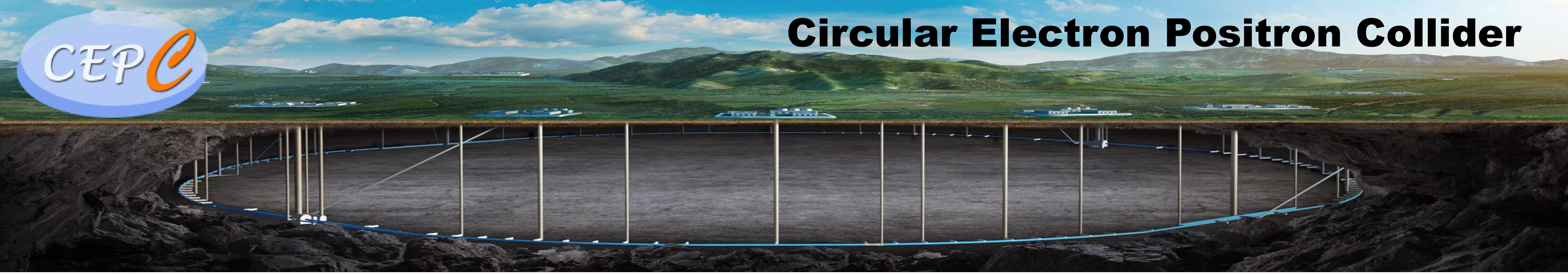

Collective effects studies in CEPC

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Outline

- Impedance requirements from the collective effects
- Impedance modeling and optimizations
  - Masks/absorbers
  - Feedback kickers
  - Injection and extraction kickers
  - Collimators for the machine protection
- Summary and outlooks

Main beam parameters (30MW)

Parameter [unit]	Higgs	Z	W	tt
Beam energy E_k [GeV]	120	45.5	80	180
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	5	115	16	0.5
Emittance (H/V) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam current [mA]	16.7	803.5	84.1	3.3
Bunch number	268	11934	1297	35
Bunch Population [10^{10}]	13	14	13.5	20
Momentum compaction α_p [10^{-5}]	0.71	1.43	1.43	0.71
Bunch length σ_z (natural/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) [10^{-4}]	10/17	4/13	7/14	15/20
Betatron tune ν_x/ν_y	445.10/445.22	317.10/317.22	317.10/317.22	445.10/445.22
Synchrotron tune	0.049	0.035	0.062	0.078
Radiation damping [ms]	44/44/22	816/816/408	150/150/75	14/14/7

Design queries

Small α_p

Short natural σ_z

Slow damping at low E_k

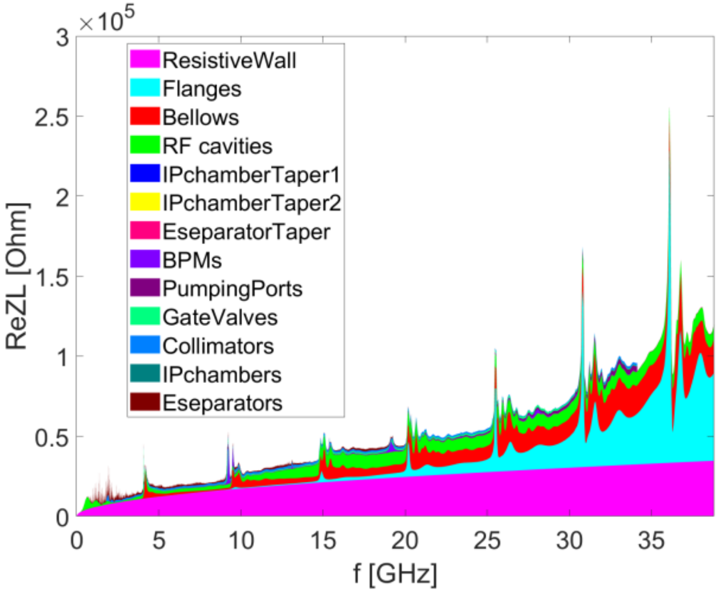
Impedance requirements from the collective effects

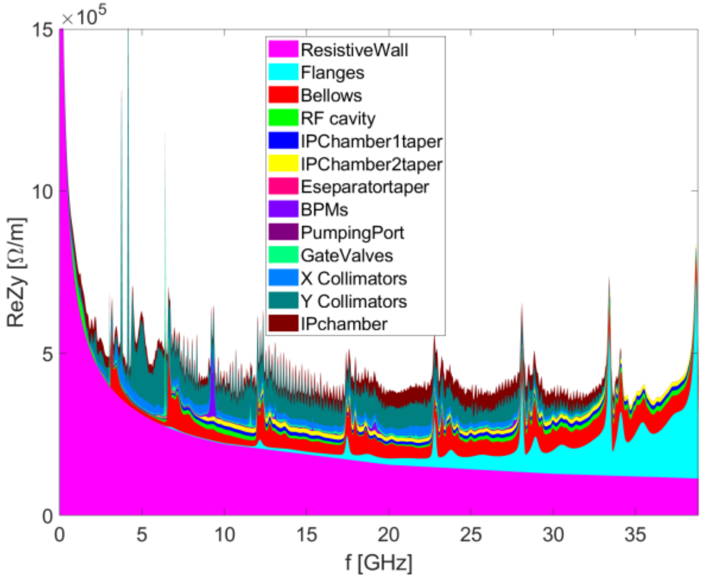
- Potential restrictions from the collective effects and their mitigations are investigated **based on TDR impedance model**

  → no apparent show stopper for Higgs, W and tt

  → Important restriction for Z – performance can be reached with the mitigations

- More detailed studies with more robust impedance model and instability calculations are under going.





Single bunch effects (broadband impedance)

- Rough estimation of the single bunch instability threshold

	Higgs	Z	W	$t\bar{t}$
Longitudinal threshold $Z_{\|\|}/n$, mΩ	6.5	0.7	4.1	14.4
Transverse threshold k_y, V/pC/m	69.7	12.4	40.2	109.8

- Longitudinal case
  - Bunch lengthening/distortion, energy spread increase, synchrotron tune shift & spread, normally without beam loss ⇒ perturb beam-beam interaction & luminosity

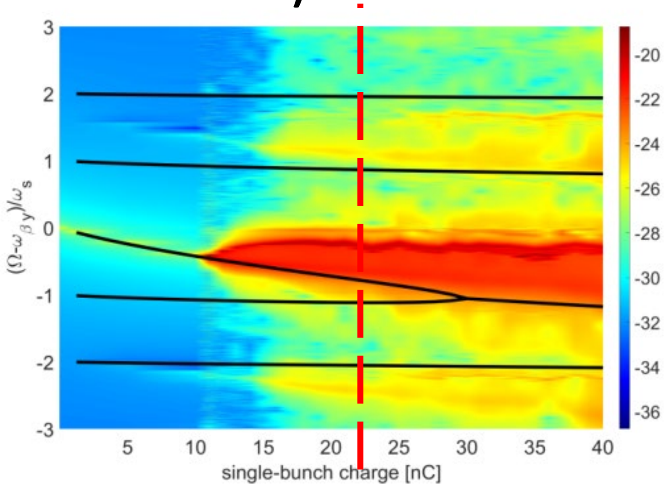
Mechanism	Status and mitigation strategies
Microwave instability (particle tracking simulations)	Higgs: $N_{b,th} \approx 5\ N_{b,design}$, bunch lengthening of 30% at $N_{b,design}$ Z: $N_{b,th} \approx 0.5\ N_{b,design}$, bunch lengthening and beam energy spread increase of 140% and 35%, coupled with beam-beam ⇒ brightness degradation for some working point → mitigations: careful parameter tuning.

Single bunch effects (broadband impedance)

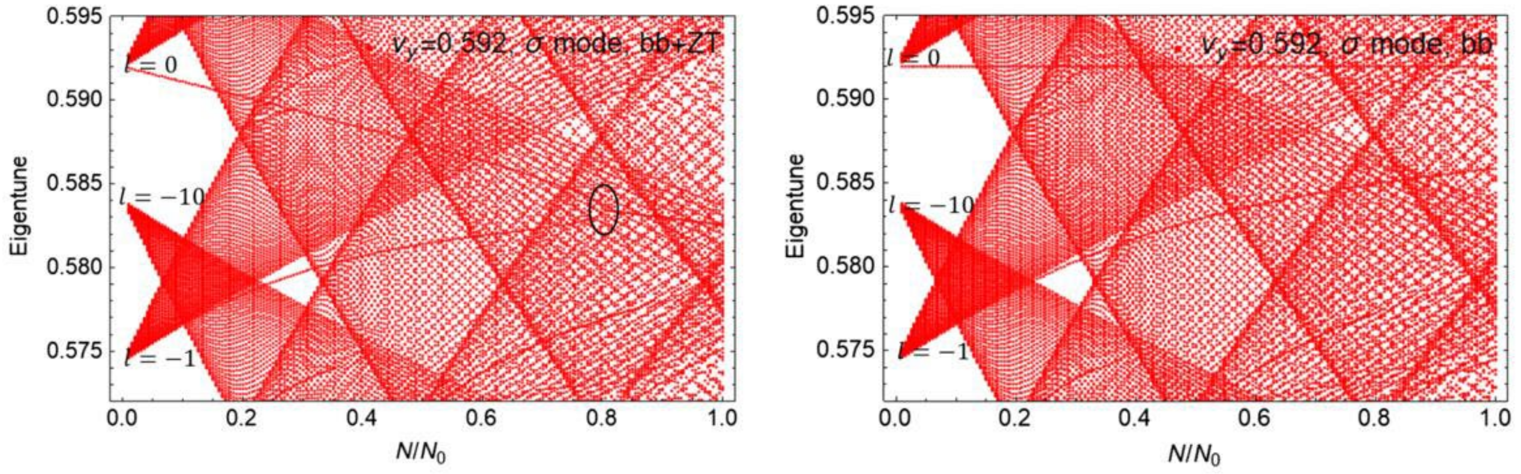
- Transverse case
  - Fast instability through transverse mode coupling, normally with beam loss ⇒ couple with both longitudinal impedance and beam-beam, which induce even lower current threshold

Mechanism	Status and mitigation strategies
Transverse mode coupling instability (particle tracking simulations)	Higgs: $N_{b,th} \approx 3\ N_{b,design}$, some safety margin reserved. Z: $N_{b,th} \approx 0.4\ N_{b,design}$ ⇒ Restrict bunch current and beam-beam unstable → mitigations: Bootstrapping injection, bunch-by-bunch feedback with positive ξ, larger emittance.

Z mode (With ZT and ZL):



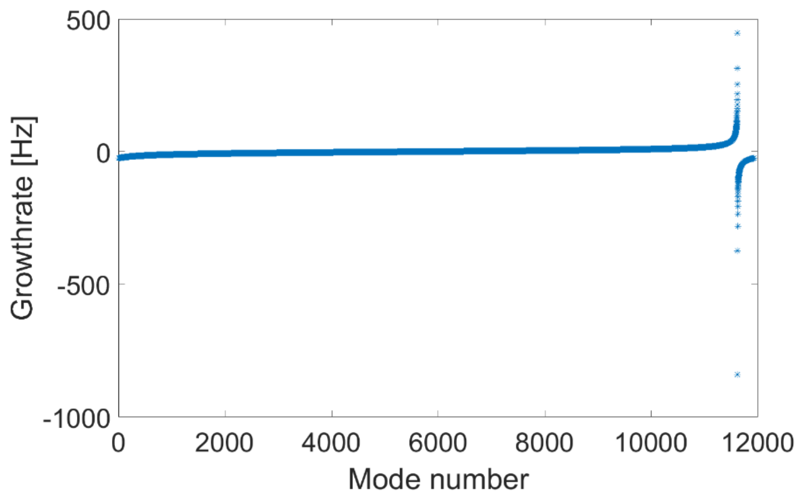
Z mode (With ZY and beam-beam): Y. Zhang, PRAB 26, 064401 (2023)



Impedance requirements from the collective effects

- Coupled bunch effects (narrowband impedance)

Mechanism	Status and mitigation strategies
Transverse resistive wall instability	Higgs: well damped by the synchrotron radiation damping Z: $\tau_{\perp}$ = 2ms << SR damping $\Rightarrow$ Restrict total beam current $\rightarrow$ mitigations: bunch-by-bunch feedback W: $\tau_{\perp}$ = 38ms << SR damping $\Rightarrow$ Restrict total beam current $\rightarrow$ mitigations: bunch-by-bunch feedback



Instability growth rate versus mode number @Z

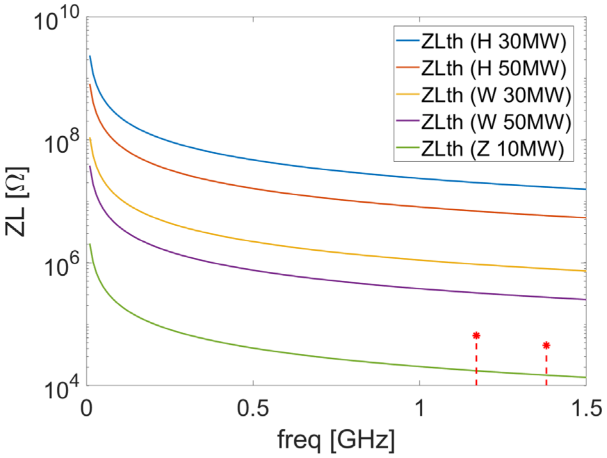
Consider only synchrotron radiation damping, thousands of modes could be unstable @Z:

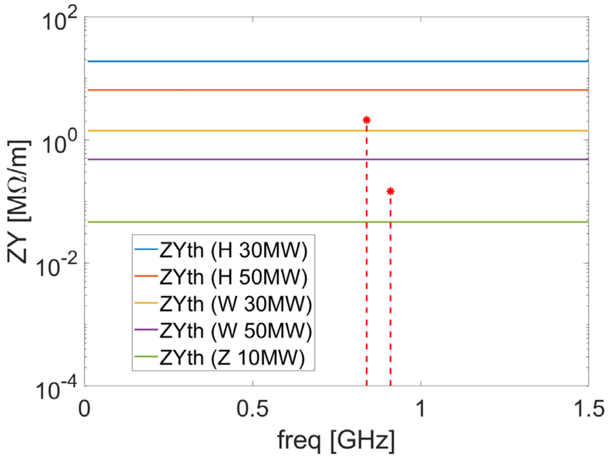
- Most critical mode at frequency of 2.338kHz with growth time of ~2 ms
- First five unstable modes have growth time of <5ms (15 revolution turns)

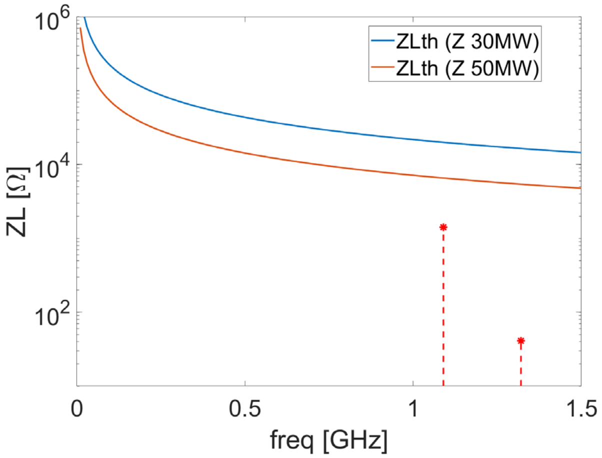
Impedance requirements from the collective effects

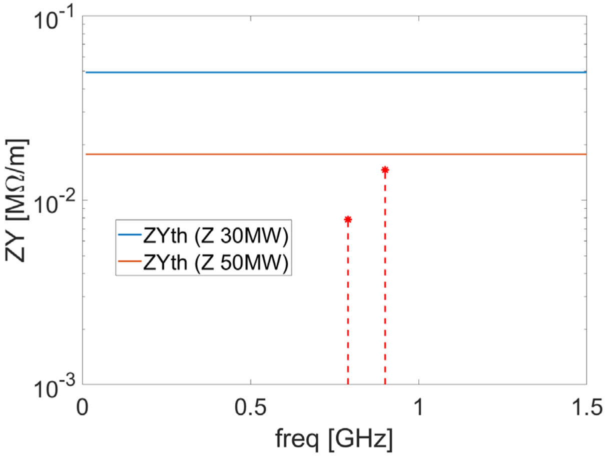
- Coupled bunch effects (narrowband impedance)

Mechanism	Status and mitigation strategies
CBI due to the RF HOMs (with measured Qe)	Higgs: impedance well below the SR threshold Z (10MW, with 2cell cavity): $\tau_{\perp}$ = 19ms, $\tau_{\|\|}$ = 114ms << SR damping $\Rightarrow$ Restrict beam current $\rightarrow$ mitigations: bunch-by-bunch feedback, HOM damper Z (30MW&50MW, with 1cell cavity): impedance well below the SR threshold W: $\tau_{\perp}$ = 105ms < SR damping $\rightarrow$ mitigations: bunch-by-bunch feedback, HOM damper









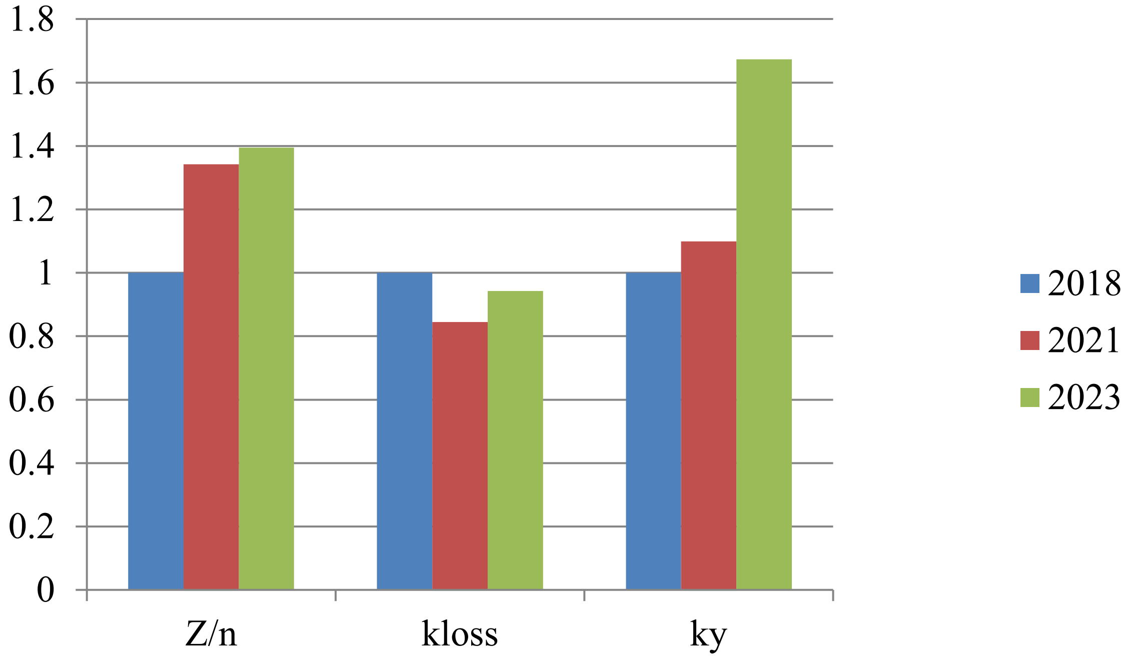
Impedance evolution

- The impedance model will be continuously updated along with the development of the hardware designs.
  - The effective impedances varies along with the development of the impedance model => apparent increases on both Z/n and ky are shown.

2018 Elliptical cross section (CDR)

2021 Circular cross section
More contributors included (TDR)

2023_V1 More detailed chamber material, collimator updated and betatron function weighing is considered.



Evaluate with rms bunch length of 3mm

Impedance evolving

- The impedance model will be continuously updated along with the development of the hardware designs ⇒ impedance increase is expected with more contributors included.
- Main constraints from impedance are focused on Z, enough safety margin is reserved for other energies.

Considering the elements been missing, a larger increment is expected in the transverse plane, while less influence in longitudinal.

⇩

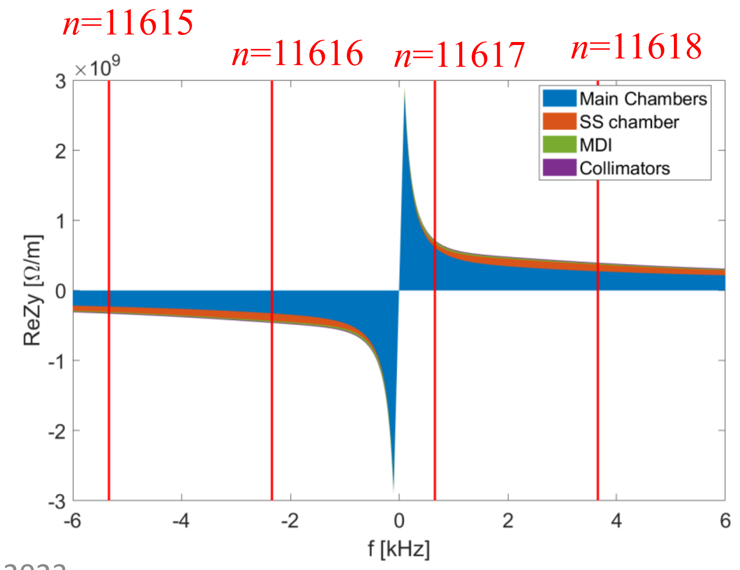
TMCI restriction could be met

⇩

Better understanding of the physics and further mitigations: bunch-by-bunch feedback, positive ξ, larger emittance

⇨

Limited influence on the transverse resistive wall instability
⇒ Instability growth time from 2.2ms→1.7ms with more detailed chamber material, collimators have little contribution



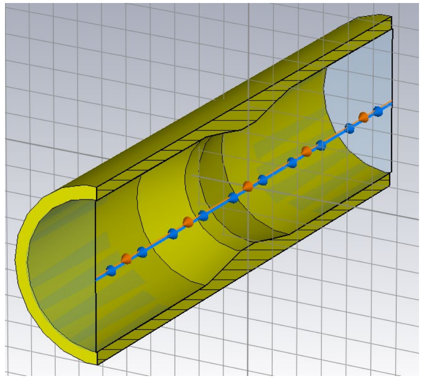
Impedance modeling and optimizations

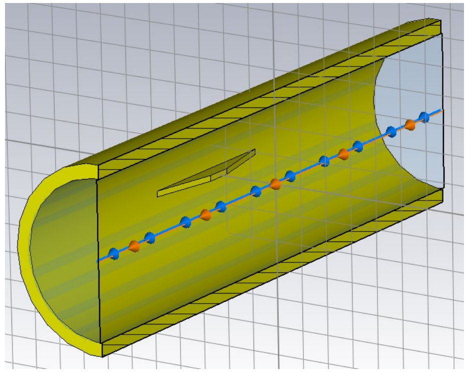
- New developed impedance components
  - Masks/absorbers
  - Transverse feedback kickers
  - Longitudinal feedback kickers
  - Injection and extraction kickers
  - Collimators for machine protection

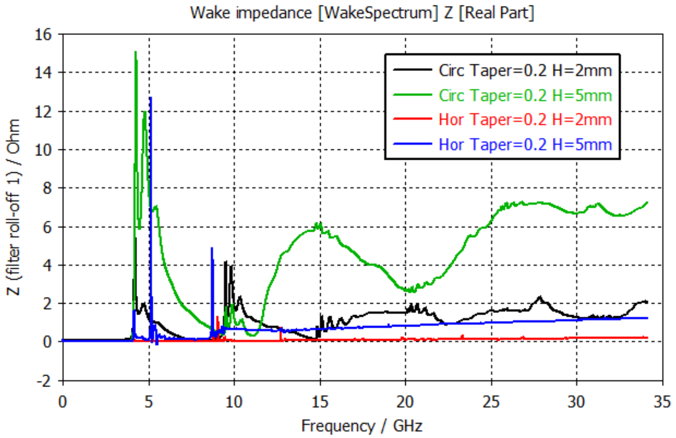
Masks/absorbers

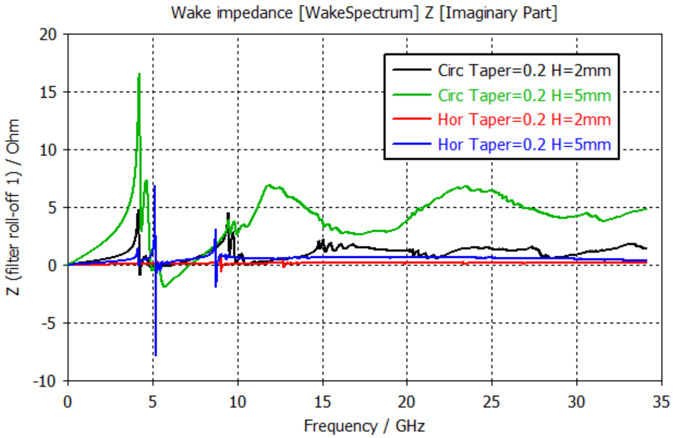
- Masks will be installed before each bellows with RF shielding and BPM to protect the downstream elements, with possible height of 2~5mm and total number of ~17k.
- Impedance for cylindrical symmetrical mask and only horizontal mask is compared.

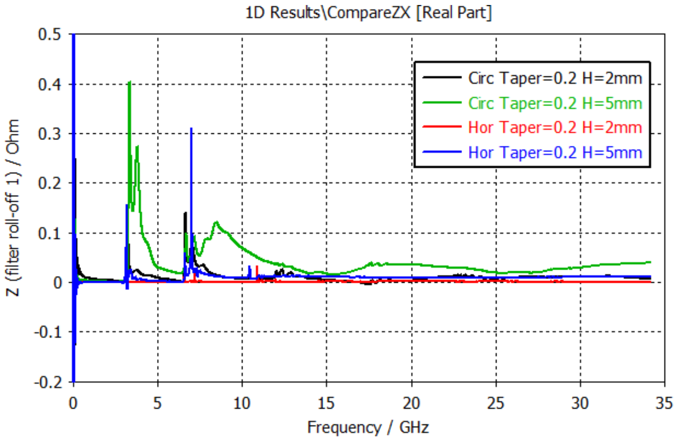
Longitudinal thickness: 10mm
Horizontal mask： vertical heigh 2mm

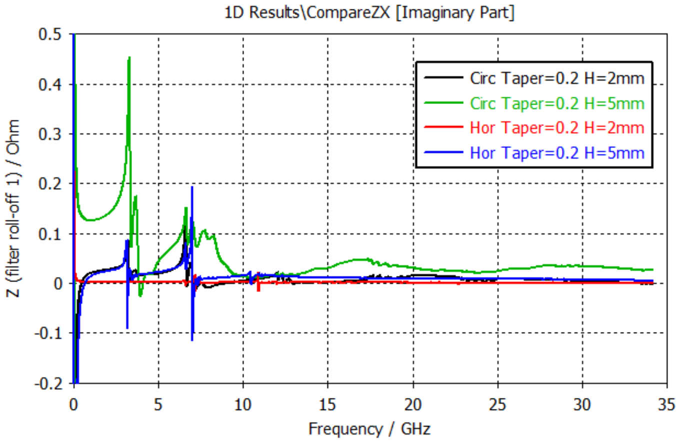








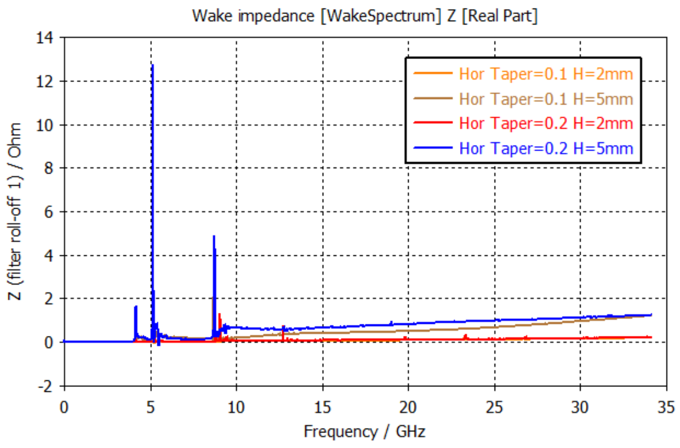


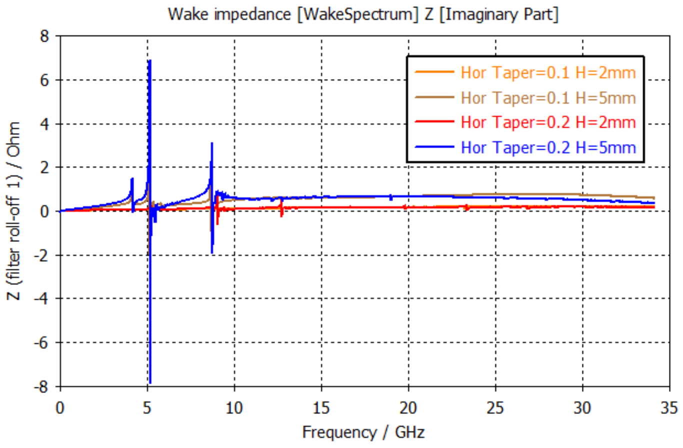


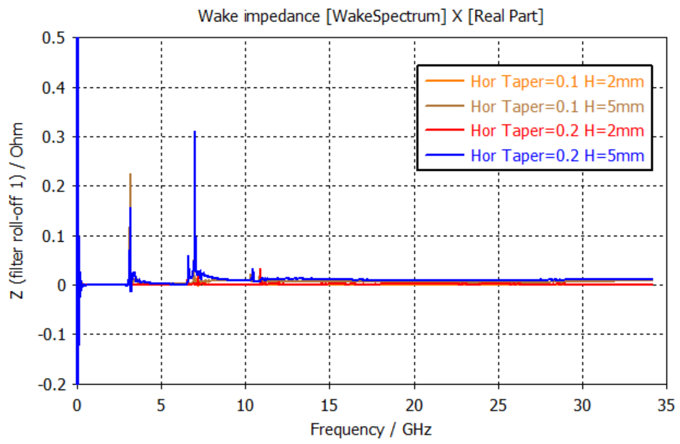
- ☐ **Impedance increase with mask height**
- ☐ **Lower impedance for horizontal mask**

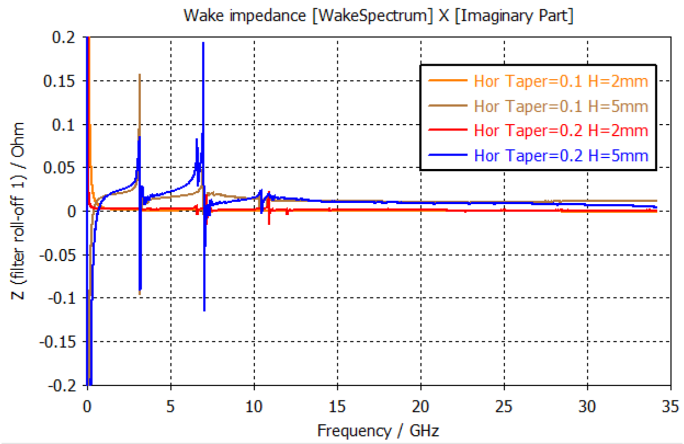
Masks/absorbers (cont.)

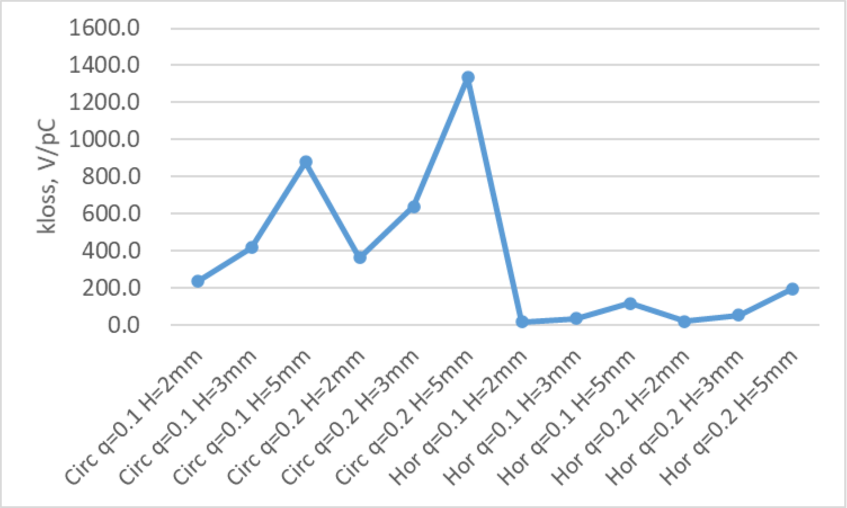
- Different tapering angle: lower impedance with flat taper, not apparent at small height

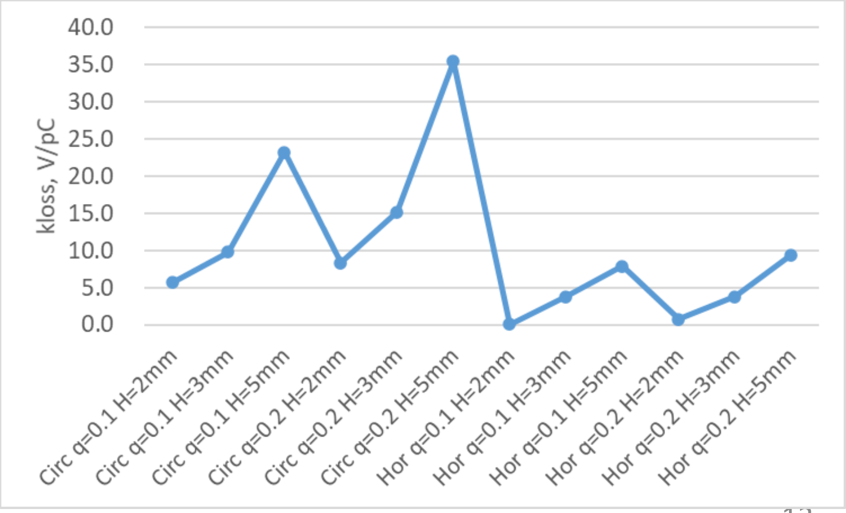










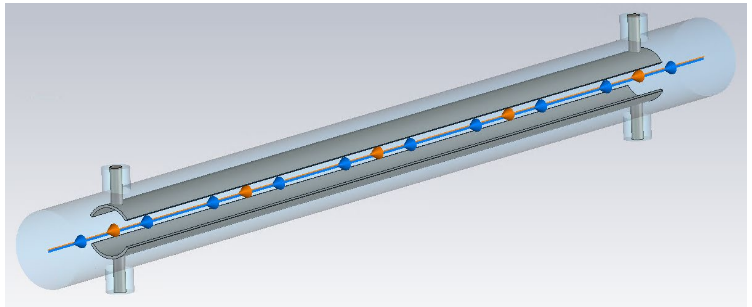


- **Considering the their contribution to the total impedance budget, the mask height should below 3mm, and horizontal mask recommended.**

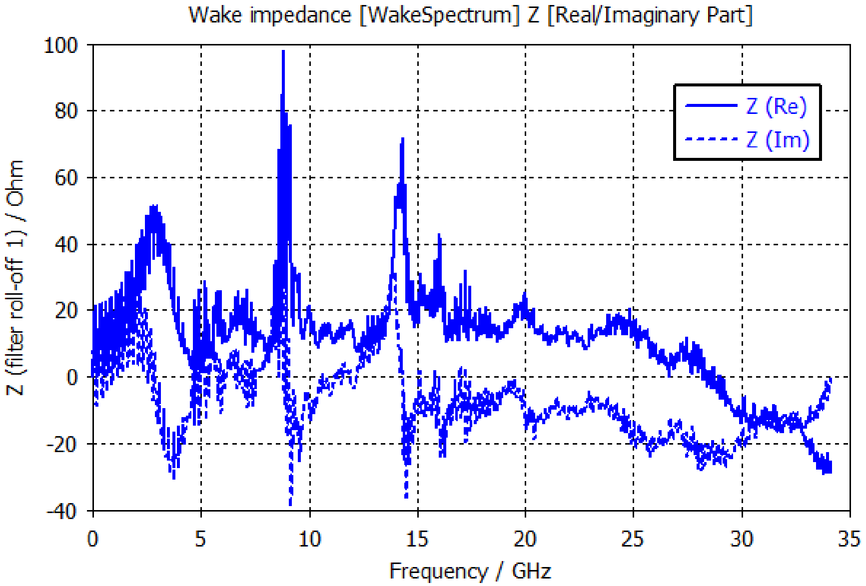
Transverse feedback kickers

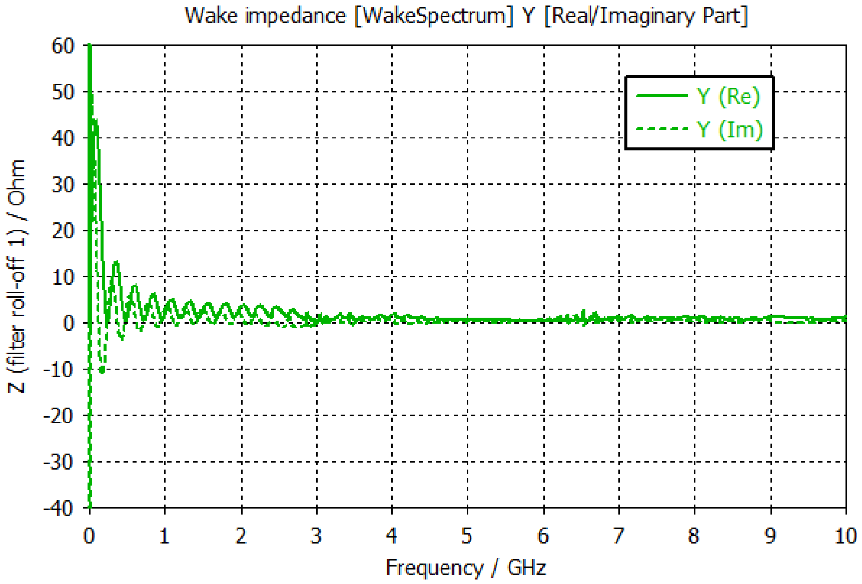
Courtesy of Xiaoyu Liu

- Four transverse feedback kickers are required for the efficient bunch-by-bunch feedback of the TRWI in Z operation mode (Damping time ≤1ms).
- Preliminary simplified model been used in the impedance evaluations
- k_{loss}=0.53V/pC, k_y=14.48V/pC/m @sigz=3mm (small contribution to the total broadband impedance budget)



Slot pipe kicker (distance between electrodes = 34mm, beam pipe aperture=28mm)

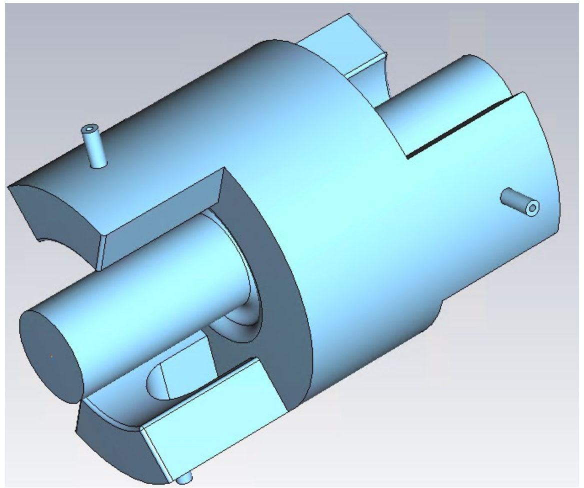


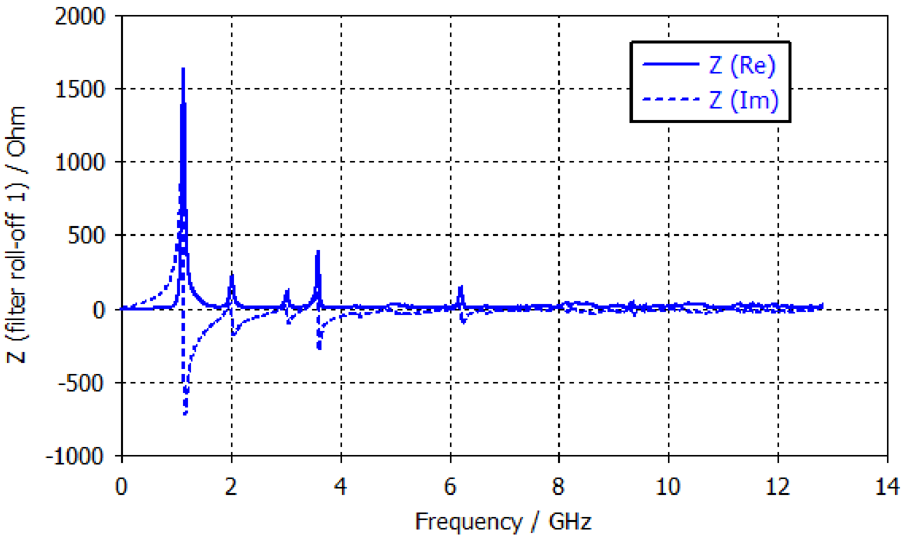


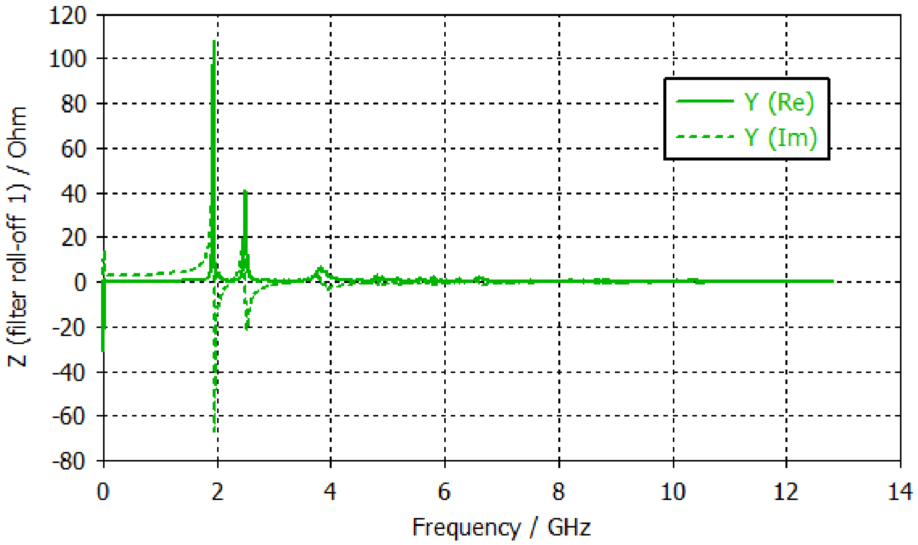
Longitudinal feedback kickers

Courtesy of Xiaoyu Liu

- Four longitudinal feedback kickers are required for the bunch-by-bunch feedback of the RF HOMs in Z operation mode (Damping time $\leq$12ms).
- k_{loss}=0.75V/pC, k_y=7.67V/pC/m @sigz=3mm (small contribution to the total broadband impedance budget)
- Narrowband resonances above the SR threshold for Z$\Rightarrow$ further optimizations are needed.





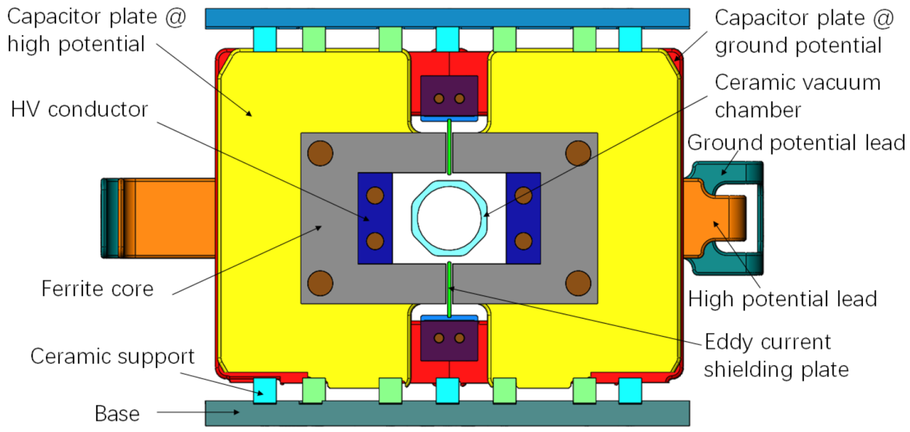


Injection and extraction kickers

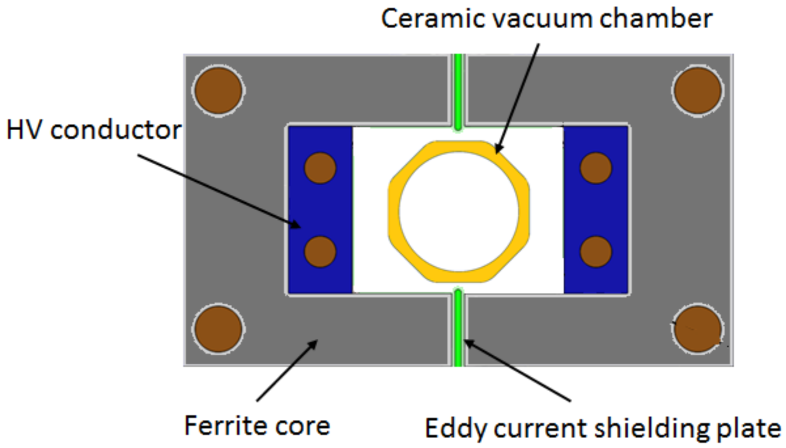
Courtesy of Jinhui Chen

- To accommodate top-up injection at different energy modes:
  - An on-axis swap-out injection system (Higgs & tt, lumped parameter kicker magnets with ferrite cores+Lambertson)
  - An off-axis injection system (W &Z, 4 delay-line dipole kicker+septum)
  - A dump extraction system (4 delay-line dipole kicker+Lambertson)

Delay-line kicker



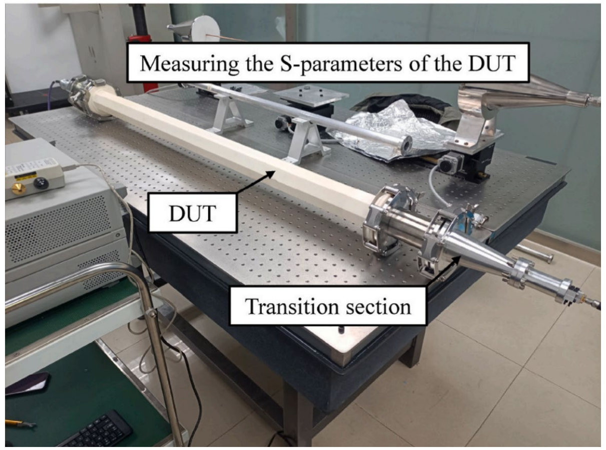
Ferrite core lumped parameter kicker

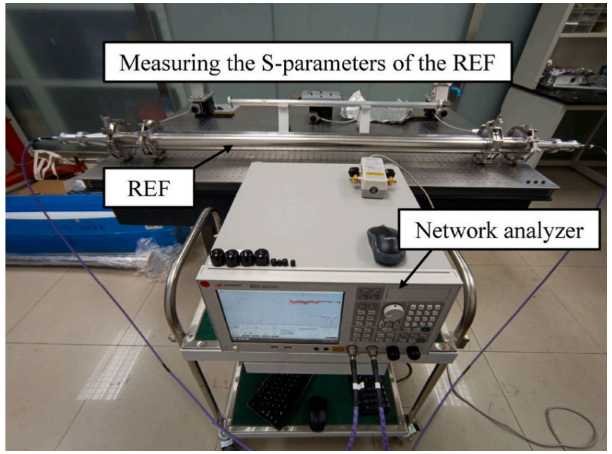


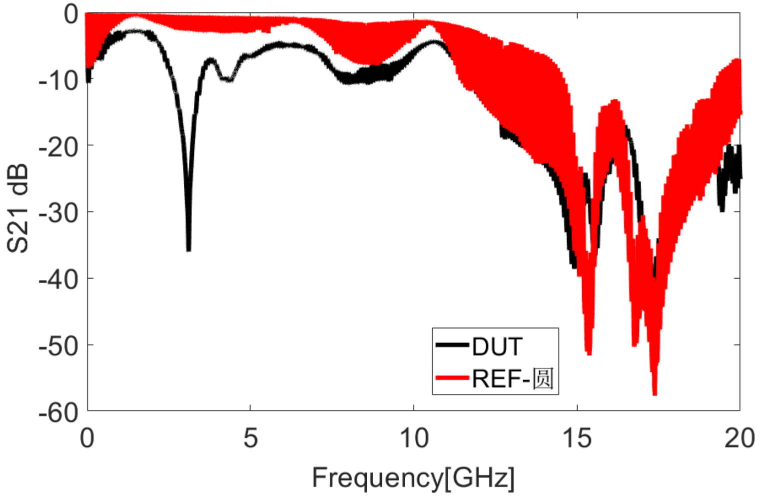
Ceramic chamber with TiN-Ag metallic coating of ladder pattern

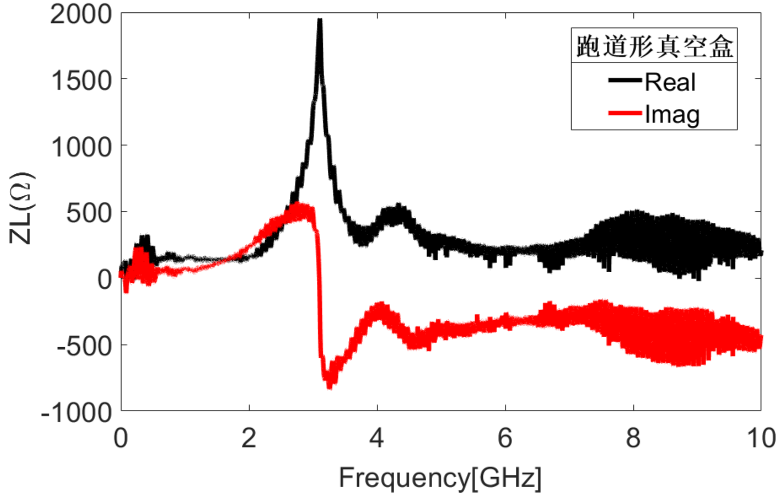
Impedance of injection and extraction kickers

- The prototype of the ceramic chamber features a racetrack-shaped inner contour with a wall thickness of 5mm: inner aperture 75mm*56mm
- Impedance measurement performed with coaxial-wire method.

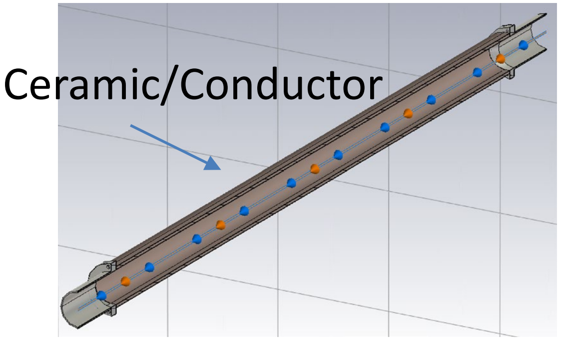


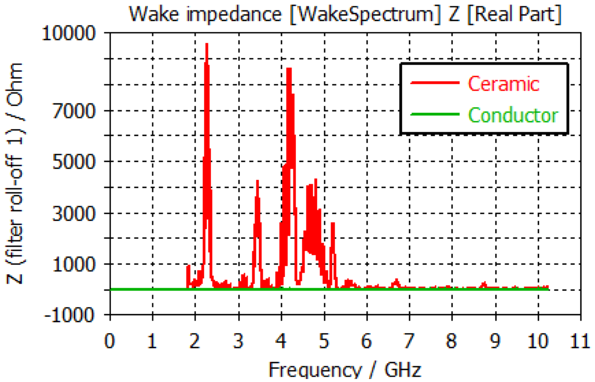






Test model



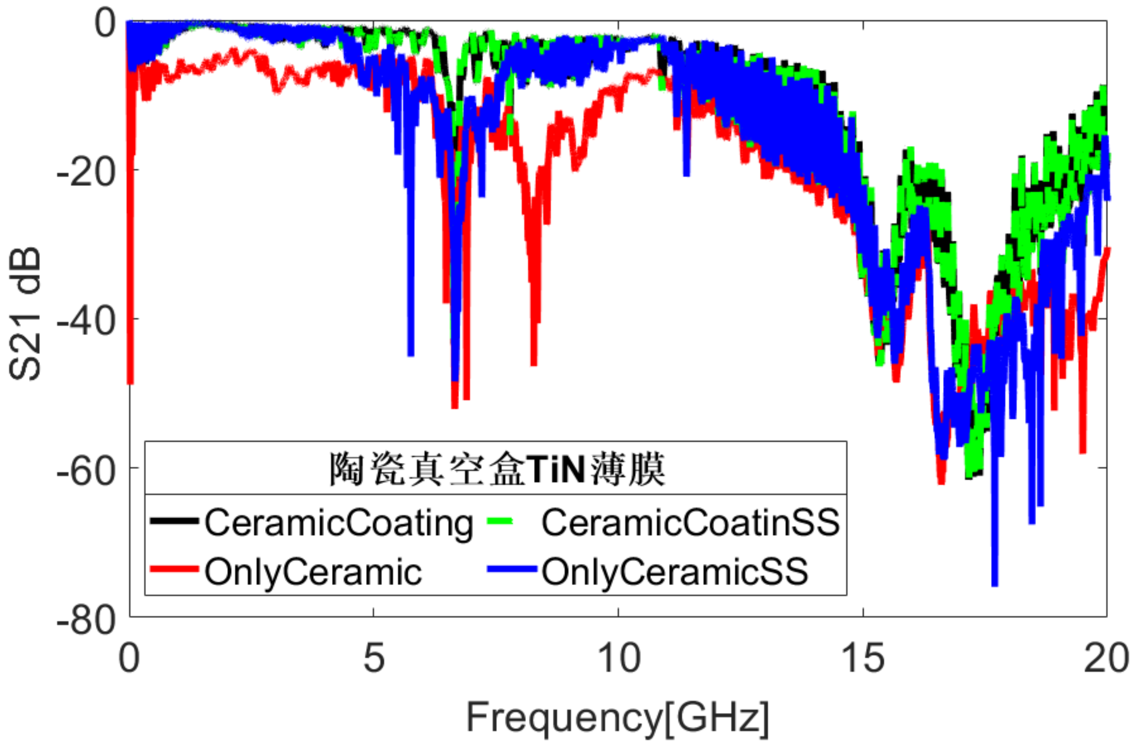


Impedance partially shielded by the ladder coating.

Impedance of injection and extraction kickers

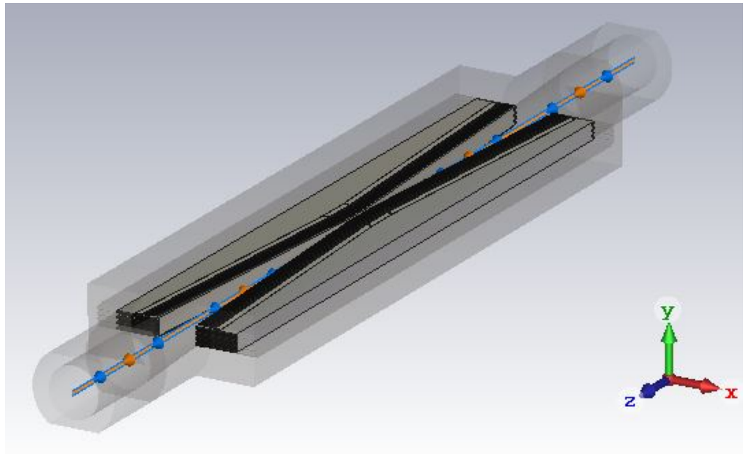
- The prototype of the ceramic chamber features a racetrack-shaped inner contour with a wall thickness of 5mm: inner aperture 75mm*56mm
- Impedance measurement performed with coaxial-wire method.
- Further test: Full TiN coating can well shield the field, except at every low frequency

- Further studies on investing the impedance of the ladder pattern coating is under going



Collimators for machine protection

- Impedance evaluation of the preliminary design of the collimators for the machine protection
  - 18 horizontal+12 vertical extra collimators
  - Rough estimation take the same impedance model as for the IR region (with collimator jaw gap of 4.4mm)
  - Local betatron functions at the collimators are considered



- Their contributions to the transverse broadband impedance is the main concern $\rightarrow$ Comparable to the total TDR transverse impedance budget $\Rightarrow$ further optimizations are required.
- Their contributions to the longitudinal impedance budget are trivial.

New developed impedance model

- The transverse impedance budget increased dramatically ⇐ mainly contributed by the collimators for the machine protection (rough model has been used)
  - Influences: single bunch current threshold, beam-beam interaction/luminosity reach
  - Careful machine protection & collimator design with low impedance + instability mitigations

2018 — Elliptical cross section (CDR)

↓

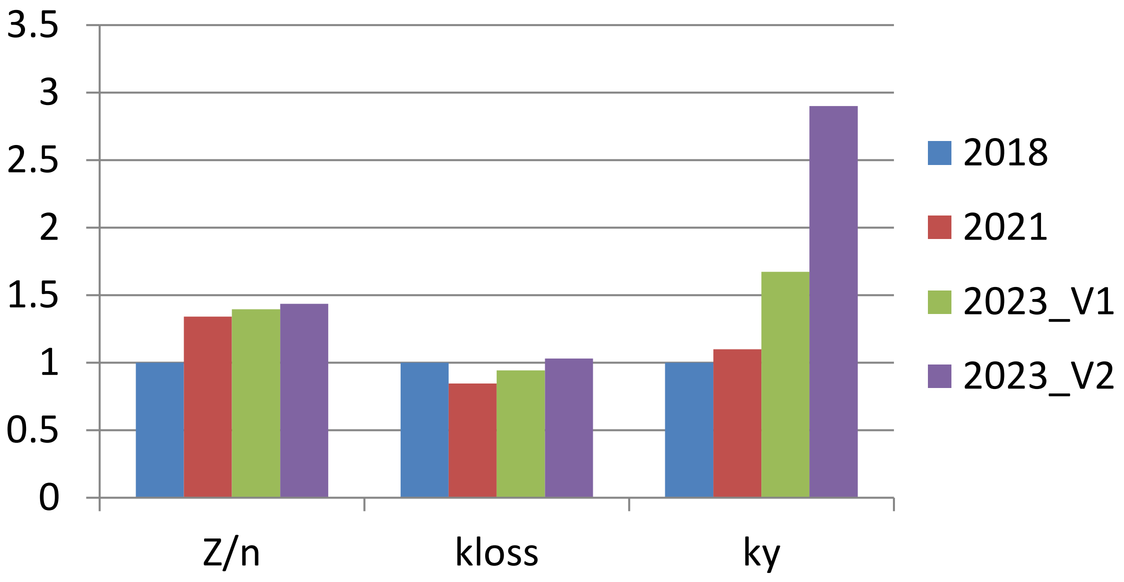
2021 — Circular cross section
More contributors included (TDR)

↓

2023_V1 — More detailed chamber material, collimator updated and betatron function weighing is considered.

↓

2023_V2 — Collimators for machine protection, masks and feedback kickers included



Evaluate with rms bunch length of 3mm

Summary and outlooks

- Impedance requirement from the collective instabilities has been investigated based on the TDR impedance model.
  - Main constraint from transverse single bunch instability and resistive wall instability for Z operation mode, mitigation strategies have been proposed.
  - Also influence on the beam-beam interaction from longitudinal impedance @Z.
- Impedance model has been developed with new elements included
  - Collimators from the machine protections show large contribution to the total transverse impedance budget - Careful machine protection & collimator design with low impedance are suggested, as well as stronger instability mitigations to be investigated.
  - Impedance contributions from masks/absorbers, and feedback kickers still can be well controlled.
  - Impedance from injection/extraction elements needs further investigations.
- Impedance will be continuously updated and optimized, along with the development of the hardware designs.
- More consistent investigation of the instabilities and their mitigations are under going.

Thank you for your attention!