Lecture HDG-2: Modelling and Simulating Accelerator Magnets

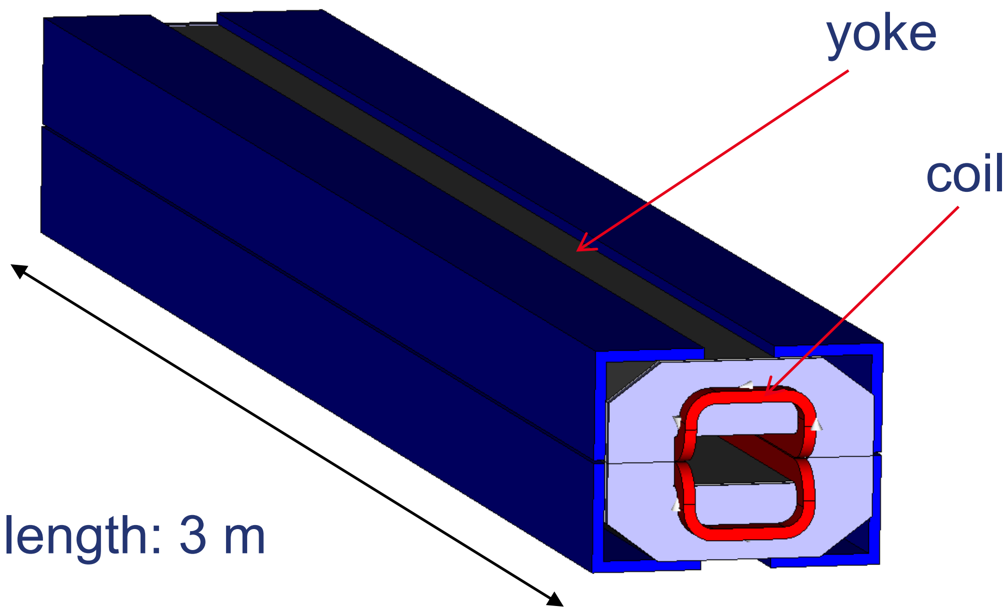
Prof. Dr.-Ing. Herbert De Gersem

TECHNISCHE UNIVERSITÄT DARMSTADT

CERN Accelerator School 2023

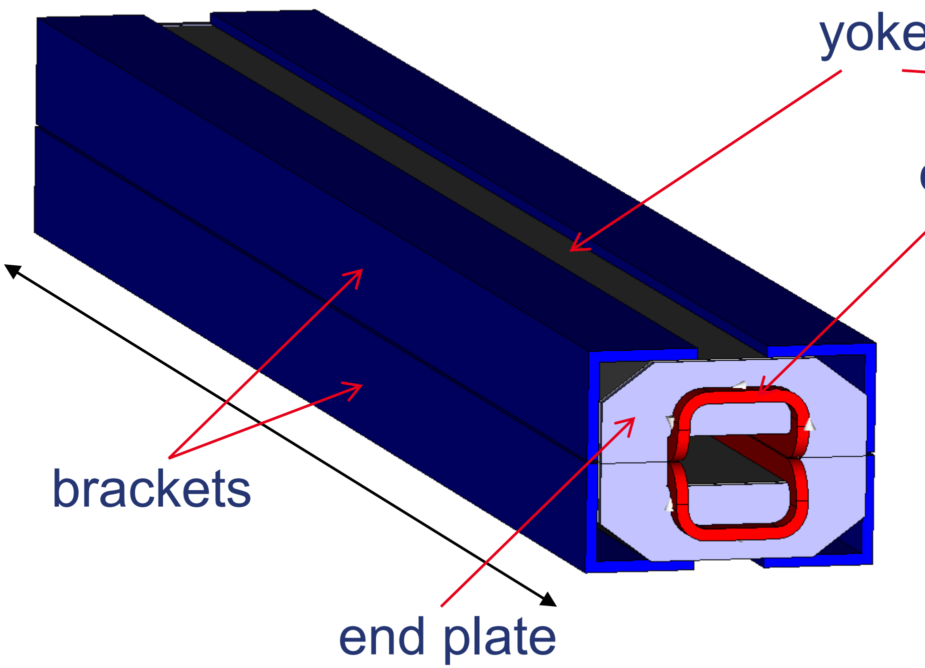
Sankt-Pölten, Austria, 20 November - 1 December 2023

Example: accelerator magnet



comparably simple ?

Example: GSI-SIS-100 magnet



SIS100 dipole (prototype)

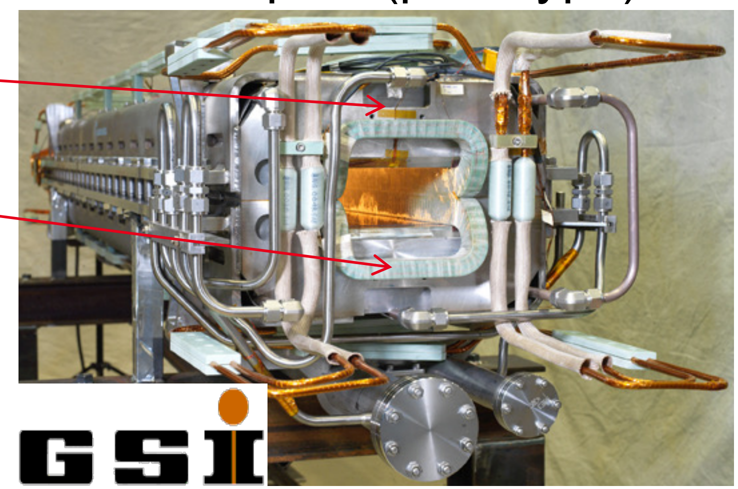


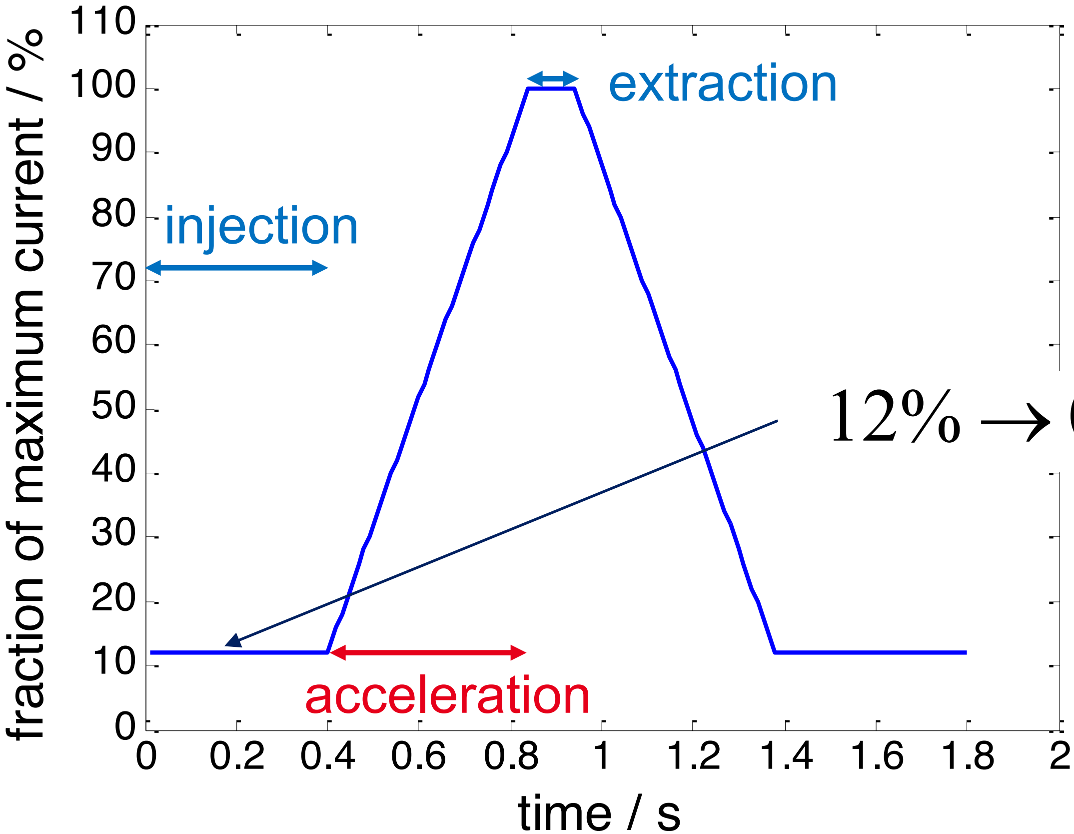
photo: J. Guse, GSI (www.gsi.de)

many geometric details
superconductive coils
helium cooling
mechanical deformation
radioactive hazards

length: 3 m

Example: GSI-SIS-100 magnet

excitation profile



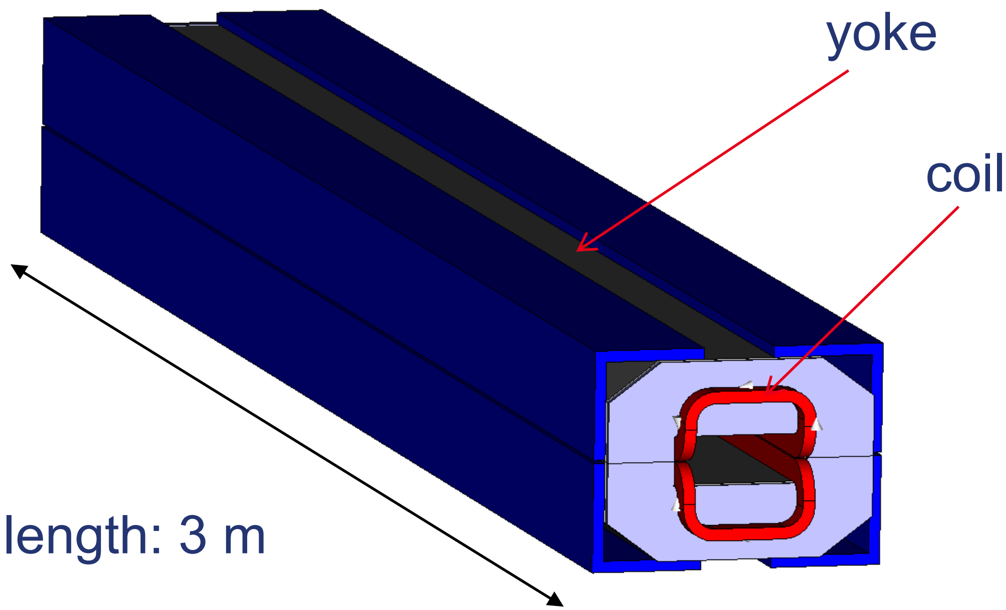
$$12\% \rightarrow 0.24\ \mathrm{T}$$

eddy currents

quench of superconductors

hysteresis

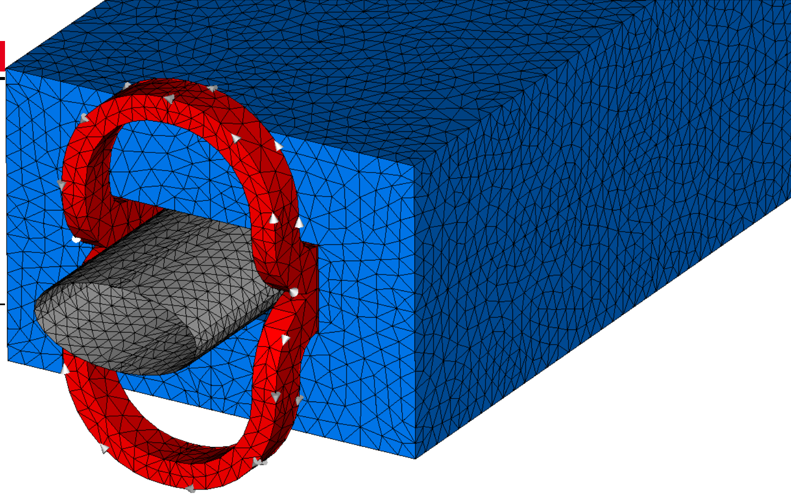
Example: accelerator magnet



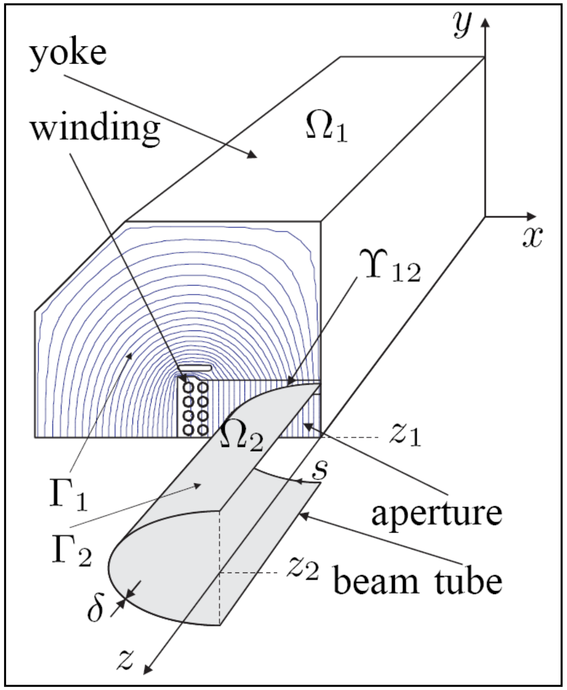
~~comparably simple ?~~

unexpected complexity !

Overview



- magnet simulation (standard 3D FE solver)
- challenges
  - geometrical details
  - materials
  - transient effects
  - high accuracy
- magnet simulation (dedicated 3D FE solver)
- hybrid models
- stochastic models
- conclusions



Magnetoquasistatic formulation

differential equation: $$\nabla \times \left(\nu \nabla \times \vec{A} \right) + \sigma \frac{\partial \vec{A}}{\partial t} = \vec{J}_{\mathrm{s}}$$

reluctivity

magnetic vector potential

conductivity

applied current density

Discretisation in space

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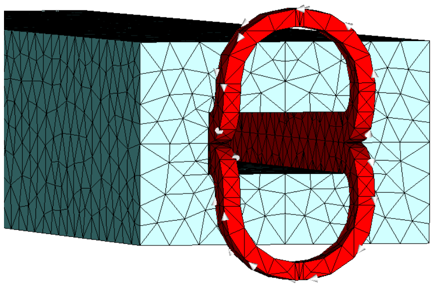
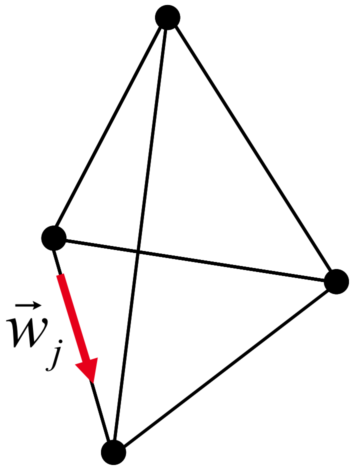
differential equation: $$\nabla \times \left(\nu \nabla \times \vec{A} \right) + \sigma \frac{\partial \vec{A}}{\partial t} = \vec{J}_\mathrm{s}$$

spatial discretisation $$\vec{A} \approx \vec{A}_\mathrm{FE} = \sum_j \widehat{a}_j \vec{w}_j$$

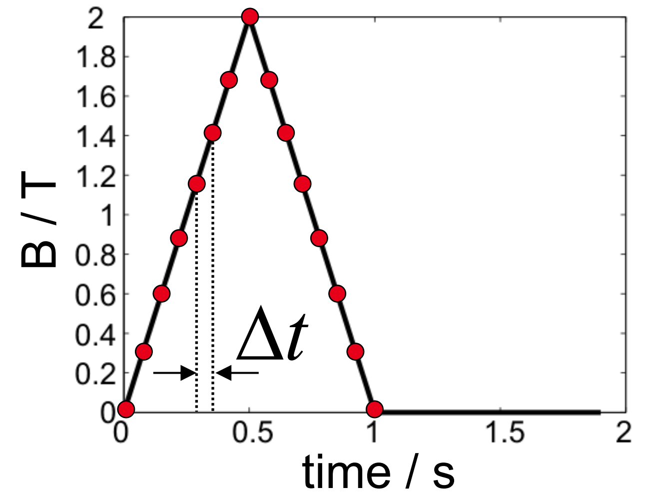
semi-discrete system: $$\mathbf{K}_\nu \widehat{\mathbf{a}} + \mathbf{M}_\sigma \frac{\mathrm{d}\widehat{\mathbf{a}}}{\mathrm{d}t} = \widehat{\widehat{\mathbf{j}}}_\mathrm{s}$$



shape functions:
edge finite elements
(curl-conforming)



Discretisation in time



differential equation

spatial discretisation

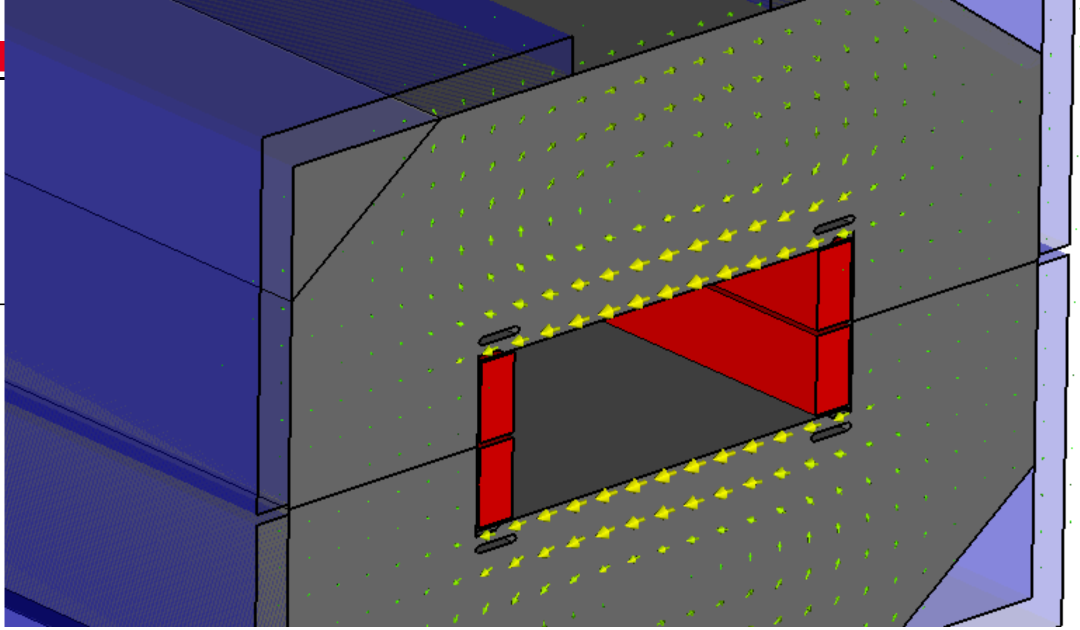
semi-discrete system: $\mathbf{K}_\nu \widehat{\mathbf{a}} + \mathbf{M}_\sigma \frac{\mathrm{d}\widehat{\mathbf{a}}}{\mathrm{d}t} = \widehat{\widehat{\mathbf{j}}}_\mathrm{s}$

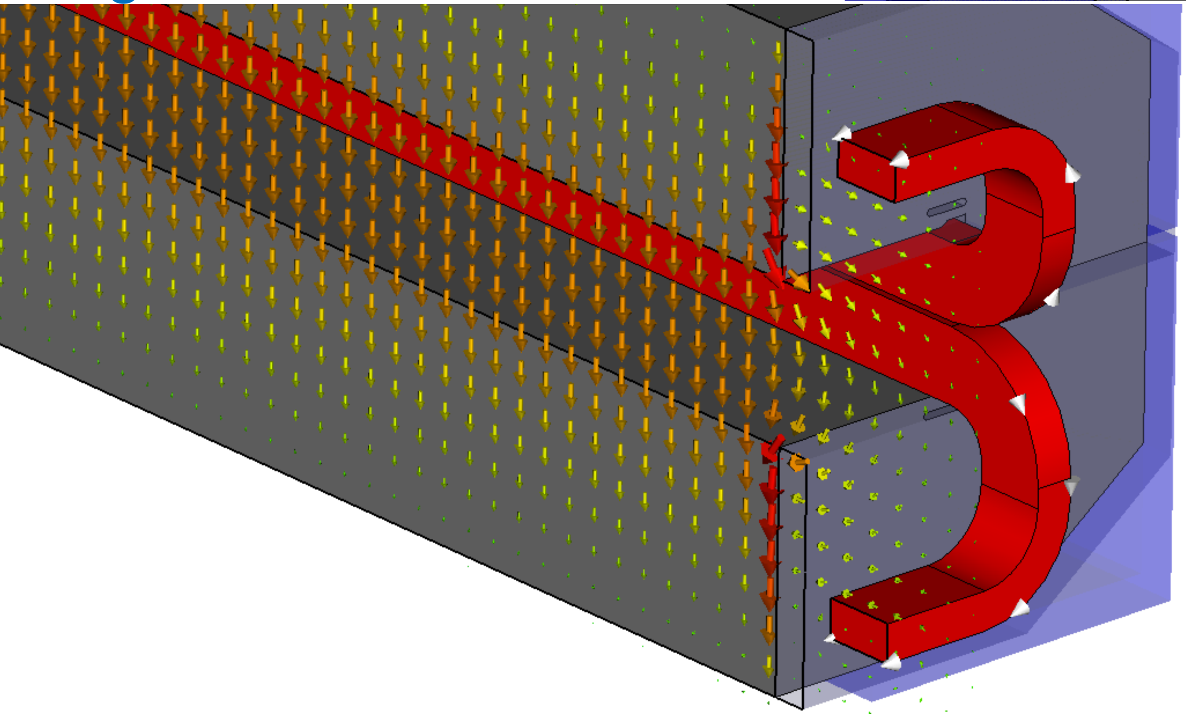
temporal discretisation

discrete system: $\left(\mathbf{K}_\nu + \alpha \mathbf{M}_\sigma\right) \widehat{\mathbf{a}}_{k+1} = \mathrm{RHS}$

Results

magnetic field





eddy currents
in the end plane

simulation by
CST EMStudio®

Electromagnetic field solvers

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- commercial
  or academic
  or freeware
- low-frequency
  and/or high-frequency
- circuit
  and/or 2D fields
  and/or 3D fields
- problem specific
  or multi-purpose
- electromagnetic fields
  and/or multi-physics
- cheap or expensive

non-exhaustive list !!

CEDRAT

ANSYS

infolytica corporation

CST

JMAG

FEKO Comprehensive Electromagnetic Solutions

opera simulation software

Superfish

FEMM

ROXIE

FiQuS

COMSOL MULTIPHYSICS

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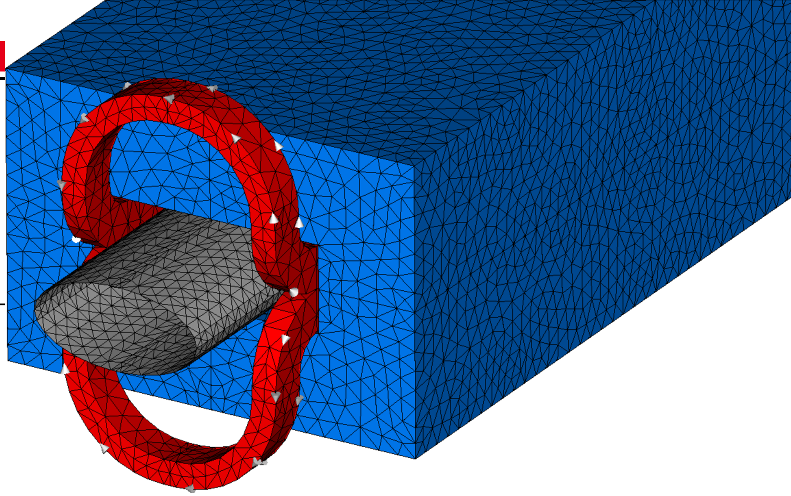
Overview



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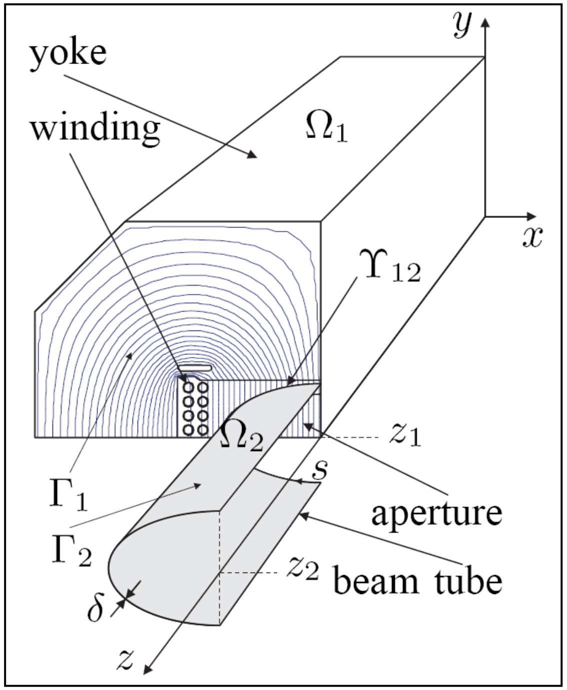


Challenge 1: Detailed geometry

yoke

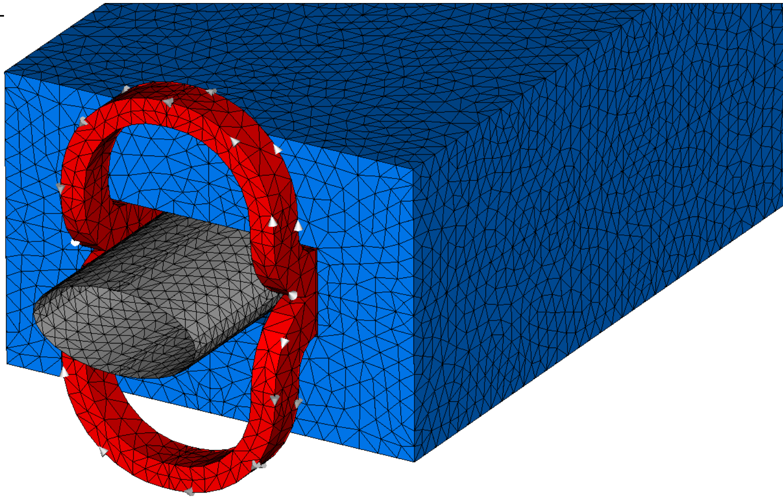
- length (meter)
  vs. lamination thickness (mm)
- shimming, holes

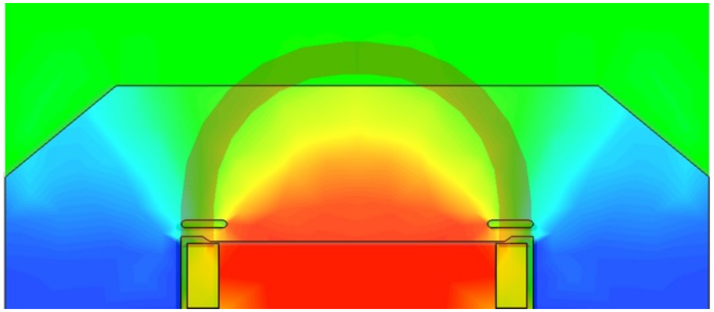
beam tube

- < 1mm thick

end-winding parts

- determine the eddy currents
  in the end plates





Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)

$$\bar{\bar{\nu}}(\vec{B}) = R^T \begin{bmatrix} \nu_{\mathrm{rol}} & & \\ & \nu_{\mathrm{trans}} & \\ & & \nu_{\mathrm{trans}} \end{bmatrix} R$$

ν_{rol} reluctivity in the rolling direction

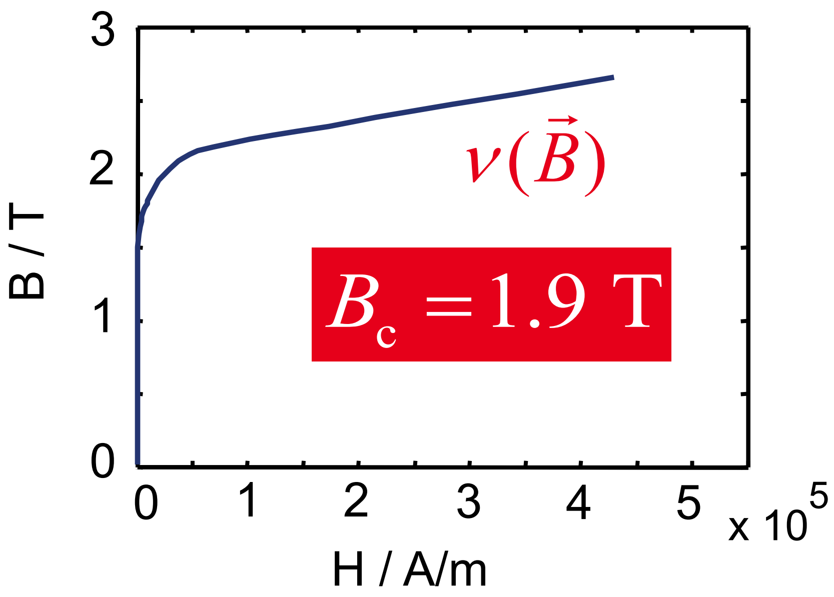
ν_{trans} reluctivity in the transversal direction

R local rotation matrix

Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)
- nonlinear (saturation)



Newton method

Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)
- nonlinear (saturation)
- hysteretic (remanent field)

Jiles-Atherton model

Preisach model

estimation of losses by Steinmetz-Bertotti

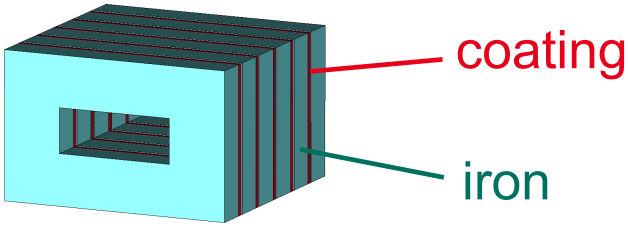
Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)
- nonlinear (saturation)
- hysteretic (remanent field)
- composite (lamination)

stacking factor

$$\gamma_{\text{st}} \approx 0.95 \leq\sim 1$$



(simple) homogenisation along lamination direction

$$\frac{1}{\nu_{xy}} = \frac{\gamma_{\text{st}}}{\nu_{\text{Fe}}} + \frac{1-\gamma_{\text{st}}}{\nu_0}$$

perpendicular to laminates

$$\nu_z = \gamma_{\text{st}}\nu_{\text{Fe}} + \left(1-\gamma_{\text{st}}\right)\nu_0$$

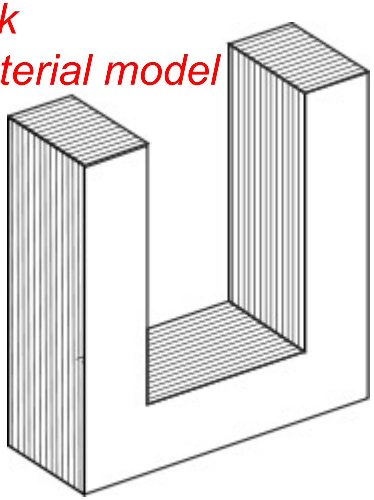
Challenge 2: Materials

yoke iron:

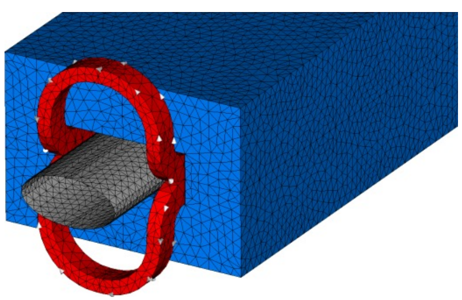
- anisotropic (rolling & transverse direction)
- nonlinear (saturation)
- hysteretic (remanent field)
- composite (lamination)

multiscale simulation

bulk material model

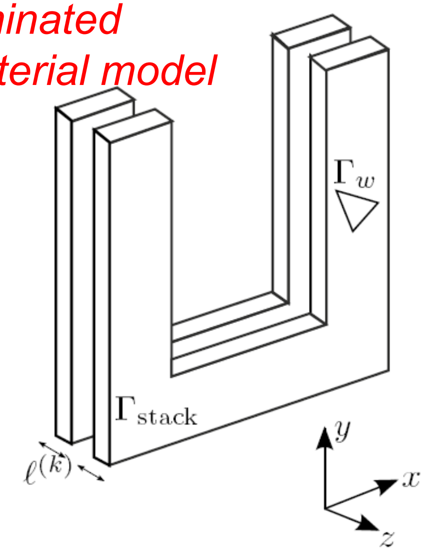


magnetic field



eddy currents

laminated material model



communication (*“handshaking”*)

Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)
- nonlinear (saturation)
- hysteretic (remanent field)
- composite (lamination)
- variability

→ stochastics, sensitivity

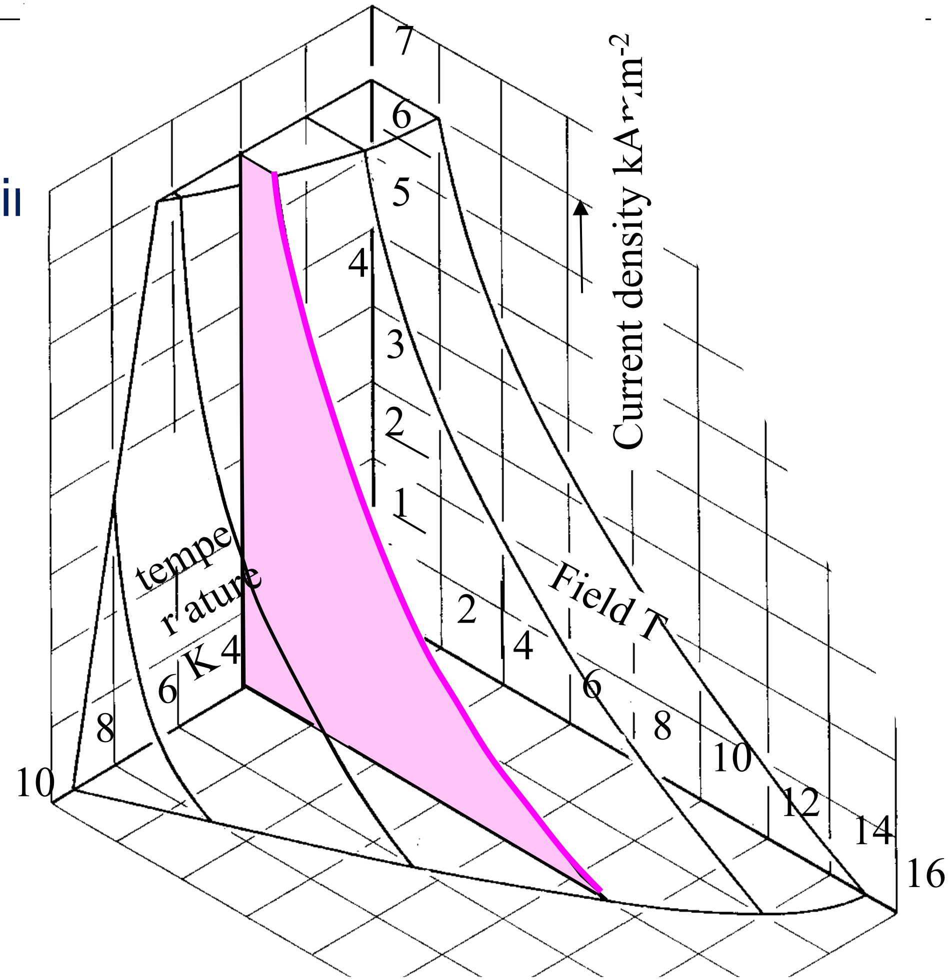
Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse di
- nonlinear (saturation)
- hysteretic (remanent field)
- composite (lamination)
- variability

superconductor:

- critical current
- temperature
- magnetic field



Challenge 3: Transient phenomena

lamination

- hysteresis + remanence

Jiles-Atherton model

Preisach model

estimation of the remanence
(based on data from material vendor)

Challenge 3: Transient phenomena

lamination

- hysteresis + remanence
- eddy currents

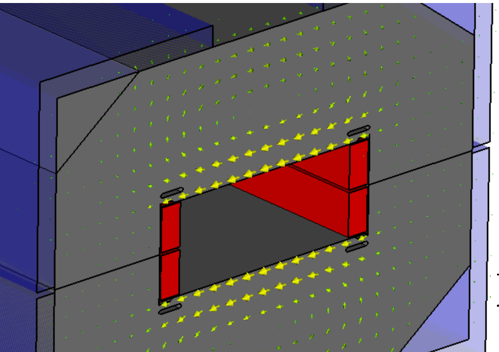
$$\nabla \times \left(\nu \nabla \times \vec{A} \right) + \sigma \frac{\partial \vec{A}}{\partial t} = \vec{J}_{\mathrm{s}}$$

eddy current term

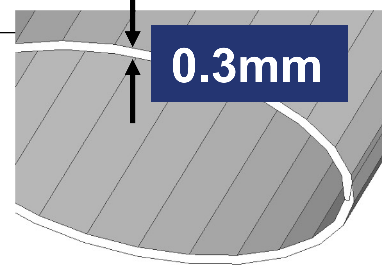
+ (simple) homogenisation $\sigma_{xy} = \gamma_{\mathrm{st}} \sigma_{\mathrm{Fe}}$

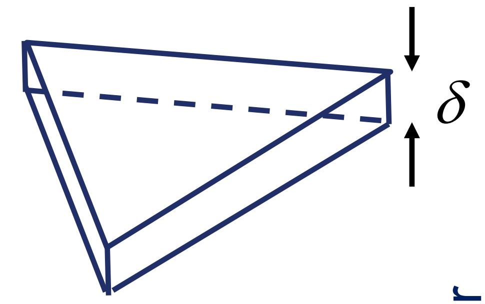
$$\sigma_z = 0$$

or + multi-scale model (hand-shaking)



Challenge 3: Transient phenomena





lamination

- hysteresis + remanence
- eddy currents

beam tube

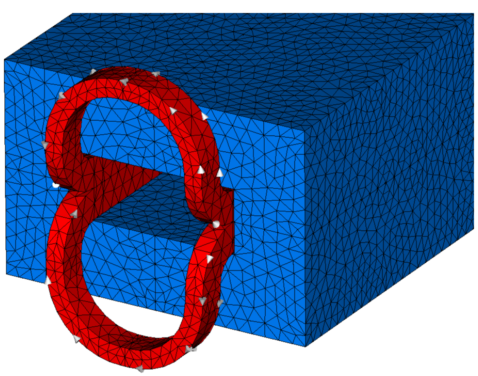
- eddy currents

shell elements

additional matrix contributions $\mathbf{K}_\delta$ and $\mathbf{M}_\delta$

assembling into system matrix by $\mathbf{Q}$

$$\mathbf{K}_\nu + \sigma\mathbf{M}_\sigma \quad + \quad \mathbf{Q}^{\mathrm{T}}\left(\mathbf{K}_\delta + \alpha\mathbf{M}_\delta\right)\mathbf{Q} \quad = \quad \mathbf{K}_{\mathrm{full}} + \alpha\mathbf{M}_{\mathrm{full}}$$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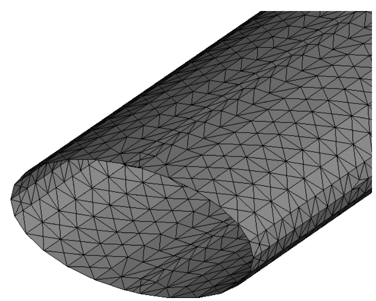
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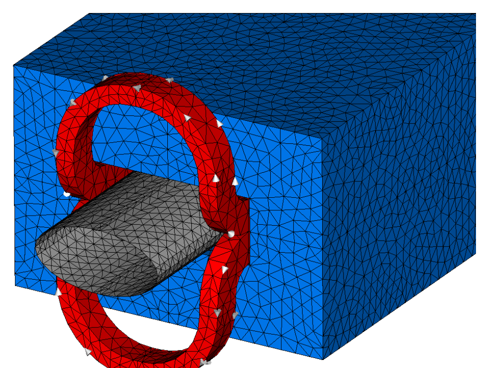


+ Jens Trommler

Challenge 3: Transient phenomena

lamination
- hysteresis + remanence
- eddy currents

beam tube
- eddy currents

superconductor
- persistent currents

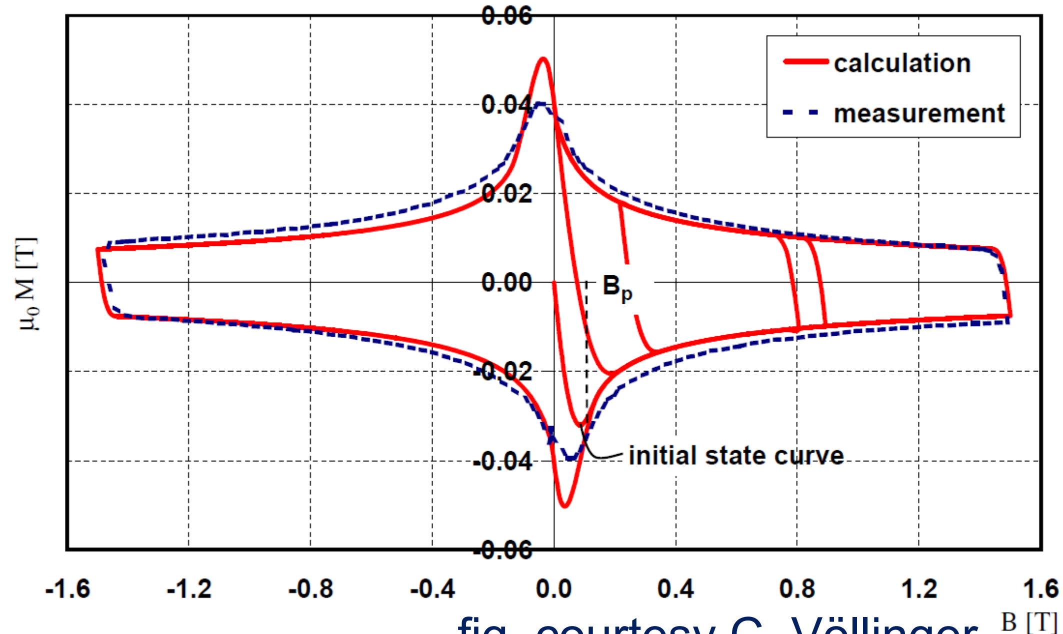
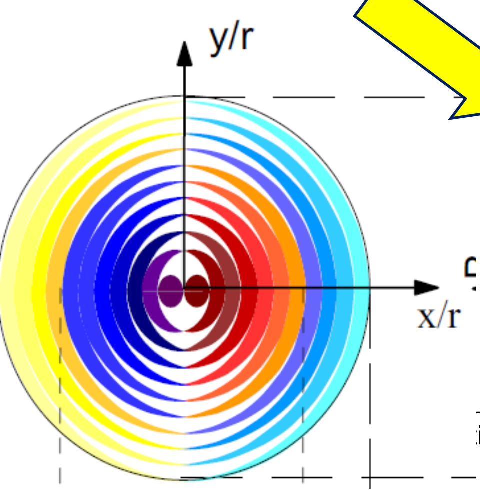


fig. courtesy C. Völlinger



Bean model → magnetisation (Christine Völlinger) implemented in ROXIE

fig. courtesy C. Völlinger

Challenge 3: Transient phenomena

lamination

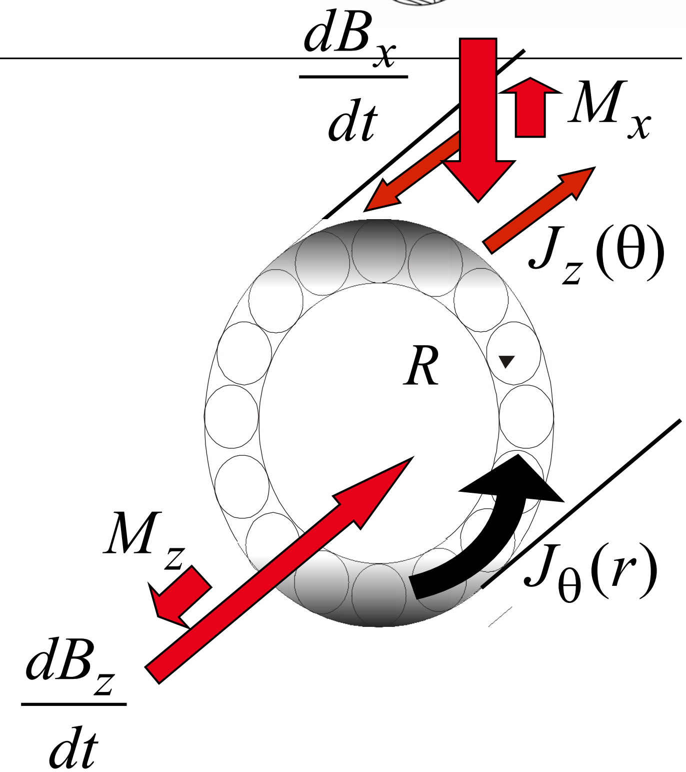
- hysteresis + remanence
- eddy currents

beam tube

- eddy currents

superconductor

- persistent currents
- coupling currents
- cable eddy currents



$$\nabla\times\left(\nu\nabla\times\vec{A}\right)+\sigma\frac{\partial\vec{A}}{\partial t}+\nabla\times\left(\nu_0\overline{\overline{\tau}}_{\mathrm{cb}}\nabla\times\frac{\partial\vec{A}}{\partial t}\right)=\vec{J}_{\mathrm{s}}$$

additional magnetisation

Challenge 4: High accuracy requirements

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losses

- dimensioning of the cooling system
- hot spots
- quench

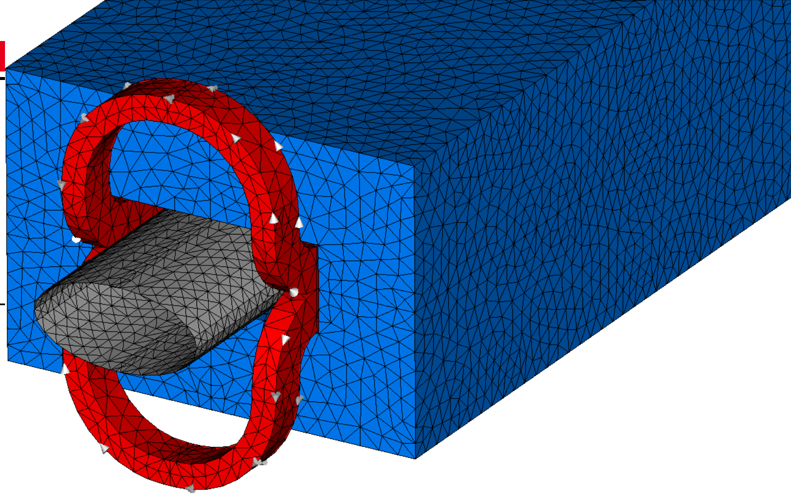
aperture field

- multipoles during injection, ramping and extraction
- + influence of eddy currents

huge models

parallelisation, multi-core computers

Overview



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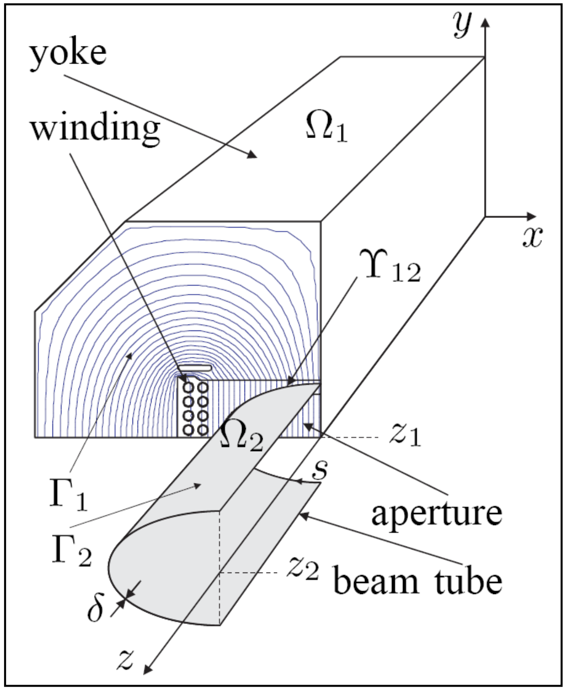
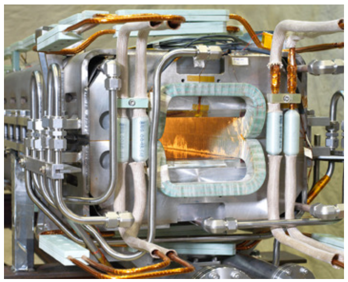
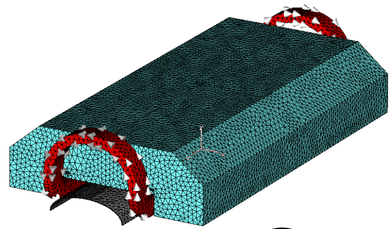
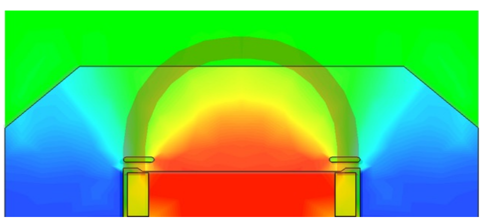


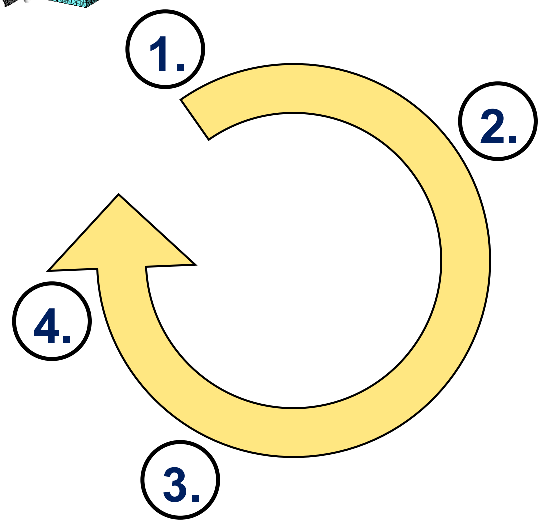
Dedicated Simulation Tool





CST Studio Suite®
- CAD modelling
- meshing
- visualisation





Matlab
- postprocessing
- visualisation

FEMSTER, LLNL

TRILINOS, Sandia Labs

own software
- FE assembly (higher order FEs)
- transient solver
- nonlinear materials
- system solver

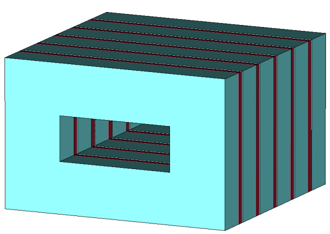
parallelisation

+ Stephan Koch, Jens Trommler

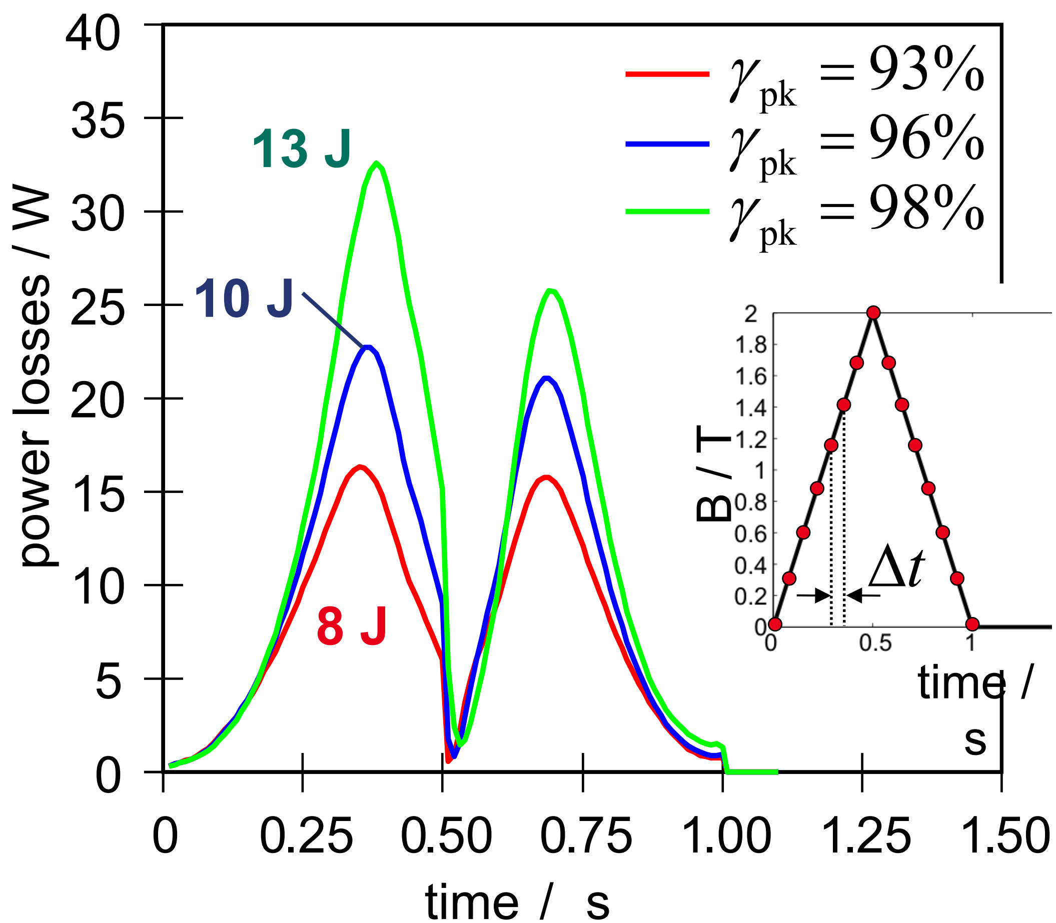
Results: Eddy-Current Losses

eddy-current losses
over one cycle

for different
stacking factors γ_{pk}



loss energy: $W = \int_0^T P \mathrm{d}t$



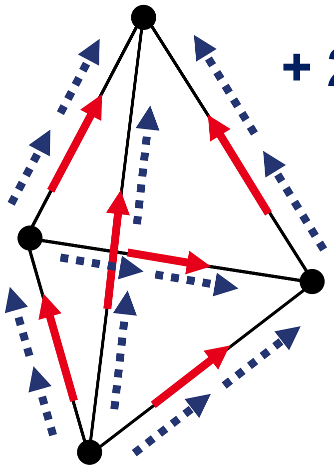
+ Stephan Koch, Jens Trommler

Results: Loss Energy

- discretization:
  - increase number of elements
  - increase order of approximation

$$\vec{A} \approx \vec{A}_{\mathrm{FE}} = \sum_j a_j \vec{w}_j^{\mathrm{tv}}$$

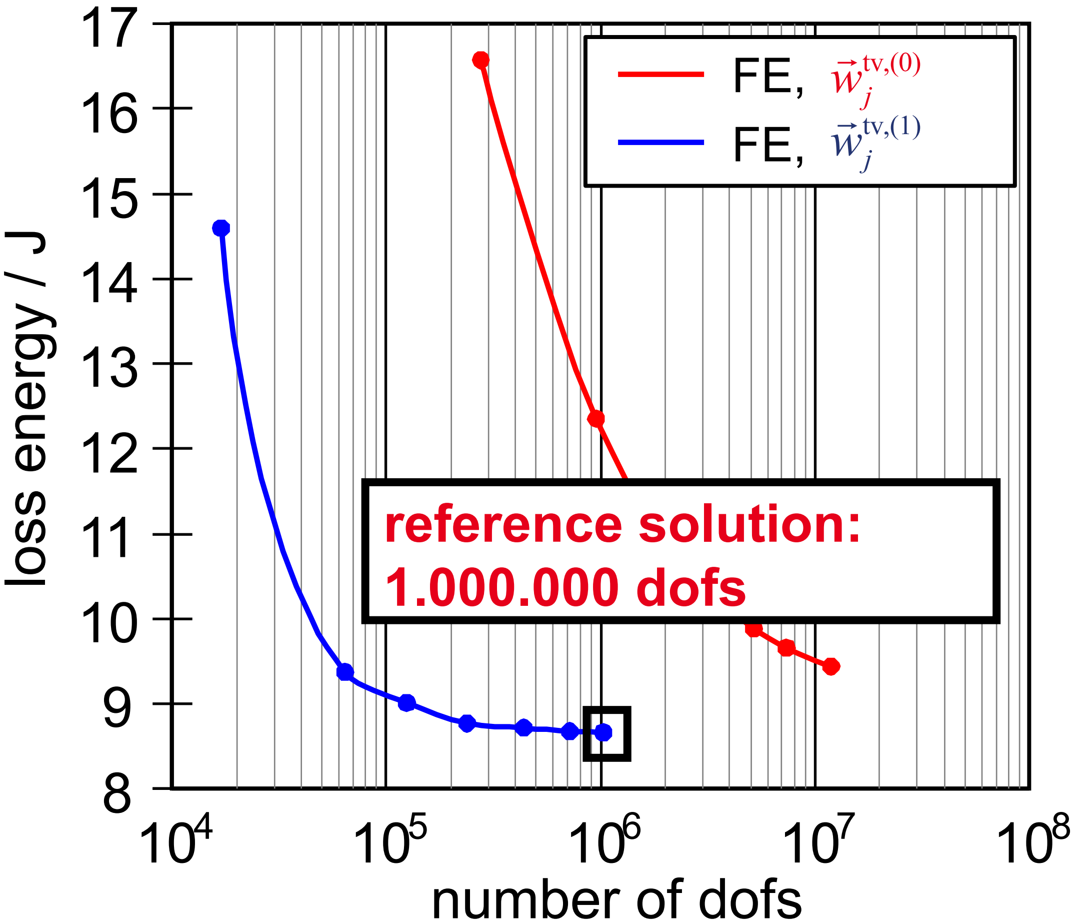
degrees of freedom:



+ 2 per face

$\vec{w}_j^{\mathrm{tv},(0)} \quad n_{\mathrm{dof}} = 6$

$\vec{w}_j^{\mathrm{tv},(1)} \quad n_{\mathrm{dof}} = 20$

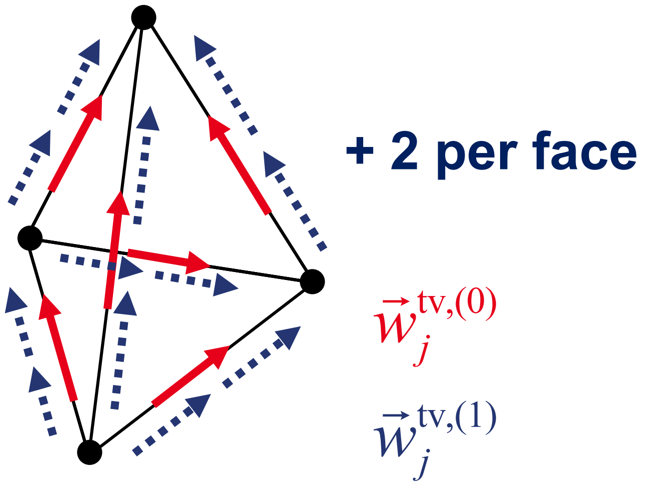


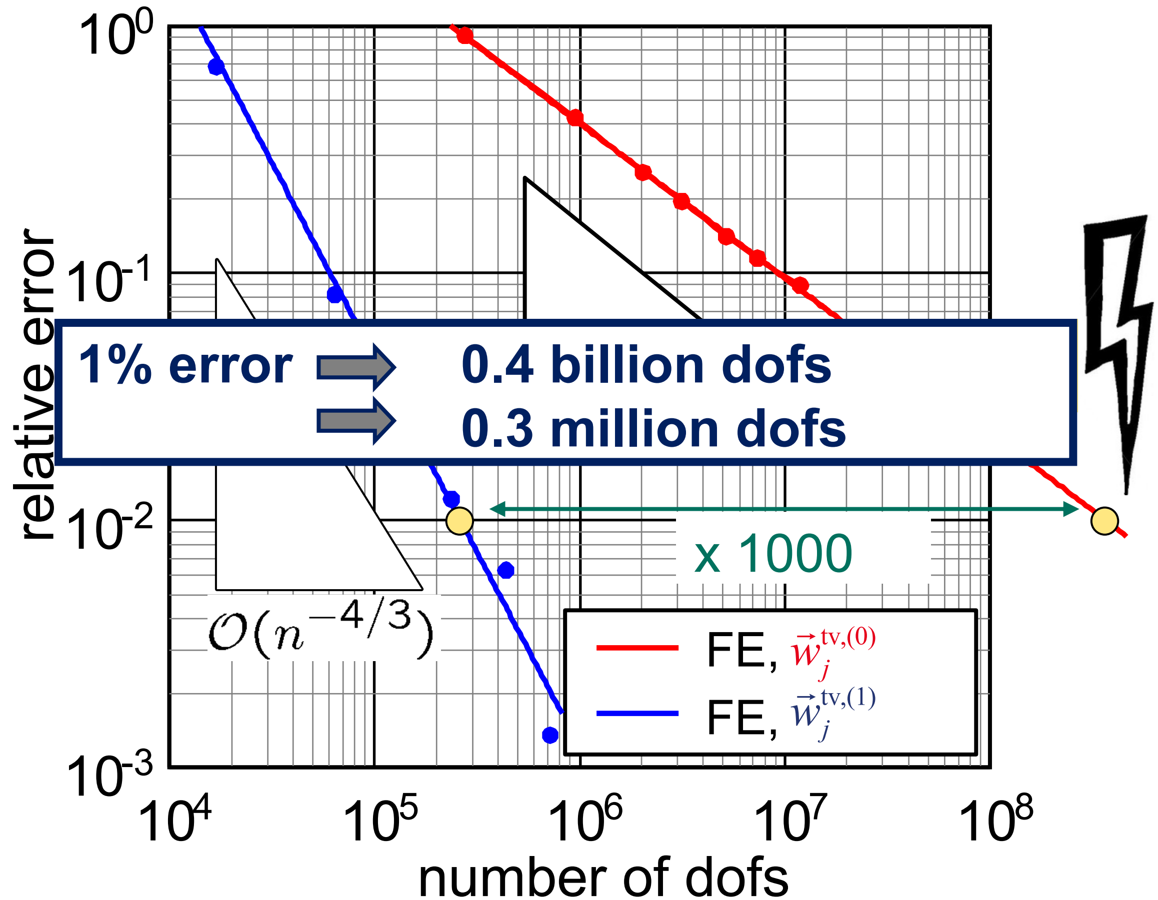
+ S. Koch, J. Trommler

Convergence: Loss Energy

- relative error with respect to reference solution

degrees of freedom:

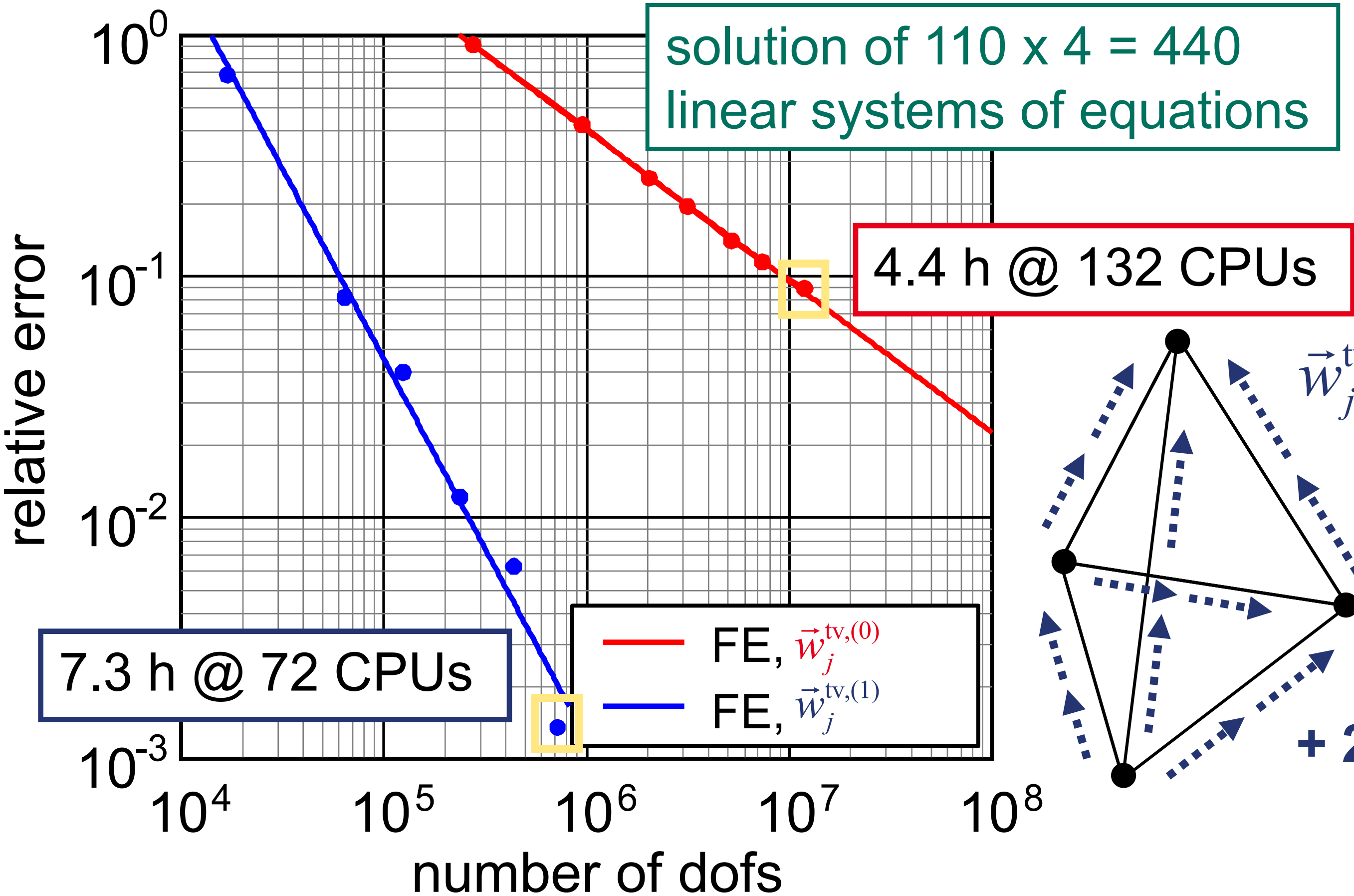


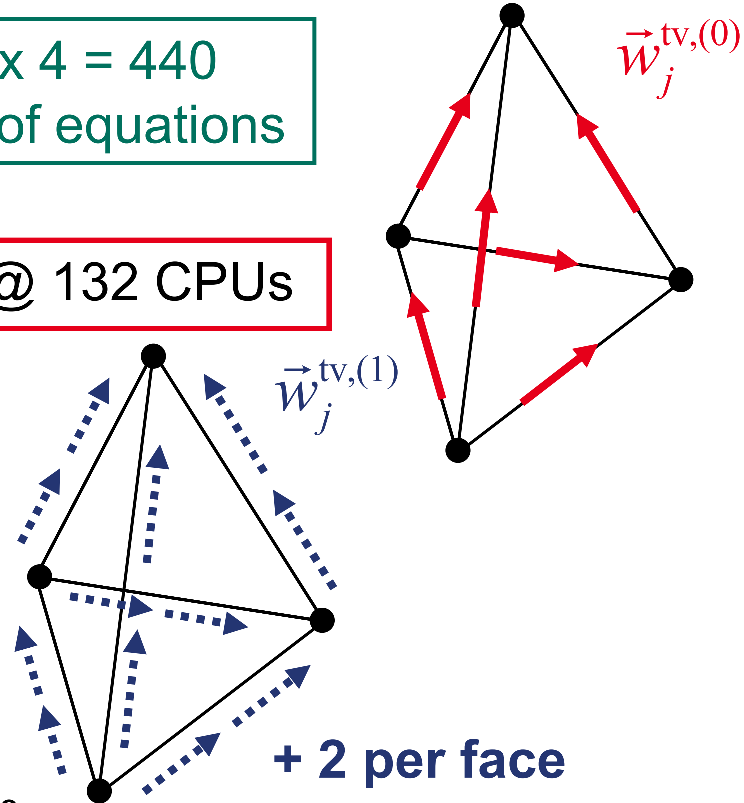


1% error ⇒ 0.4 billion dofs
⇒ 0.3 million dofs

+ S. Koch, J. Trommler

Comparison: Shape Functions





+ S. Koch, J. Trommler

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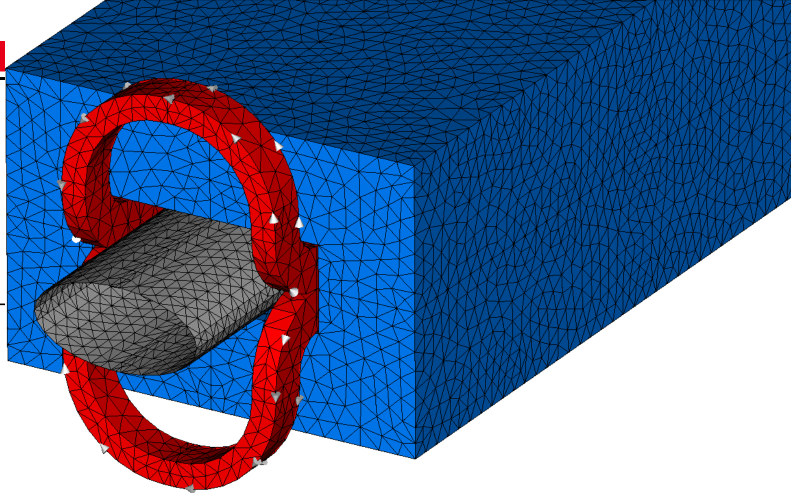

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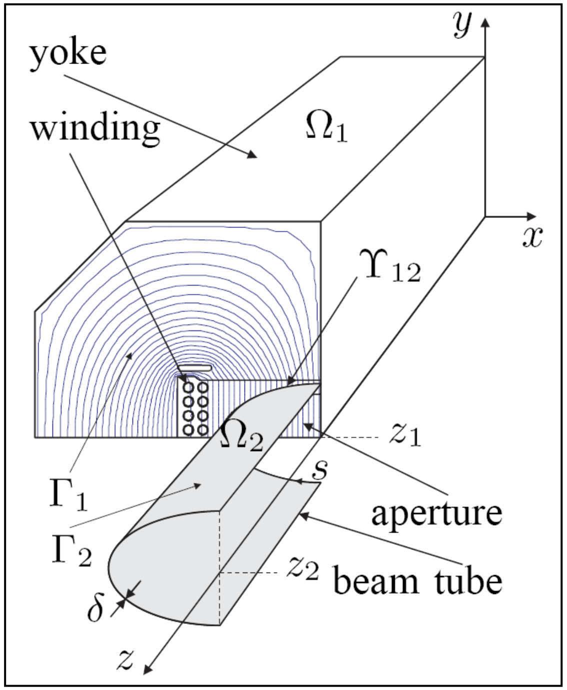
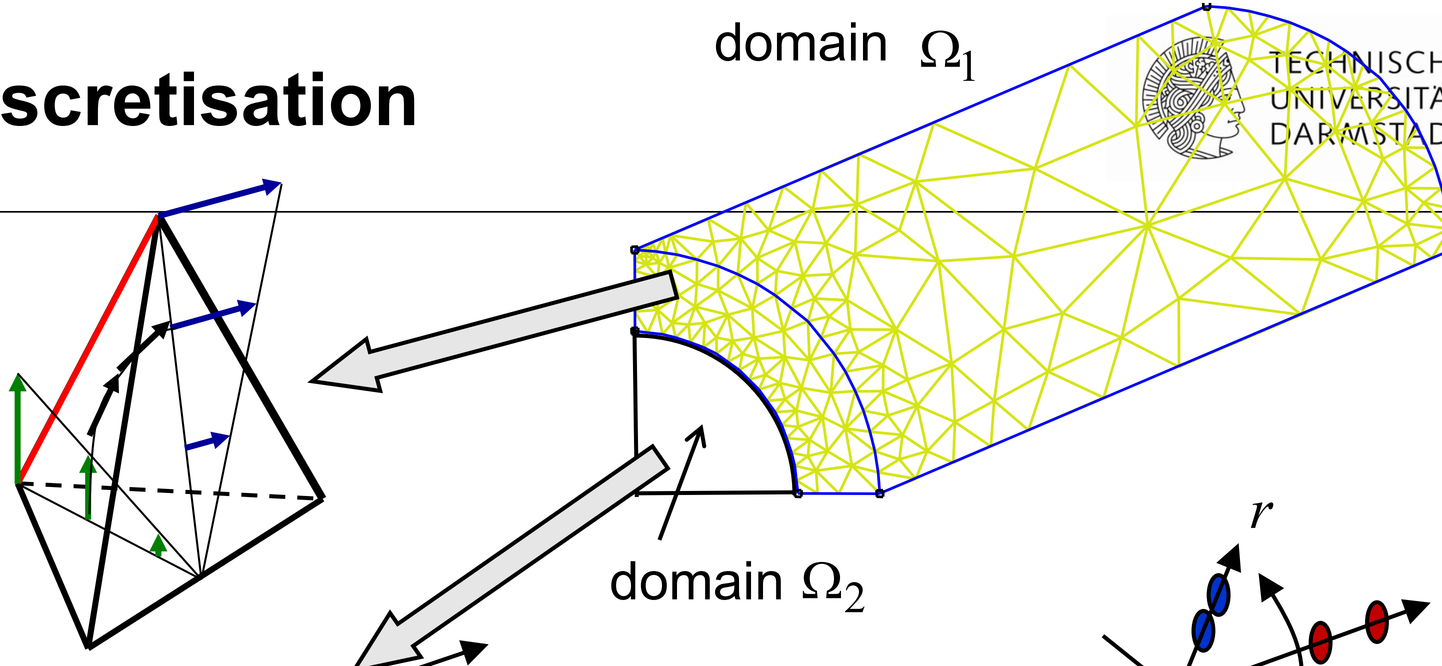
  - transient effects
  - high accuracy
- magnet simulation
  (dedicated 3D FE solver)
- hybrid models
- stochastic models
- conclusions

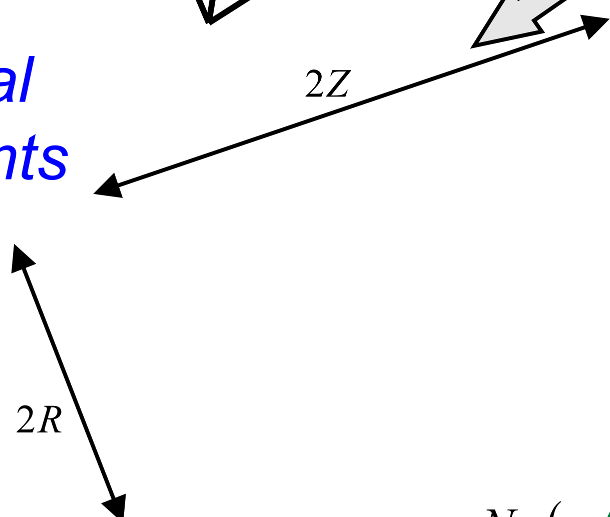


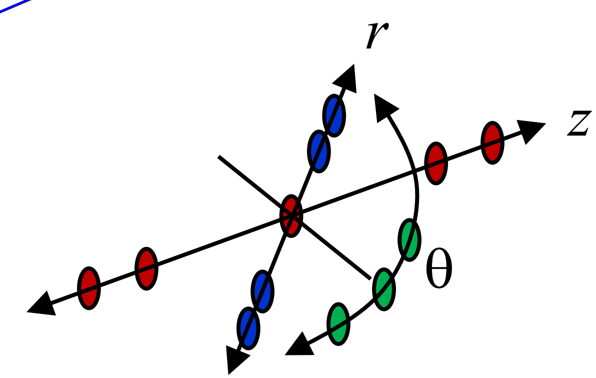
Hybrid discretisation

(edge) finite elements



spectral elements



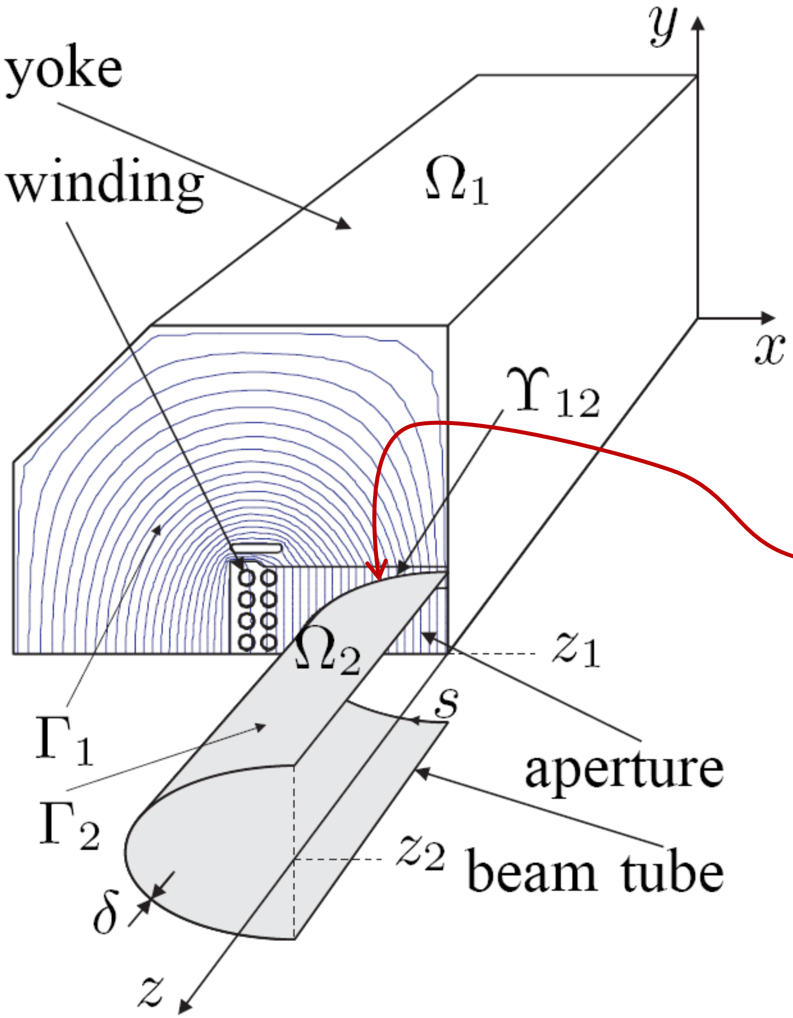


Legendre distribution in *r*
equidistant distribution in *θ*
Legendre distribution in *z*

$$N_q(r,\theta,z) = N_{q_1,q_2,\lambda}(r,\theta,z) = P_{q_1}\left(\frac{r}{R}\right)e^{-j\lambda_q\theta}P_{q_2}\left(\frac{z}{Z}\right)$$

+ Markus Clemens

Beam-tube end model



standard 2D model

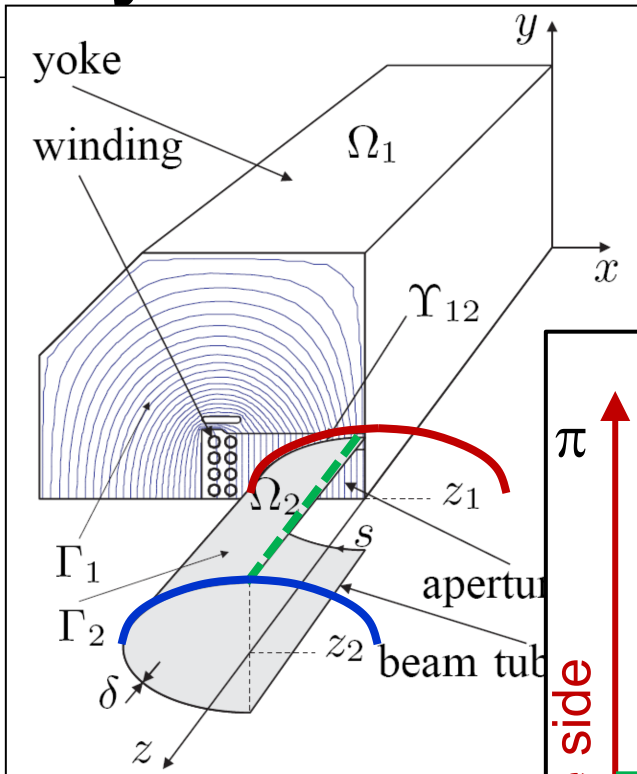
cross-section Γ_1 of volume Ω_1

common interface Y_{12}

additional 2D model for the beam-tube end

cross-section Γ_2 of volume Ω_2

Eddy-current closing paths

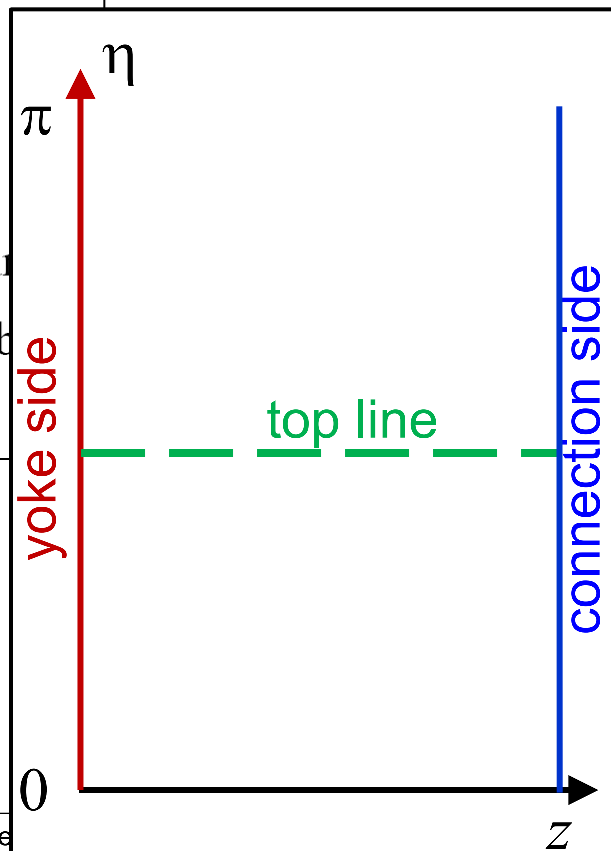


yoke side

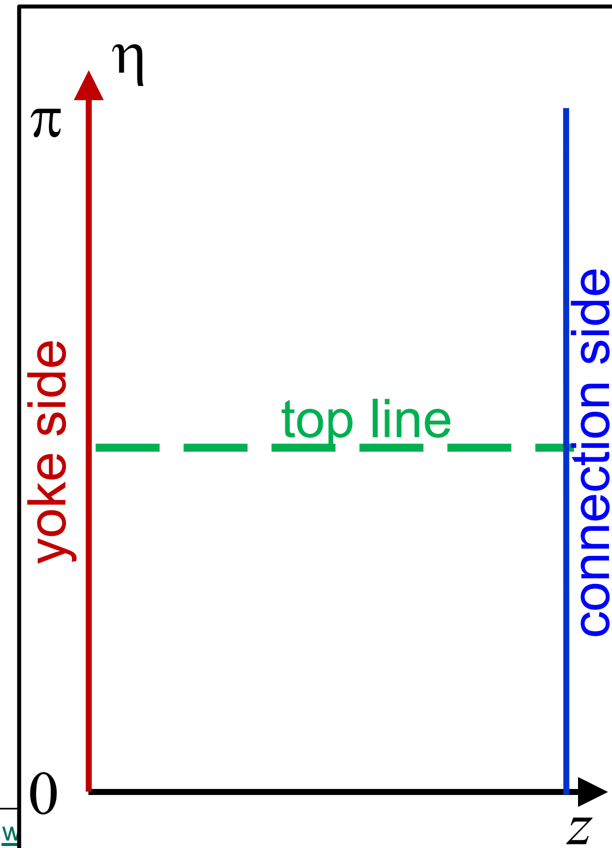
top line

connection side

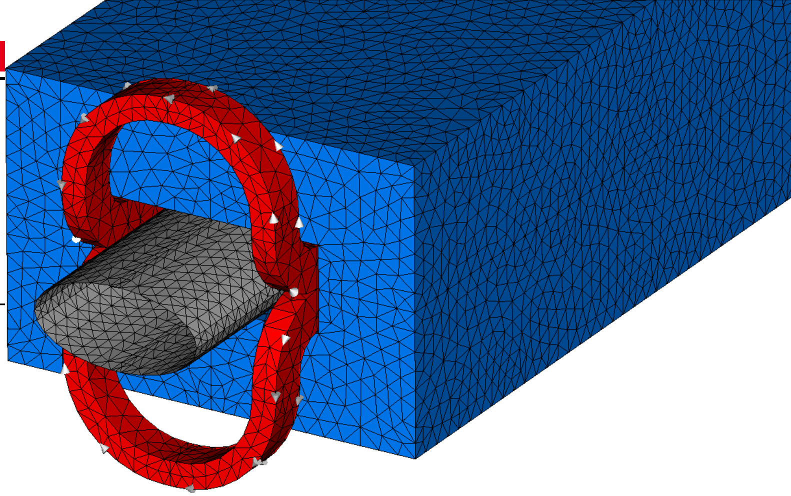
connected beam tube



disconnected beam tube



Overview



- magnet simulation
  (standard 3D FE solver)
- challenges
  - geometrical details
  - materials
  - transient effects
  - high accuracy
- magnet simulation
  (dedicated 3D FE solver)
- hybrid models
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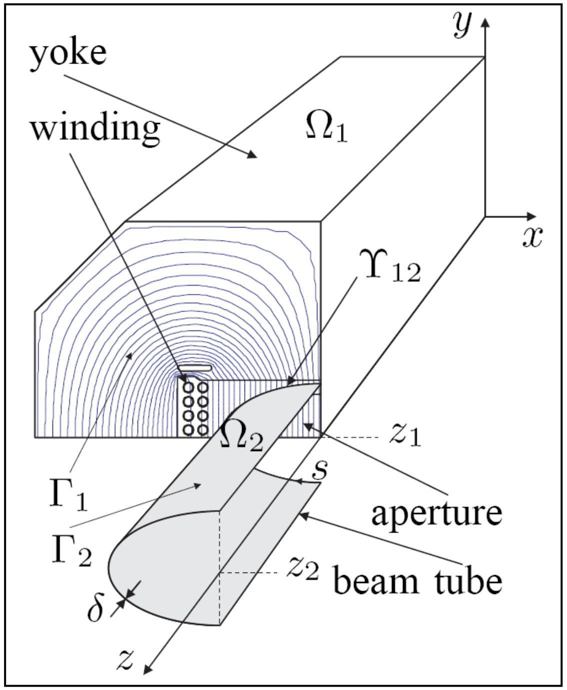
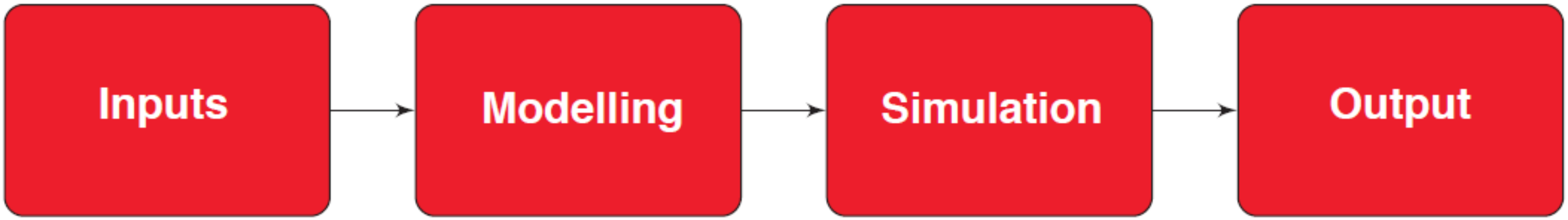
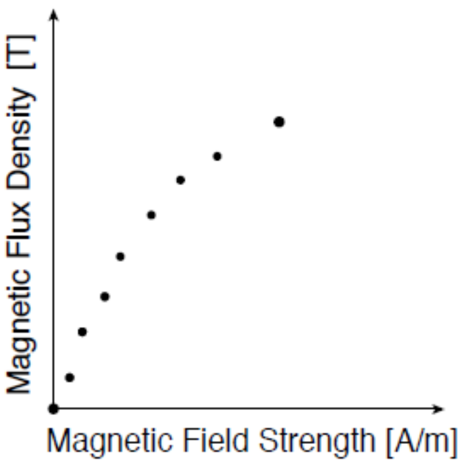
- conclusions

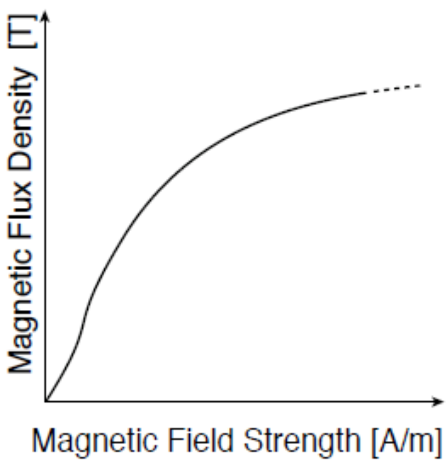


Uncertainty quantification

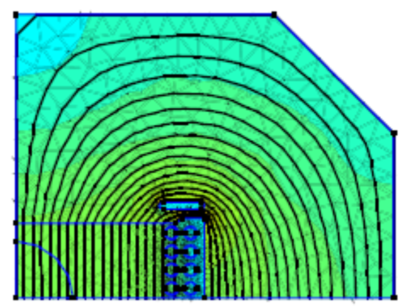




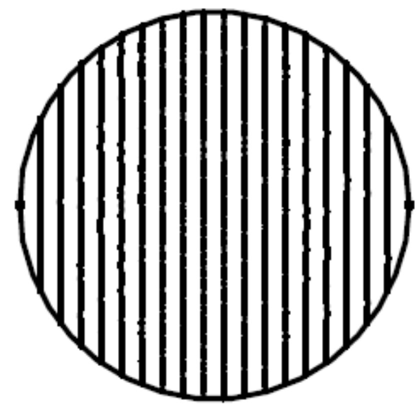
Measurement



Model of saturation



Accelerator Magnet



Multipoles b_i

+ Ulrich Römer, Sebastian Schöps

Overview

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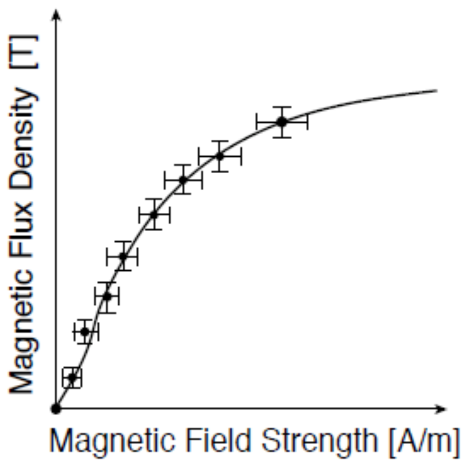
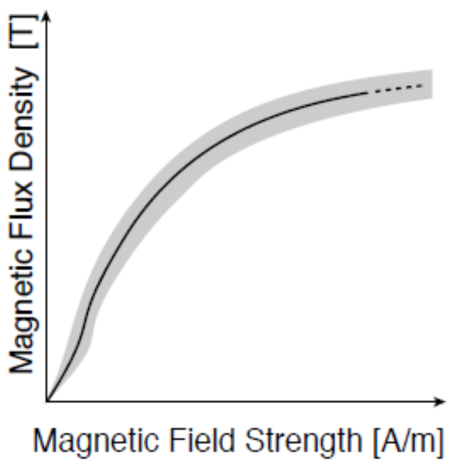
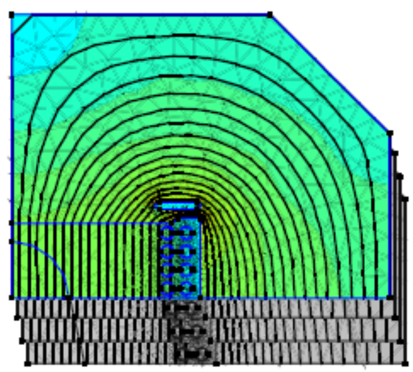
(Uncertain) Inputs → (Stochastic) Modelling → (Multiple) Simulations → (Uncertain) Output



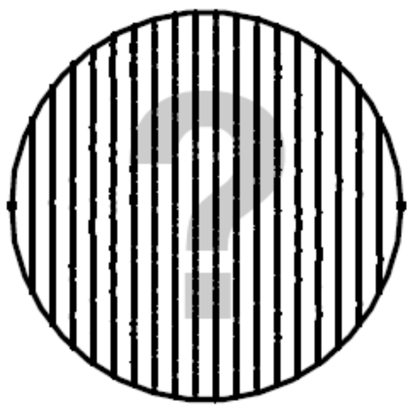
Measurement



Model of saturation



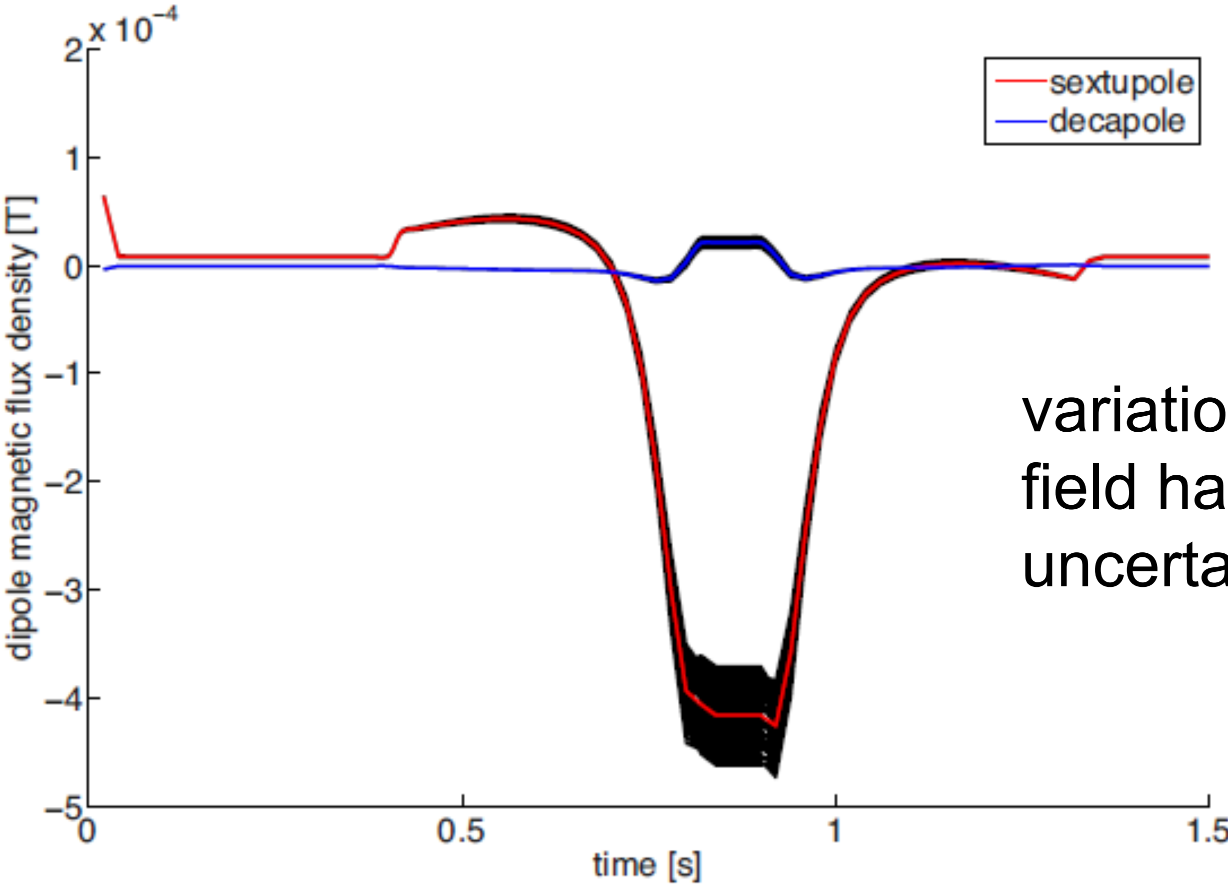
Accelerator Magnet



Multipoles b_i

+ Ulrich Römer, Sebastian Schöps

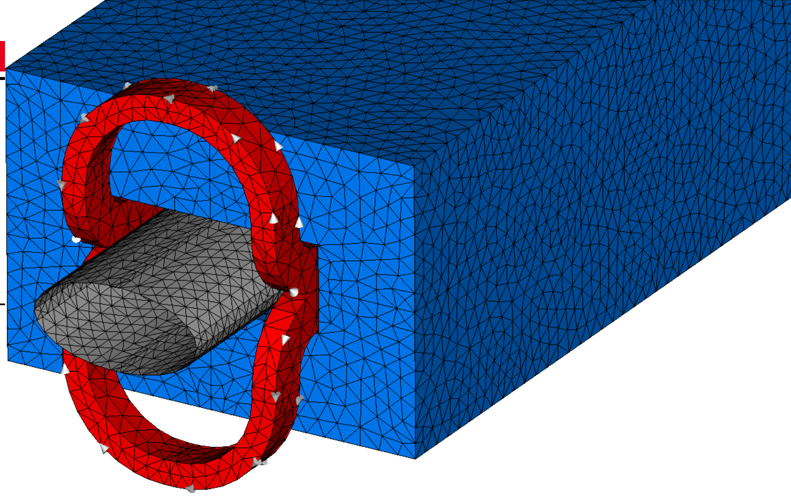
Uncertainty quantification



variation on the
field harmonics due to
uncertain BH-characteristic

+ Ulrich Römer, Sebastian Schöps

Conclusions



- nonlinear 3D transient magnetic simulation feasible with off-the-shell software
- challenges remain and are problem specific
  - geometrical details
  - materials
  - transient effects
  - high accuracy
- dedicated methods and software