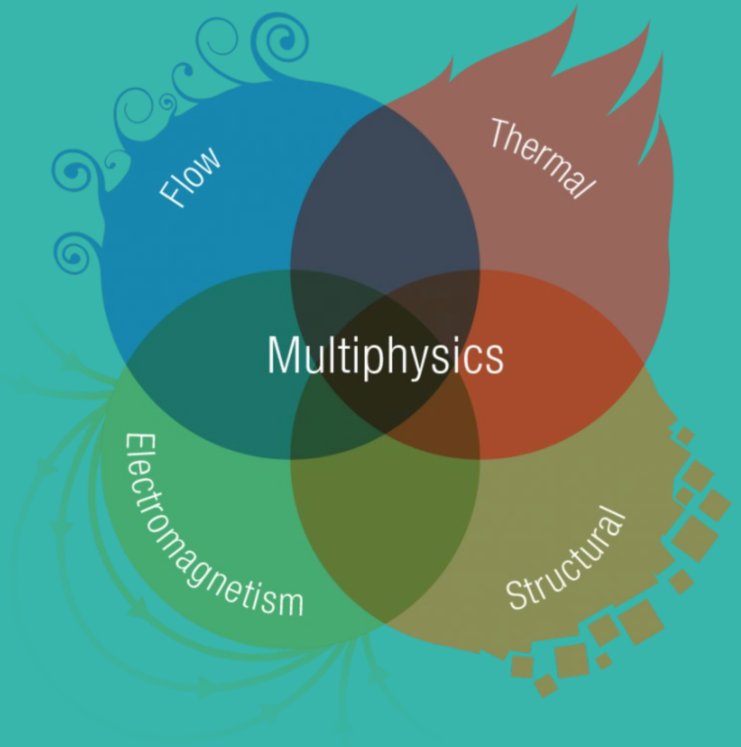

Modelling of high-temperature superconductors

KOEN DE MARE

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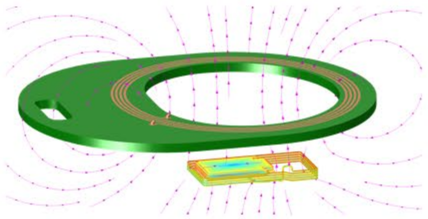
Content

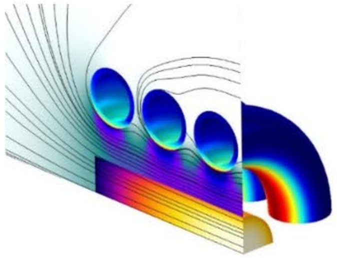
Introduction

- Demcon group:
  - Engineering group, Netherlands
  - +1000 employees
  - Product and one-off development
- **Demcon Multiphysics**:
  - Physics consultancy division
  - 20 employees
  - Active in flow, thermal, electromagnetism, structural, etc.

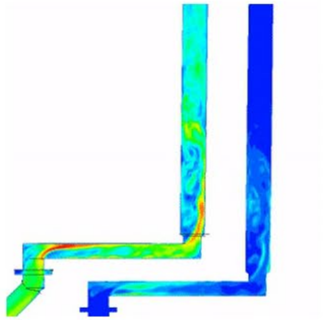
Electromagnetics



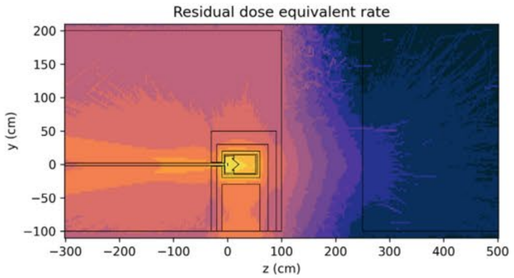
Thermal engineering



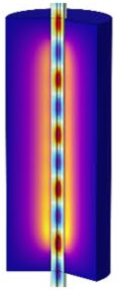
Fluid flows



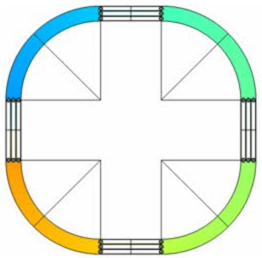
Nuclear physics



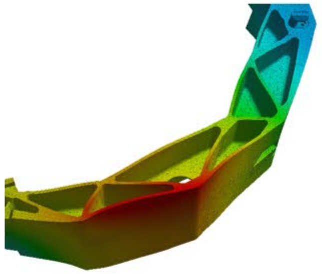
Plasma physics



Acoustics and vibrations



Structural mechanics



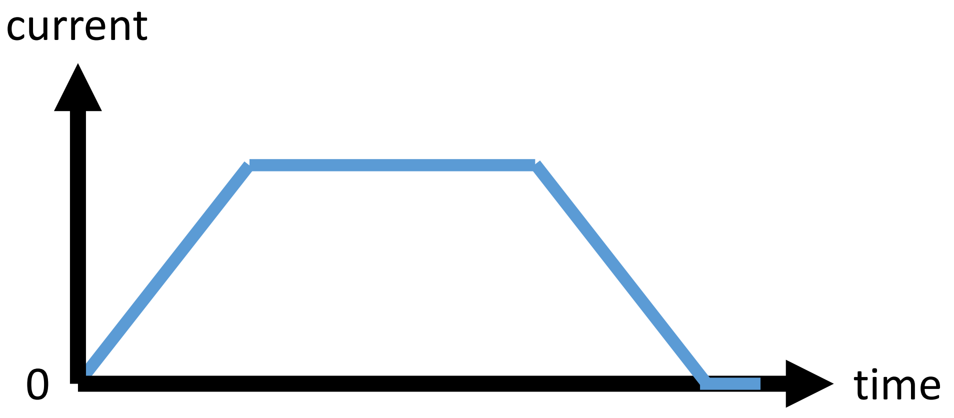
Experiments

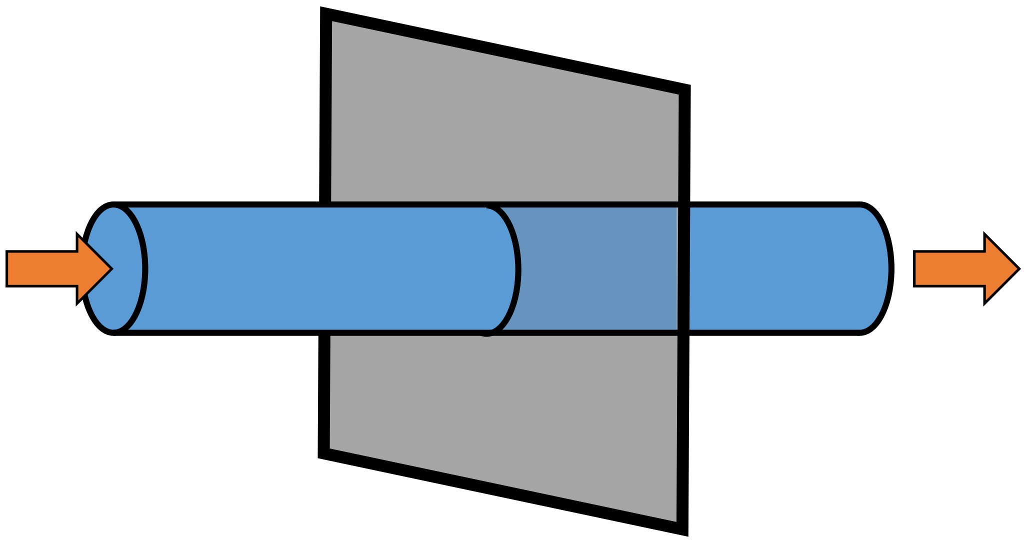
Multiphysics engineer

Toy model: round wire

- Based on COMSOL demo: “superconducting wire”
- Illustrates the behavior of high-temperature superconductors

- Round wire of high-temperature superconductor
- Modeled in 2D
- Current increased and then decreased

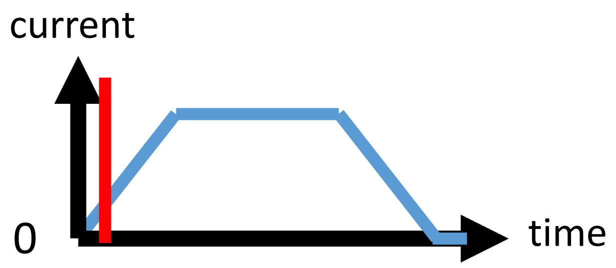


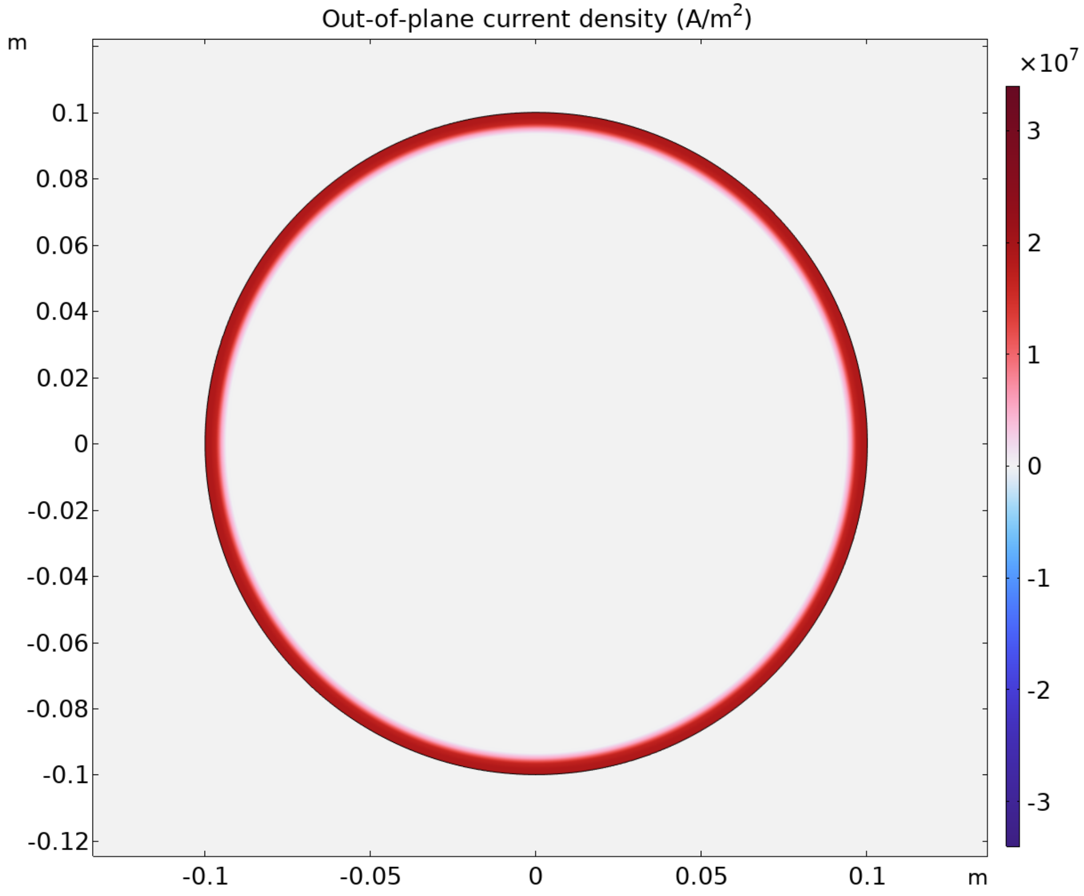


Toy model: round wire

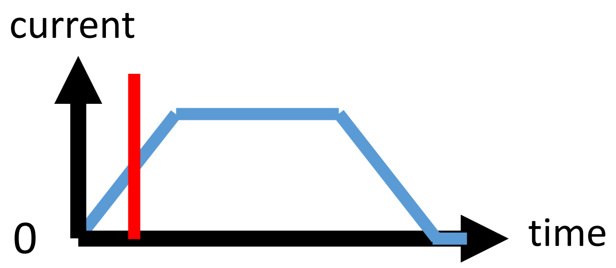
- Imposing a small current

- Skin effect: currents initially flow on the surface
  - Same as in regular conductors, but in regular conductors the current quickly spreads out

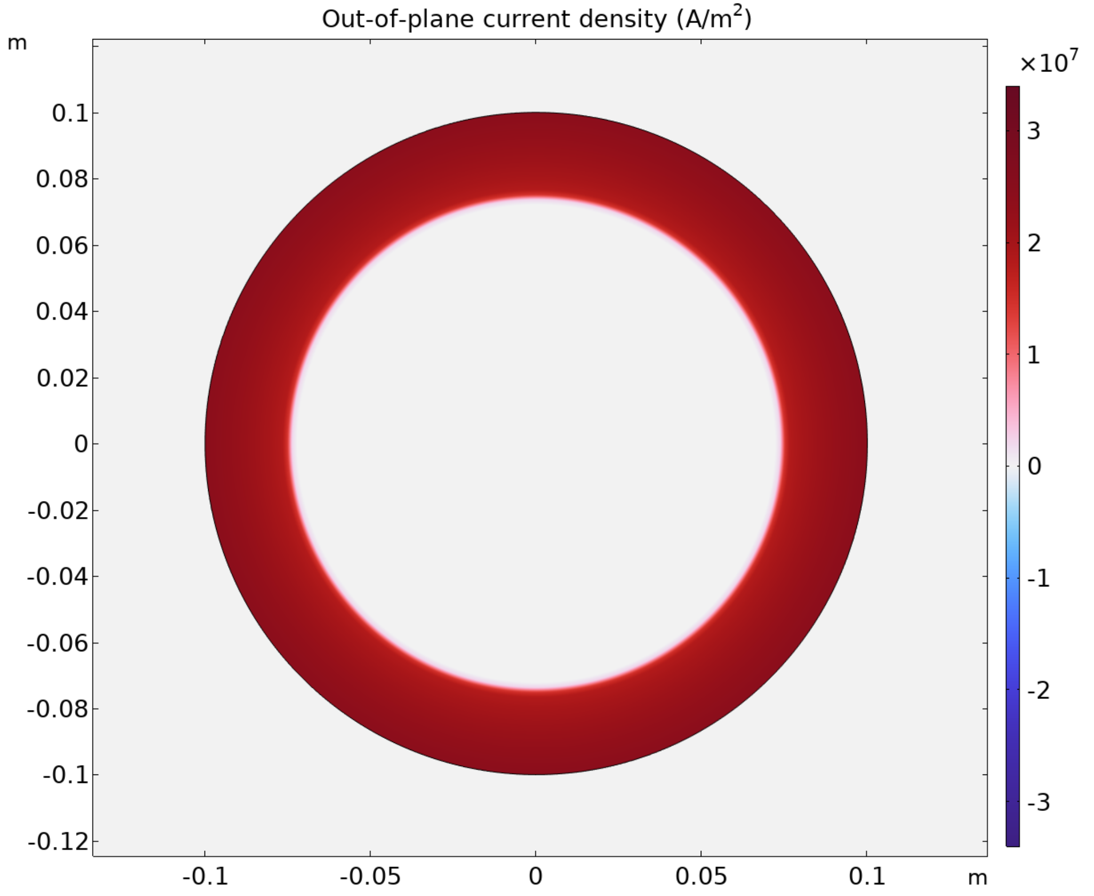




Toy model: round wire

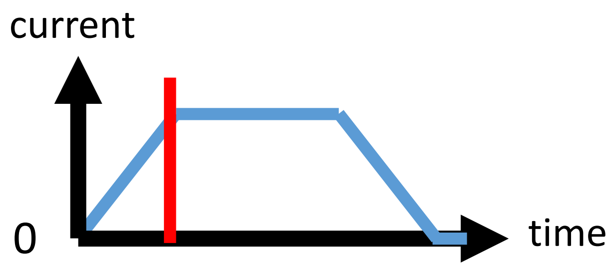


- Ramping up the current



- The current density at the surface has reached the critical current density
  - $E(J) = E_c * |J\ /\ J_c|^n$
  - $J_c = 2\text{E}7\ \text{A m}^{-2}$
  - $n = 15$
- A significant electric field develops locally
- This prevents the local current increasing further

Toy model: round wire



- Ramping up the current further

- The current front moves futher inward
- On the outside of the wire, the current with the electric field causes losses
    - Superconductors have losses when *changing* the imposed electric current
    - This heats up the cryogenic environment, so important effect for applications

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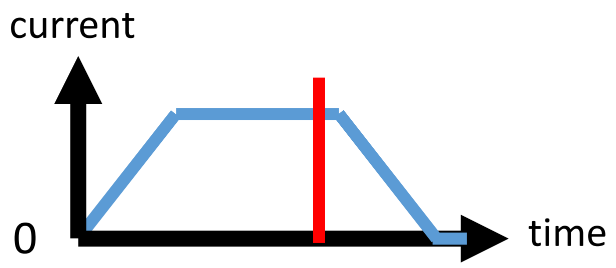
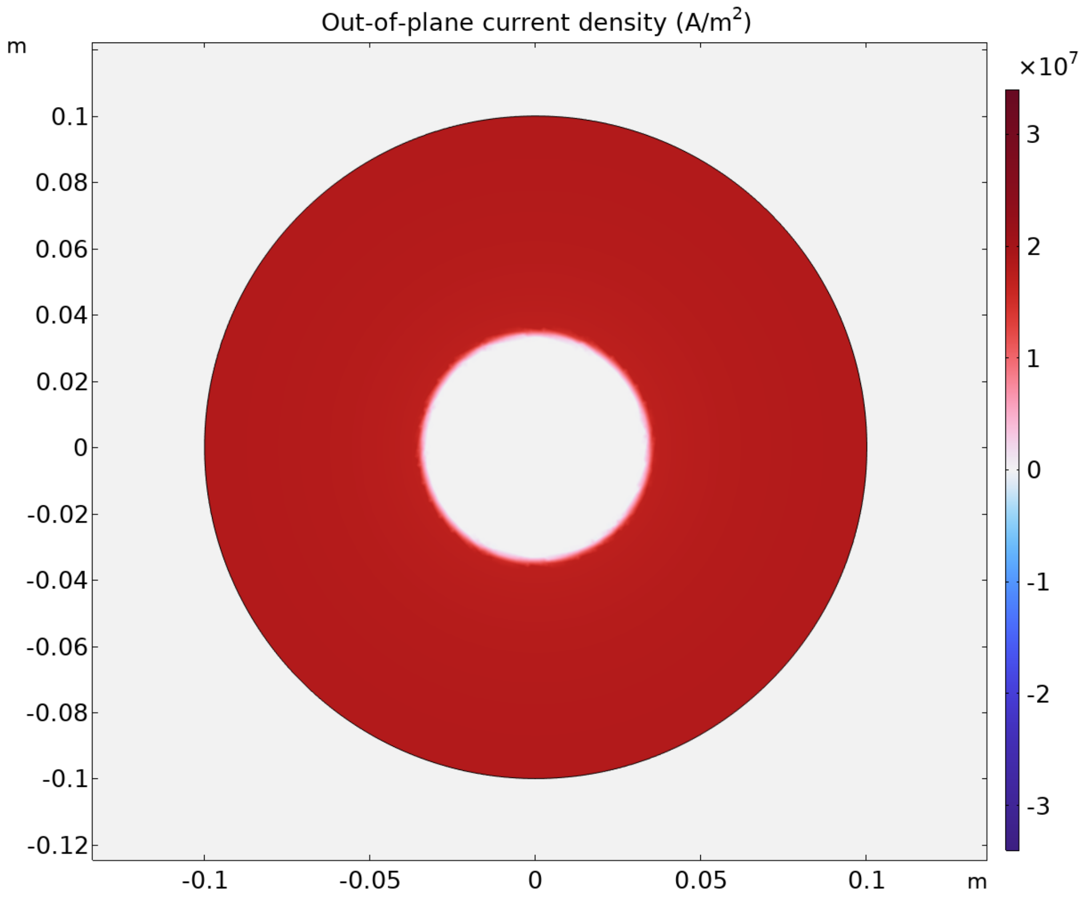
Toy model: round wire

- Keeping the current constant



- Redistribution of the current
- Now everywhere just below the critical current density



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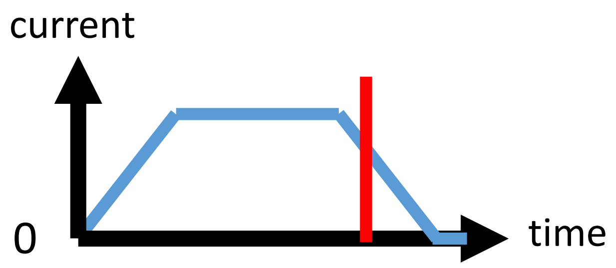
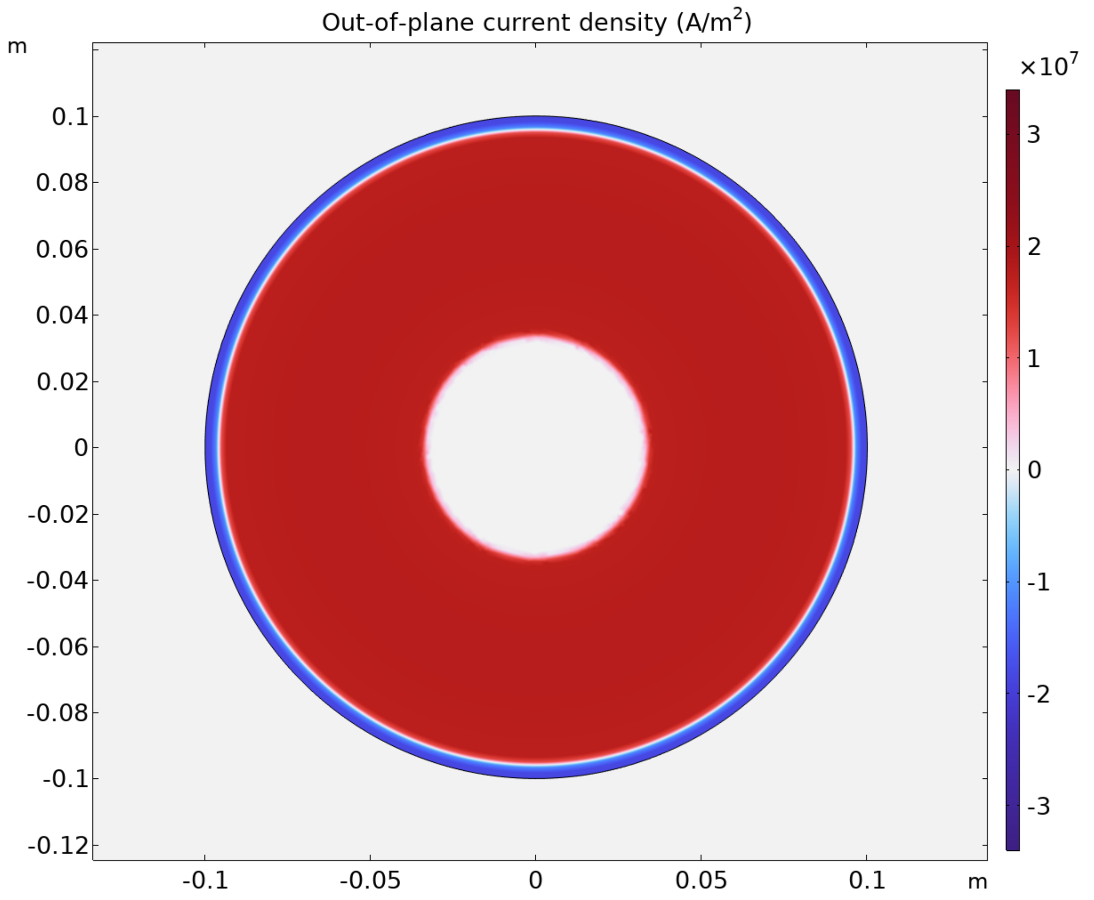
Toy model: round wire



- Decreasing the applied current



- Again, changing currents occur on the outside of the conductor due to skin effect

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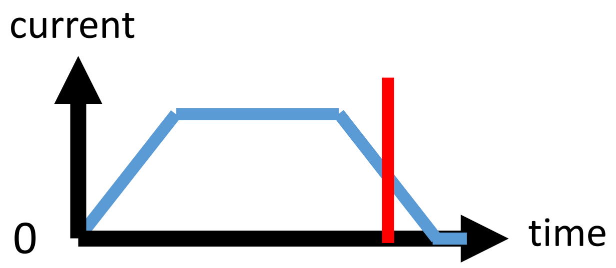
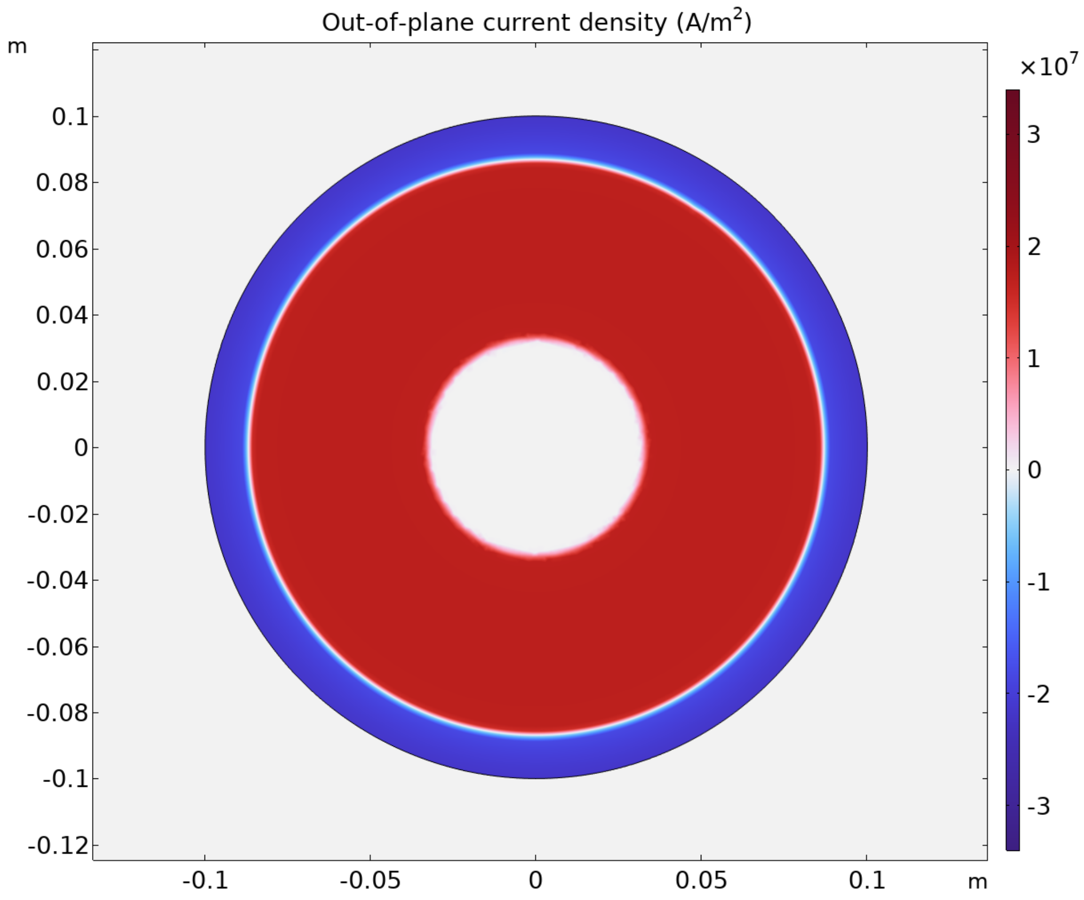
Toy model: round wire



- Decreasing the applied current further

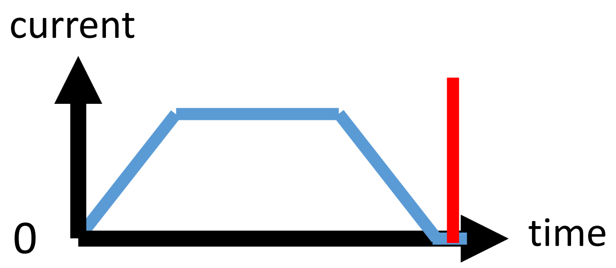
- The negative current reaches the critical current density
- The negative current front moves inwards
- Electric losses occur

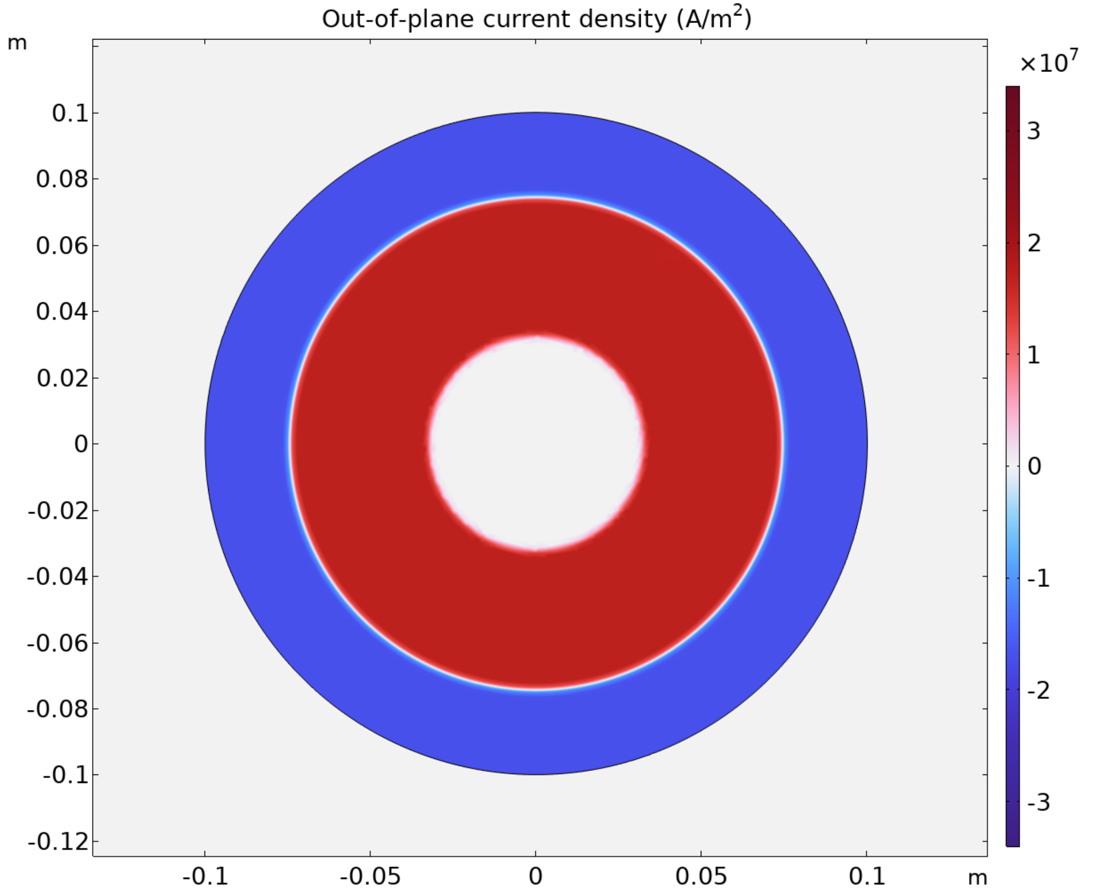


Toy model: round wire

- Settling on 0 applied current

- Nonzero current distribution remains





What makes simulating superconductors challenging?

- Hysteresis effects: time domain simulation required
- Sharp step in current density distribution: small mesh elements required
- Small mesh elements require small timesteps
- Strong non-linearity of $E(J)$ curve

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- Hysteresis effects: time domain simulation required
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- Small mesh elements require small timesteps
- Strong non-linearity of $E(J)$ curve

- Only 2D models or 3D models of small components are workable
- Efficient modelling choices are still required
  - Good understanding of the physics is important to make valid approximations

Application: tokamak fusion reactors

- Increased magnetic field strength improves nuclear fusion efficiency massively
- High-temperature superconductors can operate in larger magnetic fields than low-temperature superconductors
- Nuclear fusion projects have caused demand for high-temperature superconducting material in large quantities

- High-temperature superconductor is manufactured as a thin layer deposited on long tapes
- Many of these tapes are stacked to form the wires

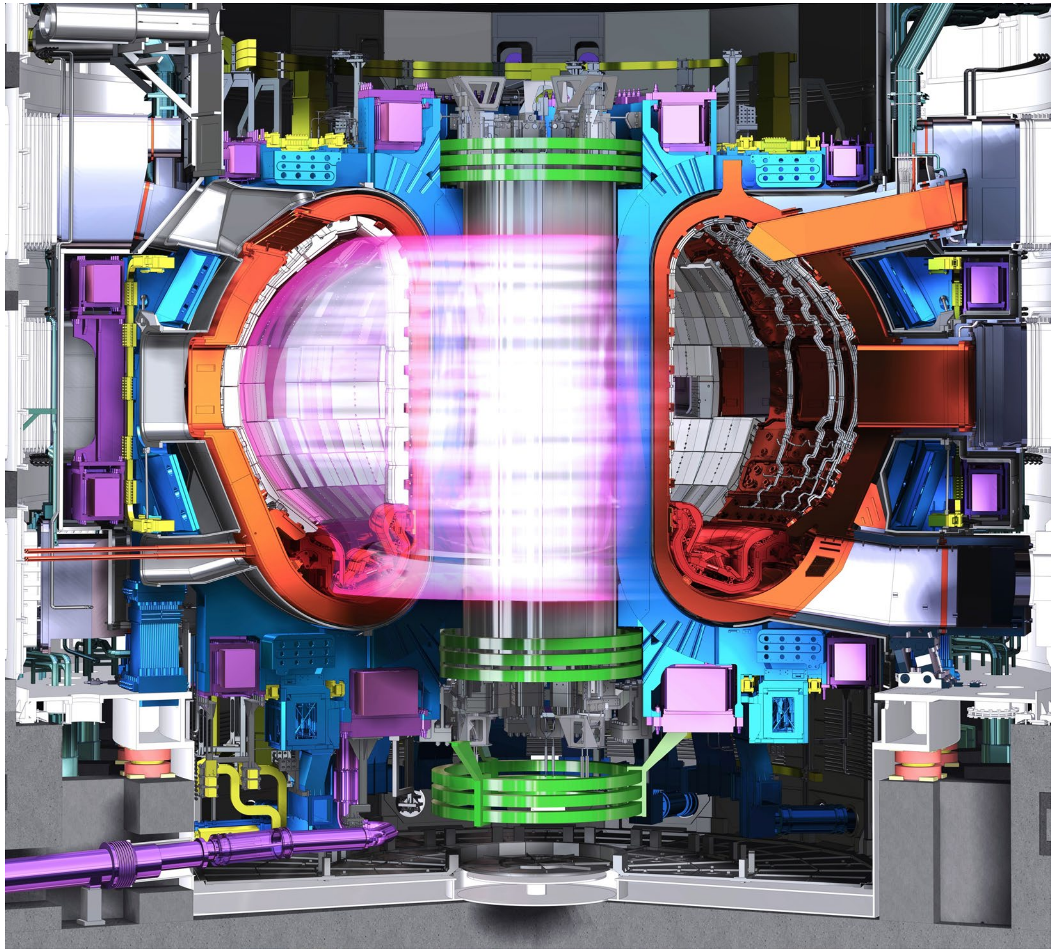

Image courtesy: ITER

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- We are working on AC losses modelling for the STEP fusion reactor
- I'll focus on its central solenoid coil now

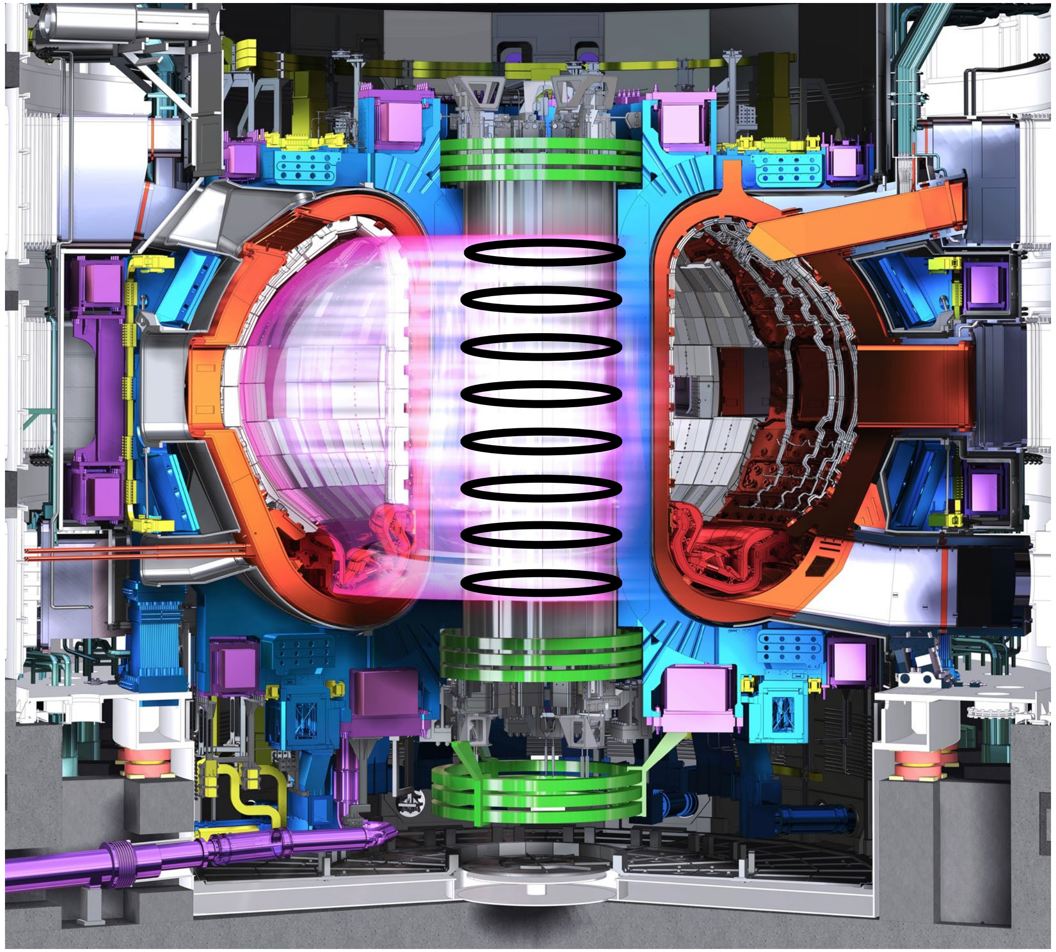


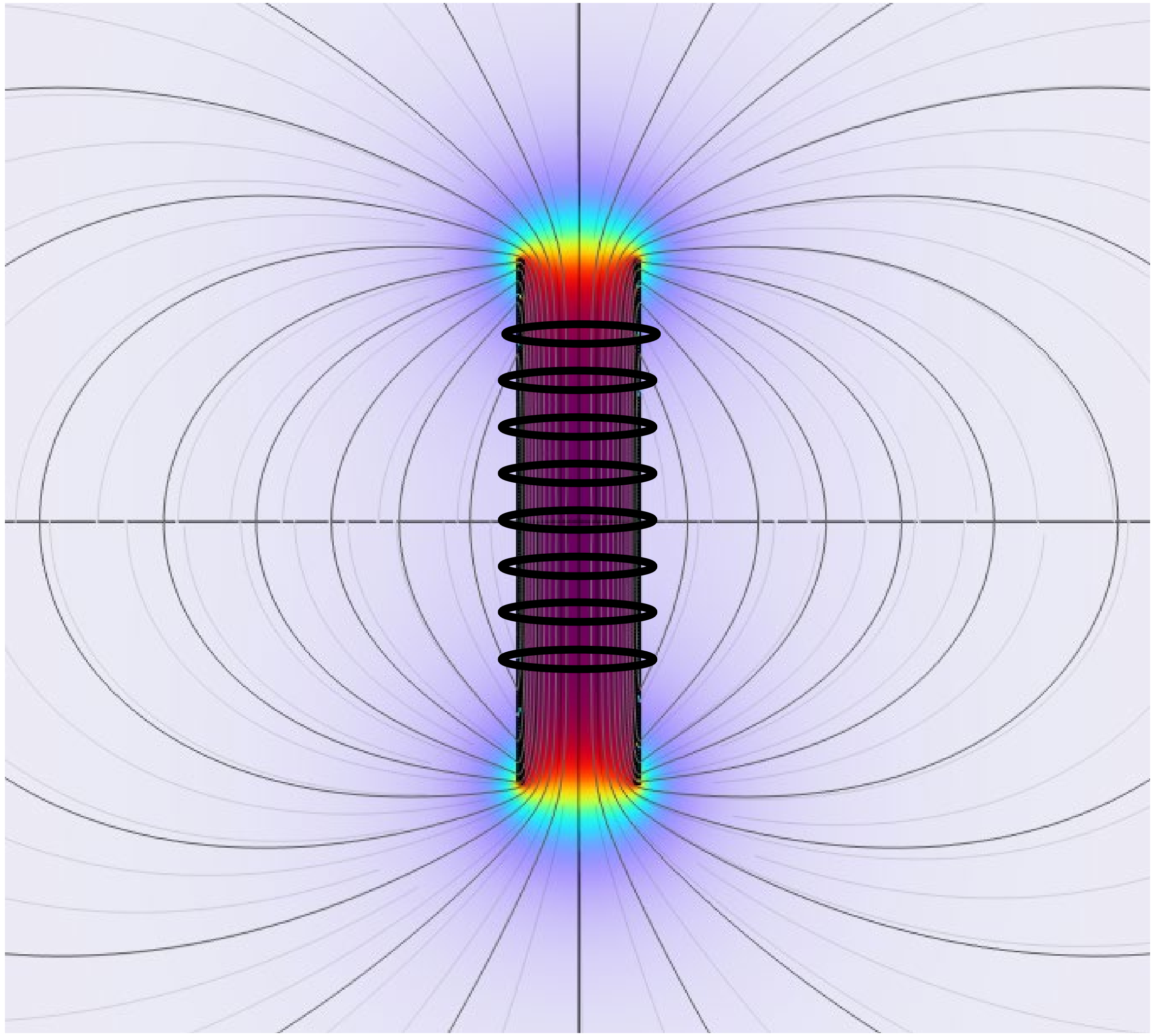
Image courtesy: ITER

Central solenoid coil

Purpose:

- Changing the current accelerates the ions in the plasma

Magnetic field strength



Central solenoid coil

Purpose:

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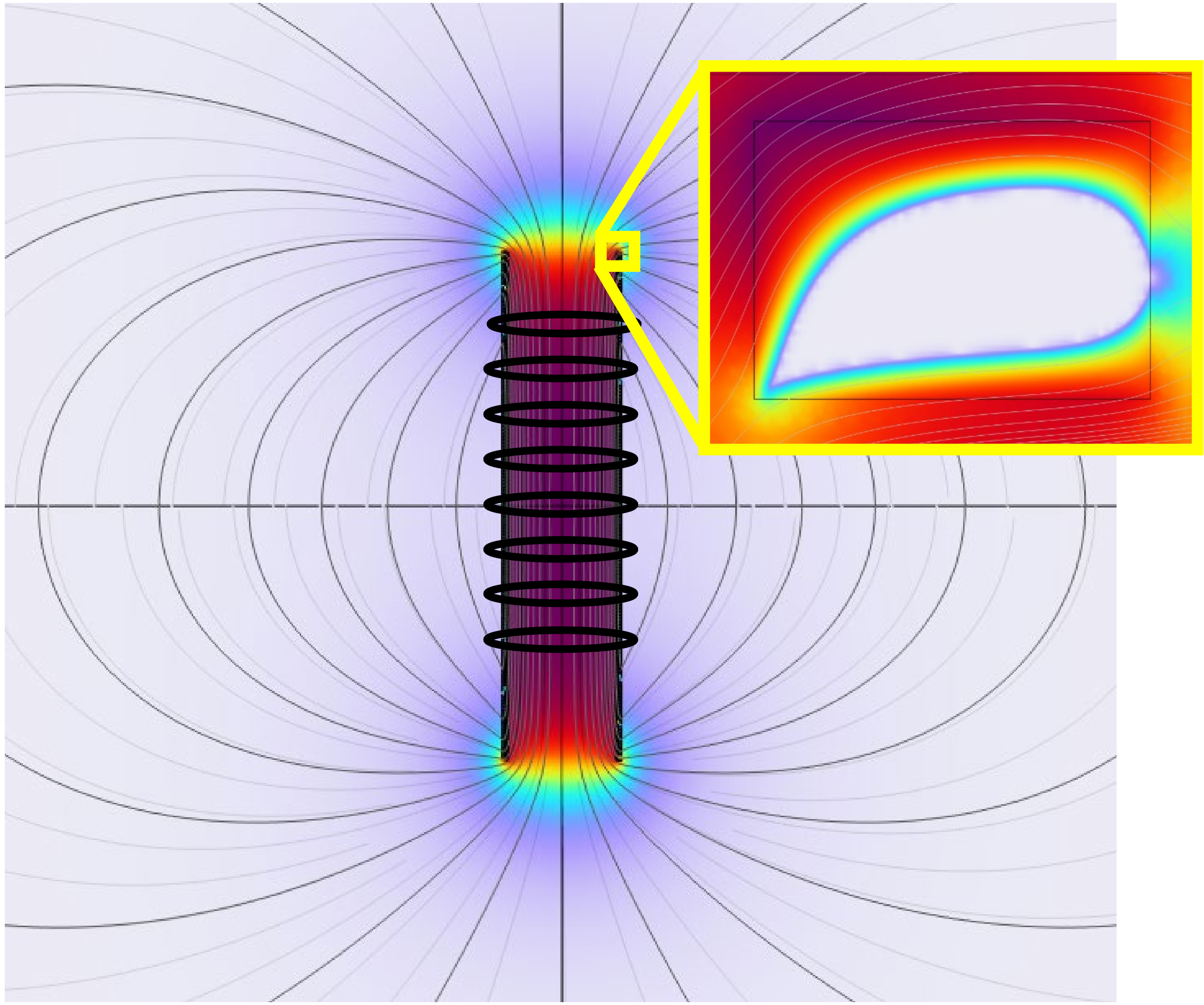
Behavior of superconductor:

- Skin effect attempts to keep the magnetic field out of the individual wires

Magnetic field strength



Central solenoid coil

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Behavior of superconductor:

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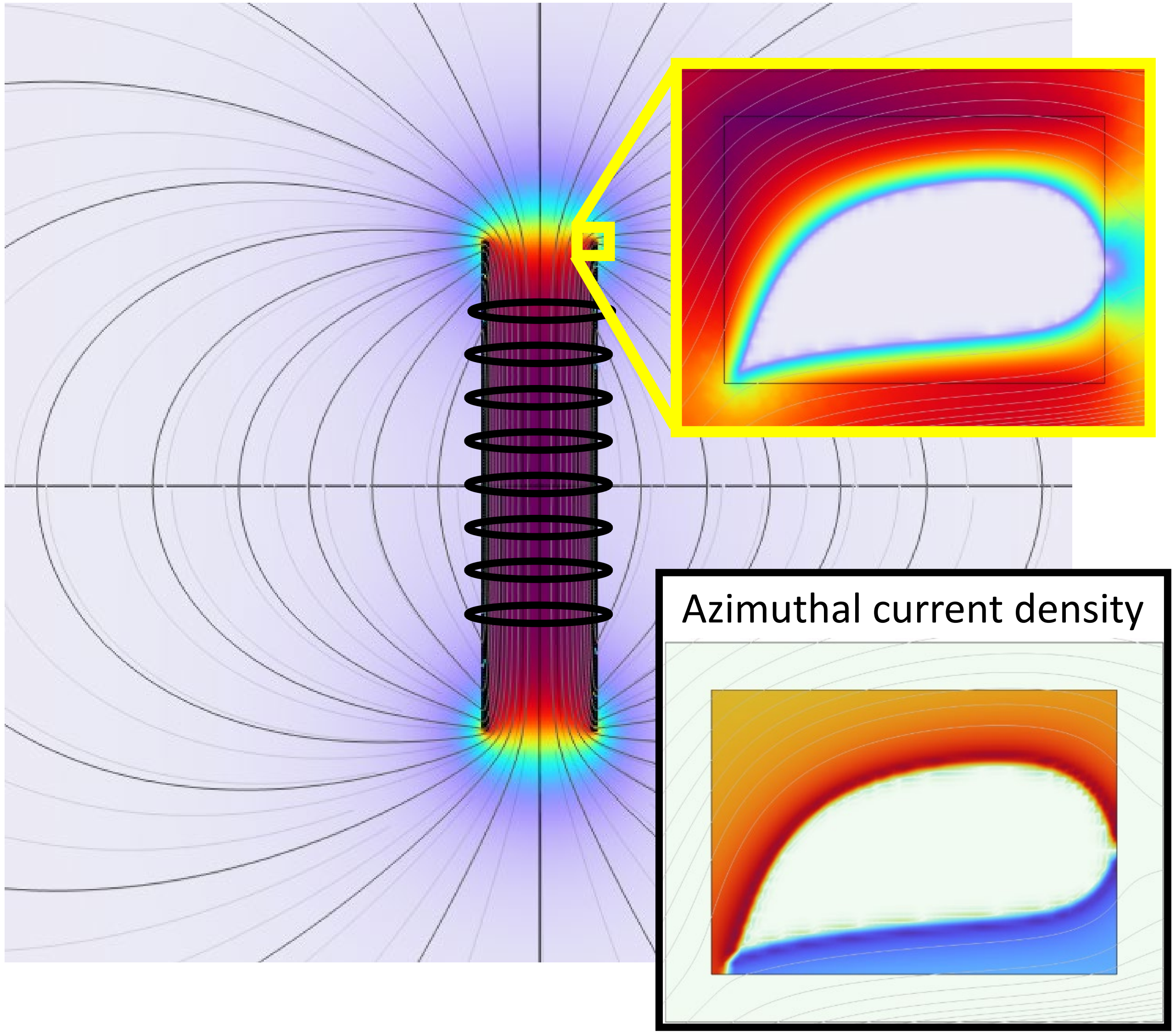
- We see regions with positive, zero and negative azimuthal current density
- Nontrivial superconductor losses when ramping

Magnetic field strength



Central solenoid coil

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- Changing the current accelerates the ions in the plasma

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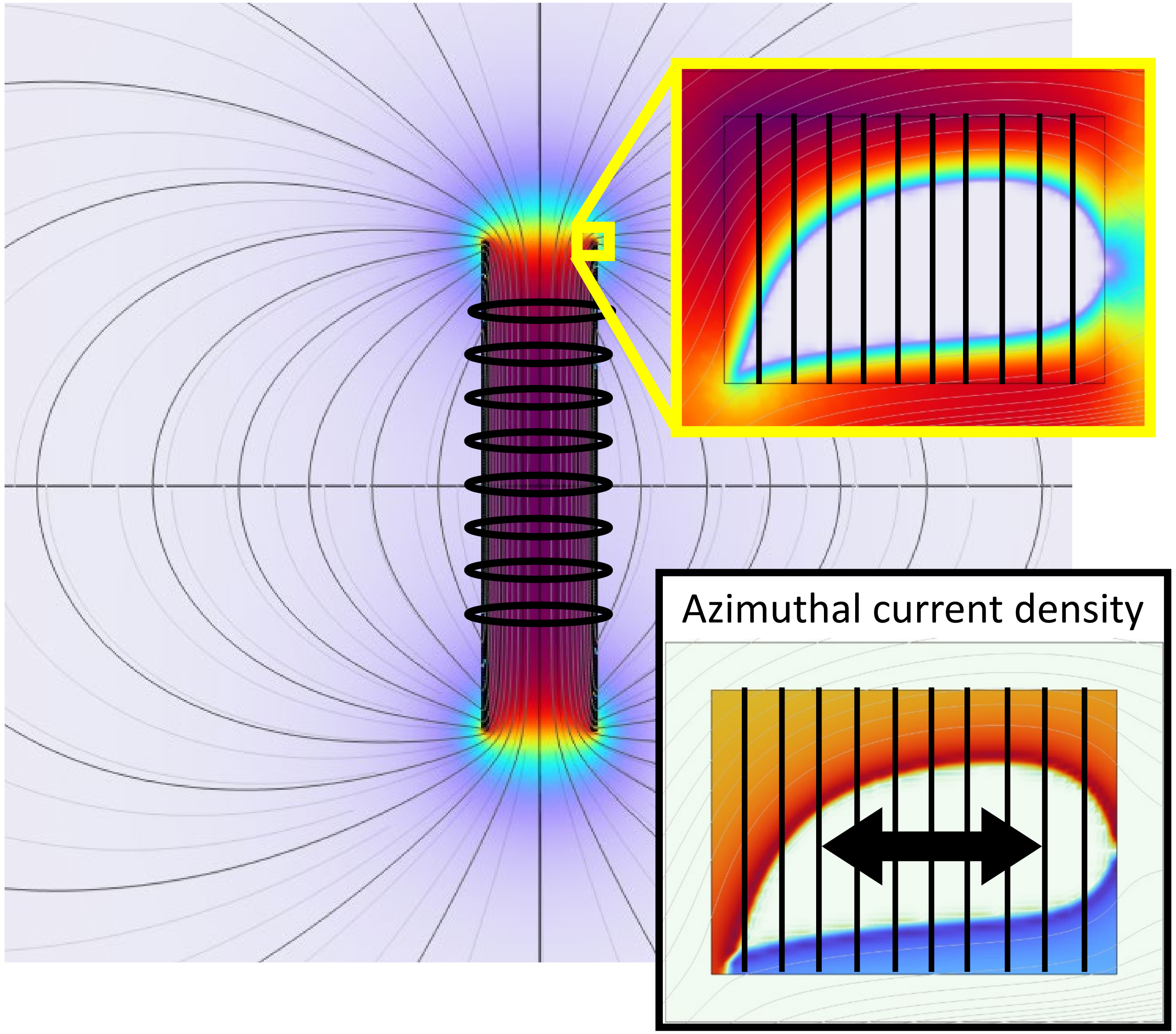
- We see regions with positive, zero and negative azimuthal current density
- Nontrivial superconductor losses when ramping
- Current flowing between the various tapes within the wire gives additional losses

Magnetic field strength

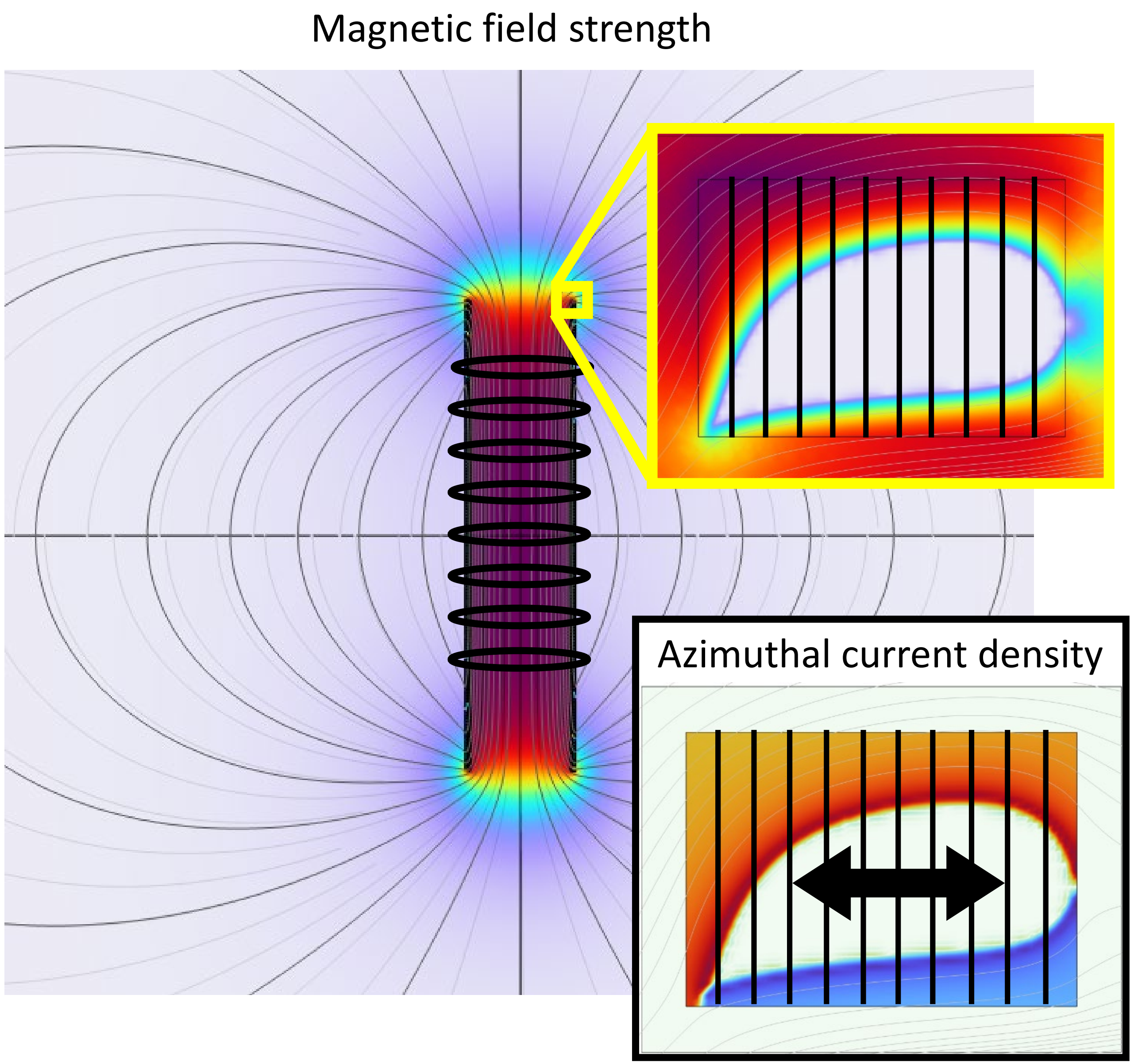


Central solenoid coil

Some used approximations:

- 2D axisymmetric model
- Tape stack is homogenized
- Current flowing between the adjacent tapes modelled approximately

- Such approximations reduce the problem to a manageable complexity



Summary

- High-temperature superconductors are increasingly mature, commercial technology
- Simulating high-temperature superconductors is possible, but remains challenging
- Requires custom models
  - Using specialized physics equations
  - Using carefully chosen approximations

- Contact: koen.de.mare@demcon.com