Modelling of the influence of electromagnetic force on melt convection and dopant distribution during floating zone growth of silicon

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ERAF
EIROPAS REĢIONĀLĀS ATTĪSTĪBAS FONDS

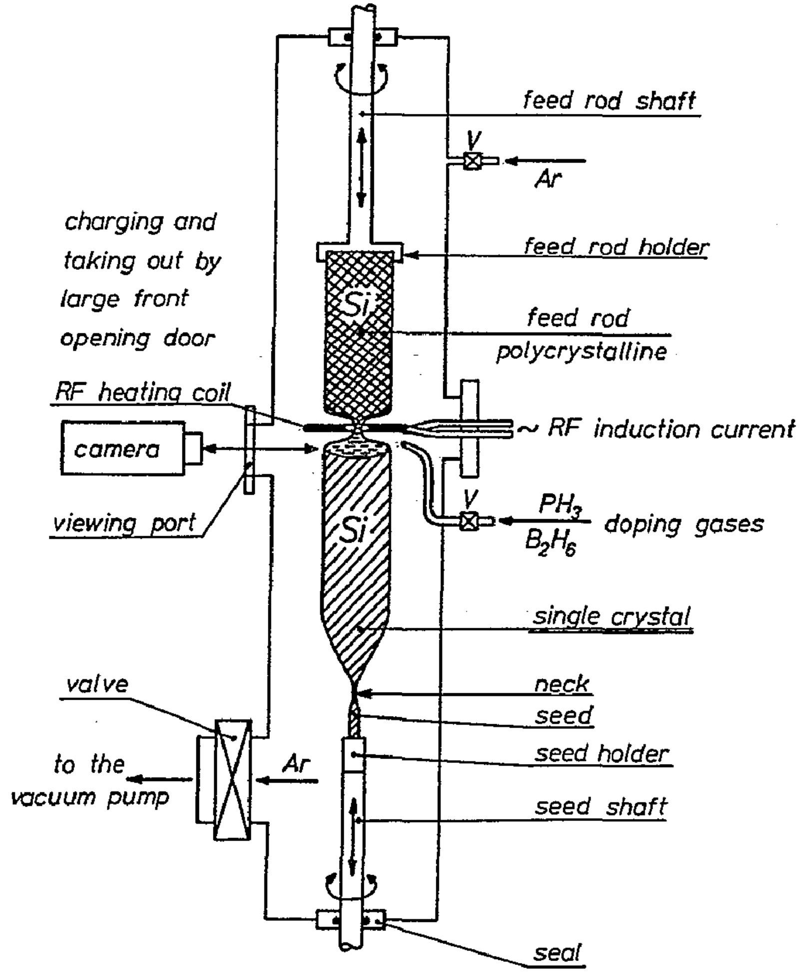
EIROPAS SAVIENĪBA

IEGULDĪJUMS TAVĀ NĀKOTNĒ

Introduction

Si single crystal growth with FZ technique

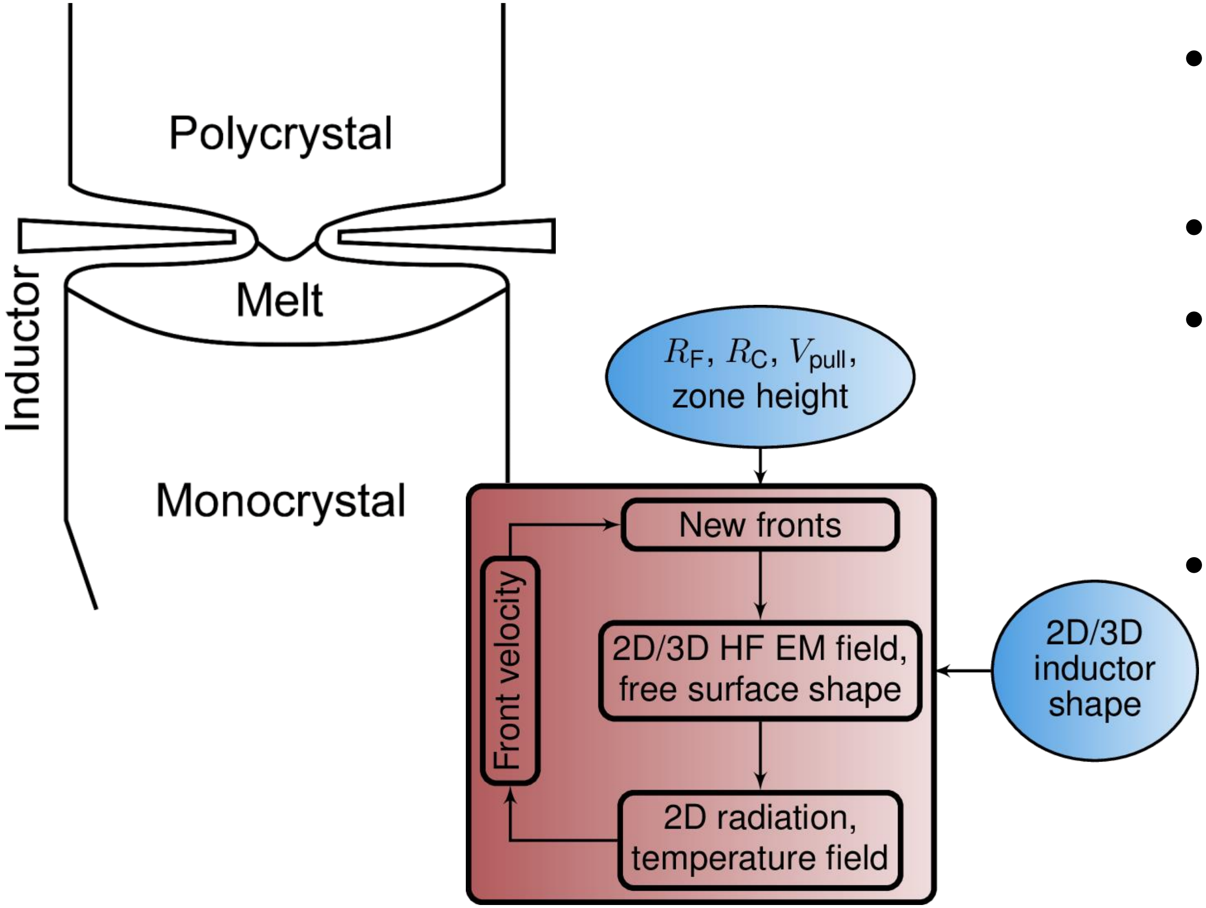
Courtesy of Dr. H. Riemann (ICG, Berlin)



W. Zulehner. Mater. Sci. Eng. B, 73(1):7-15, 2000

Introduction

Axisymmetric quasi-stationary FZ model

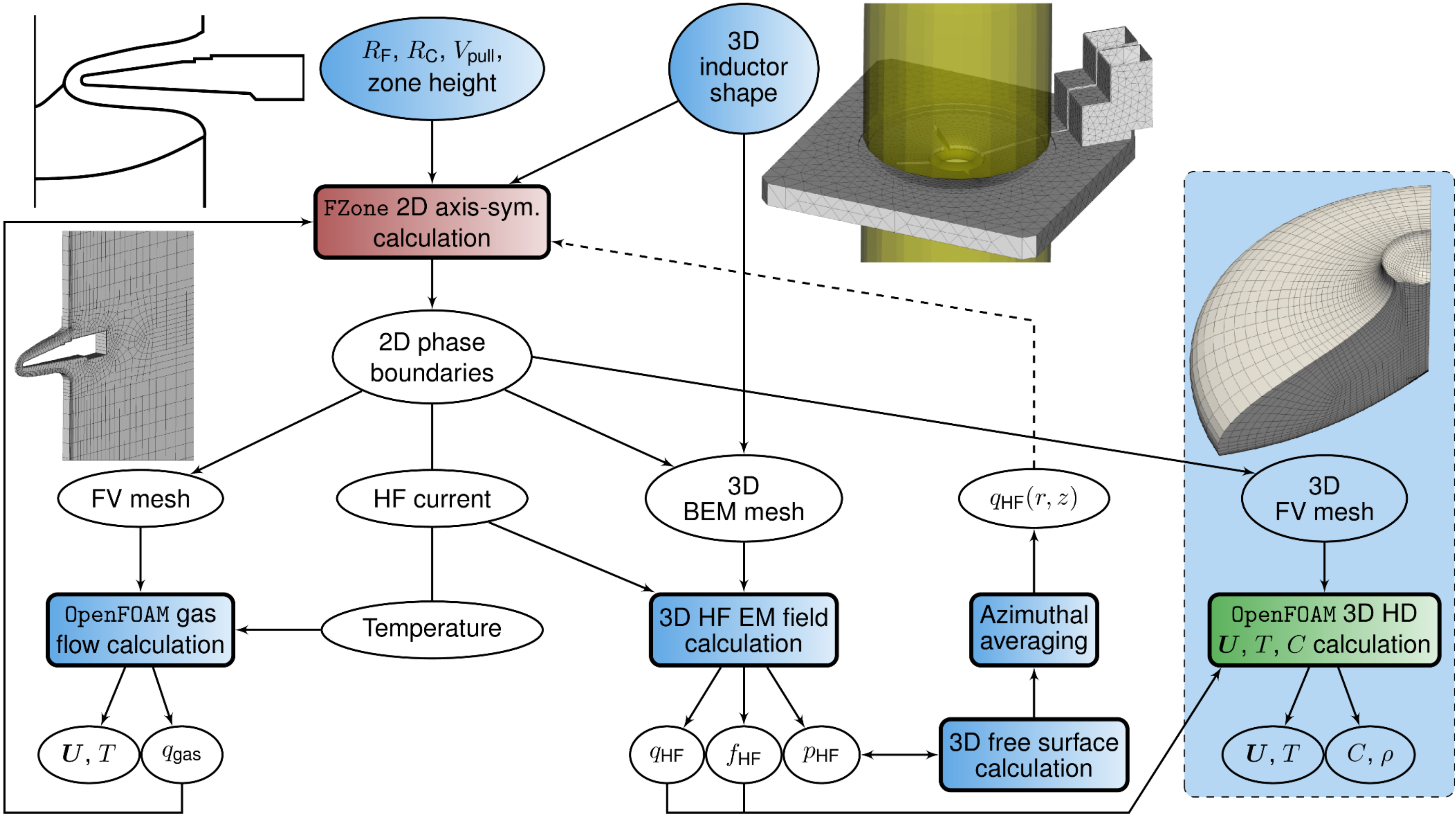


- **High-frequency EM field**
- Thermal radiation
- Heat transfer in crystals, melt and reflector
- Free melt surface shape, solid-liquid interface and open melting front positions

- Model implemented in the program **FZone** (Ratnieks, 2003)
- Further development of the model is still ongoing

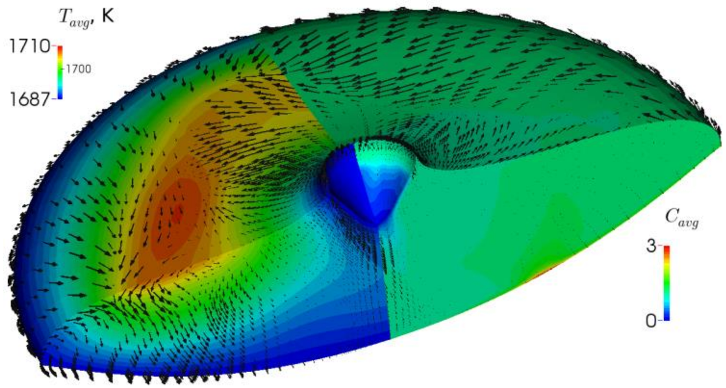
Introduction

Actual mathematical model



Mathematical models

3D melt flow and dopant transport



The continuity and momentum equations

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

$$\frac{\partial \boldsymbol{U}}{\partial t} + (\boldsymbol{U}\nabla)\boldsymbol{U} = -\frac{\nabla p}{\rho_0} + \nu \nabla^2 \boldsymbol{U} + \boldsymbol{g}\beta(T - T_0)$$

EM and Marangoni surface forces

$$\boldsymbol{f} = \frac{1}{4}\mu_0 \delta \nabla_s j^2 + M \nabla_s T$$

The temperature equation

$$\frac{\partial T}{\partial t} + (\boldsymbol{U}\nabla)T = \frac{\lambda}{\rho c_p} \nu \nabla^2 T$$

The dopant transport equation

$$\frac{\partial C}{\partial t} + (\boldsymbol{U}\nabla)C = D\nabla^2 C$$

Segregation boundary condition

$$D\frac{\partial C}{\partial n} = V_{\mathrm{pull}}(1 - k_0) C \cos\theta$$

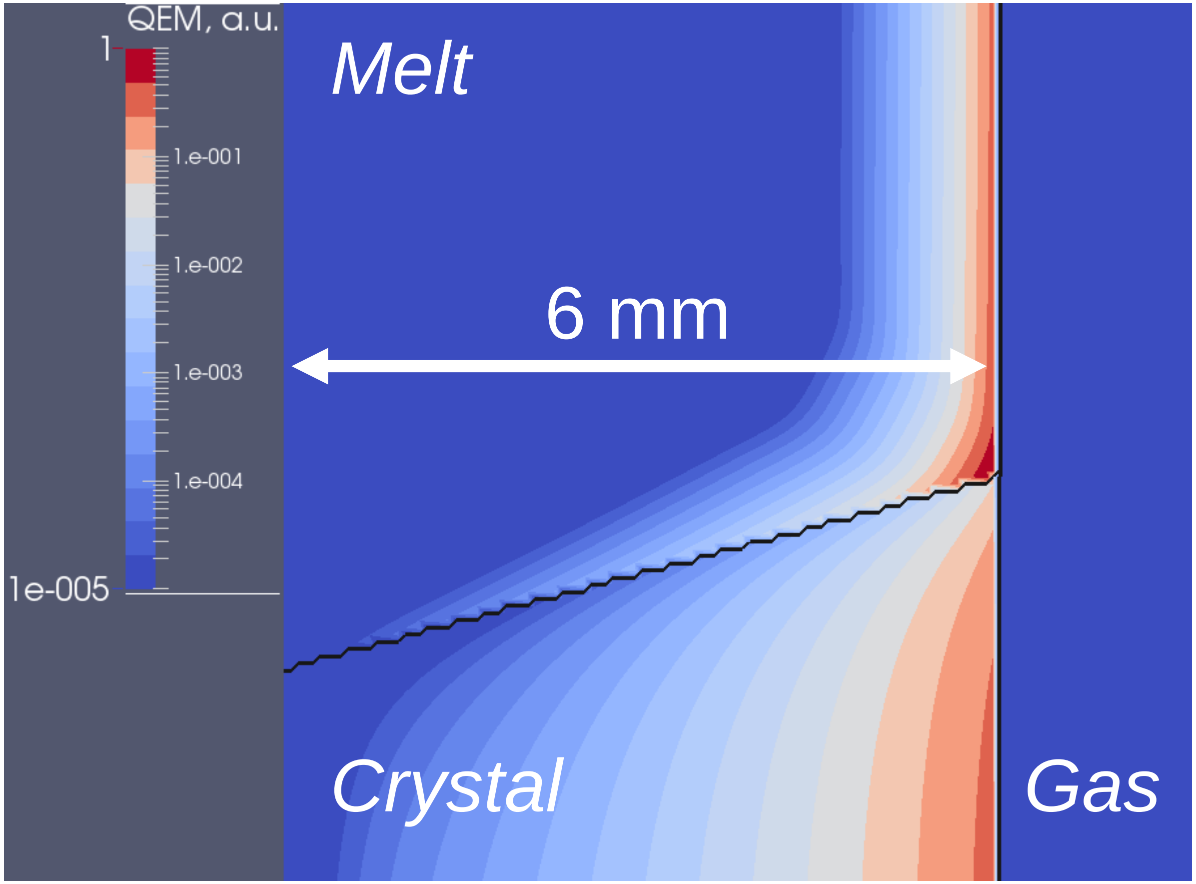
Resistivity of a crystal

$$\rho = \frac{1}{k_0 C}$$

Mathematical models

EM correction at external triple point

The HF approximation is not precise in the vicinity of solid-liquid interface, where skin depth changes 5 times

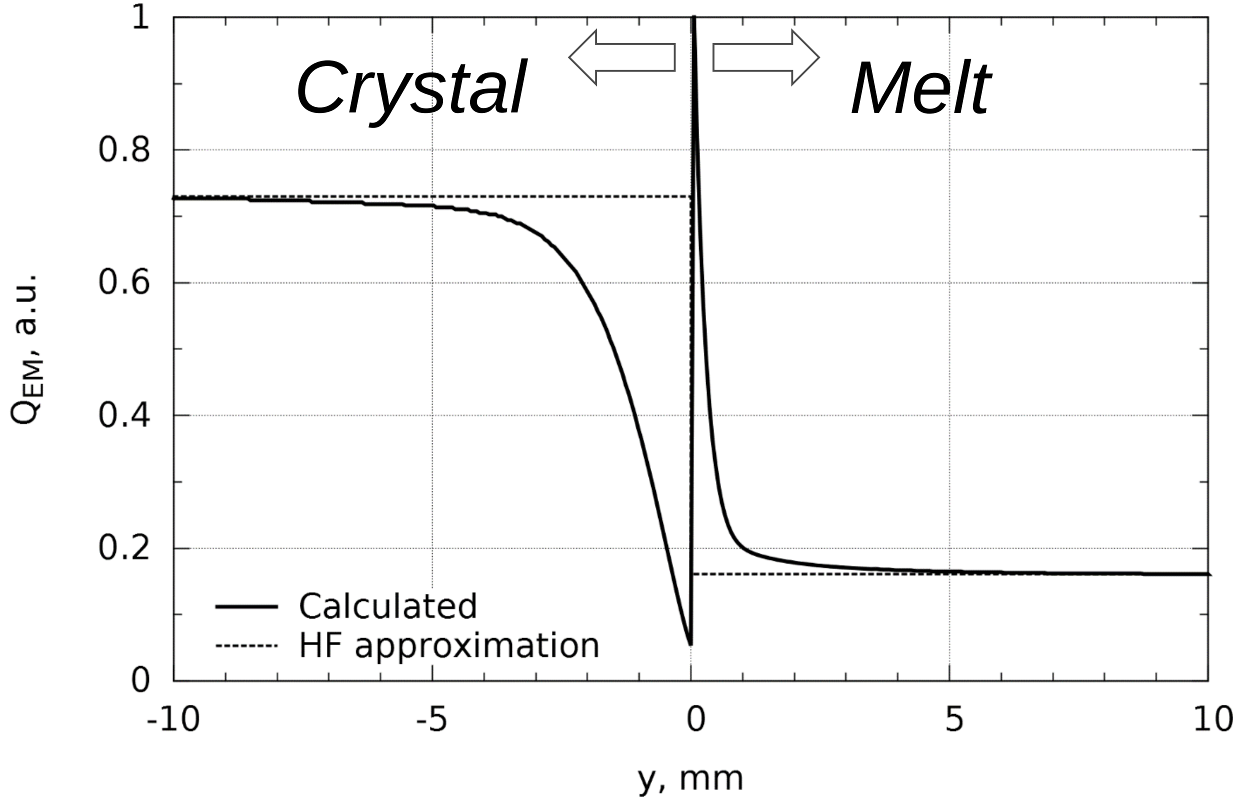


- A local analysis of the EM field distribution in the vicinity of external triple point was carried out (complex vector potential formulation)
- At the ETP, more power is induced in the melt and less in the crystal

< Induced EM power density

Mathematical models

EM correction at external triple point

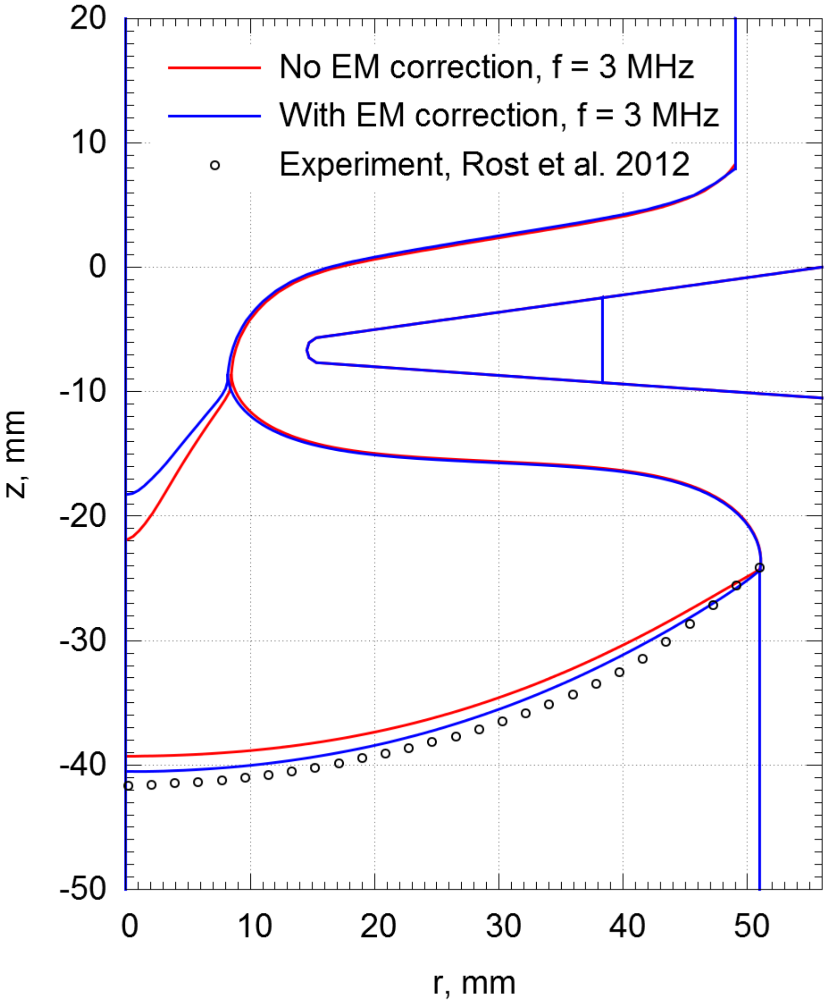


^ Linear induced EM power

- At the ETP, more power is induced in the melt and less in the crystal
- The result of local analysis was included in FZone as correction to EM heat sources at free melt and crystal side surfaces

Calculation results

Shapes of phase boundaries

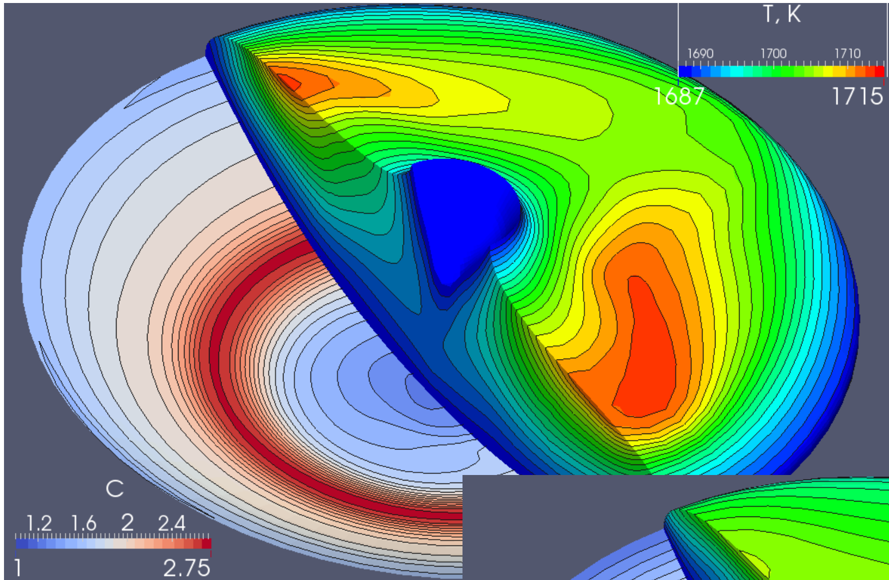


- 4” FZ system (ICG, Berlin) is considered
  - – H.-J. Rost, R. Menzel, A. Luedge, H. Riemann. JCG, 360:43-46, 2012
- When EM correction at ETP is included, higher inductor current is required to hold prescribed zone height (32.5 mm) and it leads to larger deflection of crystallization interface
- Crystallization interface shape with EM correction considered is closer to the experimental one

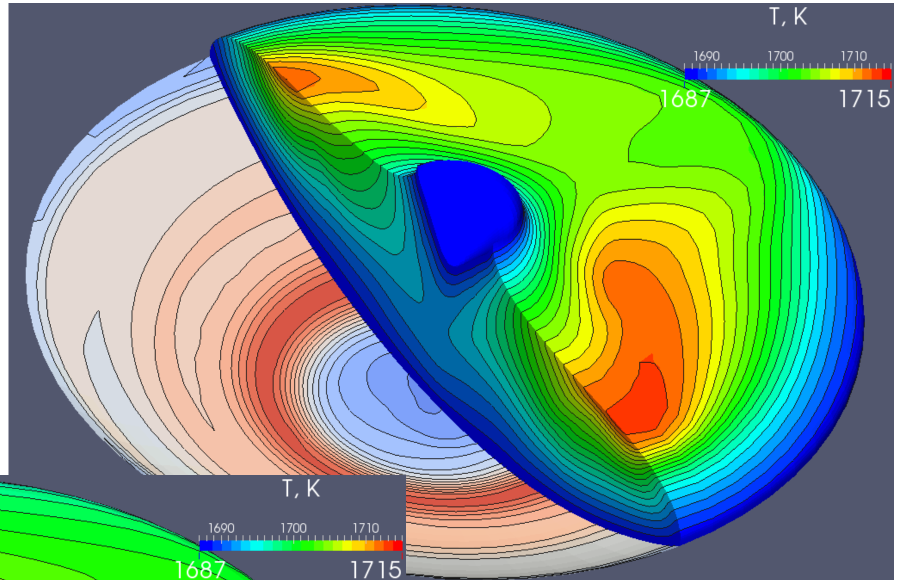
Calculation results

Melt temperature and dopant concentration

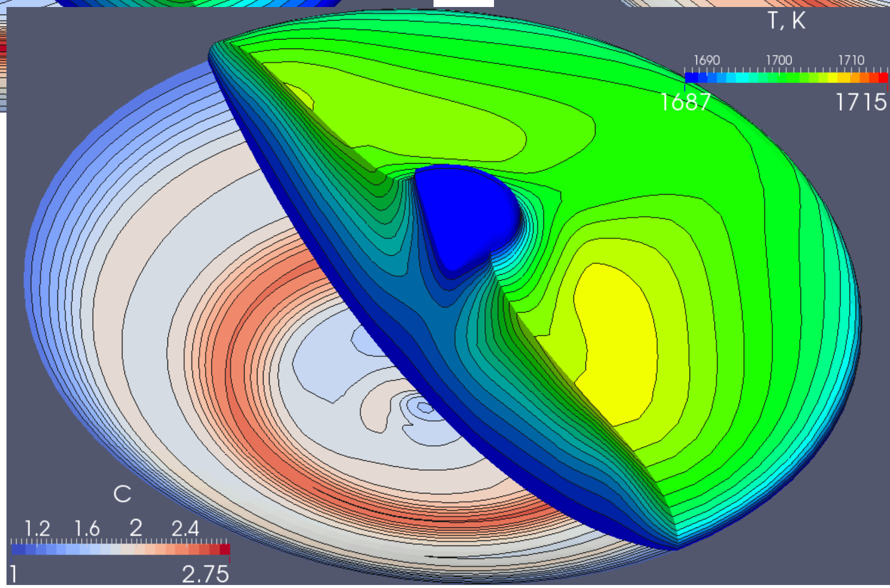
No EM correction



With EM correction



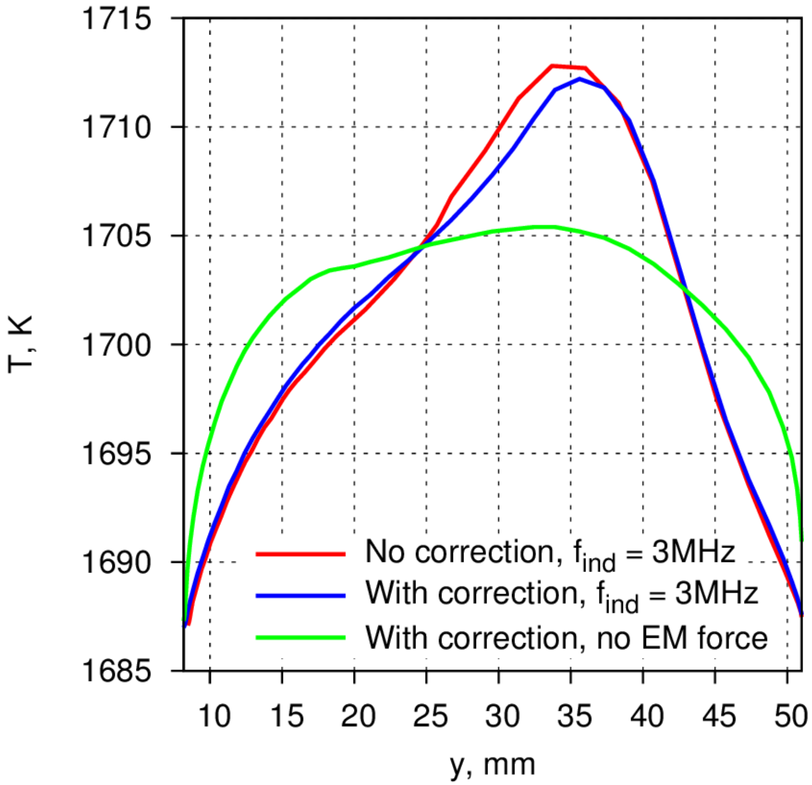
With EM correction, no EM force



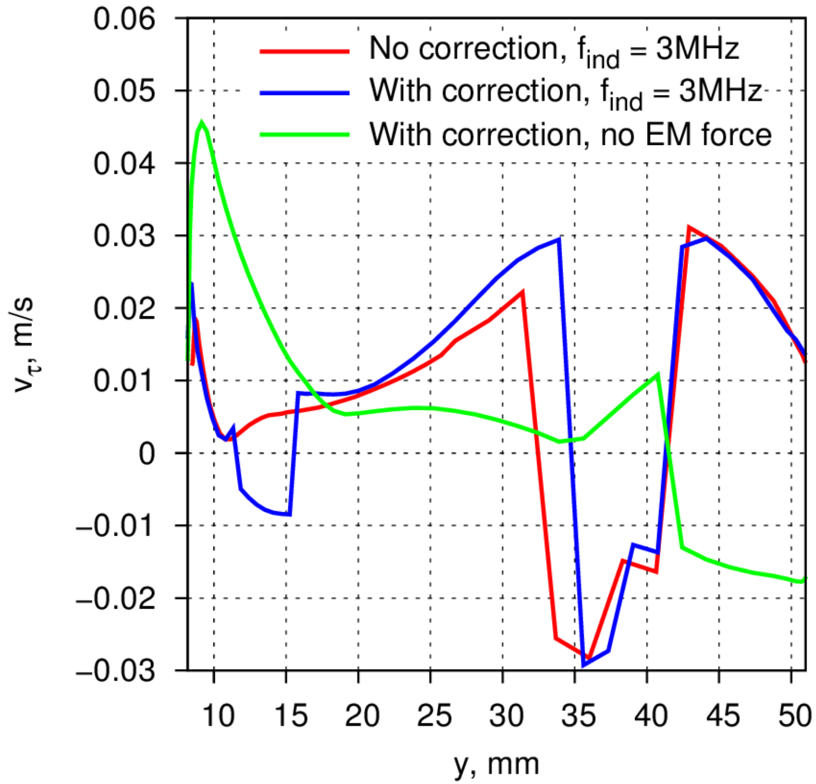
Calculation results

Melt temperature and velocity at free surface

Temperature



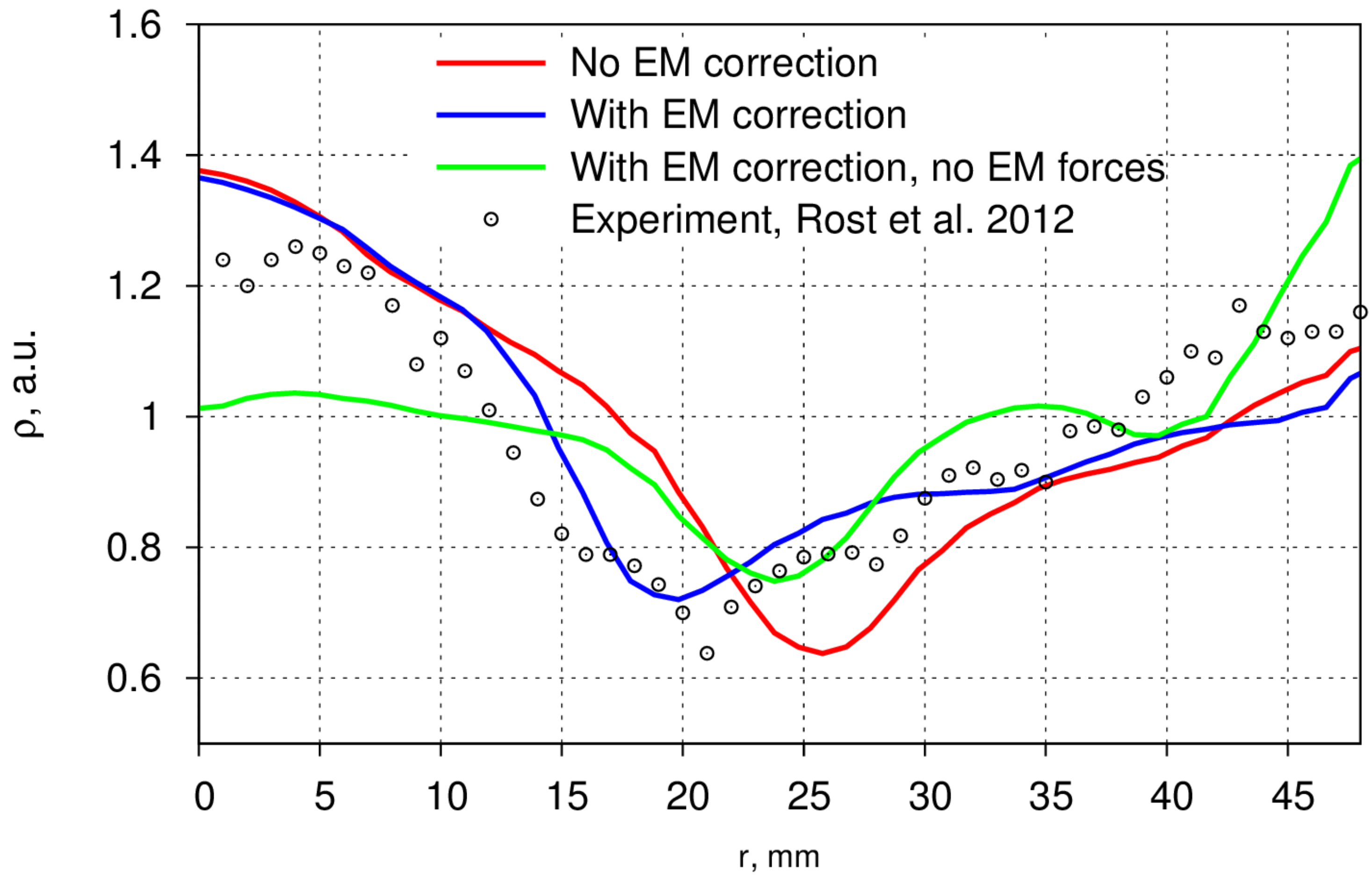
In-plane velocity



For a comparison, case with no EM force is also presented

Calculation results

Radial resistivity variation



$\Sigma(\rho-\rho_{exp})^2$ a.u.
0.80
0.38
0.88

For a comparison, case with no EM force is also presented

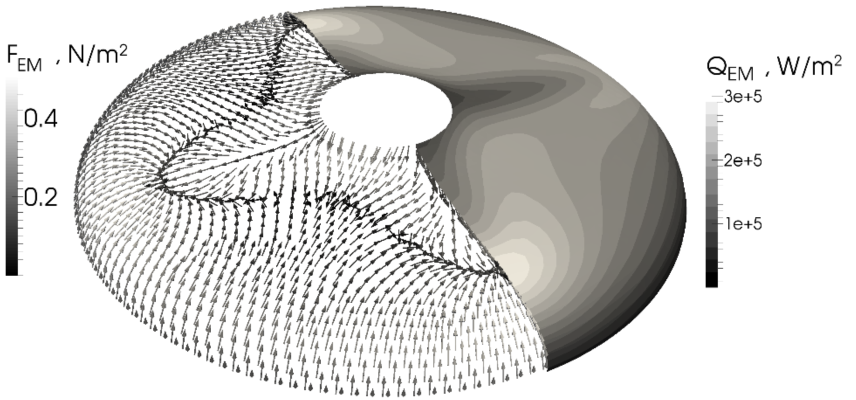
Conclusions and outlook

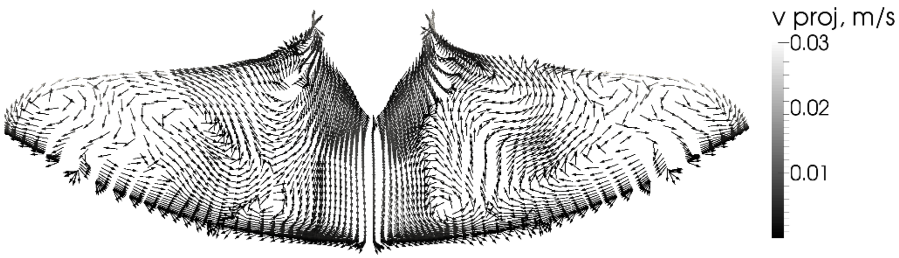
1. For silicon, the HF approximation cannot be used in the first 3 mm from a solid-liquid interface
2. Calculations with EM correction showed a better agreement of crystallization interface shape and RRV profile with experiment
3. The next aim of the study could be implementation of EM correction in 3D melt flow calculations, to observe its direct influence on the 3D melt flow and dopant distribution

Calculation results

Induced EM power density, EM force and meridional flow velocity

No EM correction





With EM correction