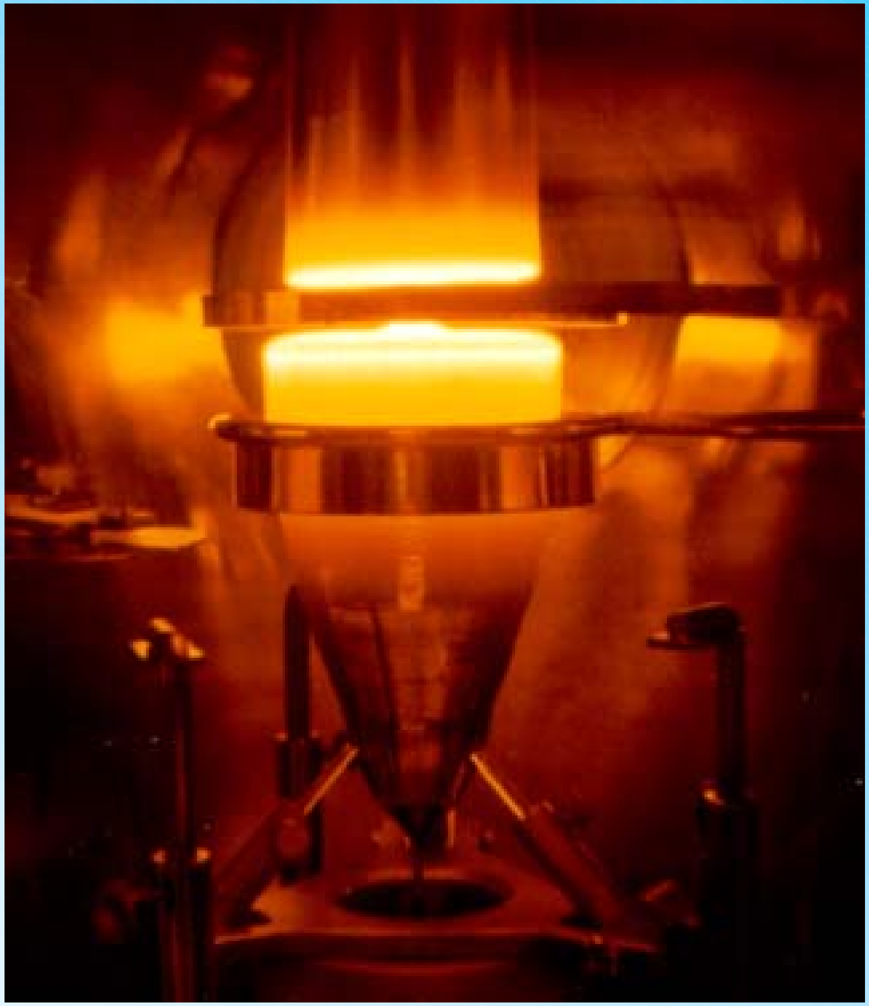
EU COST action P6 “Magnetofluiddynamics“
Working Group “Use of magnetic fields in crystal growth”
Workshop
Use of magnetic fields in crystal growth
13.-14. June 2002, University of Latvia, Riga, Latvia

Numerical modelling of industrial FZ silicon crystal growth with magnetic fields

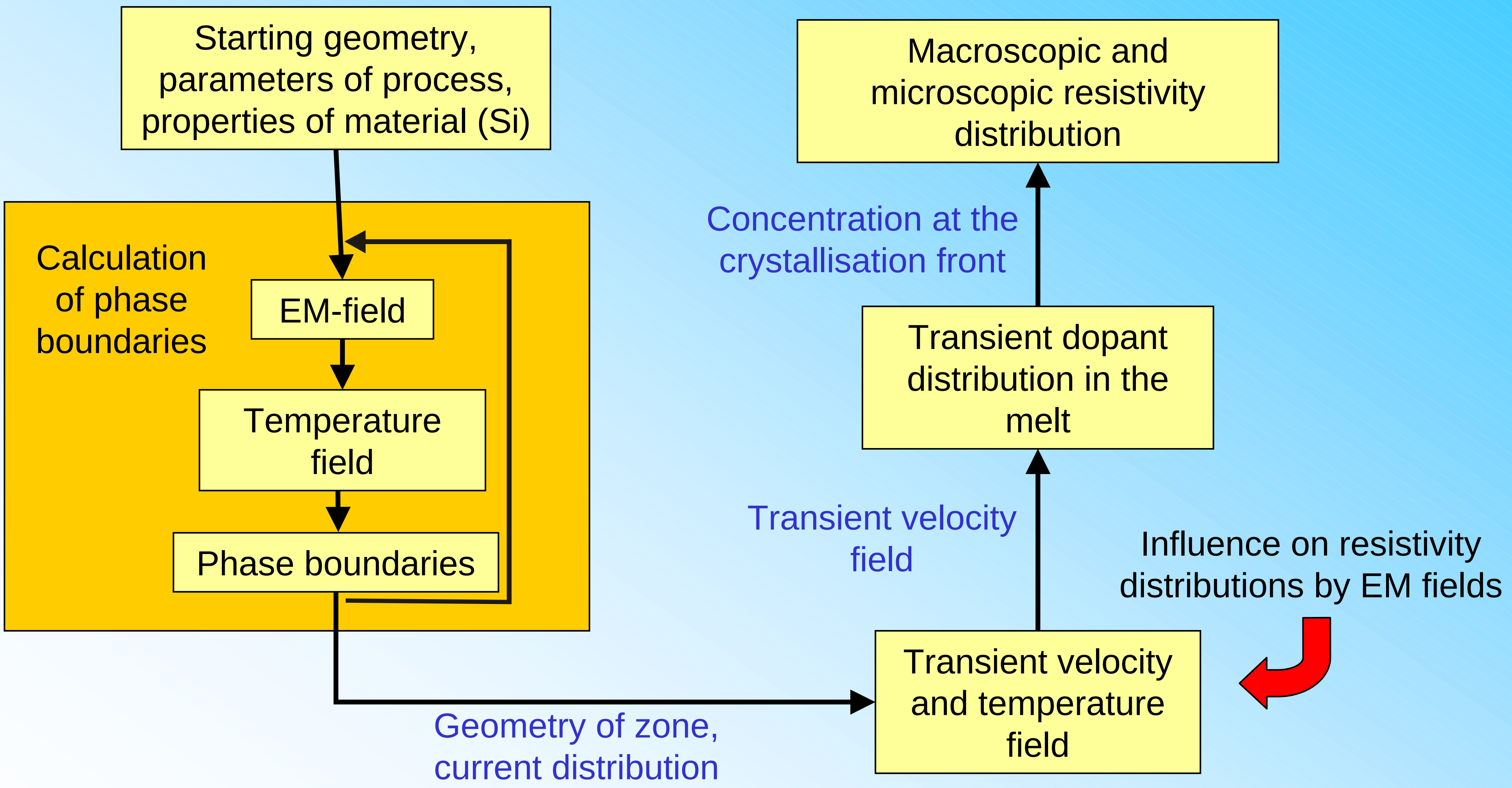
A. Muiznieks[1,2], G. Raming[3]
[1]Institute for Electrothermal Processes, University of Hanover, Germany
[2]Department of Physics, University of Latvia
[3]Wacker Siltronic AG, Burghausen, Germany

Floating Zone (FZ) Growth Process

- 99 % semiconductor devices from single silicon crystals
- Two industrial processes: Czochralski (95 %) and Floating Zone (5 %)
- FZ-Process: crystals up to 150 mm, 200 mm in development
- Goals:
  - cylindrical large diameter crystals
  - homogeneous dopant distribution
  - few impurities and defects



System of models



Starting geometry, parameters of process, properties of material (Si)

Calculation of phase boundaries

EM-field

Temperature field

Phase boundaries

Geometry of zone, current distribution

Transient velocity and temperature field

Transient velocity field

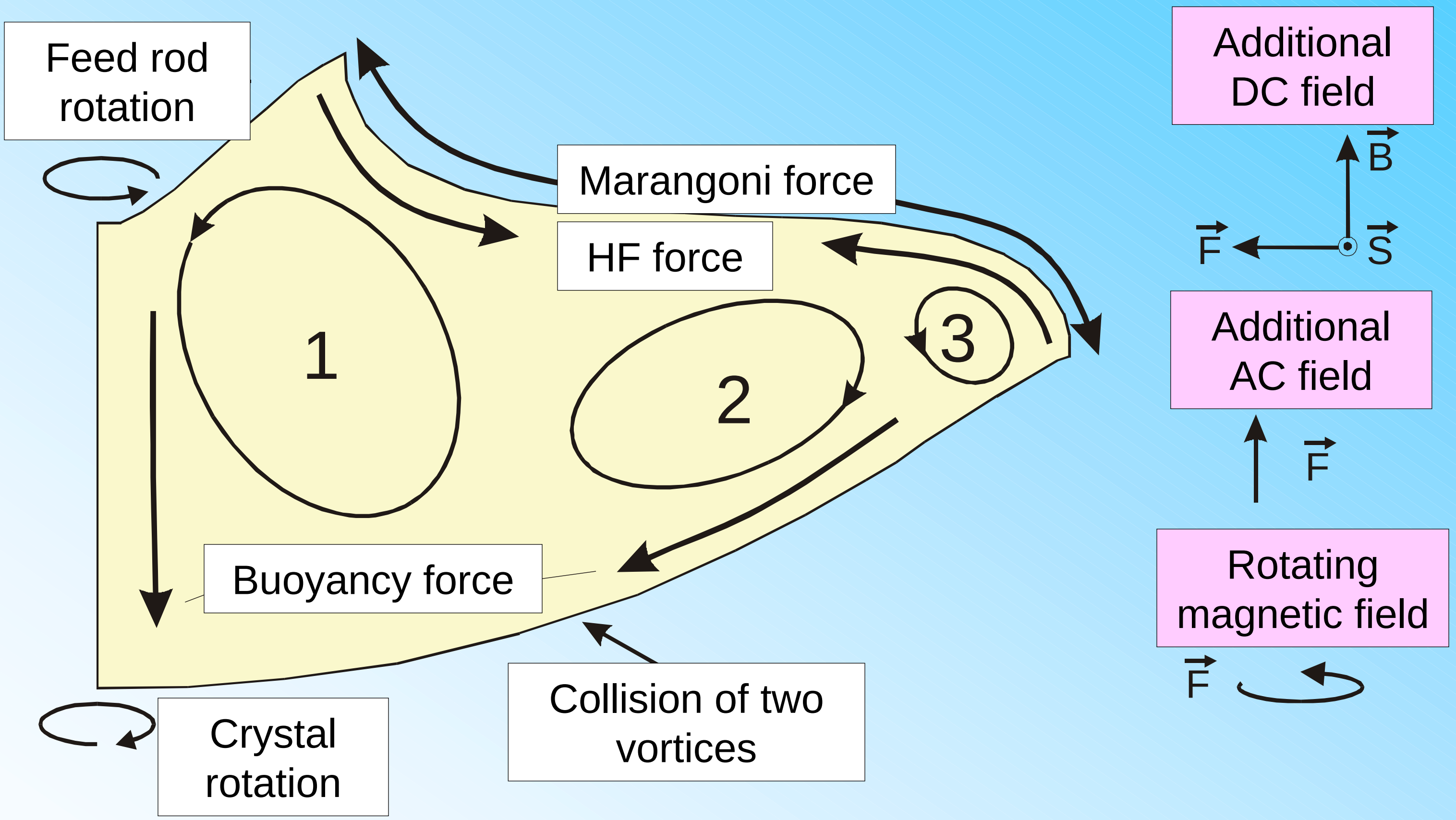
Transient dopant distribution in the melt

Concentration at the crystallisation front

Macroscopic and microscopic resistivity distribution

Influence on resistivity distributions by EM fields

Acting forces in the melt



Feed rod rotation

Marangoni force

HF force

Buoyancy force

Crystal rotation

Collision of two vortices

Additional DC field

Additional AC field

Rotating magnetic field

Melt flow is responsile for the resistivity distribution in the crystal

2D - calculations: 4“-process

Process parameters

Pulling velocity: 3.4 mm/min

Crystal rotation: 5,10,15 rpm

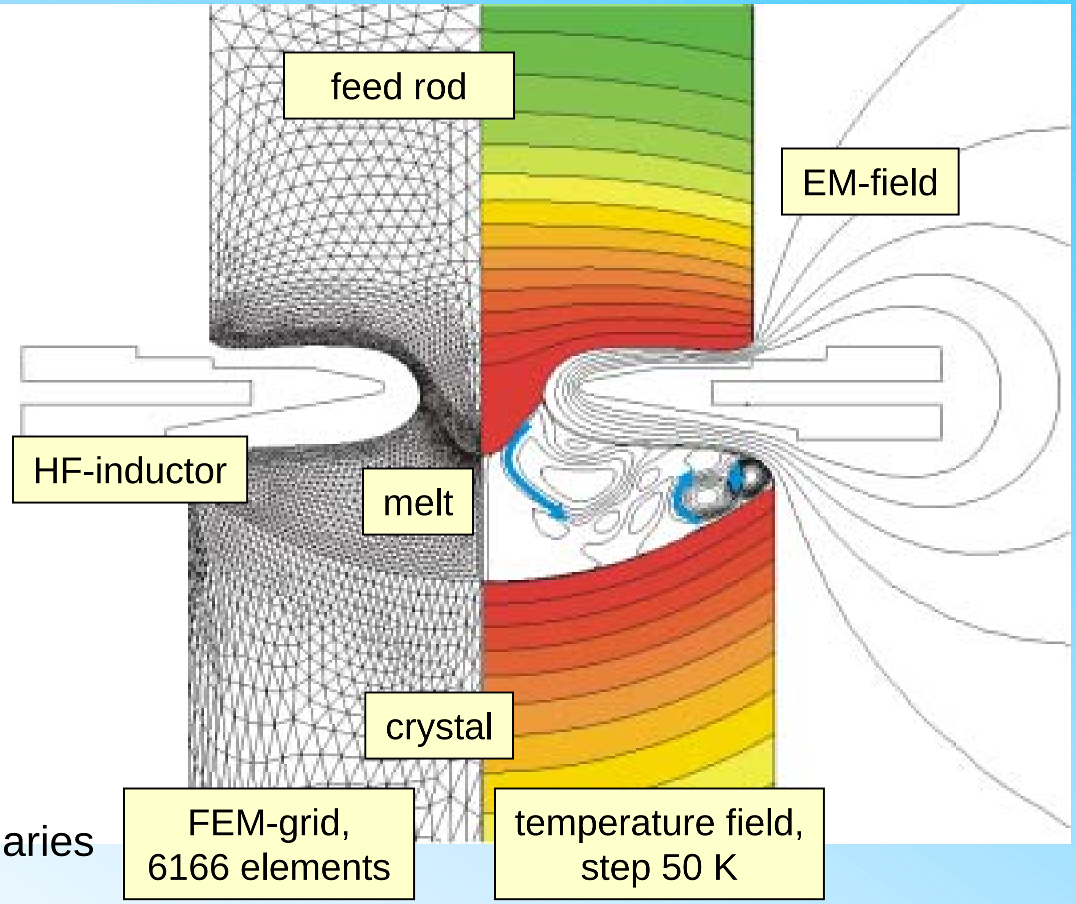
Feed rod rotation: -15 rpm

HF inductor current: 970 A

Frequency: 2.8 MHz

Crystal radius: 52.5 mm

Feed rod radius: 48.6 mm

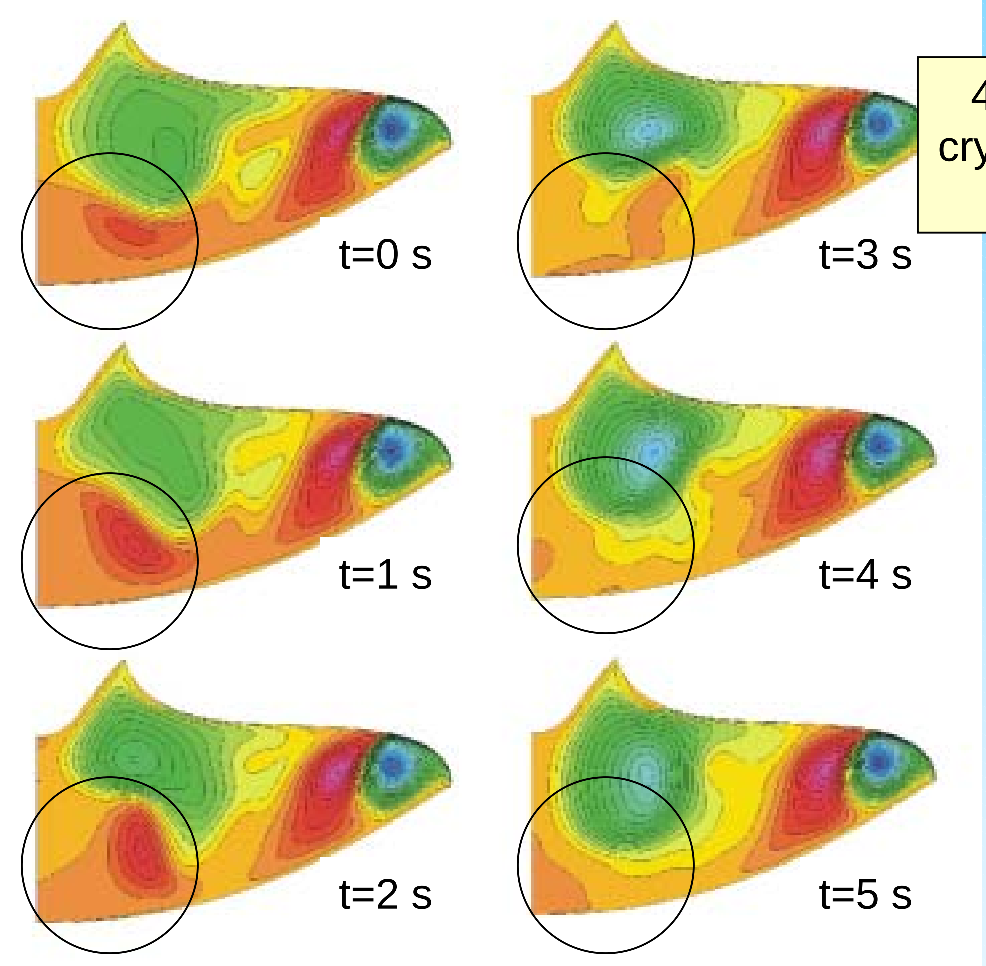


Results of calculations

EM-field, temperature field, phase boundaries

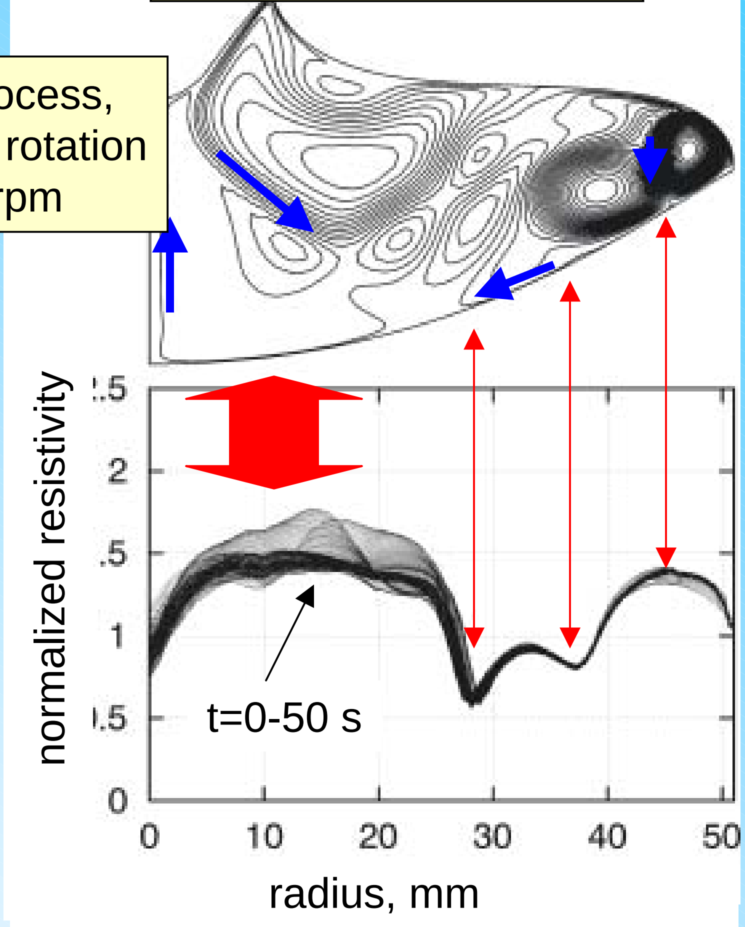
2D - calculations: characteristic melt flow

Package: CFD-ACE



Self developed program

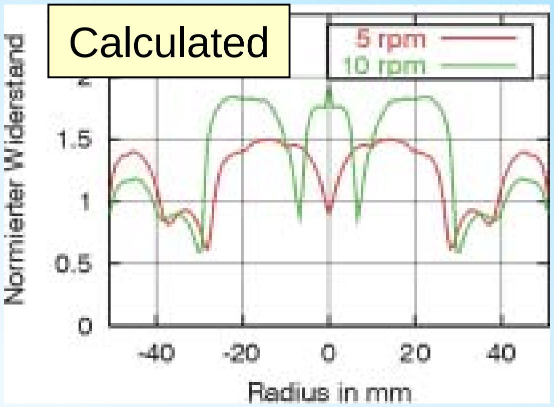
4“ process,
crystal rotation
5 rpm



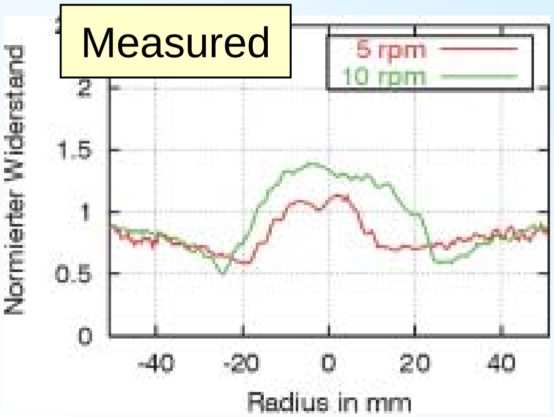
2D - calculations: comparison of resistivity profiles

Macroscopic radial resistivity profiles

Calculated

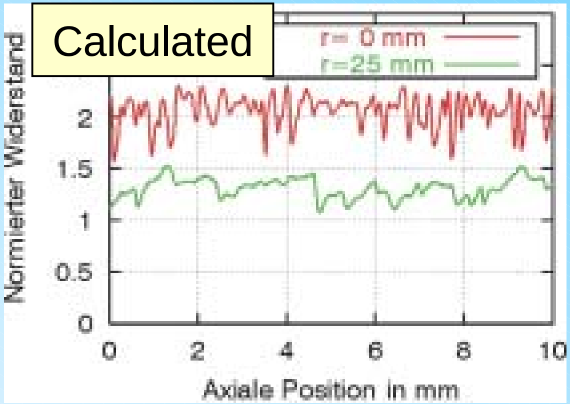


Measured

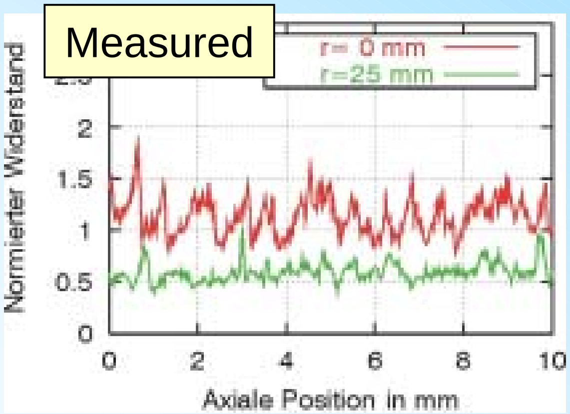


Microscopic axial resistivity profiles

Calculated



Measured

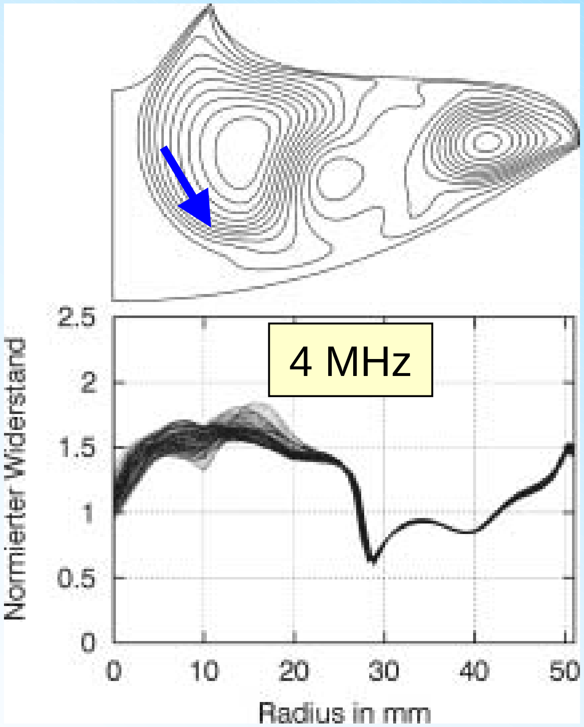


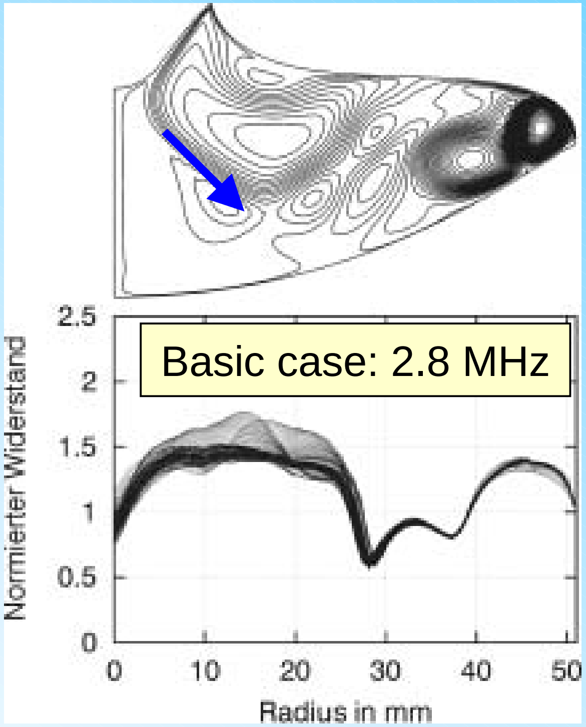
Agreements

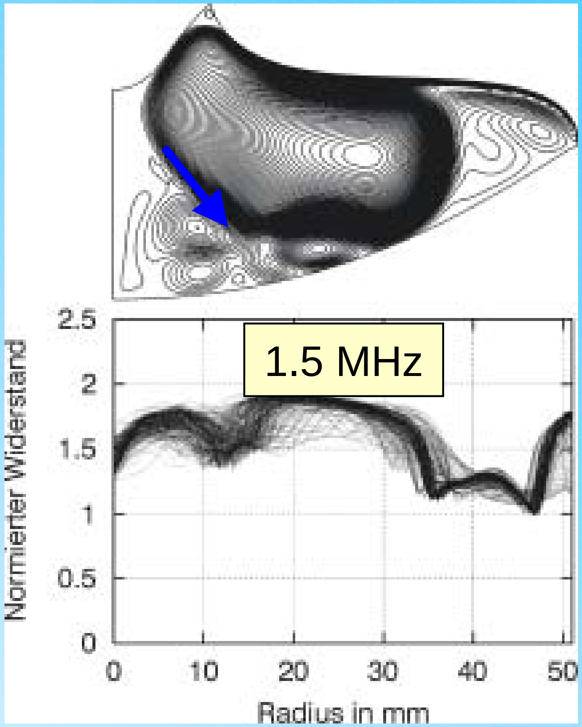
- Step shaped radial profiles
- Level in the middle grows with rotation rate
- Minimum has higher radius value at higher rotation rates
- Oscillations in the middle are stronger
- Oscillations period ca. 5 s = 0.28 mm

2D - calculations: HF-EM-field

Assumption: Heat power constant → EM-force ~ 1/frequency

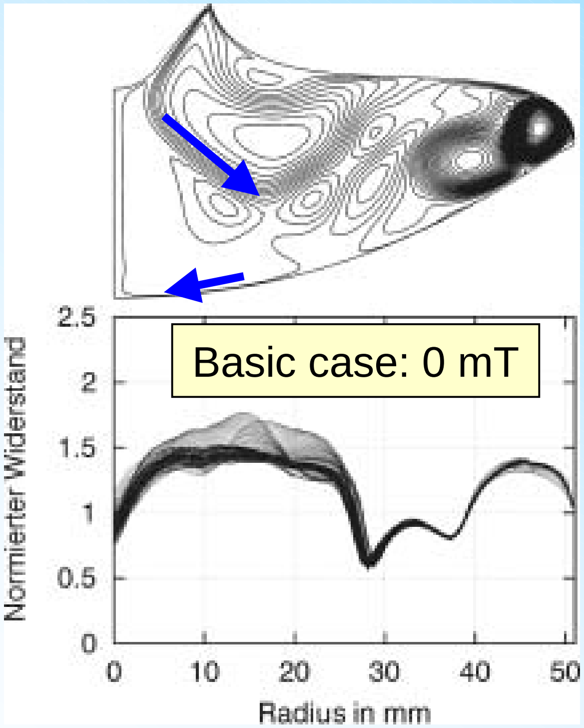


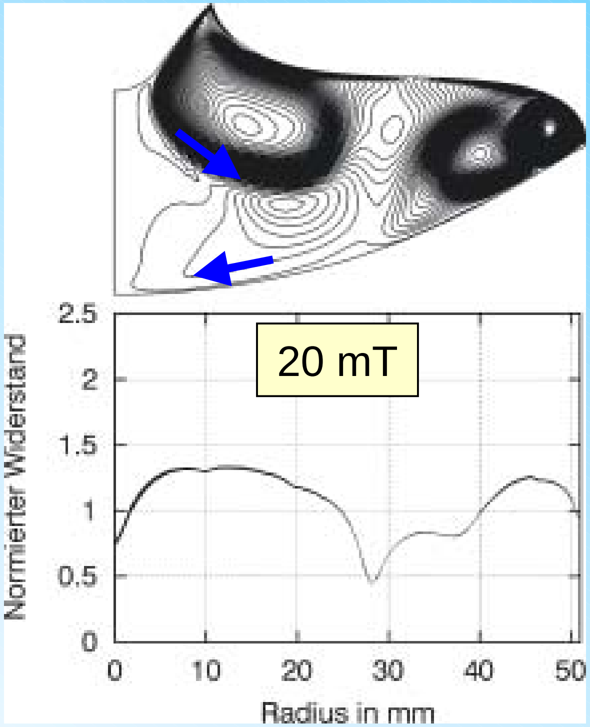


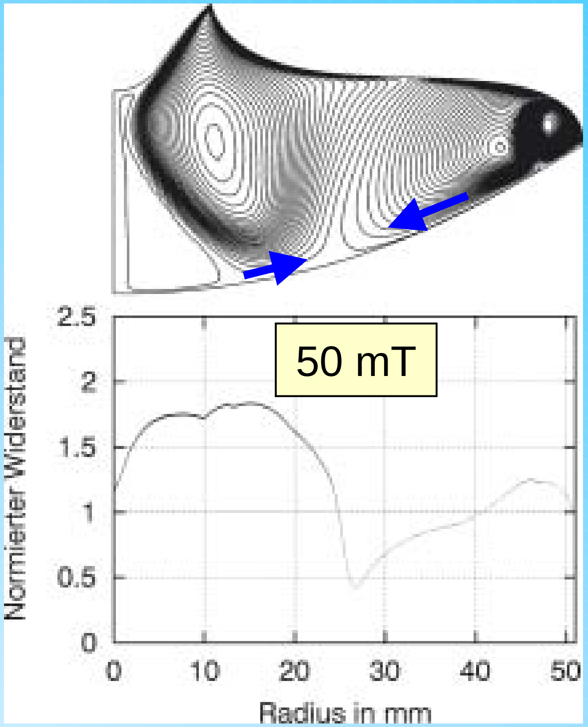


→ More intensive mixing at lower frequency:
- more homogeneous radial resistivity distribution
- stronger microscopic oscillations

2D - calculations: axial DC-field


Basic case: 0 mT


20 mT


50 mT

DC field damps melt flow:

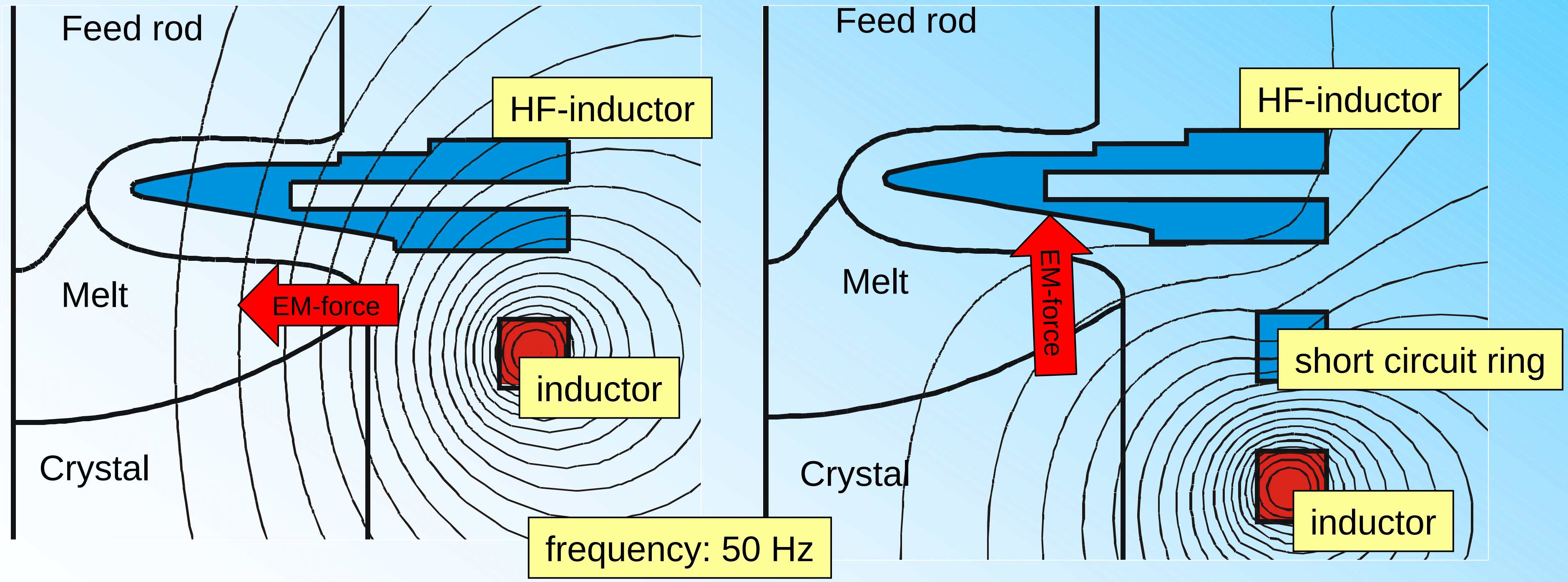
➡ - more inhomogeneous radial resistivity distribution
- less microscopic oscillations

2D - calculations: additional AC-field

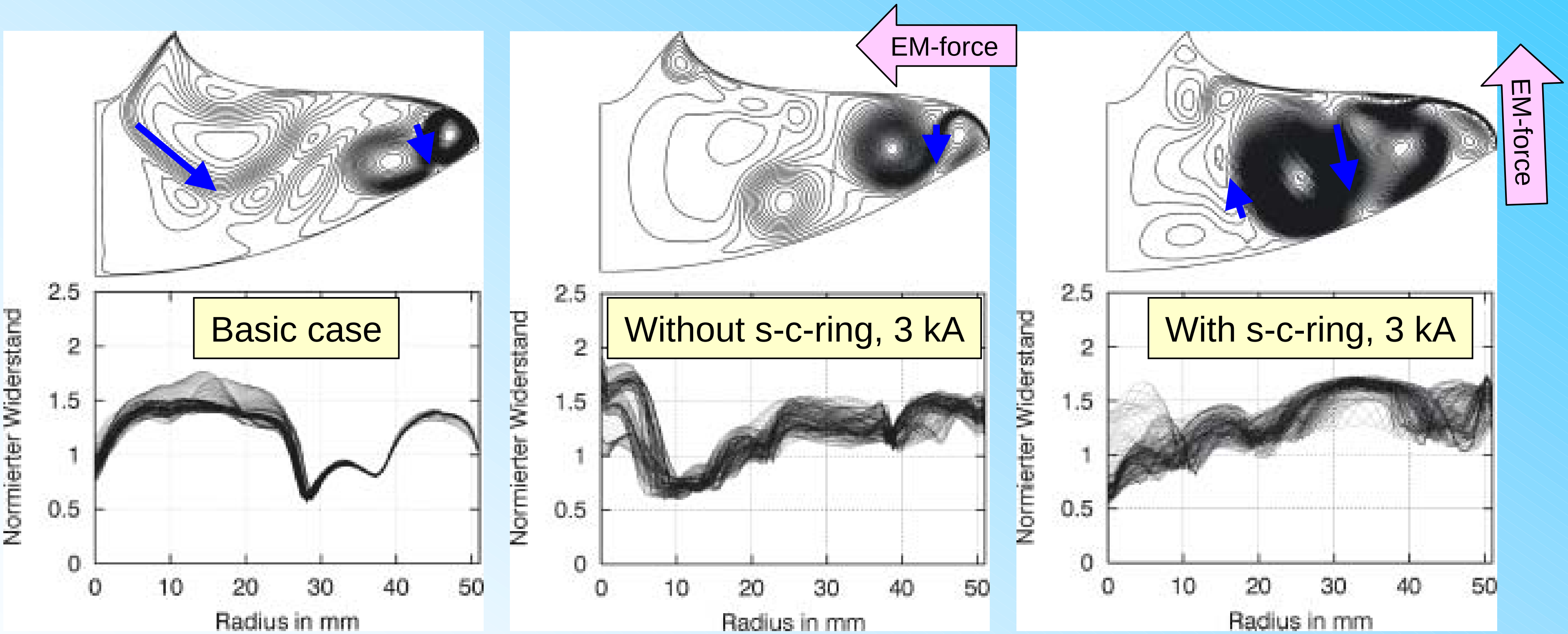
Geometry of additional inductors → EM-field calculation → Forces for melt flow

Without short circuit ring

With short circuit ring



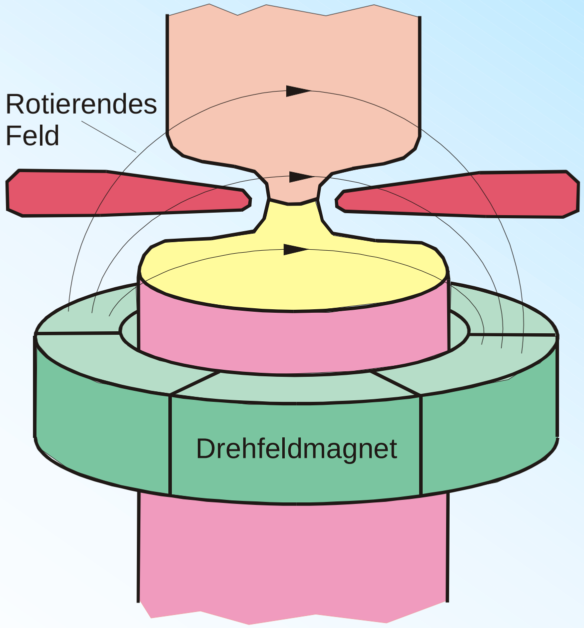
2D - calculations: additional AC-field

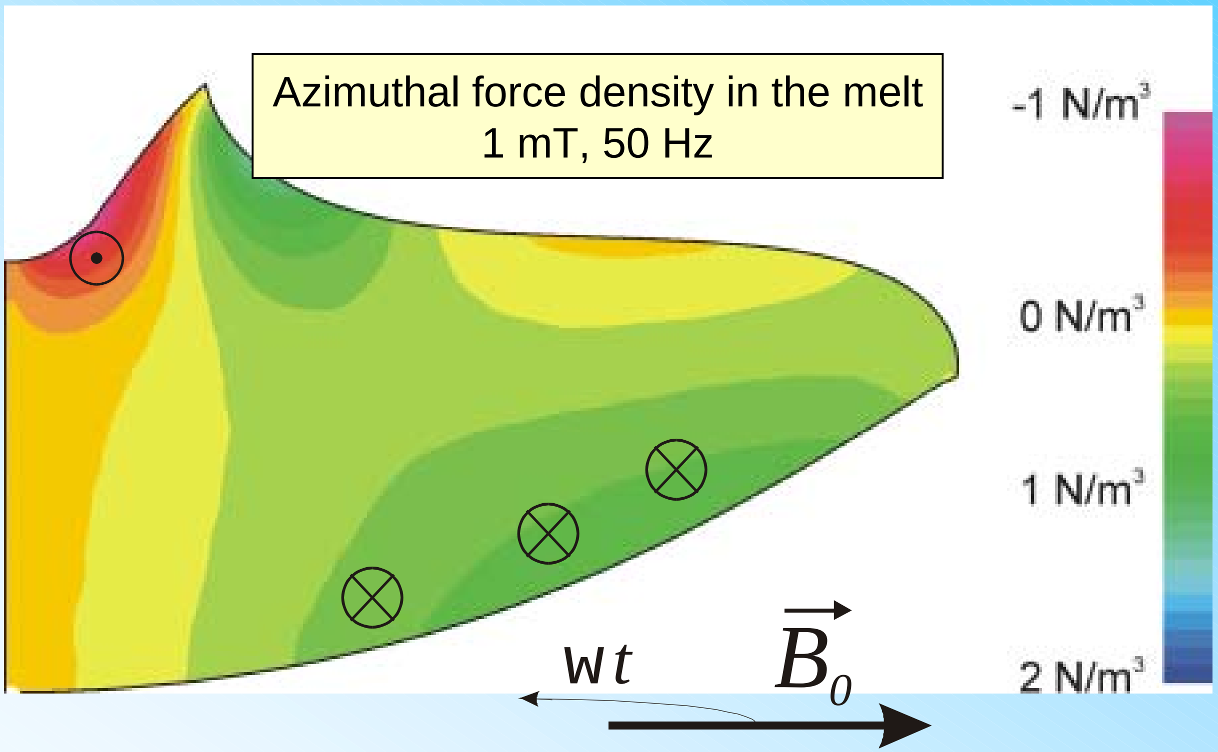


Additional AC-field amplifies melt mixing
- more homogeneous radial resistivity profiles
- stronger microscopic oscillations

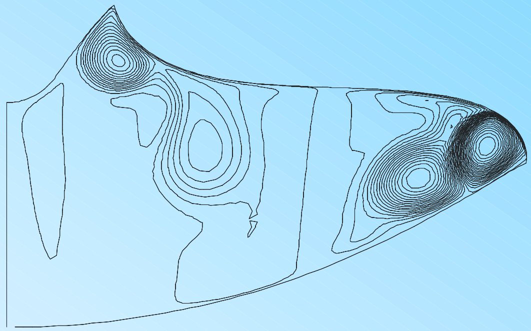
2D - calculations: rotating field

Homogeneous transversal magnetic field, rotating around crystal axis → Calculation of EM field distribution → **Forces in the melt**

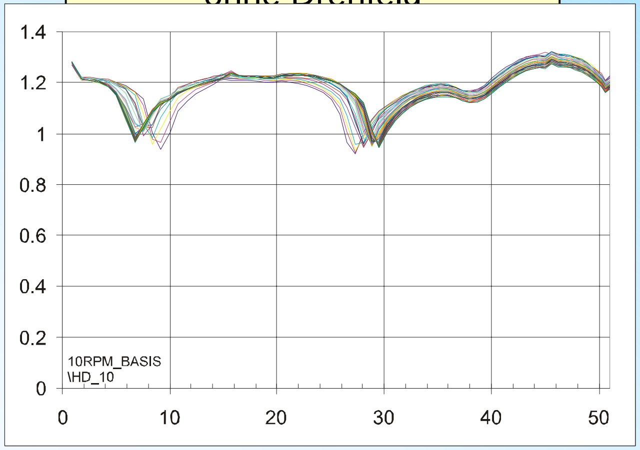


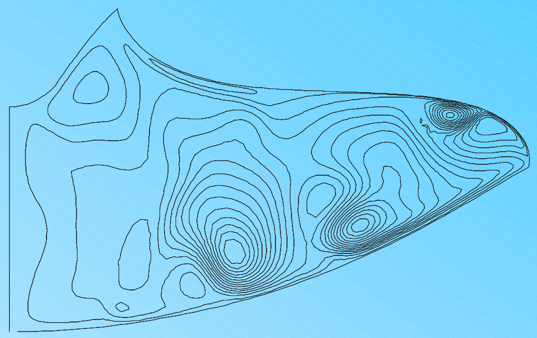

Azimuthal force density in the melt
1 mT, 50 Hz

2D - calculations: rotating field, the best case

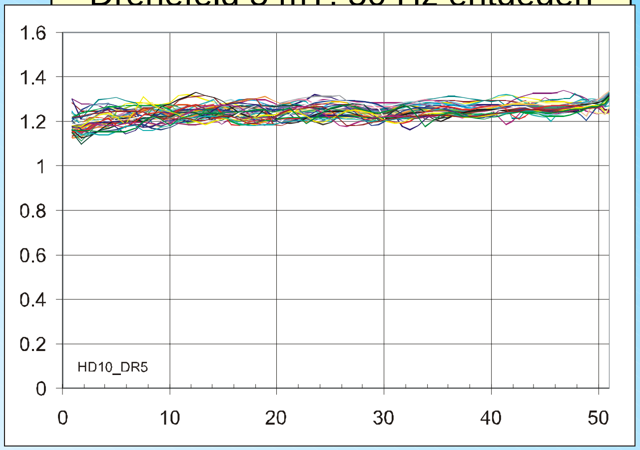


Rotation des Kristalls 10 rpm, ohne Drehfeld





Rotation des Kristalls 10 rpm, Drehefeld 5 mT, 50 Hz entgegen



➡ Industrial experiment (WSAG) has proved this result

3D - calculations: motivation and EM-calculation

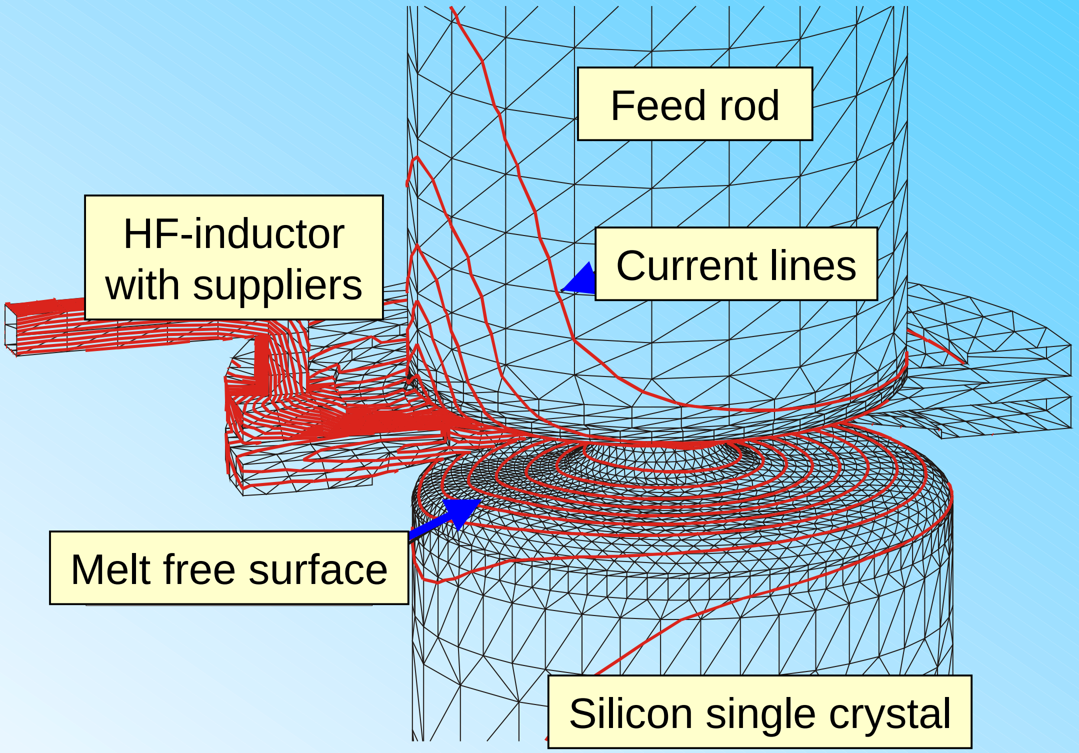
Motivation

- HF-induktor is always unsymmetric (unsymmetric forces and heat sources)
- Displacement of axis
- 3D instabilities

Procedure

- Calculation of 3D-EM-field
- Interpolation of heat sources and EM forces on HD grid
- Transient HD calculation: melt flow, temperature field, concentration field and resistivity distribution

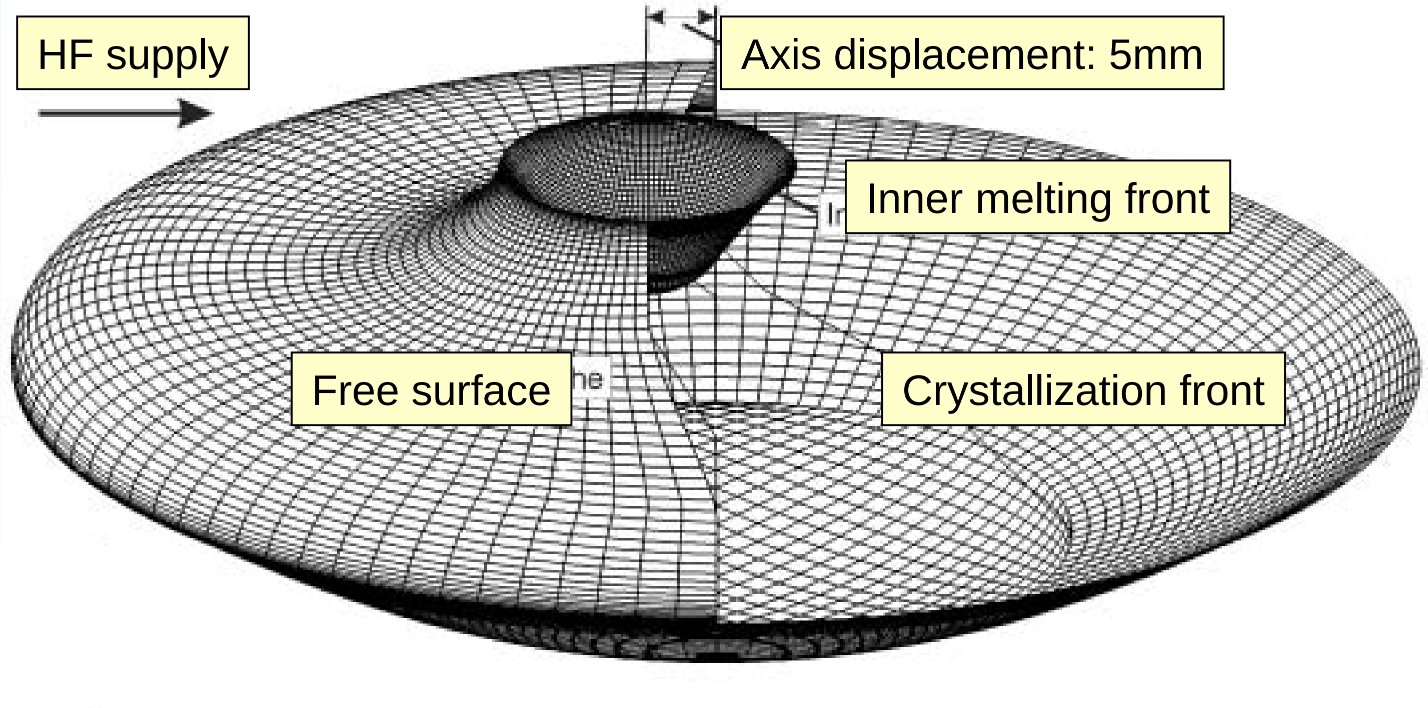
Discretisation of silicon surfaces and calculated current distribution



3D - calculations: hydrodynamics

- Package CFD-ACE with user-defined subroutines
- 220.536 Finite-Volumes
- Transient calculation

- Shape of zone from 2D-phase boundaries calculation
- Up to 5 mm axis displacement investigated



HF supply

Axis displacement: 5mm

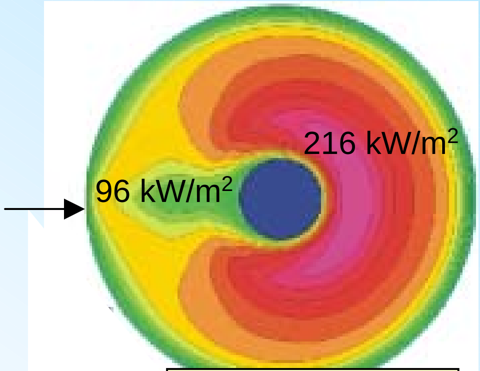
Inner melting front

Free surface

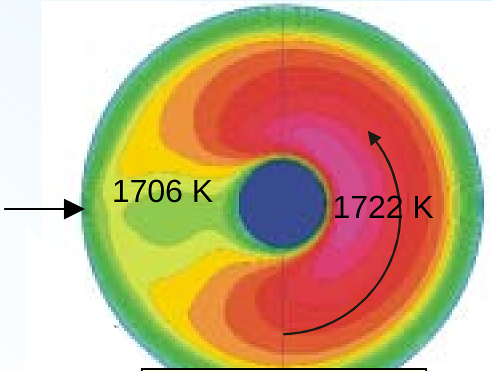
Crystallization front

3D - calculations: heat sources, temperature and melt flow

Without axis displacement

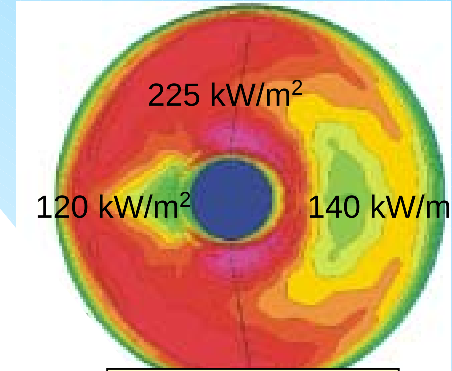


Heat sources

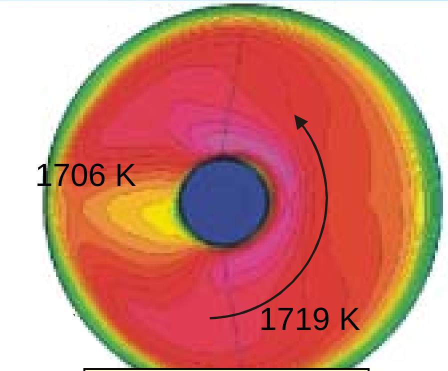


Temperature

With axis displacement

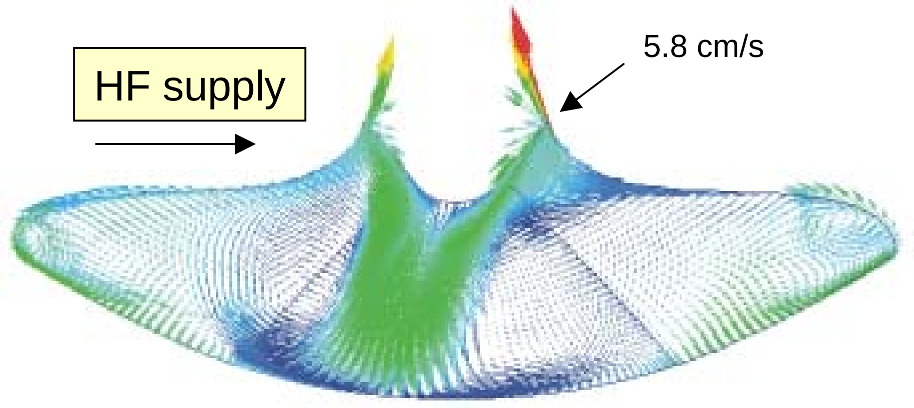


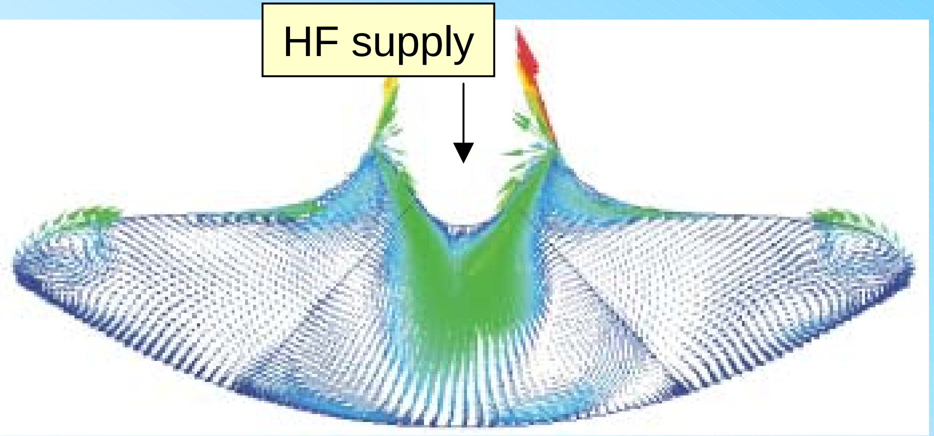
Heat sources



Temperature

Velocity field in two cross-sections



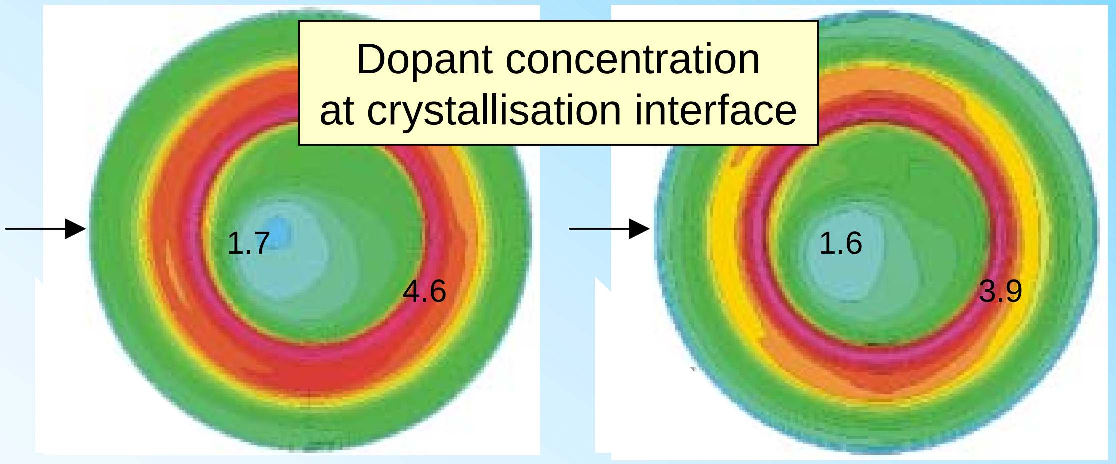


3D - calculations: resistivity distributions

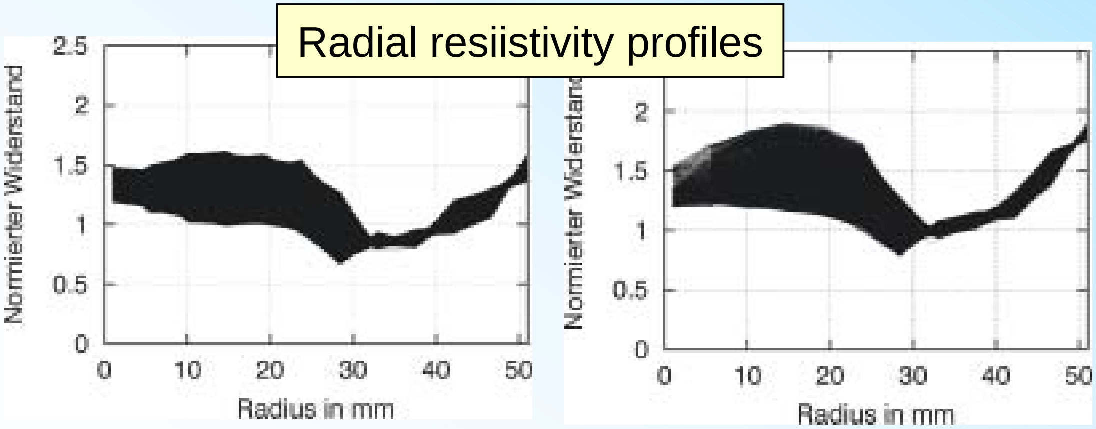
Without displacement of axis

With displacement of axis

Dopant concentration at crystallisation interface



Radial resiistivity profiles



Summary

- Melt flow has 3D character
- Displacement of axis has no strong influence
- Averaged resistivity distribution similar to 2D-results
- Transient features similar to 2D-calculations

Conclusions

- Industrial FZ growth systems for large silicon single crystals using EM fields are analysed
- Tools for 2D and 3D mathematical modelling are developed, verification with experiment is carried out (experiment at ICG-Berlin, WSAG-Burghausen)
- Investigation of influence of various magnetic fields on the melt flow and resistivity distribution is carried out
- The rotating magnetic field is found as the best way to improve the homogeneity of the resistivity distribution