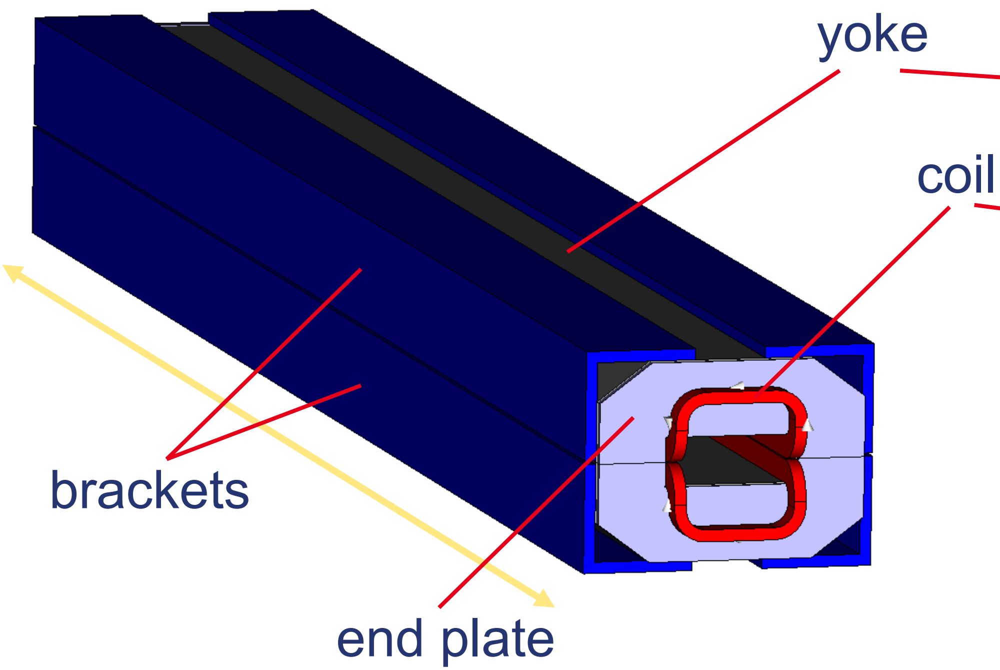
Simulating Hysteresis and Remanence in Accelerator Magnets

Herbert De Gersem, Stephan Koch, Ulrich Römer, Sebastian Schöps

Example: GSI-SIS-100 magnet



SIS100 dipole (prototype)

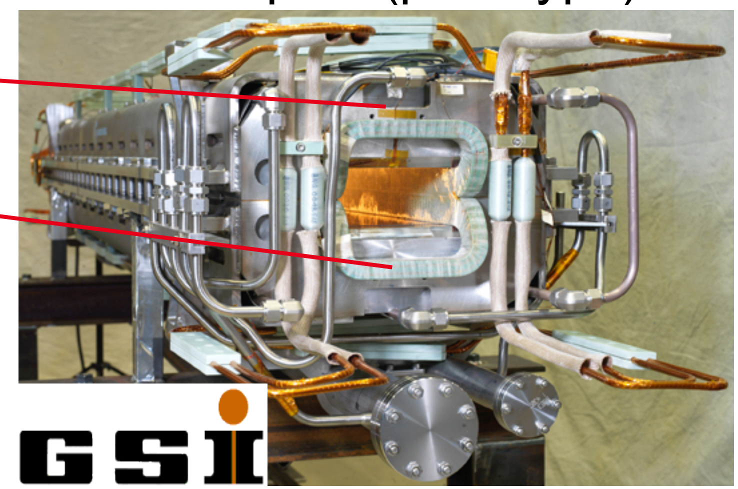
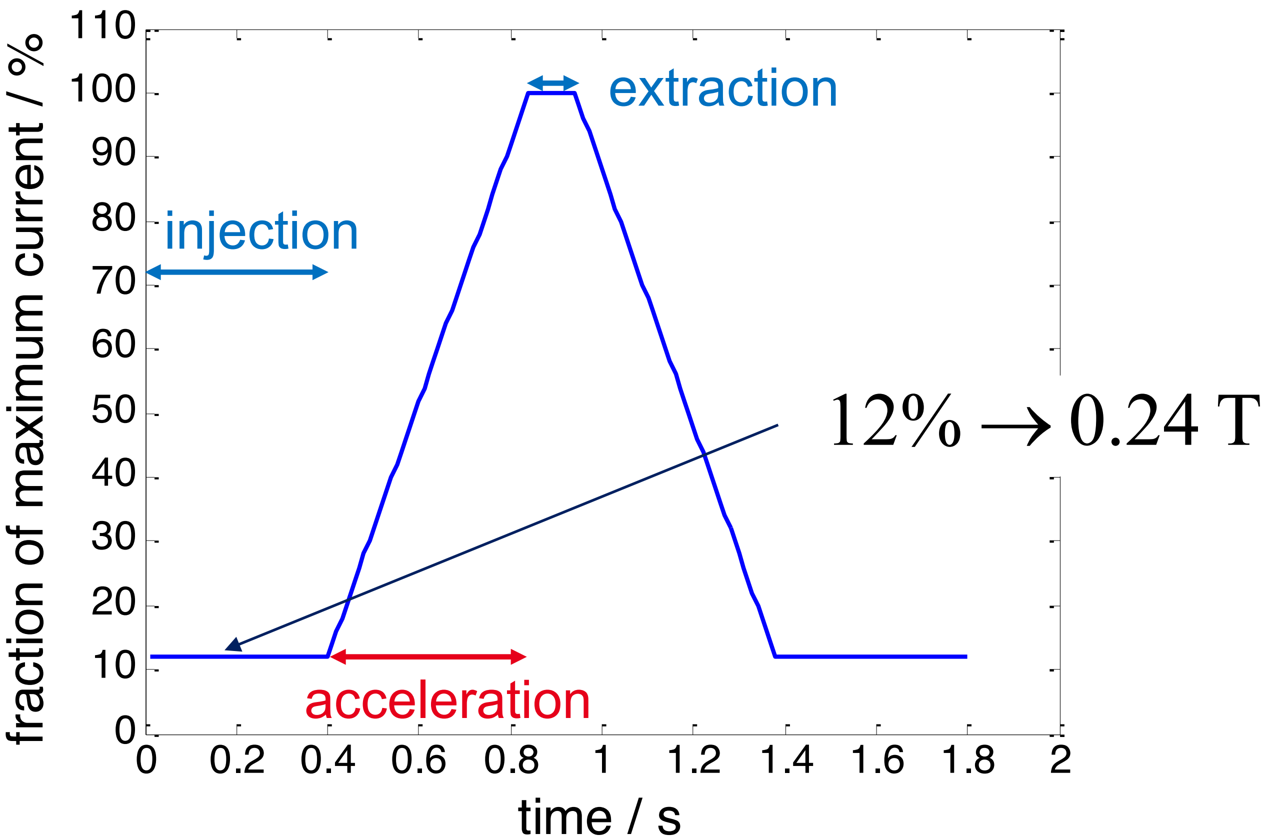


photo: J. Guse, GSI (www.gsi.de)

length: 3 m

Example: GSI-SIS-100 magnet

excitation profile



Magnetoquasistatic formulation

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

reluctivity

magnetic vector potential

conductivity

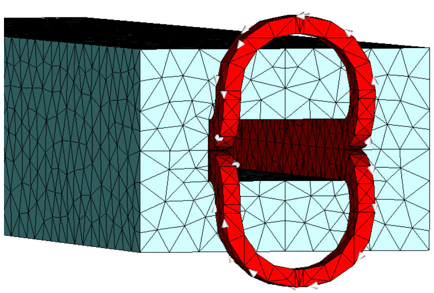
applied current density

Discretisation in space

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

spatial discretisation $\vec{A}(x,y,z)=\sum_j u_j\,\vec{v}_j(x,y,z)$

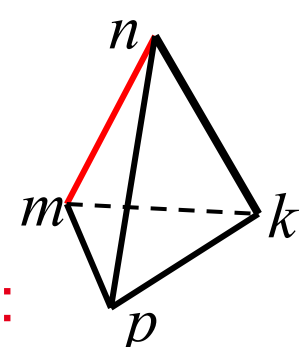
semi-discrete system: $\mathbf{K}_\nu\mathbf{a}+\mathbf{M}_\sigma\frac{\mathrm{d}\mathbf{a}}{\mathrm{d}t}=\mathbf{j}_\mathrm{s}$

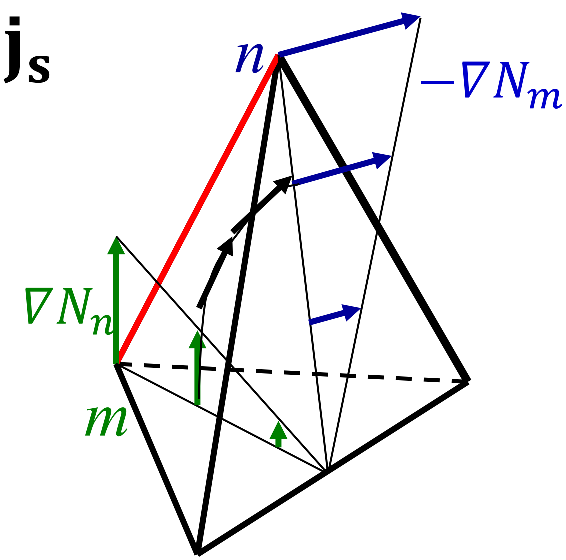


shape functions:

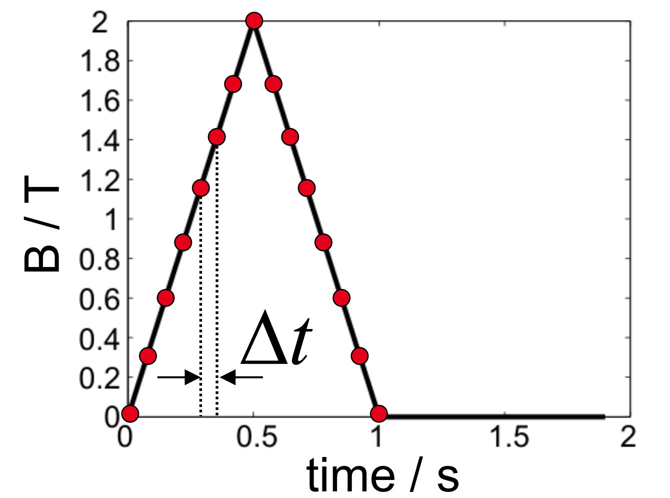
edge finite elements

(curl-conforming) $\vec{v}(\vec{x})=N_m\nabla N_n-N_n\nabla N_m$





Discretisation in time



differential equation

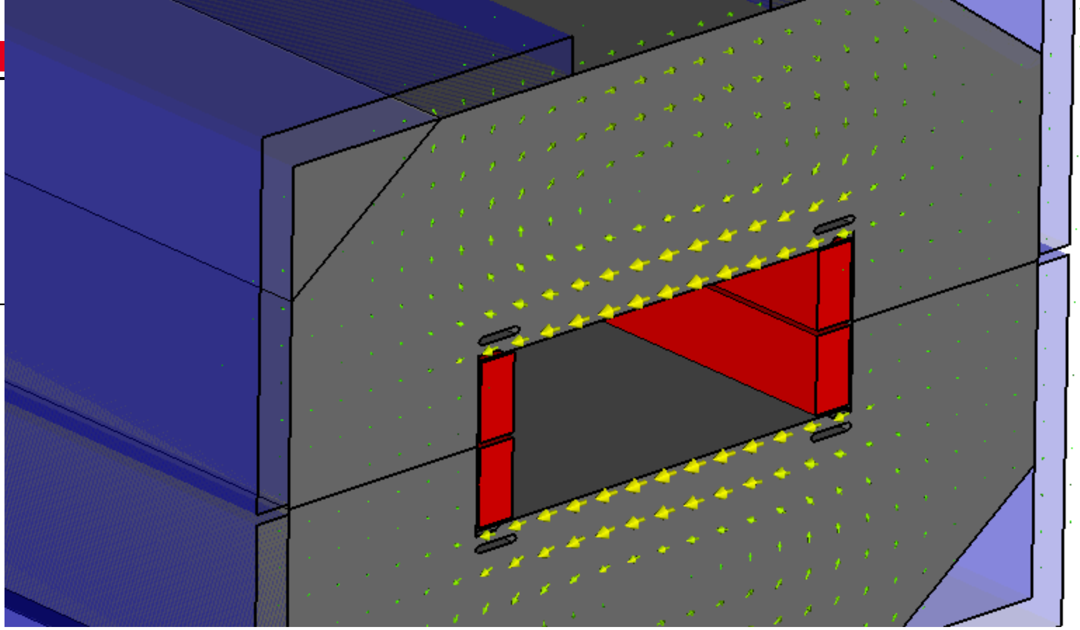
spatial discretisation

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

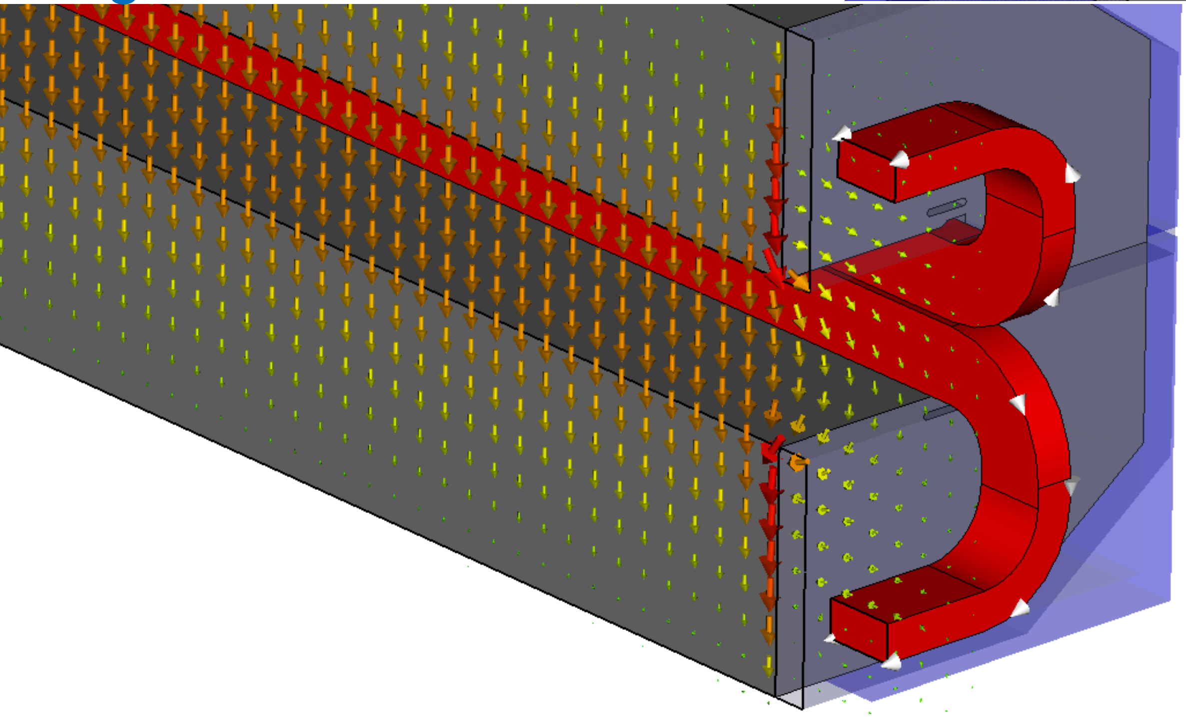
temporal discretisation

discrete system: $(\mathbf{K}_\nu + \alpha \mathbf{M}_\sigma)\mathbf{a} = \boldsymbol{RHS}$

Results



magnetic field

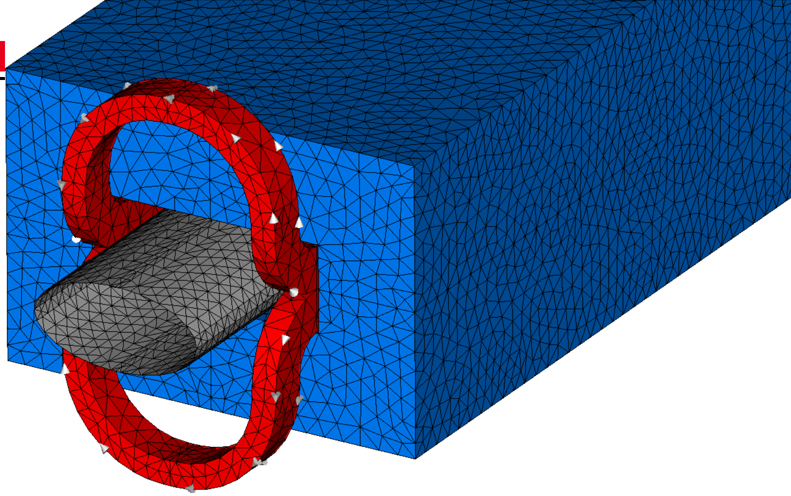


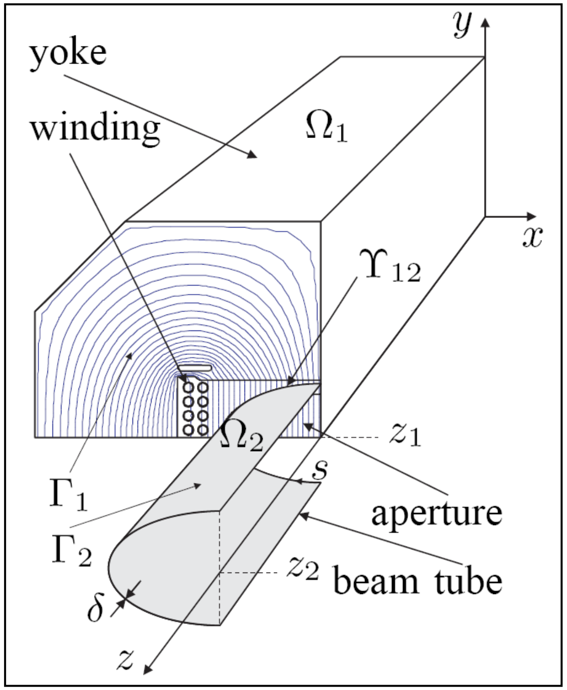
eddy currents
in the end plane

simulation by
CST EMStudio®

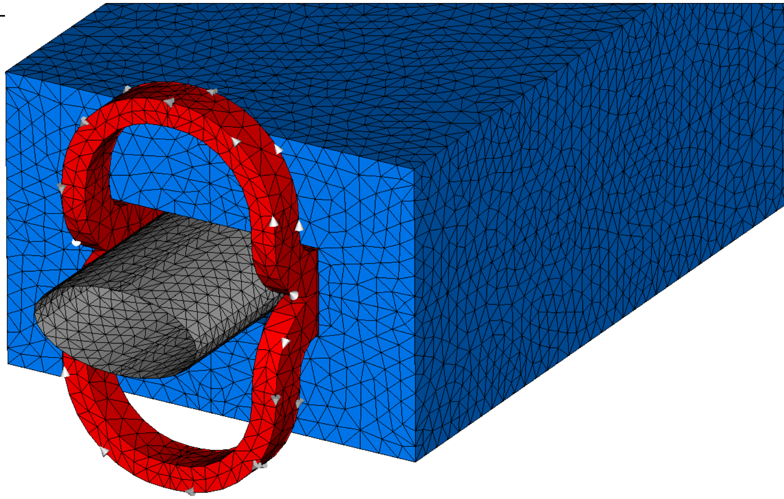
Overview

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





Challenge 1: Detailed geometry



yoke

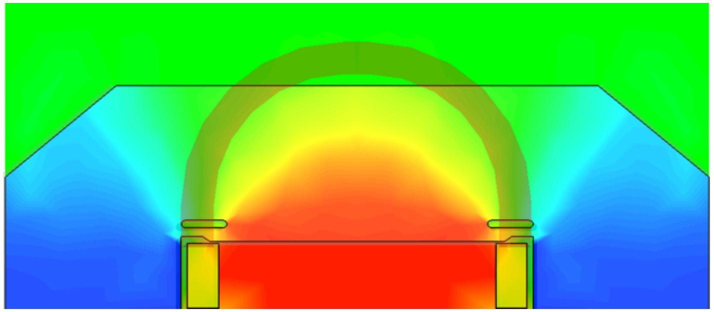
- length (meter)
  vs. lamination thickness (mm)
- shimming, holes

beam tube

- < 1mm thick

end-winding parts

- determine the eddy currents
  in the end plates



Challenge 2: Materials

yoke iron:

- anisotropic (rolling & transverse direction)

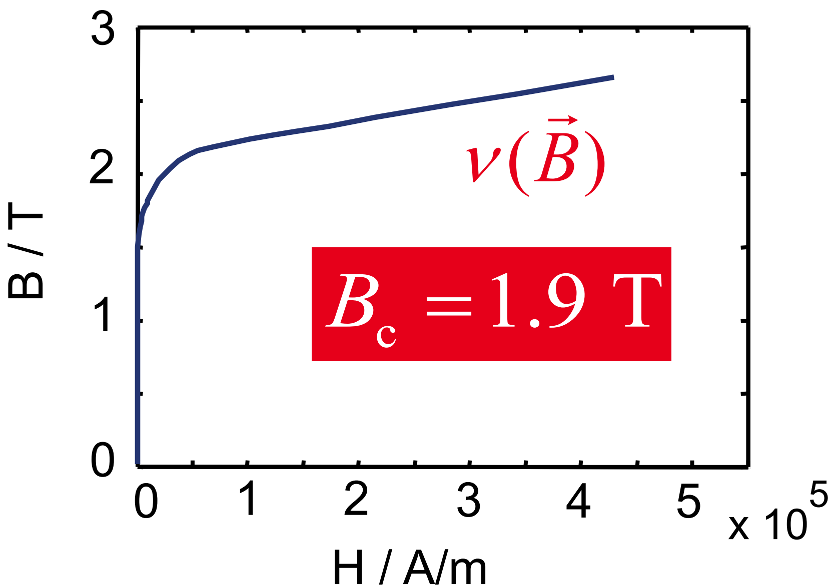
$$\bar{\bar{\nu}}(\vec{B}) = R^T \begin{bmatrix} \nu_{\mathrm{rol}} & & \\ & \nu_{\mathrm{trans}} & \\ & & \nu_{\mathrm{trans}} \end{bmatrix} R$$

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

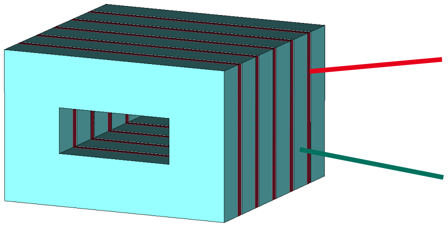
Challenge 2: Materials

yoke iron:

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

stacking factor

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



(simple) homogenisation along lamination direction

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

perpendicular to laminates

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

Challenge 2: Materials

yoke iron:

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

stochastics, sensitivity

(see recent research
of Ulrich Römer and Sebastian Schöps, TU Darmstadt)

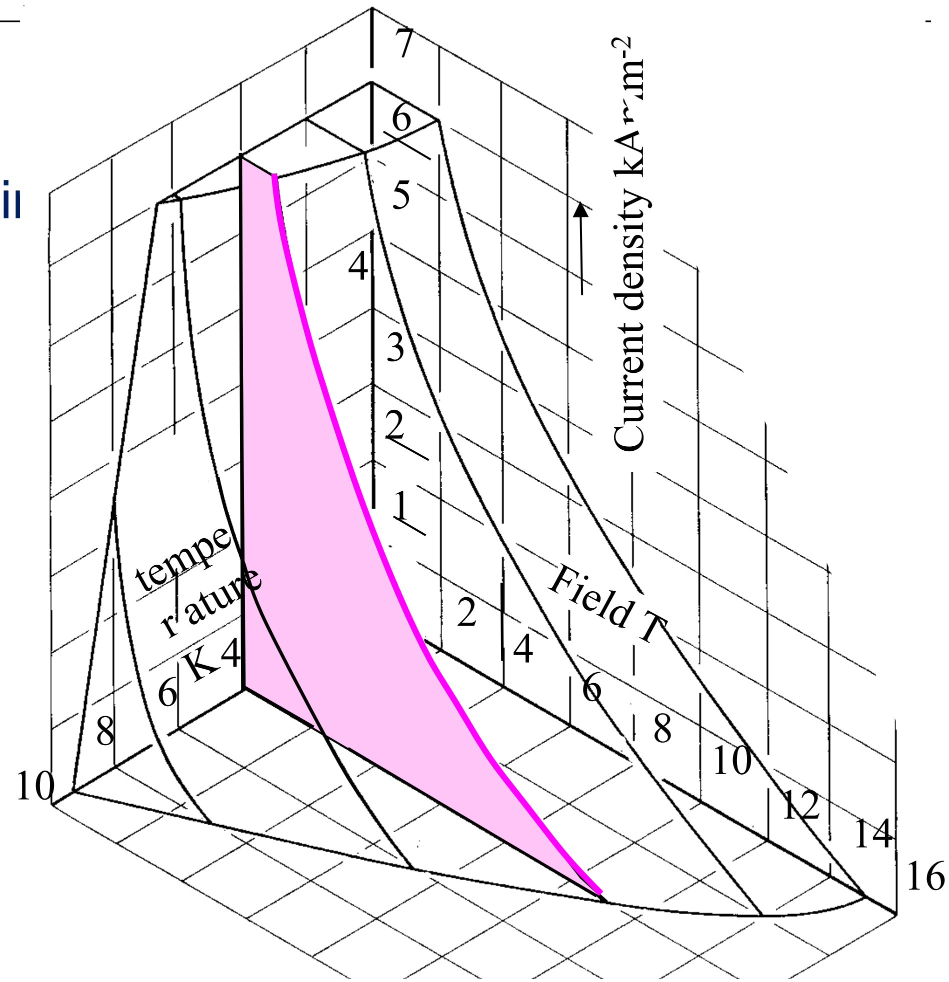
Challenge 2: Materials

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

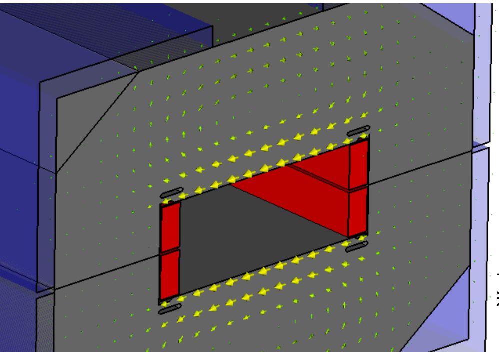
$$\nabla \times \left(\nu \nabla \times \vec{A} \right) + \boxed{\sigma \frac{\partial \vec{A}}{\partial t}} = \vec{J}_{\mathrm{s}}$$

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

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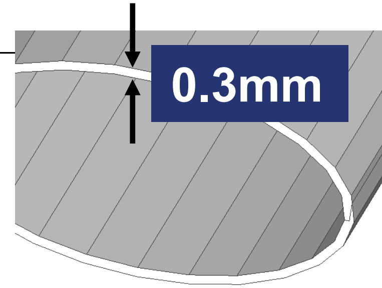
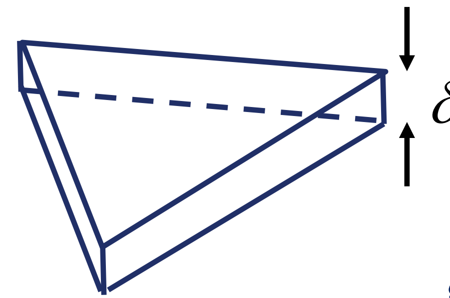




lamination

- hysteresis + remanence
- eddy currents

beam tube

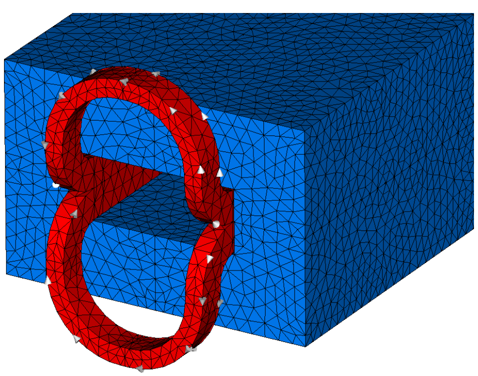
- eddy currents

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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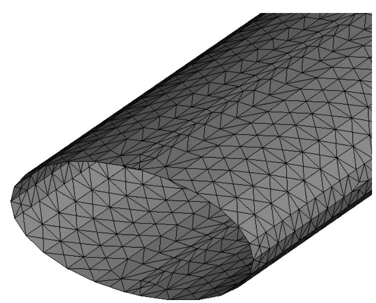

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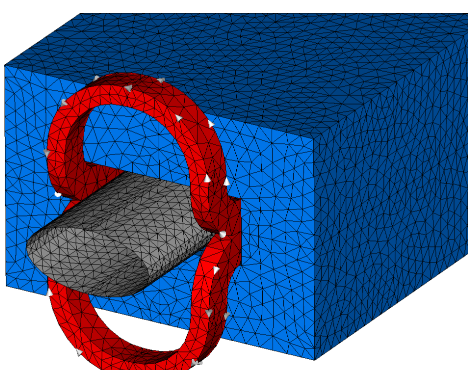


+ Jens Trommler

Challenge 3: Transient phenomena

lamination

- hysteresis + remanence
- eddy currents

beam tube

- eddy currents

superconductor

- persistent currents

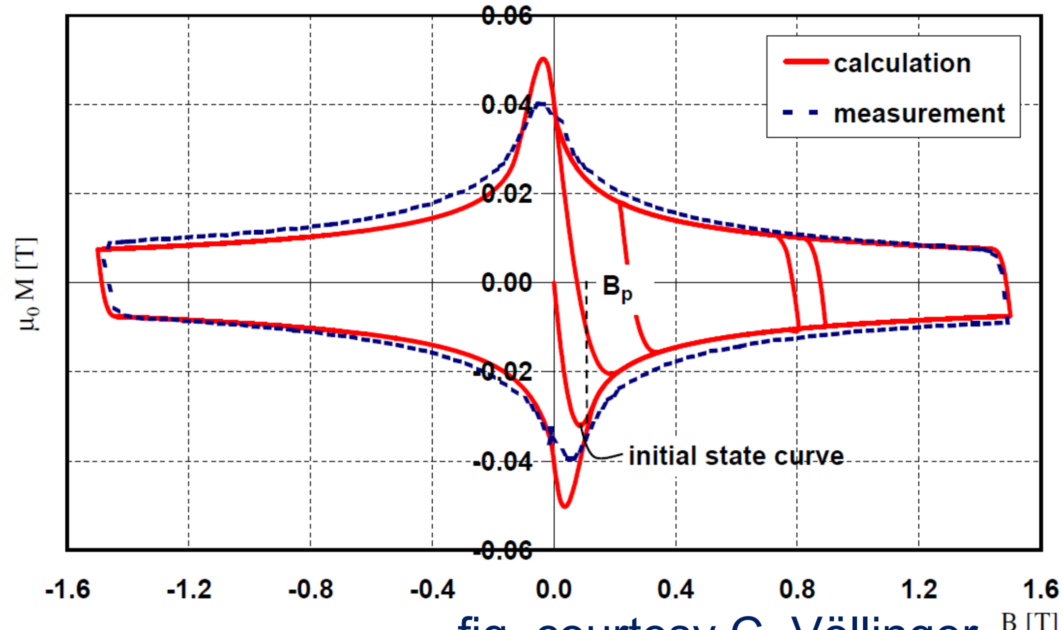


fig. courtesy C. Völlinger

Bean model → magnetisation (Christine Völlinger) implemented in ROXIE

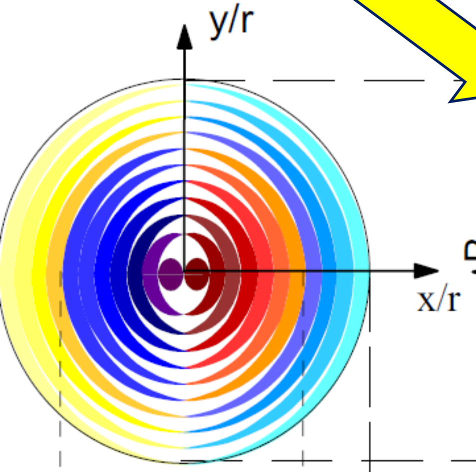
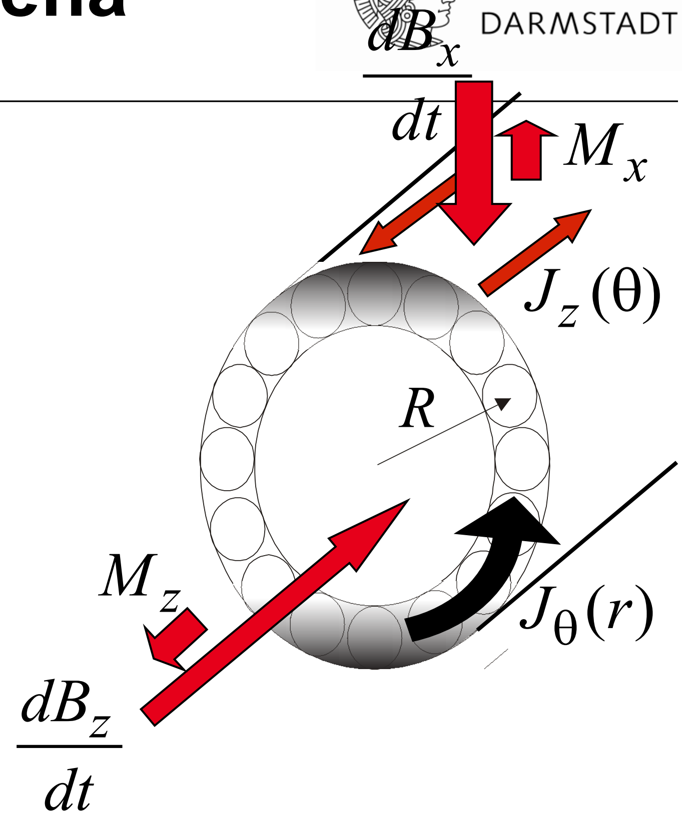


fig. courtesy C. Völlinger

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

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

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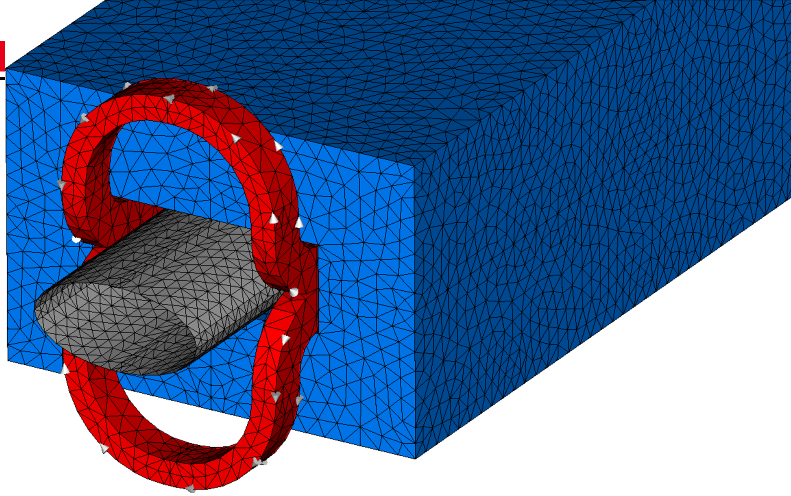
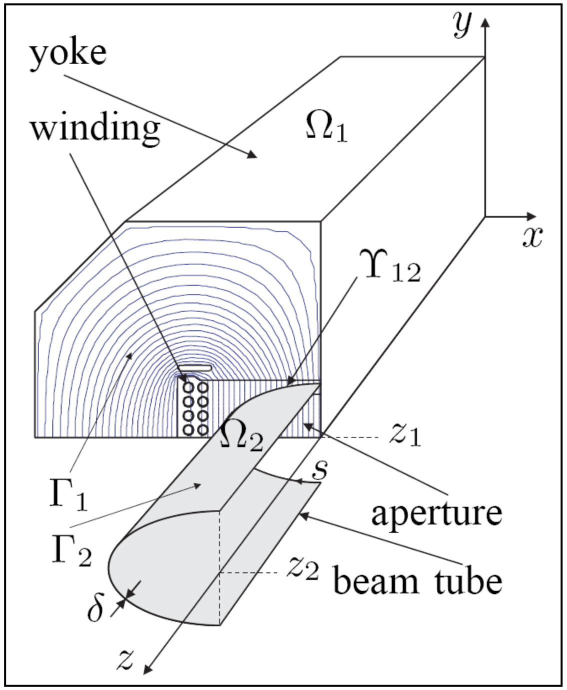
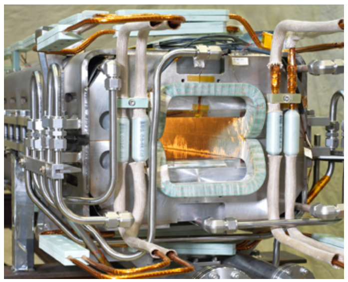
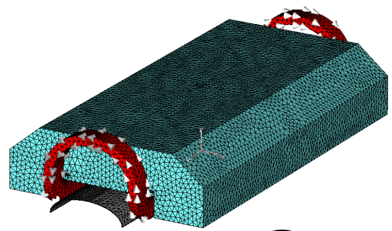




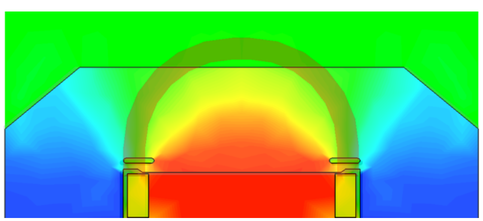
Dedicated Simulation Tool



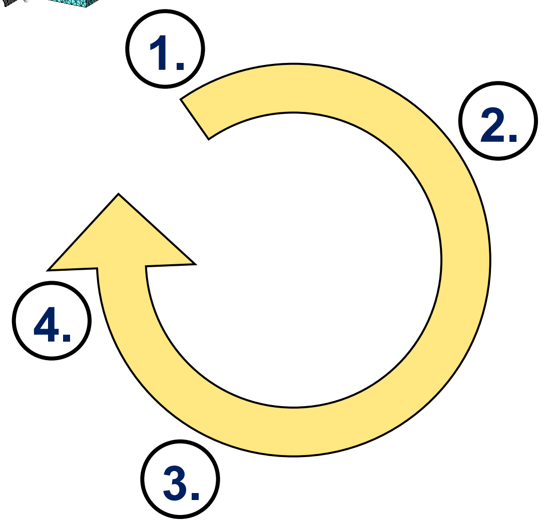


CST Studio Suite®
- CAD modelling
- meshing

- visualisation



+ Stephan Koch, Jens Trommler



Matlab
- postprocessing
- visualisation

FEMSTER, LLNL

TRILINOS, Sandia Labs

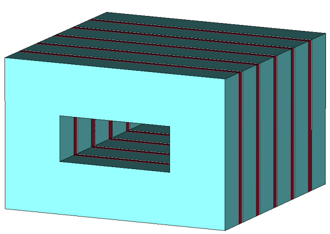
own software
- FE assembly (higher order FEs)
- transient solver
- nonlinear materials
- system solver

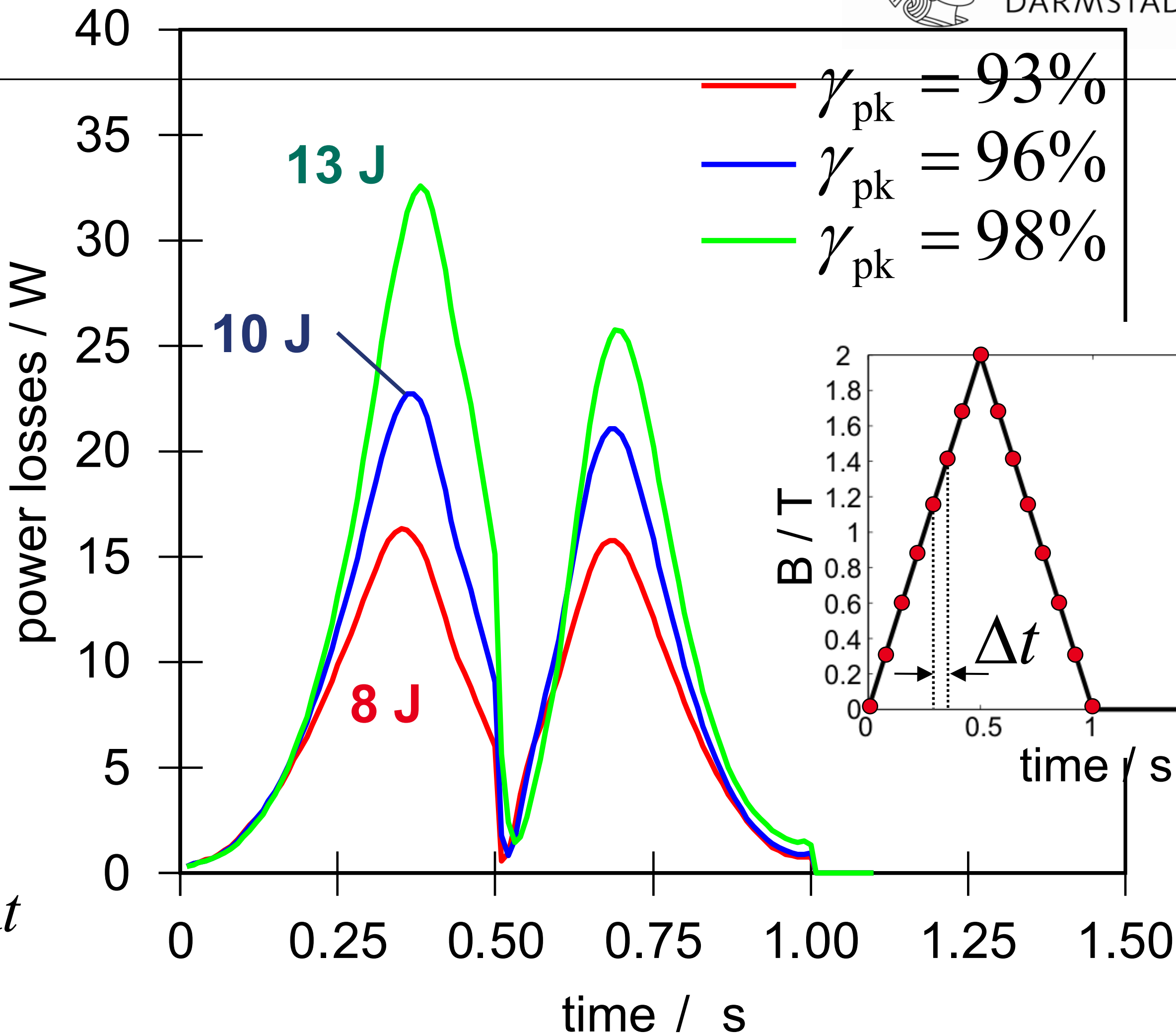
parallelisation

Results: Eddy-Current Losses

eddy-current losses over one cycle

for different stacking factors γ_{pk}





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

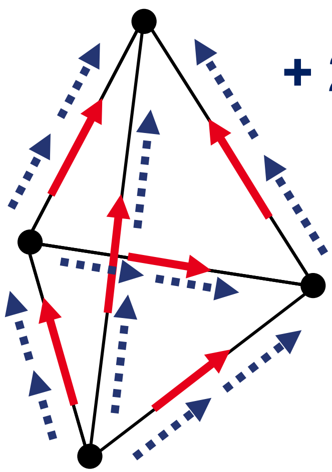
+ Stephan Koch, Jens Trommler

Results: Loss Energy

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

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

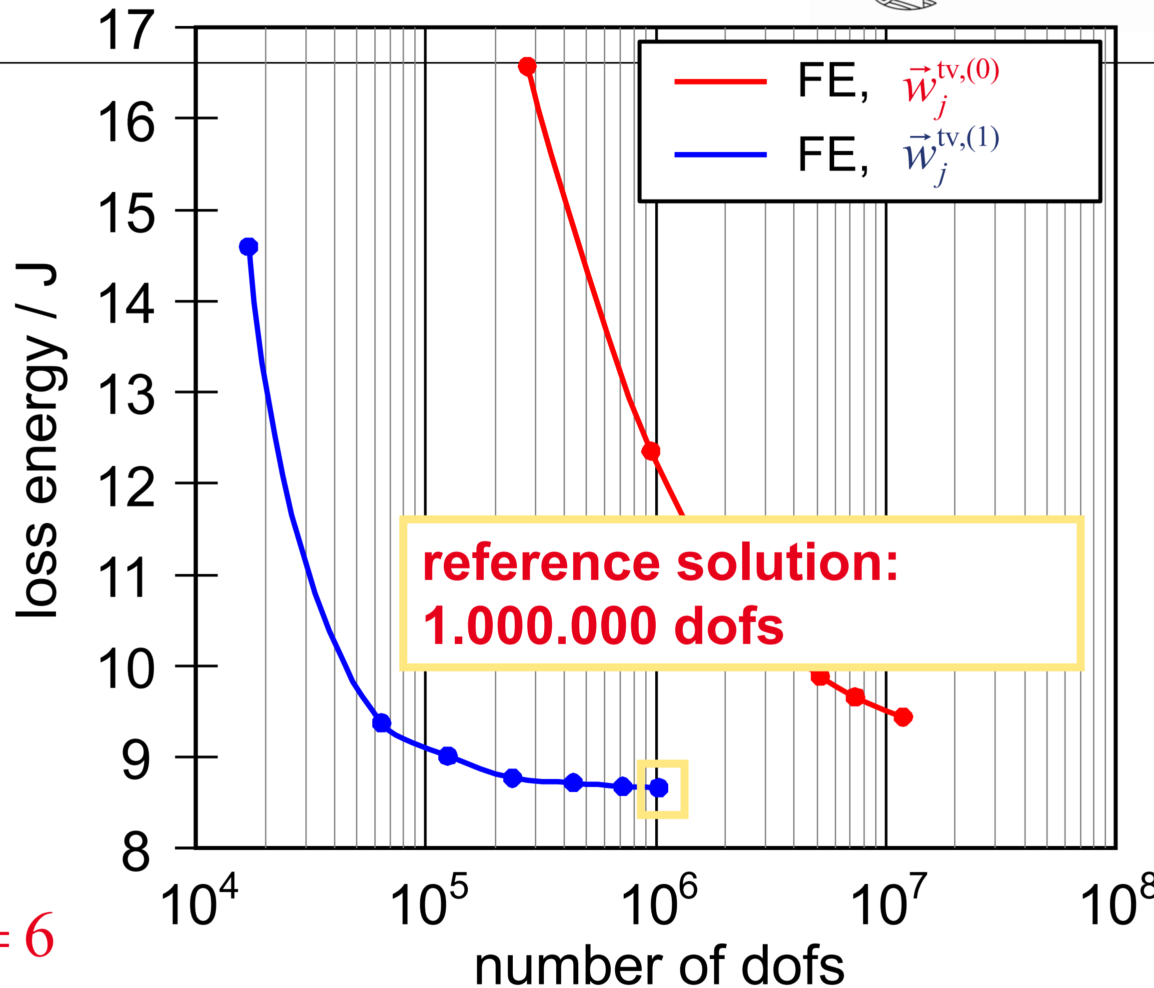
degrees of freedom:



+ 2 per face

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

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



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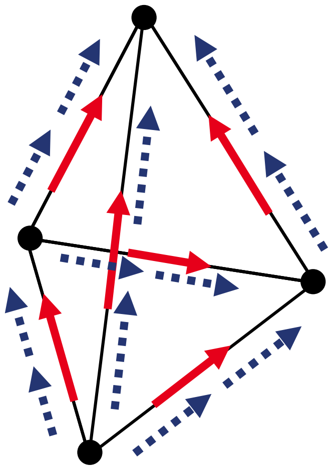
Convergence: Loss Energy

- relative error with respect to reference solution

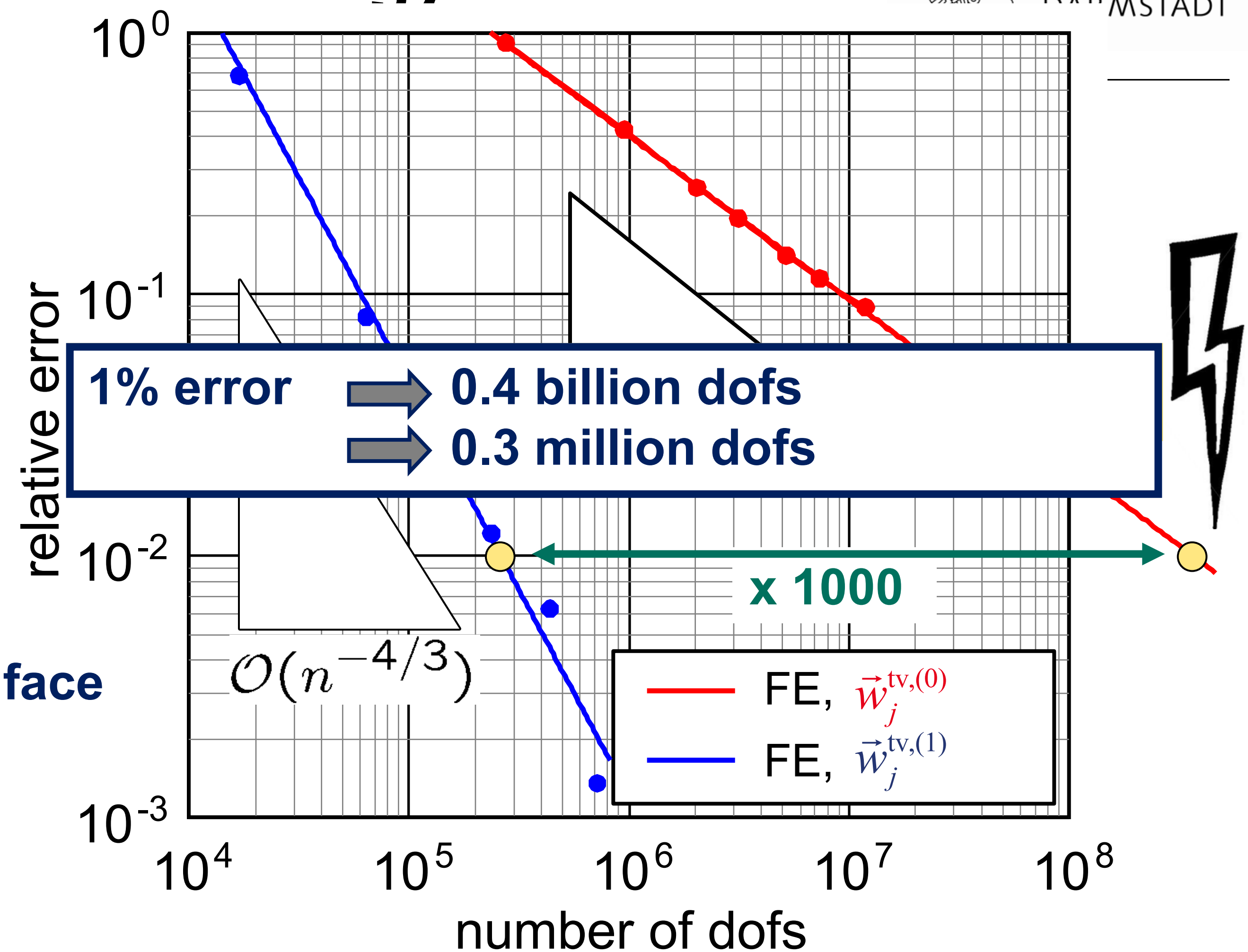
degrees of freedom:



+ 2 per face

$\vec{w}_j^{\mathrm{tv},(0)}$

$\vec{w}_j^{\mathrm{tv},(1)}$



1% error ⇒ **0.4 billion dofs**
⇒ **0.3 million dofs**

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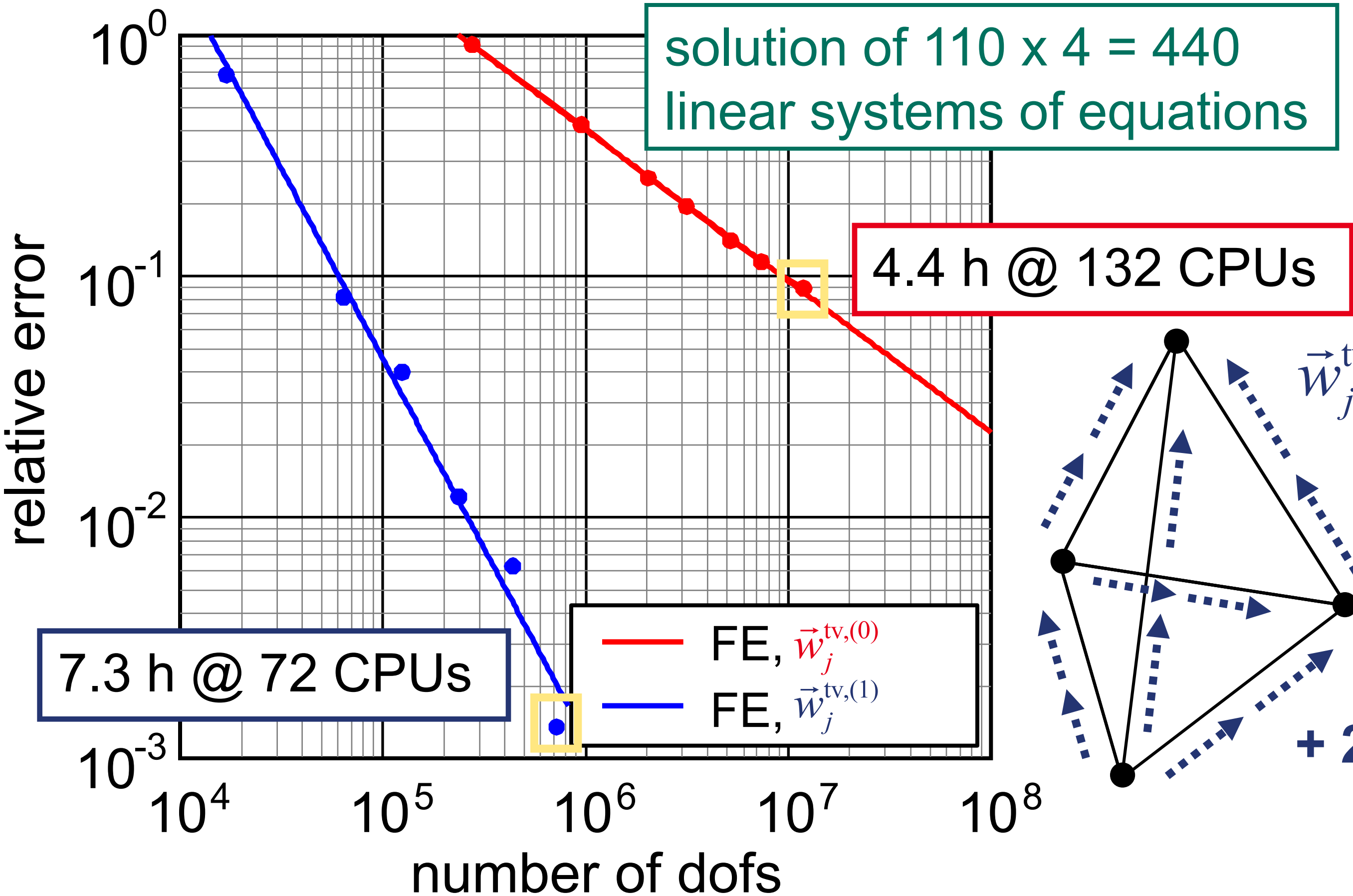
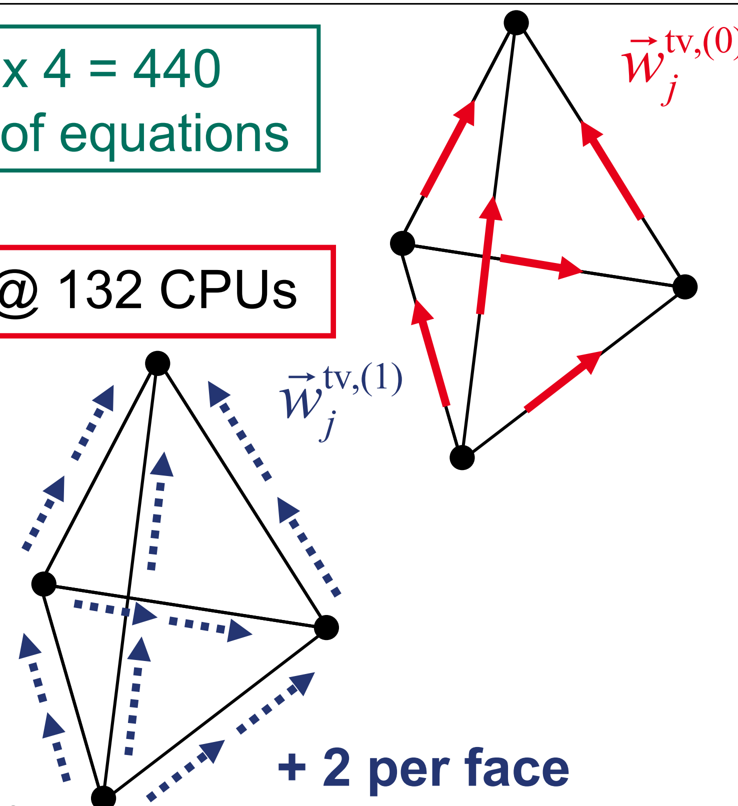
Comparison: Shape Functions





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Overview

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  (standard 3D FE solver)
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  - geometrical details
  - materials
  - transient effects
  - high accuracy
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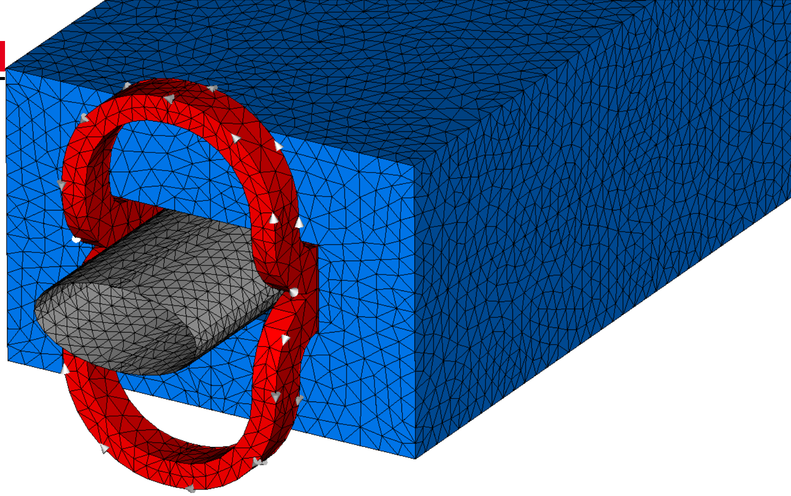
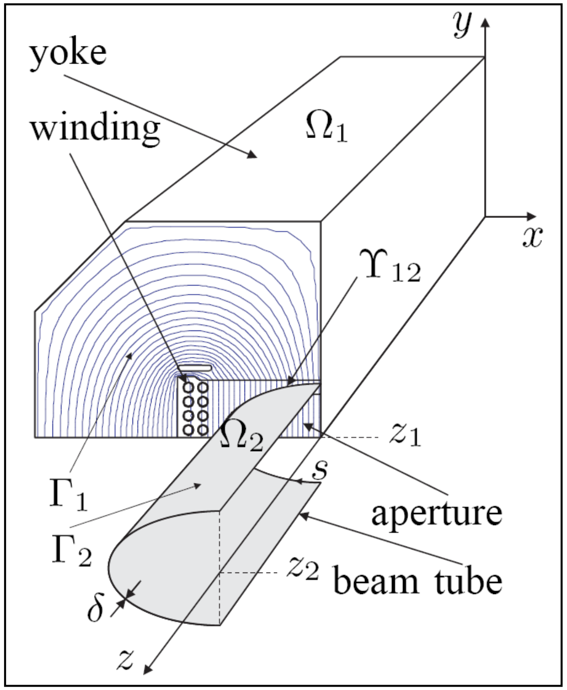
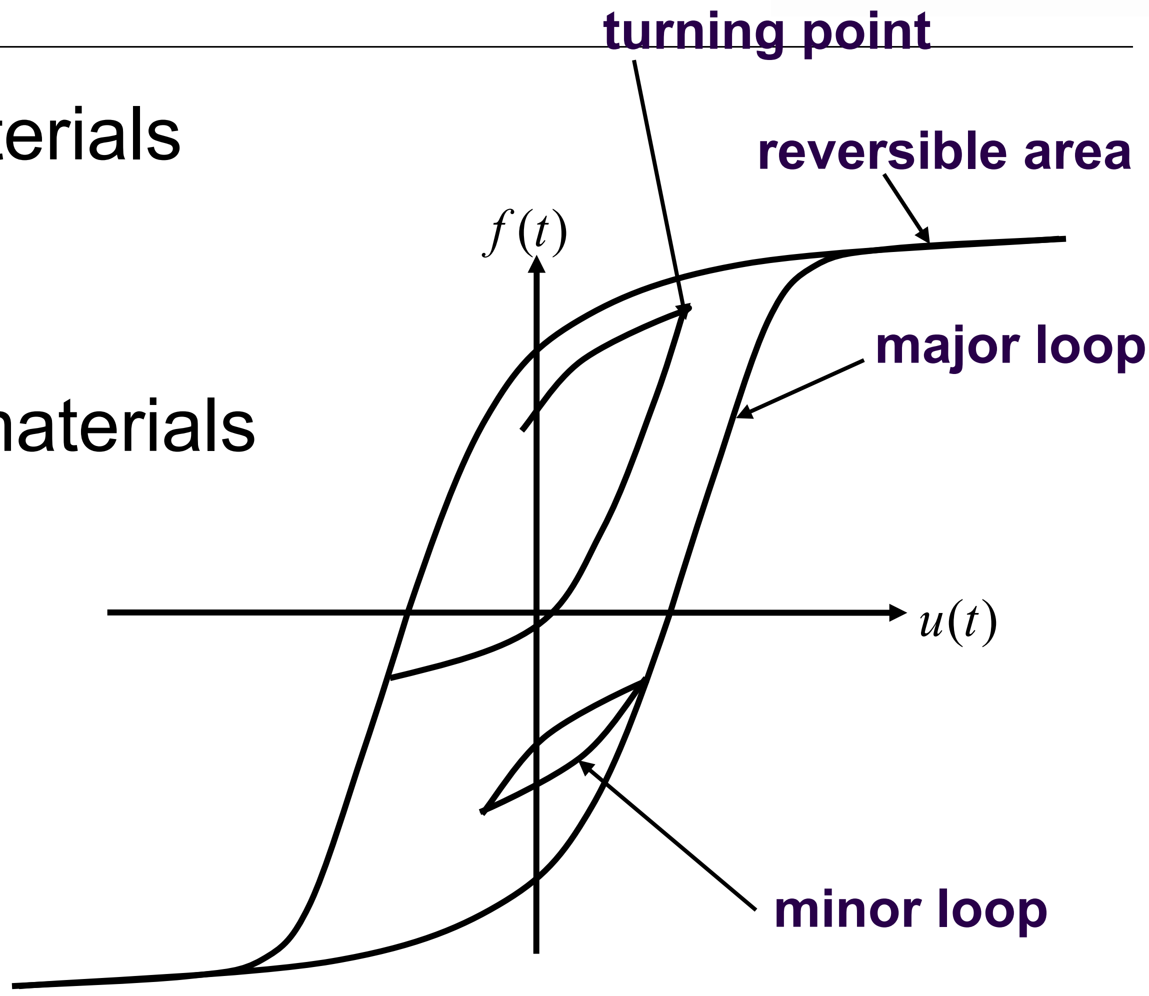
- hysteresis modelling
- conclusions





Hysteresis

- Ferromagnetic materials
  - remanence
  - hysteresis losses
- Superconductive materials
- Friction



Hysteresis and Field Modelling

- transient field simulation + hysteresis model
- transient field simulation + simple hysteresis model

  e.g. hysteresis losses: complex permeability

$$\left.\begin{aligned} B(t) &= \hat{B}\cos(\omega t) \\ H(t) &= \hat{H}\cos(\omega t - \varphi) \end{aligned}\right\} \Rightarrow \underline{\mu} = \frac{\hat{B}}{\hat{H}} e^{j\varphi}$$

- post-processing step + simple hysteresis model

  e.g. hysteresis losses: Steinmetz formula

$$p_{\text{hyst}} = \sigma_{\text{hyst}} k_{\text{hyst}} \frac{f}{50\ \text{Hz}} \left(\frac{|\vec{B}|}{1\ \text{T}} \right)^2$$

- post-processing step + simple remanence model

  e.g. remanence: look-up table

Hysteresis Models

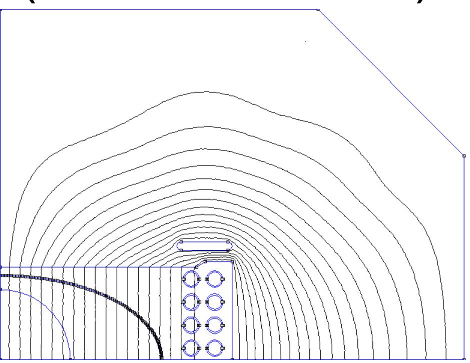
- Preisach model
- Jiles-Atherton model
- Stone-Wolfarth model
- ...

Preisach model

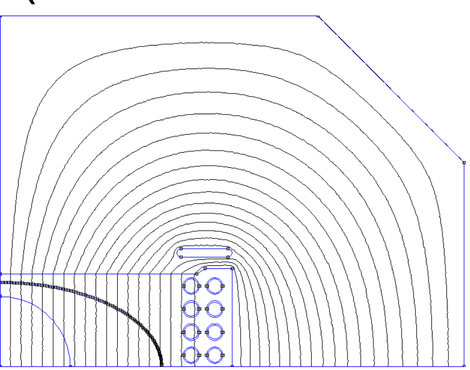
I.D. Mayergoyz, „Mathematical Models of Hysteresis“, Springer-Verlag, New York, 1991, pp. 1-44.

SIS100: Remanence at Injection

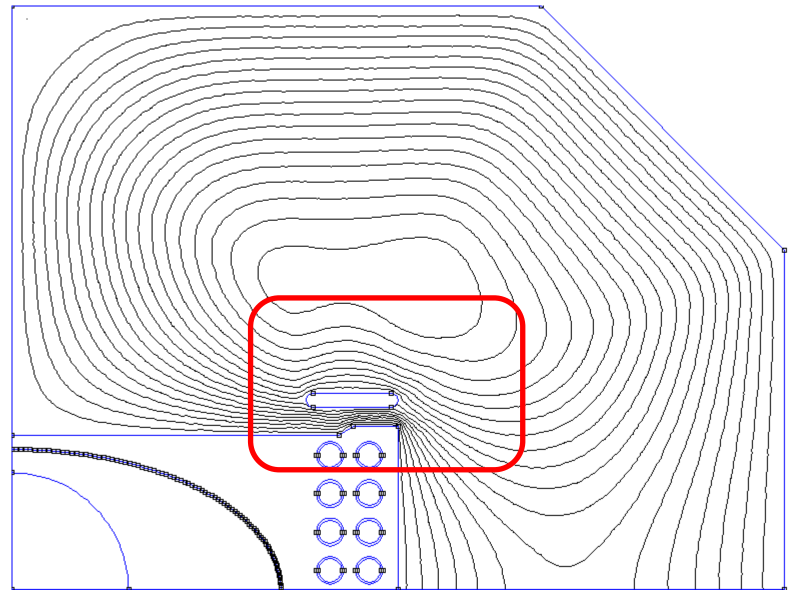
injection field
(with remanence)



injection field
(without remanence)



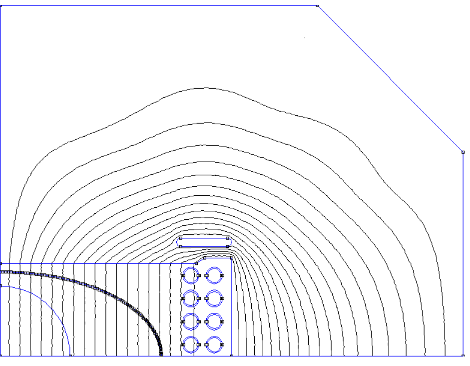
remanent field



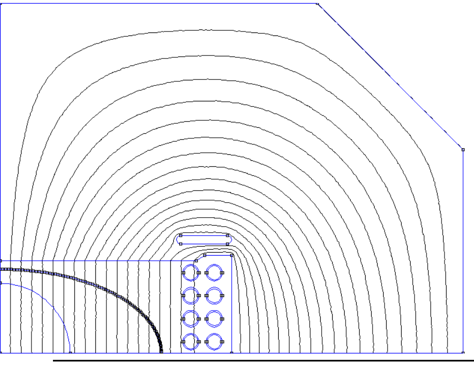
region with heavy saturation
acts as „source“ of
magnetisation

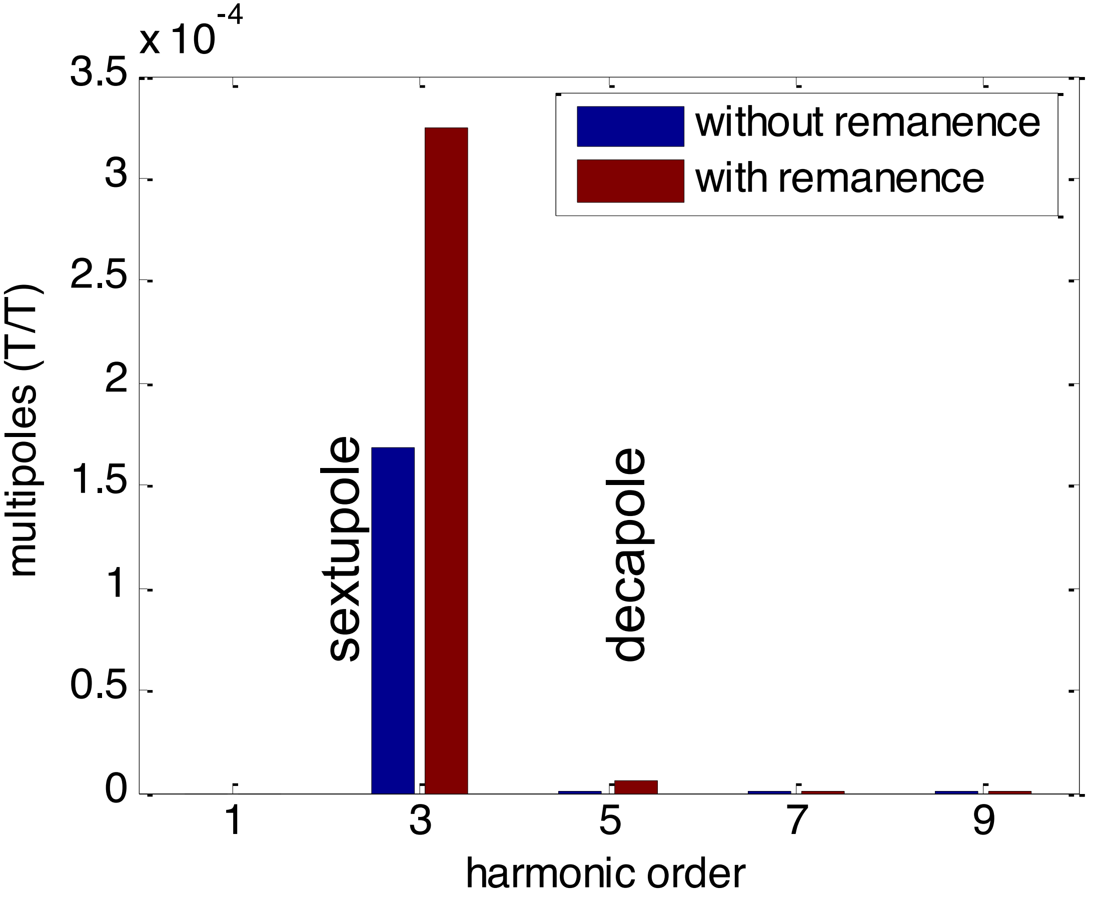
SIS100: Remanence at Injection

injection field
(with remanence)

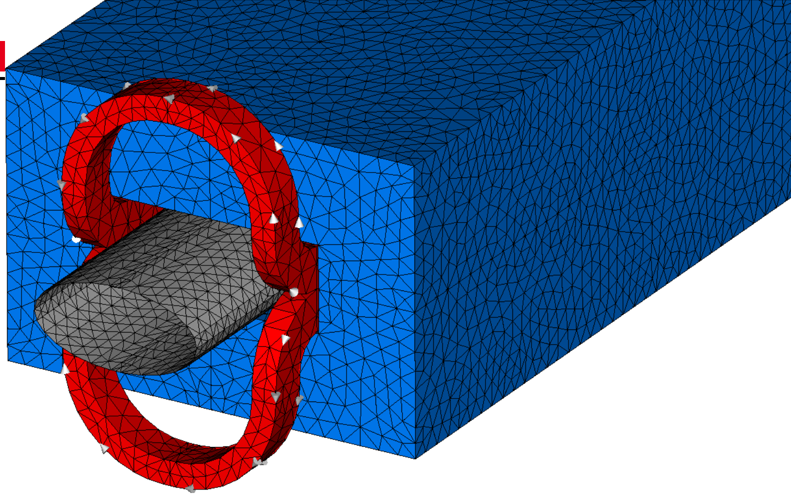


injection field
(without remanence)

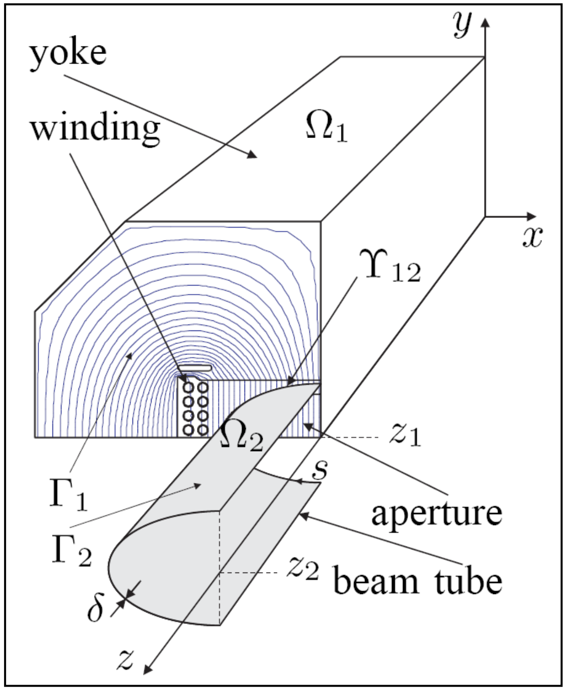




Conclusions



- nonlinear 3D transient magnetic simulation feasible with of-the-shell software
- challenges remain and are problem specific
    - geometrical details
    - materials
    - transient effects
    - high accuracy
- hysteresis modelling (Preisach)



necessity of accurate material models and measurement data