Impedance Computation in the Frequency Domain

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ICFA mini-Workshop on "Electromagnetic wake fields and impedances in particle accelerators"

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- When do we need 3D?
  →Applications of 2D impedance computation
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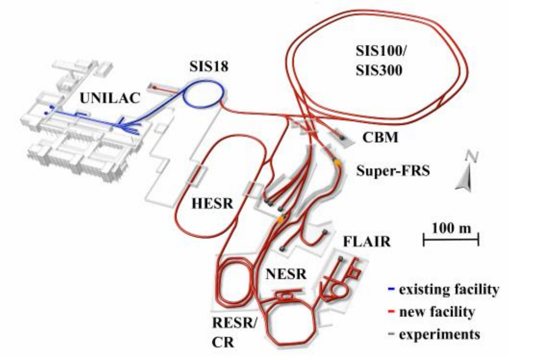
- Details for FIT and FEM
  →Implementation of 2D impedance code
- Results for test cases
- Conclusion and Outlook



Time domain vs. Frequency domain

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- Time domain calculations e.g. by CST Particle Studio, GdfidL, Echo,… (Wake Potential)
- Impedances obtained by FFT
- Limitation by uncertainty relation $\Delta t \Delta f \geq 1$
- Long wake length for low frequency $\Delta z \geq \frac{\beta c}{\Delta f} \approx 300\ \mathrm{m}\ @\ 1\ \mathrm{MHz}$
- Time step *dt* is limited by CFL critereon (for explicit time-stepping)→ Resolving structure details makes *dt* small…
- Total computation time proportional to #timesteps
- High computational effort for low velocity (large extension of source fields)
- Time domain simulation requires fitting of dispersive material data (FD) on some impulse response model (TD)

Time domain vs. Frequency domain (2)

- FD approach does not have those problems… (but other ones…)
- FD is suitable for low and medium frequencies

When do we need 3D in FD? (1)

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- 2D is sufficient for: Large length. What is large?
- Large longitudinal electrical length: “distributed impedance“

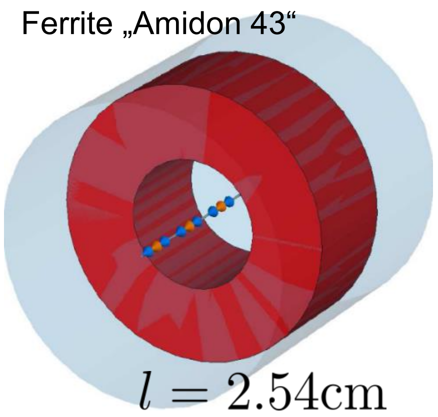
$$\Theta_{\|} = \frac{2\pi f l}{\beta c}\sqrt{\mu_r \varepsilon_r} \gg 1$$

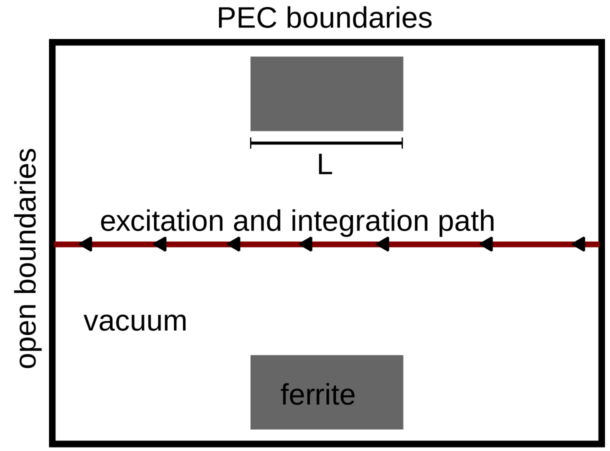
$$Z_{lumped} \ll Z_{dist}$$

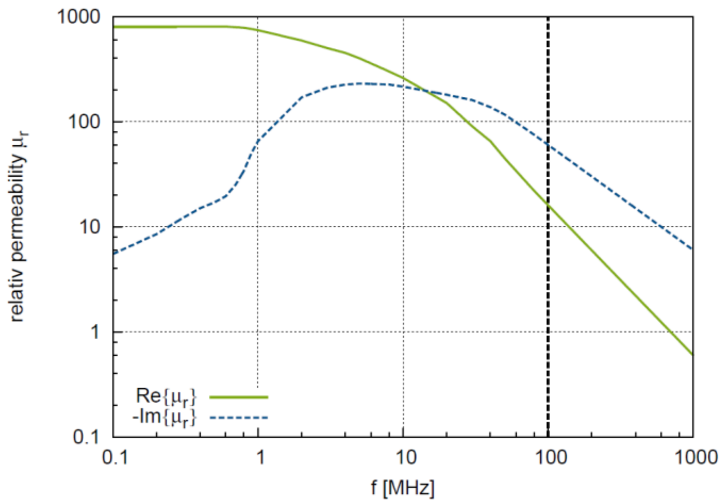
$$\frac{\partial Z_{\|}(\omega, z)}{\partial z} = Z_{\|}^{total}(\omega)\delta(z - z_0) \qquad \frac{\partial Z_{\|}(\omega, z)}{\partial z} = \frac{Z_{\|}^{total}(\omega)}{l}$$

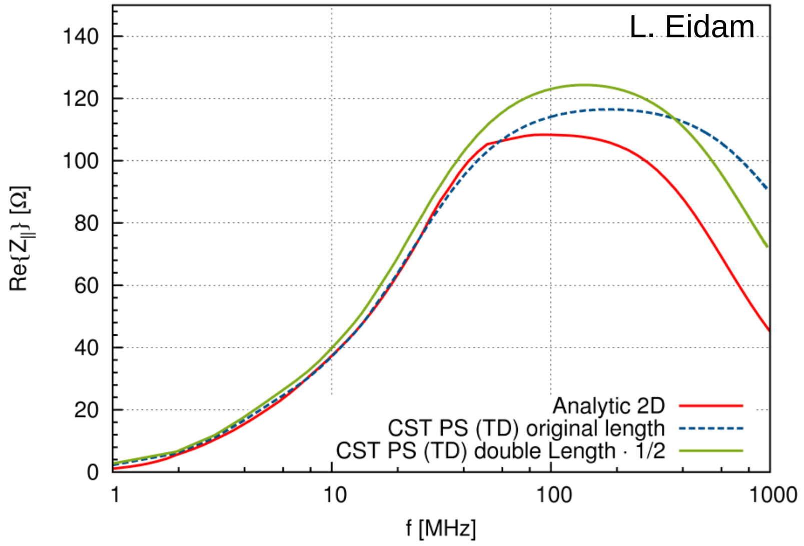
A POSTERIORI JUSTIFICATION

When do we need 3D in FD? (2)









Time domain simulation requires fitting of material data on some impulse response model

Model Equation

→Ferrite Material in FD

- From Maxwell‘s equations we have

$$\nabla \times \underline{\mu}^{-1}\nabla \times \underline{\vec{E}} + i\omega\kappa\underline{\vec{E}} - \omega^2\varepsilon\underline{\vec{E}} = -i\omega\underline{\vec{J}}_{ext}$$

- Charge implicitly included by continuity eq.

$$\underline{\mu} = \mu' - i\mu''$$

$$\underline{\varepsilon} = \varepsilon' - i\varepsilon''$$

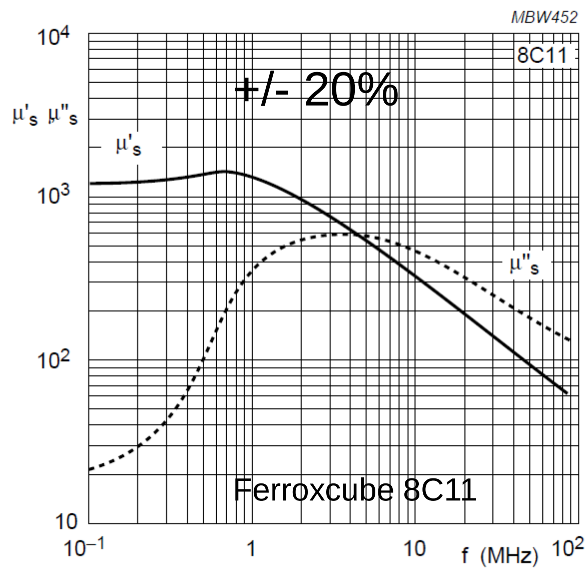
← Magnetization / Polarization Losses

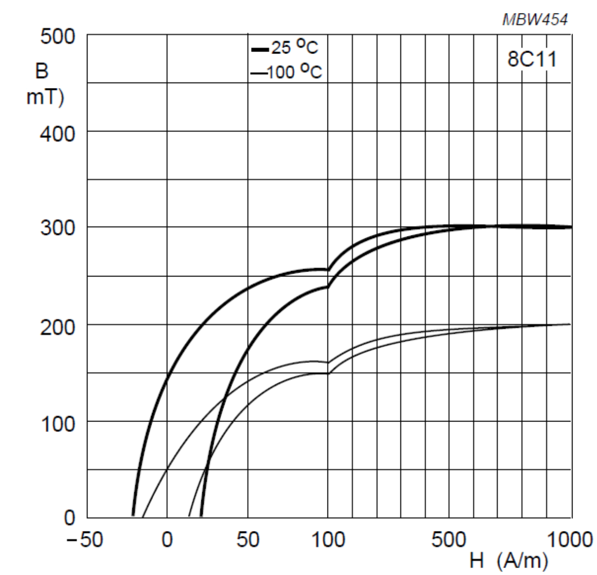
→ Unbiased small-signal complex permeability

→ Linearized! Hysteresis loop approximated by ellipse in H-B space

→ Remanence neglected

→ Scalar!





Maxwell-Grid-Equations (MGE)

$$\nabla \times \underline{\mu}^{-1} \nabla \times \underline{\vec{E}} + i\omega\kappa\underline{\vec{E}} - \omega^2 \varepsilon \underline{\vec{E}} = -i\omega \underline{\vec{J}}_{ext}$$

$$\oint_{\partial A} \vec{E} \cdot d\vec{s} = -\frac{d}{dt}\int_A \vec{B} \cdot d\vec{A}$$

$$\oint_{\partial A} \vec{H} \cdot d\vec{s} = \int_A \left(\frac{\partial \vec{D}}{\partial t} + \vec{J}\right) \cdot d\vec{A}$$

$$\oint_{\partial V} \vec{D} \cdot d\vec{A} = \int_V \rho \, dV$$

$$\oint_{\partial V} \vec{B} \cdot d\vec{A} = 0$$

FIT →

$$\mathbf{C}\widehat{\mathbf{e}} = -\frac{d}{dt}\widehat{\widehat{\mathbf{b}}}$$

$$\widetilde{\mathbf{C}}\widehat{\mathbf{h}} = \frac{d}{dt}\widehat{\widehat{\mathbf{d}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\widetilde{\mathbf{S}}\widehat{\widehat{\mathbf{d}}} = \mathbf{q}$$

$$\mathbf{S}\widehat{\widehat{\mathbf{b}}} = \mathbf{0}$$

FIT is a mimetic discretization based on the INTEGRAL FORMULATION of Maxwell‘s equations (Weiland 1977)

$$\widetilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\mathbf{C}\underline{\widehat{\mathbf{e}}} + i\omega\mathbf{M}_{\kappa}\underline{\widehat{\mathbf{e}}} - \omega^2\mathbf{M}_{\epsilon}\underline{\widehat{\mathbf{e}}} = -i\omega\underline{\widehat{\widehat{\mathbf{j}}}}_{ext}$$

Constitutive work of B.Doliwa on impedance computation with FIT has to be acknowledged
→„Maxwell iteration“

Finite Integration Technique (FIT) in FD

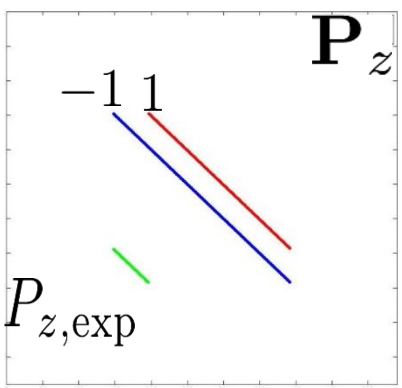
Mimetic Discretization by ***Finite Integration Technique*** (diagonal material matrices)

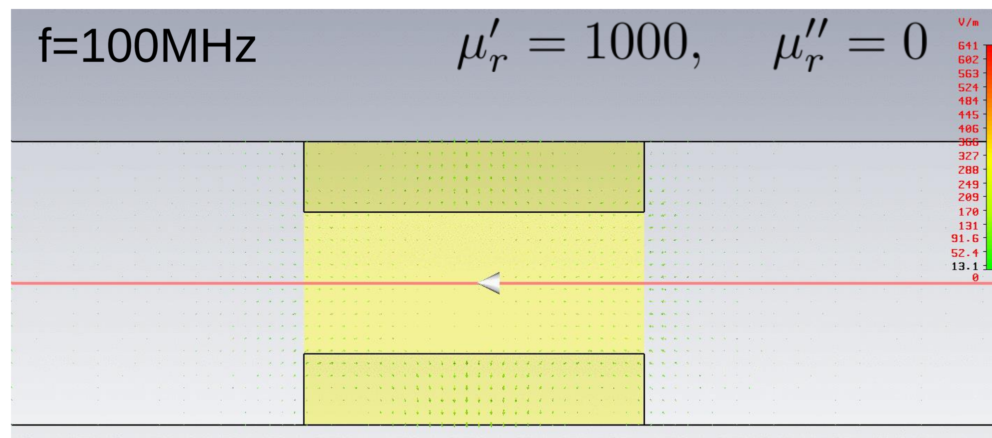
$$\widetilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\mathbf{C}\underline{\widehat{\mathbf{e}}} + i\omega\mathbf{M}_{\kappa}\underline{\widehat{\mathbf{e}}} - \omega^2\mathbf{M}_{\epsilon}\underline{\widehat{\mathbf{e}}} = -i\omega\underline{\widehat{\widehat{\mathbf{j}}}}_{ext}$$

Complex linear system of size $3N_p$, indefinite ill-conditioned matrix

- Matrix can be symmetrized but still Non-Hermitean in case of lossy material (complex Eigenvalues)
- Longitudinal Phaseshift given a priori
  →Periodic boundary conditions:

$$P_{z,\mathrm{exp}} = e^{\frac{-i\omega(L+\Delta z_{\mathrm{e}})}{\beta c}}$$





More details: U.Niedermayer and O. Boine Frankenheim, Proc. of ICAP 2012 and references therein

Definition of coupling impedances in FD

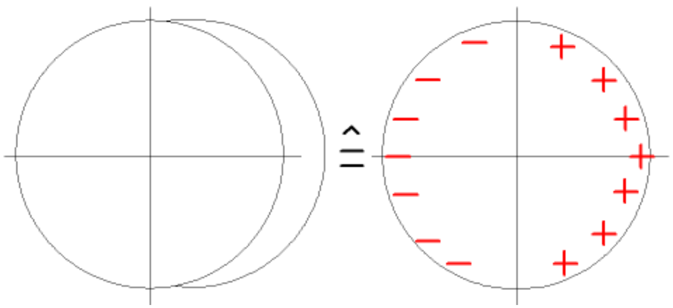
→ Volume integral definition best applicable on mesh

Uniform cylindrical beam: Radius of the beam, Displacement of the beam

$$\sigma(\varrho,\varphi) \approx \frac{q}{\pi a^2}\left(\Theta(a-\varrho) + \delta(a-\varrho) d_x \cos\varphi\right)$$

$$\underline{J}_{s,z}(\varrho,\varphi,z,\omega) = \sigma e^{-i\omega z/v}$$

$$\underline{\varrho}_s(\varrho,\varphi,z,\omega) = \frac{1}{v}\sigma e^{-i\omega z/v}$$



- Rigid beam
- Finite integration length due to decay of scattered fields

$$\underline{Z}_{\parallel}(\omega) = -\frac{1}{q^2}\int_{beam} \underline{\vec{E}} \cdot \underline{\vec{J}}_{\parallel}^{\,*} \mathrm{d}V$$

$$\underline{Z}_{\perp,x}(\omega) = -\frac{v}{(q d_x)^2 \omega}\int_{beam} \underline{\vec{E}} \cdot \underline{\vec{J}}_{dip}^{\,*} \mathrm{d}V$$

$$Z_{\parallel}(\widehat{\underline{\mathbf{e}}}(\omega)) = \frac{1}{q^2}\widehat{\underline{\mathbf{e}}} \cdot \widehat{\widehat{\underline{\mathbf{j}}}}_s^{*}$$

$$Z_{\perp}(\widehat{\underline{\mathbf{e}}}(\omega)) = \frac{\beta c}{\omega(q\cdot 2d_x)^2}\widehat{\underline{\mathbf{e}}} \cdot \widehat{\widehat{\underline{\mathbf{j}}}}_s^{\mathrm{dip}*}$$

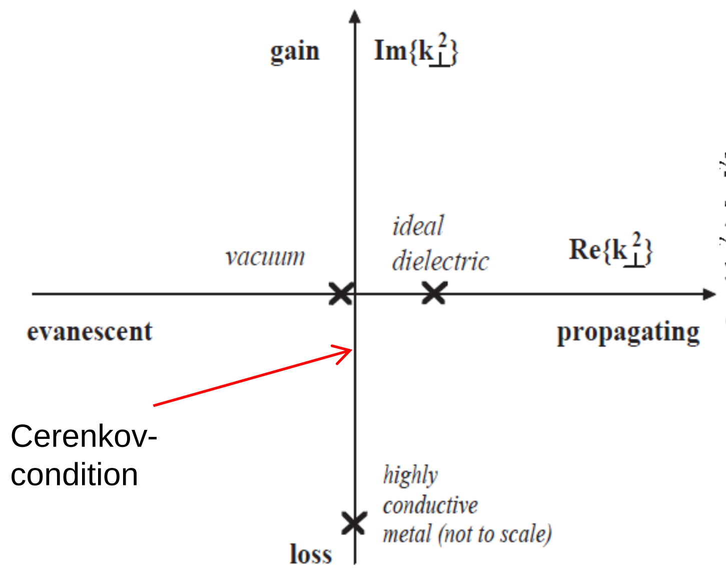
Imaginary part dominated by SPACE CHARGE for low beta!

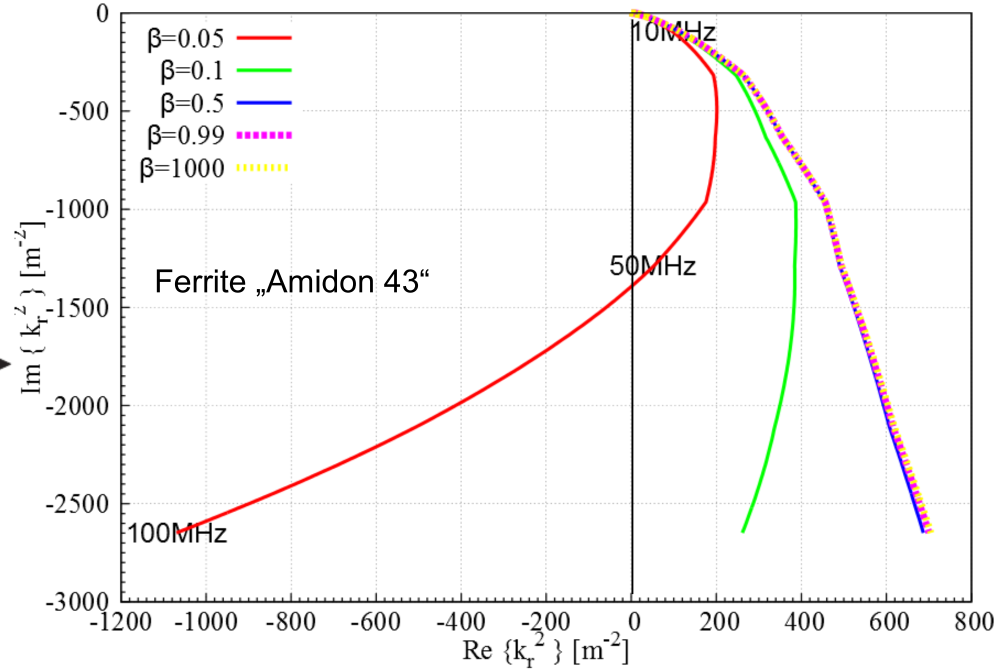
A glance on the dispersion relation

$$(\Delta_\perp + k_\perp^2)E_z = rhs \qquad k_\perp^2 + k_z^2 = \omega^2 \underline{\mu} \underline{\epsilon} \qquad \partial_z \to -i\frac{\omega}{\beta c_0}$$

$$k_\perp^2 = \frac{\omega^2}{c_0^2}\left[n^2(1-\tan\delta_\mu \tan\delta_\varepsilon) - \frac{1}{\beta^2} - in^2(\tan\delta_\mu + \tan\delta_\varepsilon)\right]$$

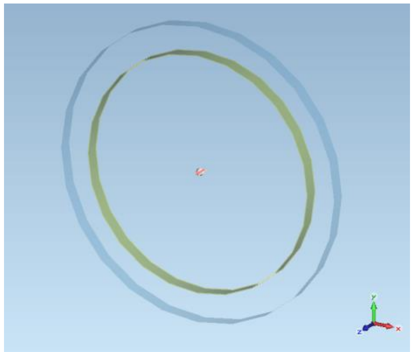
n: lossless refraction index





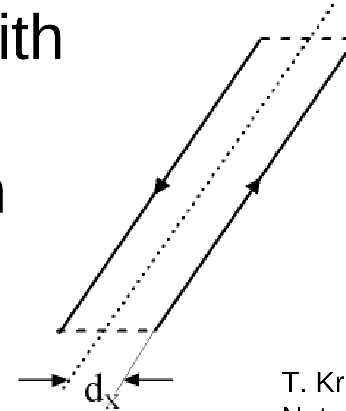
- Required transverse mesh resolution will always depend on β
- Radial model (approximation) $\beta \to \infty, \text{i.e. } \partial_z \to 0$

Simplified numerical method (according to “radial model“)



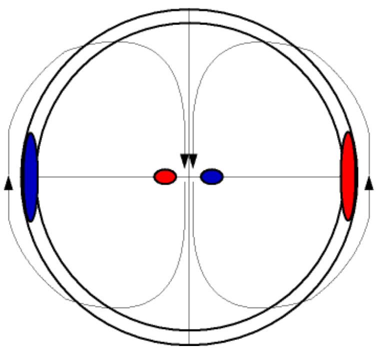
- Power loss calculation with CST EM Studio
- MQS Frequency-Domain

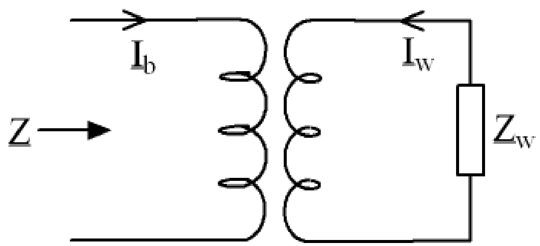
$$\delta P = \frac{1}{2} \int_{pipe} \underline{\vec{E}} \cdot \underline{\vec{J}}^{*} \mathrm{dV}$$



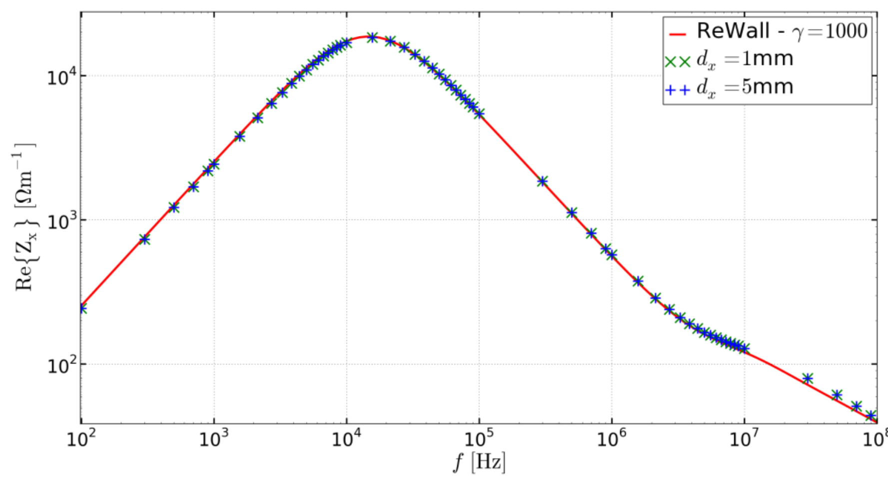
T. Kroyer, CERN-AB-Note-2008-017

$$\frac{\mathrm{Re}\left\{\underline{Z}_{\perp,x}(\omega)\right\}}{l} = \frac{c}{\omega d_x^2} \frac{1}{I^2} \frac{\delta P}{\delta z}$$





Transformer between dipolar beam-current and wall-current



G. Nassibian and F. Sacherer, NIM A 1978
L. Vos, CERN-AB-2003-005 ABP

Coil measurement (according to "radial model")

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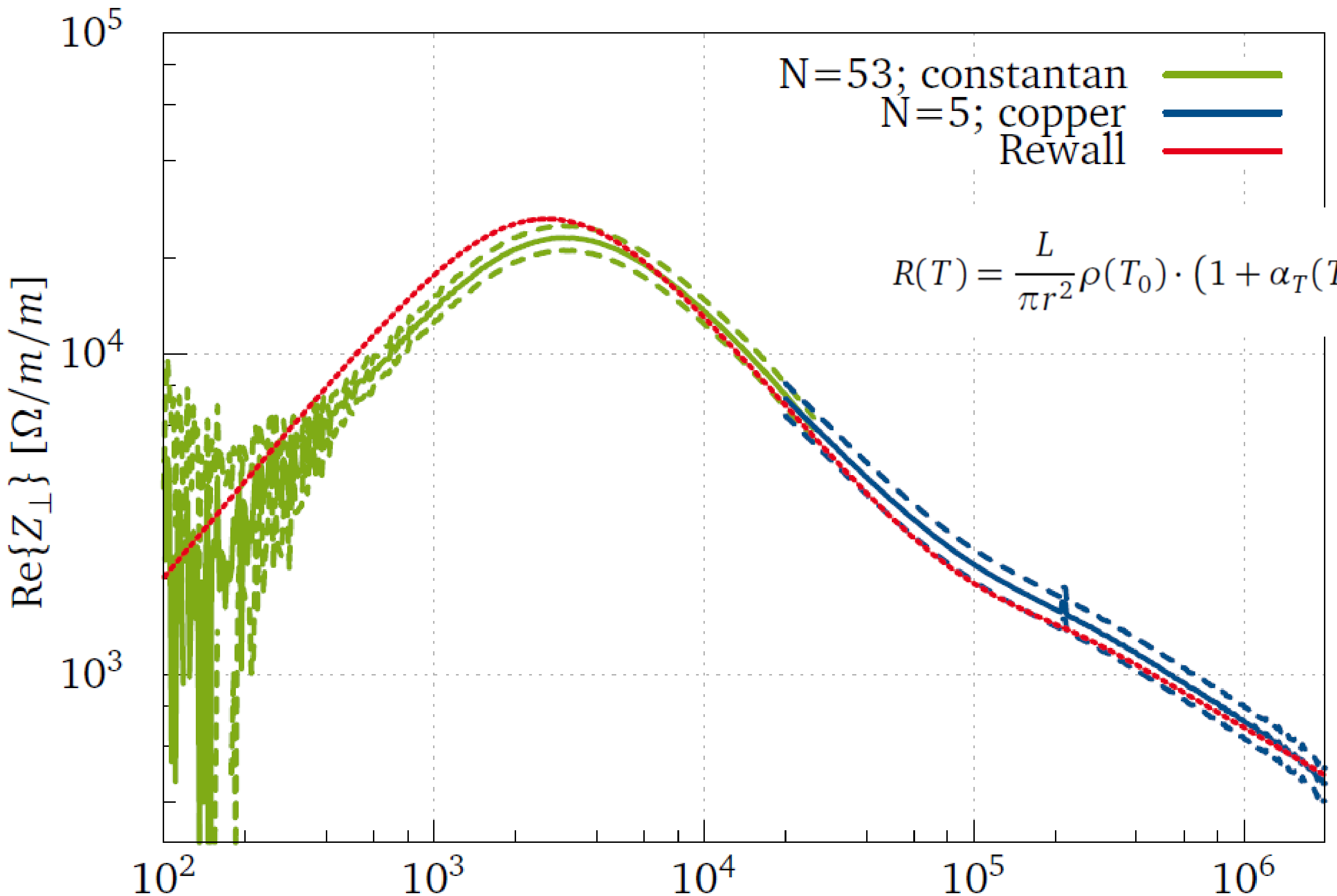
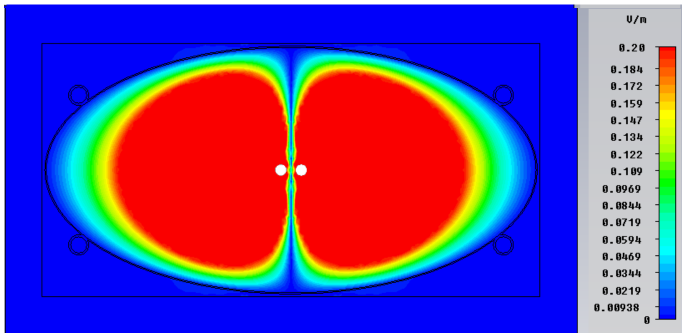
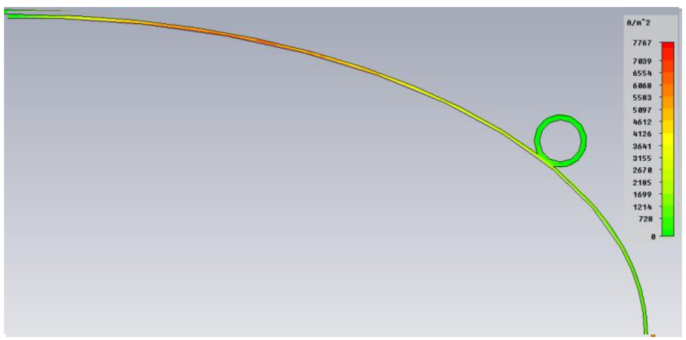


$$R(T) = \frac{L}{\pi r^2}\rho(T_0)\cdot(1+\alpha_T(T_0)\cdot(T-T_0))$$

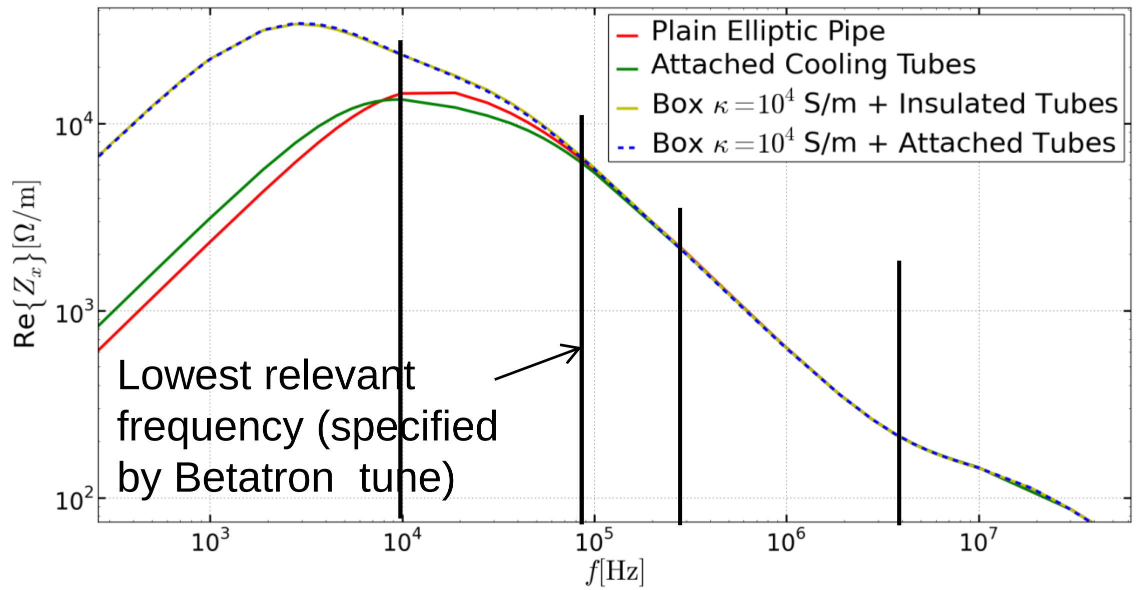
L.Eidam

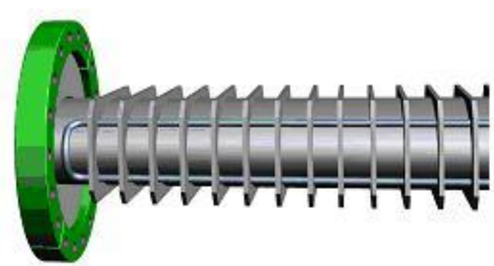
Numerical calculation for SIS100 dipole chamber (FD power loss calculation)





Longitudinal E-field and wall current for $f = 300\,\mathrm{kHz}$



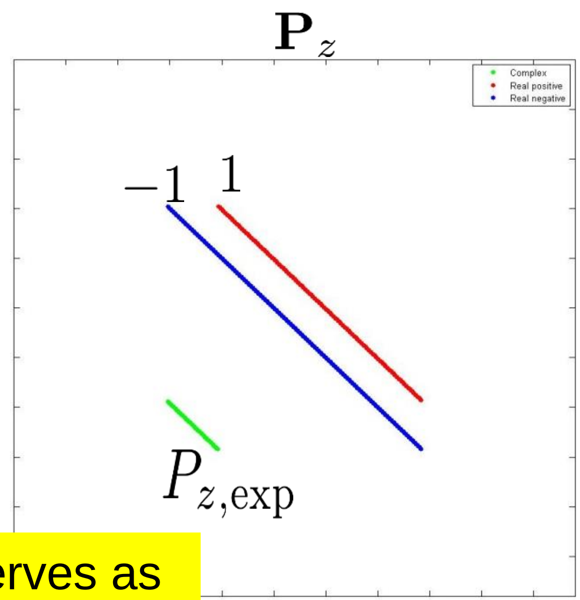


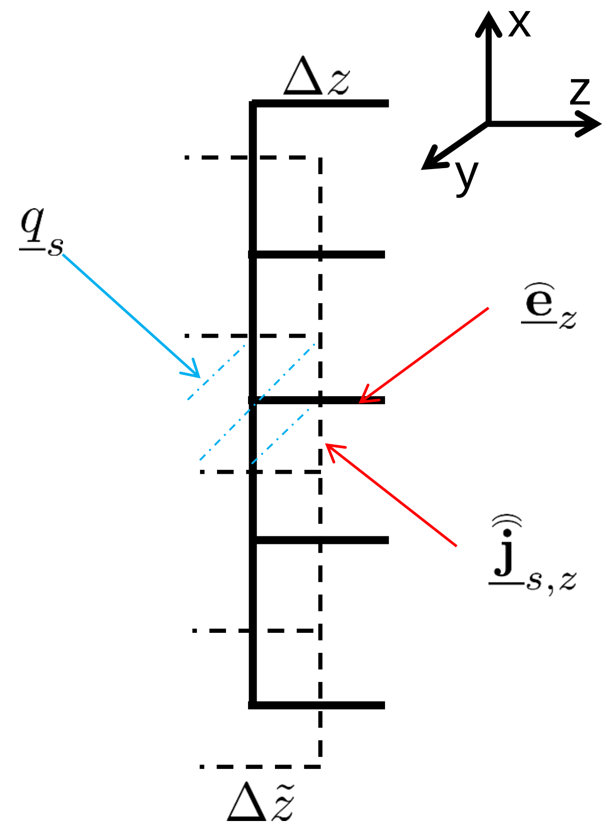
U.Niedermayer and O. Boine-Frankenheim, *Analytical and numerical calculations of resistive wall impedances for thin beam pipe structures at low frequencies*, NIM A, 2012

FIT in 2D (…back to full Maxwell)

Consider the a setup that is one cell long and has periodic boundary conditions

$$P_{z,\mathrm{exp}} = e^{\frac{-i\omega(L+\Delta z_{\mathrm{e}})}{\beta c}}$$





$$\mathbf{P_z} = -\mathbf{1} + \mathbf{e}^{-\mathbf{i}\omega\triangle\mathbf{z}/\mathbf{v}}$$

$$\tilde{\mathbf{P}}_\mathbf{z} = -\mathbf{P}_\mathbf{z}^\mathbf{H}$$

The 2D solution also serves as boundary condition for 3D
→ Similar as waveguide port but enforced mode instead of Eigen-mode

Space charge impedance as test-case (plain perfectly conducting beam pipe)

$$1 - \frac{1}{\beta^2} = -\frac{1}{\beta^2\gamma^2}$$

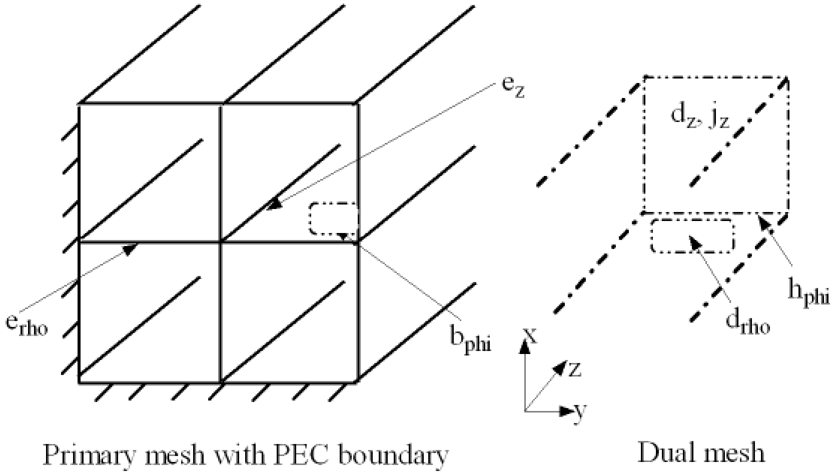
$$\left(I - \frac{\Delta z \Delta \tilde{z}}{v^2}\mathbf{M}_{\mu^{-1}}\mathbf{M}_{\epsilon^{-1}}\right) = -\frac{1}{\beta^2\gamma^2} I$$

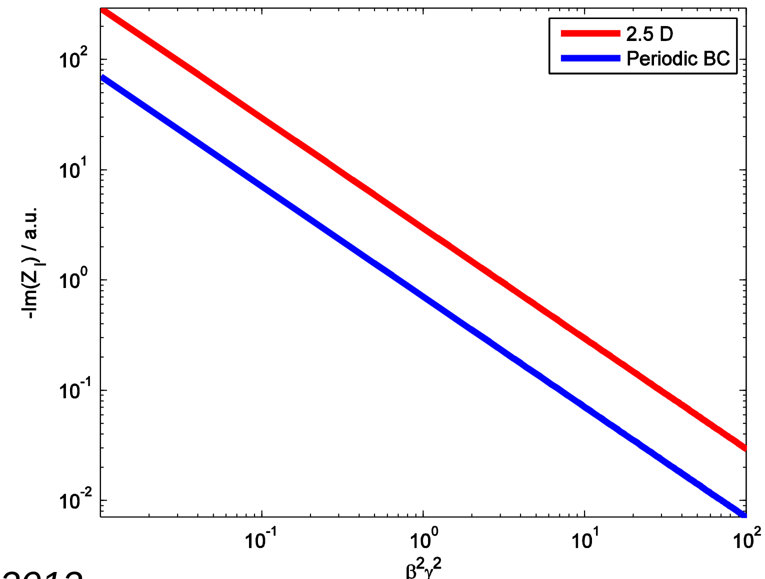
$$\left(\triangle_\perp - \frac{\omega^2}{\beta^2\gamma^2 c^2}\right)\underline{E}_z = -\frac{i\omega\mu\sigma}{\beta^2\gamma^2} e^{-i\omega z/v}$$

MQS

$$\underline{Z}_\parallel^{SC} = -i\omega \frac{\mu_0 g l}{4\pi\beta^2\gamma^2}$$

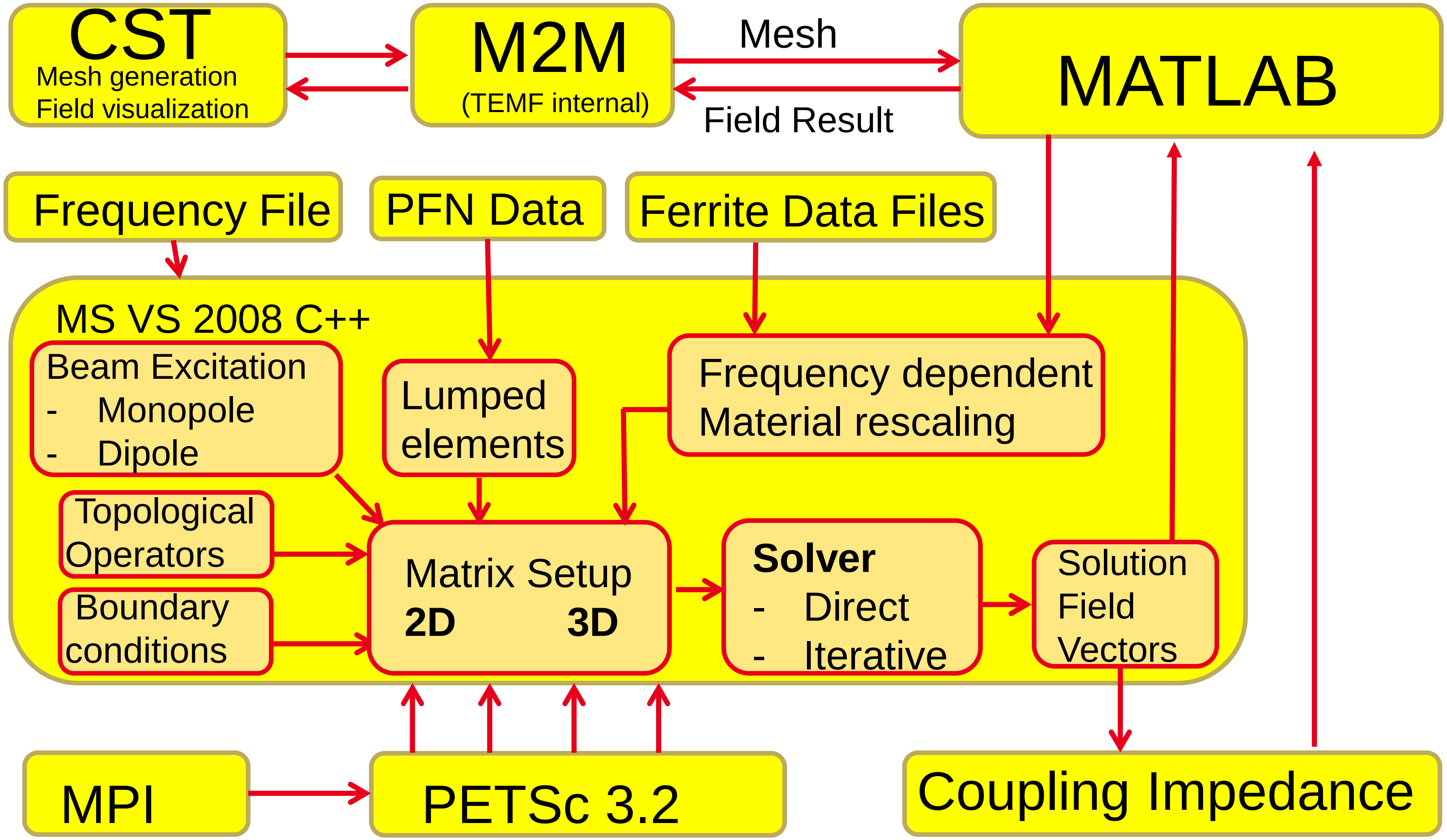
$$\underline{\widehat{\mathbf{e}}}_z = \frac{-i\omega}{4\beta^2\gamma^2 - \omega^2\delta_\perp^2/c^2}\mathbf{M}_\mu \underline{\widehat{\widehat{\mathbf{j}}}}_{ext}$$





U.Niedermayer and O. Boine Frankenheim, Proc. of ICAP 2012

Implementation



Finite Element Method (FEM)

- Approximate a basis in a function space by a finite number of basis functions (“finite elements“)

$$u(x) \approx \bar{u}(x) = \sum_{j=1}^{N} u_j \varphi_j(x)$$

- The elements should have the following properties
  → compact support
  → continuous
  → linearly independent
- Usually on unstructured tetrahedral / triangular mesh
- Unstructured mesh approximates arbitrary geometry well
- Nondiagonal material matrices do not matter as much as in TD
- A large effort to implement from scratch!

FEniCS (www.fenicsproject.org)

(A. Logg, K. Mardal, A. Wells)

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- Use a compiler instead of a PhD student to go from weak formulation of PDE to running code! ☺
- Automated solution of PDE
  → compiler for weak formulations of PDE (UFL/FFC)
- Can be run by Python script
- Creates C++ code that runs the linear algebra backend
- Provides a Functional Analysis framework
  → work with “continuous“ functions on the mesh
- Mesh from GMSH *(C. Geuzaine, J. Remacle)*
  http://geuz.org/gmsh/

FEM for the 2D impedance problem

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$$\nabla \times \underline{\nu} \nabla \times \underline{\vec{E}} + i\omega\kappa \underline{\vec{E}} - \omega^2 \varepsilon \underline{\vec{E}} = -i\omega \underline{\vec{J}}_s$$

$$\underline{\nu} = \frac{1}{\underline{\mu}} = \frac{\mu' + i\mu''}{|\underline{\mu}|^2}$$

$$\underline{\vec{E}} = \begin{pmatrix} \vec{E}^r_\perp \\ E^r_z \end{pmatrix} + i \begin{pmatrix} \vec{E}^i_\perp \\ E^i_z \end{pmatrix}$$

$$\vec{E}_\perp \times \vec{n}|_{\partial\Omega} = 0$$

$$E_z|_{\partial\Omega} = 0$$

- Nodal functions only for scalar components
- Edge functions “Nedelec elements“ for vector components
  →Too much continuity for nodal elements
  (normal component cannot jump on material edge)
- Divergence free Nedelec elements (lowest order edge functions)

→Helmholtz split

Helmholtz Split

$$\nabla \times \frac{1}{\underline{\mu}} \nabla \times \underline{\vec{E}} + i\omega\kappa\underline{\vec{E}} - \omega^2\varepsilon\underline{\vec{E}} = -i\omega\underline{\vec{J}}_s$$

$$\underline{\vec{E}} = \underline{\vec{E}}_{curl} + \underline{\vec{E}}_{div} \qquad \underline{\vec{E}}_{div} = -\nabla\underline{\Phi}$$

$$\nabla \cdot \underline{\varepsilon}\nabla\underline{\Phi} = -\underline{\varrho} = -\frac{1}{\beta c}\underline{J}_{s,z}$$

$$\underline{\vec{R}} = \omega^2\underline{\varepsilon\vec{E}}_{div} - i\omega\underline{\vec{J}}_s \qquad \nabla \cdot \underline{\vec{R}} = 0$$

“Continuity Equation“

$$\nabla \times \frac{1}{\underline{\mu}} \nabla \times \underline{\vec{E}}_{curl} + i\omega\kappa\underline{\vec{E}}_{curl} - \omega^2\varepsilon\underline{\vec{E}}_{curl} = \underline{\vec{R}}$$

Statics solver
(combined E-static and stationary current)

$$\nabla \cdot \underline{\varepsilon} \nabla \underline{\Phi} = -\underline{\varrho}$$

$$\underline{\varepsilon} = \varepsilon + \frac{\kappa}{i\omega}$$

$$\nabla \cdot \varepsilon \nabla \Phi^r + \nabla \cdot \frac{\kappa}{\omega} \nabla \Phi^i = -\varrho^r$$

$$\nabla \cdot \varepsilon \nabla \Phi^i - \nabla \cdot \frac{\kappa}{\omega} \nabla \Phi^r = -\varrho^i$$

Boundary Conditions

$$\int_\Omega \varepsilon \nabla \Phi^r \cdot \nabla v^r \mathrm{d}V + \int_\Omega \nabla \frac{\kappa}{\omega} \Phi^i \cdot \nabla v^r \mathrm{d}V + \int_{\partial\Omega} \ldots = \int_\Omega \varrho^r v^r \mathrm{d}V$$

$$\int_\Omega \varepsilon \nabla \Phi^i \cdot \nabla v^i \mathrm{d}V - \int_\Omega \nabla \frac{\kappa}{\omega} \Phi^r \cdot \nabla v^i \mathrm{d}V + \int_{\partial\Omega} \ldots = \int_\Omega \varrho^i v^i \mathrm{d}V$$

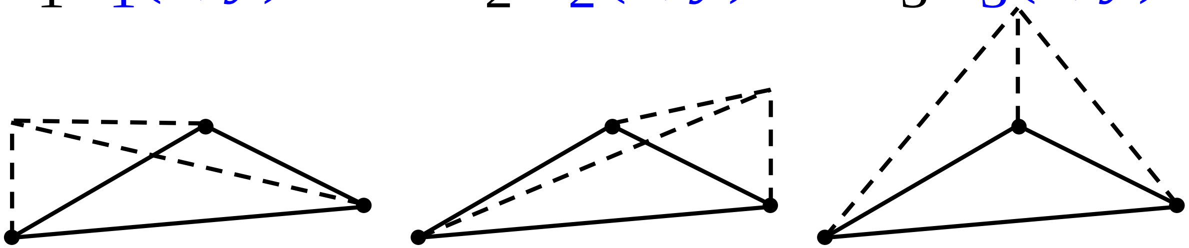
Solve with Galerkin approach and nodal-functions, then project gradients on H(curl)

$$\underline{\vec{E}}_{div} = -\nabla \underline{\Phi}$$

Nodal functions (2D)

Lowest order: “Hat functions“

$$\varphi(x,y) = u_1 N_1(x,y) + u_2 N_2(x,y) + u_3 N_3(x,y)$$



Pictures: H. De Gersem

$$N_i = a_i + b_i x + c_i y$$

- Local Basis
- a, b, c such that $N_i(\vec{x}_j) = \delta_{ij}$
- Local to Global map required

Rotational part (1)
(Edge elements)

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- Nedelec Elements

  → **Tangential continuity** (H(curl)-conforming)

$$\vec{E}^r_\perp(\vec{x}) = \sum_{i=1}^{N} e_i^r \vec{w}_i(\vec{x})$$

$$\vec{w}_i(\vec{x}) = N_k \nabla N_l - N_l \nabla N_k$$

$$N_i = a_i + b_i x + c_i y$$

$$\int_{l_j} \vec{\omega}_i \cdot \vec{t}_j \mathrm{d}s = \delta_{ij}$$

Rotational part (2)

Rewriting the curlcurl Operator

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$$\nabla \times \underline{\vec{E}} = \left(\begin{array}{cc|c} 0 & -\partial_z & \partial_y \\ \partial_z & 0 & -\partial_x \\ \hline -\partial_y & \partial_x & 0 \end{array}\right) \underline{\vec{E}} = \left(\begin{array}{c|c} iZ & A \\ & \\ \hline B & 0 \end{array}\right) \underline{\vec{E}} \qquad \partial_z \to -i\frac{\omega}{\beta c}$$

$$Z = \begin{pmatrix} 0 & +\frac{\omega}{\beta c} \\ -\frac{\omega}{\beta c} & 0 \end{pmatrix} \qquad Z^2 = -\frac{\omega^2}{\beta^2 c^2} \qquad A = \begin{pmatrix} \partial_y \\ -\partial_x \end{pmatrix} = -B^T$$

$$\nabla \times \underline{\nu} \nabla \times \underline{\vec{E}} = \begin{pmatrix} A\nu_r B - \nu_r Z^2 & -Z\nu_i A \\ -B\nu_i Z & B\nu_r A \end{pmatrix} \begin{pmatrix} \vec{E}^r_\perp \\ E^r_z \end{pmatrix} - \begin{pmatrix} A\nu_i B - \nu_i Z^2 & Z\nu_r A \\ B\nu_r Z & B\nu_i A \end{pmatrix} \begin{pmatrix} \vec{E}^i_\perp \\ E^i_z \end{pmatrix}$$
$$+ i \begin{pmatrix} A\nu_r B - \nu_r Z^2 & -Z\nu_i A \\ -B\nu_i Z & B\nu_r A \end{pmatrix} \begin{pmatrix} \vec{E}^i_\perp \\ E^i_z \end{pmatrix} + i \begin{pmatrix} A\nu_i B - \nu_i Z^2 & Z\nu_r A \\ B\nu_r Z & B\nu_i A \end{pmatrix} \begin{pmatrix} \vec{E}^r_\perp \\ E^r_z \end{pmatrix}$$

Only AB and BA are 2nd order operators

Boundary Conditions

$$\int_\Omega (A\nu_r B\vec{E}^r_\perp) \cdot \vec{v}^r \mathrm{d}V = \int_\Omega (\nu_r B\vec{E}^r_\perp)(B\vec{v}^r)\mathrm{d}V + \int_{\partial\Omega} \cdots$$

$$\int_\Omega (B\nu_r A E^r_z) v^r \mathrm{d}V = \int_\Omega (\nu_r A E^r_z) \cdot (A v^r)\mathrm{d}V + \int_{\partial\Omega} \cdots$$

Rotational part (3)

Weak Formulation of the whole CurlCurl Equation

$$(\nabla \times \nu \nabla \times \vec{E})^r - \omega\kappa\vec{E}^i - \omega^2\varepsilon\vec{E}^r = \vec{R}^r$$
$$(\nabla \times \nu \nabla \times \vec{E})^i + \omega\kappa\vec{E}^r - \omega^2\varepsilon\vec{E}^i = \vec{R}^i$$

Inner product

$\int_\Omega \mathrm{d}V$

$$a_\varepsilon = -\omega^2\left(\left(\vec{v}_\perp^r, \varepsilon\vec{E}^r\right) + \left(\vec{v}_\perp^i, \varepsilon\vec{E}^i\right) + (v_z^r, \varepsilon Ez^r) + (v_z^i, \varepsilon Ez^i)\right)$$

$$a_{RHS} = \left(\vec{v}_\perp^r, \vec{R}_\perp^r\right) + \left(\vec{v}_\perp^i, \vec{R}_\perp^i\right) + (v_z^r, R_z^r) + (v_z^i, R_z^i)$$

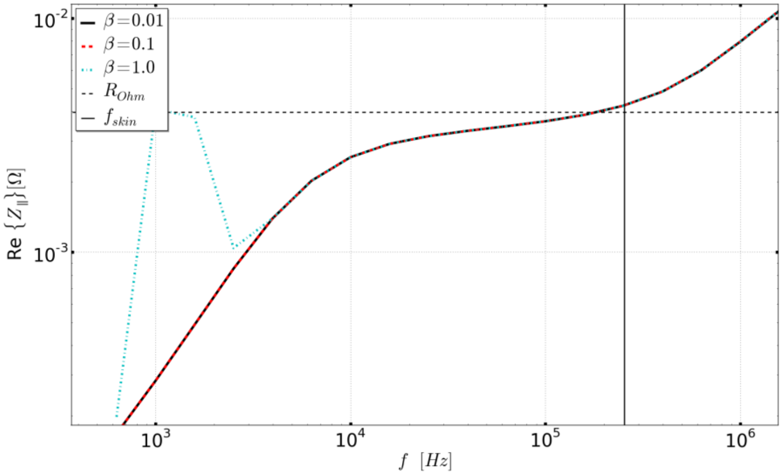
$$\mathrm{SOLVE}(\mathrm{a}_{\mathrm{curlcurl}} + \mathrm{a}_\kappa + \mathrm{a}_\varepsilon == \mathrm{a}_{\mathrm{RHS}})$$

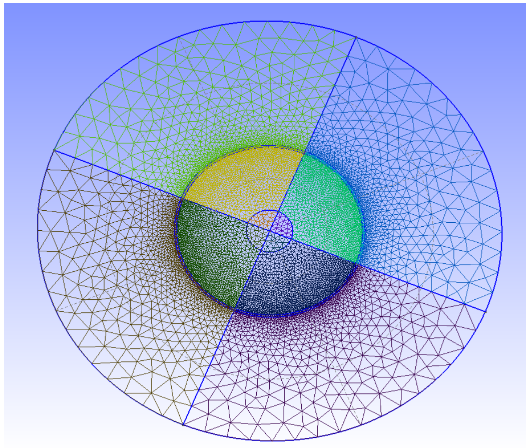
28 terms in the weak formulation

#DOFs (lowest order) = 2* #edges +2* #vertices)

```
Z=assemble(inner(Ezr,Jzr)*dx)+i*assemble(inner(Ezi,Jzr)*dx)
```

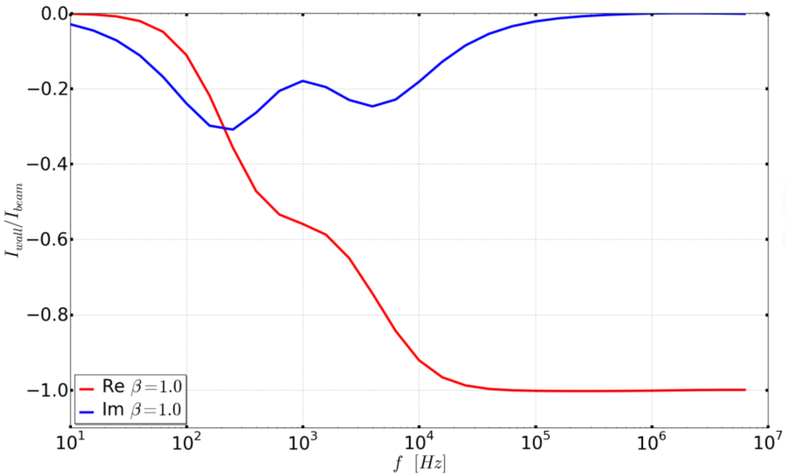
Numerical Examples: Thin beam pipe (FEM)

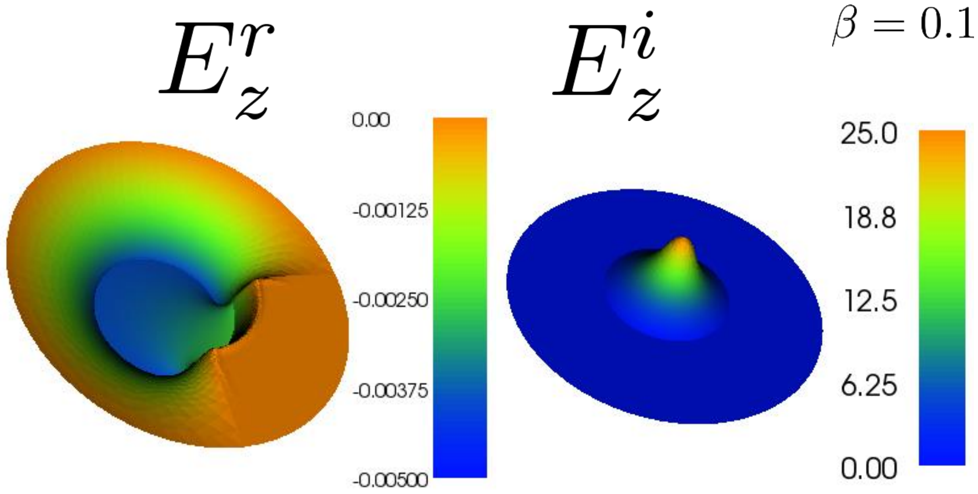




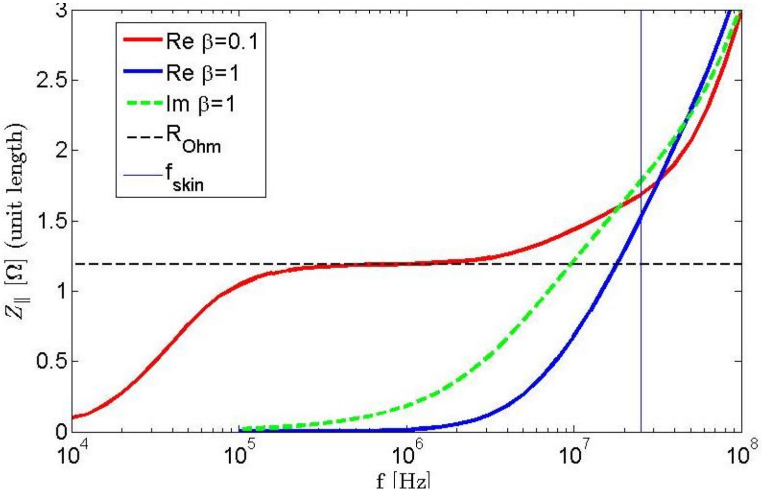
$f = 0.1$ MHz

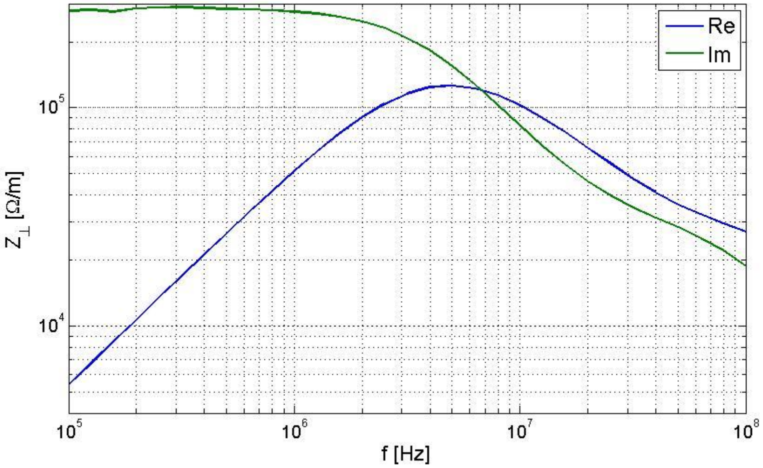
$\beta = 0.1$

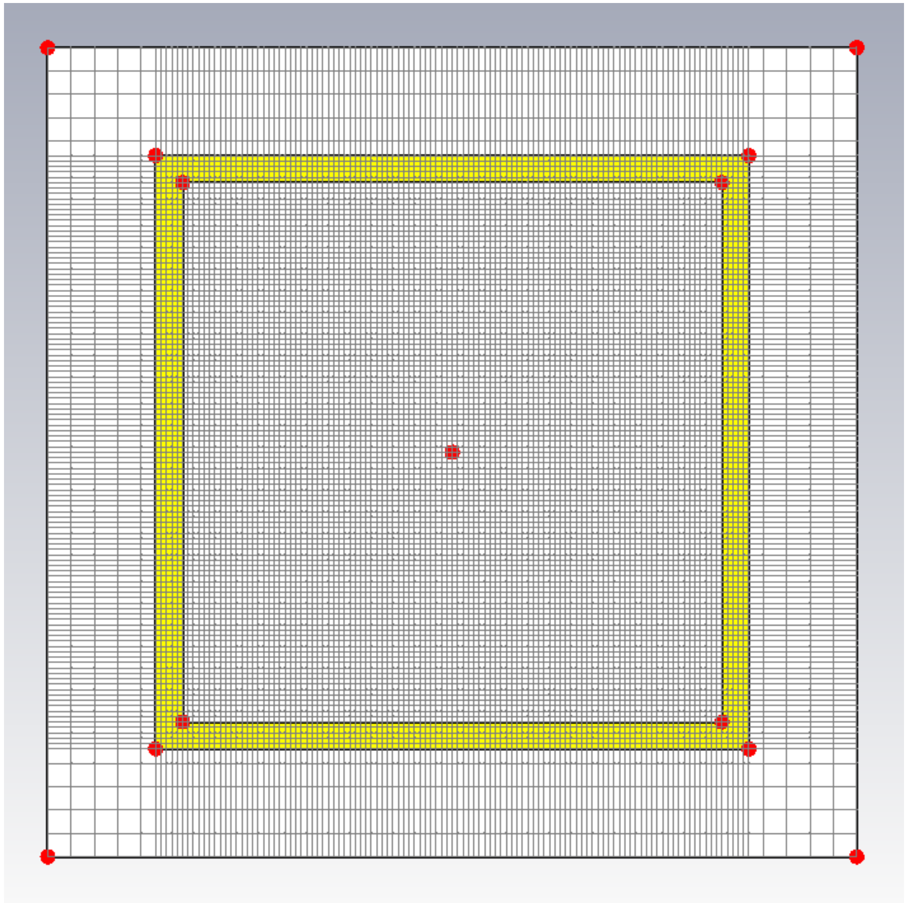




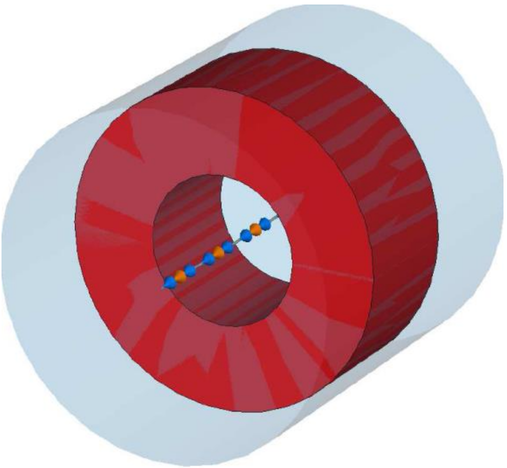
Numerical Examples: Rectangular beam pipe (staircase FIT)
(no Helmholtz split)

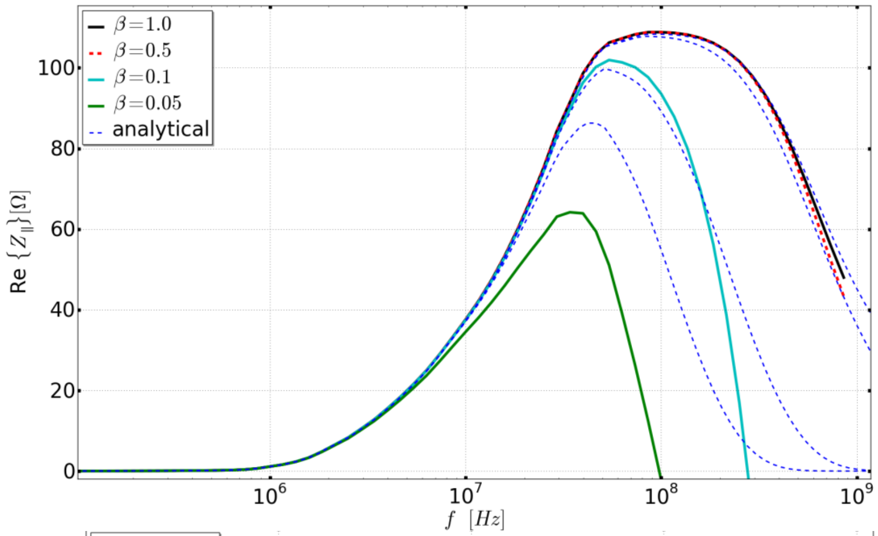


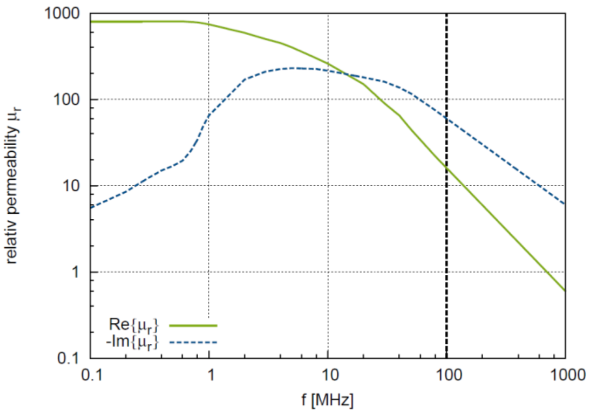


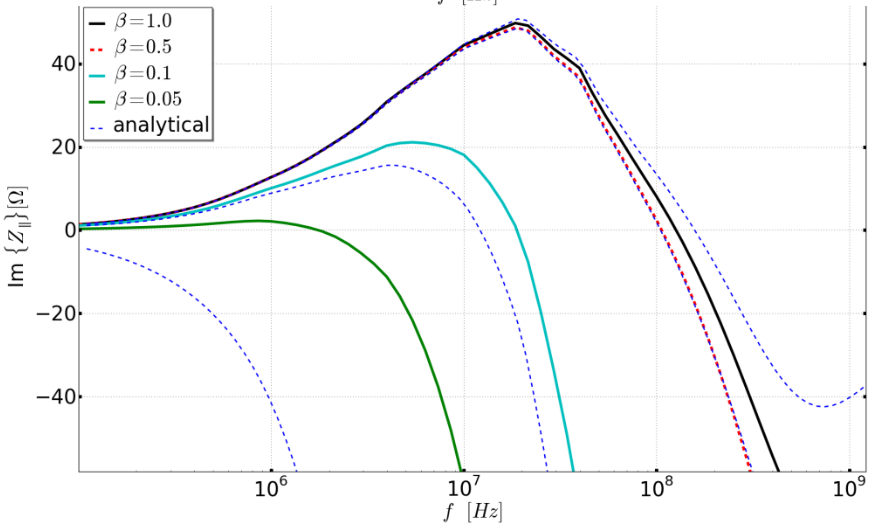


Numerical Examples: Ferrite Ring (FEM)

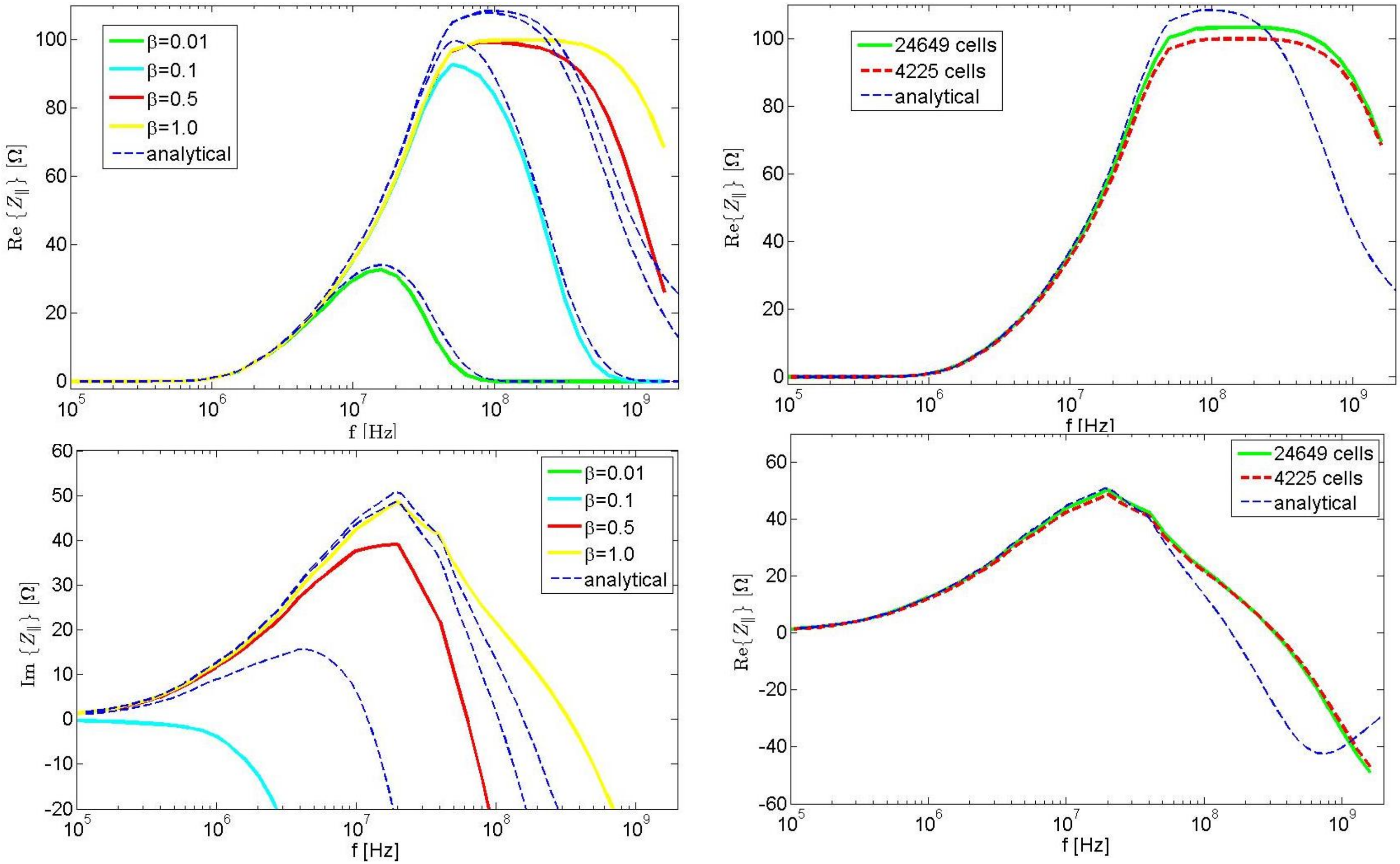








Numerical Examples: Ferrite Ring (FIT)



Comparison of ***my*** FIT and FEM implementations

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- Both solvers have recently been developed…
- Not been pushed to the limit yet!
- Not optimized, not parallelized, no nice interface
- Therefore, no performance comparison!

FIT (2D/3D)

- Windows based C++
- Linear algebra package PETSc
  →complex numbers available
- HEX mesh from CST
- Bad convergence on curved structures due to staircase mesh
- Extremely slow in 3D

FEM (2D)

- Linux based Python
- FEniCS framework (open source)
- Different linear algebra backends
- TET mesh from GMSH
- Helmholtz split necessary for lowest order
- No complex numbers but coupled systems can be treated easily

Conclusion and Outlook

- Both methods work well in 2D
- Convergence studies yet to be done
  → difficult since convergence depends on
  frequency, beta, material parameters, dimensions...
- Small skin depth hard to treat
  → Surface impedance boundary conditions (SIBC)
- Thin layers hard to treat
  → Thin sheet approaches
  → Impedance transmission conditions

Outlook: 3D simulation in Frequency Domain

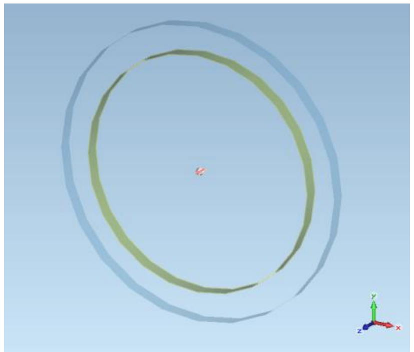
- For both FIT and FEM possible
- Good parallel LES solvers necessary
  → They have to be able to deal with ill conditioned systems
- Requires the presented 2D solvers as beam entry and exit boundary conditions
  → Don‘t try to imprint analytical beampipe solution!
- For simulation above beam pipe cutoff also a waveguide port Eigenmode solver required
- ***Large*** development effort…

  …ongoing at TEMF

THE END

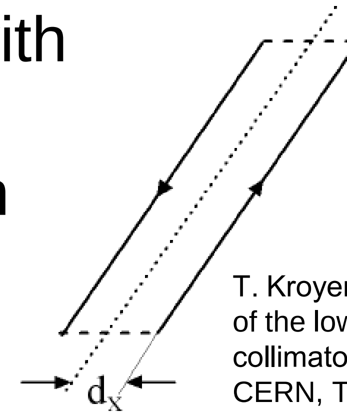
- Thank you for your kind attention
- Any questions?

Simplified numerical method (according to “radial model“)



- Power loss calculation with CST EM STUDIO®
- MQS Frequency-Domain

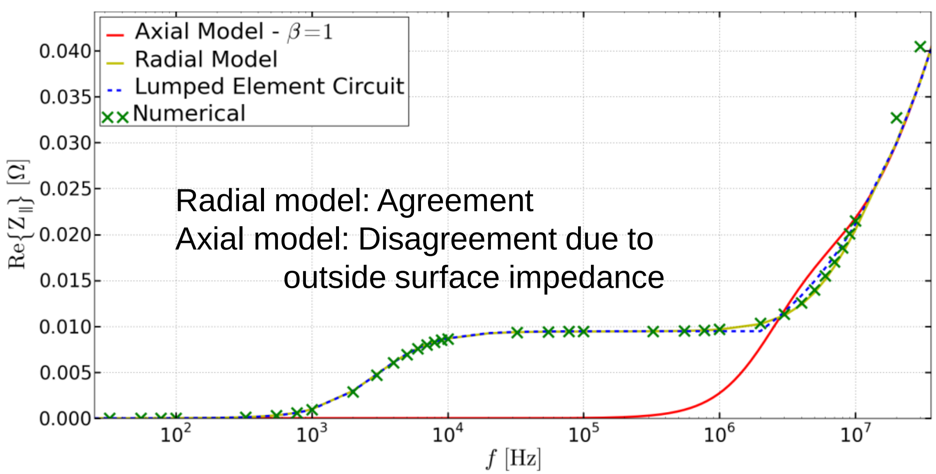
$$\delta P = \frac{1}{2} \int_{pipe} \underline{\vec{E}} \cdot \underline{\vec{J}}^{*} \mathrm{dV}$$

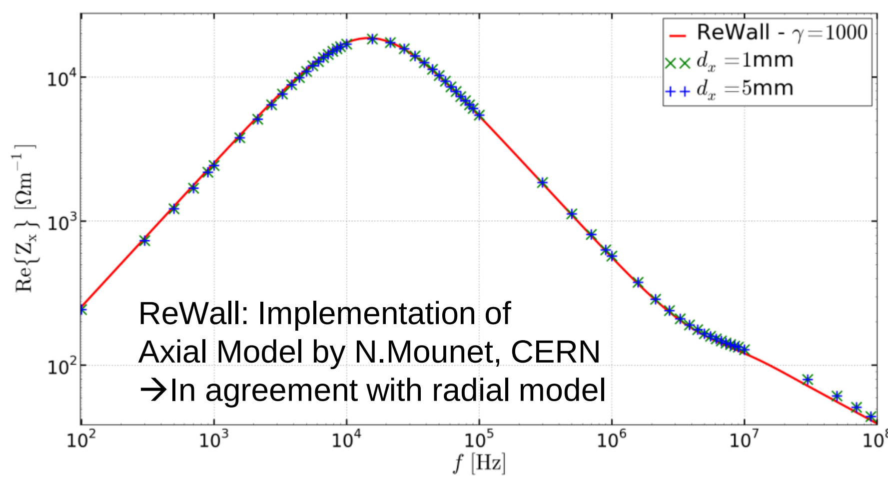


T. Kroyer, “Simulation of the low frequency collimator impedance” CERN, Tech.Rep., 2008

$$\frac{\mathrm{Re}\{\underline{Z}_{\|}\}}{l} = \frac{1}{I^2}\frac{\delta P}{\delta z}$$

$$\frac{\mathrm{Re}\left\{\underline{Z}_{\perp,x}(\omega)\right\}}{l} = \frac{c}{\omega d_x^2}\frac{1}{I^2}\frac{\delta P}{\delta z}$$





Transformer Model

NUCLEAR INSTRUMENTS AND METHODS 159 (1979) 21-27 ; © NORTH-HOLLAND PUBLISHING CO.

METHODS FOR MEASURING TRANSVERSE COUPLING IMPEDANCES IN CIRCULAR ACCELERATORS

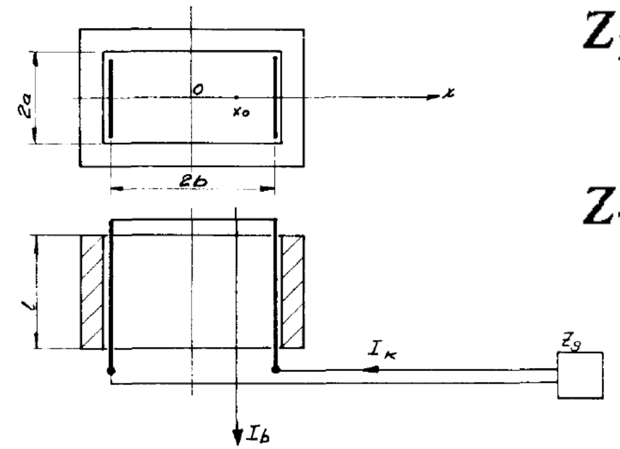
G. NASSIBIAN and F. SACHERER*

CERN, CH-1211 Geneva, Switzerland

Received 26 June 1978

$$Z_\mathrm{L} = \frac{\omega^2 \mu_0^2 x_0^2 l^2}{4a^2 Z_\mathrm{k}}\ \Omega,$$

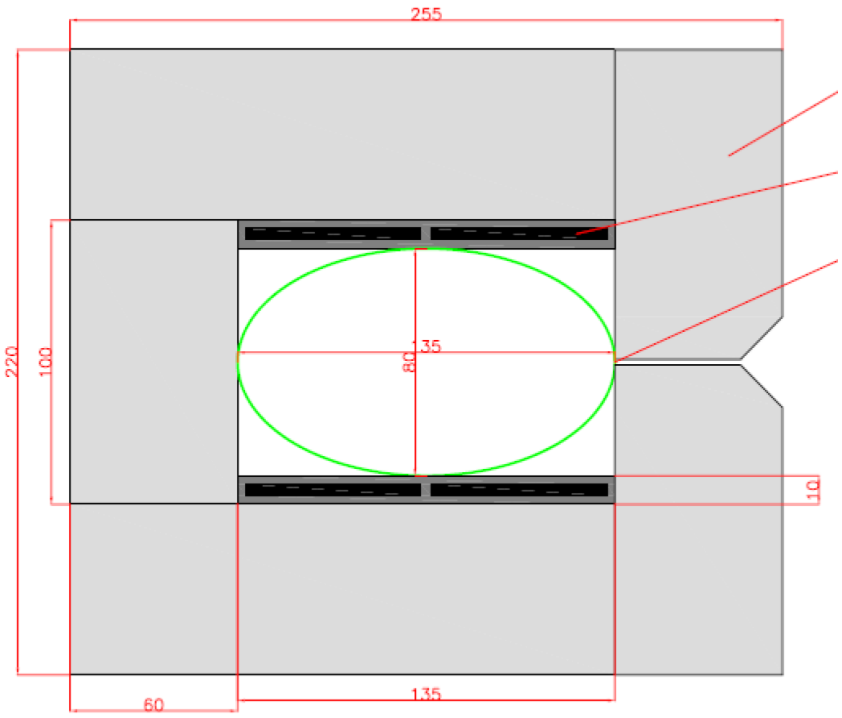
$$Z_\mathrm{T} = \frac{c\omega\mu_0^2 l^2}{4a^2 Z_\mathrm{k}}\ \Omega/\mathrm{m}$$



$$Z_\mathrm{k} = \mathrm{j}\omega L + Z_\mathrm{g},$$

- Longitudinal impedance is zero at the center
- Both scale inversely with the Network impedance

The Kicker magnet



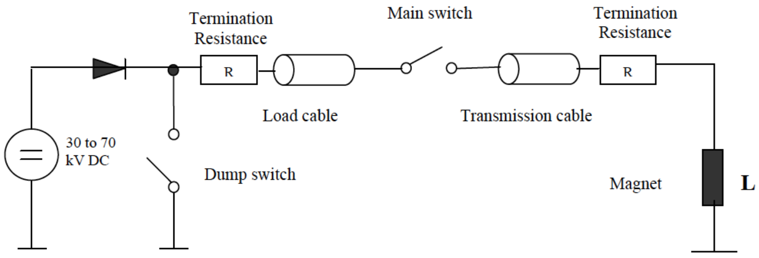


Figure 2.8-160: Schematic circuit diagram of a monopolar kicker

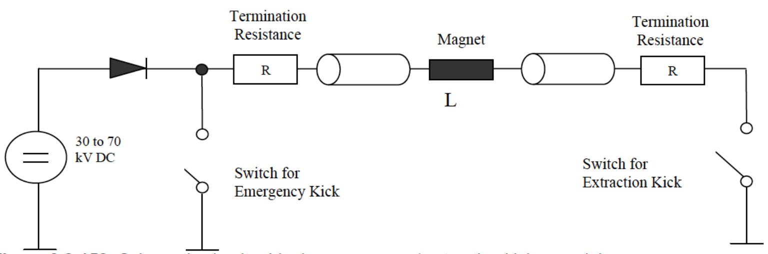


Figure 2.8-158: Schematic circuit – bipolar emergency / extraction kicker module

The PFN of the bipolar kicker

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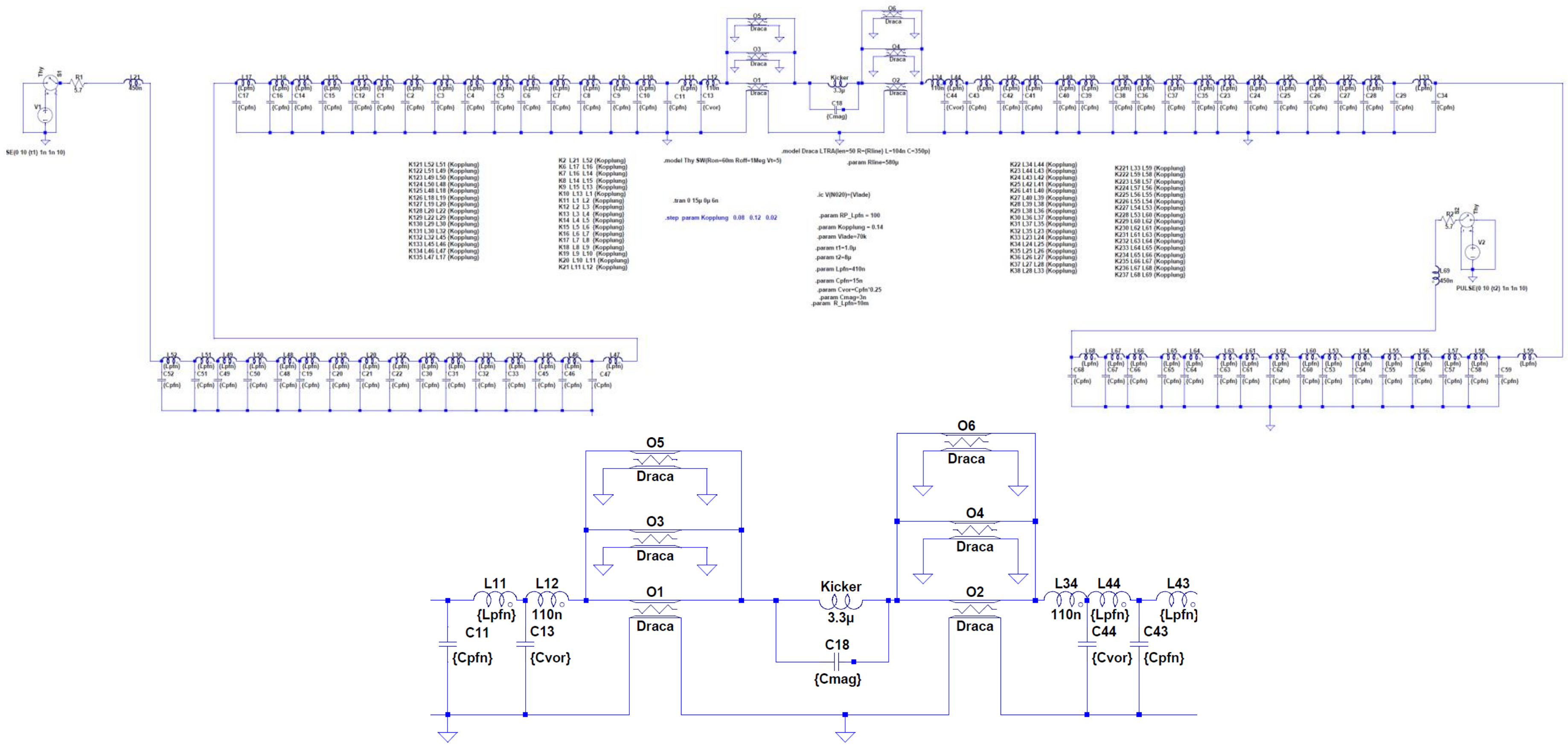
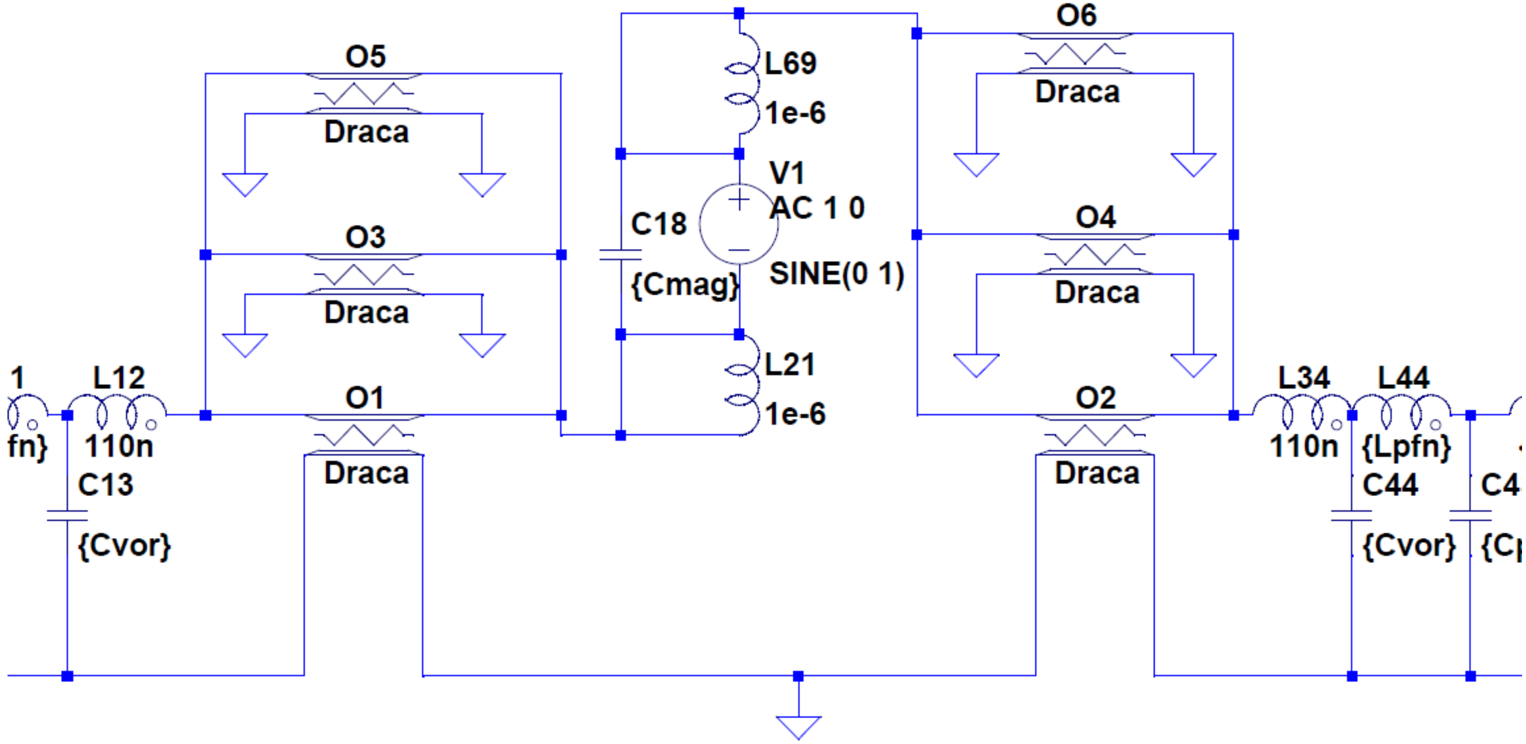
Bipolarer Kicker SIS 100 Extraction / Emergency

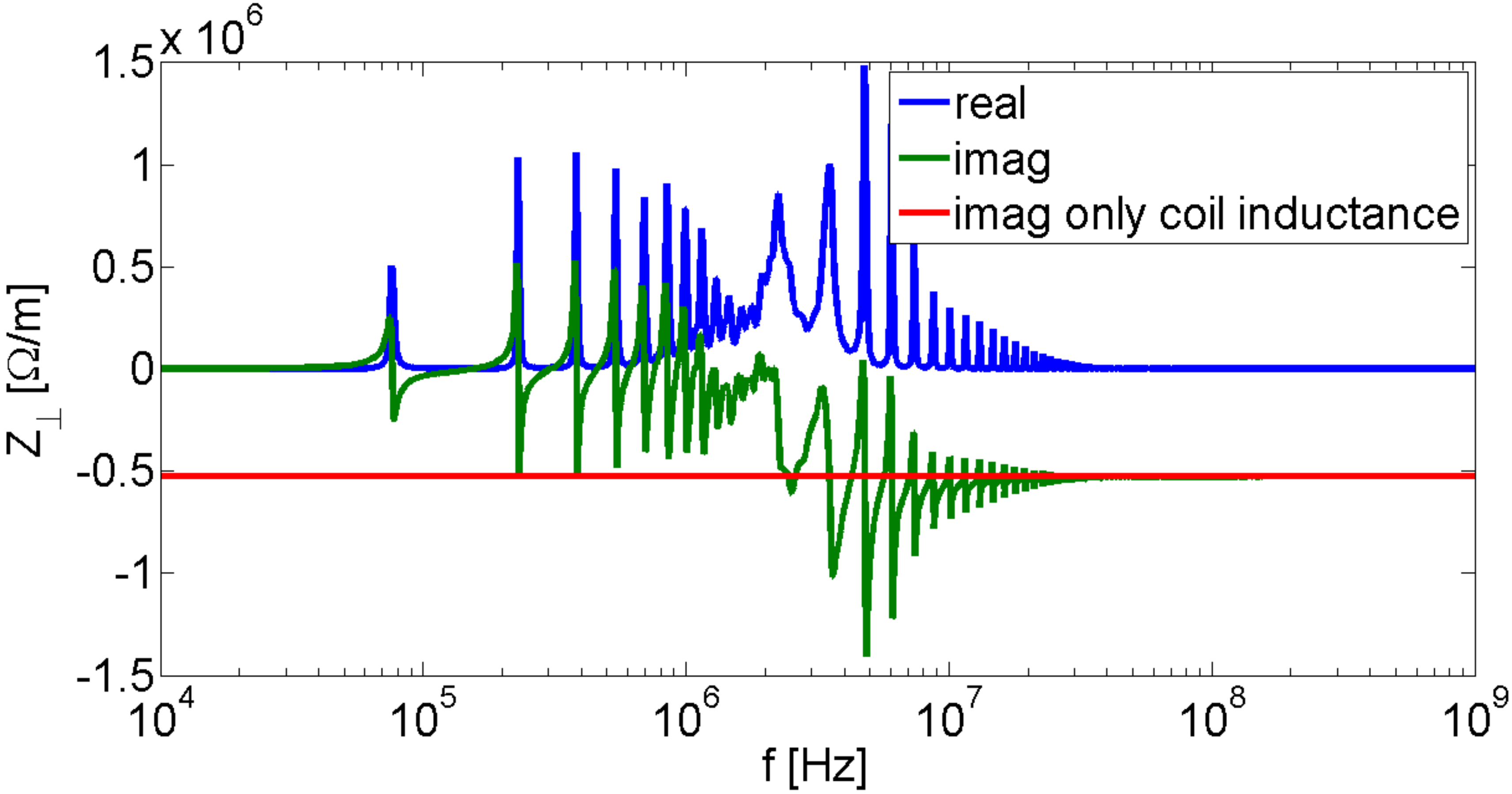


PFN Impedance determination

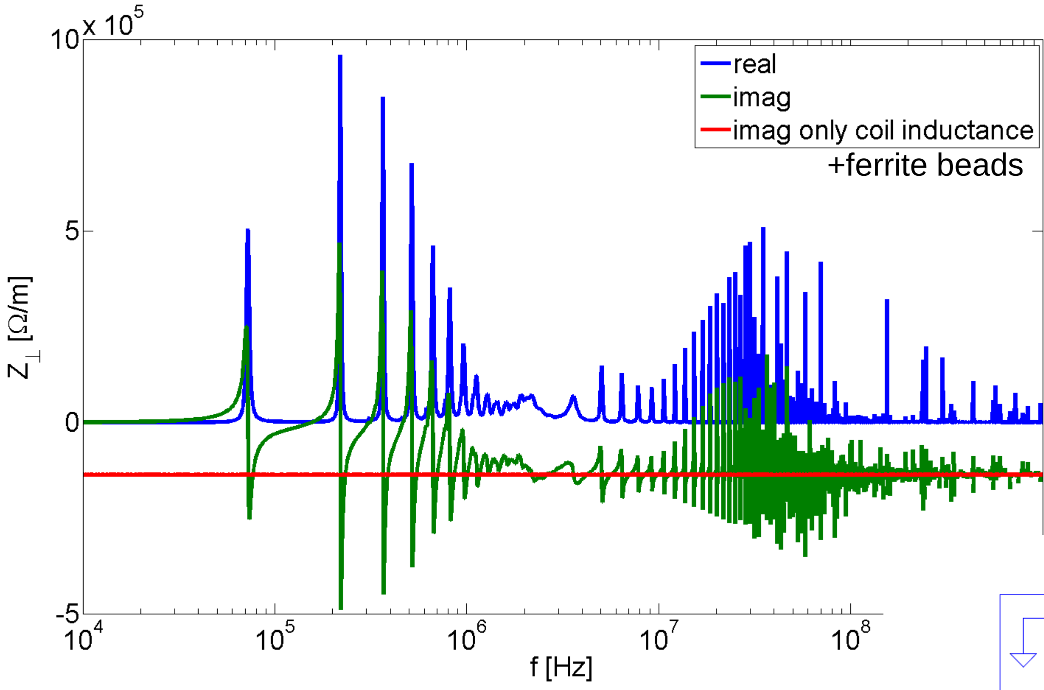


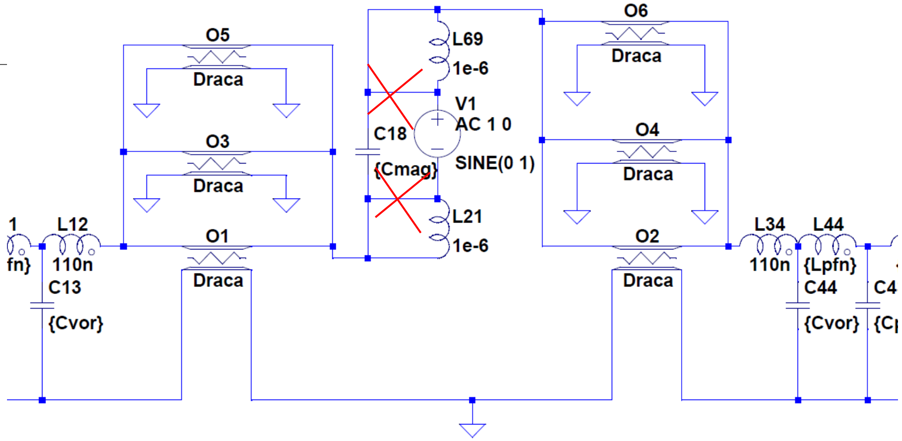
- Can also be measured like this with NWA

Transverse impedance

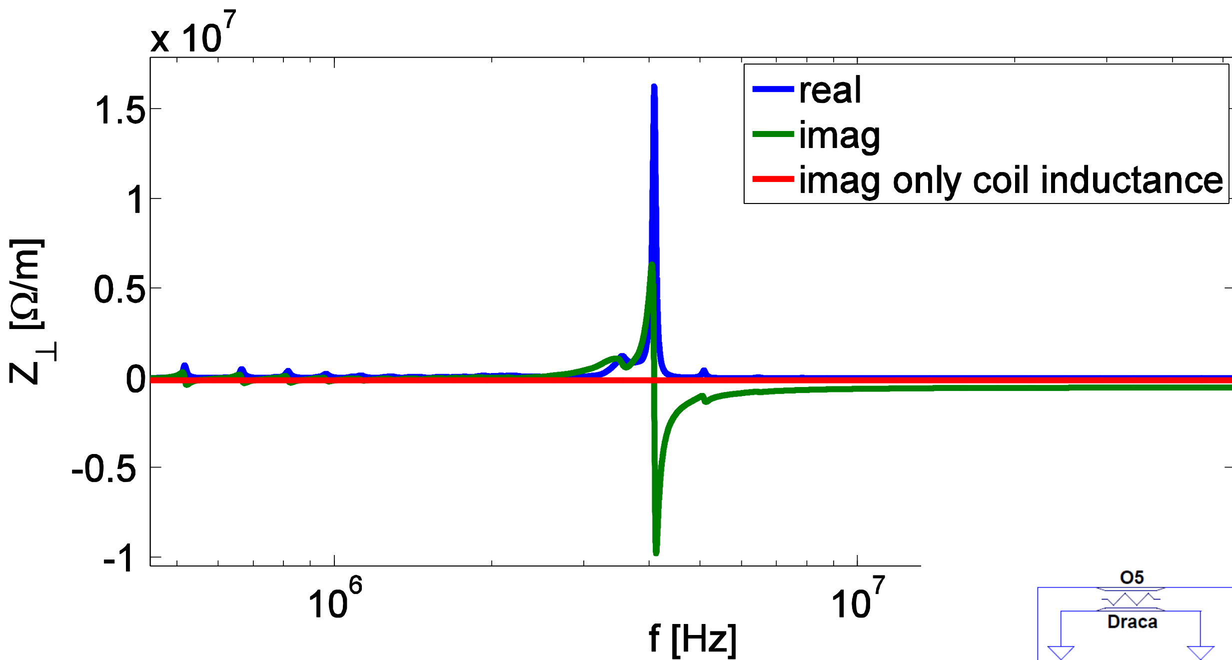


Optimization with ferrite bead (saturates at kicker puls current)





Cmag inside ferrites→Resonance!



$$f_r = 4\ \mathrm{MHz}$$