Numerical quasi stationary and transient analysis of annular linear electromagnetic induction pump (EMIP)

L.Goldsteins, L.Buligins, Y.Fautrelle, C.Biscarrat.

presented by Linards Goldsteins

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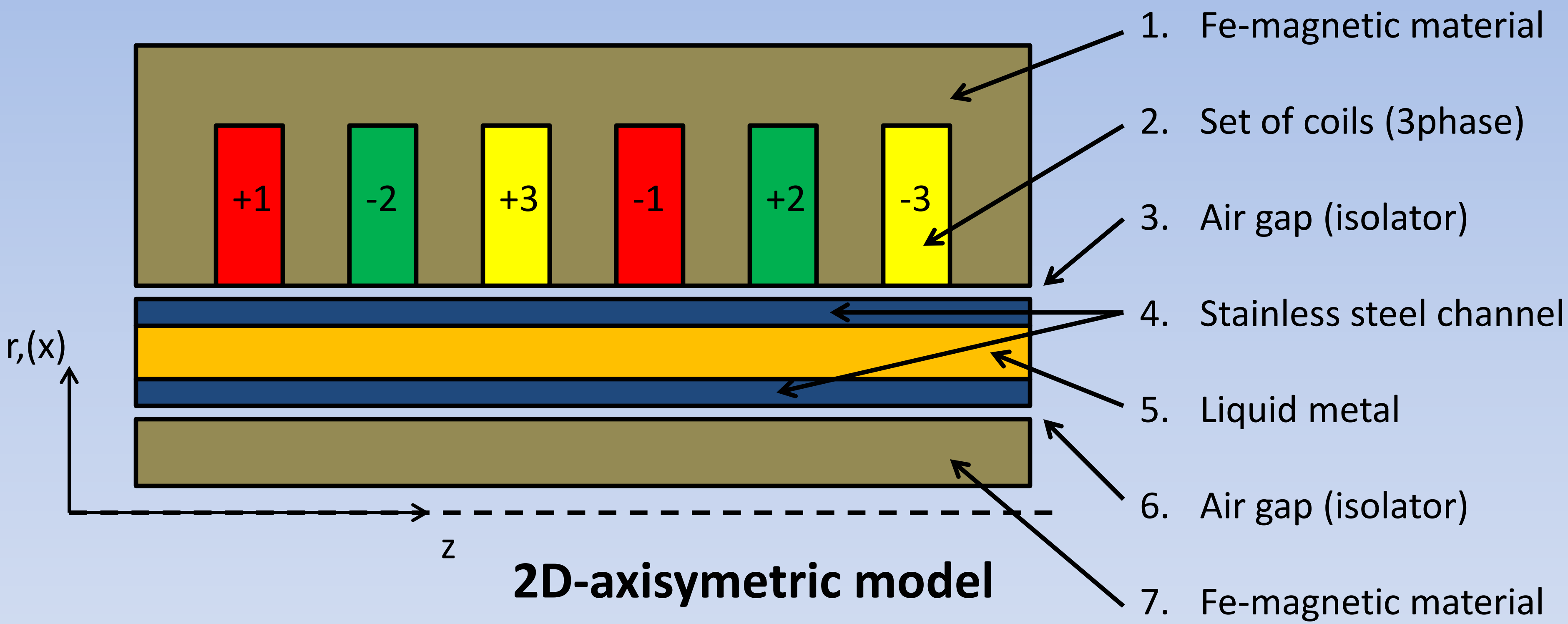
Summary

1. Introduction of EMIP
2. Mathematical formulation of problem
3. Considered geometry
4. Boundary conditions and mesh
5. Four simulation approches
6. Results
7. Conclusion

1. Introduction of EMIP

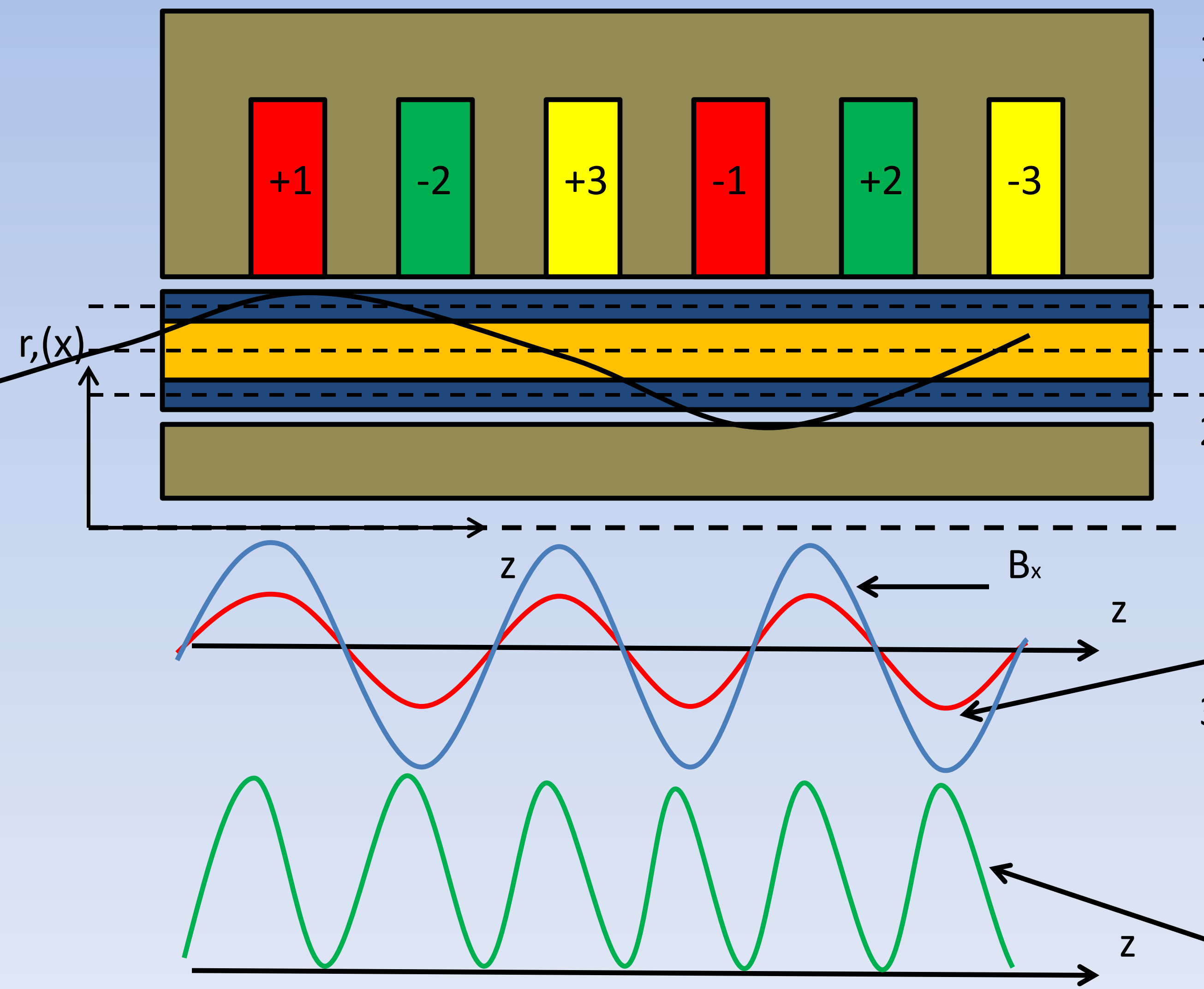


2D-axisymetric model

Such system basically is linear induction motor and therefore works rather similarly.

1. Introduction of EMIP

$$B_x(x,z,t) = B_x(x)\cos(\omega t - \alpha z) = Re\left[B_x(x)e^{i\alpha(v_B t - z)}\right]$$



1. Inductor creates **perpendicular component of magnetic field in form of travelling wave** in the liquid metal...

2. ...magnetic field **induces currents** in the liquid metal...

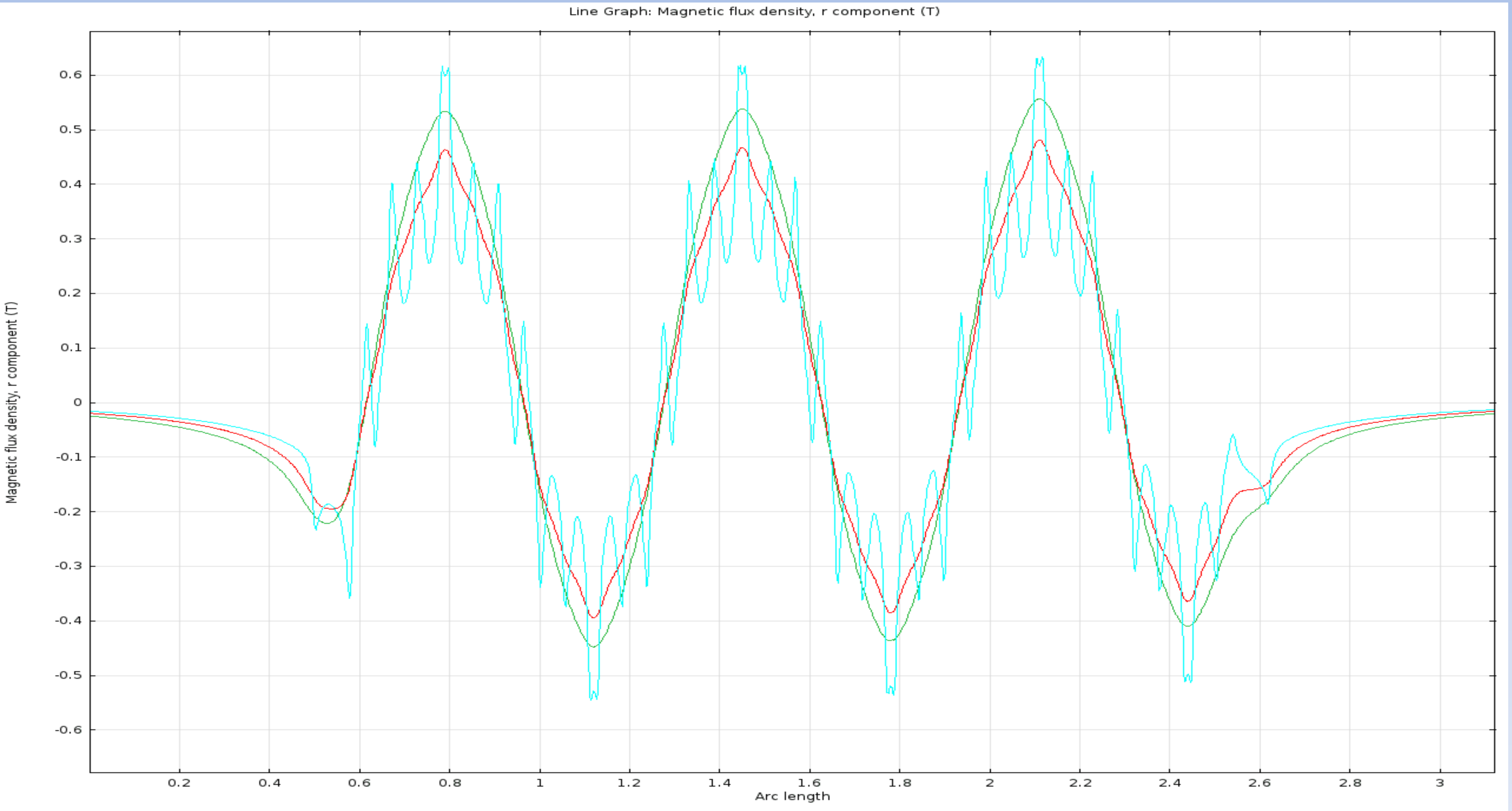
$j_y \sim \sigma(v_B - v_m)\ B_x$

3. **...cross product (j x B) creates EM force** pulsating with double input frequency.

$f_z = j \times B \sim \sigma(v_B - v_m)\ B_x$^2

1. Introduction of EMIP

Example of *real* distribution of **magnetic field perpendicular component**.
The **closer to inductor – the more higher harmonics.**



2. Mathematical formulation of problem

Maxwell equations:

$$\begin{cases} \nabla \boldsymbol{E} = 0 & (1) \\ \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} & (2) \end{cases} ; \qquad \begin{cases} \nabla \boldsymbol{B} = 0 & (3) \\ \nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} & (4) \end{cases} ;$$

Ohms law:

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \quad (5)$$

Definition of vector potential:

$$\begin{cases} \nabla \times \boldsymbol{A} = \boldsymbol{B} & (7) \\ \nabla \boldsymbol{A} = 0 & (8) \end{cases} ;$$

Navier-Stokes equation:

$$\rho \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \nabla) \boldsymbol{v} \right] = -\nabla p + \eta \Delta \boldsymbol{v} + \boldsymbol{f}_{EM} \quad (6)$$

+ turbulence k-ε model.

Continuity equation:

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

velocity

EM force

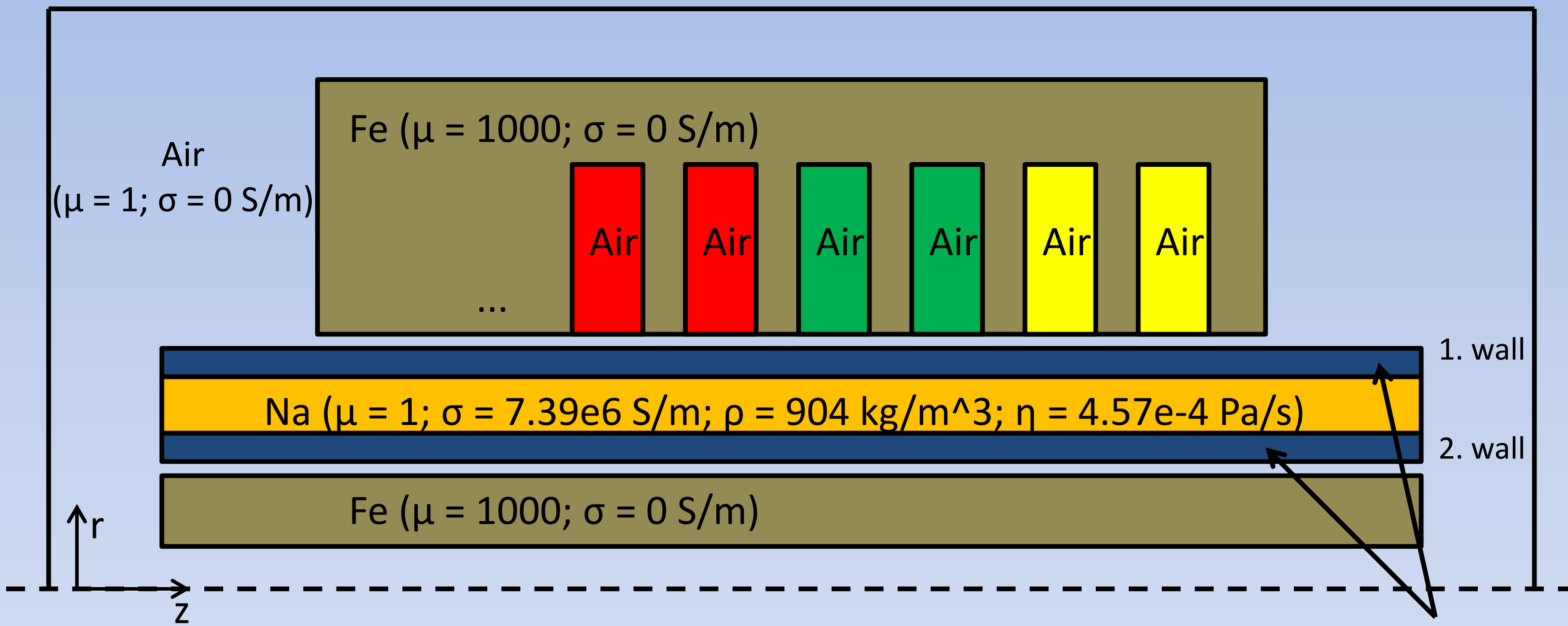
Induction equation:

$$\Delta \boldsymbol{A} = \mu_0 \sigma \left[\frac{\partial \boldsymbol{A}}{\partial t} - (\boldsymbol{v} \times \nabla \times \boldsymbol{A}) \right] - \mu_0 \boldsymbol{j}_e$$

$$\boldsymbol{j} = \sigma \left[-\frac{\partial \boldsymbol{A}}{\partial t} + (\boldsymbol{v} \times \nabla \times \boldsymbol{A}) \right] \quad (10)$$

$$\boldsymbol{f}_{EM} = \boldsymbol{j} \times \boldsymbol{B} \quad (11)$$

3. Considered geometry

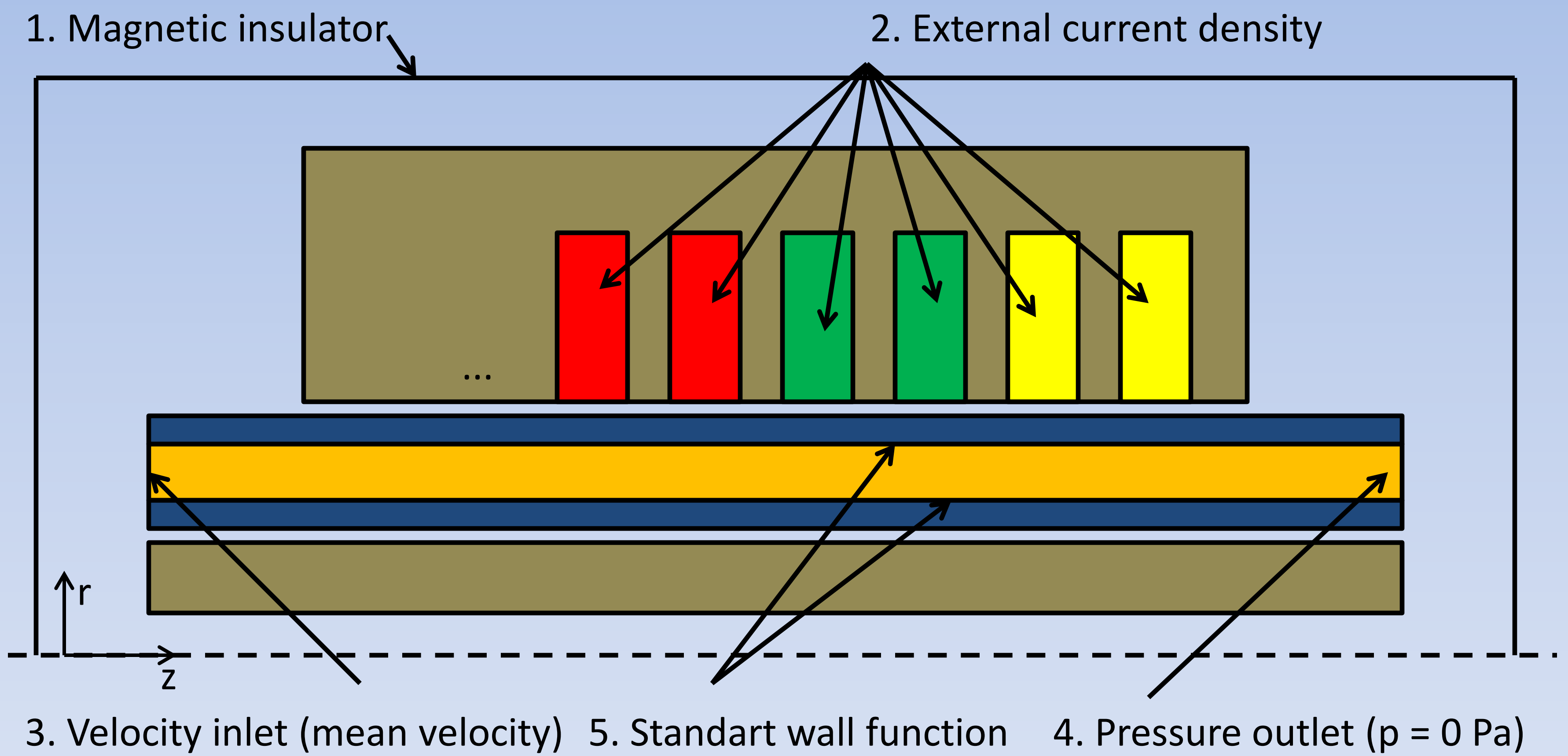


Principal sketch of geometry.

Key features:

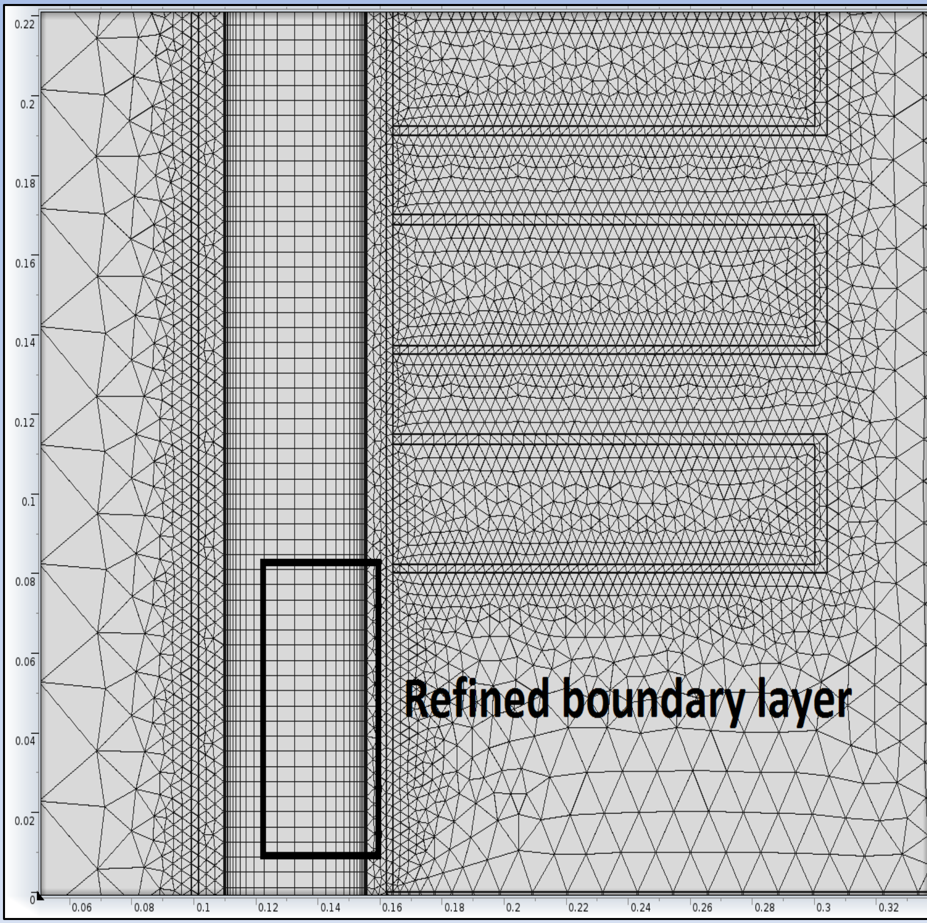
1. Problem was set to be **2D-axisymetric**
2. **36 coils** (2 coils per phase)
3. Channel made **longer than active region** (inductor)
4. Fe-magnetic core is the **same lenght as channel**

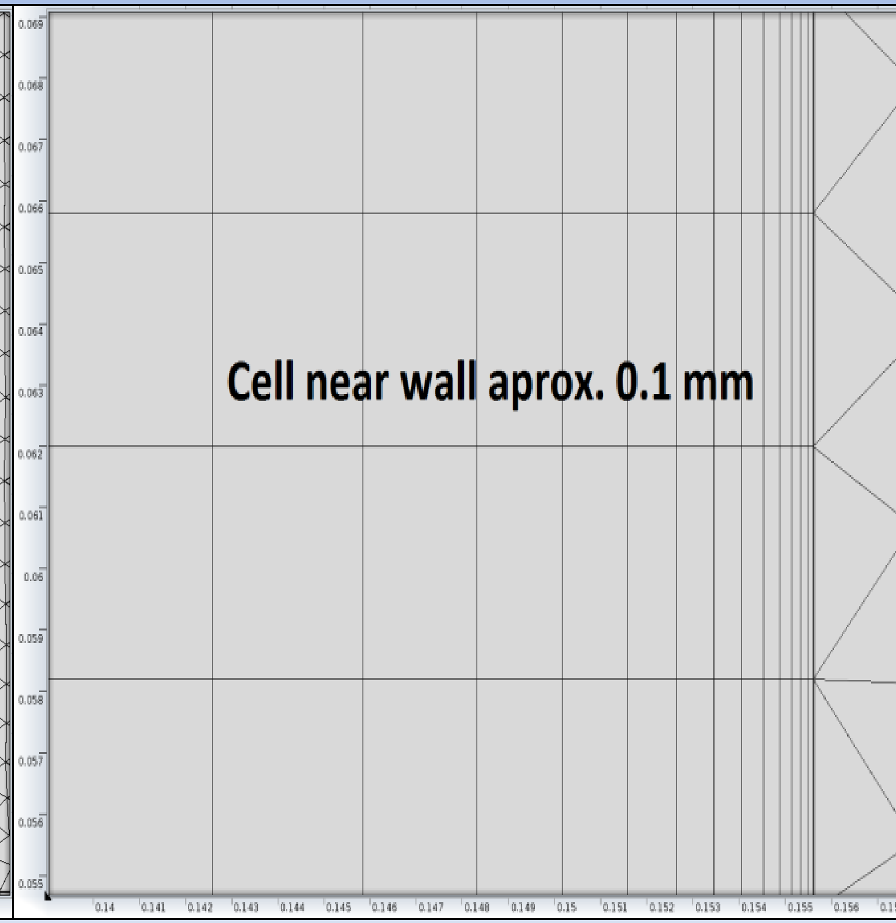
4. Boundary conditions and mesh



In the problem setup one should **add Lorenz term (v x B) in electromagnetic** part as well as **specify EM force in hydrodynamic** part to couple both physics!

4. Boundary conditions and mesh





Cells in total: ~132K
Cells in fluid: 60K

Near wall treatment that: $y^* \leq 11.06$ for good wall funtion aproximation.

5. Four simulation approaches

Problem was solved using **four approaches of different complexity**:

1. Quasi-stationary (QS) (**frequnecy domain**) Solid body (SB) - **QS approach for EM equations**, but Hydrodynamic (HD) equations aren't solved - **liquid metal with constant velocity**.

2. Transient (**time domain**) SB - Transient approach for **EM equations, but HD equations aren't solved**. Time step: $\Delta t = 0.001$ s.

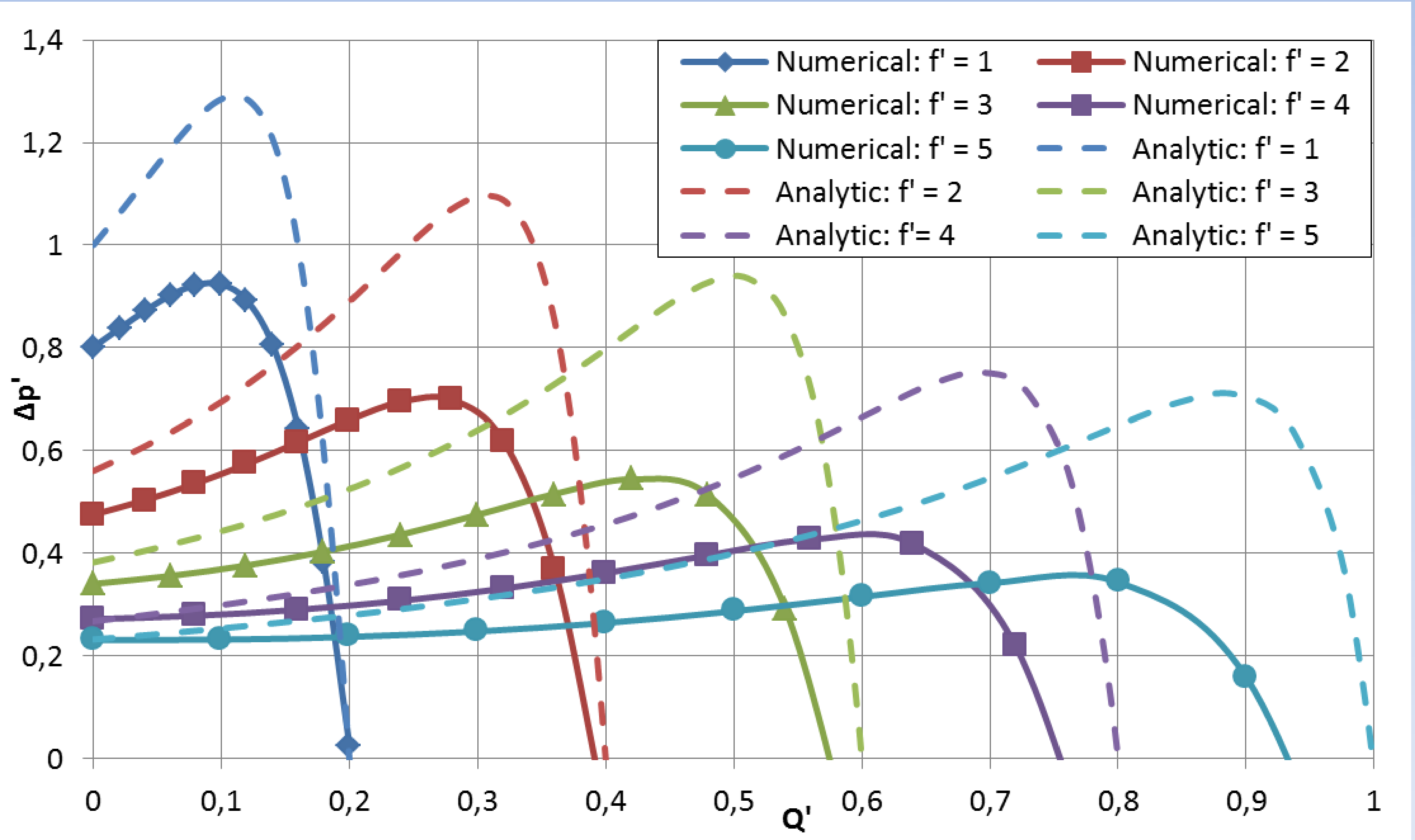
3. QS MHD – six steps of **QS EM equations and stationary HD** equations are solved using **k – ε turbulence model.**

4. Transient MHD – **EM and HD equations are solved transiently** using **k – ε turbulence** model with time step: $\Delta t = 0.002$ s.

6. Results

1. Quasi-stationary solid body

Obtained integral p-Q curves **compared with simplified analytical solution** (main harmonic).

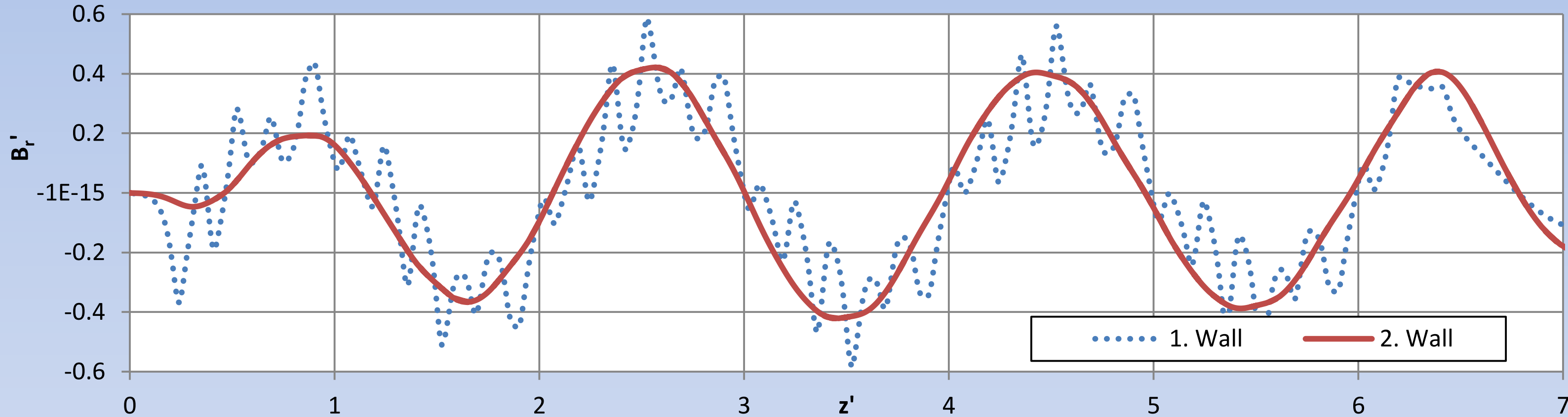


6. Results

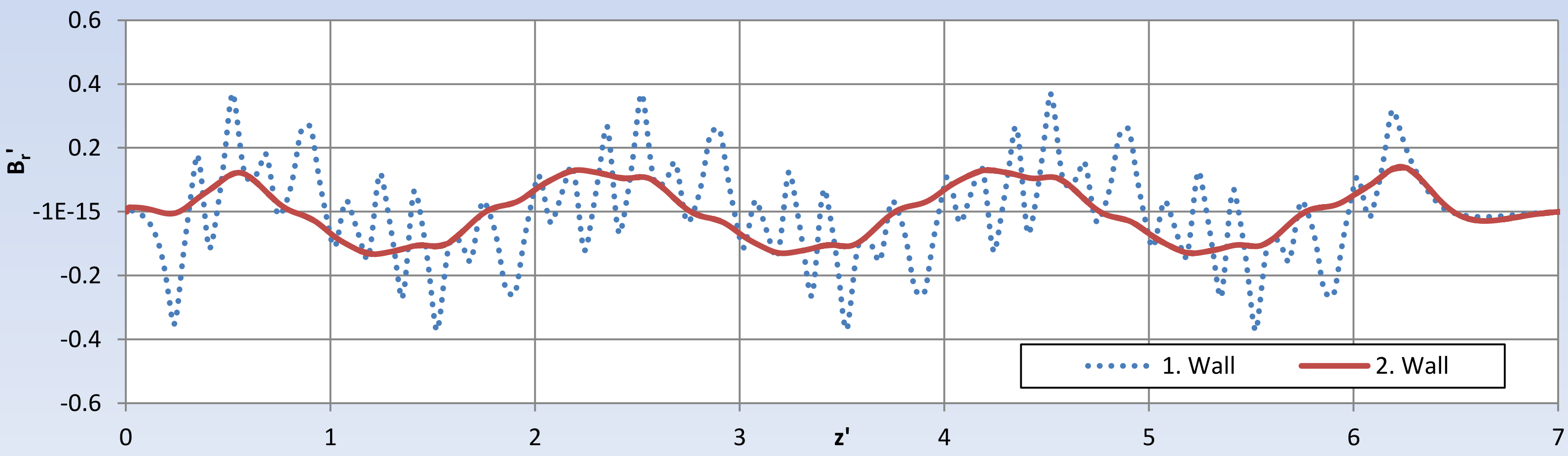
2. Quasi-stationary MHD

Distribution of B_r over length of the channel. **The penetration of field** into liquid metal.

High liquid metal velocity – low magnetic Reynolds number



Low liquid metal velocity – high magnetic Reynolds number

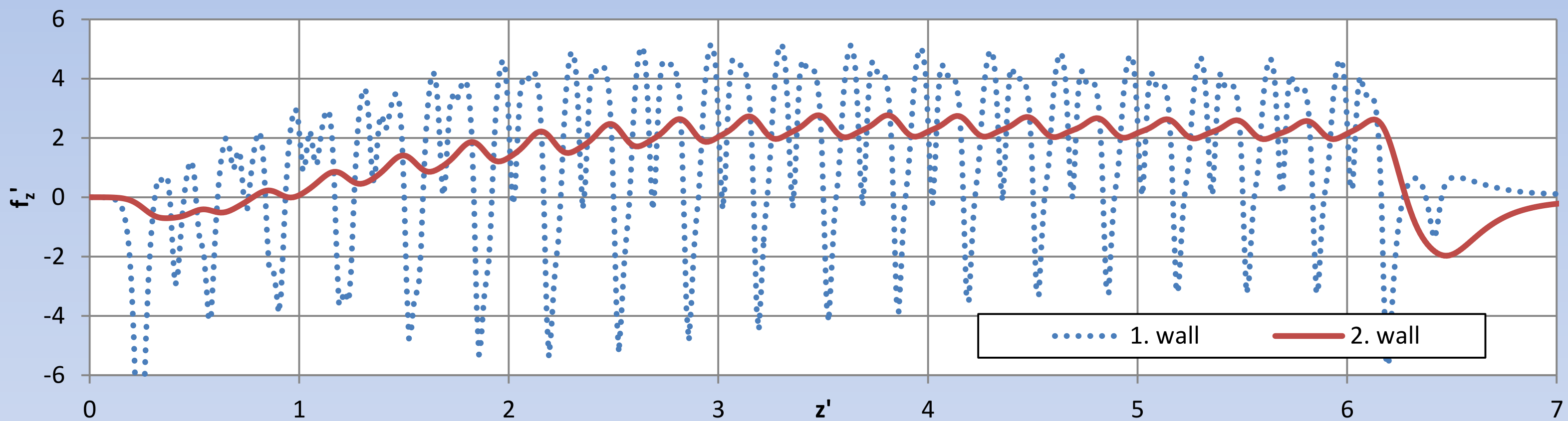


6. Results

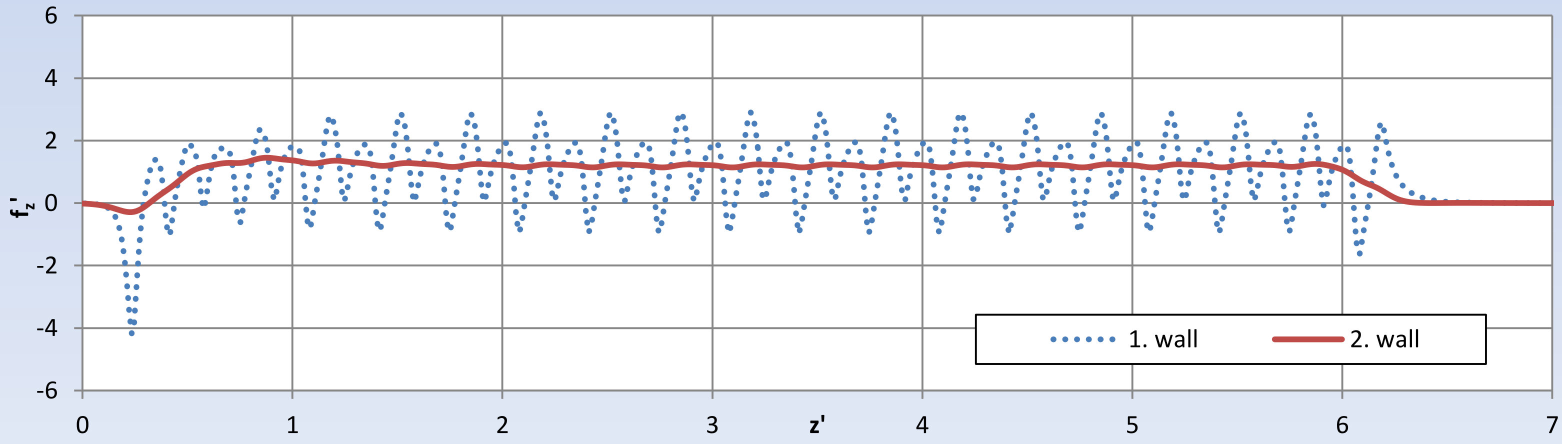
2. Quasi-stationary MHD

Distribution of f_z over length of the channel. **Negative forces near inductor** (higher harmonics).

High liquid metal velocity – low magnetic Reynolds number



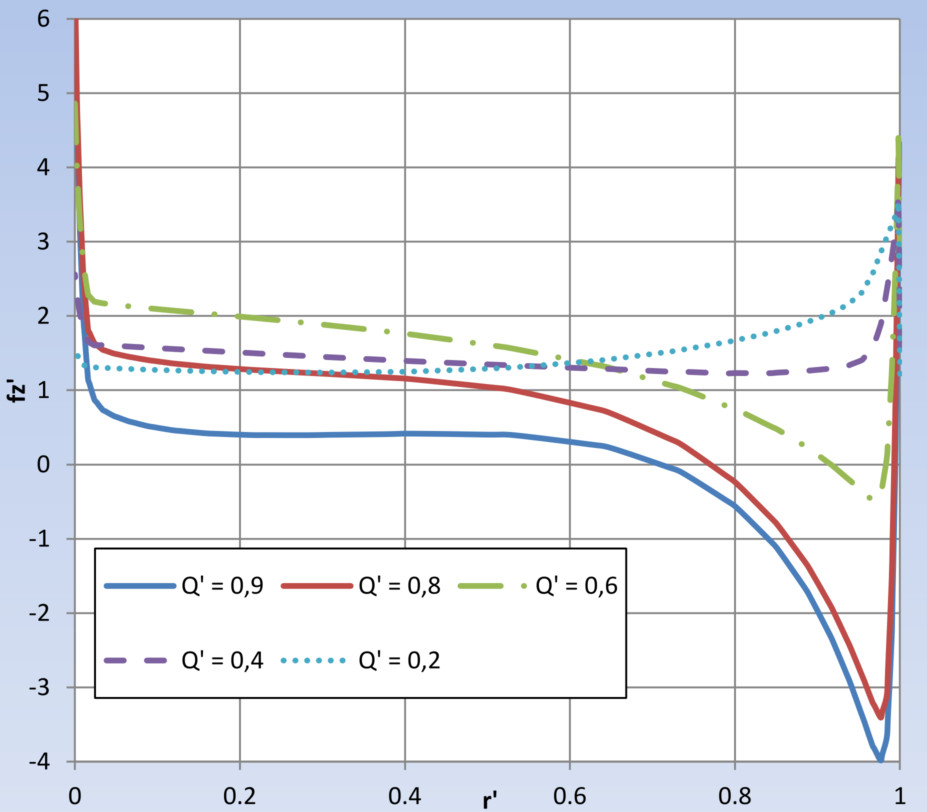
Low liquid metal velocity – high magnetic Reynolds number



6. Results

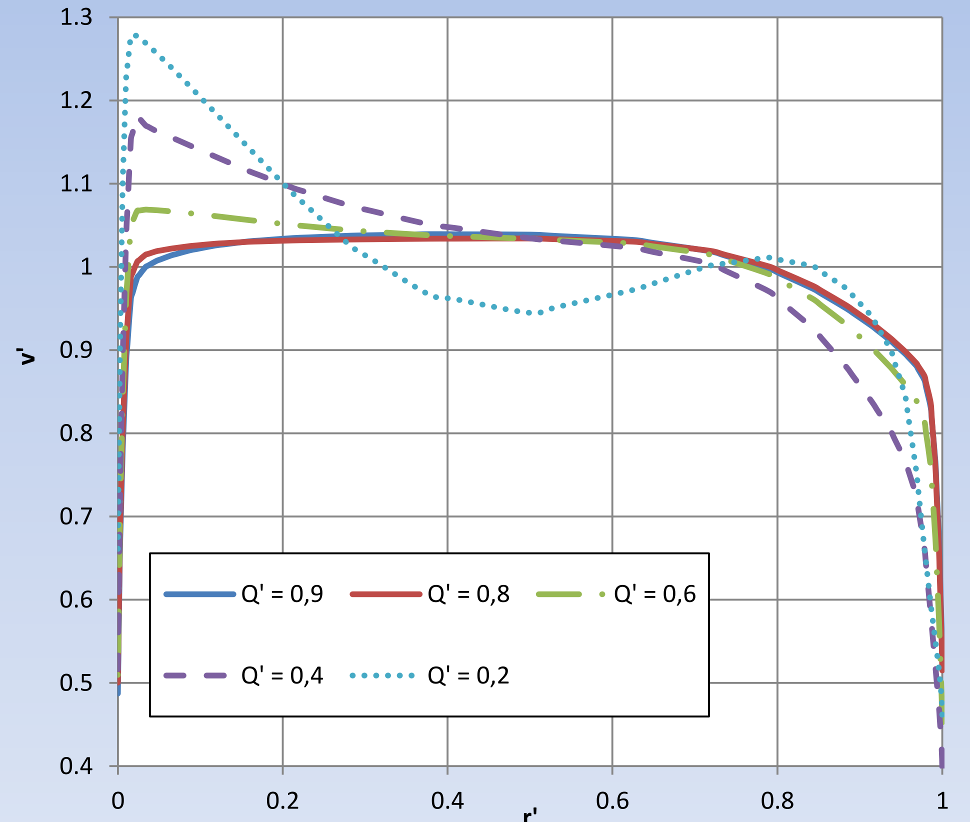
2. Quasi-stationary MHD

Profiles of f_z and v over hight of the channel in liquid metal. **Interaction parameter**.



2. wall 1. wall

Axial force profiles



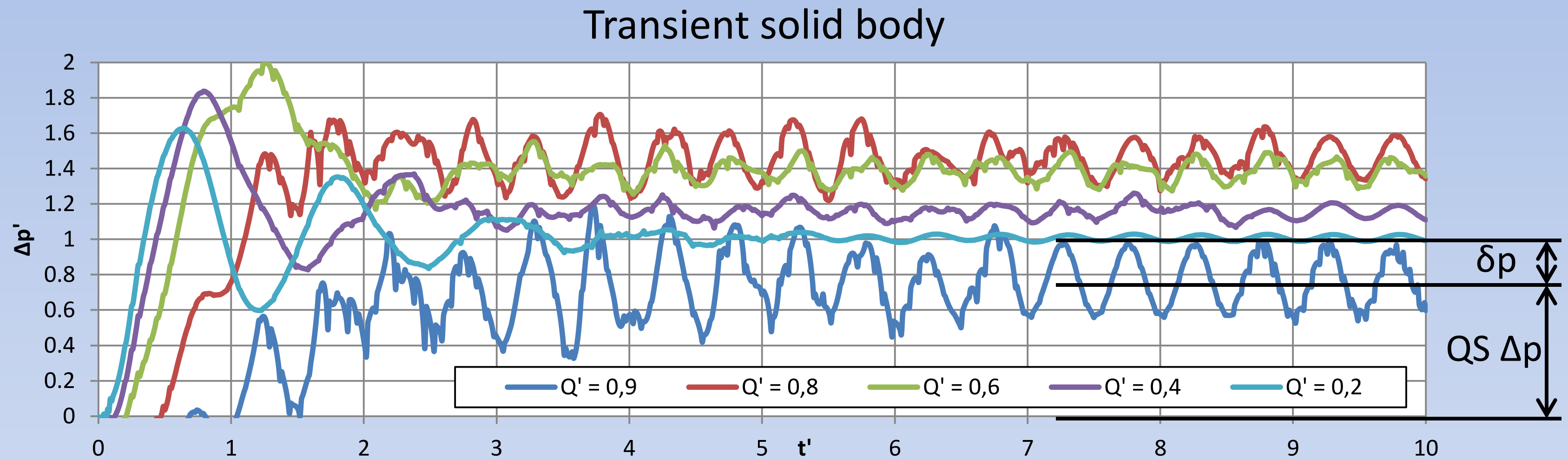
2. wall 1. wall

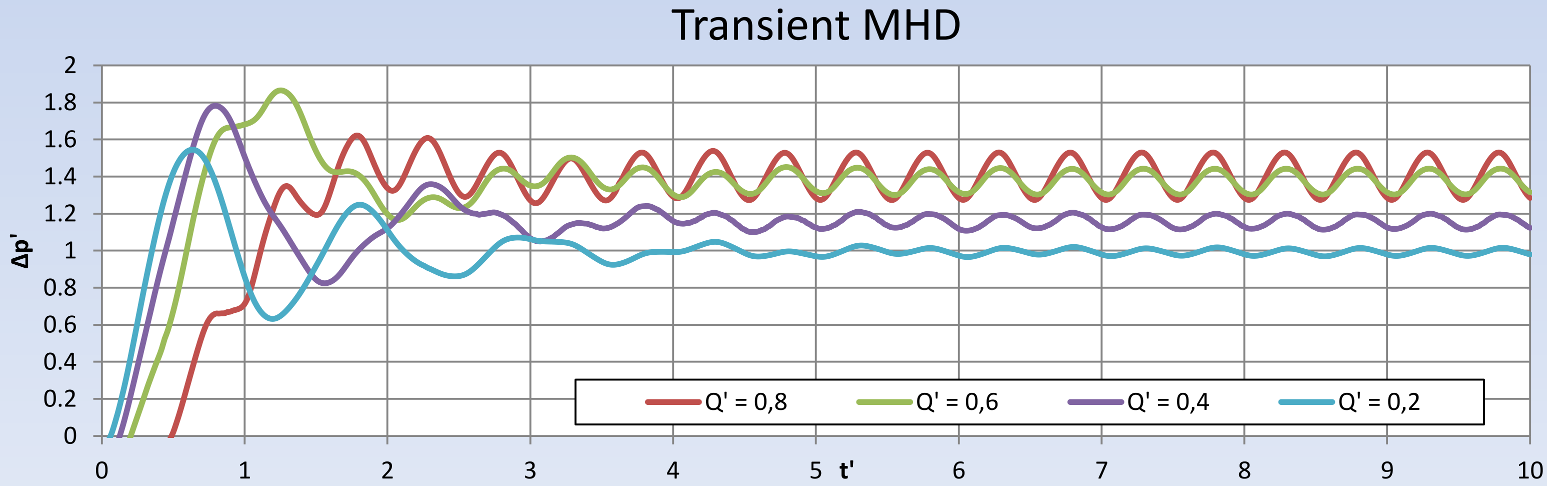
Axial velocity profiles

6. Results

3,4. Transient solid body and MHD

Transient development of pressure. **Double supply frequency (DSF) pulsations.**

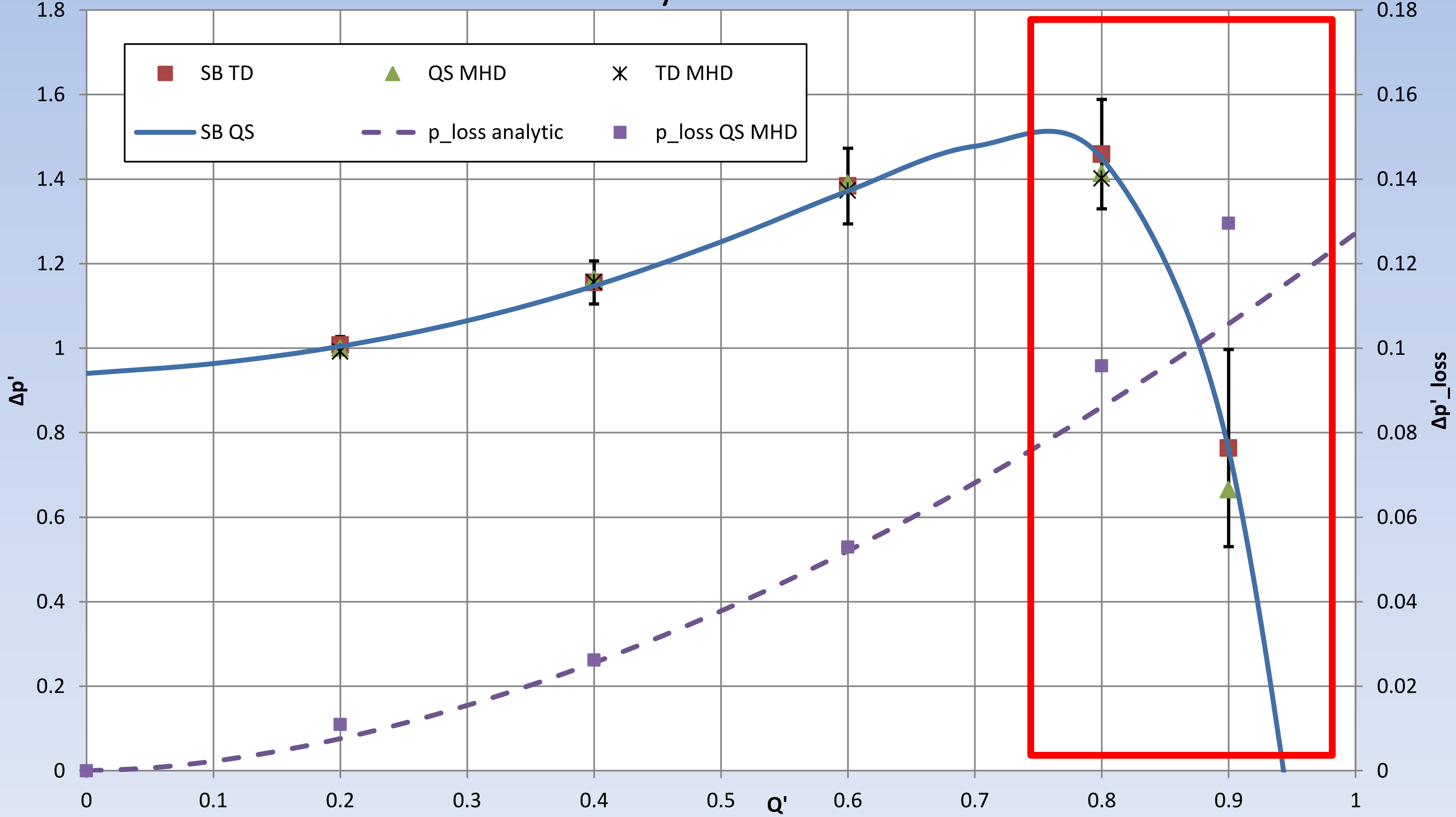




6. Results

Comparison of p-Q results.

Developed pressure in all four cases is rather similar. Double supply frequency pulsations. Hydraulic losses.



7.Conclusion

1. **COMSOL Multiphysics® is capable tool** for EMIP analyis of different complexity.
2. **Strong influence of magnetic field higher harmonics** on integral characteristics is observed.
3. Time averaged **p – Q characteristic of EMIP in all four approaches are quite the same**, therefore simple **QS SB approach can be used**.
4. **QS MHD** approach can be very useful to **analyze axial force and velocity and to compute pressure losses** in EMIP.
5. **Transient SB approach** can be successfully used to **estimate amplitude of pulsations** and is very similar with transient MHD approach.
6. **Transient MHD approach is most time consuming and complex** and should be used if one is interested in **transient MHD solutions**.

Thank you for attention!
Questions?