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Numerical Computation of Kicker Impedances: *Towards a Complete Database for the GSI SIS-100/300 Kickers*

Burkhard Doliwa and Thomas Weiland

TEMF, TU Darmstadt

(i) The Goal

(ii) Numerical Approach

(iii) Simulation *vs.* Analytical Results

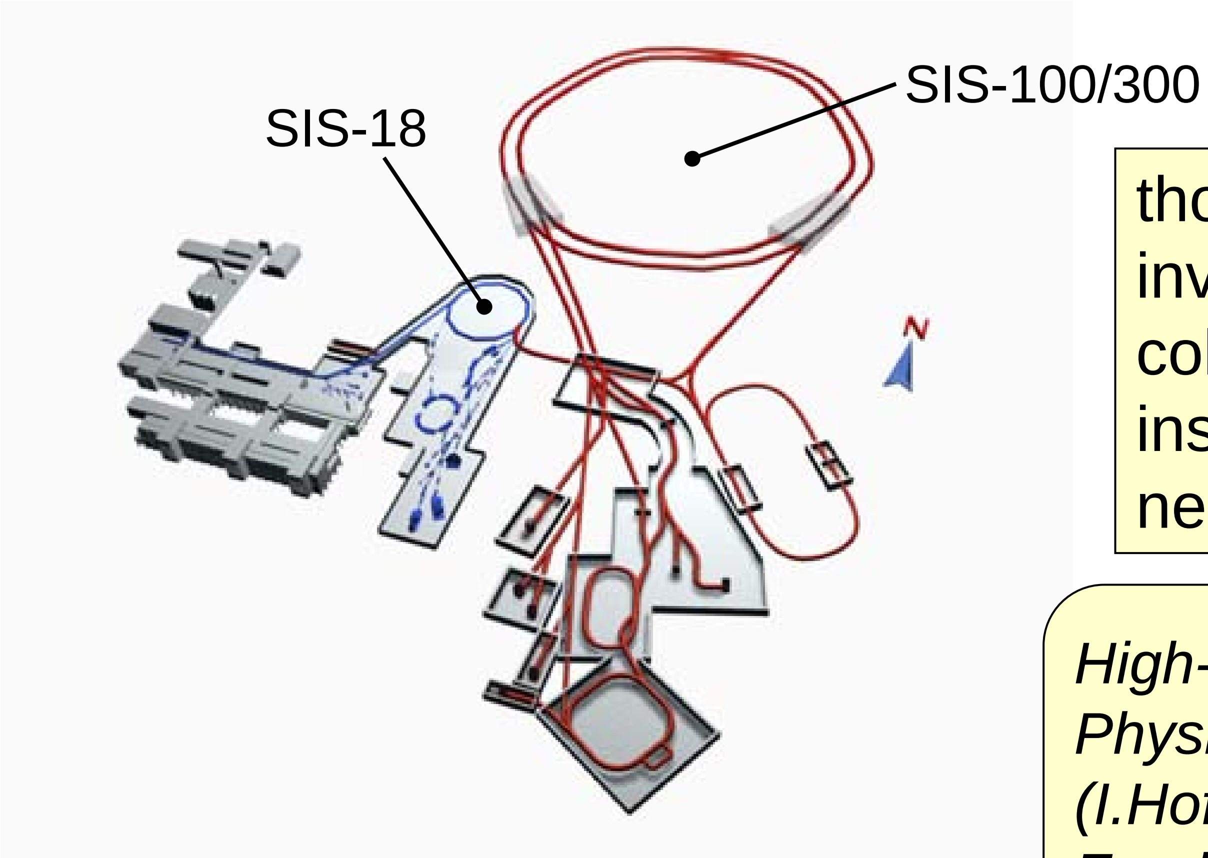
(iv) SIS-100 Extraction/Emergency Kicker

(i) The Goal

demands on beam quality in *FAIR*:

– high intensity (up to $N=10^{12}$/s for U^{28+})

– low momentum spread ($\Delta p/p<10^{-3}$)



thorough investigation of collective beam instabilities needed!

High-Current Beam Physics Group at GSI (I.Hofmann, O.Boine-Frankenheim)

➢ issue: *impedance budget*

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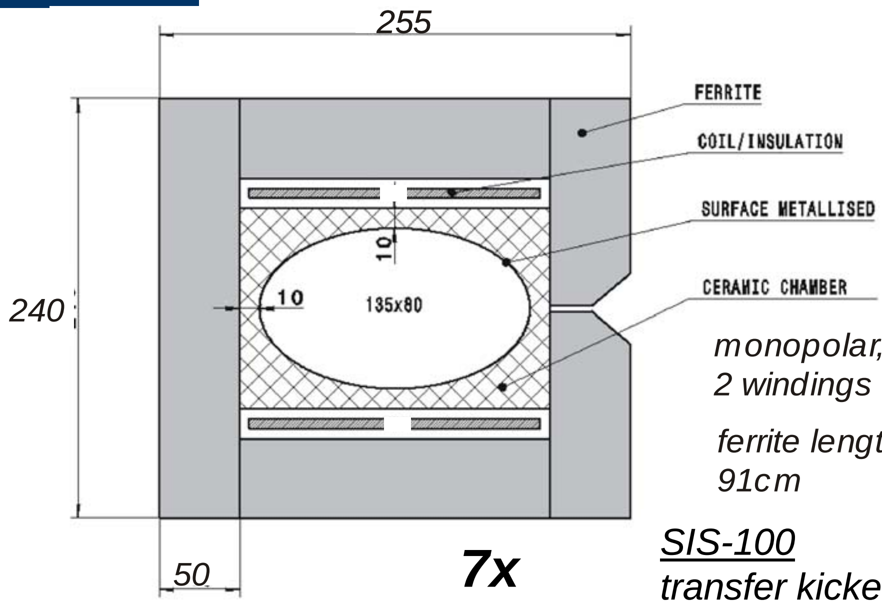
The SIS-100 Kickers

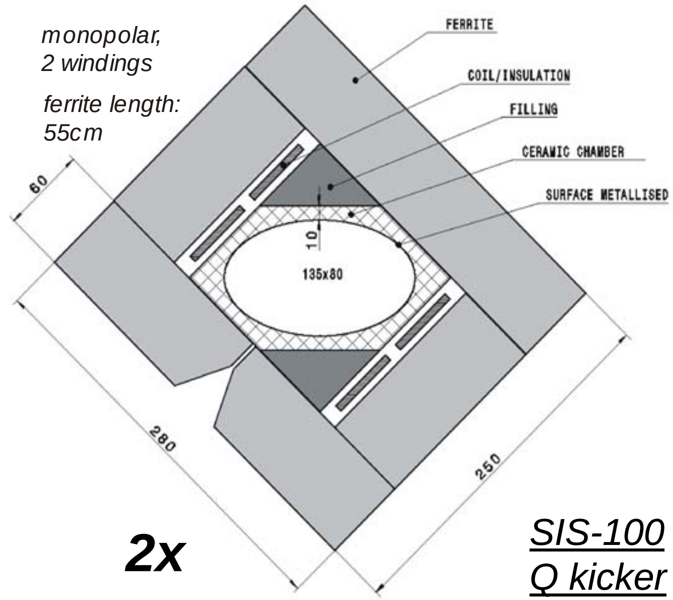


monopolar,
2 windings

ferrite length:
91cm

7x

SIS-100
transfer kicker

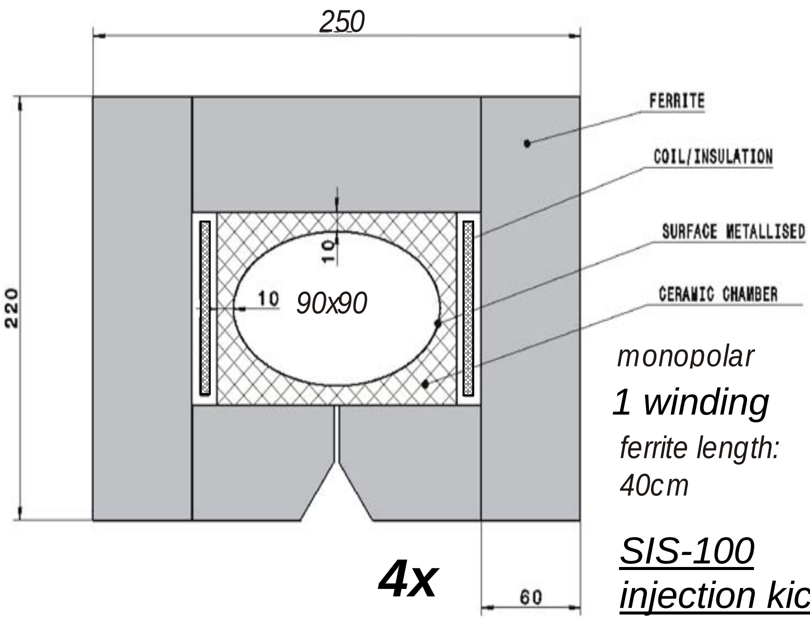


monopolar,
2 windings

ferrite length:
55cm

2x

SIS-100
Q kicker

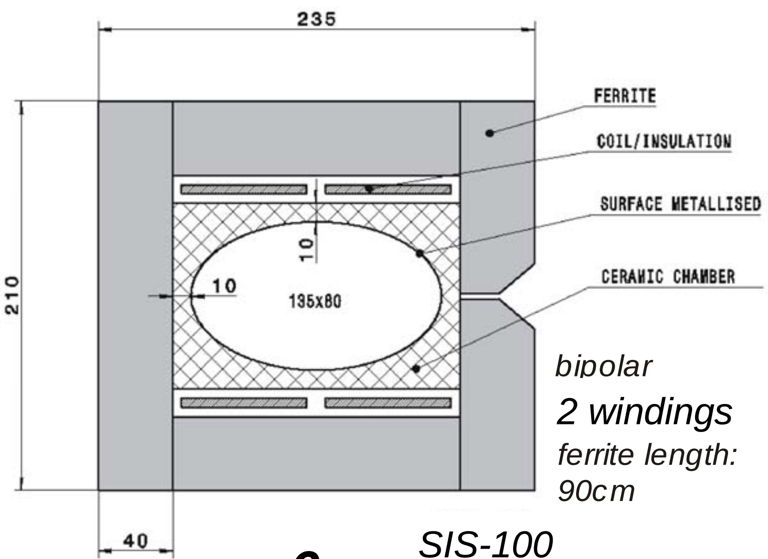


monopolar
1 winding

ferrite length:
40cm

4x

SIS-100
injection kicker



bipolar
2 windings

ferrite length:
90cm

6x

SIS-100
extr./emergency kicker

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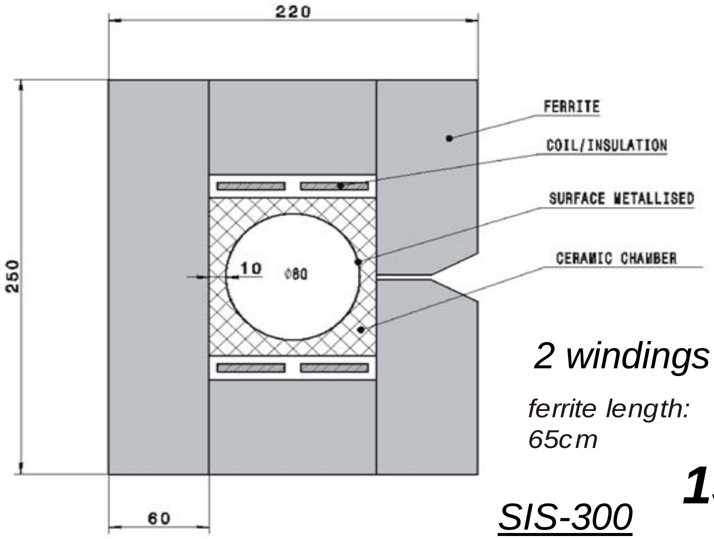
The SIS-300 Kickers

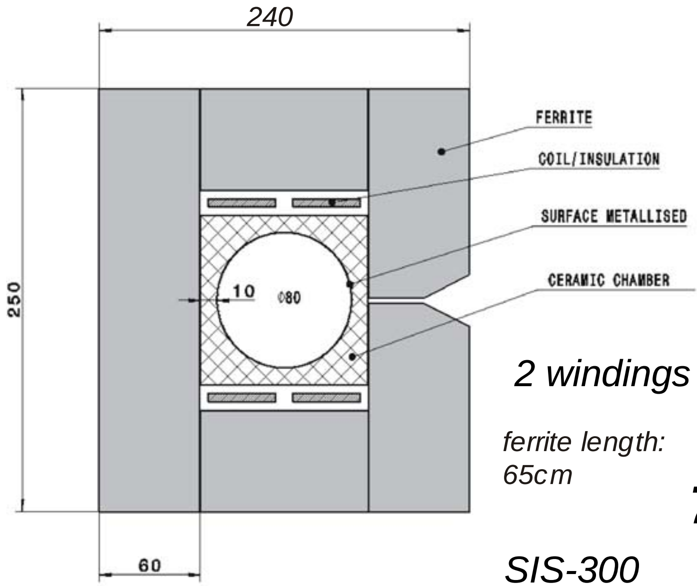


2 windings

ferrite length: 65cm

13x

monopolar *SIS-300 emergency kicker*



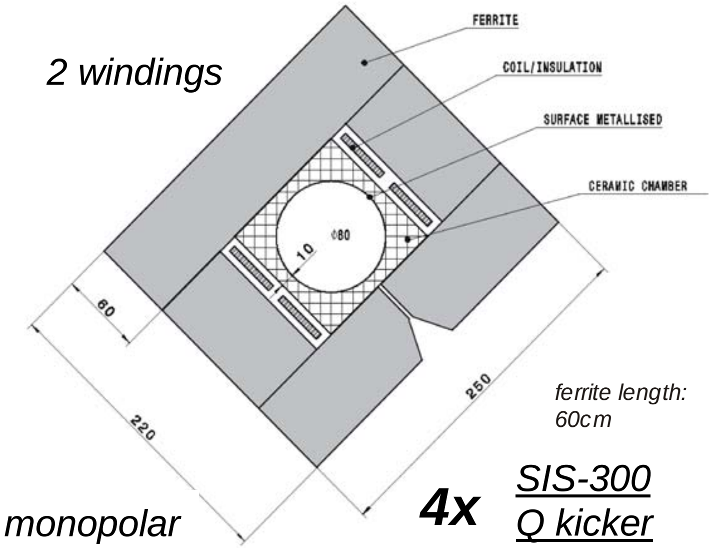
2 windings

ferrite length: 65cm

7x

monopolar *SIS-300 transfer kicker*

2 windings



ferrite length: 60cm

4x *SIS-300 Q kicker*

monopolar

SIS-100 **total length: 14.47m**
total weight: 3036kg

SIS-300 **total length: 15.40m**
total weight: 3280kg

➢ *large contributions to ring impedances expected!*

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Coupling Impedances

$v=\beta c$

- longitudinal:

$$Z_{||}(\omega) = -\frac{1}{q^2}\int dz\ e^{i\omega z/v} E_z \Big|_{x,y=0} \qquad (\Omega)$$

$$\mathbf{j}^{||}(x,y,z;\omega) = \hat{\mathbf{z}} q \delta(x)\delta(y) e^{-i\omega z/v}$$

- horizontal:

$$Z_x(\omega) = \frac{i}{qd}\int dz\ e^{i\omega z/v}(E_x - vB_y)\Big|_{x,y=0} \qquad (\Omega/\text{m})$$

$$\mathbf{j}^{(x)}(x,y,z;\omega) = \hat{\mathbf{z}} q \delta(x-d)\delta(y) e^{-i\omega z/v}$$

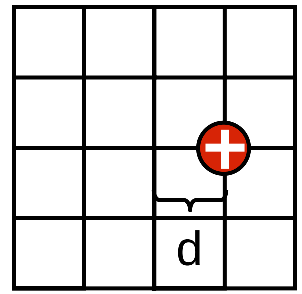
- vertical:

$$Z_x(\omega) = \frac{i}{qd}\int dz\ e^{i\omega z/v}(E_y + vB_x)\Big|_{x,y=0} \qquad (\Omega/\text{m})$$

$$\mathbf{j}^{(y)}(x,y,z;\omega) = \hat{\mathbf{z}} q \delta(x)\delta(y-d) e^{-i\omega z/v}$$

Twin-Wire Excitation

$$Z_x(\omega) = \frac{\mathrm{i}}{qd}\int dz\ e^{\mathrm{i}\omega z/v}(E_x - vB_y)_{(x=0,y=0)}$$



- from Faraday's law, $-B_y = \frac{1}{\mathrm{i}\omega}(\partial_z E_x - \partial_x E_z)$

$$Z_x(\omega) = \frac{v}{\omega qd}\int dz\ (\partial_z\{E_x e^{\mathrm{i}\omega z/v}\} - e^{\mathrm{i}\omega z/v}\partial_x E_z)$$

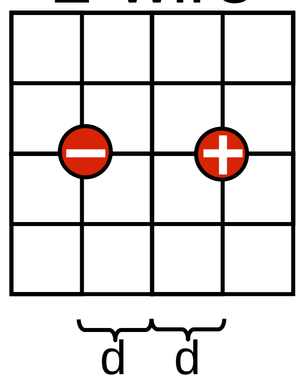
- dropping the 1st term yields

$$Z_x(\omega) \approx \frac{-v}{2\omega qd^2}\int dz\ e^{\mathrm{i}\omega z/v}(E_z(x=d) - E_z(x=-d))$$

$$Z_x(\omega) \approx \frac{-v}{\omega q^2(2x_0)^2}\int d^3\mathbf{r}\ \mathbf{j}^{(2x)}(\mathbf{r};\omega)^* \cdot \mathbf{E}^{(2)}(\mathbf{r};\omega)$$

$$\mathbf{j}_x^{(2x)}(\mathbf{r};\omega) = \hat{\mathbf{z}}q\{\delta(x-d) - \delta(x+d)\}\delta(y)e^{-\mathrm{i}\omega z/v}$$

2-wire



(ii) Numerical Approach

task: compute the EM fields excited by the beam

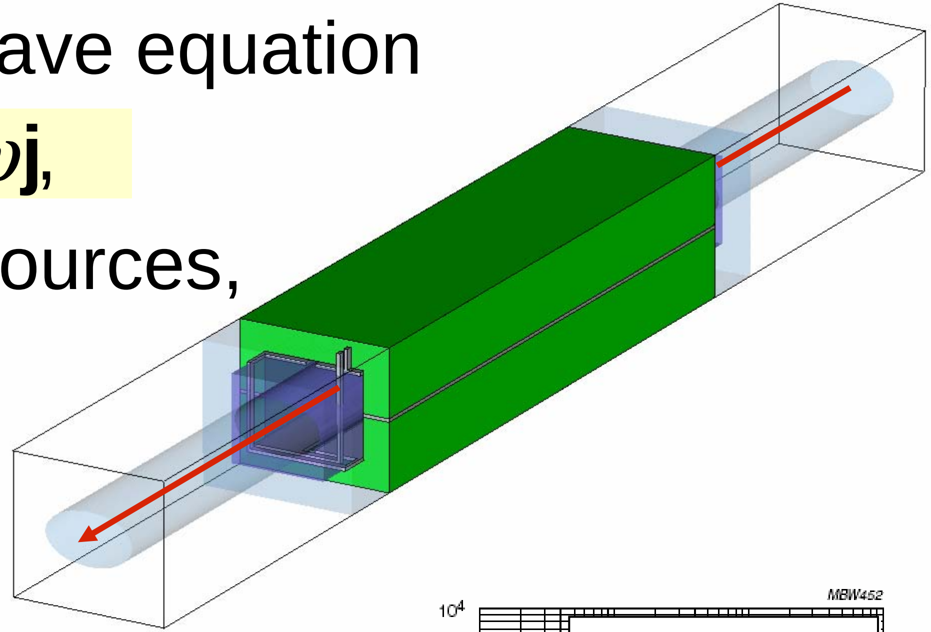
- chosen formulation: wave equation

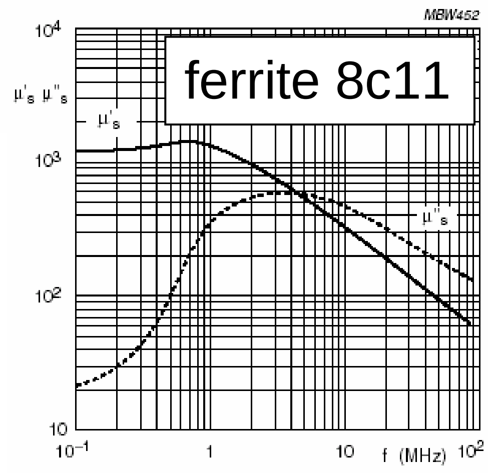
$$\partial x \mu^{-1} \partial x \mathbf{E} - \omega^2 \varepsilon \mathbf{E} = -\mathrm{i}\omega \mathbf{j},$$

- subject to one of the sources,

$$\mathbf{j} \in \{ \mathbf{j}^{||}, \mathbf{j}^{(2x)}, \mathbf{j}^{(2y)} \}$$

- complex $\mu(\omega)$
- non-trivial geometry
- beam-adapted boundary conditions





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Discrete Wave Equation

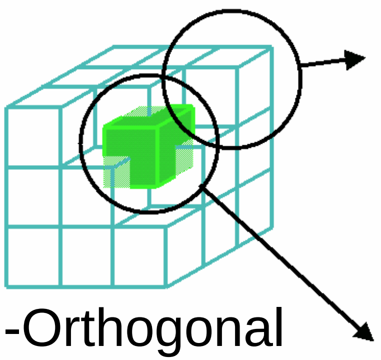
- Faraday's and Ampere's laws:

$$\left.\begin{aligned}\partial x\mathbf{E} &= -\mathrm{i}\,\omega\mu\mathbf{H}\\ \partial x\mathbf{H} &= \mathrm{i}\,\omega\varepsilon\mathbf{E}+\mathbf{j}\end{aligned}\right\}\Rightarrow\ \partial x\,\mu^{-1}\partial x\mathbf{E}-\omega^2\varepsilon\mathbf{E}=-\mathrm{i}\,\omega\mathbf{j}$$

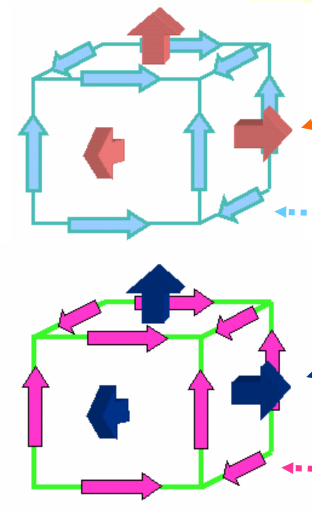
- discretization: Finite Integration Technique (FIT)

$$\left.\begin{aligned}\mathbf{Ce} &= -\mathrm{i}\,\omega\mathbf{M}_\mu\mathbf{h}\\ \mathbf{C}^T\mathbf{h} &= \mathrm{i}\,\omega\mathbf{M}_\varepsilon\mathbf{e}+\mathbf{j}\end{aligned}\right\}\Rightarrow\ \mathbf{C}^T\mathbf{M}_\mu^{-1}\mathbf{Ce}-\omega^2\mathbf{M}_\varepsilon\mathbf{e}=-\mathrm{i}\,\omega\mathbf{j}$$

(linear system of equations)



Dual-Orthogonal Grid



$$b_i = \int_{\text{face } i} d\mathbf{a}\cdot\mathbf{B}$$

$$e_i = \int_{\text{edge } i} d\mathbf{s}\cdot\mathbf{E}$$

$$d_i = \int_{\text{dual face } i} d\mathbf{a}\cdot\mathbf{D}$$

$$h_i = \int_{\text{dual edge } i} d\mathbf{s}\cdot\mathbf{H}$$

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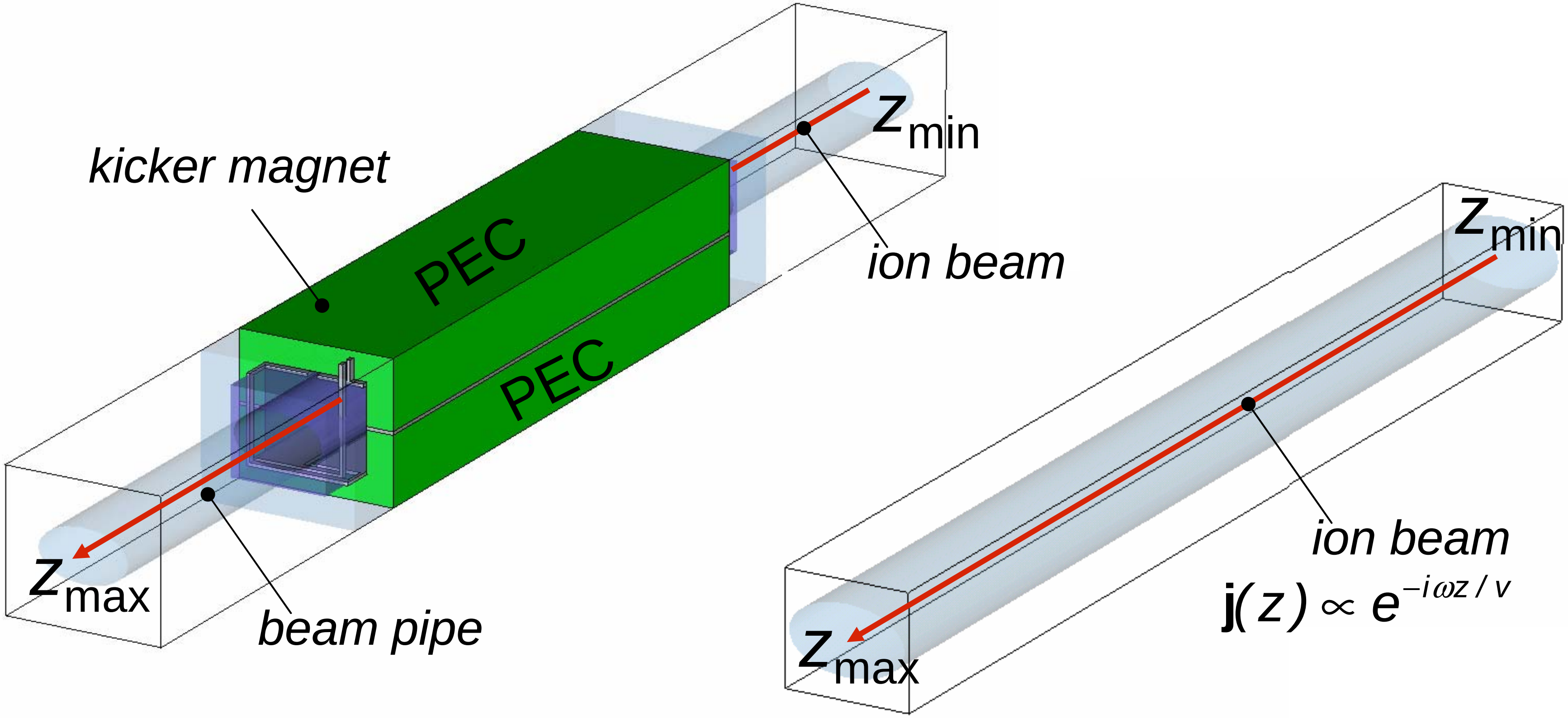
Boundary Conditions

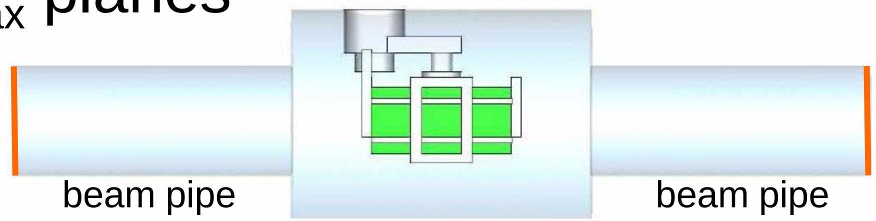
- perfectly-conducting background material assumed:



- which b.c. to choose at beam-entry / exit planes ?
- ∞ beam pipe: $\mathbf{j}(z) \propto e^{-i\omega z/v} \Rightarrow \mathbf{E}(z), \mathbf{B}(z) \propto e^{-i\omega z/v}$
- $f<f_{cutoff}$: no propagating beam-pipe modes

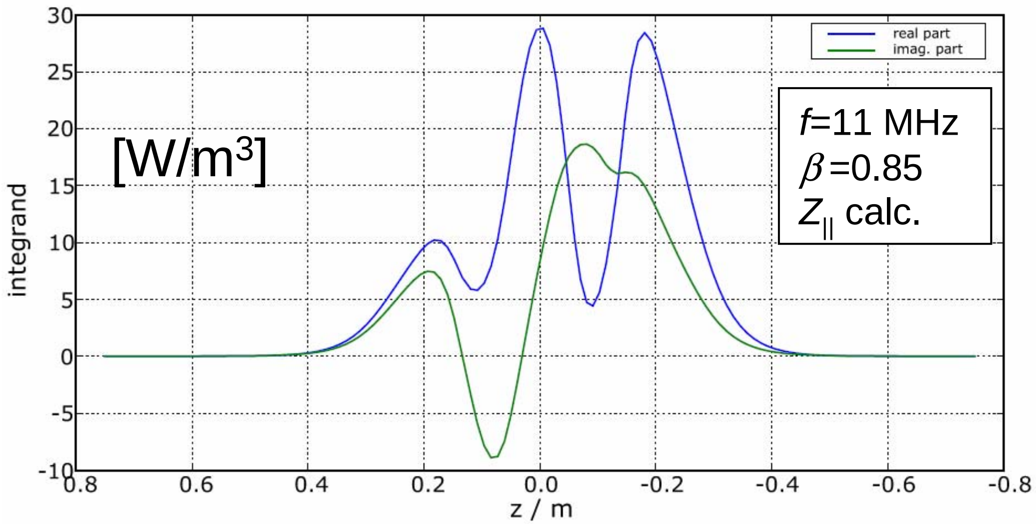
Beam-Adapted Boundary Conditions

- in beam pipes: $\mathbf{E}(z), \mathbf{B}(z) \propto e^{-i\omega z/v} \Rightarrow \frac{\partial}{\partial z} \rightarrow -i\frac{\omega}{v}$
  - ➢ quasi-2D wave equation
- for 3D problem:
  - – solve 2D at z_{min} and z_{max} planes
  - – use 2D solutions as 3D dirichlet b.c.



- illustration:

$$Z_{\parallel} \propto \int dz \ j_z^{(\parallel)}(z)\, E_z(z)\Big|_{x=y=0}$$



[see also: M. Balk et al., proc. IEEE AP-S/URSI 2003]

Solution of the Linear Equations

$$\mathbf{C}^T\mathbf{M}_\mu^{-1}\mathbf{C}\mathbf{e} - \omega^2\mathbf{M}_\varepsilon\mathbf{e} = -i\omega\mathbf{j}$$

$$\mathbf{e} = \mathbf{e}_0 + \mathbf{e}_{\mathrm{dyn}}$$ *(Helmholtz split)*

$$\mathbf{C}\mathbf{e}_0 = 0, \quad \mathbf{G}^T\mathbf{M}_\varepsilon\mathbf{e}_0 = -\frac{1}{i\omega}\mathbf{G}^T\mathbf{j}$$ *(electrostatics)*

(wave equ.)

$$\mathbf{G}^T\mathbf{M}_\varepsilon\mathbf{e}_{\mathrm{dyn}} = 0$$ *(discretely divergence-free)*

$$\mathbf{C}^T\mathbf{M}_\mu^{-1}\mathbf{C}\mathbf{e}_{\mathrm{dyn}} - \omega^2\mathbf{M}_\varepsilon\mathbf{e}_{\mathrm{dyn}} = -i\omega\mathbf{j} + \omega^2\mathbf{M}_\varepsilon\mathbf{e}_0$$

(rescaling)

$$\mathbf{M}_\varepsilon^{-1/2}\mathbf{C}^T\mathbf{M}_\mu^{-1}\mathbf{C}\mathbf{M}_\varepsilon^{-1/2}\mathbf{e}'_{\mathrm{dyn}} - \omega^2\mathbf{e}'_{\mathrm{dyn}} = -i\omega\mathbf{M}_\varepsilon^{-1/2}\mathbf{j} + \omega^2\mathbf{e}'_0$$

$$\left(\mathbf{e}'_{\mathrm{dyn}} = \mathbf{M}_\varepsilon^{1/2}\mathbf{e}_{\mathrm{dyn}}\right)$$ *(complex-symmetric, solve by COCG)*

The Impedance Code

Features:

- based on the Finite Integration Technique (FIT)*
- CAD and meshing by *CST MICROWAVE STUDIO*®
- 3D / 2D modules
- special beam boundary conditions
- integrated post-processing $\rightarrow \quad Z_{\|}(\omega), \quad Z_{x,y}(\omega)$
- hybrid *Python* / *C*$^{++}$ implementation:
  - pre- and postprocessing, EM field problem formulation
  - linear-algebra subroutines (*Trilinos*, Sandia)

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* T. Weiland, *AEU-Int. J. Electron. Commun.*, 31(3):116–120, 1977.

(iii) Simulation *vs.* Analytical Results

- Tsutsui's formula for $Z_{||}(\omega)$ in simple, 2D ferrite structures
- Zotter's formula for $Z_x(\omega)$ in axi-symmetric 2D chambers

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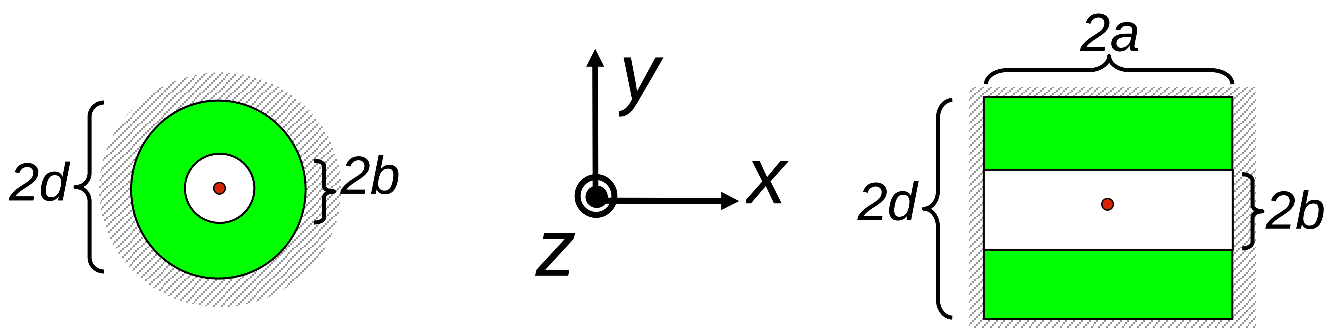
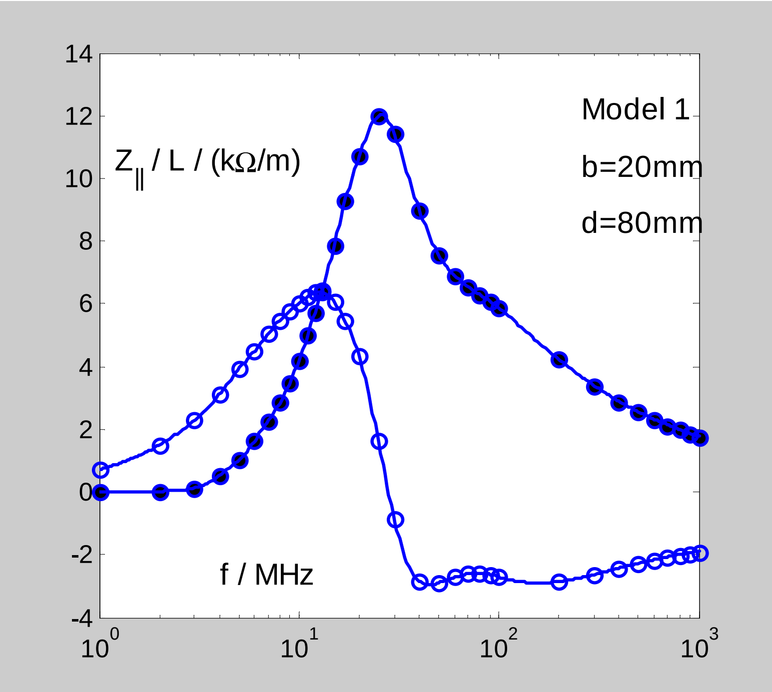
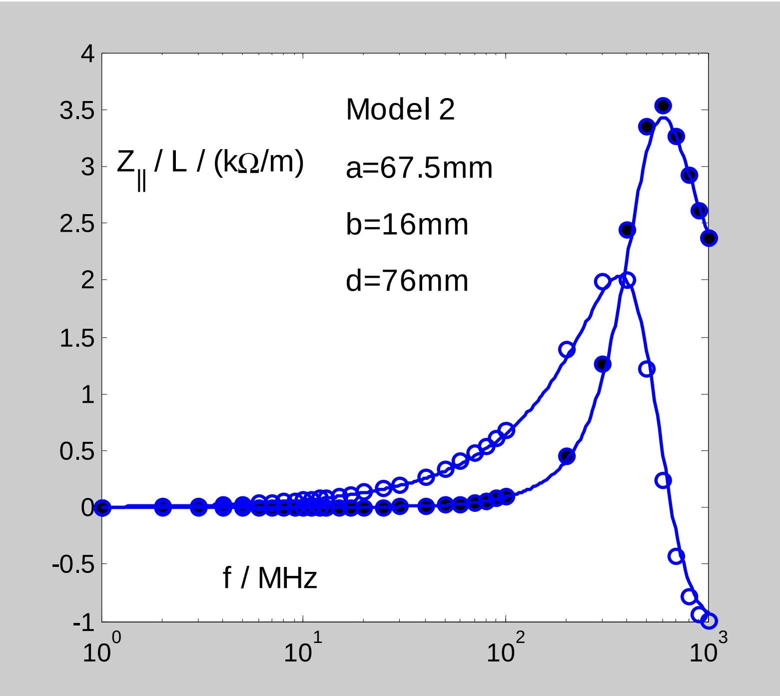
2D Ferrite Structures: $Z_{||}(\omega)$

- analytical formulas from [Tsutsui, CERN-2000-004 AP]







ferrite 4a4

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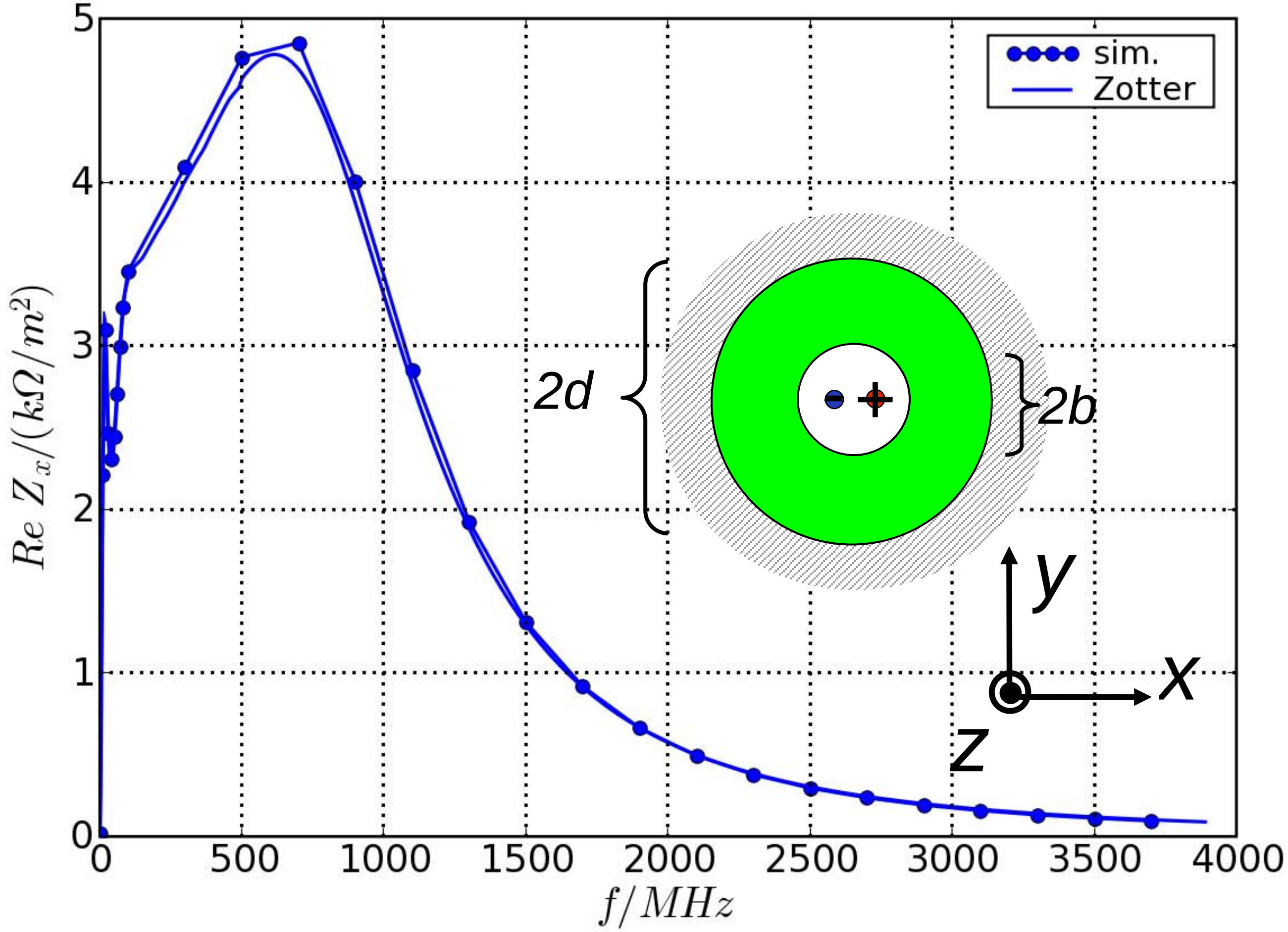
2D Ferrite Structures: $Z_x(\omega)$

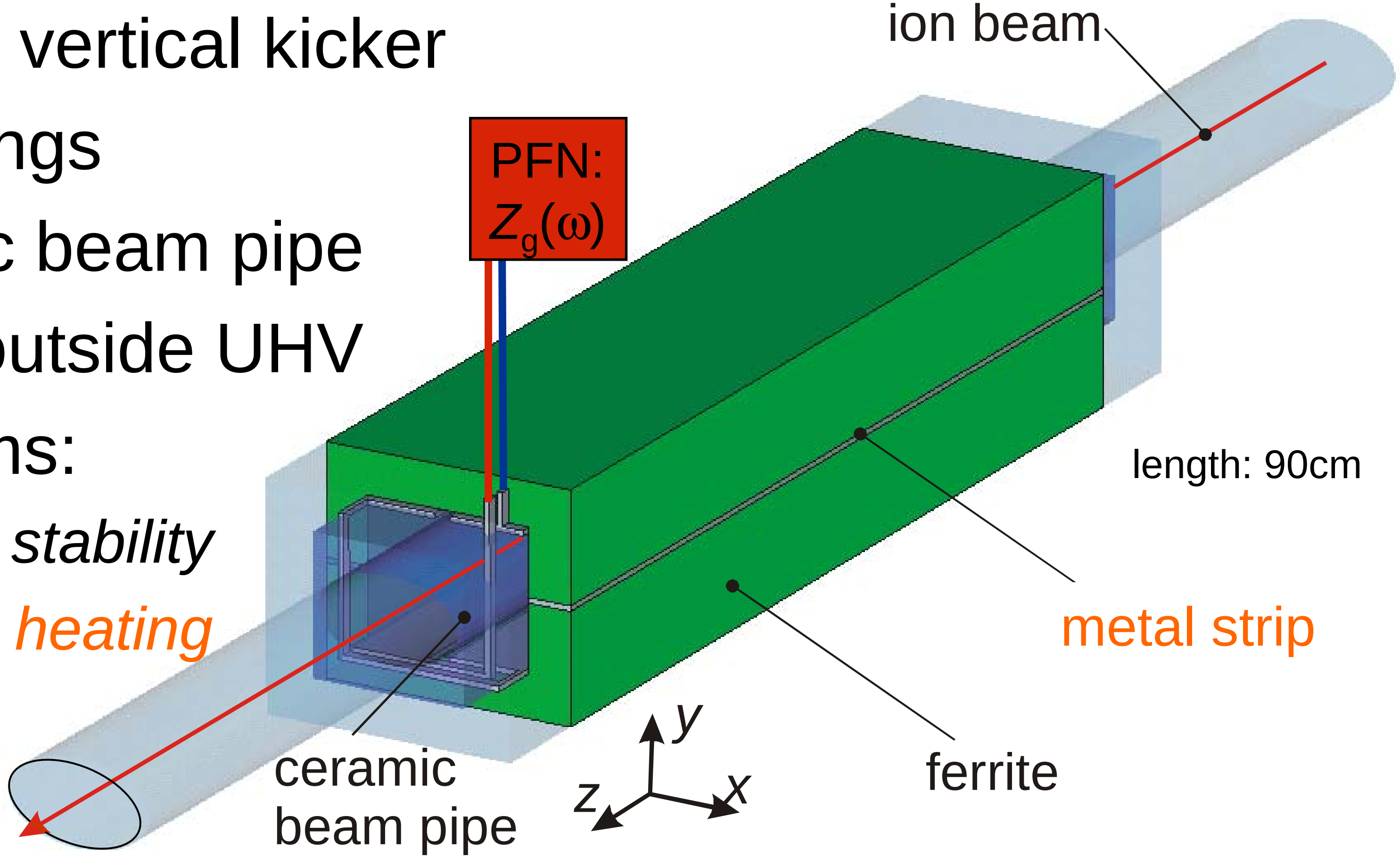
- analytical formulas from
  [B.W. Zotter, CERN-AB-2005-043, 2005]



ferrite 4a4

(iv) SIS-100 Extraction/Emergency Kicker

- bipolar, vertical kicker
- 2 windings
- ceramic beam pipe
- ferrite outside UHV
- ➢ problems:
  - *beam stability*
  - *ferrite heating*



- f < 250MHz: PFN footprint in Z_y
- 250MHz < f < f_{cutoff}=1.325GHz: ferrite-dominated

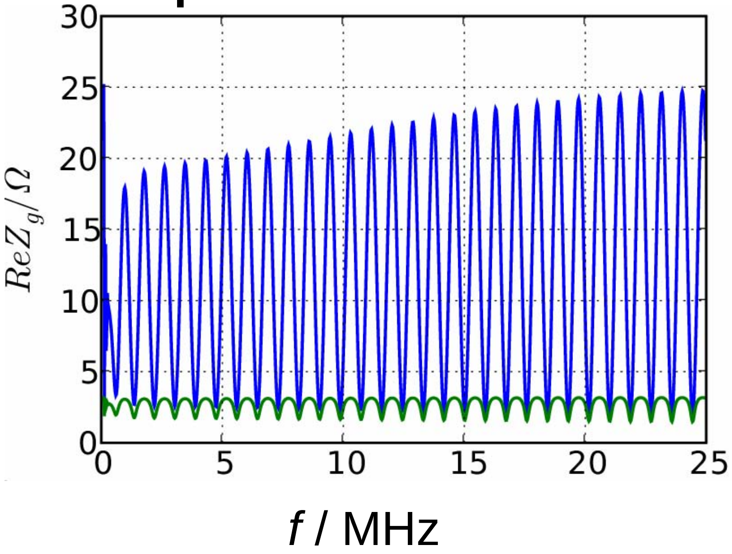
Effect of the PFN

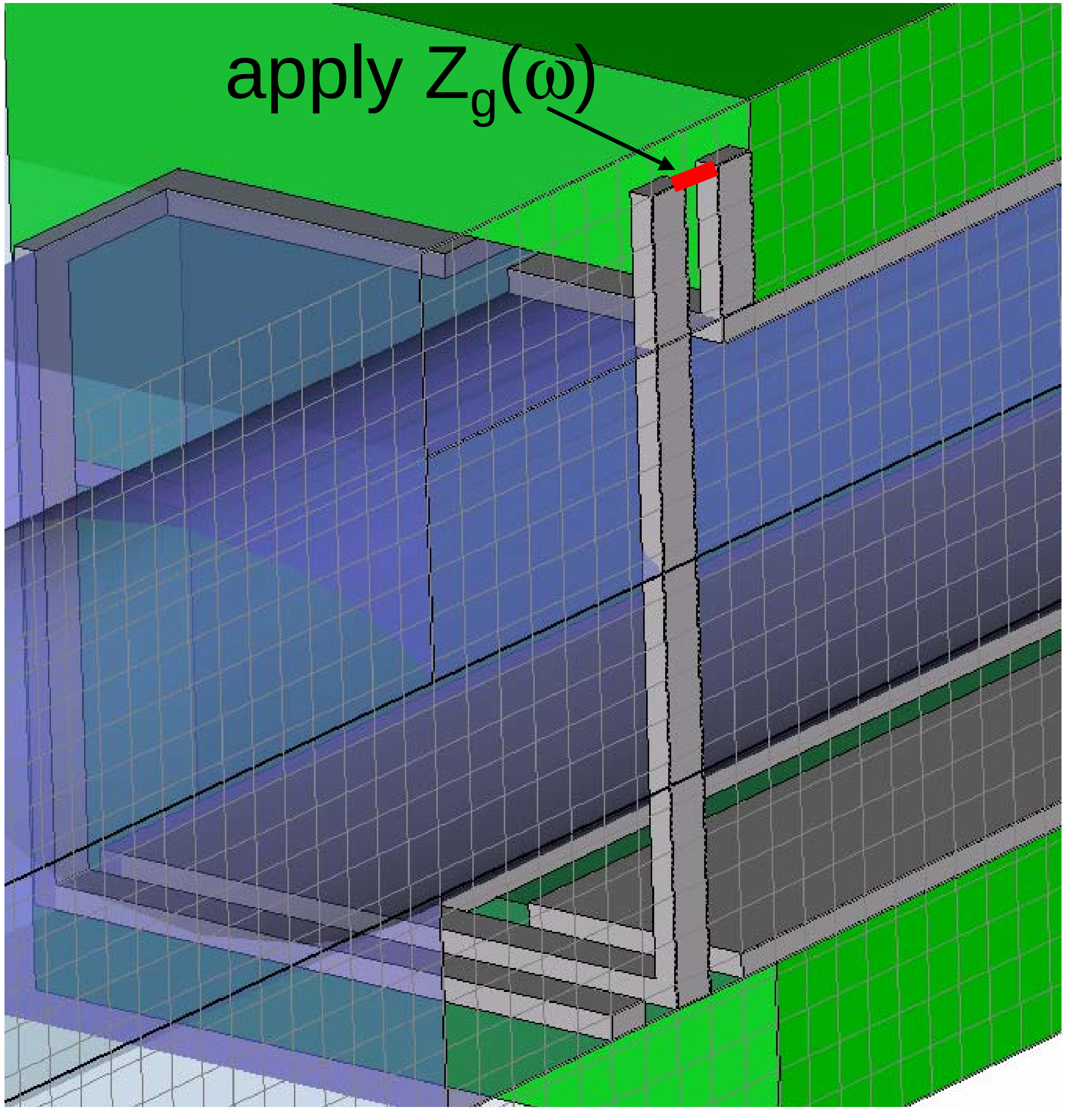
- external PFN included by lumped impedance $Z_g(\omega)$

$$(\mathbf{M}_\varepsilon)_{jj} \rightarrow$$

$$(\mathbf{M}_\varepsilon)_{jj} + \frac{1}{\mathrm{i}\omega Z_g(\omega)}$$

bipolar PFN:





Inductive PFN Coupling

- flux induced by currents:

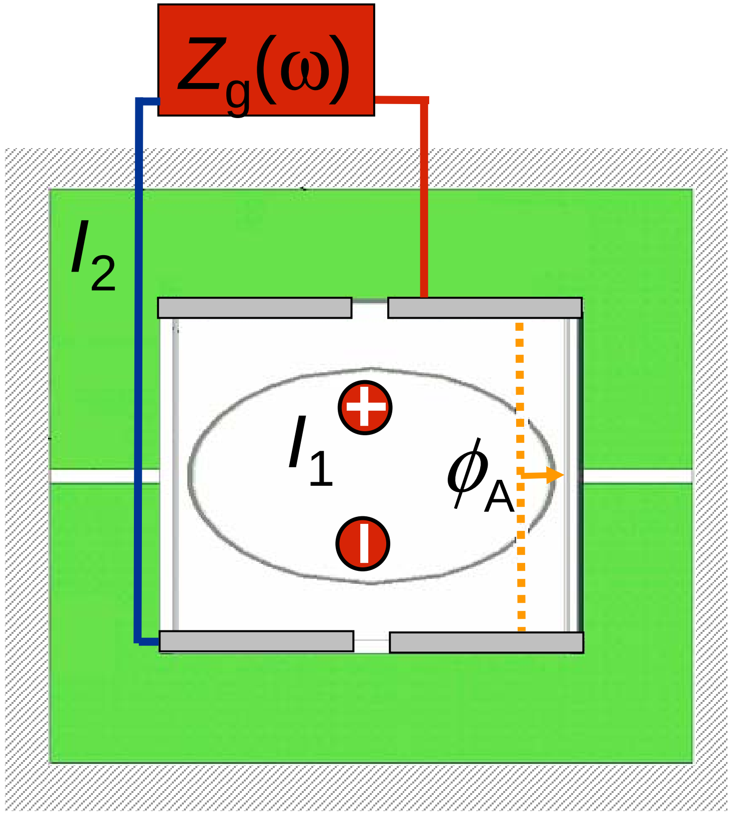
$$\mathrm{i}\omega\phi_{\mathrm{A}} = AI_1 + BI_2$$

- coil and PFN in series:

$$2\mathrm{i}\omega\phi_{\mathrm{A}} = -Z_{\mathrm{g}}\, I_2$$

- thus,

$$I_2 = \frac{-2A}{2B + Z_{\mathrm{g}}} I_1$$



$$\mathrm{j}^{(2y)} \propto I_1$$

- yielding

$$\mathrm{j}^{(2y)*} \cdot \mathrm{E} = I_1(CI_1 + DI_2) = \left(C - \frac{2AD}{2B + Z_{\mathrm{g}}} \right) I_1^2$$

Parameterization

$$Z_y \propto \frac{1}{I_1^2} \int dV \; \mathrm{j}^{(2y)*} \cdot \mathrm{E}$$

[compare Nassibian and Sacherer, NIM, 1979]

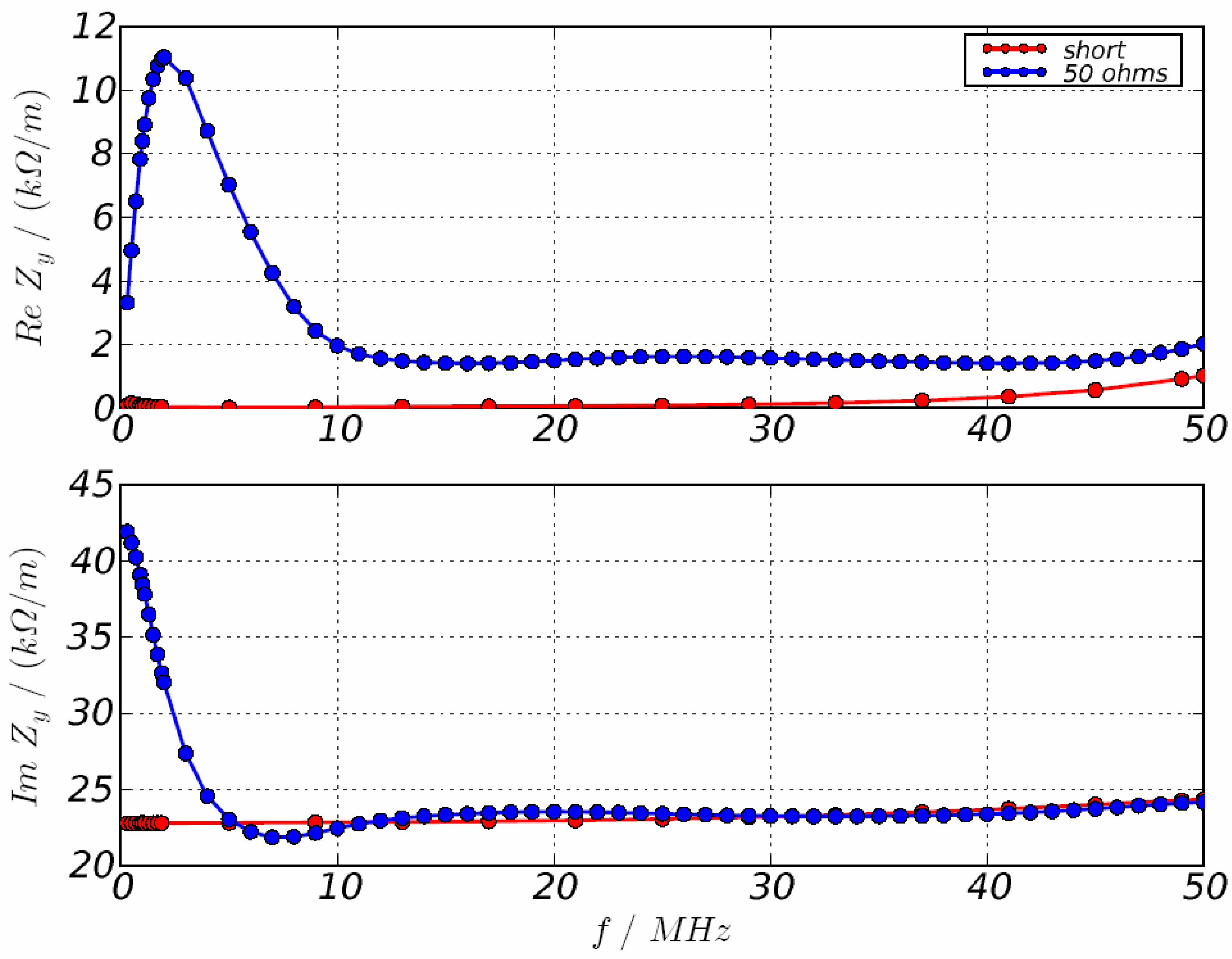
$$Z_y(\omega, Z_\mathrm{g}) = a(\omega) - \frac{b(\omega)}{c(\omega) + Z_\mathrm{g}(\omega)}$$

- computing $Z_y(\omega)$ for three situations, e.g.

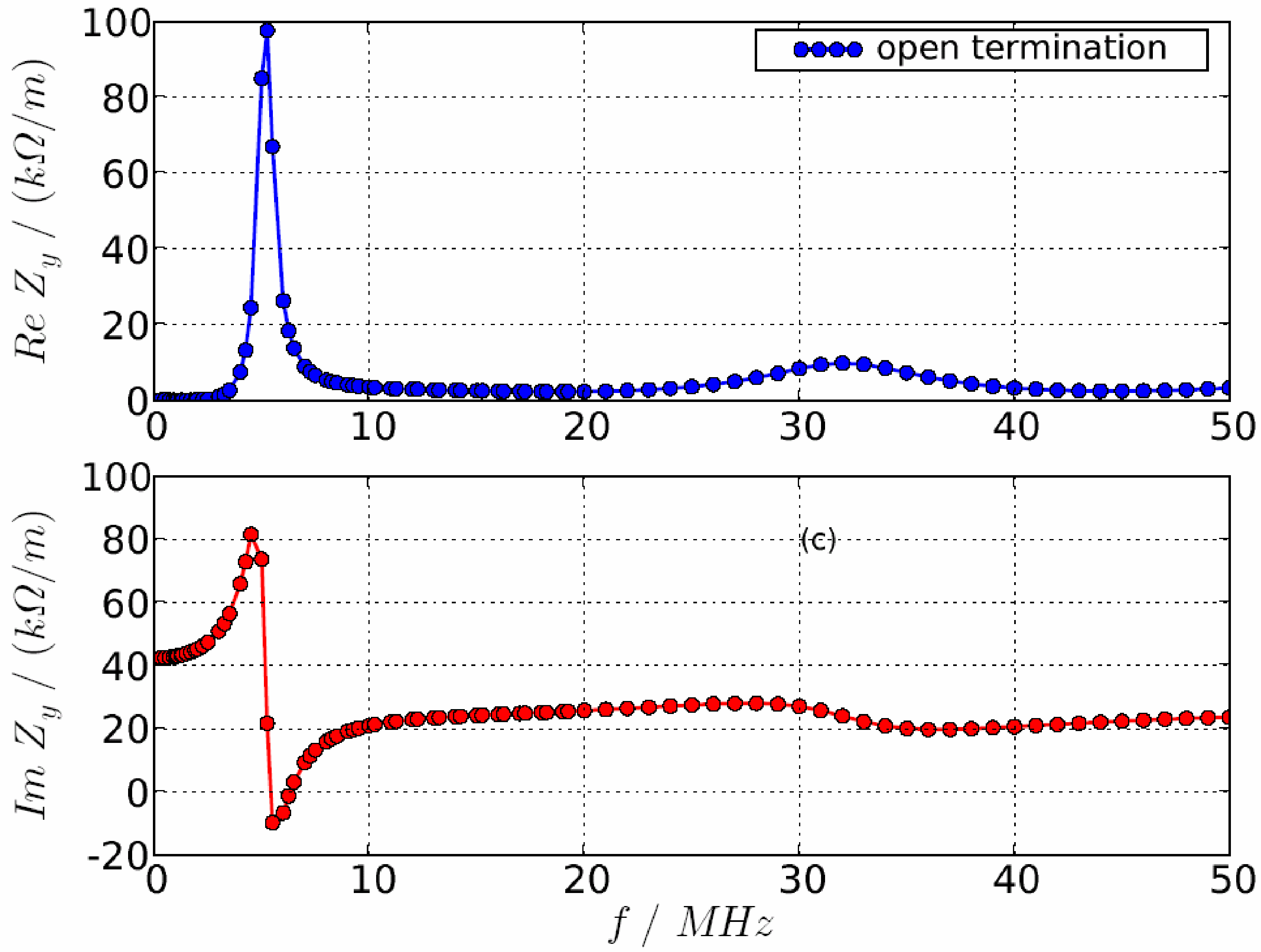
$$Z_\mathrm{g}(\omega) \in \{\, 0,\ \infty,\ 50 \,\}\Omega$$

determines the coefficients $a(\omega)$, $b(\omega)$, $c(\omega)$

$Z_g(\omega)=0\Omega,\ 50\Omega$

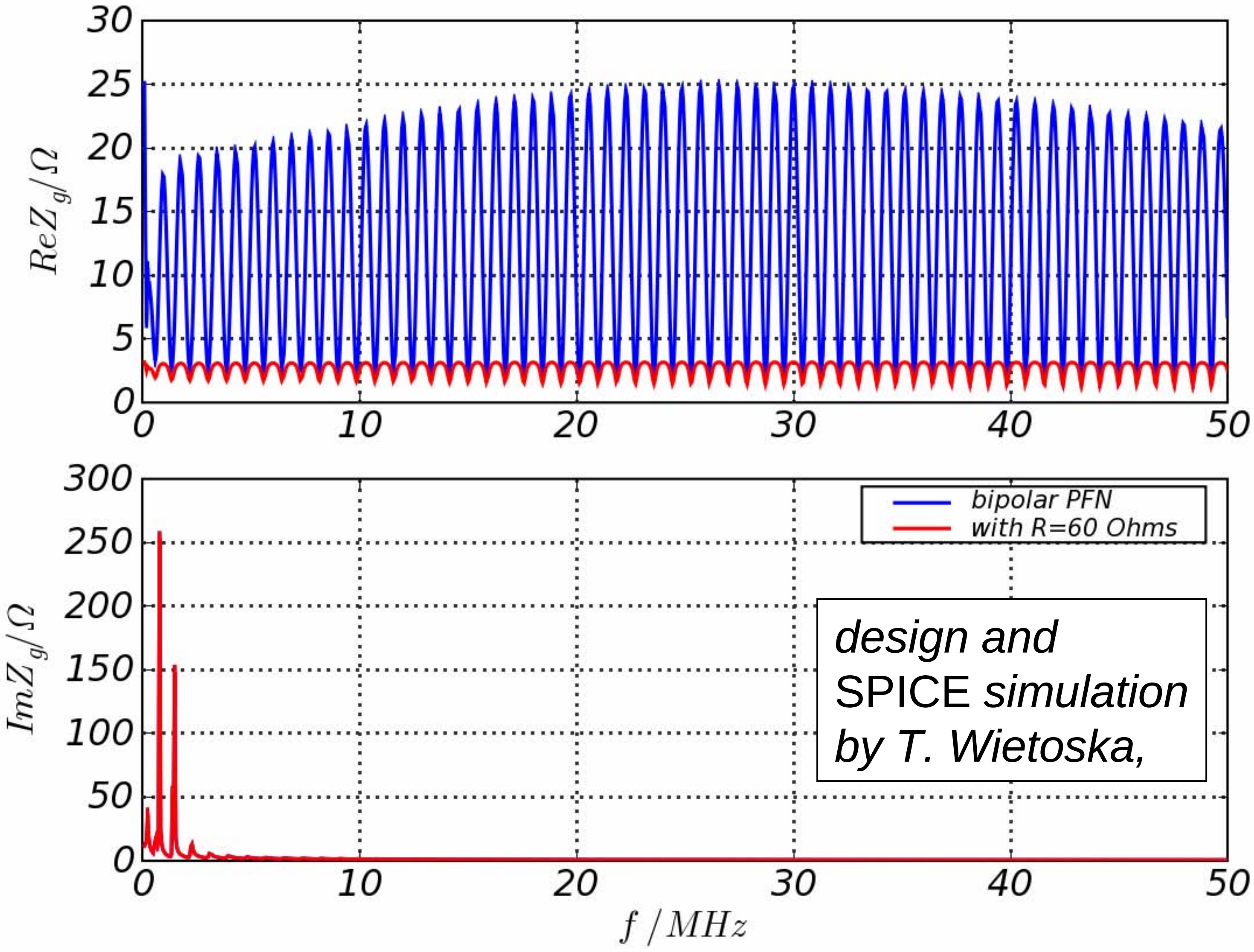


Open Termination

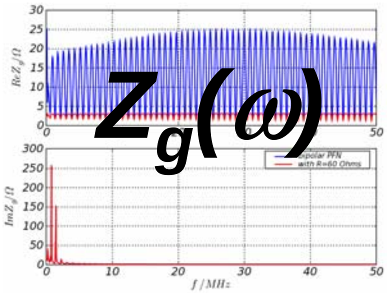


Impedance of the Real PFN

- two versions: with and without 60Ω damping resistance:



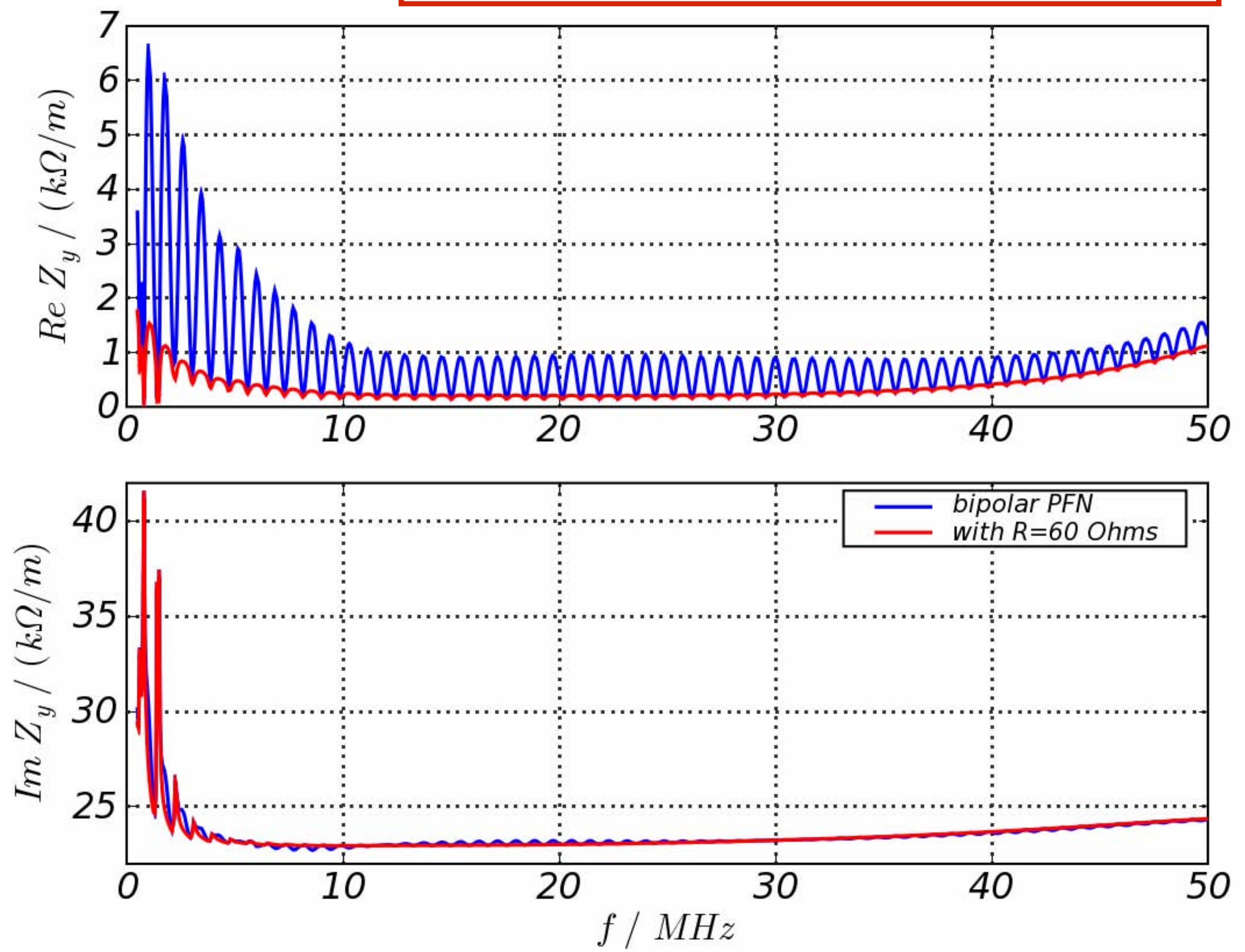
Computing Z_y



+

$$Z_y(\omega, Z_g) = a(\omega) - \frac{b(\omega)}{c(\omega) + Z_g(\omega)}$$

=



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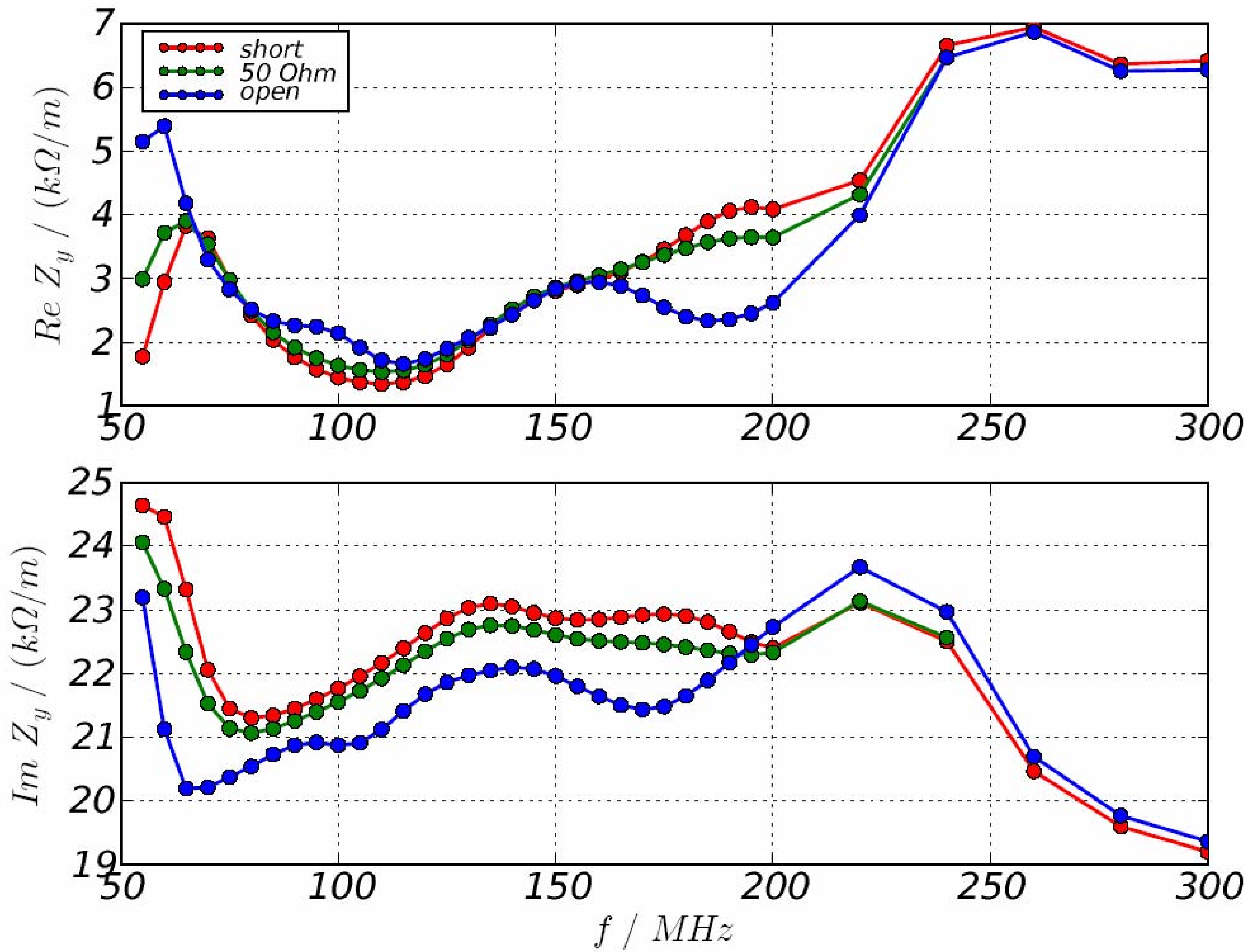
End of PFN-dominated regime



Summary

- ✓ development of a 2D/3D impedance code
- ✓ FIT, frequency domain wave equation
- ✓ special beam boundary conditions
- ✓ checks against analytical results
- ✓ SIS 100 extraction/emergency kicker
- ✓ PFN model

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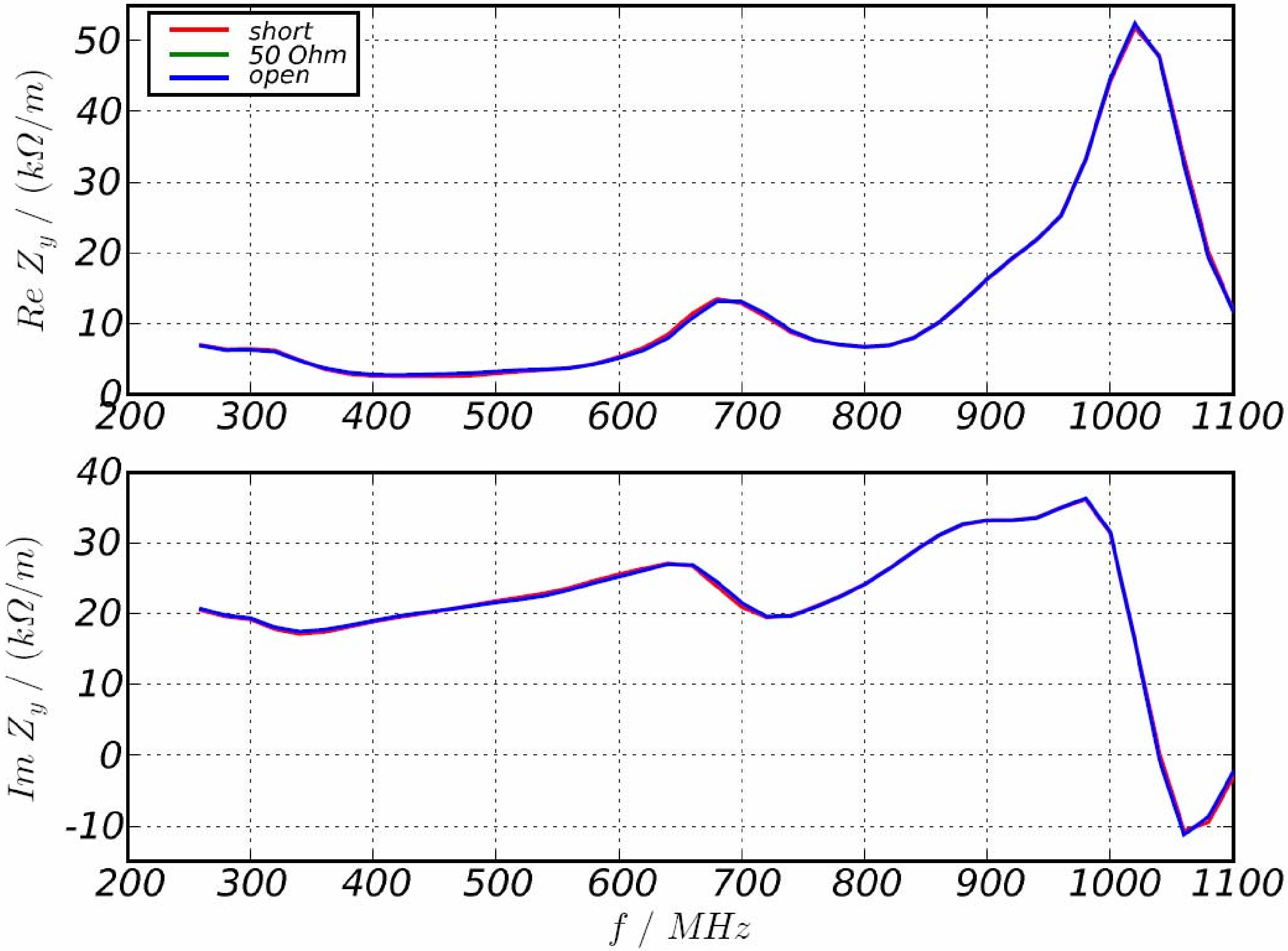
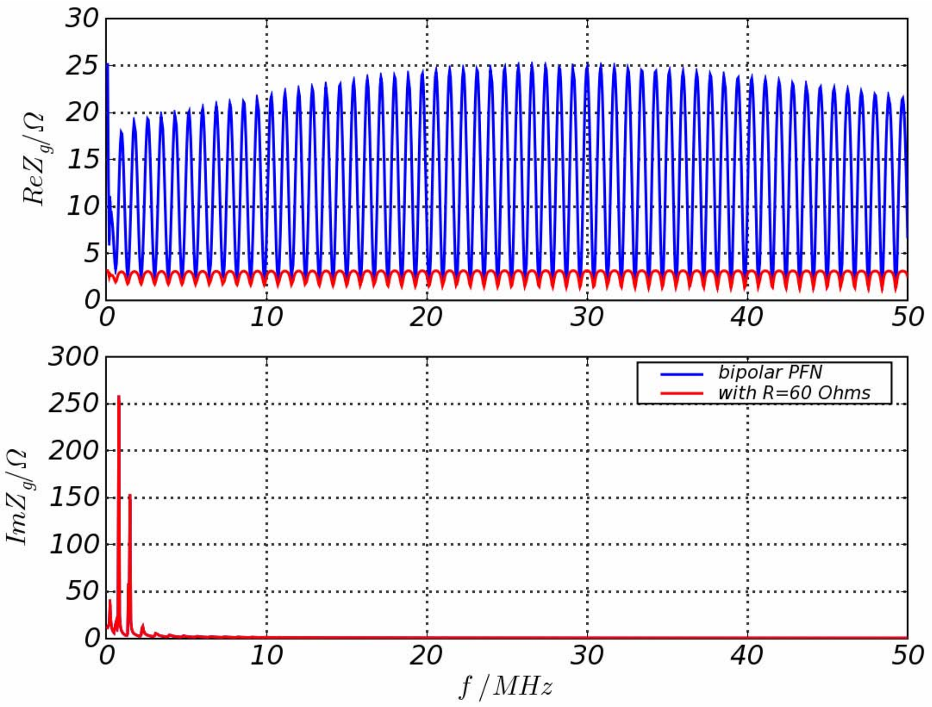
Acknowledgements

We thank the DFG (contract GK 410/3)
and the GSI for funding this work.

Thank you for your attention.


short
50 Ohm
open
$Re\ Z_y$ / $(k\Omega/m)$
0
10
20
30
40
50
200
300
400
500
600
700
800
900
1000
1100
$Im\ Z_y$ / $(k\Omega/m)$
-10
0
10
20
30
40
200
300
400
500
600
700
800
900
1000
1100
f / MHz

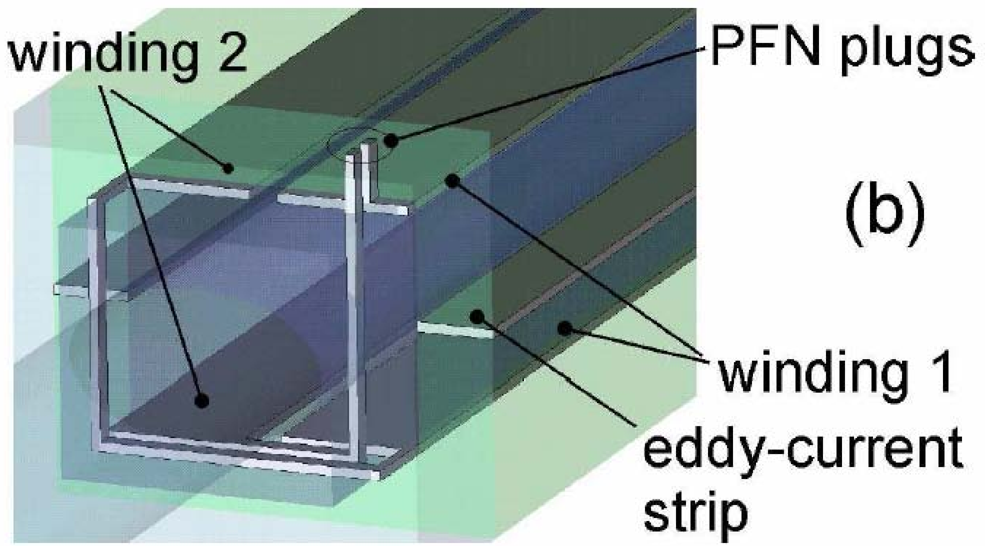
Computing Z_y



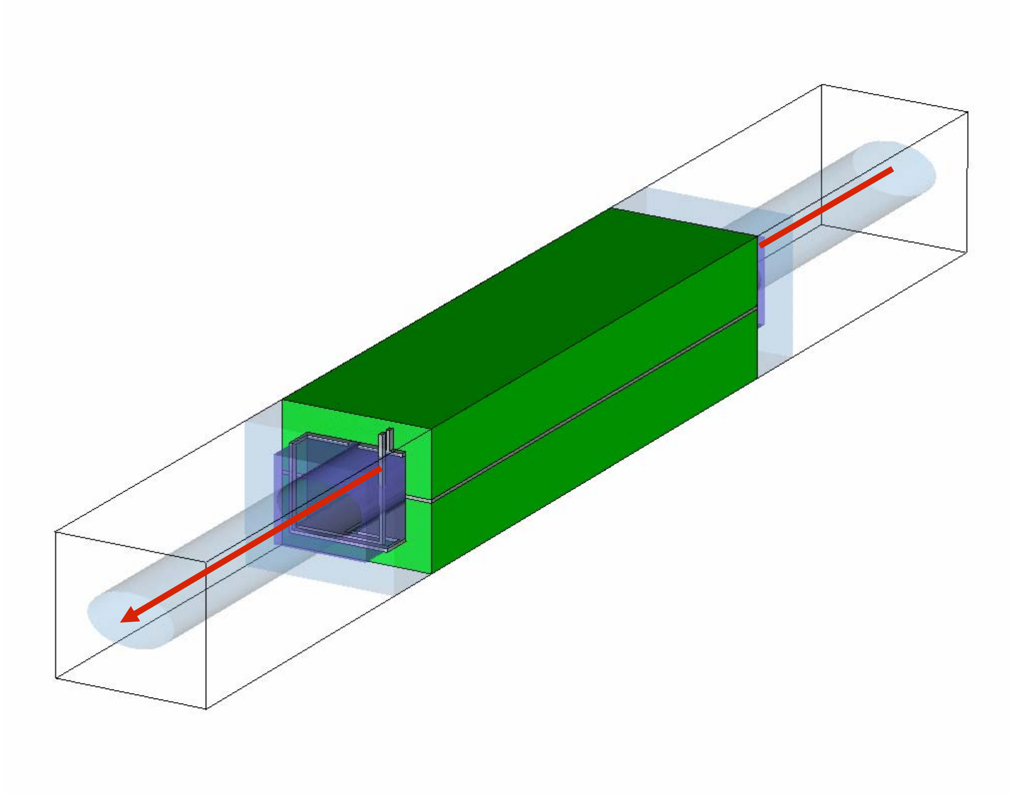
+

$$Z_y(\omega, Z_g) = a(\omega) - \frac{b(\omega)}{c(\omega) + Z_g(\omega)}$$

SIS-100 Extraction/Emergency Kicker



The SIS-100 Kickers



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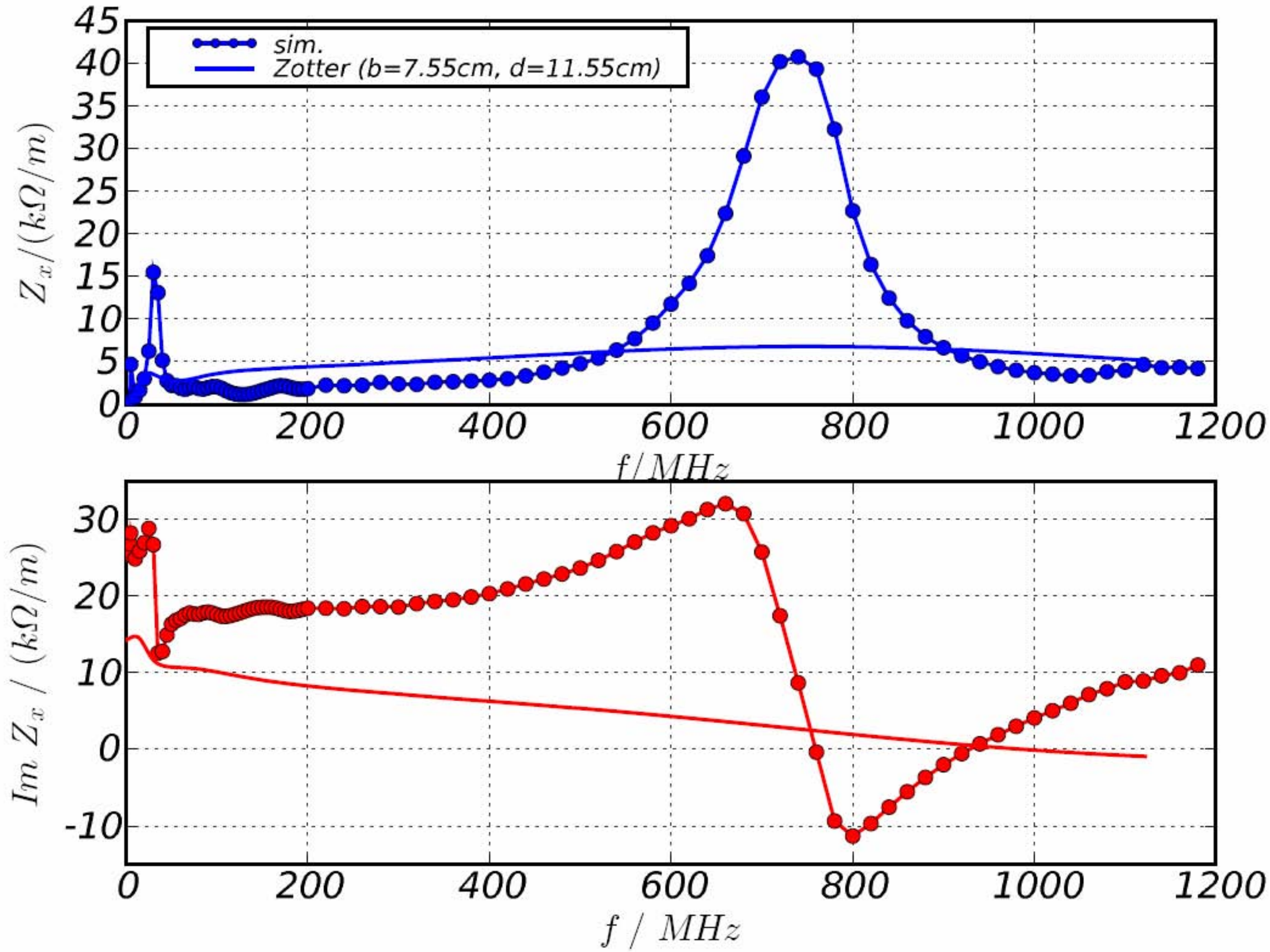
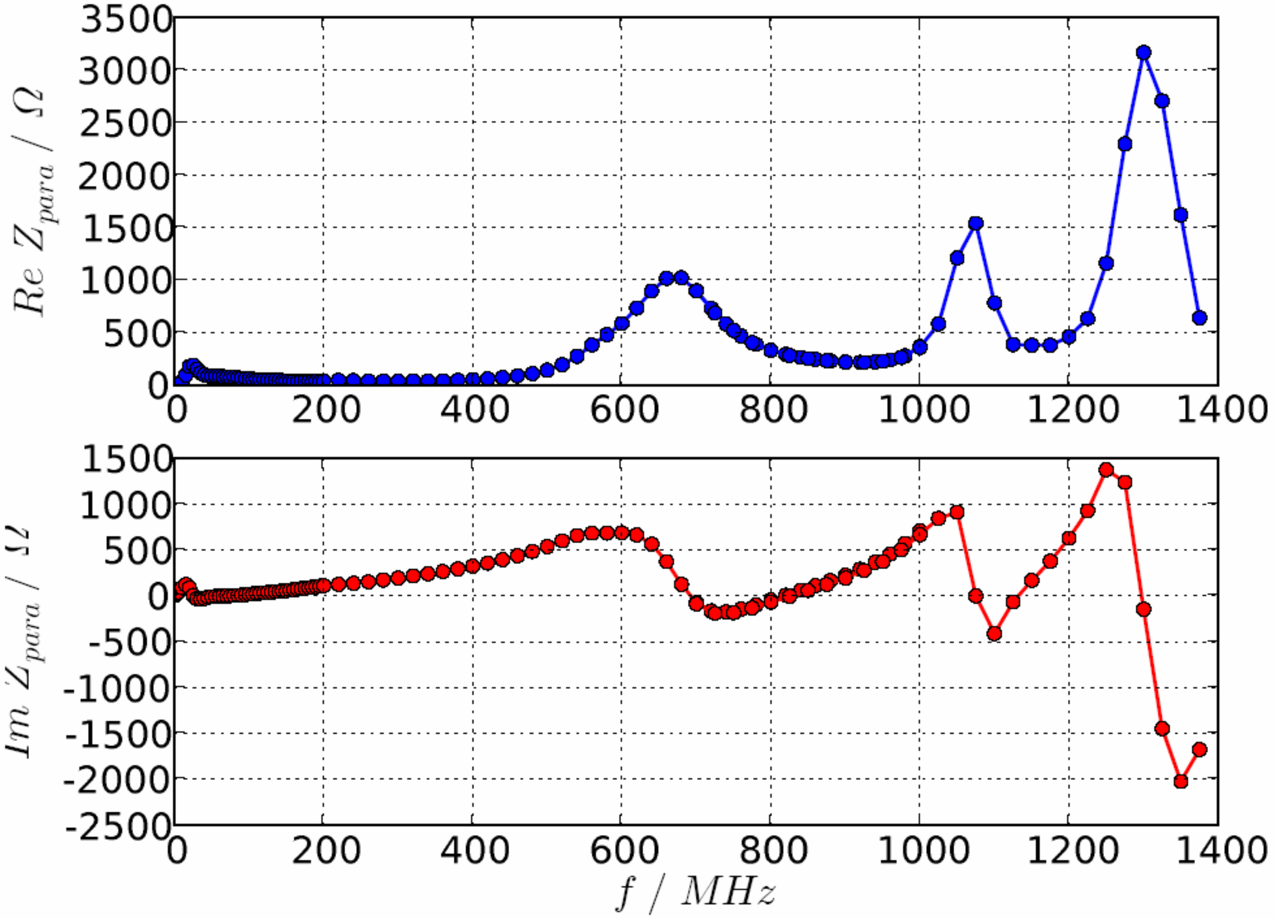
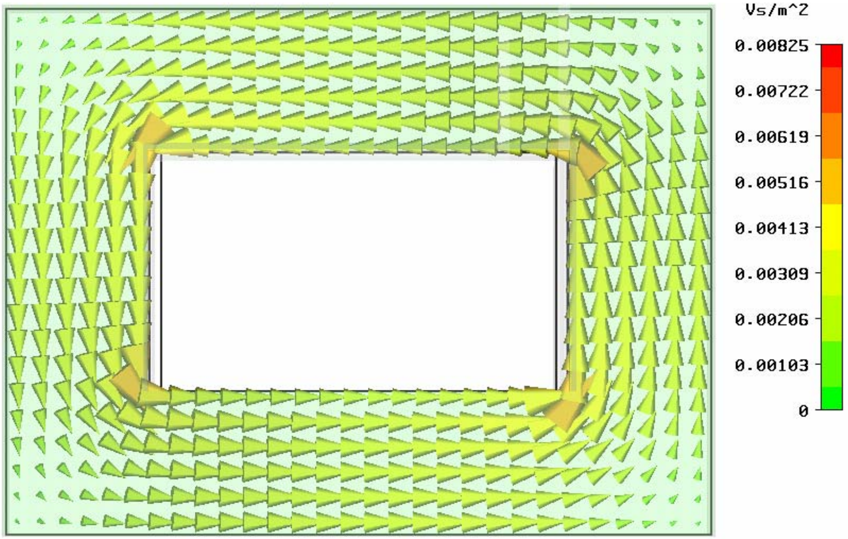
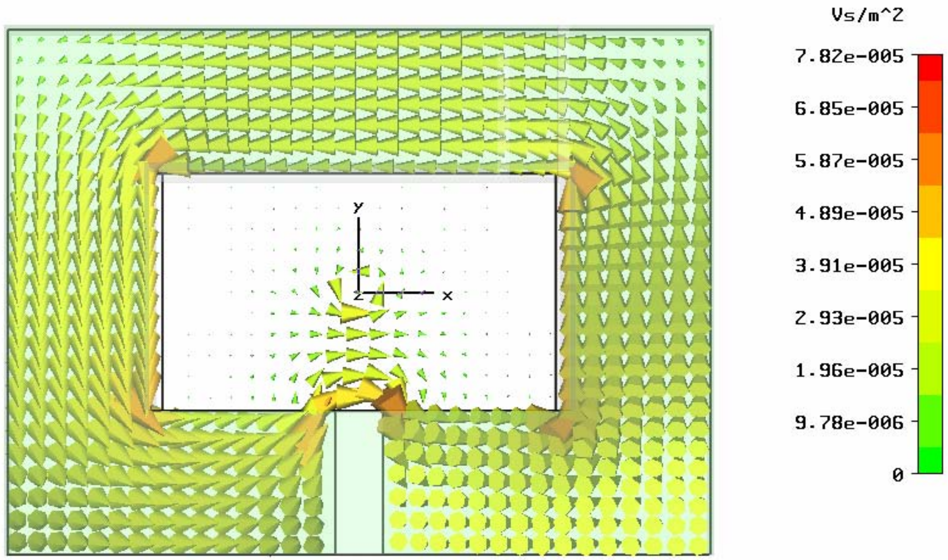

sim.
Zotter (b=7.55cm, d=11.55cm)
$Z_x/(k\Omega/m)$
f/MHz
$Im\ Z_x\ /\ (k\Omega/m)$
$f\ /\ MHz$
0
200
400
600
800
1000
1200
45
40
35
30
25
20
15
10
5
-10


3500
3000
2500
2000
1500
1000
500
0
Re Z_{para} / Ω
0
200
400
600
800
1000
1200
1400
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
Im Z_{para} / Ω
f / MHz

Reduction of Kicker Heating





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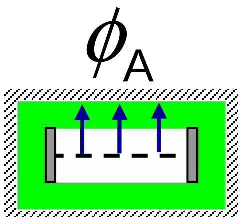

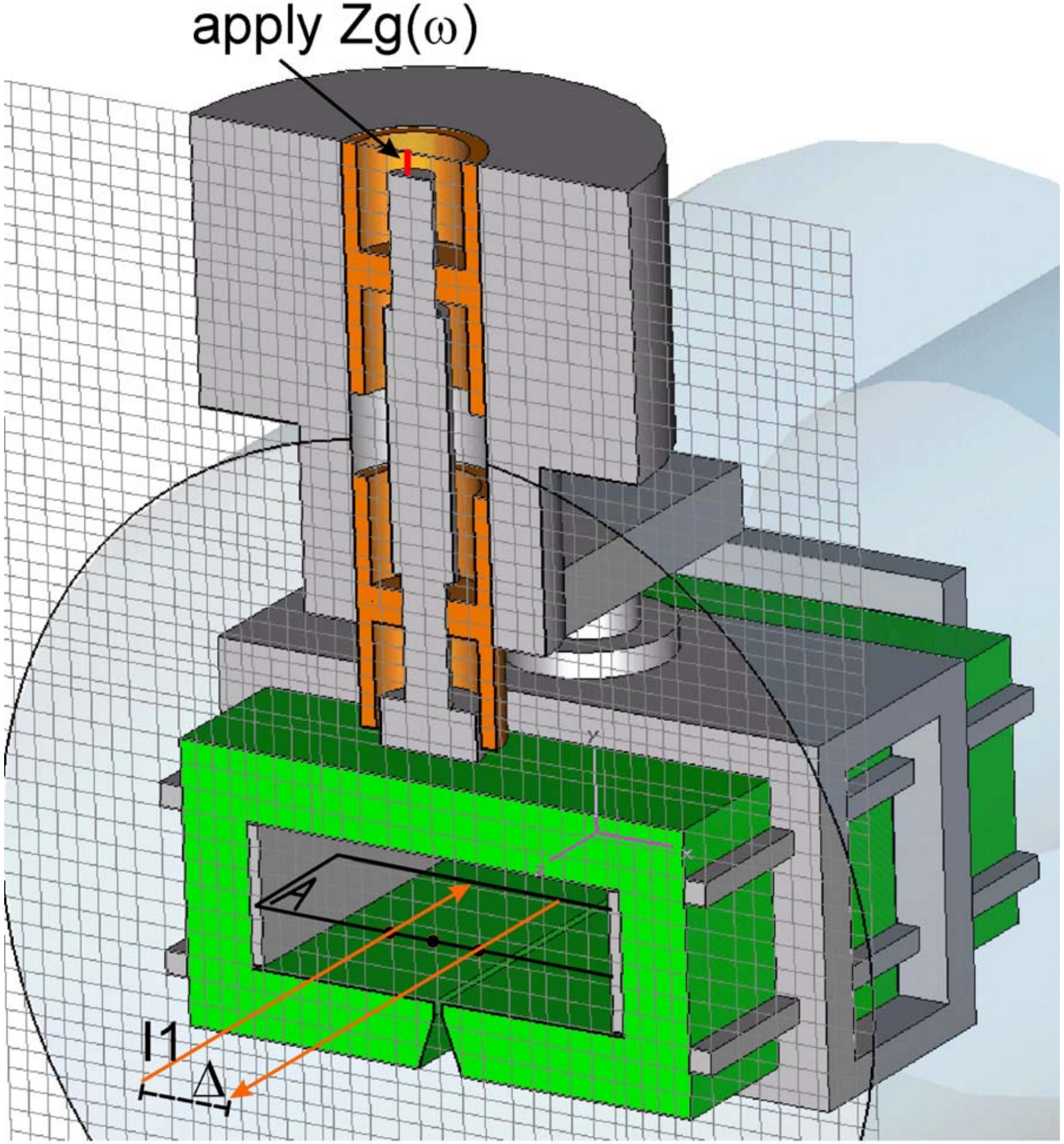

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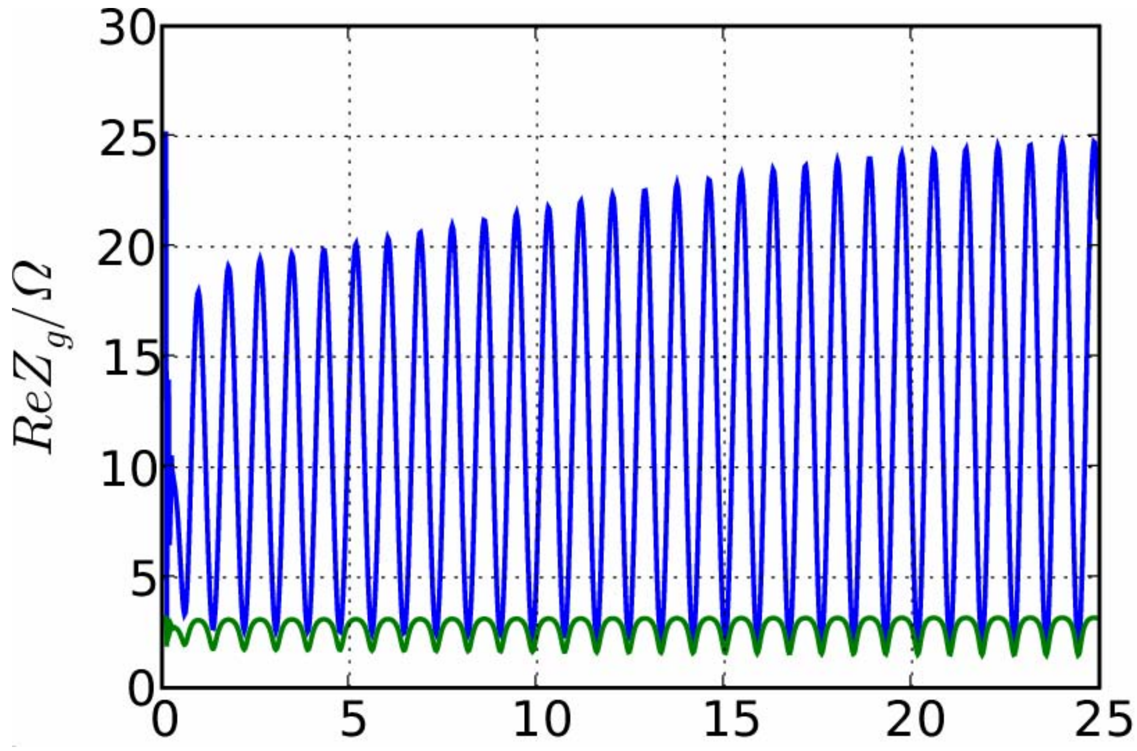
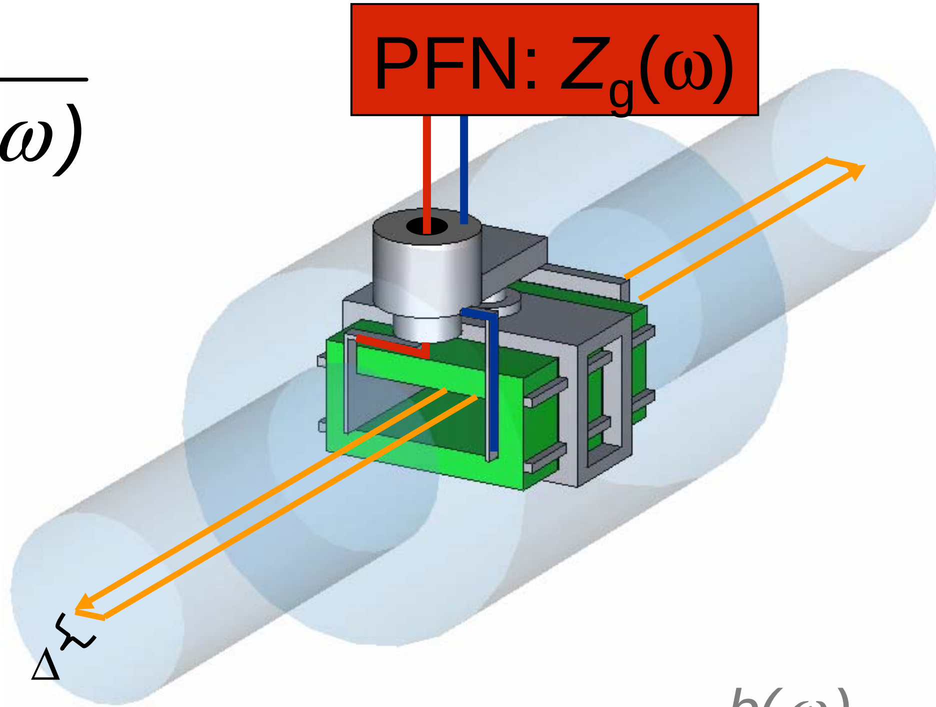
- with / without 60-Ω damping resistor



Transformer Picture

[Nassibian and Sacherer, NIM, 1979]

$$Z_x(\omega) = \frac{\beta c}{\Delta^2} \frac{\omega M^2}{\mathrm{i}\omega L + Z_g(\omega)}$$



- coil self inductance: L
- mutual inductance beam-coil: $M \propto \Delta$
- nearly identical to our formula

$$Z_x(\omega) = a(\omega) - \frac{b(\omega)}{c(\omega) + Z_g(\omega)}$$

➢ *no uncoupled contribution*

➢ *M and L are real, frequency independent*

Outline

(A) What to compute?

(B) Computational Approach

(C) Checks agains Analytically Models

(D) SIS-100 Extraction/Emergency Kicker

in collaboration with

Udo Blell, Oliver Boine-Frankenheim
Vladimir Kornilov, Ahmed Al-khateeb

Gesellschaft für Schwerionenforschung, Darmstadt

(F) Outlook

- consideration of all SIS-100 kickers (extraction/emergency, transfer, Q)
- modeling of feed-throughs
- code improvement:
  - adoption of finite-element library FEMSTER
  - *3D* simulation of metalized ceramic pipe
  - parallelization
- validation against measurements

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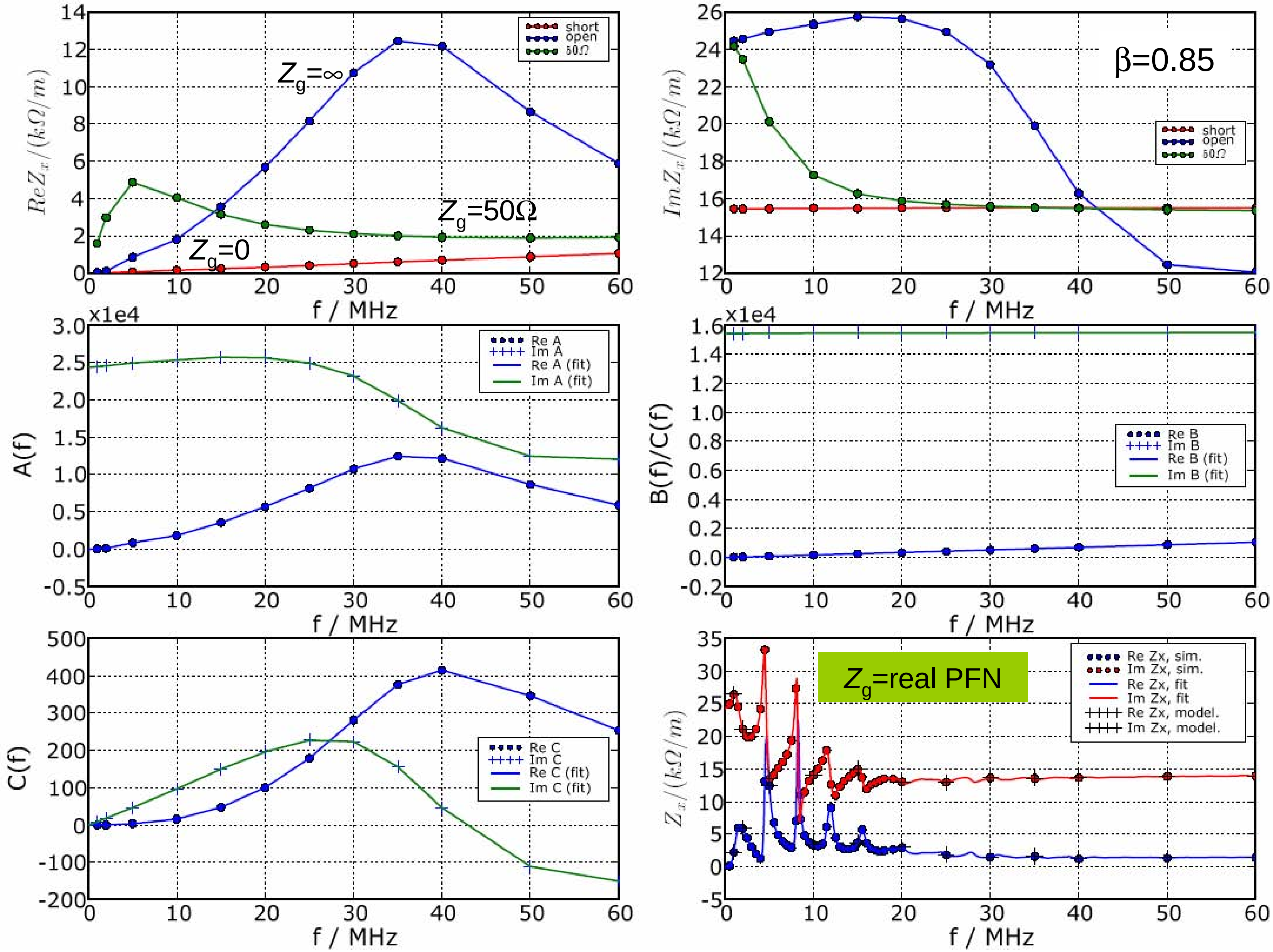
Check of the Parameterization



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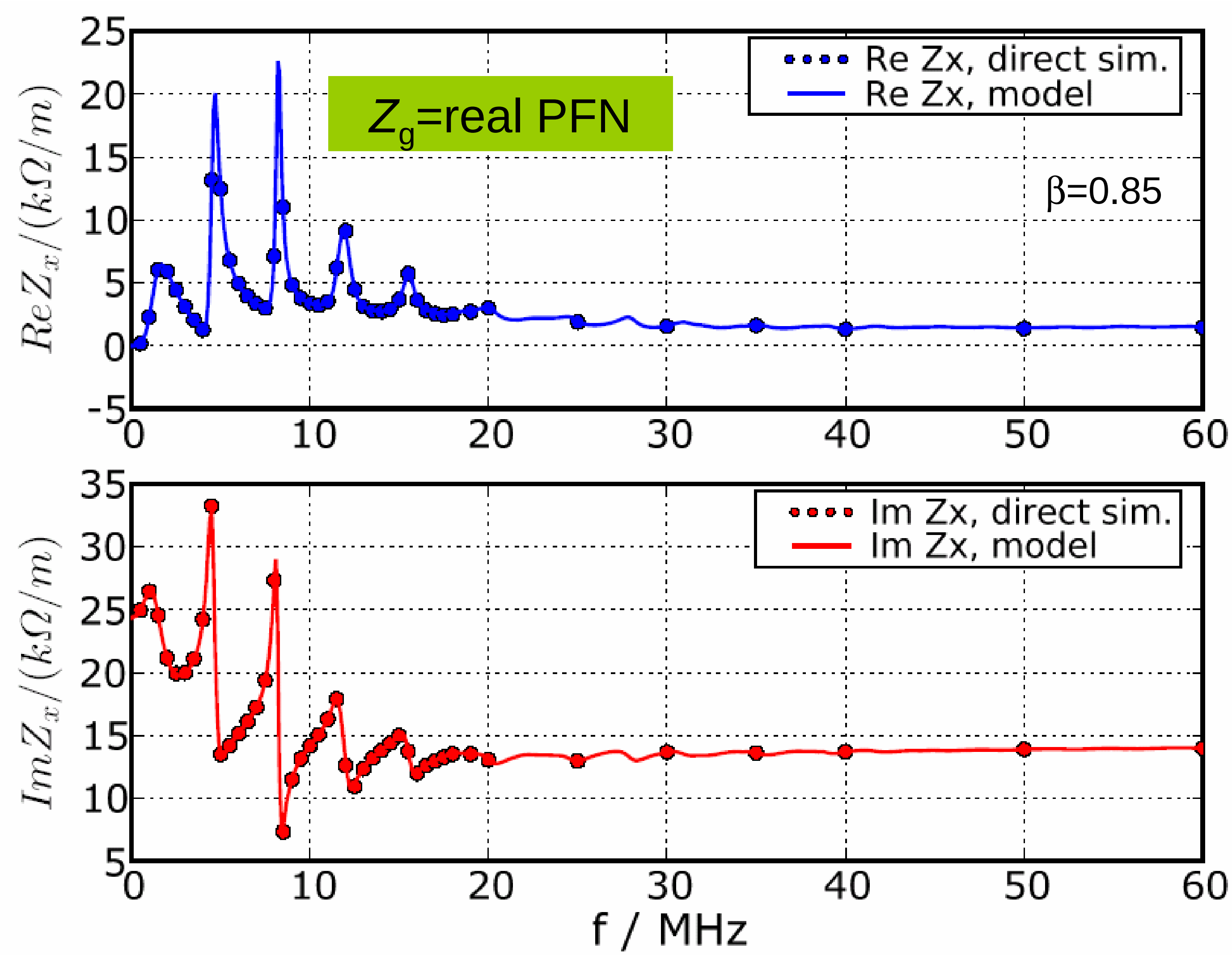
Check of the Parameterization



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The SIS-100/300 Kickers

SIS-100	*type*	*kick*	*#modules*	*#windings*	*total length*	*weight*
injection	mono	x	4	1	1.6m	183kg
transfer	mono	y	7	2	6.37m	174kg
extr/emerg.	bi	y	6	2	5.4m	126kg
Q	mono	xy	2	2	1.1m	165kg
					14.47m	**3036kg**

SIS-300	*type*	*kick*	*#modules*	*#windings*	*total length*	*weight*
transfer	mono	y	7	2	4.55m	139kg
emerg.	mono	y	13	2	8.45m	131kg
Q	mono	xy	4	2	2.4m	151kg
					15.40m	**3280kg**

➢ *large contributions to ring impedances expected!*

Implications for SIS-18 Beam Stability

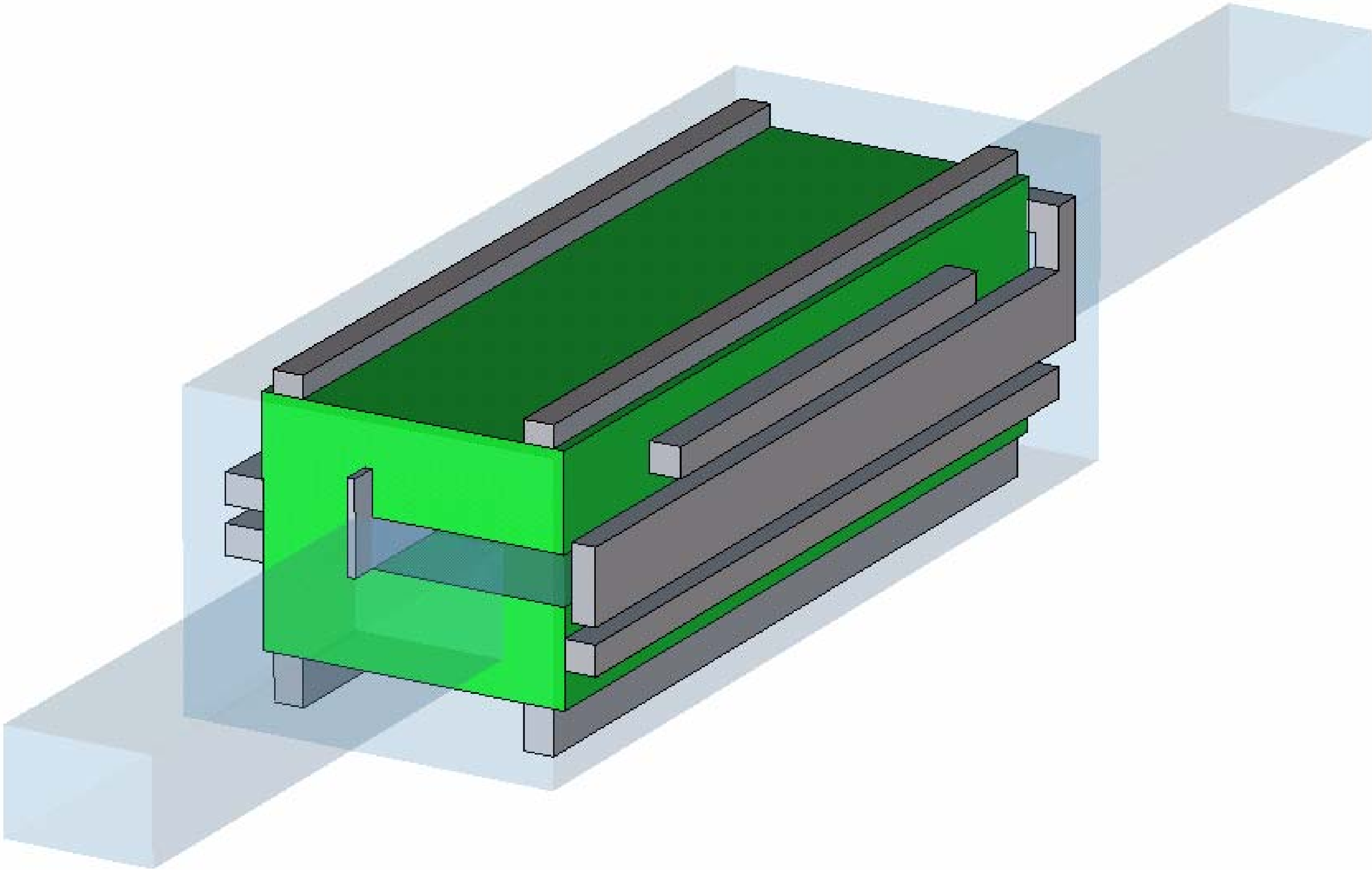
- dominant parasitic contribution: resistive walls
- the 9 kicker modules may drive instabilities, e.g.

U^{28+} *coasting-beam, flat-top 100 ms*
f=2.1 MHz
Z_x*(r.w.)=27 k*Ω*/m,* Z_x*(kicker)=9x4=36k*Ω*/m*

➢ $\tau = 22ms$ *leading to beam loss* [V. Kornilov]

MKE Kicker (*preliminary*)

- correct dimensions, missing details
- ferrite 8C11 instead of 4A4



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Influence of Eddy-Current Strip