T11.00009

Axisymmetric Bubble Growth and Detachment Subject to Inhomogeneous Magnetic Fields in Microgravity

Álvaro Romero-Calvo
Graduate Research Assistant
Rafael del Pino Fellow
alvaro.romerocalvo@colorado.edu

Miguel Herrada
Professor
Universidad de Sevilla

Gabriel Cano-Gómez
Associate Professor
Universidad de Sevilla

Hanspeter Schaub
Professor
Glenn L. Murphy Chair in Engineering

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Ann and H. J. Smead Aerospace Engineering Sciences Department
University of Colorado, **Boulder**


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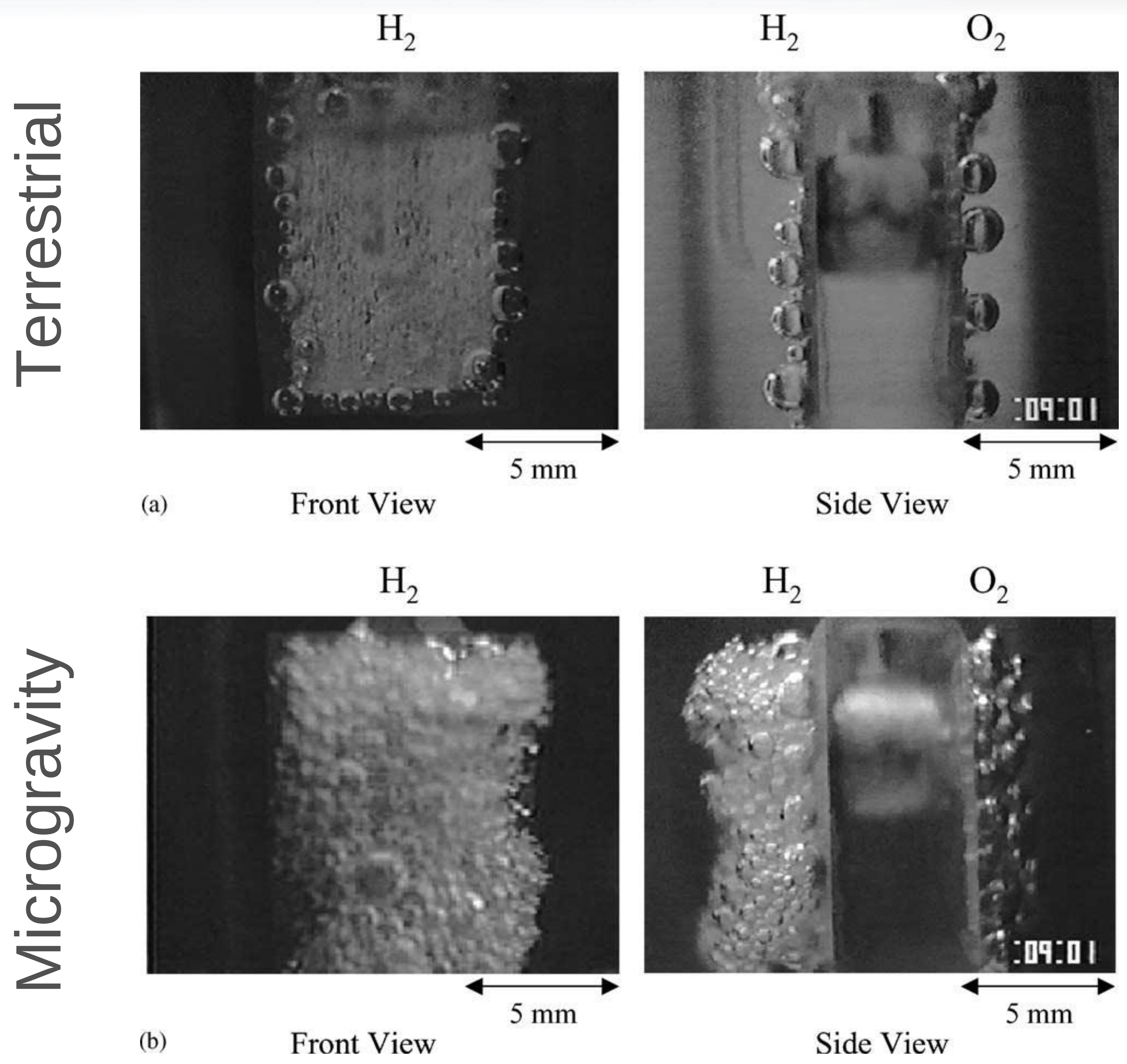
MF430

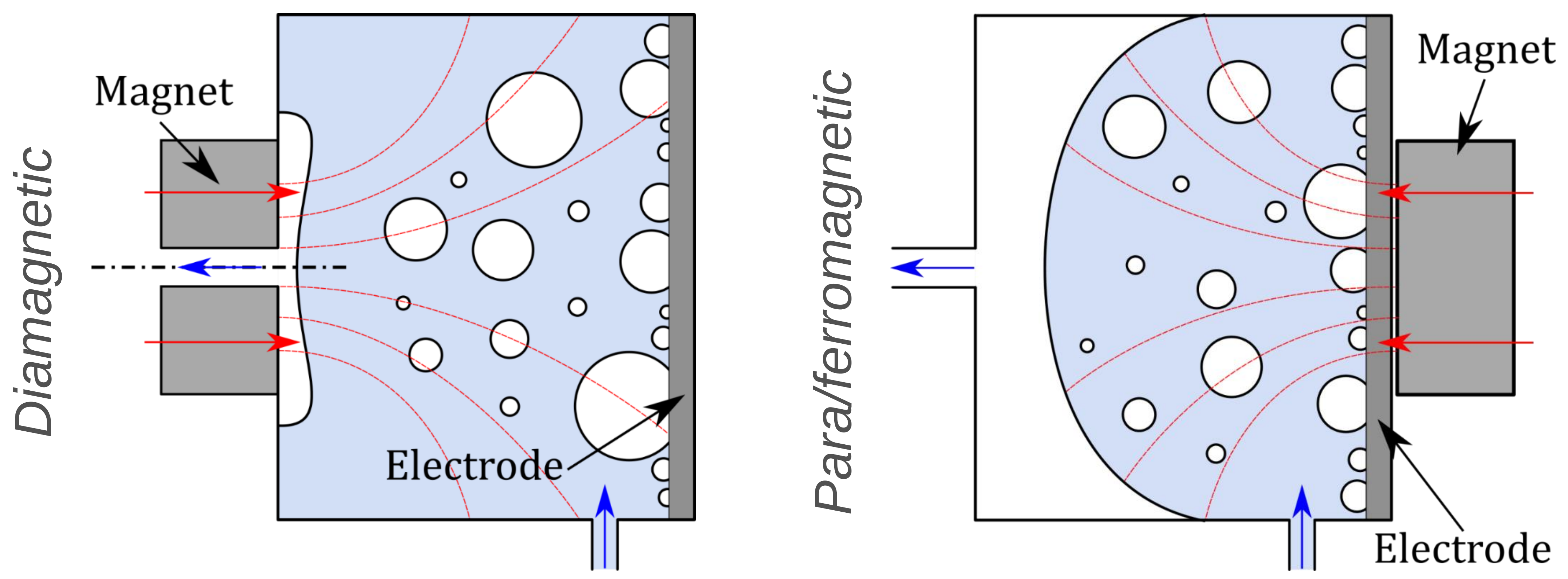
Motivation

Bubble generation



H. Matsushima et al., Water electrolysis under microgravity. Part 1. Experimental technique, Electrochimica Acta (48), 4119-4125, 2003

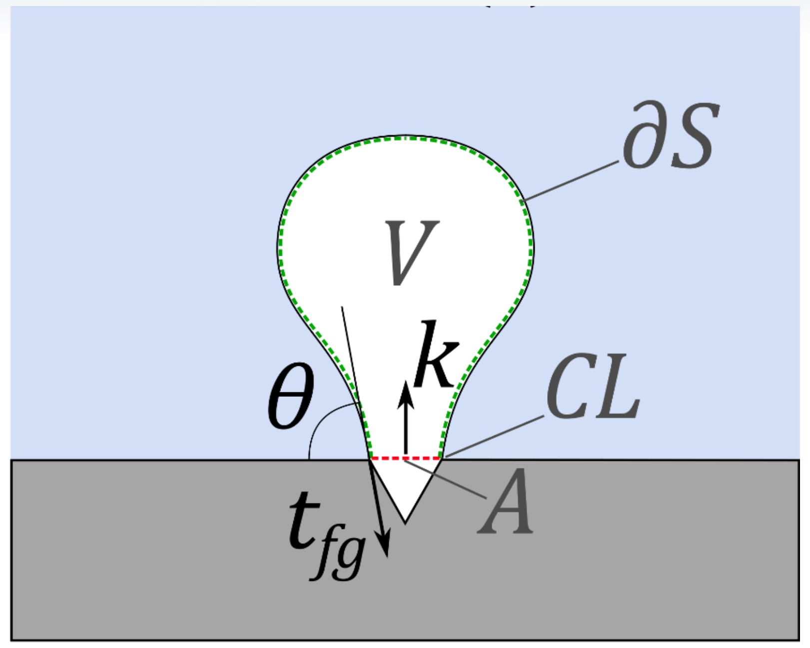
Magnetic phase separation



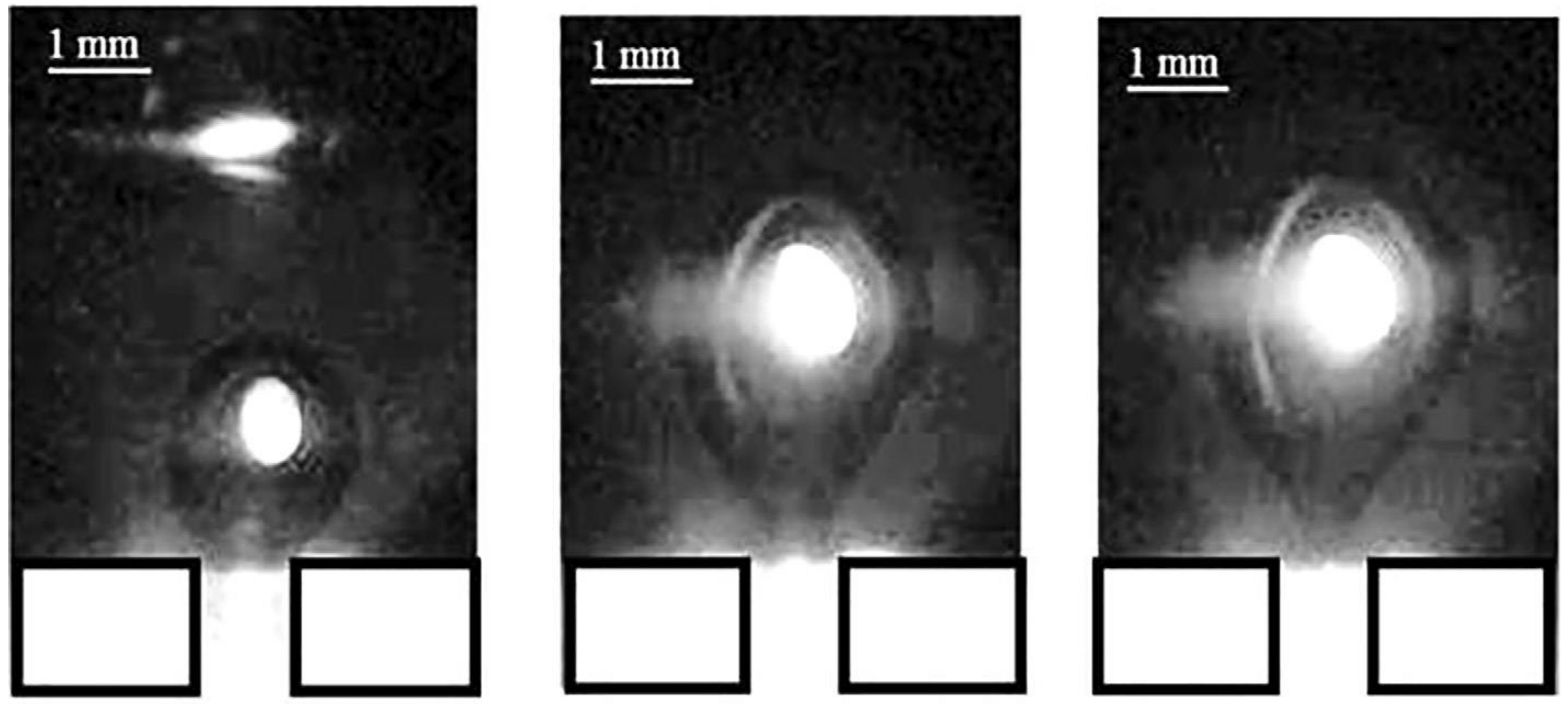
Á. Romero-Calvo et al., Magnetically enhanced electrolysis and phase separation in low-gravity, Journal of Spacecraft and Rockets, under review

- Bubble departure diameter?
- Interface shape?
- Natural oscillation frequencies?

Magnetic bubble dynamics in microgravity



Á. Romero-Calvo et al., Magnetically enhanced electrolysis and phase separation in low-gravity, Journal of Spacecraft and Rockets, under review



$t = 0.010$ s $t = 0.020$ s $t = 0.021$ s

H. Yamasaki et al., Dynamic behavior of gas bubble detached from single orifice in magnetic fluid, Journal of Magnetism and Magnetic Materials (501), 166446, 2020

Coupled fluid-magnetic problem

Incompressible Navier-Stokes Eqs.

$$\nabla \cdot \boldsymbol{v} = 0,$$

$$\rho \frac{D\boldsymbol{v}}{Dt} = \rho \boldsymbol{g} + \boldsymbol{f}_p + \boldsymbol{f}_\nu + \boldsymbol{f}_m,$$

Viscous term Magnetic term

Steady-State Maxwell Eqs.

$$\nabla \cdot \boldsymbol{B} = 0,$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}_e,$$

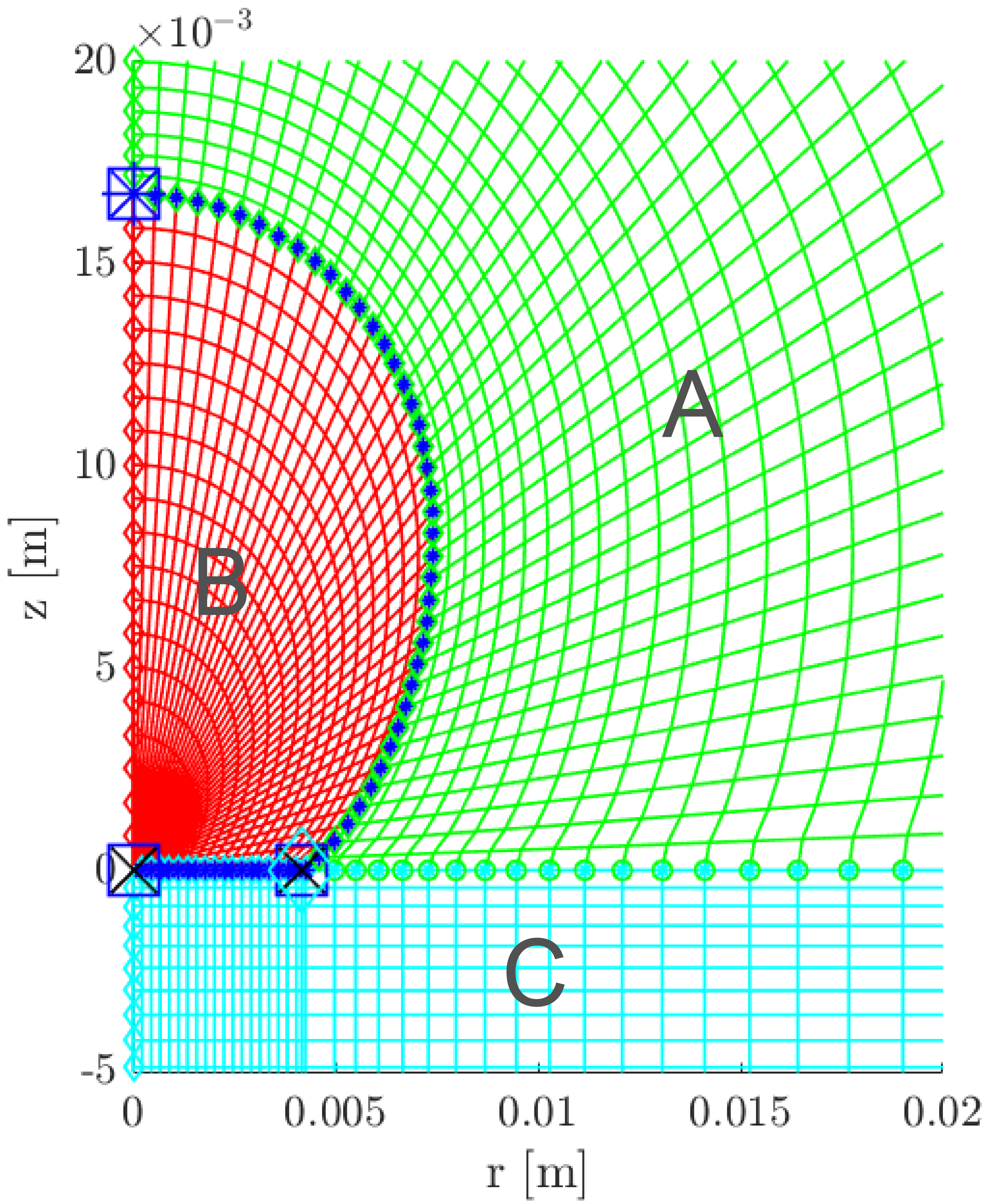
+BCs

Liquid position determines magnetic solution

Need for **coupled** fluid-magnetic simulations

Coupled magnetohydrodynamic model

A: Bubble, B: Ferrofluid, C: Solid



- **Axisymmetric** geometry, loads, and BCs
- Simulation domain divided into **3 regions**:
  - Quasi-elliptical mappings in A and B
  - Analytical mapping in C
  - 2nd order finite differences
  - **Takes advantage of ψ uncoupling!**
- The discretized system is solved with a **monolithic**, **fully implicit,** Newton-Raphson approach in a **single time step**
- **Outcomes:**
  - Bubble interface
  - Departure volume
  - Stability properties & natural oscillations
  - Time-dependent simulation

Governing equations

Navier-Stokes equations (fluid domains)

Mass balance

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rw)}{\partial r} = 0,$$

Momentum balance (r)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p^*}{\partial r} + \eta\left(\frac{\partial^2 u}{\partial r^2} + \frac{\partial(u/r)}{\partial r} + \frac{\partial^2 u}{\partial z^2}\right) + \mu_0\left(M_r\frac{\partial H_r}{\partial r} + M_z\frac{\partial H_r}{\partial z}\right),$$

Momentum balance (z)

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p^*}{\partial z} + \eta\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) + \mu_0\left(M_r\frac{\partial H_z}{\partial r} + M_z\frac{\partial H_z}{\partial z}\right),$$

Static Maxwell equations (all domains)

$$\nabla\cdot\boldsymbol{H} = -\nabla\cdot\boldsymbol{M},$$
$$\nabla\times\boldsymbol{H} = \boldsymbol{J}_e.$$

$$H_r = -\frac{1}{r}\frac{\partial\Psi}{\partial z} - \frac{\partial\Phi}{\partial r}$$
$$H_z = \frac{1}{r}\frac{\partial\Psi}{\partial r} - \frac{\partial\Phi}{\partial z}$$

$$\nabla\cdot\boldsymbol{H} = -\left[\frac{\partial^2\Phi}{\partial z^2} + \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r}\right]$$

$$\nabla\times\boldsymbol{H} = -\frac{1}{r}\left[\frac{\partial^2\Psi}{\partial r^2} + \frac{\partial^2\Psi}{\partial z^2} - \frac{1}{r}\frac{\partial\Psi}{\partial r}\right]\boldsymbol{u}_\phi$$

For fluid domain

$$\frac{\partial^2\Phi}{\partial z^2} + \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} = \frac{1}{1+\chi^{\text{vol}}(H)}\left(H_r\frac{\partial\chi^{\text{vol}}}{\partial r} + H_z\frac{\partial\chi^{\text{vol}}}{\partial z}\right),$$

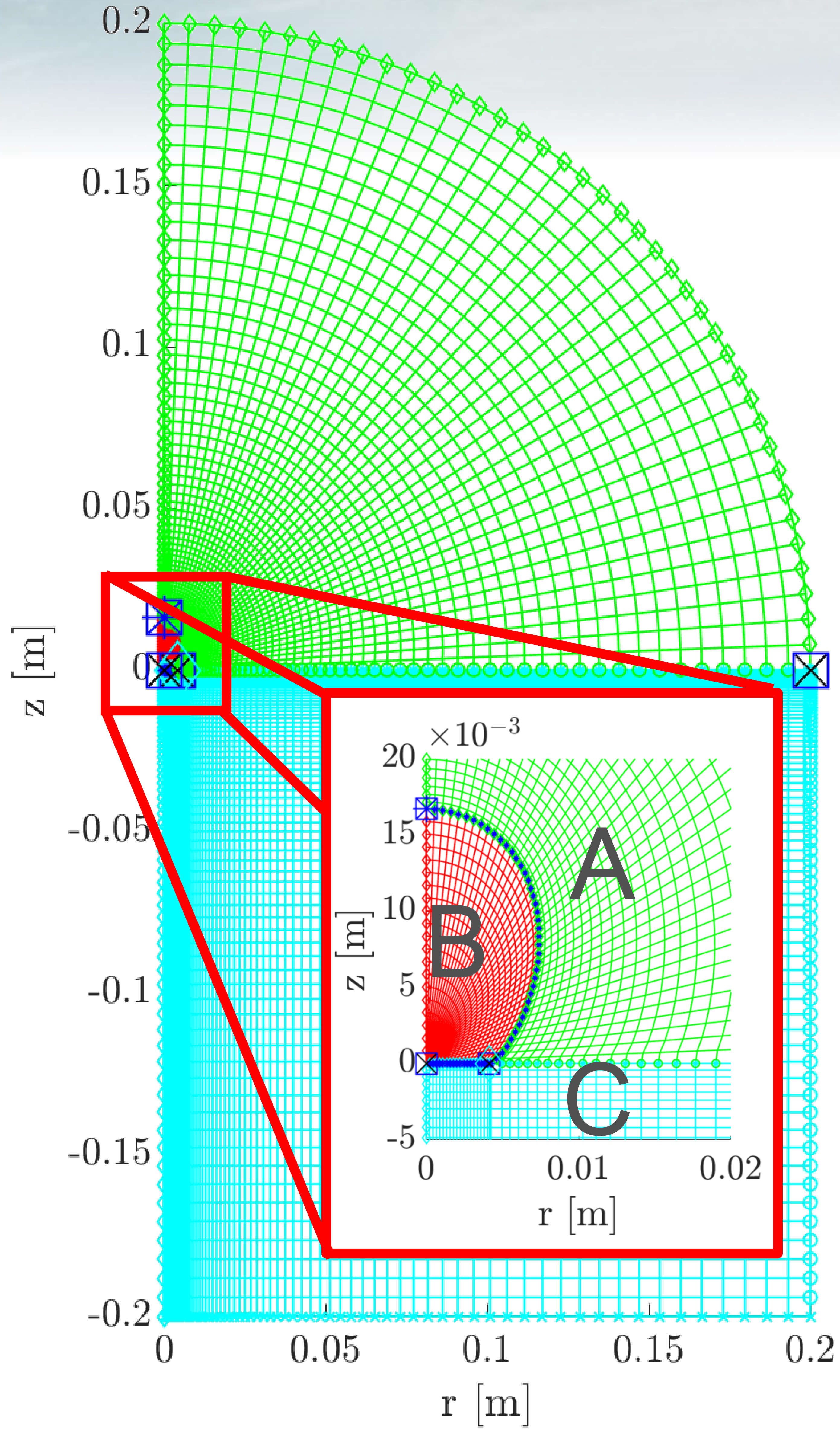
Constitutive Relation

$$\chi^{\text{vol}} = a_M\frac{\arctan(c_M H)}{H} + b_M\frac{\arctan(d_M H)}{H} + e_M$$

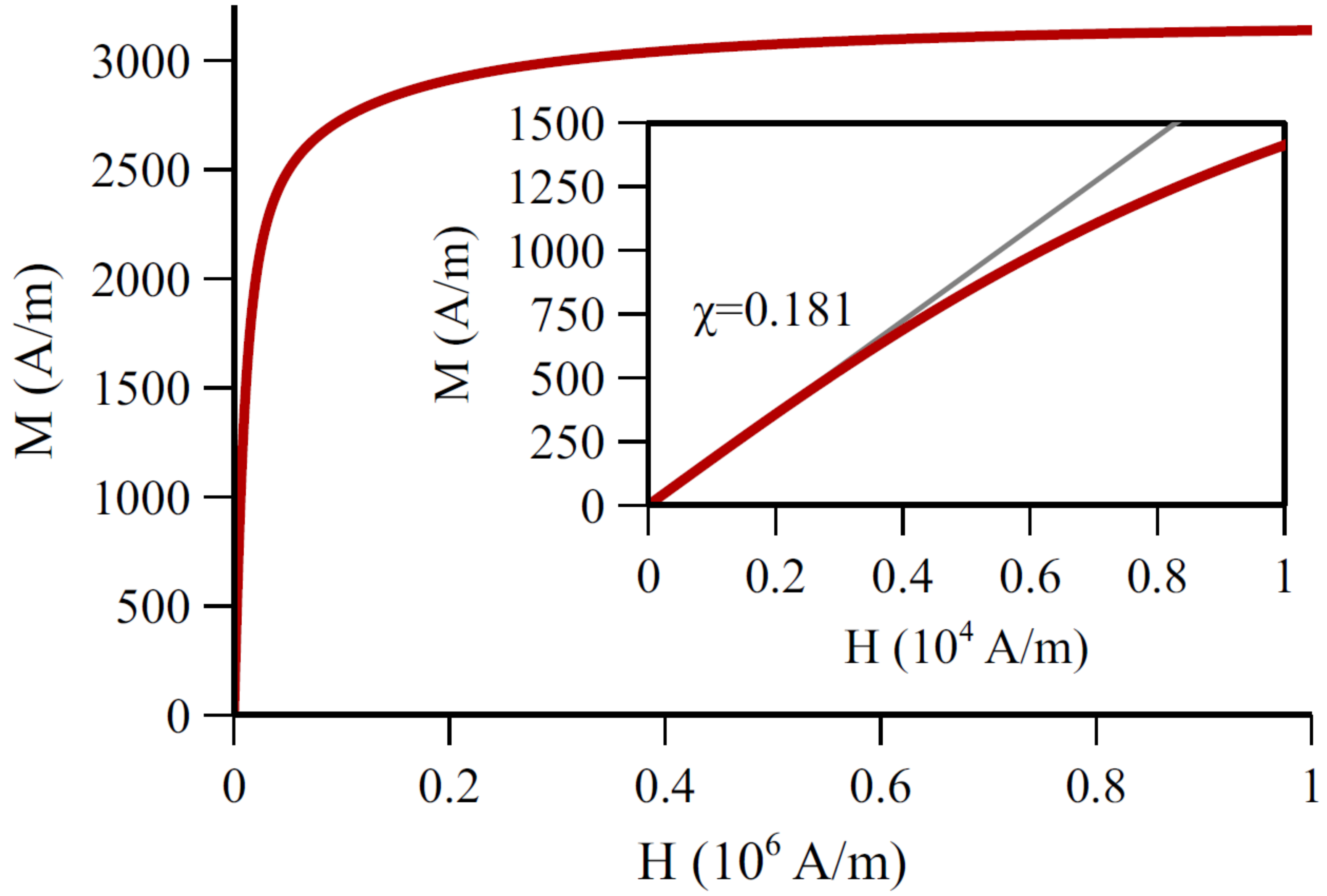
ψ is uncoupled!!

Romero-Calvo Á et al., "Coupled Monolithic Magnetohydrodynamic Model for Axisymmetric Multiphase Flows", Journal of Computational Physics, *under review*

Configuration



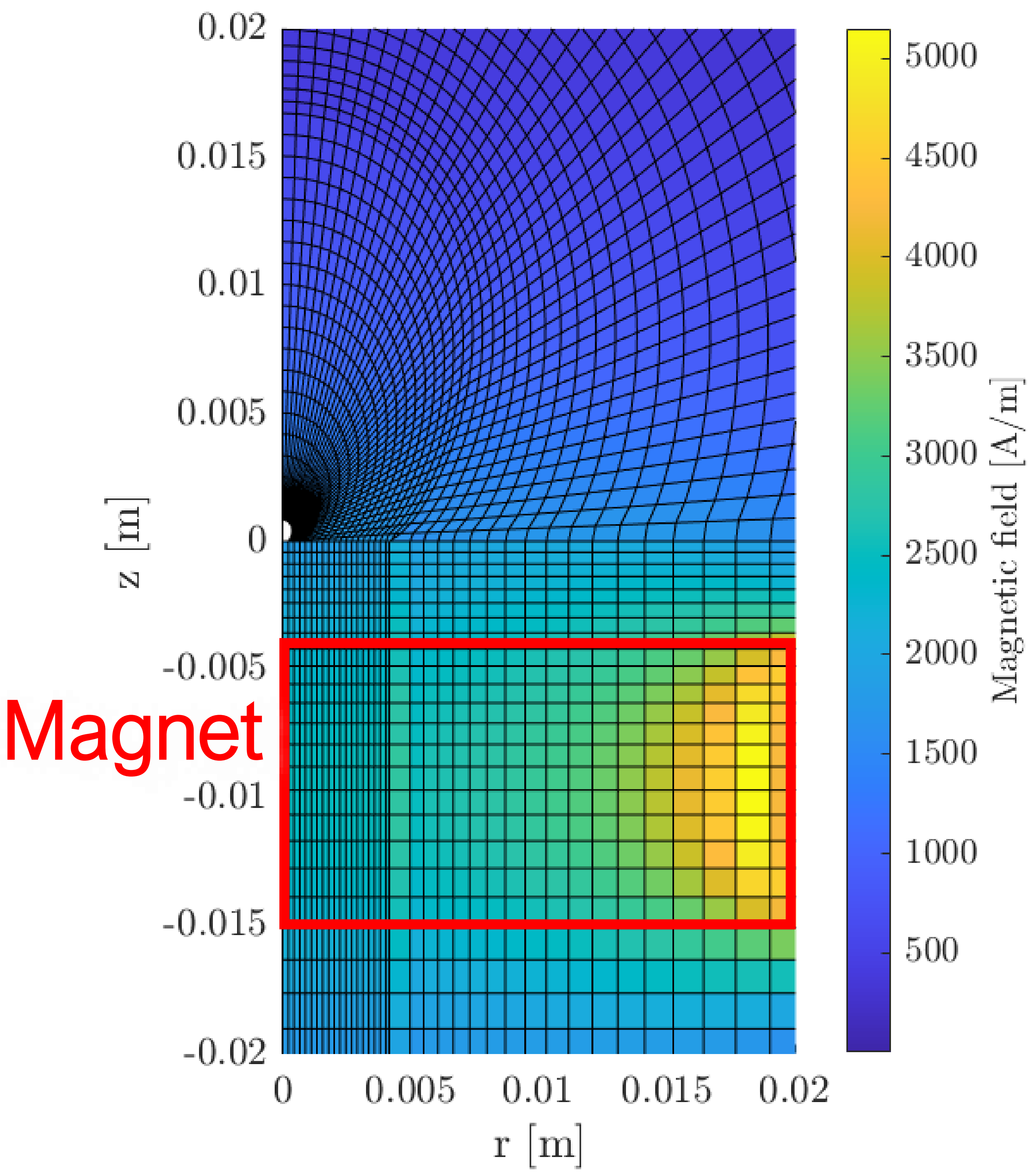
- Materials:
  - 2.1 cm^3 non-pinned **air bubble**
    - $\rho = 1.225\ \mathrm{kg/m^3}$, $\eta = 1.81 \cdot 10^{-2}\ \mathrm{mPa \cdot s}$
    - Variable contact angle θ_c, $\sigma = 62.4\ \mathrm{mN/m}$
  - 1:10 vol EMG-700 **water-based ferrofluid**
    - $\rho = 1012\ \mathrm{kg/m^3}$, $\eta = 1.445\ \mathrm{mPa \cdot s}$
    - Magnetization curve
  - **Virtual magnet** in C



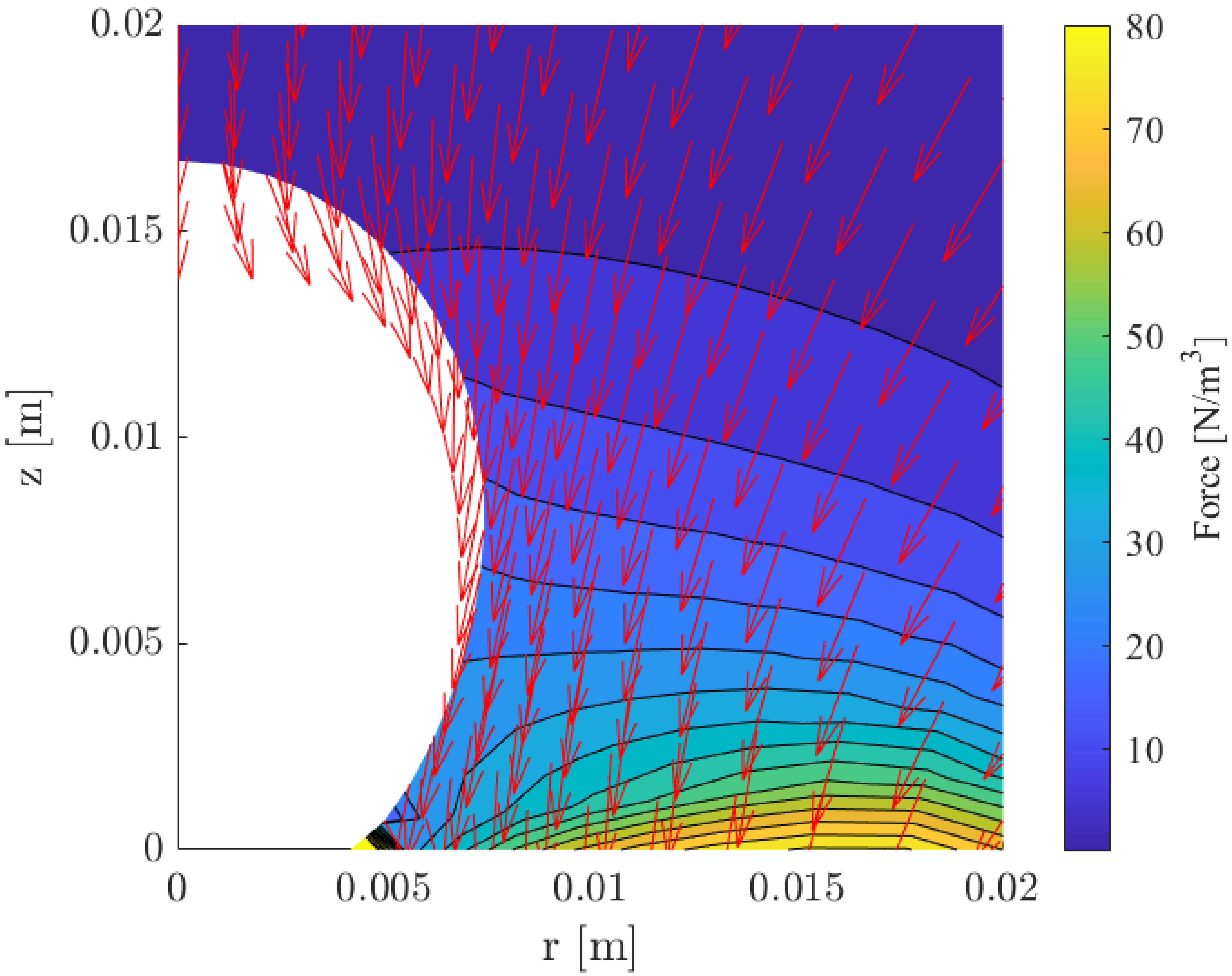
- Boundary conditions:
  - **Magnetic**: Insulation in external contours, continuity A-C, B-C, partial continuity A-B, axisymmetry in axis
  - **Fluids**: Non-penetration & zero-velocity in external contour, A-C, and B-C, normal & tangential ferrohydrodynamic balances in A-B, axisymmetry in axis.
  - **Solid (C)**: Moving nodes, employed only for magnetic BCs

Magnetic field & force (M=10 kA/m)

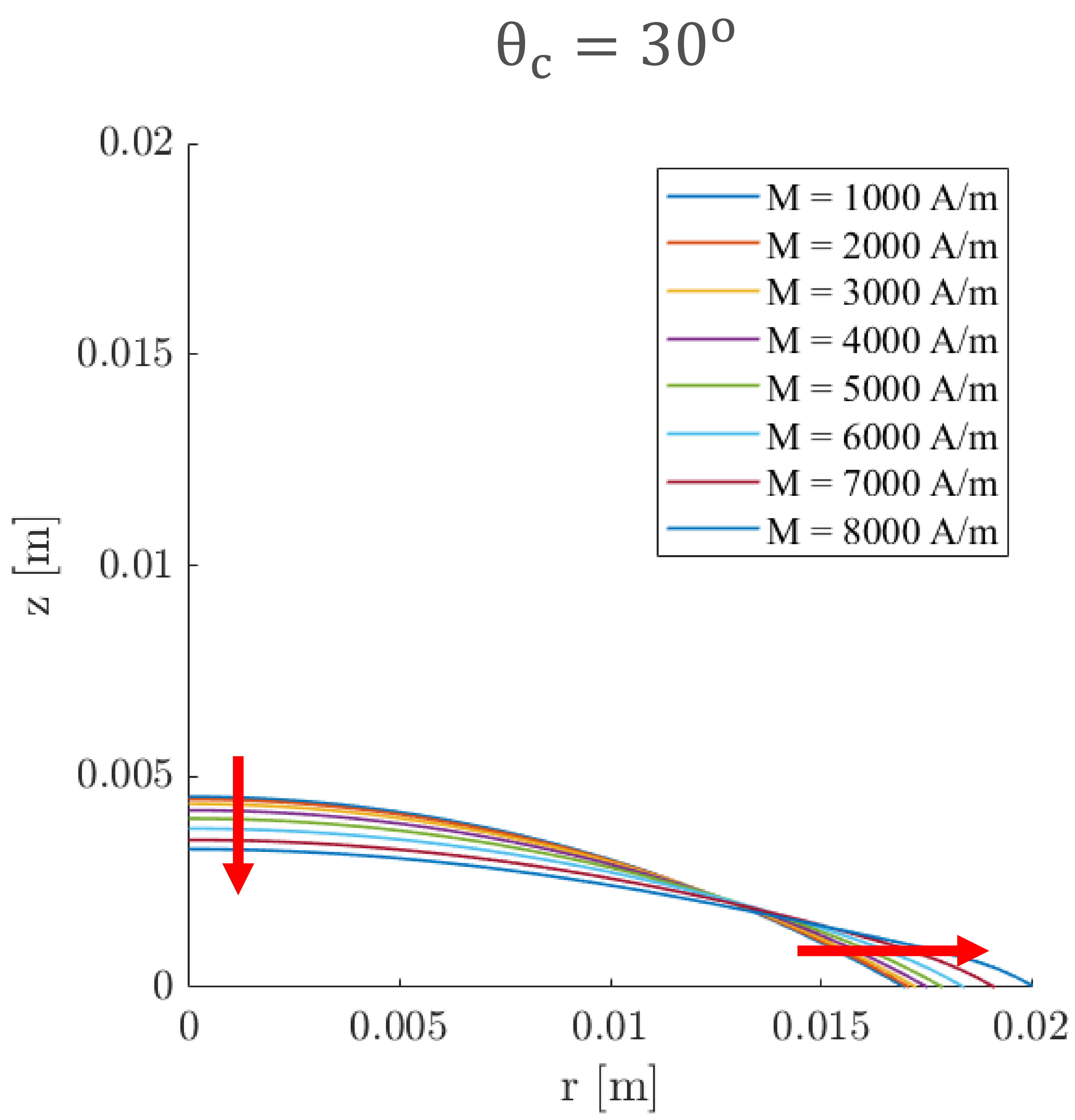
Magnetic field

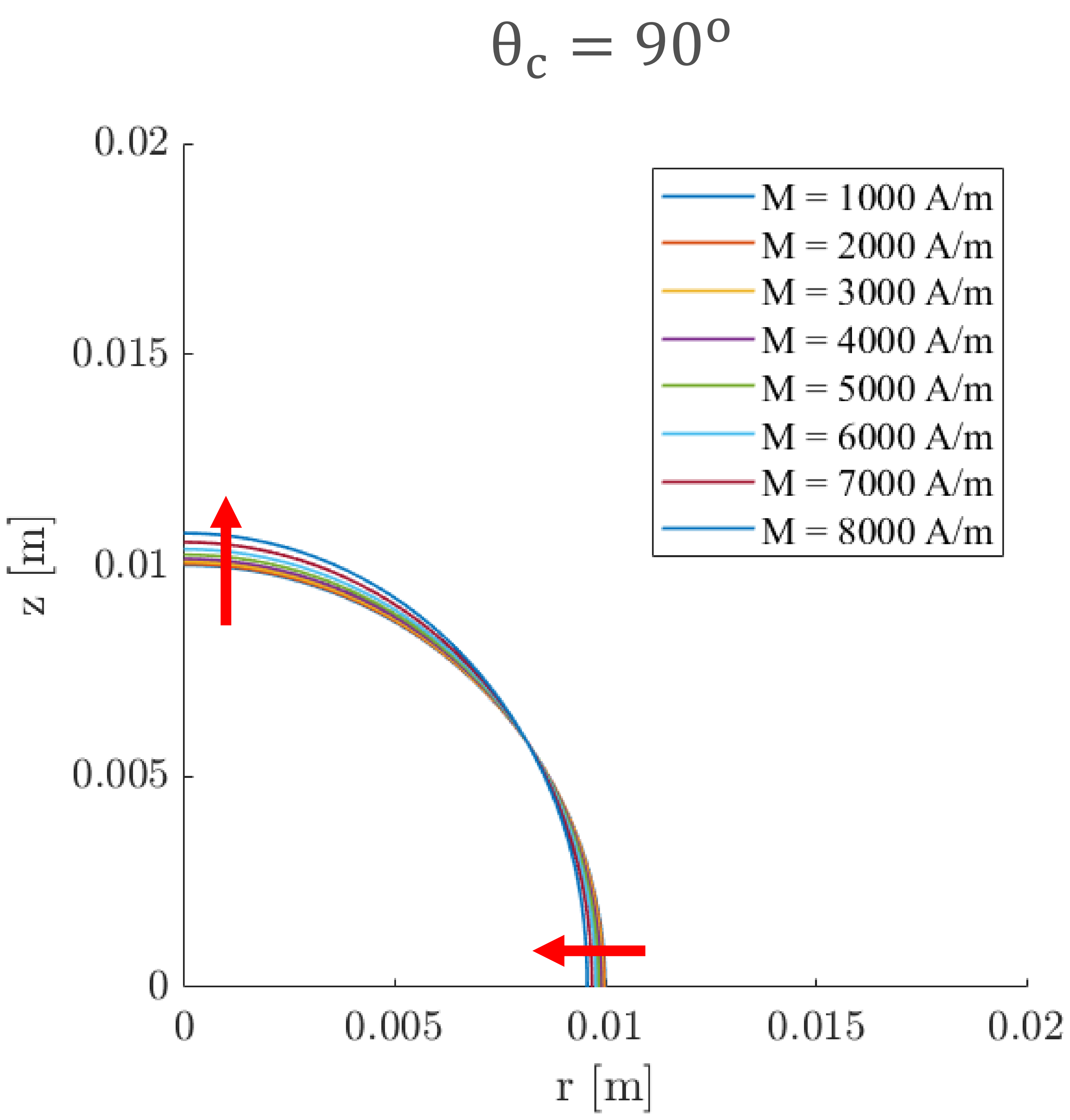


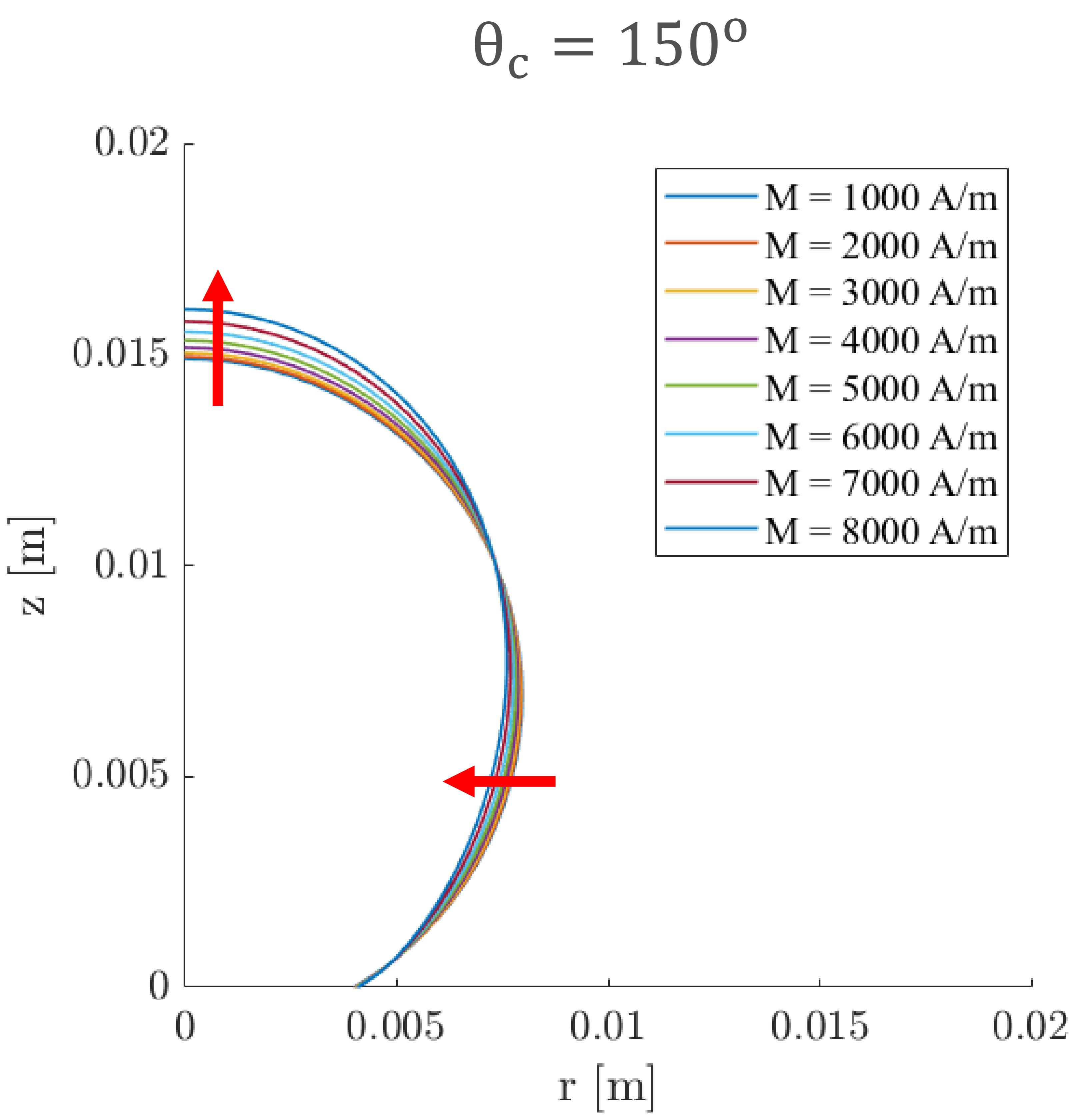
Magnetic force



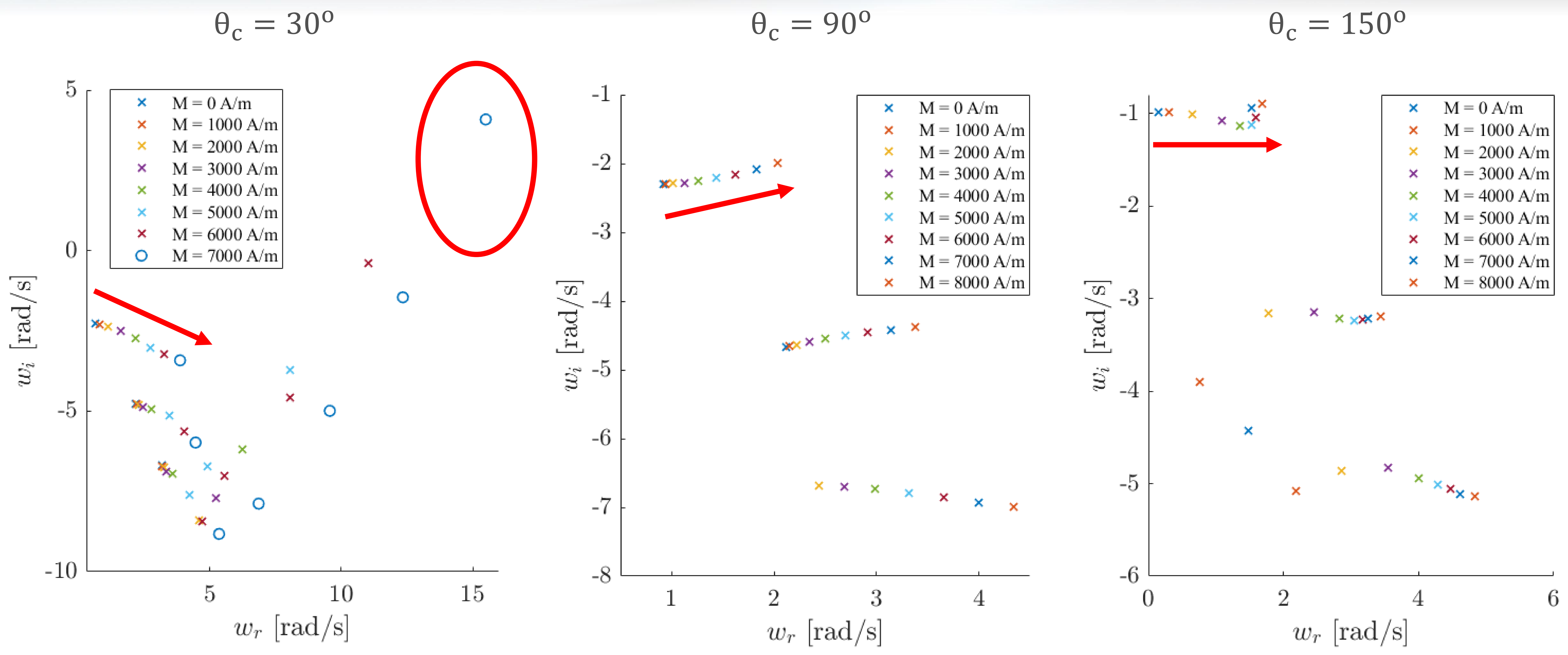
Equilibrium interface





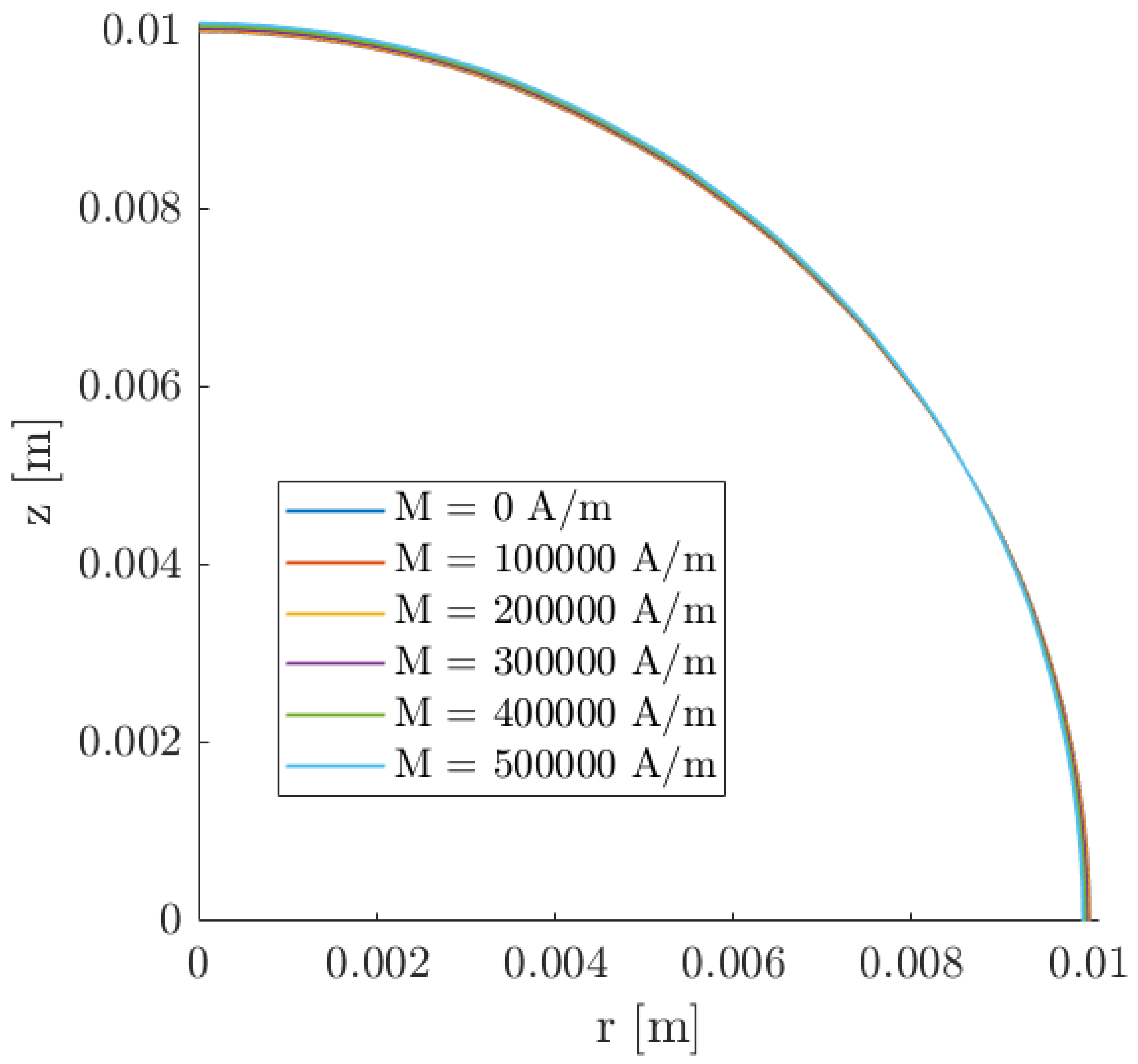


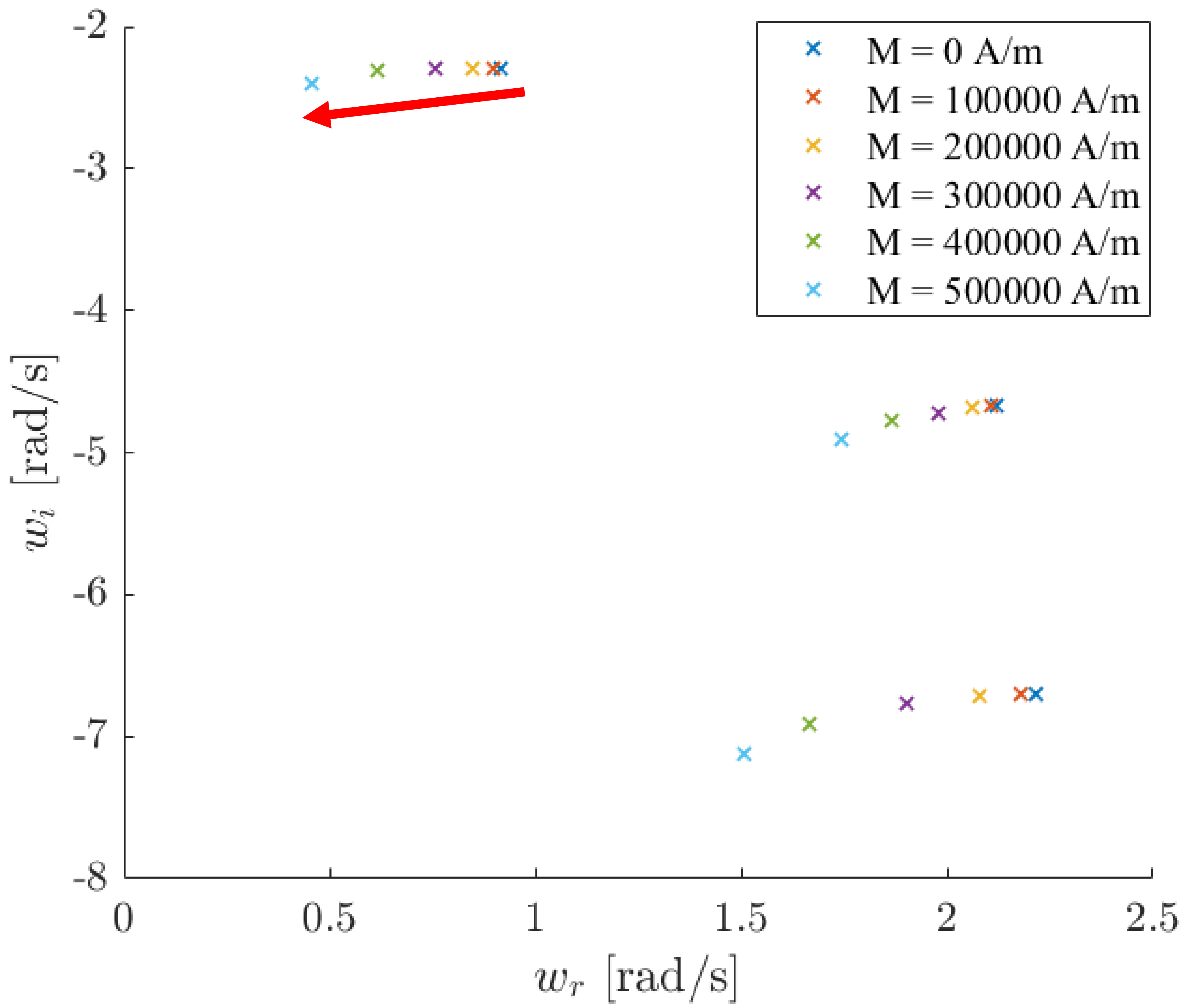
Complex frequencies



DI water

Diamagnetic liquid with $\chi = -9.04 \cdot 10^{-6}$





Questions…?

alvaro.romerocalvo@colorado.edu
linkedin.com/in/alvaroromerocalvo/
researchgate.net/profile/Alvaro_Romero-Calvo