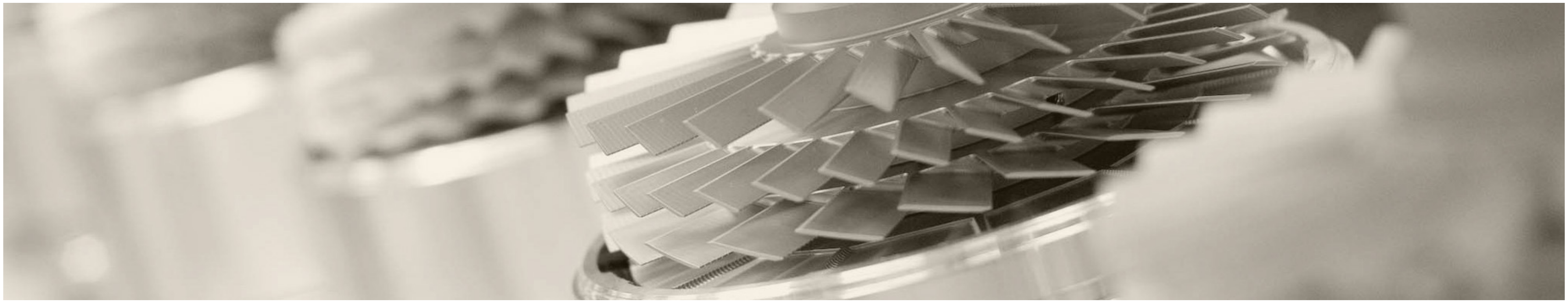
Current Techniques and Challenges in the Design of Vacuum Pumps

Leinsweiler, 2011-05-17

Magnus Janicki

Oerlikon Leybold Vacuum, Cologne



Agenda

Introduction

Screw Vacuum Pumps

- Functional principle
- Design Problems
- Simulation with a Cell Model
- Challenges

Turbo Molecular Pump

- Function
- Design Problems
- Solutions via Simulation
  - Monte Carlo Test Particle Method
  - Laminar Flow Calculation (Hagen-Poiseuille)
  - 3D Monte Carlo Test Particle for stationary parts
- Challenges

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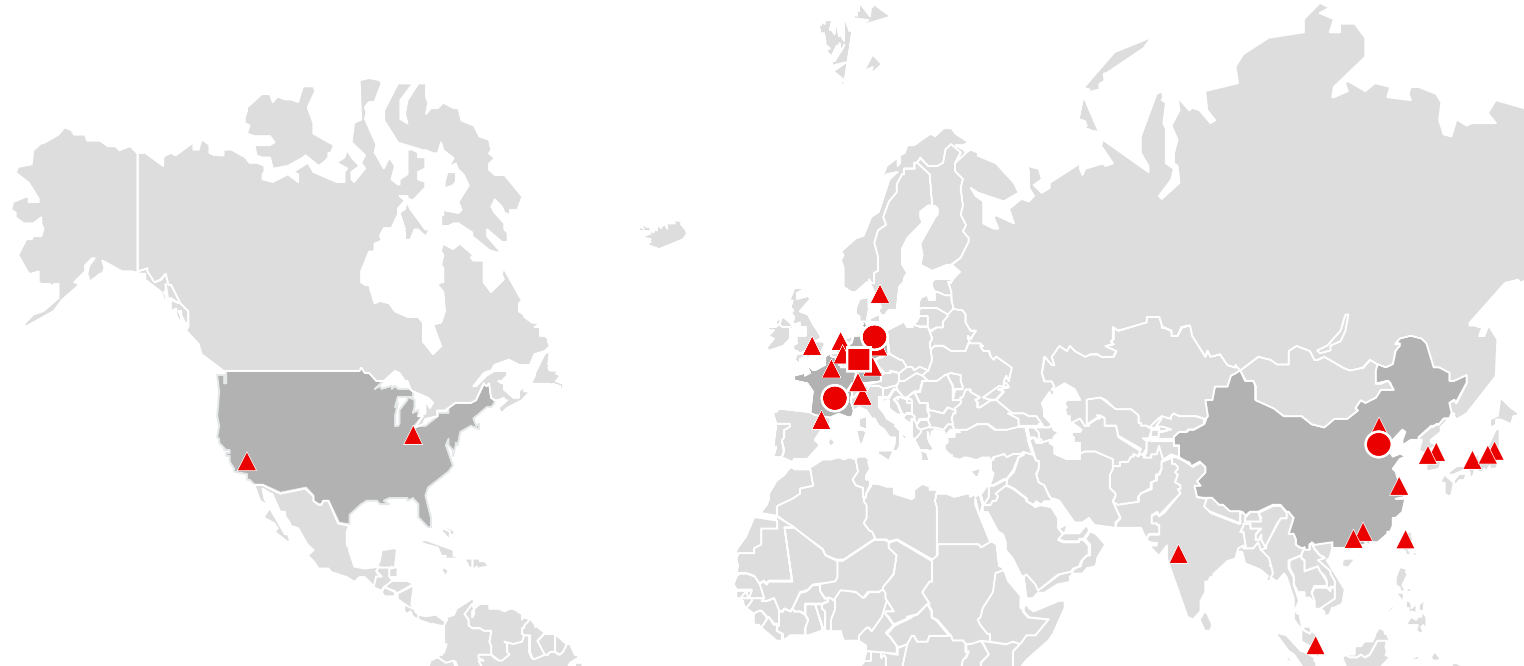

18 Legal Entities

4 Production Sites

30 Sales & Service Sites

>50 Agents / Distributors

1,477 Employees

Valence, France

Cologne, Germany

Dresden, Germany

Tianjin, China

- ■ Headquarter
- ● Production
- ▲ Office

Vacuum Pumps

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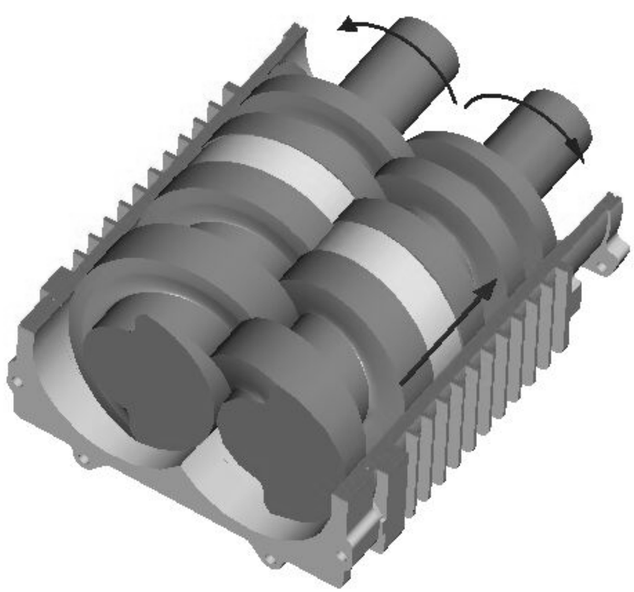
Screw Vacuum Pump

Screw vacuum pumps are used since the 80s

- Fore vacuum pump ➔ compressing against atmosphere
- High pumping capacity
- Inlet pressure from 10^{-3} mbar to 1000 mbar



- Two rotating screw without contact
- Dry pump ➔ no contamination of gas or oil
- High energy efficiency due to inner compression ratio

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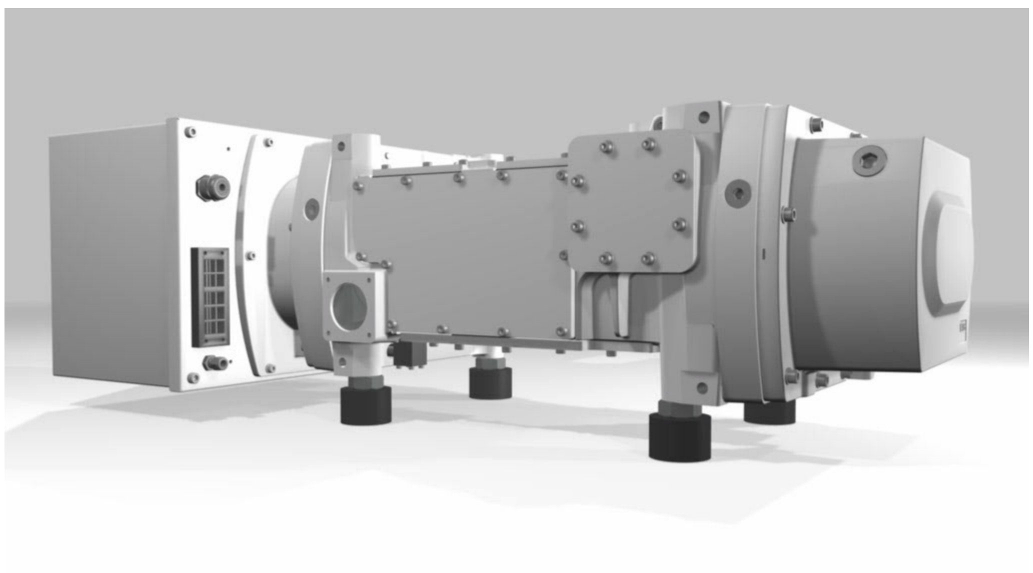
Screw Vacuum Pump - Functional Principal

- Gas enters the pump on the suction side
- Tooth cavities form chambers that transport the gas volume to the exhaust
- Volume of cavities may decrease ➔ volumetric compression
- Backward gas flow through clearances ➔ isochoric compression
- Gas leaves pump on discharge side

Vacuum performance of a screw pump is mainly defined by

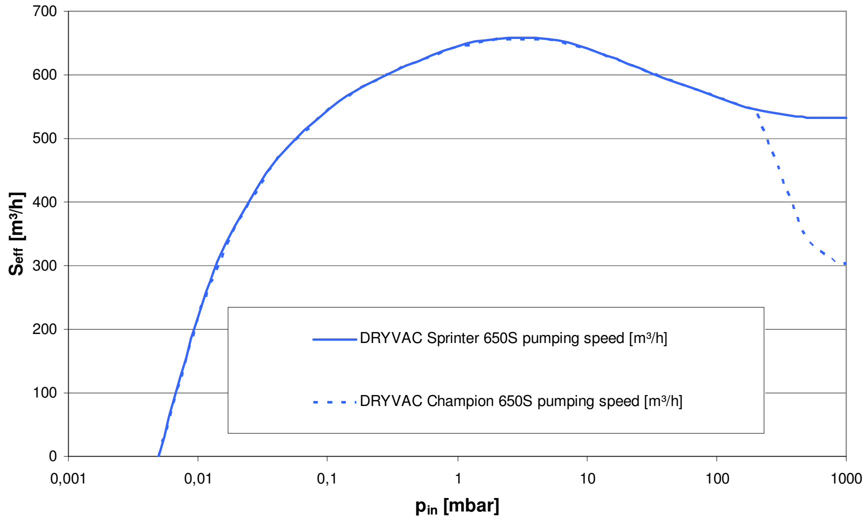
- Forward transport volume flow
- Backward clearance flow

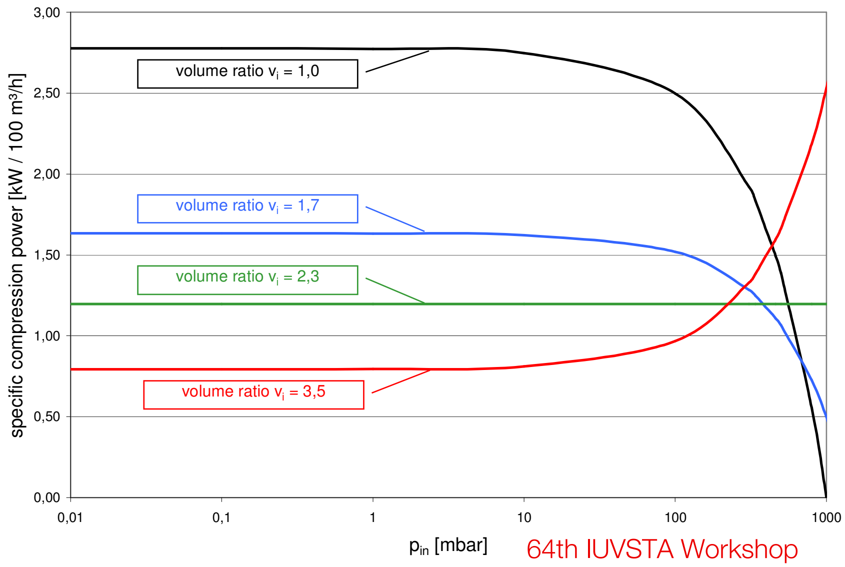
Gas flow from molecular over transient to viscous flow regime



Screw Vacuum Pump - Design Goals

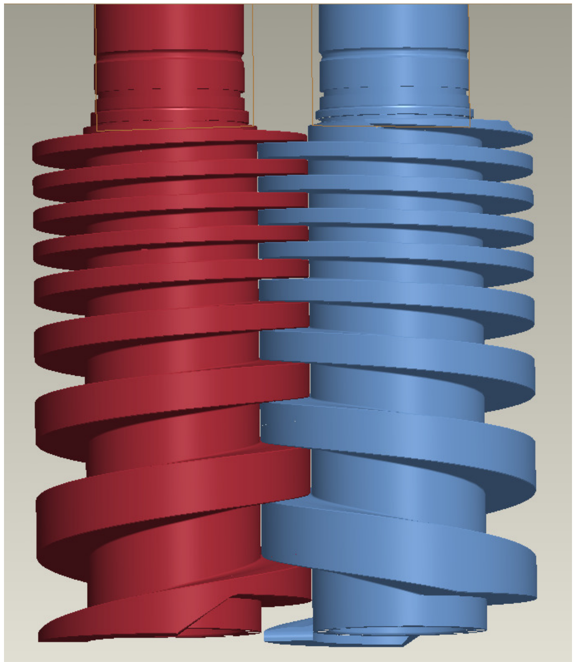
Technical goals in the design of screw vacuum pumps
- Vacuum performance
  - Pumping speed
  - Ultimate pressure
- Energy efficiency
  - Low maximum power consumption
  - Low average power consumption
- Safe operation in different applications
  - Controlled thermal behavior





Cell Model for screw pumps

- Simulation of the thermodynamic process of displacement machines with many cells
- Approach:
  - trapped volumes are *cells* with homogenous gas conditions regarding
    - pressure
    - temperature
    - mixture
  - clearances are connections between cells
  - calculation of mass flow by time step model
    - transport
    - leakage through clearances



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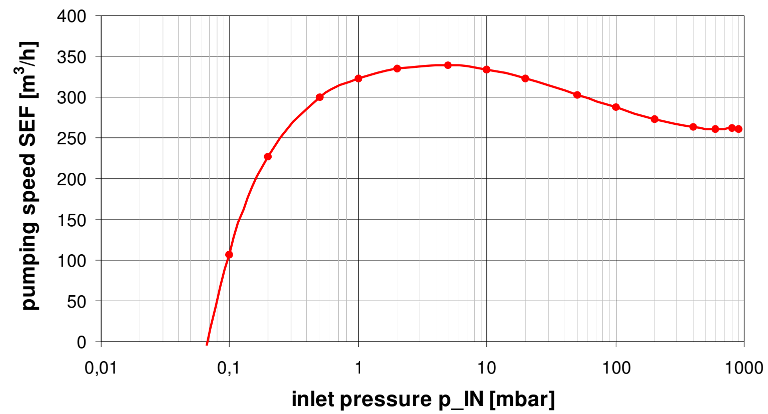
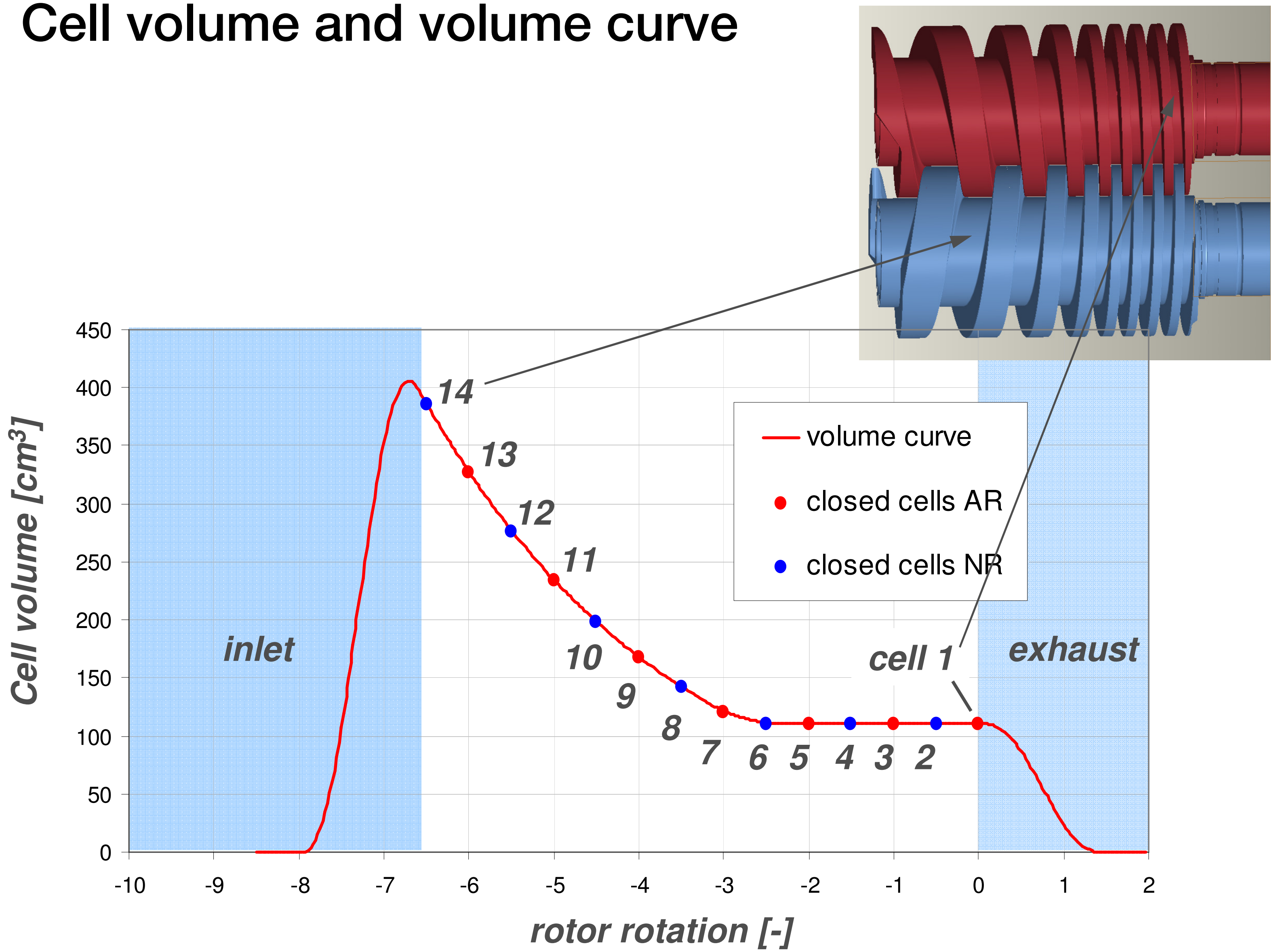
Cell Model for screw pumps

- Input data:
  - rotor geometry
  - clearance height
  - inlet and exhaust pressure and temperature
  - rotor speed
  - cell temperature
  - gas ballast or purge gas flow

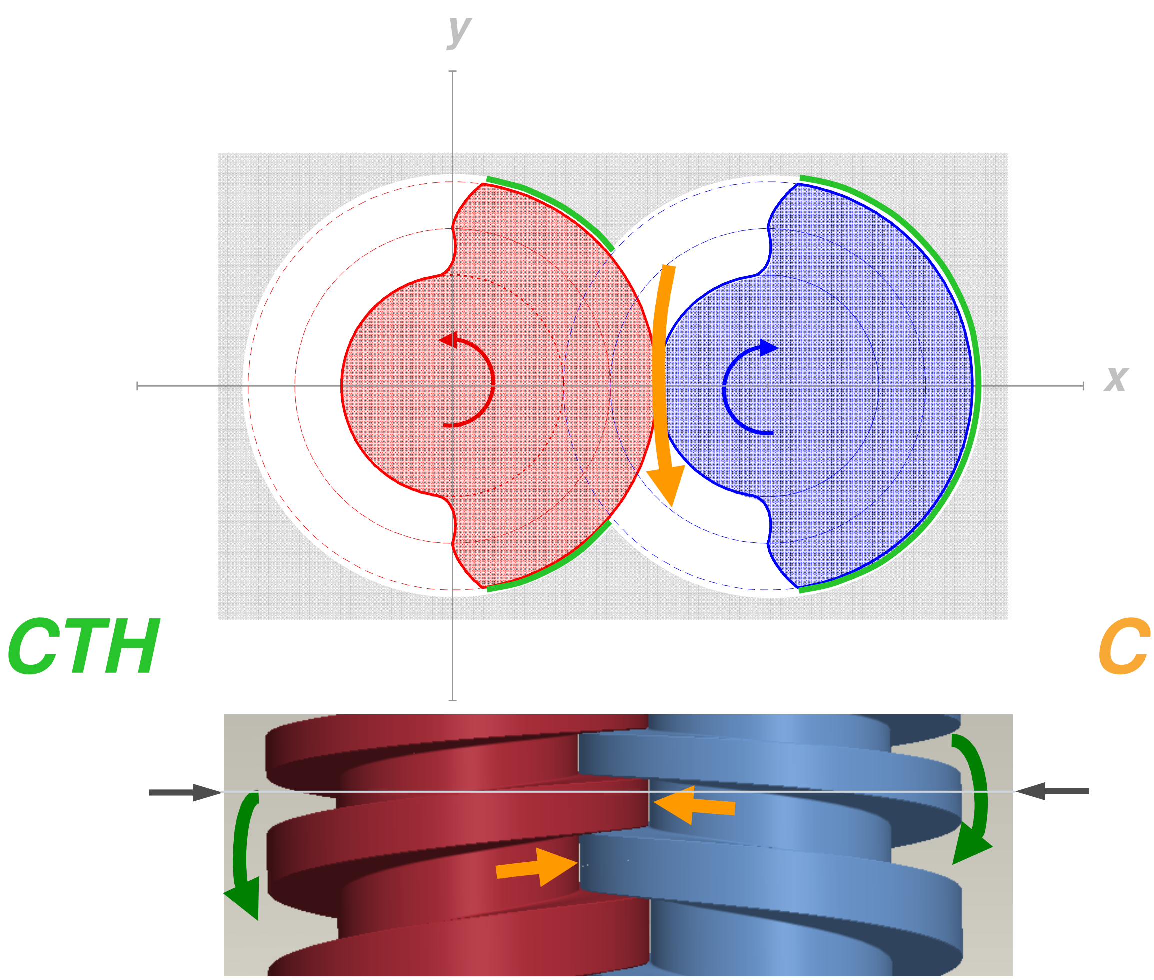
- Simulation results:
  - pumping speed
  - power consumption
  - cell pressure
  - bearing load
  - clearance leakage flow
  - gas ballast flow



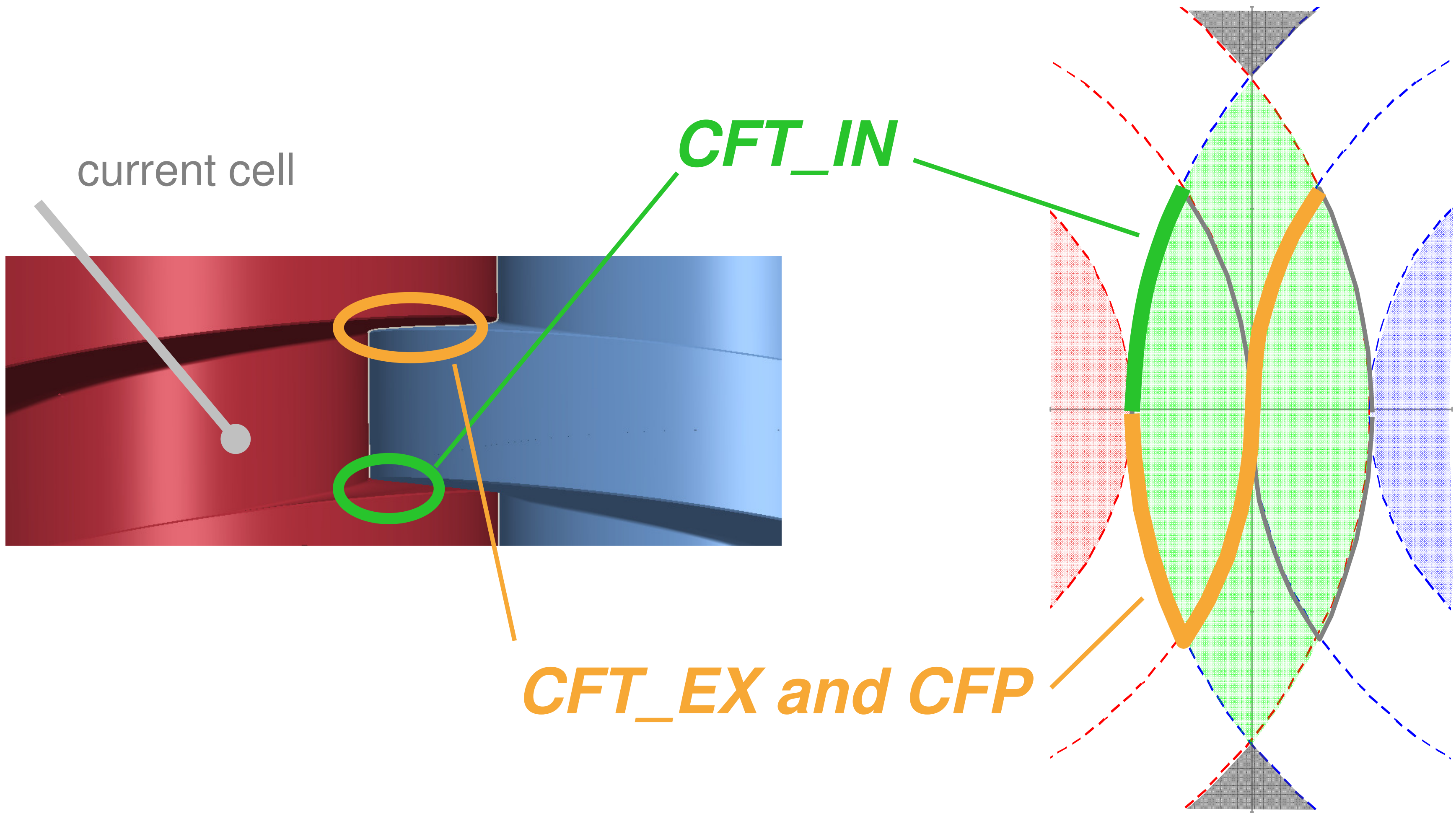
Cell volume and volume curve



CTH clearance tip to housing and *CTR* clearance tip to root



CFP clearance flank pitch and *CFT* clearance flank tip



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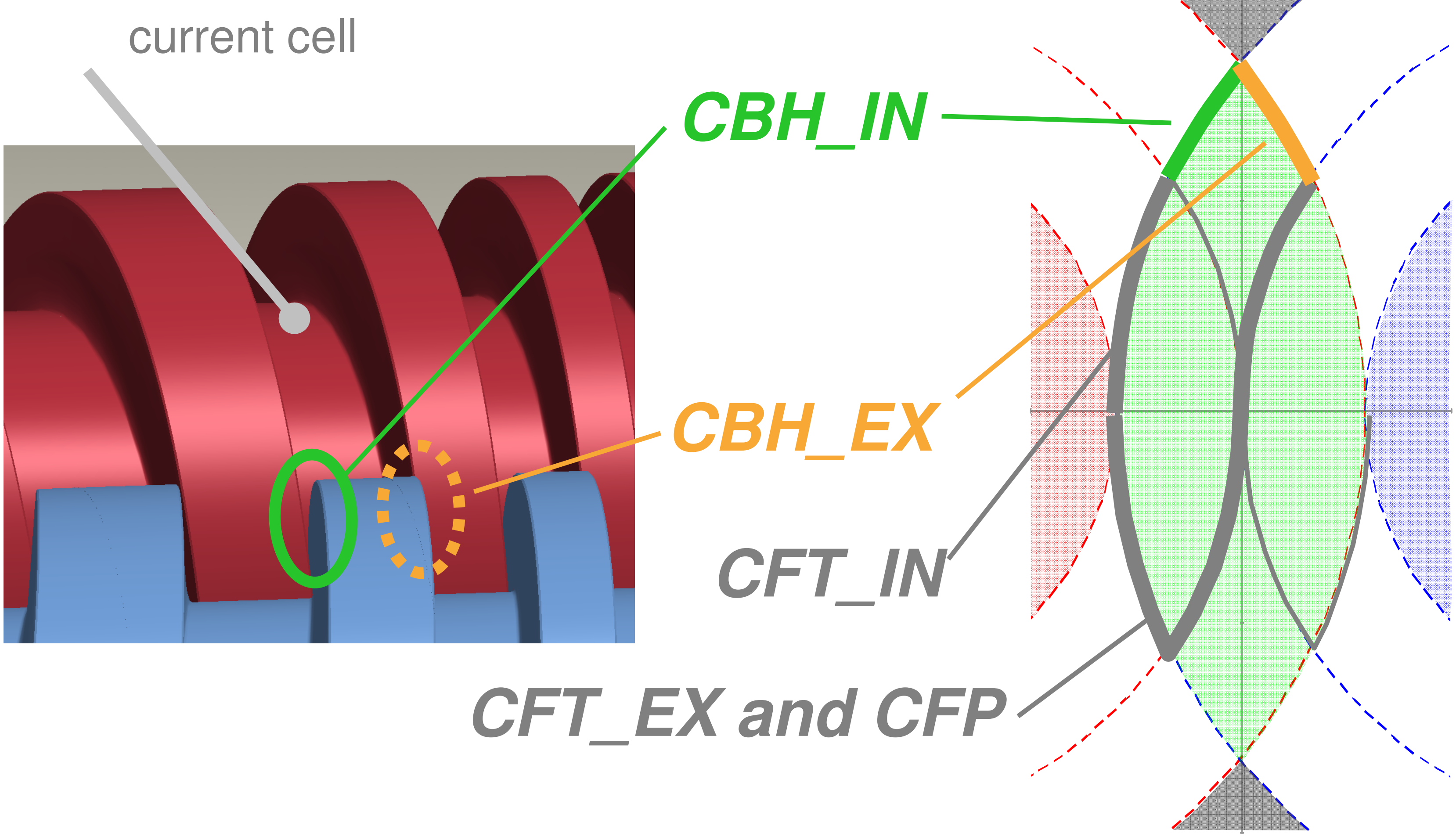
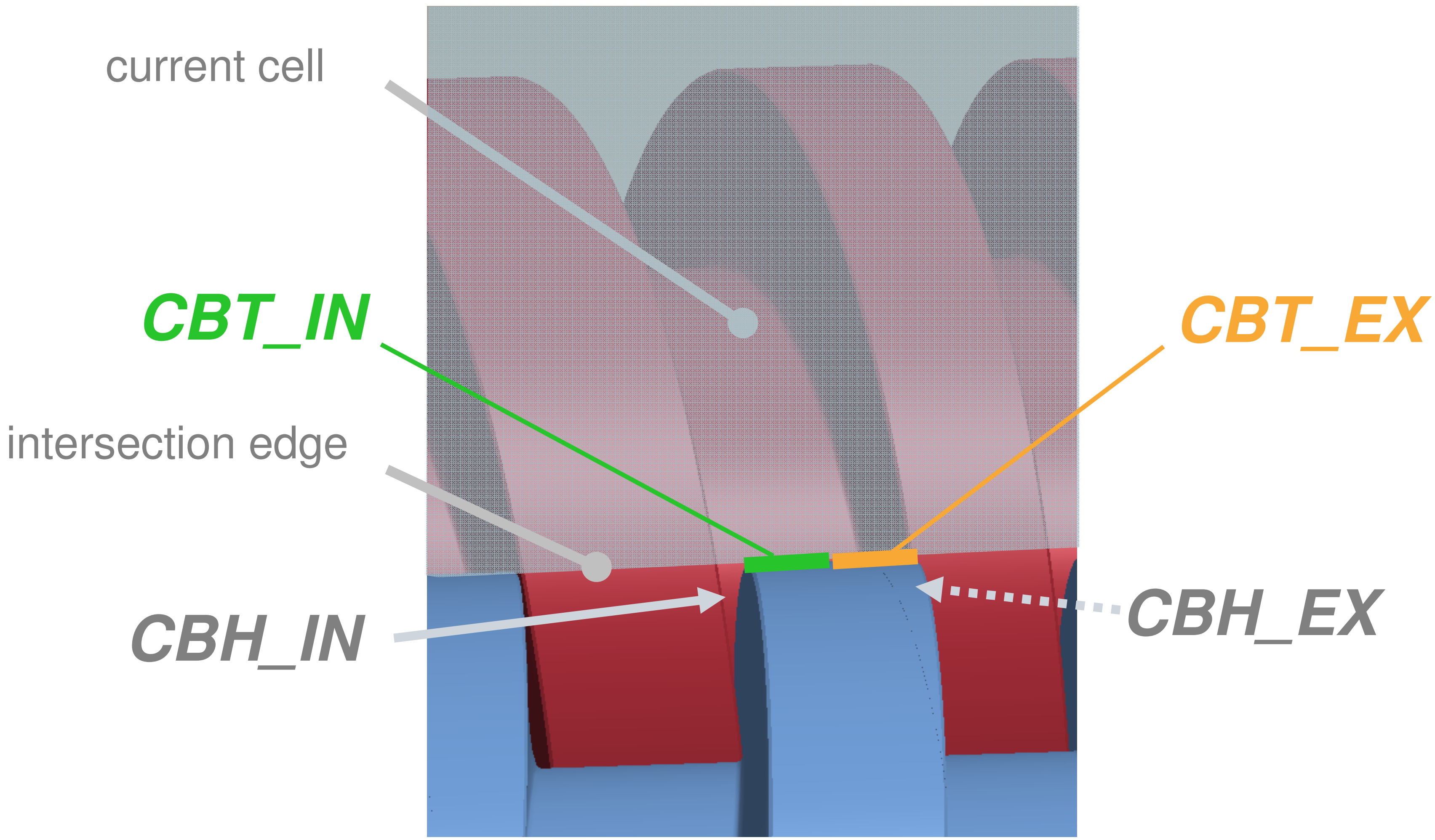
CBH clearance blow hole



CBT clearance blow hole tail



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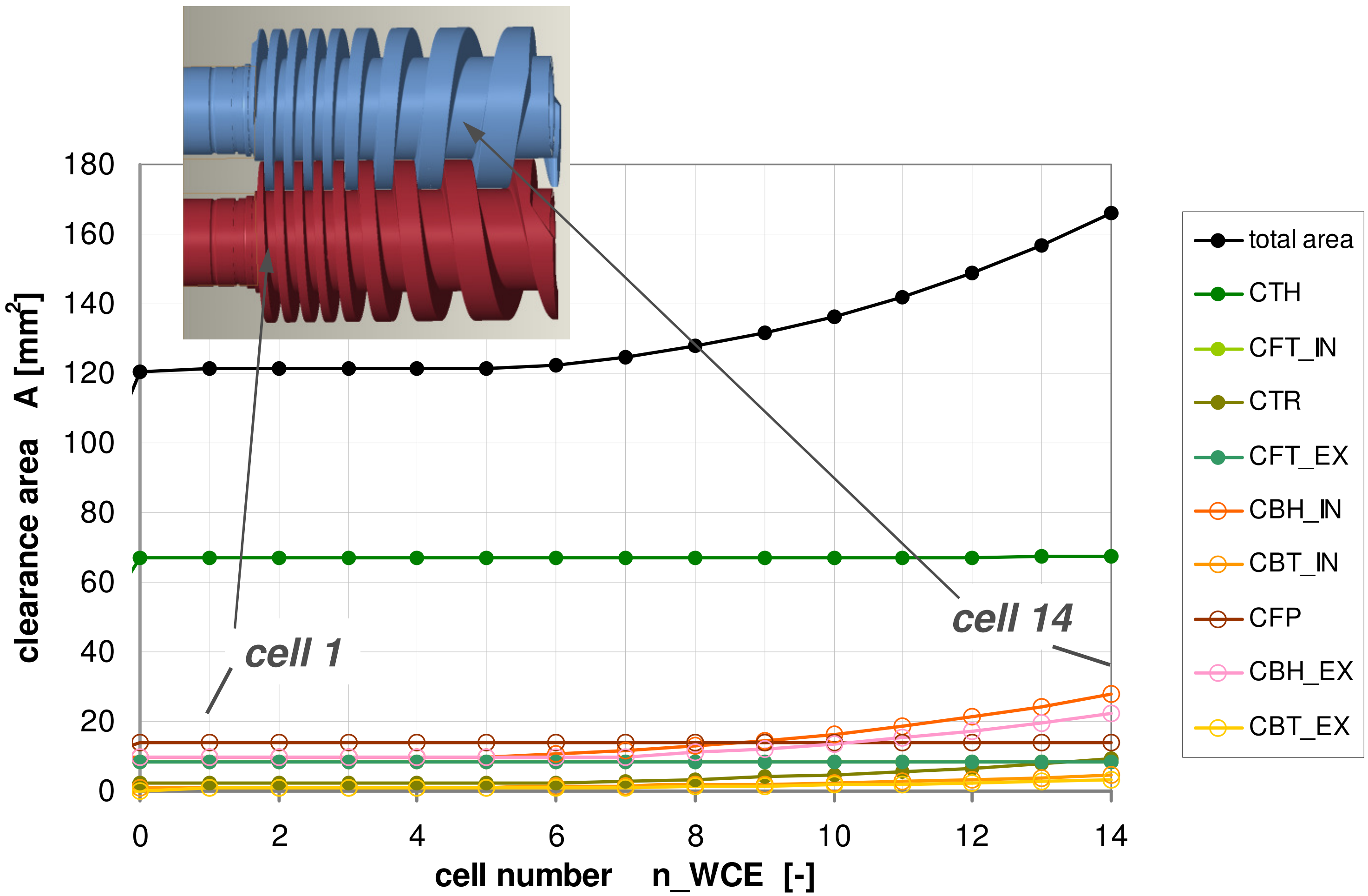
Clearance area for constant clearance height



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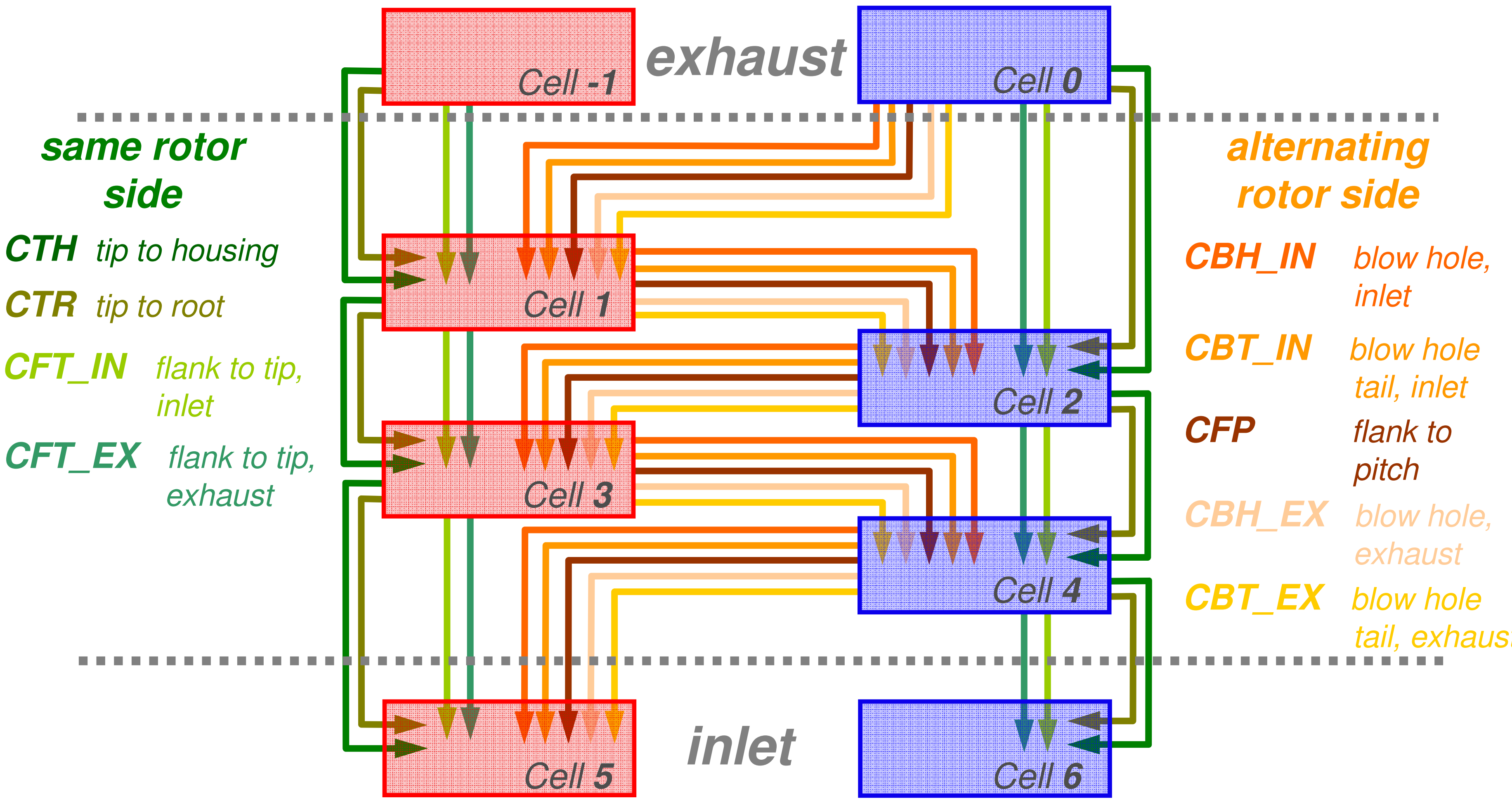
Connection between cells (NOS=1)



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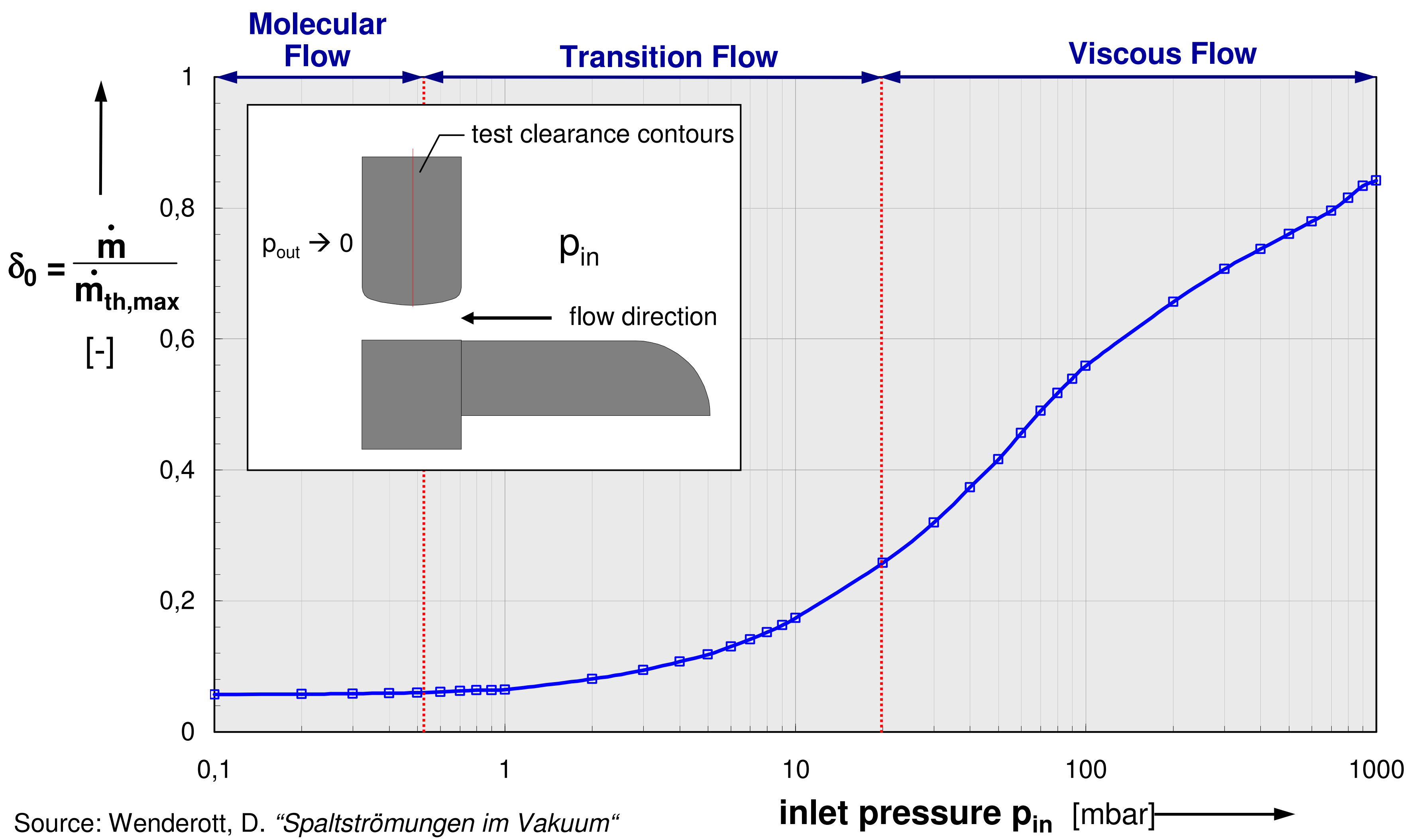
Calculation of leakage flow through clearances



Source: Wenderott, D. *“Spaltströmungen im Vakuum“*

Iterative solution of thermodynamic cell network

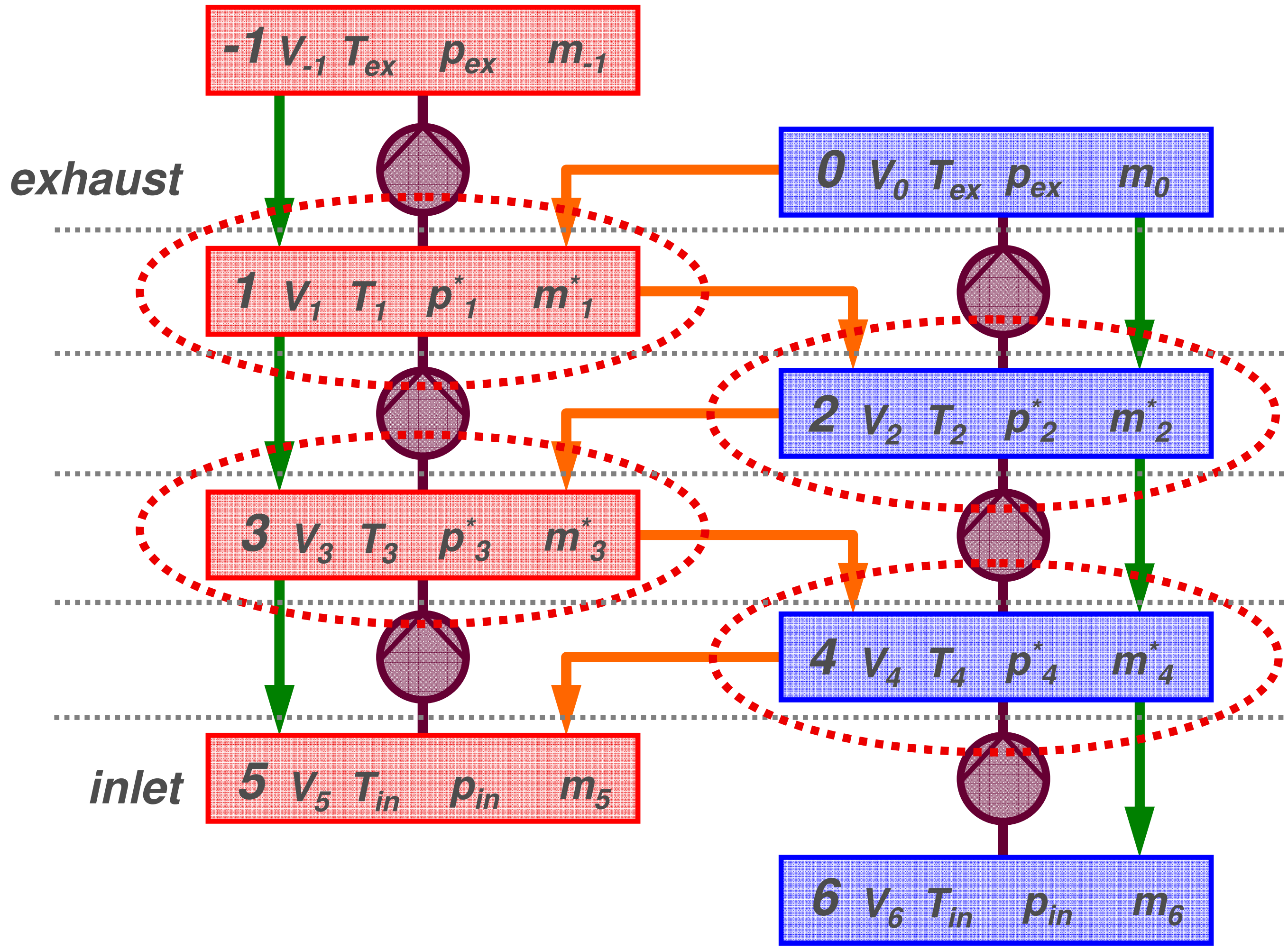
cells:

$$\dot{m}_{in} = \dot{m}_{out}$$

cross sections:

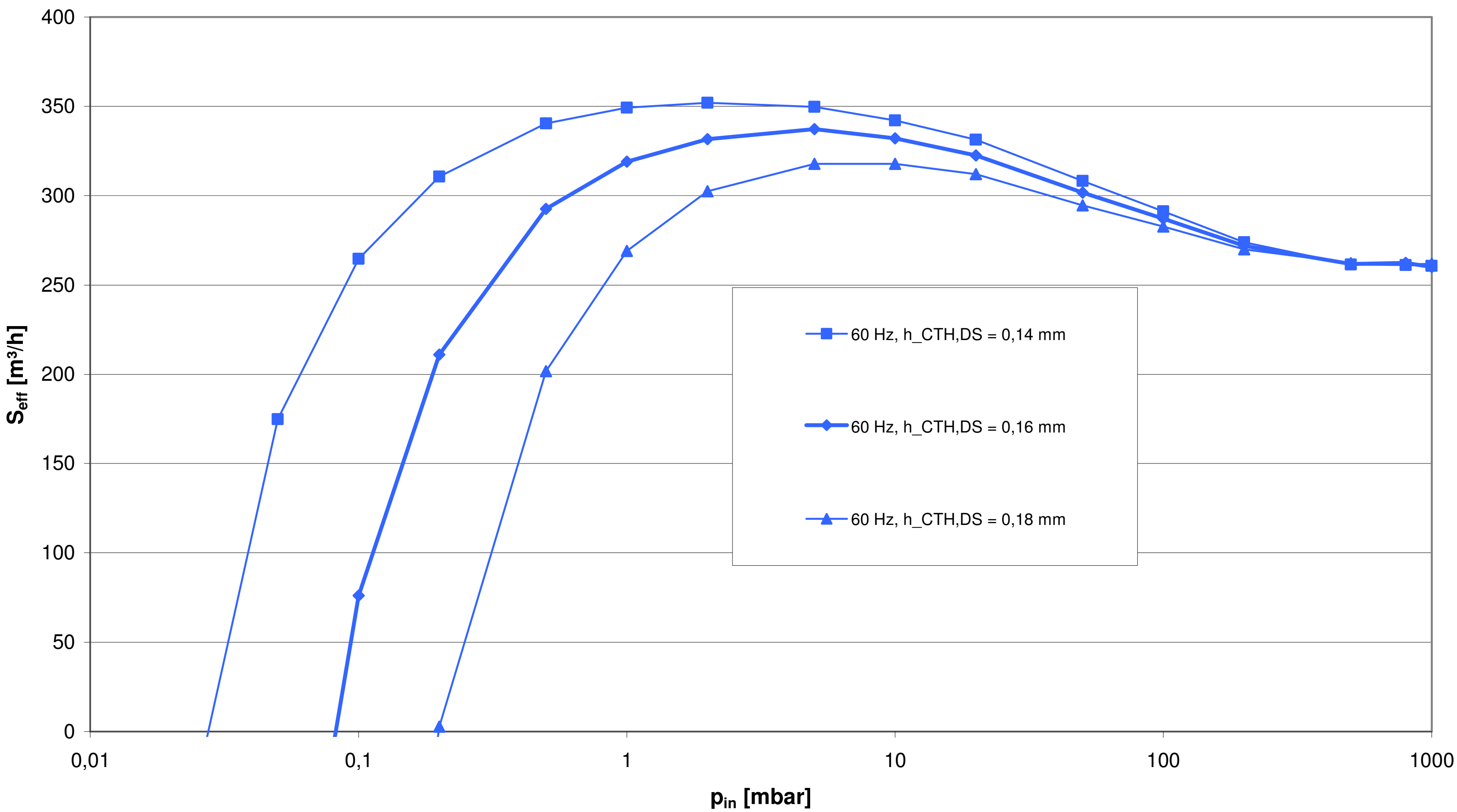
$$\dot{m}_{CS} = const$$

$$\dot{m}_{CS} = S \cdot \varrho_{in}$$



Simulated pumping speed of SP250 @ 60Hz, cold start

Variation of discharge side housing gap heights +- 0,02 mm



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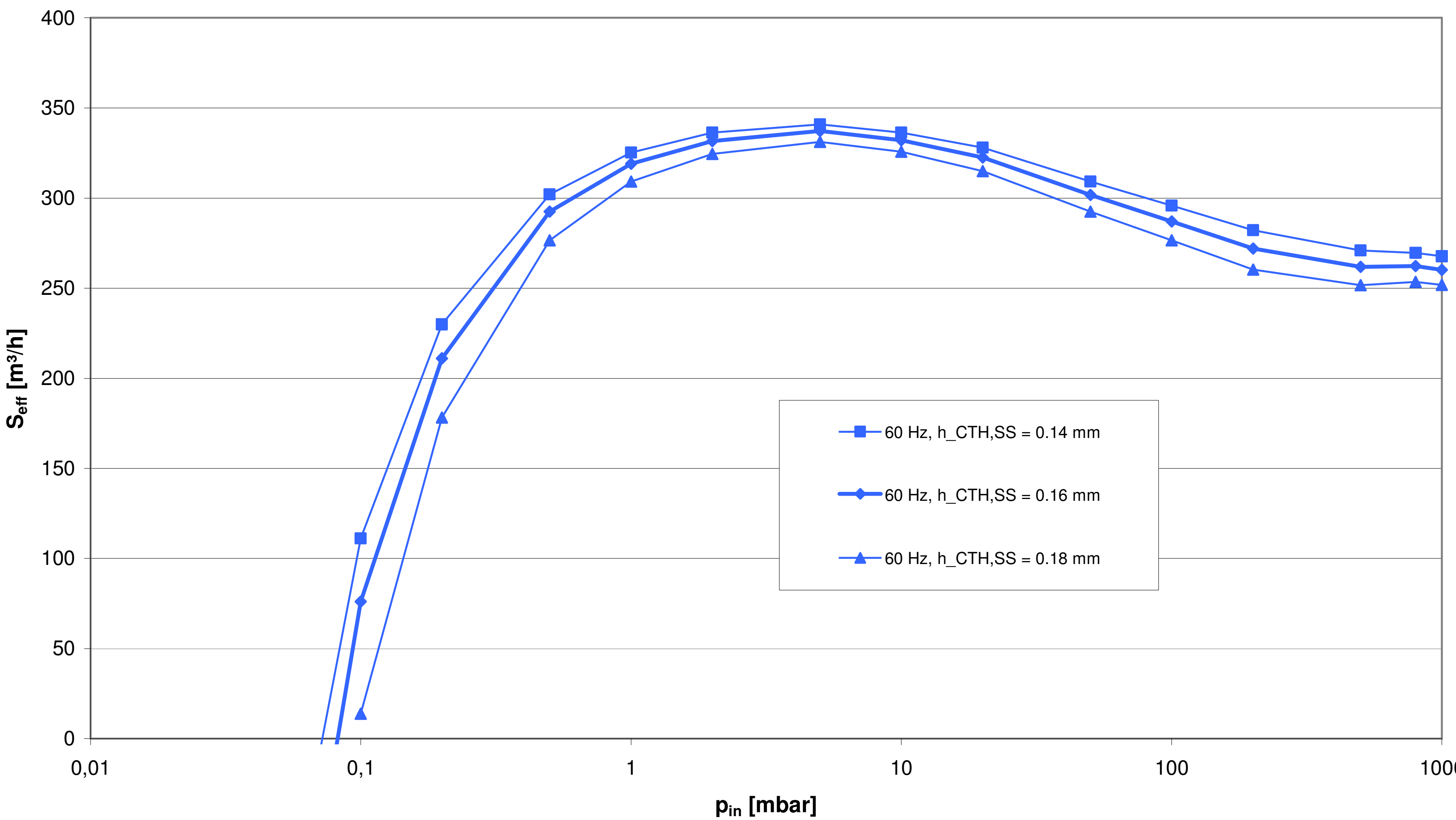
Simulated pumping speed of SP250 @ 60Hz, cold start

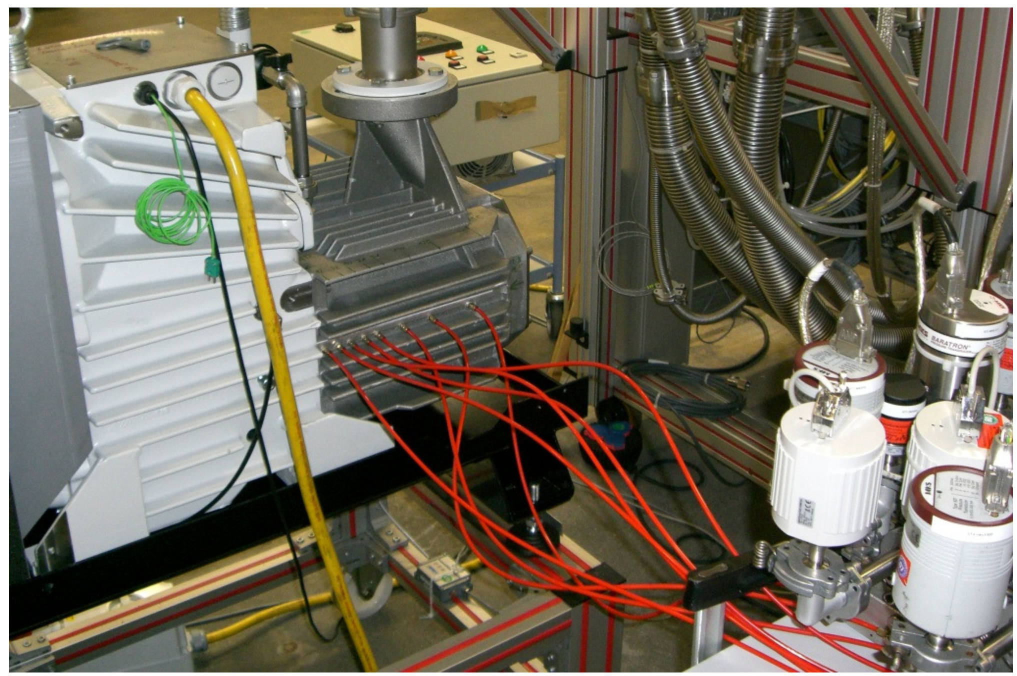
Variation of suction side housing gap heights +- 0,02 mm



Validation of the simulation tool

Validation of the simulation tools by experiments

- Measurement of the operating behaviour of a SP250
- in cold state → with cold clearances (known)
- pumping speed
- pressure measurement at 8 different stages
- rotor speed: 50 Hz, 60 Hz
  (40 Hz, 30 Hz)
- p_{in} = 0,001 .. 1000 mbar
- automated



Aim is the comparison of

- pumping speed curves
- compression curves

in simulation and measurement

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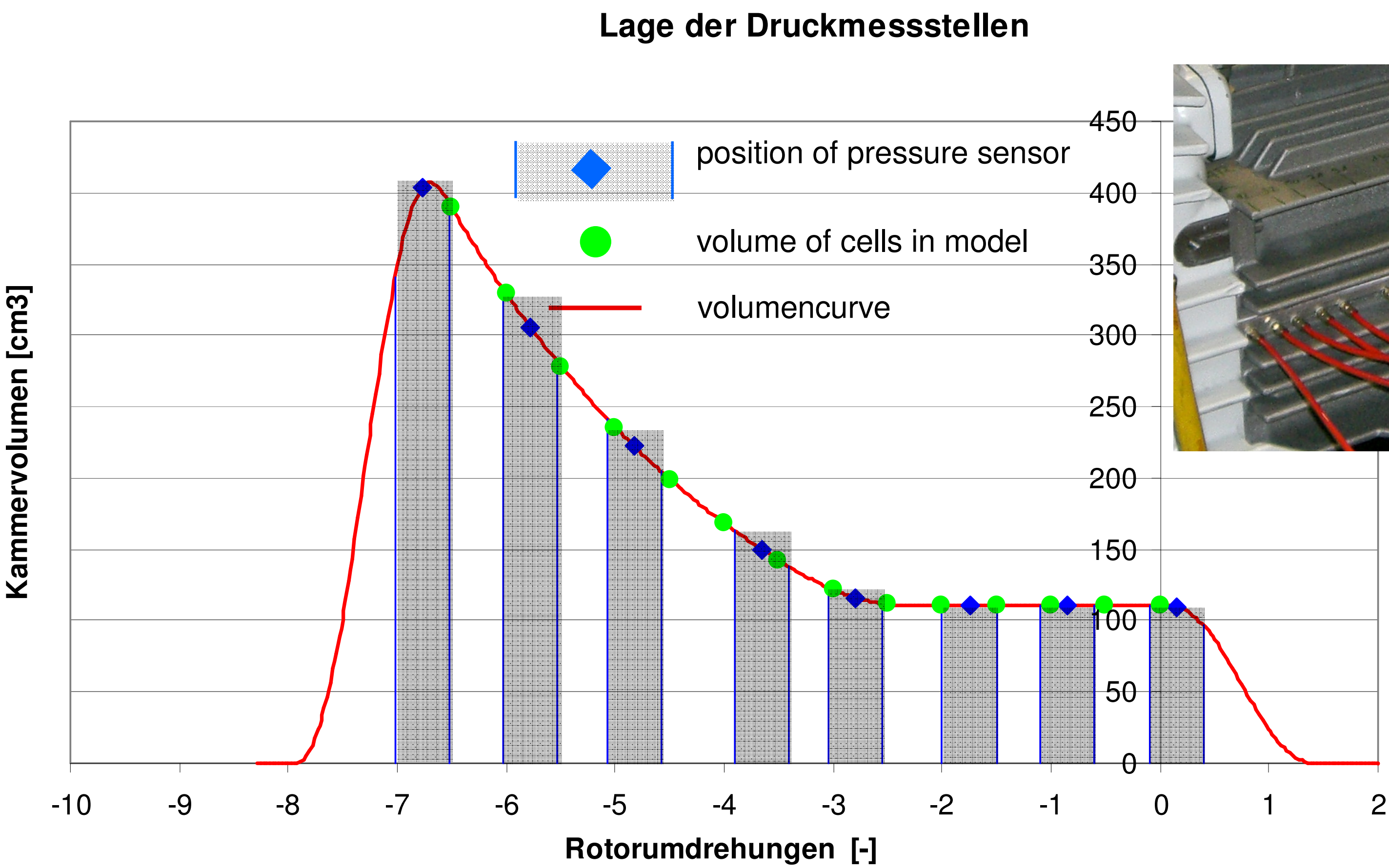
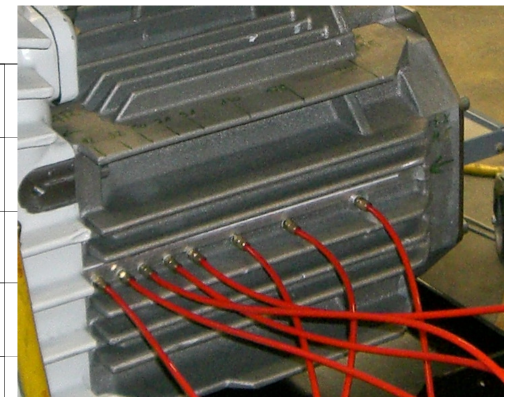
Position of sensor bores in pump housing





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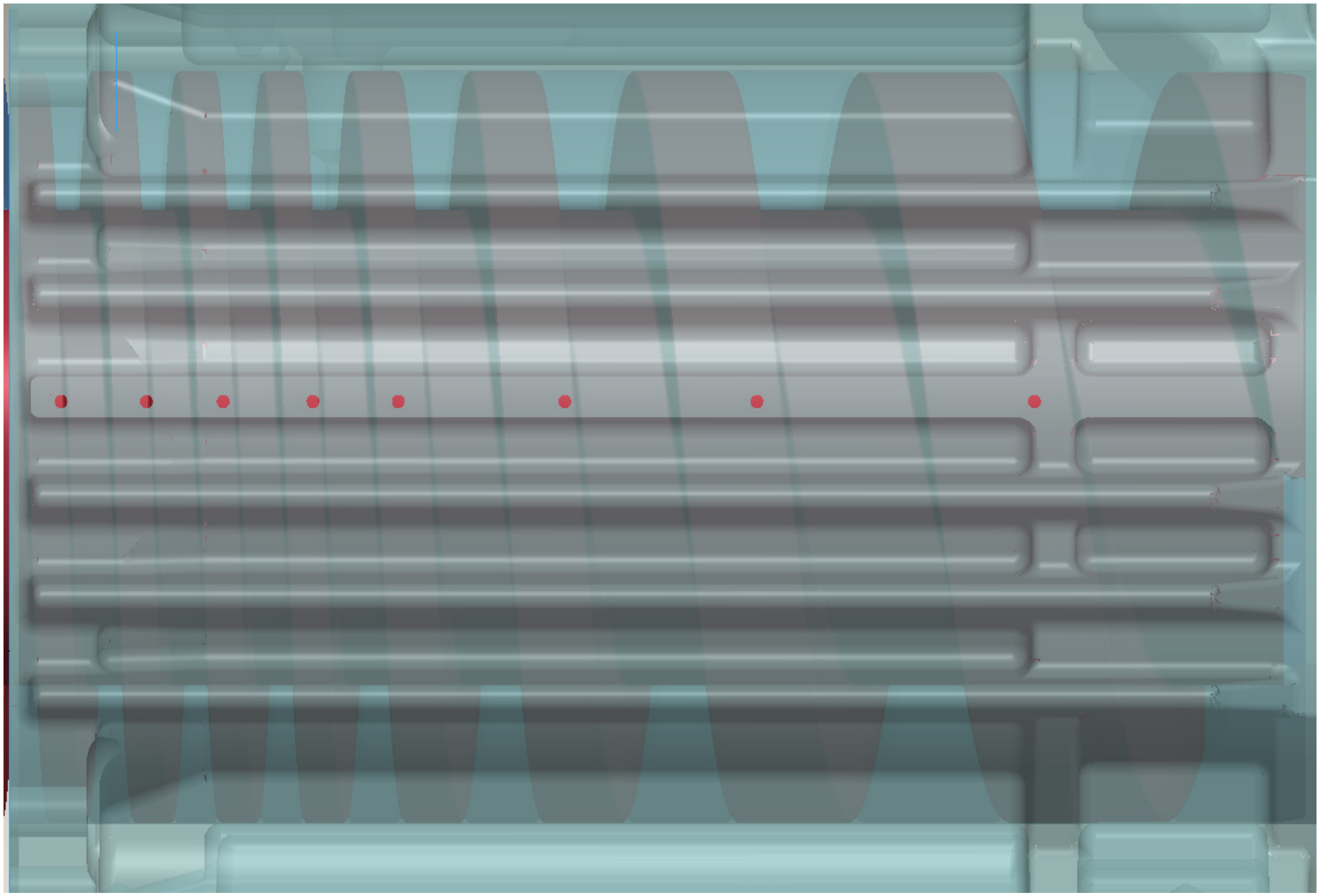
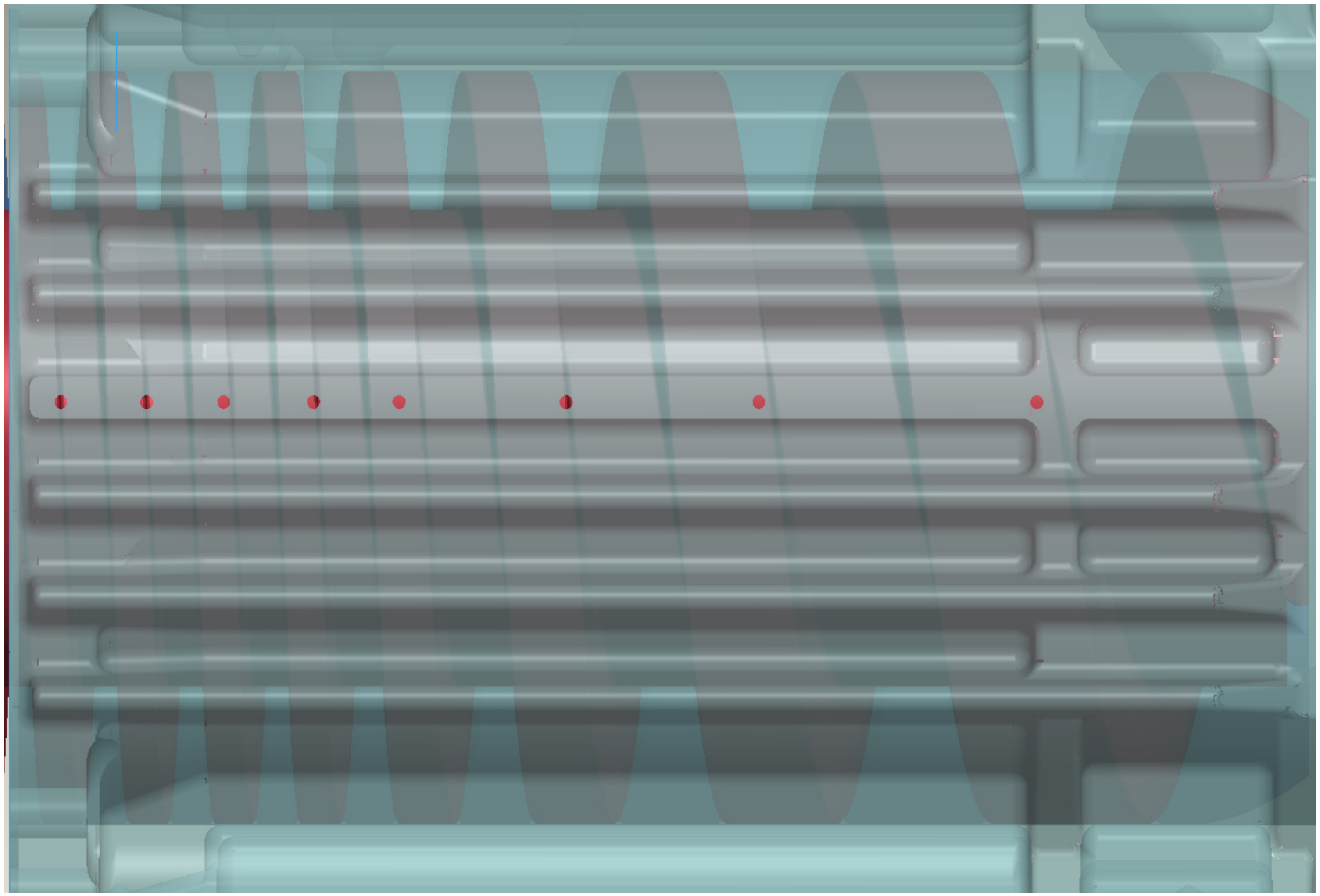
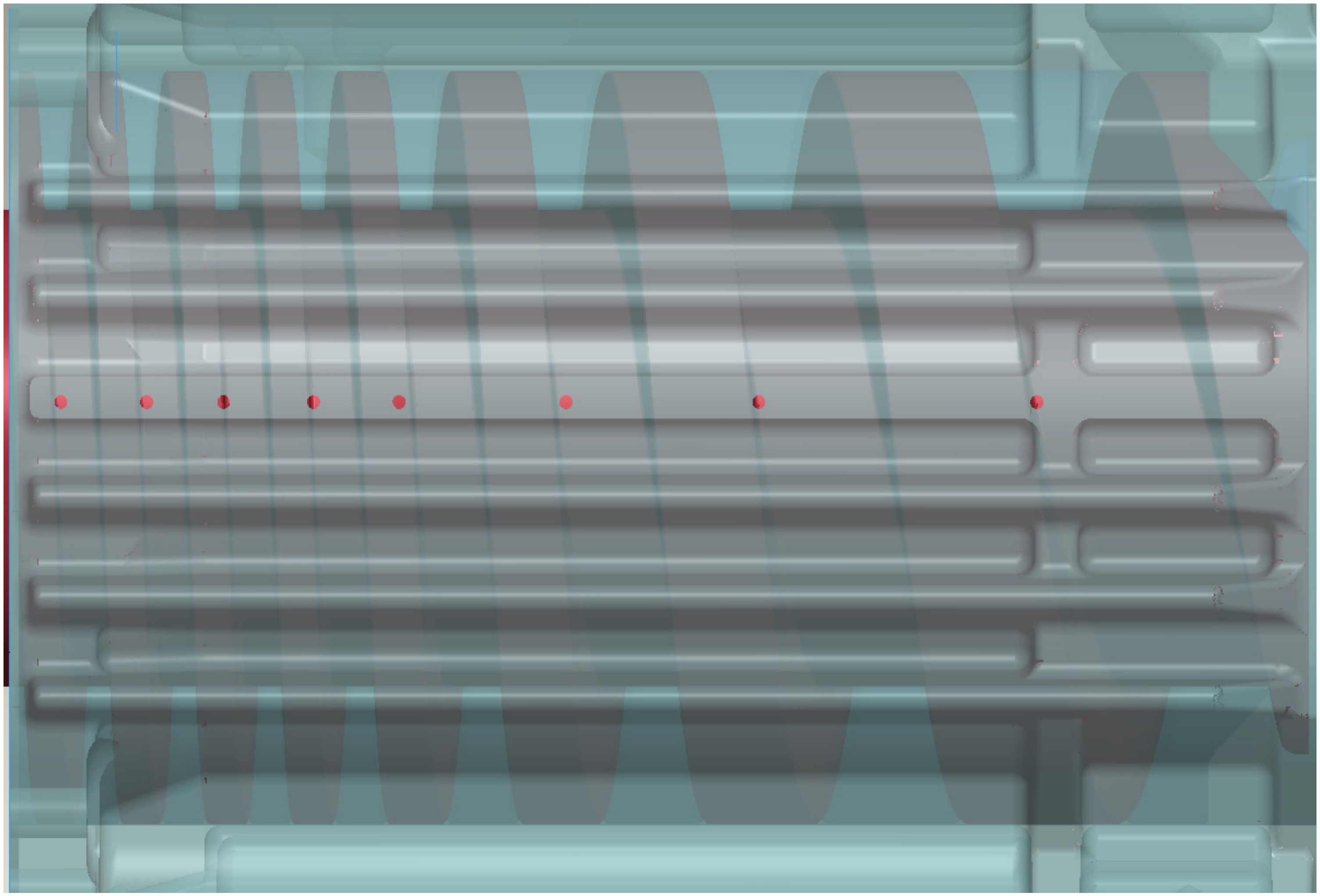
Cell movement during SP250 compression measurement (10°)



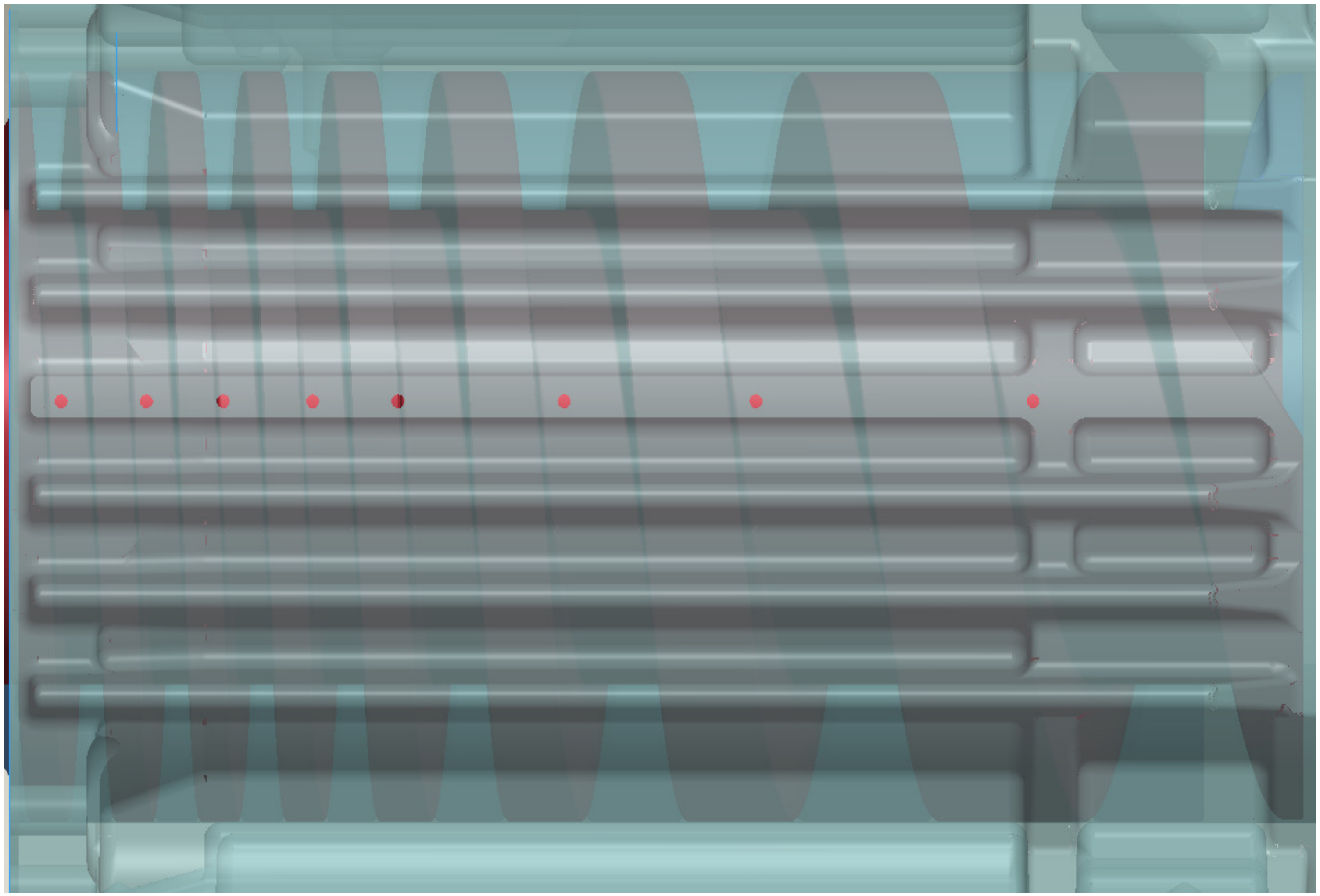
Cell movement during SP250 compression measurement (30°)



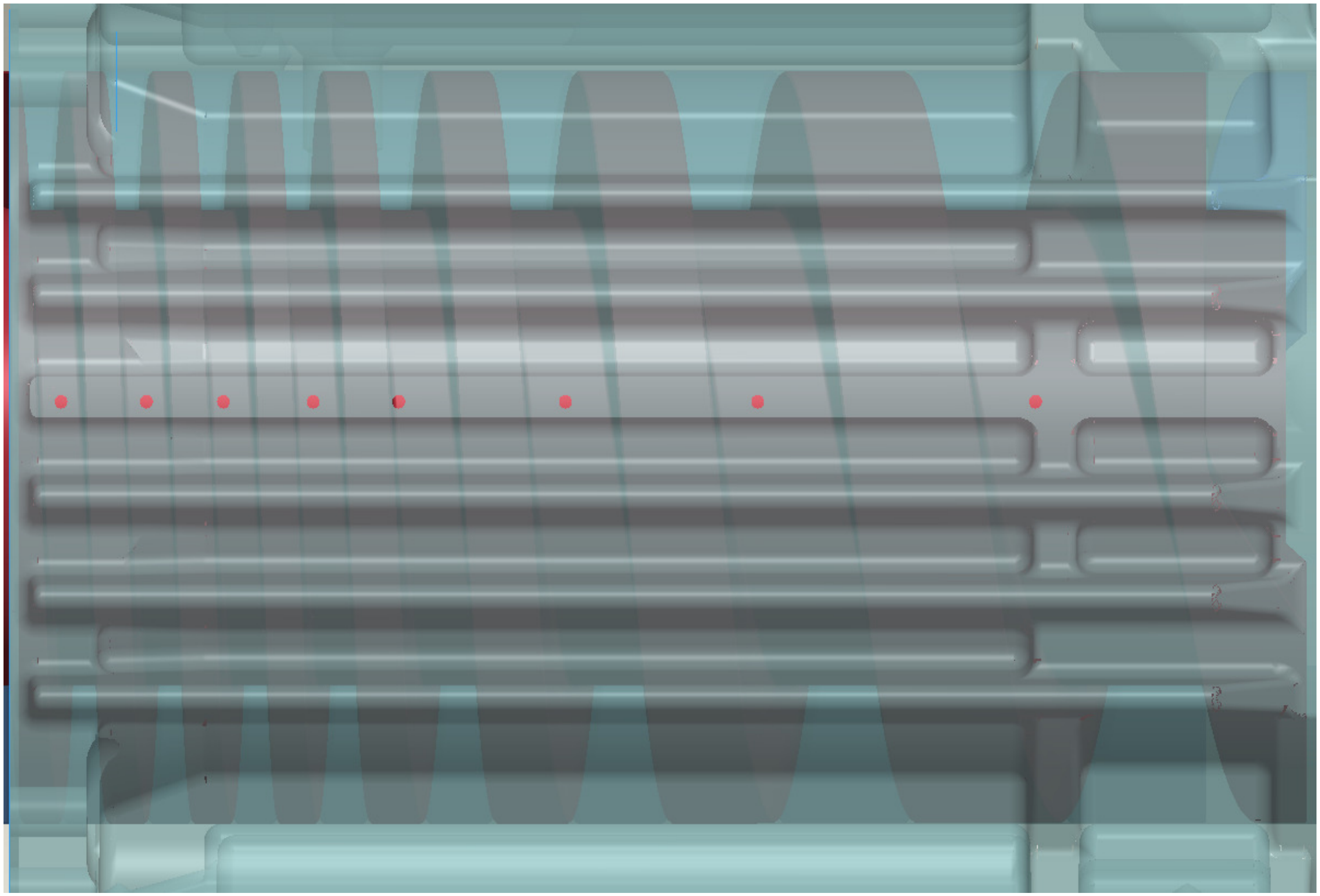
Cell movement during SP250 compression measurement (60°)



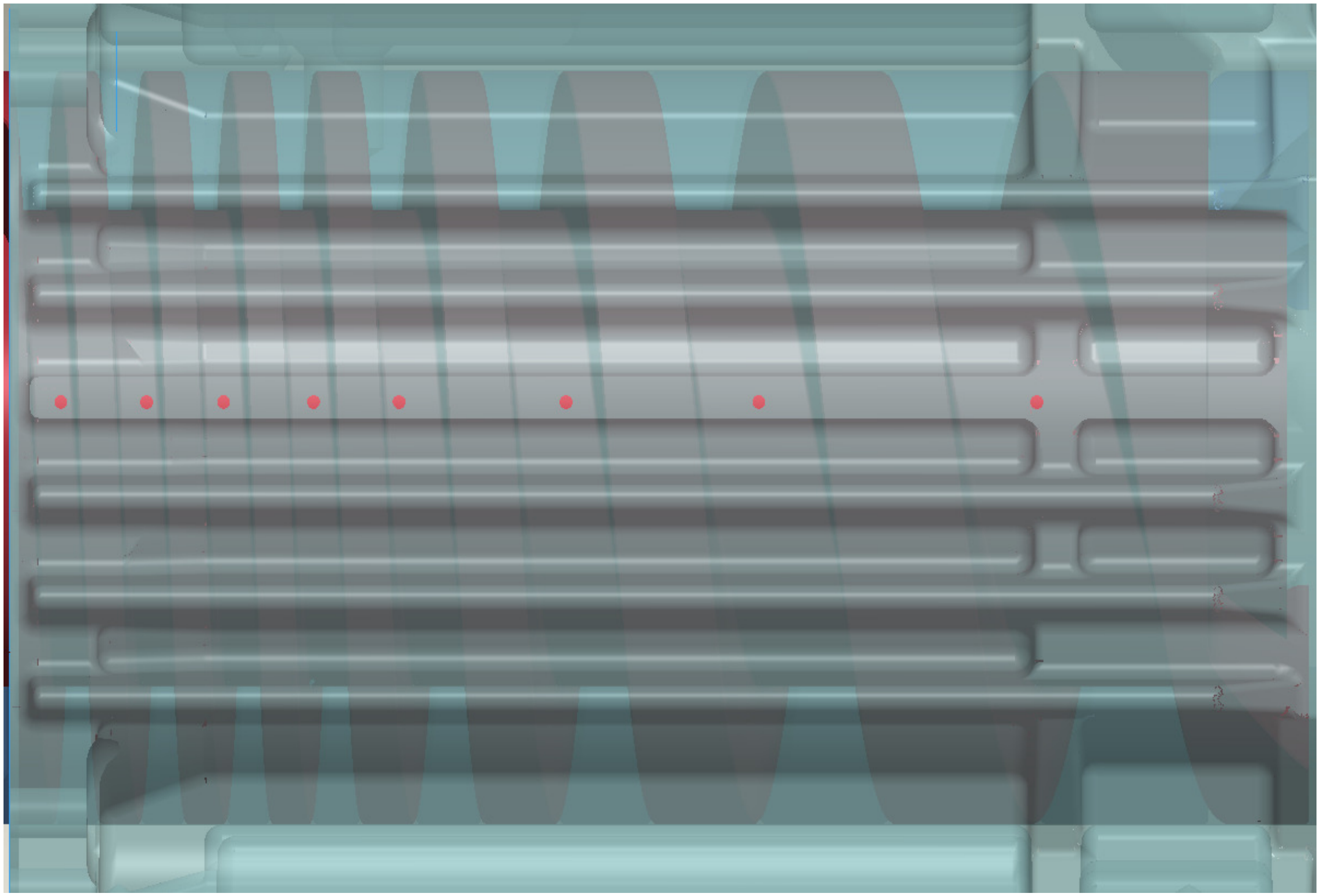
Cell movement during SP250 compression measurement (90°)



Cell movement during SP250 compression measurement (120°)



Cell movement during SP250 compression measurement (150°)



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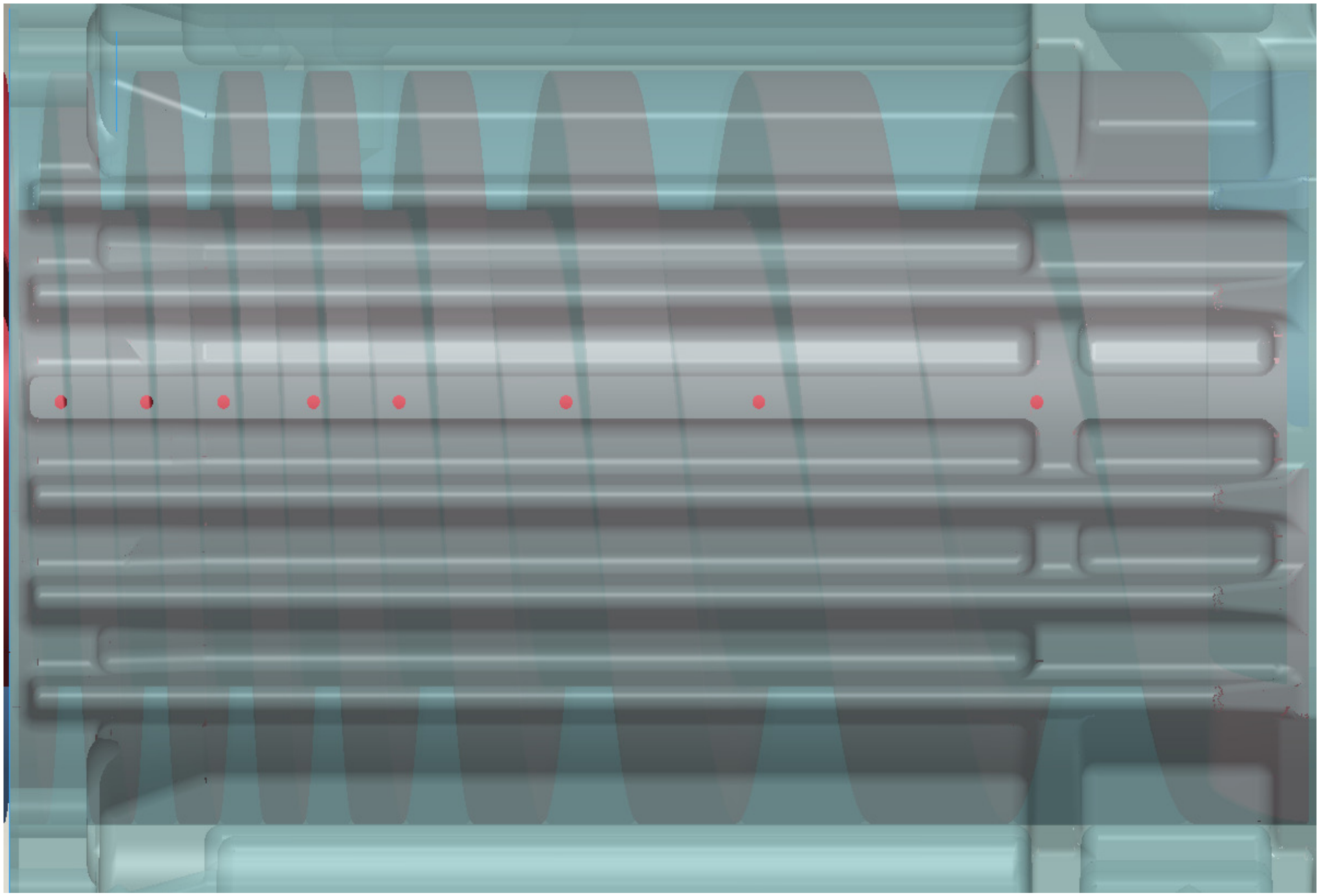
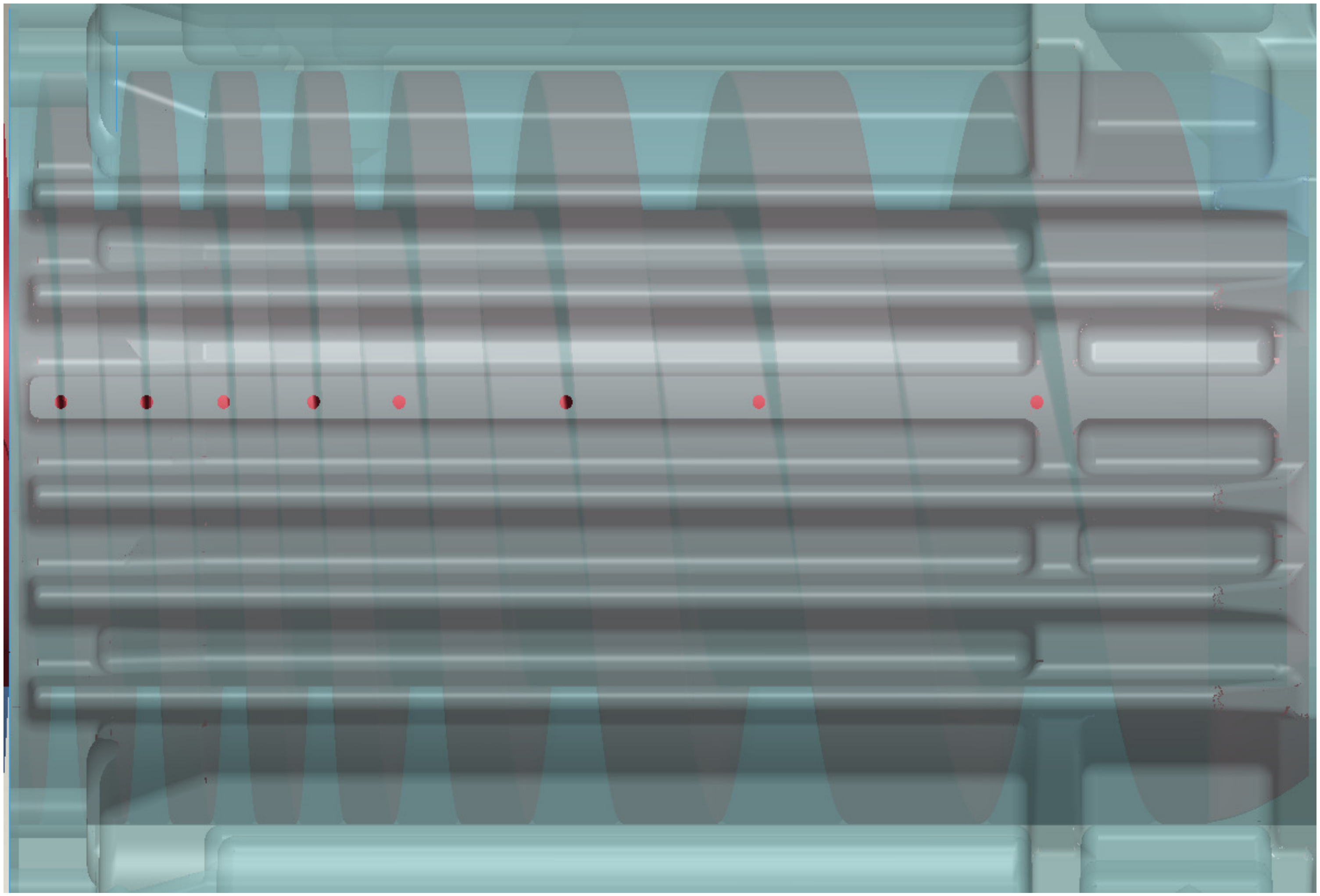
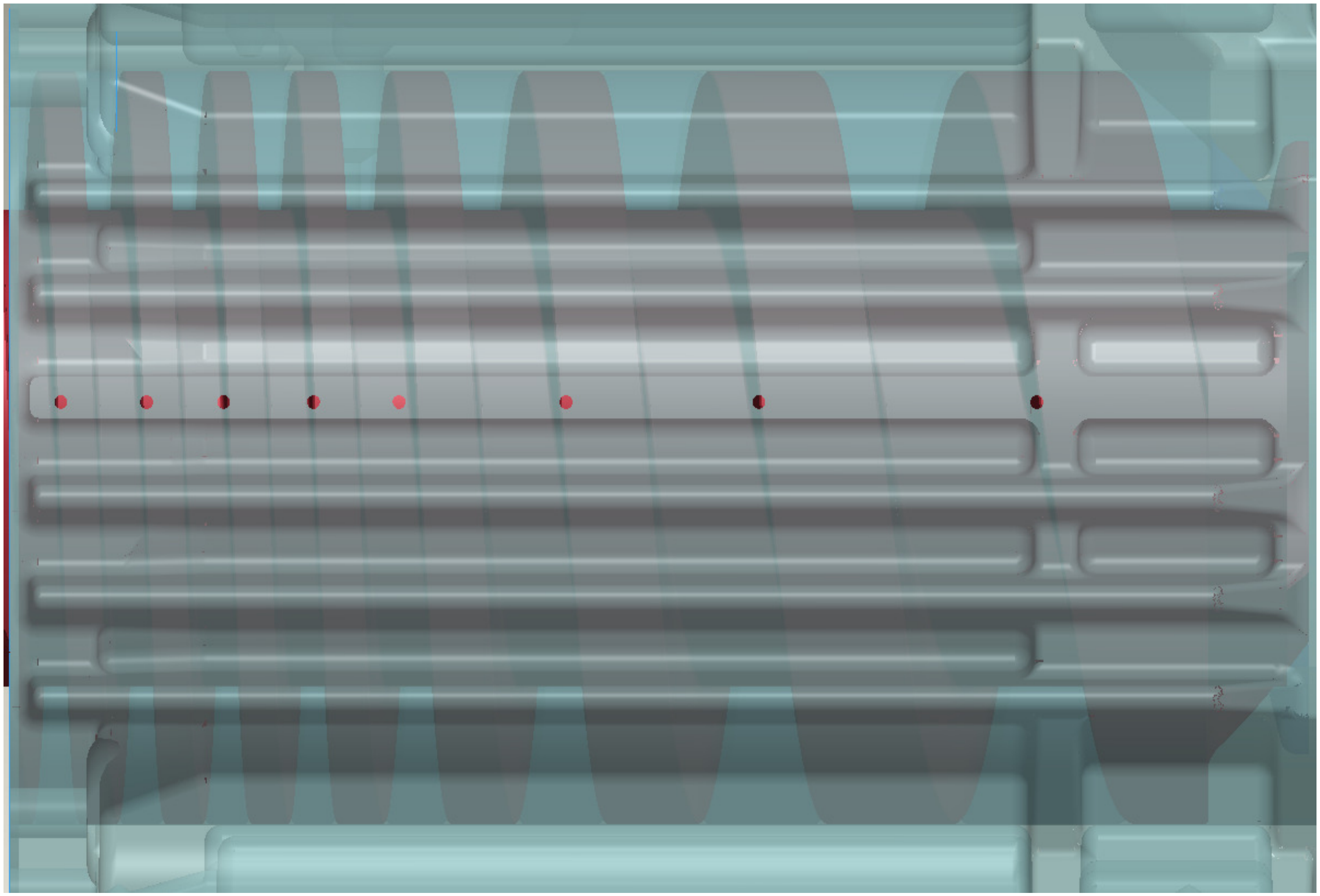
Cell movement during SP250 compression measurement (180°)



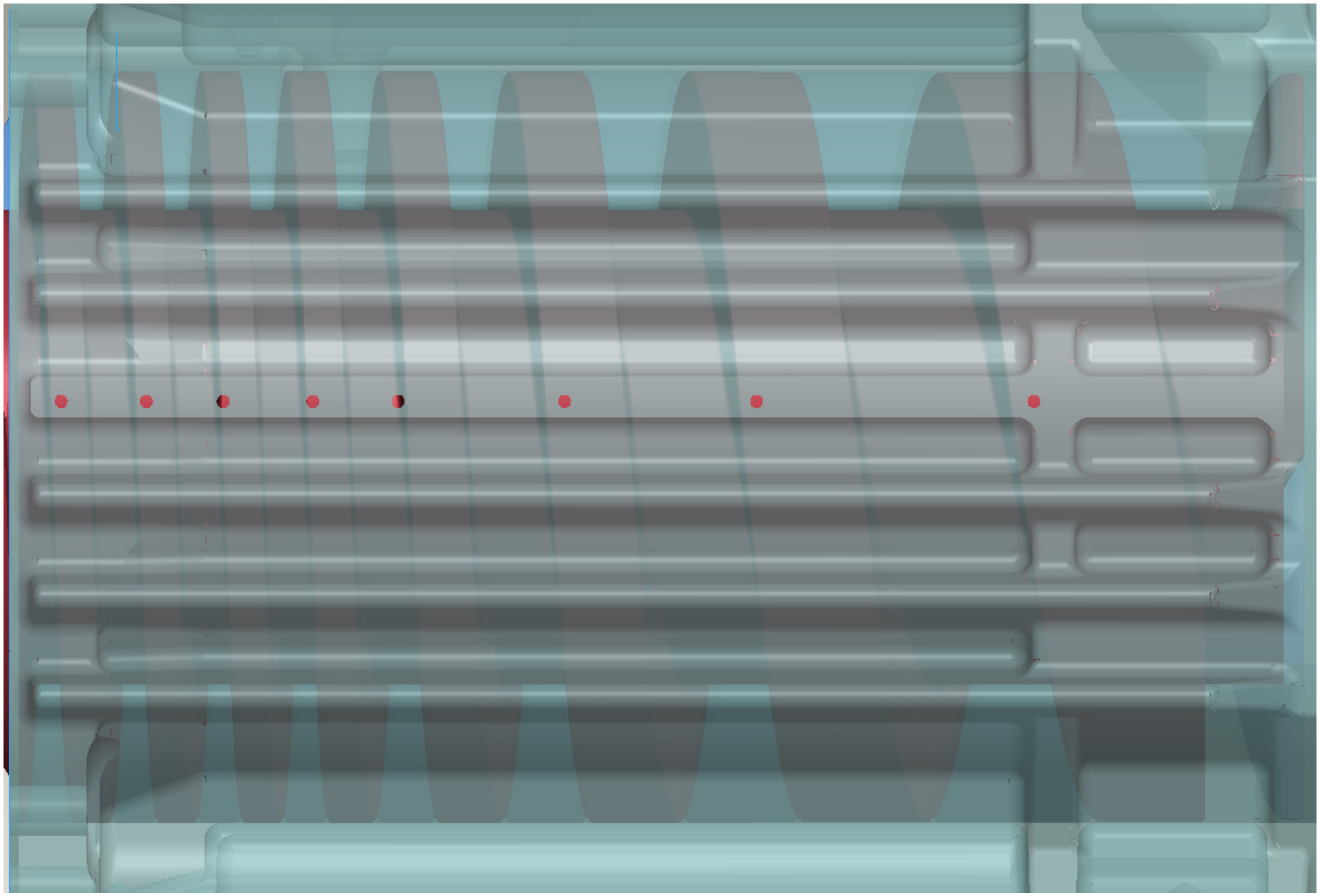
Cell movement during SP250 compression measurement (210°)



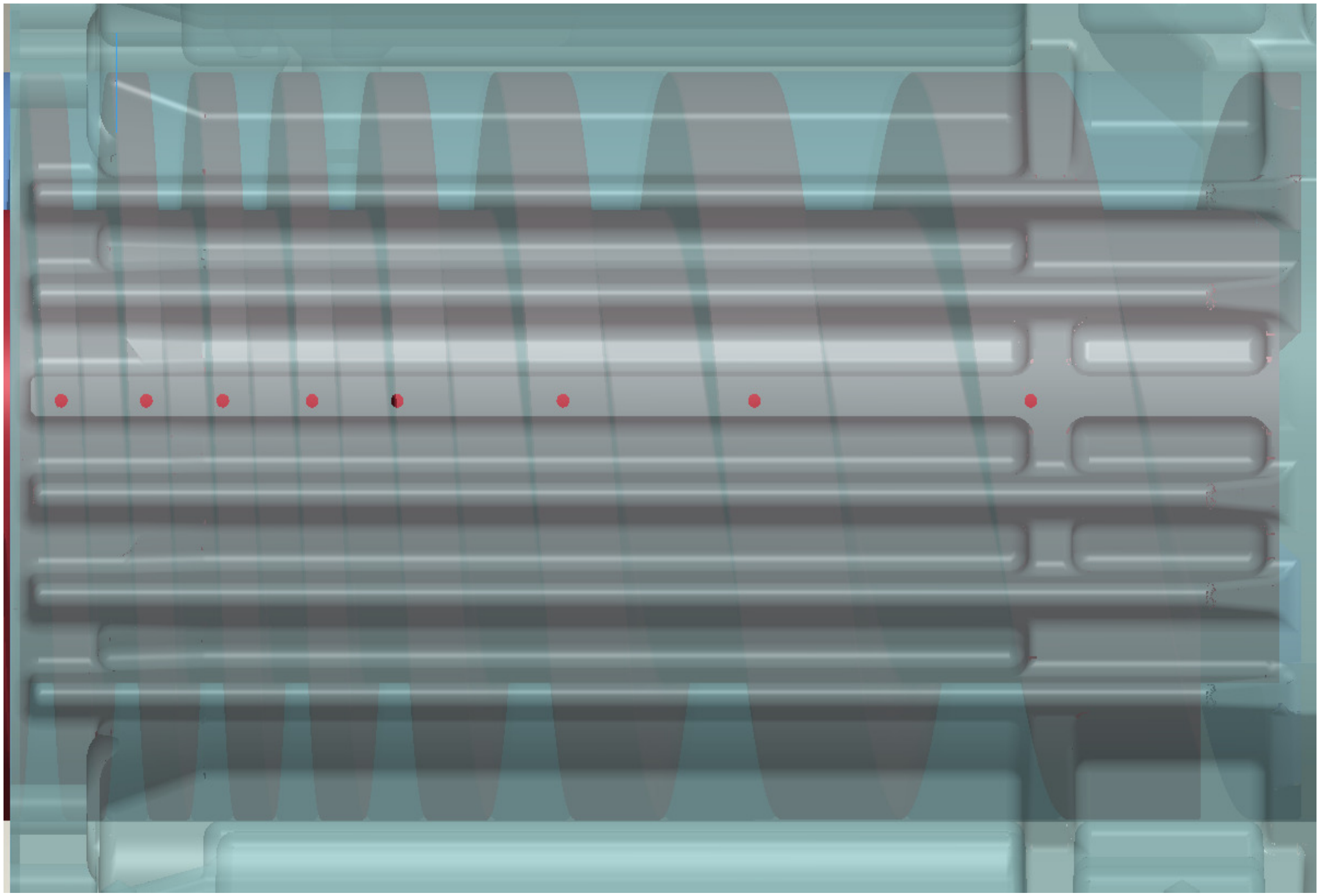
Cell movement during SP250 compression measurement (240°)



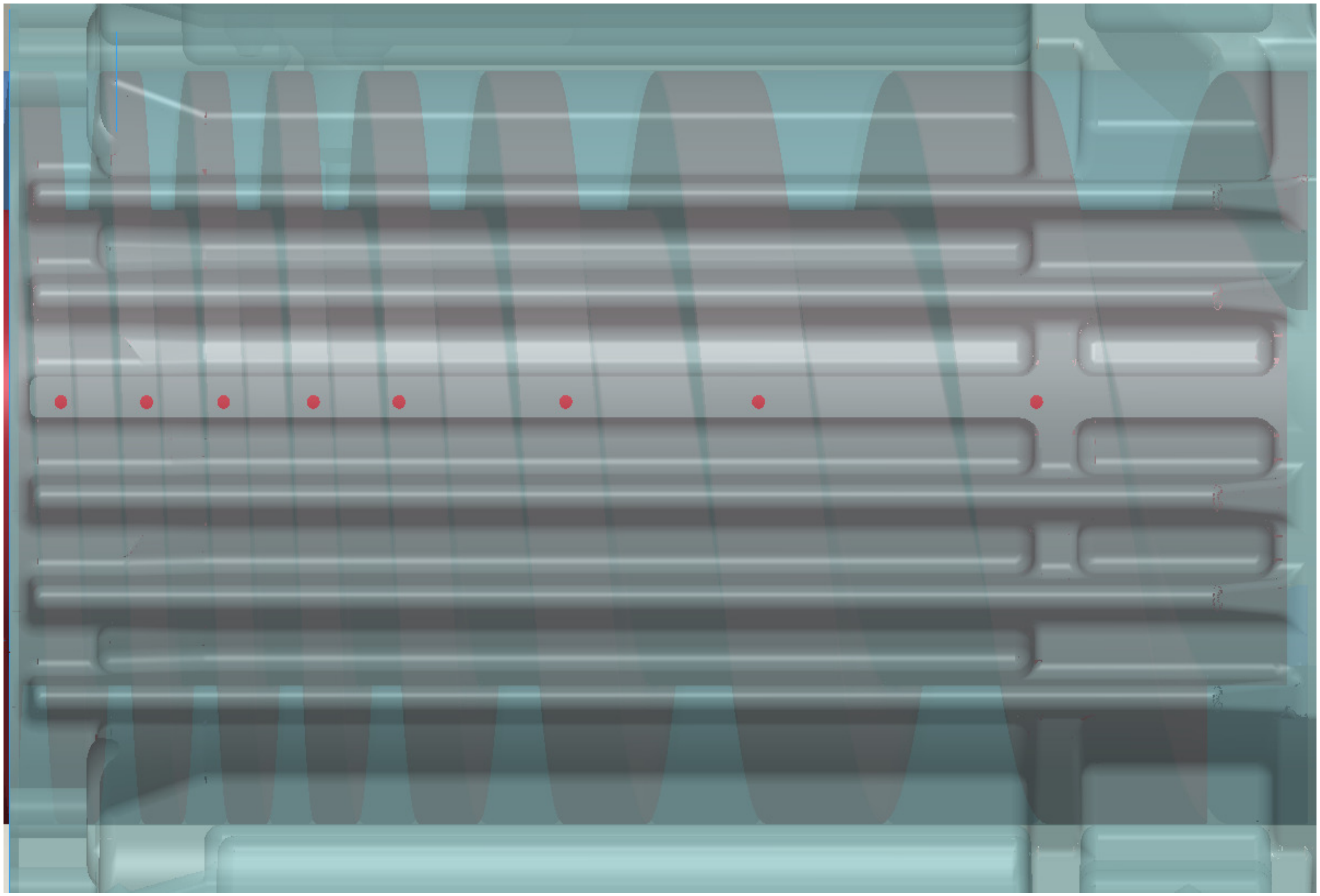
Cell movement during SP250 compression measurement (270°)



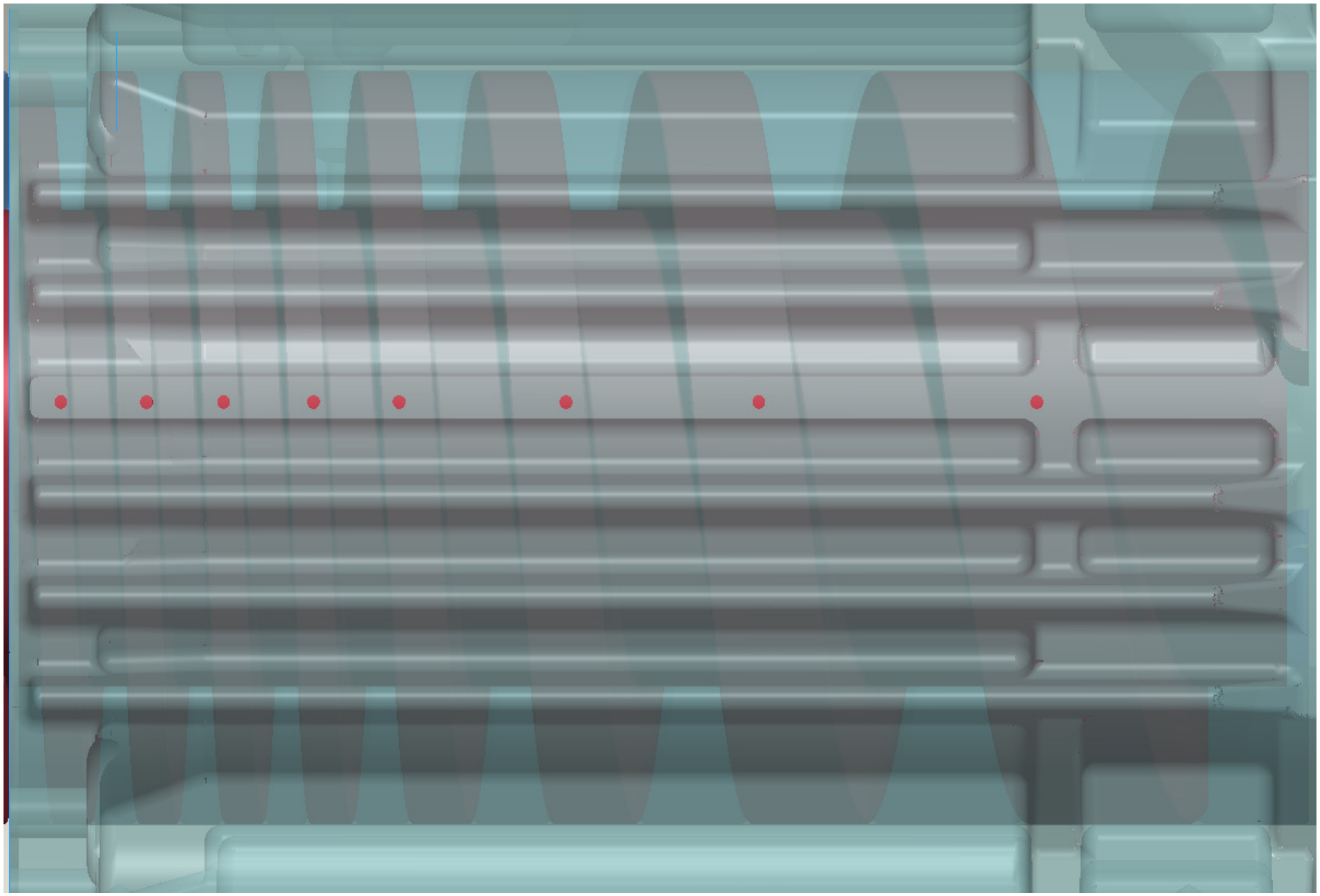
Cell movement during SP250 compression measurement (300°)



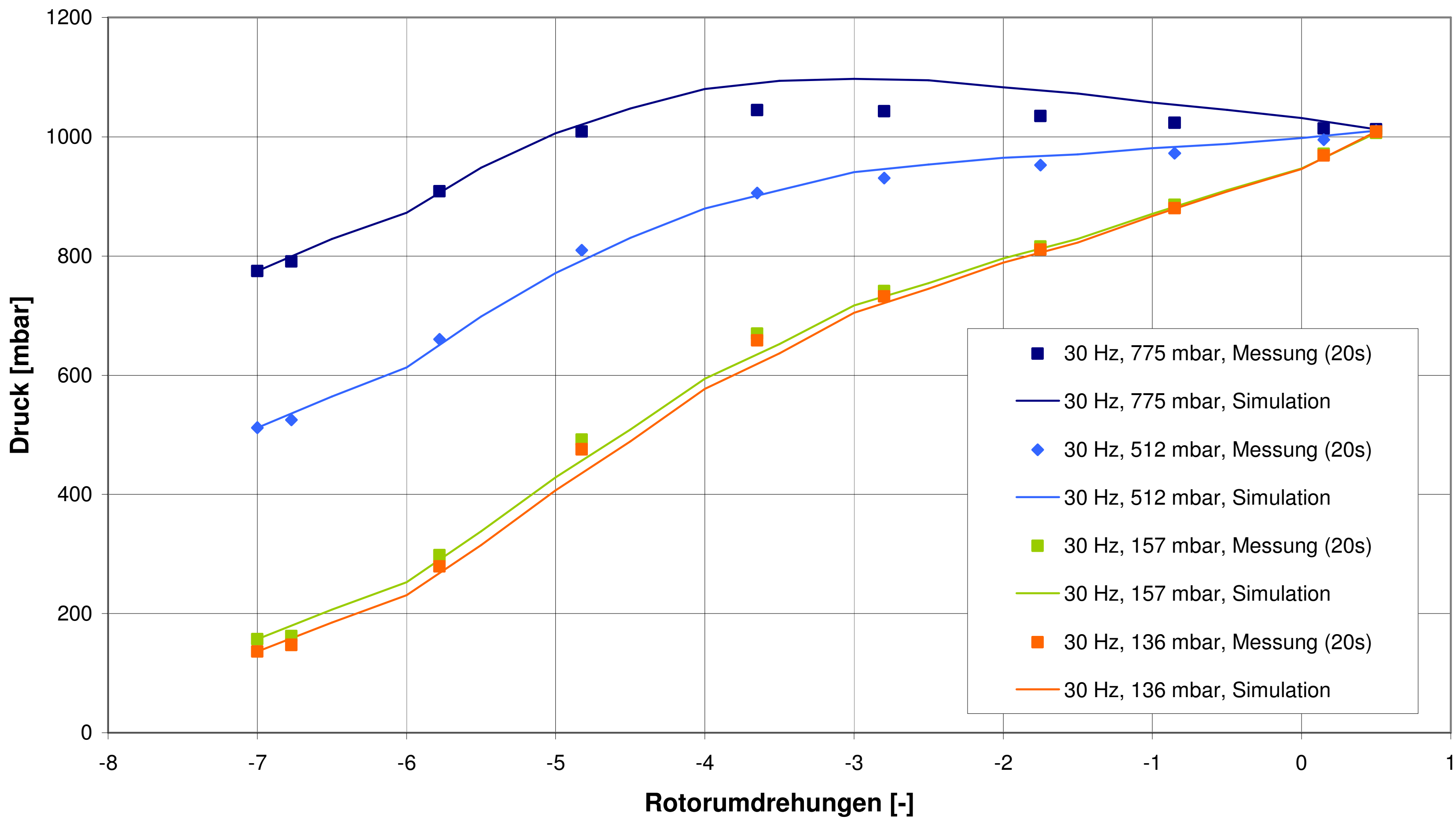
Cell movement during SP250 compression measurement (330°)



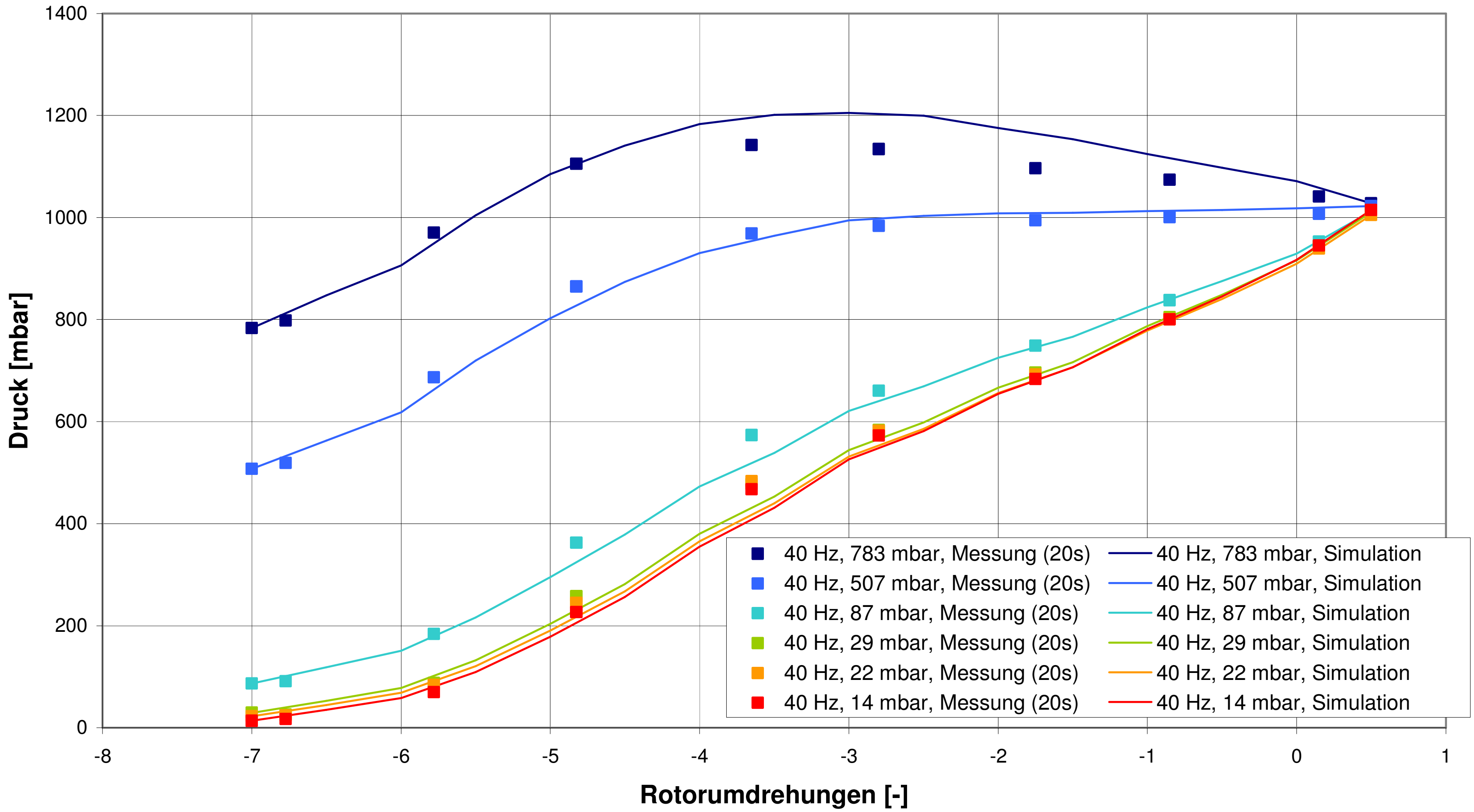
Cell movement during SP250 compression measurement (350°)



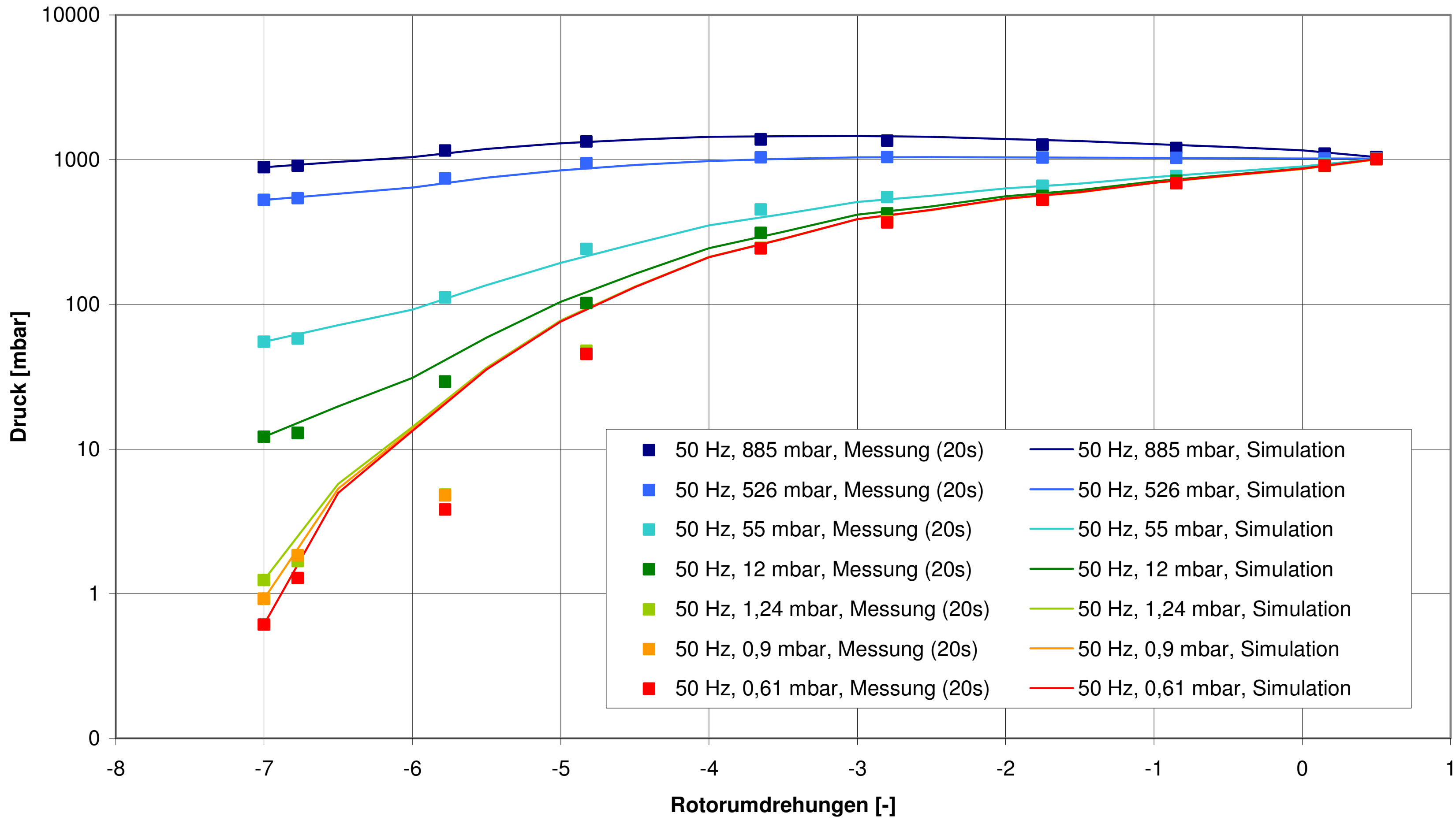
Pressure distribution SP250, 30 Hz
Simulation vs. Measurement 20s after cold start



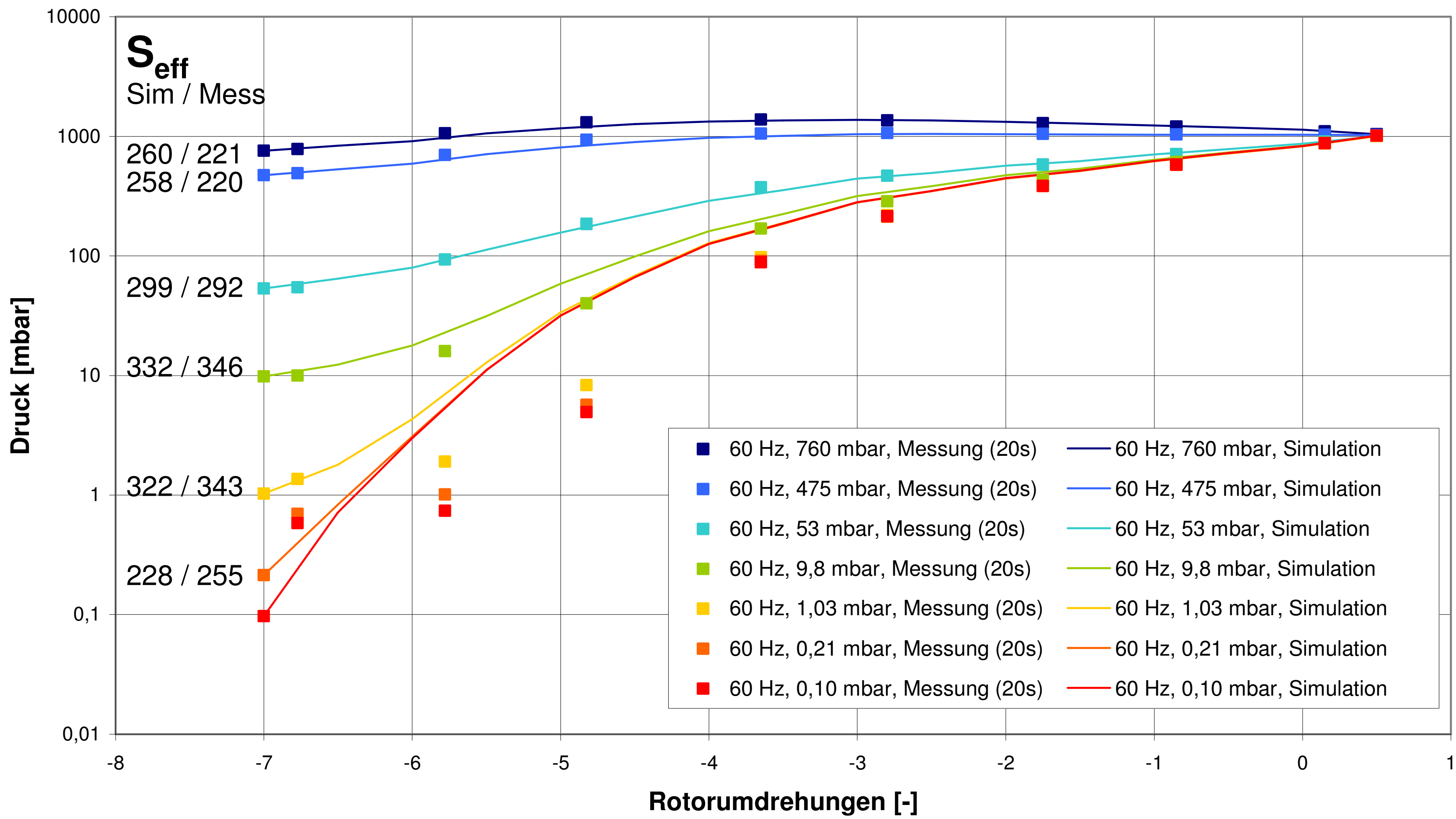
Pressure distribution SP250, 40 Hz
Simulation vs. Measurement 20s after cold start



Pressure distribution SP250, 50 Hz
Simulation vs. Measurement 20s after cold start



Pressure distribution SP250, 60 Hz
Simulation vs. Measurement 20s after cold start



Simulation of screw vacuum pumps with a cell model

The simulation my means of cell model

- allows the calculation of the compression cycle in the pump
  - by calculation of leakage through clearances
  - and making up the balance between forward transport and backward leakage
- gives a good accuracy regarding
  - pumping speed,
  - pressure distribution and
  - compression power.
- can be used for the variational design of screw pumps

Opportunities in the simulation of screw pumps

The following parts of the simulation can be improved:

- Thermal simulation of the process and the pump parts
  - Heat Transfer between the gas and the surrounding surfaces
  - Calculation of gas temperature during compression
  - FEM simulation for the pump parts
  - Recalculation of clearance heights on the basis of simulated pump deformation
- Simulation of mixed gas flows in the clearances
  - Empirical flow models limit the simulation capability to certain gases
  - Theoretical / physical models would increase simulation capabilities
- Instationary simulation of inlet and exhaust flow

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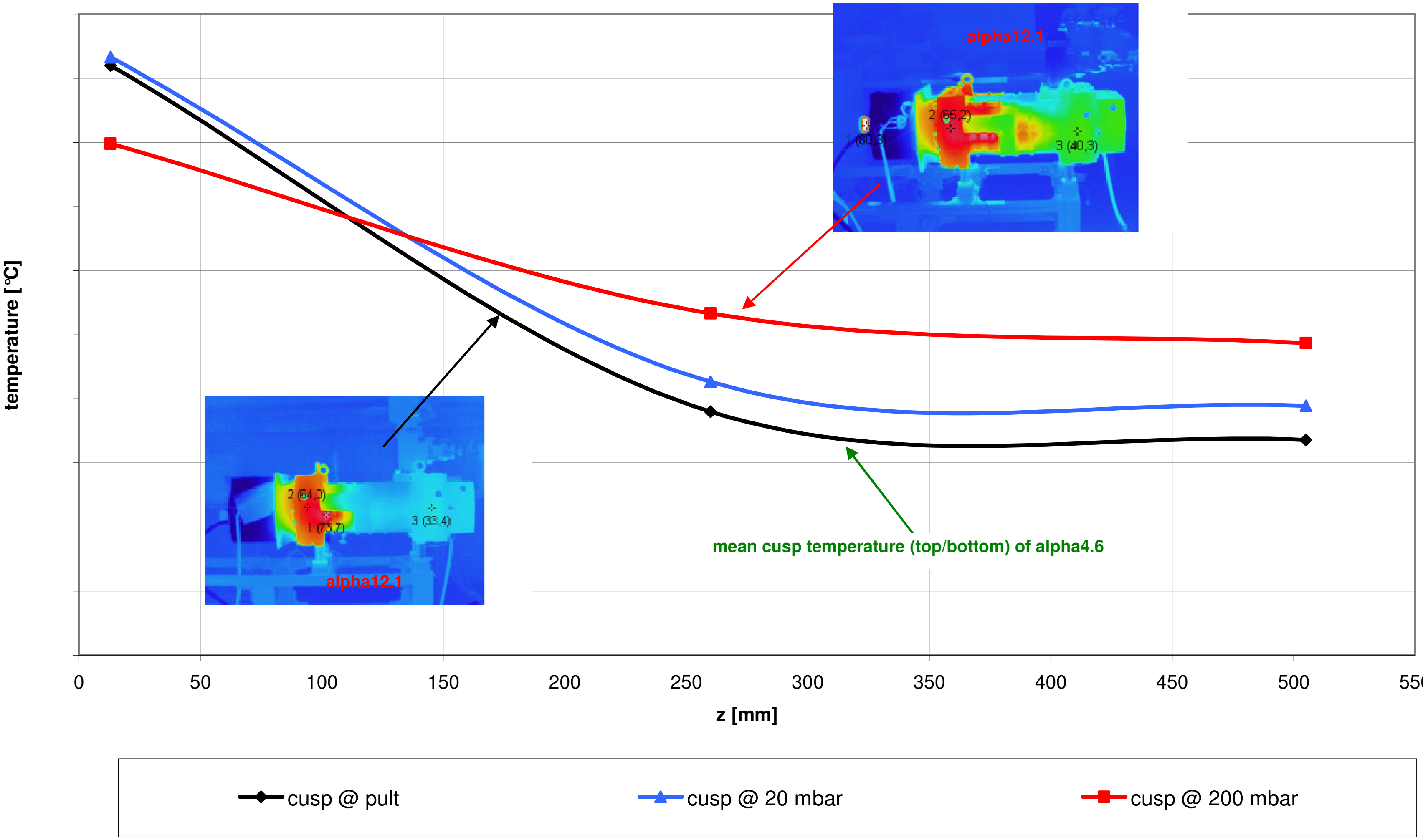
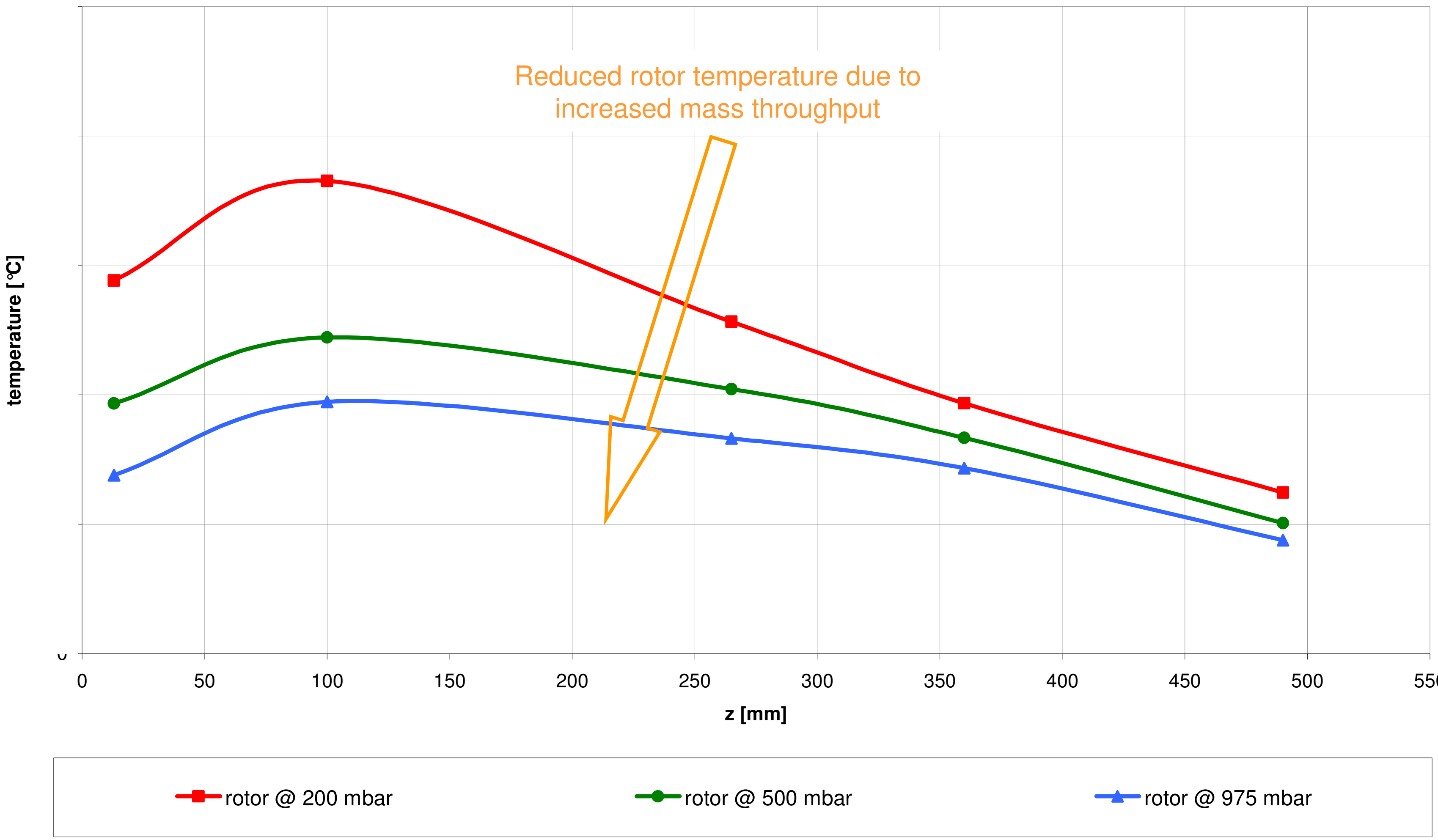
Thermal behaviour of screw pump housing



DRYVAC Sprinter 650 S
Rotor temperature distribution 200 – 975 mbar @ 120 Hz



Vacuum Pumps

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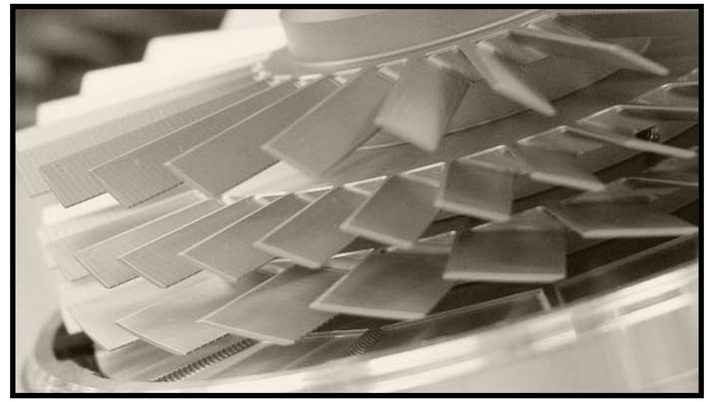
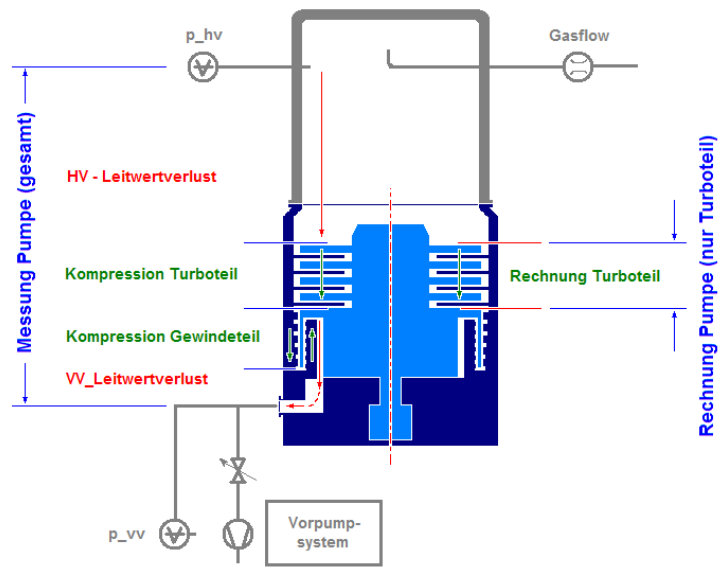
Turbo Molecular Pump (TMP)

- Molecular pumping principals were described 1913 by W. Gaede
- Turbo molecular pump was invented 1958 by W. Becker
- Inlet pressure normally < 0.01 mbar
- Exhaust pressure normally < 0.5 mbar
- Higher exhaust pressures possible with Holweck or Siegbahn stages
- Fore vacuum pump necessary to compress to atmosphere, e.g.
  - Rotary vane pump
  - Diaphragm pump
  - Screw pump
- Gas flow is mainly molecular but may reach also the transient flow regime





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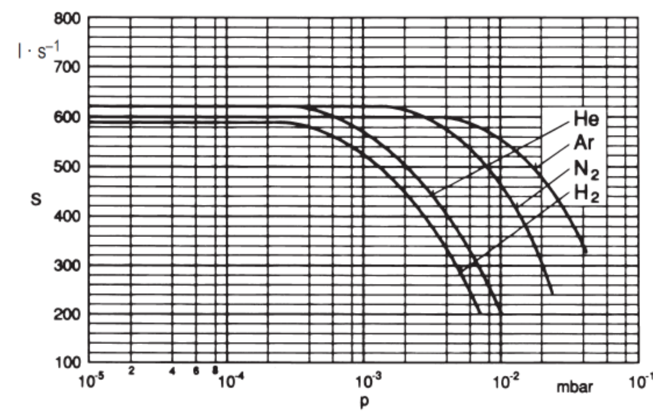
Turbo Molecular Pump – Design Goals

Technical goals in the design of TMP:

- Optimization of Vacuum Performance
  - Pumping speed
  - Kompression
  - For different gases

- High Lifetime
  - Thermal Household
  - Mechanical stress

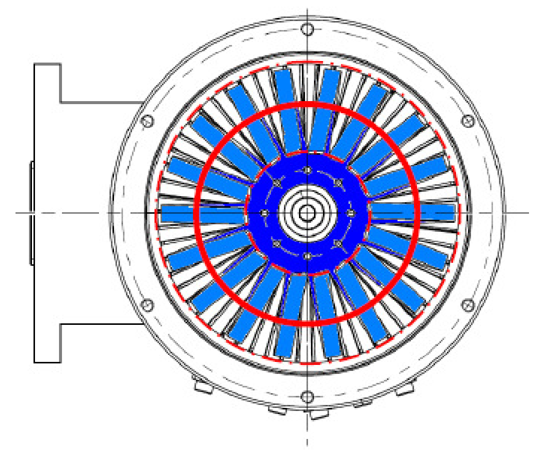
- Flexible solutions for the customer

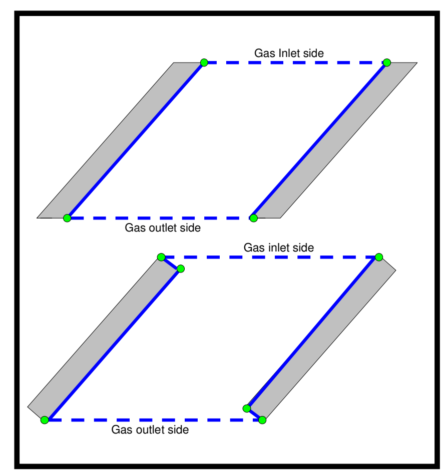


Test Particle Method – TMP Modelling

Step 1: Generating Boundary Conditions

- The blade geometry is generated in,
  - 2 dimensions only, therefore particle movement down the blade is not considered
  - At the RMS radius only. Initial models were calculated at multiple radii along the blade, but it was discovered that using RMS obtains similar results.
- Both machined and pressed blade profiles can be modelled with variable angle, height and thickness.

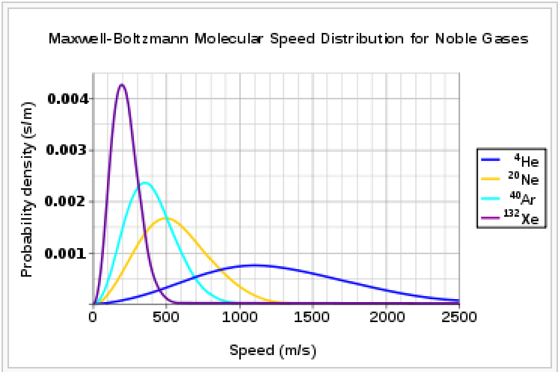




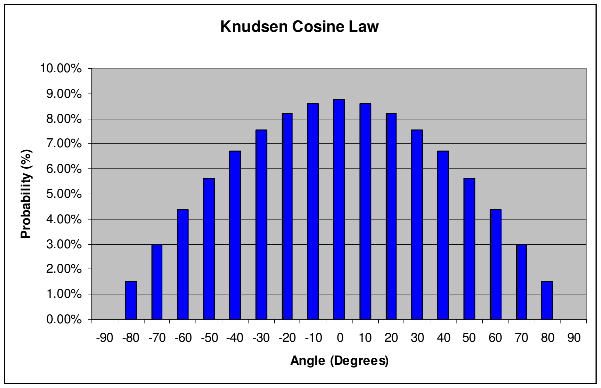
Test Particle Method – TMP Modelling

Step 2: Tracking Particle Movement

- For each particle traveling off a surface or starting at the inlet or outlet,
  - The initial velocity is randomly generated using the Maxwell-Boltzmann molecular speed distribution.
  - The initial vector angle is randomly generated using the Knudsen Cosine Law.
  - If a particle contacts a moving blade the blade velocity and vector is added.
  - The particle is tracked as it travels through the turbo pump until it exits either at the top or bottom of the pump.



$$f(v) = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3} v^2 \exp\left(\frac{-mv^2}{2kT}\right)$$



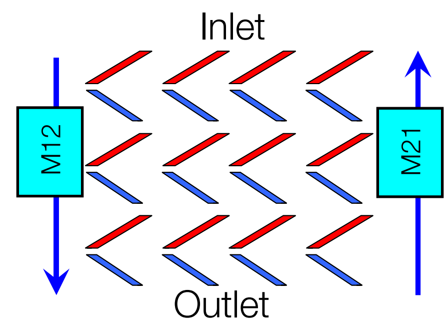
Test Particle Method – TMP Modelling

Step 3: Calculating Transmission Probability

- The overall gas transmission probability is calculated for the turbo mechanism and defined as,
  - Gas transmission probability from inlet to outlet (M12)
  - Gas transmission probability from outlet to inlet (M21)

Step 4: Calculating Speed & Compression

- From the gas transmission probability the pump performance can be calculated,
  - S_{max} – Maximum pumping speed (at K = 1)
  - K_{max} – Maximum compression (at S = 0)



Gas Arrival Rate (per unit area)

$$J = \frac{1}{4} \cdot n \cdot \overline{V}$$

n is the number density

Average Thermal Velocity

$$\overline{V} = \sqrt{\frac{8 \cdot R_o \cdot T}{\pi \cdot M}}$$

$$S_{\max} = \frac{\overline{V}}{4} \cdot (A_{inlet} \cdot M12 - A_{outlet} \cdot M21)$$

$$K_{\max} = \frac{A_{inlet}}{A_{outlet}} \bullet \frac{M12}{M21}$$

Reference
Empirical and numerical calculations in two dimensions for predicting the performance of a single stage turbomolecular pump
Schneider, T. N. Katsimichas, S. de Oliveira, C. R. E. Goddard, A. J. H.

Modelling Validation

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Class 1000 ISO160	Pumping Speed		Compression	
	Model	Test Data	Model	Test Data
Nitrogen	750l/s	730l/s	7E10	3E6
Helium	945l/s	990l/s	1E4	1E4
Hydrogen	911l/s	800l/s	5E2	2E3

Accuracy
~3 to 13%

Class 300 ISO 100	Pumping Speed		Compression	
	Model	Test Data	Model	Test Data
Nitrogen	252l/s	225l/s	3E10	4E8
Helium	227l/s	261l/s	6E3	6E3
Hydrogen	187l/s	200l/s	3E2	5E2

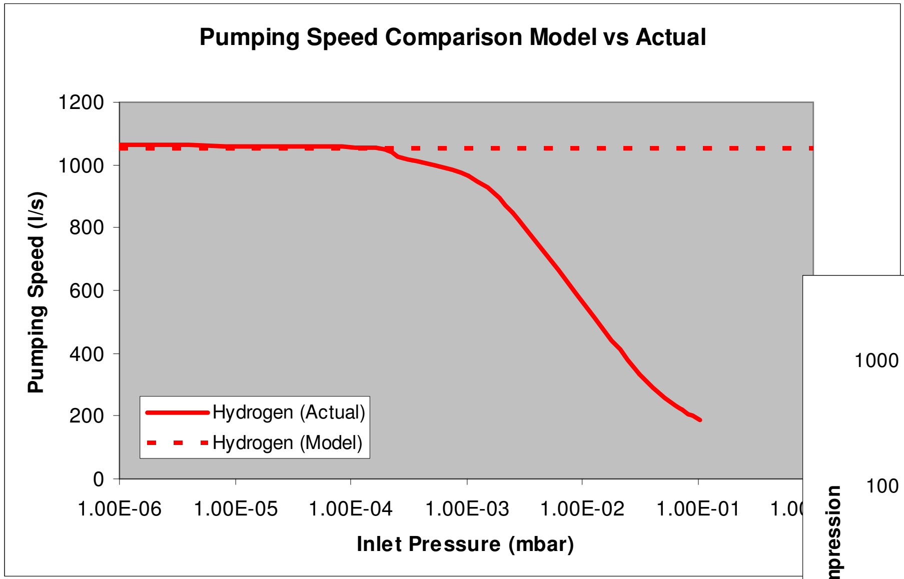
Accuracy
~7 to13%

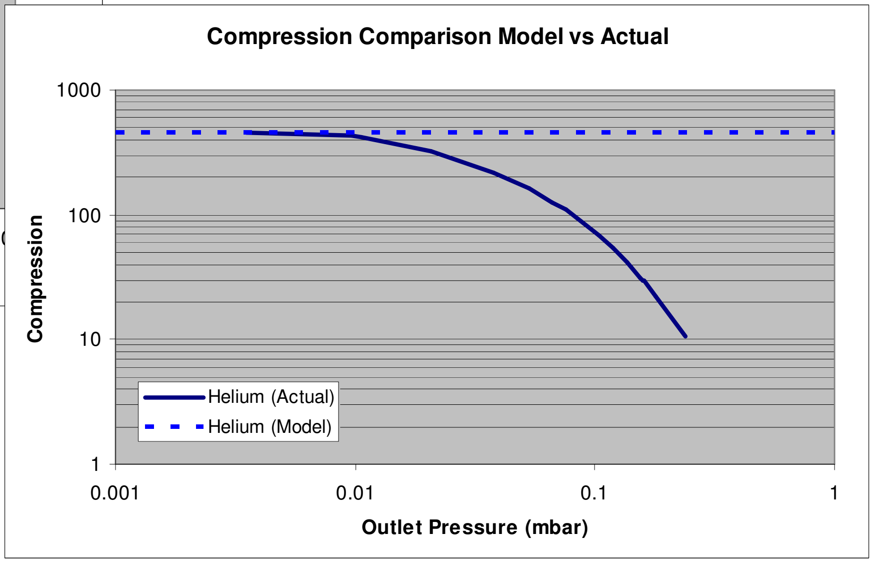
Class 50 ISO 63	Pumping Speed		Compression	
	Model	Test Data	Model	Test Data
Nitrogen	49l/s	48l/s	1E7	1E5
Helium	37l/s	36l/s	4E2	3E2
Hydrogen	31l/s	28l/s	6E1	5E1

Accuracy
~2 to 10%

Modelling Results

- The model assumes molecular flow in all pressure regions hence the values of pumping speed and compression do no decrease as inlet pressure increases.
- Model is only suitable in the molecular flow region!!!





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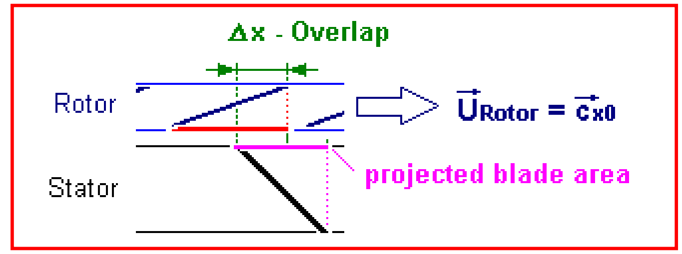
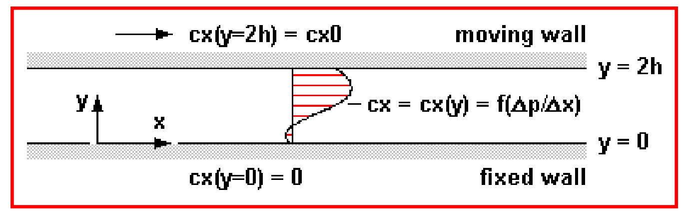
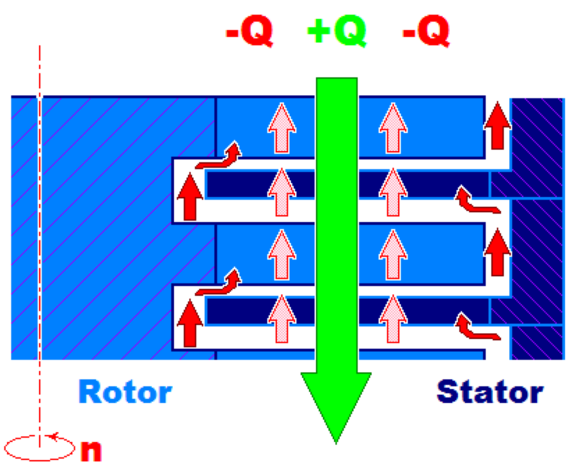
Performance Simulation of TMPs
Viscous Flow Model

Simulation of TMP Performance with a viscous flow model

- 2 dimensional geometry (RMS)
- Stationary flow
- Velocity profile depending on pressure difference (Hagen-Poiseuille)
- Pressure dependent viscosity
- Forward flow reduced by clearance flows in reverse direction







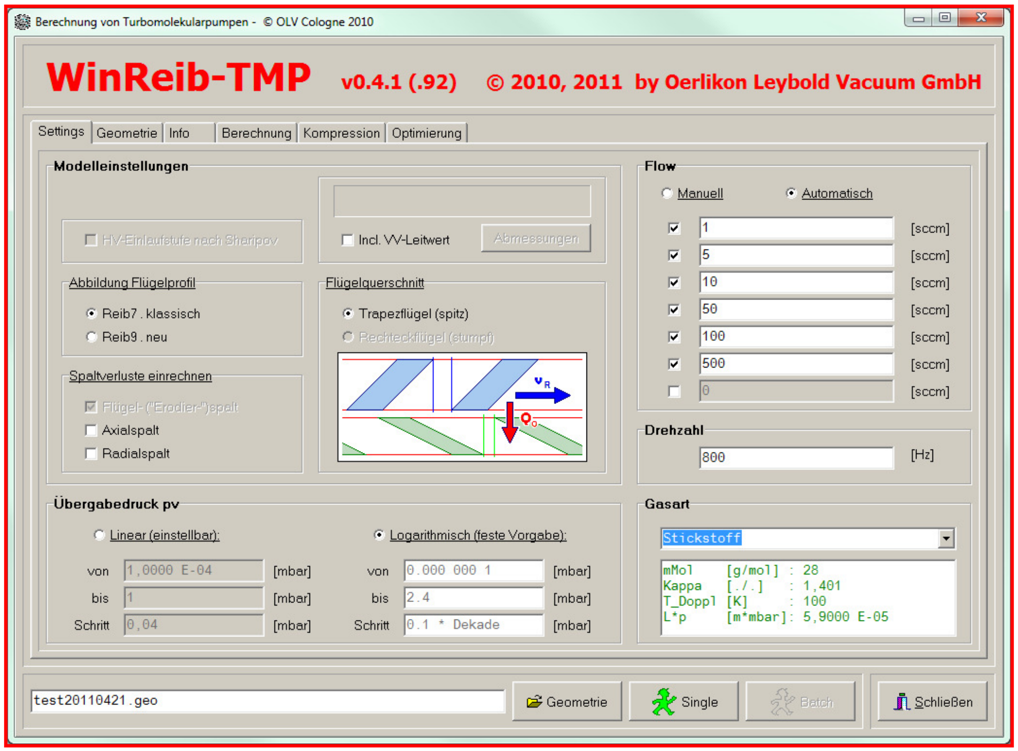
$$\frac{\partial^2 c_x}{\partial y^2} = \frac{1}{\eta} \cdot \frac{\partial p}{\partial x} \quad \text{with} \quad \eta = \frac{\rho}{2} \cdot c' \cdot l' \cdot \frac{h}{h + l'}$$

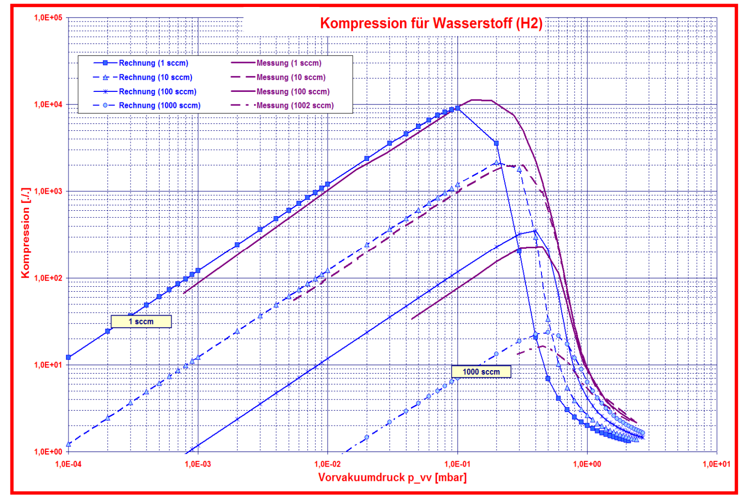
$$S = \dot{\bar{V}} = l_F \cdot h \cdot c_{x0} \cdot \int_0^2 \left[\frac{c_x}{c_{x0}} d\left(\tfrac{y}{h}\right) \right]$$

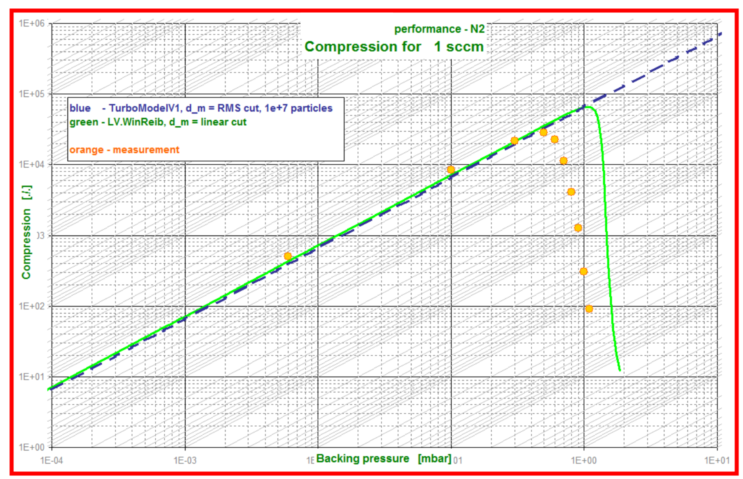
Performance Simulation with viscous flow model

Simulation of the vacuum performance

- Shows generally good accuracy
- Allows a fast simulation of multiple design variations



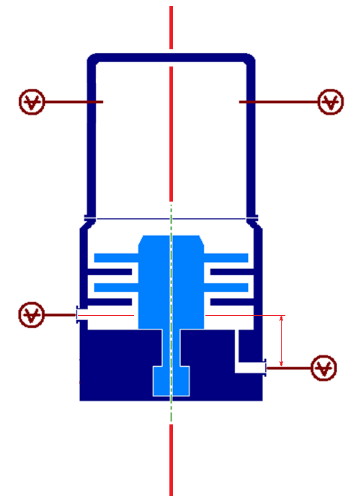


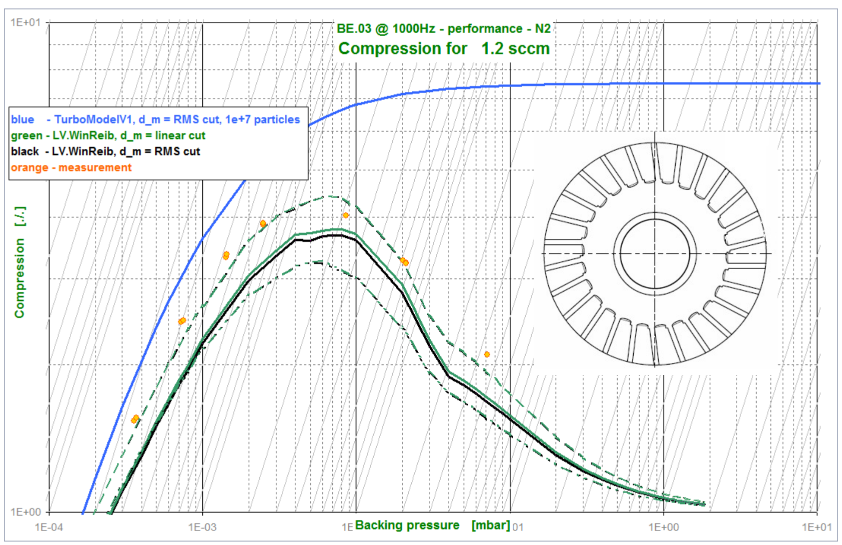


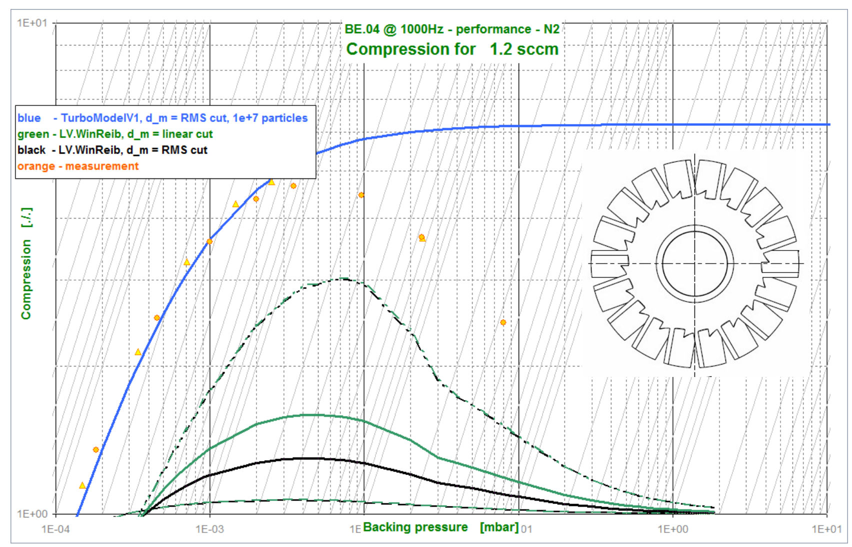
Validation of TMP Performance Simulation

Experimental Validation

- Measurement of single / double stages
- Pressure measurement directly before and behind stages
- Variation of clearances and blade parameters



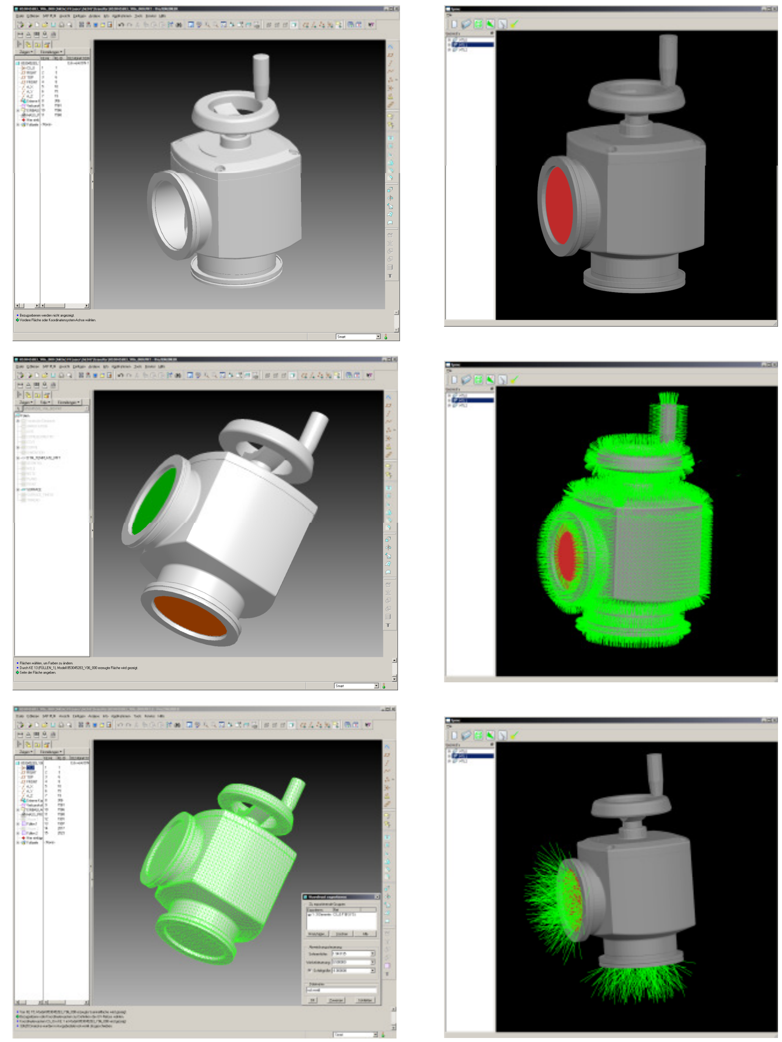




Molecular gas flow simulation through stationary parts

Simulation tool MCFlow for molecular gas flow through stationary parts

- Test particle Monte Carlo method (3D)
- Part geometry from CAD system (ProE)
- Grouping of surfaces in CAD system
- Export of surface geometry to MCFlow
- Specification of inlet and outlet
- Calculation of throughput probabilities
    - Gas type independent
    - 10.000 particle take ~5s
    - Result: Throughput probabilities
- Visualization of flow paths
- Implementation in C++



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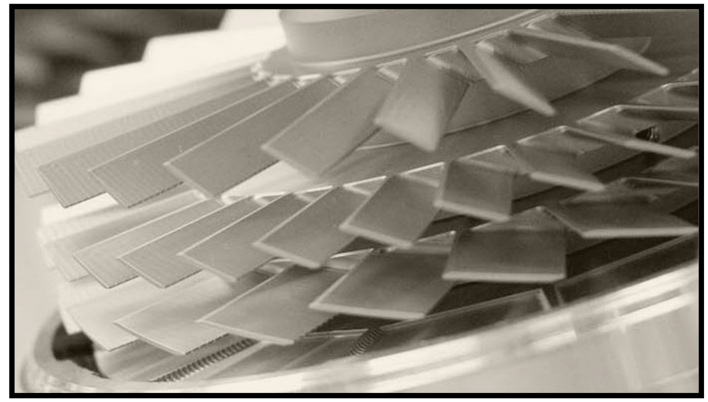
Performance Simulation of Turbo Molecular Pumps

A turbo molecular pumping (TMP) mechanism performance can be modelled

- in the molecular flow region by using a Test Particle Monte Carlo method to compute the gas transmission probabilities through the mechanism.
- In the viscous to transient flow regime by using a viscous flow model (Hagen-Poisseuille) with adopted viscosity.

Modelling accuracy is acceptable for all gas types.



Challenges in the simulation of Turbo Molecular Pumps

The following parts of the simulation can be improved:

- One (combined) flow model to simulate all flow regimes
  molecular ➔ transient ➔ viscous

- Thermal simulation of the process and the pump parts
  - Heat Transfer between the gas and the surrounding surfaces
    - Housing
    - Rotor Blades
    - Holweck stage
  - Calculation of gas temperature during compression
  - FEM simulation for the pump parts

- 3D – model including the influences of complex flow channels inside the pump

- Simulation of mixed gas flows