MODELLING OF MAGNETOHYDRODYNAMIC FLOW CONTROL FOR CONTINUOUS CASTING OF STEEL

A review of ISW's research activities

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JOHANNES KEPLER UNIVERSITÄT LINZ

INSTITUT FÜR STRÖMUNGSLEHRE UND WÄRMEÜBERTRAGUNG

metallurgical competence center

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

voestalpine ONE STEP AHEAD.

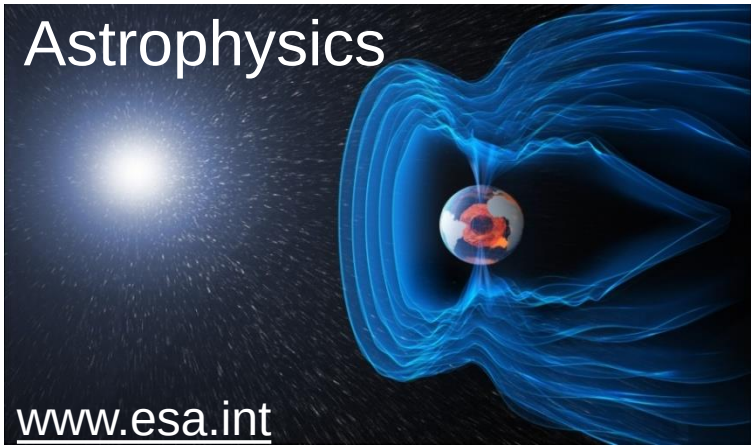
PRIMETALS TECHNOLOGIES

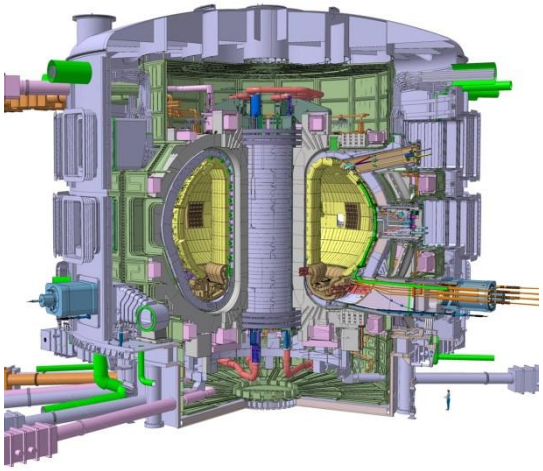
RHI MAGNESITA

OVERVIEW

- Magnetohydrodynamics in general and in the steel industry
- Short introduction to magnetohydrodynamics
- Research activities of ISW
  - EMS round bloom strand casting
  - EMBR slab/thin slab casting
  - EMLS in the secondary cooling zone
  - Latest: EMLA/EMLB/EMLS for slab casting
- Summary & Outlook

MAGNETOHYDRODYNAMICS (MHD)





Fusion reactors

http://de.wikipedia.org/wiki/Tokamak
http://www.fusion.kit.edu/85.php

MHD APPLICATIONS IN THE STEEL INDUSTRY

- Electric Arc Furnace (EAF)
- Electroslag Remelting (ESR)
- Induction heating
- Electromagnetic stirring in the ladle
- Electromagnetic rotary stirring/breaking (EMRS/EMBR) in the tundish
- EMBR at the stopper rod gap
- EMRS in the submerged entry nozzle
- Electromagnetic rotational stirring (EMS) for bloom/billet casting
- EMBR for (thin) slab casting
- Electromagnetic linear accelerating/braking/stirring (EMLA/EMLB/EMLS) for slab casting (mould and/or secondary cooling zone)

SHORT INTRODUCTION TO MAGNETOHYDRODYNAMICS

- Maxwell‘s equations

  Gauss‘s law $\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$

  Gauss's law for magnetism $\nabla \cdot \vec{B} = 0$

  Faraday‘s Law $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

  Ampere‘s Law $\nabla \times \vec{H} = \vec{j} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$

- Ohm‘s Law $\vec{j} = \sigma(\vec{E} + \vec{u} \times \vec{B})$

  Electromotive field

- Constitutive Equation $\vec{B} = \mu_M \vec{H}$

- Navier Stokes Equations

  Lorentz forces

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\,\vec{u} = -\frac{1}{\rho}\nabla p + \nu \Delta \vec{u} + \frac{1}{\rho}(\vec{j} \times \vec{B}) \quad \text{and} \quad \nabla \cdot \vec{u} = 0$$

SHORT INTRODUCTION TO MAGNETOHYDRODYNAMICS

- Induction equation for magnetic flux density $\vec{B}$

$$\frac{\partial \vec{B}}{\partial t} + (\vec{u} \cdot \nabla)\,\vec{B} = \frac{1}{\sigma \mu_M} \Delta \vec{B} + (\vec{B} \cdot \nabla)\,\vec{u}$$

$$\nabla \cdot \vec{B} = 0$$

- or in terms of the magnetic vector potential $\vec{A}$ (with $\vec{B} = \nabla \times \vec{A}$)

$$\frac{\partial \vec{A}}{\partial t} = \vec{u} \times \nabla \times \vec{A} + \frac{1}{\sigma \mu_M} \Delta \vec{A}$$

$$\nabla \cdot \nabla \times \vec{A} = 0$$

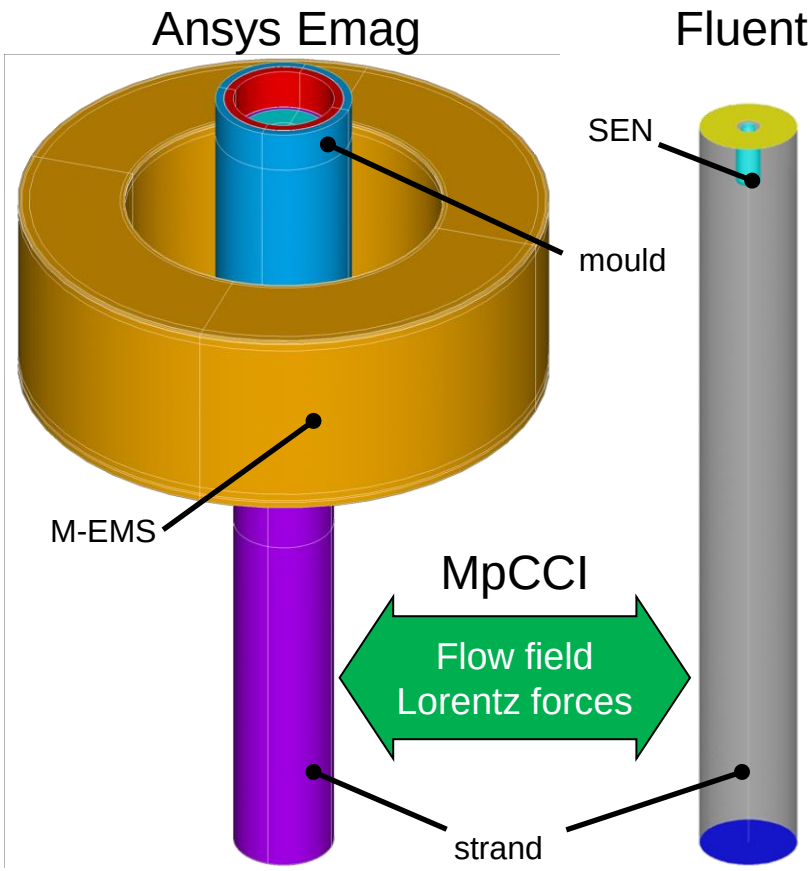
- Navier Stokes Equations

Lorentz forces

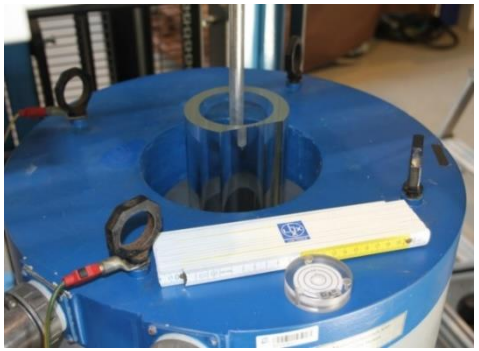
$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\,\vec{u} = -\frac{1}{\rho} \nabla p + \nu \Delta \vec{u} + \frac{1}{\rho}(\vec{j} \times \vec{B}) \quad \text{and} \quad \nabla \cdot \vec{u} = 0$$

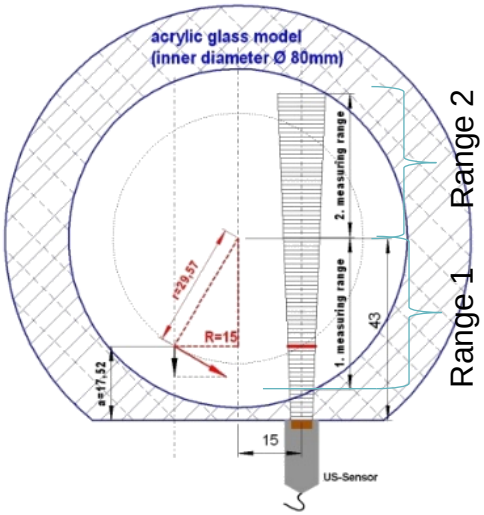
EMS FOR ROUND BLOOM CASTING NUMERIC MODEL & EXPERIMENT

Simulation setup

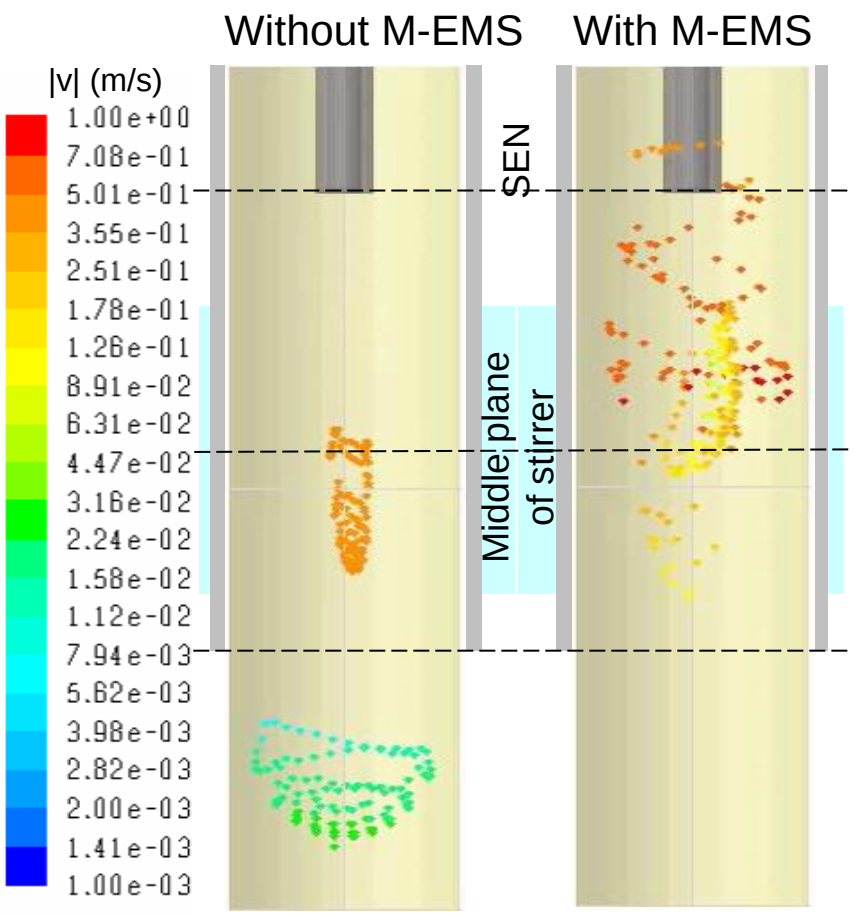


Experimental setup

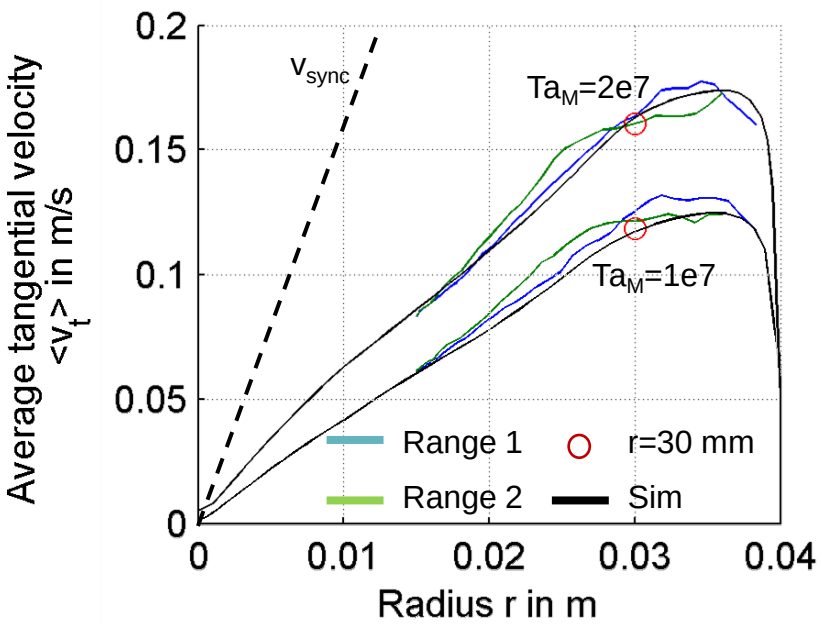




EMS FOR ROUND BLOOM CASTING
NUMERIC RESULTS & VALIDATION



Validation



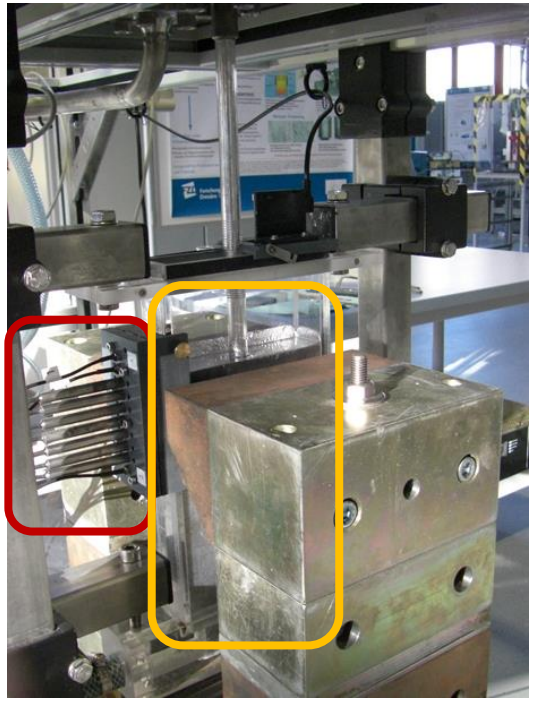
$$Ta_M = \frac{\sigma \omega B_0^2 R^4}{\rho \nu^2} = \frac{magnetic\ forces}{viscous\ forces}$$

EMBR FOR SLAB CASTING SIMULATION & EXPERIMENT SETUP

Experimental setup:

1:10 scale (140x35 mm²)

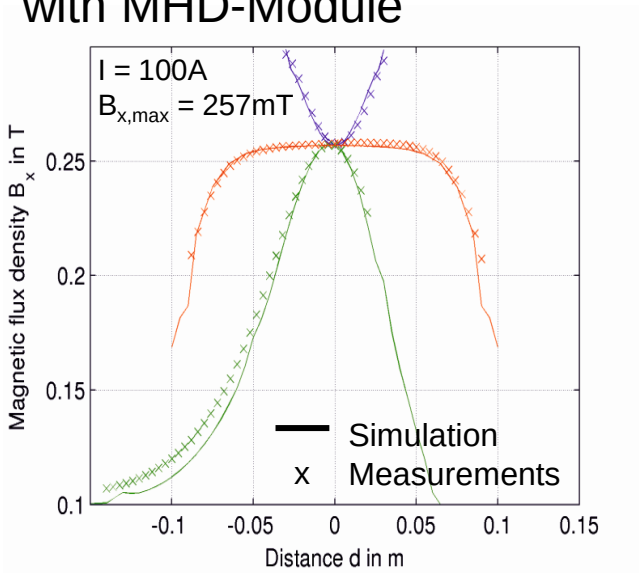
RulerEMBR (≤315 mT)

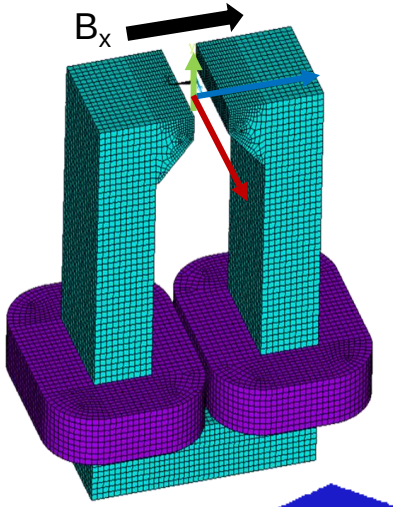


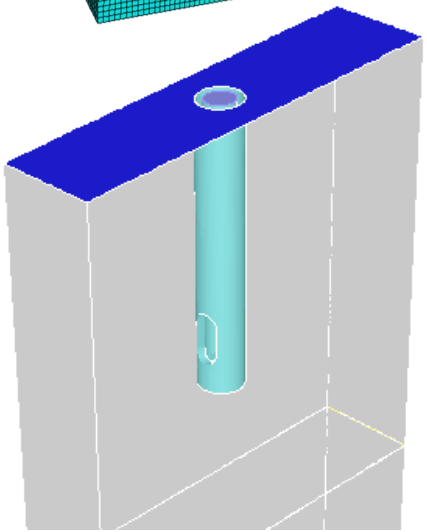
Numeric Model:

Emag: Electromagnetic field calculated for a resting fluid

Fluent: Electromagnetic field imported; forces calculated with MHD-Module



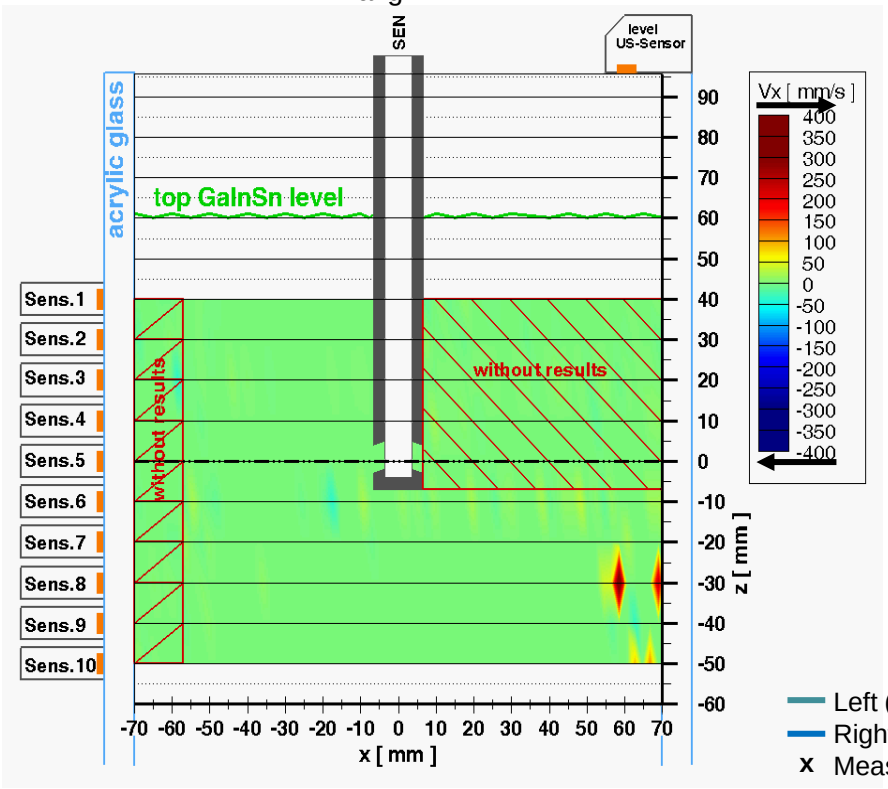




EMBR FOR SLAB CASTING MEASUREMENTS & VALIDATION

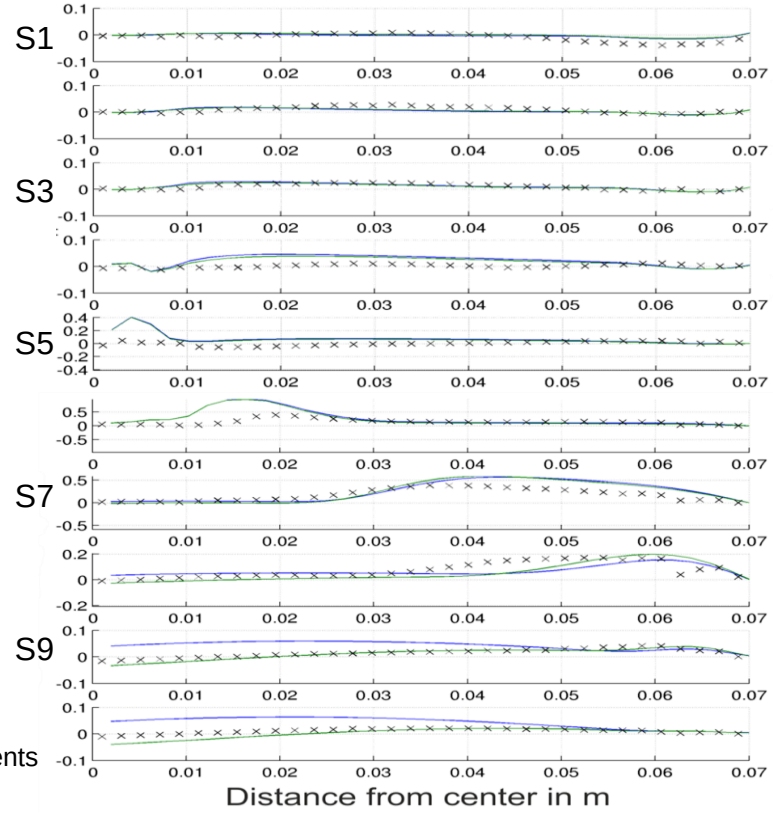
Experimental results

Inlet velocity: v_{avg}= 1.42 m/s



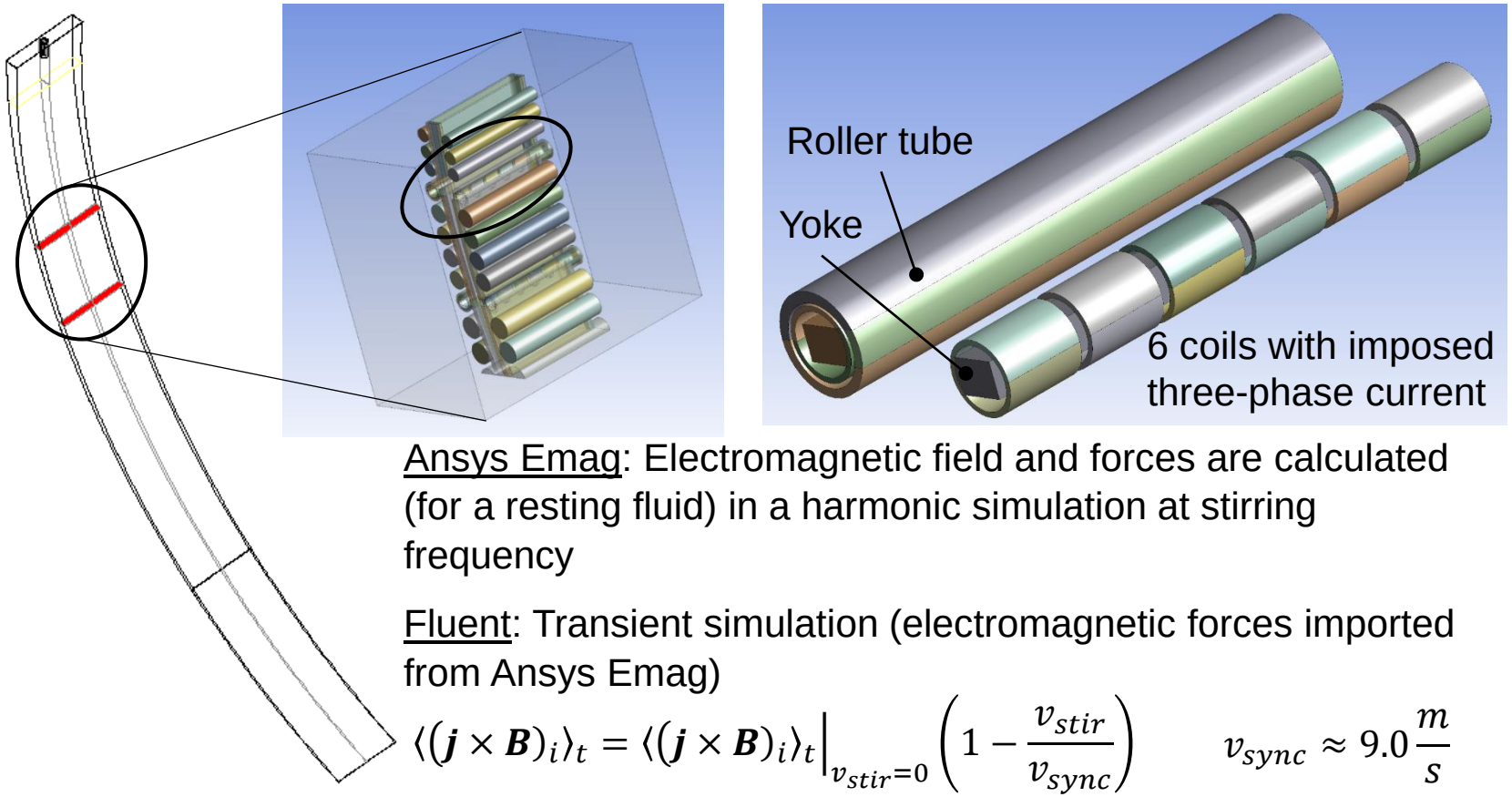
Validation

Avg. horizontal velocity @ B=257 mT



EMLS IN SLAB CASTING IN THE SECONDARY COOLING ZONE

Numeric model



Ansys Emag: Electromagnetic field and forces are calculated (for a resting fluid) in a harmonic simulation at stirring frequency

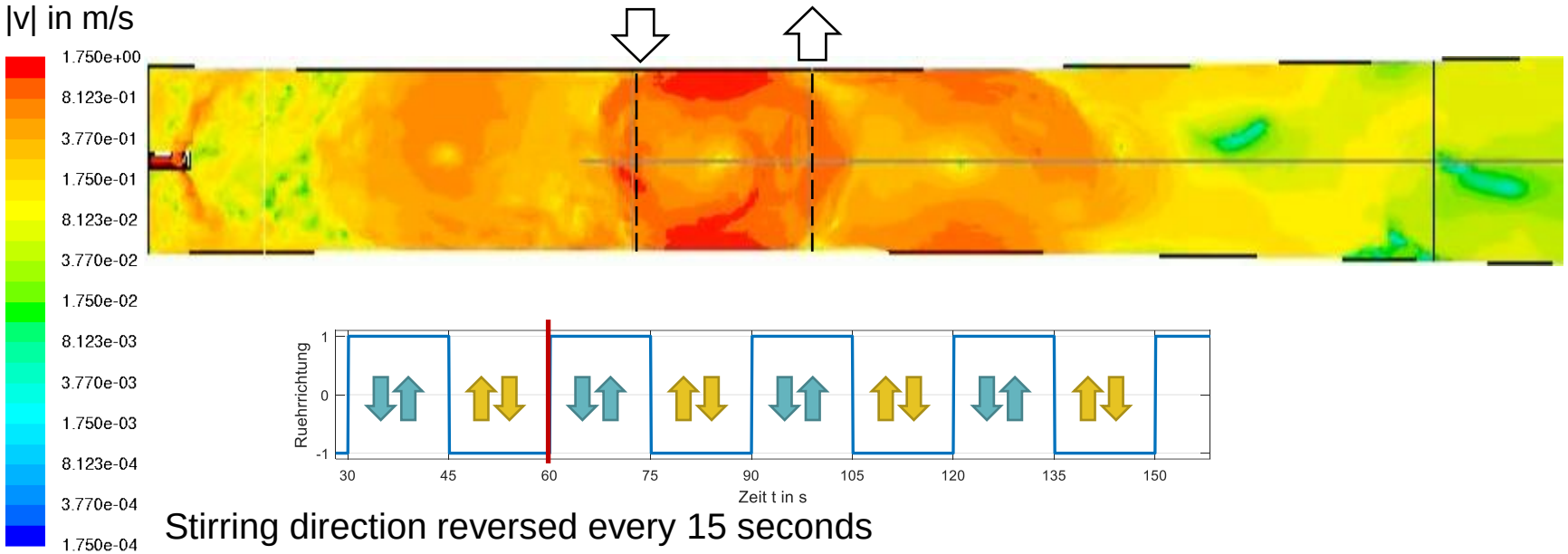
Fluent: Transient simulation (electromagnetic forces imported from Ansys Emag)

$$\langle (\boldsymbol{j} \times \boldsymbol{B})_i \rangle_t = \langle (\boldsymbol{j} \times \boldsymbol{B})_i \rangle_t \Big|_{v_{stir}=0} \left(1 - \frac{v_{stir}}{v_{sync}}\right) \qquad v_{sync} \approx 9.0 \frac{m}{s}$$

EMLS IN SLAB CASTING IN THE SECONDARY COOLING ZONE

Results

Velocity magnitude in middle plane

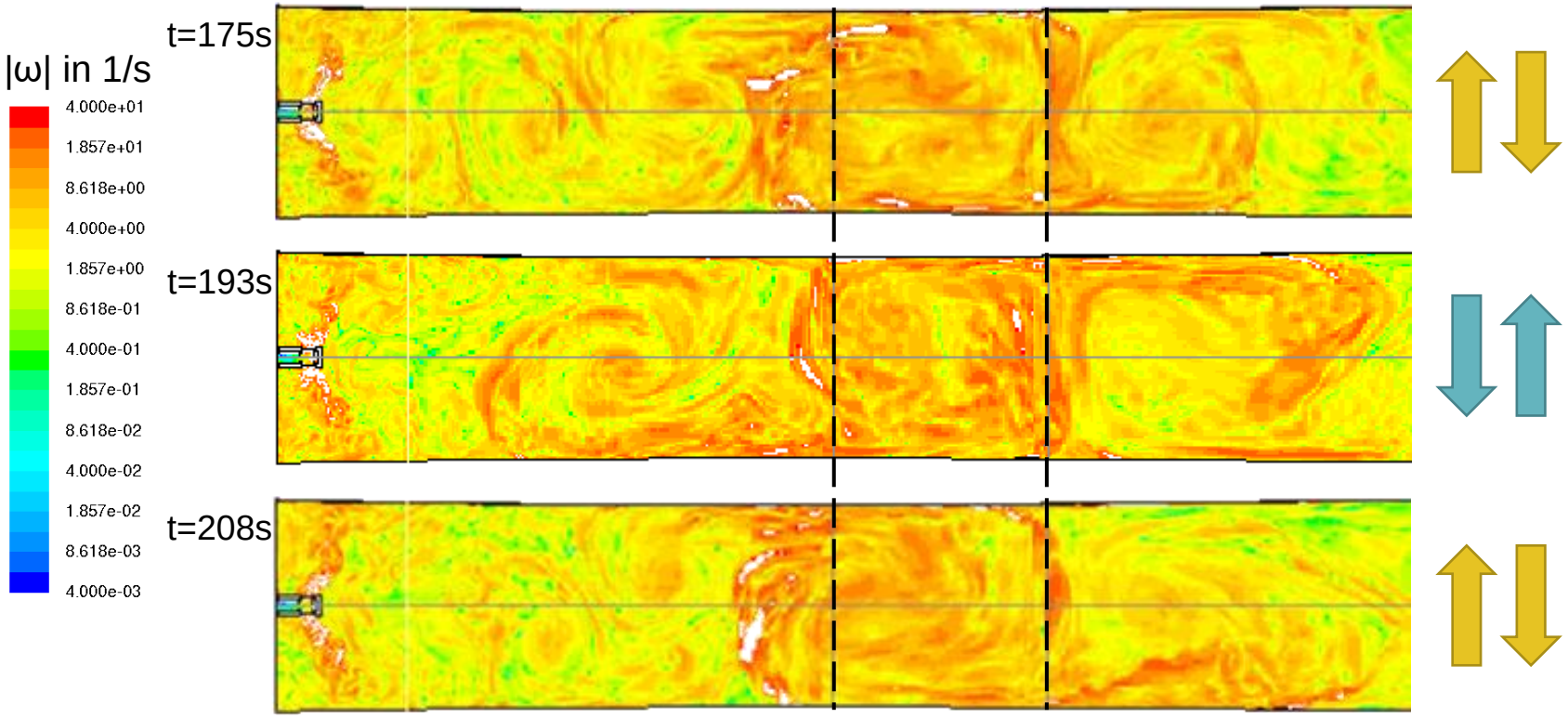


Stirring direction reversed every 15 seconds

EMLS IN SLAB CASTING IN THE SECONDARY COOLING ZONE

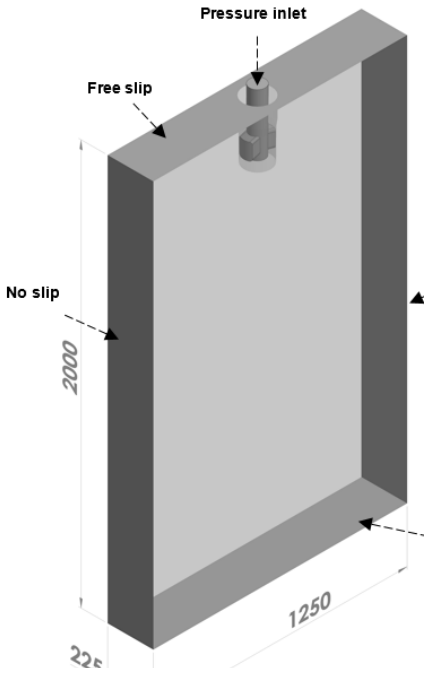
Results

Vorticity magnitude in middle plane



EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION – SIMULATIONS

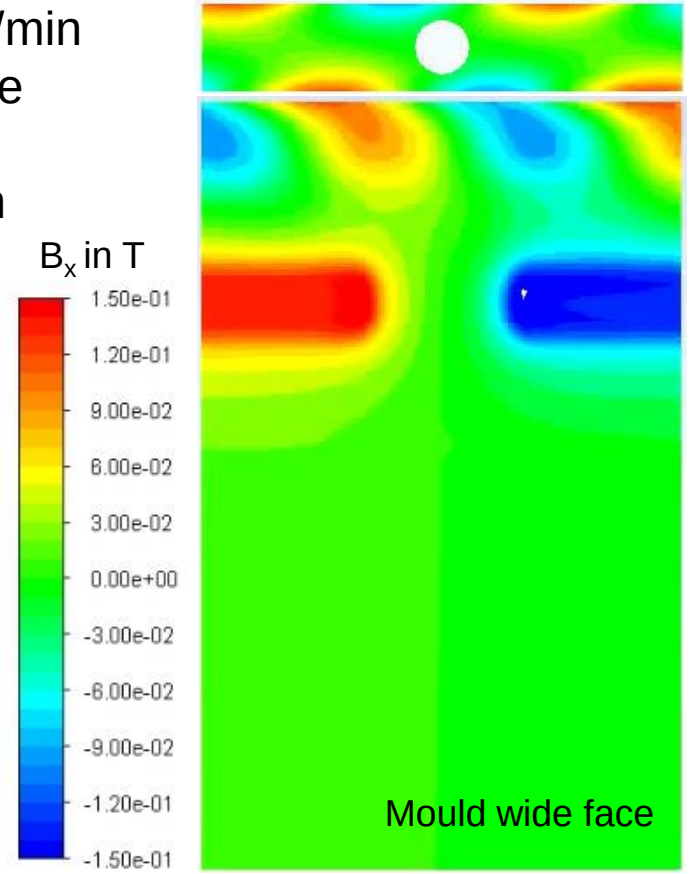
Numeric model



Casting speed: v_{in}=1.0 m/min

- Traveling field near free surface
- Static field at jet region

Free surface

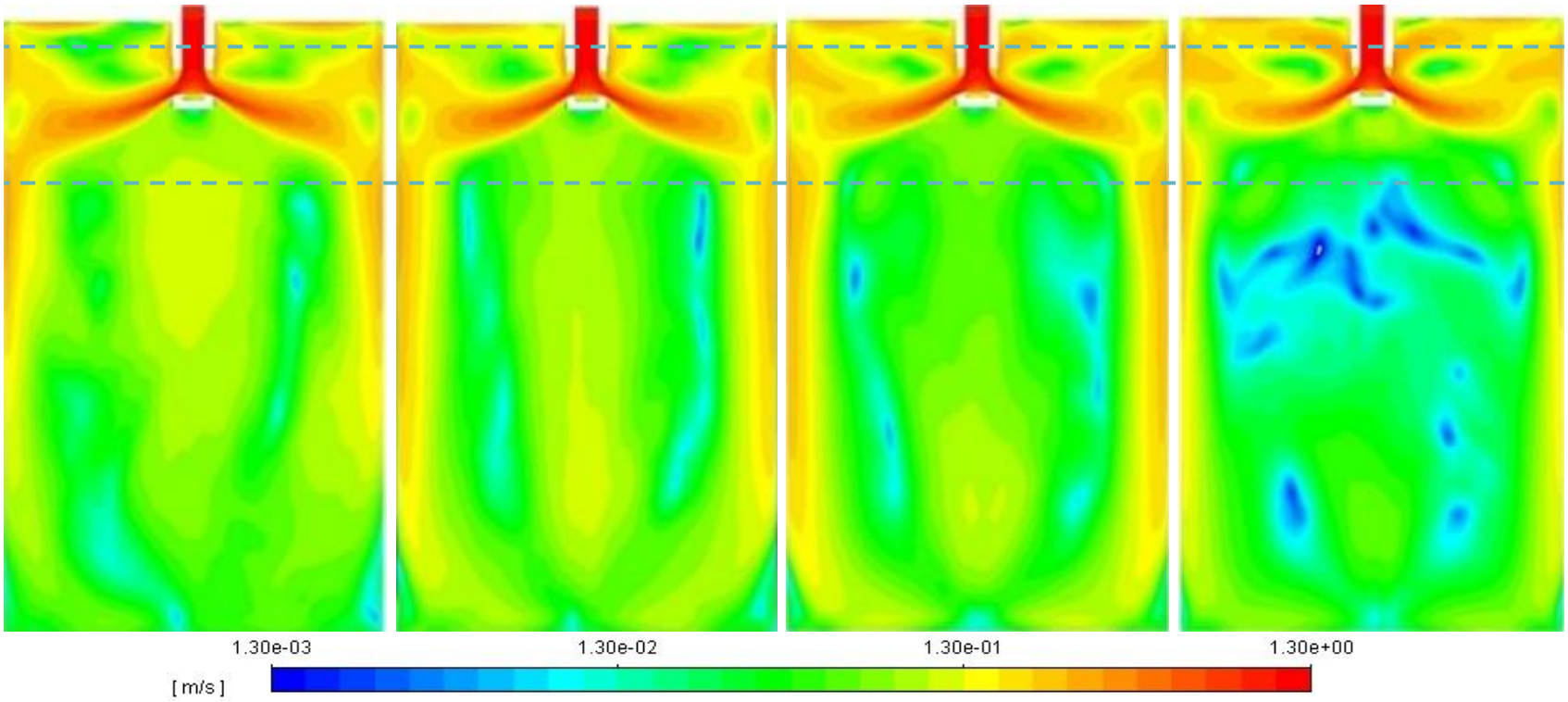


Ansys Maxwell: Calculation of the fields
Fluent: Electromagnetic field imported; forces calculated with MHD-Module

EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION – SIMULATIONS

Results

Time averaged velocity magnitude at mould middle plane



EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION – SIMULATIONS

Results

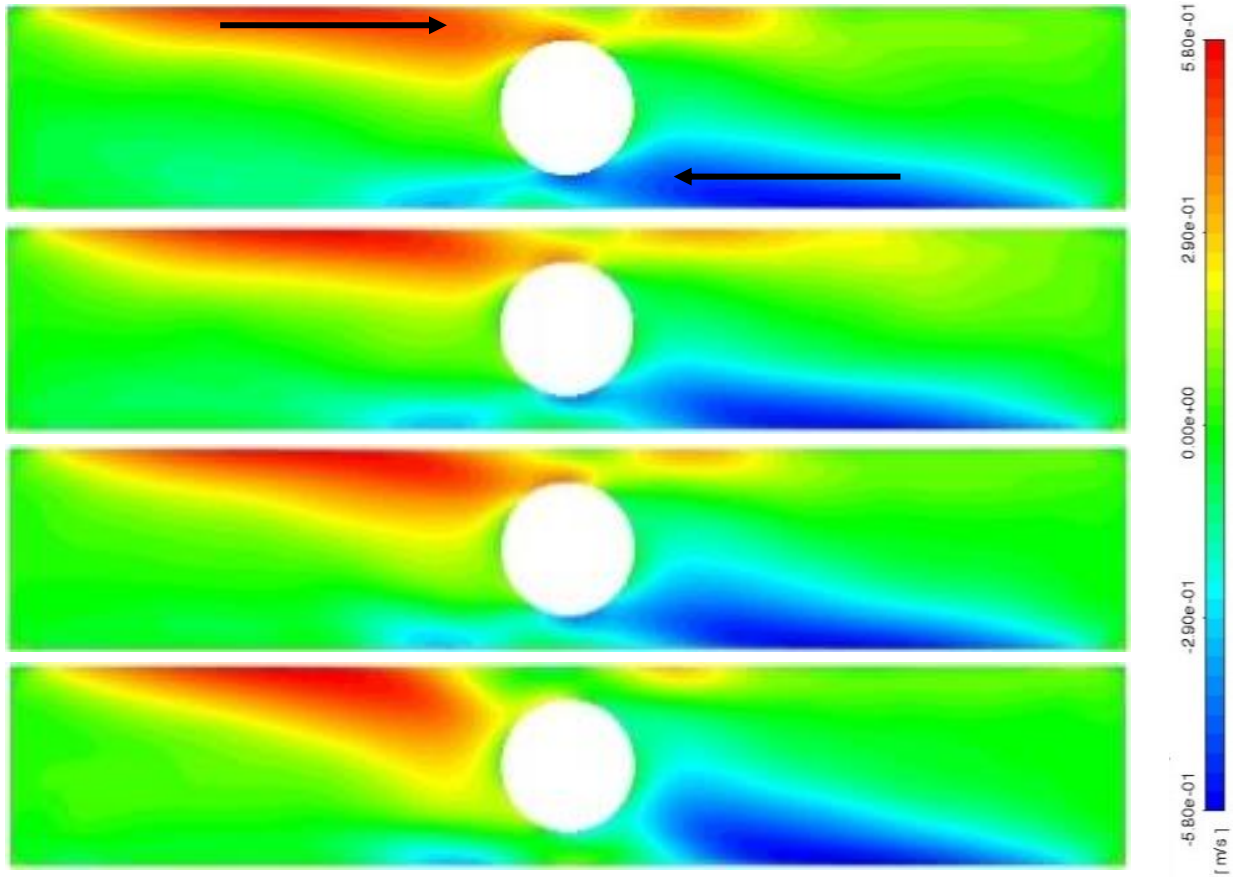
Time averaged horizontal velocity at stirrer middle plane

only EMRS
0.14 T

EMRS + EMBR
0.14 T + 0.15 T

EMRS + EMBR
0.14 T + 0.30 T

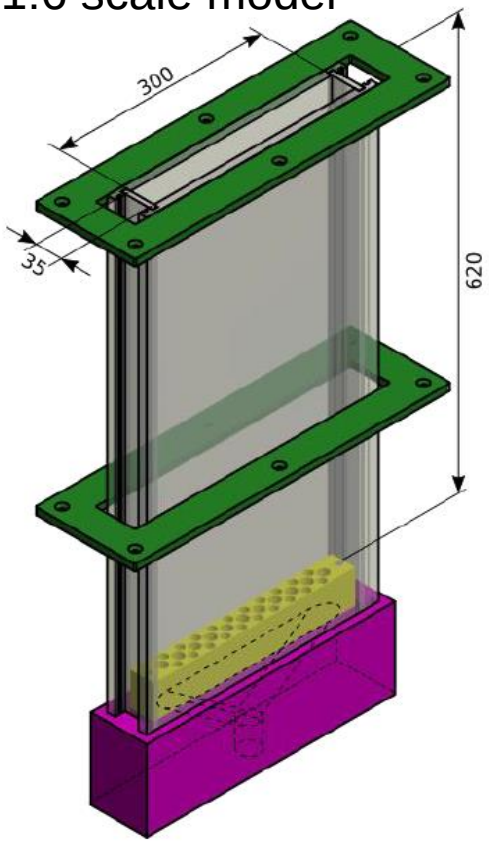
EMRS + EMBR
0.14 T + 0.50 T



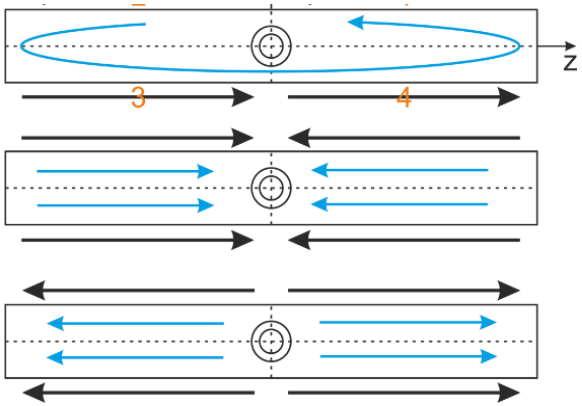
EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION - MEASUREMENTS

Experimental setup

1:6 scale model



Stirring system with 6 coils
(only traveling field setup)



UDV-Sensors

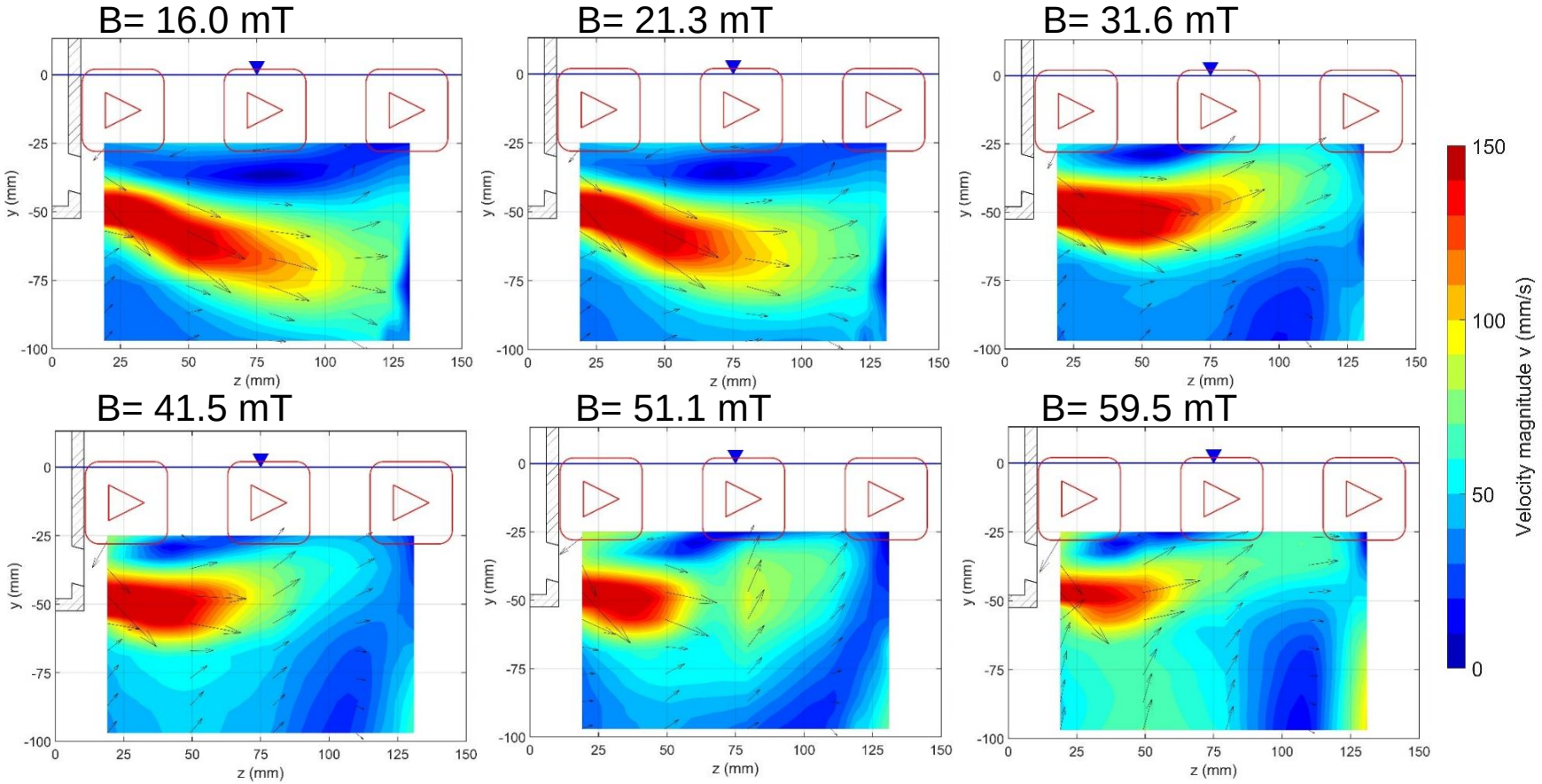
- 10x1 array
- 3x3 array

Measured velocities

- Horizontally
- Vertically

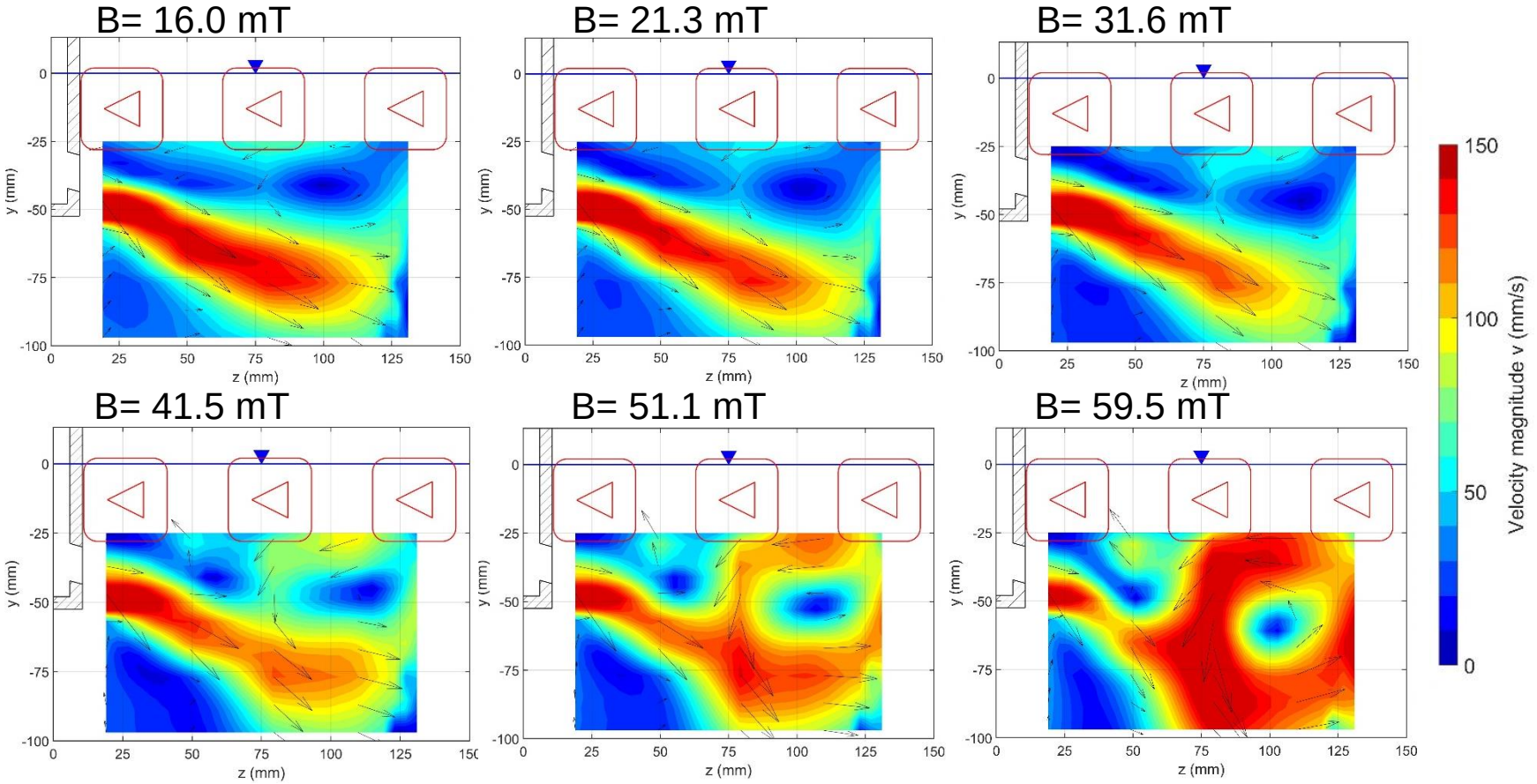
EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION - MEASUREMENTS

2D velocity field for outward configuration (f=5 Hz)



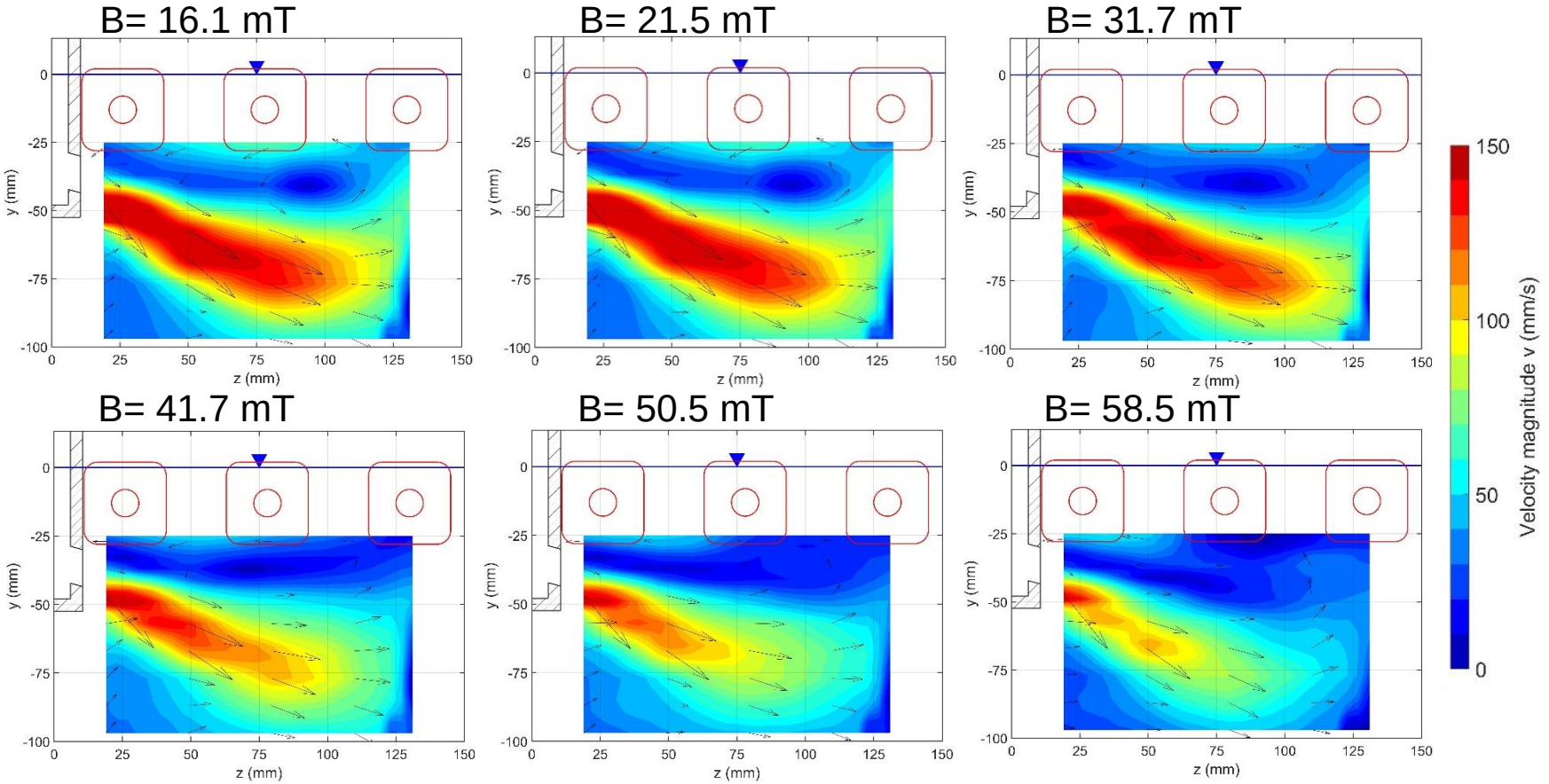
EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION - MEASUREMENTS

2D velocity field for inward configuration (f=5 Hz)



EMLA/EMLS/EMRS IN SLAB CASTING MOULD REGION - MEASUREMENTS

2D velocity field near the mould wall for stirring configuration (f=5 Hz)



SUMMARY & OUTLOOK

- Broad range of numeric modelling approaches largely grouped by
  - Casting format
  - Magnetic field setup (static, traveling, rotating)
  - Computational effort vs. accuracy and attention to detail
- Measurements for validation where conducted successfully (if an experimental setup is feasible)

- Develop/Enhance our models for faster and more detailed simulations
  - Open source solvers for CFD and electromagnetic calculations
  - Impact of magnetic fields on turbulence
  - Addition of Argon gas injections
- More investigations regarding traveling magnetic fields