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Dynamic Behaviour of Laminated Magnets with Solid Tension Bars

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Background

An important criterion in the design of fast-ramping accelerator magnets is their field distribution in the time-transient regime, where eddy current effects in different components of the magnet become more or less significant. Keeping the magnetic cycle as short as possible is a frequent design goal. The length of a magnetic cycle is limited by the minimum ramp time T_r and the stabilization time T_s after the end of the ramp until transient effects have attenuated below a defined threshold. Ramp rate *dB/dt* and the stabilization time are linked: the faster the ramp rate, the longer the stabilization time. Whereas the ramp rate can only be adjusted within a limited range, the stabilization time, determined by the allowed remaining field error ε_r, the field error at the end of the ramp time ε_0, and the time constant τ, can vary in a wide range over several orders of magnitude depending on the magnetic design.

Objectives

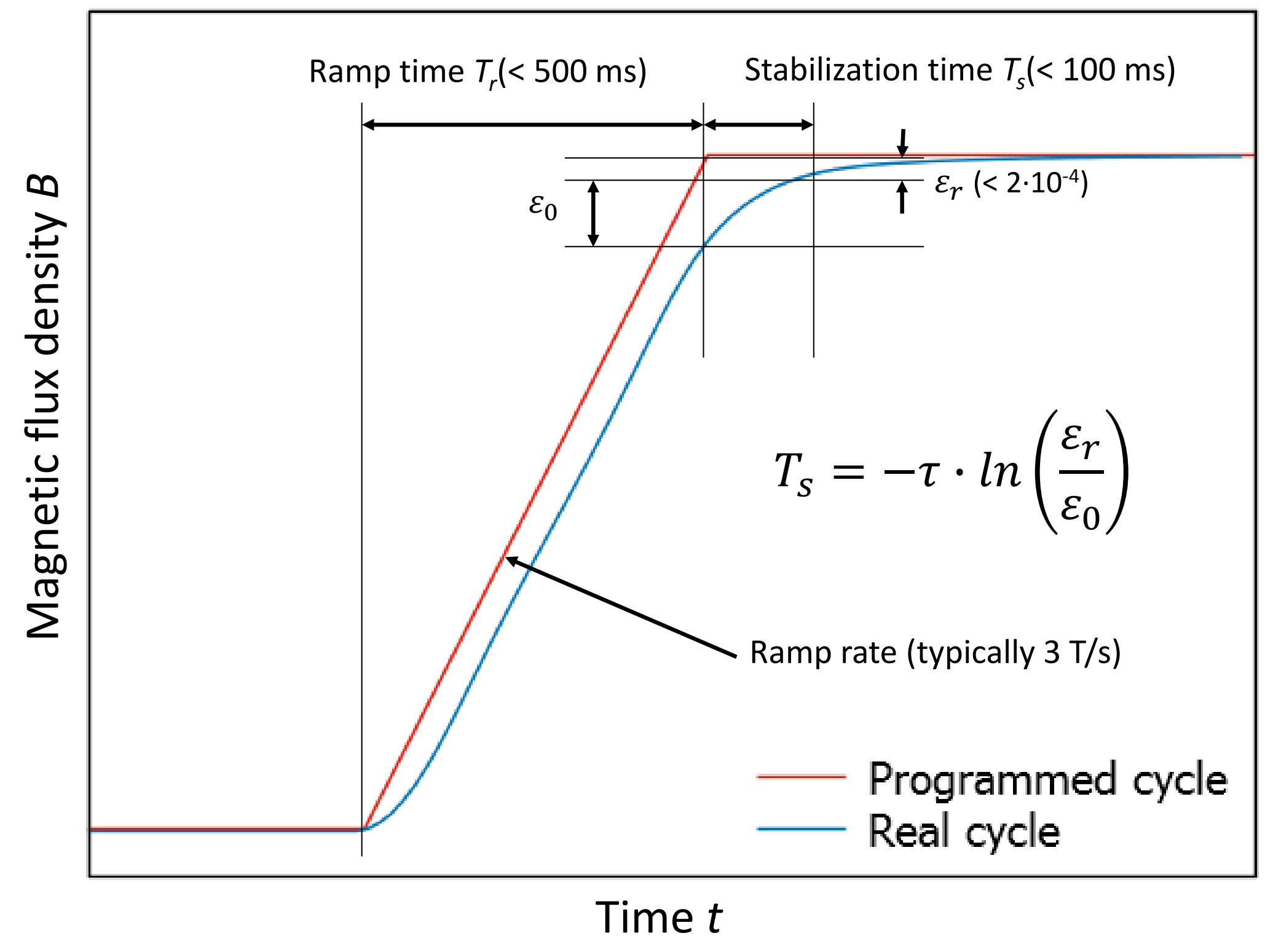
- ❖ Investigate the effects of eddy currents in different components of a synchrotron dipole and their impact on the dynamic behavior of the magnet.
- ❖ Optimize the magnetic design to keep the stabilization time low.

Conclusion

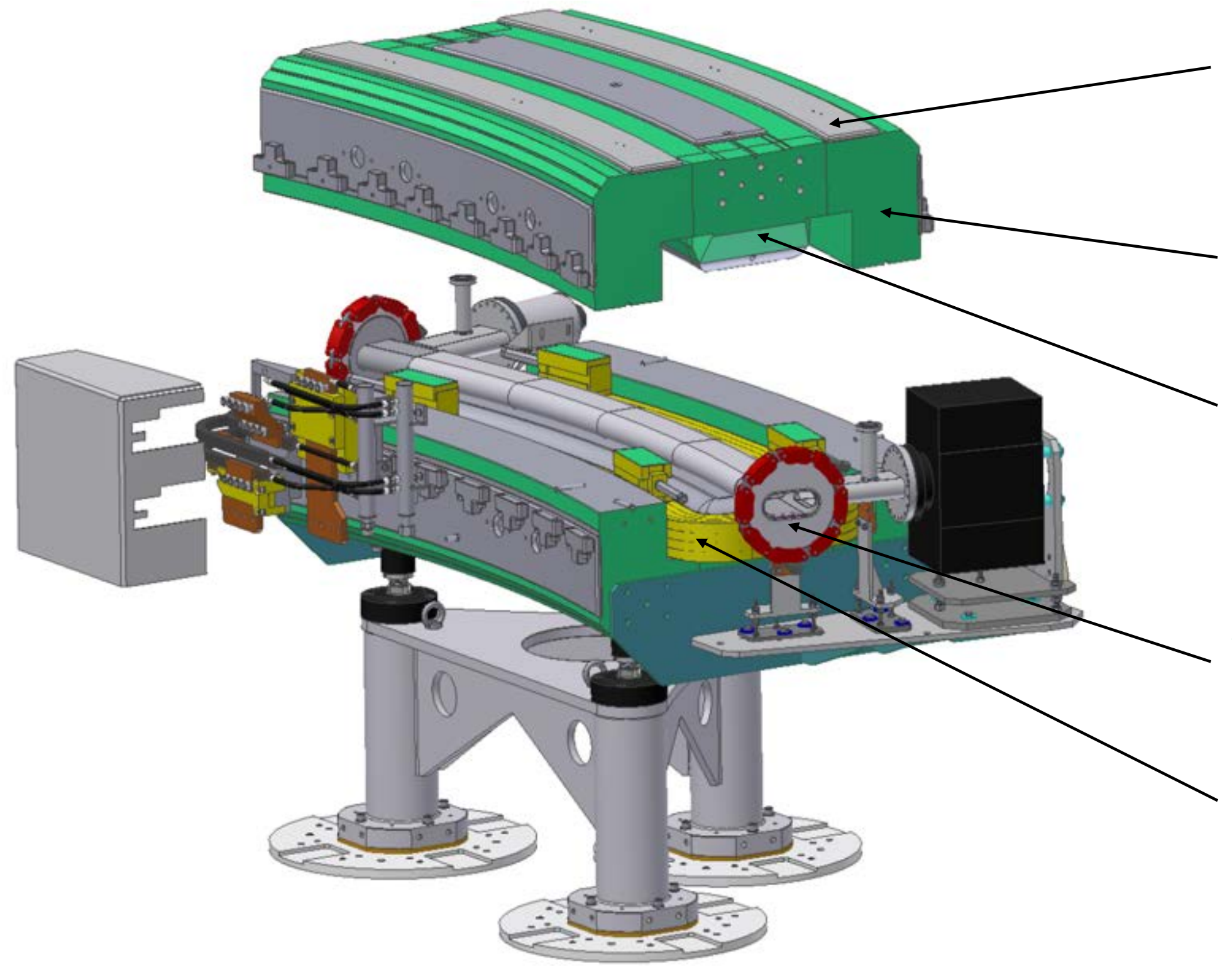
- ❖ A laminated magnetic circuit with solid tension bars made of low-carbon steel, although submitted to moderate field levels and ramp rates, can suffer from field attenuation and long stabilization times which are no longer negligible.
- ❖ Two factors play a governing role: the flux density in the magnetic circuit and the variation of the field in time.
- ❖ The developed theory is in good agreement with numerical computations and magnetic field measurements.
- ❖ Effective counter-measures to reduce these unwanted eddy current effects and improve the dynamic behaviour of the magnet are:
  - an increase of the laminated cross-sections to decrease the reluctance of the magnetic circuit,
  - an increase of the air gap between the laminated yoke and the solid tension bars
  - tension bars made of stainless steel or other material owning a similar low relative permeability.
- ❖ Magnetic measurements have clearly proven that these counter-measures are successful.

Problem

Magnetic cycle



Eddy current sources



Solid tension bars: to be investigated

Solid end-plates: not present ⇨ $\tau = 0$

Laminated yoke: for 1 mm thick laminations ⇨ $\tau \approx 0.6$ ms

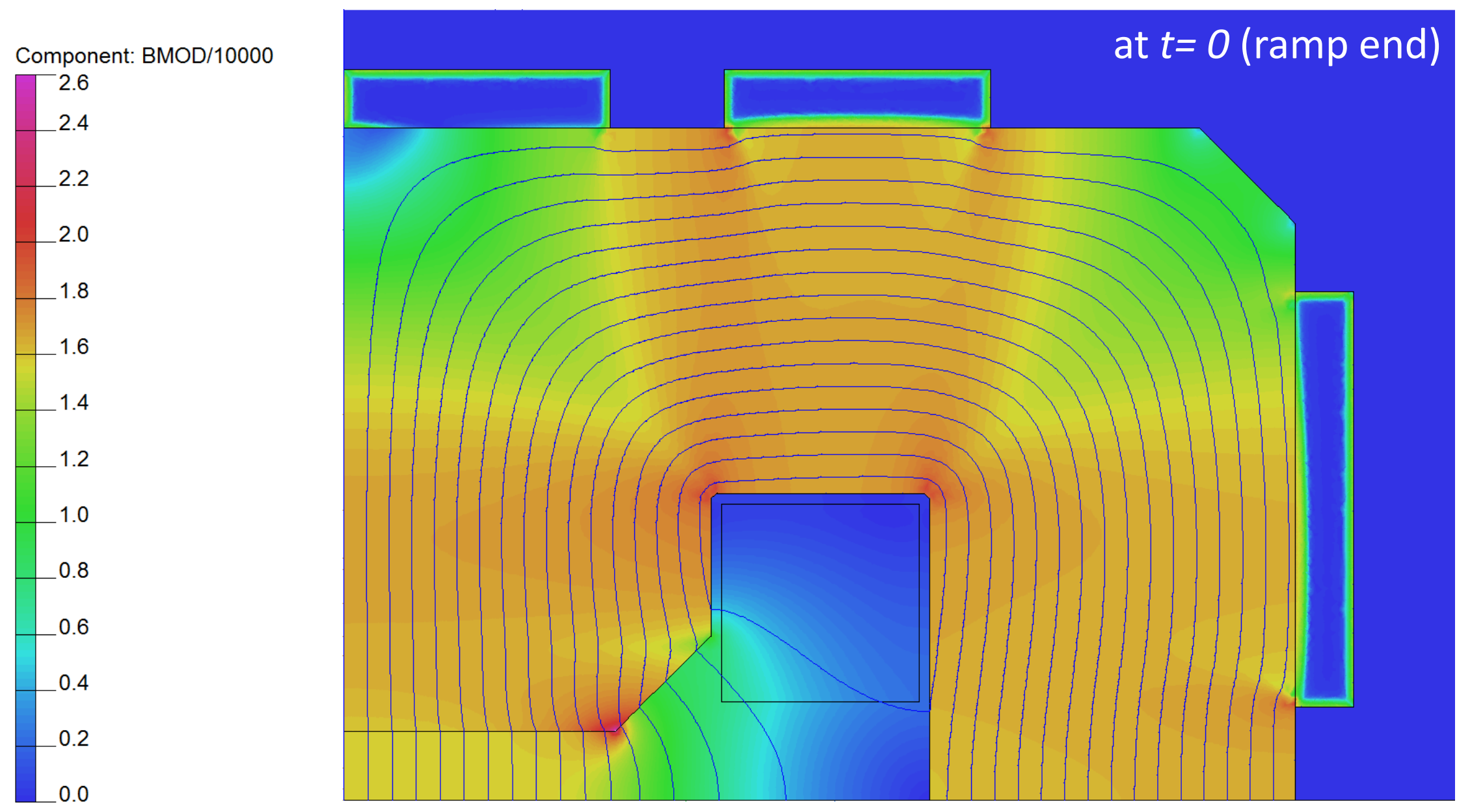
Pole ends: to be compensated by pole-end shimming (Rogowsky profile)

Vacuum chamber: thin-wall corrugated stainless steel chamber ⇨ τ <<

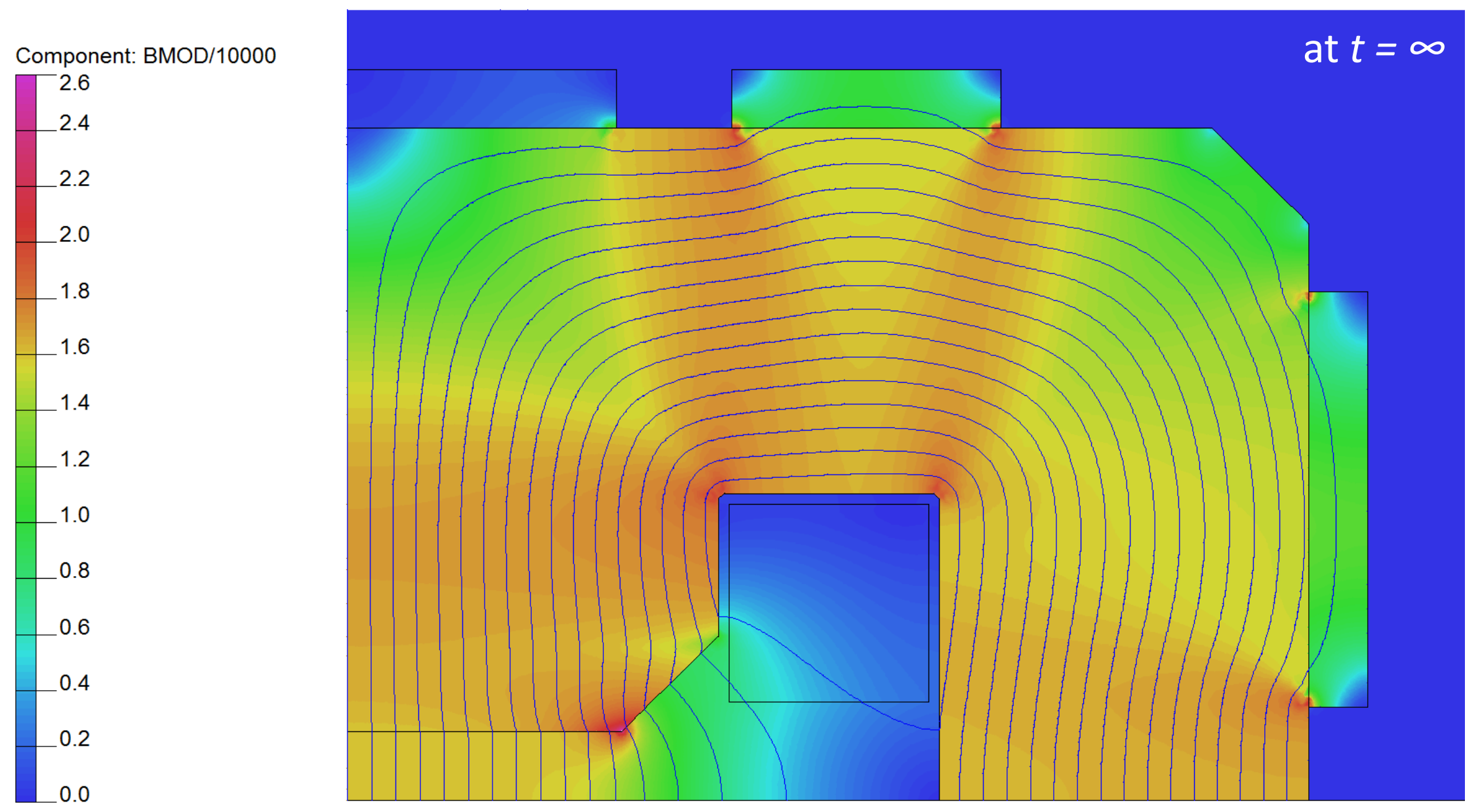
Coil conductor: main flux in magnetic circuit and aperture ⇨ τ <<

Theory

If parts of the magnetic circuit see elevated levels of flux density, which reduce the local permeability and increase the overall reluctance, the magnetic flux deviates into regions of higher permeability respectively lower reluctance. In case these regions support eddy currents this can have an impact on the dynamic behaviour.



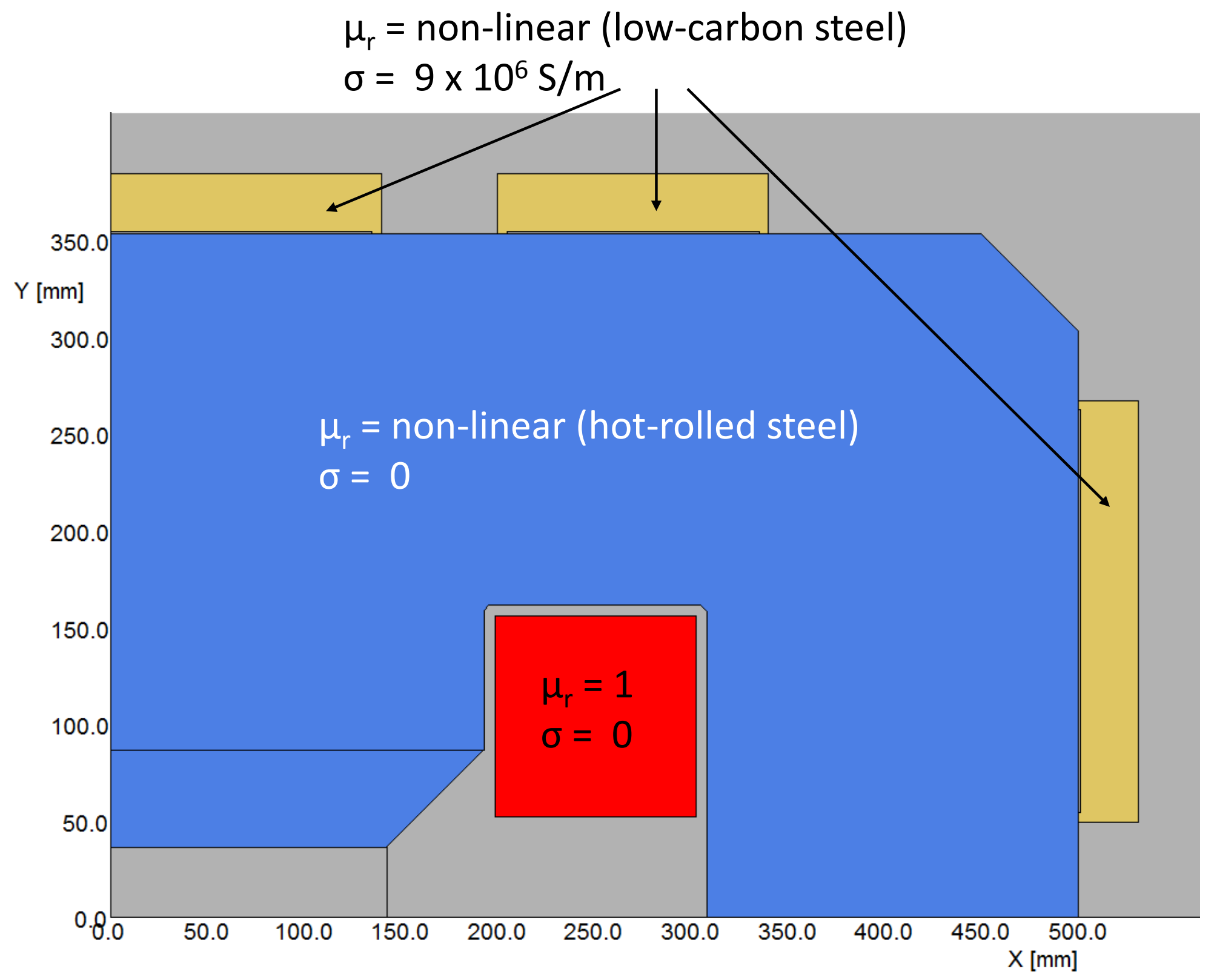
At the beginning of the ramp, eddy currents hinder the magnetic flux from penetrating the tension bars; the tension bars cannot contribute to carry magnetic flux and the reluctance of the circuit is high.



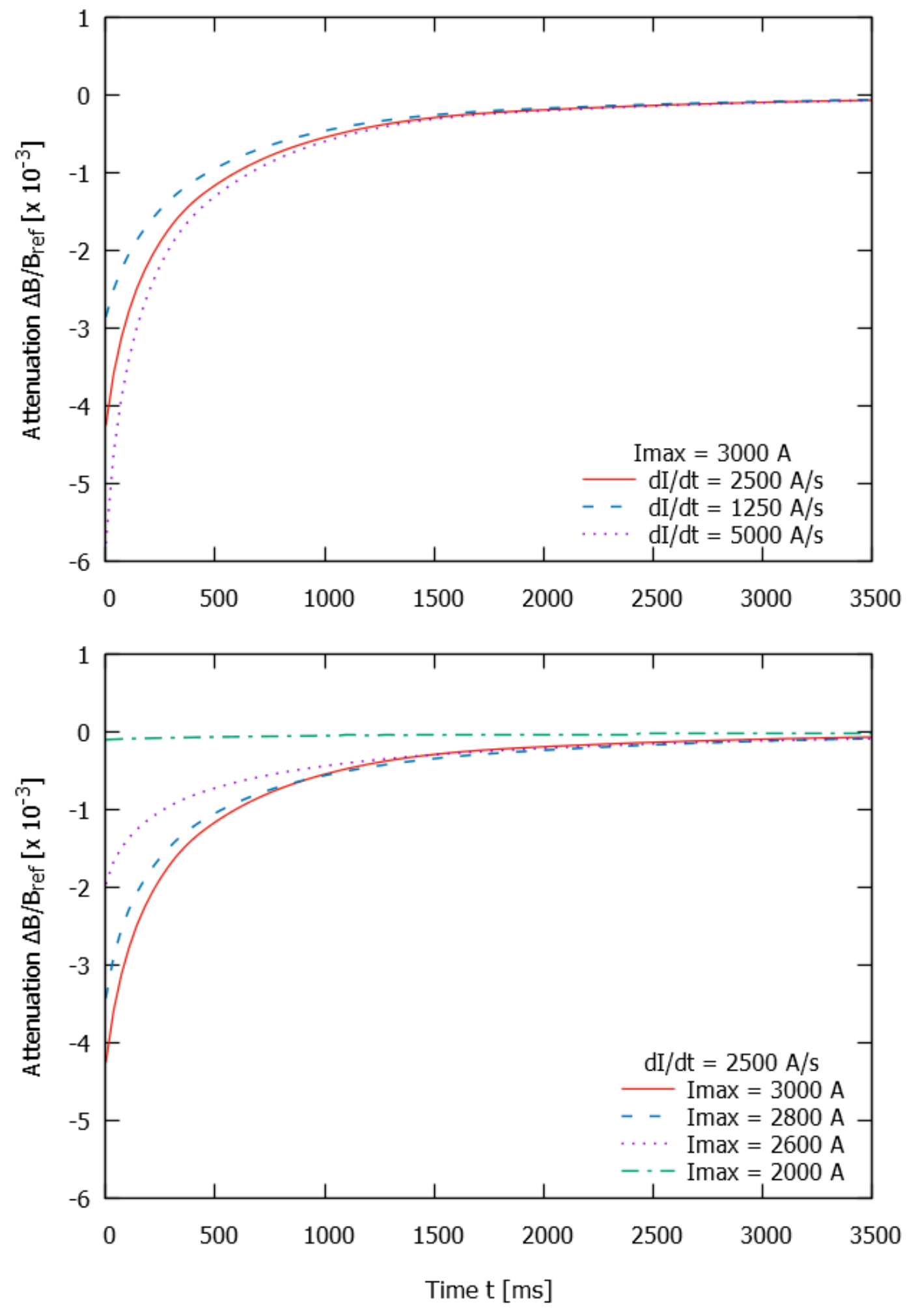
After the end of the ramp, eddy currents start to decay and the magnetic flux can successively enter the tension bars decreasing the reluctance of the magnetic circuit. This leads to a steady increase of the flux density until all eddy currents in the tension bars have diminished.

Results

Simulations



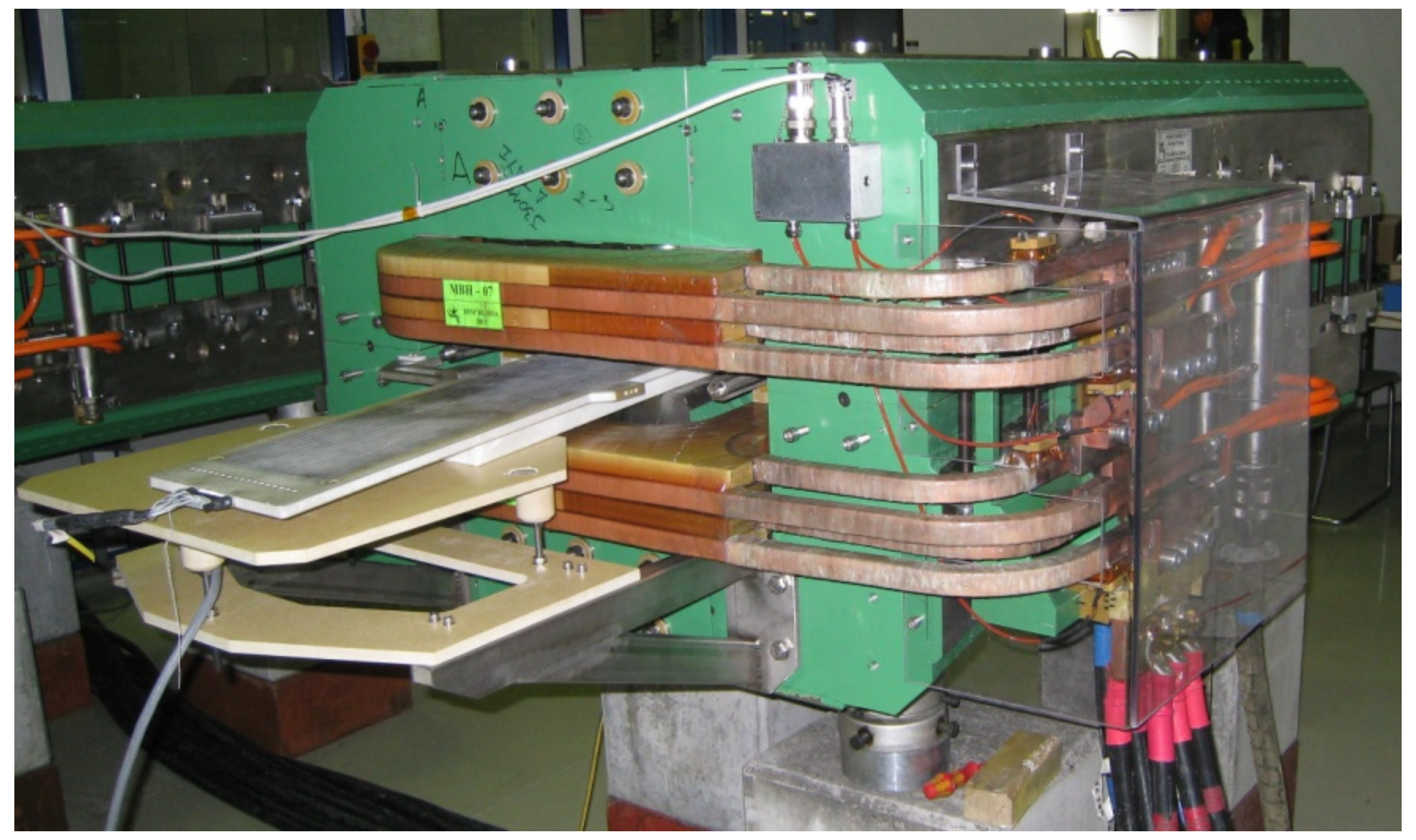
Parametrized FE-model (one quarter) using Vectorfields OPERA® transient solver. Only a two-dimensional solution has been envisaged because it delivers sufficient information and computation time is significantly shorter.

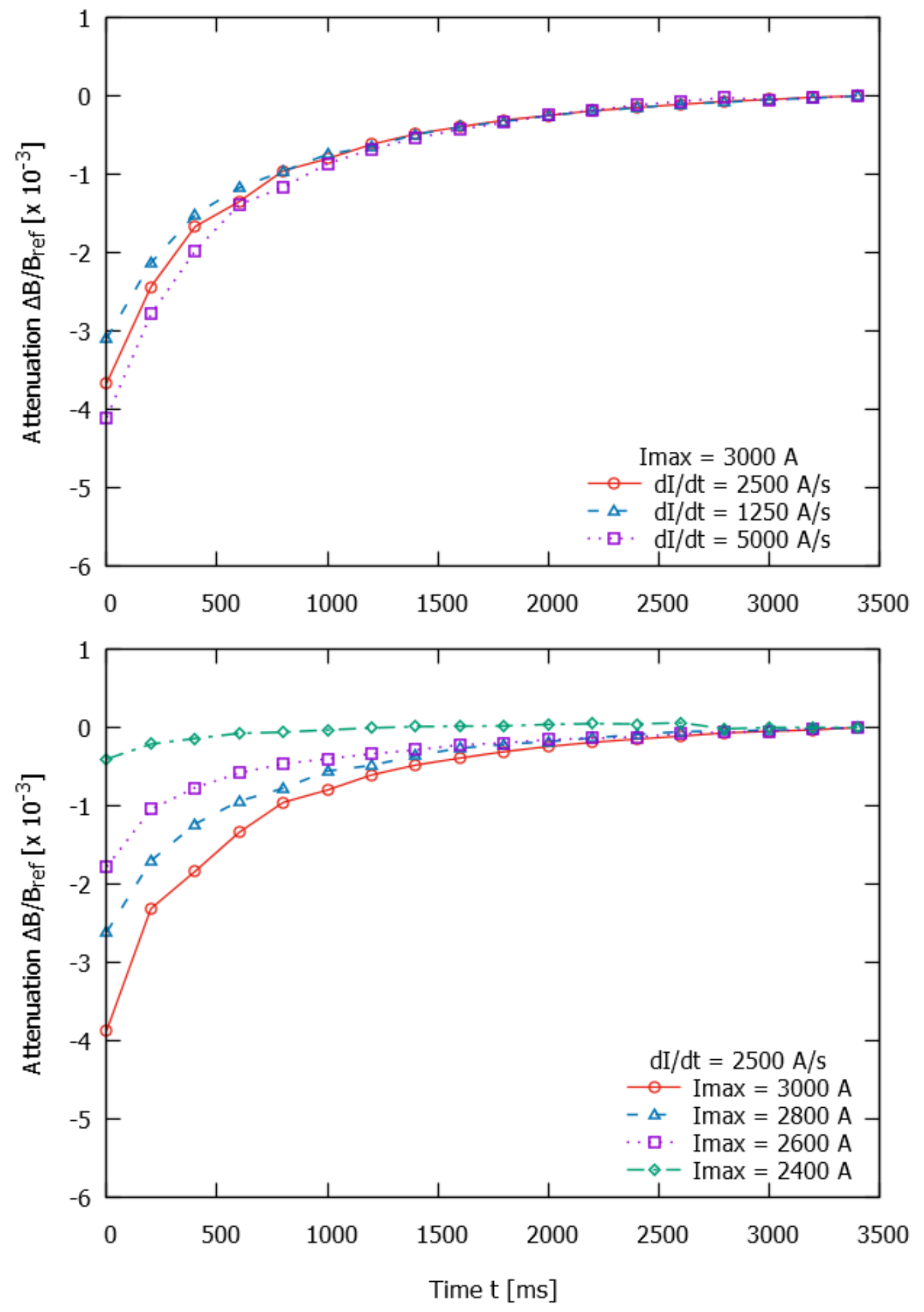


Numerical simulation (a) at constant I_{max} and variable *dI/dt* and (b) at constant *dI/dt* and variable I_{max}

Measurements

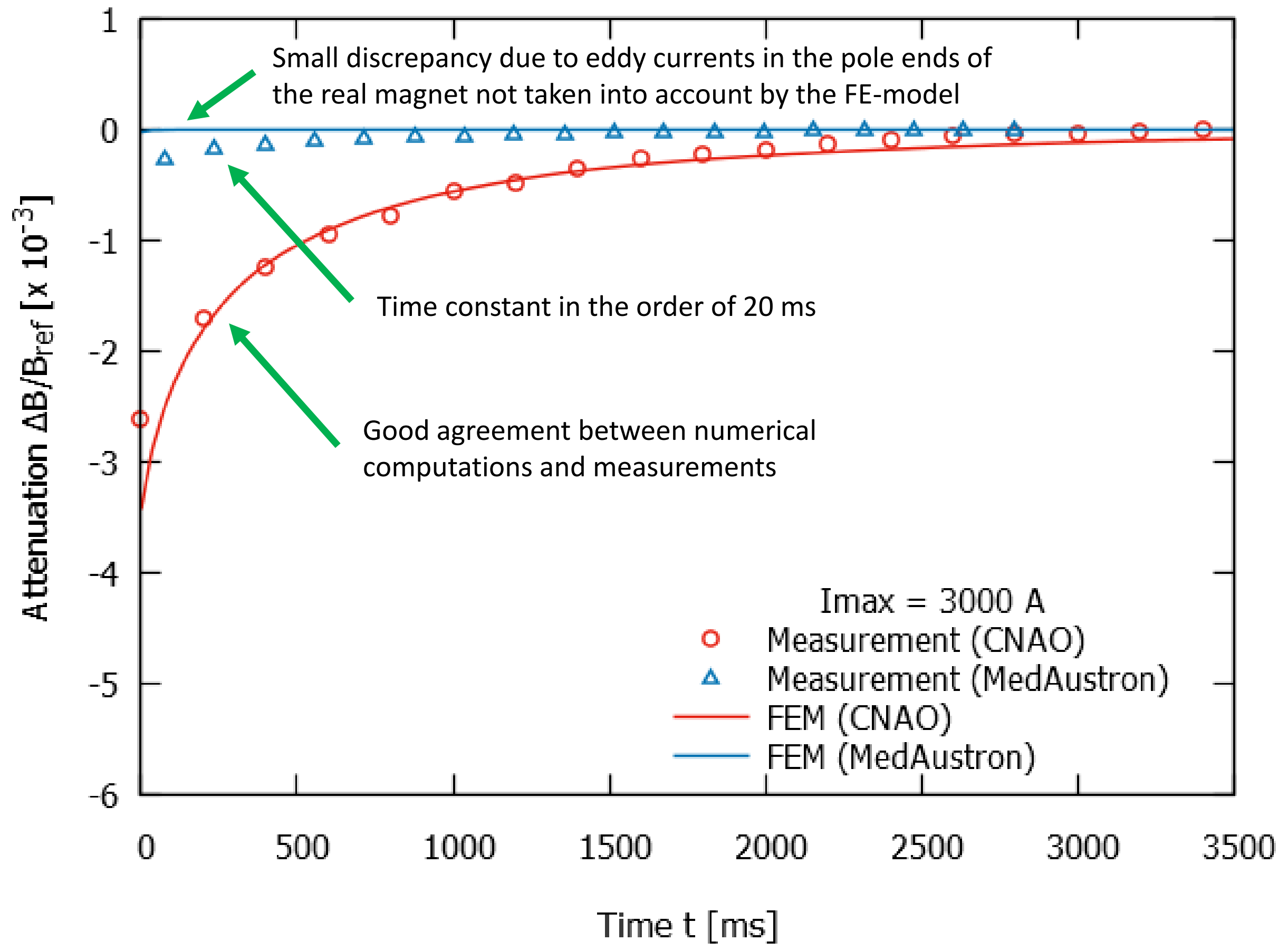
The CNAO and the MedAustron synchrotron dipoles are very similar - in particular the cross-section. The main difference is that the CNAO magnets comprise solid tension bars which are made of low-carbon steel, whereas the MedAustron tension bars are made of stainless-steel. The magnetic measurements on both magnets have been performed with an array of induction-coil magnetometers, a so-called flux-meter.





CNAO measurement (a) at constant I_{max} and variable *dI/dt* and (b) at constant *dI/dt* and variable I_{max}

Comparison



Comparison between CNAO (dI/dt = 2500 A/s) and MedAustron (dI/dt = 5640 A/s)

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