Numerical Simulation Tools and Methods used at ETP

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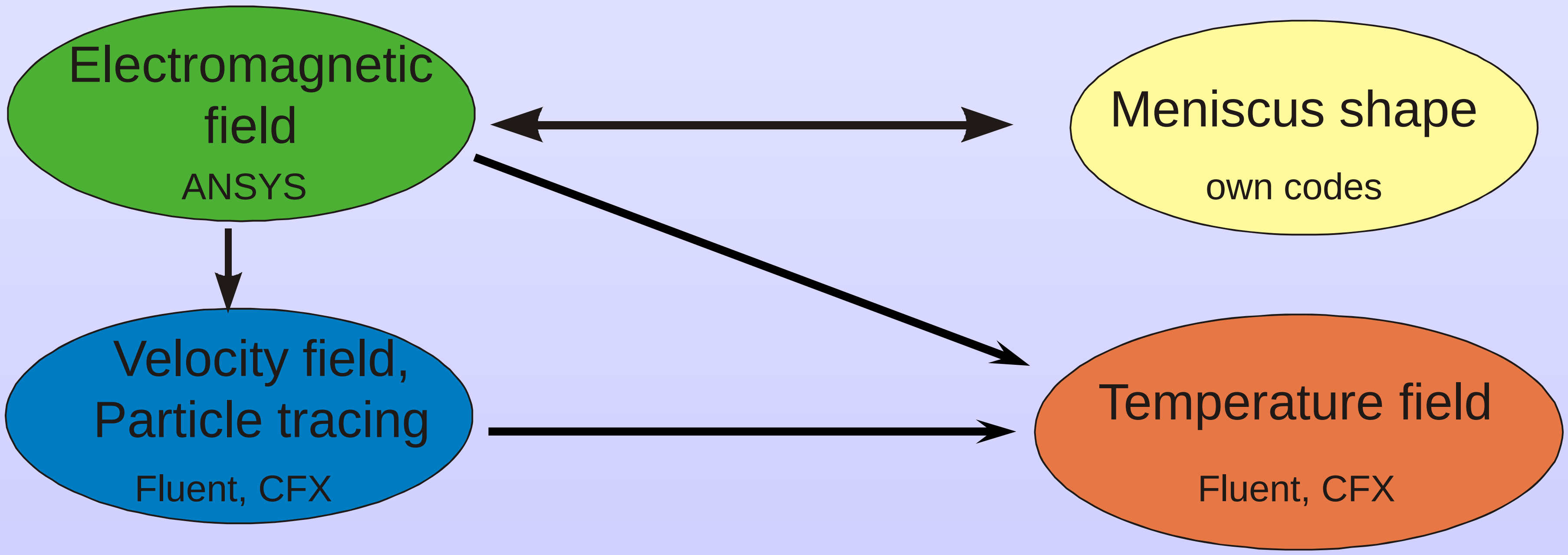
Content

- **Numerical simulation of melt flows in induction furnaces**
- **Analysis and design of complex induction heating processes**
- **Simulation of complex 3D temperature fields in systems for crystal growing of photovoltaic cells**
- **Optimal design and process control of induction heated systems using mathematical optimization**
- **Conclusion and future challenges**

Numerical simulation of melt flows in induction furnaces

- **Tools and general aspects**
- **Induction crucible furnace**
- **Induction channel furnace**
- **Induction skull melting**

Physical correlations in induction furnaces and used tools



ETP

Induction furnaces for melting

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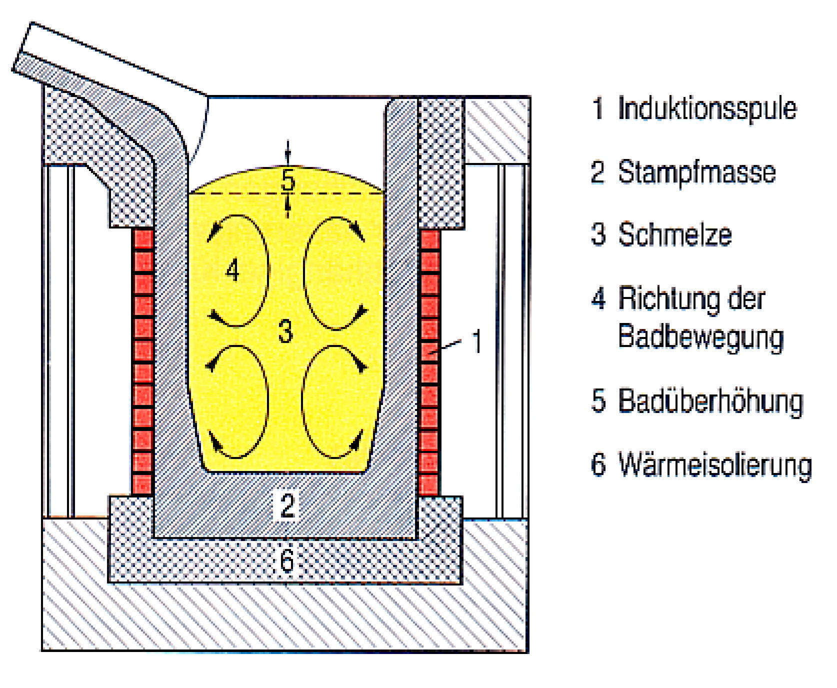
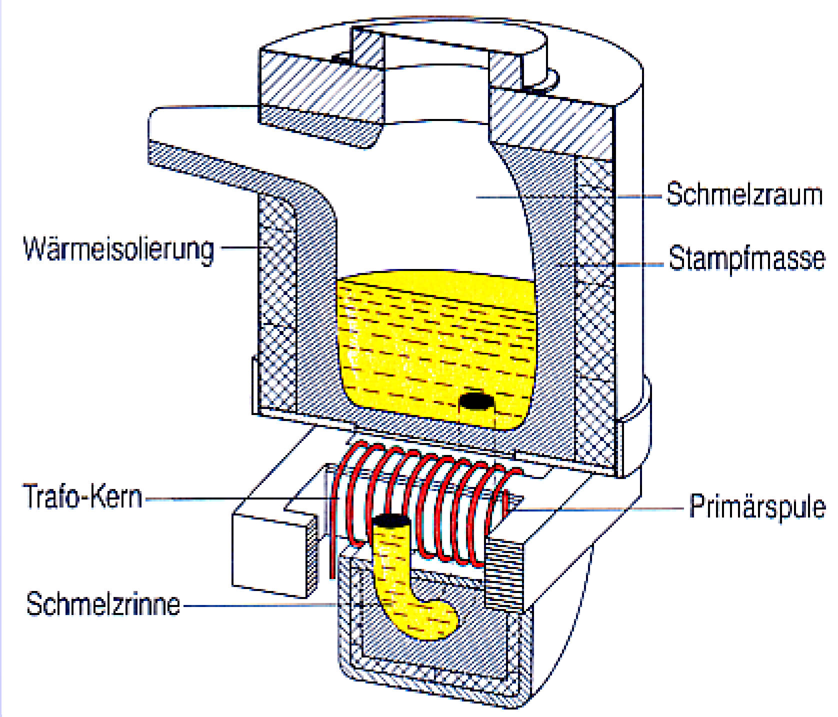
Induction crucible furnace



- Used mainly for melting
- Medium high efficiency
- Operating frequency: 50 ... 1000 Hz

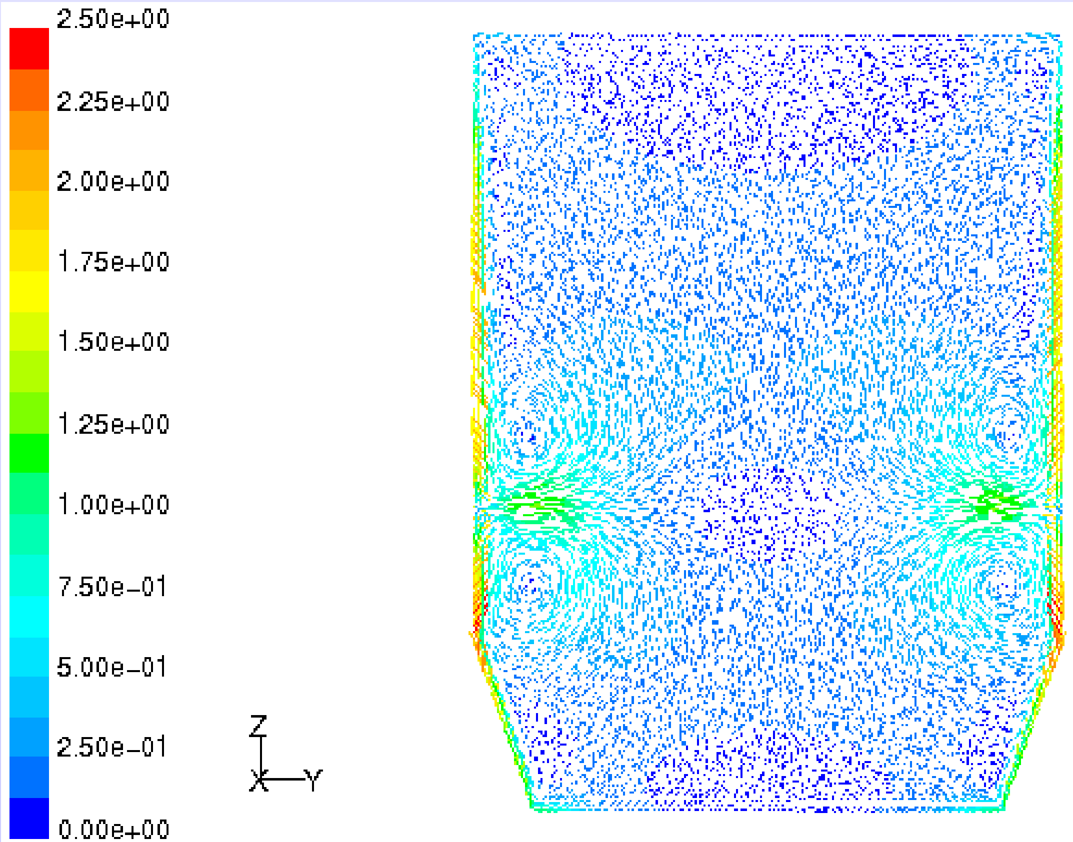
Induction channel furnace



- Used mainly for holding and pouring
- High efficiency
- Operating frequency: 50 Hz, 60 Hz

Source: RWE-Information Prozesstechnik

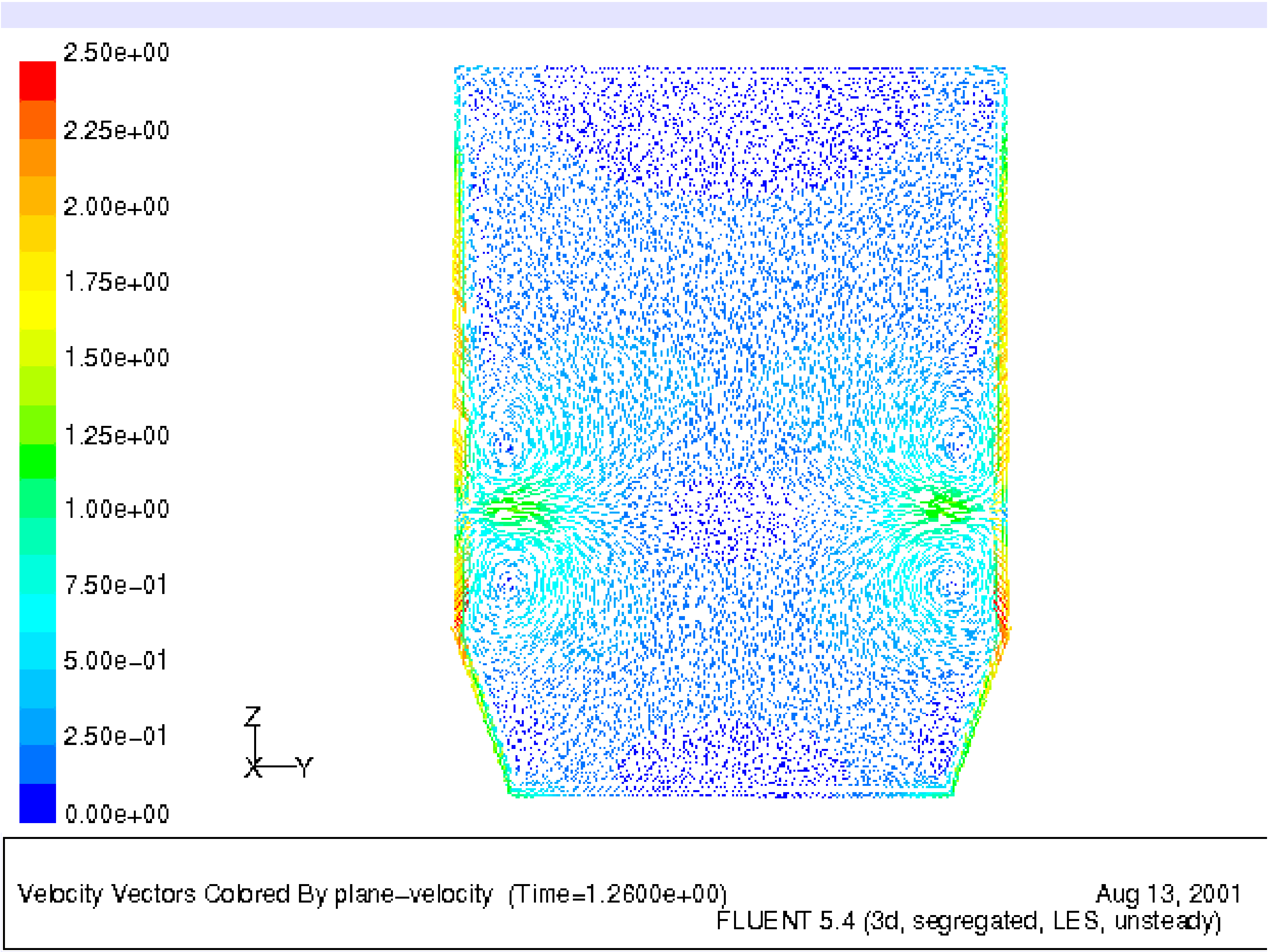
Transient 3D-Large Eddy Simulation of the melt flow in an industrial used induction crucible furnace



Medium frequency induction crucible furnace:

- 12 t grey cast iron
- power 9,3 MW
- frequency 230 Hz

crucible diameter: 1,20 m
crucible height: 1,30 m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2.25e+00
2.00e+00
1.75e+00
1.50e+00
1.25e+00
1.00e+00
7.50e-01
5.00e-01
2.50e-01
0.00e+00
Z
Y
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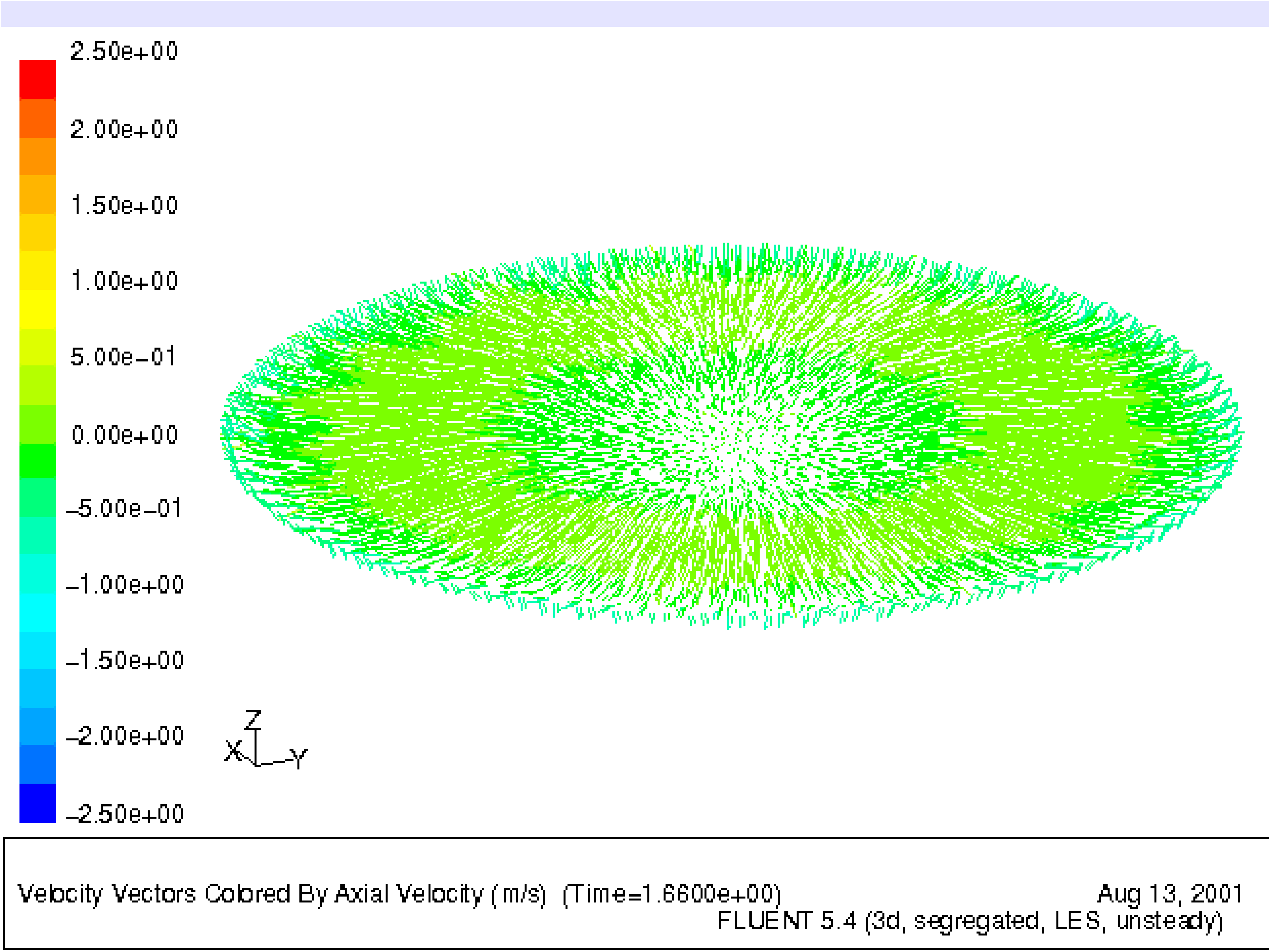
Velocity Vectors Colored By plane-velocity (Time=1.2600e+00)
Aug 13, 2001
FLUENT 5.4 (3d, segregated, LES, unsteady)


2.50e+00
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5.00e-01
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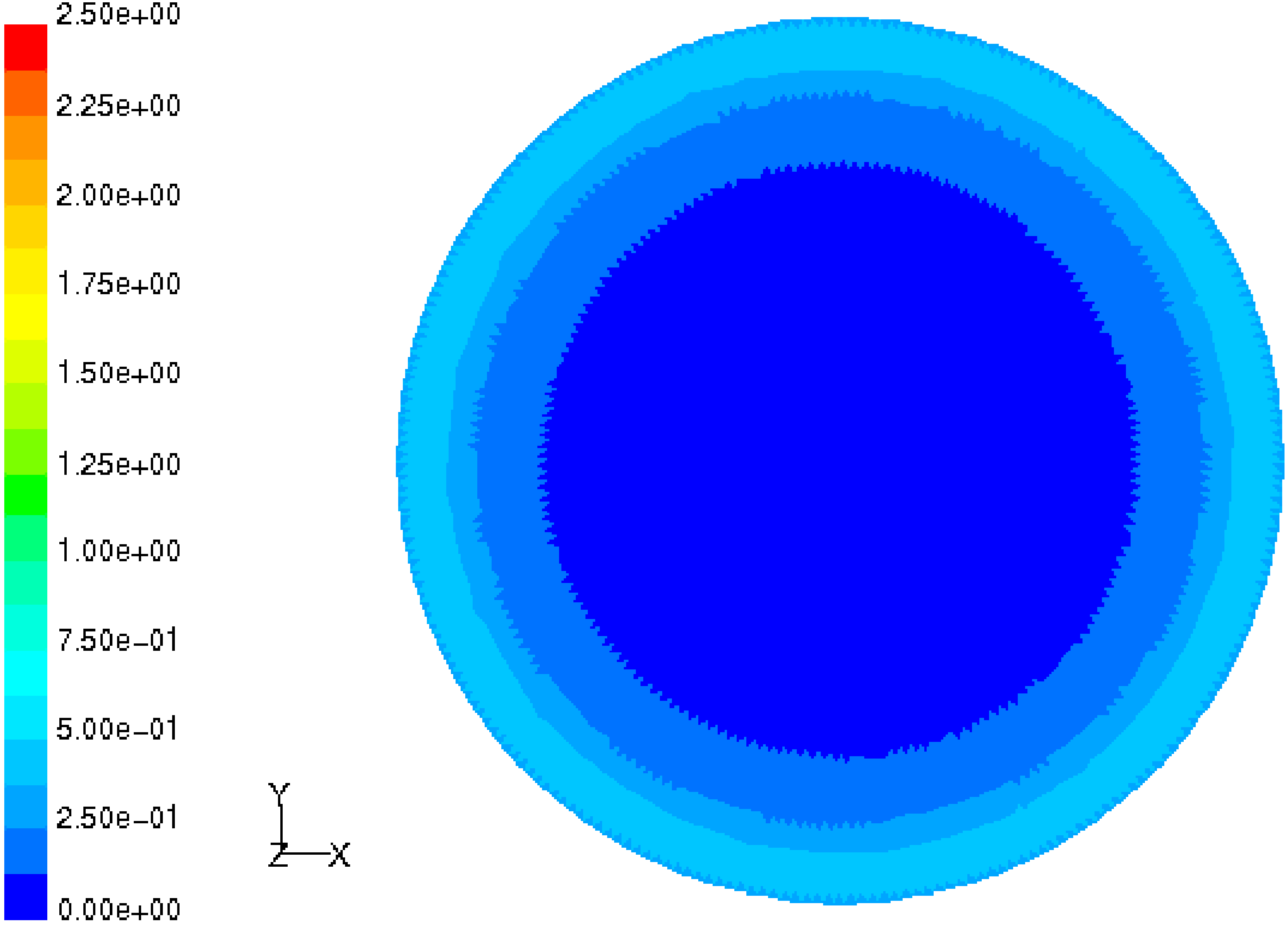
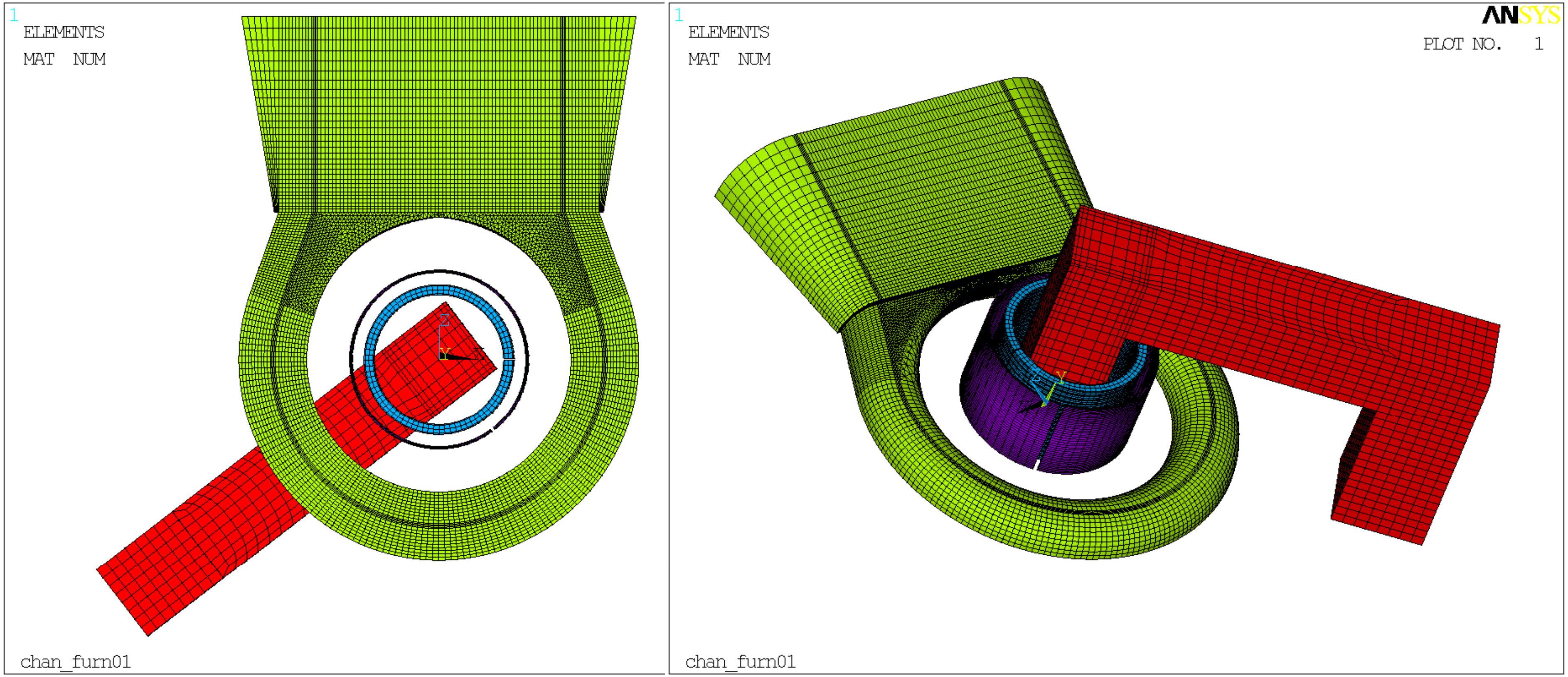
-5.00e-01
-1.00e+00
-1.50e+00
-2.00e+00
-2.50e+00
Z
X
Y
Velocity Vectors Colored By Axial Velocity (m/s) (Time=1.6600e+00)
Aug 13, 2001
FLUENT 5.4 (3d, segregated, LES, unsteady)



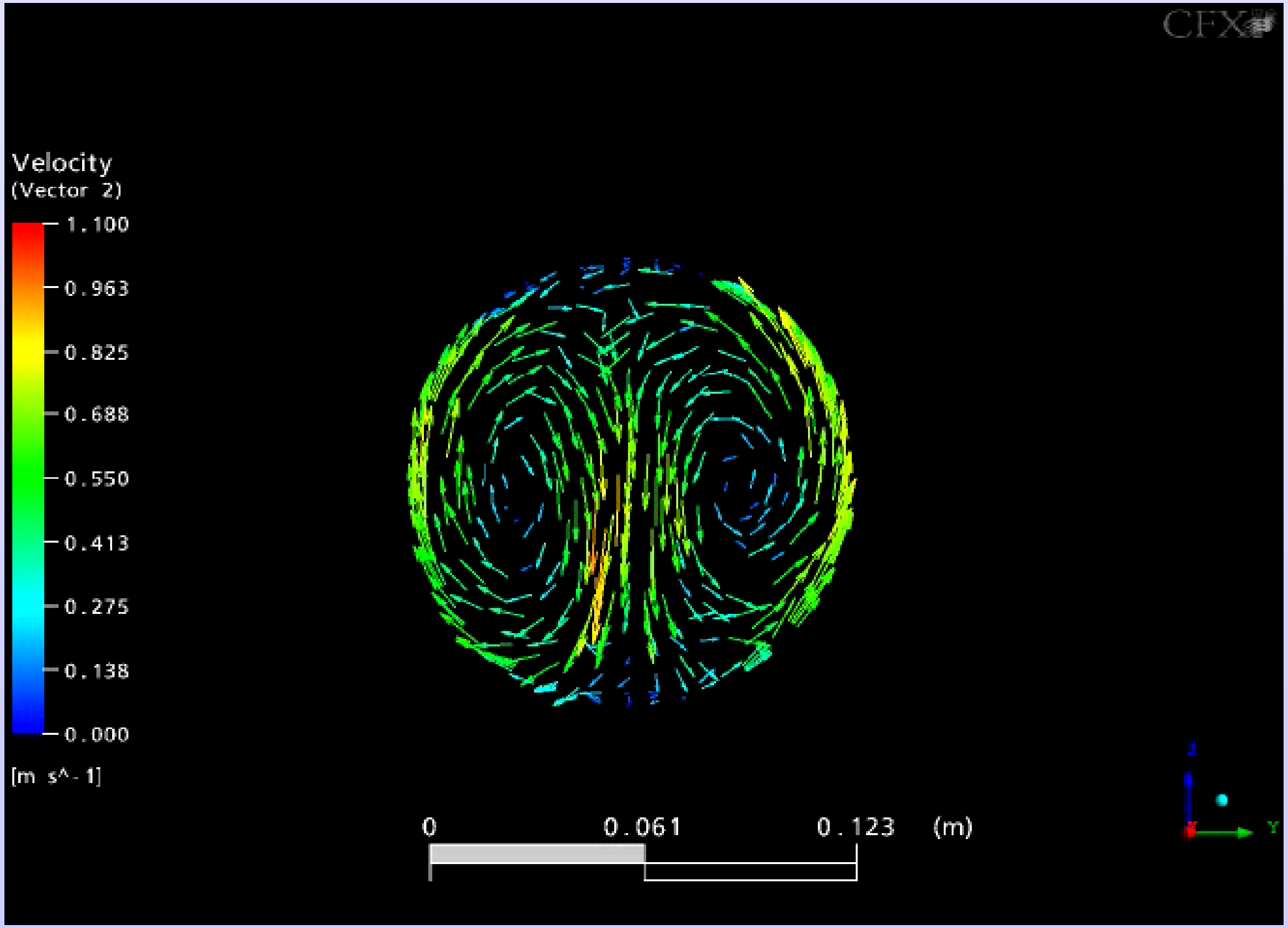
Contours of Velocity Magnitude (m/s) (Time=1.2600e+00)

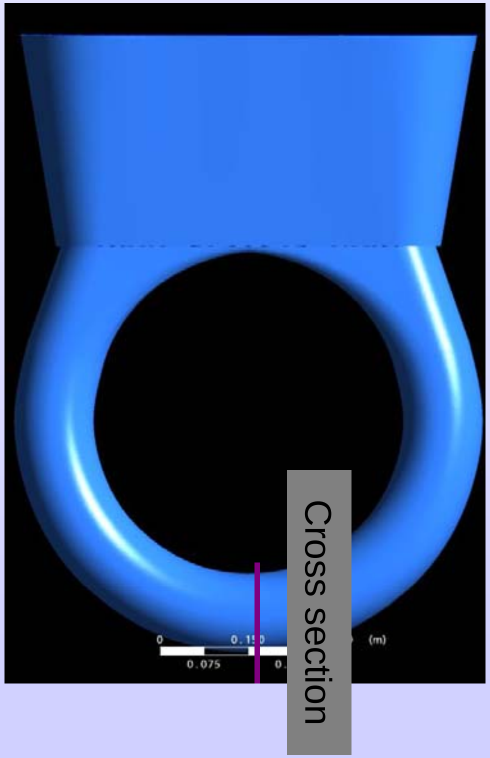
Aug 13, 2001
FLUENT 5.4 (3d, segregated, LES, unsteady)

3D-Simulation model for electromagnetic calculation of the channel inductor
(power density and electromagnetic force density)

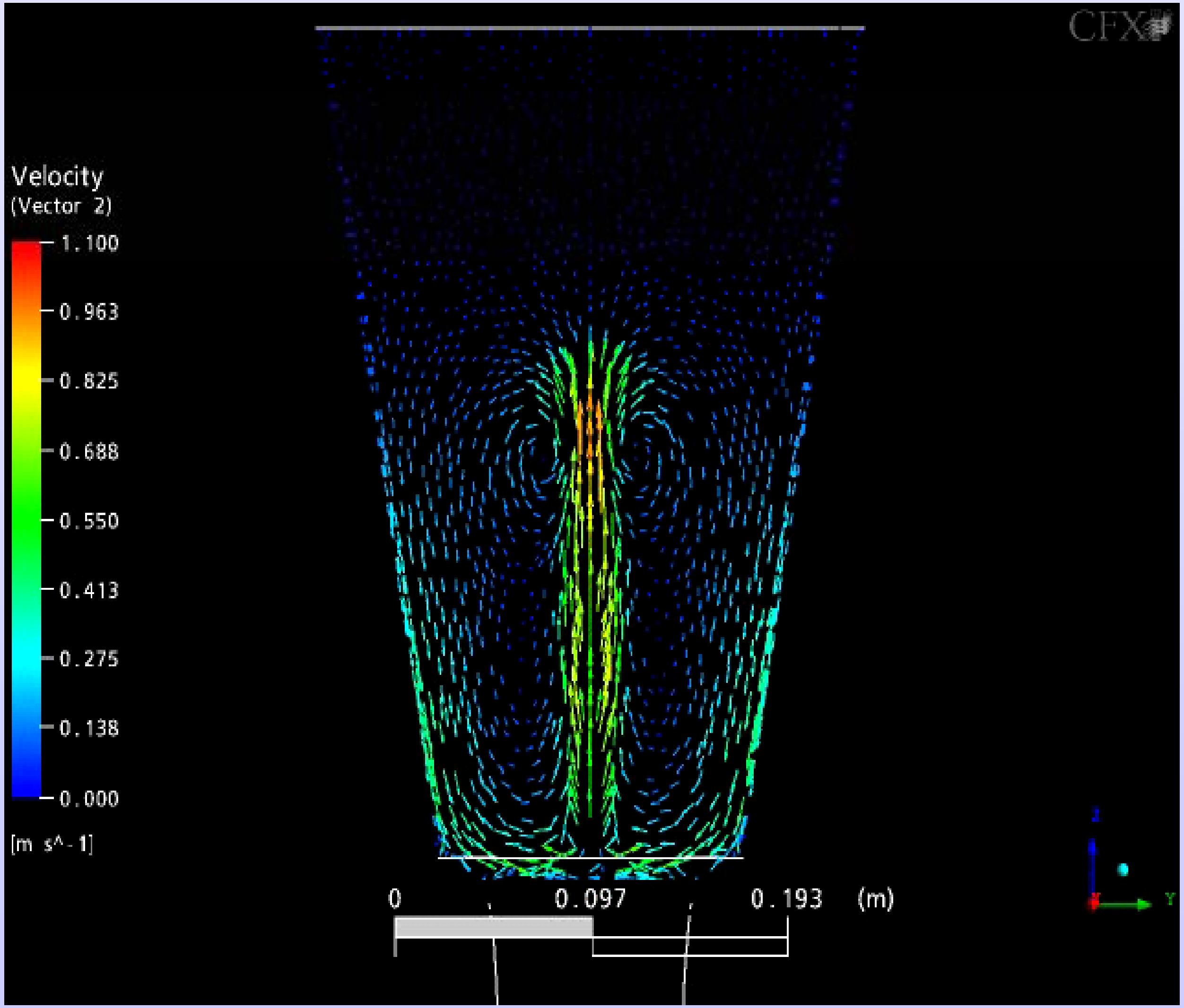


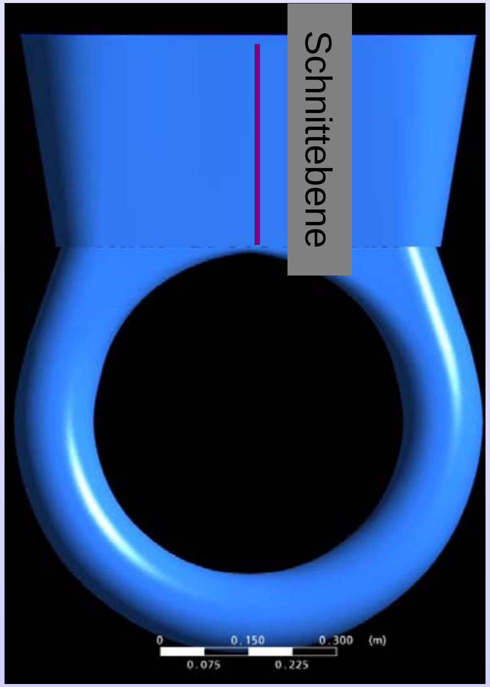
3D transient simulation of the melt flow in cross section of the channel (LES model)



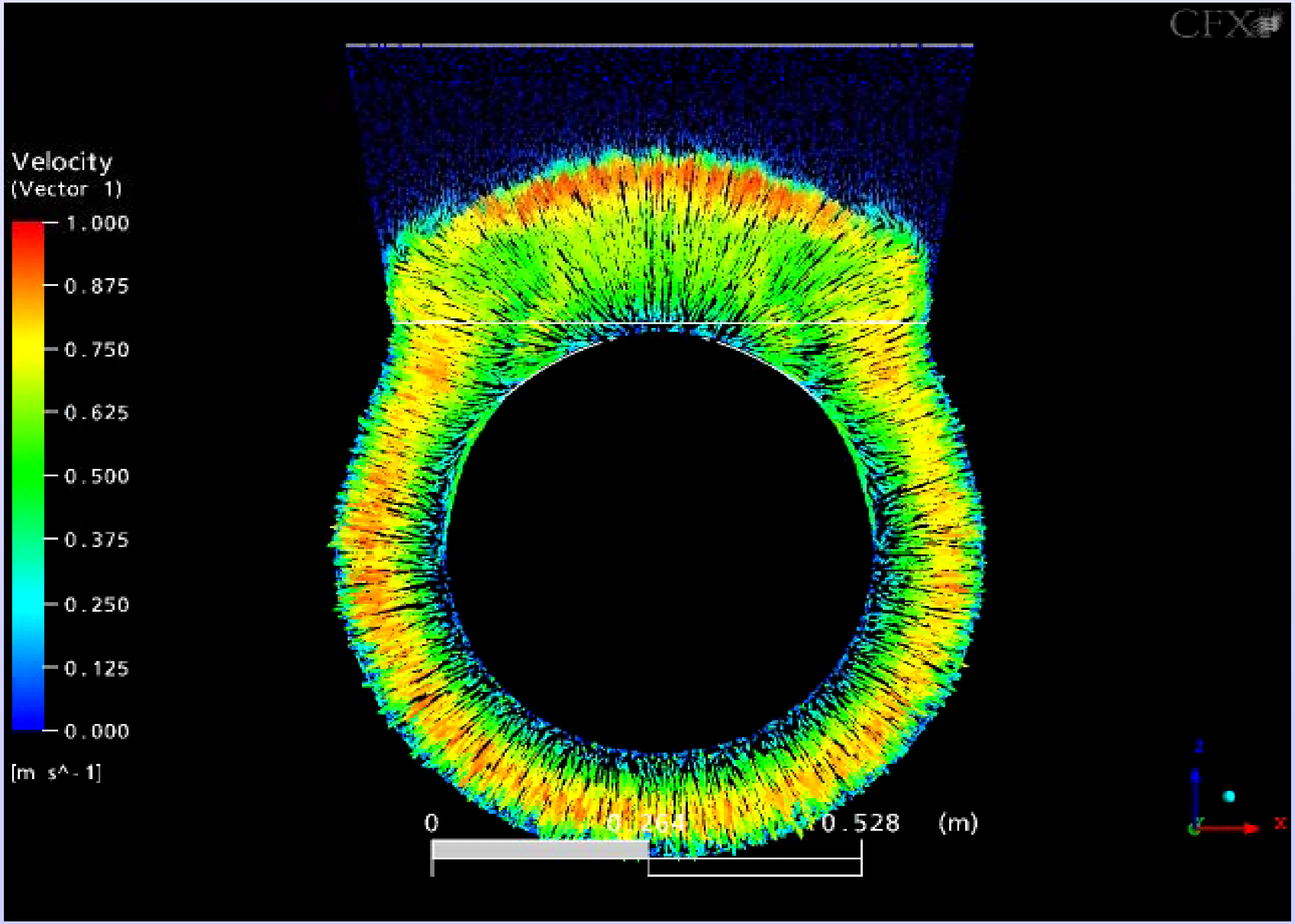


3D transient simulation of the melt flow in the bath (LES model)



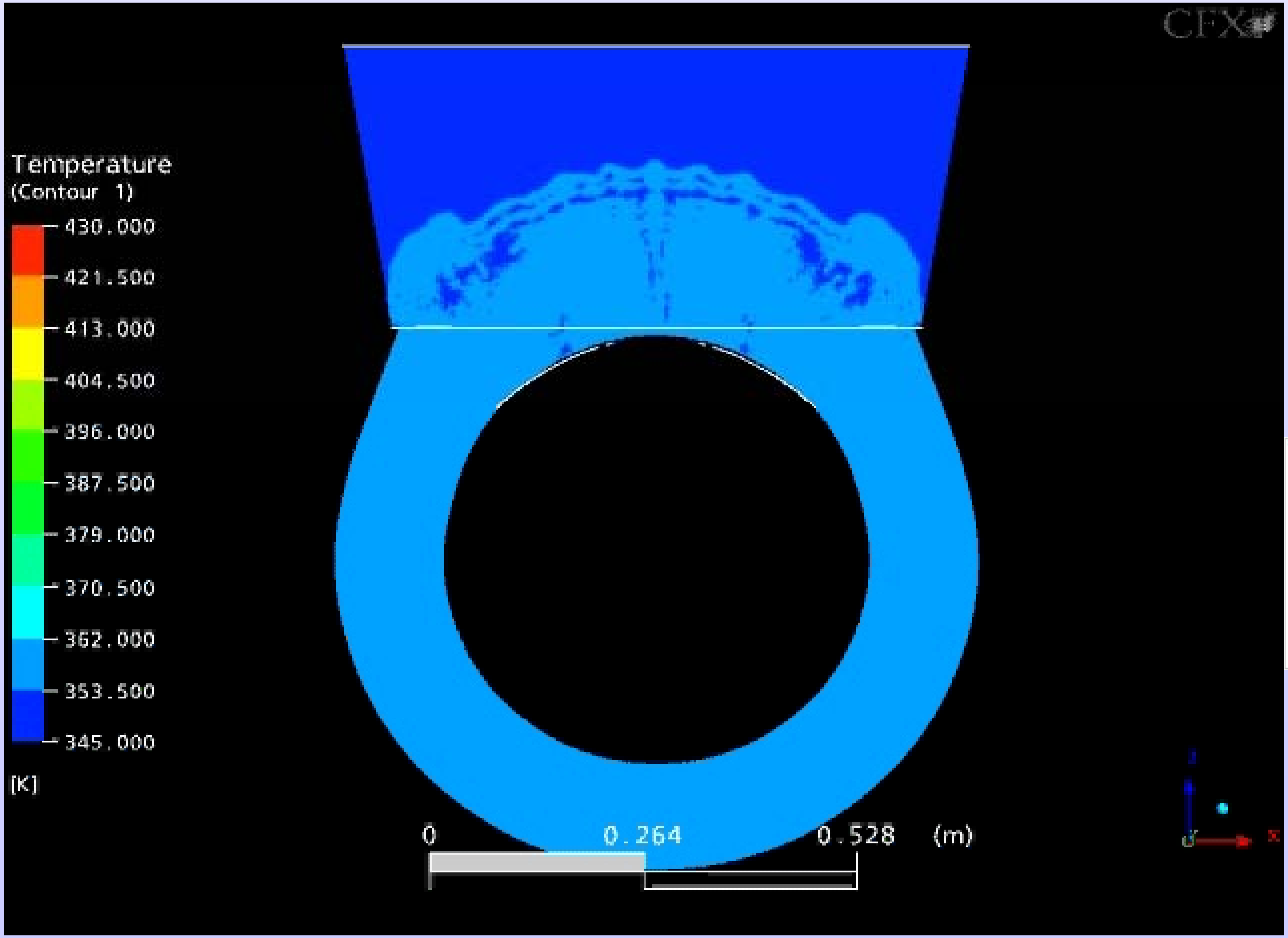


3D transient simulation of the melt flow in the channel (LES model)

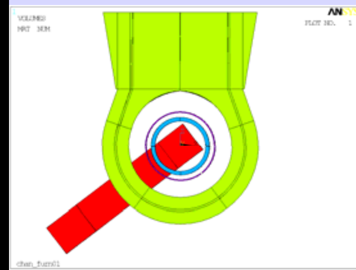


v_0= 0 m/s

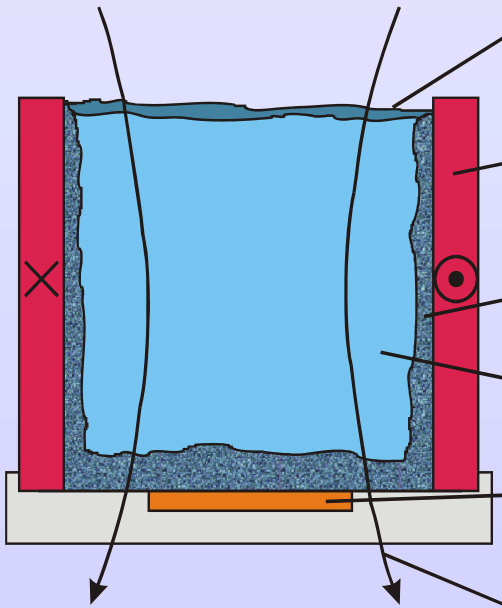
3D transient simulation of the temperature distribution in the channel (LES model)



T_0= 80°C



Principle of induction skull melting technology



Intensive cooling of inductor and bottom

- formation of a skull
- skull protects against impurities

Advantages of induction skull melting

High process temperatures

High power density

High purity of the melt and the final product

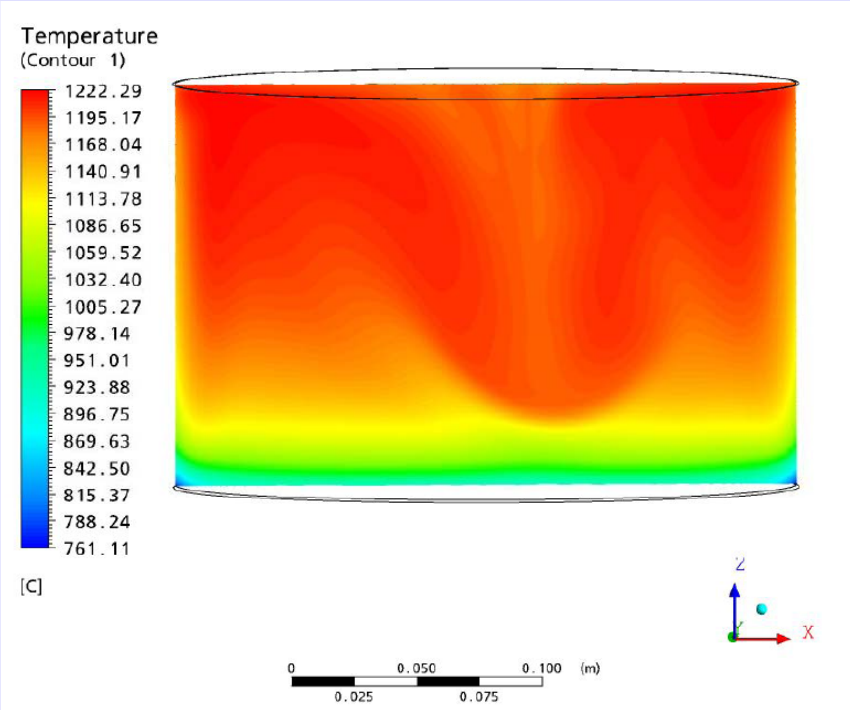
High efficiency

Process can be realized in different gas atmospheres or in vacuum

Compact melting equipment

Hydrodynamic thermal simulation
(Glass 1)

Glass with medium electrical conductivity, medium viscosity

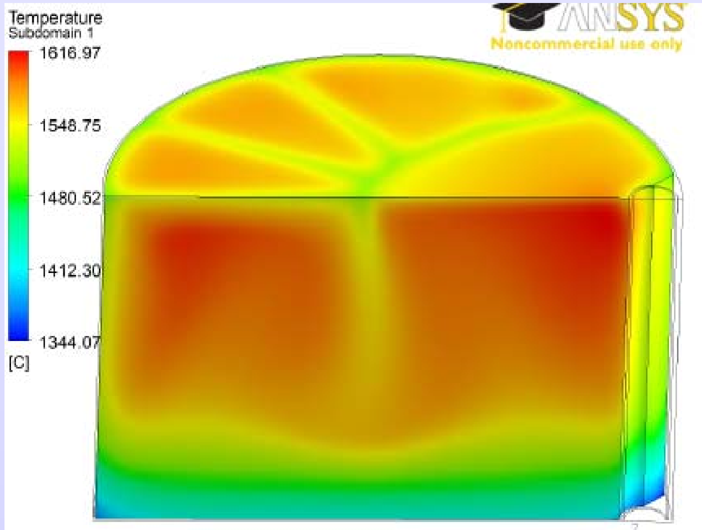


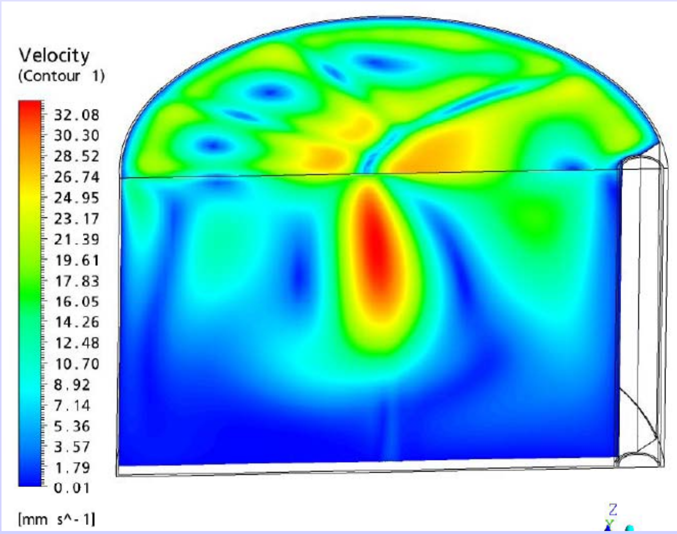
The temperature distribution is devided in 3 areas with different temperature levels.

The surface shows pattern of bifurcated channels created by Marangoni convection.

Hydrodynamic thermal simulation
(Glass 2)

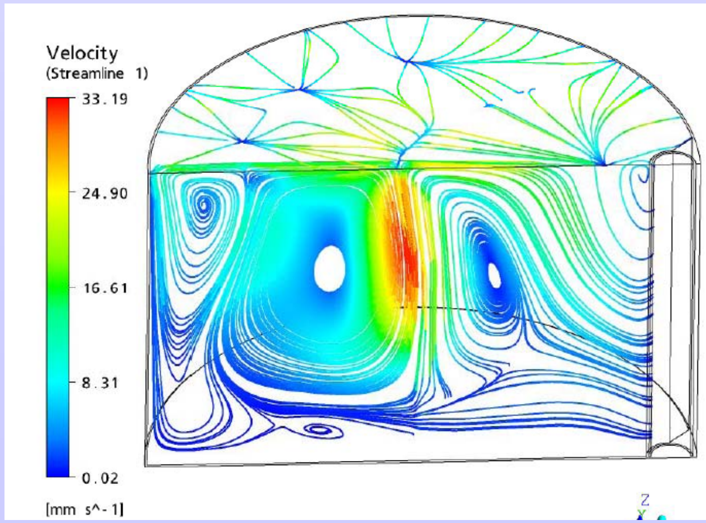
Glass with high electrical conductivity, high viscosity





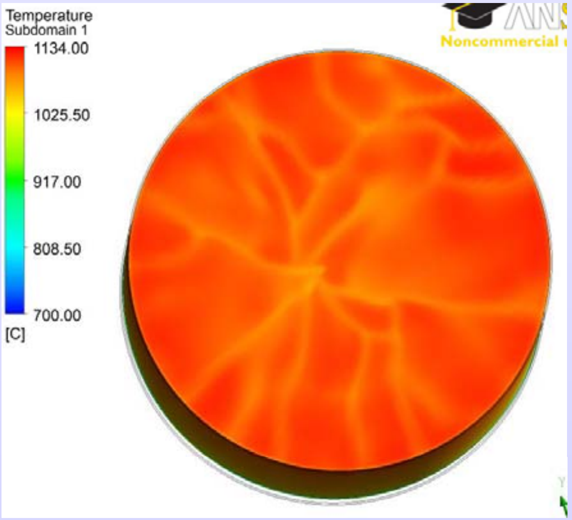
Also channels at the melt surface, but less and without bifurcation

Stream lines with typical inner and outer flow eddies



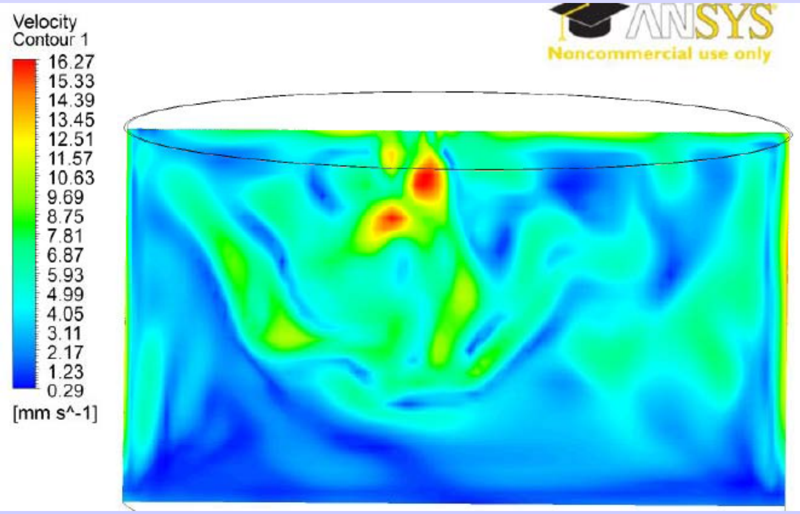
Hydrodynamic thermal simulation
(Glass 3)

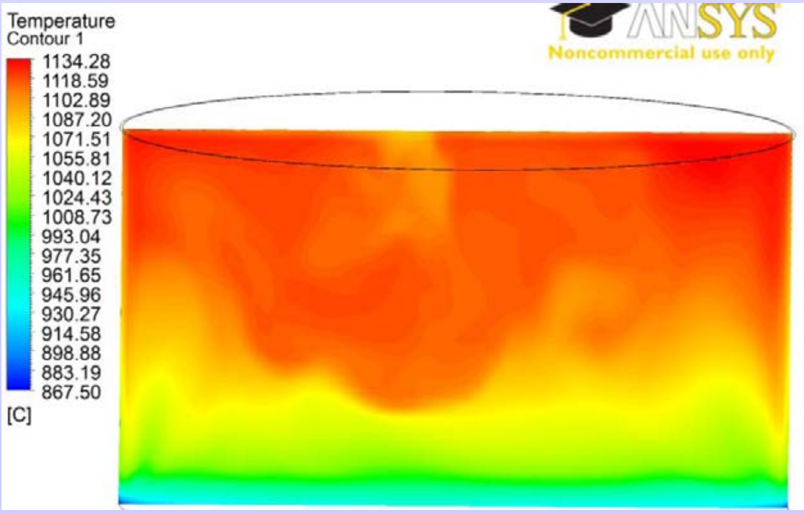
Glass with medium electrical conductivity,
medium viscosity



Chaotic distribution of channels at the melt surface

Higher turbulence due to lower viscosity





Analysis and design of complex induction heating processes

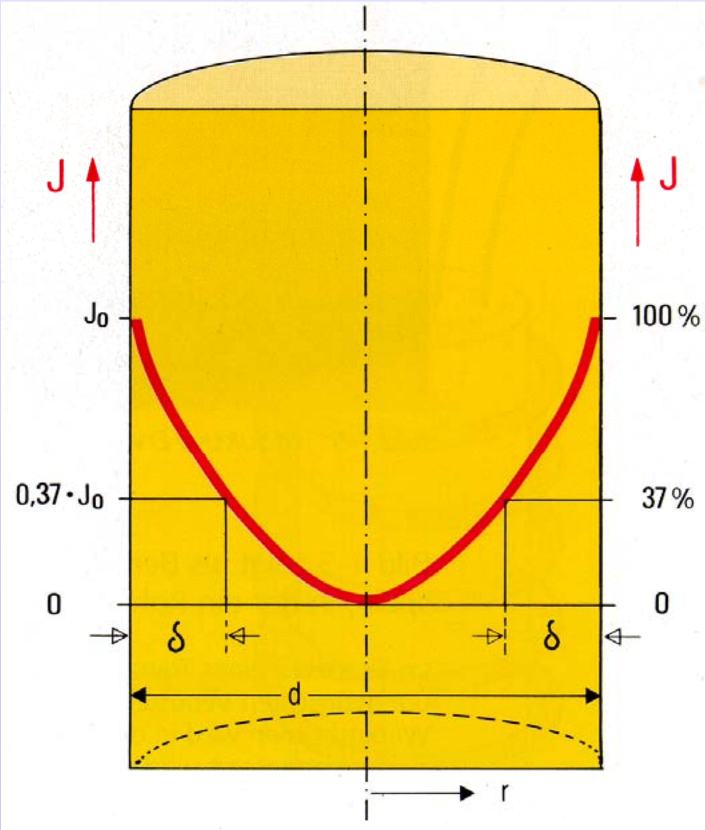
- **Tools and general aspects**
- **Surface hardening of worm gears**

Tools for modelling of induction heating processes

Engineering tools	→ 2D-program HIHTEC (BEM)	● electromagnetic → integral parameters ● preliminary investigation, optimization
Special programs	→ 3D-program package HIHTEC (BEM, FDM)	● electromagnetic, thermal → integral + distributed parameters ● parametrical studying, mathem. optimization
Universal commercial packages	→ 3D-program package ANSYS (FEM)	● electromagnetic, thermal, mechanical → integral + distributed parameters ● verification, complicated systems, partial optimization
combined tools	→ Combined 3D-programs (BEM, FDM, FEM)	● electromagnetic, thermal → distributed parameters ● nonlinear systems

Skin effect

Current density distribution in a cylindrical work-piece (approximation)



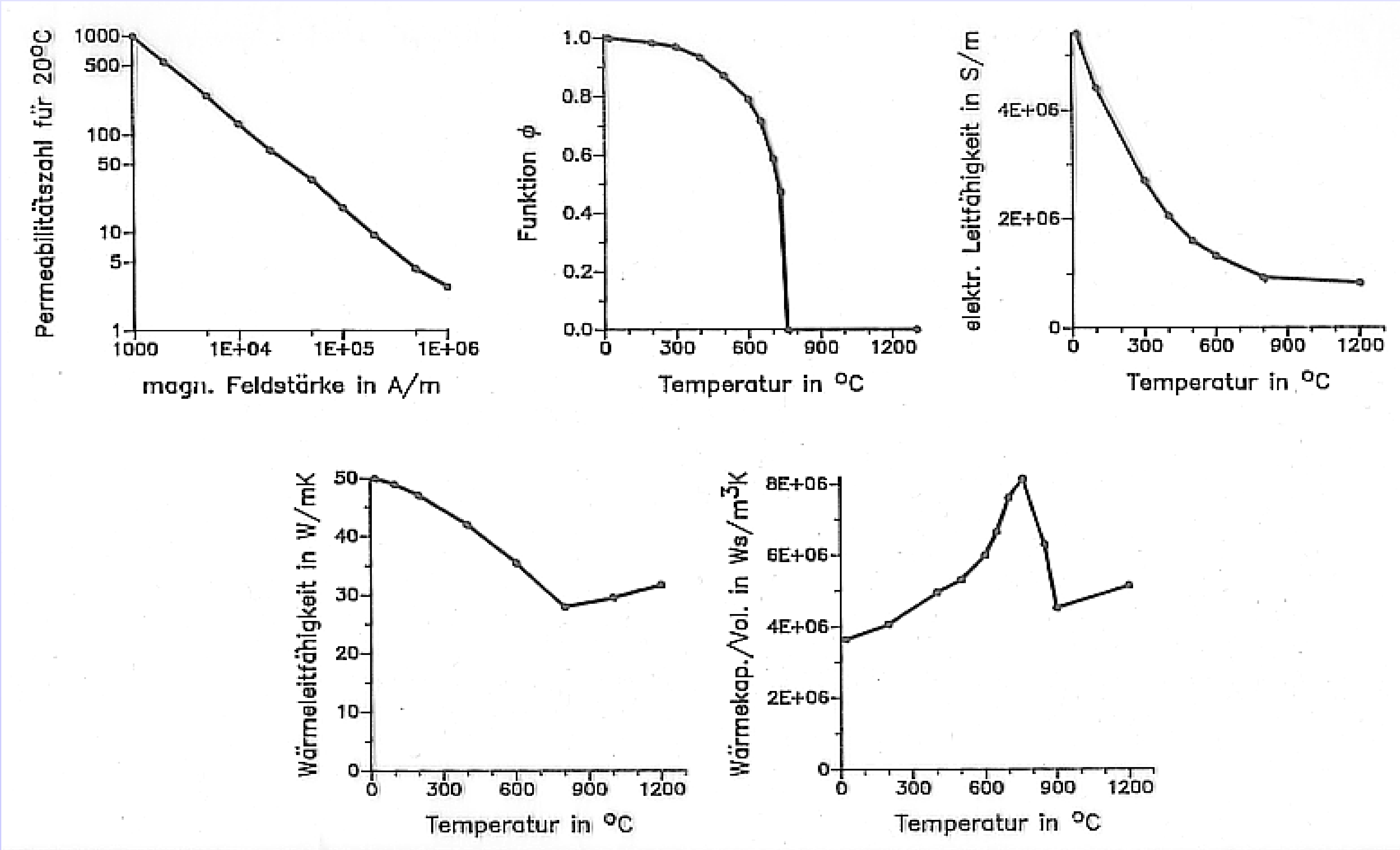
Electromagnetic penetration depth

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}}$$

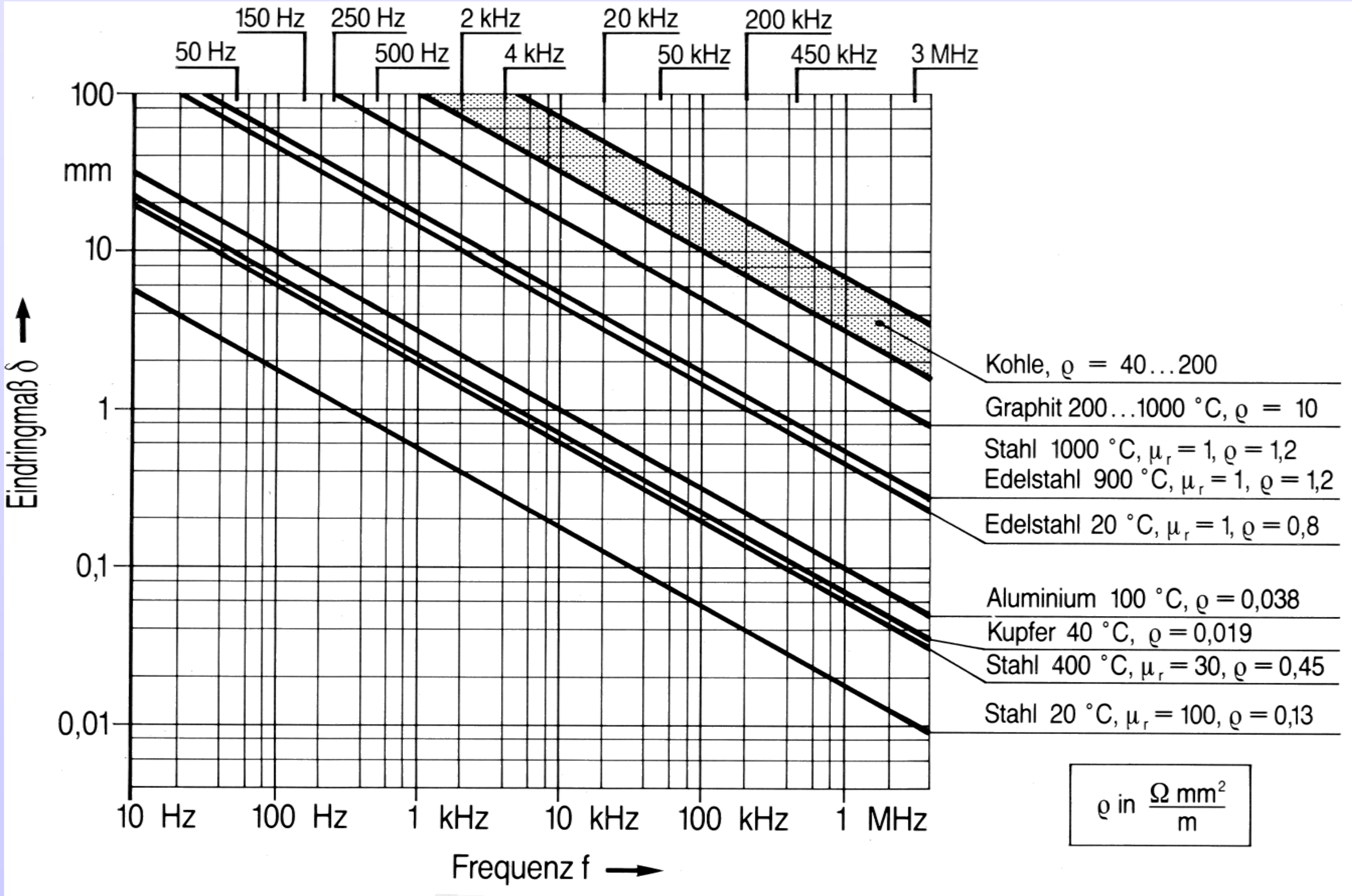
The exponential distribution of current and magnetic field is exactly valid only for **plane** surfaces (approximately valid for cylinders for $d/\delta > 4$)

Source: RWE-Information Induction Heating

Electrical and thermal properties of steel (C 45)



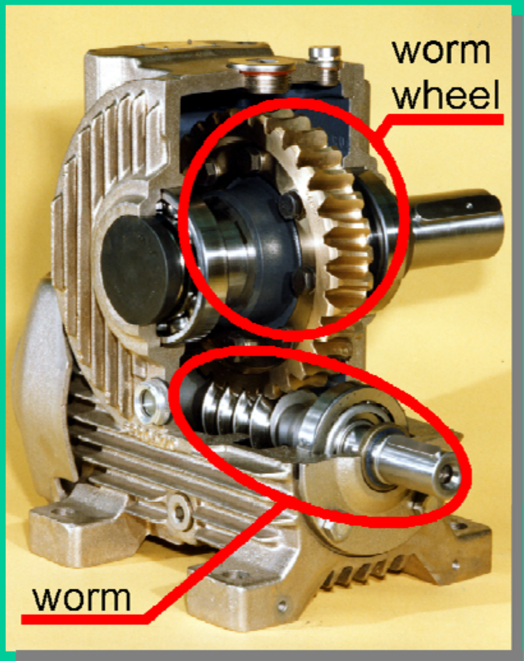
Electromagnetic penetration depth dependent on frequency



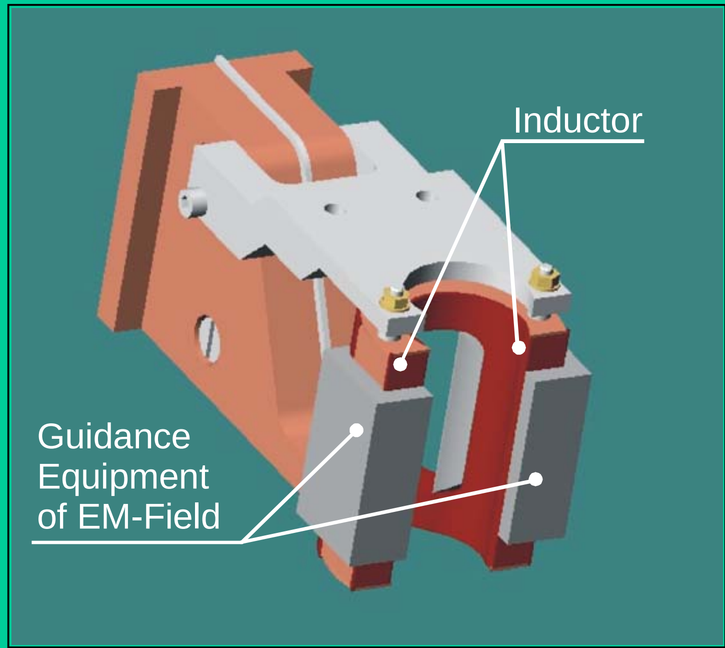
Source: RWE-Information

Surface hardening of worm gears with dual frequency

Worm-Gear



Line-Inductor

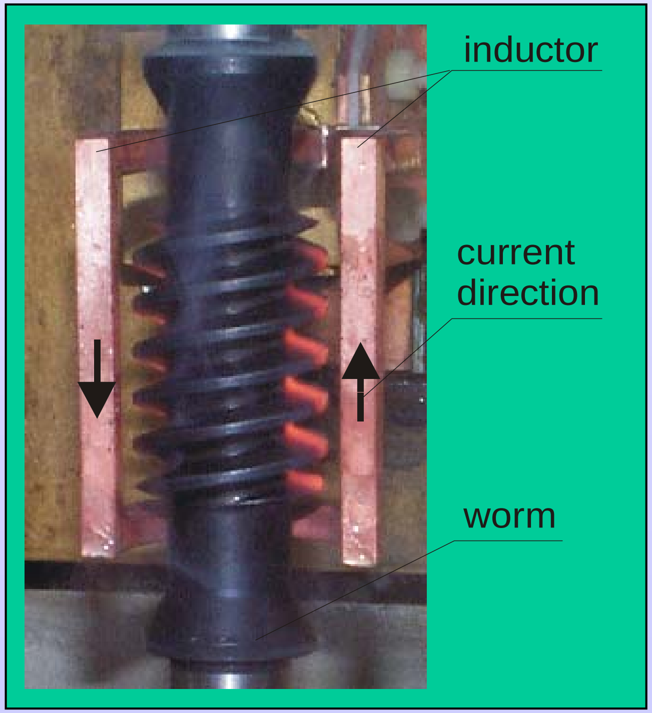


- Aim: temperature-distribution close to the contour

  → uniform hardening-profile at the surface region

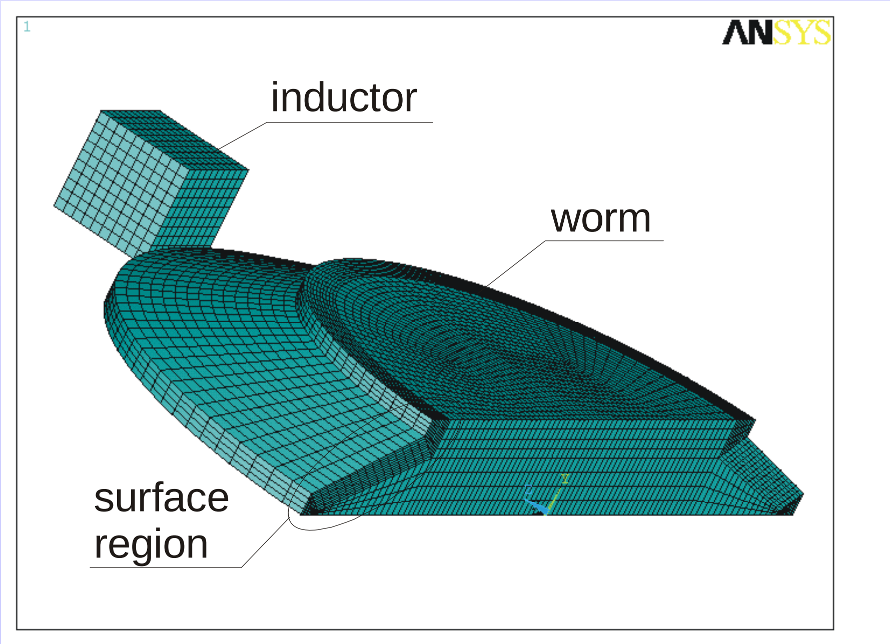
Simulation model

- Boundary Conditions:
  - heating-time: 1 s
  - maximum temperature: 950 °C
  - rotating worm



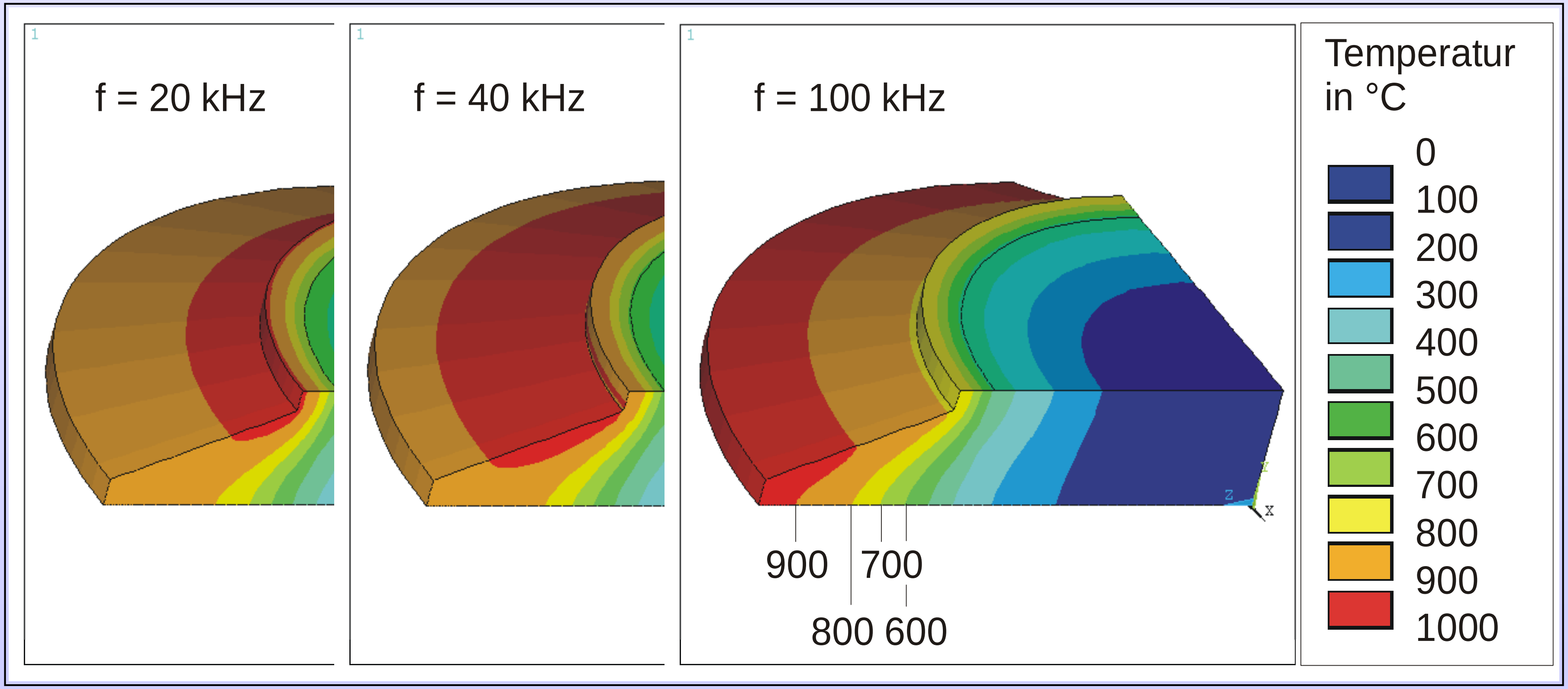
Worm with inductor

Symmetry Conditions:
- long inductor
- 180° in circular direction
- gradient angle was not taken into account



Net of the simulation model

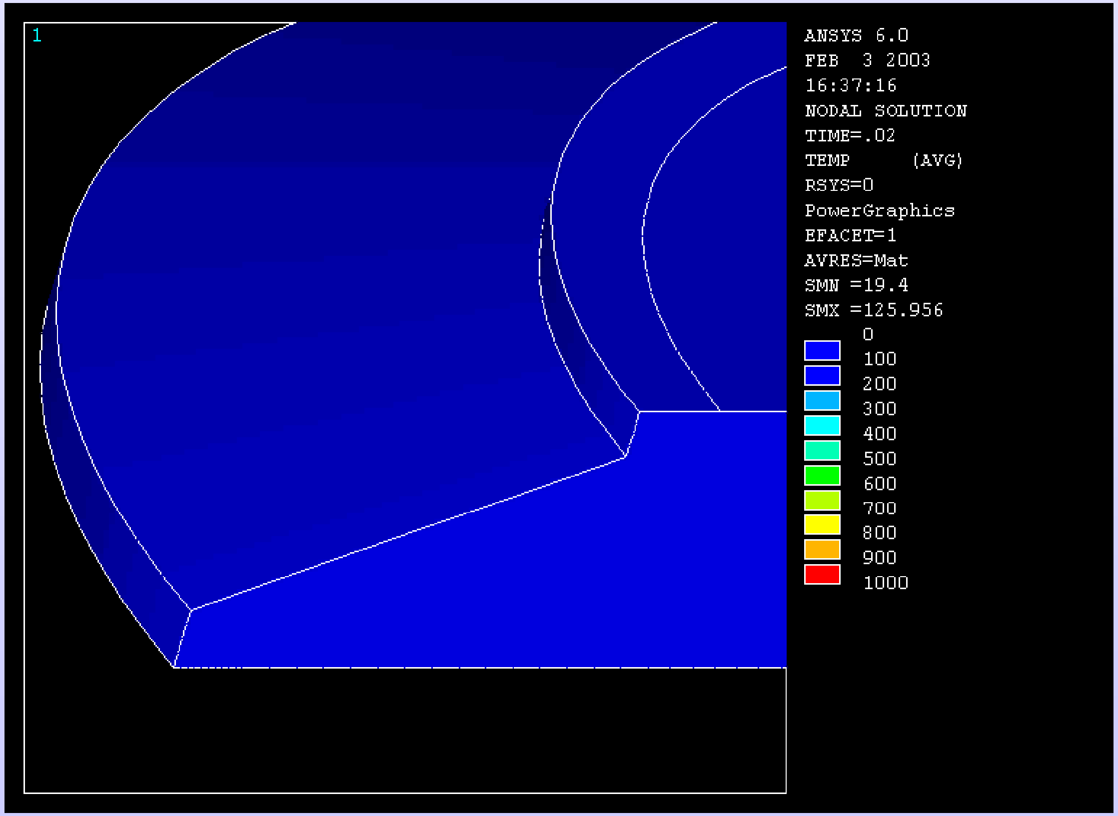
Induction surface hardening of worm gear with single frequency



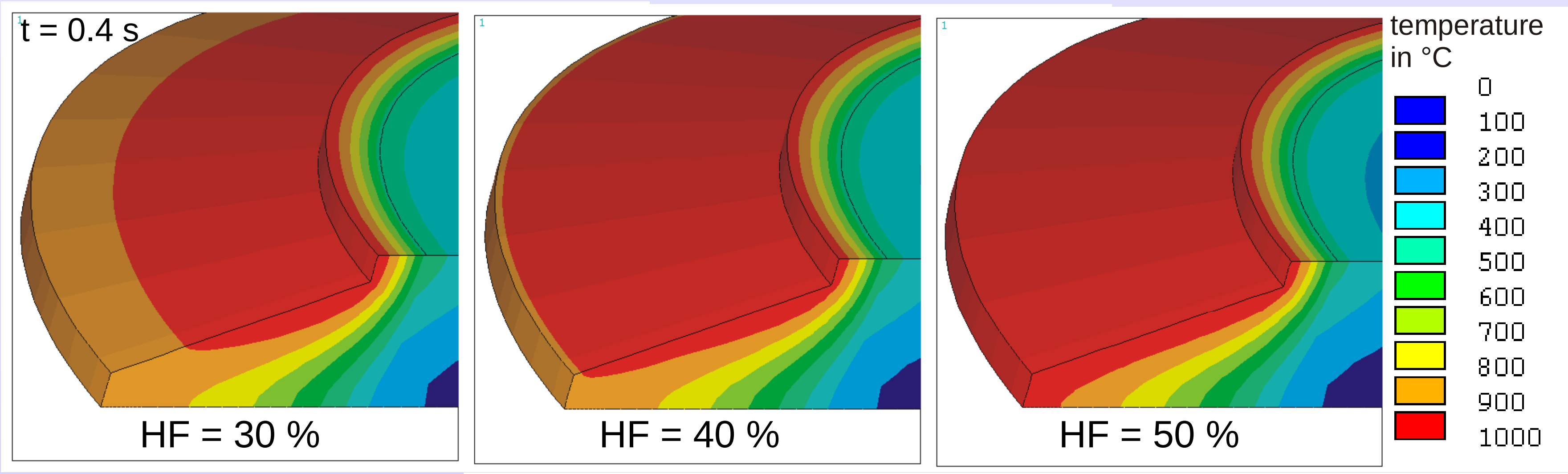
➢ No optimal solution for hardening of warm gears by single frequency

Transient induction heating process using dual frequency (15 kHz + 300 kHz)

50% MF
50% HF



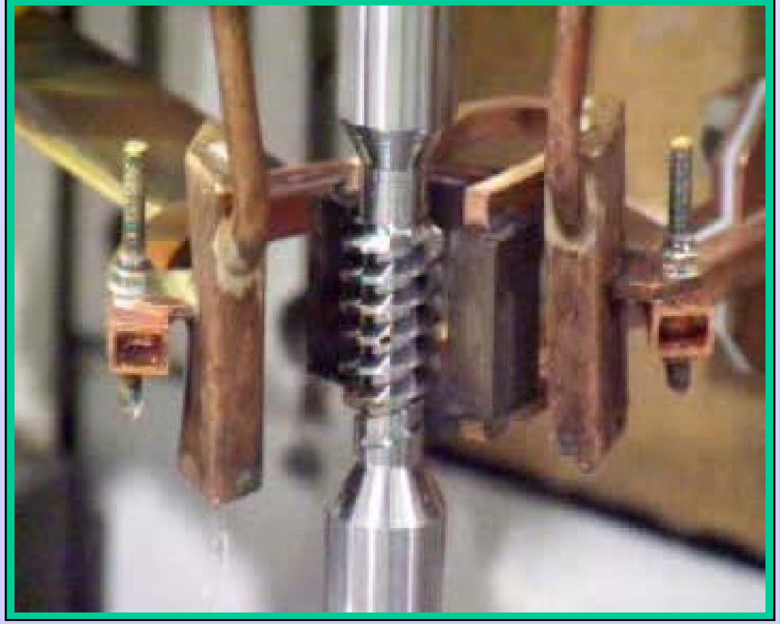
Induction surface hardening of worm gear with dual frequency technology



- Heating-area can be adjusted via power-ratio of MF/HF
- Getting a heating-profile close to the contour of the worm is possible
- This heating-profile enables reaching the desired hardening-profile
- Short heating time necessary to reduce the influence of heat conduction

Experimental hardening

- 75 kW generator
  (75 kW MF, 75 kW HF)
- Heating time 1,3 s

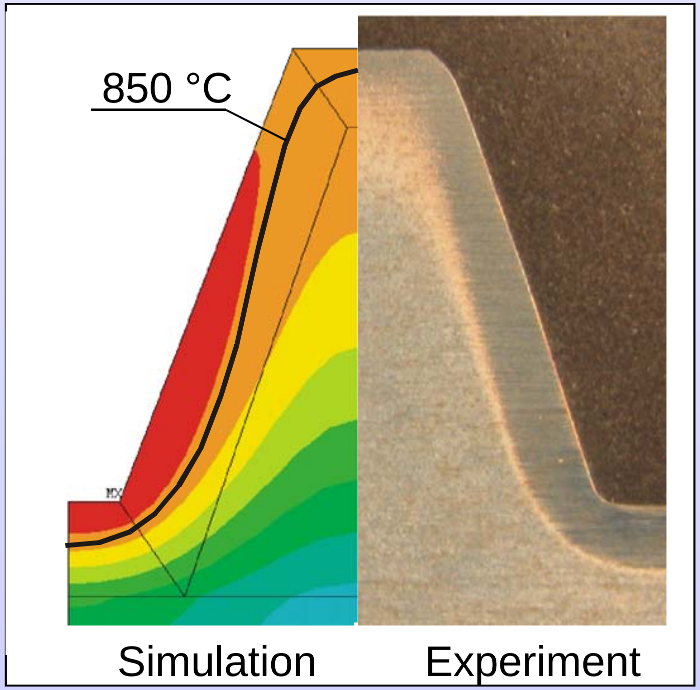


- 600 kW generator
  (400 kW MF, 200 kW HF)
- Heating time 0,35 s

Comparison of temperature and hardness distribution

Simulation- und hardening data

- Double frequency heating
- Total power 600 kW
- Pre heating:
  - Heating time: 0,5 s
  - HF-power: 10 %
  - MF-power: 0 %
- Heating:
  - Heating time: 0,3 s
  - HF-power: 30 %
  - MF-power: 70 %



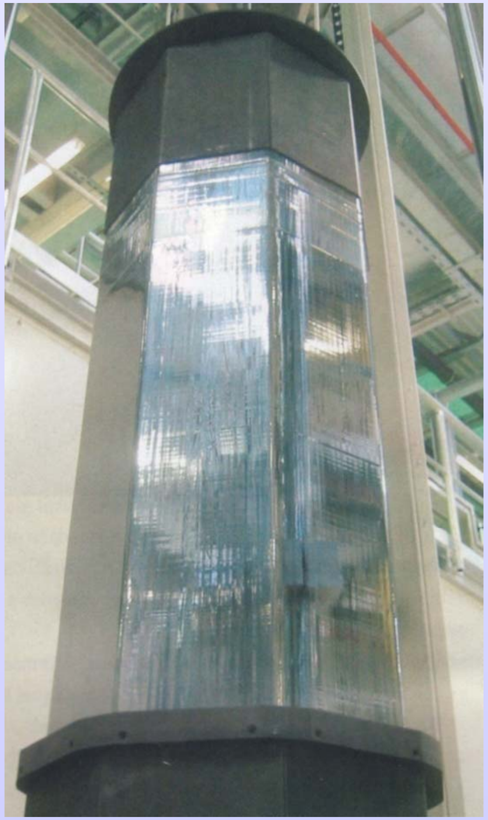
Conclusion

- Good agreement between simulated temperature und final hardness profile
- The final hardening profile can be excellently predicted by numerical simulation of the temperature distribution only

Simulation of complex 3D temperature fields in systems for crystal growing of photovoltaic cells

- **EFG process**
- **String ribbon growing process**

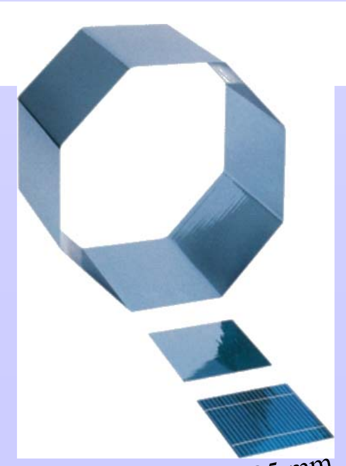
Edge-defined **F**ilm-fed **G**rowth **(EFG)**



A silicon tube is pulled directly from the silicon melt.

Facts

- 6 to 7-meter-long hollow silicon tubes
- wall thickness of 330 µm with the final thickness of the cells
- a laser cutting process results into 125 mm x 125 mm wafers

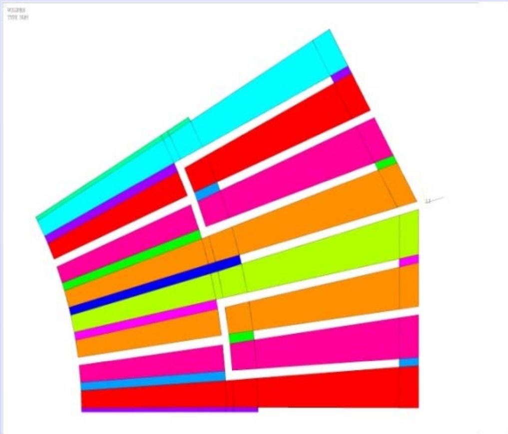


Performance of process and wafers

- fast throughput (with feed of 20 mm/min)
- reliable production process
- EFG process allows to reduce the demand of silicon due to less material losses (no sewing losses)
- high wafer quality in material grade and strength

New resistance heated EFG system

New EFG system
larger diameter, tube with 12 sides (dodecagon)



Advantages due to resistance heating

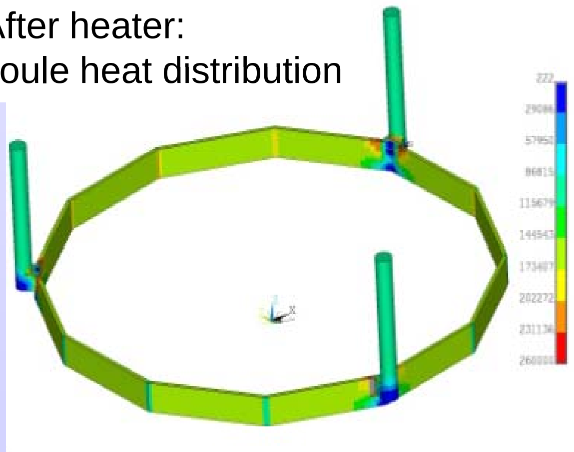
- individual adjustable 12-zoned resistance main heater
- no electromagnetic coupled system like the inductive heated melting furnace
  ⇨ e.g. no influence of the difference of phase on the temperature distribution
- 12 sided silicon tube increases significantly the yield per pull

Numerical models

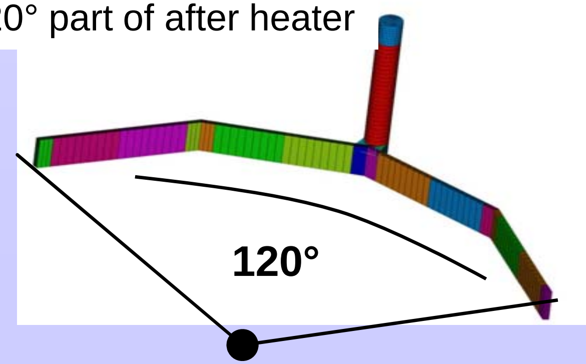
Electromagnetic model

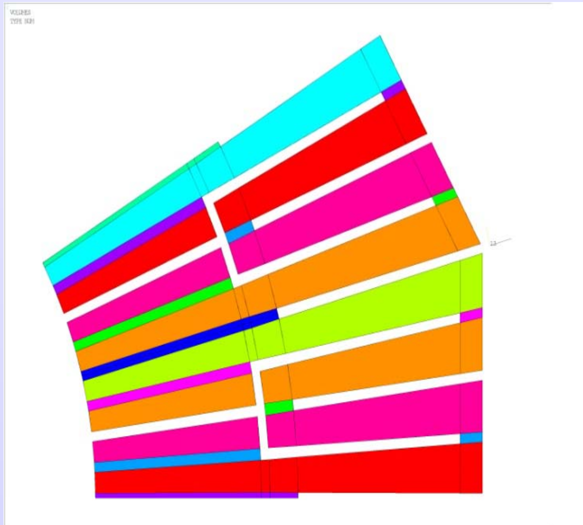
- different symmetries of main and after heater
  - ⇨ two separate models: coupled 30° model for main heater and 120° thermal model for after heater
  - ⇨ import of heat sources into the 120° thermal model

After heater:
Joule heat distribution

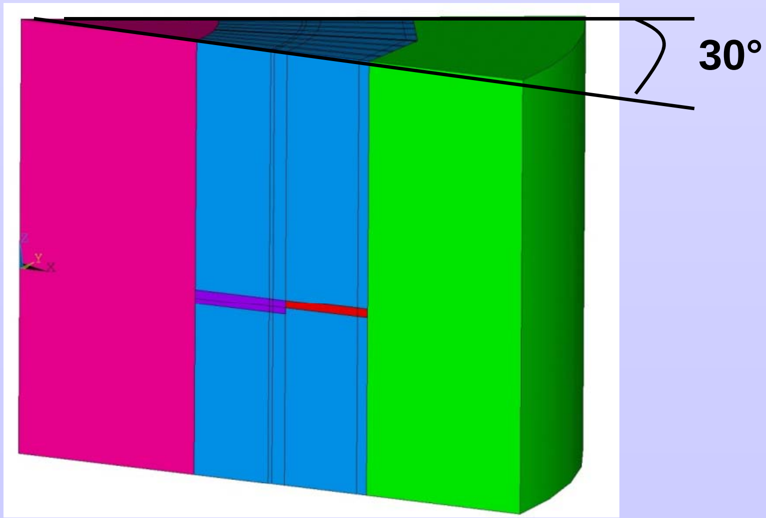


120° part of after heater

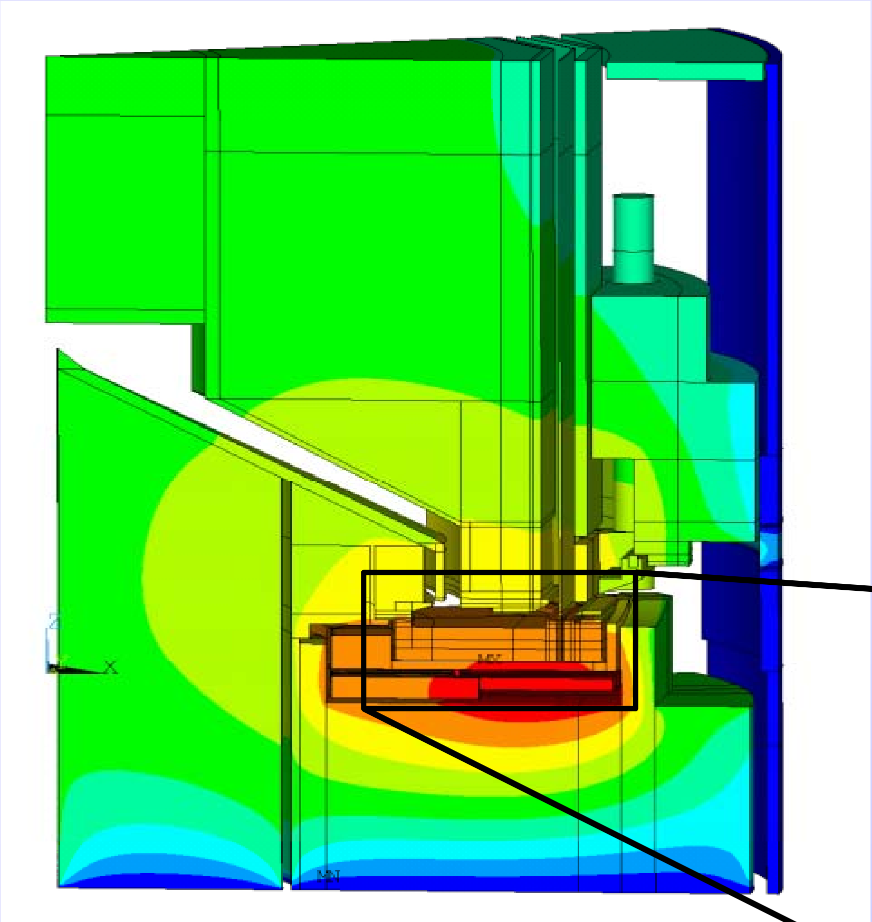




Main heater

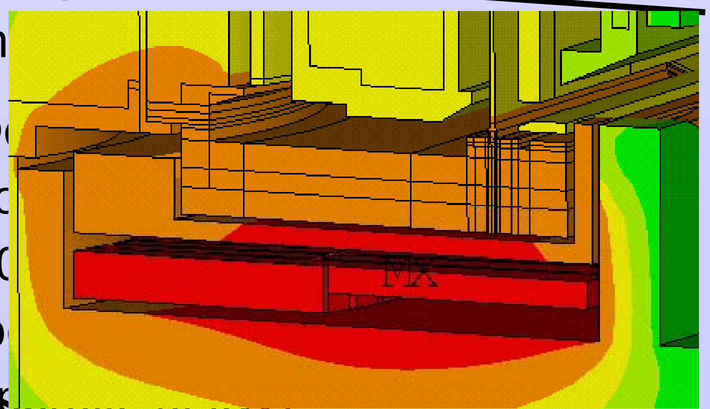


Temperature distribution calculated by coupled 30° model

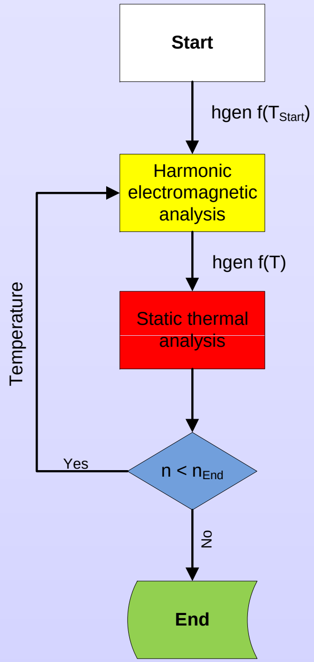


Result of temperature distribution
(after 3 iteration loops)

- Temperature dependent thermal analysis of joule heat generation in main and after heater
- 30°-geometry for faster calculation (approx. 20% in size compared to 120°-m
- De
  co
  50
  lo
  approx. 1,2kW)

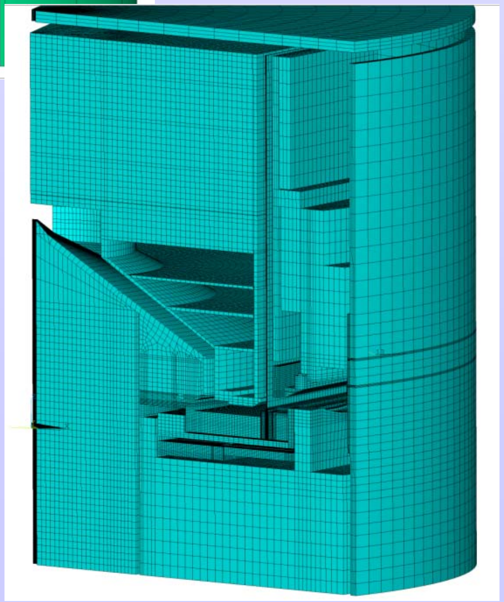


Cut out at larger scale

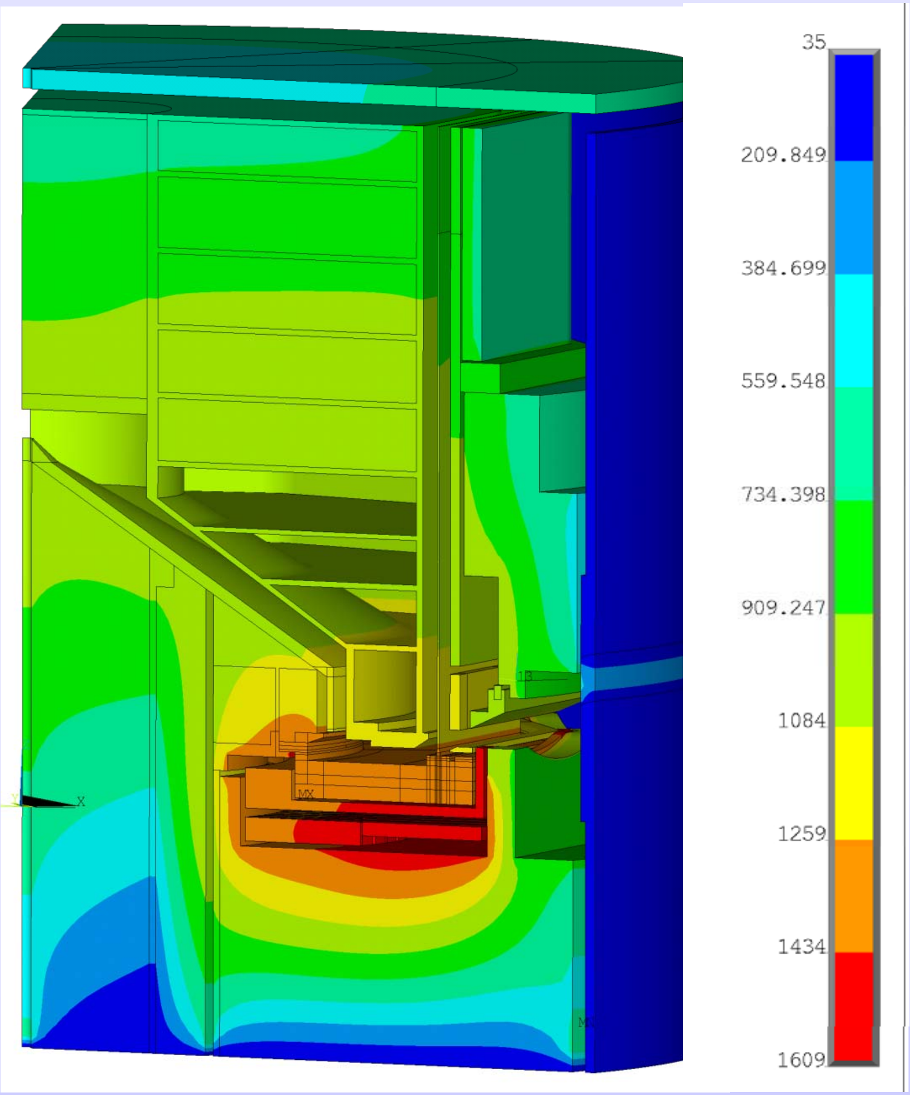


Temperature distribution calculated by thermal 120° model

Zones of numerical model



Mesh



Temperature distribution

Data of the models

Coupled 30° model

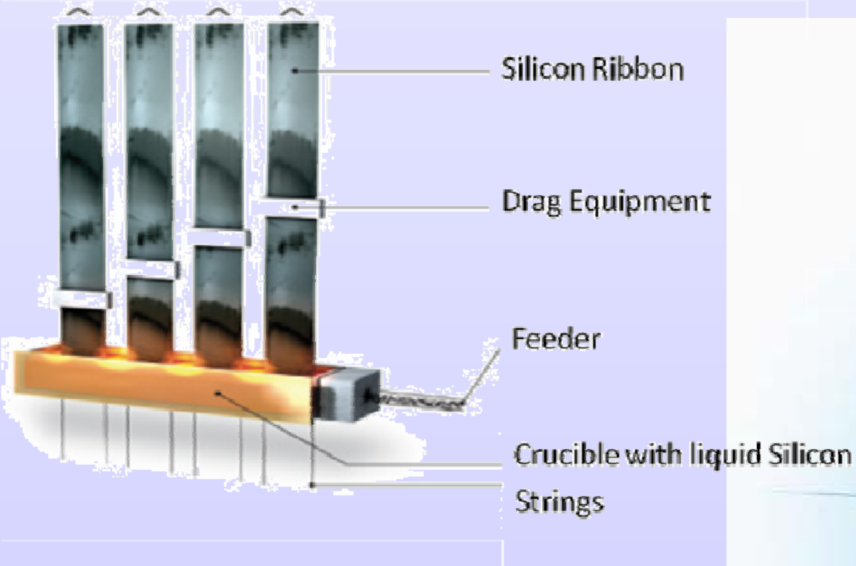
- required harddisk space ~ 245 GByte (about 220 GByte viewfactor-matrix)
- calculation time: approx. 75 h (max. 2 cores*, intel Core 2 Quad 9450, 8 GB-RAM) 3 iterations loops
- approx. 786.000 notes
- approx. 285.700 radiation surfaces
- RAM-usage ~ 7,9 GByte

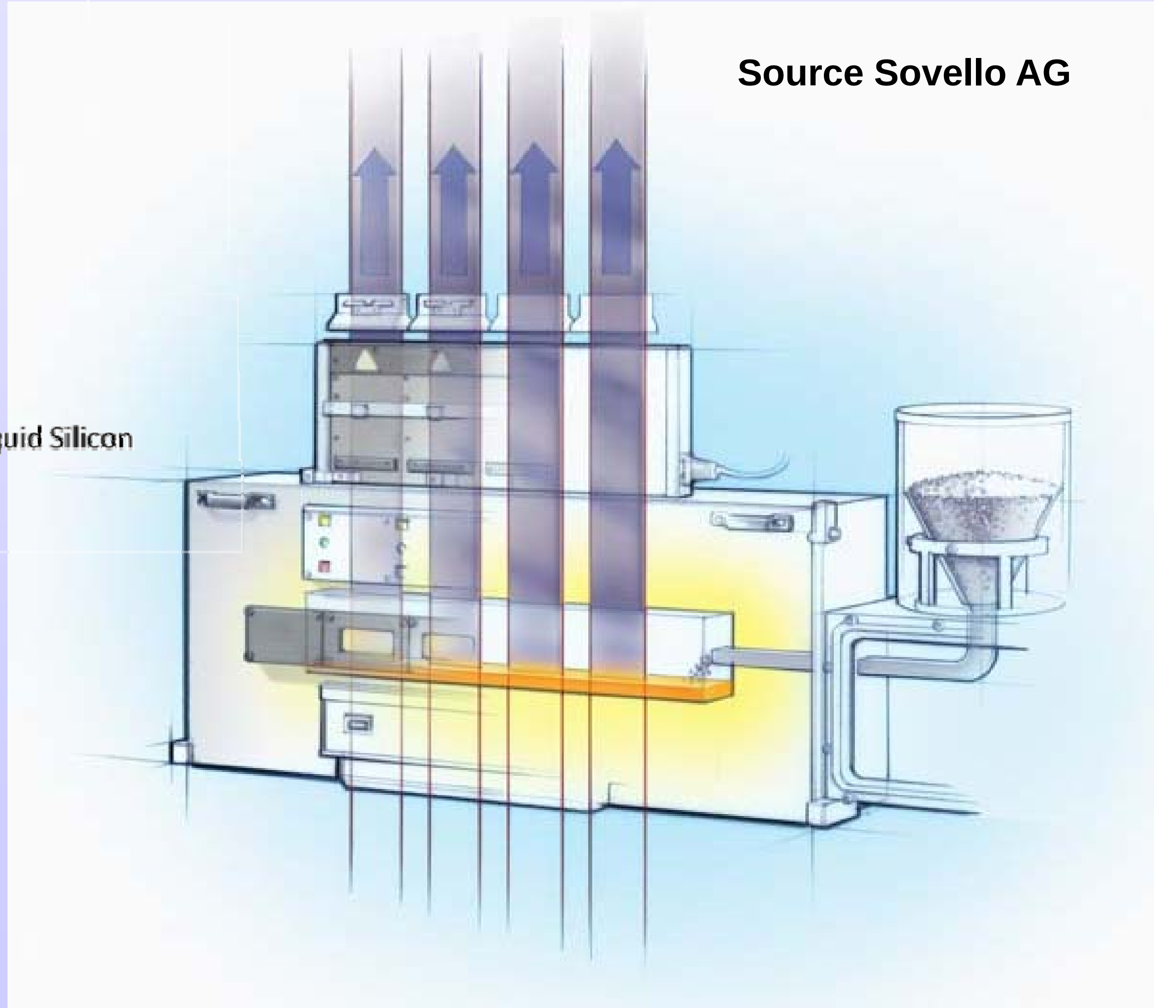
Thermal 120° model

- required harddisk space ~ 1165 GByte (about 1100 GByte viewfactor-matrix)
- calculation time: approx. 150 h (max. 2 cores*, intel Core 2 Quad 9450, 8 GB-RAM) for stationary solution
- approx. 1.800.000 notes
- approx. 654.000 radiation surfaces
- RAM-usage ~ 11,6 GByte

*radiation calculations are always single core calculations in Ansys

String ribbon process

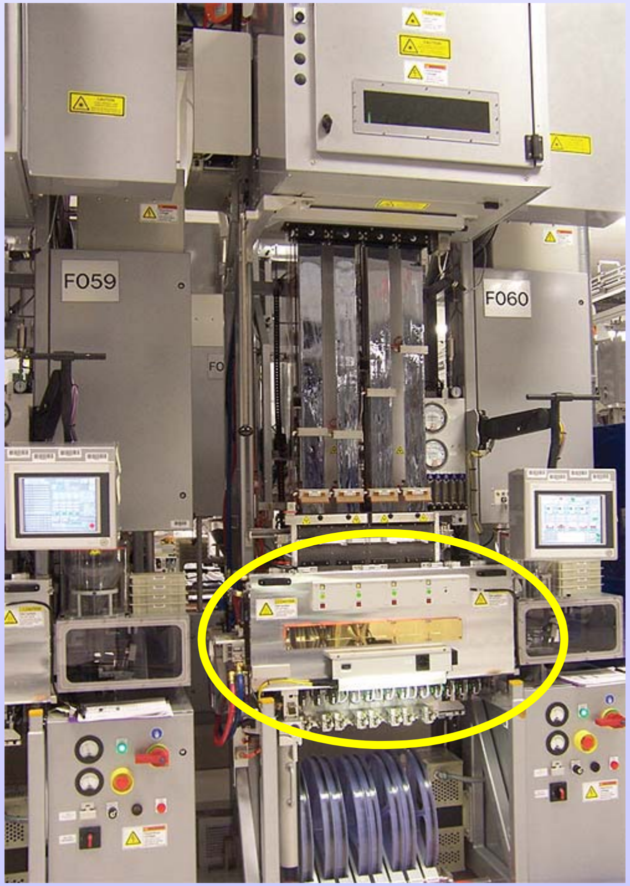


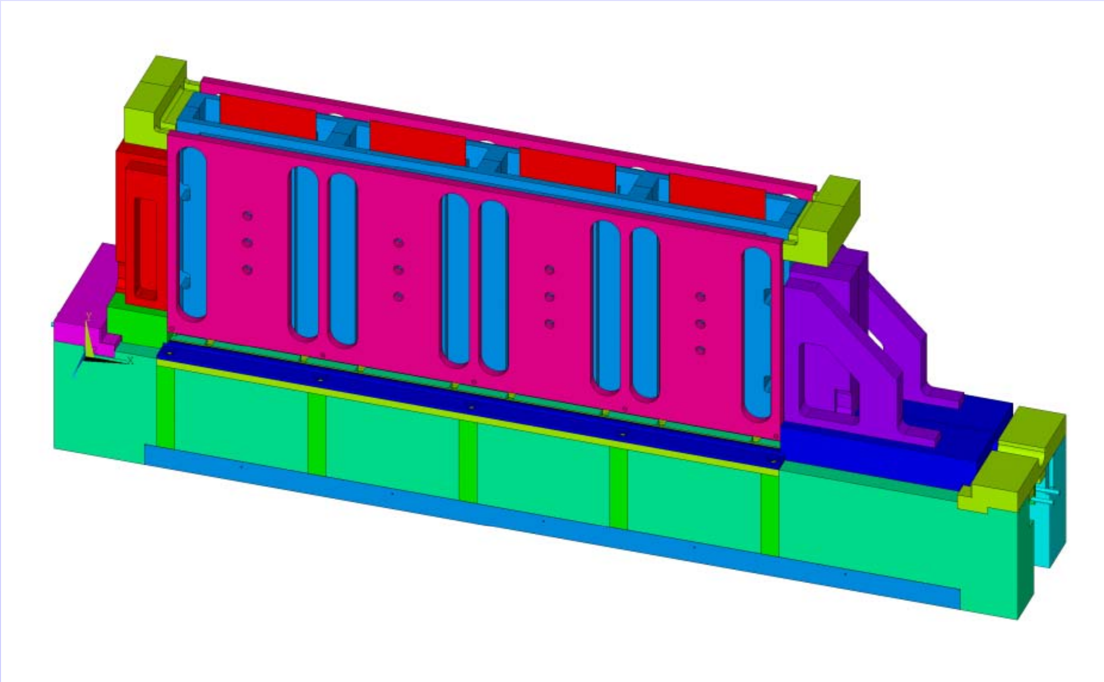


Advantages of the process:

- great temperature tolerance and excellent growth stability
- no need of wafer sawing
- low power consumption
- average cell efficiency above 15%

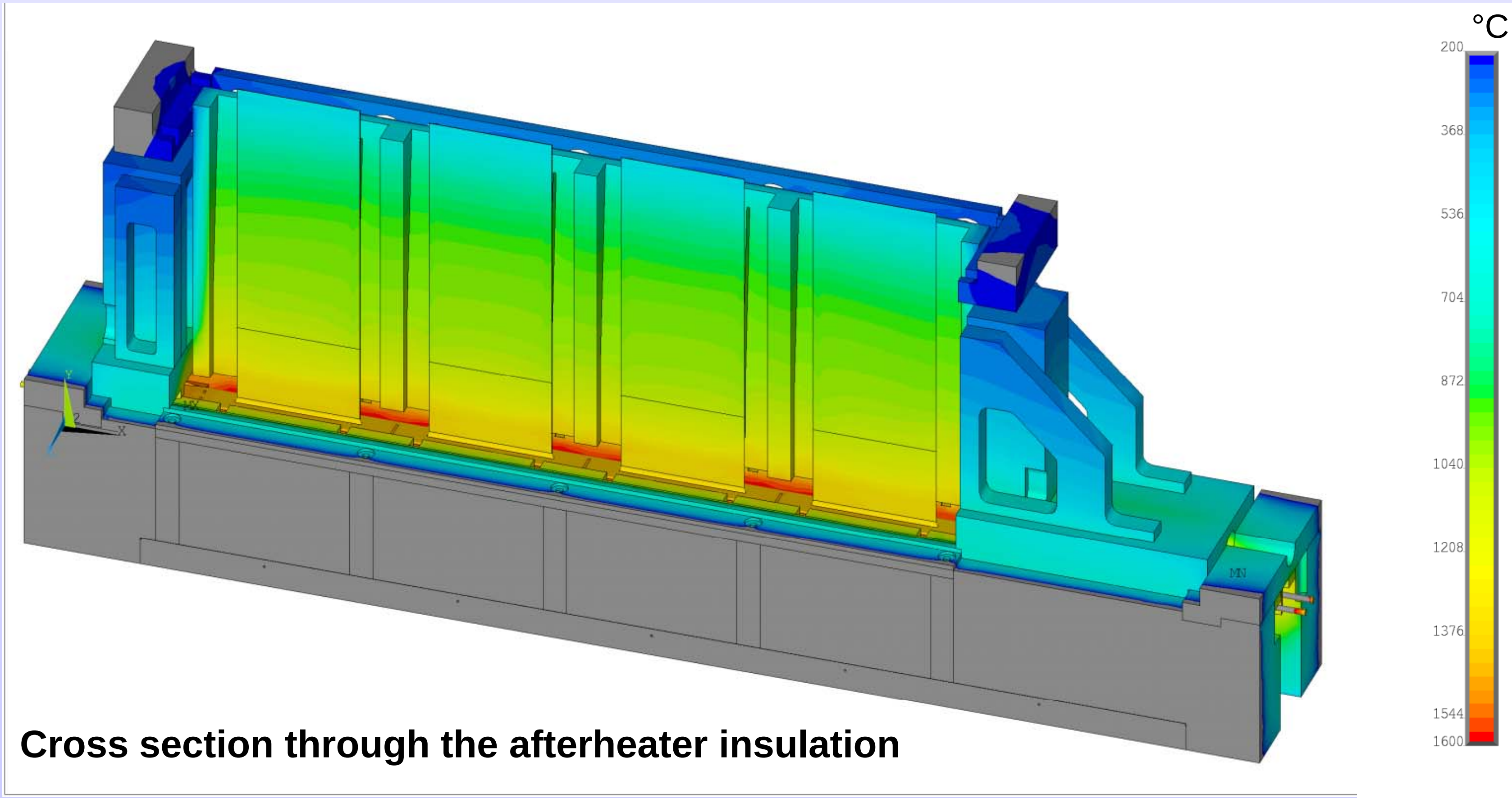
Numerical model





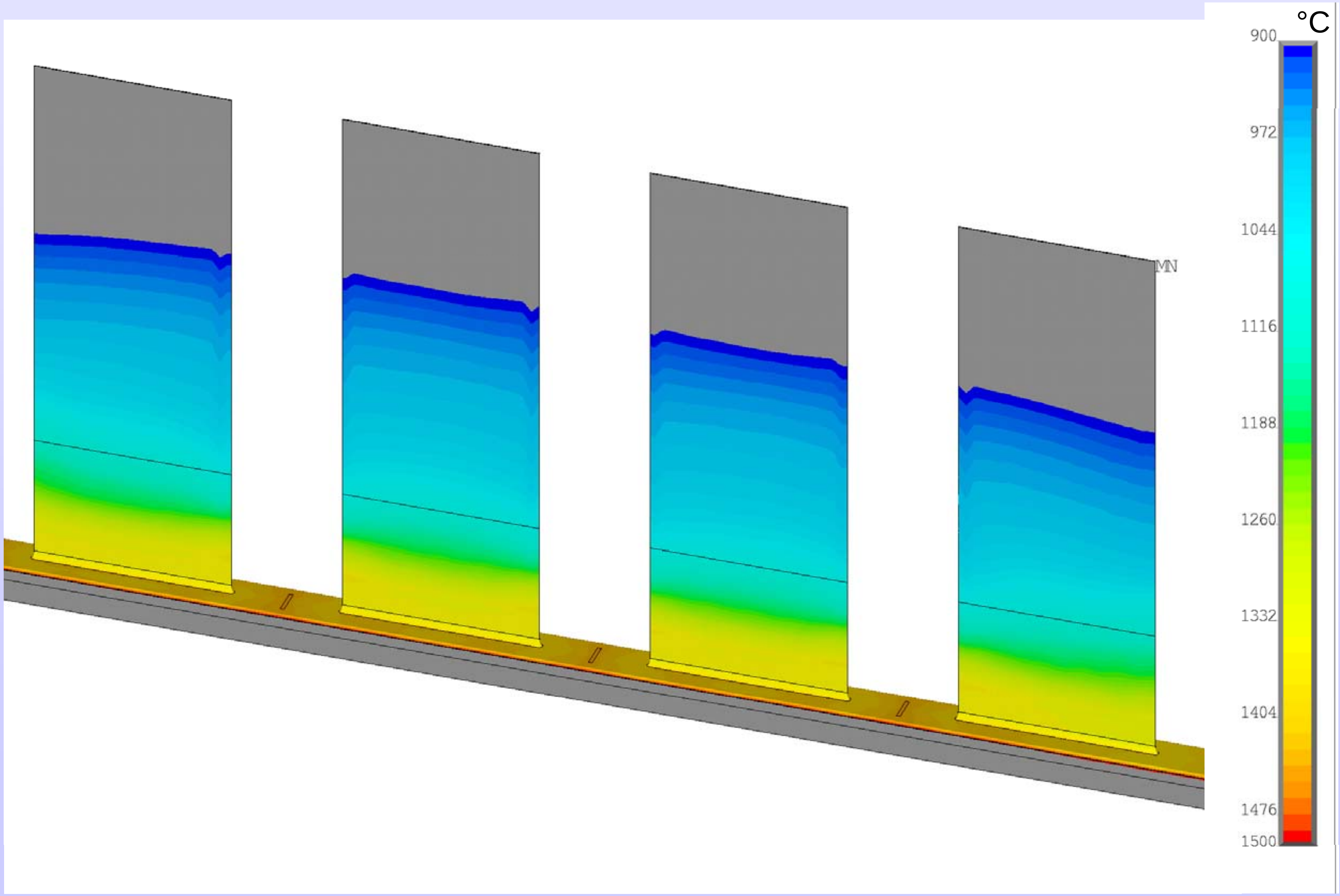
Sovello: Quad furnace in production line

Temperature distribution in the system



Cross section through the afterheater insulation

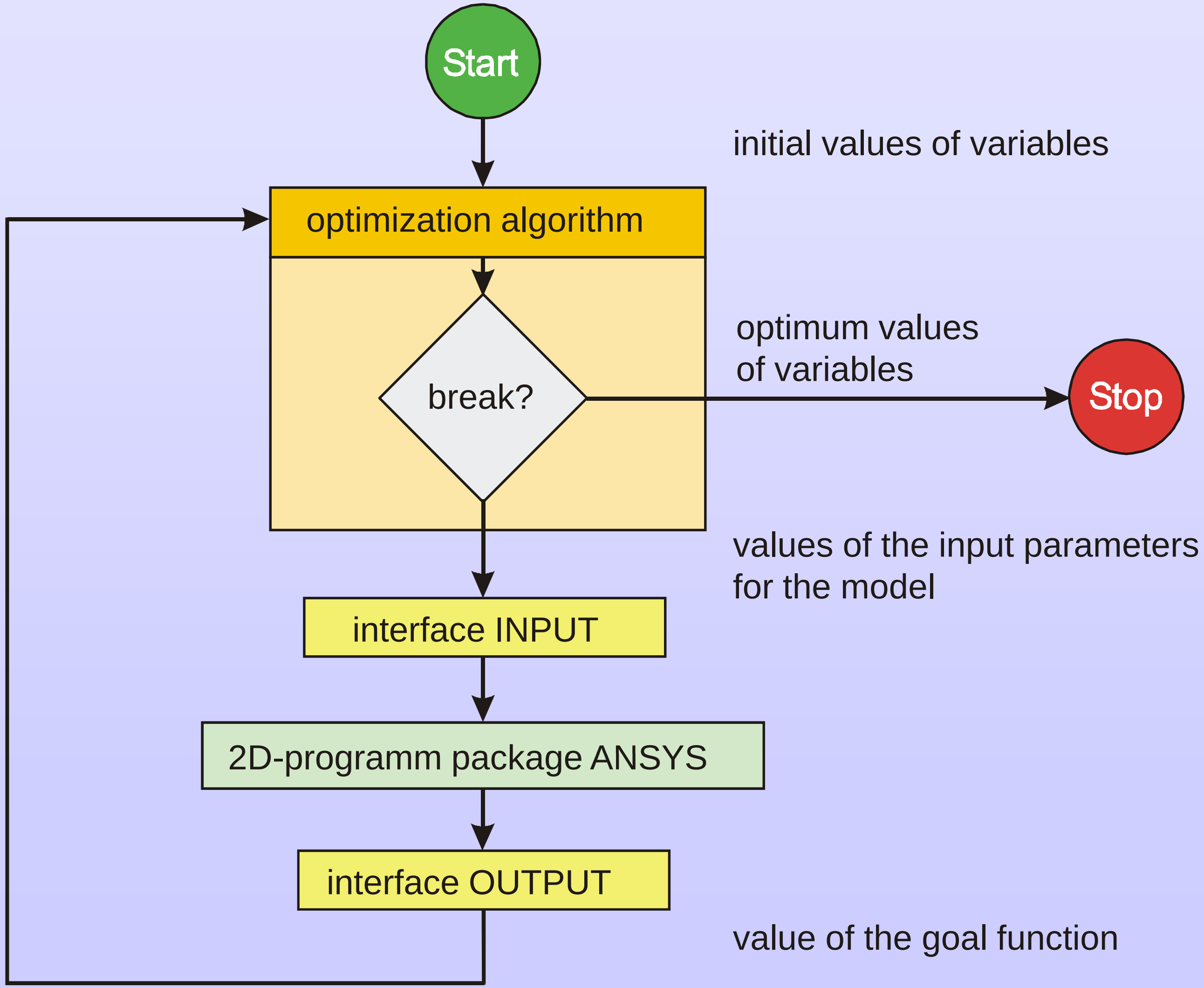
Temperature distribution in crucible, melt, meniscus and ribbons



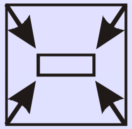
Optimal design and process control of induction heated systems using mathematical optimization

- **Tools and general aspects**
- **Transverse flux heating**
- **Planetary reactors for epitaxy processes**

2D model combined with optimization algorithm



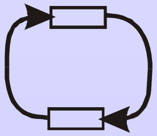
Concept of optimal design



1. Basic investigations η cos φ

Parameter studies and expert solution

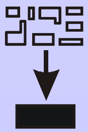
Analytical dependences



2. Optimisation of distributed values $\vartheta(x)$

Mathematical optimisation

Operation and installation data



3. Final analysis and technical realisation

Detailed investigations

Numerical and experimental

ETP

Leibniz Universität Hannover

Design of a transverse flux heater

Requirements

Strip

- Material: Copper + alloys
- Width: fixed: 420 mm
- Thickness: variable: 0,3 mm - 1,5 mm

Temperature

- Heating up: from 20 °C to 300 °C
- Temp. profile: homogeneous (+-4%)

Pre heating before gas fired furnace of an annealing line

→ Improvement of productivity

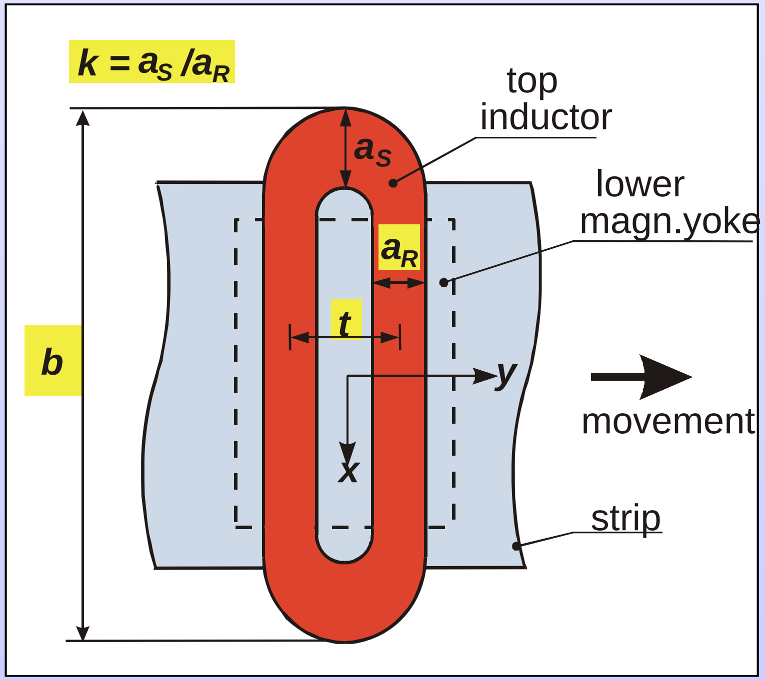
Analytical investigation

Working areas

- Pol pitch *t*: 80 mm to 300 mm
- Frequency *f* in Hz for CuZn37:

d	*t* = 80 mm	*t* = 300 mm
0,3 mm	1870 Hz	500 Hz
0,8 mm	700 Hz	190 Hz
1,5 mm	370 Hz	100 Hz

Design of a transverse flux heater by means of mathematical optimization

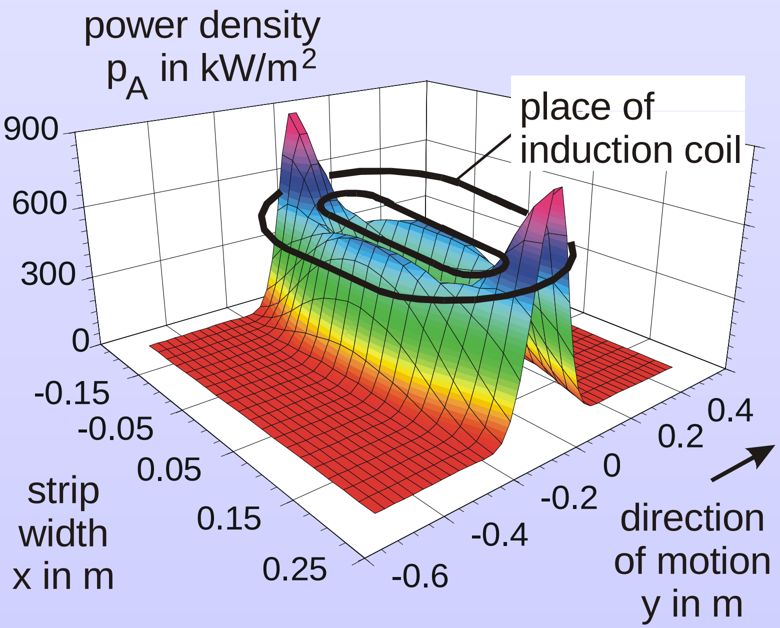


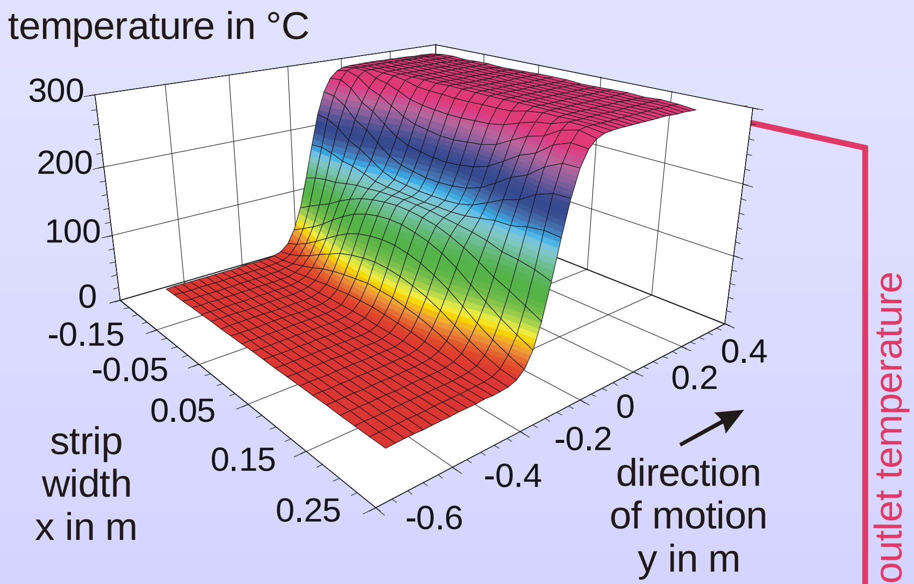
design variables	limits	results
inductor length b	350 mm - 600 mm	462 mm
cond. width a_R	32 mm - 160 mm	122 mm
coil head factor k	0,3 - 1,5	0,6
pol pitch t	80 mm - 300 mm	220 mm
(frequency $f = fopt$	190 Hz - 700 Hz	255 Hz)

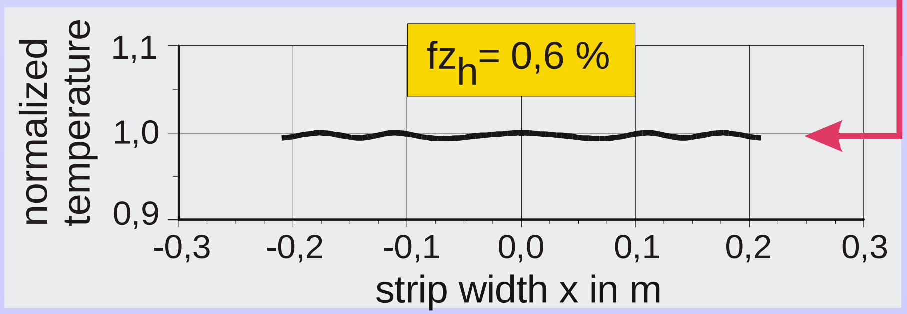
minimum of goal function:

→ f_{zh} =0,6 % with η_{el} = 94,4 %, cos φ = 0,79

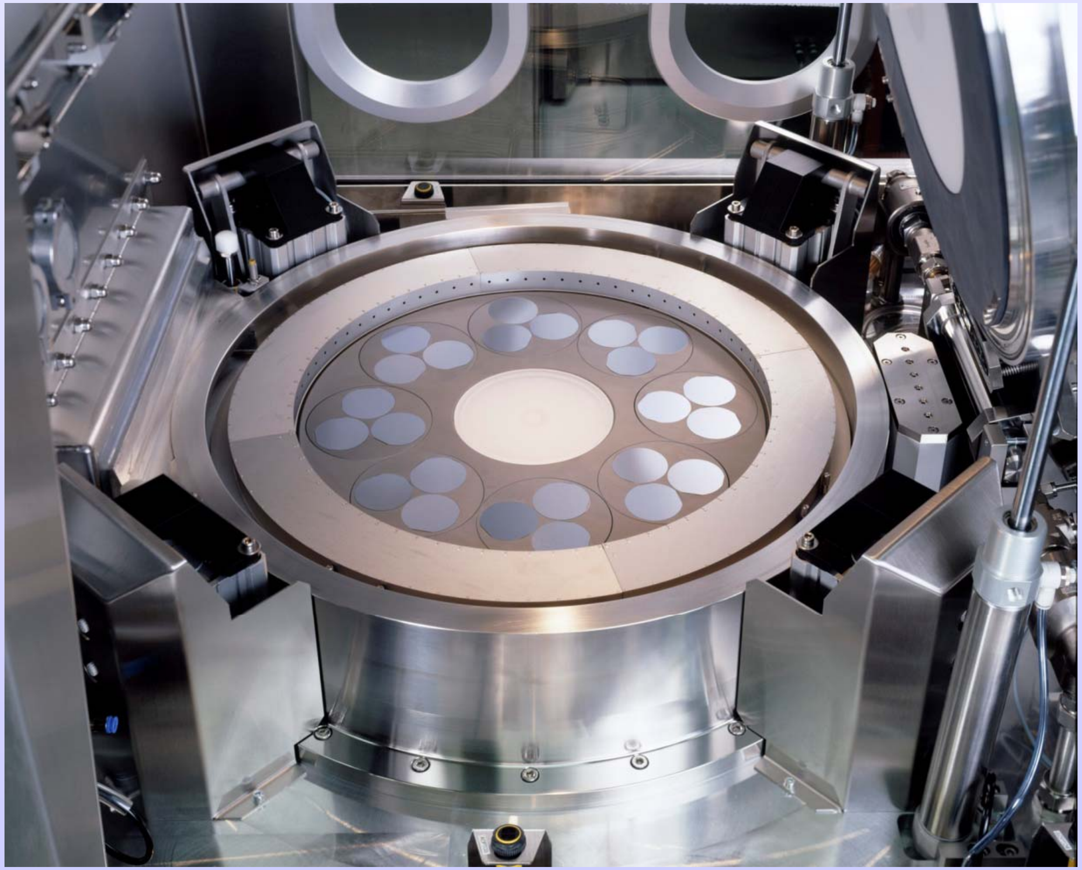
Results of optimization for fixed strip width







Planetary reactors for epitaxy processes

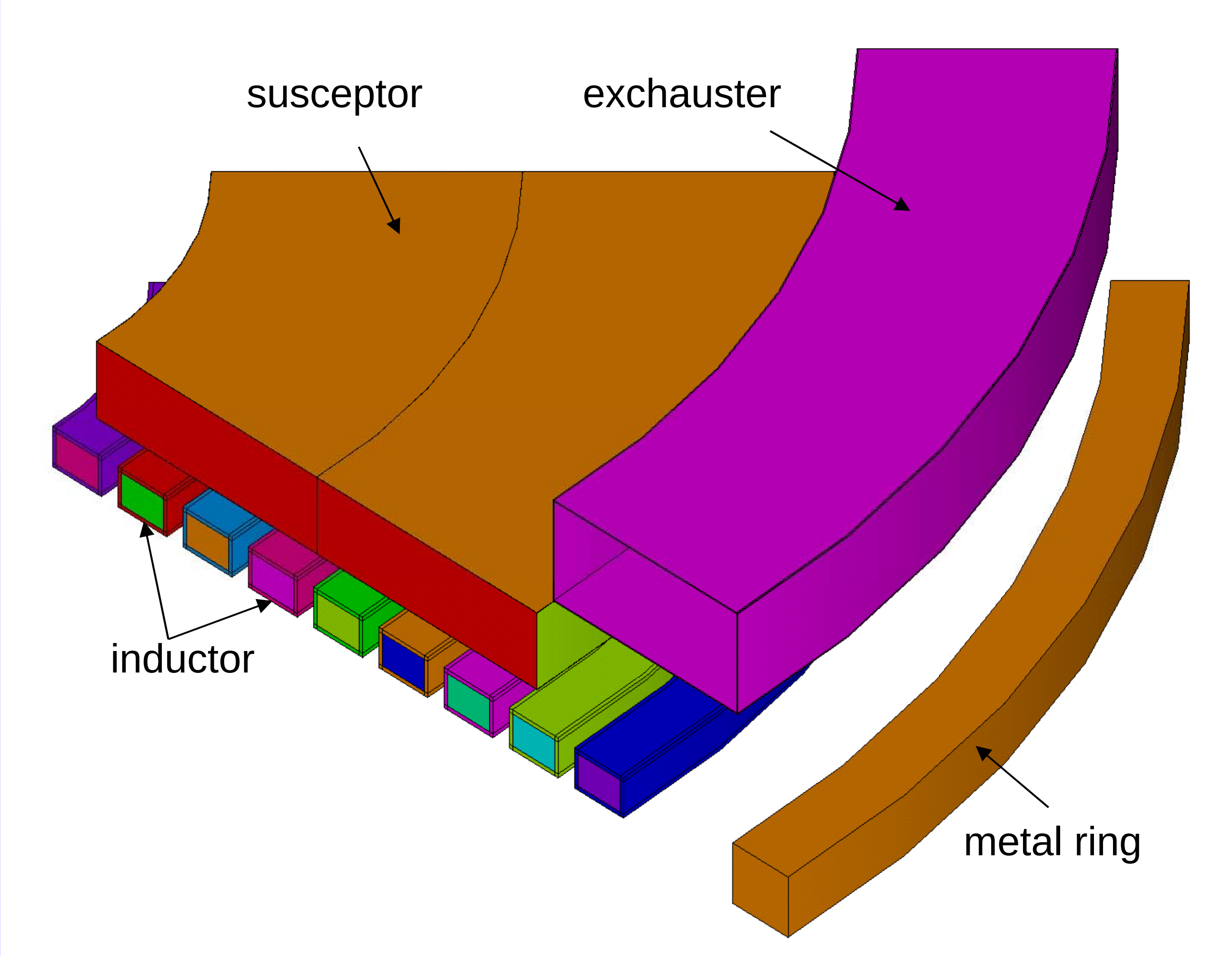


Typical planetary reactor for epitaxy processes

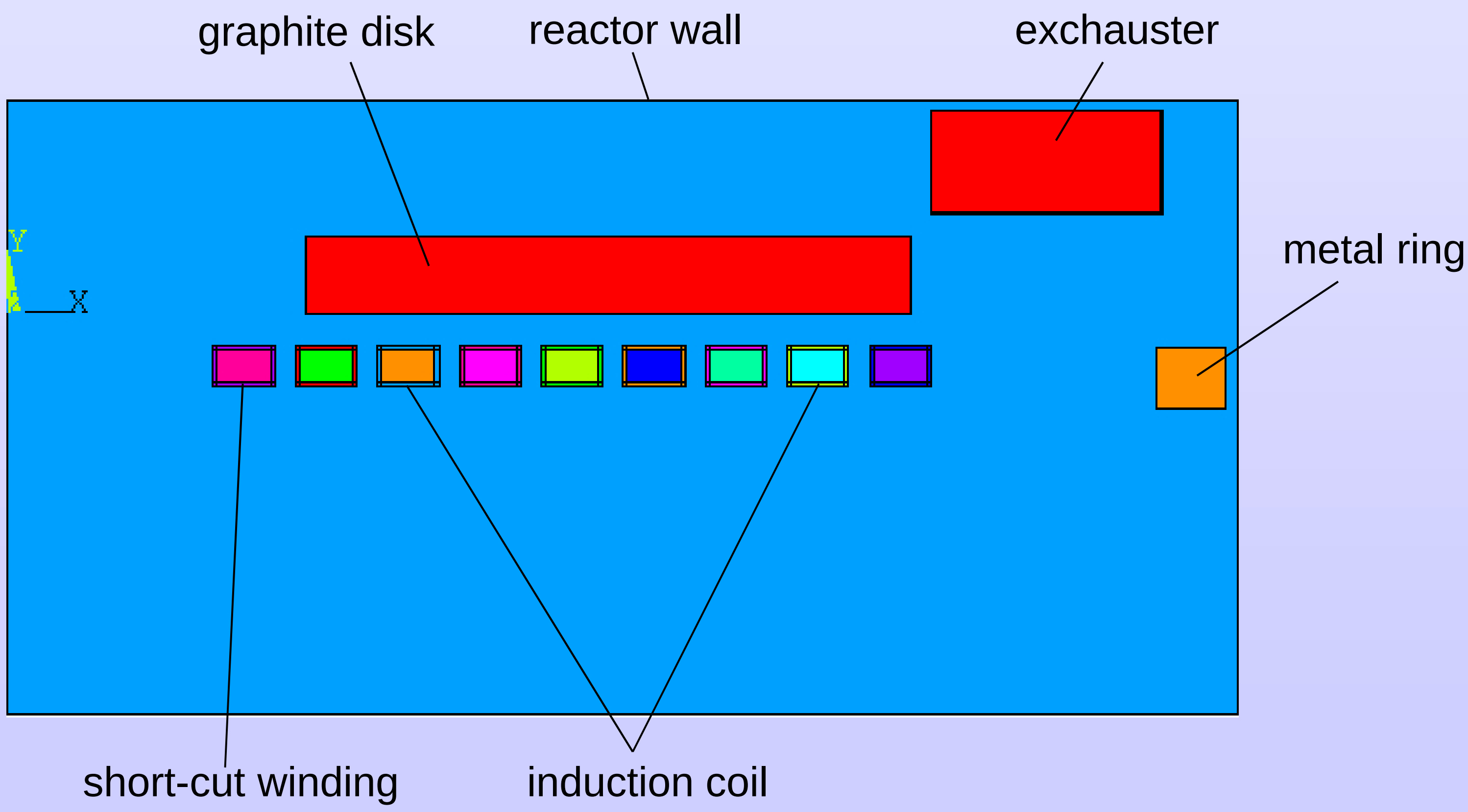
The process temperature above 1100ºC is provided by induction heating of the graphite susceptor.
The susceptor is covered with SiC layer because of chemically agressive gas.

The SiC layer lifetime determines the susceptor lifetime.
Problem:
Temperature gradients in the graphite create cracks in te SiC layer.

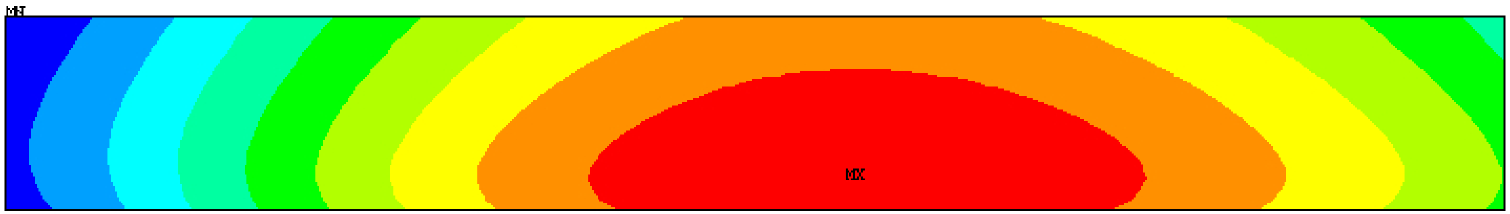
3D model of planetary reactor



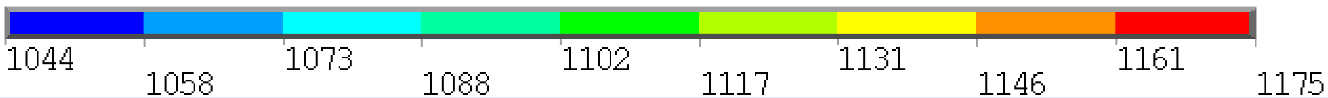
Numerical modelling – 2D approach



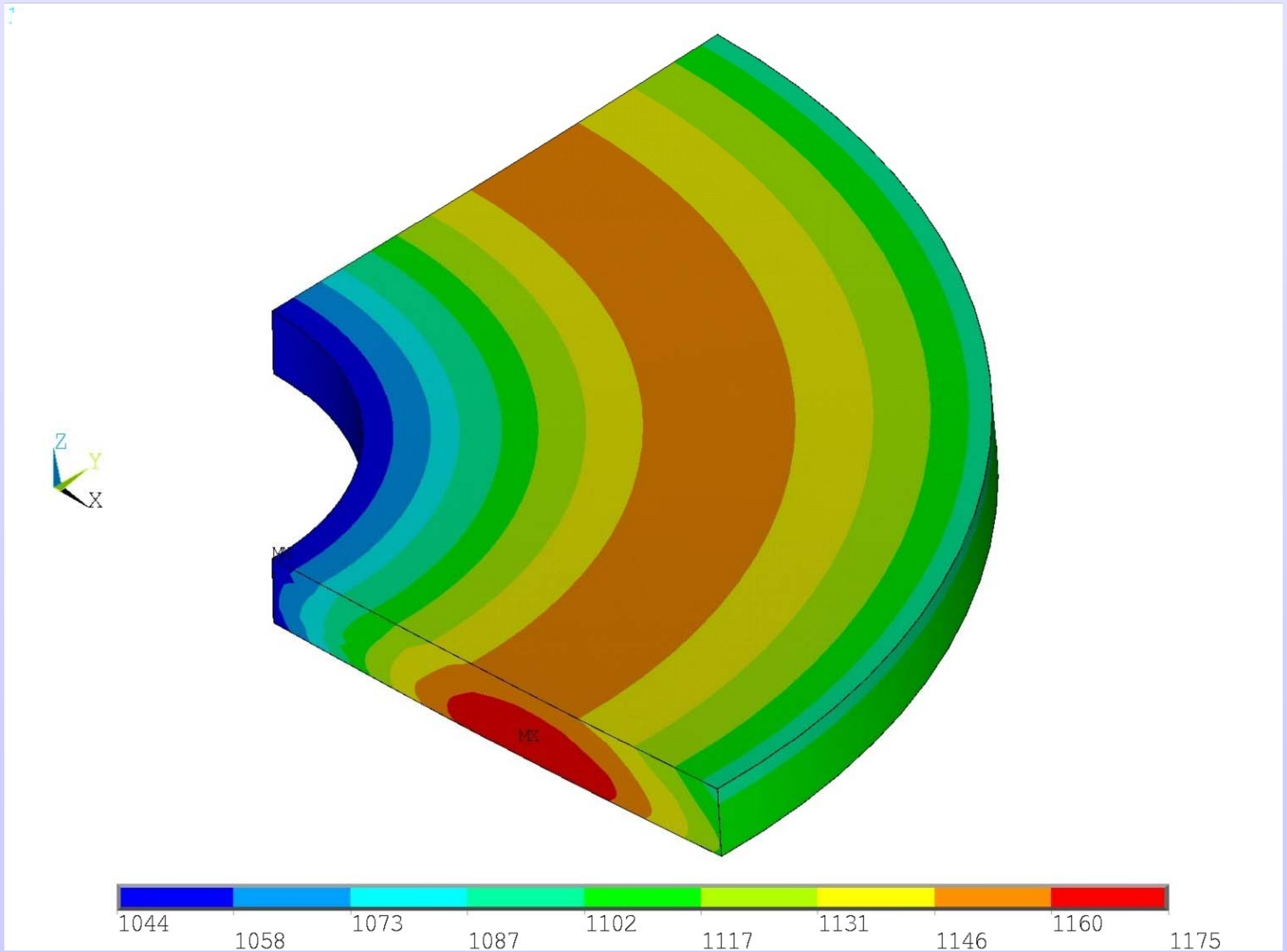
2D temperature distribution in the susceptor for the existing system



Temperature deviation ±66K



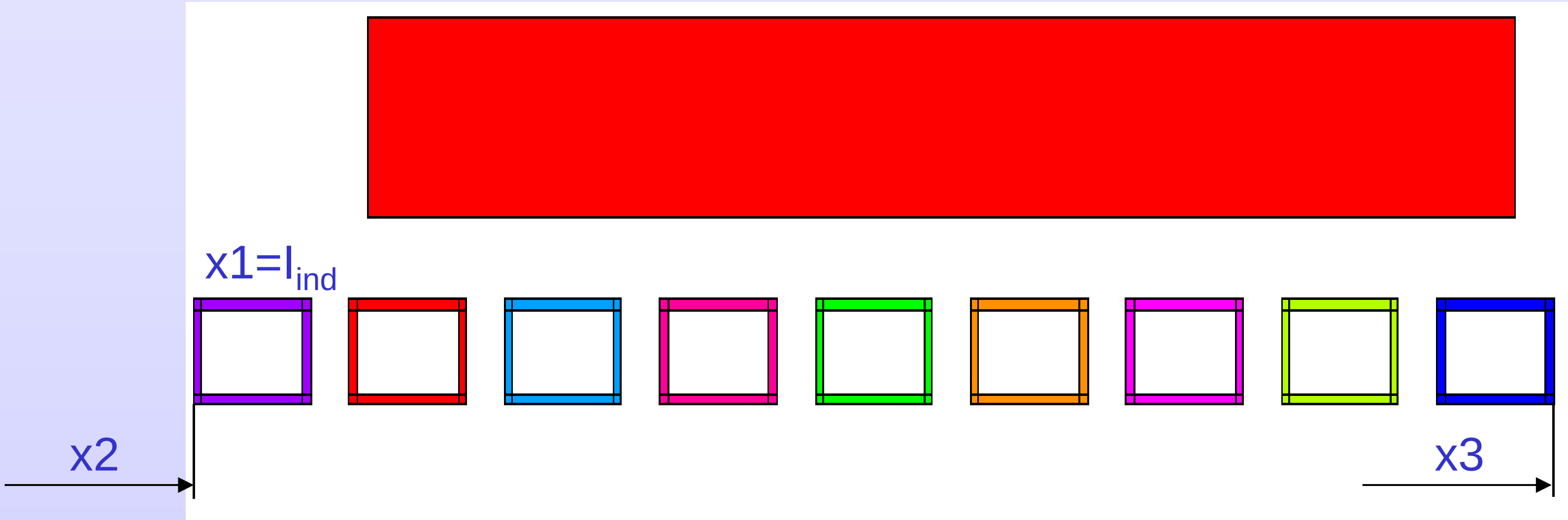
2D temperature distribution interpolated for 3D structural analysis



Maximum strain in the SiC layer for the temperature distribution is

215 Mpa

Definition of optimization variables and goal function



Independent variables for optimization:

x1 – current in the coil

x2 – inner radius of the coil

x3 – outer radius of the coil

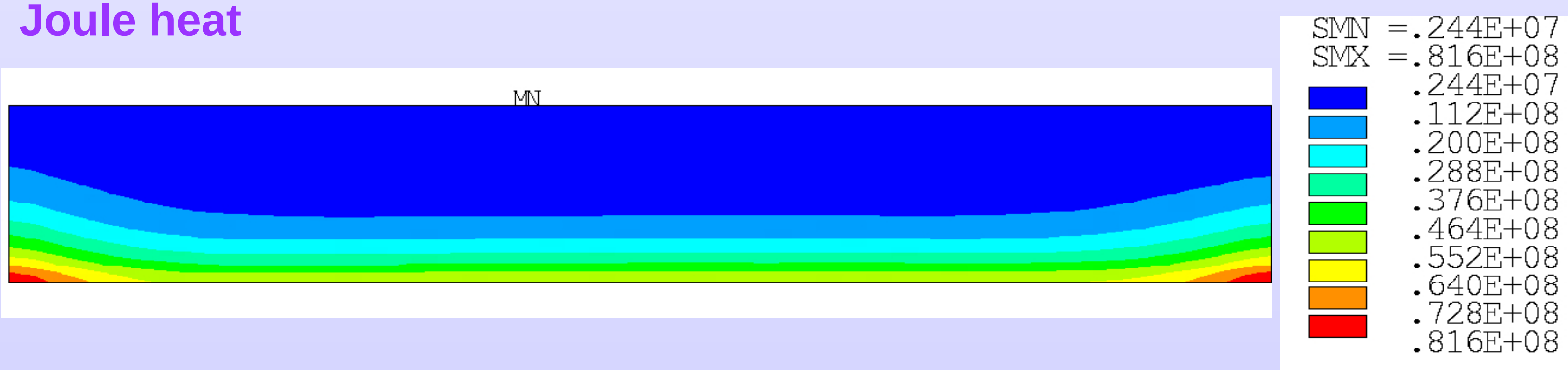
(uniform spacing between the coil windings)

Goal function to be minimized:

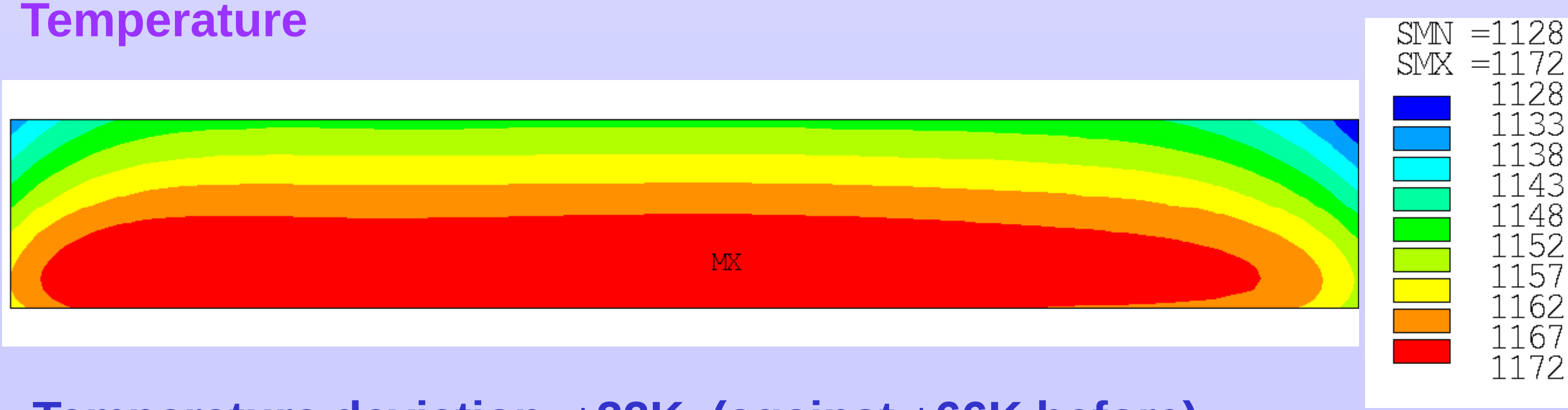
F=max{abs[T(x,y)-1150]}

Joule heat distribution and temperature field in the susceptor for the optimized system

Joule heat

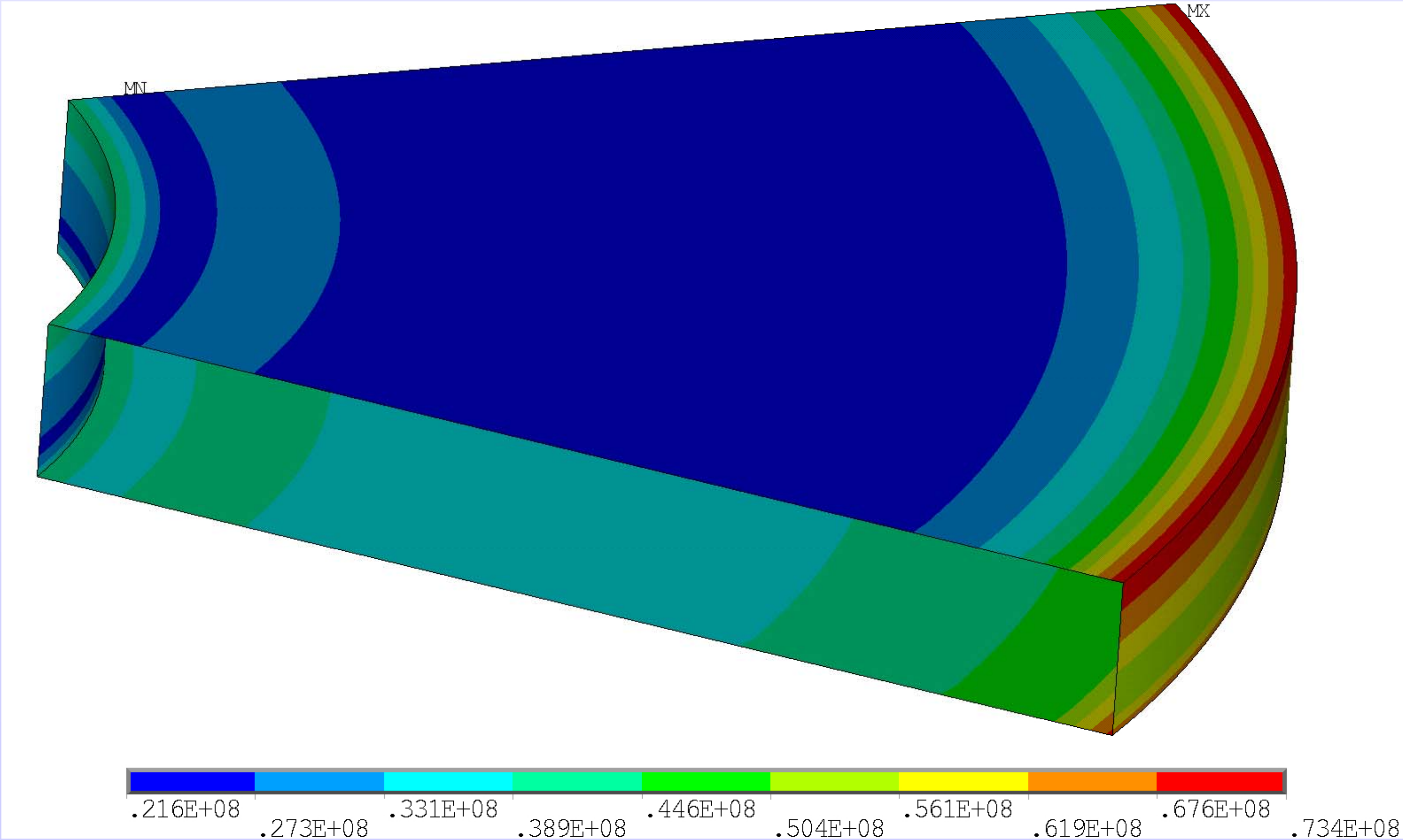


Temperature



Temperature deviation ±22K (against ±66K before)

Tangential component of strain in SiC layer for the optimized system



Maximum strain in the SiC layer - 73 Mpa (against 215 Mpa before)

Conclusion

- **Numerical simulation is an effective tool for the design and control of induction melting and heating processes**
- **2D and 3D numerical models help to analyse, to investigate and to optimize induction melting and heating systems and processes**
- **Mathematical optimization in combination with numerical models can reduce time and costs to find the optimal design or control of an induction heating process**

Future challenges

- **Faster calculation of complex turbulent electromagnetic driven flow fields**
- **Coupled electromagnetic and flow fields taking into account the dynamic of the melt free surface**
- **Simulation of melt flow including crystallization or solidification process at solid-liquid interfaces**
- **Simulation of 3D coupled electromagnetic-thermal processes with consideration of the field and temperature dependent permeability**
- **Simulation of stress and of material conversion during and after cooling of work-pieces like for surface hardening**
- **Development of simulation tools using OpenFOAM**

Thank you for your attention !