FINITE ELEMENT SIMULATION OF FAST CORRECTOR MAGNETS FOR PETRA IV

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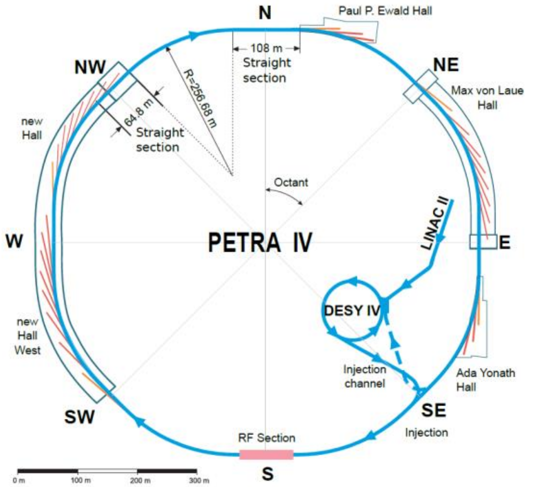

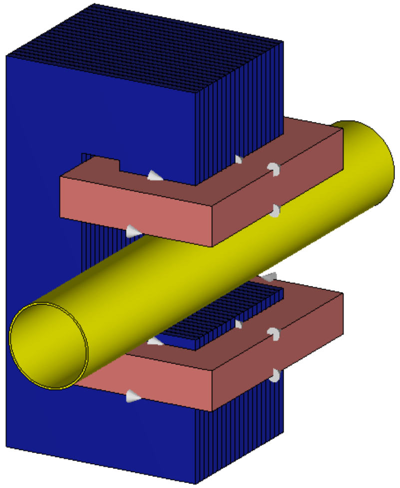

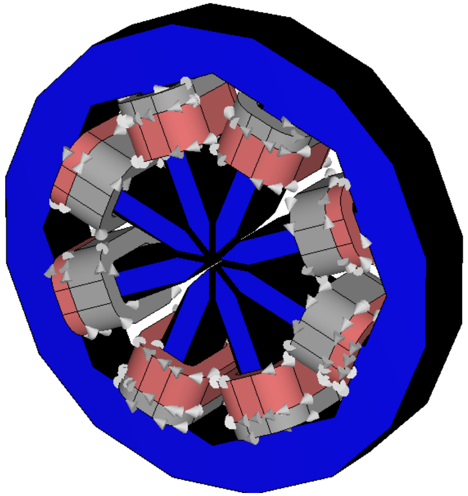

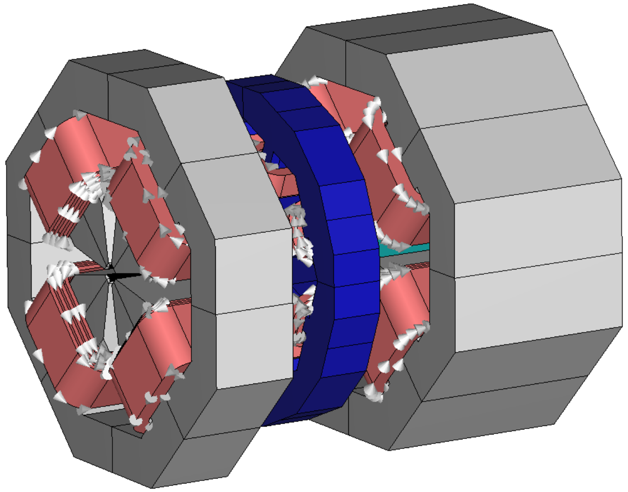

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PETRA IV Conceptual Design Report

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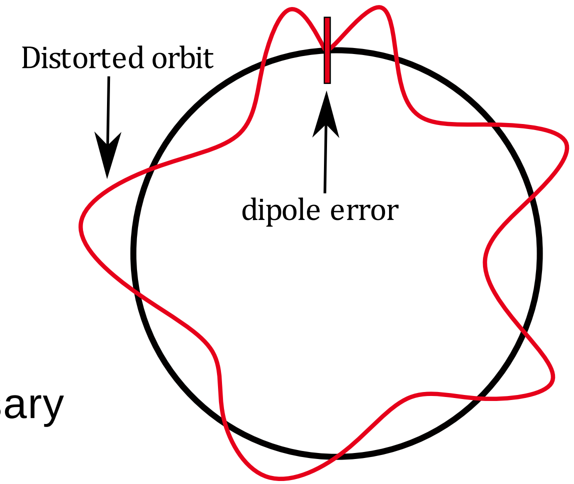
INTRODUCTION

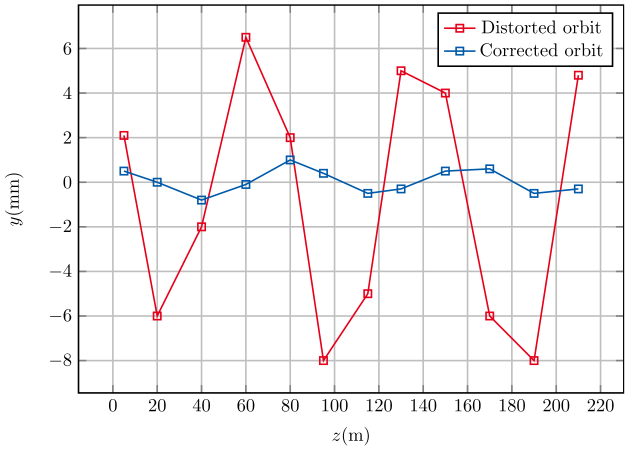


- Circular accelerators need dipole magnets to correct orbit distortions
- **PETRA IV**: ultra-low emittance synchrotron radiation source

➔ fast orbit feedback system, **corrector magnets with frequencies in kHz range** necessary

- **Strong eddy currents ➔** power losses, time delay, and field distortion
- **Simulation challenging** due to small skin depths and laminated yoke

➔ Need for technique to simplify simulations



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THEORY

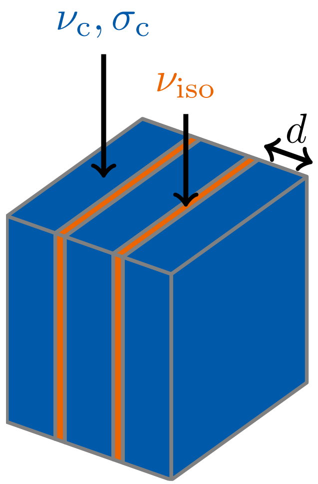
- Magnetoquasistatic PDE: $\nabla \times (\nu(\vec{r})\nabla \times \underline{\vec{A}}(\vec{r})) + j\omega\sigma(\vec{r})\underline{\vec{A}}(\vec{r}) = \underline{\vec{J}}_s(\vec{r})$
- Replace reluctivity $\nu(\vec{r})$ and conductivity $\sigma(\vec{r})$ in the laminated yoke with spatially constant tensors

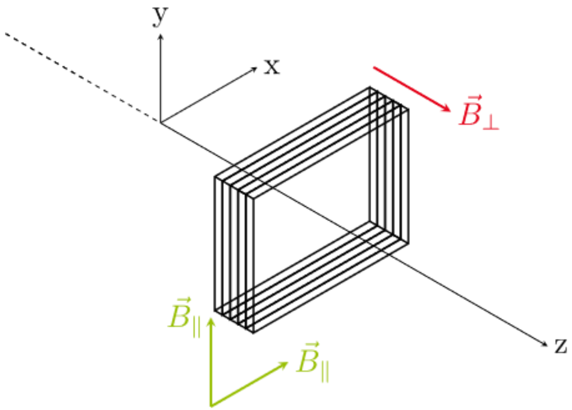
$$\nu(\vec{r}) \rightarrow \underline{\bar{\bar{\nu}}} = \frac{1}{8}\sigma_c d\delta\omega(1+j)\frac{\sinh((1+j)\delta^{-1}d)}{\sinh^2\left((1+j)\delta^{-1}\,d/2\right)}\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix} + \nu_c\begin{bmatrix}0&0&0\\0&0&0\\0&0&1\end{bmatrix}$$

$$\sigma(\vec{r}) \rightarrow \bar{\bar{\sigma}} = \gamma\sigma_c\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix}$$

Skin depth $\delta = \sqrt{2/\omega\sigma_c\mu_c}$
Stacking factor $\gamma = \frac{V_c}{V_{\text{Yoke}}}$

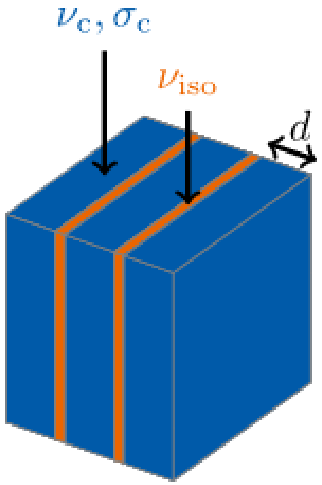
P. Dular et al., 2003
L. Krählenbühl et al., 2004
H. De Gersem et al., 2012

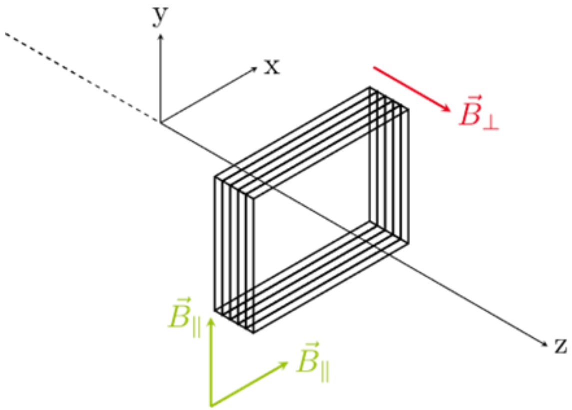




APPLICATION

- Frequency-dependent, complex-valued and anisotropic materials **can be implemented in LF frequency domain solver of CST Studio Suite®**
- Homogenization captures losses due to eddy currents induced by in-plane and perpendicular flux components
- Homogenization is valid also for high frequencies, i.e., $\delta \ll d$
- Restriction to frequency domain simulations
- Non-linear material properties and hysteresis are neglected





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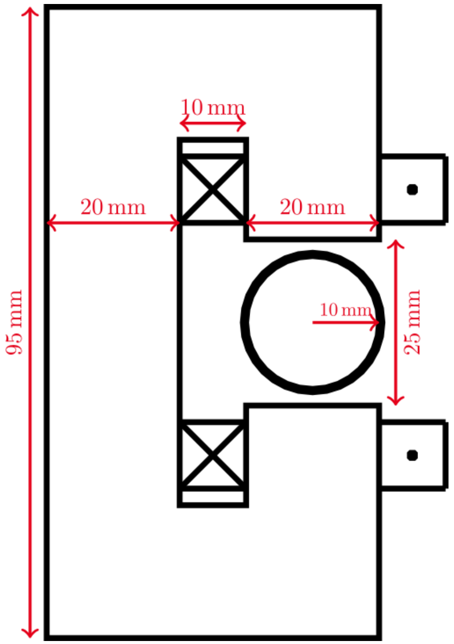
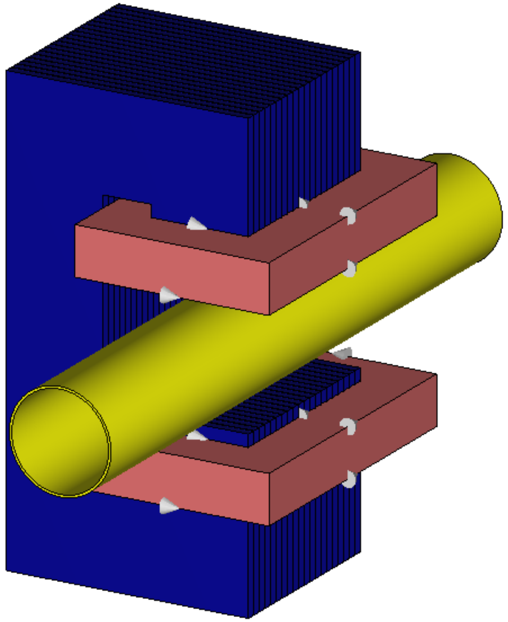
MODEL DESCRIPTION

- **Iron yoke:** length = 40 mm, lamination thickness = 1.83 mm
- **Copper beam pipe:** thickness = 0.5 mm, length = 140 mm
- **Coils**: current **=** 10 A (peak), # turns = 250
- **Frequency domain simulation** via **CST Studio Suite**®





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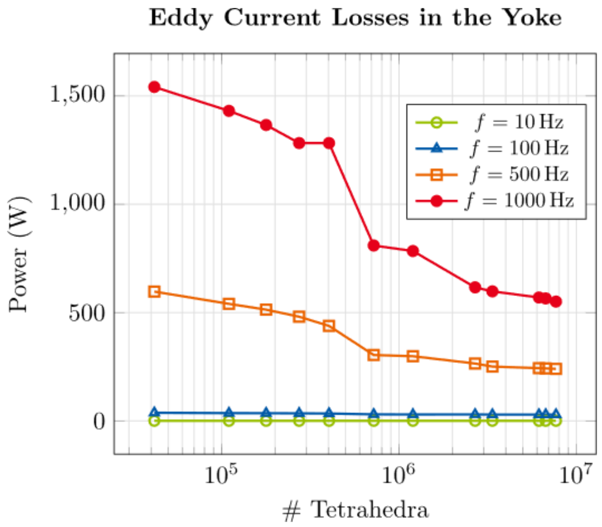
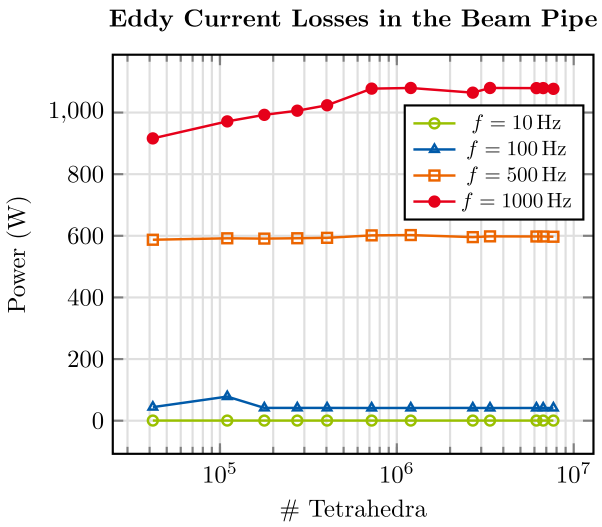
SIMULATION OF THE FULL MODEL

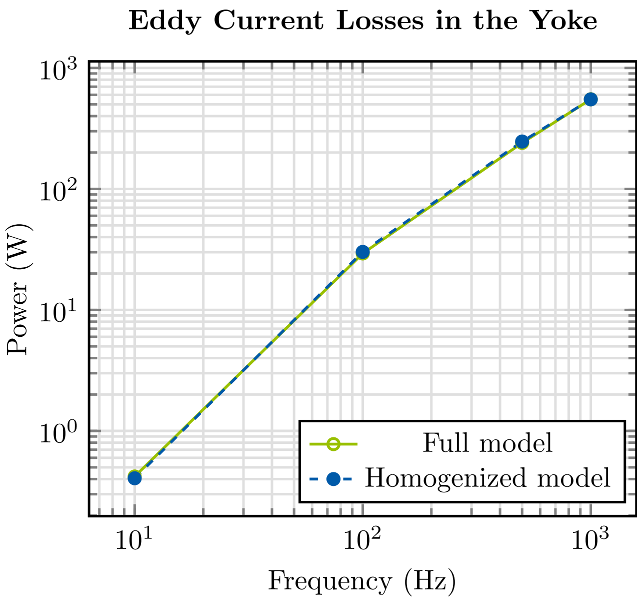


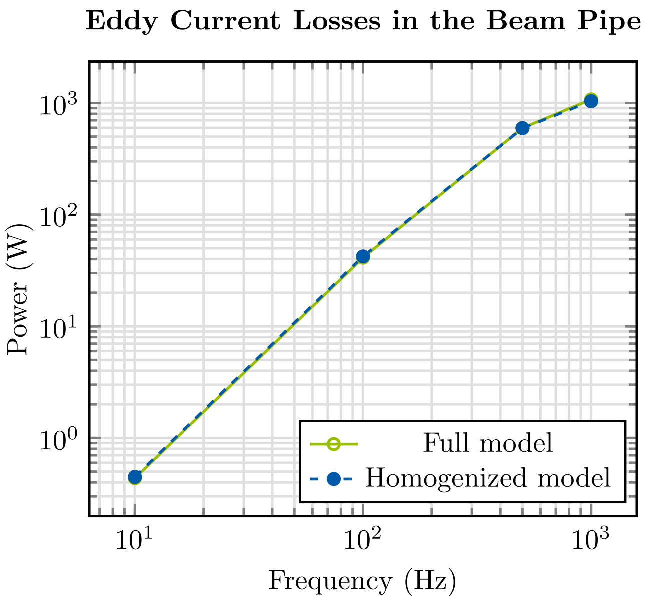


# Tetrahedra	$4.2 \cdot 10^4$	$4.0 \cdot 10^5$	$1.2 \cdot 10^6$	$3.4 \cdot 10^6$	$7.7 \cdot 10^6$
Simulation time	2 min	20 min	1 h	7.5 h	21.5 h

- Strong mesh dependence of power losses at higher frequencies
  - ➔ Obtaining reliable results is difficult
  - ➔ Need for simplified model

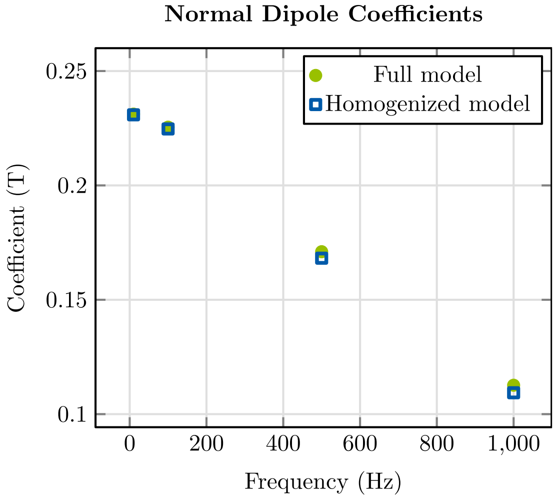
HOMOGENIZED VS. FULL MODEL

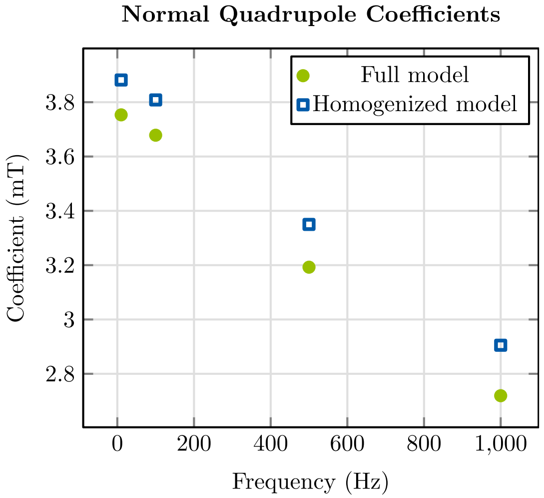


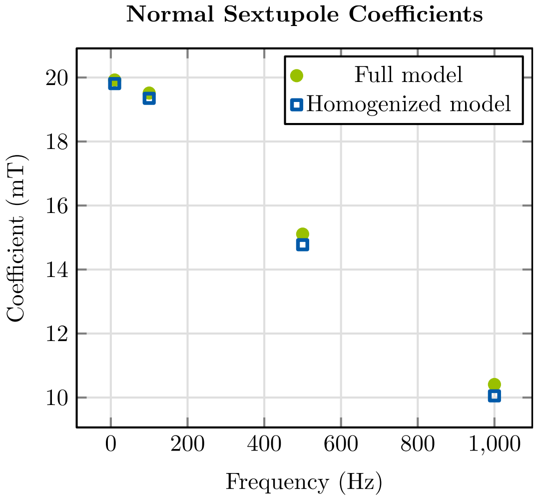


- Good approximation of losses in yoke & beam pipe (max. relative error 4 %)
- Simulation time reduced from several hours to 4 min

HOMOGENIZED VS. FULL MODEL







- Homogenization technique yields accurate approximation of multipole coefficients
➔ Aperture field accurately represented

Multipole coefficient	Average rel. error
Dipole	1 %
Quadrupole	5 %
Sextupole	2 %

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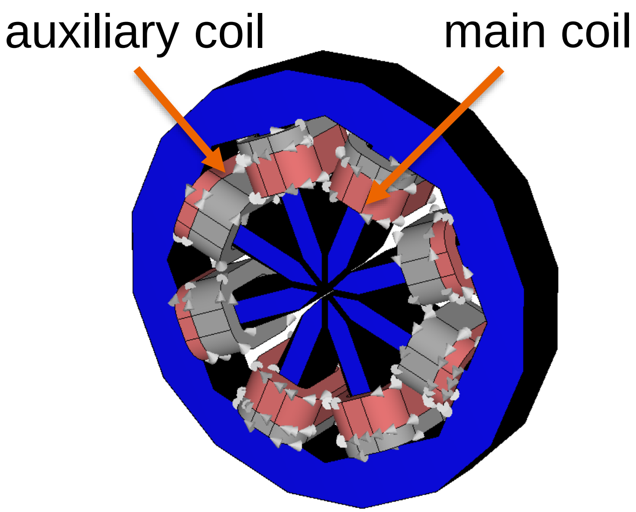
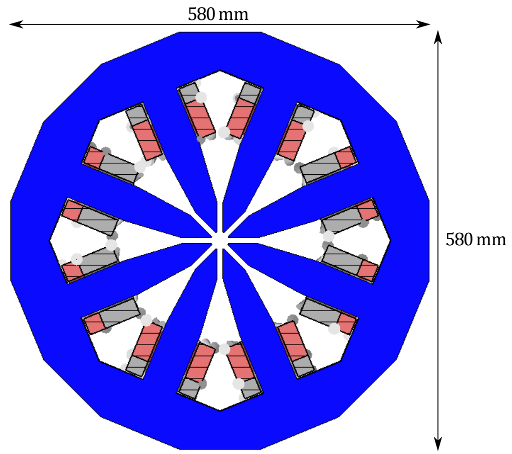
MODEL DESCRIPTION

- **Dipole** corrector with **octupole-like design**
- **Coils**:
  - 4 main coils: current = 27.4 A (peak), # turns = 53
  - 4 auxiliary coils: current = 27.4 A (peak), # turns = 22
- **Iron yoke:**
  - Diameter = 580 mm, length = 90 mm
  - Lamination thickness = 0.5 mm
- At first **no beam pipe**

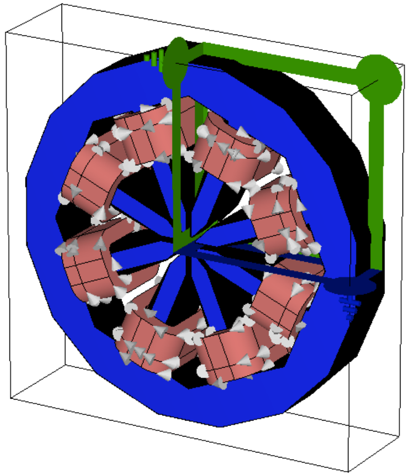


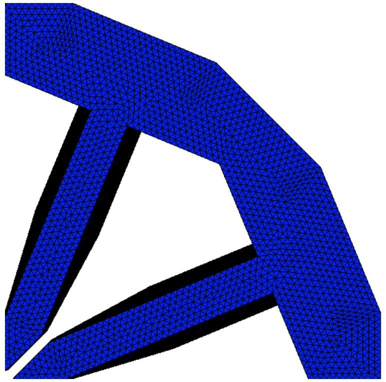


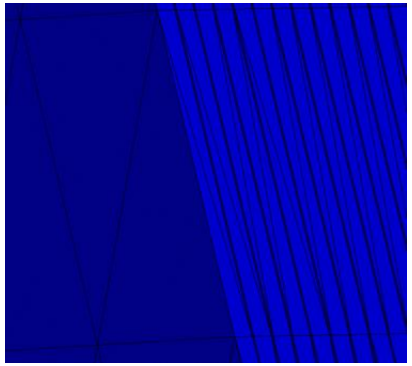
Design by A. Aloev (DESY), inspired by APS

SIMULATION OF THE FULL MODEL

- **Frequency domain simulation** via **CST Studio Suite®**
- Three symmetry planes, test frequencies $f = 10\ \mathrm{Hz}, 100\ \mathrm{Hz}, 500\ \mathrm{Hz}, 1\ \mathrm{kHz}$
- Long simulation times even for relatively coarse meshes
- Finest mesh: # tetrahedra = $2.3 \cdot 10^6$ ➔ simulation time = 26 h
- Skin depth cannot be resolved ➔ power loss still mesh-dependent







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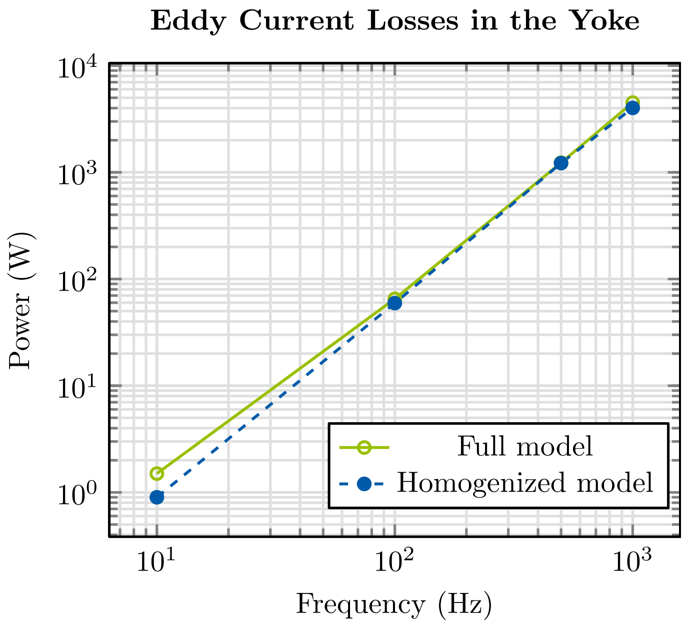
HOMOGENIZED VS. FULL MODEL



Multipole coefficient	Average rel. deviation
Dipole	1 %
14-pole	1 %
18-pole	3 %

Keep in mind:
Power losses in full model are still mesh-dependent !

- Similar power losses
- Good agreement in multipole coefficients
- Simulation time reduces from 26 h to 5 min

➔ Homogenized model can be used for further studies

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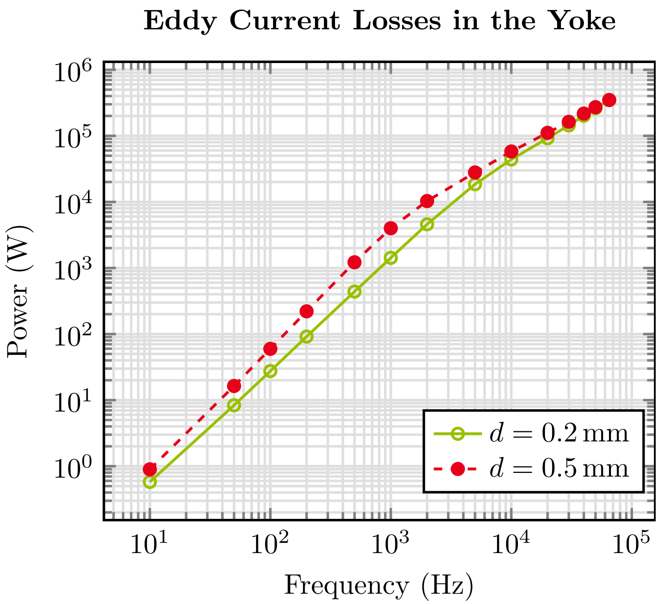
LOSSES FOR DIFFERENT LAMINATION THICKNESSES

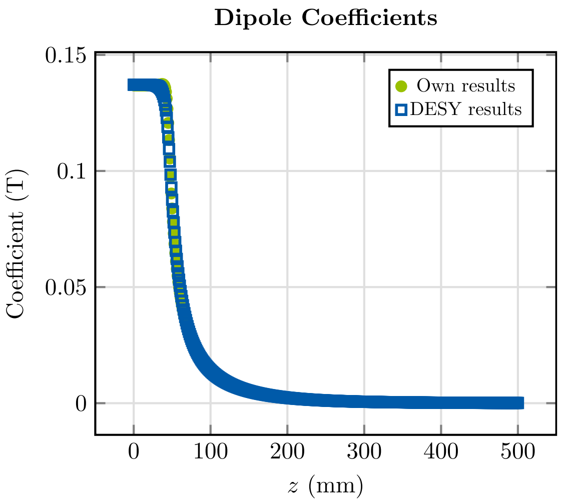


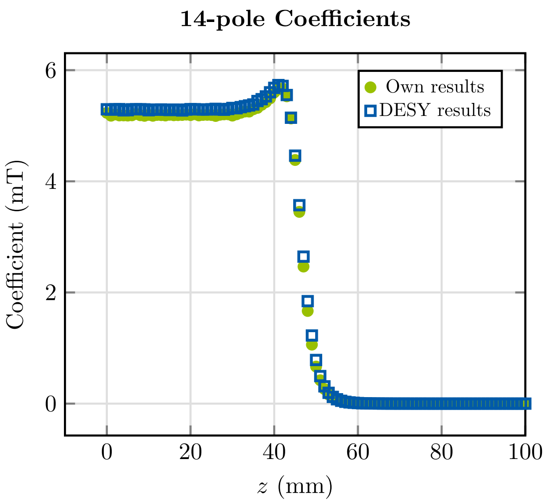
f (Hz)	**Eddy current losses** (W)			
	$d = 0.2$ mm	$d = 0.3$ mm	$d = 0.4$ mm	$d = 0.5$ mm
10	$5.8 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$7.6 \cdot 10^{-1}$	$9.0 \cdot 10^{-1}$
100	$2.8 \cdot 10^{1}$	$3.4 \cdot 10^{1}$	$4.6 \cdot 10^{1}$	$6.0 \cdot 10^{1}$
500	$4.4 \cdot 10^{2}$	$6.2 \cdot 10^{2}$	$9.0 \cdot 10^{2}$	$1.2 \cdot 10^{3}$
1000	$1.4 \cdot 10^{3}$	$2.1 \cdot 10^{3}$	$3.1 \cdot 10^{3}$	$4.0 \cdot 10^{3}$
10000	$4.4 \cdot 10^{4}$	$4.9 \cdot 10^{4}$	$5.5 \cdot 10^{4}$	$5.8 \cdot 10^{4}$
30000	$1.4 \cdot 10^{5}$	$1.6 \cdot 10^{5}$	$1.6 \cdot 10^{5}$	$1.6 \cdot 10^{5}$
65000	$3.5 \cdot 10^{5}$	$3.6 \cdot 10^{5}$	$3.6 \cdot 10^{5}$	$3.5 \cdot 10^{5}$

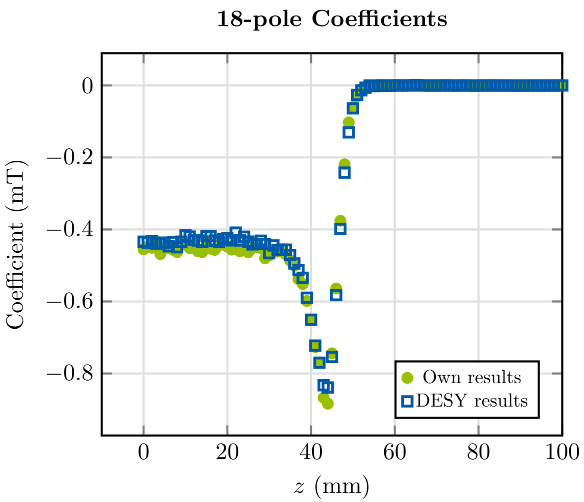
Simulation uses the same current for all frequencies !

- Use homogenization to investigate losses up to 65 kHz
- Vary $d = 0.2 - 0.5$ mm, keep $\gamma \approx 0.91$ constant
- At low frequencies, the lamination thickness has strong influence on the losses
- At very high frequencies, the lamination thickness has no influence on the losses

LONGITUDINAL MULTIPOLE DISTRIBUTION (STATIC)







- Compute multipole coefficients along longitudinal axis of the magnet
- Comparison with DESY for static case ➔ good agreement

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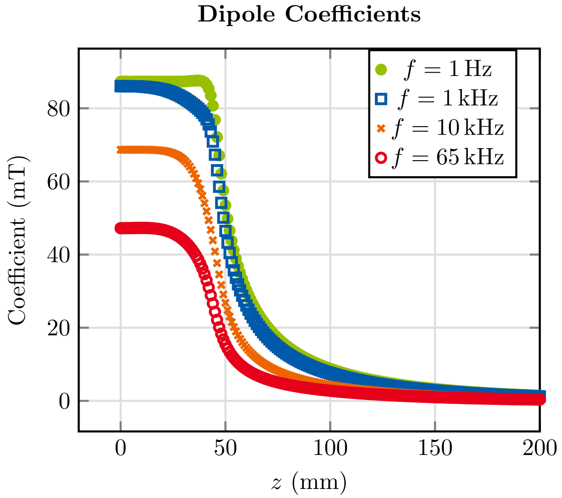
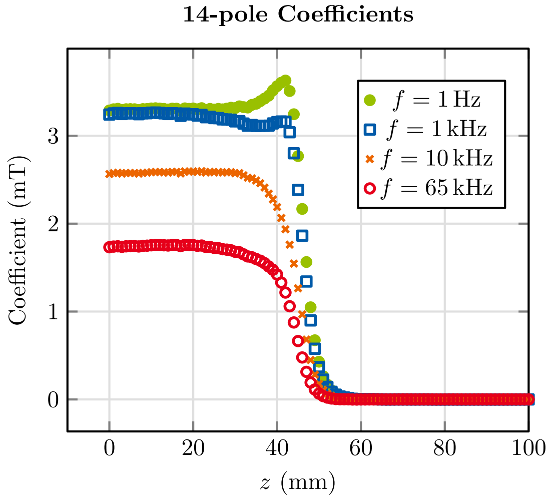
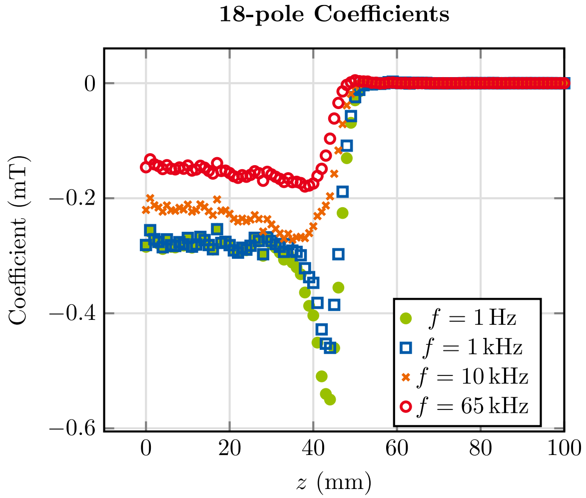
LONGITUDINAL MULTIPOLE DISTRIBUTION (TIME-HARMONIC)







- **Updated # turns & current:**

➔ Main coils: 65 turns, 15 A
➔ Aux. coils: 27 turns, 15 A

- 65 kHz vs. 1 Hz:

➔Int. dipoles: −57 %
➔Int. 14-poles: −52 %
➔Int. 18-poles: −54 %

f (Hz)	**Int. dipole** (mT m)	**Int. 14-pole** (µT m)	**Int. 18-pole** (µT m)
1	11.6	316.4	−30.3
1000	10.7	300.4	−28.6
10000	7.6	229.0	−21.5
65000	5.0	150.3	−13.9

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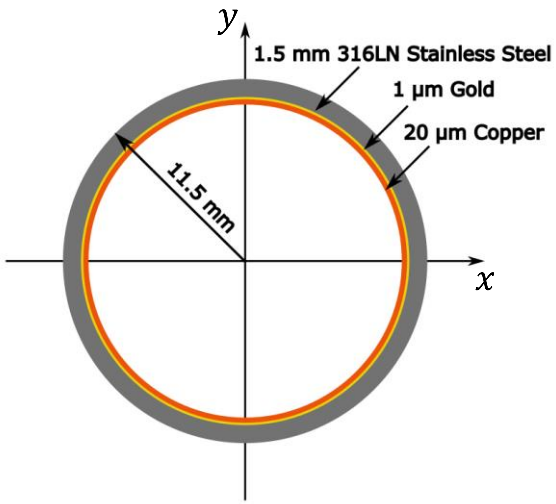
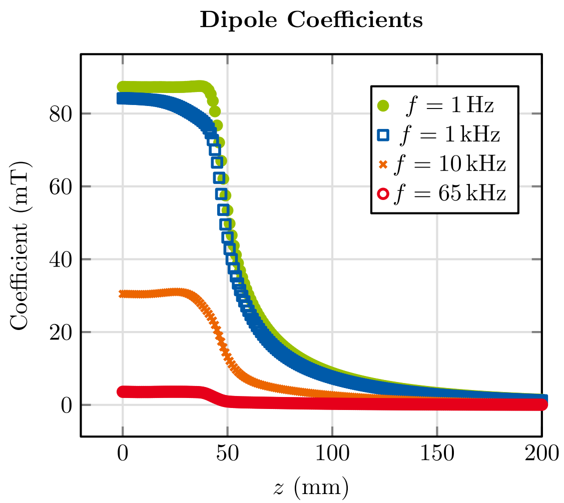
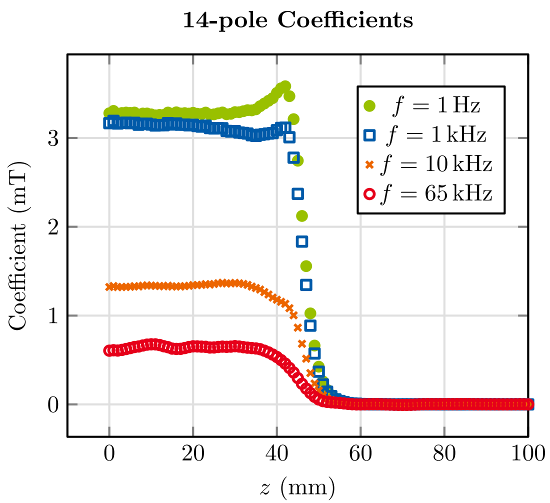
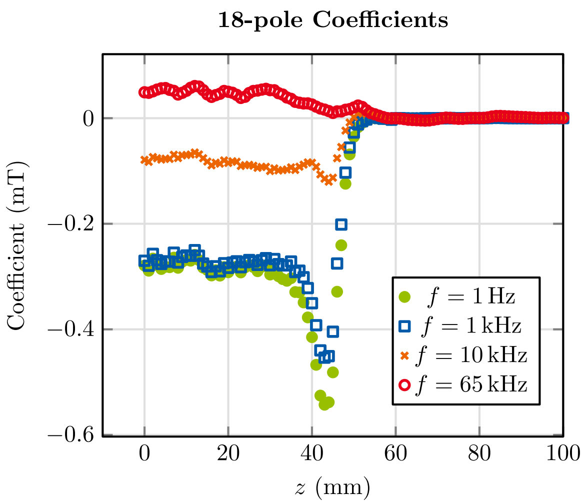
INCLUSION OF BEAM PIPE









f (Hz)	**Int. dipole** (mT m)	**Int. 14-pole** (µT m)	**Int. 18-pole** (µT m)
1	11.5	313.3	−30.6
1000	10.5	292.7	−28.1
10000	3.6	122.6	−8.3
65000	0.4	57.4	4.3

- General shape similar to model without beam pipe
- 65 kHz vs. 1 Hz:

➔Int. dipoles: −97 % (−57 %)
➔Int. 14-poles: −82 % (−52 %)
➔Int. 18-poles change sign (−54 %)

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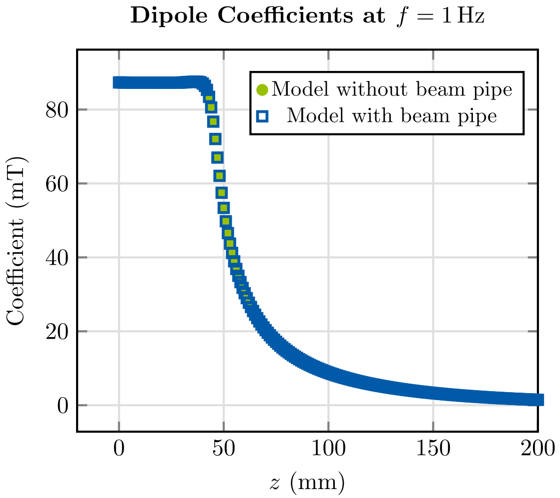
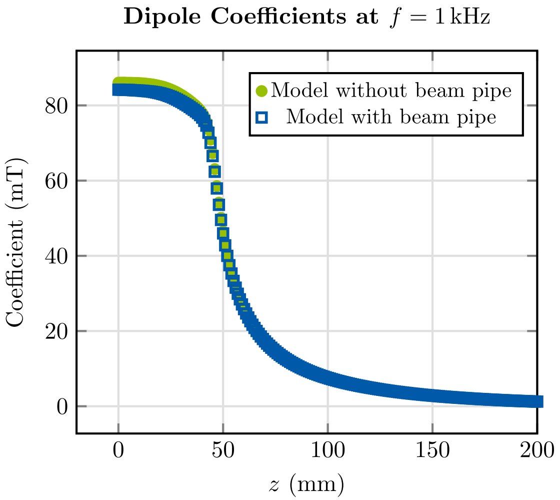
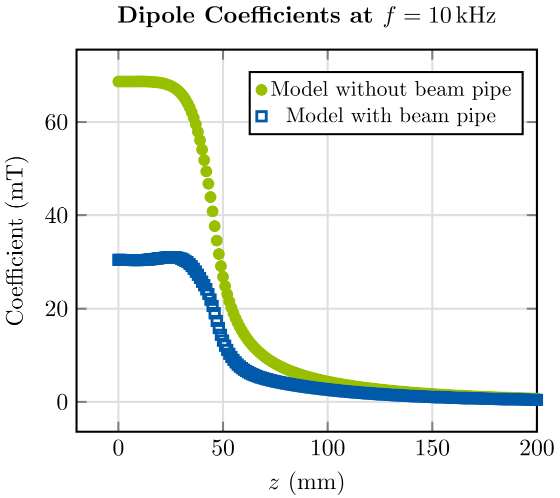
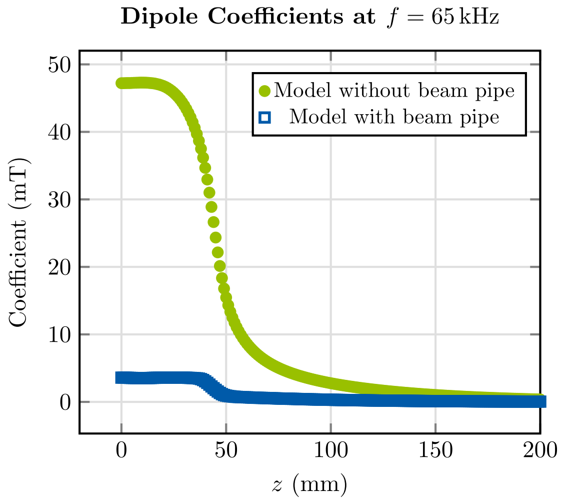
INCLUSION OF BEAM PIPE









- **Up to $f \approx$ 1 kHz**: Only minor differences between the two models
- **For $f >>$ 1 kHz**: Strong attenuation of dipole field due to eddy currents in beam pipe
- At higher frequencies, beam pipe leads to greater effective length of the magnet

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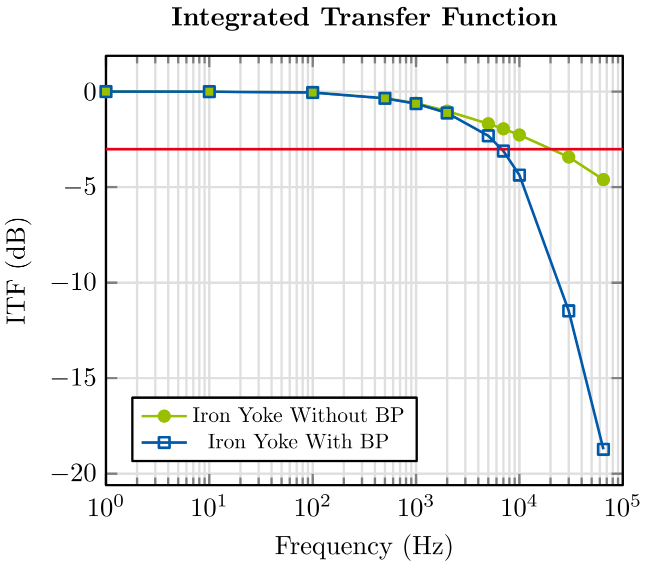
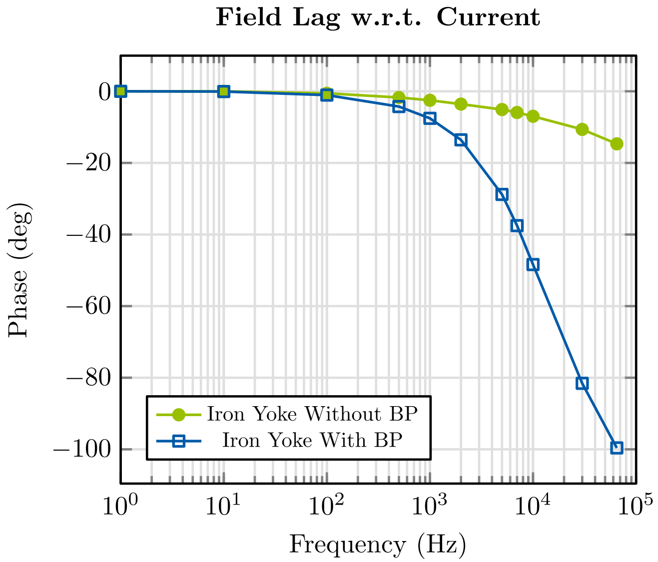
INTEGRATED TRANSFER FUNCTION AND FIELD LAG





$$\mathrm{ITF}(f) = \frac{\int_l B_1(z,f)\,\mathrm{d}z}{\int_l B_1(z,f = 1\mathrm{Hz})\,\mathrm{d}z}$$

Yoke material	3 dB bandwidth	Phase shift at bandwidth
Iron	7 kHz	38°
M-19 Steel	10 kHz	46°
1010 Steel	7 kHz	38°

Yoke material	Average relative permeability*	Conductivity (MS/m)
Iron	5690	10.4
M-19 Steel	4166	1.9
1010 Steel	2780	6.993

- **Beam pipe** is made out of **316 LN SS** ($\sigma = 1.351 \cdot 10^6, \mu_\mathrm{r} = 1.01$) and has an **outer radius of 11 mm** and a **thickness of 1 mm**

* Values are computed from results of static simulations with non-linear BH-curve

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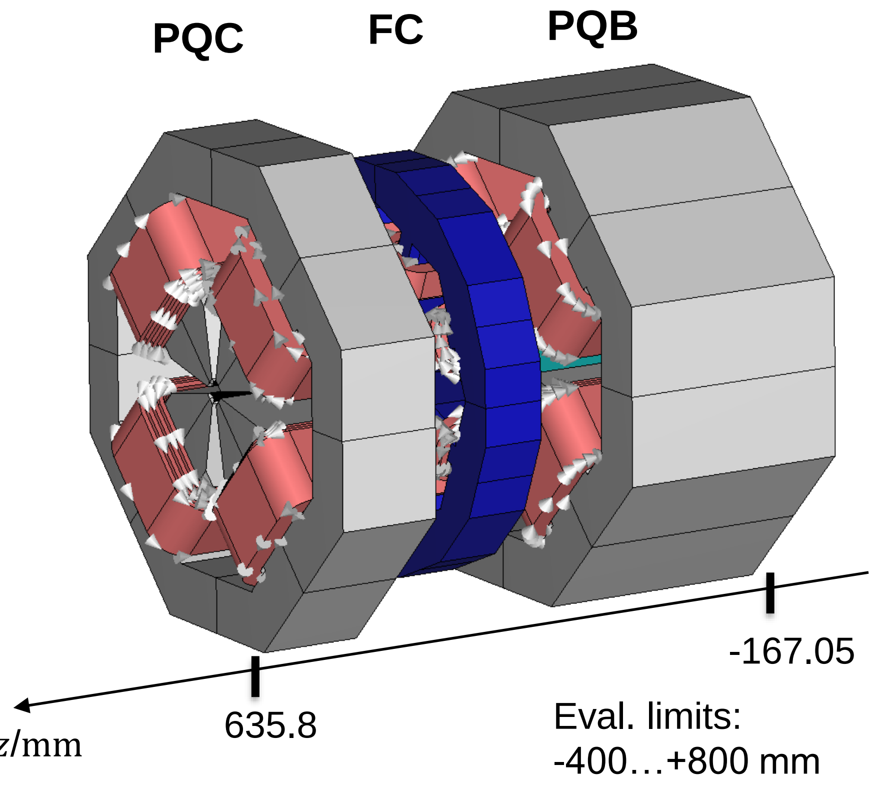
MODEL DESCRIPTION

- Corrector magnet (FC) with two neighboring quadrupole magnets (PQB & PQC)
- AC currents in corrector coils, DC currents in quadrupole coils
- All yokes are 1010 steel, PQB quadrupoles have Vacoflux-50 poles
- Quadrupole yokes are solid, corrector yoke is laminated
- Beam pipe made out of 316LN SS with outer radius of $11\ \mathrm{mm}$ and thickness of $1\ \mathrm{mm}$
- Distance between corrector yoke and quadrupole yokes $\sim 11.5\ \mathrm{cm}$

Material	Average Relative Permeability*	Conductivity (MS/m)
1010 Steel (PQC)	1450	6.993
1010 Steel (PQB)	1810	6.993
Vacoflux-50 (PQB)	5000	2.38
1010 Steel (FC)	2780	6.993

Coils	Ampere turns
PQB	5728.1 At
FC (main)	975 At
FC (aux.)	405 At
PQC	5659.5 At



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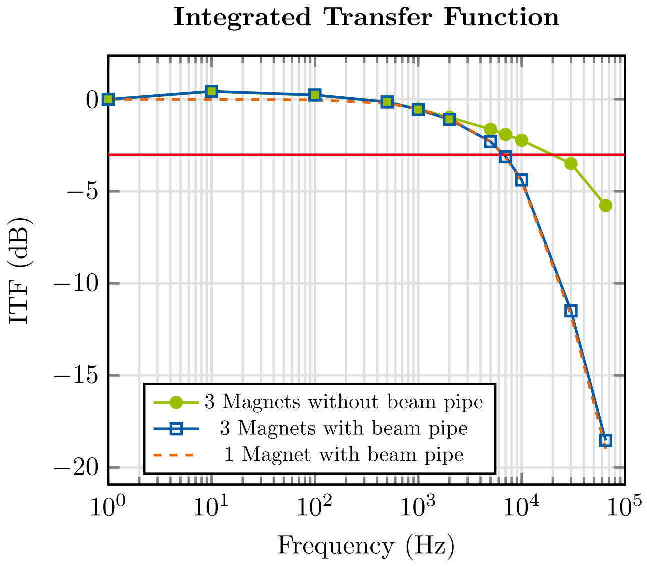
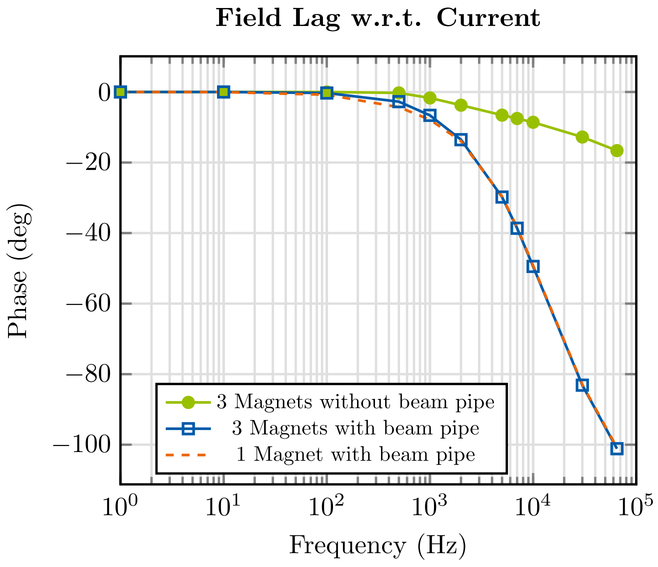
INTEGRATED TRANSFER FUNCTION AND FIELD LAG

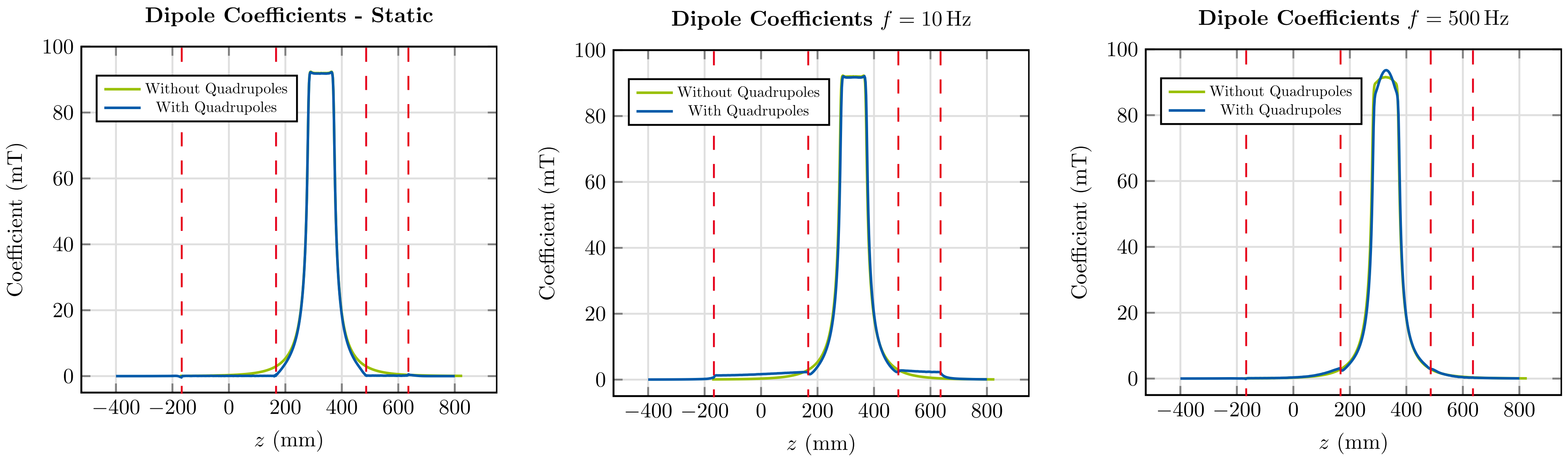




	Model without beam pipe	Model with beam pipe
3 dB bandwidth	20 kHz	7 kHz
Phase shift at bandwidth	11°	39°

- Very similar results as for the model without neighboring quadrupoles
- **Main difference**: at low frequencies, a ~0.5 dB peak is occurring in the ITF of the model with the neighboring quadrupoles

DIPOLE COEFFICIENTS ALONG THE AXIS



Simulation with beam pipe

- **At low frequencies** ($f \leq 100$ Hz), we observe a **parasitic dipole** component **inside the quadrupole magnets**
- This dipole component is due to eddy currents induced in the quadrupole yokes by the AC corrector field

➔ Peak in ITF at low frequencies

➔ Shift of the center of mass (~ 0.5 cm at most)

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CONCLUSION/OUTLOOK

- Validation of homogenization technique using **toy model**
  - ➔ Good approximation of multipoles and power losses
  - ➔ Simulation time reduced from several hours to a few minutes
- Application to **corrector magnet model**
  - Power losses for different lamination thicknesses
  - Longitudinal multipole distributions
  - Integrated transfer function and field lag
  - Cross-talk with neighboring magnets

  } Homogenization enables us to study this over the frequency range of interest from **DC up to 65 kHz**
- **Ongoing investigations:**
  - Simulations with different variations of the beam pipe and cooling channels
  - Approximate treatment of non-linear material properties

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