Updated status of the PSB impedance model

C. Zannini and G. Rumolo

Thanks to: E. Benedetto, N. Biancacci, E. Métral,
B. Mikulec, N. Mounet, T. Rijoff, B. Salvant, W. Weterings

Overview

- Introduction
- Present PSB impedance model
  - Indirect space charge
    - Numerical form factor for ISC computation
  - Resistive wall
  - Extraction kicker
  - Broadband impedance of step transitions
  - KSW
- Global PSB impedance model
  - Comparison with tune shift measurements
  - Summary and future plans
- Other devices studied
  - Shielding of pumping ports
  - Insulated flanges

Impedance calculations for $\beta < 1$

Analytical calculation (applies only to simple structures)

3D EM simulation (CST Particle Studio)

In the LHC, SPS, PS CST EM simulation are performed in the ultra-relativistic approximation ($\beta = 1$)

$\beta_{inj}^{PSB} \cong 0.3$ $\beta_{ext}^{PSB} \cong 0.9$

The use of 3D EM simulations for $\beta < 1$ is not straightforward at all

3D CST EM simulation for $\beta < 1$

$$Z^{total}(\beta) = Z(\beta) + Z^{SC}_{direct}(\beta)$$

contribution due to the interaction of beam and external surroundings

Depend only on the source

To single out the impedance contribution $Z(\beta)$ the direct space charge must be removed

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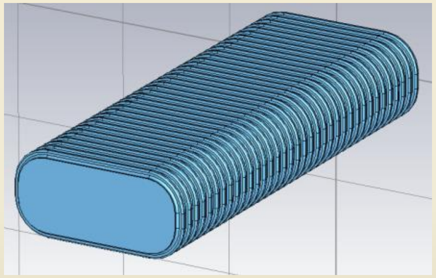
Present PSB transverse impedance model

- Elements included in the database:
  - Analytical calculation of the resistive wall impedance that takes into account the different PSB vacuum chambers weighted by the respective length and beta function. Also the iron in the magnet is taken into account

Beam pipe



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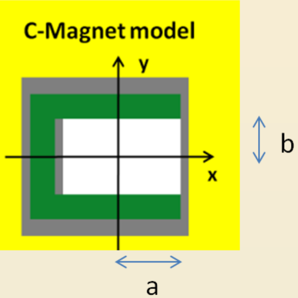

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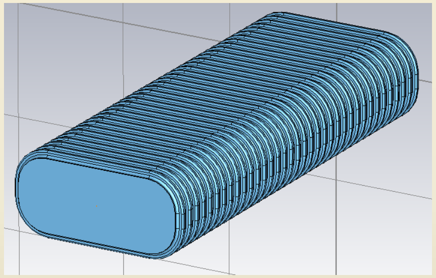

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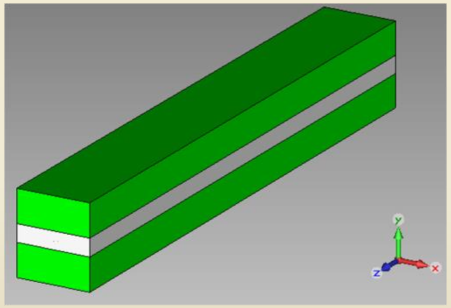

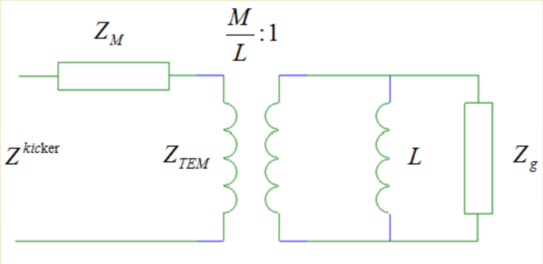

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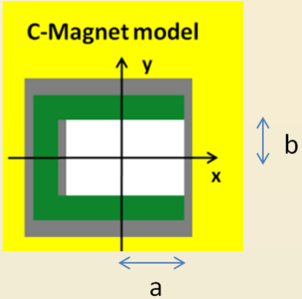

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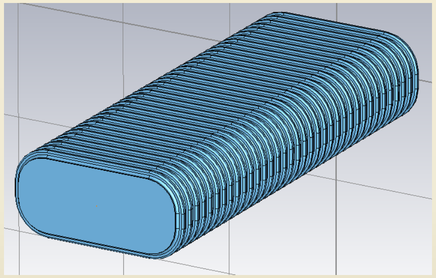

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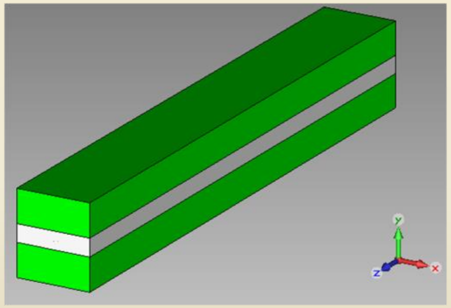
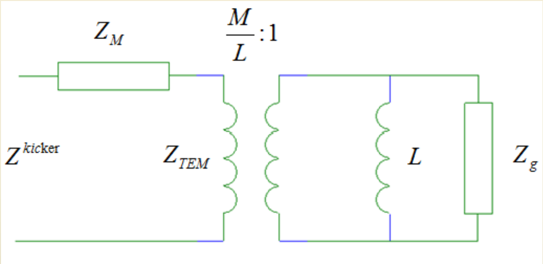
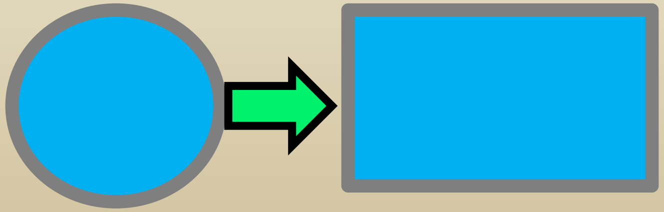




Indirect space charge impedance



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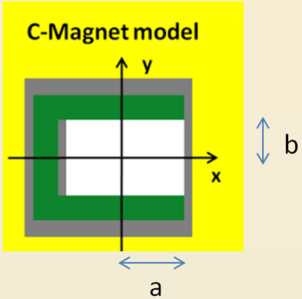

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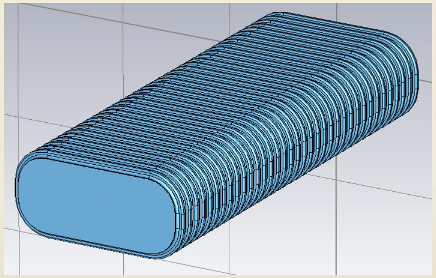

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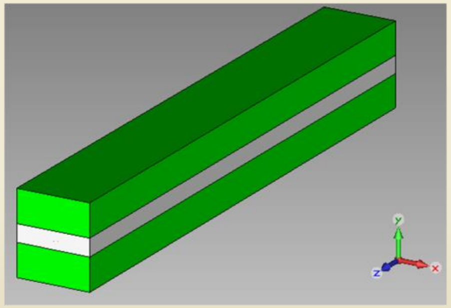

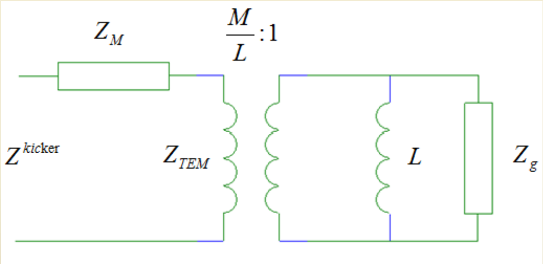

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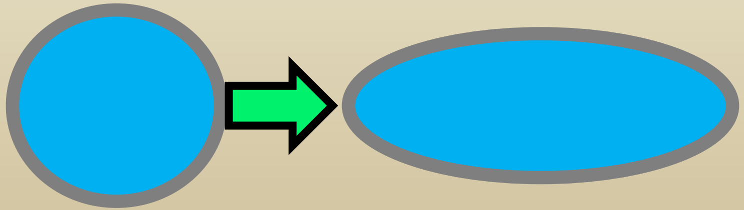

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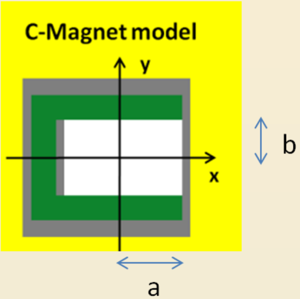

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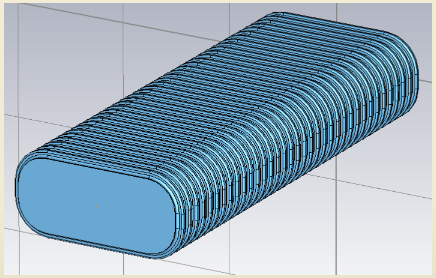

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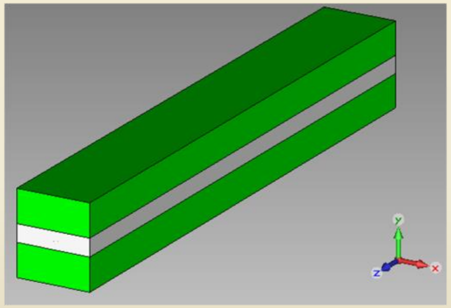
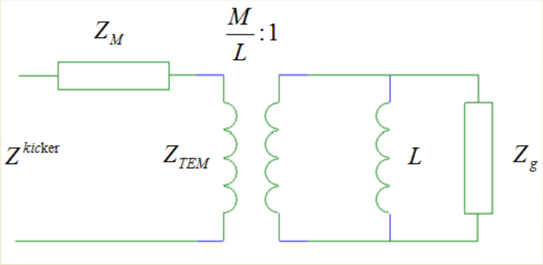
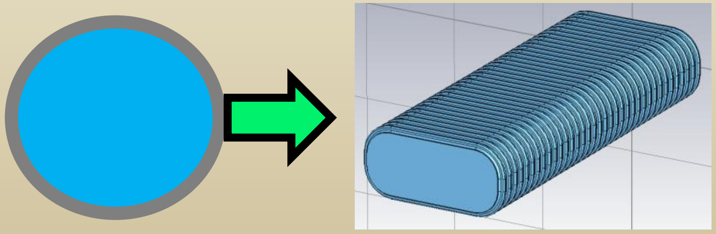




Indirect space charge impedance



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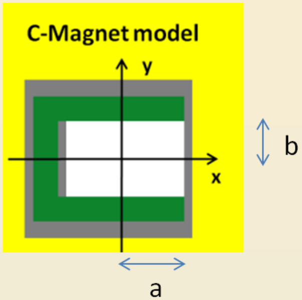

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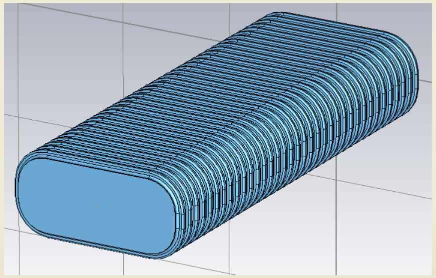

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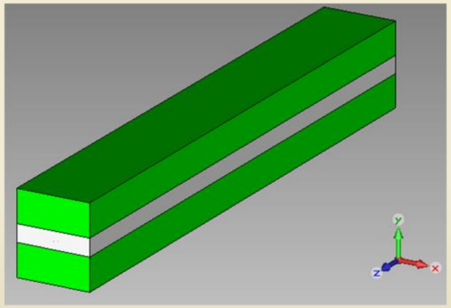

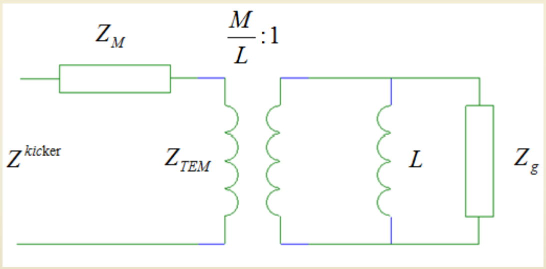

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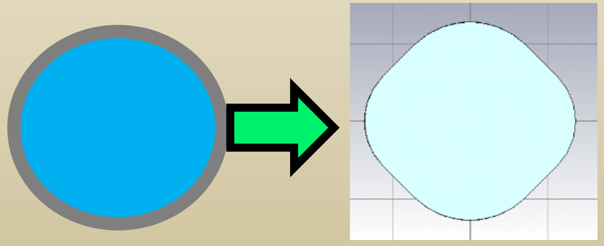

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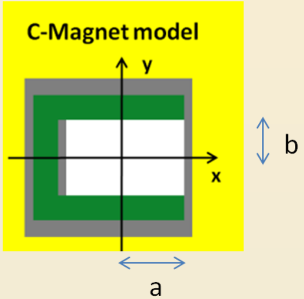

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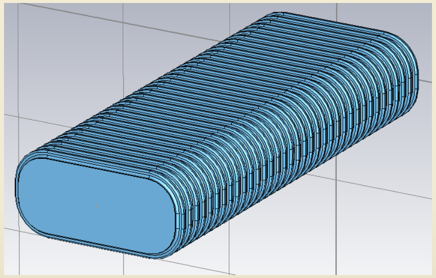

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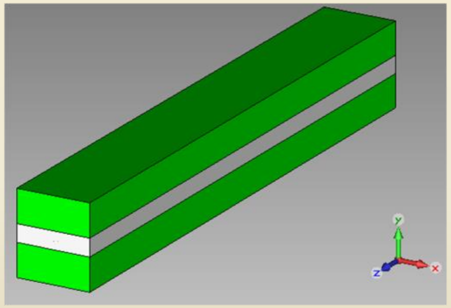

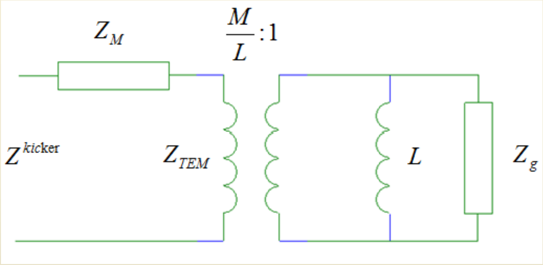

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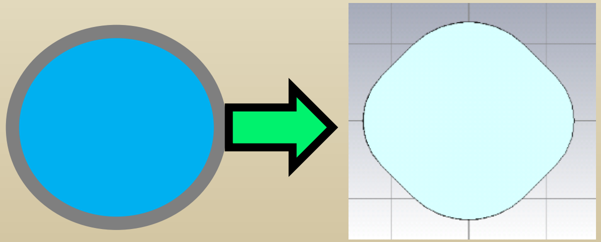
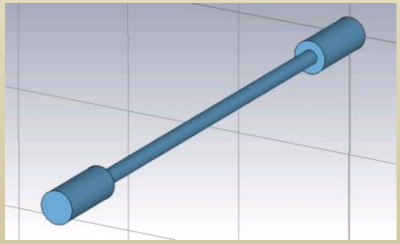


Step transitions



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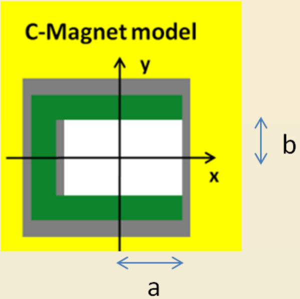

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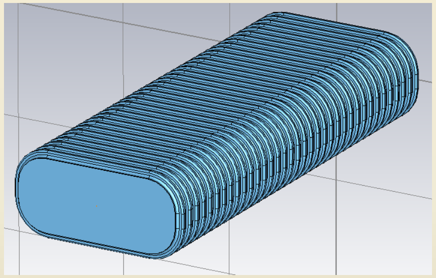
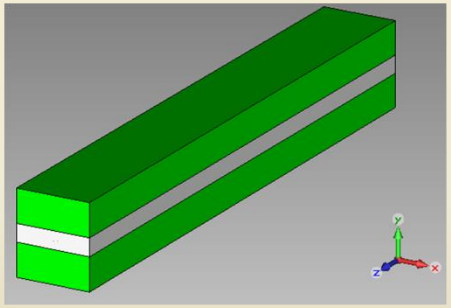
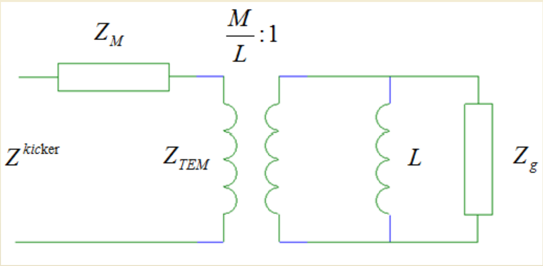


Extraction Kicker





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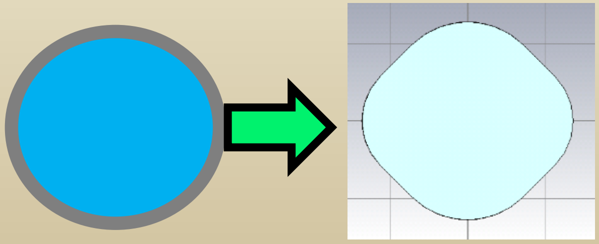
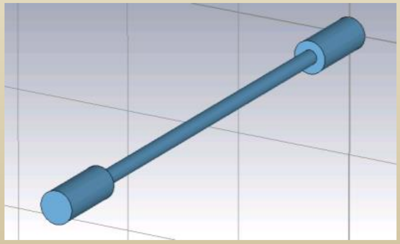
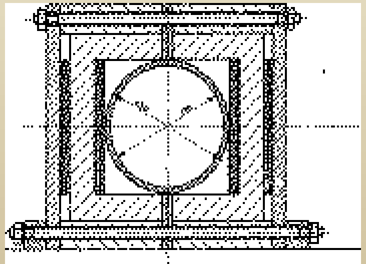


Step transitions



KSW



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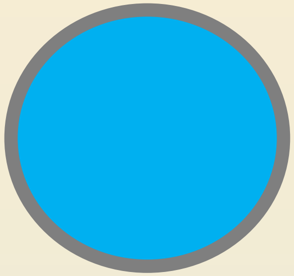
Indirect space charge

Analytical calculation based on the PSB aperture model (provided by O. Berrig)

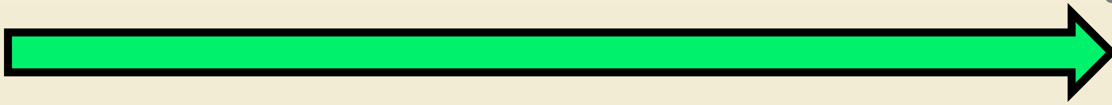
$[a, b, L, \beta_x , \beta_y , \text{Apertype}]_i$

$$Z_{x,y}^{ISC} = \frac{1}{\langle \beta_{x,y} \rangle} \sum_{i=1}^{N} Z_i^{ISC} \beta_{x_i,y_i}$$

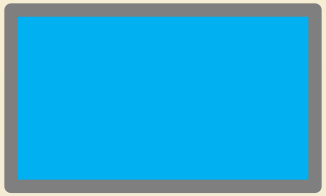
Circular pipe



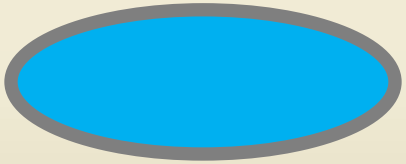
K. Y. Ng, *Space charge impedances of beams with non-uniform transverse distributions*



Rectangular pipe

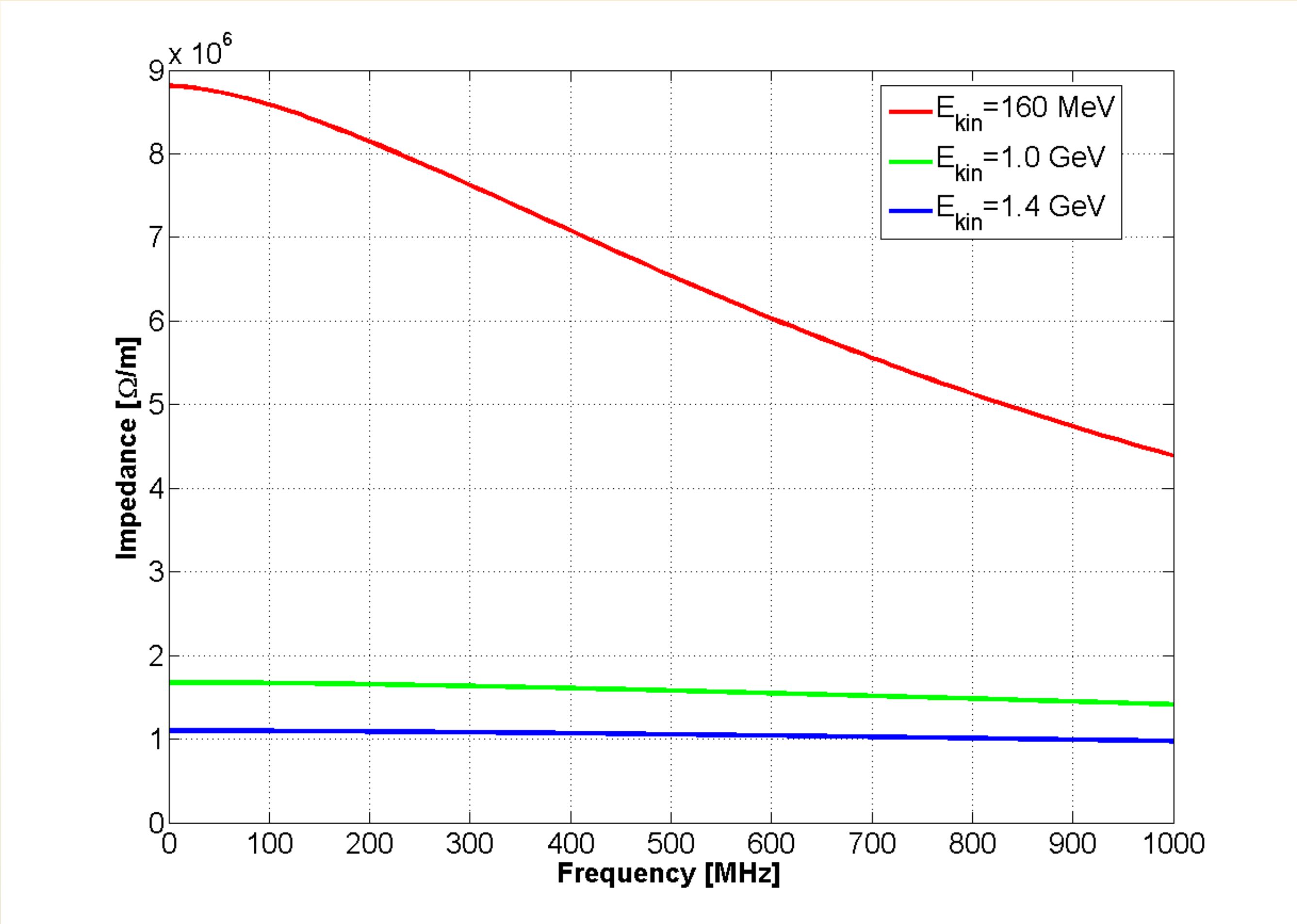


Elliptic pipe



$$Z_{\perp} = \frac{jZ_0 L}{2\pi\beta\gamma^2} \frac{K_1\left(\frac{k_0 b}{\beta\gamma}\right)}{I_1\left(\frac{k_0 b}{\beta\gamma}\right)} \frac{k_0^2}{2\beta^2\gamma^2}$$

PSB: indirect space charge impedance



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Indirect space charge: refinement of the calculation

Using numerical form factors

$$F_{x,y}^{G} = \frac{Z_{x,y}^{G}}{Z^{round}}$$

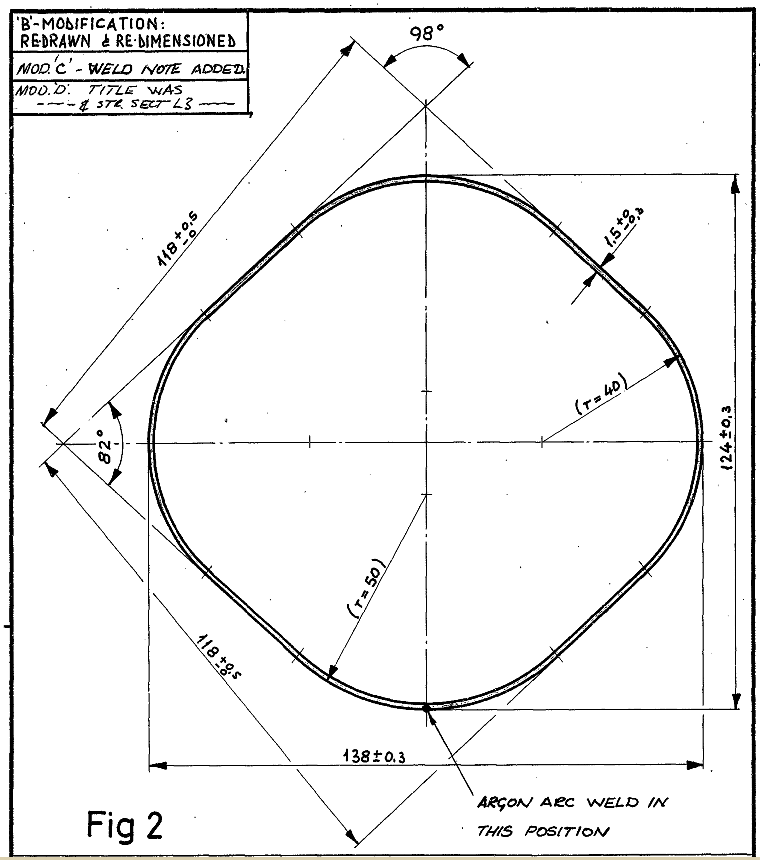
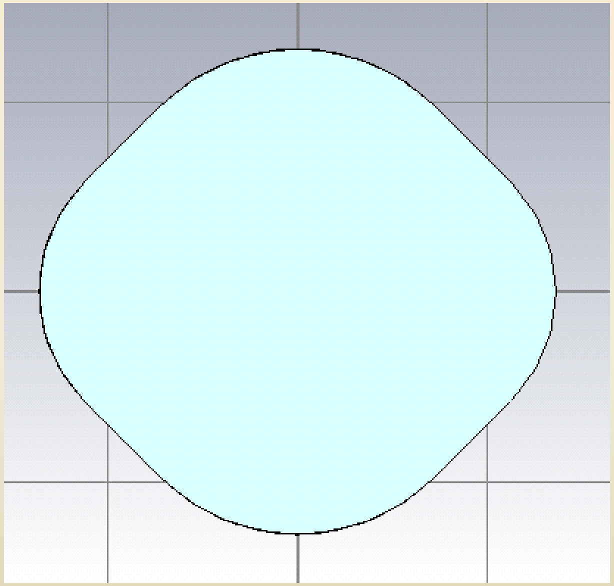


Fig 2

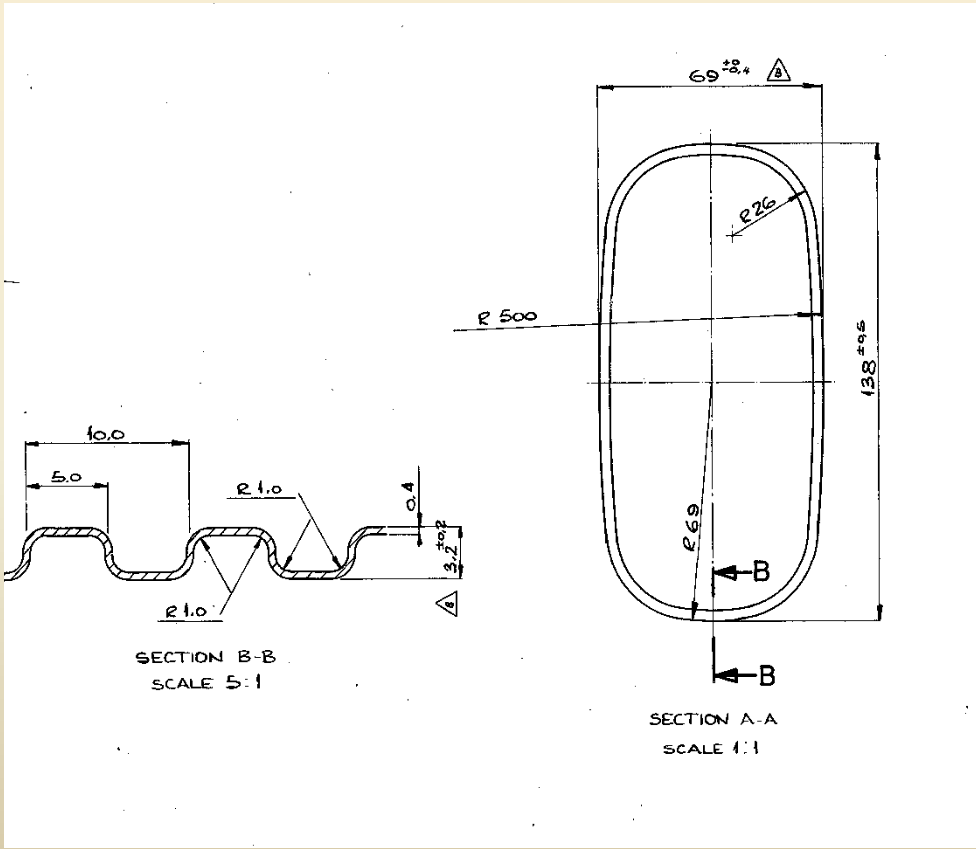


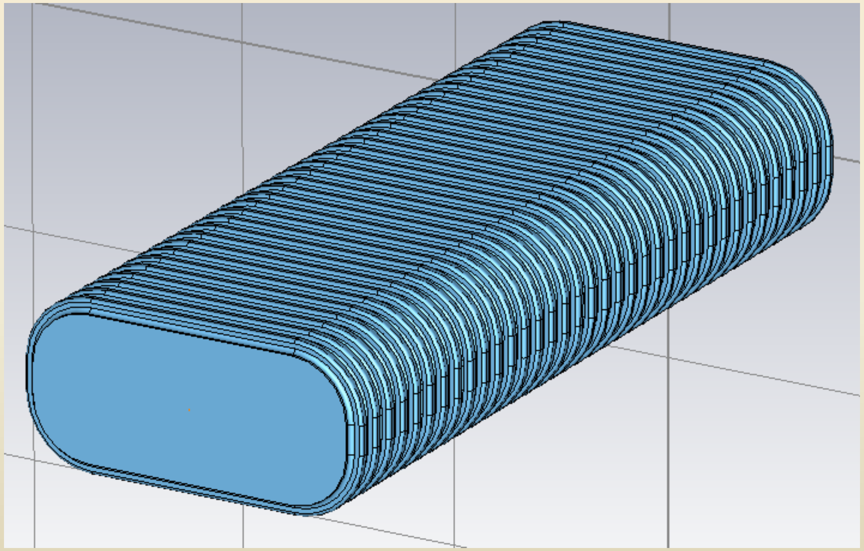
$$F_{y}^{diamond} = 1.46$$

Indirect space charge: refinement of the calculation

Using numerical form factors

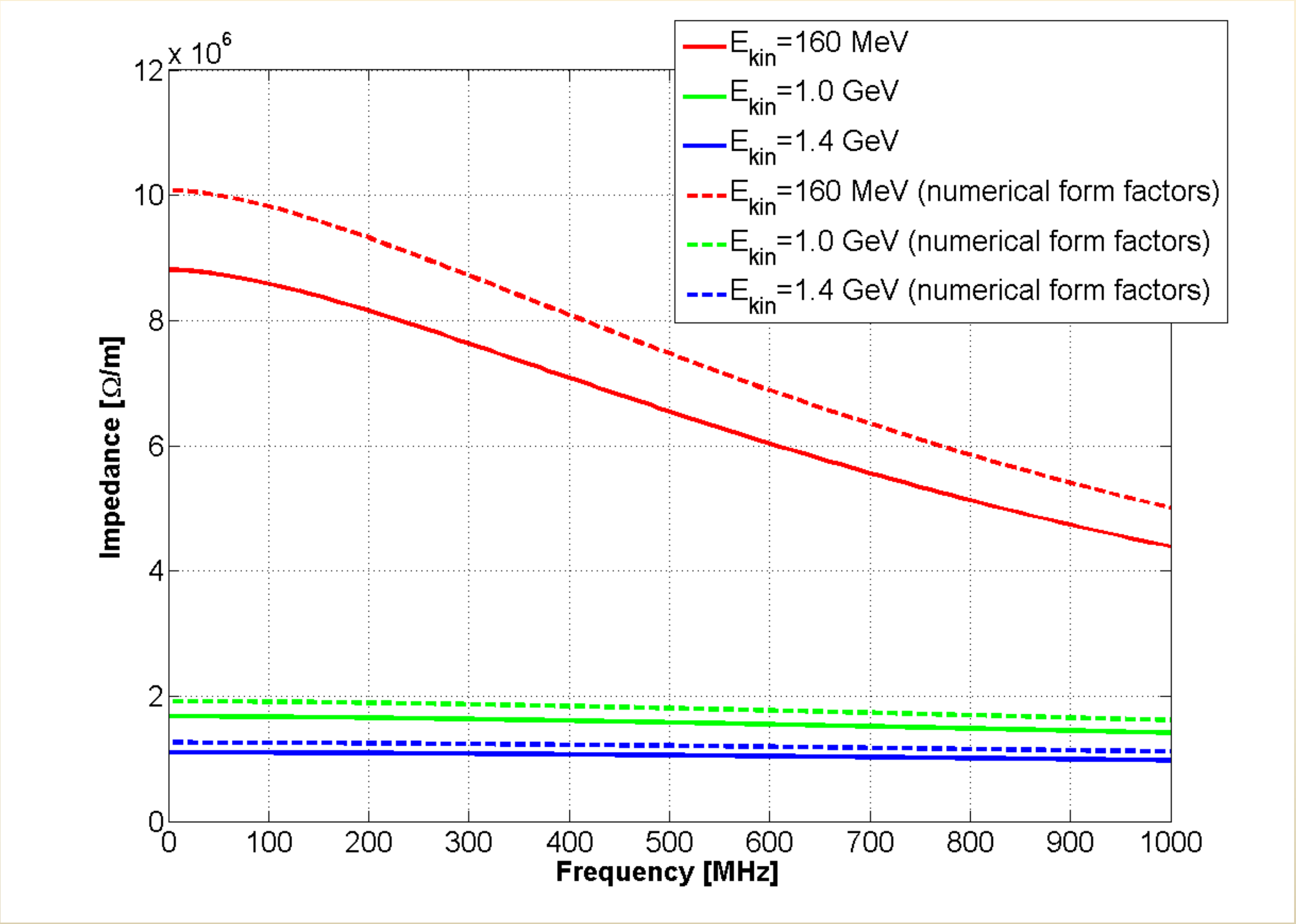
$$F^{G} = \frac{Z^{G}}{Z^{round}}$$





$$F_{y}^{dipoles} \cong 1.24$$

PSB: indirect space charge impedance



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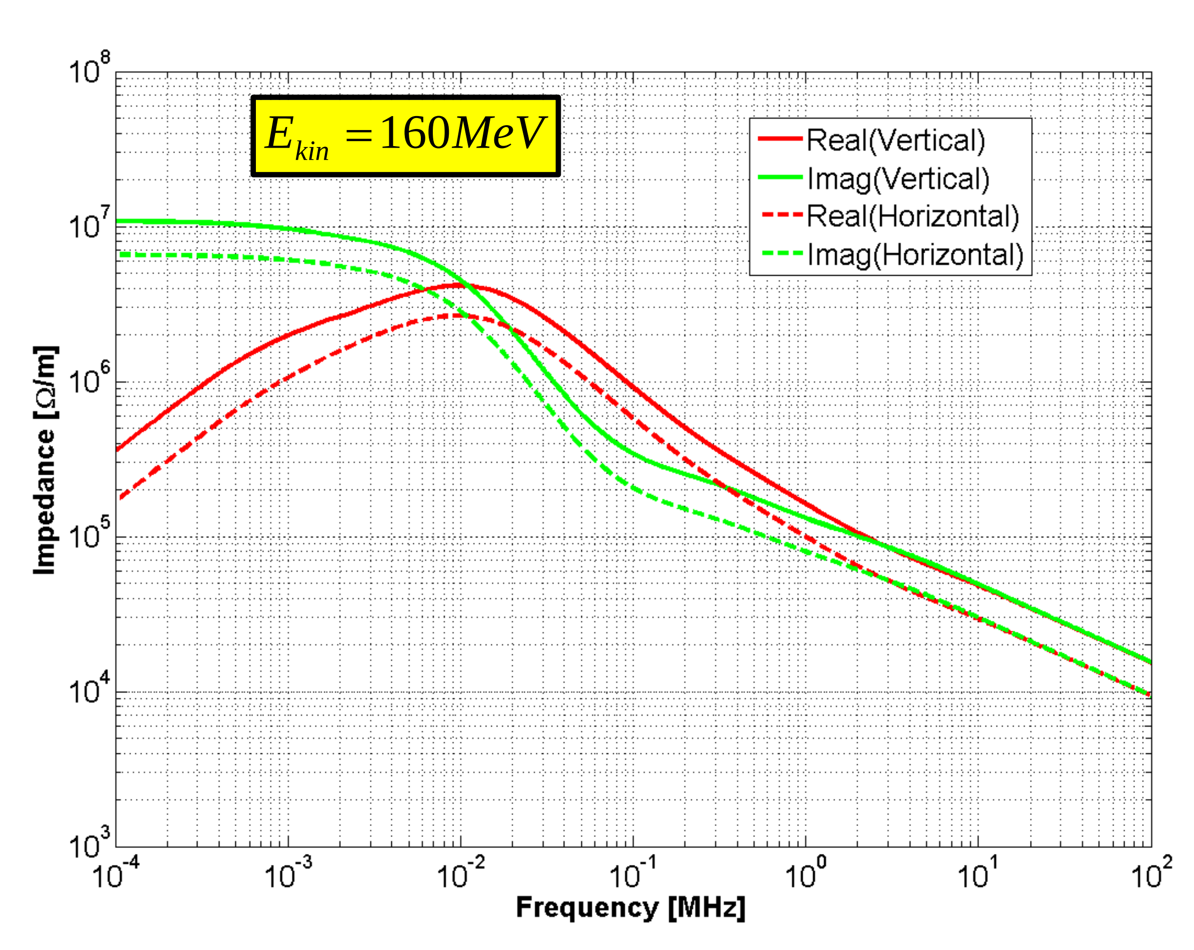
Resistive wall impedance

	Wall thickness	Wall (σ_{el})	Background material
Dipoles	0.4 mm	7.7 10^5 S/m	Iron (silicon steel)
Quadrupoles	1.5 mm	1.3 10^6 S/m	Iron (silicon steel)
Straight sections	1 mm	1.3 10^6 S/m	Vacuum



Analytical calculation based on the PSB aperture model (provided by O. Berrig)

$[a, b, L, \beta_x, \beta_y, \text{Apertype}]_i$

↓

Calculation performed with the TLwall code

↓

$$Z_{x,y}^{RW} = \frac{1}{\langle \beta_{x,y} \rangle} \sum_{i=1}^{N} Z_i^{RW} \beta_{x_i,y_i}$$

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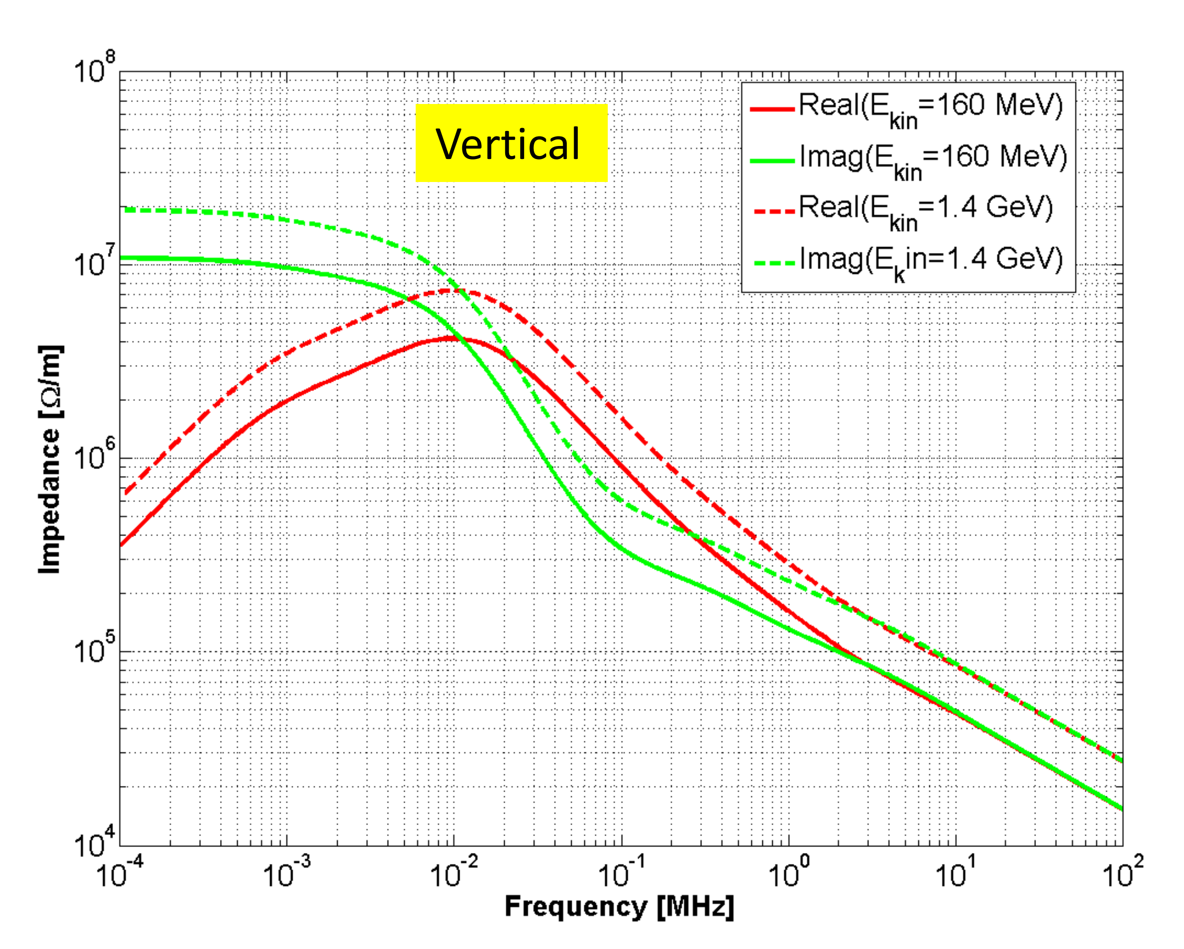

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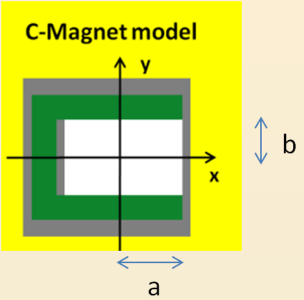
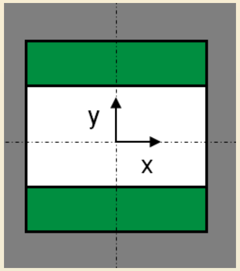
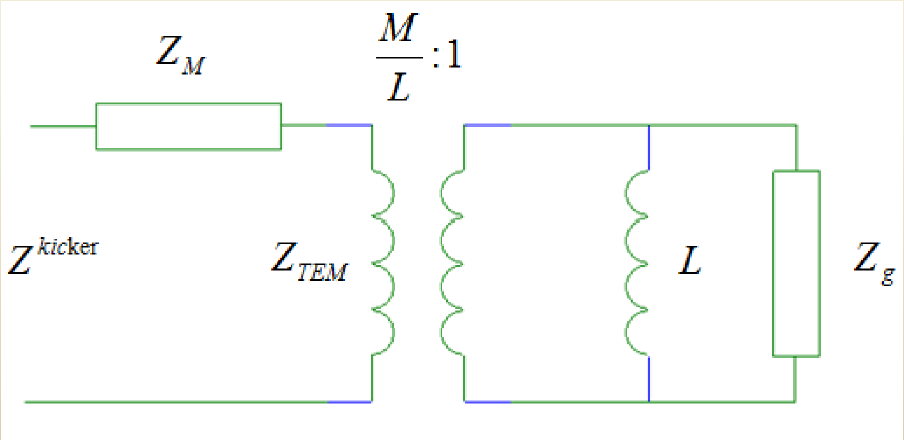
A theoretical calculation for the C-Magnet model

$$Z^{\text{kicker}} = Z_{\text{TEM}} + Z_{\text{M}}$$



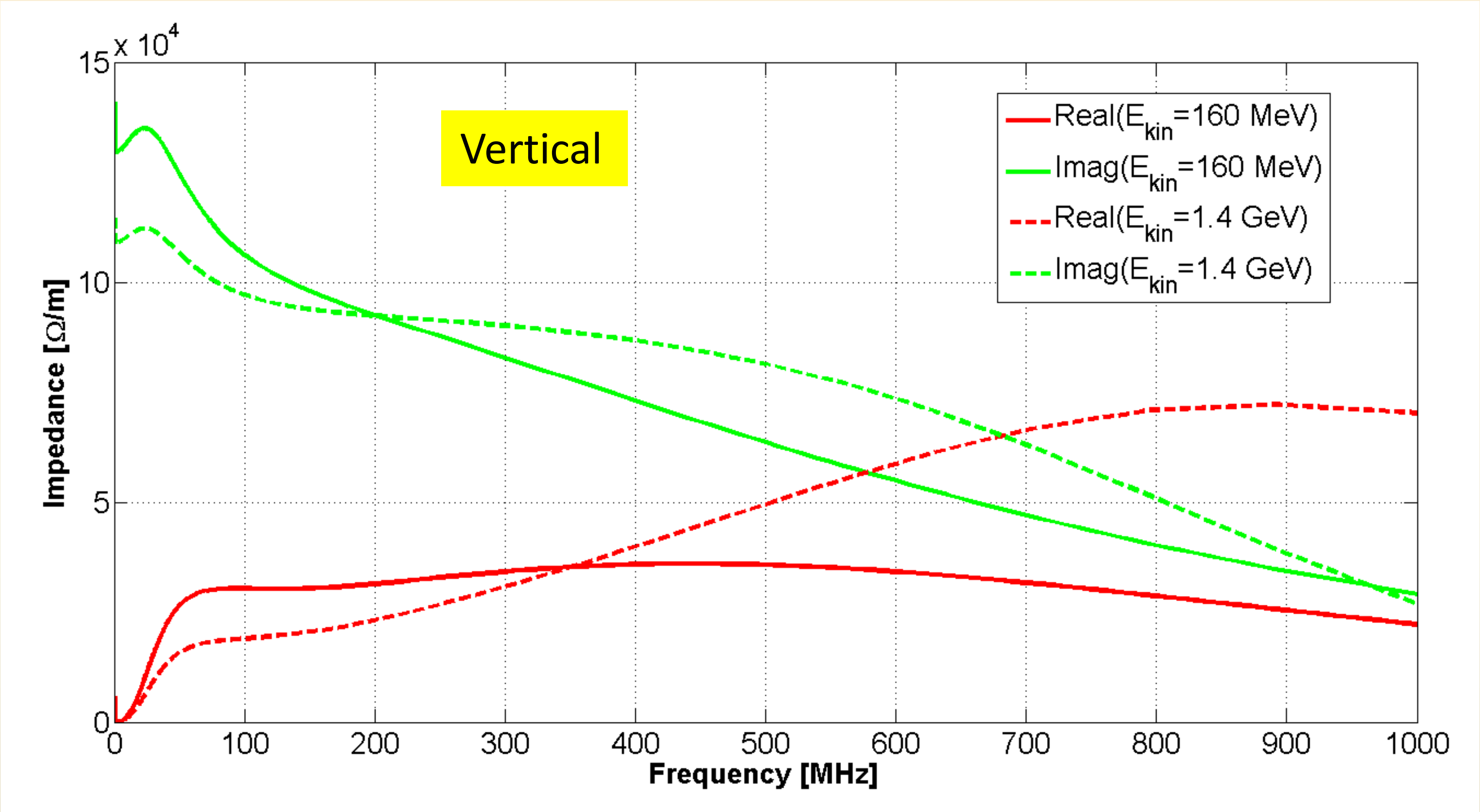
Z_M is the impedance calculated using the Tsutsui formalism



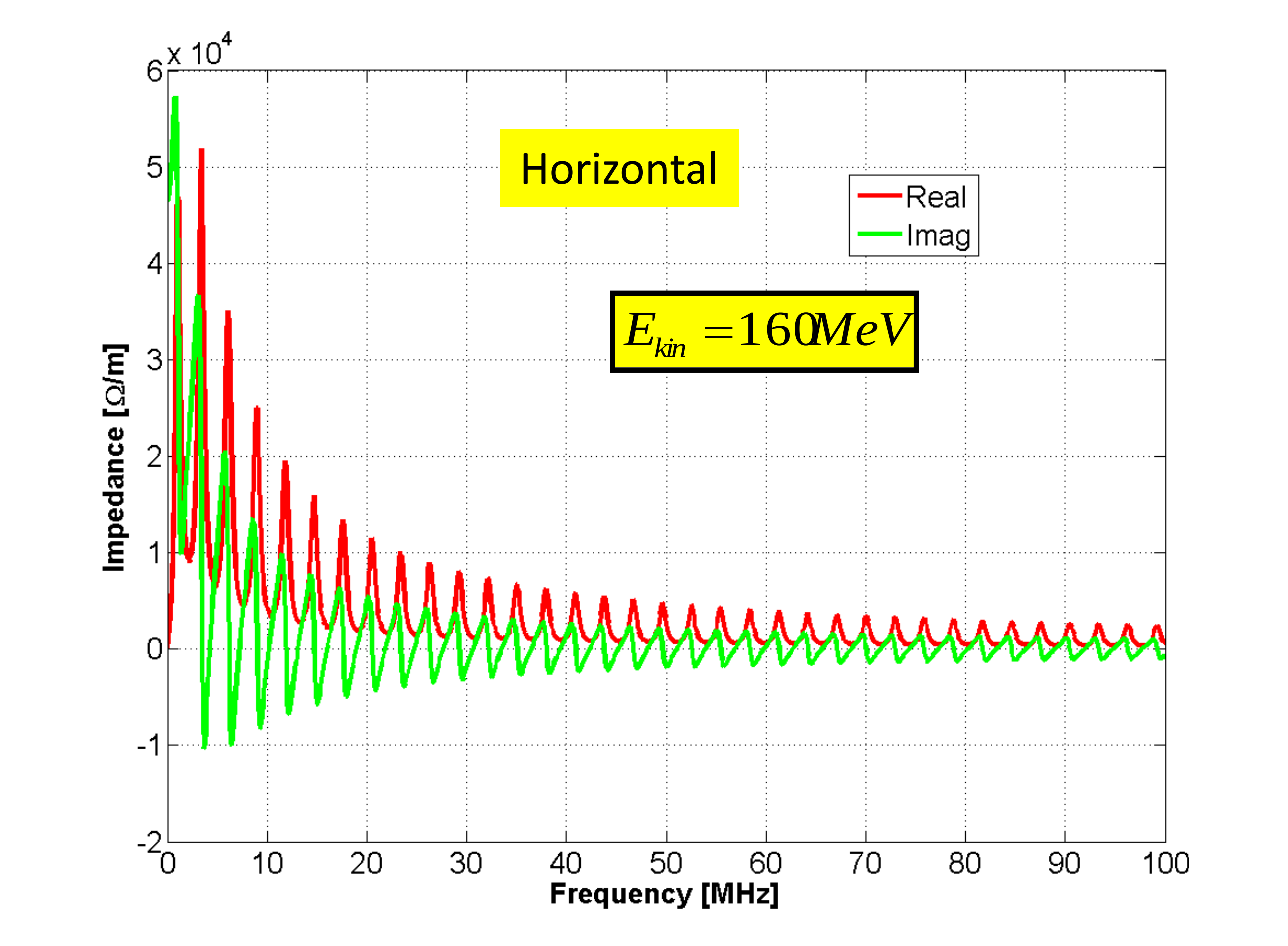


$$Z_{TEM} = \left(\frac{M}{L}\right)^2 \frac{j\omega L Z_g}{j\omega L + Z_g}$$

PSB extraction kicker: impedance due to the ferrite loaded structure Z_M



PSB extraction kicker: impedance due to the coupling to the external circuits Z_{TEM}



Cables in the open-short configuration

Overview

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  - Broadband impedance of step transitions
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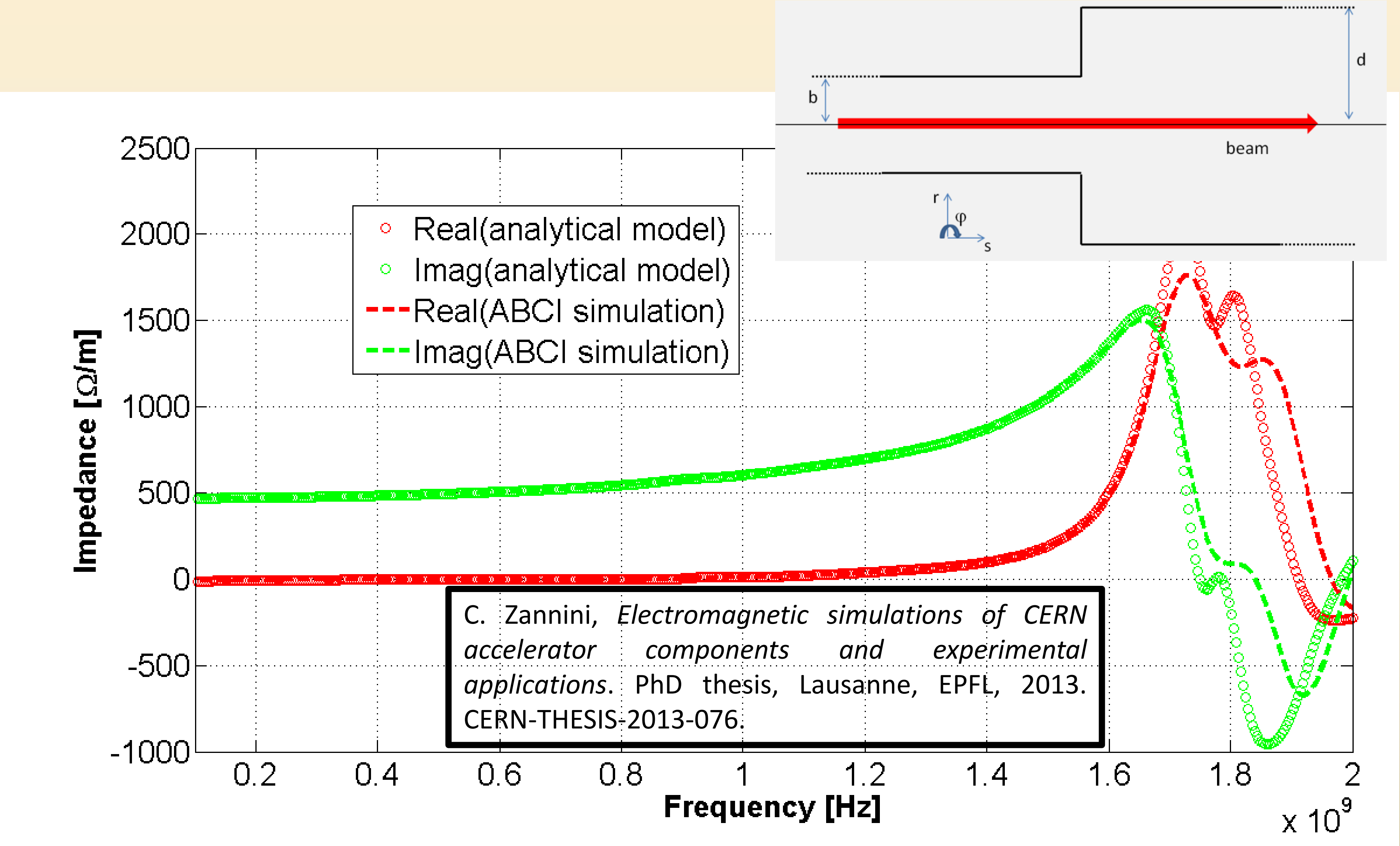
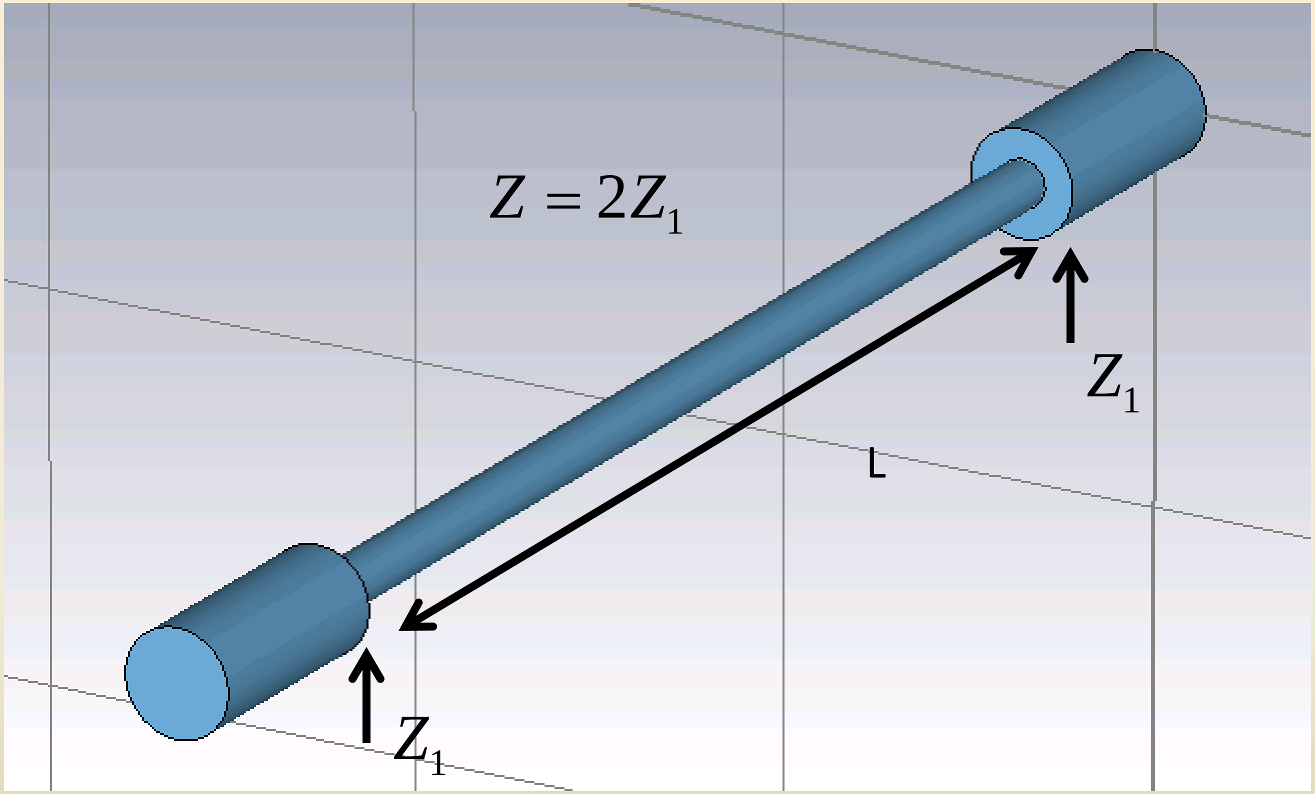
  - Insulated flanges

Broadband impedance of a step transition



C. Zannini, *Electromagnetic simulations of CERN accelerator components and experimental applications*. PhD thesis, Lausanne, EPFL, 2013. CERN-THESIS-2013-076.

Broadband impedance of step transitions



$$Z^{bb}_{transitions} = \sum_{i=1}^{N} Z^{bb}_{i} n_i$$

Weak dependence on the relativistic beta and L

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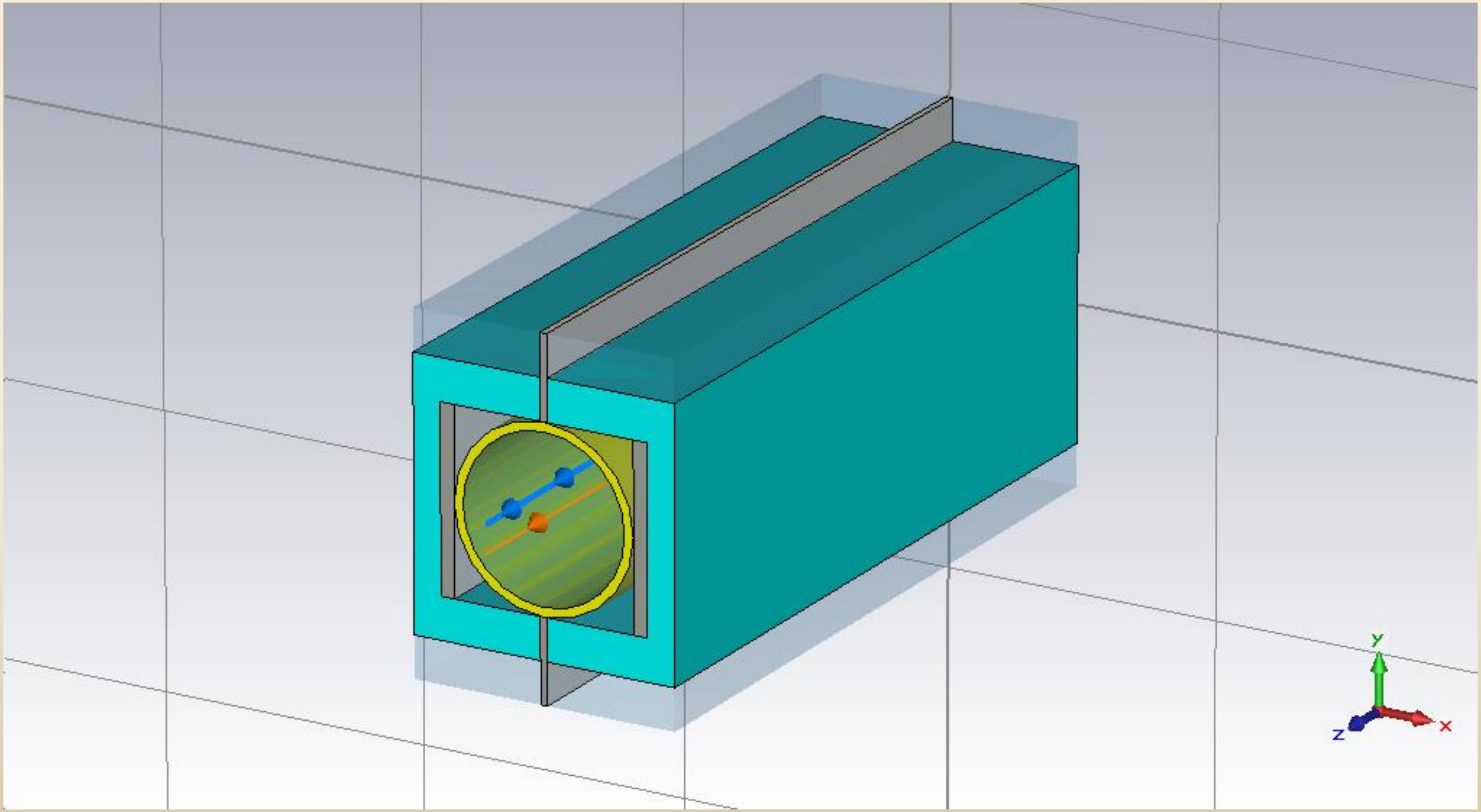
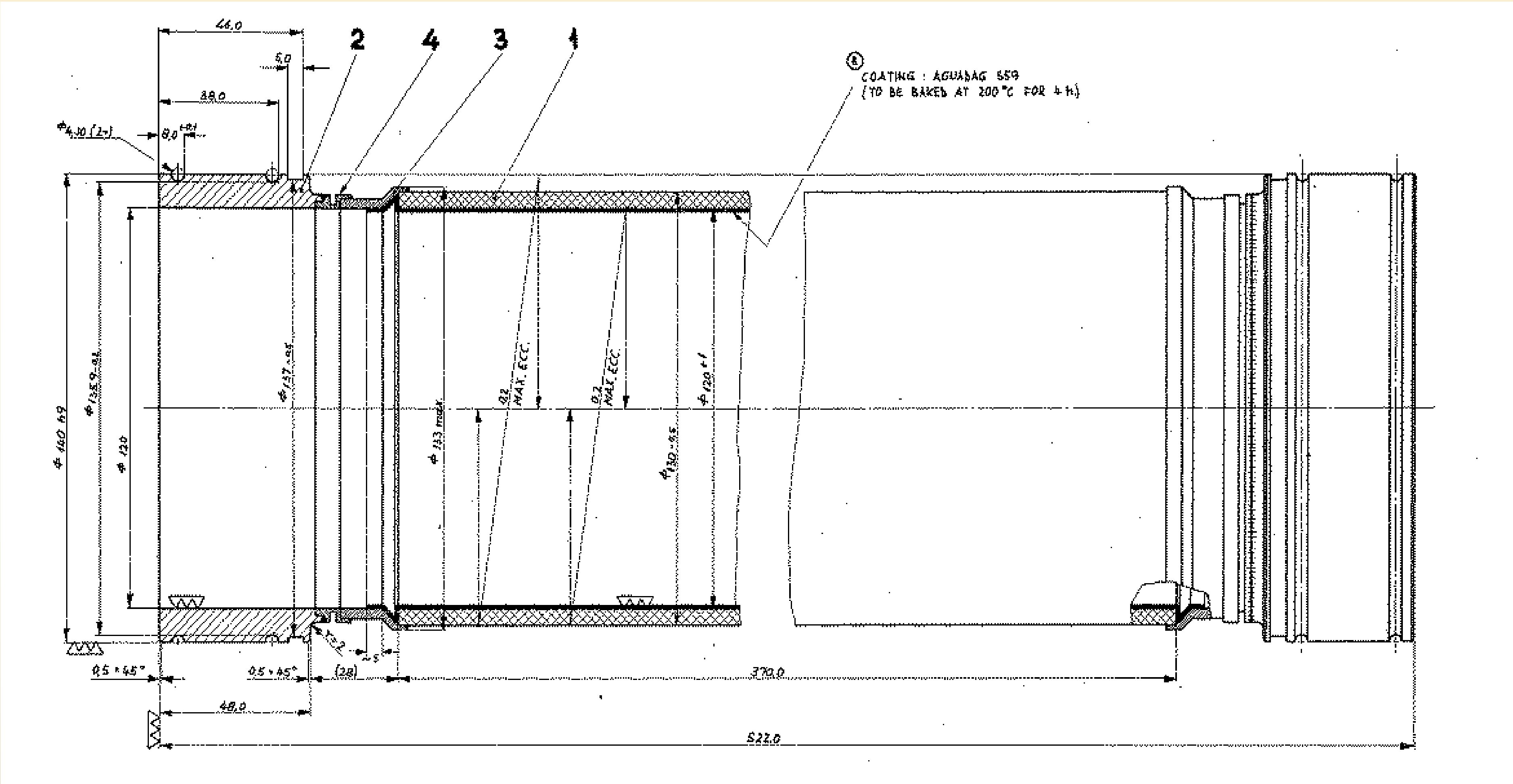
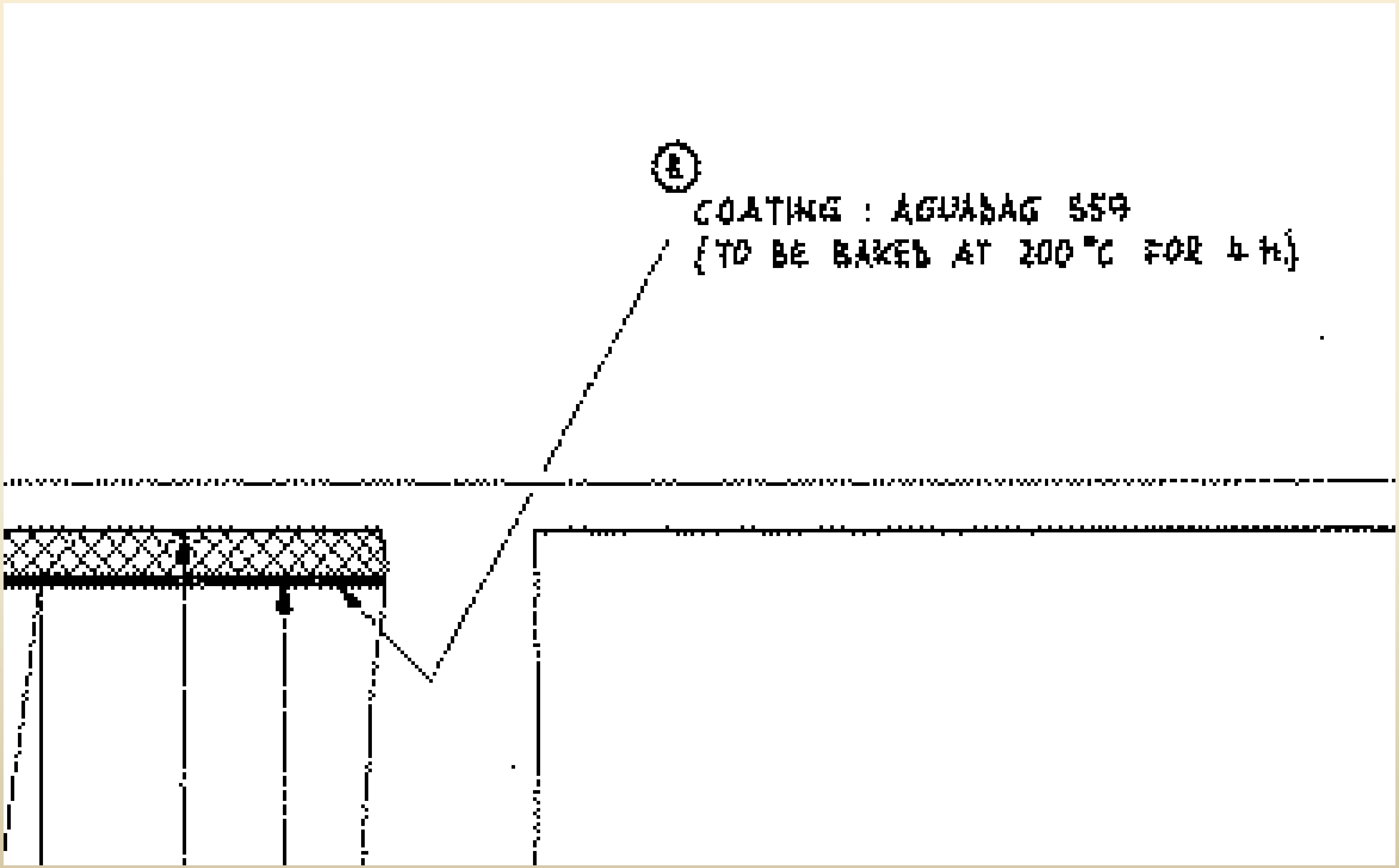
3D model of the KSW kicker



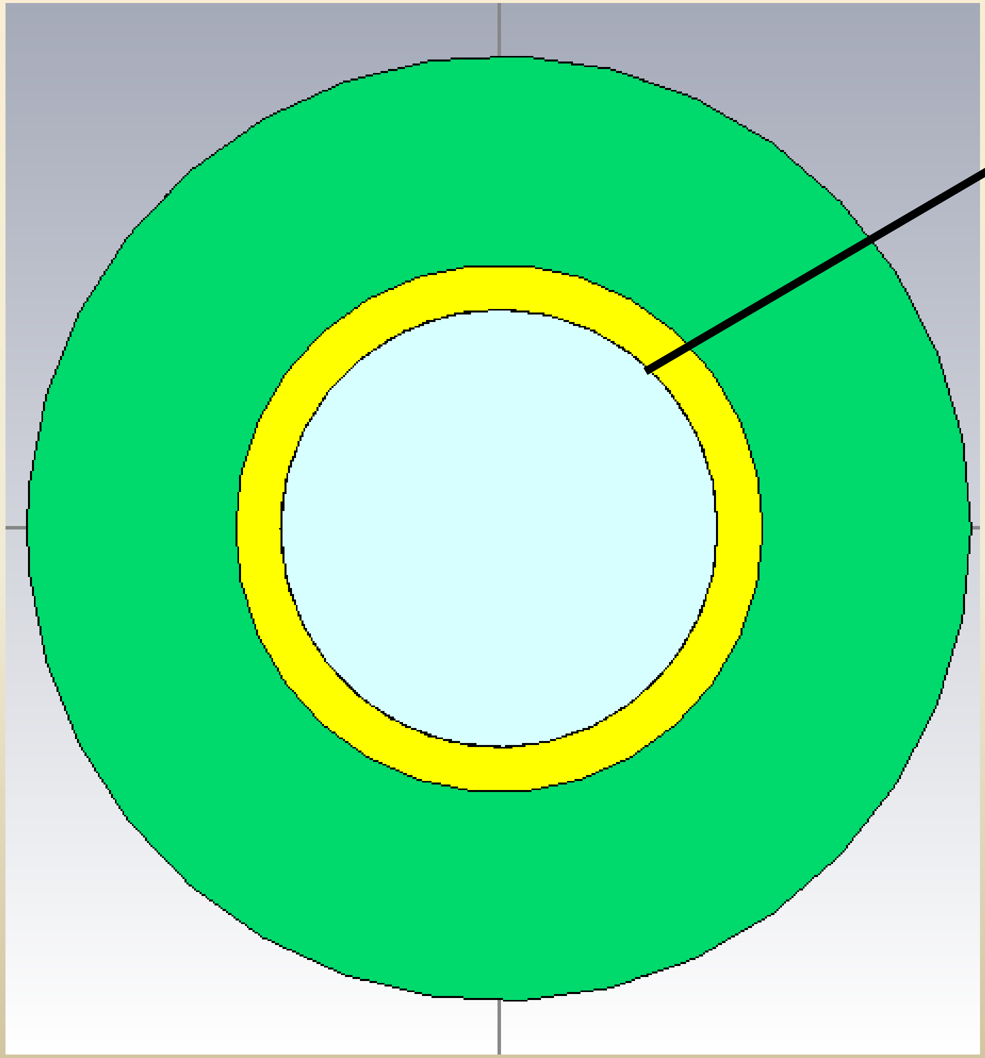
Coating of the ceramic chamber



Coating of the ceramic chamber



Analytical model: axially symmetric multilayer structure



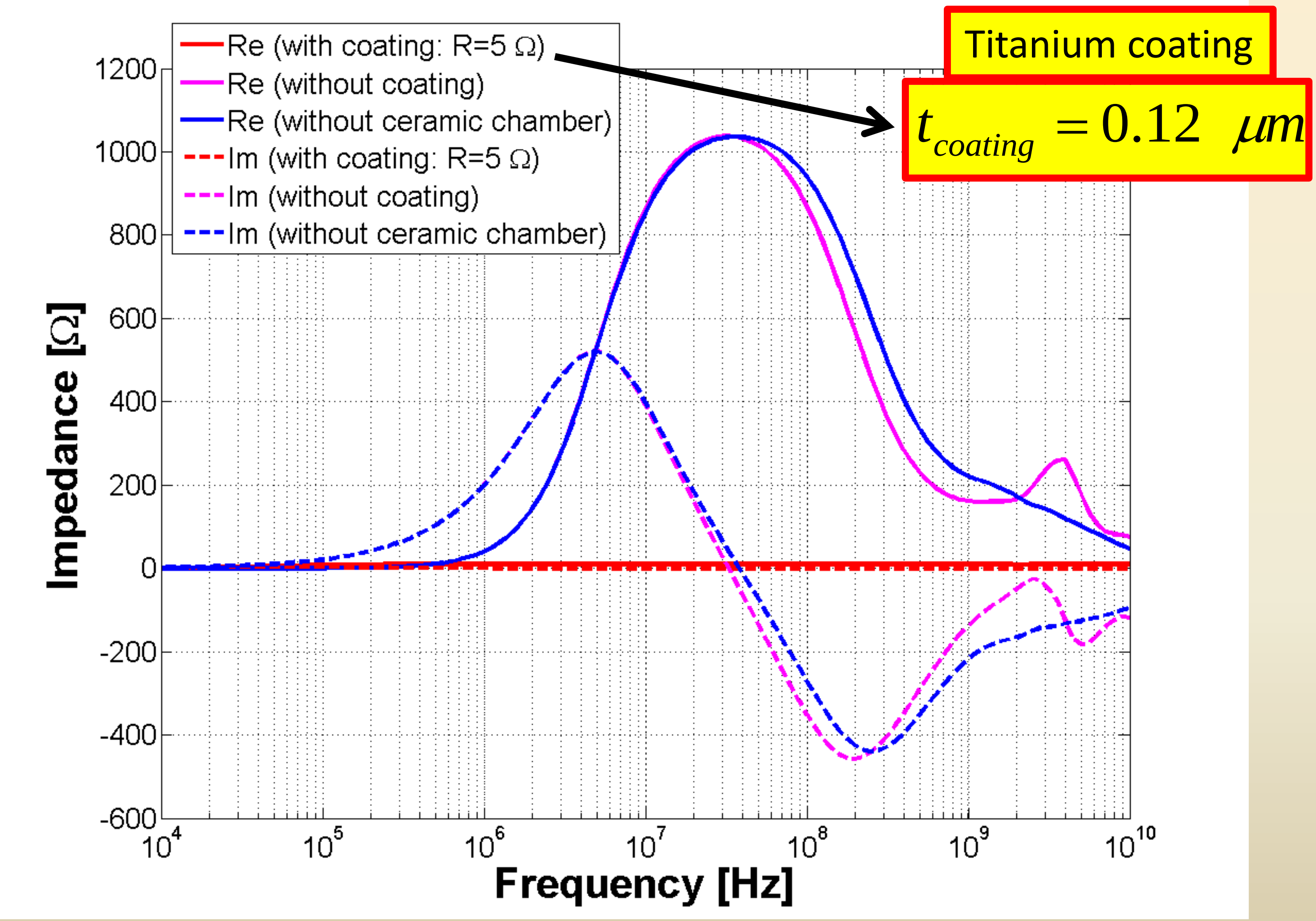
Assuming uniformity of the coating thickness

Resistance of the coating

$$R = \frac{\rho_{coating} L}{2\pi\, r\, t_{coating}}$$

The beam coupling impedance strongly depends on the resistance of the coating

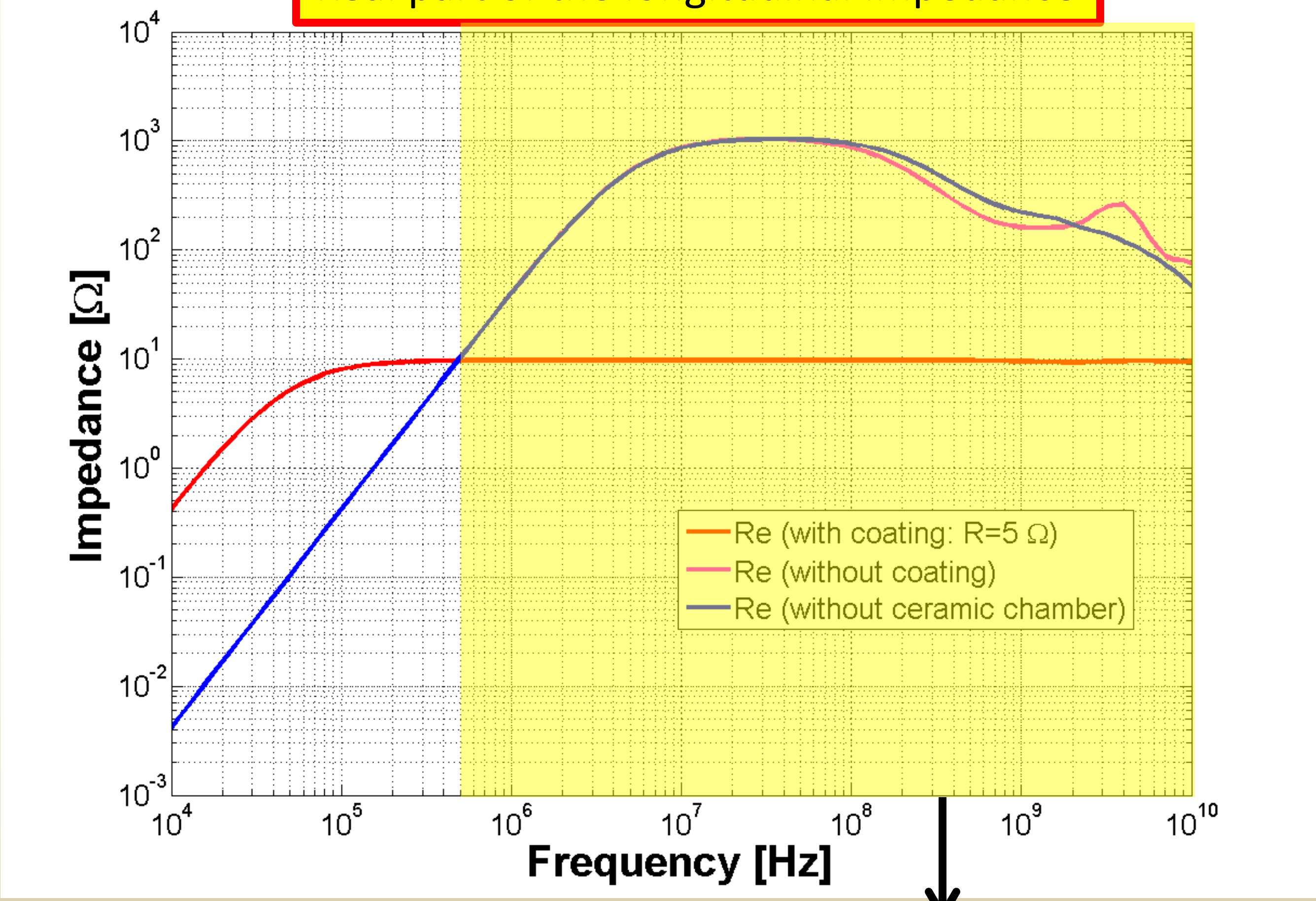
Effect of the ceramic chamber on the KSW longitudinal impedance



The shielding (coated ceramic chamber) strongly reduces the longitudinal impedance

Effect of the ceramic chamber on the KSW longitudinal impedance

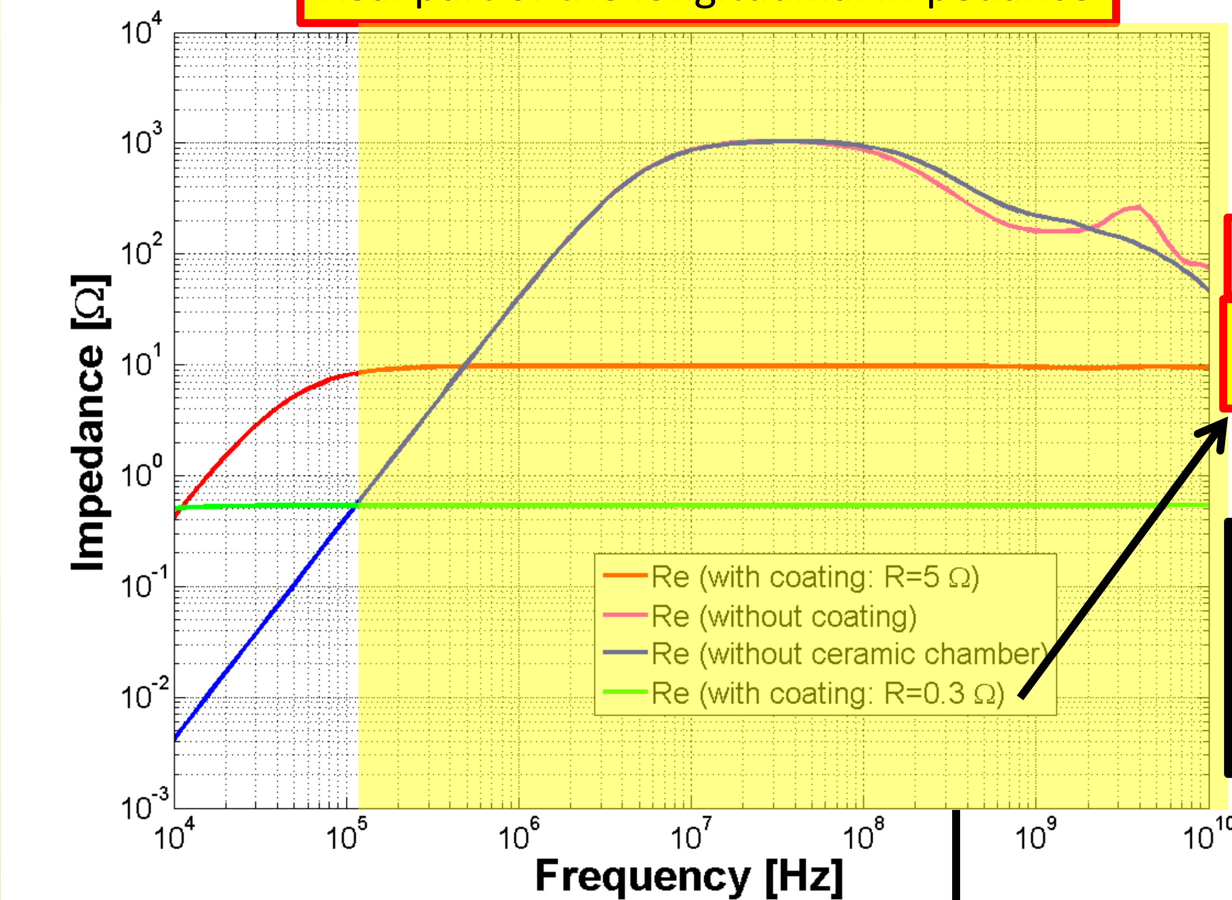
Real part of the longitudinal impedance



$f > 500 \ kHz$

Effect of the ceramic chamber on the KSW longitudinal impedance

Real part of the longitudinal impedance



Titanium coating

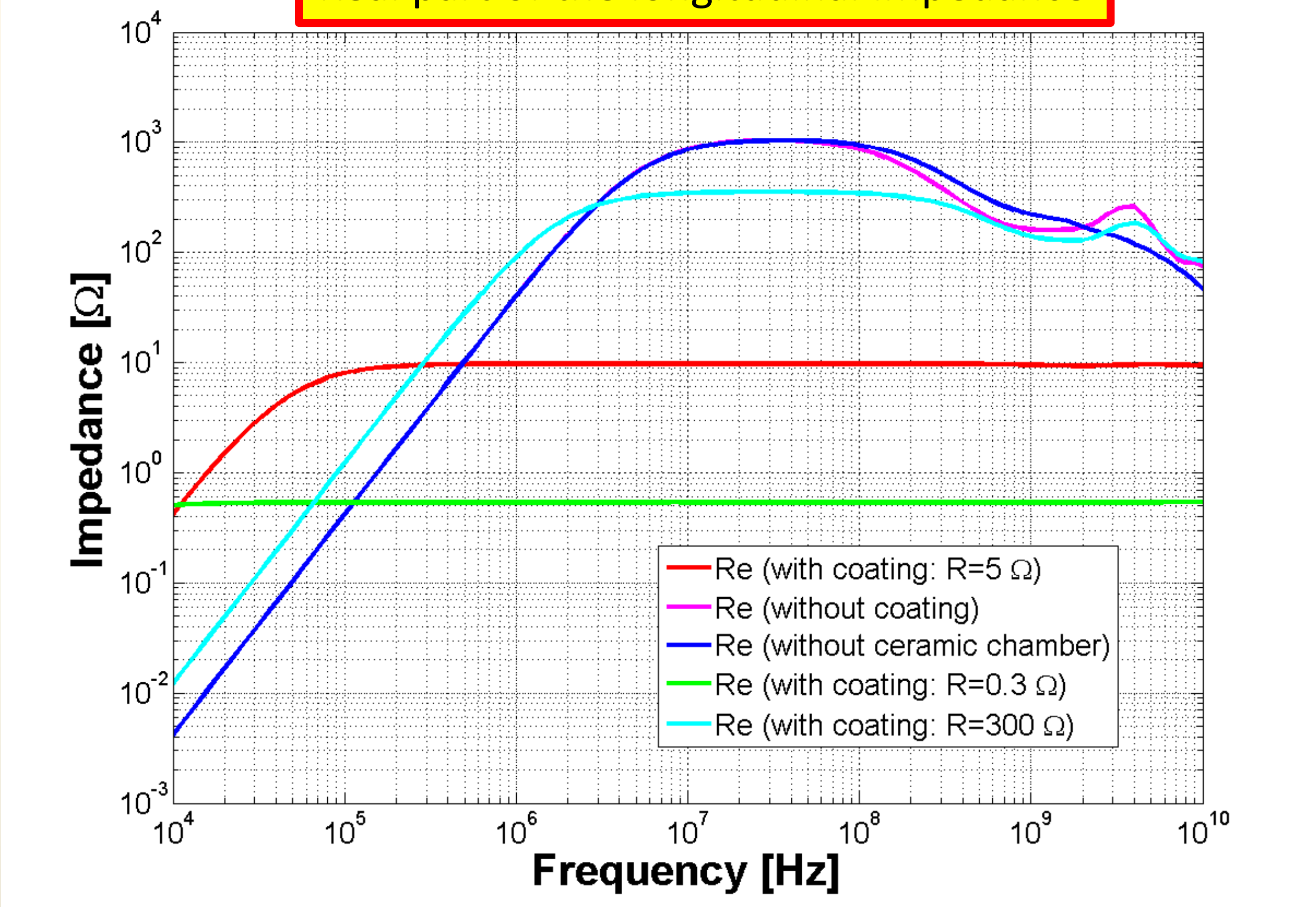
$t_{coating} = 2 \ \mu m$

Minimum R defined by the required kicker rise time

$f > 110 \ kHz$

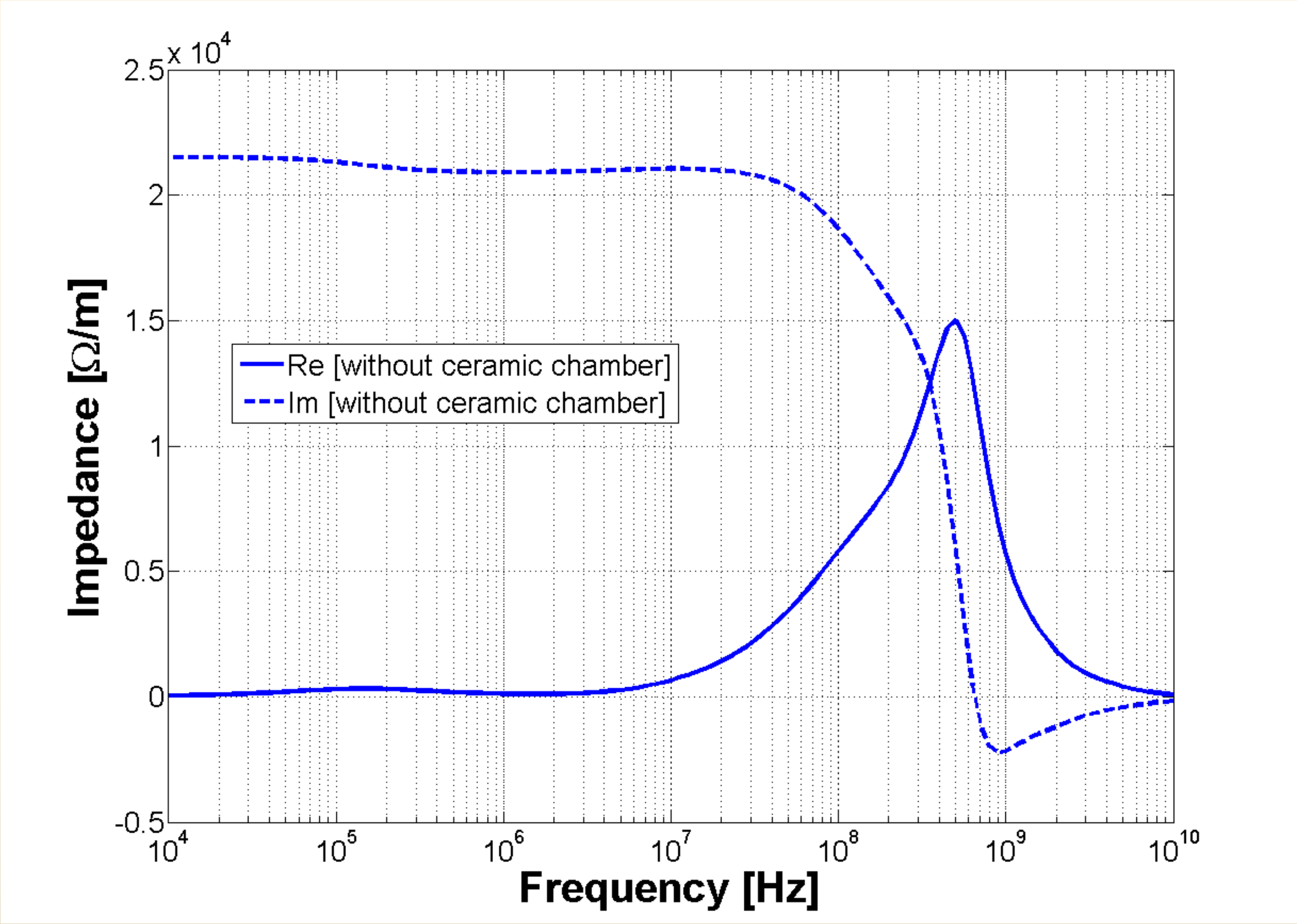
Effect of the ceramic chamber on the KSW longitudinal impedance

Real part of the longitudinal impedance

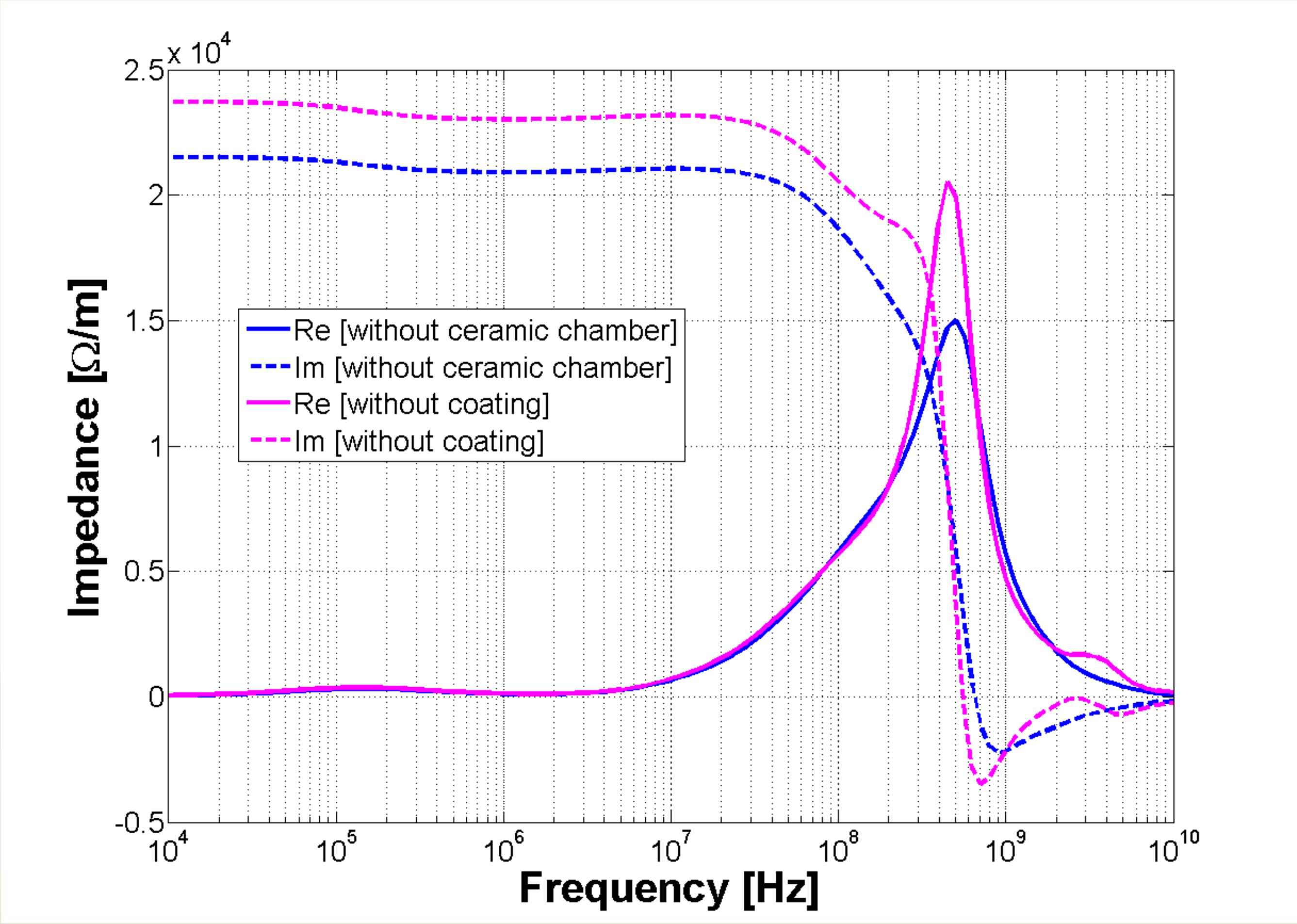


Increasing the coating resistance the impedance should converge to the case without coating

Effect of the ceramic chamber on the KSW transverse impedance

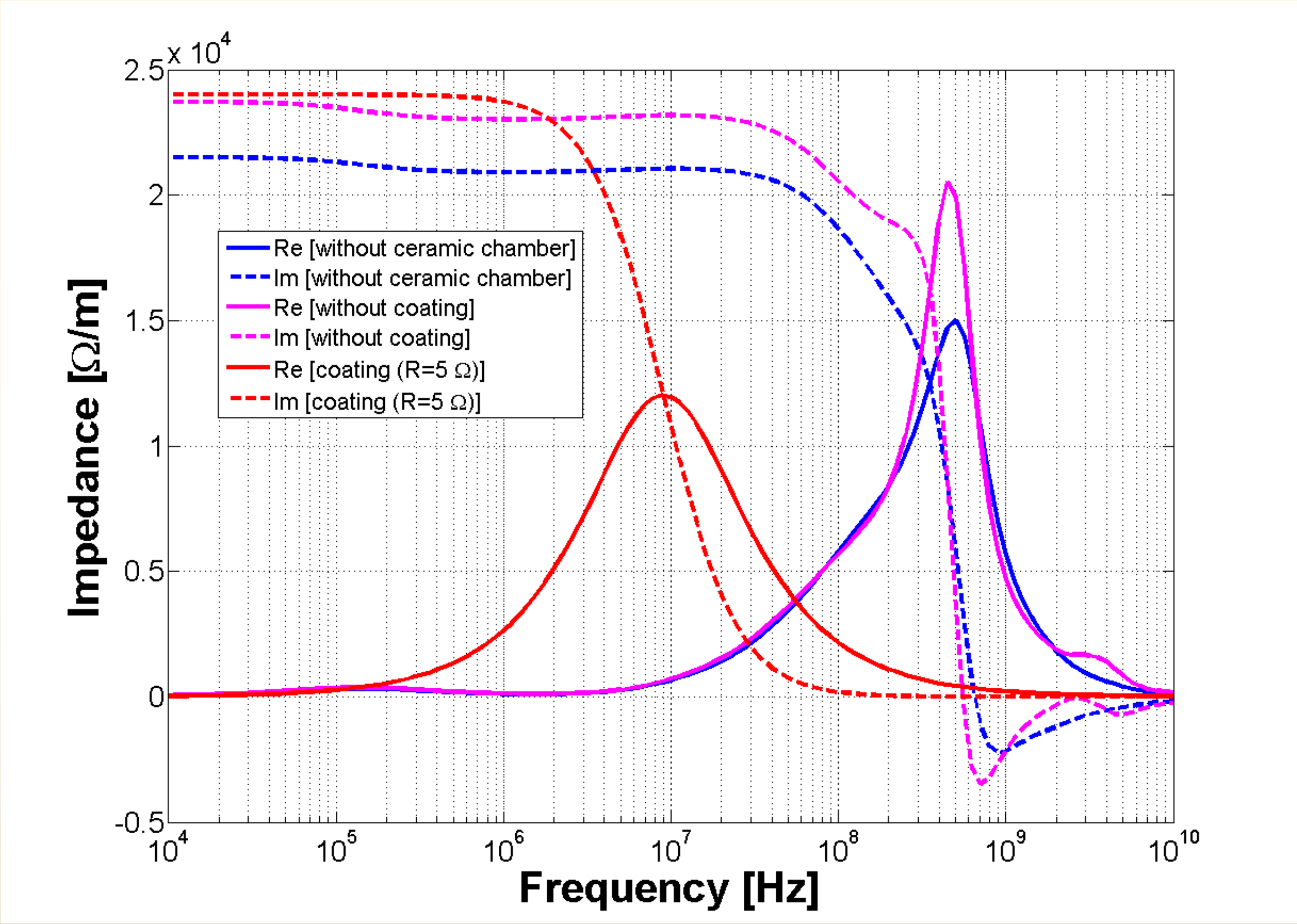


Effect of the ceramic chamber on the KSW transverse impedance



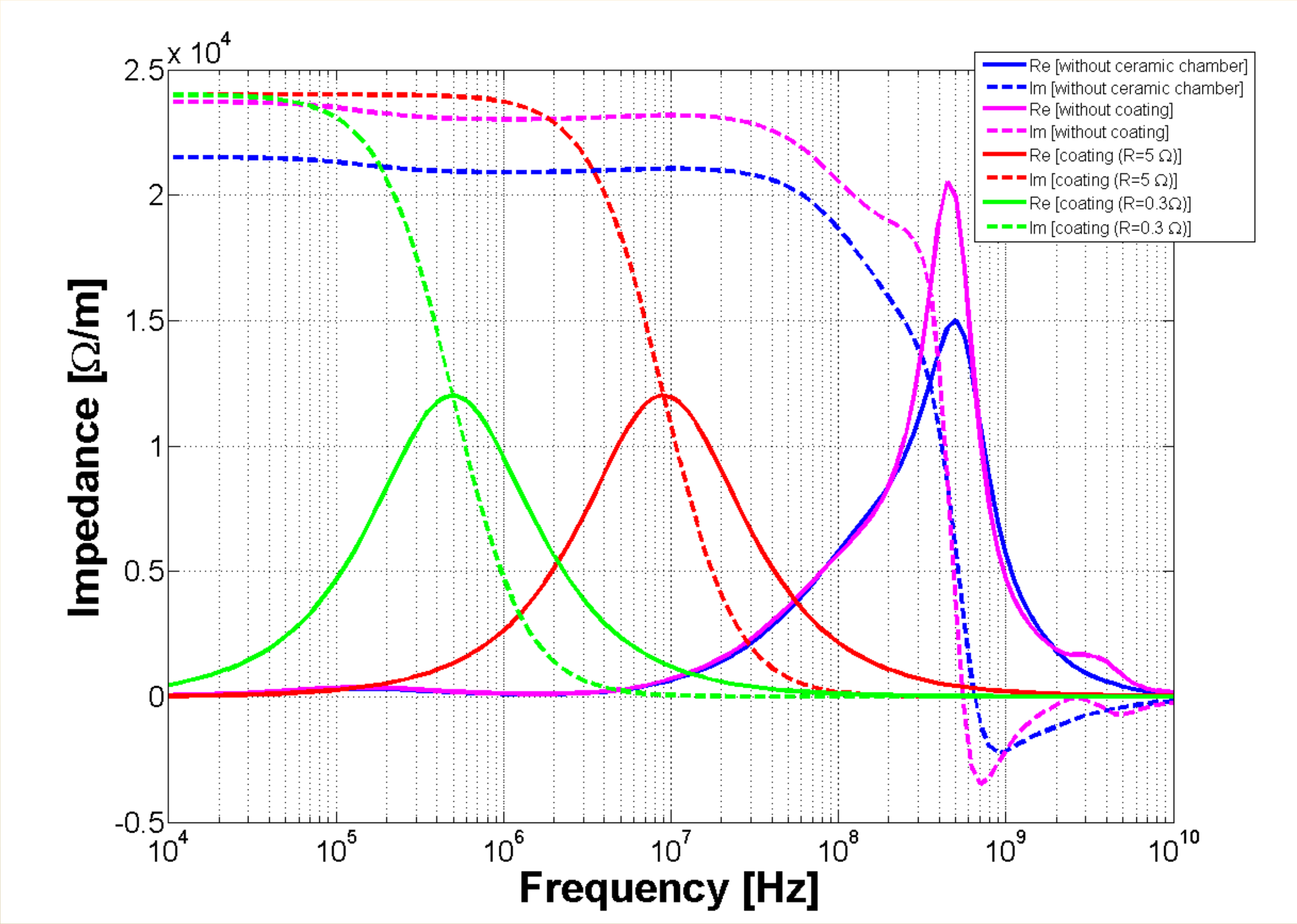
Increase of the impedance due to the smaller aperture

Effect of the ceramic chamber on the KSW transverse impedance



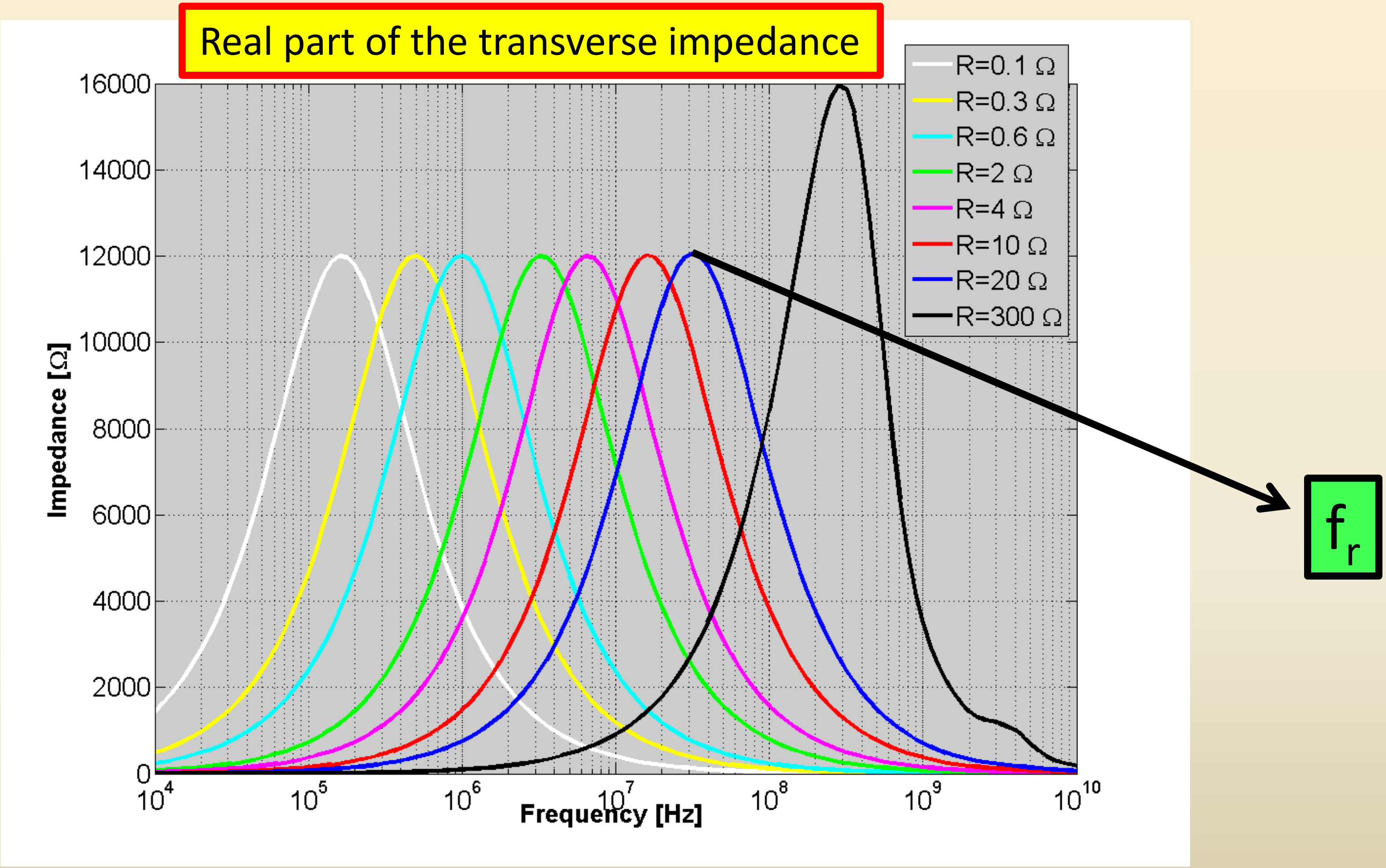
The coating shifts the impedance spectrum to lower frequencies

Effect of the ceramic chamber on the KSW transverse impedance



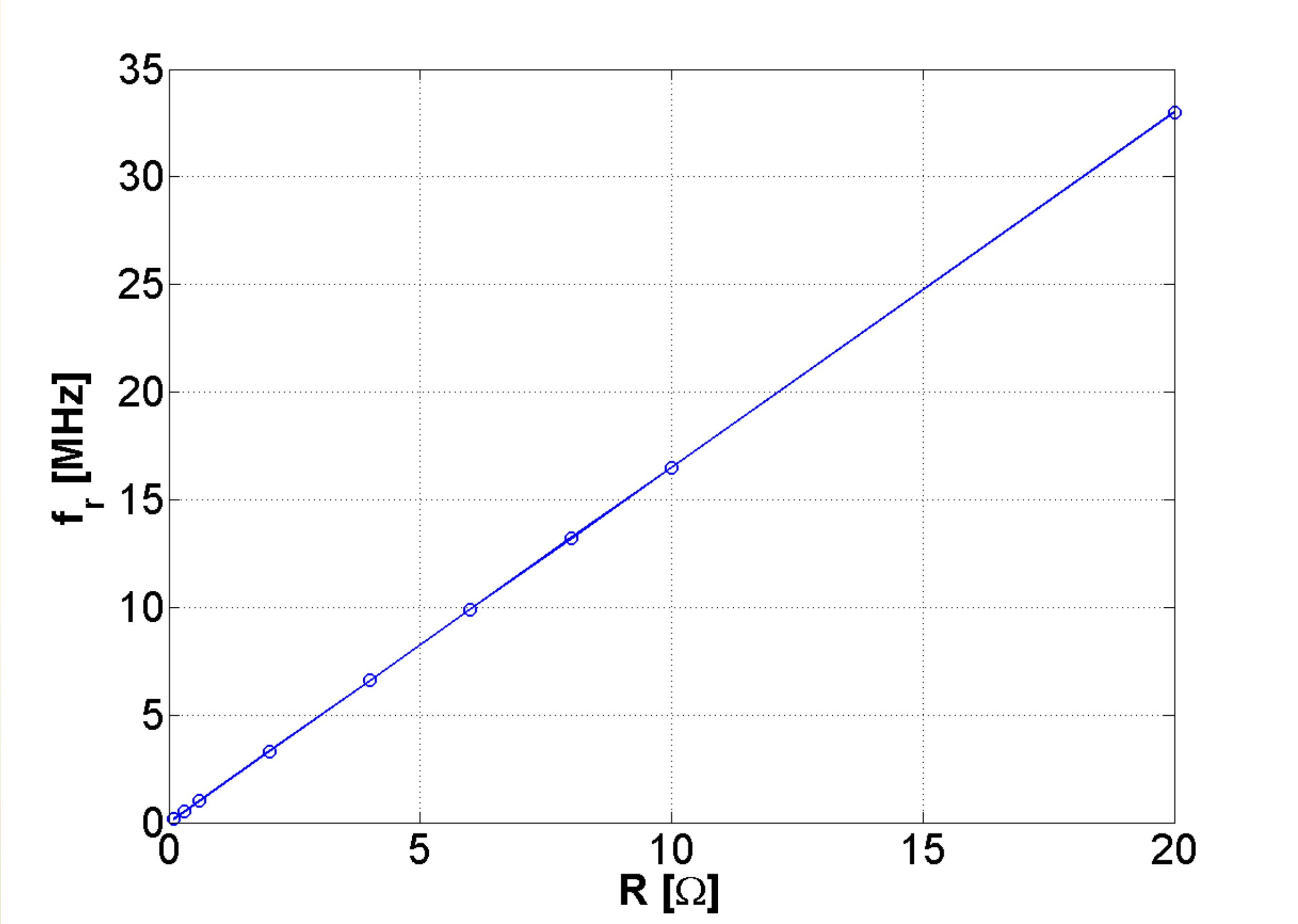
The frequency shift is proportional to the coating resistance

Effect of the ceramic chamber on the KSW transverse impedance



The frequency shift is proportional to the coating resistance

Effect of the ceramic chamber on the KSW transverse impedance



$$f_r \propto R$$

KSW: transverse impedance optimization

Shift the KSW impedance spectrum out of the PSB frequency range of interest

Frequency range of interest

$$f_I \leq f \leq f_{beam}$$

First possible unstable betatron line

Maximum frequency excited by the beam

KSW: transverse impedance optimization

Shift the KSW impedance spectrum out of the PSB frequency range of interest

Frequency range of interest

$$f_I \leq f \leq f_{beam}$$

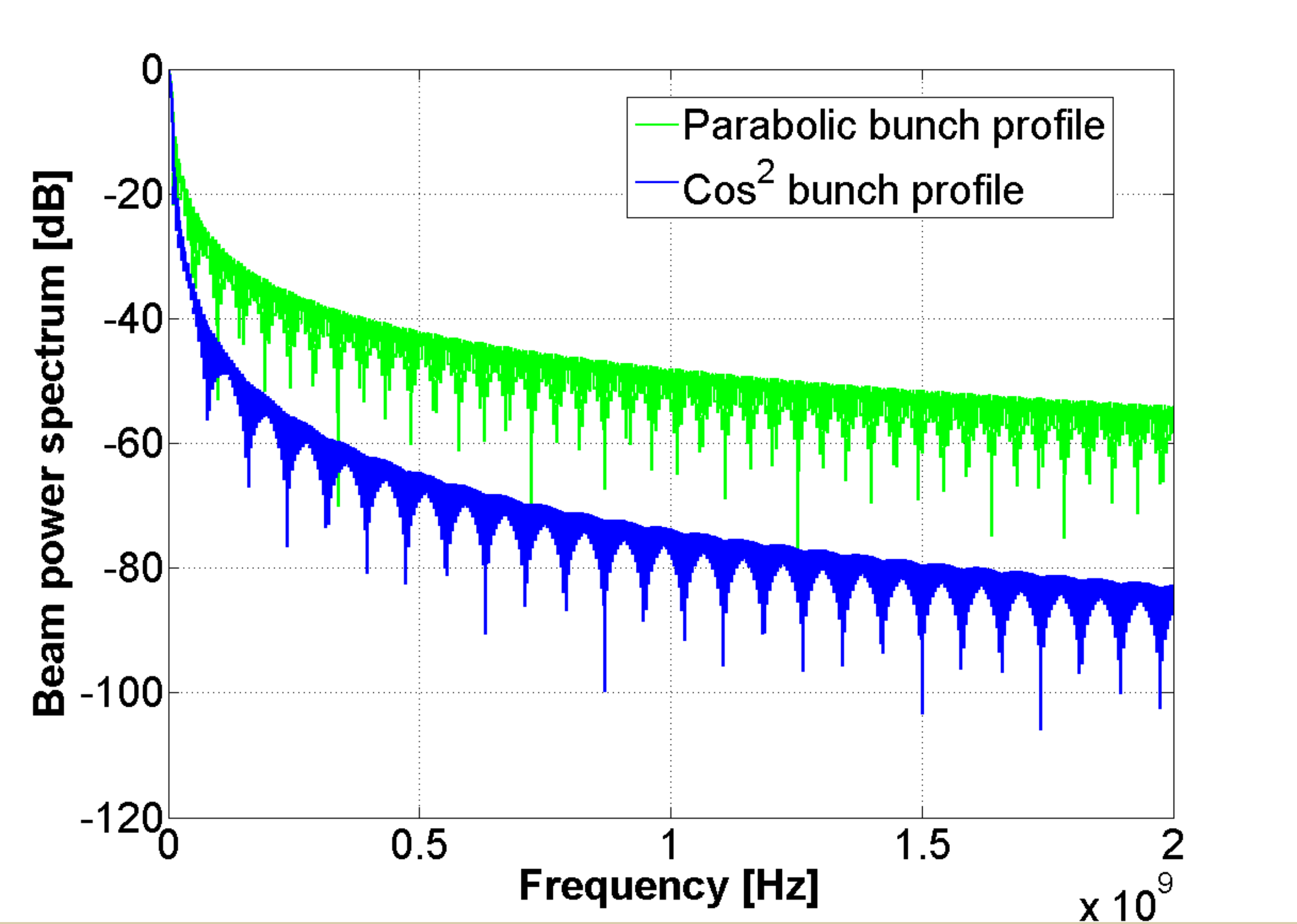
First possible unstable betatron line

$\beta \cong 0.3 \quad f_I \cong 340\,KHz$

Maximum frequency excited by the beam

Worst case at extraction (smallest bunch length)

Determination of f_{beam} for a generic element of impedance Z



Normalized beam power spectrum

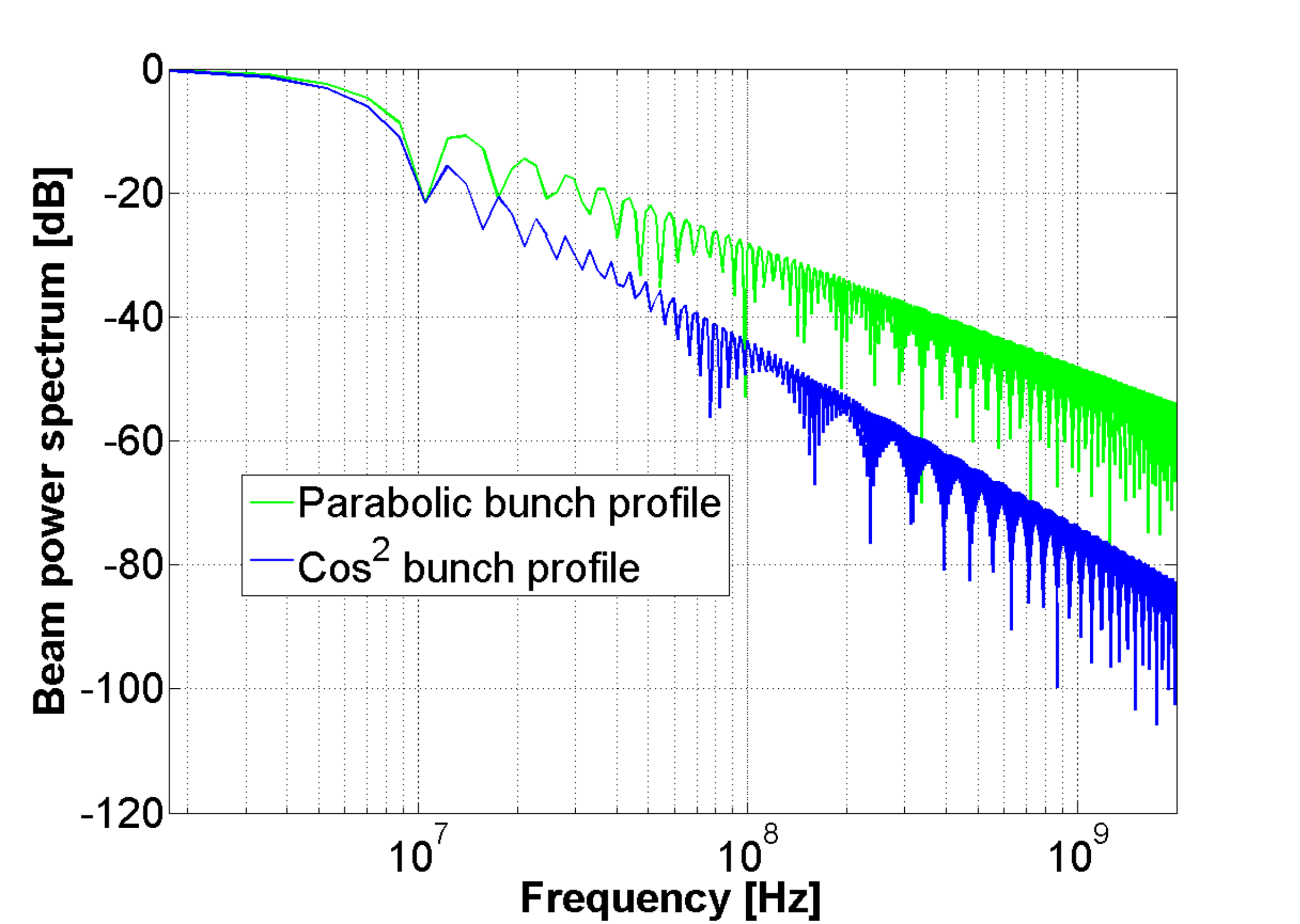
$$Z_{beam} = Z\, P_N$$

$$Z_{beam} < Z_{budget}^{elem}$$

$$P_N < \frac{Z_{budget}^{elem}}{Z}$$

$$f_{beam}(Z)$$

Determination of f_{beam}: example for the KSW transverse impedance



$$Z_{budget}^{KSW} = 100\ \Omega / m$$

$$f_{beam} \cong 40\ MHz$$

$$Z_{budget}^{KSW} = 1\ \Omega / m$$

$$f_{beam} \cong 400\ MHz$$

KSW: transverse impedance optimization

Frequency range of interest

$$f_I \leq f \leq f_{beam}$$

$$0.34 MHz \leq f \leq 40\, MHz$$

$$0.2\ \Omega \leq R \leq 24\ \Omega$$

$$R << 0.2\ \Omega$$

$$R >> 24\ \Omega$$

Shift of the KSW impedance spectrum significantly out of the PSB frequency range of interest

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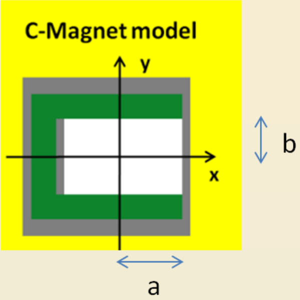
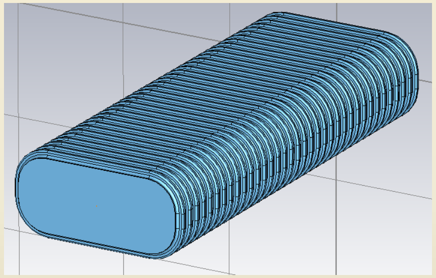
Present PSB transverse impedance model

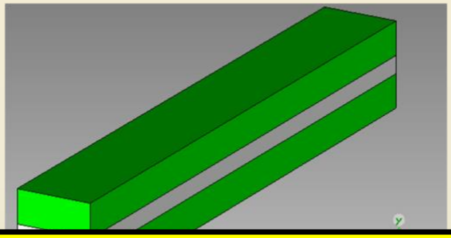
- Elements included in the database:
  - Analytical calculation of the resistive wall impedance that takes into account the different PSB vacuum chambers weighted by the respective length and beta function. Also the iron in the magnet is taken into account
  - Extraction kicker
    - impedance due to the ferrite loaded structure
    - impedance due to the coupling to the external circuits (analytical calculation)
  - Indirect space charge impedance (analytical calculation)
  - Broadband impedance of step transitions
  - KSW magnets

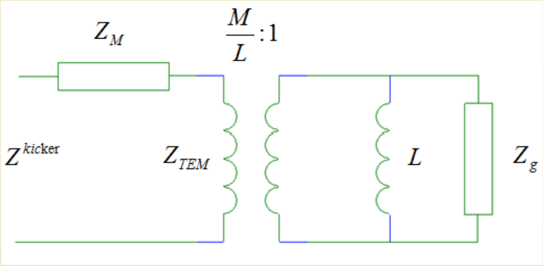


Beam pipe



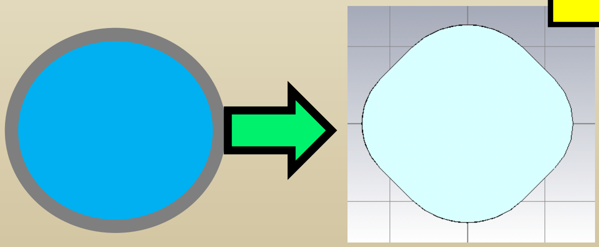
Extraction Kicker

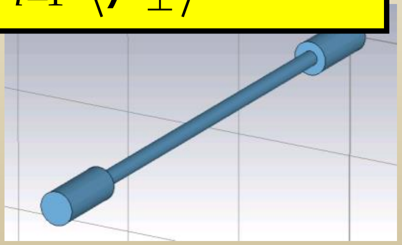




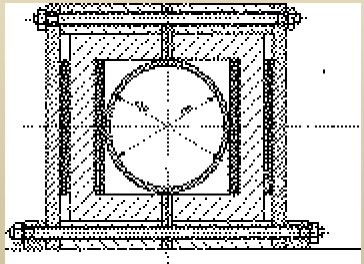
$$Z_{\perp}^{PSB}(f)=\sum_{i=1}^{N}\frac{\beta_{\perp}^{i}}{\langle\beta_{\perp}\rangle}Z_{\perp}^{i}(f)$$

Indirect space charge impe

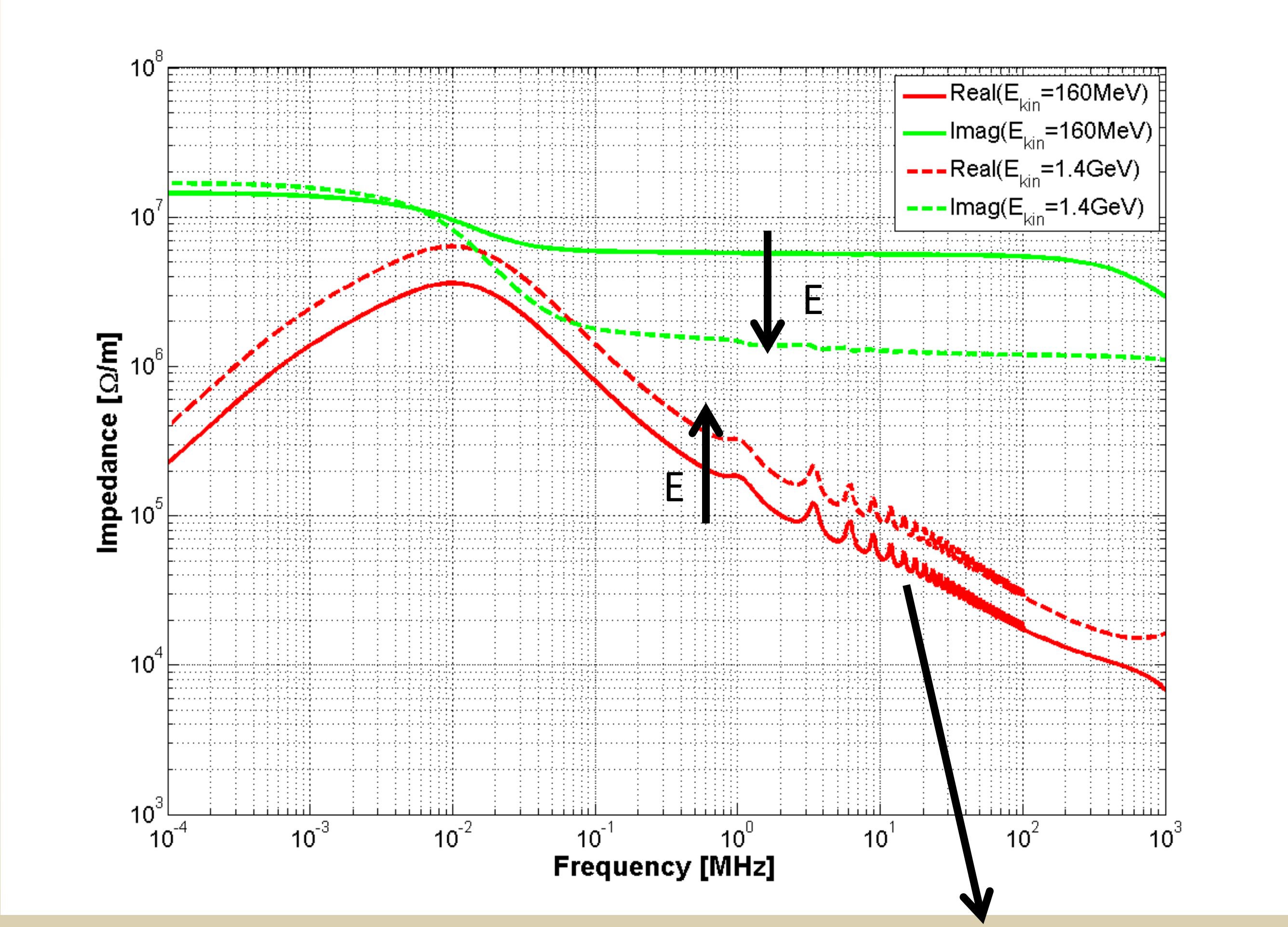




KSW

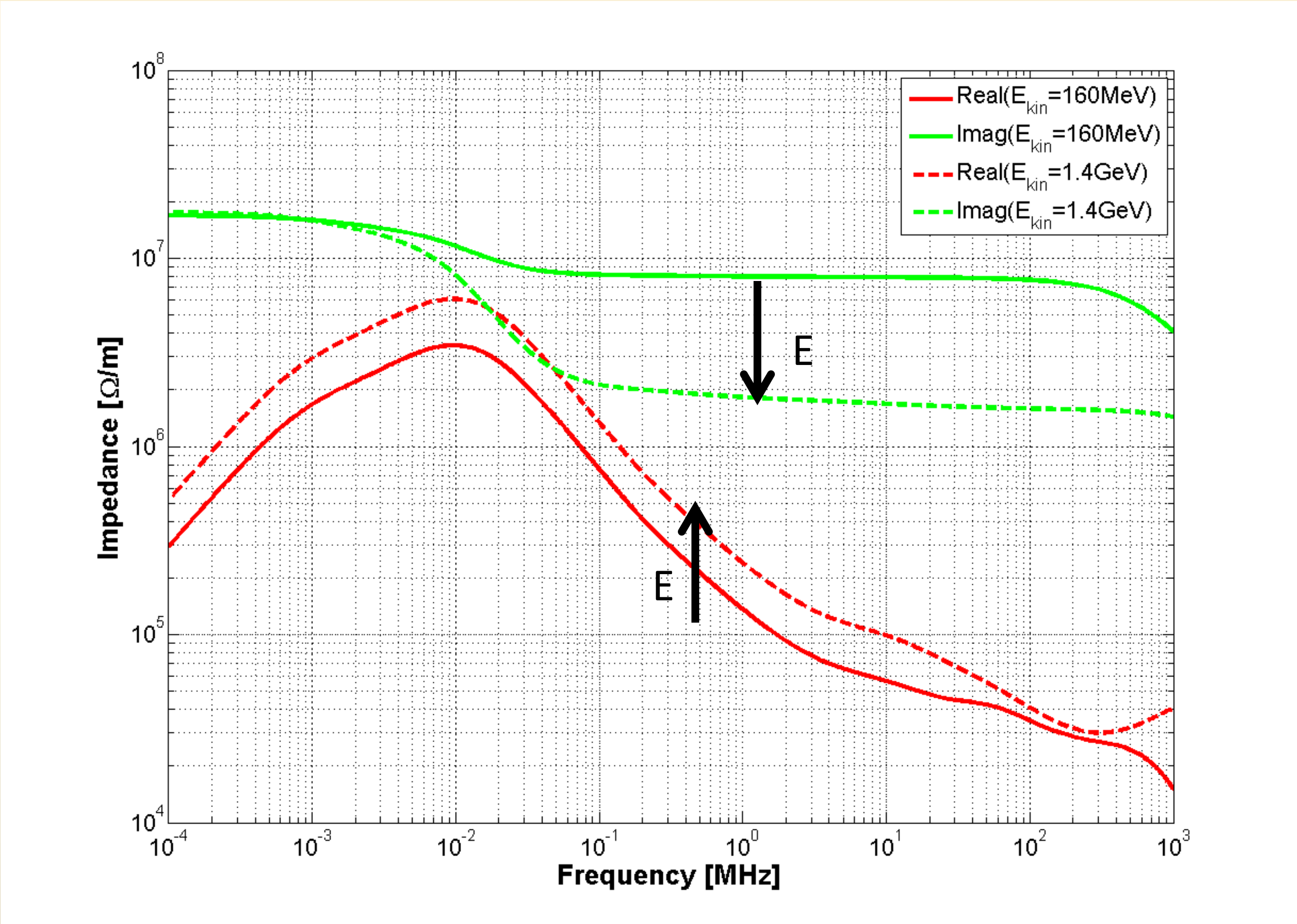


Total horizontal driving impedance of the PSB



Contributions of the extraction kicker due to the coupling with external circuits

Total vertical driving impedance of the PSB



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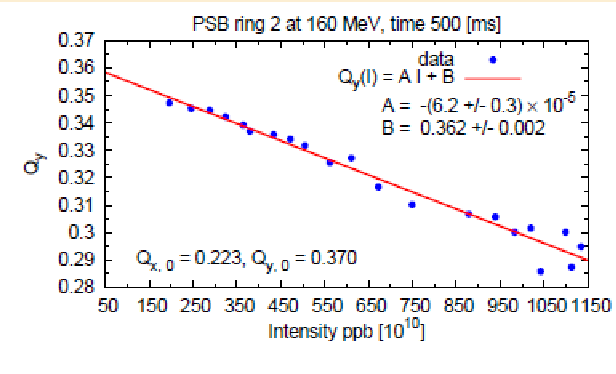
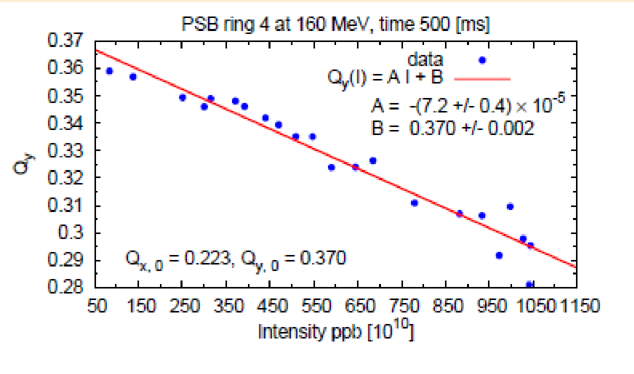
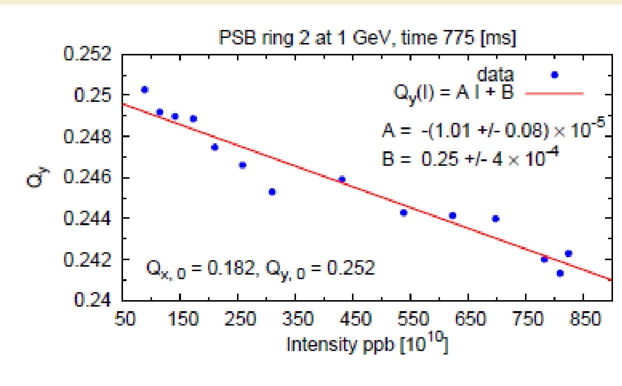
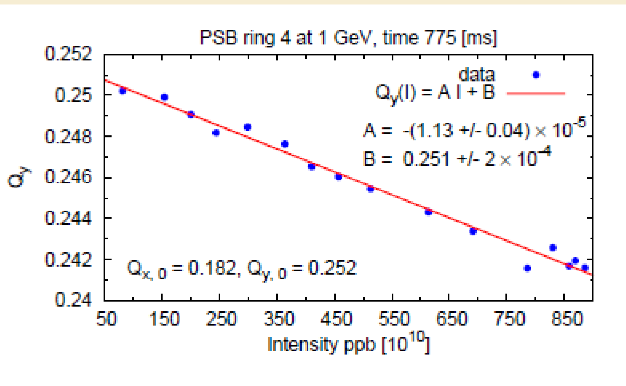
Measurement data

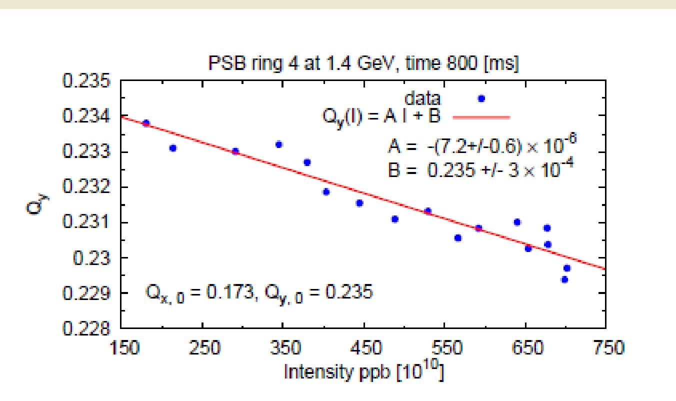


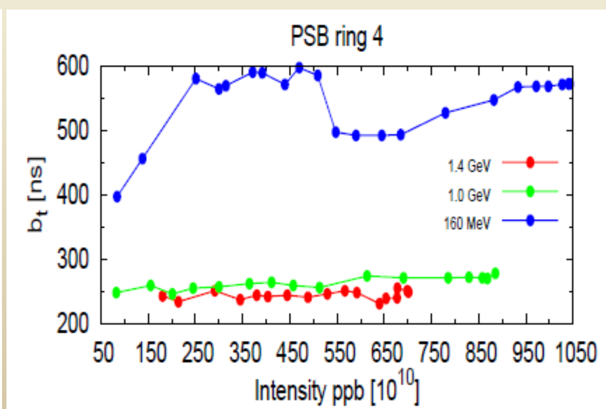






D. Quatraro, *Collective effects for the LHC injectors: non-ultrarelativistic approaches*. PhD thesis, Bologna, University of Bologna, 2011. CERN-THESIS-2011-103.



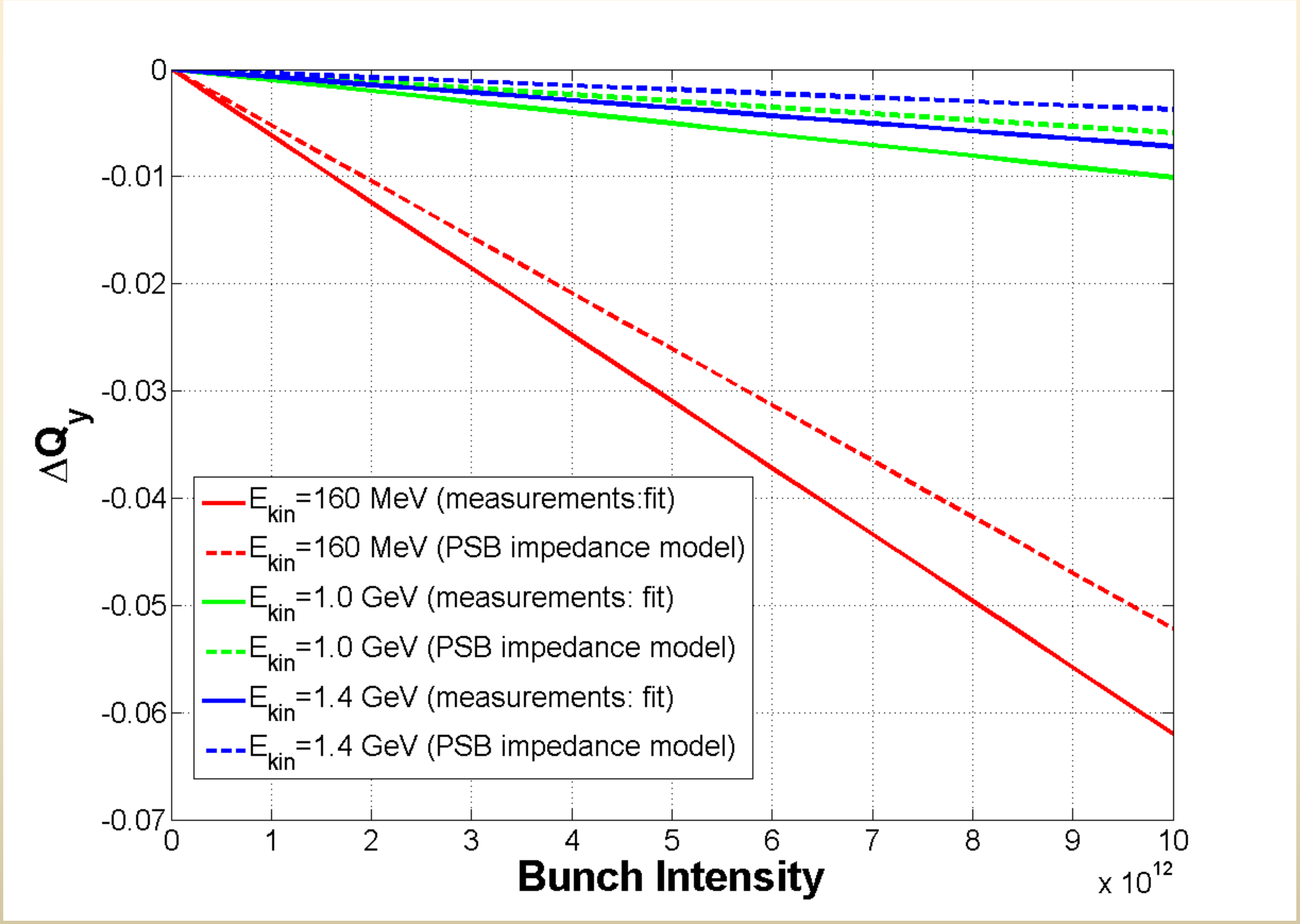


Effective impedance of the PSB

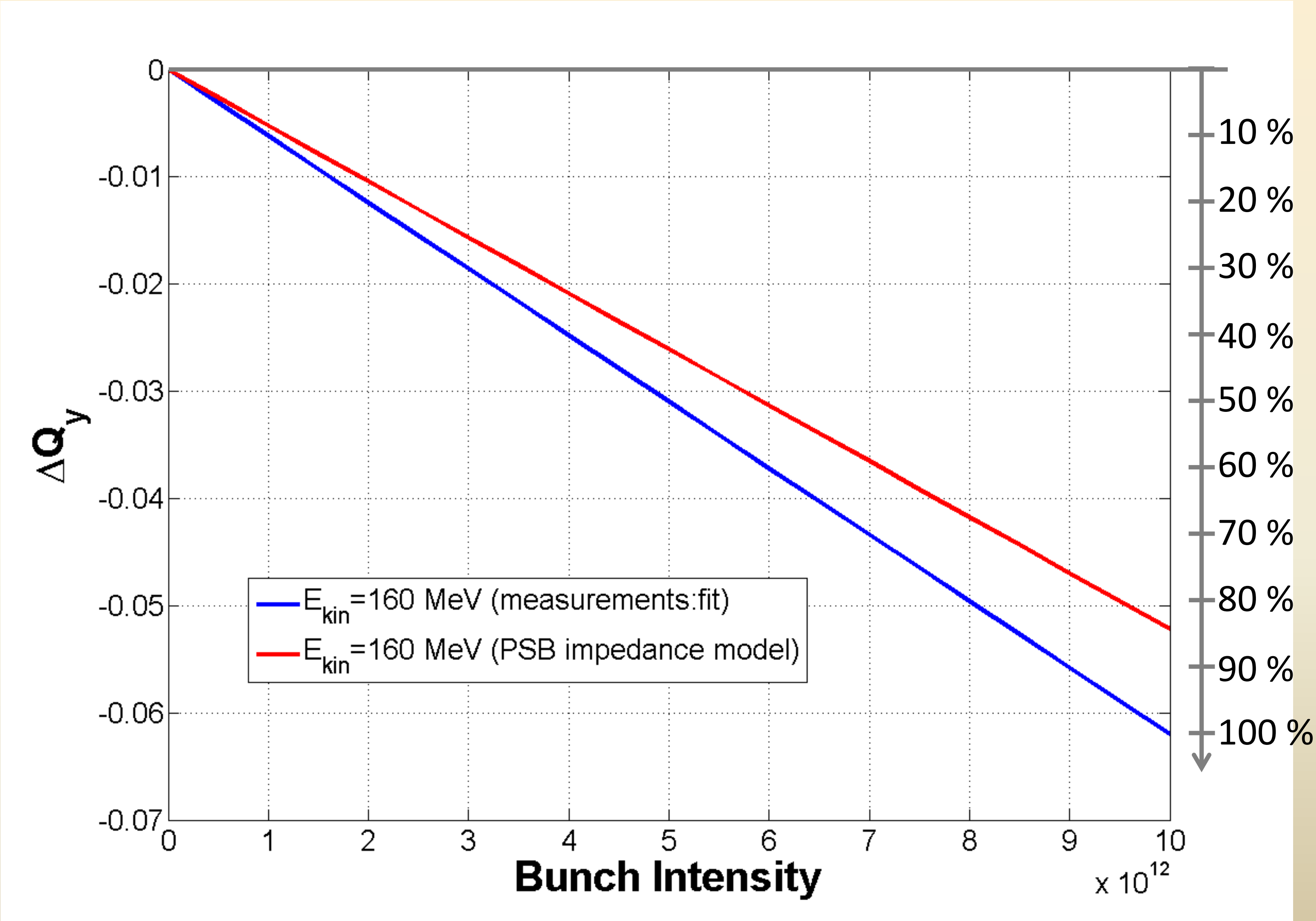
$Z_{eff_{x,y}}$ [MΩ/m]	E_{kin}=160 MeV	E_{kin}=1.0 GeV	E_{kin}=1.4 GeV
Indirect space charge	1.50/10.00	0.29/1.91	0.19/1.25
Kicker cables	0.0084/0	0.012/0	0.0105/0
Kicker ferrite	-0.044/0.13	-0.04/0.11	-0.04/0.11
Steps	0.53/0.63	0.53/0.63	0.53/0.63
Resistive wall	0.03/0.05	0.04/0.07	0.04/0.07
KSW	0/0.013	0/0.0013	0/0.0004
Total (expected)	2.03/10.9	0.83/2.7	0.73/2.0
Total (measured)	?/13.0	?/4.6	?/3.8

Measurements at different energies are consistent with a missing ~2 MΩ/m

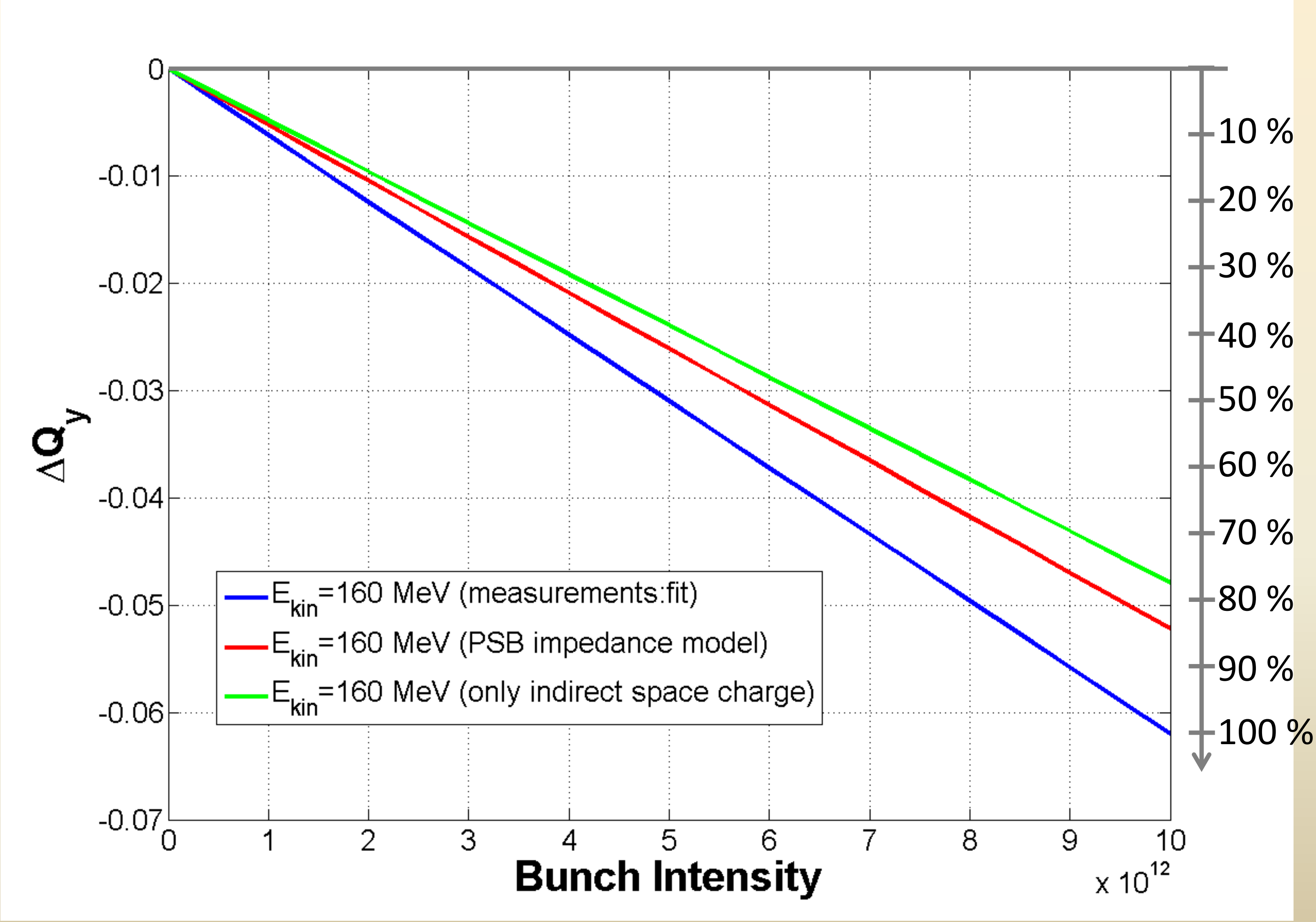
Comparison between measurements and model of the vertical coherent tune shifts at different energies



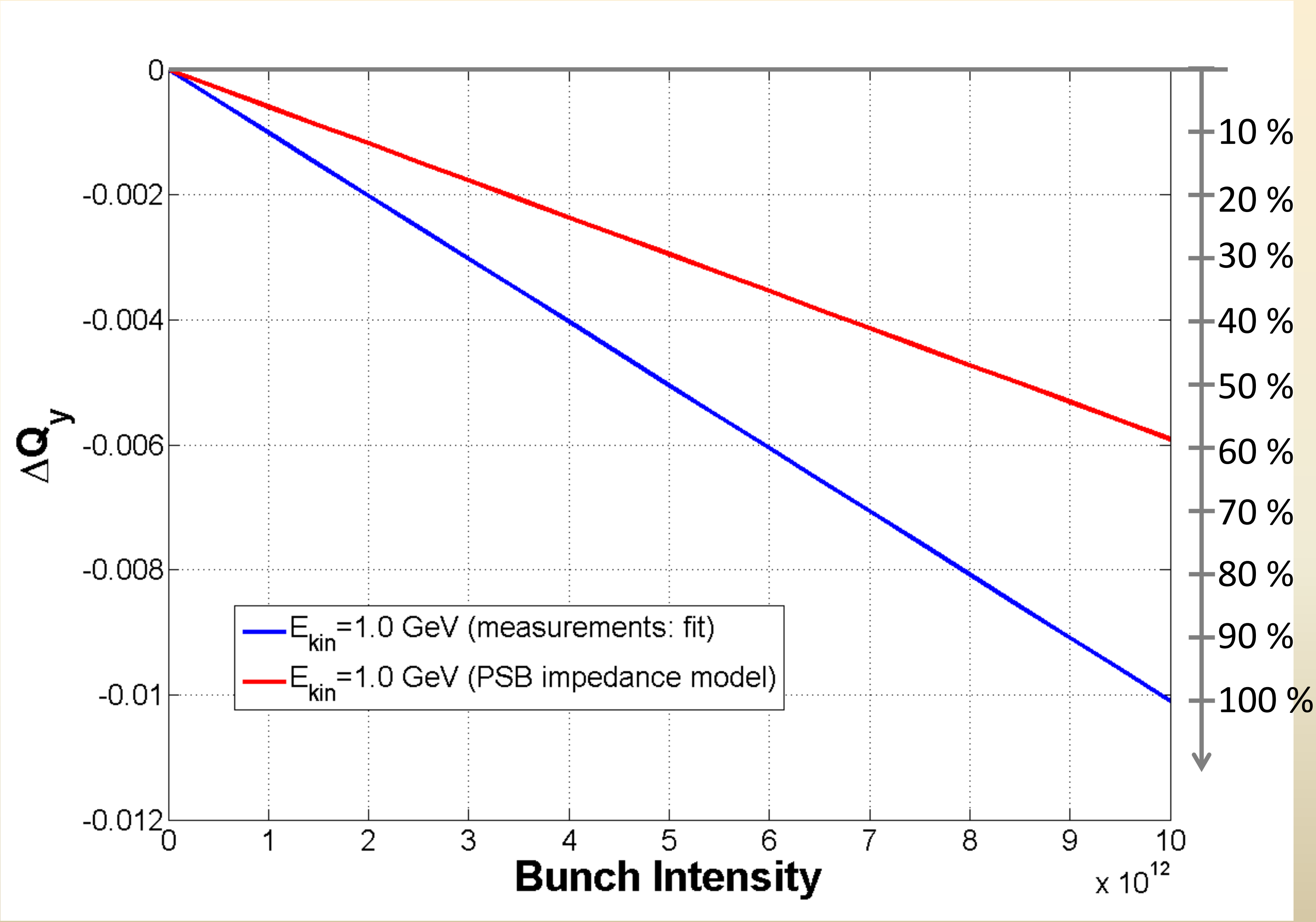
Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=160 MeV



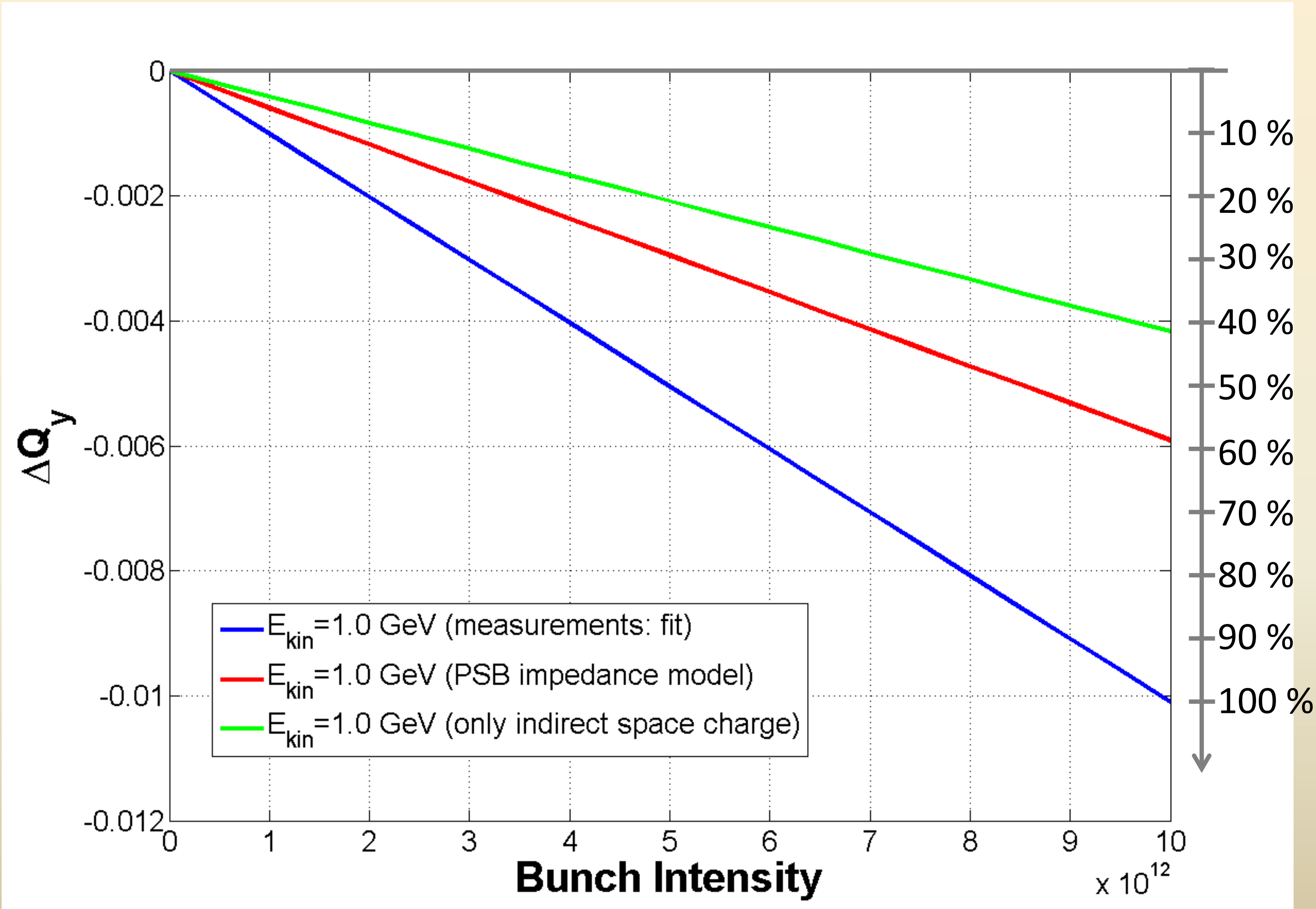
Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=160 MeV



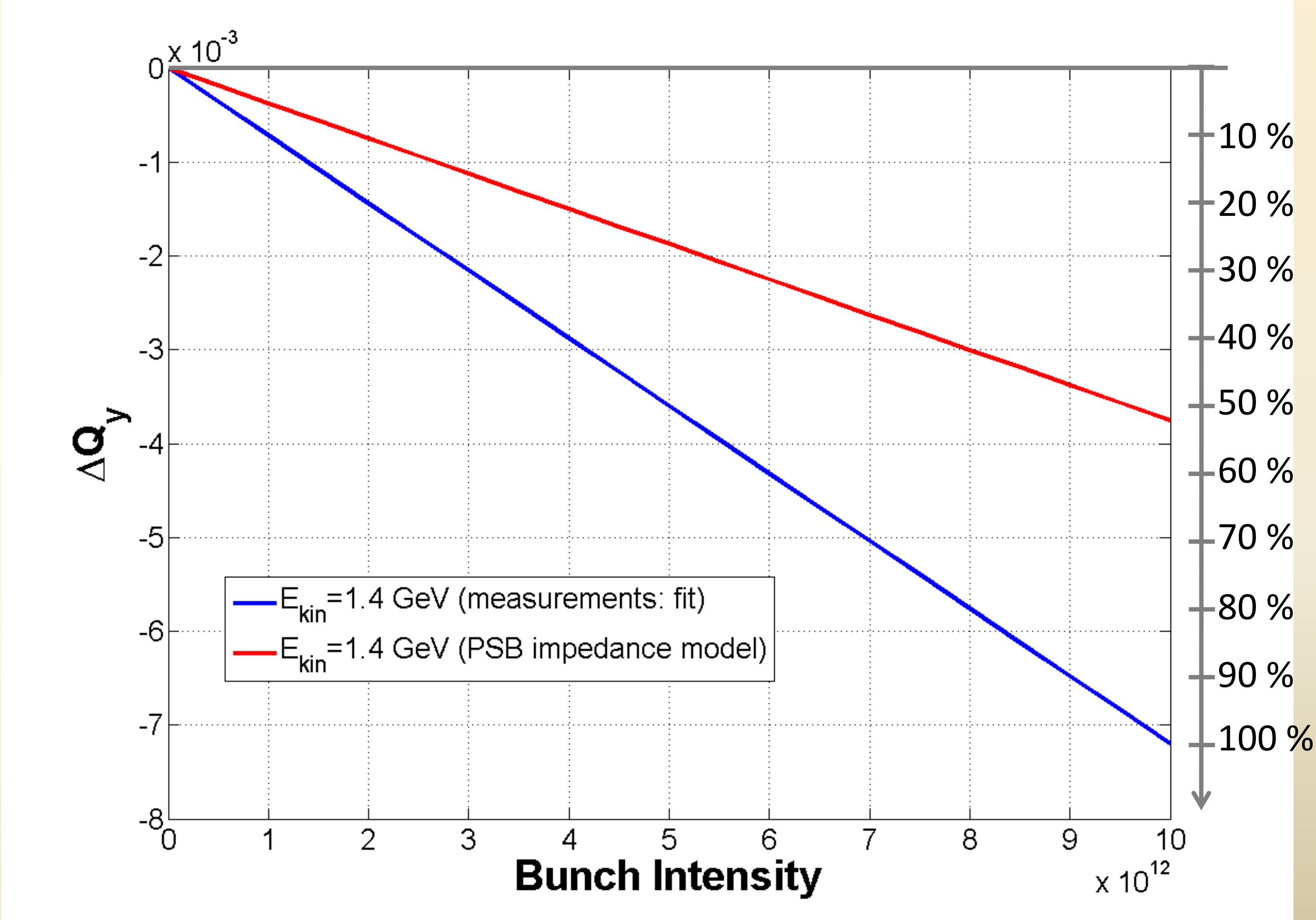
Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=1.0 GeV



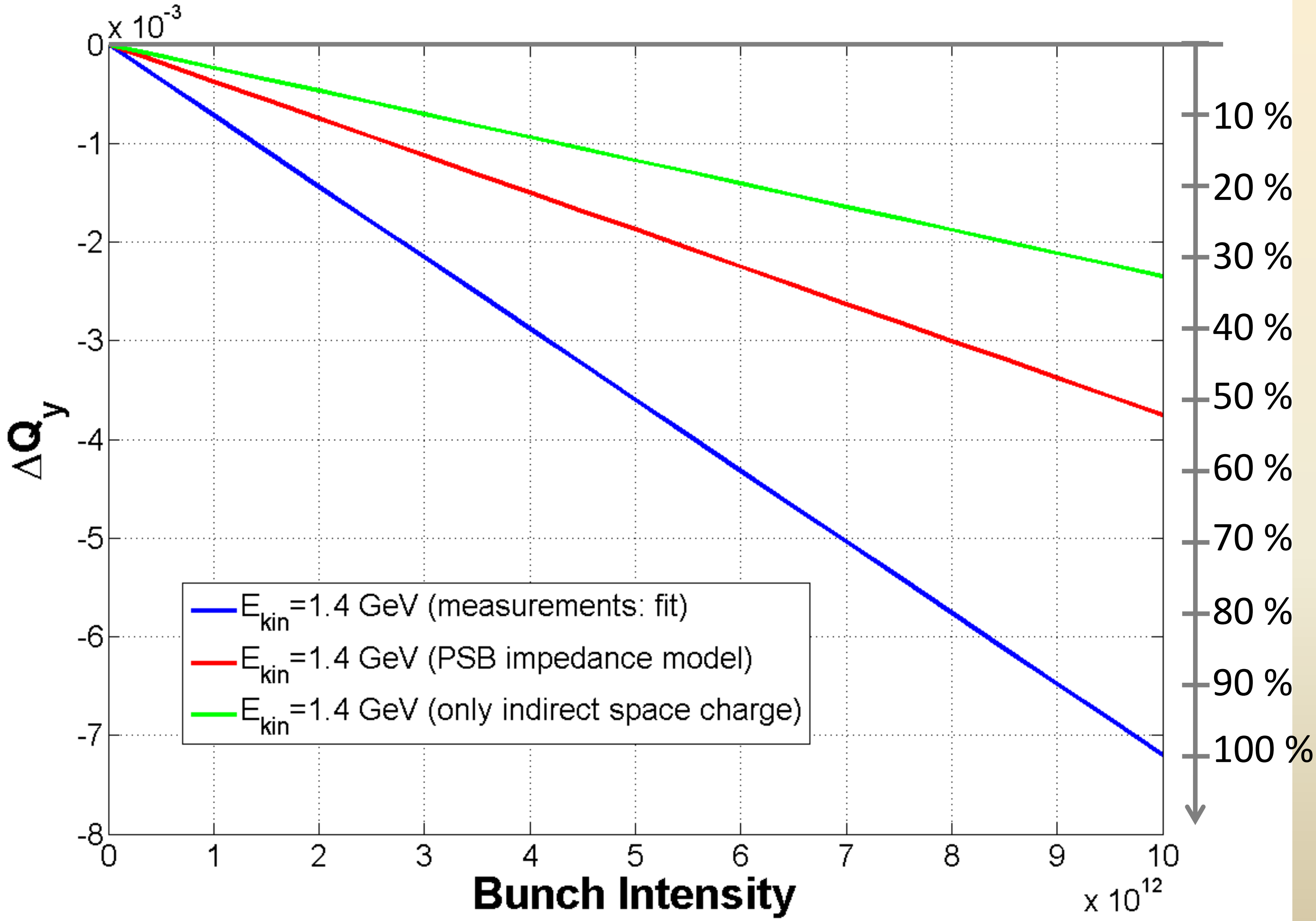
Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=1.0 GeV



Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=1.4 GeV



Comparison between measurements and model of the vertical coherent tune shift at E_{kin}=1.4 GeV



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Summary and future plans

- Measurements at different energies are consistent with a missing ~2 MΩ/m of the PSB impedance model
- Measurements of the coherent horizontal and vertical tune shift
- Update of the model according to new understandings and identification of significant impedance sources

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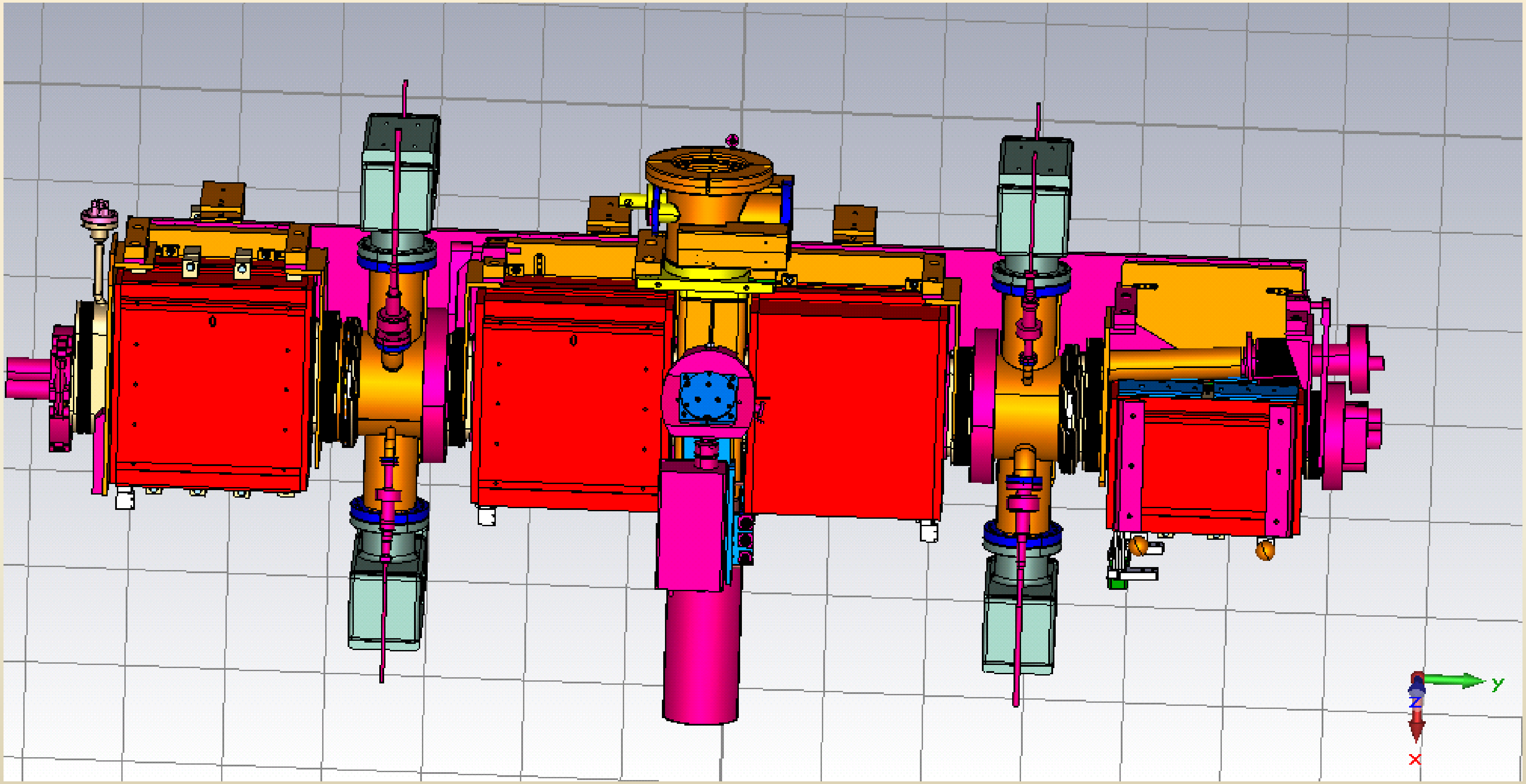
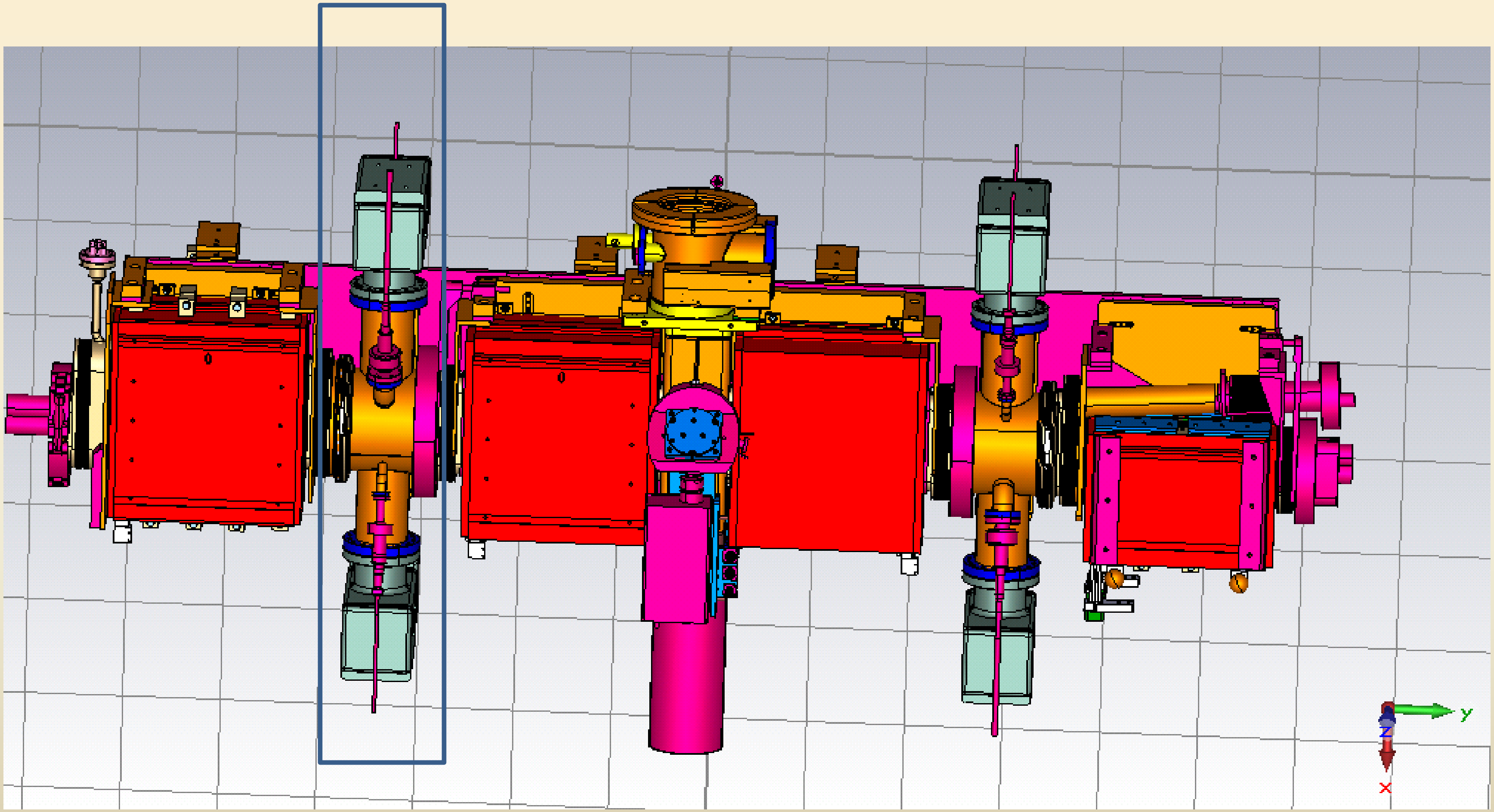
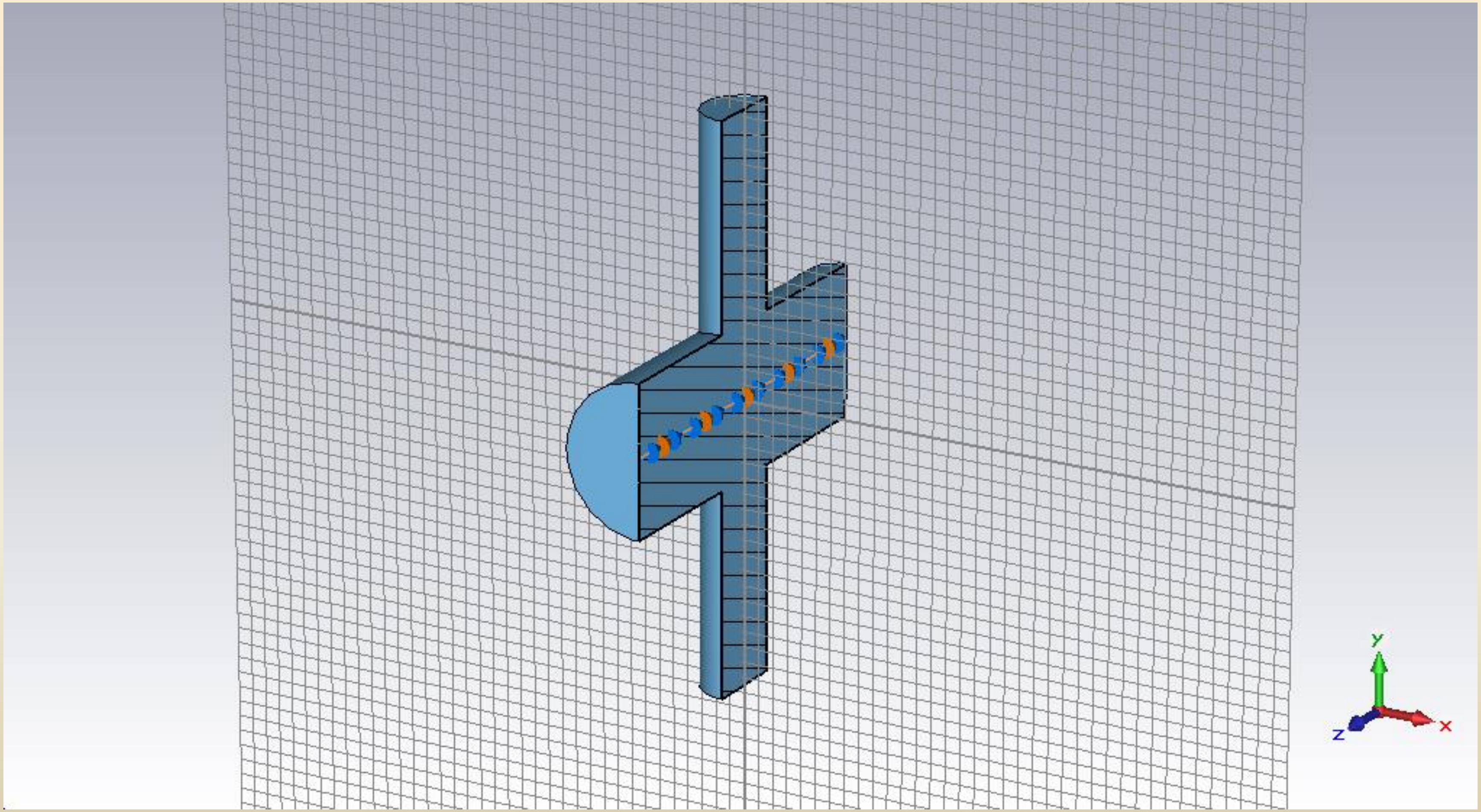
Impedance of pumping ports



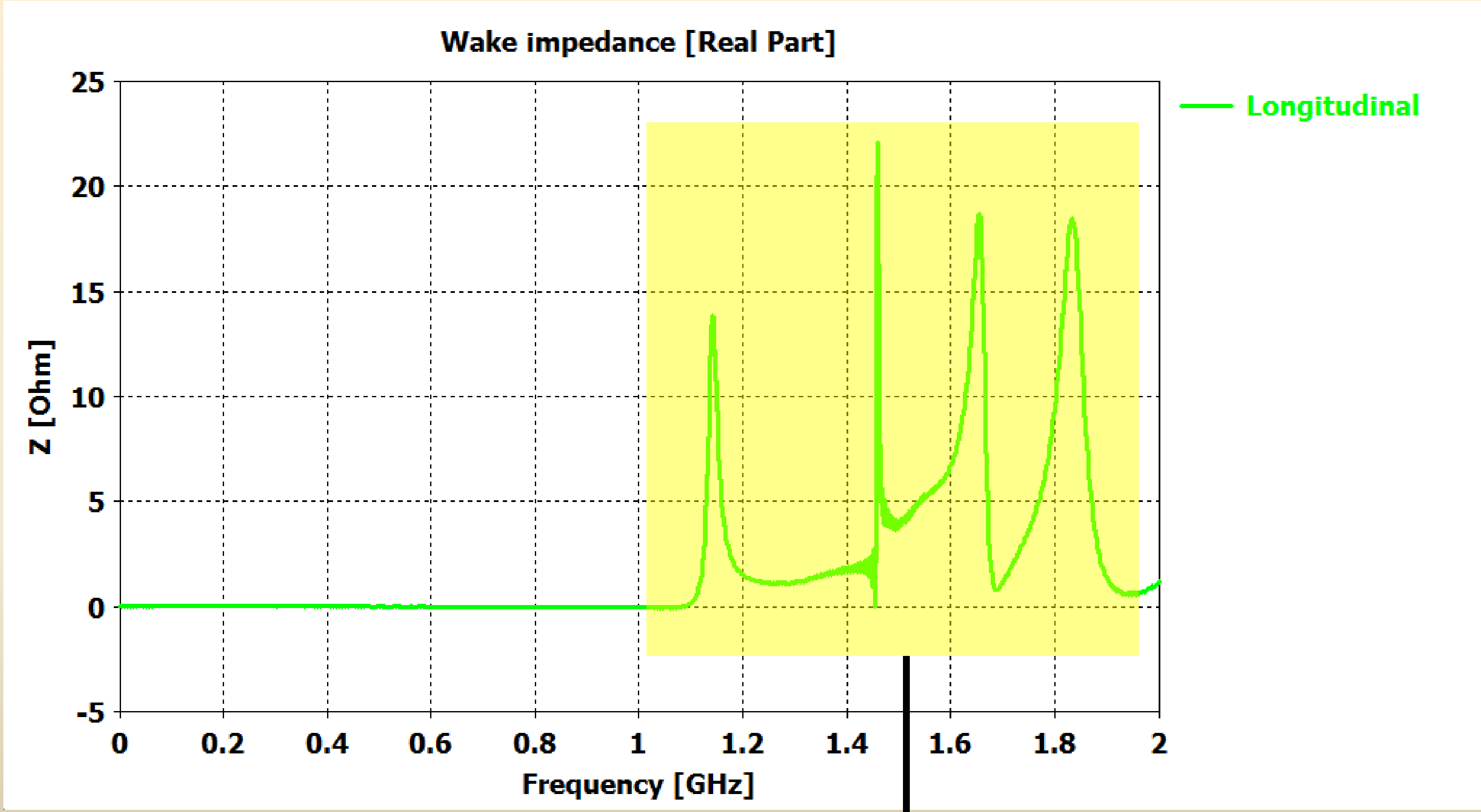
Impedance of pumping ports



Impedance of pumping ports

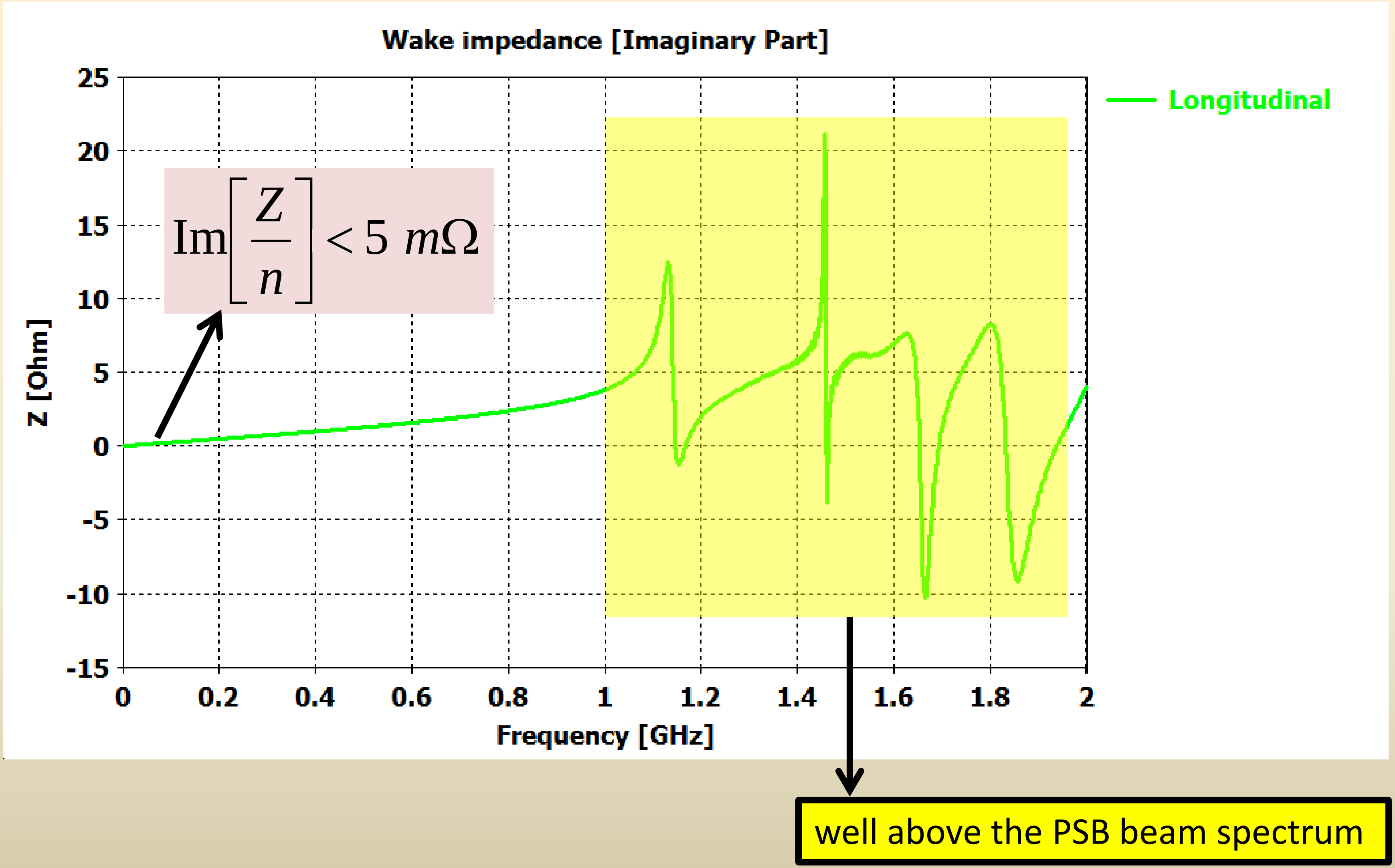


Longitudinal impedance

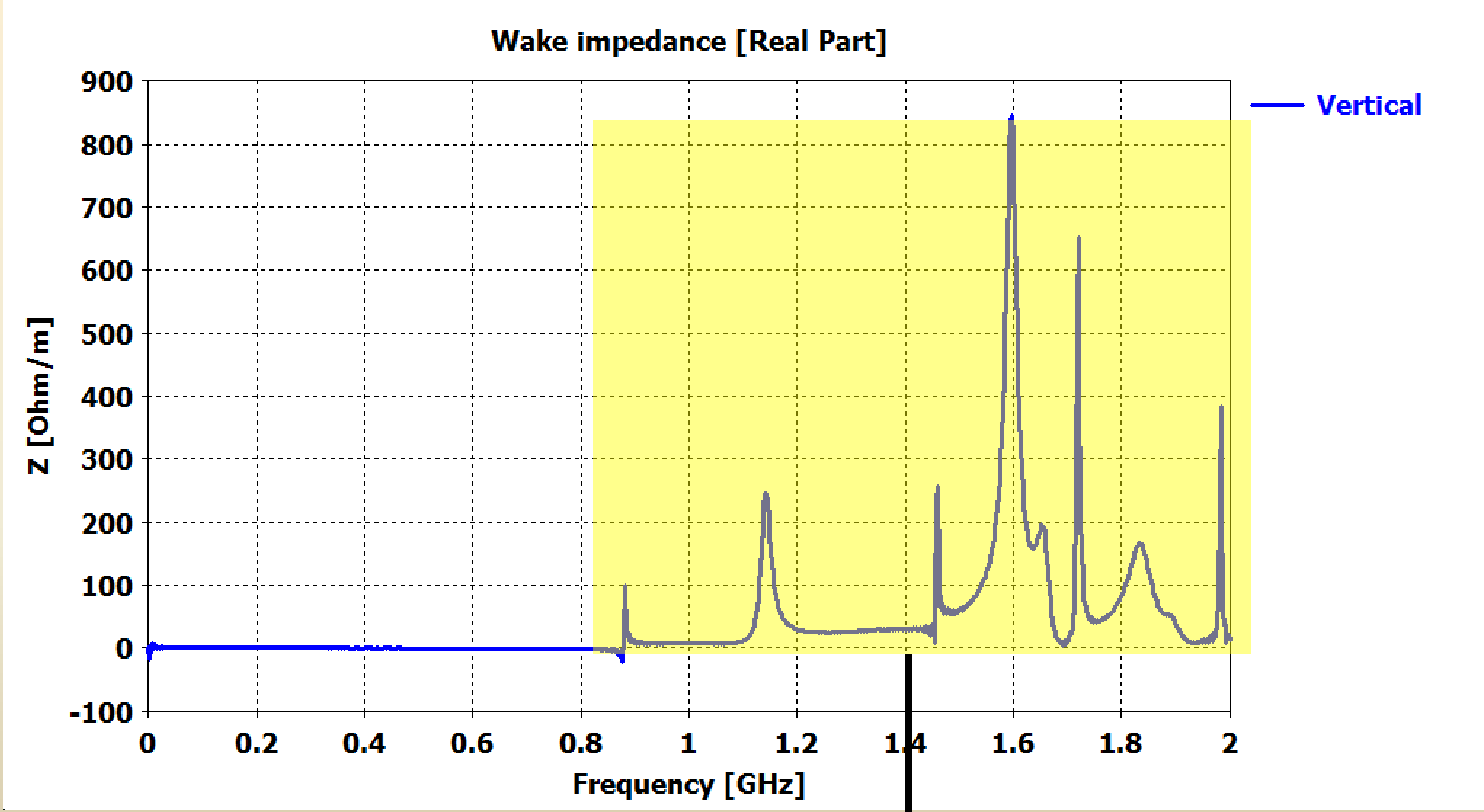


well above the PSB beam spectrum

Longitudinal impedance

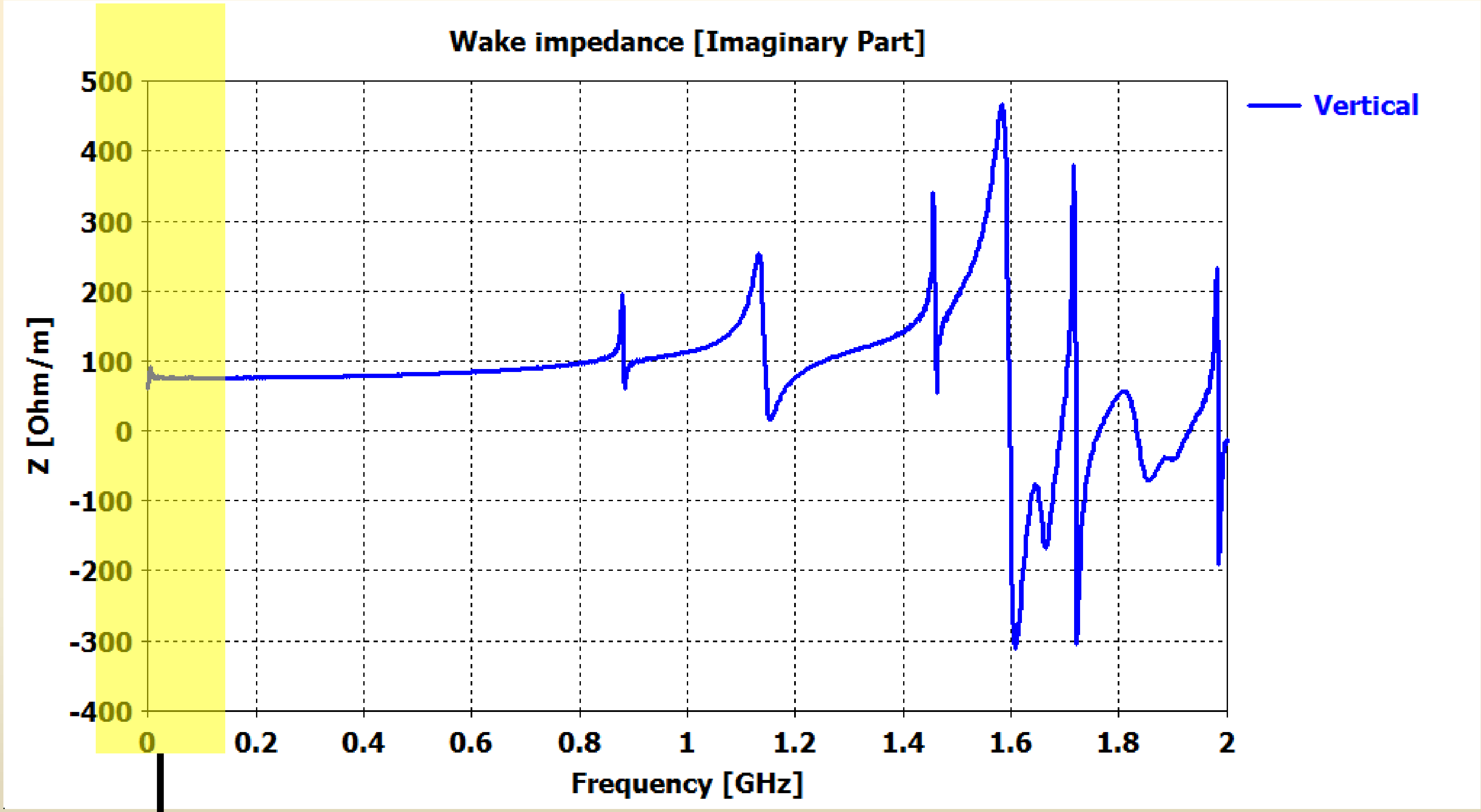


Transverse impedance



well above the PSB beam spectrum

Transverse impedance



$$Z_y^{eff} \cong 100 \;\; \Omega / m$$

The effective vertical impedance for 1 pumping port is expected to be well below 0.01% of the total PSB broadband impedance

Summary: impedance considerations on the pumping ports of the new PSB H- injection region

Obviously, a proper shielding can only be beneficial in terms of impedance, although no special issues from the beam coupling impedance point of view are expected even without shielding.

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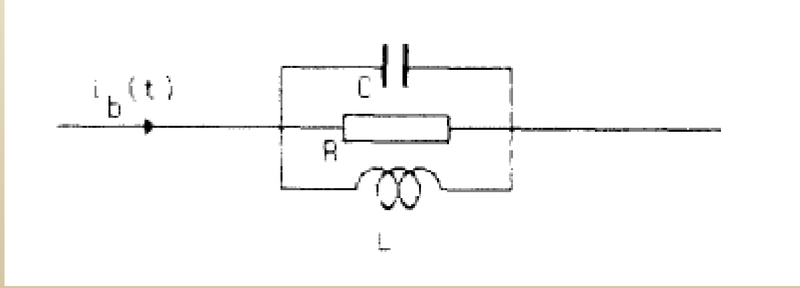
Insulated flanges

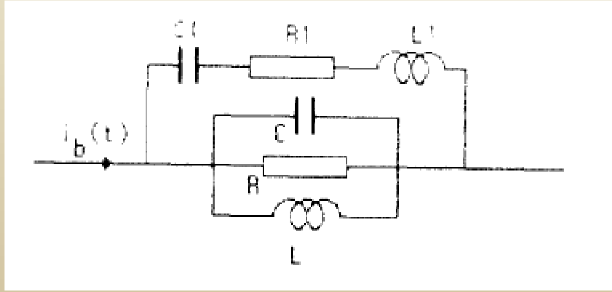
- In circular accelerators with high acceleration rate the fast variation of the main magnetic field induce currents in the ground loop.
- To overcome the problem one has to cut the vacuum chamber in several sectors and reconnect them with isolated flanges.
- The isolated flange forms a capacitor which inserted in series with the ground loop constitutes a parallel RLC equivalent circuit.
- To shift the resonant frequency to a much lower value and to reduce the longitudinal impedance, the so called RF-bypass are connected in parallel to the flange.

R. Cappi, RF bypass on the proton synchrotron vacuum chamber flanges

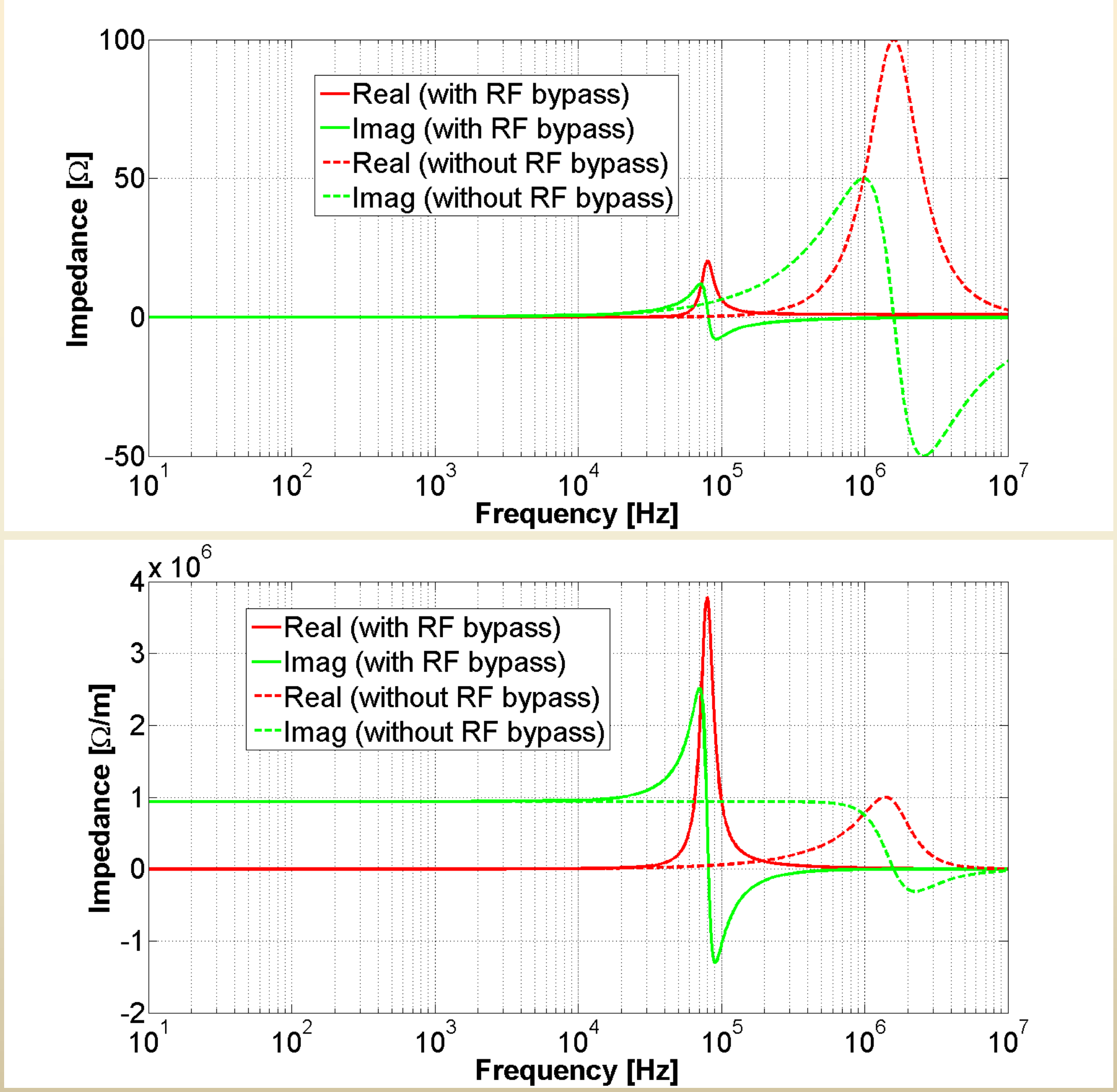
Without RF-bypass



With RF-bypass



Beam coupling impedance of insulated flanges: example



$C = 1$ nF

$L = 10$ μH

$R = 100$ Ω

$C_{bypass} = 0.4$ μF

$R_{bypass} = 1$ Ω

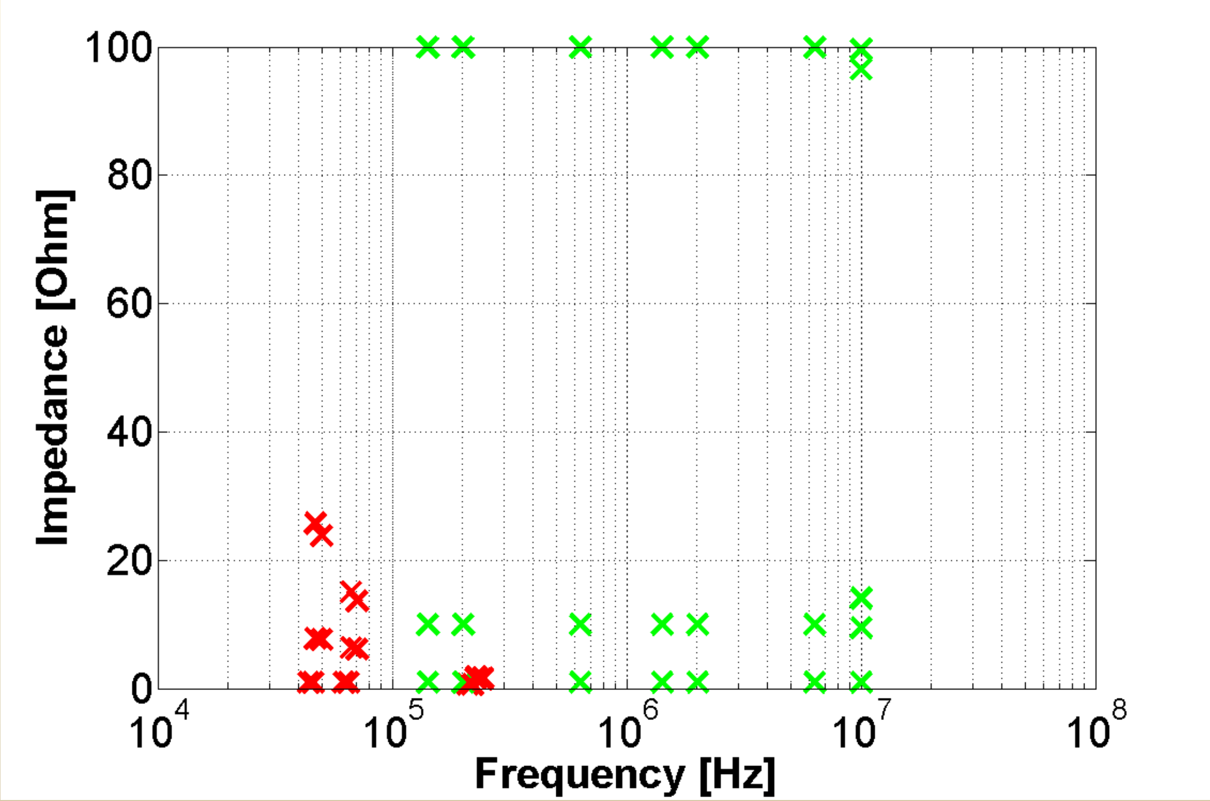
Insulated flanges

Parameter sweep analysis

C=0.01-100 nF   L=0.5-15 μH   R=1-100 Ω

C_{bypass}=0.4 μF R_{bypass}=1 Ω

Case of study two bypasses in parallel



Conclusion on the beam coupling impedance of insulated flanges

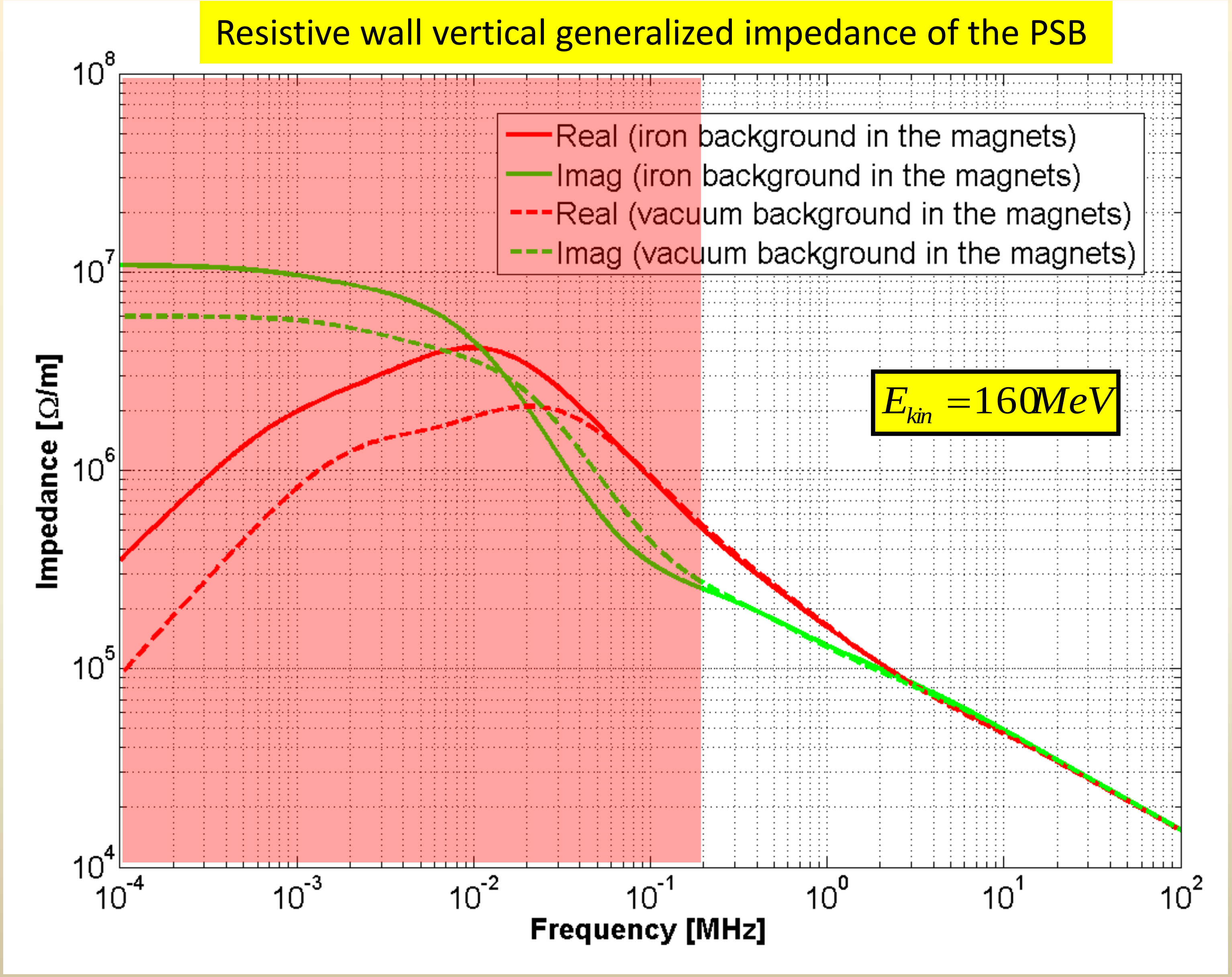
The RF bypass is expected to shift the impedance spectrum to low frequency (well below the first possible unstable betatron line of the PSB) avoiding possible detrimental effect which could not be excluded in the case without RF bypass.

Additional impedance sources not discussed here

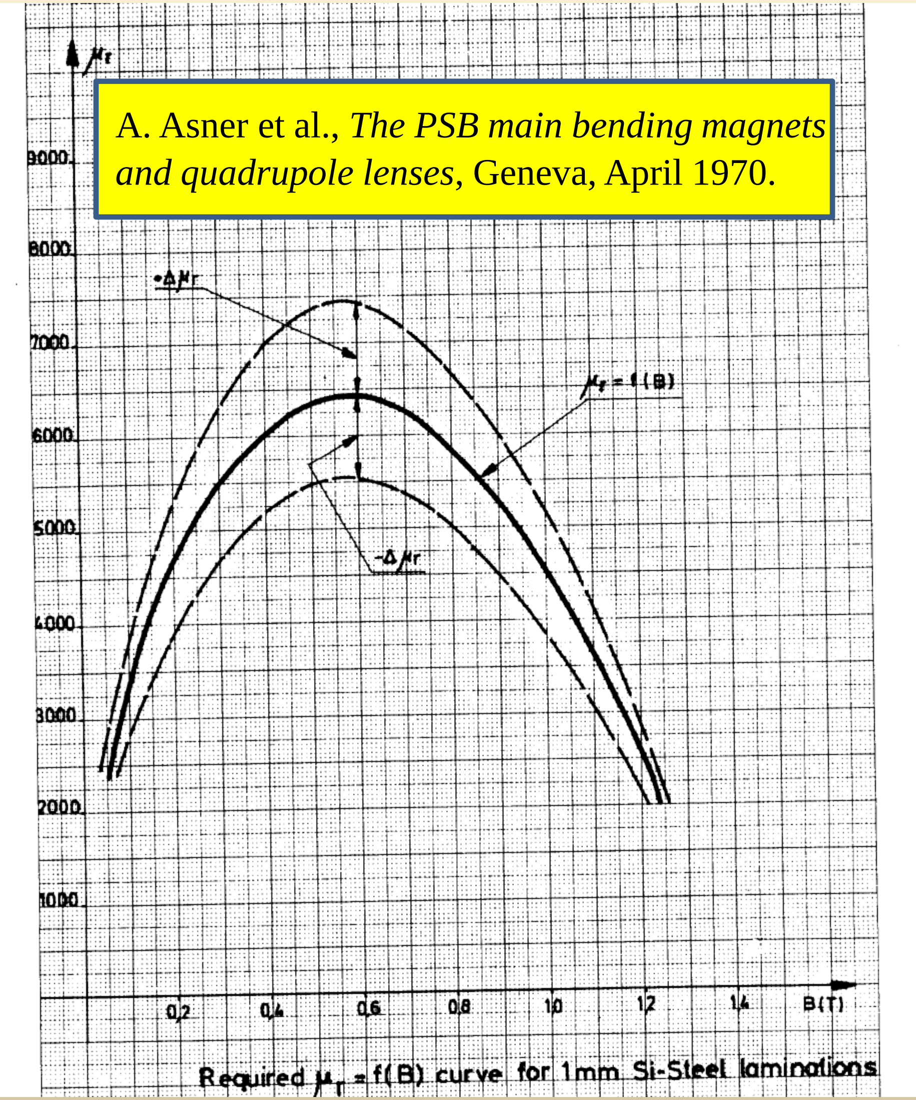
- Vacuum chamber of the new H- injection region
  - Comparison between Inconel undulated chamber and titanium coated ceramic chamber
- Finemet cavities
  - The longitudinal impedance does not depend on the relativistic beta
- Foil section of the new H- injection region
  - Preliminary simulations do not show narrow impedances below 100 MHz

Thank you for your attention

Resistive wall impedance: impact of the iron



Resistive wall impedance



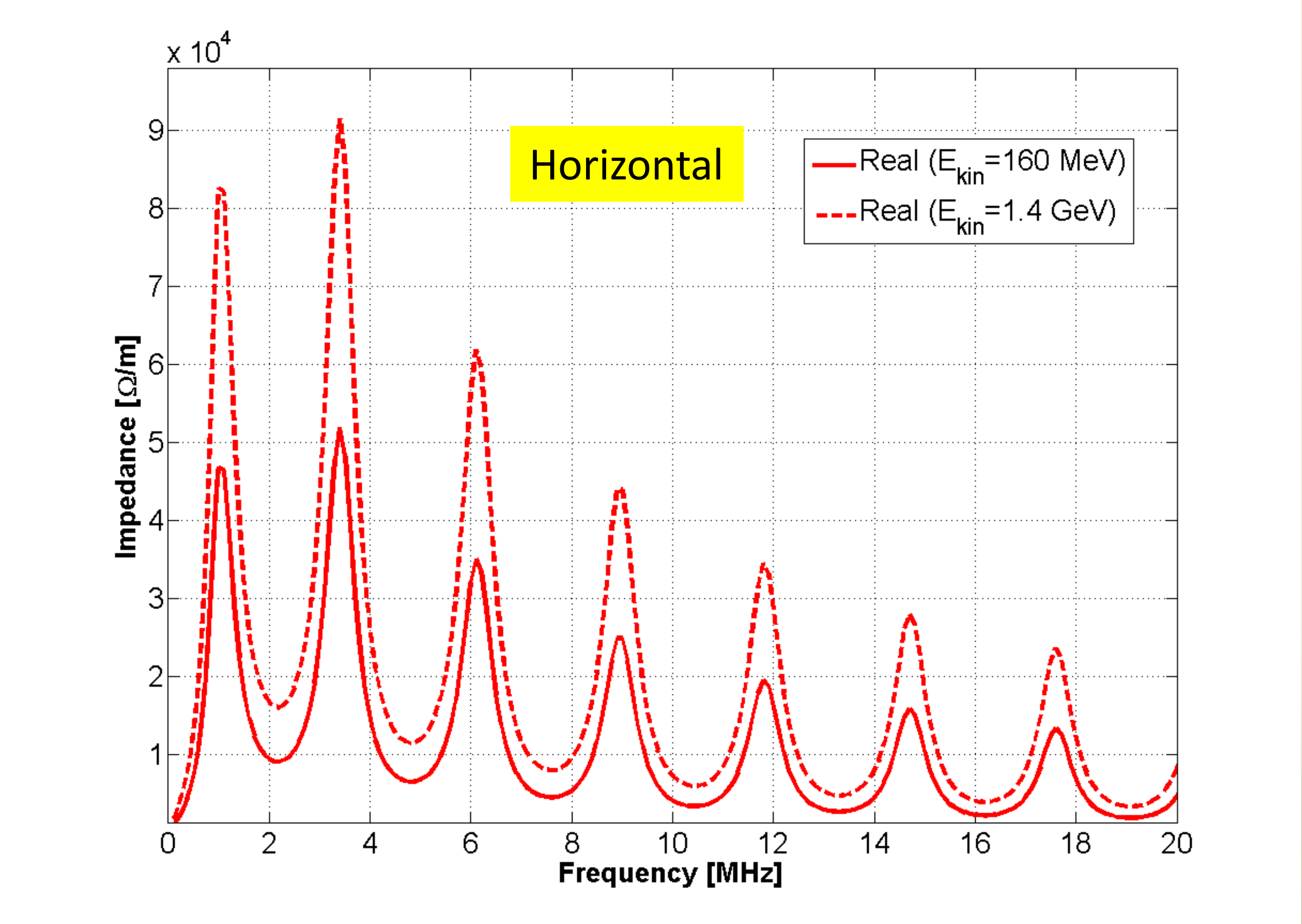
A. Asner et al., *The PSB main bending magnets and quadrupole lenses*, Geneva, April 1970.

$$\mu = \mu_0\, \mu_r(B) = \mu_0 \left(1 + \frac{\mu_i(B)}{1 + j\, f / f_{rel}} \right)$$

f_{rel} = 10 kHz

K. G. Nilanga et al., *Determination of complex permeability of silicon-steel for use in high frequency modelling of power transformers*, IEEE TRANS. ON MAGNETICS, VOL. 44, NO. 4, APRIL 2008.

PSB extraction kicker: impedance due to the coupling to the external circuits Z_{TEM}



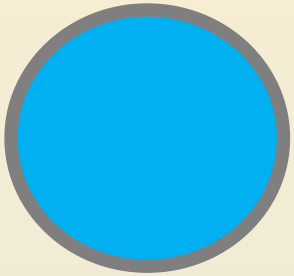
Cables in the open-short configuration

Indirect space charge

Analytical calculation based on the PSB aperture model (provided by O. Berrig)

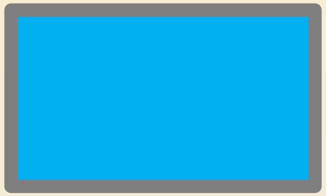
$$Z_{x,y}^{ISC} = \frac{1}{\langle \beta_{x,y} \rangle} \sum_{i=1}^{N} Z_i^{ISC} \beta_{x_i,y_i}$$

Circular pipe

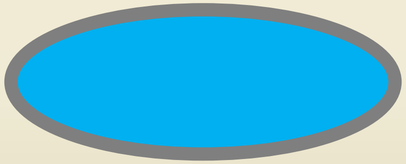


K. Y. Ng, *Space charge impedances of beams with non-uniform transverse distributions*

Rectangular pipe



Elliptic pipe



$$Z_{\perp} = \frac{jZ_0 L}{2\pi\beta\gamma^2} \frac{K_1\left(\frac{k_0 b}{\beta\gamma}\right)}{I_1\left(\frac{k_0 b}{\beta\gamma}\right)} \frac{k_0^2}{2\beta^2\gamma^2}$$

$$Q_p = -\frac{jpk_0^2 Z_0 L}{2\pi\beta^3\gamma^3}$$

$$-j\frac{Z_x^{\mathrm{driv}}}{L} = \frac{1}{p}\left[E_r^v - \beta Z_0 H_\varphi^v\right]_{\substack{r=0\\ \varphi=0}} = \frac{jQ_p}{2p\gamma}A_1$$

$$E_s^v + E_s^{SC} = 0 \quad r = b$$

$$A_m = -\frac{K_m\left(\frac{k_0 b}{\beta\gamma}\right)}{I_m\left(\frac{k_0 b}{\beta\gamma}\right)}$$

Definition of impedance

$$Z_{\parallel}(x, y, x_0, y_0, \omega)\,[\Omega] = -\frac{1}{q_0}\int_0^L E_s(x, y, s, x_0, y_0, \omega)\, e^{jks}\, ds$$

Longitudinal component of the electric field in (x, y) induced by a source charge placed in (x_0, y_0)

$$E_s^{tot} = E_s + E_s^{SC}$$

EM simulator uses the total fields

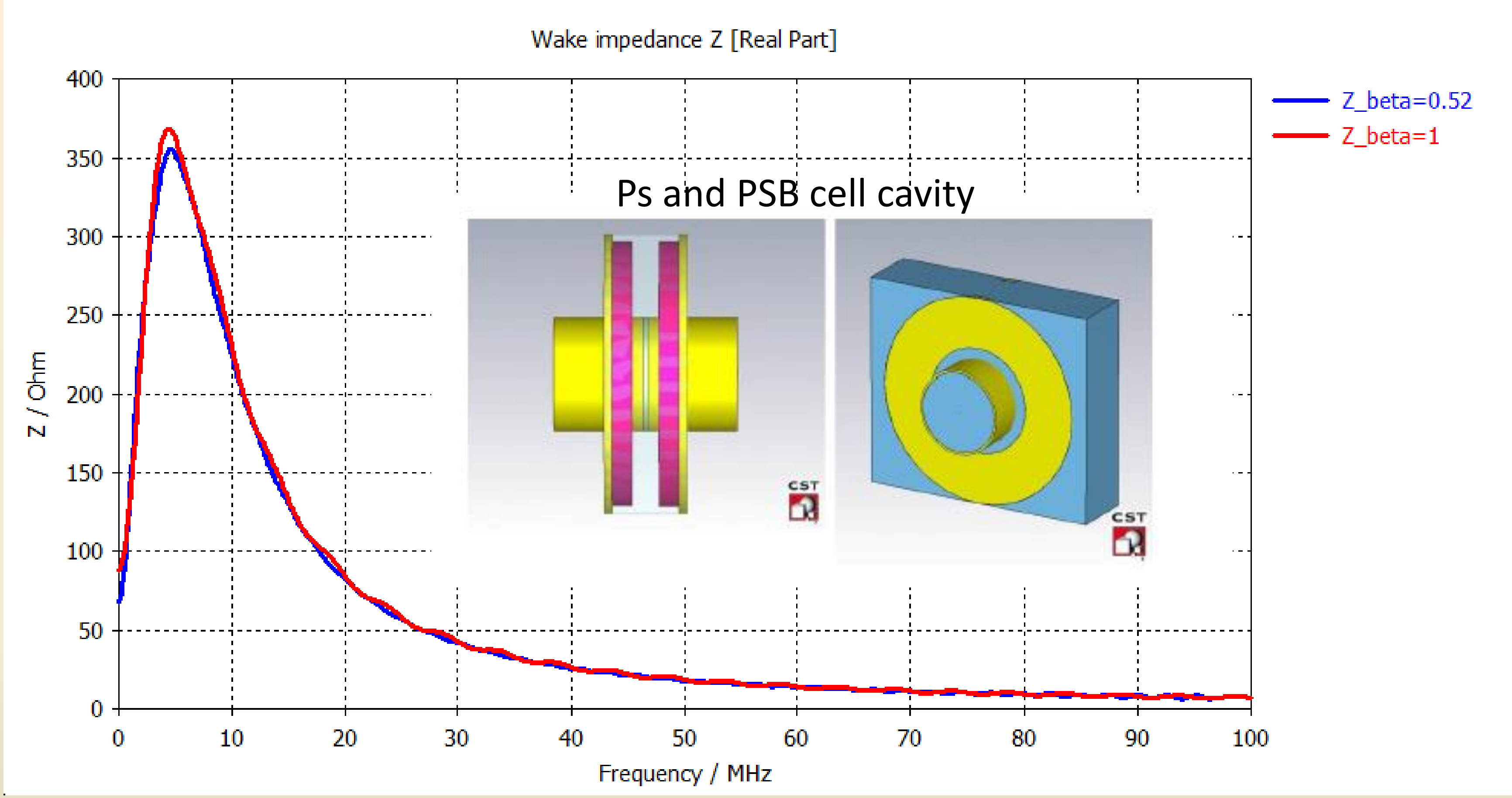
$$Z(\beta)$$

contribution due to the interaction of beam and accelerator components

Depend only on the source

$$Z_{direct}^{SC}(\beta)$$

Finemet cavities



The impedance does not depend on the relativistic beta

S. Persichelli et al., *Finemet cavities impedance studies*, CERN-ACC-NOTE-2013-0033, 2013.