Approach for low impedance design of the FCC DR vacuum chamber

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Outline

- Introduction
- Damping ring parameters
- Wake field and impedance basic definitions
- Higher order mode suppression in RF cavities
- Choice of BPM shape
- Strip-line kickers
- Longitudinal feedback kickers
- Pumping slots/holes in the hidden positions
- Bellows
- DCCT

Introduction

This work reviews some optimization strategies which can be applied for the design of the FCC-ee Damping Ring vacuum chamber components and hardware, aimed at reducing their beam coupling impedances while preserving the operational capabilities of the devices.

Most of the illustrated solutions are already in use and their performances have been validated in the particle’s colliders and modern synchrotron light sources.

In addition, the work also presents several novel design solutions that extend the same low-impedance approach to the considered devices.

Damping ring parameters

Parameter	Value
Energy [GeV]	2.86
Circumference [m]	373.46
Arc cell	multi-bend
Lattice shape	six-fold symmetry
Natural emittance [nm rad] (WGL on/off)	1.3 / 2.3
Bunch length [mm]	5.1
Damping time $\tau_{x,y}$ (WGL on/off) [ms]	16.9 / 29.4
Natural chromaticity (x/y)	–38.2 / –28.3
Natural energy spread (WGL on/off) [10^{-4}]	7.1 / 5.2
Betatron amplitude max (x/y) [m]	9.66 / 6.49
Betatron amplitude min (x/y) [m]	0.5 / 1.1
Tune (Q_x, Q_y)	27.8707 / 22.3728
Momentum compaction (WGL on/off) [10^{-3}]	1.55 / 1.57
Revolution period [μs]	1.2457
Dipoles #, length [m], field [T]	180 × 0.7 1.13 / 0.34 / 0.39
Wigglers #, length [m], field [T]	3, 3.5, 1.8
Cavities #, length [m], voltage [MV]	1, 1.5, 4
Max. # Bunches stored / Bunch current [mA]	40 / 4
Store time	5 τ_y
Energy loss per turn (WGL on/off) [keV]	422.2 / 246.7
SR power loss in wigglers [kW]	27.83
Kicker rise time [ns]	50

Longitudinal beam dynamics parameters

	V= 4MV	V= 8MV
U_0 [KeV]	422.13	
DE	0. 7219 • 10^{-3}	
Ω_s [KHz]	10.4545	14.7849
T_0 [μsec]	1.26134	
ω_0 [s^{-1} rad]	4.98134E+6	
ν_s	0.00209874	0.002968
L_{bunch}[m]	0.00511	0.00361
φ_s [rad]	0.10573	0.0527913

Assuming that each pulse from the e(p)LINAC consists of 4 bunches carryng at last 5 nC each, filling the DR with 10 pulses implies to reach the following upper limits:

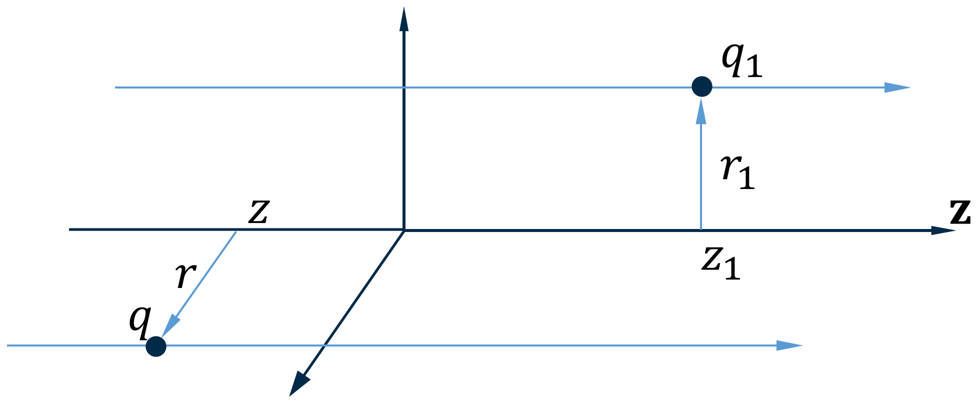
N_{part} ~ 3.12075E+10

I_{bunch} ~ 0.00396402 A

I ~ 0.158561 A

Courtesy of Dr. C. Milardi

Wake field and impedance basic definitions



The Lorentz force acting on a trailing charge q at a given position $\vec{r}, z$:

$$\vec{F}(\vec{r}, z, \vec{r_1}, z_1; t) = q[\vec{E} + \vec{v} \times \vec{B}]$$

At any instant t the leading and trailing charges have longitudinal coordinates

$$z_1(t) = vt \quad \text{and} \quad z(t) = v(t - \tau)$$

τ being the delay time between the trailing charge and the leading one.

The *longitudinal wake function* measured in *V/C* is defined as the energy lost by the trailing charge ΔU per unit of both charges q and q_1.

$$w_\parallel(\vec{r}, \vec{r_1}, \tau) = \frac{\Delta U}{q q_1} = \frac{q \int_{-\infty}^{+\infty} E_\parallel(\vec{r}, z, \vec{r_1}, z, t) dz}{q q_1} \qquad t = \frac{z_1}{v} + \tau$$

$$Z_\parallel(\omega) = \int_{-\infty}^{+\infty} w_\parallel(\tau) e^{-j\omega\tau} d\tau \qquad [\Omega]$$

bunch of particles with a longitudinal time distribution function such that:

$$q_1 = \int_{-\infty}^{+\infty} i_b(\tau) d\tau$$

https://doi.org/10.48550/arXiv.physics/0309023

The *wake potential* produced by the bunch distribution at a point with the time delay τ is simply given by the convolution of the Green function over the bunch distribution:

$$W_\parallel(\vec{r}, \tau) = \frac{1}{q_1} \int_{-\infty}^{+\infty} i_b(\tau') \, w_\parallel(\vec{r}, \tau - \tau') d\tau'$$

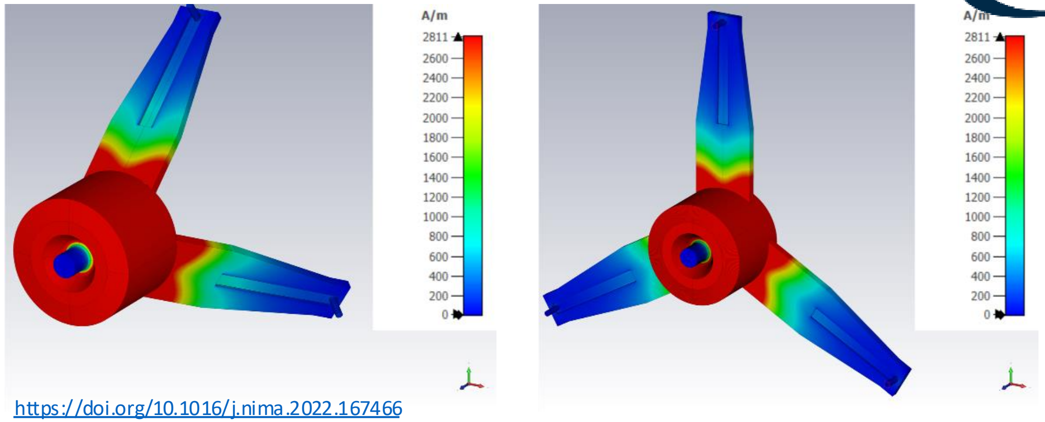
the transverse wake function as the kick experienced by the trailing charge per unit of both charges.

$$w_\perp(\tau) = \frac{\Delta p_T}{q q_1} = \frac{q \int_{-\infty}^{+\infty} (\vec{E} + \vec{v} \times \vec{B})_\perp dz}{q q_1}$$

$$Z_\perp(\omega) = j \int_{-\infty}^{+\infty} w_\perp(\tau) e^{-j\omega\tau} d\tau \qquad [\Omega]$$

Higher order mode suppression in RF cavities

- A modified broadband waveguide to coaxial line transitions placed on the cavity body was used to suppress the HOM to a harmless level.
- Different possibilities of allocating the waveguides to cavity were considered.
- Such a solution has a simple design that avoids the application of the ferrite materials under the ultra-high vacuum, and efficiently dissipates the HOM power.



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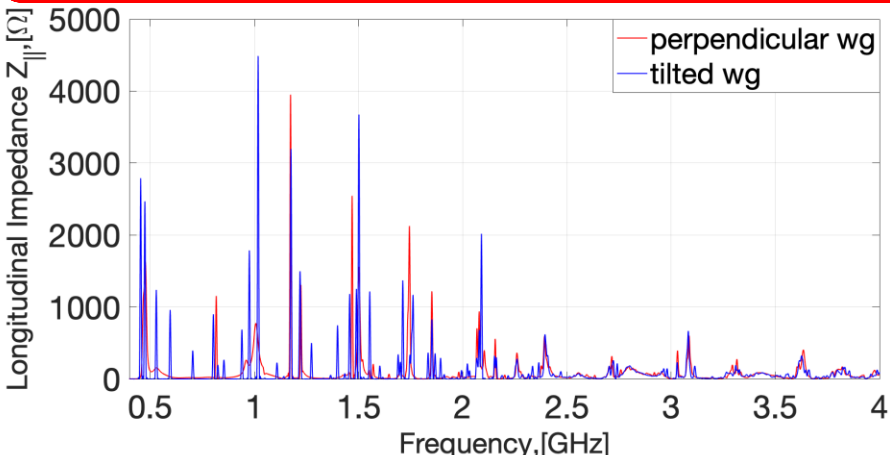
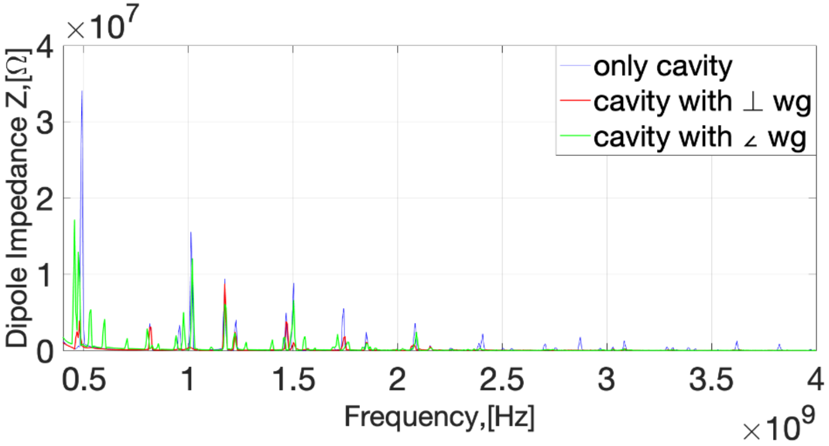
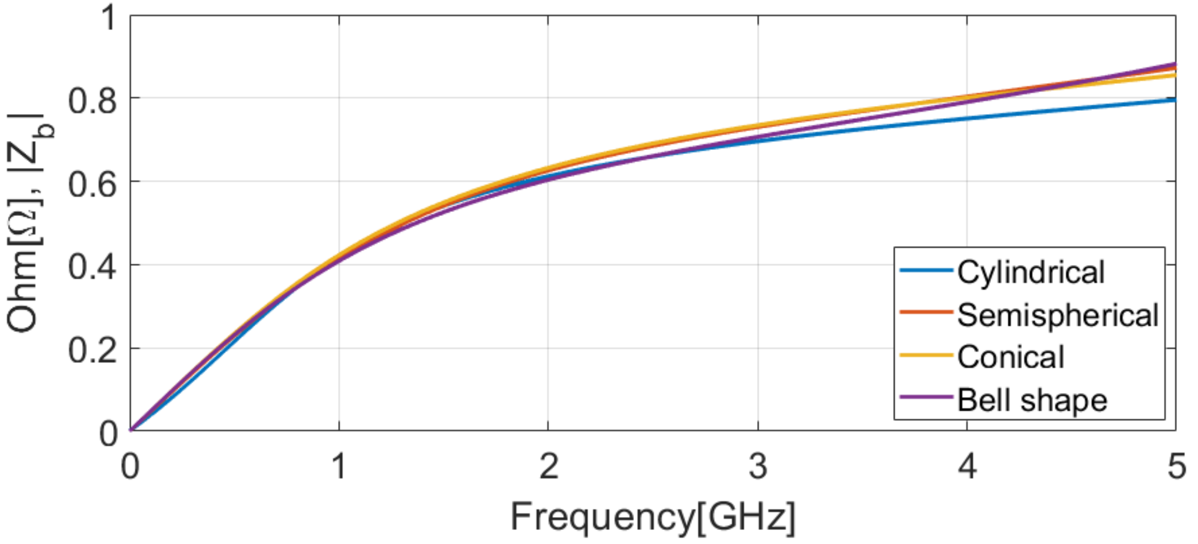
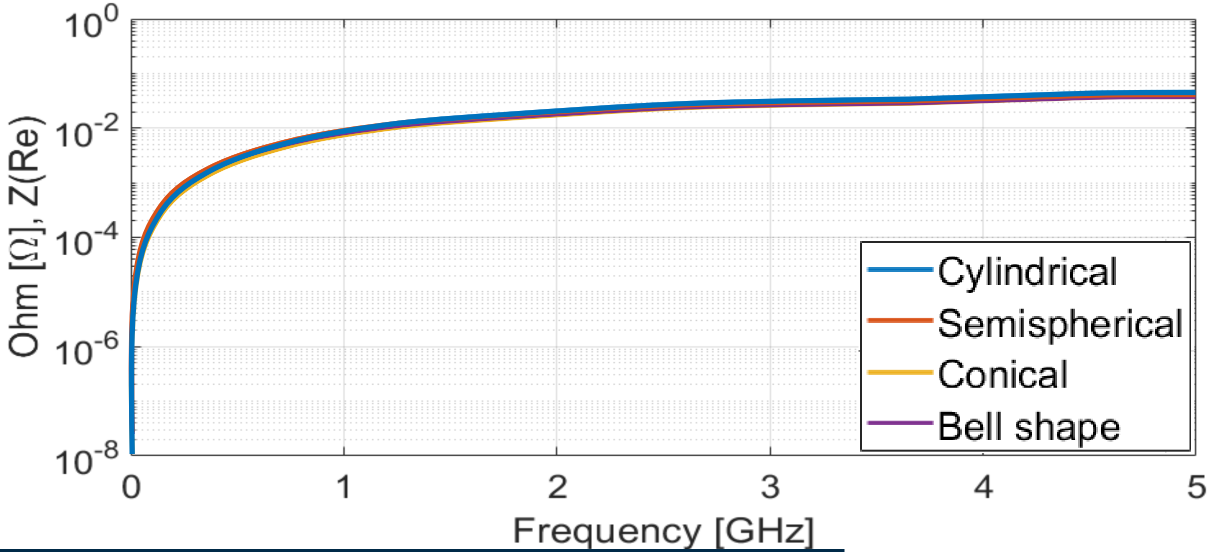




Mode Freq./GHz	R/Q Ω	Undamped Q	Damped Q perp.wg
0.476	4.88	34782	260
0.817	4	47511	800
0.957	0.9	57376	500
1.004	0.7	36969	370
1.173	5	66449	360
1.223	0.9	46709	1400
1.469	2.0	51519	1300
1.501	0.8	70188	800
1.568	0.3	111994	150

Choice of BPM shape





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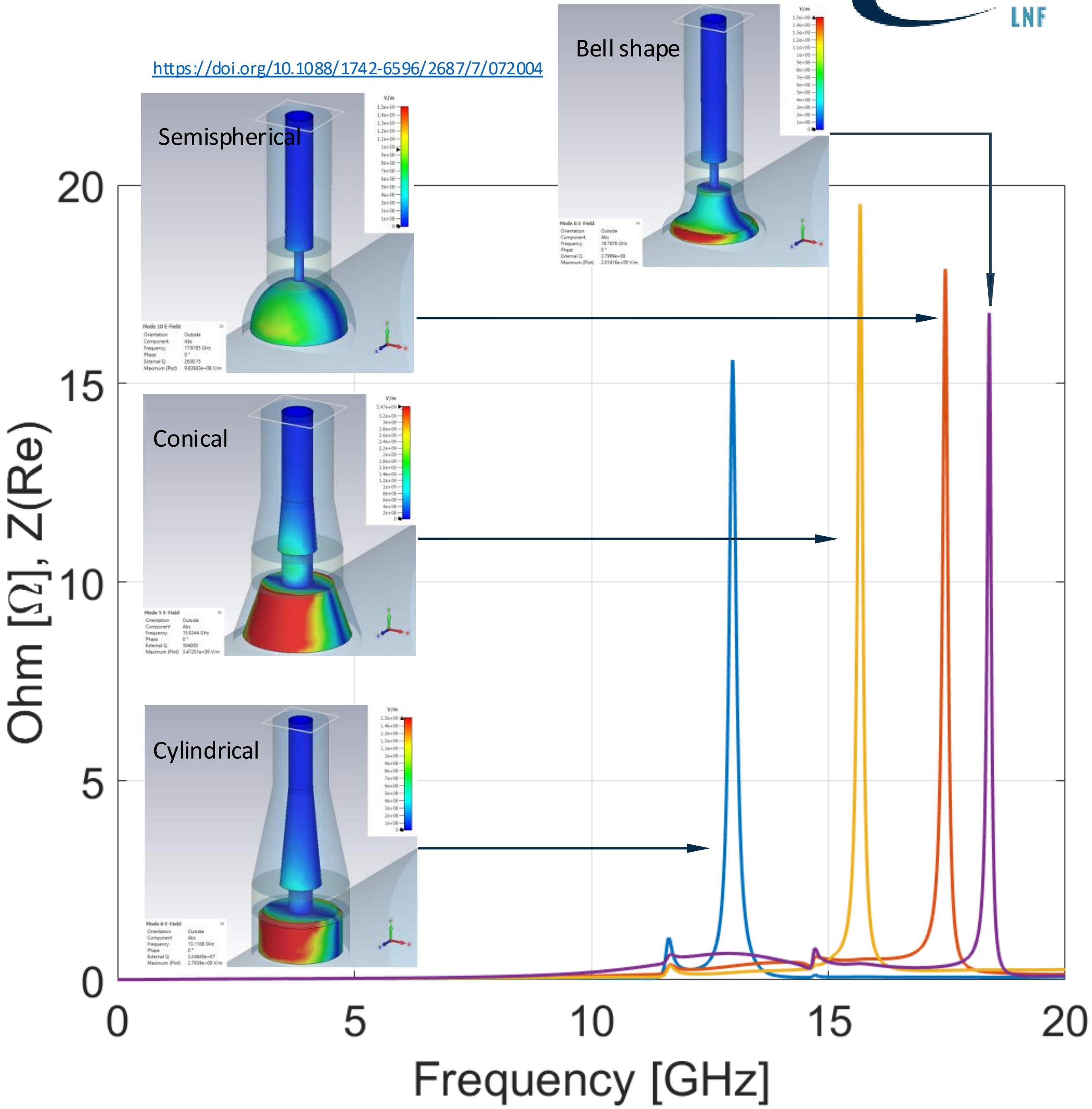

Strip-line kickers

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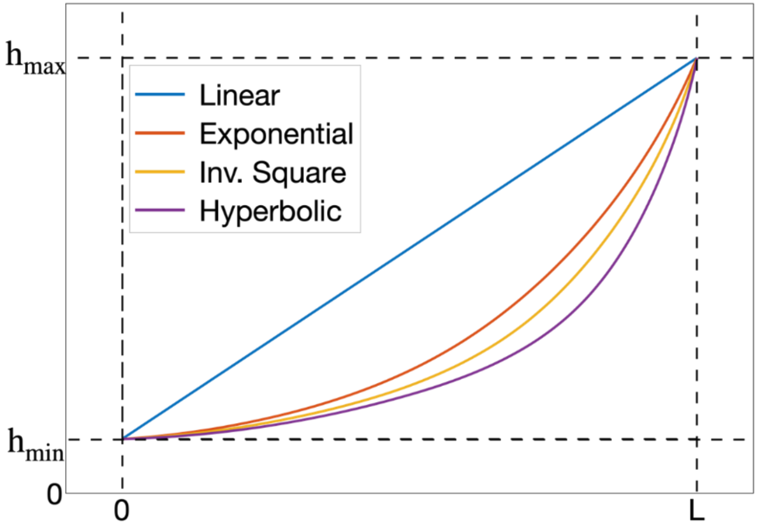
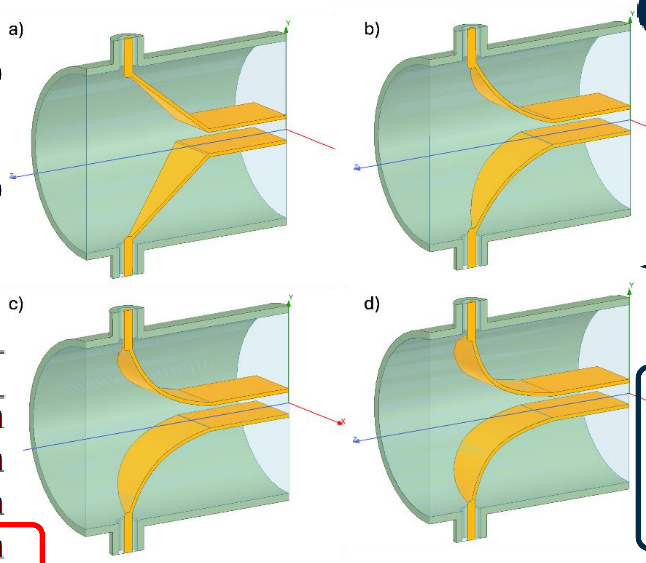


There were several studies dedicated to stripline BPM's to use nonlinear tapered transition for stripline to feed-through to optimize the characteristic impedance

	Kick-Factor x	Kick-Factor y	Unit
Linear:	-6.840428e-02	-1.327580e-01	V/pC/mm
Exponential:	-5.037268e-02	-1.068364e-01	V/pC/mm
Inverse Square:	-4.401820e-02	-9.837109e-02	V/pC/mm
Hyperbolic:	-4.080152e-02	-9.439061e-02	V/pC/mm



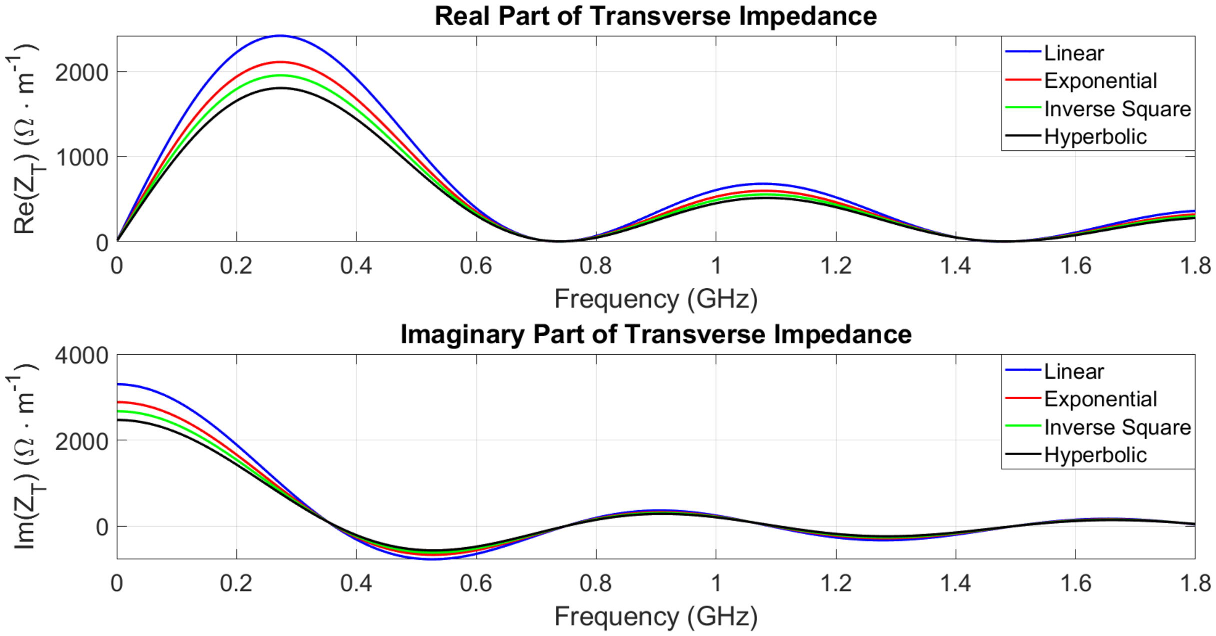
a) Linear taper
b) Exponential taper
c) Inv. Square taper
d) Hyperbolic taper

$$h(z) = h_{min}(1 + (h_{max}/h_{min} - 1)z/L)$$ Linear

$$h(z) = h_{min}(h_{max}/h_{min})^{z/L}$$ Exponential

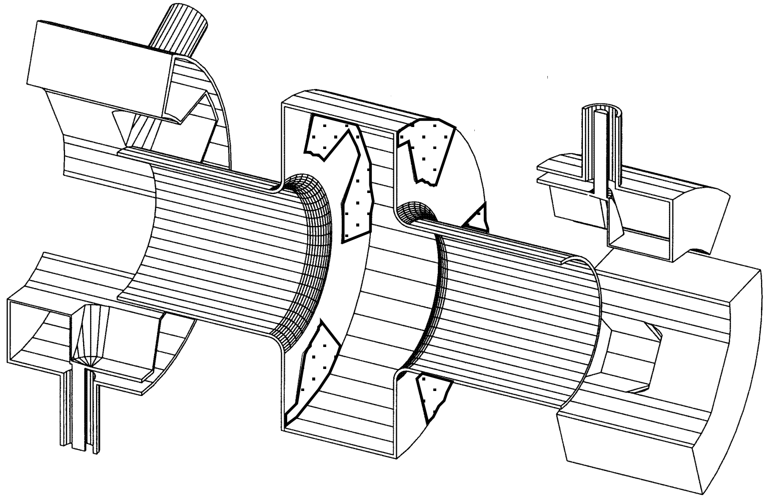
$$h(z) = \frac{h_{min}}{(1 + ((h_{min}/h_{max})^{1/2} - 1)z/L)^2}$$ Inv. Square

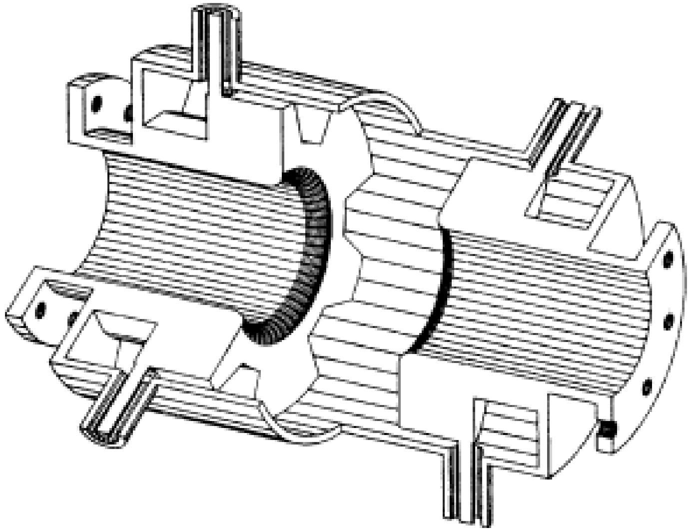
$$h(z) = \frac{h_{min}}{1 + ((h_{min}/h_{max}) - 1)z/L},$$ Hyperbolic



Longitudinal feedback kickers

An overdamped RF cavity is considered to be one of the best candidates for the longitudinal feedback kicker design.





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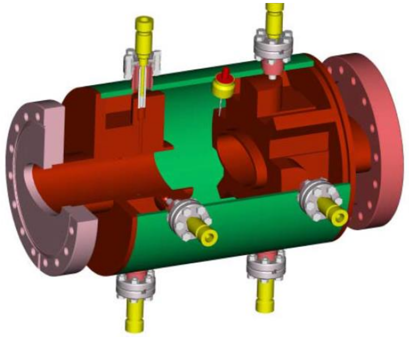
Typically, the fundamental mode quality factor of a pill-box cavity in a such design is reduced down to the value of 5-10, to handle all the coupled bunch oscillation modes on the bunch-to-bunch basis.



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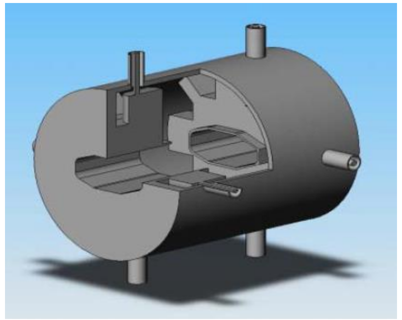

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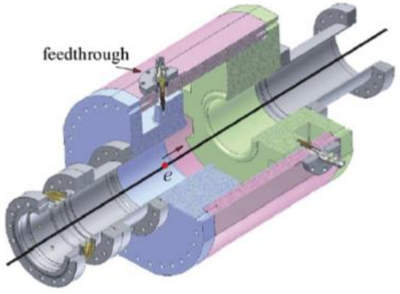
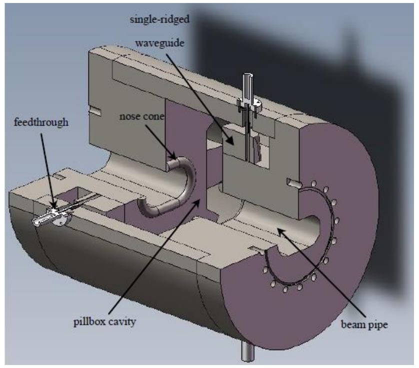


https://doi.org/10.1016/j.nima.2010.12.077



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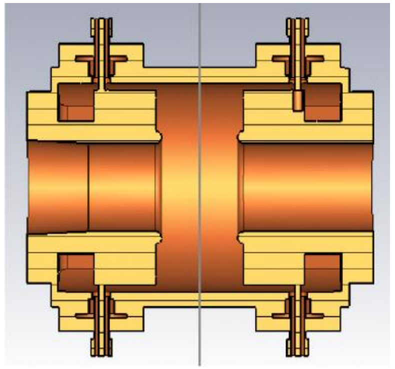

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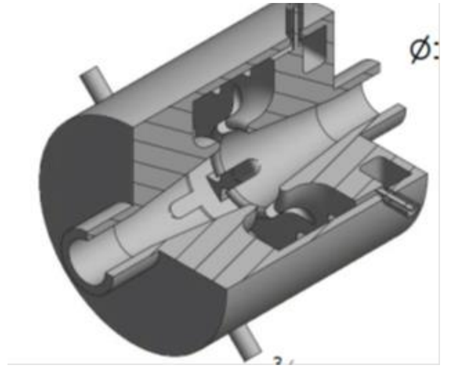

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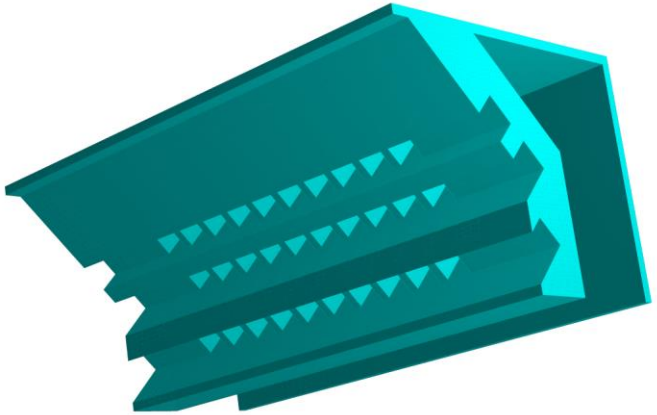
Pumping slots/holes in the hidden positions



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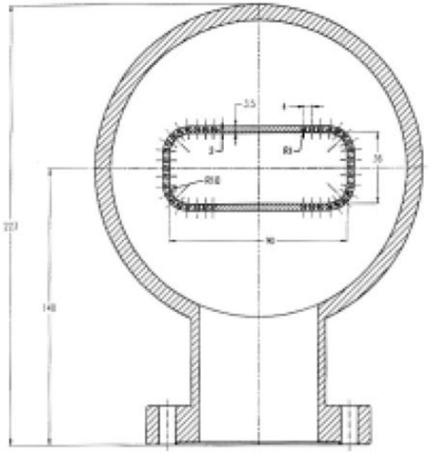

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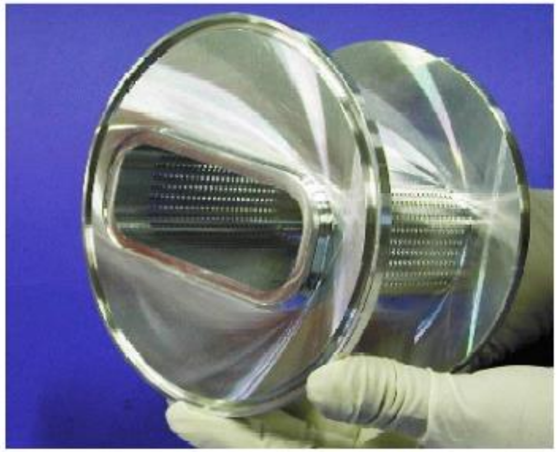


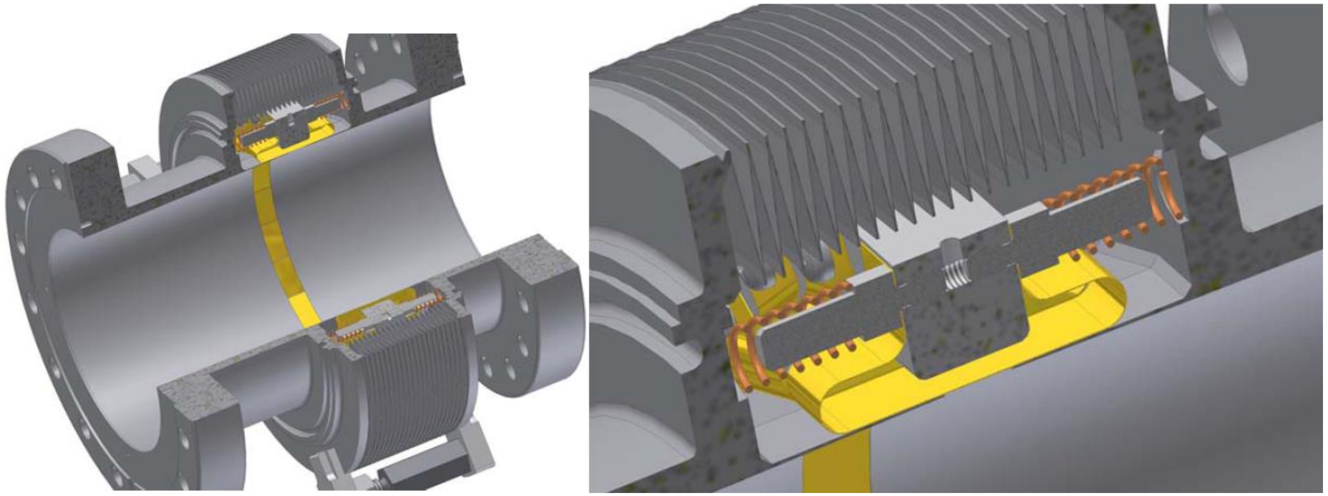
https://accelconf.web.cern.ch/e02/papers/TUPRI057.pdf

The impedance of long slots saturates when the slot length exceeds 2-3 slot widths. Thus, from the impedance point of view, it is more convenient to use long slots instead of many holes providing the same pumping speed. Moreover, differently from the long slots, many periodically placed holes can create harmful higher order modes at high frequencies.

The TM propagating modes, contributing to the longitudinal impedance, decay inside the slots if the slots depth is comparable to the slot width.

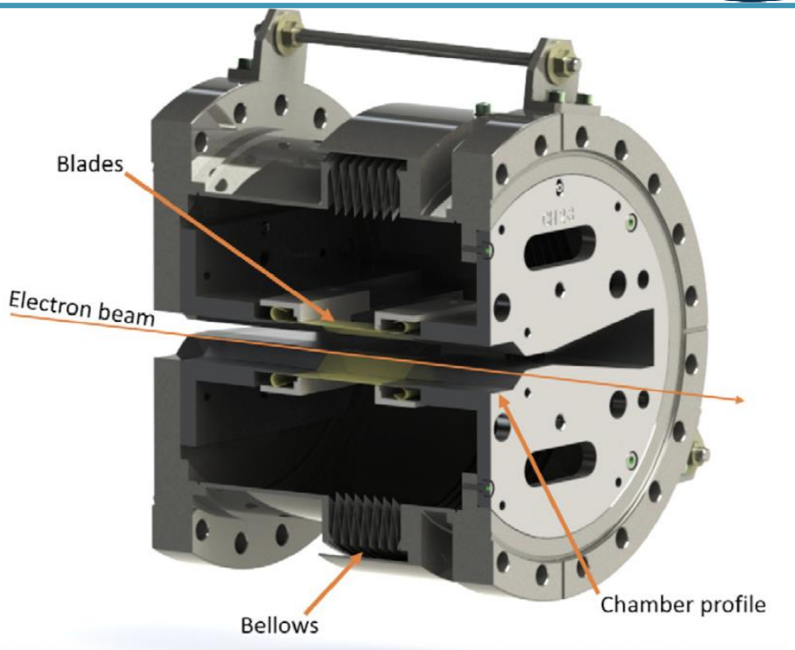
On the other hand, for the long slots TE mode travelling waves excited in a ring can radiate into the pump chamber and may damage the pumps and also create resonant HOM beyond the RF screen.

Bellows



https://accelconf.web.cern.ch/e08/papers/tupp074.pdf

Ω-shaped strip shield (no sliding contacts):
DAΦNE uses an all-metal shield made of overlapping omega-shaped strips that flex with the bellows. The continuous overlap blocks field leakage, so only weak high-frequency HOMs remain (~400 mW total power at 2 A beam current), with no damage after years of operation. The design works for any pipe cross-section and offers large stroke without the wear risks of sliding contacts.



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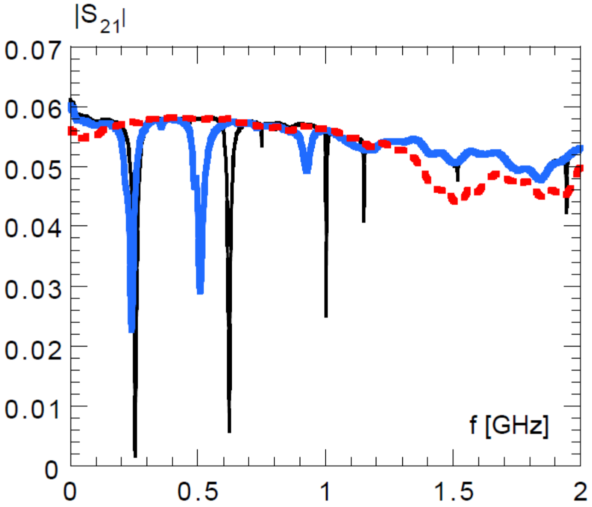
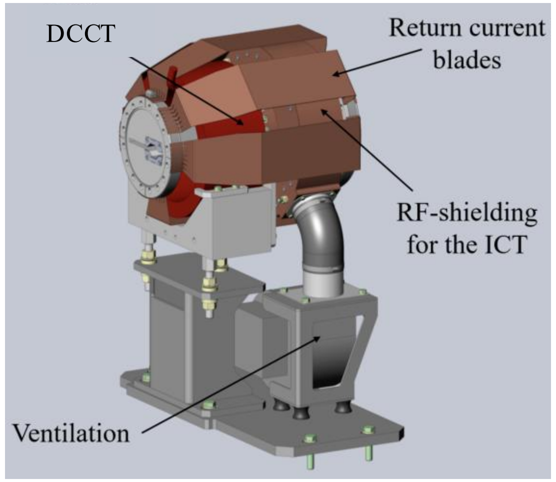
ESRF-EBS low-profile Ω bellows:
ESRF-EBS scales the omega concept for its 13 mm-high chamber, using ten copper-alloy Ω-blades (five top, five bottom) that bridge the bellows gap flush with the ellipse. The overlap keeps RF fields inside, reduces the broadband loss factor by ≈4×. After sustained 200 mA operation the bellows show no RF heating or mechanical wear, confirming the Ω-shield as a reliable low-impedance solution for diffraction-limited rings.

DCCT

A beam current monitor is yet another example of a beam diagnostics device where higher order modes can be trapped. The beam current transformer structure represents an RF cavity with a capacitive gap and an external outer volume. The HOM created in such a cavity can affect beam dynamics and also can result in overheating of the current transformer ferrite core.

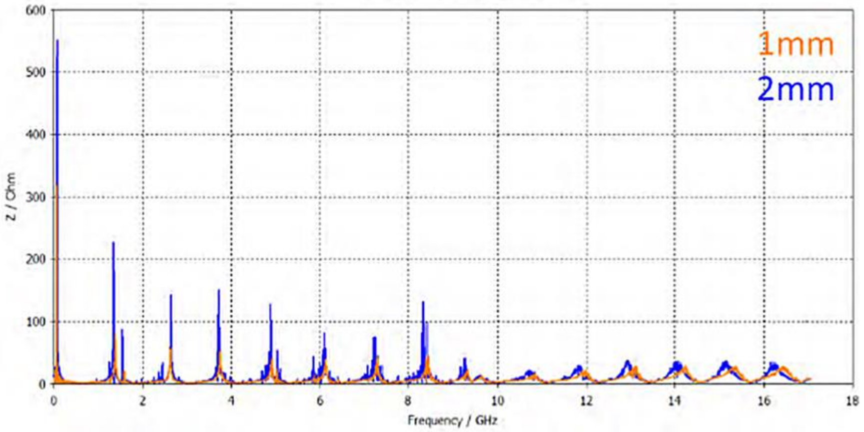
DAΦNE DCCT damps the trapped modes by welding 50 Ω resistors across the ceramic gap. The resistor ring forms a low-impedance RF path that absorbs HOM energy yet leaves the DC current unperturbed, and its voltage can be used as a convenient wall-current monitor.





https://www.esrf.fr/files/live/sites/www/files/about/upgrade/documentation/Design%20Report-reduced-jan19.pdf

ESRF-EBS instead narrows the axial gap, shortens the chamber overlap, and fills the gap with ceramic. The streamlined geometry lowers the shunt impedance and shifts the HOM frequency, cutting the broadband impedance by roughly a factor of five with no extra lossy components.



https://www.esrf.fr/files/live/sites/www/files/about/upgrade/documentation/Design%20Report-reduced-jan19.pdf

Conclusions

Structural optimisation works: adjusting cross-sections, shielding gaps, smoothing transitions, and arranging parts can lower both longitudinal and transverse impedance while keeping device's functional capabilities on the same level.

Proven solutions exist: techniques already used in different accelerator facilities (e.g. ESRF-EBS, DAΦNE) show that this approach is effective, also for machines with beam parameters similar to the FCC damping ring.

New ideas fit the same framework: several fresh design concepts extend the low-impedance strategy and can be adopted in the FCC DR.

Acknowledgments

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