Optimization of beam coupling impedance of button and stripline BPMs

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December 12, 2024

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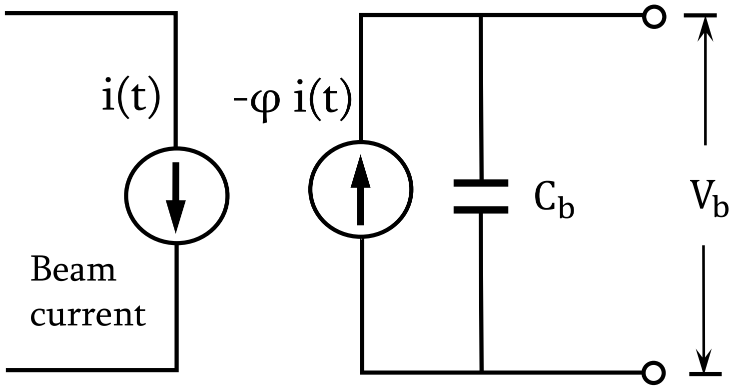
Outline

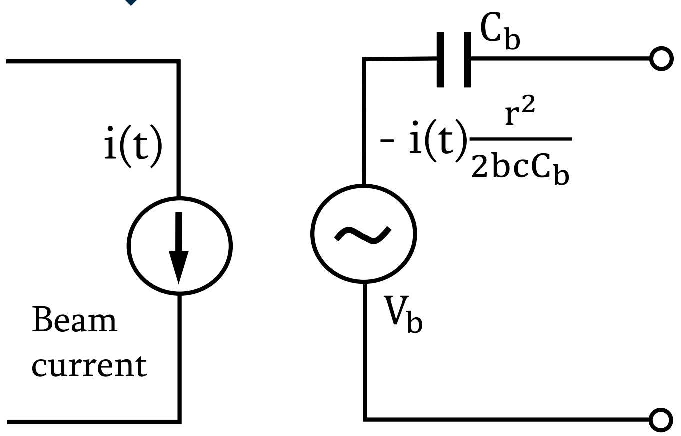
- Introduction
- Motivation
- Button BPMs
- Stripline BPMs
- Simulation and Analysis
- Conclusions

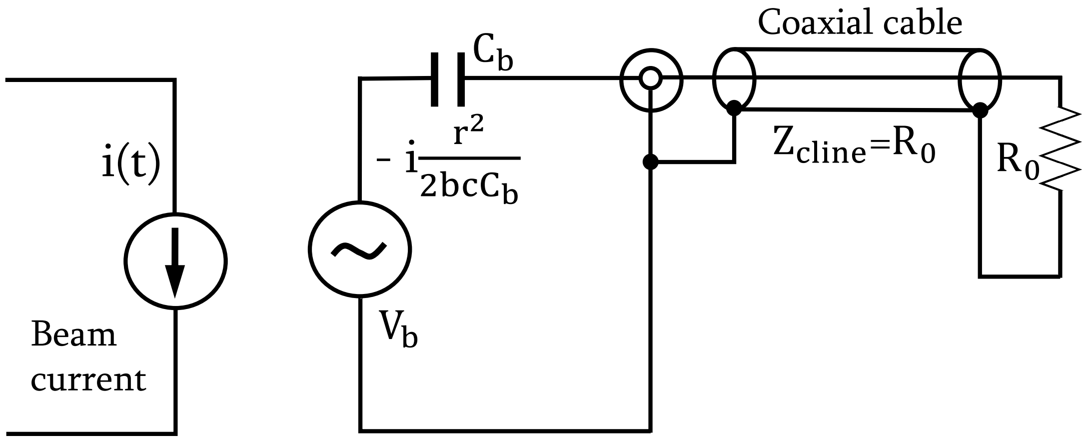
Beam Position Monitors



The usual equivalent circuit representation of the ordinary button pick-up is a current generator of the same value of the current intercepted fraction Δi_b , shunted by the electrode capacitance to ground C_b

Now, let us rearrange the above equivalent scheme into a scheme with the voltage generator





https://doi.org/10.1016/S0168-9002(97)01083-8

The button is now terminated into the resistor R_0, via a coaxial cable with the characteristic impedance $Z_0 = R_0$ in this corresponding equivalent scheme

Beam Transfer Impedance

In the frequency domain, the voltage at the termination load $\mathrm{R_0}$ is given by:

$$V_0(\omega) = V_b(\omega)\frac{R_0}{R_0 + 1/j\omega C_b} = I(\omega)\frac{r^2}{2bc}\frac{1}{C_b}\frac{j\omega R_0 C_b}{1 + j\omega R_0 C_b}$$

Here $V_0(\omega)$ and I(ω) are the spectral densities of the load voltage $V_0(t)$ and beam current $i\,(t)$, respectively.
Then, according to the definition, the transfer (signal) impedance is given by:

$$Z_b(\omega) \equiv \frac{V(\omega)}{I(\omega)} = R_0\frac{\mathrm{j}\omega r^2/2bc}{1 + j\omega R_0 C_b}$$

With definitions $\omega_1 = 1/\mathrm{R_0 C_b}$ and $\omega_2 = \mathrm{c}/2\mathrm{r}$, we can write

$$Z_b(\omega) = \varphi R_0\left(\frac{\omega_1}{\omega_2}\right)\frac{\mathrm{j}\omega/\omega_1}{1 + (\omega/\omega_1)^2}$$

$$\mathbf{Re}Z_b(\omega) = \varphi R_0\left(\frac{\omega_1}{\omega_2}\right)\frac{(\omega/\omega_1)^2}{1+(\omega/\omega_1)^2}$$

$$\mathbf{Im}Z_b(\omega) = \varphi R_0\left(\frac{\omega_1}{\omega_2}\right)\frac{(\omega/\omega_1)}{1+(\omega/\omega_1)^2}$$

Beam Coupling Impedance

In order to get the coupling impedance, we calculate the average power dissipated at the external termination R_0

$$\langle P(\omega)\rangle = \frac{1}{2}|V_0|^2\frac{1}{R_0} = \frac{1}{2}|I|^2 R_0 \varphi^2 \left(\frac{\omega_1}{\omega_2}\right)^2 \frac{(\omega/\omega_1)^2}{1+(\omega/\omega_1)^2}$$

This power is provided by the beam and can also be written as:

$$\langle P(\omega)\rangle = \frac{1}{2}|I|^2 Re\{Z_l(\omega)\}$$

By comparing these two equations we can get the expression for the real part of the longitudinal coupling impedance:

$$\mathbf{Re} Z_l(\omega) = R_0\varphi^2\left(\frac{\omega_1}{\omega_2}\right)^2 \frac{(\omega/\omega_1)^2}{1+(\omega/\omega_1)^2}$$

In a causal system the real and imaginary parts of the Fourier transform of the pulse response function are related to each other by a Hilbert transforms pair

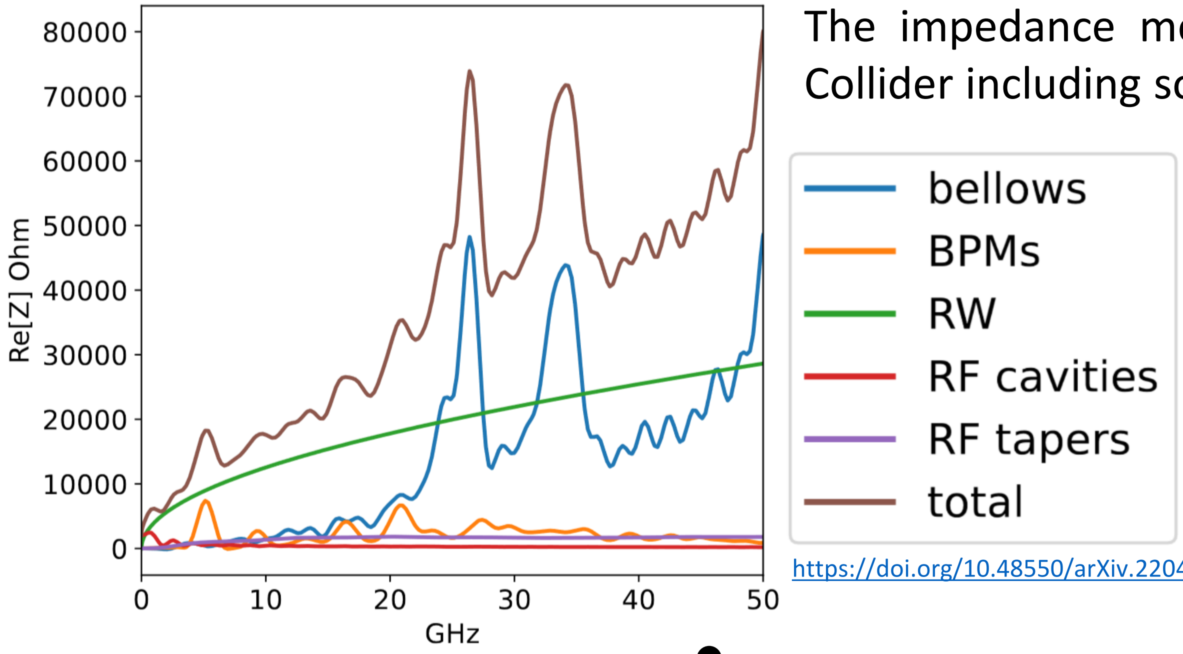
$$\mathbf{Im} Z_l(\omega) = R_0\varphi^2\left(\frac{\omega_1}{\omega_2}\right)^2 \frac{\omega/\omega_1}{1+(\omega/\omega_1)^2}$$

The annular cut also contributes to the coupling impedance, which can be estimated analytically at low frequencies.

$$Z_{l\ cut}(\omega) = \mathrm{j}\frac{Z_0\omega(r+\omega)^3}{8cb^2\left(\ln\left[\frac{32(r+\omega)}{\omega}\right]-2\right)}$$

https://doi.org/10.1109/PAC.1995.505888

Some Examples



The impedance model evaluated for Future Circular e^+e^- Collider including some of the vacuum chamber components.

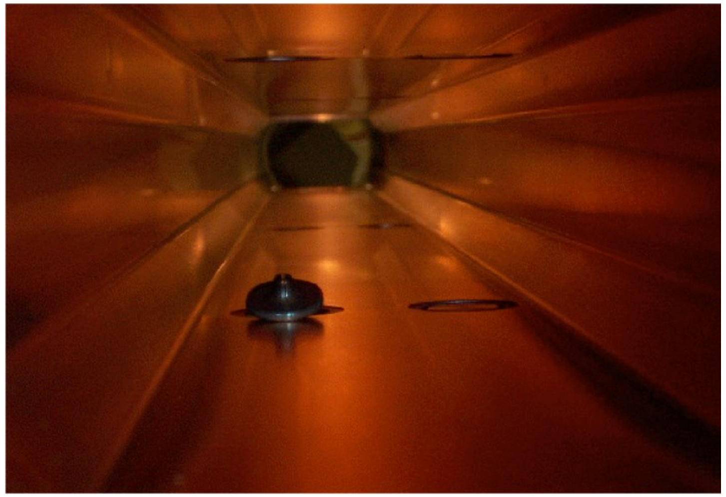
https://doi.org/10.48550/arXiv.2204.04616

- It is important to note that, the beam position monitors produce second largest contribution in the total impedance budget up to 10 GHz).

In the PEP-II B-Factory, some of the upper button electrodes heated up enough to fall off their mounts. The upper electrode fell onto the lower electrode.

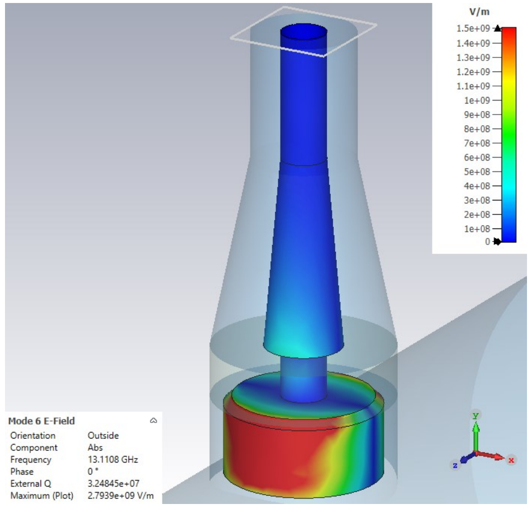
It shorted the underlying electrode and also became a large obstacle for the beam fields, increasing the current though the lower electrode. This then melted the feed-through causing a vacuum breach.

The origin of the heating was the wake field generated by an intense short bunch passing by the vacuum chamber discontinuity due to a BPM button.

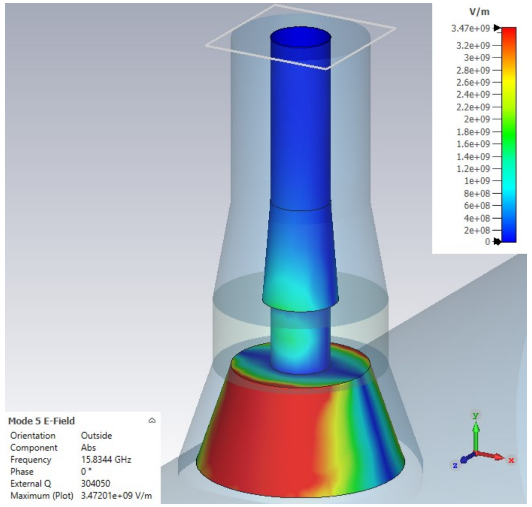


https://accelconf.web.cern.ch/ICAP2009/papers/thpsc057.pdf

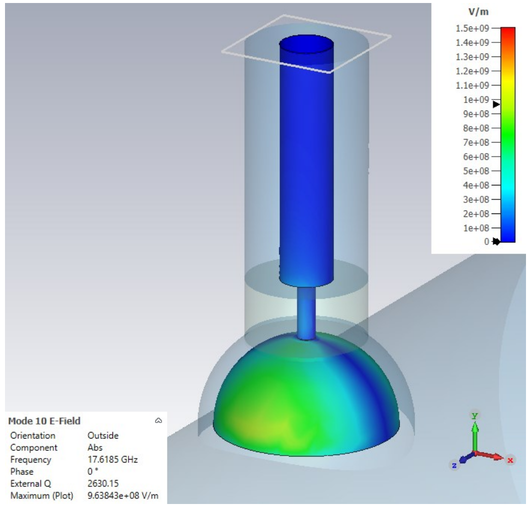
Button BPM Electrode Design Variations



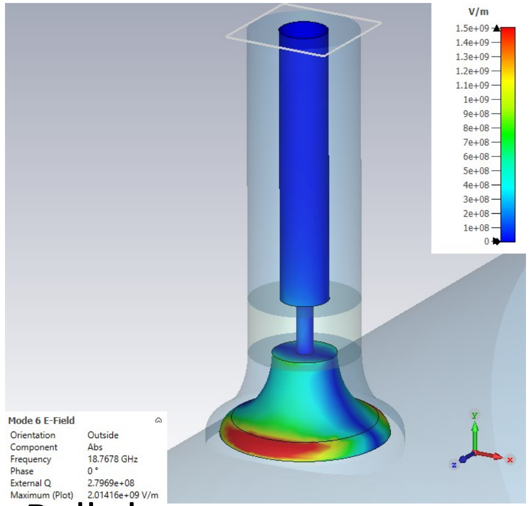
Cylindrical



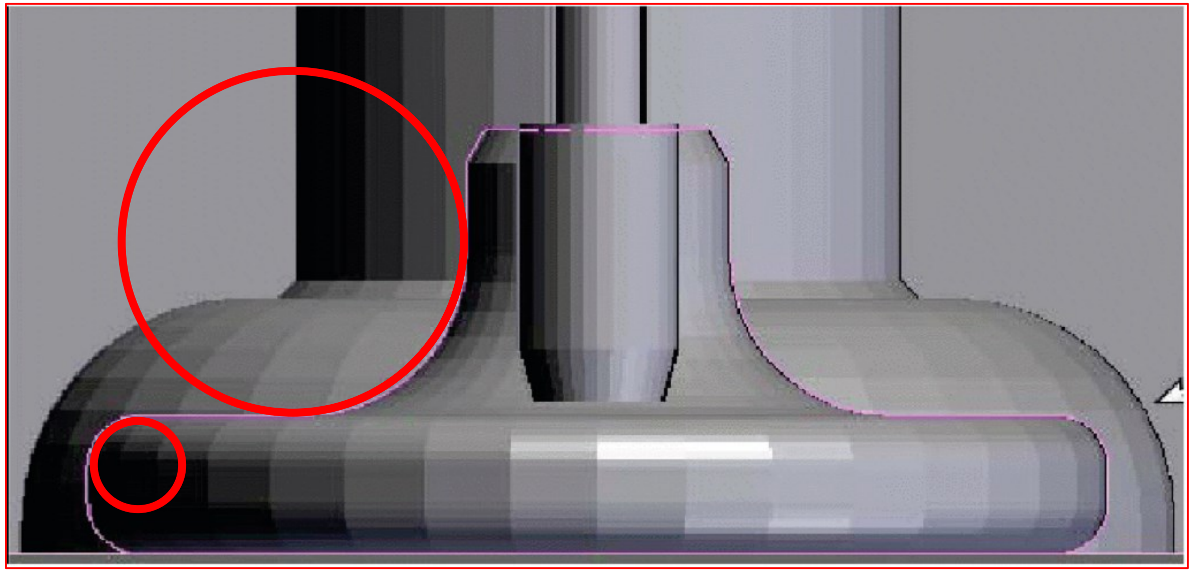
Conical

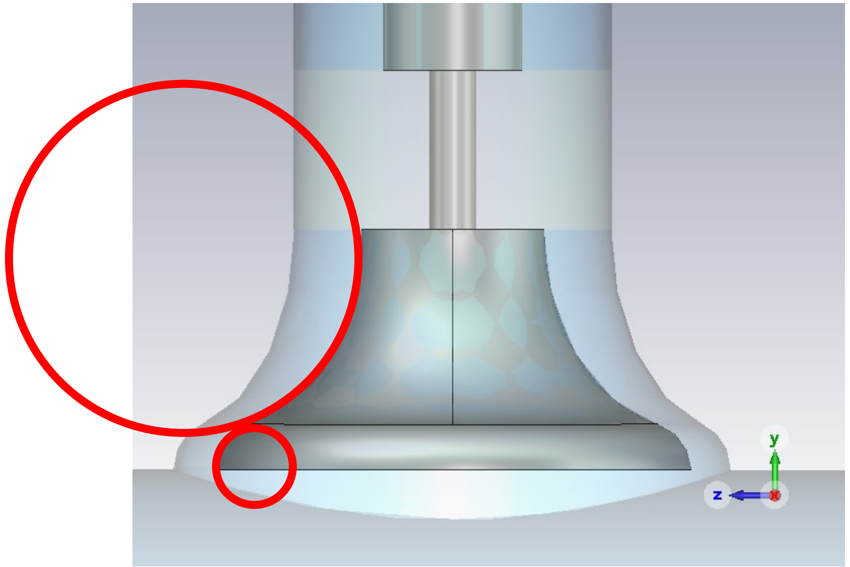


Semispherical



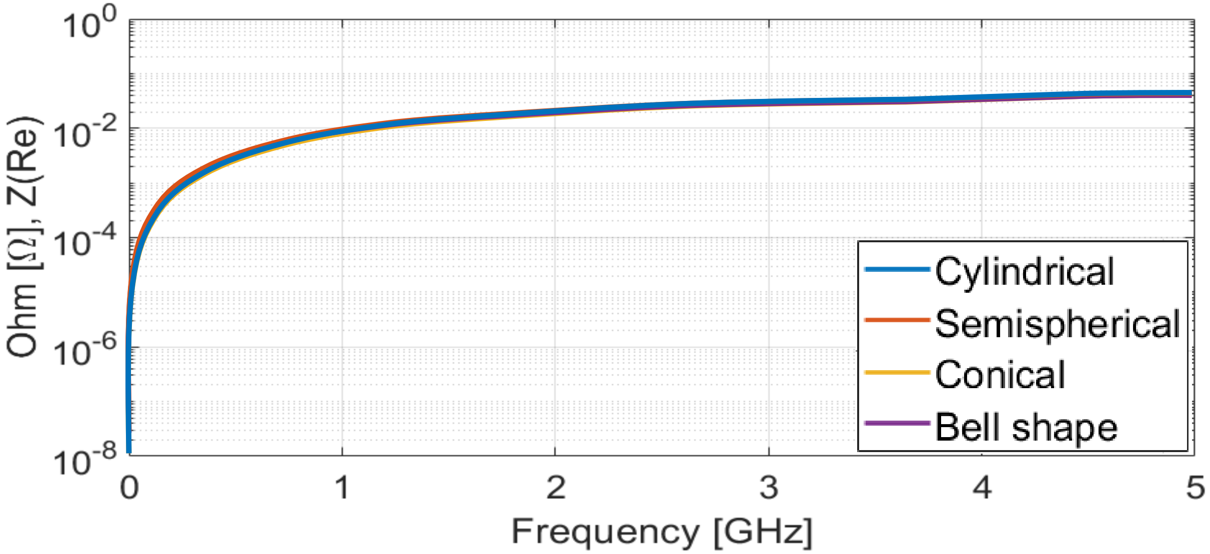
Bell shape

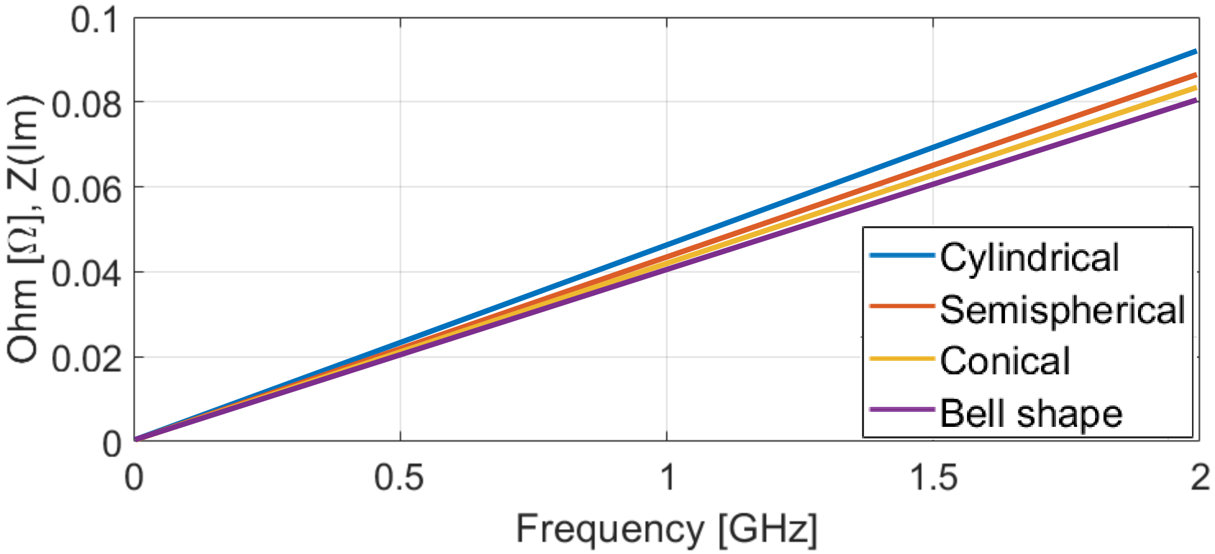


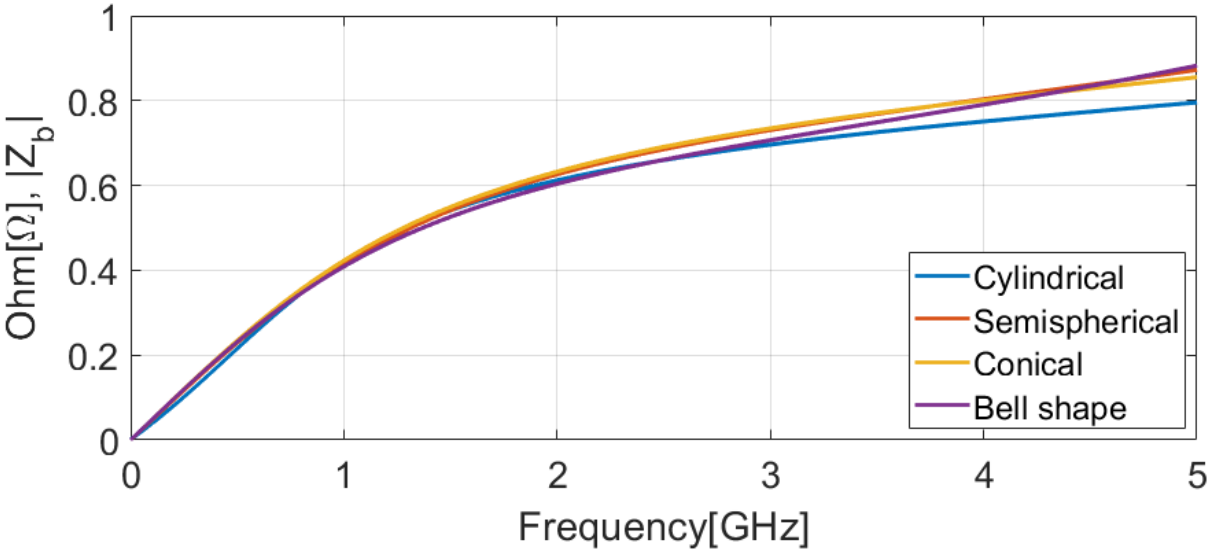


https://accelconf.web.cern.ch/ICAP2009/papers/thpsc057.pdf

Button BPM Electrode Design Variations



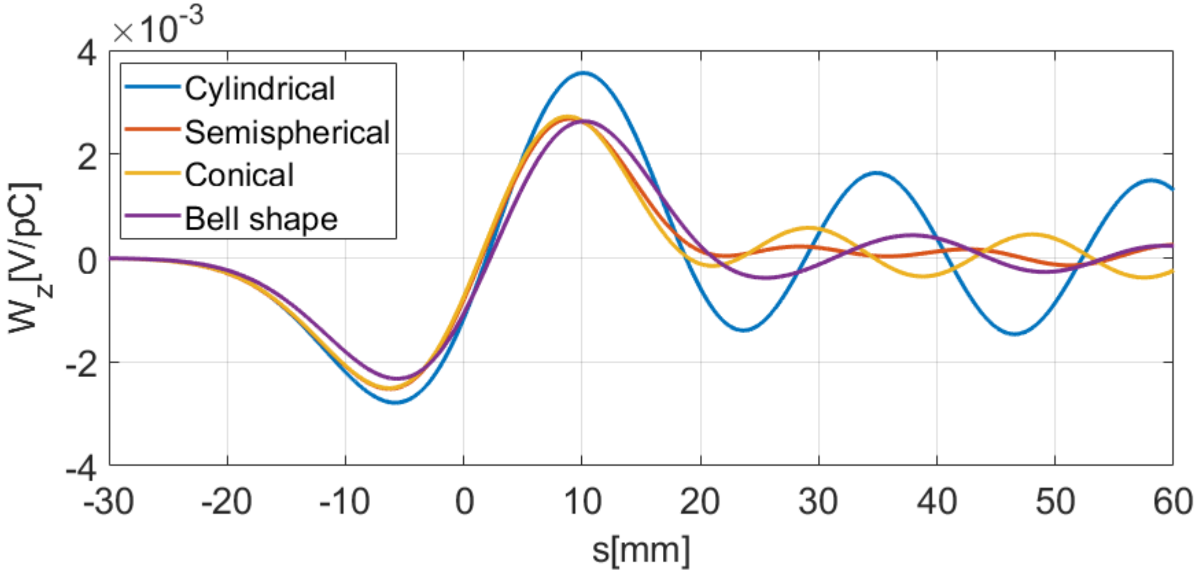


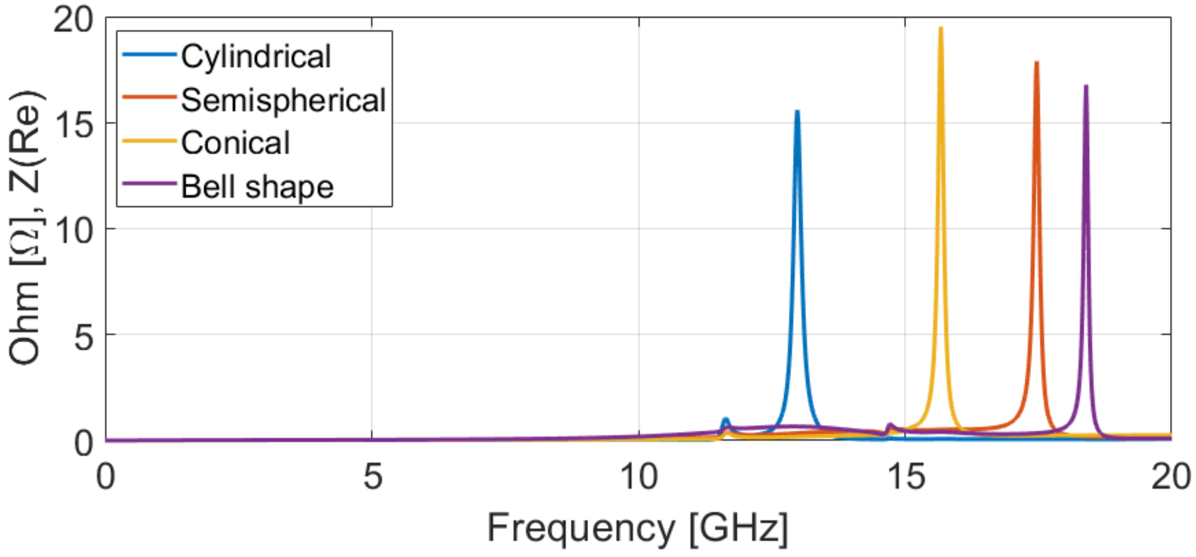


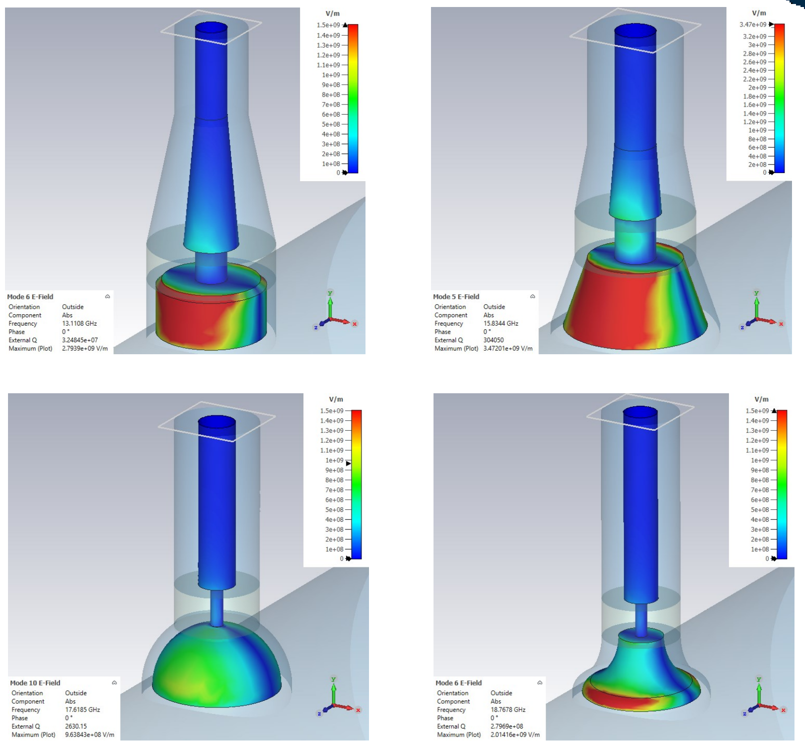
- It was examined how the button geometry can be modified to minimize the harmful effect of the resonance peak narrow-band impedance, while keeping the transfer impedance, button capacitance, and gap between the electrode and vacuum chamber on the same level.

https://doi.org/10.1088/1742-6596/2687/7/072004

Design Optimization Results for Button BPMs

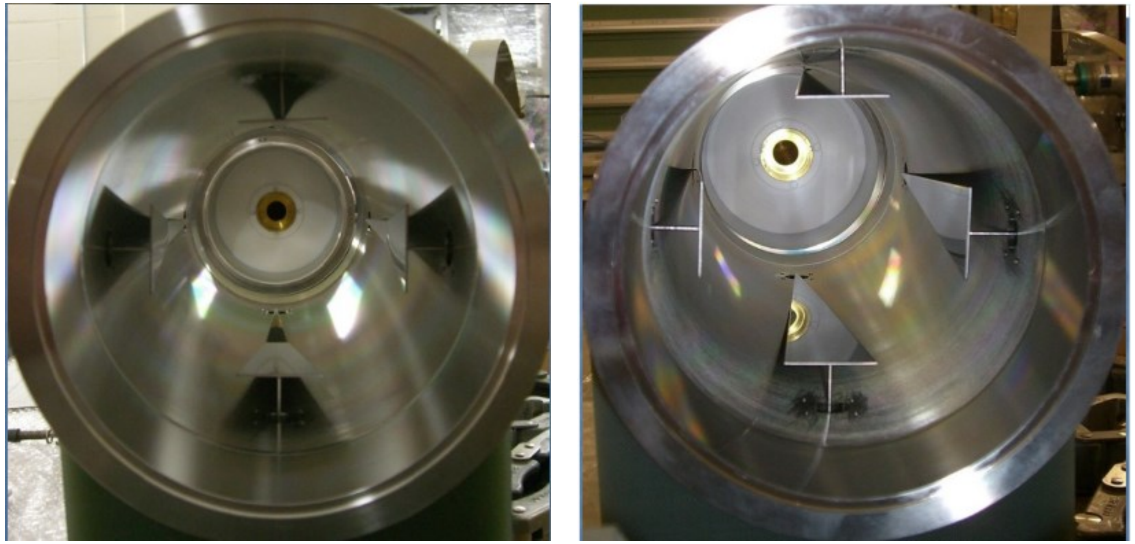






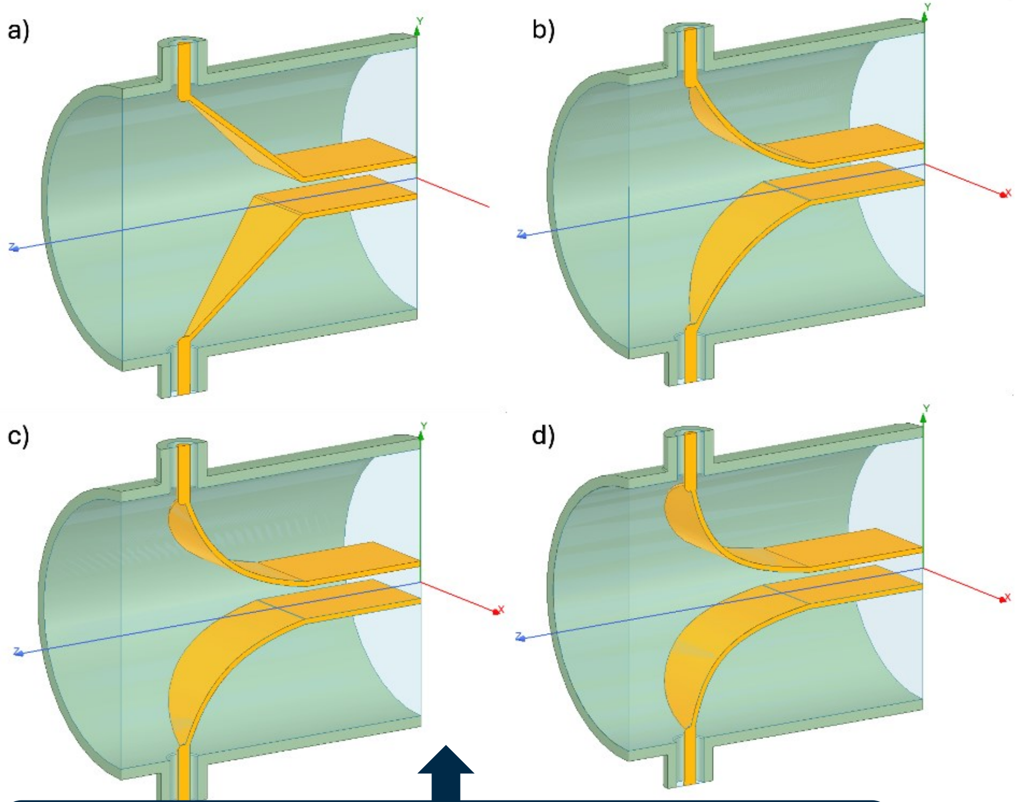
- A choice of button geometry can significantly affect the narrow-band beam coupling longitudinal impedance of BPMs in vacuum chambers.
- The issues of heating effects and coupled-bunch instabilities, caused by BPMs' contribution to both broad-band and narrow-band impedances can be effectively addressed.

Stripline BPM Design Overview



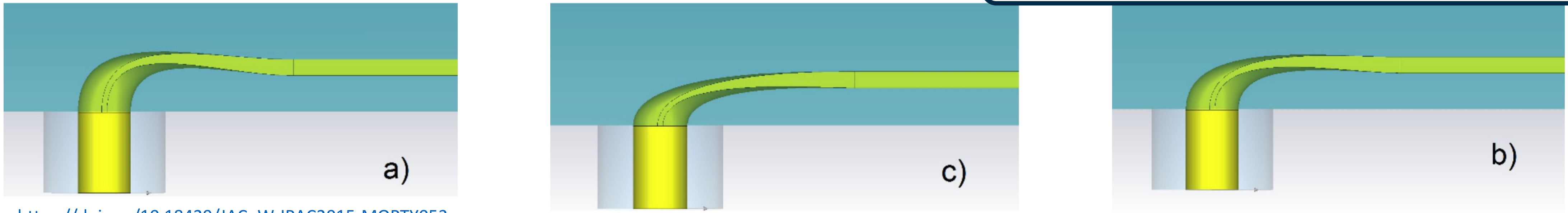
https://doi.org/10.1103/PhysRevAccelBeams.19.021003

https://doi.org/10.18429/JACoW-IBIC2024-TUP12



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

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



https://doi.org/10.18429/JACoW-IPAC2015-MOPTY053

Stripline BPM Design Overview

http://cds.cern.ch/record/210347

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

[redacted]

CERN SL/90-88 (AP)

Impedance of Slowly Tapered Structures

Kaoru Yokoya*

Function that we used for exponential tapering

https://doi.org/10.1103/PhysRevSTAB.10.074402

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 074402 (2007)

Transverse impedance of tapered transitions with elliptical cross section

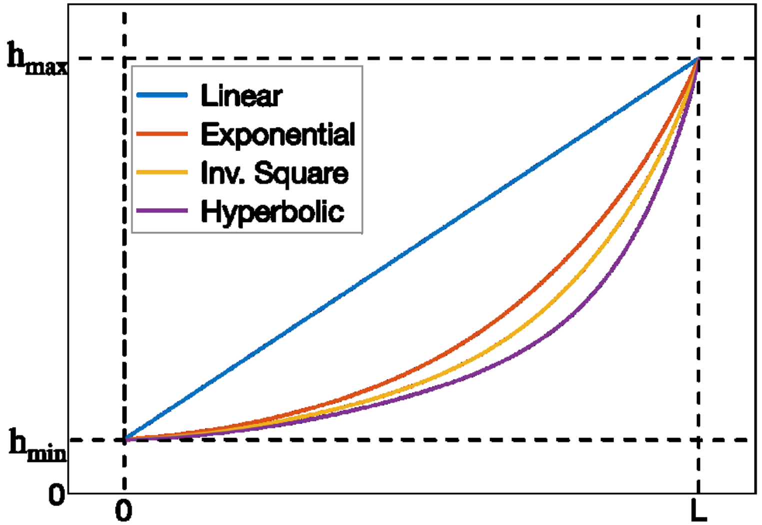
B. Podobedov and S. Krinsky

Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 23 May 2007; published 30 July 2007)

Function that was used for inv. square tapering

Design Optimization Studies for Stripline BPMs

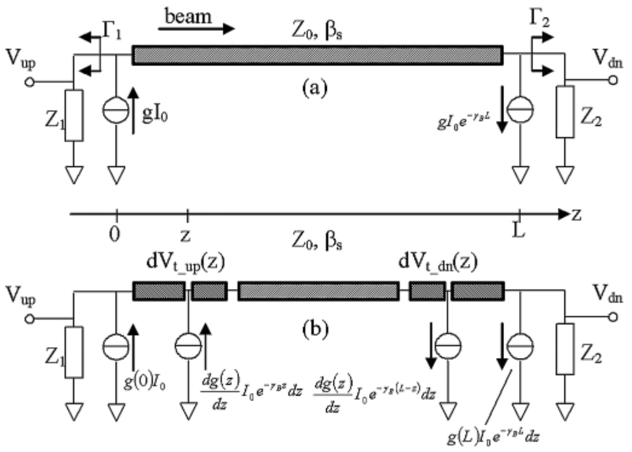


$$h(z) = h_{min}(1 + (h_{max}/h_{min} - 1)z/L)$$ Linear

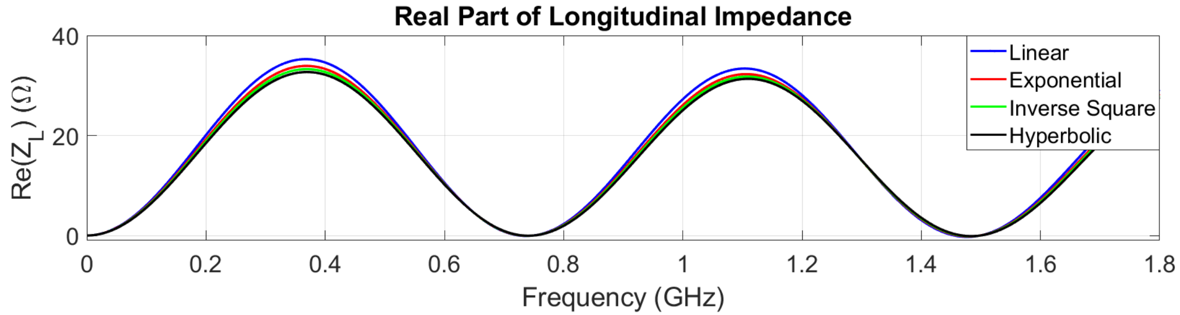
$$h(z) = h_{min}(h_{max}/h_{min})^{z/L}$$ Exponential

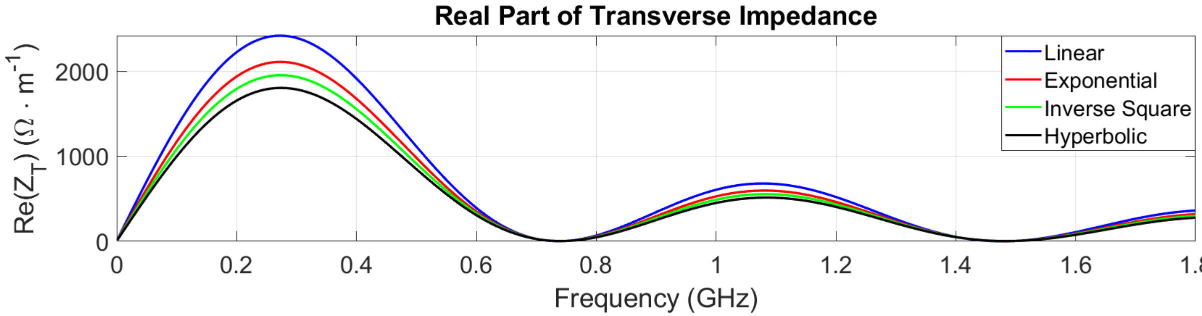
$$h(z) = \frac{h_{min}}{(1 + ((h_{min}/h_{max})^{1/2} - 1)z/L)^2}$$ Inv. Square

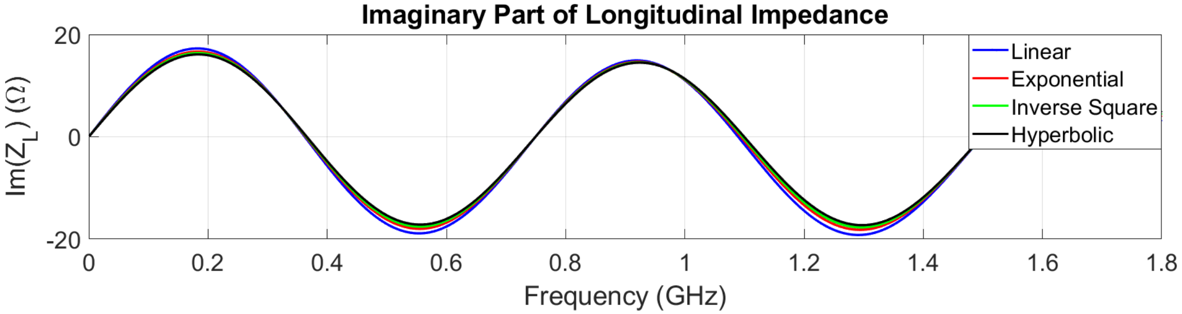
$$h(z) = \frac{h_{min}}{1 + ((h_{min}/h_{max}) - 1)z/L},$$ Hyperbolic

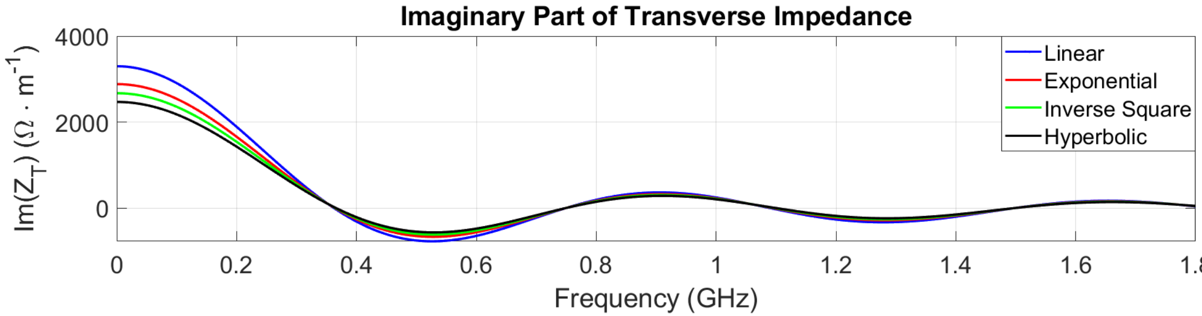


https://doi.org/10.1103/PhysRevSTAB.13.111002

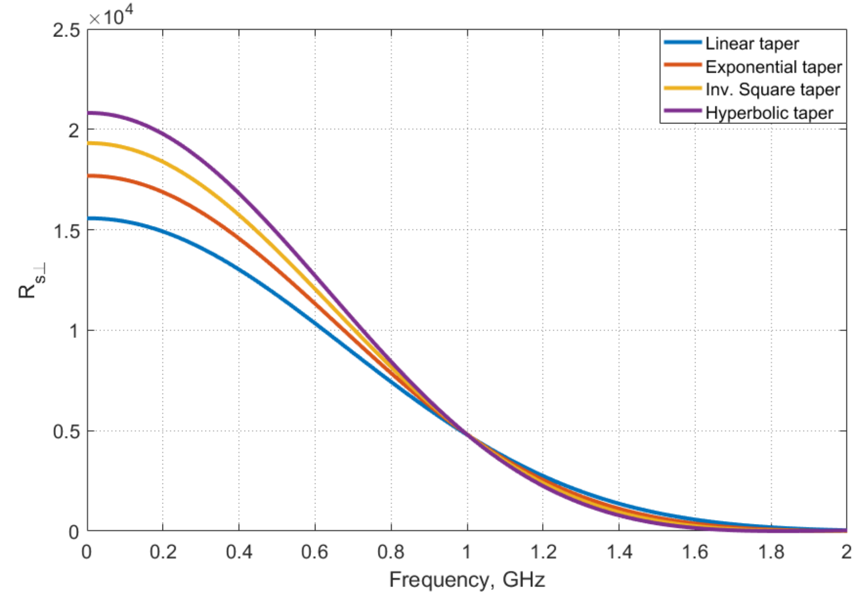


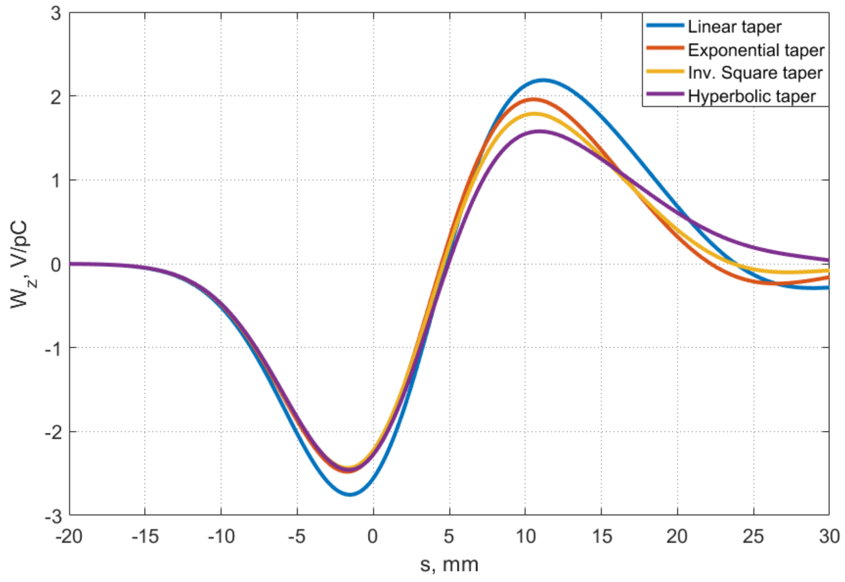


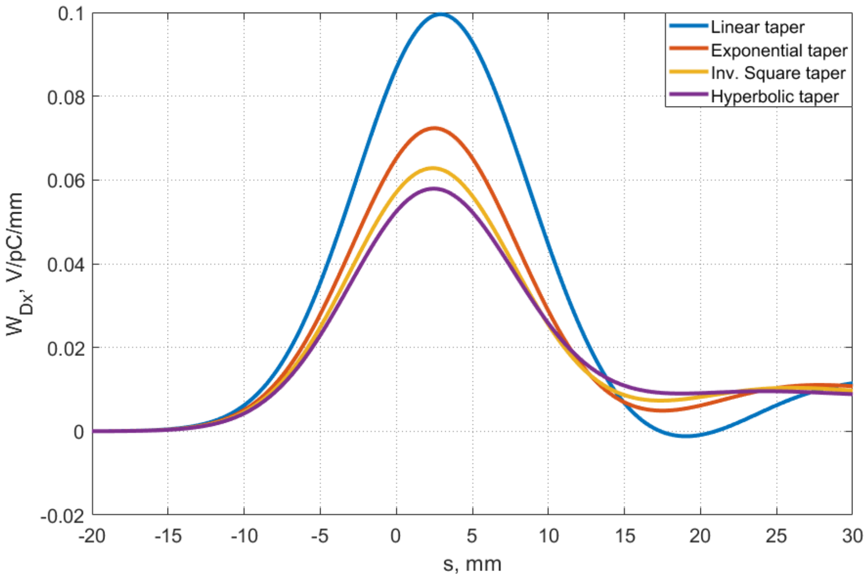


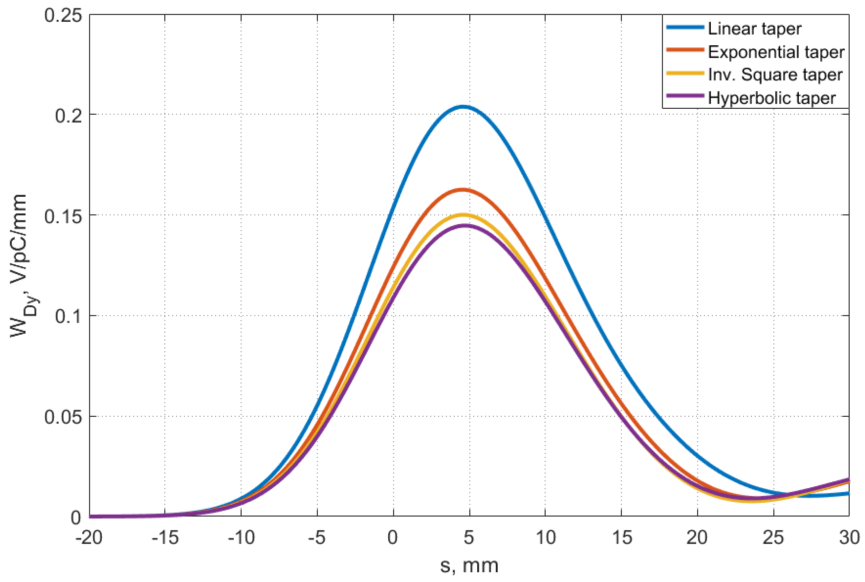


Design Optimization Results for Stripline BPMs









Design Optimization Results for Stripline BPMs

	Wake-Loss-Factor	Unit
Linear:	1.380018e+00	V/pC
Exponential:	1.196212e+00	V/pC
Inverse Square:	1.203277e+00	V/pC
Hyperbolic:	1.209588e+00	V/pC

	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

- For the stripline devices (kickers, BPMs) with the same total strip length and gap between the strips and having the same characteristic impedance, the nonlinear tapering can add several beneficial features.
- In particular, it can enhance the stripline functionality, by increasing the transverse shunt impedance.
- In addition, the nonlinear tapering results in a significant reduction of the beam coupling impedance and respective loss and kick factors.
- Overall, the choice of tapering function and structure aspect ratio significantly impacts impedance characteristics and device efficiency.

Conclusions

- Adjusting or choosing BPM button geometry can reduce harmful effects and shift narrow band resonance peak impedances towards higher frequencies, while keeping the transfer impedance, button capacitance, and gap between the electrode and vacuum chamber on the same level.

- For striplines (such as kickers and BPMs), using nonlinear tapers can improve performance by increasing transverse shunt impedance and also reduce beam coupling impedance, with the same total strip length and gap between the strips and having the same characteristic impedance.

- Overall, both button electrode geometry and stripline tapering choices can play an important role in improving efficiency and stability of these devices.

Thank you