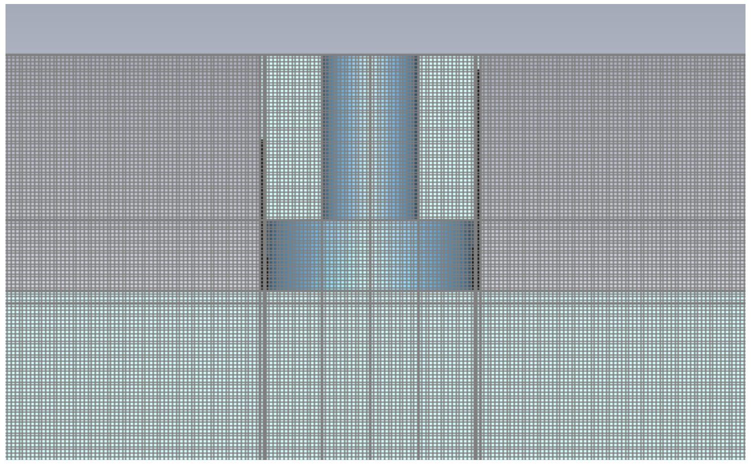


Transition between chamber

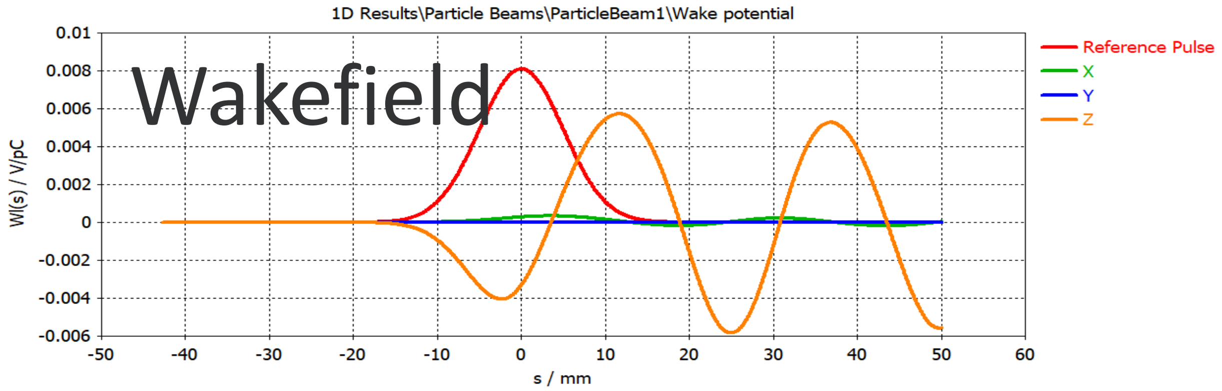

Flange with gasket

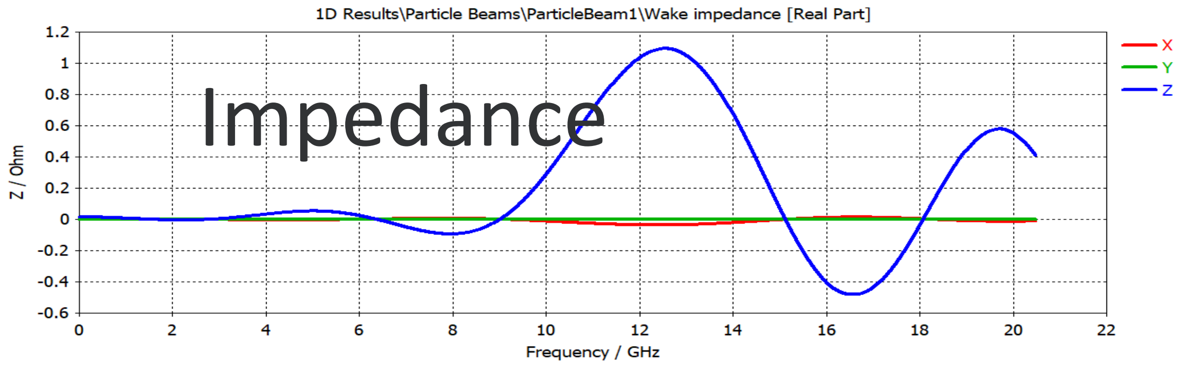
Solve the geometric impedance by CST Particle Studio

- Based on Finite Integration Technique (FIT). Calculating the wakefield in time domain. Deriving the impedance in frequency domain by the Fourier transform.
- Proper settings for boundary conditions, wakefield calculation methods and meshing sizes, convergence check.



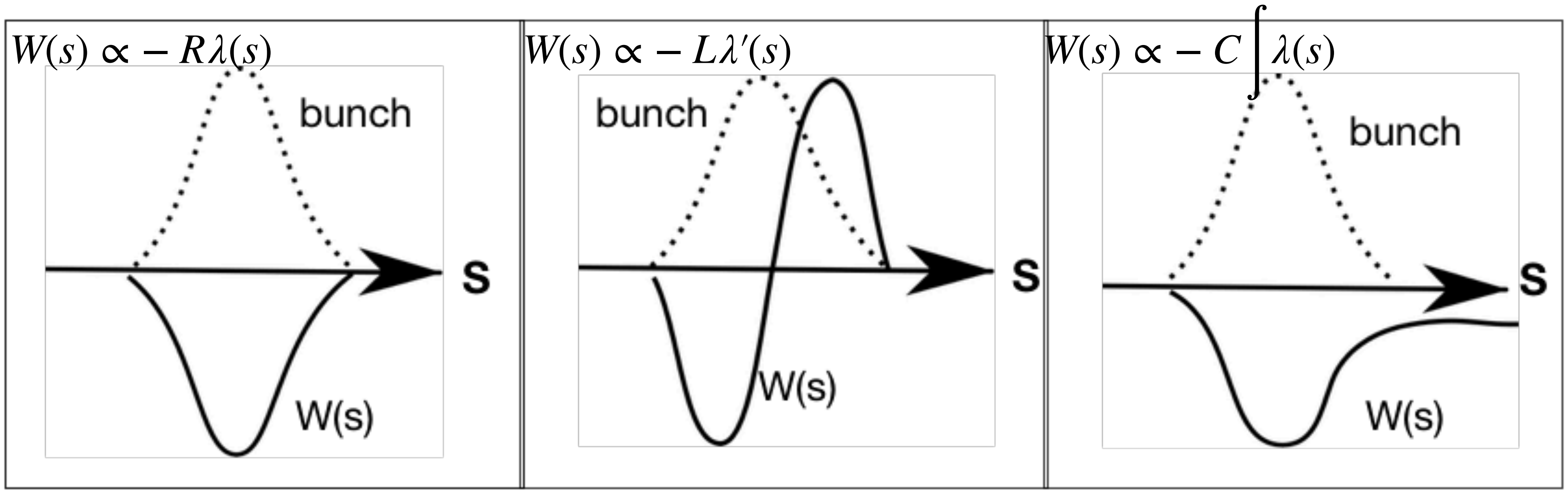
Example: AR button BPM in CST with meshing





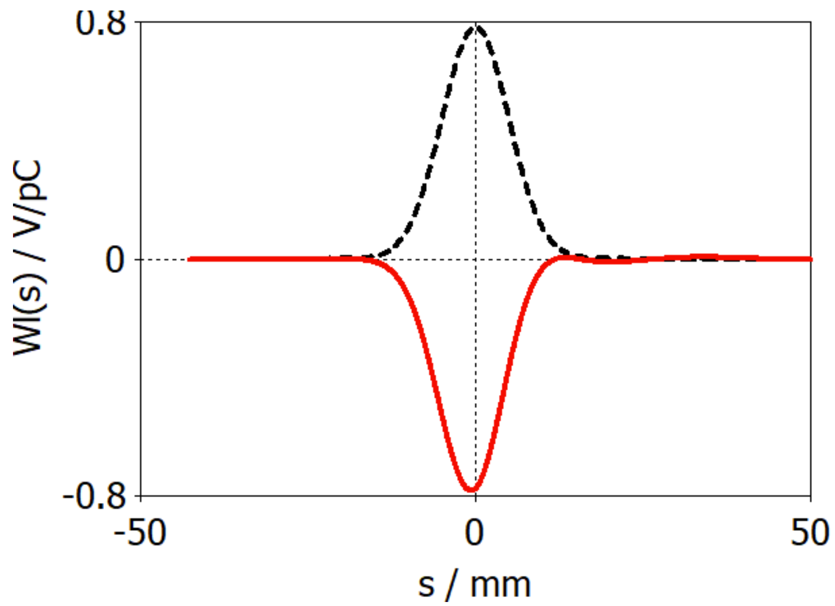
Solve the geometric impedance by CST Particle Studio

- Different categories of the wakefield vs. CST results

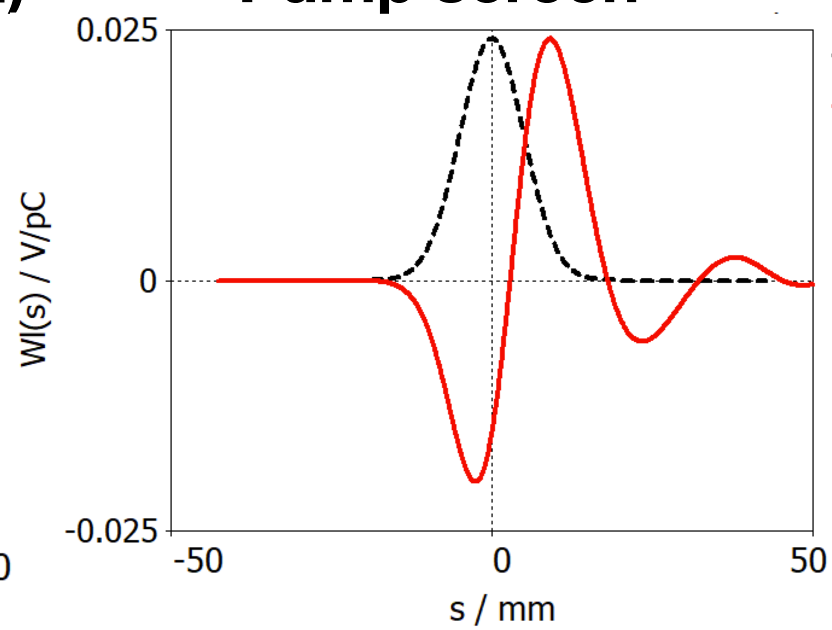


(a) Resistive (b) Inductive (c) Capacitive

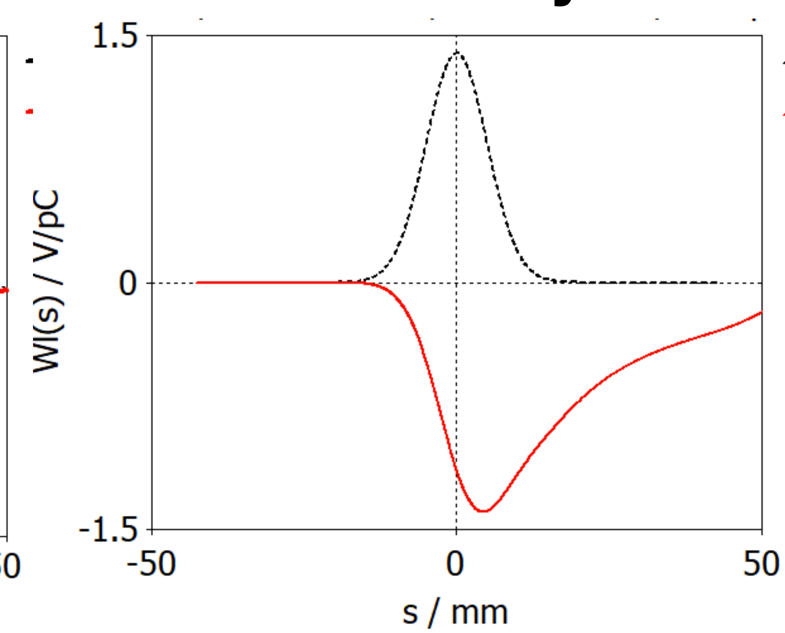
In transition (step-in model)



Pump screen

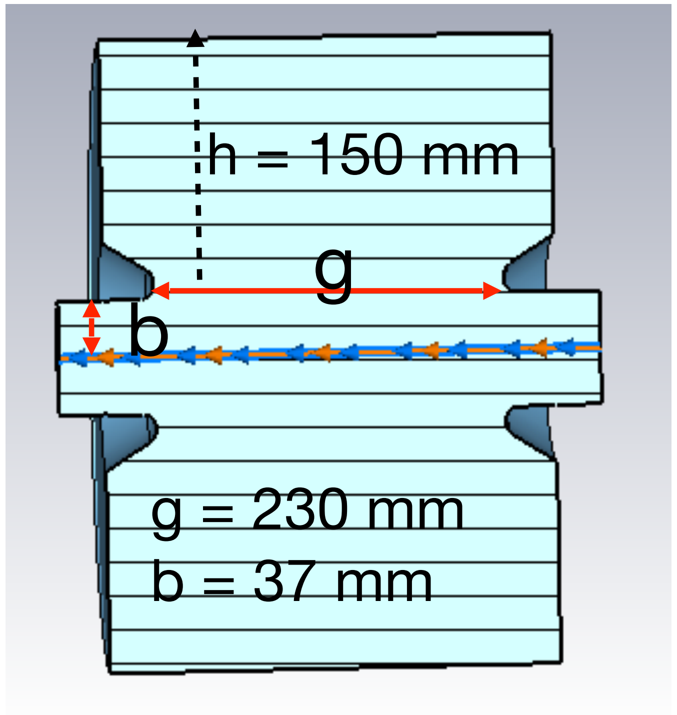


RF cavity



Cross-checked with analytical as much as applicable

- Good agreement on RF cavity loss factor



Loss factor by CST (in time domain):

$$\kappa = \int_{-\infty}^{\infty} ds\lambda(s)W_{||}(s)$$

Loss factor by Omega3P (frequency domain) +analytical:

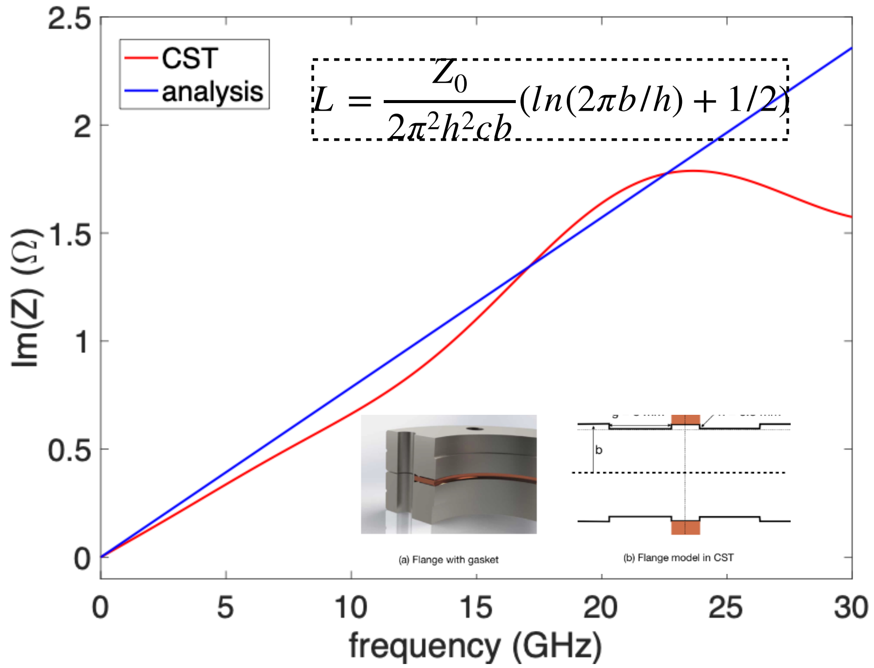
$$\kappa_{||} = \underbrace{\kappa_{FM} + \kappa_{HOM}}_{①} + \underbrace{\kappa_d}_{②}$$

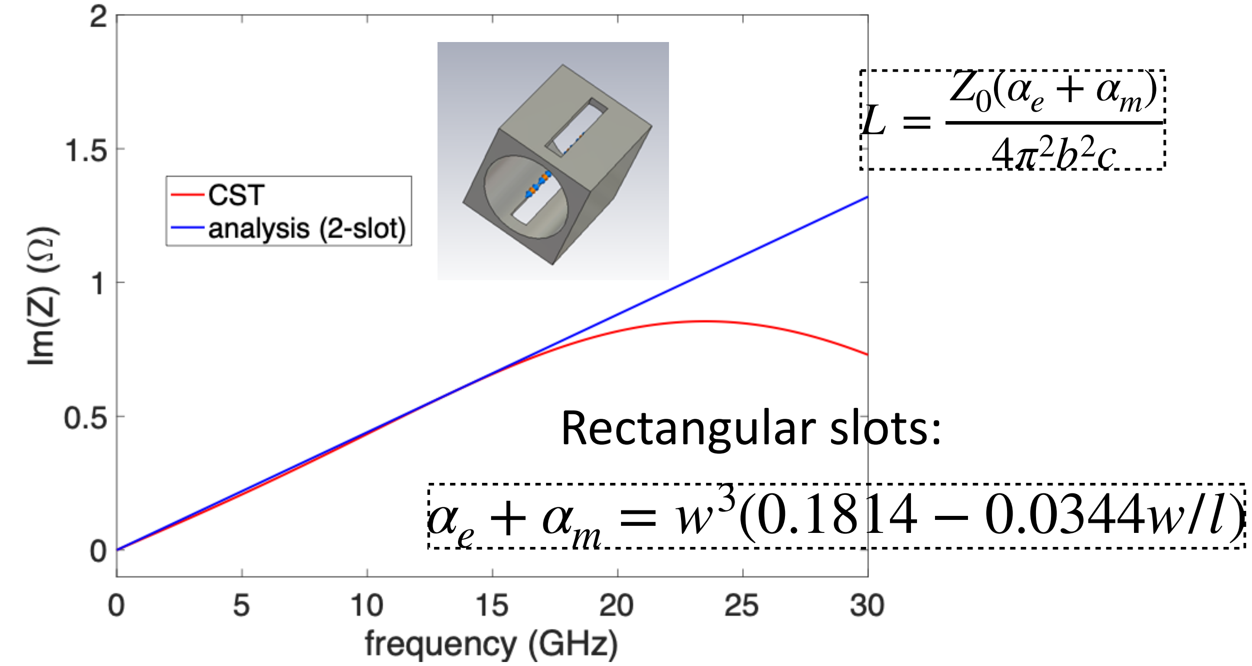
	$\sigma_z = 1$ mm		$\sigma_z = 5$ mm	
Method:	CST	Omega3P+analytical	CST	Omega3P+analytical
Loss factor (V/pC)	1.97	2.41	0.98	1.08

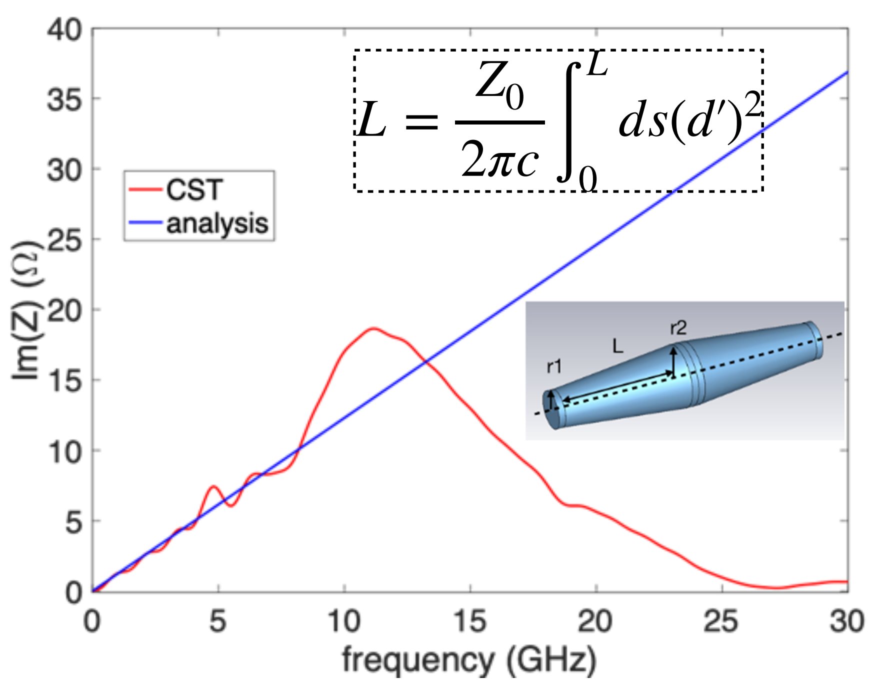
① Below cut-off frequency, discrete eigenmodes (shunt impedances calculated by Omega3P)
② Above cut-off frequency, diffraction model formula

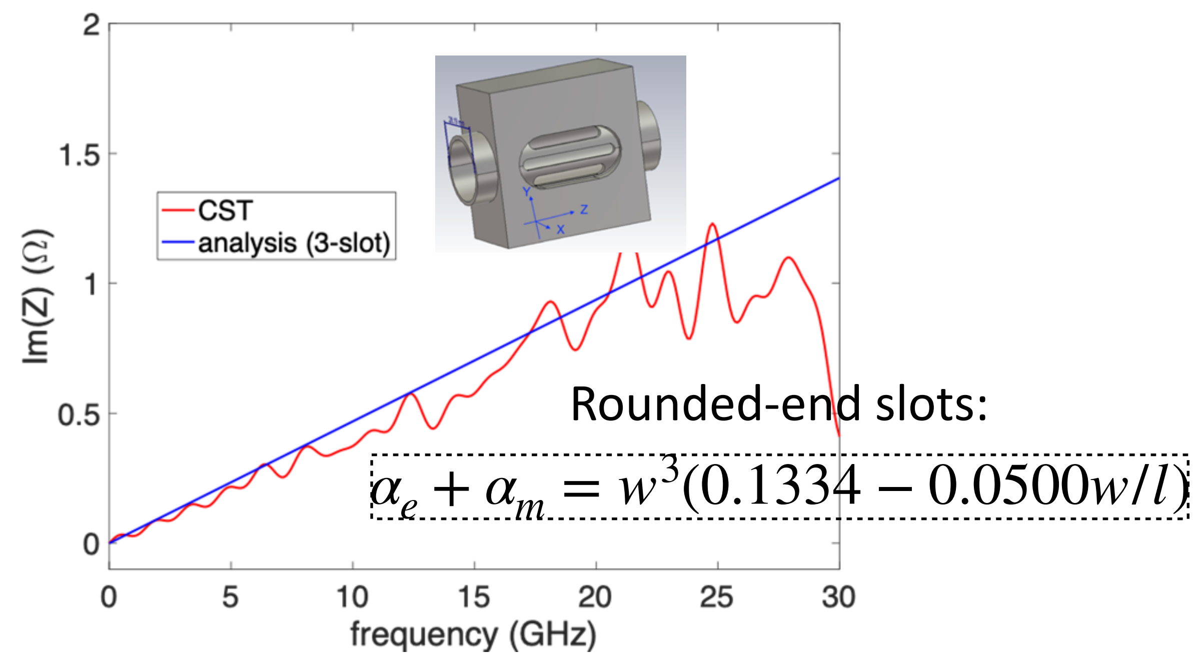
Cross-checked with analytical as much as applicable

- Good agreement on inductive impedance at low frequency* $Z_{||} = -j\omega L$









* All formulas above can be found in Accelerator Handbook

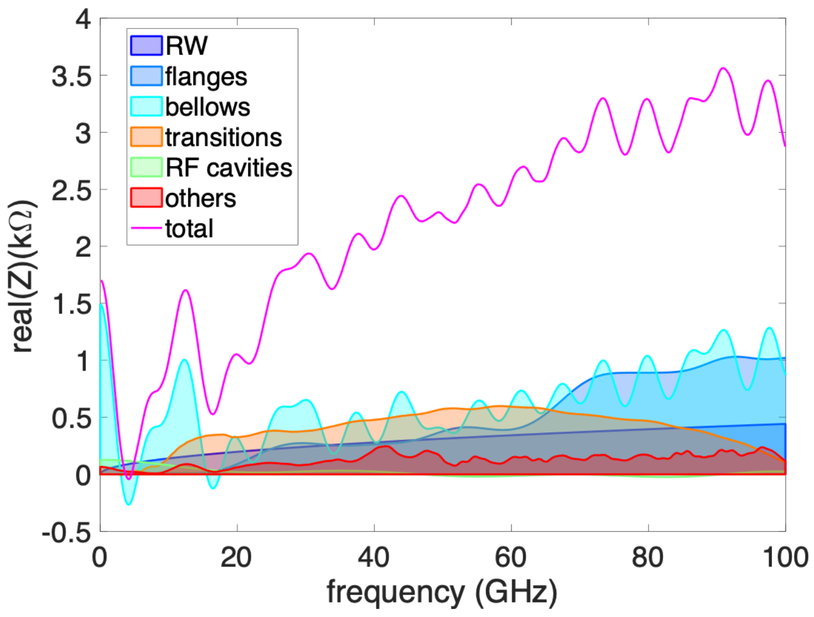
BERKELEY LAB
ATAP
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION
ALS-U ADVANCED LIGHT SOURCE

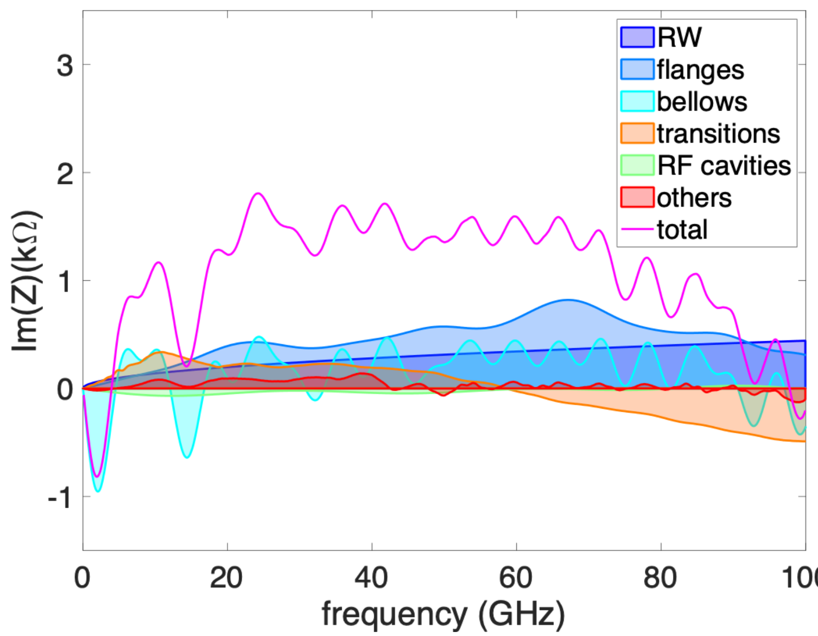
Total budget

Longitudinal budget：1

- Table: loss factor(σ_z = 5mm) and normalized impedance fitted by RL model

Component	Quan-tity	Single component			Sum up		
		Loss factor V/pC	Re(Z/n) mΩ	Im(Z/n) mΩ	Loss factor V/pC	Re(Z/n) mΩ	Im(Z/n) mΩ
Bellow	84	0.097	0.984	0.250	8.148	82.622	21.000
Cavity	2	0.980	9.930	-7.097	1.960	19.859	-14.193
Resistive wall	1	1.600	16.232	24.012	1.600	16.232	24.012
Transition_SD	12	0.041	0.413	2.109	0.492	4.959	25.311
LFB kicker	1	0.490	4.969	-3.383	0.490	4.969	-3.383
Transition_AD	36	0.004	0.018	0.871	0.144	0.660	31.369
BPM	72	0.0014	0.014	0.040	0.101	1.022	2.872
Cavity transition	2	0.088	0.898	1.973	0.176	1.796	3.946
Flange	240	0.00034	0.013	0.118	0.082	3.129	28.414
LFB transition	1	0.075	0.765	1.620	0.075	0.765	1.620
Arc pump screen	24	0.00058	0.006	0.129	0.014	0.142	3.104
Straight Pump screen	24	0.00057	0.006	0.098	0.014	0.139	2.340
Stripline kicker	1	0.0104	0.087	~ 0.000	0.010	0.087	~ 0.000
Inline pump	48	0.00012	0.001	0.032	0.006	0.059	1.545
Ring Total					13.3	136.4	128.0

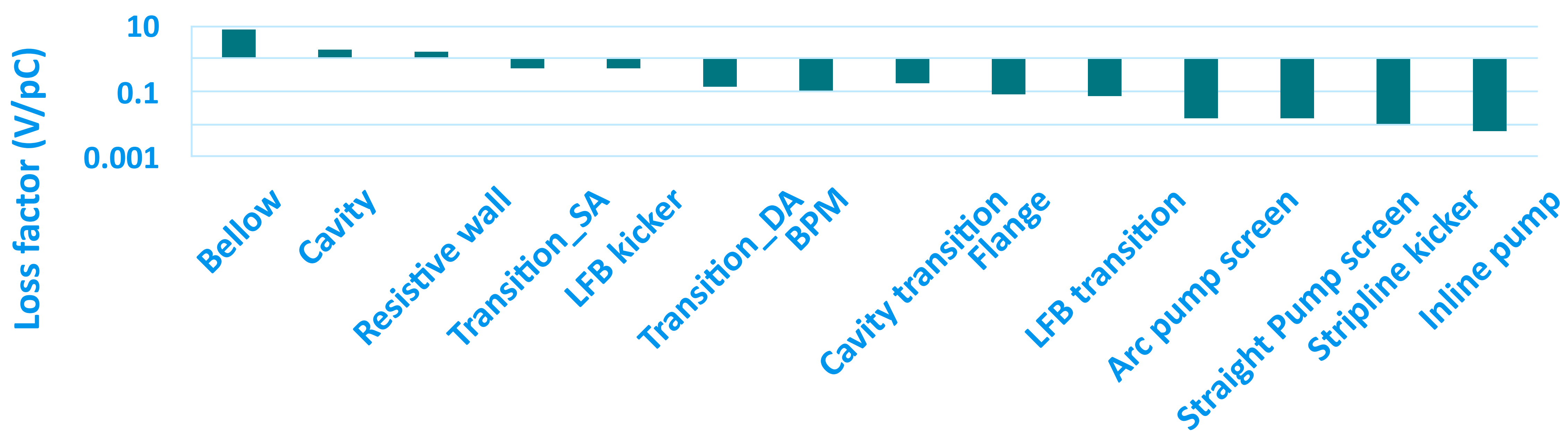


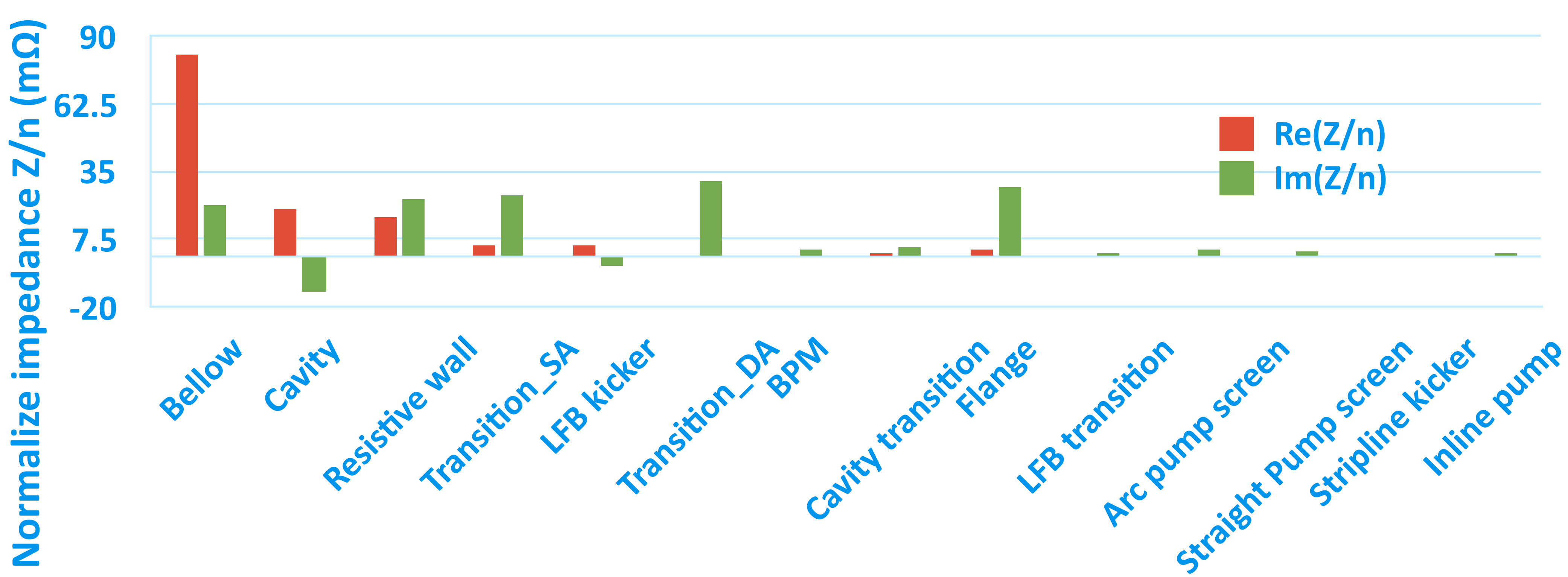


$$W_{R+L}(s) = -Rc\lambda(s) - c^2 L\lambda'(s) \qquad \frac{Z}{n} = \frac{\omega_0\sigma_z}{c}R + i\omega_0 L$$

Longitudinal budget： 2

- Loss factor/ReZ dominated by bellows, cavity and RW; overall inductive ring

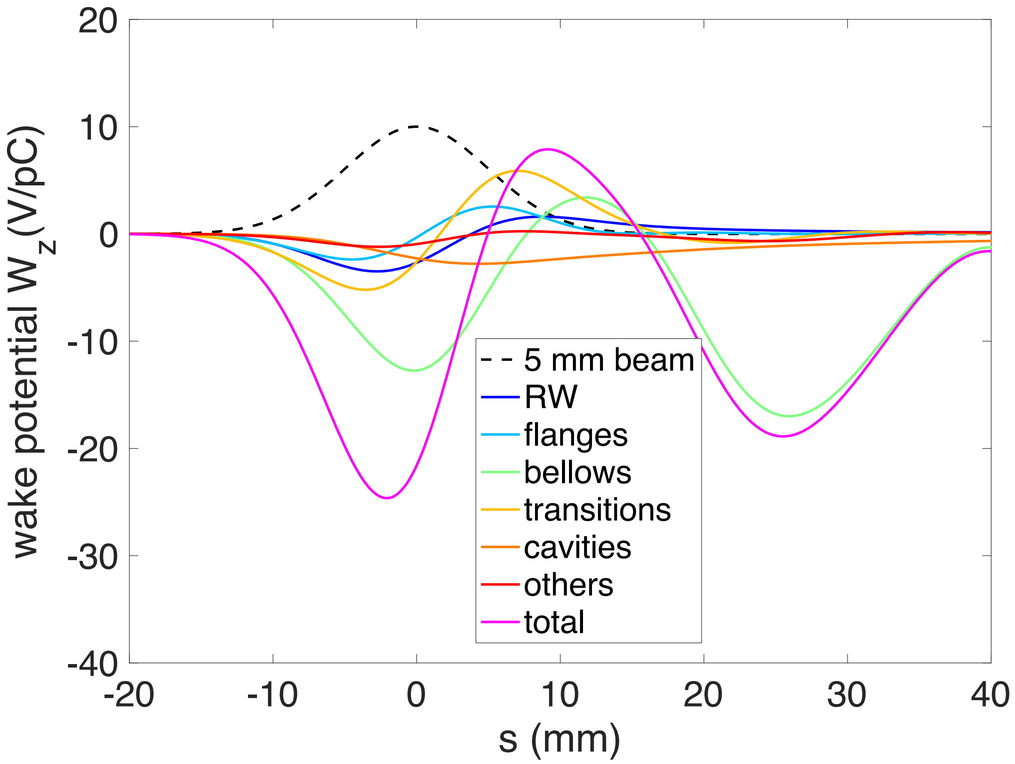




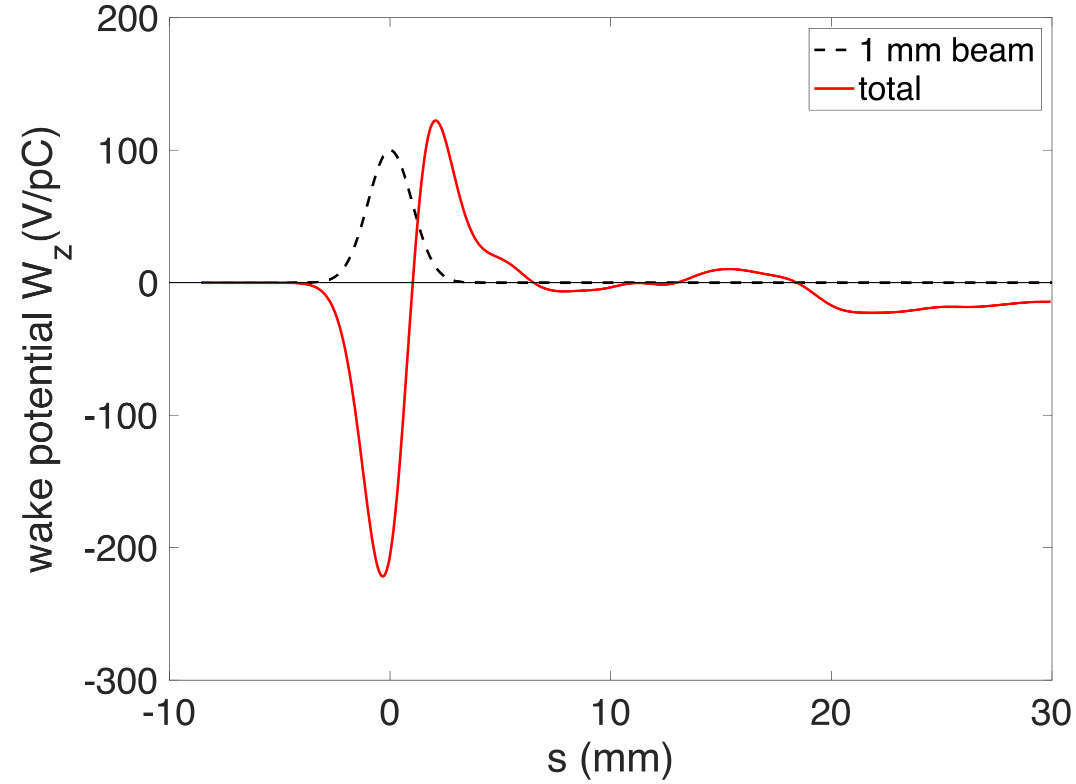
Longitudinal budget： 3

- Sum of the short range wakefield

Wakefield of σ_z = 5 mm



Wakefield of σ_z = 1 mm

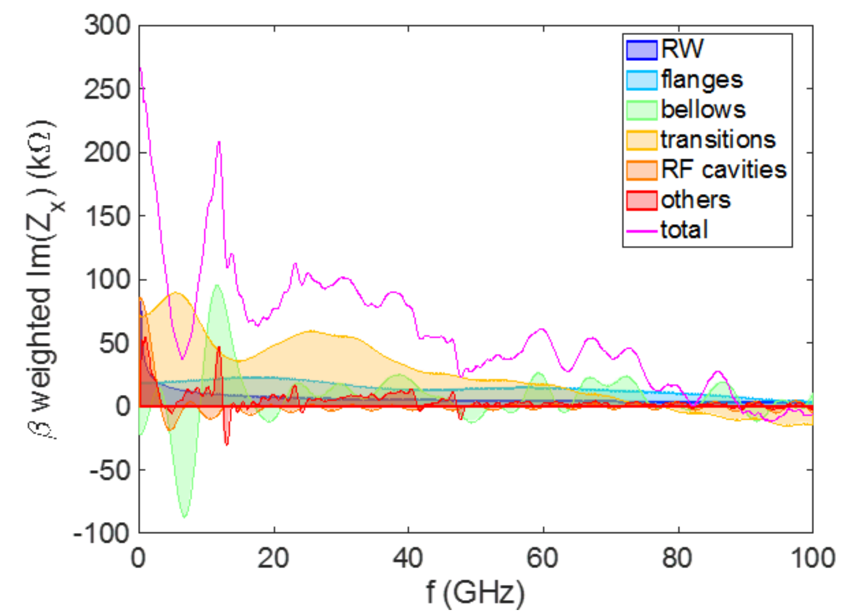


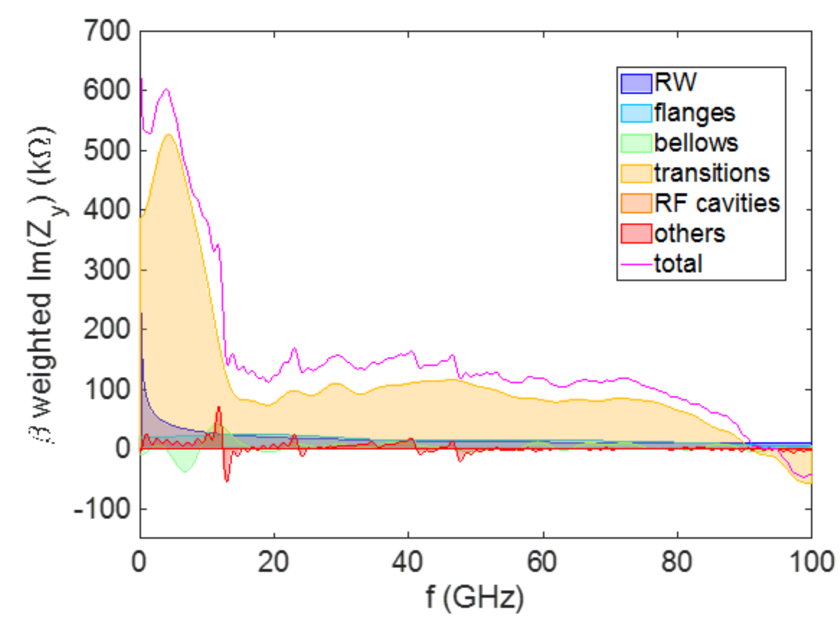
- σ_z = 5 mm wakefield: about the nominal bunch in AR.
- σ_z = 1 mm wakefield: serve as the pseudo-Green function.

Transverse budget： 1

- Table: β-weighted effective impedance and tune shift

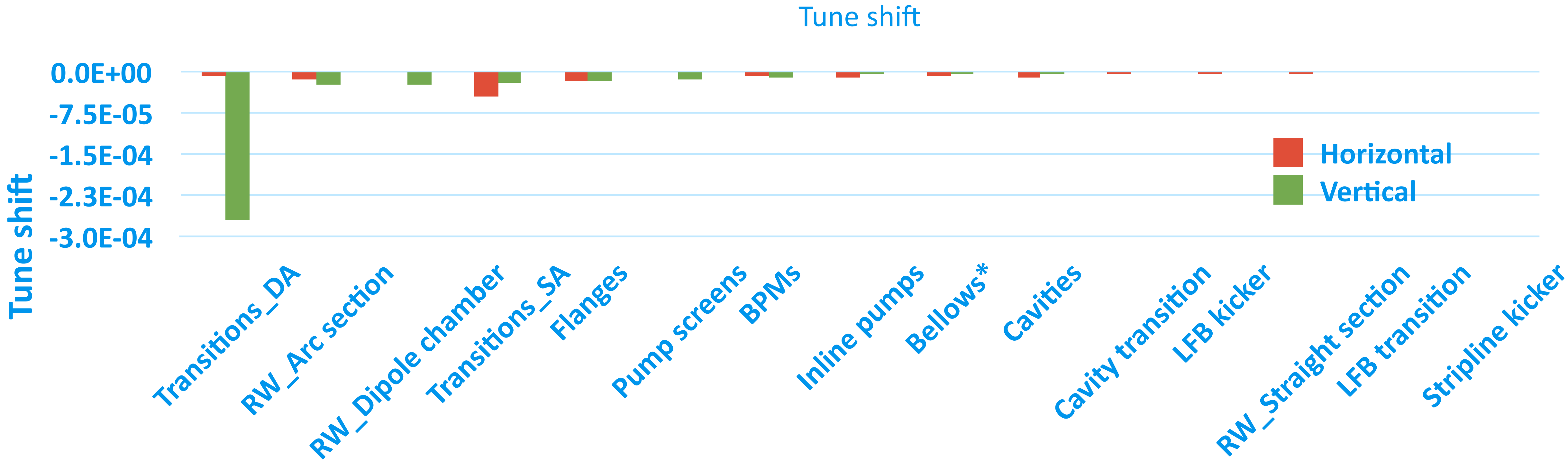
Component	Quantity	βx (m)	βy (m)	Single component (kΩ) $(\beta*Z_{eff})x$	Single component (kΩ) $(\beta*Z_{eff})y$	Sum $(\beta*Z_{eff})x$ kΩ	Sum $(\beta*Z_{eff})y$ kΩ	Sum Tune shift x $*10^{-4}$	Sum Tune shift y $*10^{-4}$
Transitions_AD	36	1.58	13.54	0.24	9.69	8.74	348.70	-0.068	-2.699
RW_Arc section	1	6.57	12.17	15.34	28.42	15.34	28.42	-0.119	-0.220
RW_Dipole chamber	1	1.73	16.64	1.49	27.74	1.49	27.74	-0.012	-0.215
Transitions_SD	12	15.0	5.85	4.88	1.90	58.53	22.83	-0.453	-0.177
Flange	240	8.09	8.77	0.09	0.09	20.66	22.40	-0.160	-0.173
Pump screen	48	14.65	5.5	0.03	0.36	1.33	17.17	-0.010	-0.133
BPM	72	7.03	11.03	0.10	0.15	6.88	10.80	-0.053	-0.084
Inline pump	48	8.85	3.88	0.28	0.12	13.31	5.62	-0.103	-0.043
Bellow*	84	9.08	3.93	0.12	0.05	10.37	4.49	-0.080	-0.035
Cavity	2	15.0	5.0	6.92	2.31	13.83	4.61	-0.107	-0.036
Cavity transition	2	15.0	5.0	2.31	0.77	4.61	1.54	-0.036	-0.012
LFB kicker	1	15.0	5.0	4.52	1.51	4.52	1.51	-0.035	-0.012
RW_Straight section	1	15.0	5.0	3.99	1.33	3.99	1.33	-0.031	-0.010
LFB transition	1	15.0	5.0	2.04	0.68	2.04	0.68	-0.016	-0.005
Stripline kicker	1	15.0	5.0	0.51	0.17	0.51	0.17	-0.004	-0.001
Ring total						166.18	498.00	-1.29	-3.85





Transverse budget： 2

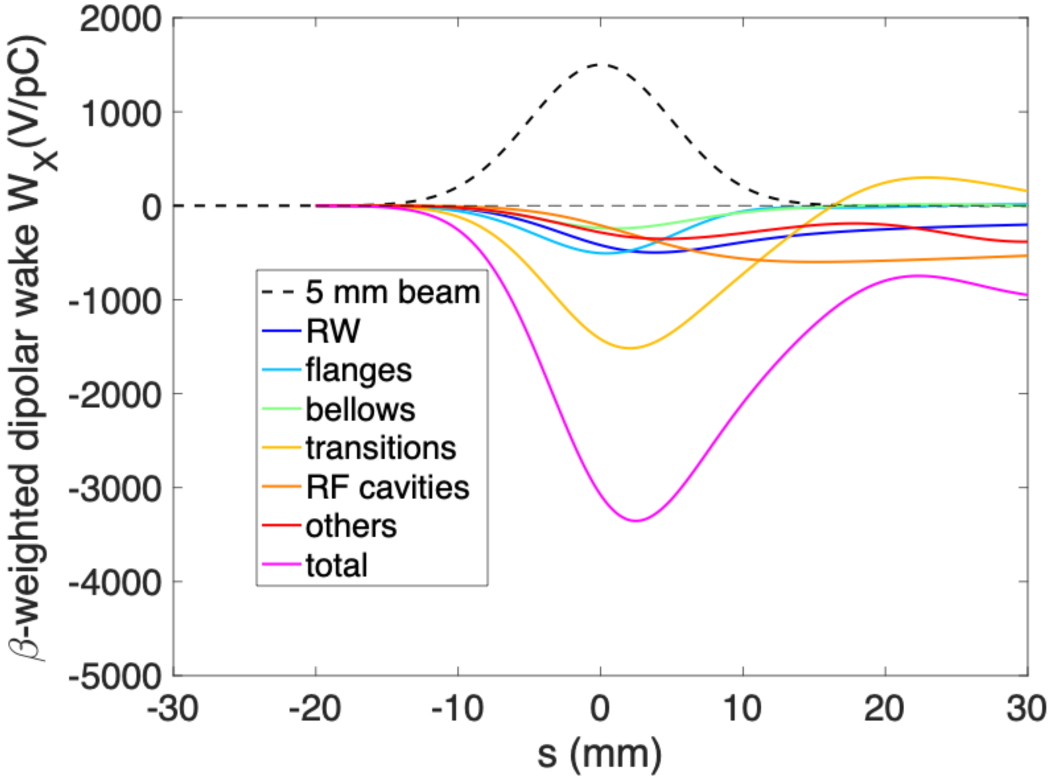
- Main contribution, vertical, transition between dipole and arc (36 pairs, ID: 14-28mm)



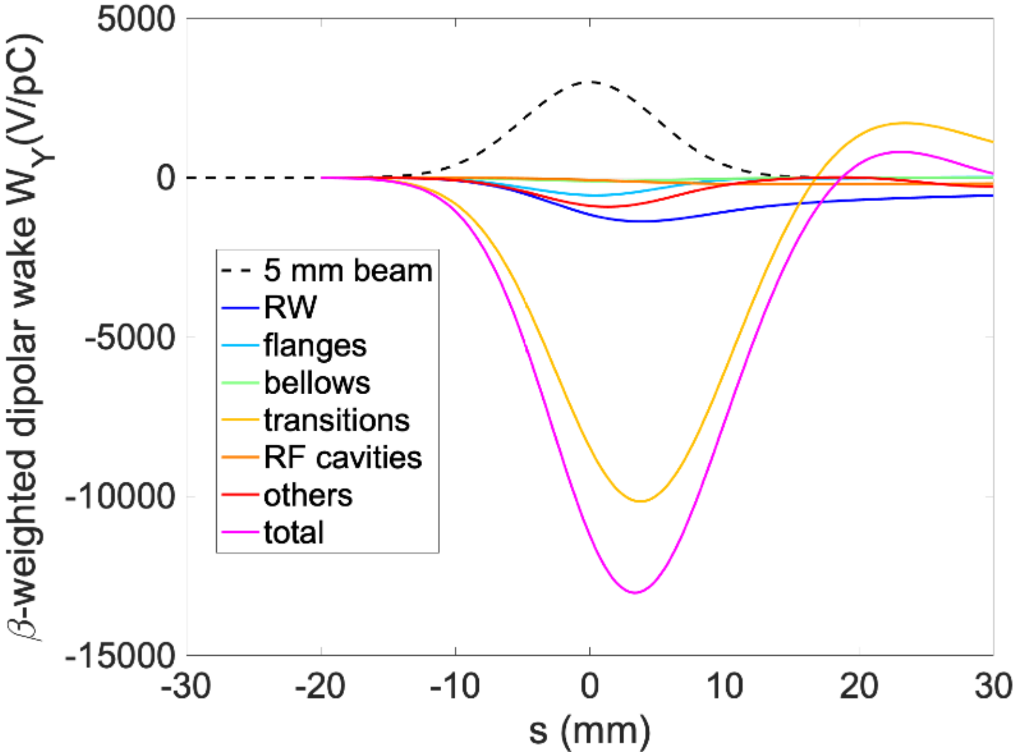
Transverse budget： 3

- Sum of the short range wakefield

Horizontal dipole wake



Vertical dipole wake

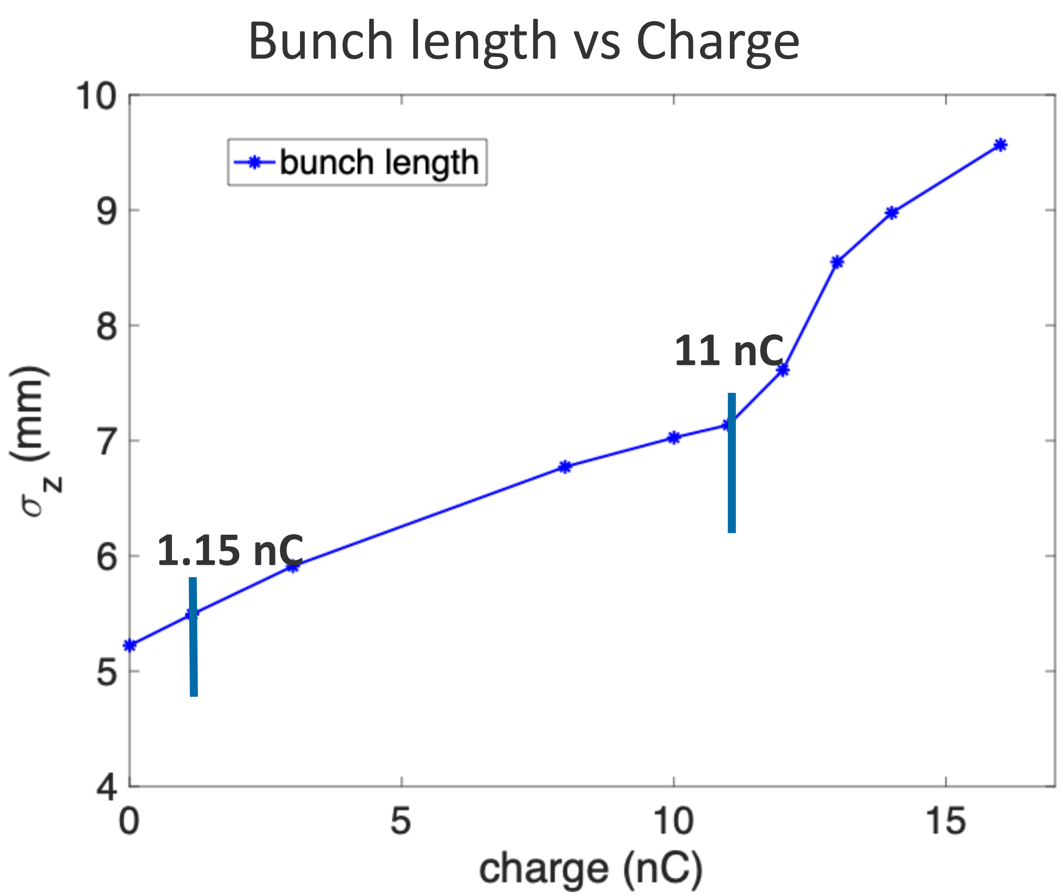


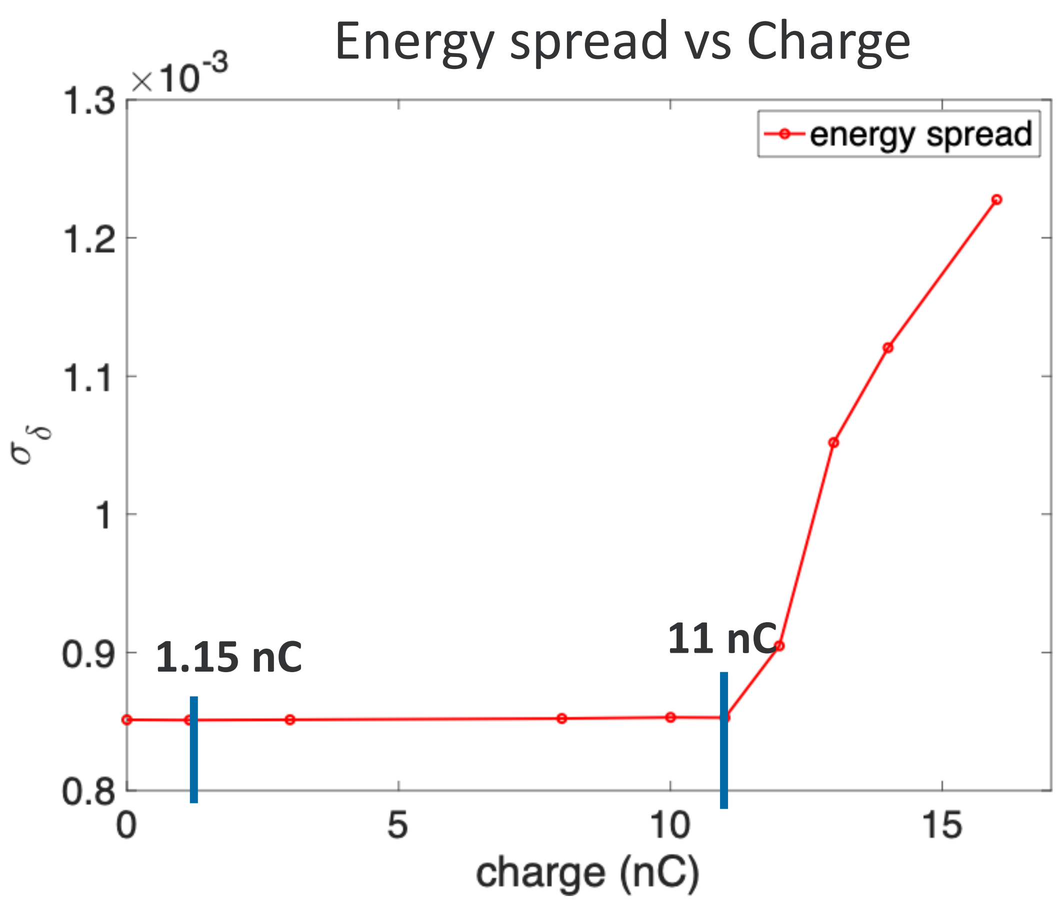
- σ_z = 5 mm wakefield: about the nominal bunch in AR.
- Analytical estimation of vertical TMCI threshold >10nC/bunch (Marco)
- σ_z = 1 mm wakefield: serve as the pseudo-Green function.

Instability study

Longitudinal: microwave instability_1

- ELEGANT simulation: onset of microwave instability at charge of ~11 nC



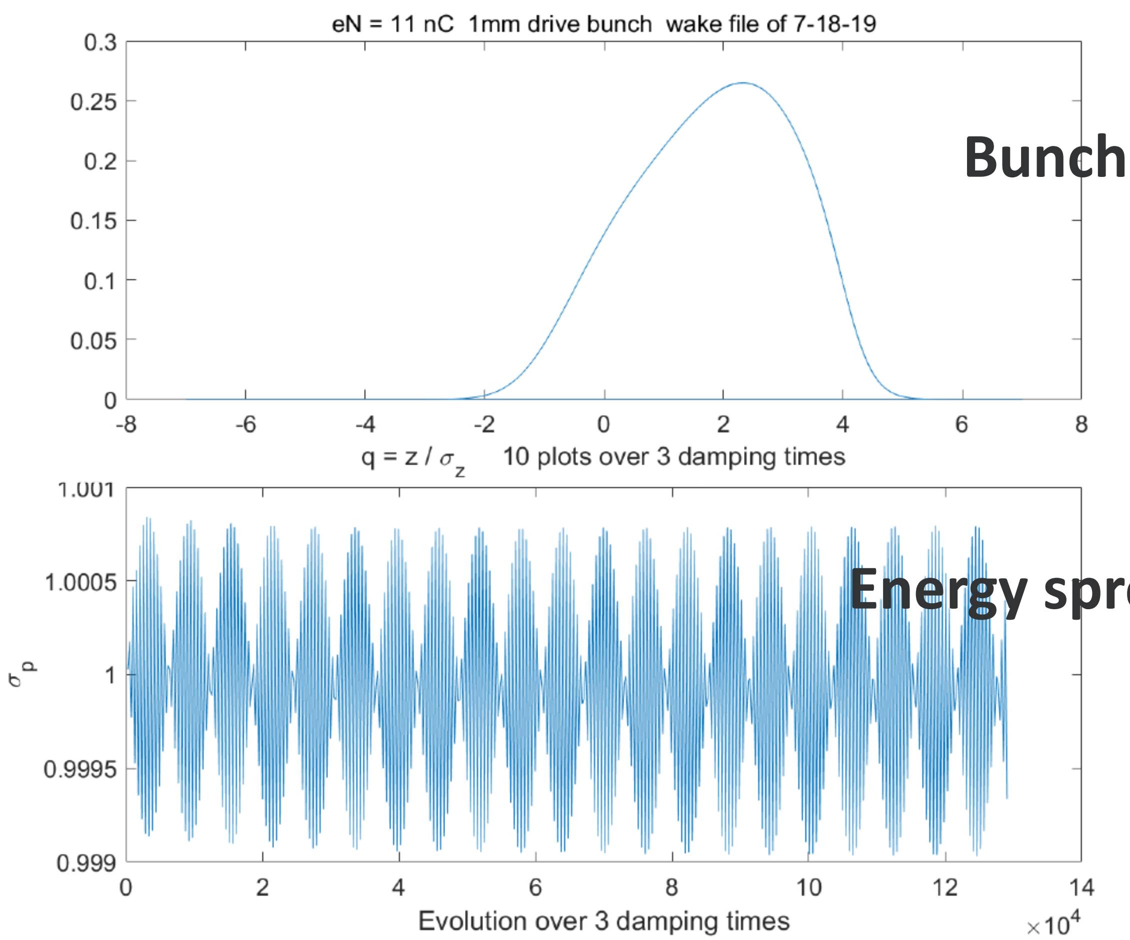


- 400 000 macro-particles in one bunch. Tracking for 20000 passes (~ $2\tau_{dz}$).
- Scan the bunch charges from 0 to 16 nC. Clear onset of microwave instability at **~ 11 nC >> 1.15 nC.**

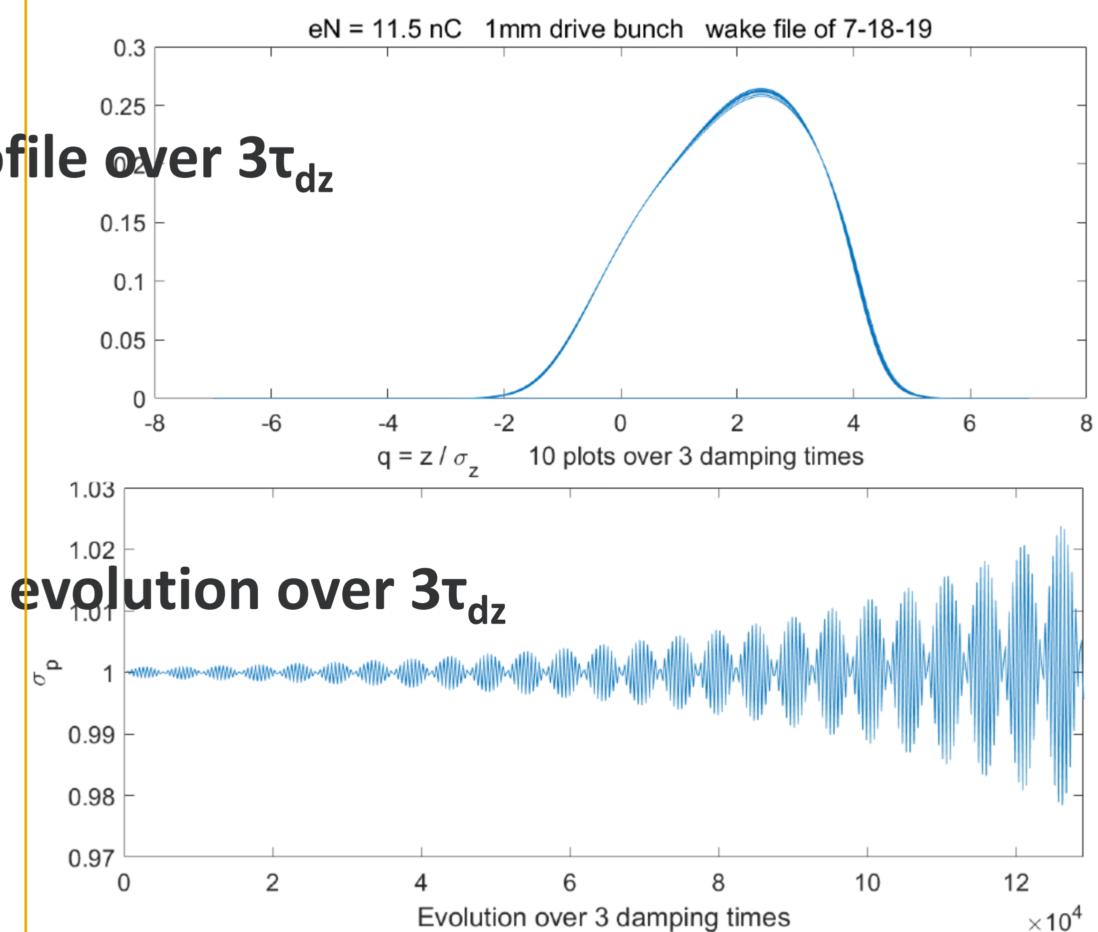
Longitudinal: microwave instability_2

- Simulation verified by solving Vlasov-Fokker-Planck (VFP) equation:

Bunch charge 11 nC, stable



Bunch charge 11.5 nC, unstable



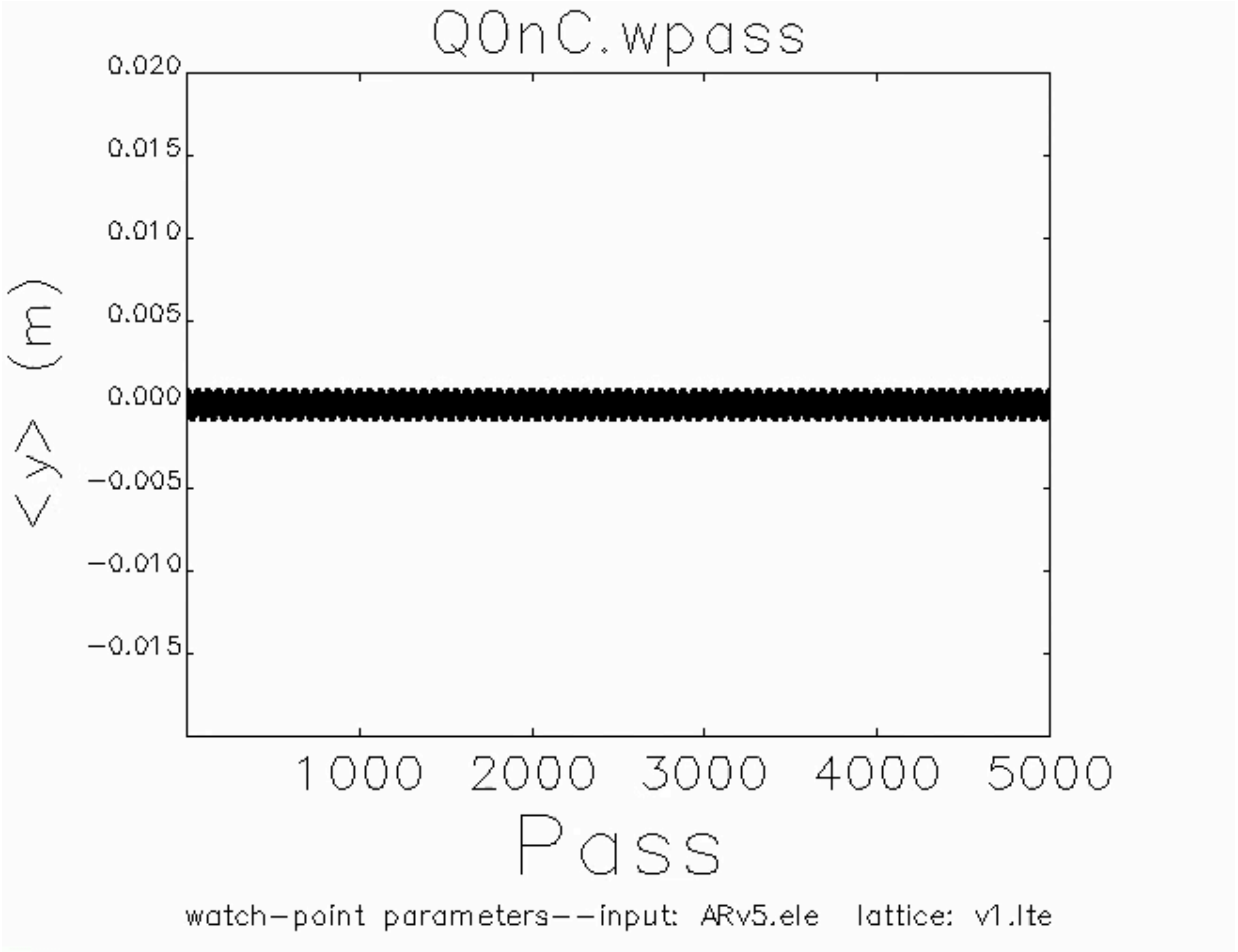
Bunch profile over $3\tau_{dz}$

Energy spread evolution over $3\tau_{dz}$

Courtesy of R. Warnock

Transverse instability

- ELEGANT simulation: onset of transverse instability at charge of ~12 nC



- Scan the bunch charges, instability shows up at **~ 12 nC >> 1.15 nC.**

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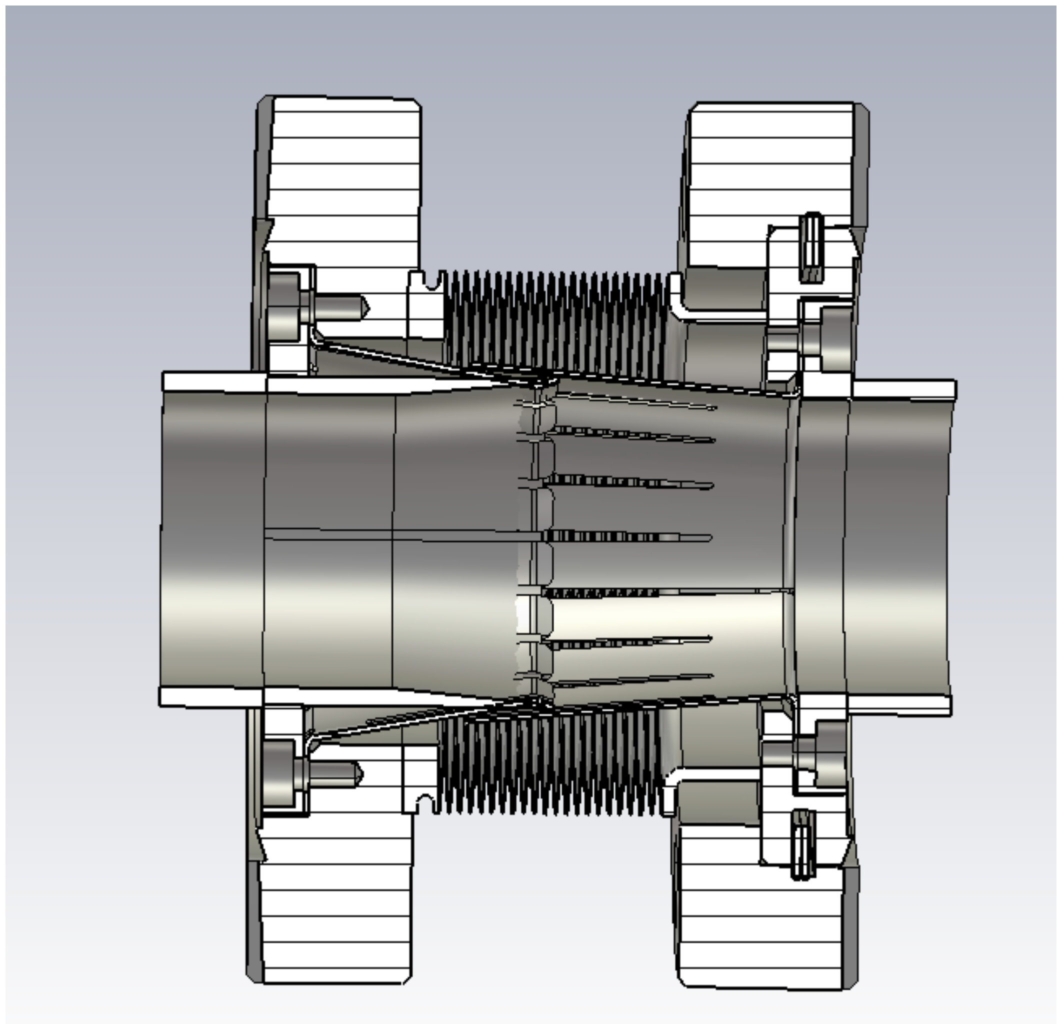
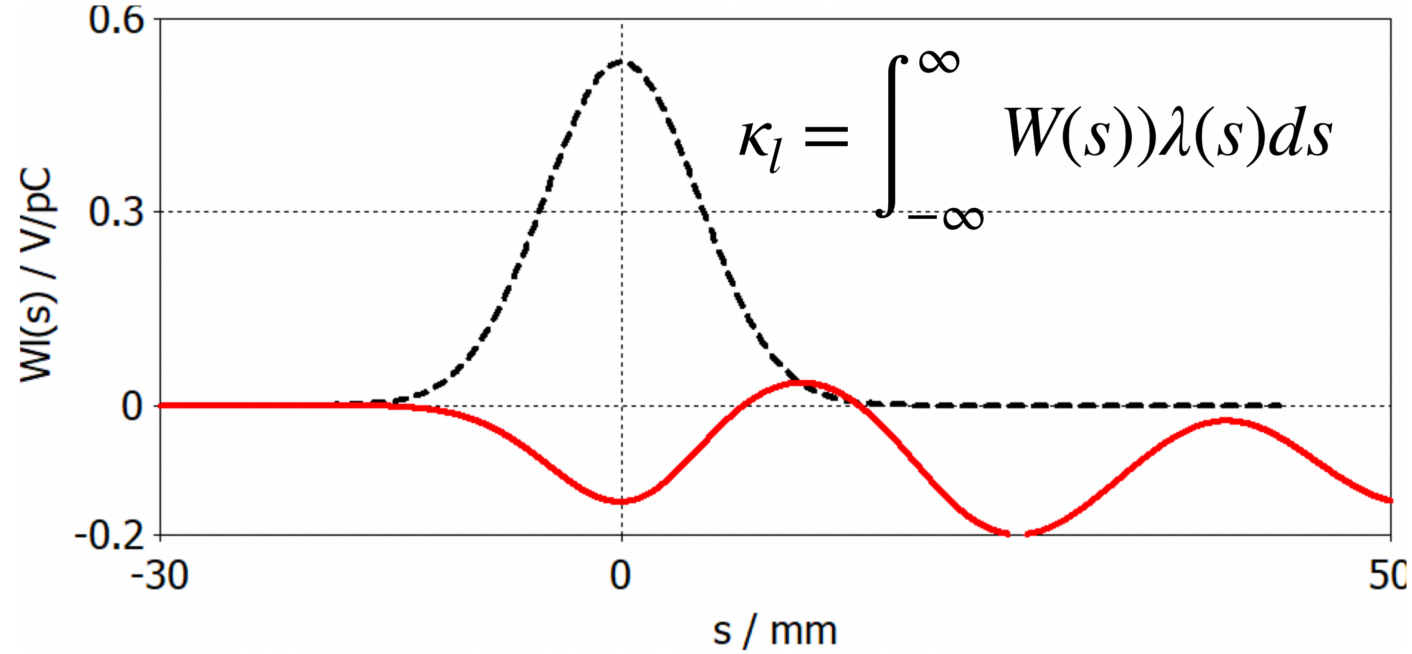
Discussion: feedback on vacuum design

Low impedance bellows with RF shielding_1

- Recall the the bellows' model, from the CAD mode by vacuum group



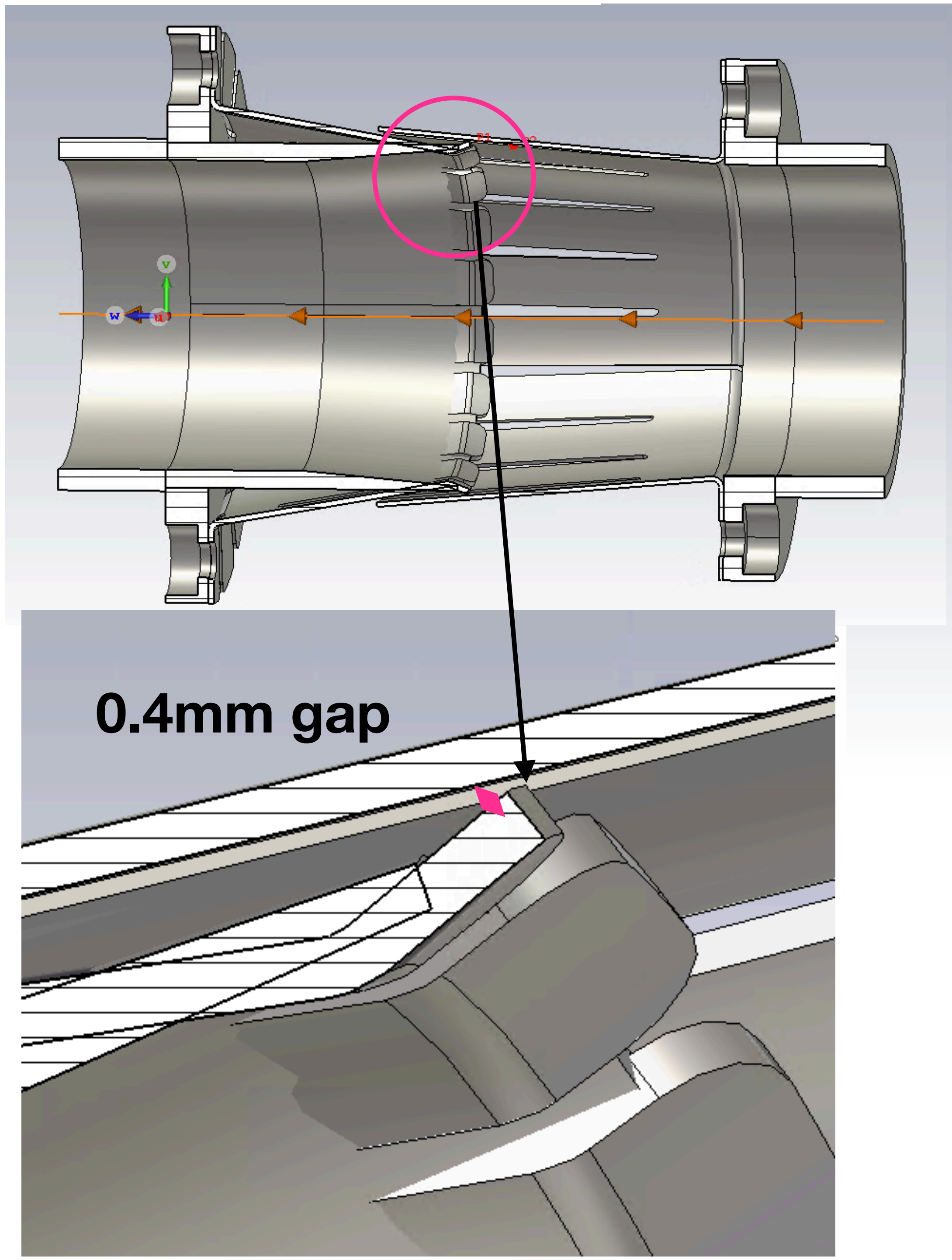


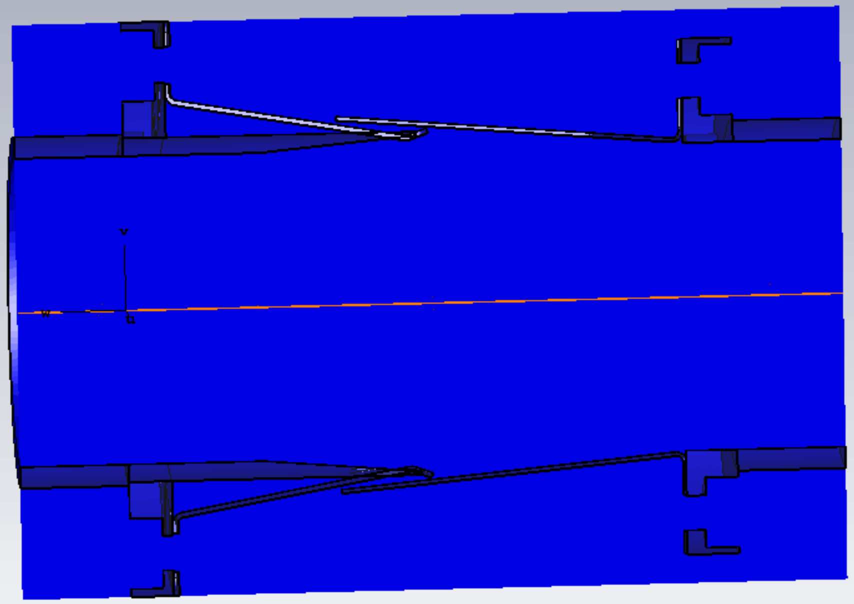
- Loss factor = 97 mV/pC per bellows @ 5mm beam
- Quite resistive/large loss factor compared with pump screen 0.58mv/pC
- 72 bellows in total, contribute the largest Re(Z/n) in the budget

What cause such large loss factor?

Low impedance bellows with RF shielding_2

- What cause such large loss factor since the slots should be inductive?

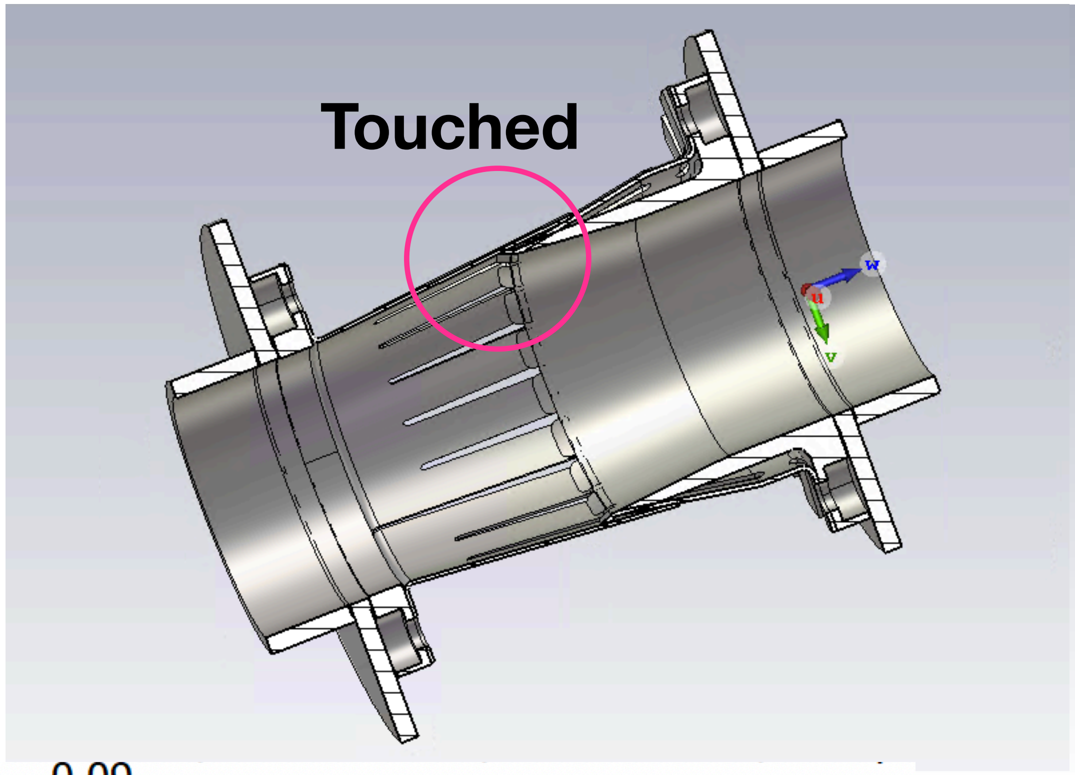


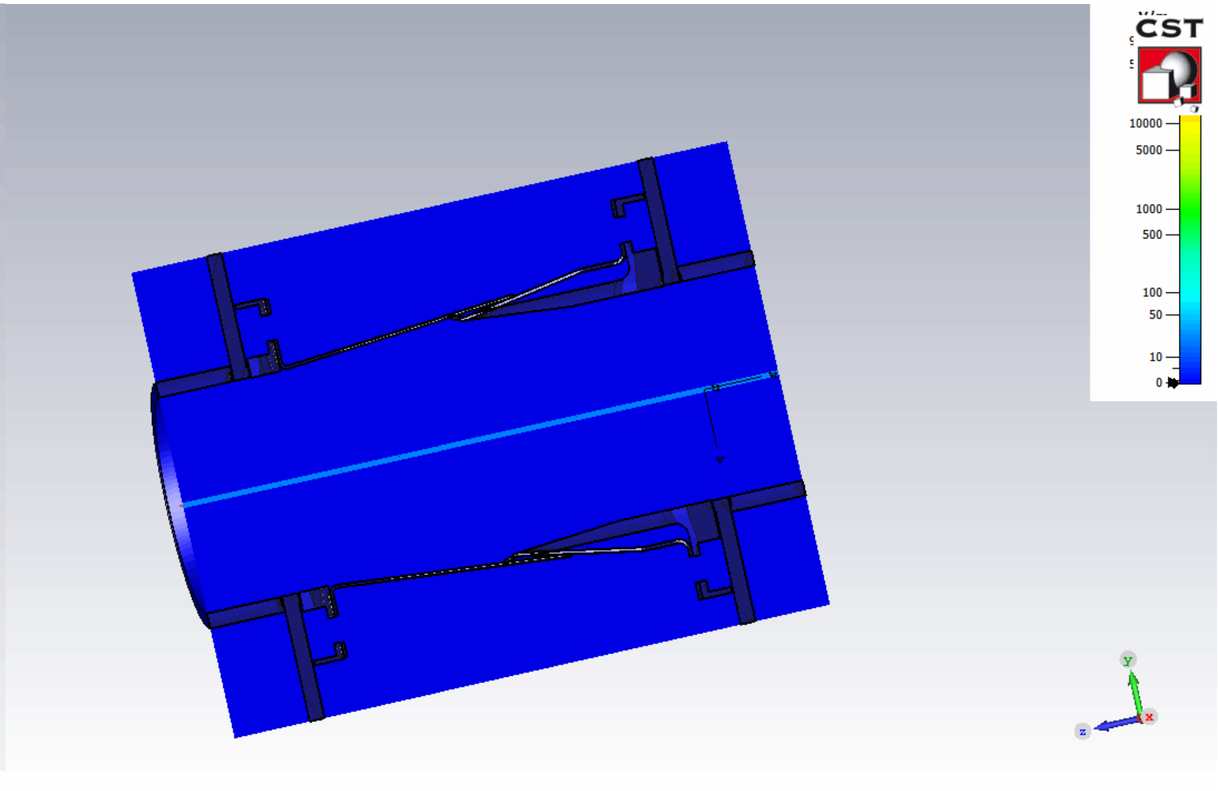


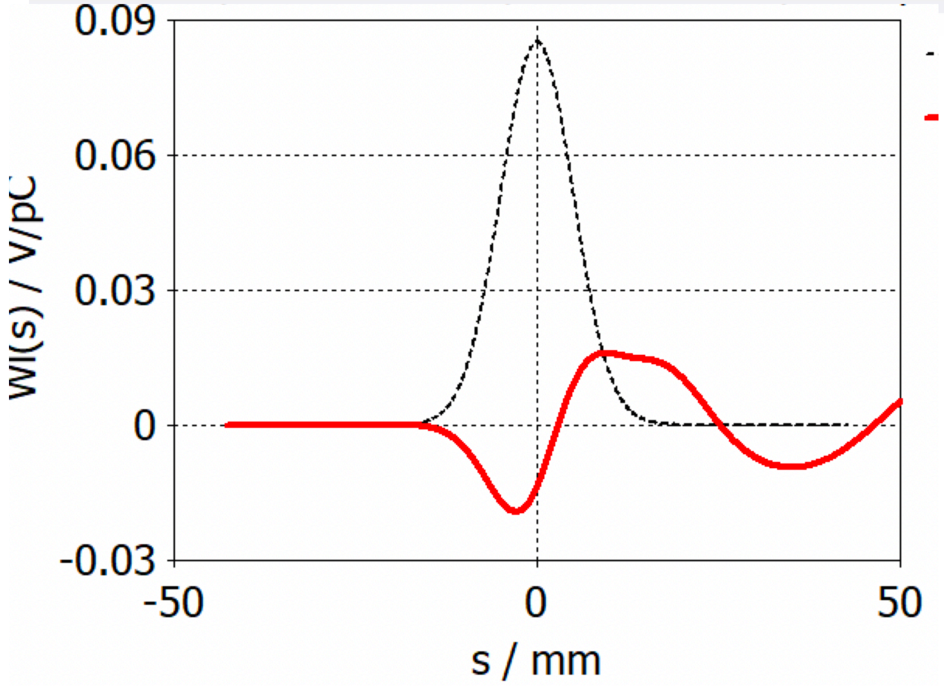
- The 0.4mm gap in the model was not seen until we check the loss factor source…

Low impedance bellows with RF shielding_3

- Update the model with good contact/ proper assembling





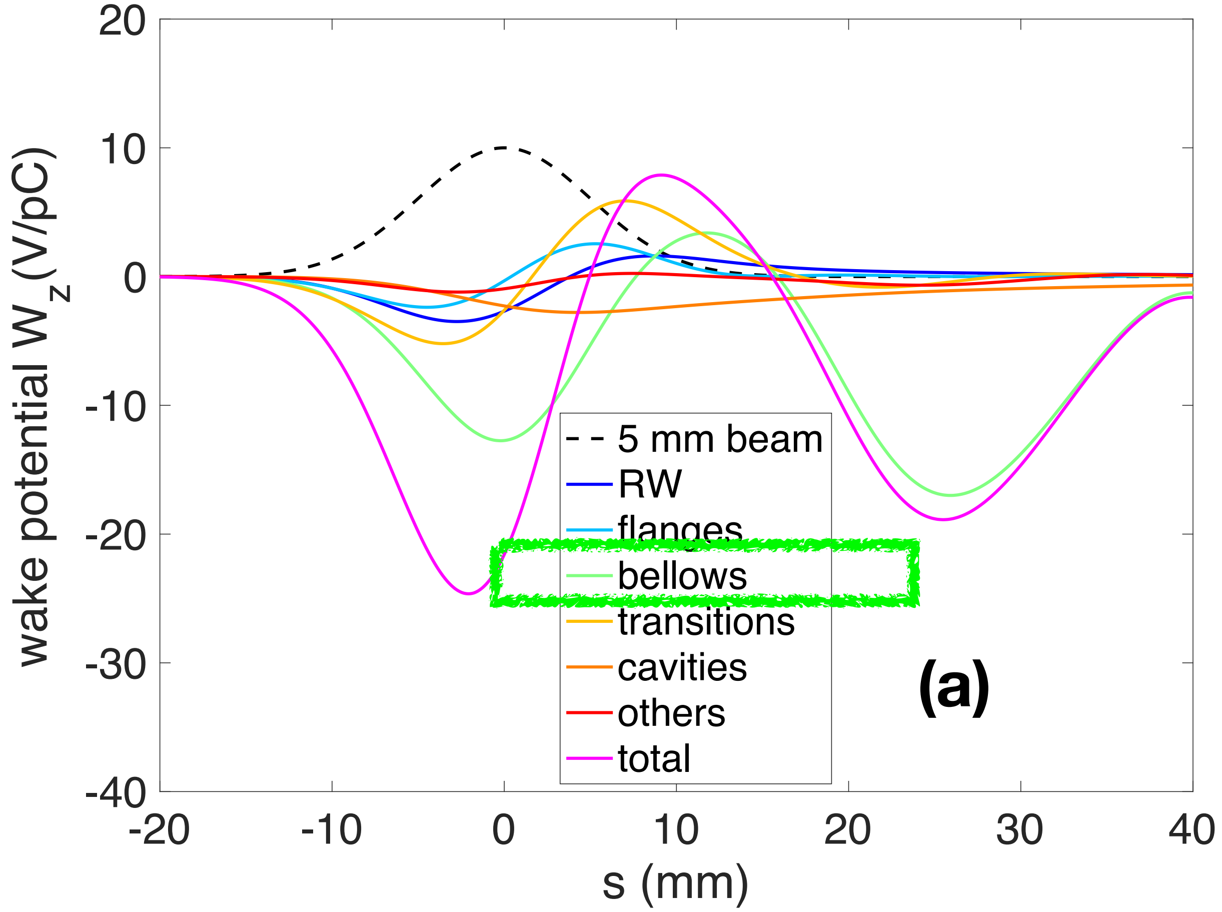


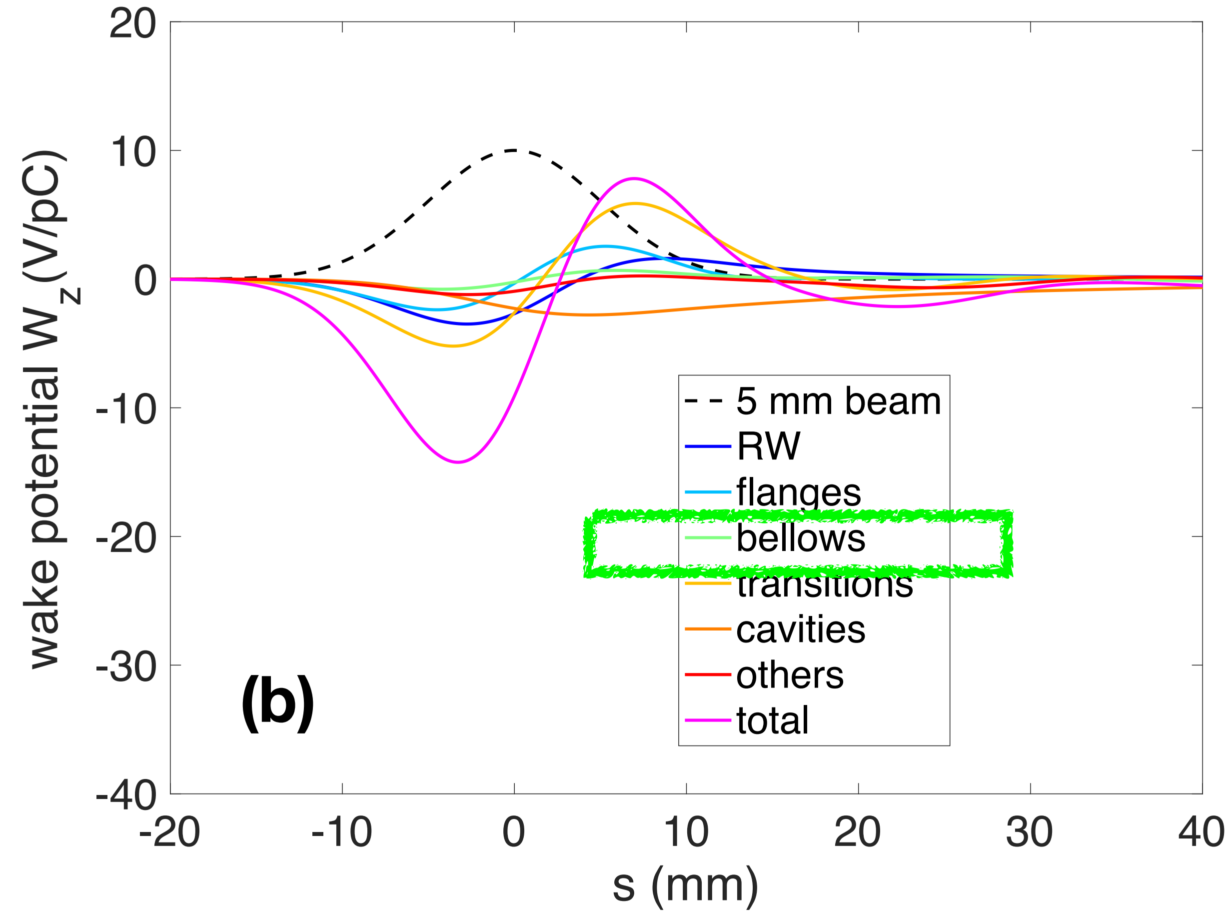
- Loss factor from 97 mV/pC down to 6.3 mV/pC
- This also indicates the requirement of accuracy assembling of the RF finger shielding during the vacuum installation, also for avoiding of vacuum heating

Low impedance bellows with RF shielding_4

- If we can control the impedance of the bellows with RF fingers

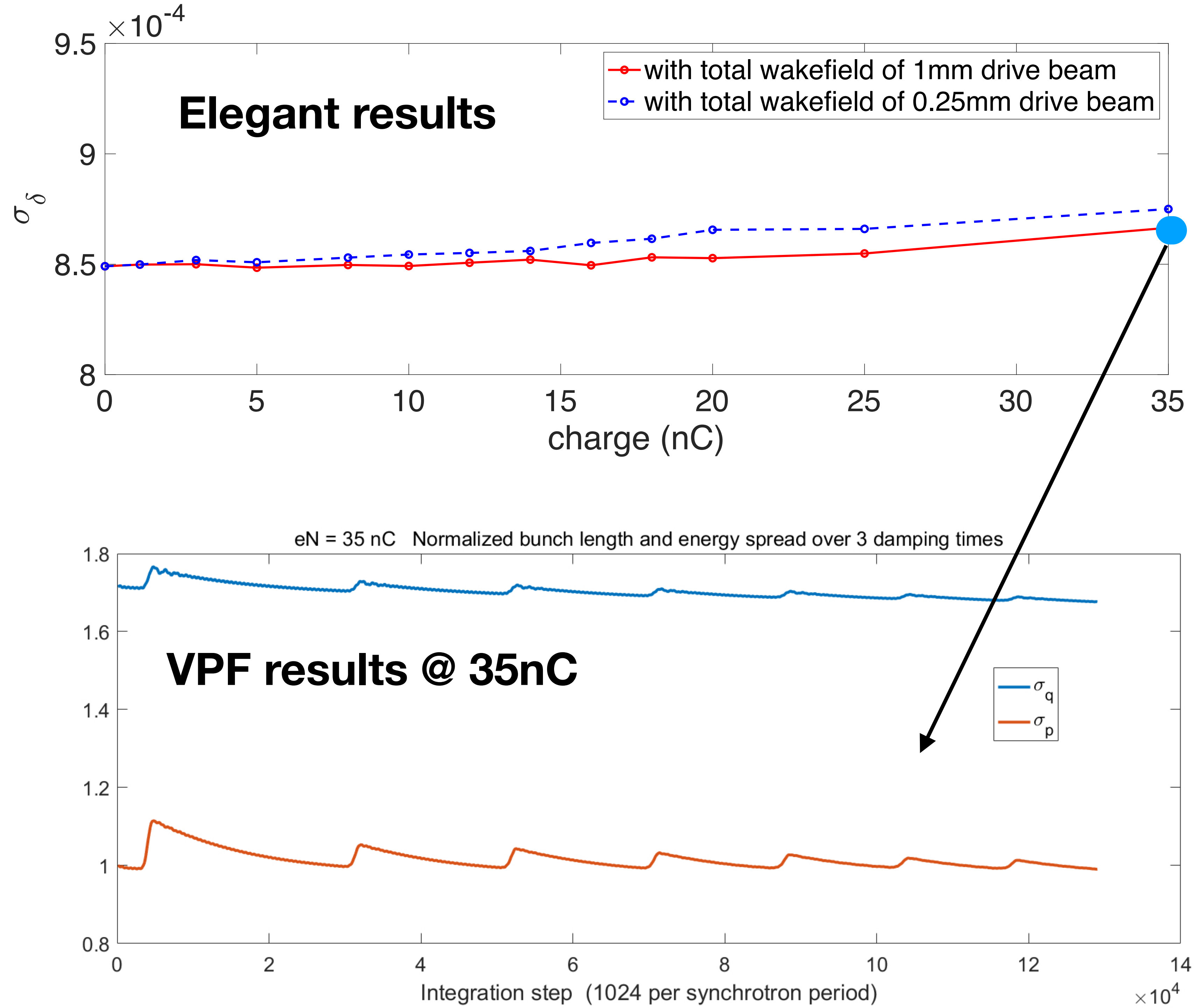
Budget discussed above → Updated with good-assembled bellows





Low impedance bellows with RF shielding_5

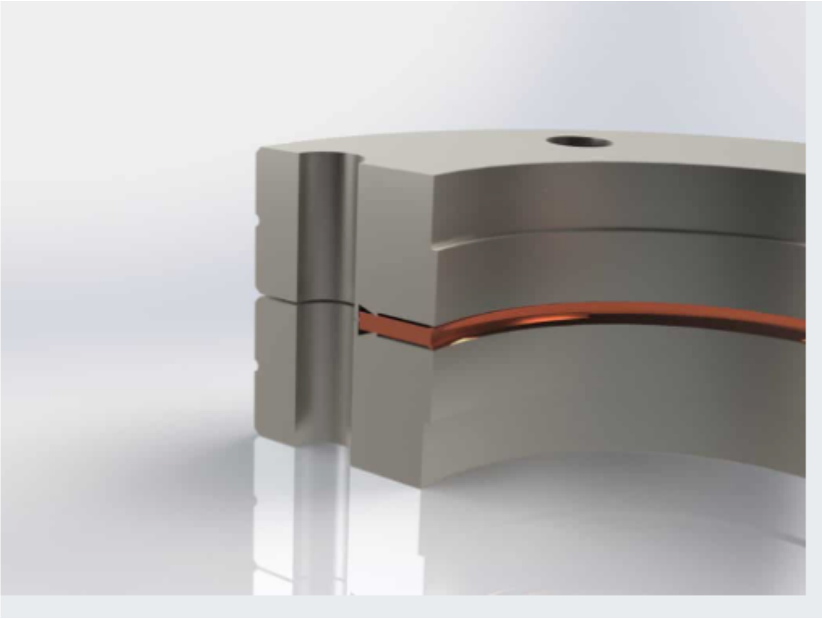
- Microwave instability threshold: slightly instability even up to 35nC



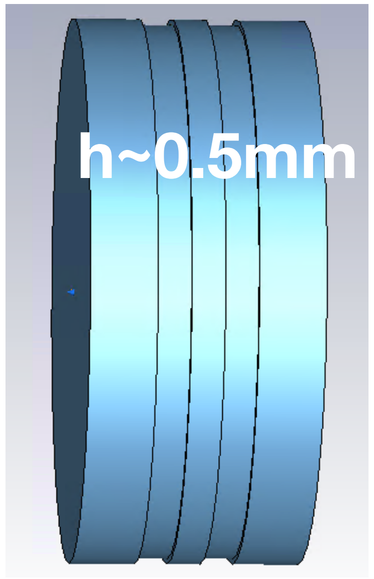
Low impedance flange with gasket_1

- The low impedance gasket used is under development by ATLAS

https://www.atlasuhv.com/products/all-metal-uhv-seals-gaskets/copper-cf-rf-flare-gaskets/

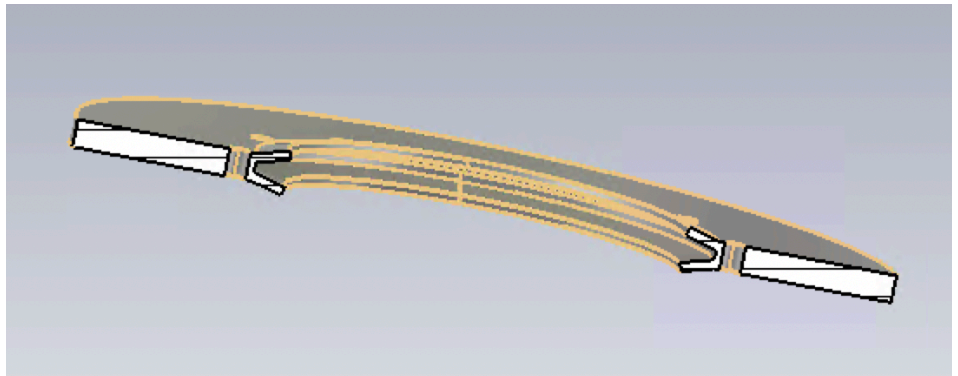


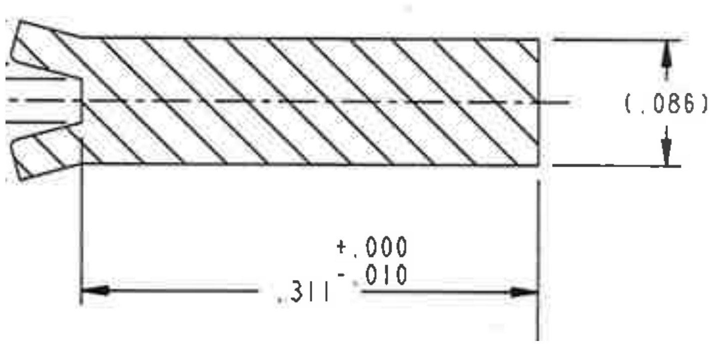
shallow gap model in CST



- Fail to install, some mechanical problem…

- Back to transitional gasket with a small cavity:





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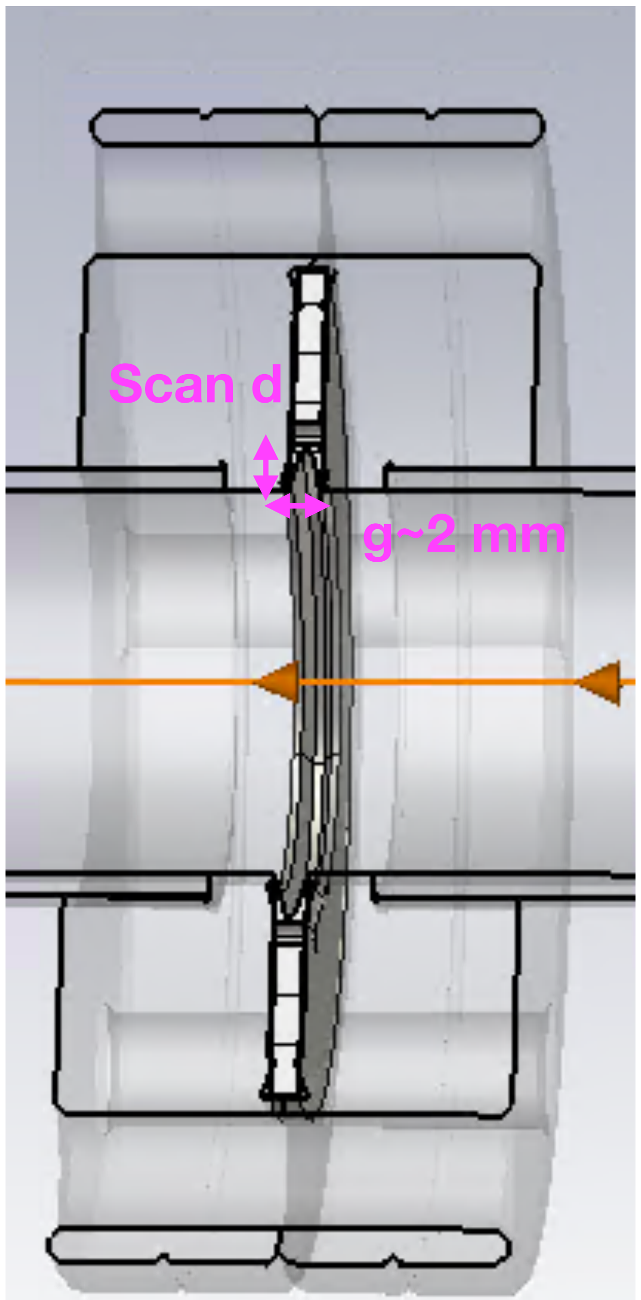
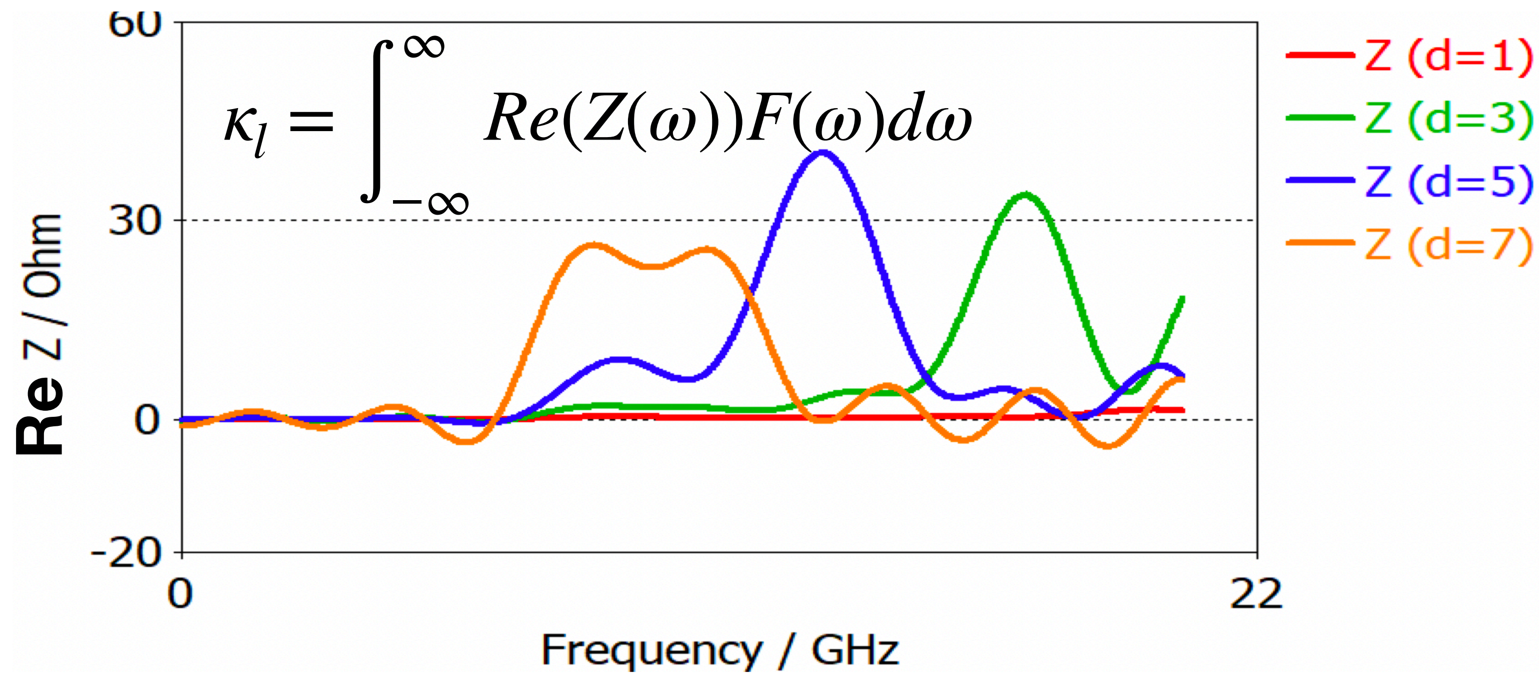
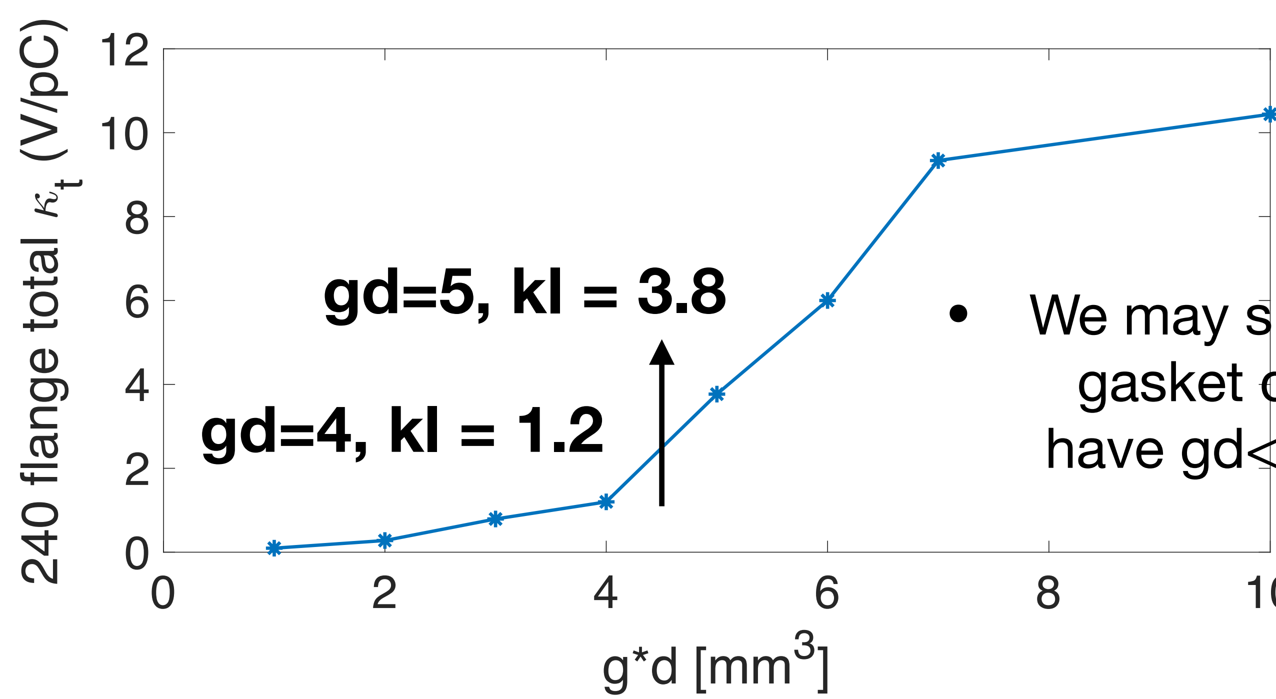
Low impedance flange with gasket_2

- Optimize the loss factor by scan parameters:







- We may suggest the gasket design to have gd<4 or gd<5

Summary

Summary & Plan

- Broad band impedance of ALS-U AR have been extensively surveyed by numerical simulation and analytical formulas. Majority of the impedance sources have been analyzed.
- Based on the current impedance model, both ELEGANT tracking and VPF solution indicate the AR bunch charge is well below the threshold of the longitudinal single bunch instability (1.15 nC vs ~11 nC). Transverse single bunch instability study shows the instability threshold charge is 12nC.
- The total impedance model will be updated as rest of the vacuum components are included, as well as the bellows and flange models are revised
- The trapped modes will be investigated in components such as button BPM, bellow, etc. for multi-bunch instability study
- Longitudinal and transverse feed back system can be added into the study in the future

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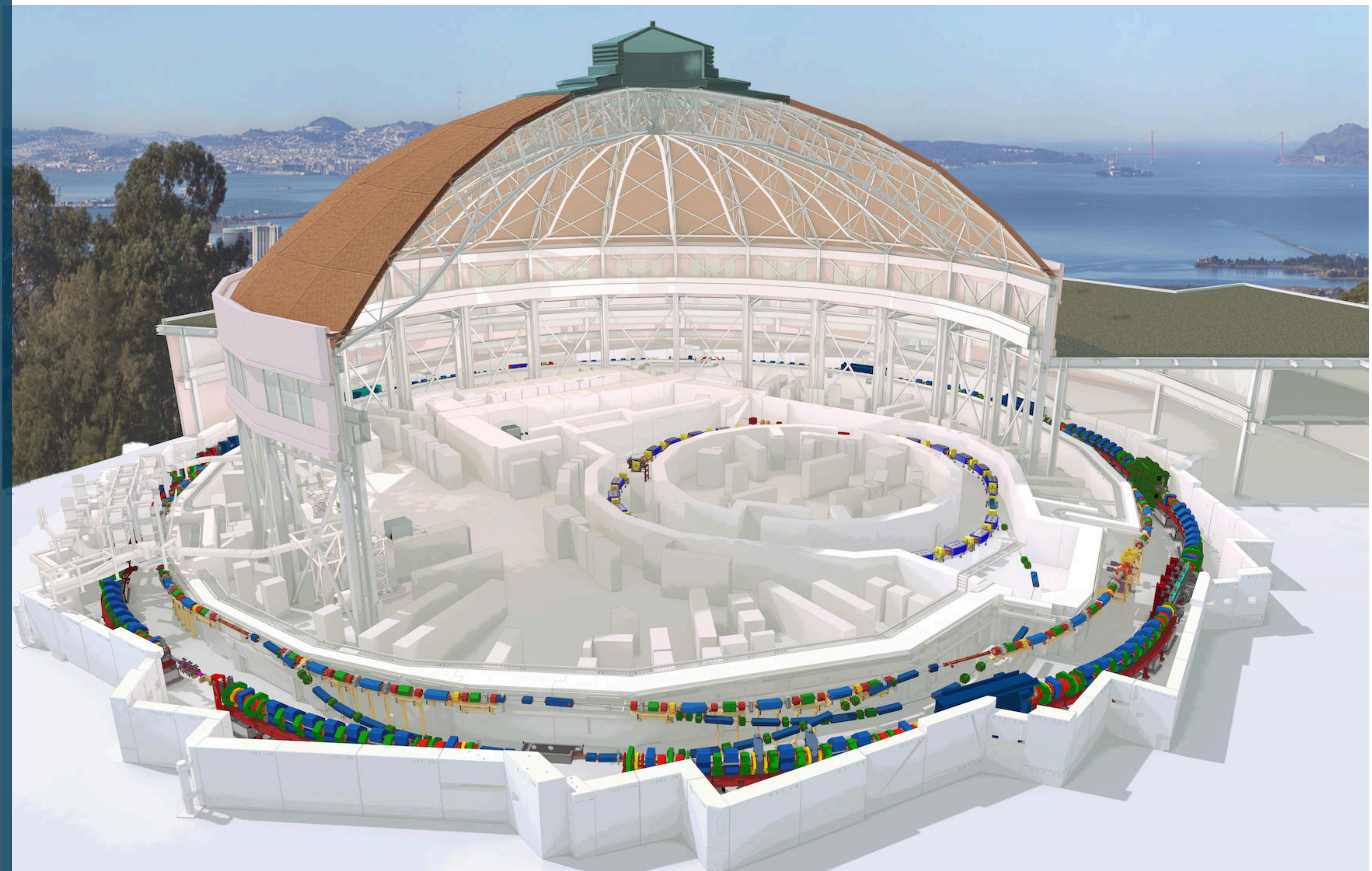
Many thanks!



SC1-05

Back ups

CST solves wake potential / not wake function

- More discussion on : short drive beam / long drive beam $Z_{||}(\omega) = -\frac{\int_{-\infty}^{\infty} W_{||}(s)e^{-j\omega s}ds}{\int_{-\infty}^{\infty} \lambda(s)e^{-j\omega s}ds}$

Structure characteristic: impedance in frequency domain / wake function or Green function in time domain $Z(\omega)$ / $G(s)$

Wake potential: convolution in time domain / production in frequency domain

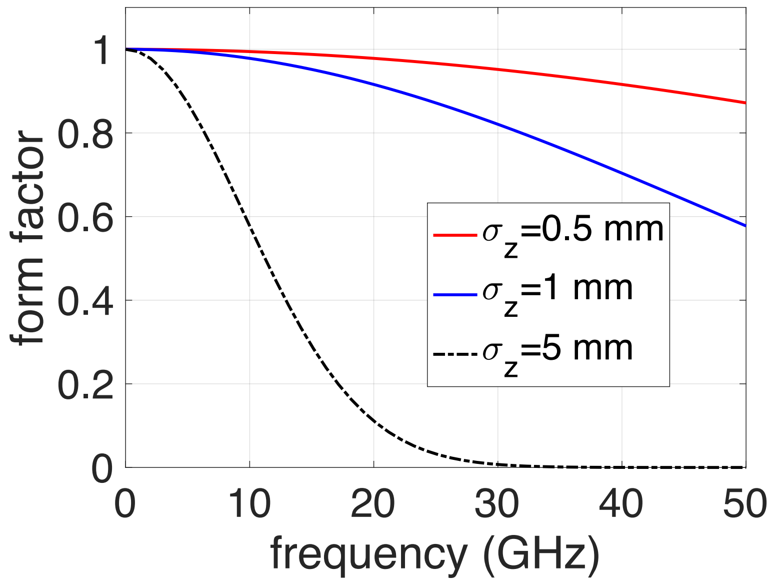
$$Z(\omega) \times F(\omega) \sim G(s) \circledast \lambda(s)$$

The from factor of a Gaussian drive beam:

$$F(\omega) = \int_{-\infty}^{\infty} ds\lambda(s)e^{-j\omega s} = \exp(-\omega^2\sigma_z^2/2c^2)$$

Cut-off frequency of calculation in CST

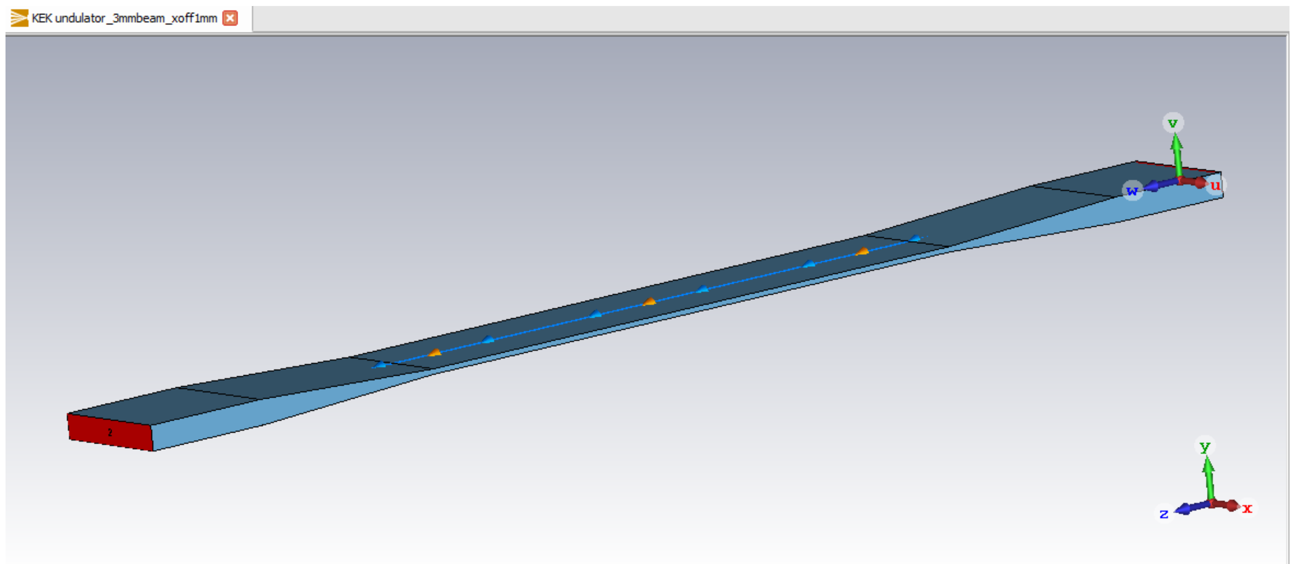
$$f_c\ [GHz] \cdot = 100/\sigma_z\ [mm]$$



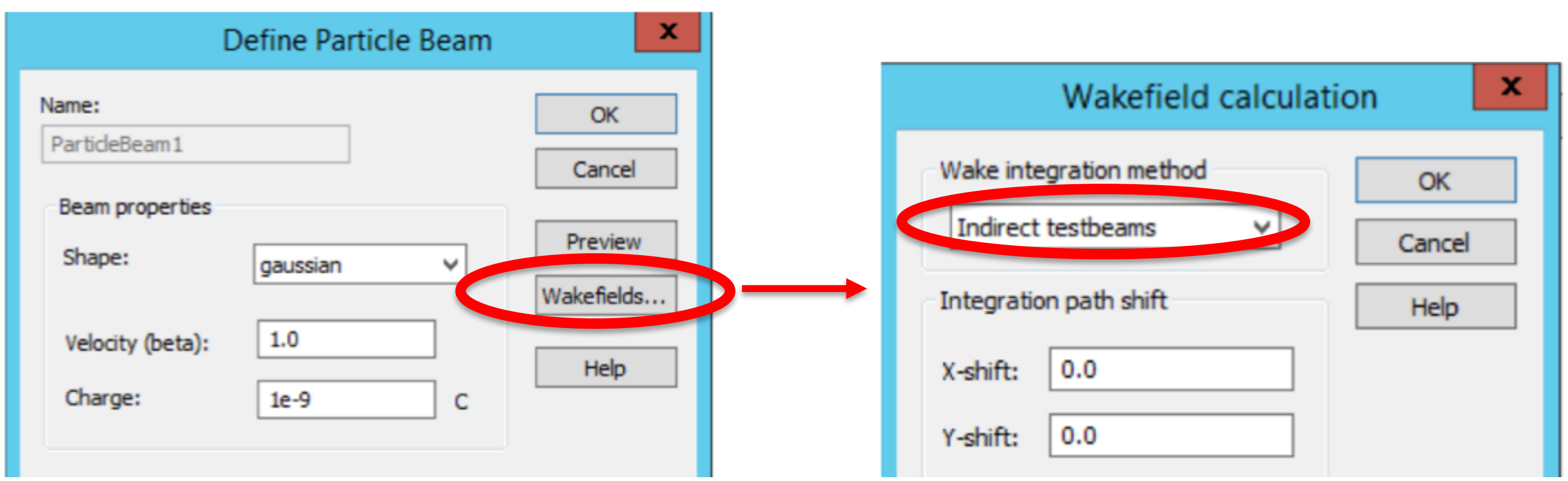
- Careful choose drive beam bunch length 1/5 or 1/10 of that of real beam in the ring

CST with proper settings

- Use it with right setting, such as boundary condition/ mesh size / integration method



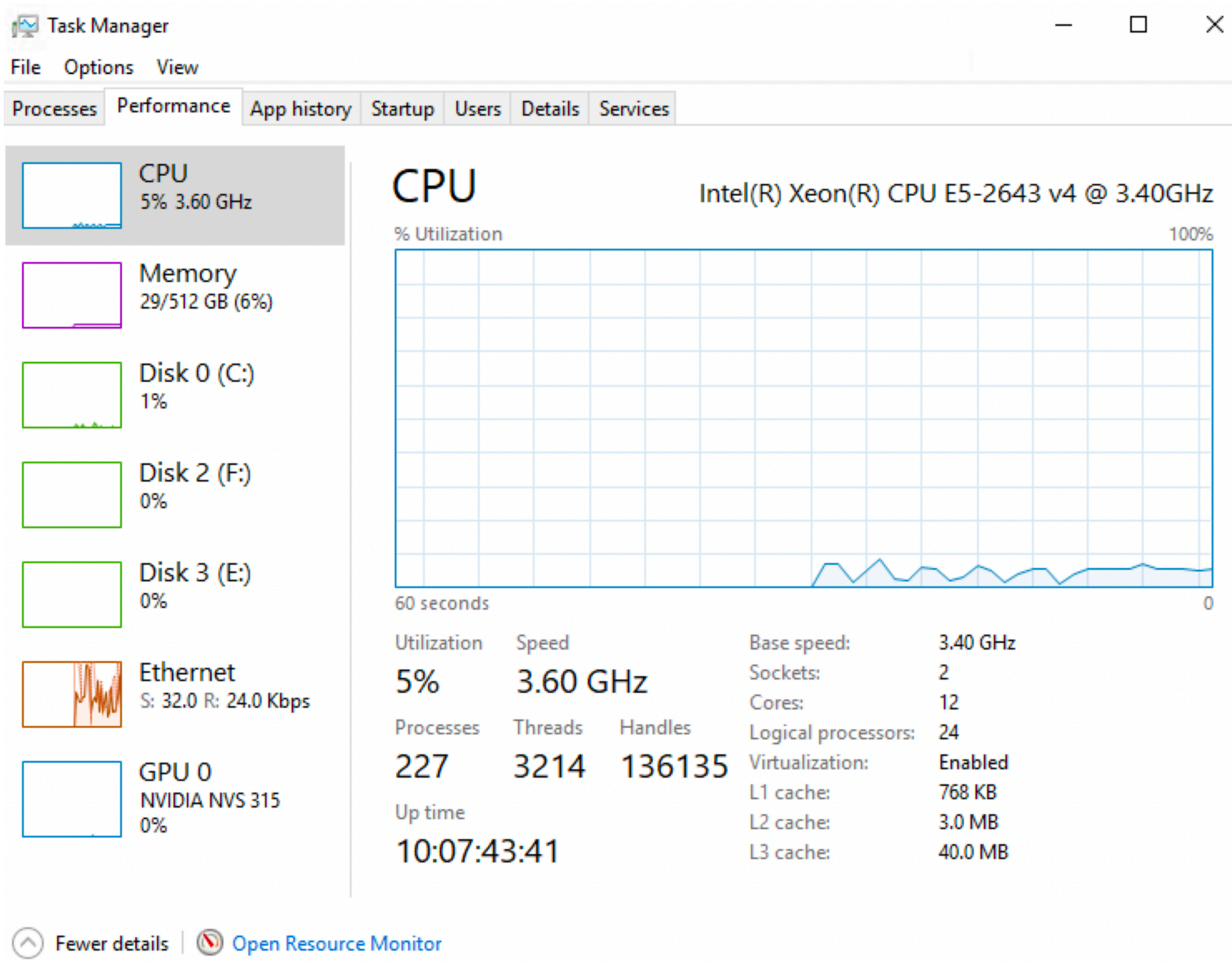
- Background: PEC / normal
- Boundary: $E_t = 0$ in X&Y || open in Z
- Suggest mesh set [1,2]: $100 \leq \frac{a\phi}{\Delta z} \cdot \frac{\sigma_z}{\Delta z}$
- Wakefield integration method: solve the infinity integration in a bright / indirect way (instead of direct one)[3] $W_{||}(x,y,s) = -\frac{1}{q}\int_{-\infty}^{\infty} dz E_z(x,y,z,\frac{s+z}{c})$



[1] Victor Smaluk, et.a.., PRAB,17,074402,2014
[2] O. Tanaka, et.al., Journal of Physics: Conference Series, 1067, 062008, 2018
[3] Igor Zagorodnov, Indirect methods for wake potential integration, PRAB, 9, 102002, 2006

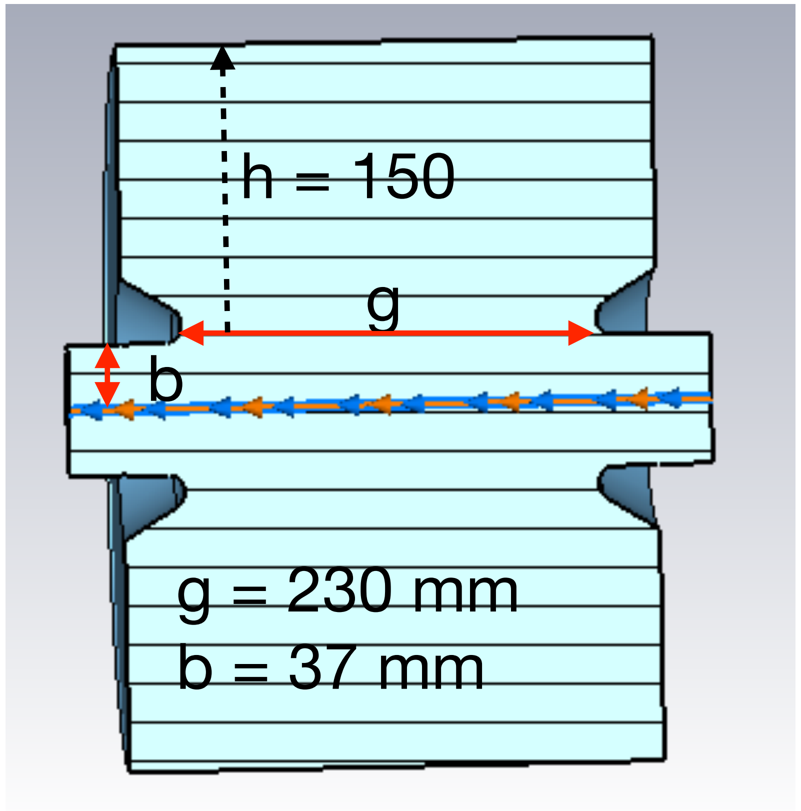
CST server at LBL

- Cores:12, logical processors: 24; maximum meshcells~1.5 billon (our RF cavity, with mesh size 100 um)



Theory of cavity wakefield and loss factor

model of RI cavity



For a resonant cavity in a storage ring, $\kappa_{||}$ is given by a sum over modes up to the cut-off frequency, plus a high frequency diffraction contribution (diffraction model [8], also Sec.3.2.4)

$$\kappa_{||} \approx \frac{\Gamma(1/4) Z_0 c}{4\pi^{5/2} b}\sqrt{\frac{g}{\sigma_z}} = 1.08 V/pC$$ (from handbook)

[8] K. Bane and M. Sands. Wakefield of very short bunches in an accelerating cavity, 1987

$$\kappa_{||,d} = \frac{Z_0 c}{4\pi^{5/2} b}\sqrt{\frac{g}{\sigma_z}} * (\Gamma(1/4) - 4\sqrt{\omega_c \sigma_z / c}) = 0.4 V/pC$$ (from [8])

The one from handbook is a asymptotic form as : $\sigma_z \to 0$; Our beam: $\sigma_z = 5\ mm$

- Diffraction model, start from the pillbox cavity edge, can be applied to calculate the loss factor that count the modes above frequency. This valid when [8]:

$$(g + 4\sigma_z) * 4\sigma_z < (h - b)^2$$

- Bellow the cut-off, we sum up the model loss factors with [1]:

$$\kappa_n = \frac{\omega_n}{4}(\frac{R}{Q})_n F(\omega_n, \sigma_z)$$

[1]. Thomas Wangler, Principles of RF linear accelerators, 1937, p295-p299.

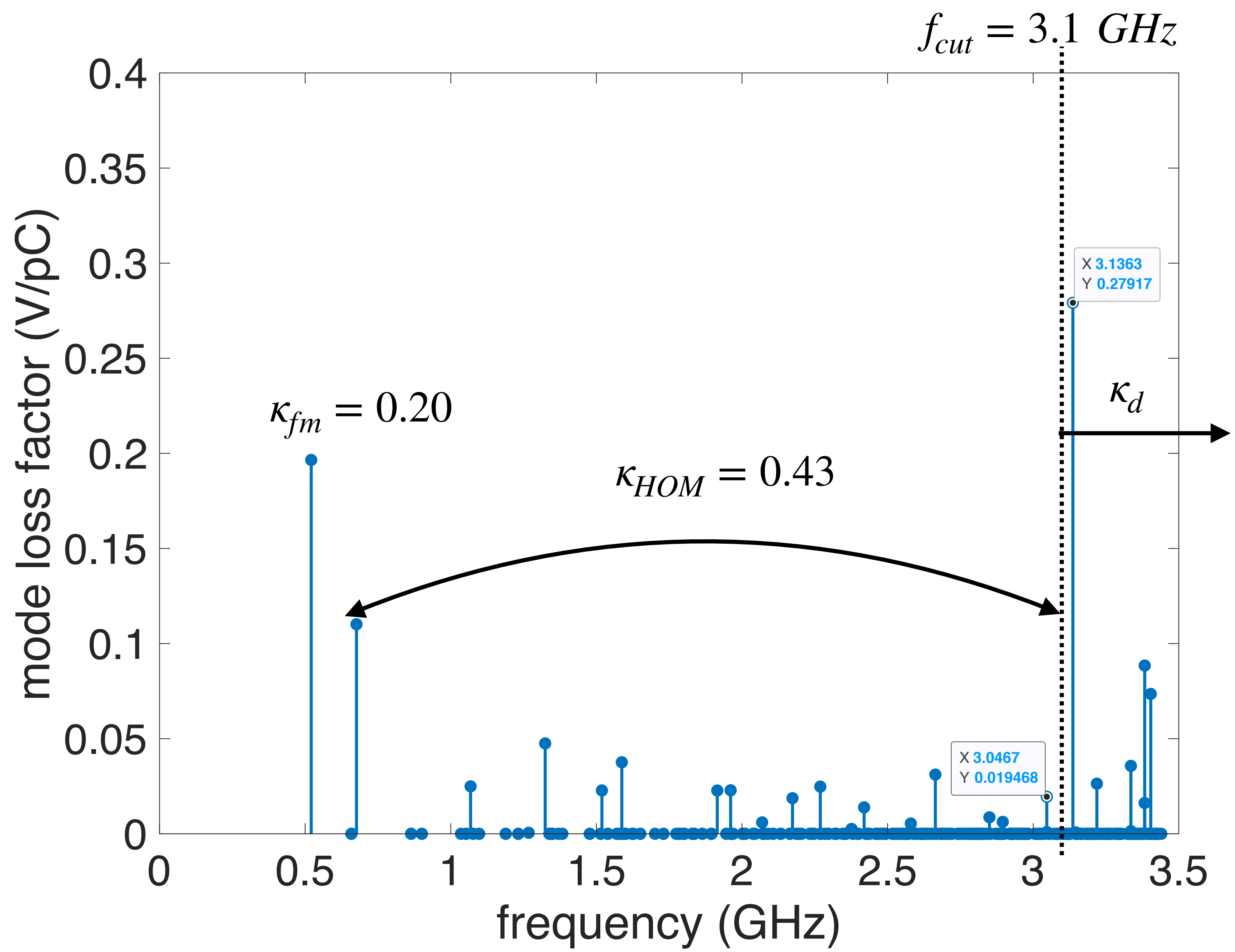
Theory of cavity wakefield and loss factor

Table of 14 modes with largest loss factor bellow cut-off frequency (~3.1 GHz)

No.	Frequency f (GHz)	R/Q*	loss factor V/pC
1(fm)	0.5208	241.0060	0.1966
2	0.6762	104.2300	0.1102
3	1.3242	23.2839	0.0475
4	1.5873	15.5068	0.0376
5	1.0680	15.0499	0.0249
6	2.2690	7.3617	0.0248
7	1.9610	7.7516	0.0229
8	1.5190	9.7950	0.0228
9	1.9152	7.8738	0.0228
10	2.1734	5.7740	0.0187
11	2.4194	3.9011	0.0139
12	2.0691	1.9336	0.0060
13	2.3764	0.7288	0.0026
14	1.2676	0.2743	0.0005

*From Tianhuan's simulation

Theory of cavity wakefield and loss factor



$$\kappa_{fm} = \frac{\omega_0}{4}(\frac{R}{Q})_0 F(\omega_0, \sigma_z)$$

$$\kappa_{HOM} = \sum_{n}^{n(f<f_c)} \frac{\omega_n}{4}(\frac{R}{Q})_n F(\omega_n, \sigma_z)$$

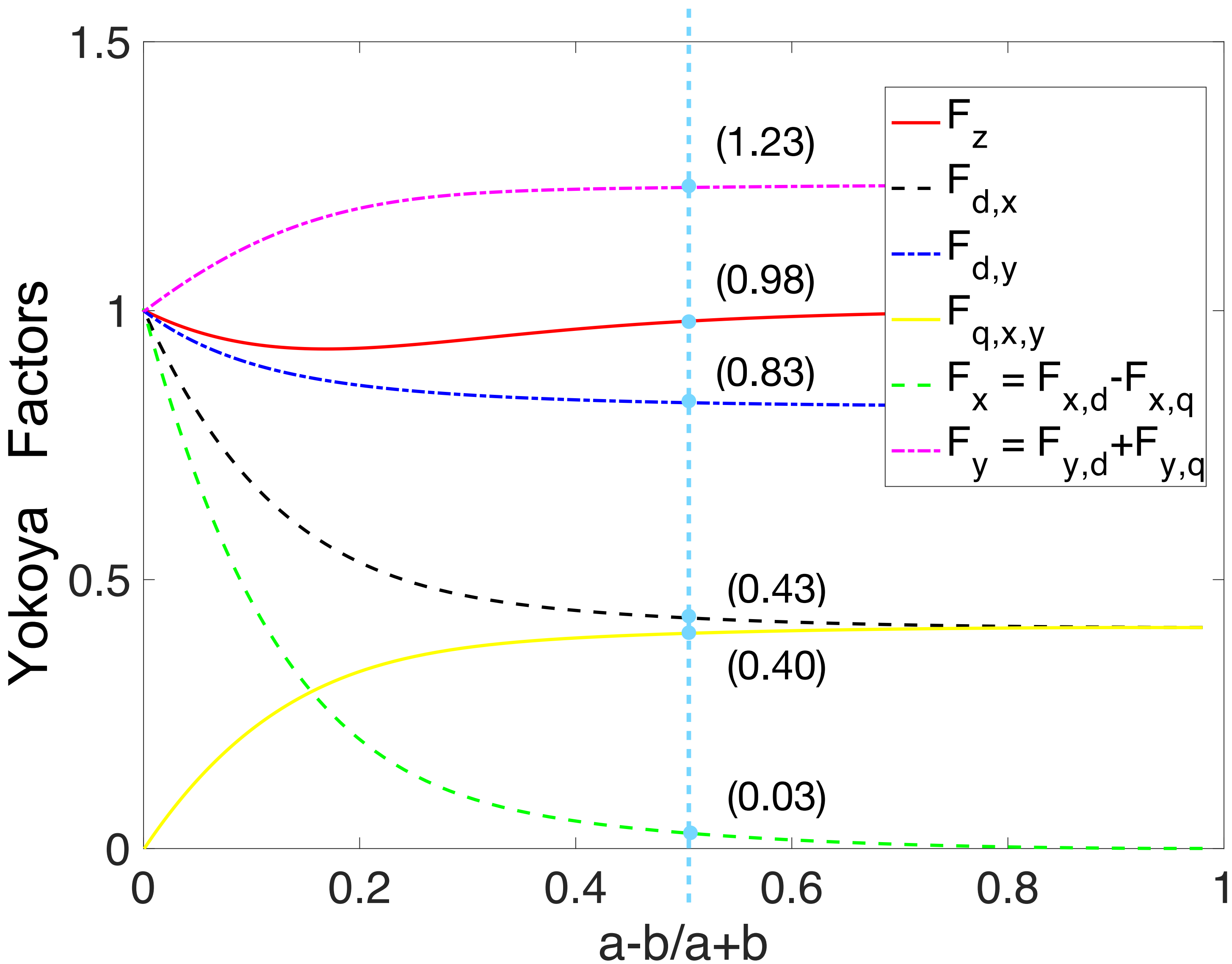
$$\kappa_{||,d} = = 0.4V/pC$$

$\kappa_t = \kappa_f m + \kappa_{HOM} + \kappa_d = 1.03V/pC$ ⟷ $\kappa_{t,CST} = = 0.98V/pC$

We can also estimate the beam power into different modes with loss factor calculation

Resistive wall in dipole chamber with Yokoya's factor

AR dipole chamber: a = 20 mm (x), b = 7 mm (y)



- Because a>b, using impedance /wakefield of round chamber with r = b is an over-estimate for all directions
- Yokaya's factor F [1]:

$$F = Z_{ellipse}/Z_{round}(r = b)$$

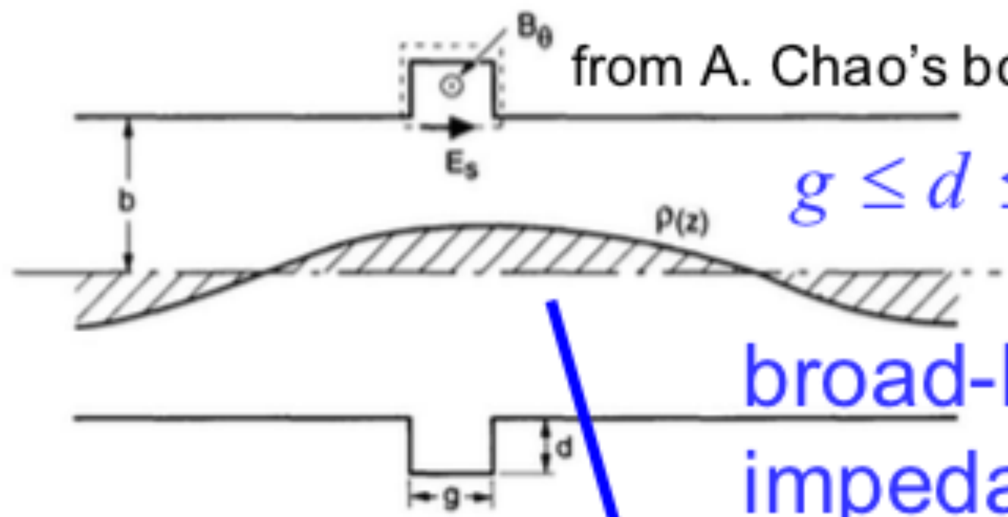
- Fy, dipole = 0.83;
- Fx, dipole = 0.43

[1] Yokoya, K, Resistive wall impedance of beam pipes of general cross section, 1993
[2] A. Chao, et.al., Tune shifts of bunch trains due to resistive vacuum chambers without circular symmetry, 2002
[3] T. F. Gunzel, Transverse coupling impedance of the storage ring at the European Synchrotron Radiation Facility, 2006

Impedance of flanges: theory to be study

impedance of flanges? *corrected*

from A. Chao's book



$g \le d \le b$

broad-band impedance model

Figure 2.17. The impedance of a small cavity ($g \le d \le b$) is predominantly inductive at low frequencies ($\omega \ll c/b$). The voltage across the cavity gap can be obtained by applying Faraday's law to the dashed circuit.

resonances & trapped modes?

lowest resonant frequency $f \sim c/(4d) \sim 4$ GHz for d=2 cm

$$Z_{\parallel}(\omega) = \frac{g Z_0}{\pi b I_0^2(\bar{b}) D}, \tag{1}$$

with

$$D = j\frac{R_0'(kb)}{R_0(kb)} - 2jk\left[\sum_{s=1}^{S} \frac{1}{\beta_s^2 b}\left(1 - e^{-j\beta_s g}\frac{\sin \beta_s g}{\beta_s g}\right) - \sum_{s=S+1}^{\infty} \frac{1}{\alpha_s^2 b}\left(1 - e^{-\alpha_s g}\frac{\sinh \alpha_s g}{\alpha_s g}\right)\right]. \tag{2}$$

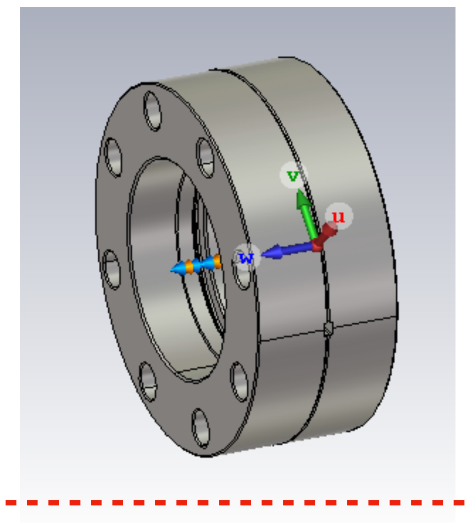
"Diffractive grating structure for coherent light source production", 2009

"Point charge passing a resonator with beam tubes", 1986

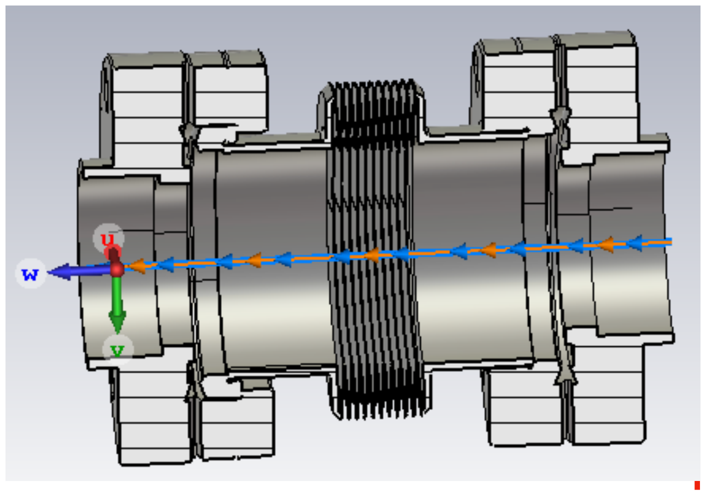
Geometry impedance sources, such as:

Small ones may be the trouble makers !

RF flanges (N>200)



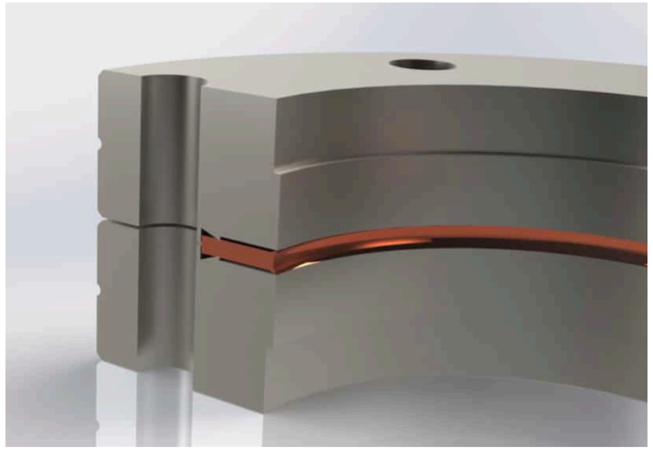
Bellows (N>50)



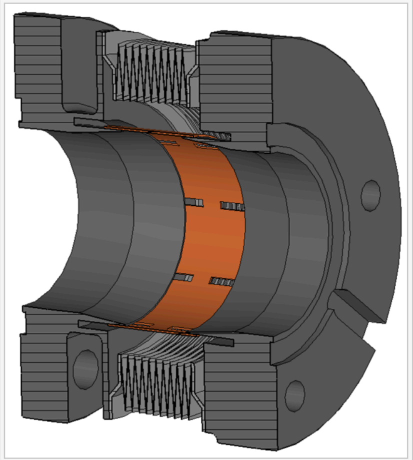
K.Y. Ng, “Impedance Issue of Corrugated Beam Pipe from CDF”, FERMILAB-TM-1847 (1993)

Karl Bane, “Impedance Calculation and Verification in Storage Rings”, SLAC-PUB-1007, 2005

Flanges with gasket

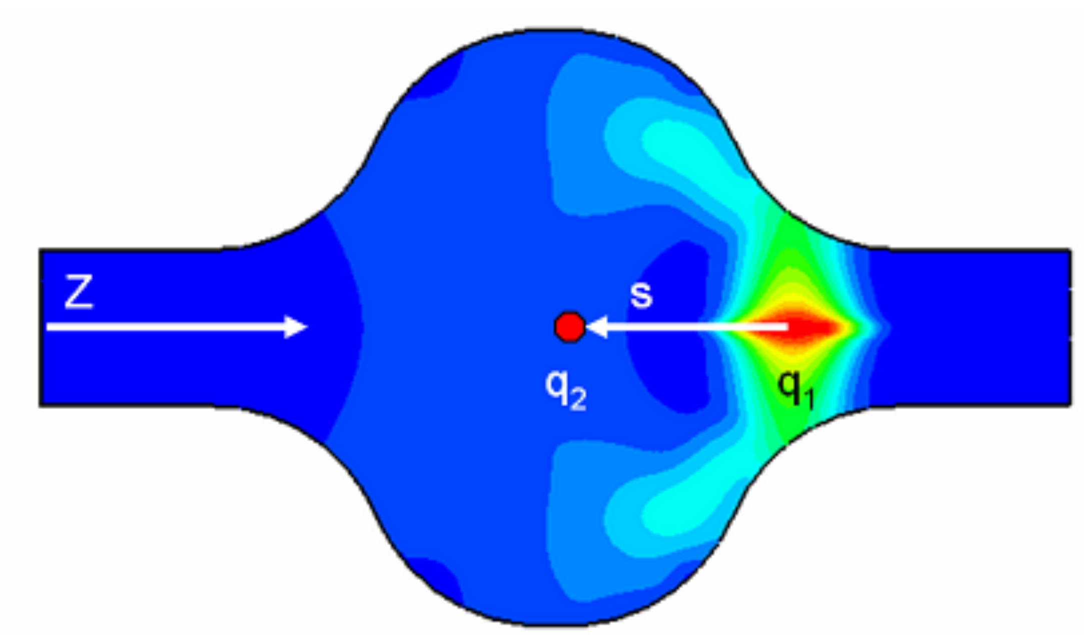


Bellows with shield



Now, use CST to simulate each component

- Know your tools before using it:



Drive beam with certain distribution $\lambda(s)$

Solve 3D electromagnetic field in time domain

Calculate the wake potential with integration:

$$W_{||}(x,y,s) = -\frac{1}{q}\int_{-\infty}^{\infty} dz E_z(x,y,z,\frac{s+z}{c})$$

Transverse wake potential from Panovsky-Wenzel theorem

$$W_{\perp}(x,y,s) = -\Delta_{\perp}\int_{-\infty}^{s} ds' W_{||}(x,y,s')$$

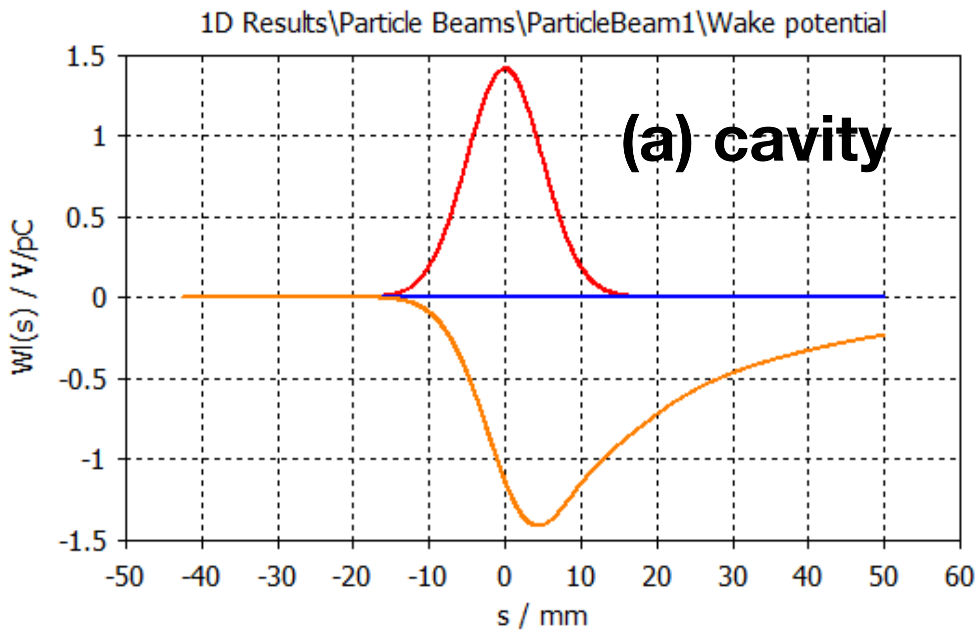
Impedance from FFT, calculation range decided by the drive beam distribution:

$$Z_{||}(\omega) = -\frac{\int_{-\infty}^{\infty} W_{||}(s)e^{-j\omega s}ds}{\int_{-\infty}^{\infty} \lambda(s)e^{-j\omega s}ds}$$

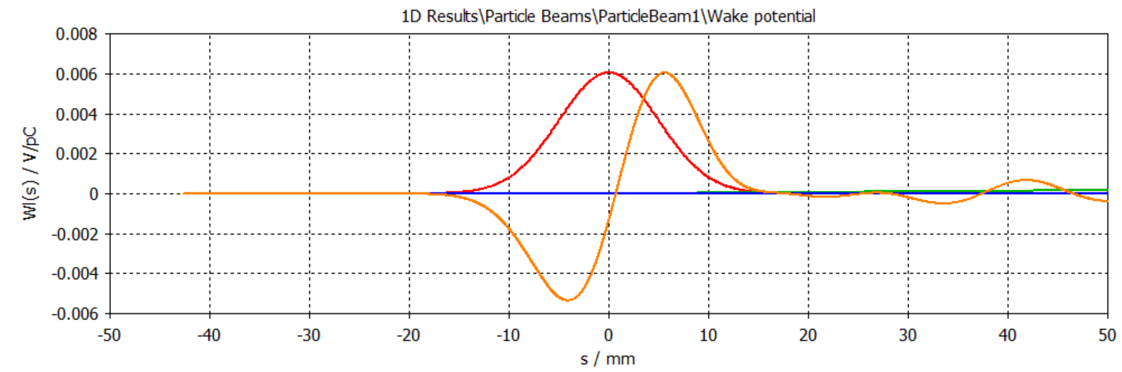
← FFT of wake potential

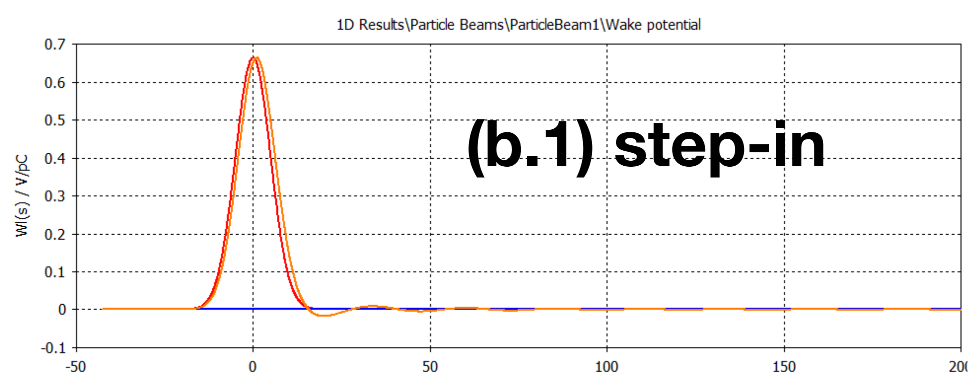
← FFT of beam distribution, from factor

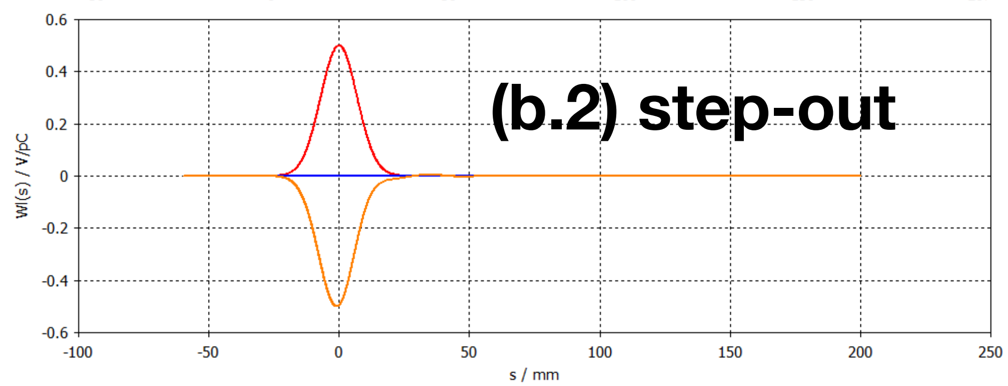
Results from CST for different components

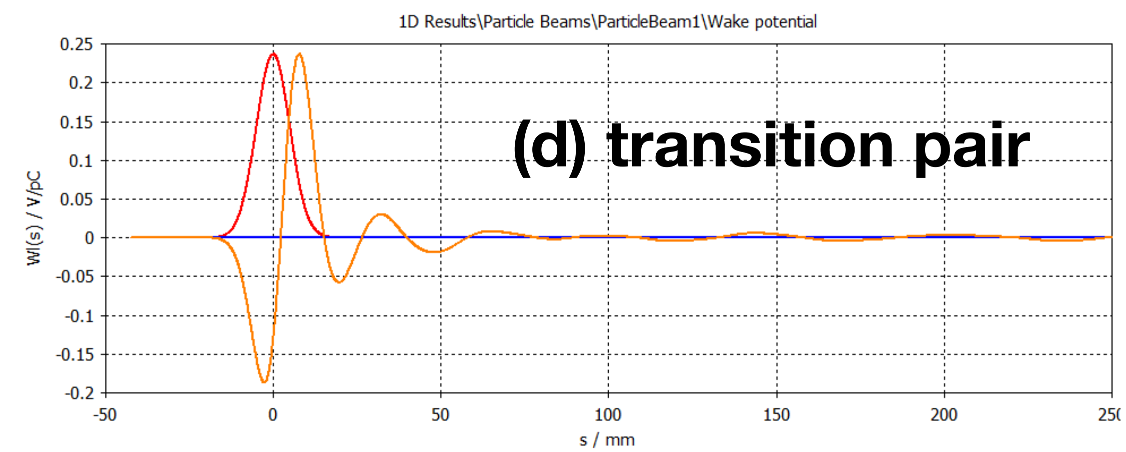


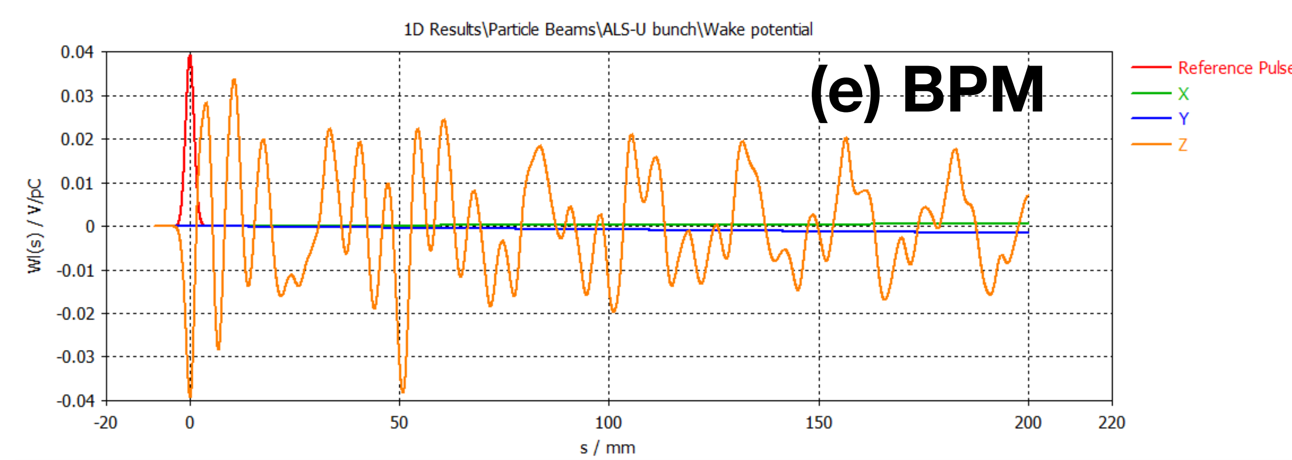
(c) pump screen











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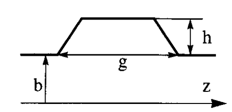
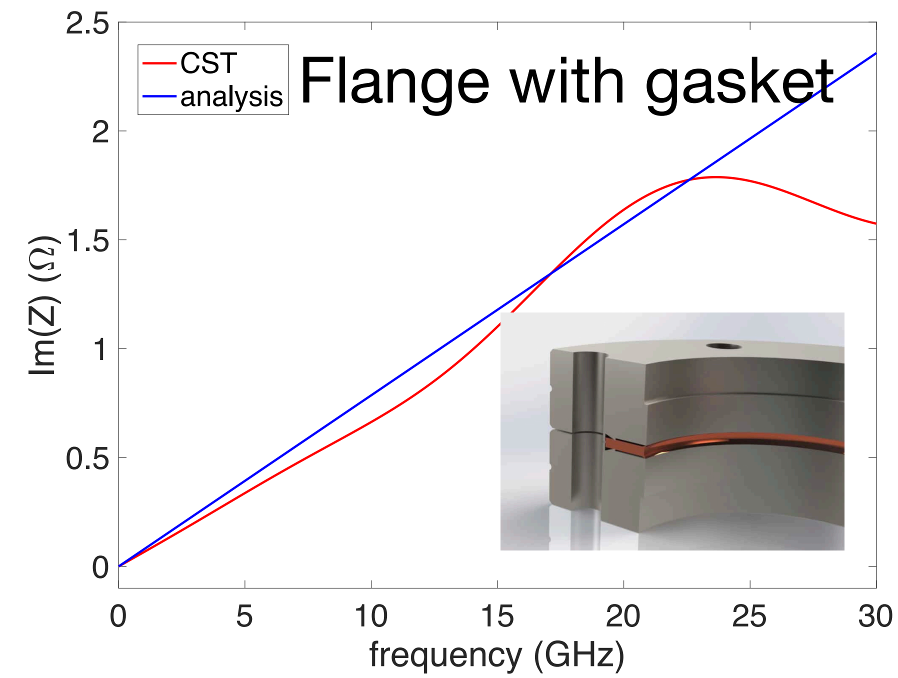
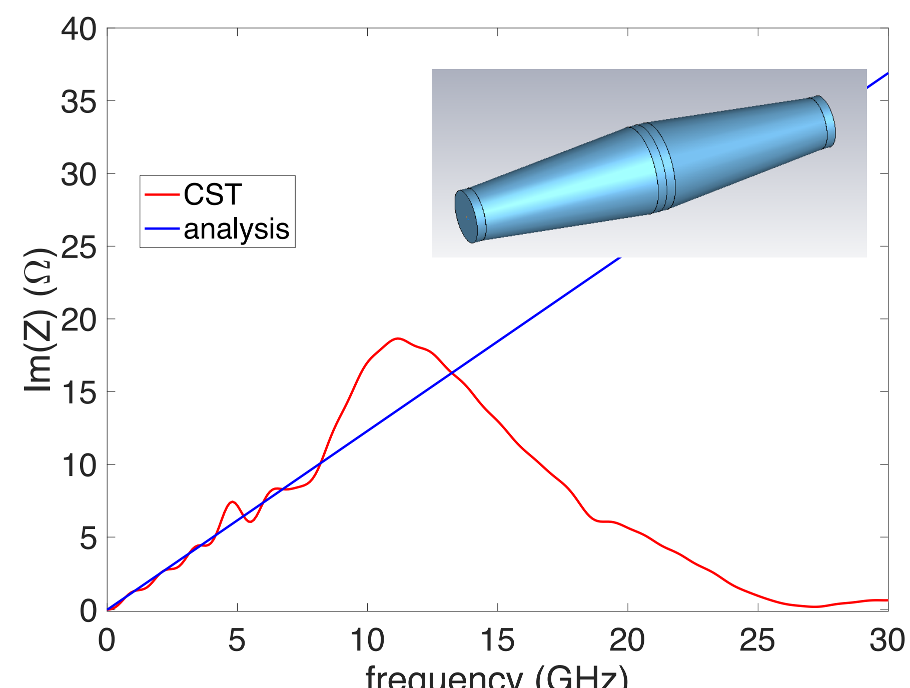
Check our CST simulations

Handbook is always there (most valid for low frequency)

Small inductive objects-2D: [27, 30] small cavities, shallow irises, and transitions at low freq. ($h \ll b$, $k \ll 1/h$); h is height of object, g is gap of cavity or length of iris; $\mathcal{L}$ is inductance. For tapered transition pair: θ is taper angle.	$Z_0^{\parallel} = -ikc\mathcal{L}, \quad Z_1^{\perp} = \frac{2}{b^2 k} Z_0^{\parallel}$	$W_0' = -c^2 \mathcal{L} \delta'(z), \; W_1 = \frac{2}{b^2} \int W_0' \, dz$
	Pill box $g \lesssim h \ll b: \; \mathcal{L} = \frac{Z_0}{2\pi cb}\left[gh - \frac{g^2}{2\pi}\right]$  Shallow iris $g \lesssim h \ll b: \; \mathcal{L} = \frac{Z_0 h^2}{4cb}$ Transition pair $g \gg h, \; h \ll b: \; \mathcal{L} = \frac{Z_0 h^2}{2\pi^2 cb}\left(\ln\frac{2\pi b}{h} + \frac{1}{2}\right)$ Tapered : $\mathcal{L} = \frac{Z_0 h^2}{\pi^2 cb}\left[\ln\left(\frac{b\theta}{h} - 2\theta\cot\theta\right) + \frac{3}{2} - \gamma_e - \psi\left(\frac{\theta}{\pi}\right) - \frac{\pi}{2}\cot\theta - \frac{\pi}{2\theta}\right]$ $\gamma_e \approx 0.57721$ is Euler's constant, $\psi(x)$ is psi function.	

Round collimator: (a) [40] low frequency $k \ll 1/d$.	$Z_1^{\perp} = -0.3i\frac{Z_0}{d}$ collimator radius $d \ll b$.	$W_1 = -0.3\frac{Z_0 c}{d}\delta(z)$ collimator radius $d \ll b$.
(b) High frequency $k \gg 1/d$; if tapered, angle $\theta \gg 1/(kd)$.	See optical model formulae (a) above	
(c) [41] For any frequency, small angle, $d'(s) \ll 1$, $kdd' \ll 1$, with $d(s)$ pipe profile versus longitudinal position s, and d' is derivative of d with respect to s.	$Z_0^{\parallel} = \frac{-iZ_0 k}{4\pi}\int ds\,(d')^2$ $Z_1^{\perp} = \frac{-iZ_0}{2\pi}\int ds\left(\frac{d'}{d}\right)^2$ $\Rightarrow$ symm. tapers of angle $\theta \ll 1$: $Z_1^{\perp} = \frac{-iZ_0}{\pi}\theta\left(\frac{1}{d} - \frac{1}{b}\right)$	$W_0' = \frac{Z_0 c}{4\pi}\int ds\,(d')^2 \delta'(z)$ $W_1 = -\frac{Z_0 c}{2\pi}\int ds\left(\frac{d'}{d}\right)^2 \delta(z)$ $W_1 = -\frac{Z_0 c}{\pi}\theta\left(\frac{1}{d} - \frac{1}{b}\right)\delta(z)$





BERKELEY LAB

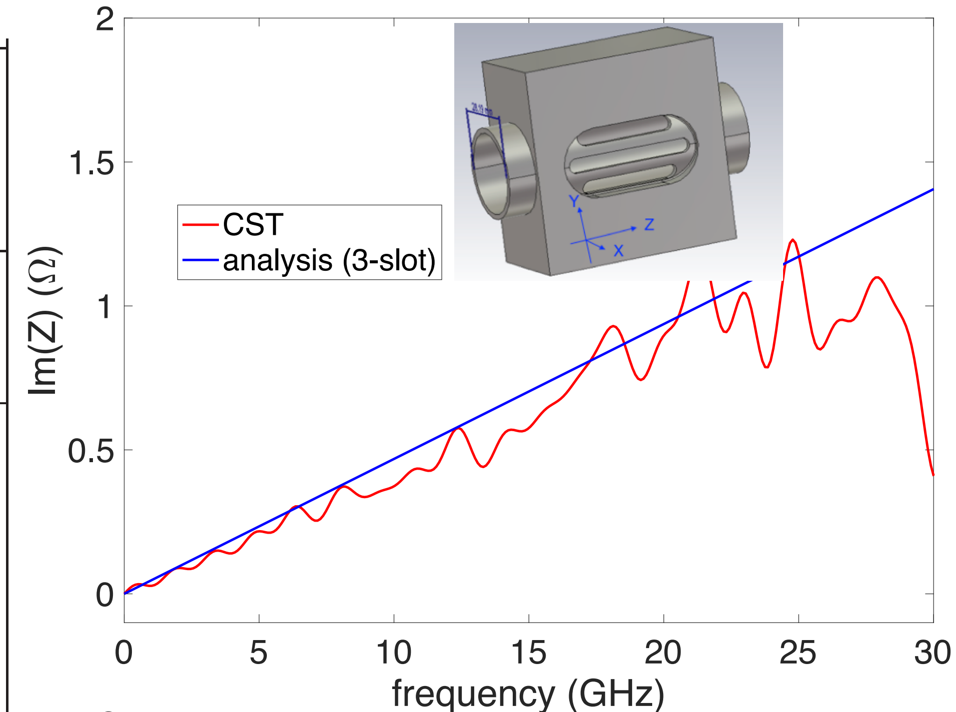
ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

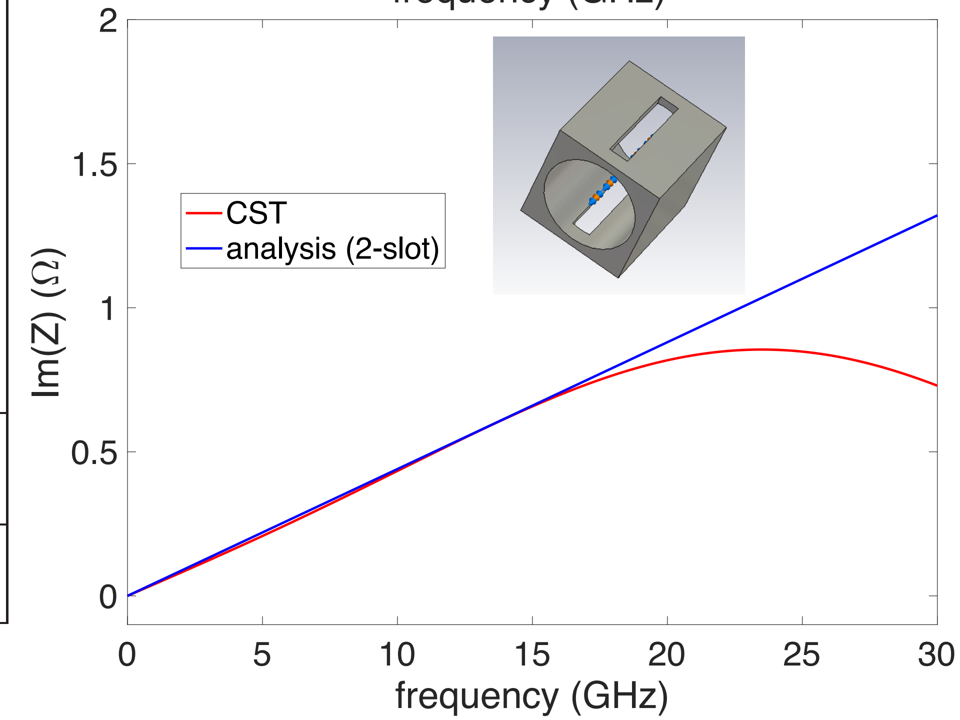
ALS-U ADVANCED LIGHT SOURCE

Check our CST simulations

Handbook is always there (most valid for low frequency)

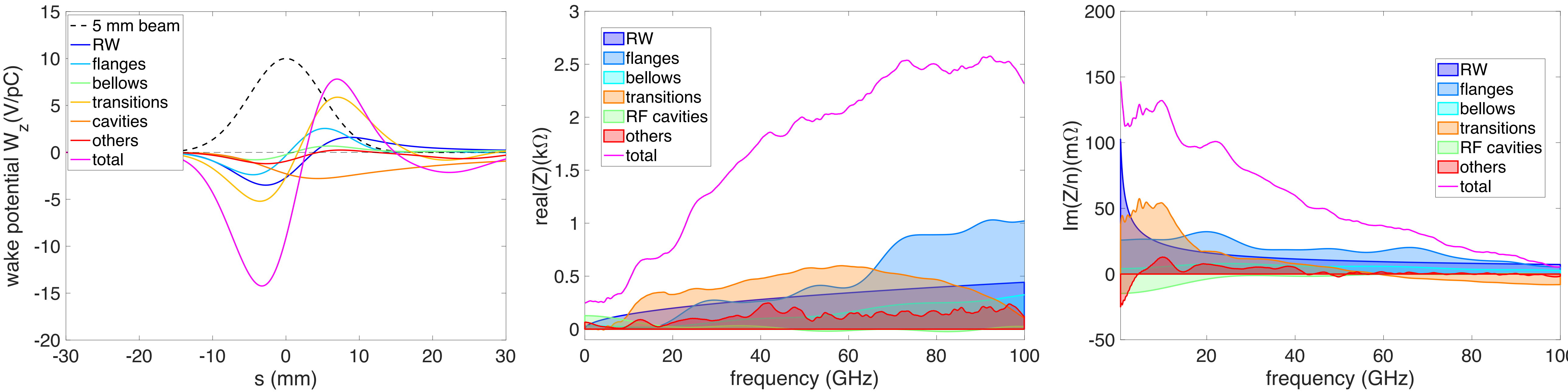
Small 3D obstacle on beam pipe: [27, 28] size $\ll b$, low freq. $k \ll 1/(\text{size})$; ϕ azimuthal angular position of object.	$Z_0^{\parallel} = -ikc\mathcal{L}$, $Z_1^{\perp} = \frac{4}{b^2 k} Z_0^{\parallel} \cos\phi$	$W_0' = -c^2 \mathcal{L}\, \delta'(z)$ $W_1 = \frac{4}{b^2} \int W_0' \cos\phi \, dz$
	Inductance $\mathcal{L} = \frac{Z_0(\alpha_e + \alpha_m)}{4\pi^2 b^2 c}$ α_e is electric polarizability, α_m magnetic susceptibility	
Elliptical hole: major and minor radii are a and d. $K(m)$ and $E(m)$ are complete elliptical functions of the first and second kind, with $m = 1 - m_1$ and $m_1 = (d/a)^2$. For long ellipse perpendicular to beam, major axis $a \ll b$, beam pipe radius, because the curvature of the beam pipe has been neglected here [29].	$\alpha_e + \alpha_m = \begin{cases} \frac{\pi a^3 m_1^2 [K(m) - E(m))]}{3E(m)[E(m) - m_1 K(m)]} \\ \frac{\pi a^3 [E(m) - m_1 K(m)]}{3[K(m) - E(m)]} \end{cases} \xrightarrow[\text{long ellipse}]{m \to 1} \begin{cases} \frac{\pi d^4 [\ln(4a/d) - 1]}{3a} & \parallel \text{ beam } d \ll b \\ \frac{\pi a^3}{3\,[\ln(4a/d) - 1]} & \perp \text{ beam } a \ll b \end{cases}$ $\alpha_e + \alpha_m \xrightarrow[m \to 0]{\text{circular}} \frac{2a^3}{3}$ circular hole $a = d \ll b$ Above are for $t \ll a$. When $t \geq a$, $\times 0.56$ when hole is circular and $\times 0.59$ when hole is long-elliptic. For higher frequency correction, add to $\alpha_e + \alpha_m$ the extra term, $+\frac{2\pi a^3}{3}\left[\frac{11k^2a^2}{30}\right]$ circular, $\begin{cases} -\frac{\pi a d^2}{3}\left[\frac{k^2 a^2}{5}\right] & \parallel \text{ beam long ellipse} \\ +\frac{2\pi a^3}{3}\left[\frac{2k^2a^2}{5[\ln(4a/d) - 1]}\right] & \perp \text{ beam long ellipse} \end{cases}$	
Rectangular slot: length L, width w.	$\alpha_e + \alpha_m = w^3(0.1814 - 0.0344w/L) \quad t \ll a, \quad \times 0.59$ when $t \geq a$	
Rounded-end slot: length L, width w.	$\alpha_e + \alpha_m = w^3(0.1334 - 0.0500w/L) \quad t \ll a, \quad \times 0.59$ when $t \geq a$	





Add up to get the impedance budget

Longitudinal wakefield and impedance



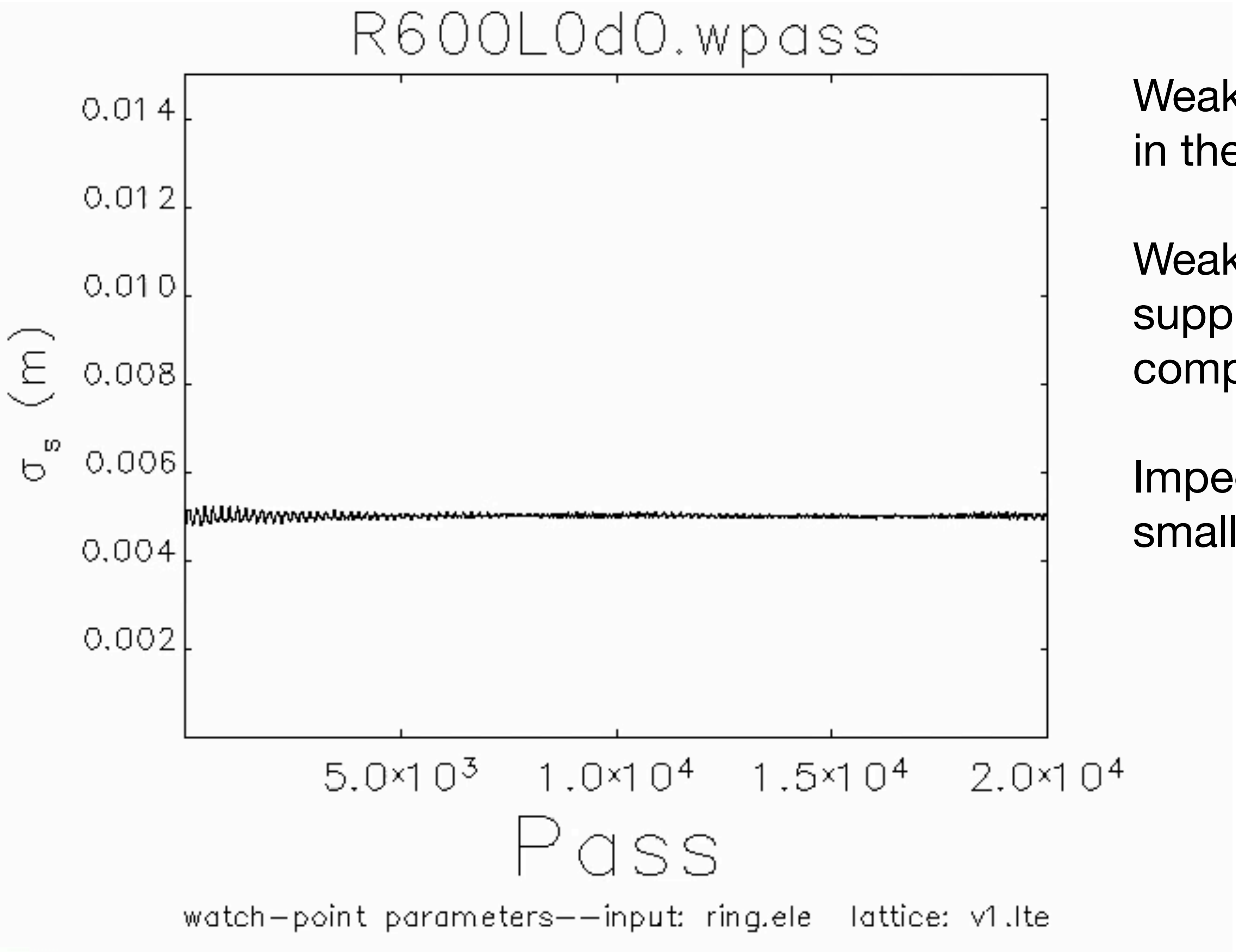
Total budget: $|Z/n| = 0.13\ \Omega$

Boussard criterion (very rough estimation):

$$Q_{th} = (2\pi)^{3/2}\frac{\alpha\sigma_z E\sigma_\delta^2}{c|Z/n|} \longrightarrow Q_{th} = 3.25\ nC > 1.15\ nC\ (AR) \quad \textbf{or} \quad |Z/n|_{th} = 0.37\ \Omega(AR)$$

Are we really safe?

reason?: results with assumed wakeifeld models



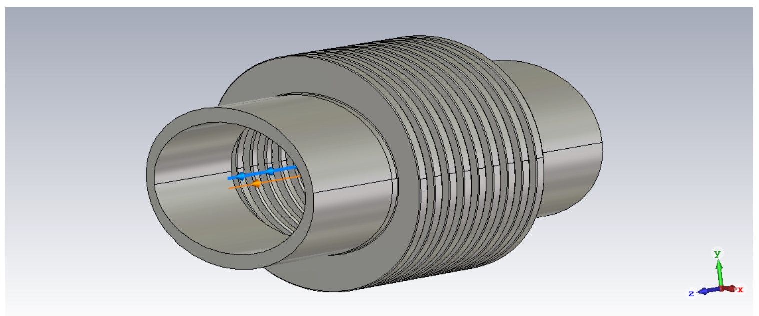
Weak instability shows up in the resistive ring

Weak instability can be suppressed by inductive components

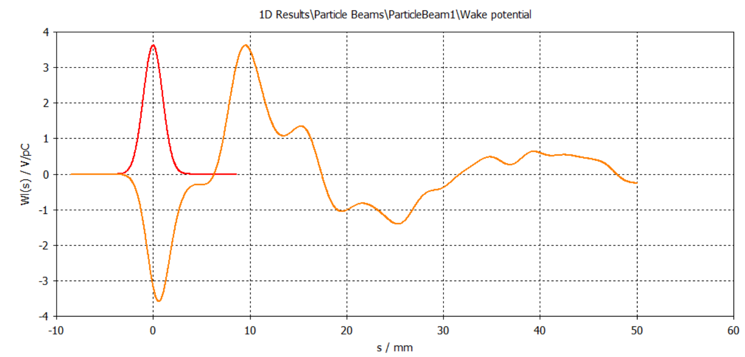
Impedance is not the smaller the better!

Category of the wakefield / impedance

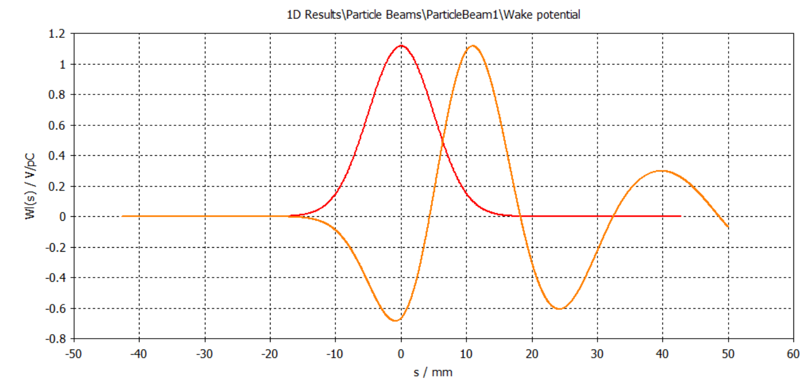
Example of resistive by short bunch / inductive by long bunch



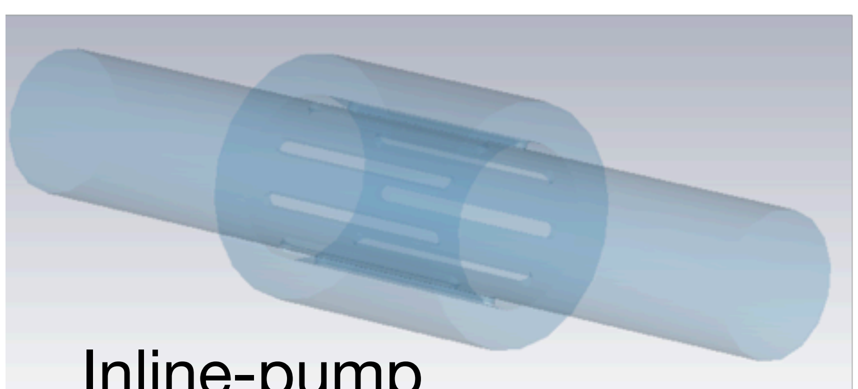
non-shiled bellows



driven by 1mm beam



driven by 5mm beam



Inline-pump