Electrical resistivity in comparison to thermal conductivity of selected alloys

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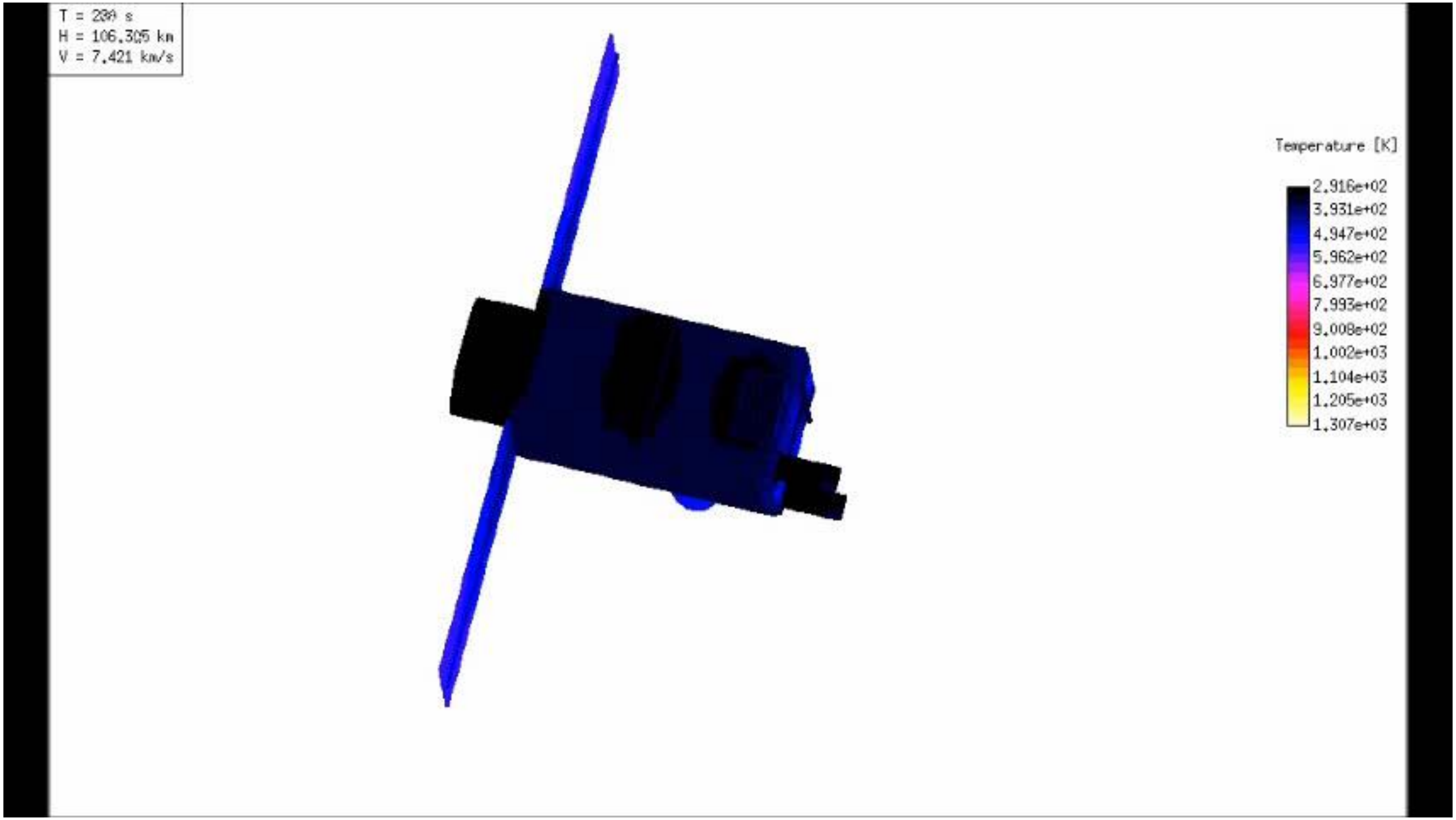
Motivation and task

- **Every month, several tons of spacecraft mass enter uncontrolledly the atmosphere**
- **International agreements require for each satellite launched into LEO to conduct either a controlled de-orbiting or to assess the possible risk for human population**
- **The demisability of a spacecraft and its components during re-entry depends on many parameters**
- **Numerical simulation of demise at re-entry of a spacecraft requires - among others - thermophysical properties up to complete melting of decay**
- **Common alloys for aerospace applications: TiAl6V4, Aluminium, stainless steel 316L, superalloys…**
- **A full set of thermophysical properties in the range room temperature to melting was measured to characterise the alloy:**
  - **Electrical resistivity**
  - **Specific heat capacity**
  - **Density and linear thermal expansion**
  - **Thermal diffusivity – thermal conductivity**
- **A comparison between thermal and electrical conductivity/resistivity was made to check the validity of the Wiedemann-Franz law**

Numerical simulation of demise at re-entry of Gensat

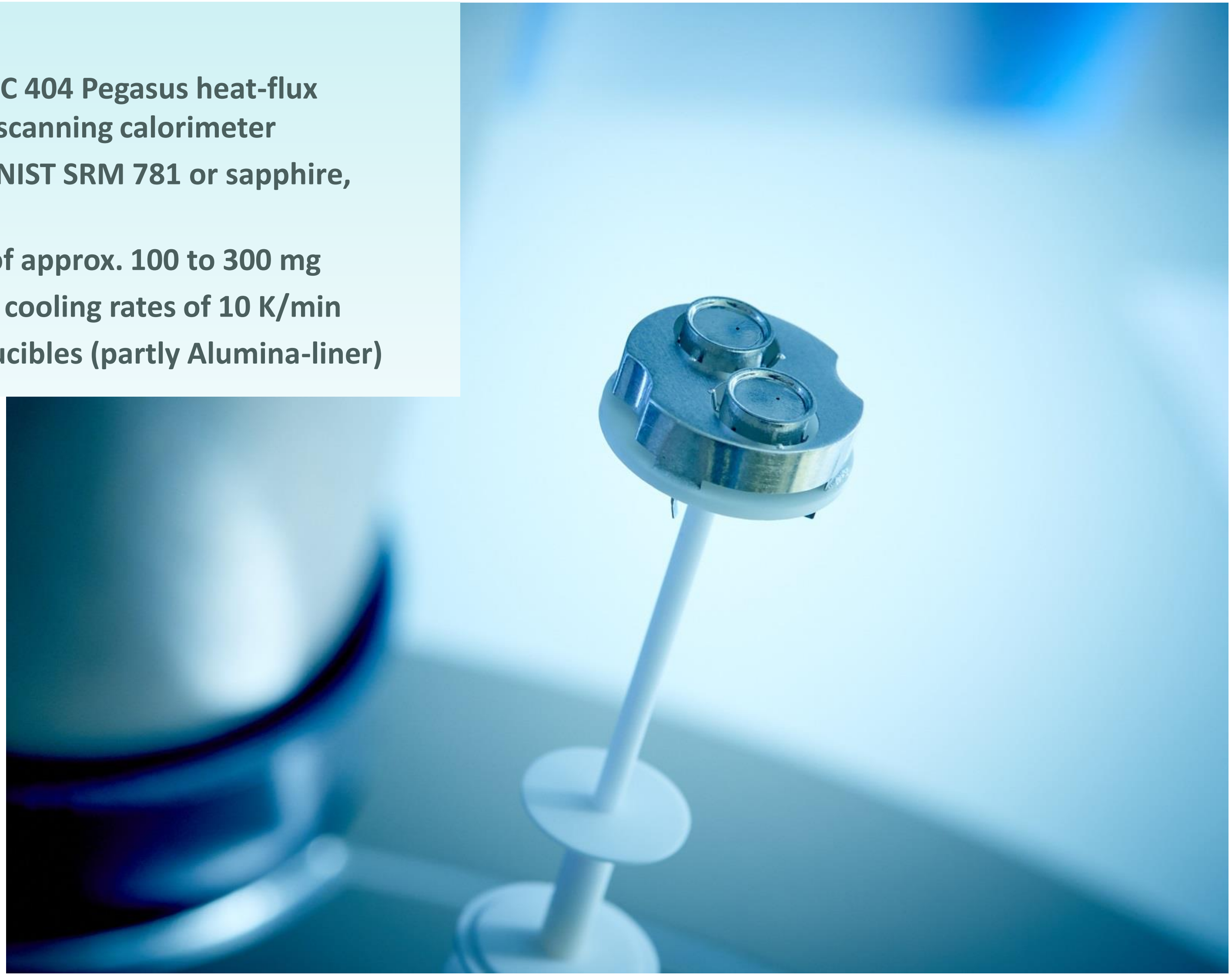


Simulated by:

Measurement of heat capacity

Measurement:

- NETZSCH DSC 404 Pegasus heat-flux differential-scanning calorimeter
- Empty pan, NIST SRM 781 or sapphire, alloy
- Specimens of approx. 100 to 300 mg
- Heating and cooling rates of 10 K/min
- Platinum crucibles (partly Alumina-liner)

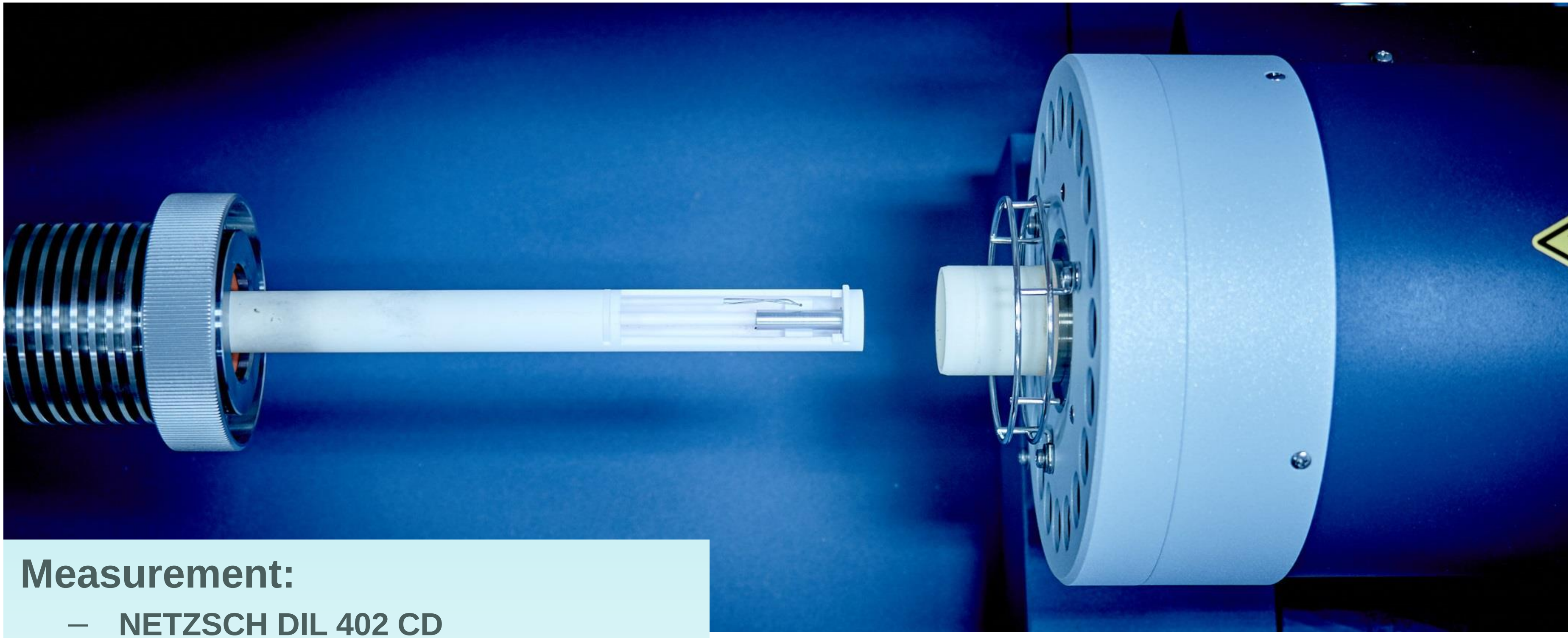


Measurement of thermal diffusivity

Measurement:

- NETZSCH LFA 427
- Specimens: 12.5 mm in diameter; 3 mm thickness
- Sand-blasted, UHV
- 500 µs laser pulse length
- Cape-Lehmann fit with pulse length and heat loss correction

Measurement of thermal expansion and density



Measurement:

- NETZSCH DIL 402 CD
- Specimens: 6 mm in diameter; 25mm in length
- Heating/cooling rate 2 K/min
- Density at room temperature by an Archimedean balance (Sartorius ED224S)

Calculation of density and thermal conductivity

- **Density ρ as a function of temperature T is calculated by density at room temperature ρ_0 and thermal expansion $\Delta l / l_0$:**

$$\rho(T) = \frac{\rho_0}{(1 + \frac{\Delta l(T)}{l_0})^3}$$

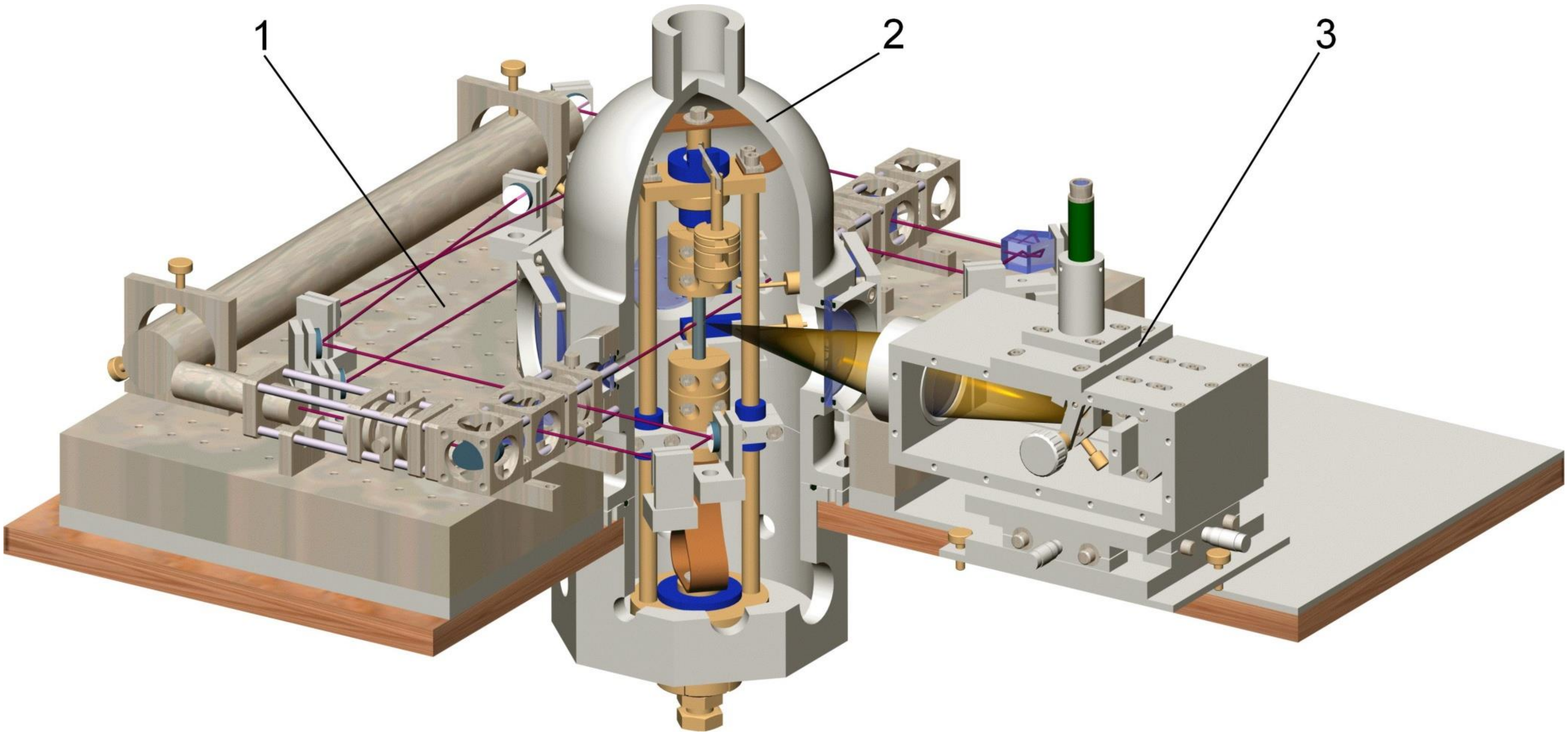
- **Thermal conductivity λ as a function of temperature T is calculated by thermal diffusivity a_0, densityρ, and heat capacity c_P:**

$$\lambda(T) = \left[a_0(T) \; (1 + \frac{\Delta l(T)}{l_0})^2 \right] \rho(T) \; c_P(T)$$

Measurement of electrical conductivity

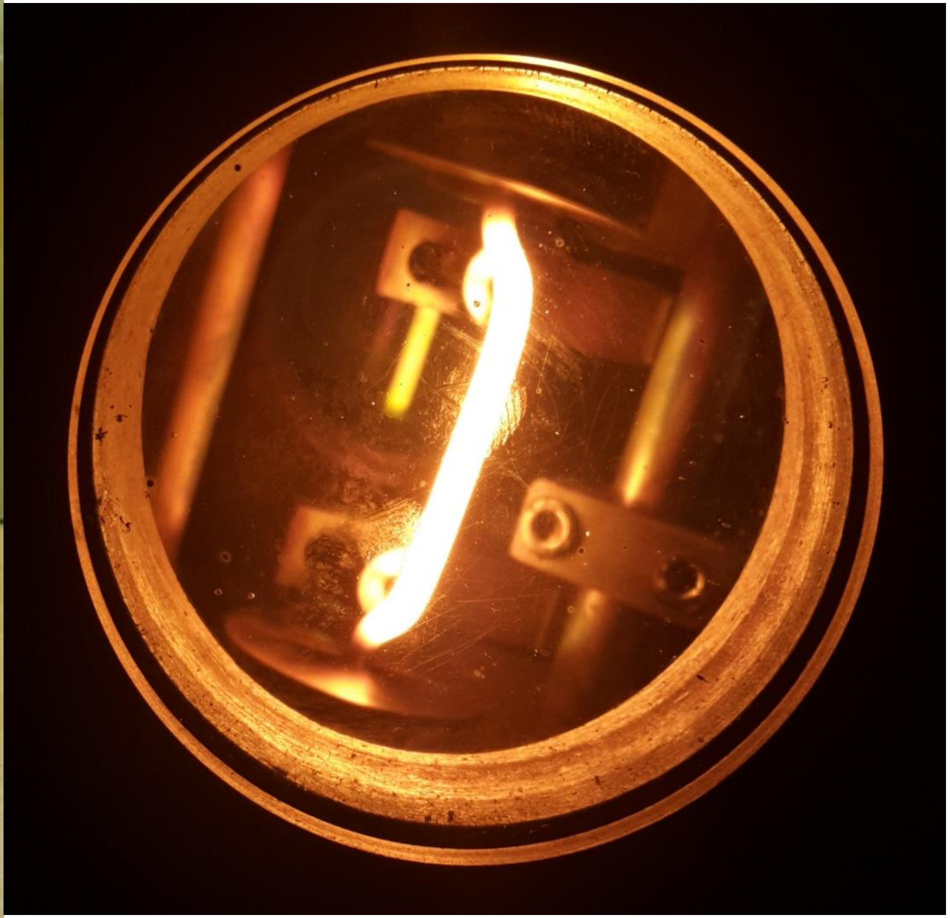
- Millisecond pulse heating system capable to provide up to 5000 A of current to heat a metallic specimen
- Four-probe measurement of current and voltage along a specific portion of the specimen
- Self-heating of the specimen, (almost) all imparted electrical energy is used to increase enthalpy of the specimen (long, thin rod approximation)
- But:
  - Specimen has a certain thickness (4 mm diameter)
  - At elevated temperatures, there are radiation losses
  - Steel - low thermal conductivity (radiation), aluminium - high thermal conductivity (conduction)
  - Long, thin rod approximation is violated
- Deviation from the long, thin rod approximation by heat loss is computed using a numerical simulation model
- From the heat capacity measurements, the enthalpy vs. temperature relation is known (no use of pyrometer – no emissivity problem)

Measurement of electrical conductivity

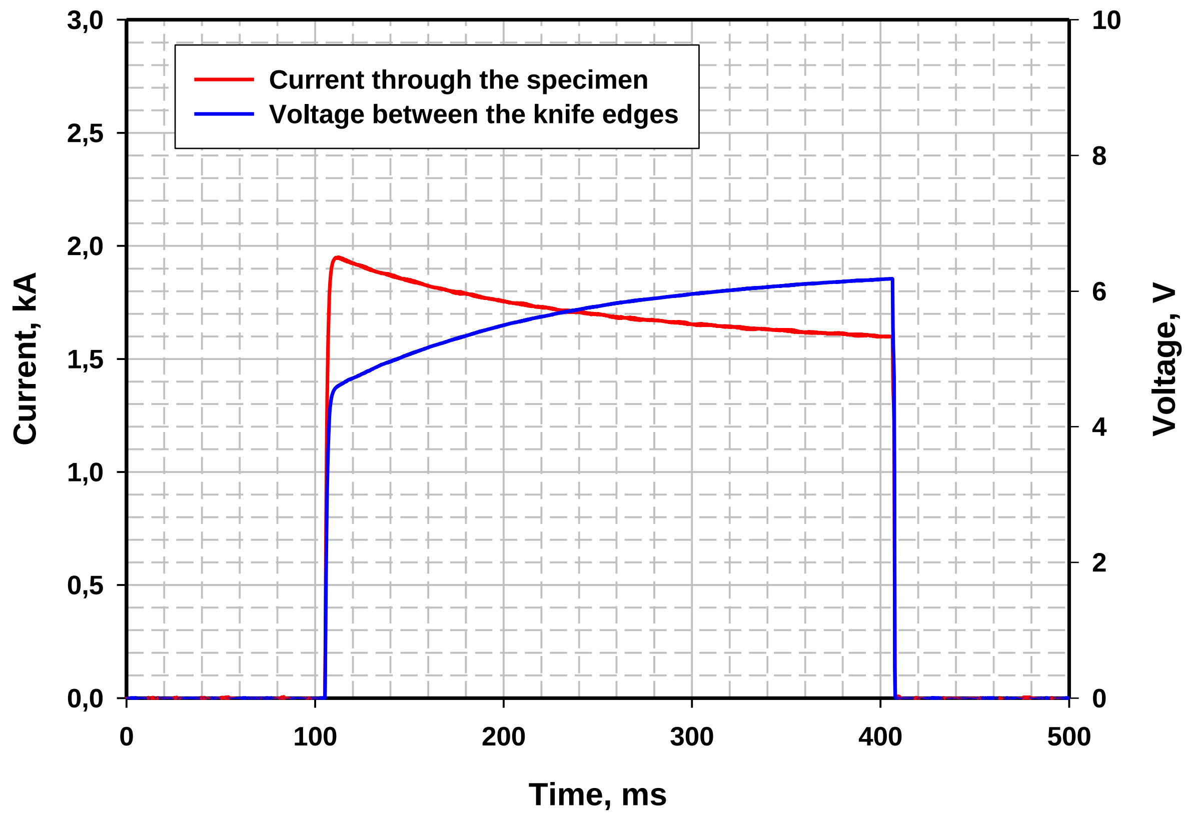


1 interferometer, 2 vessel, 3 pyrometer

Measurement of electrical conductivity



Measurement of electrical conductivity



Calculation of electrical resistivity and enthalpy

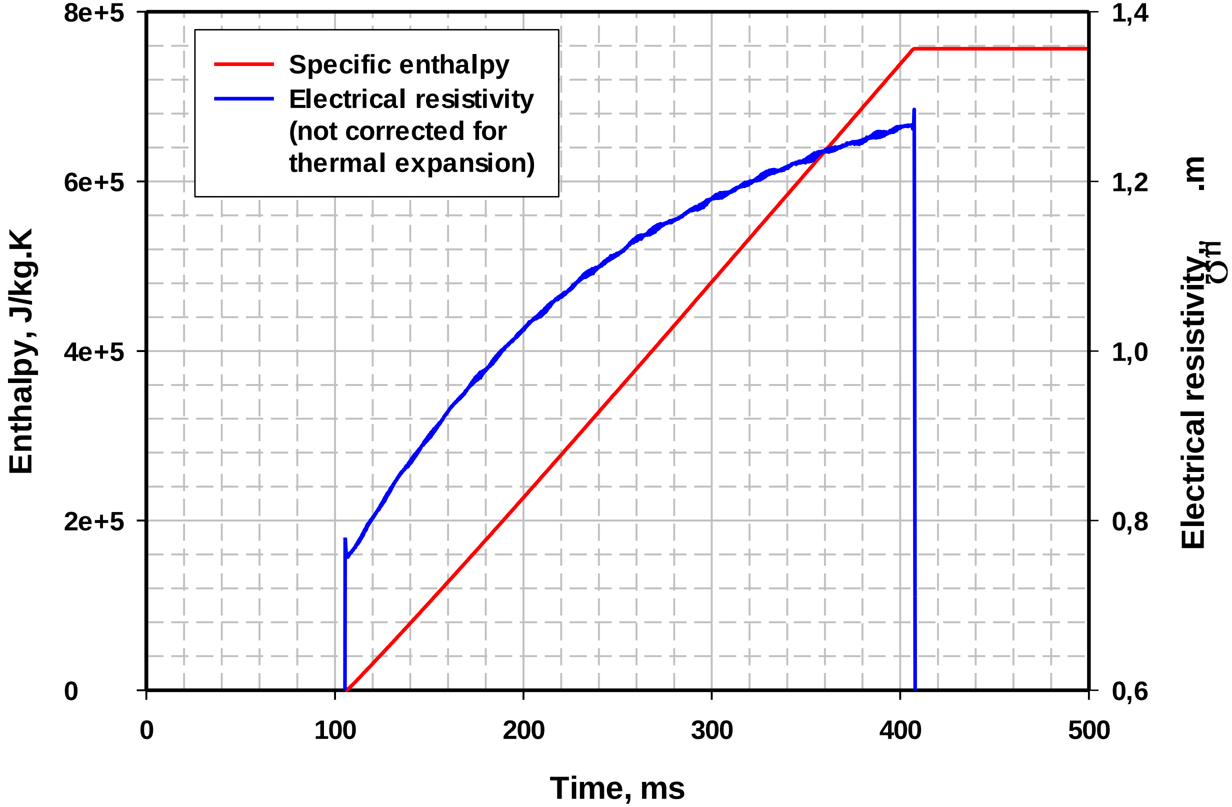
- **Electrical resistivity ρ_{el} as a function of time t is calculated by voltage U, current I, diameter d, length between the knife edges l, and thermal expansion $\Delta l/l_0$**

$$\rho_{el}\,(t) = \frac{U(t)\,d^2\,\pi}{4\,I(t)\,l}\,(1+\frac{\Delta l}{l_0})$$

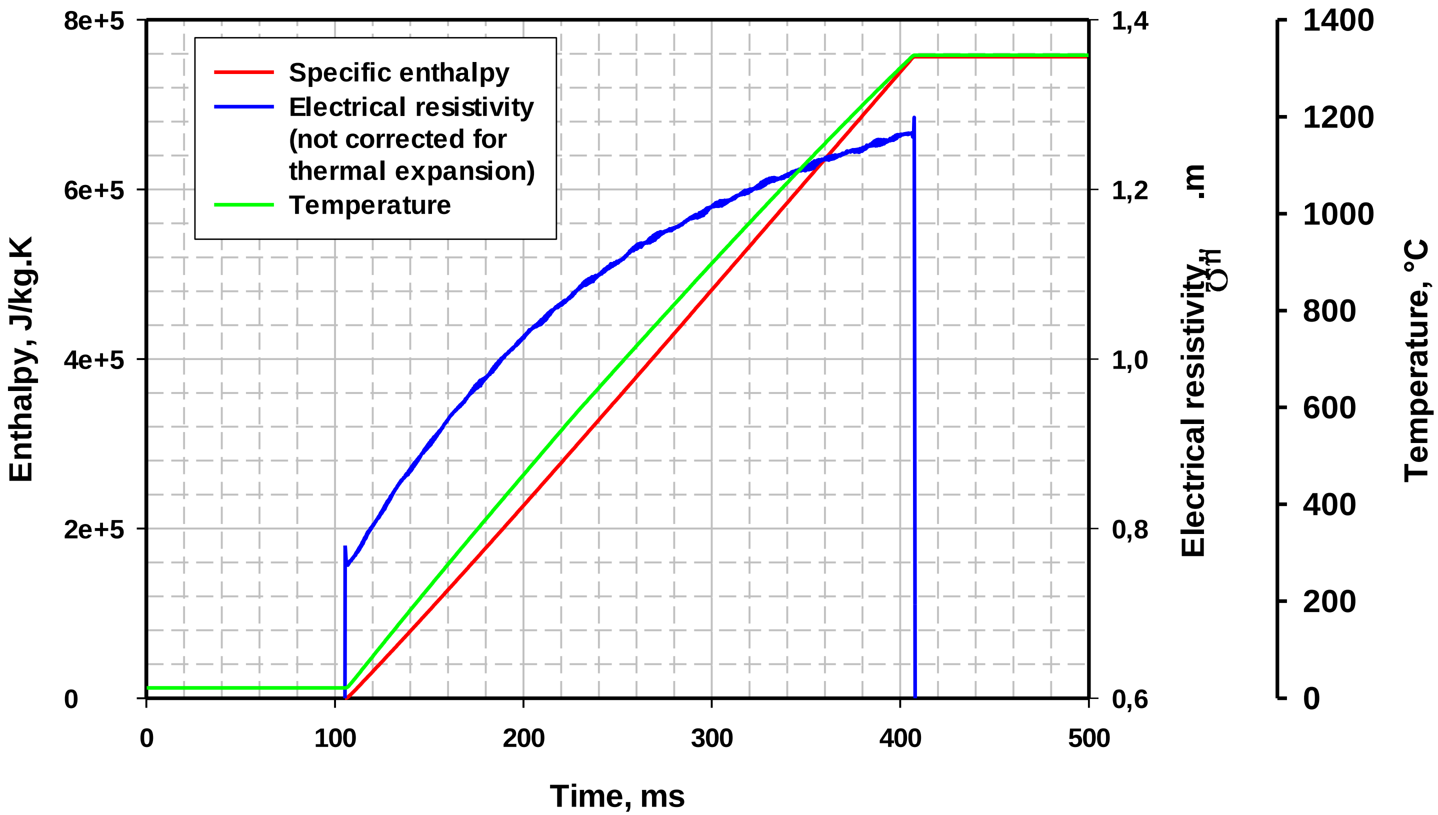
- **Specific enthalpy H as a function of time t is calculated by thermal voltage U, current I, and mass between the knife edges m :**

$$H(t) = \frac{1}{m}\int_0^t U(\tau)\,I(\tau)\,d\tau$$

Measurement of electrical conductivity

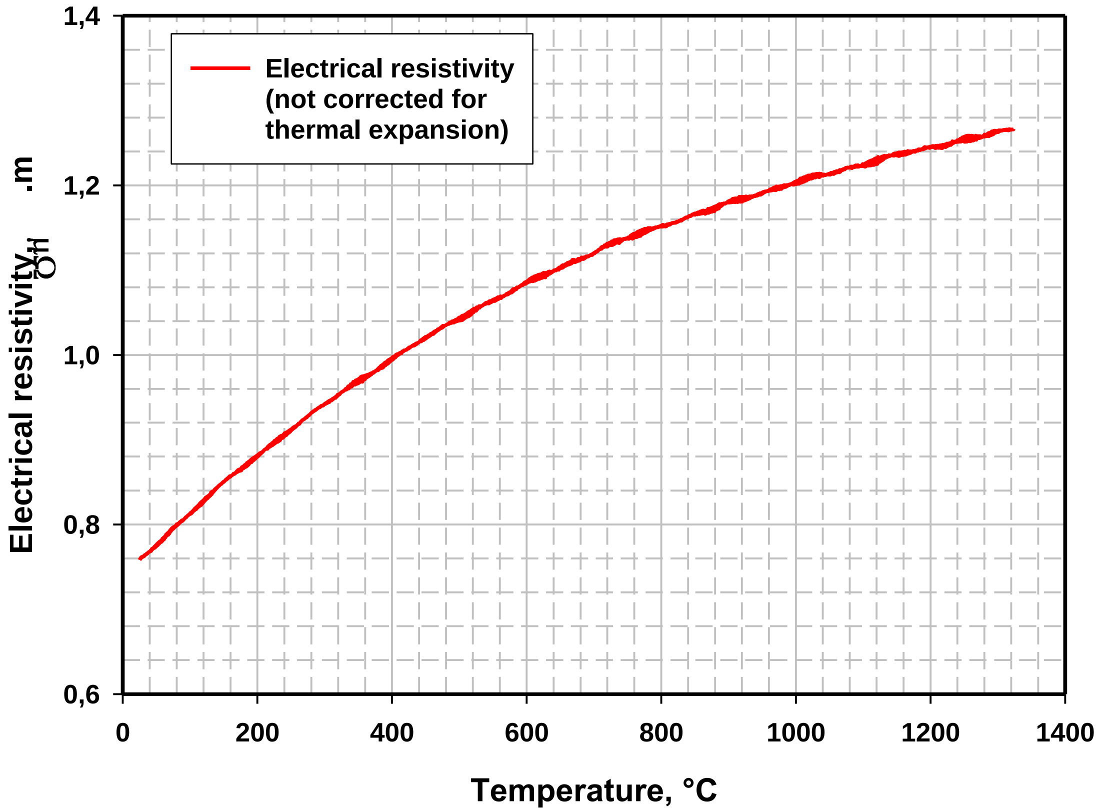


Measurement of electrical conductivity

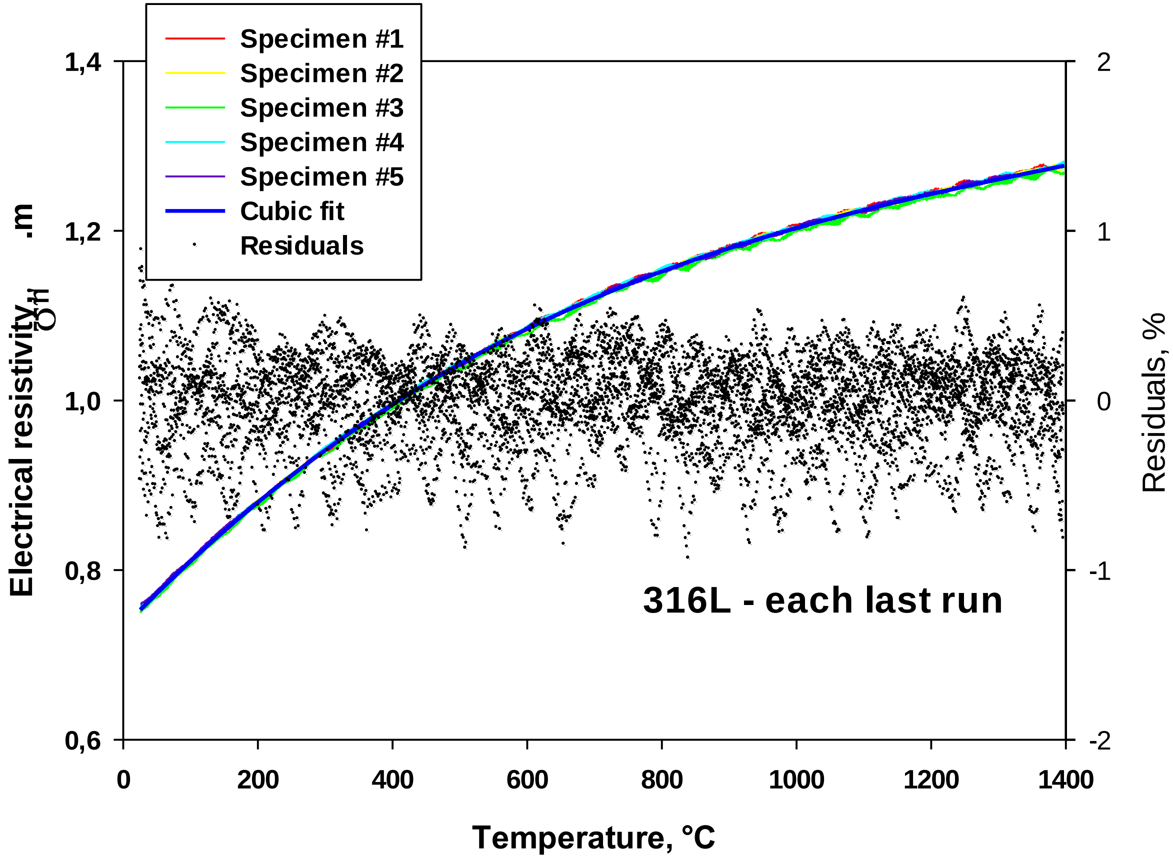


Temperature is calculated from results of the DSC measurement

Measurement of electrical conductivity

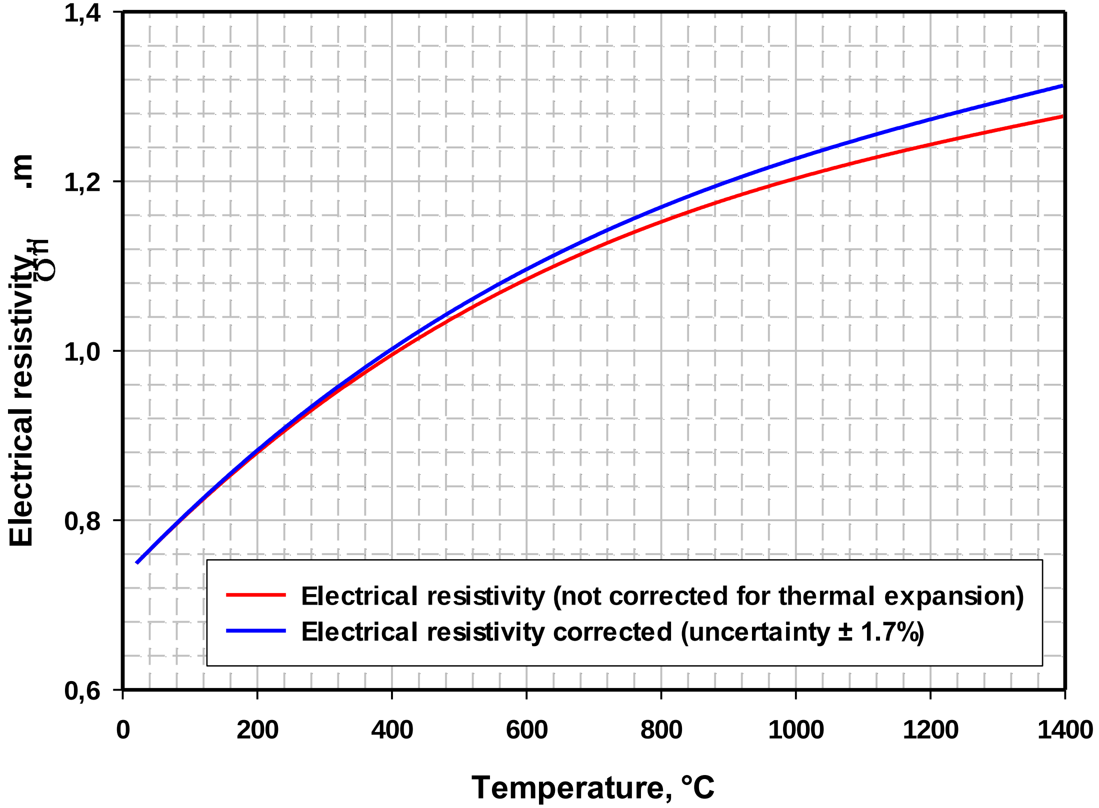


Measurement of electrical conductivity



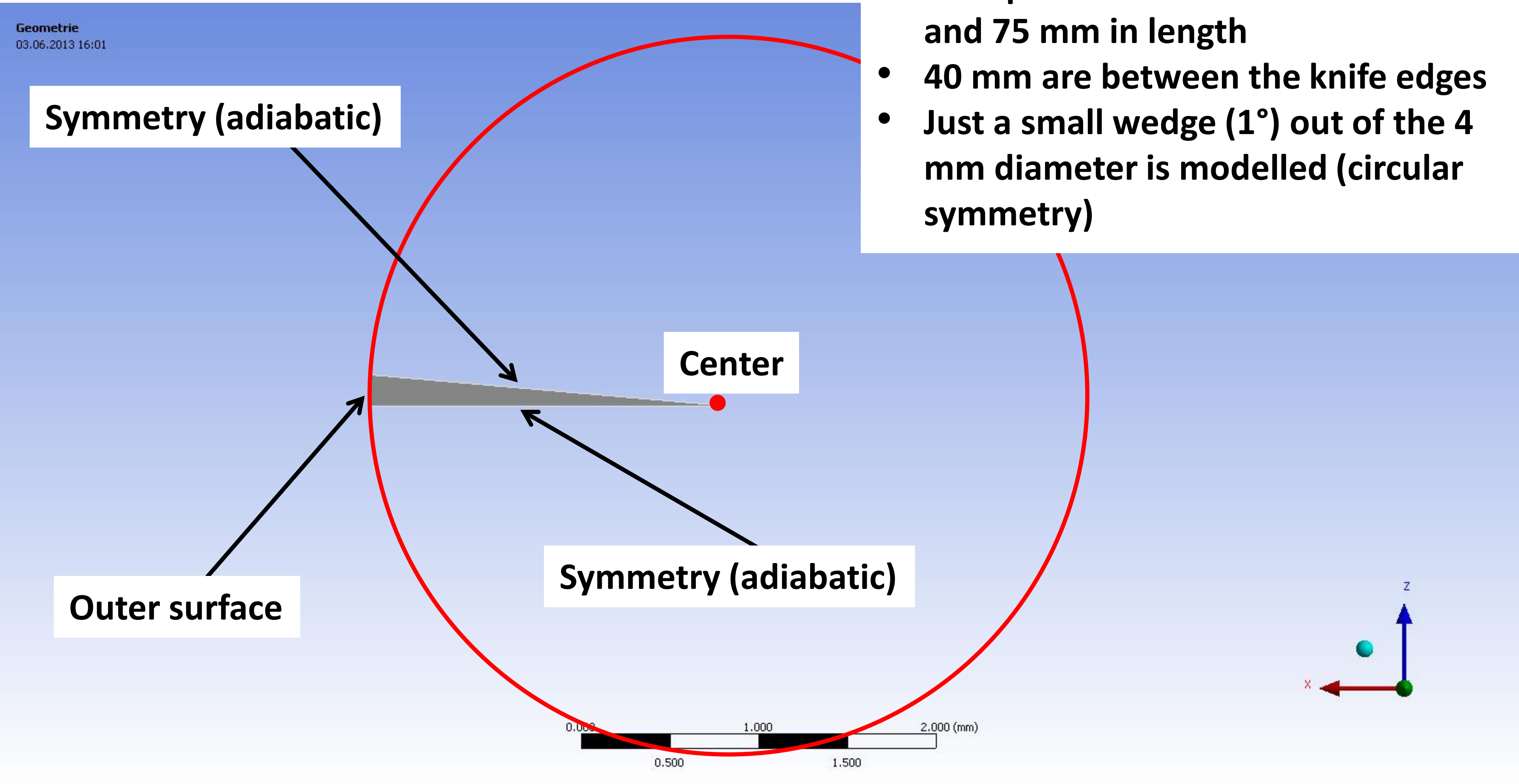
Very good reproducibility between different specimen

Measurement of electrical conductivity

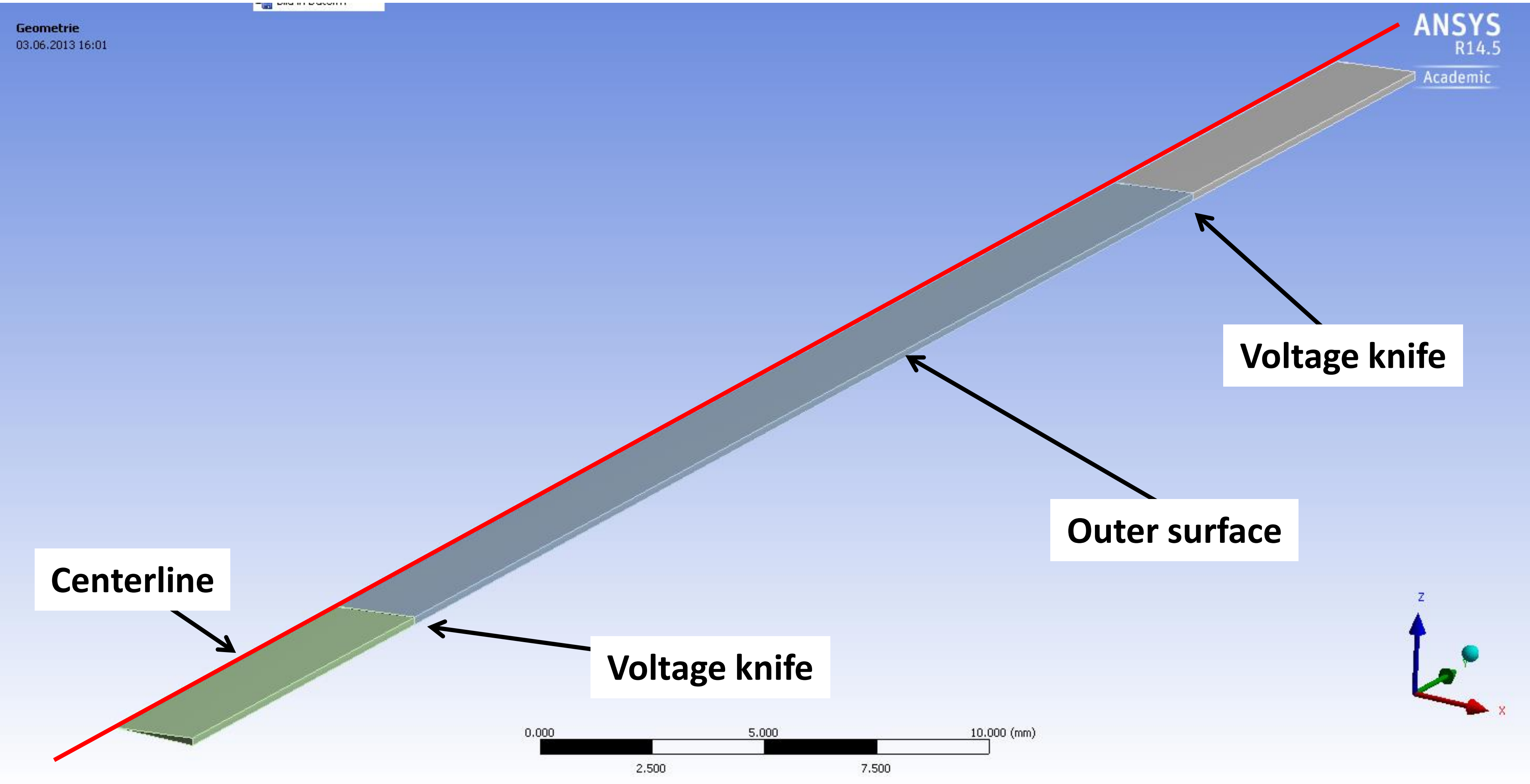


Simulation of millisecond pulse-heating

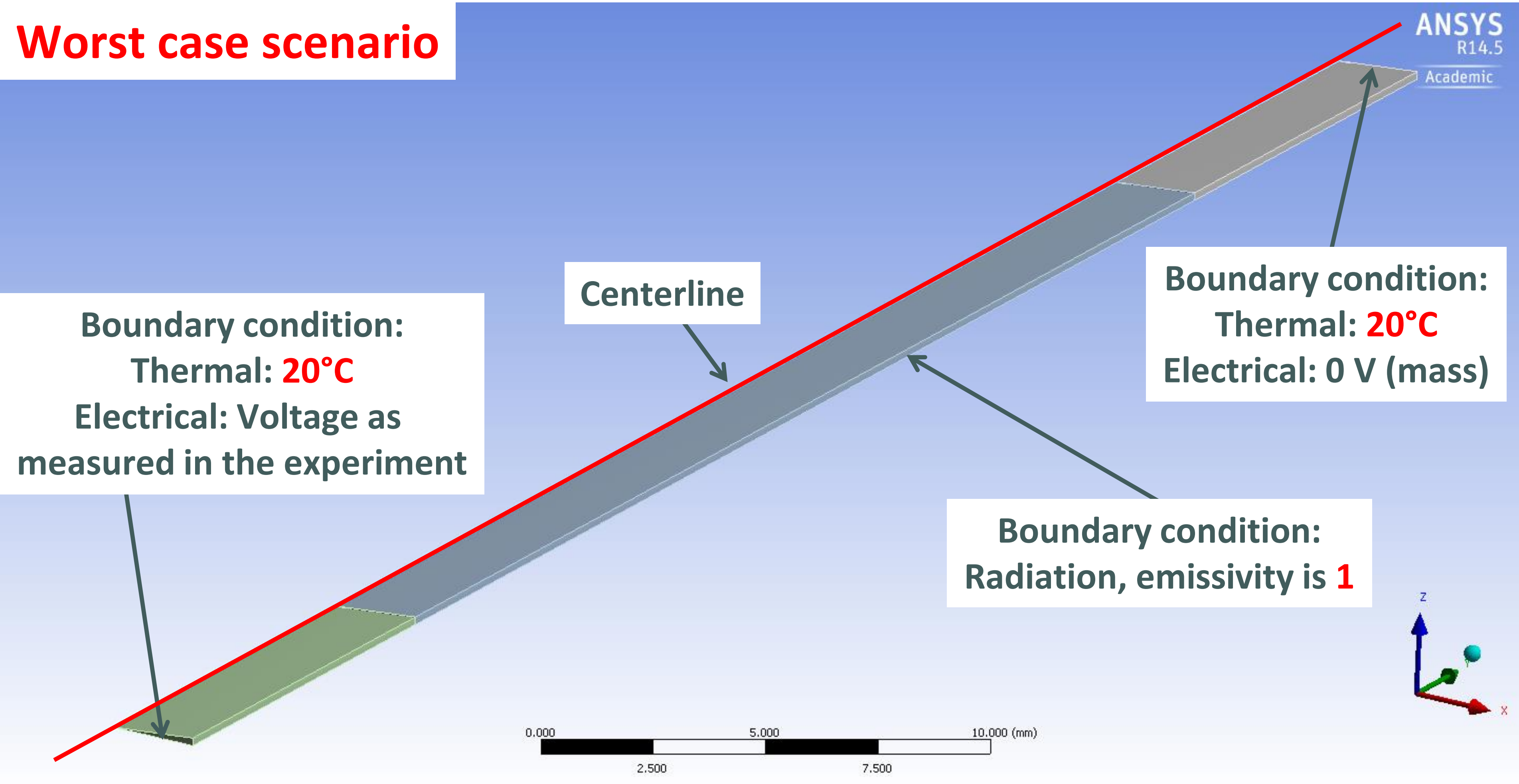
- The specimens are 4 mm in diameter and 75 mm in length
- 40 mm are between the knife edges
- Just a small wedge (1°) out of the 4 mm diameter is modelled (circular symmetry)



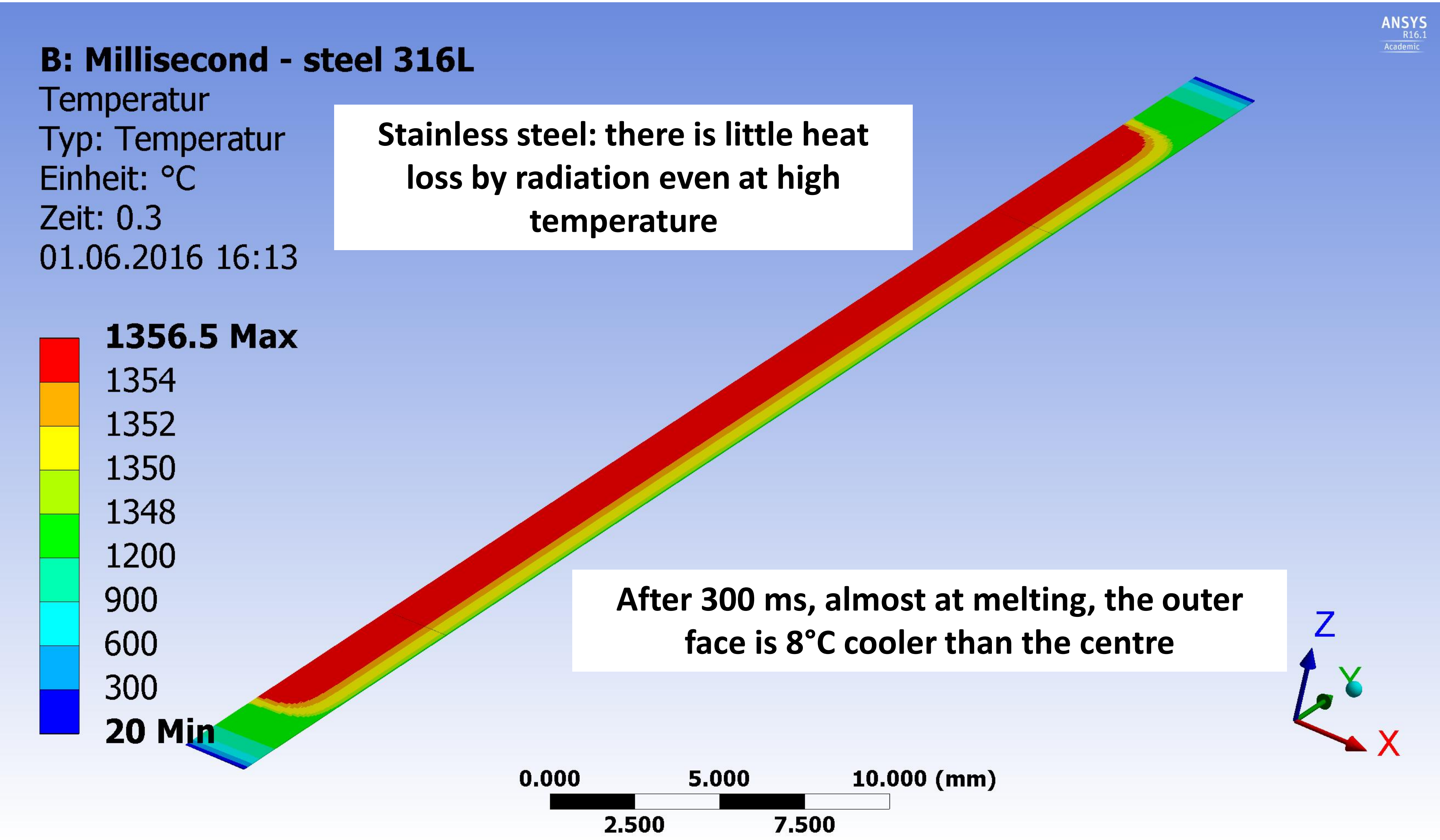
Simulation of millisecond pulse-heating



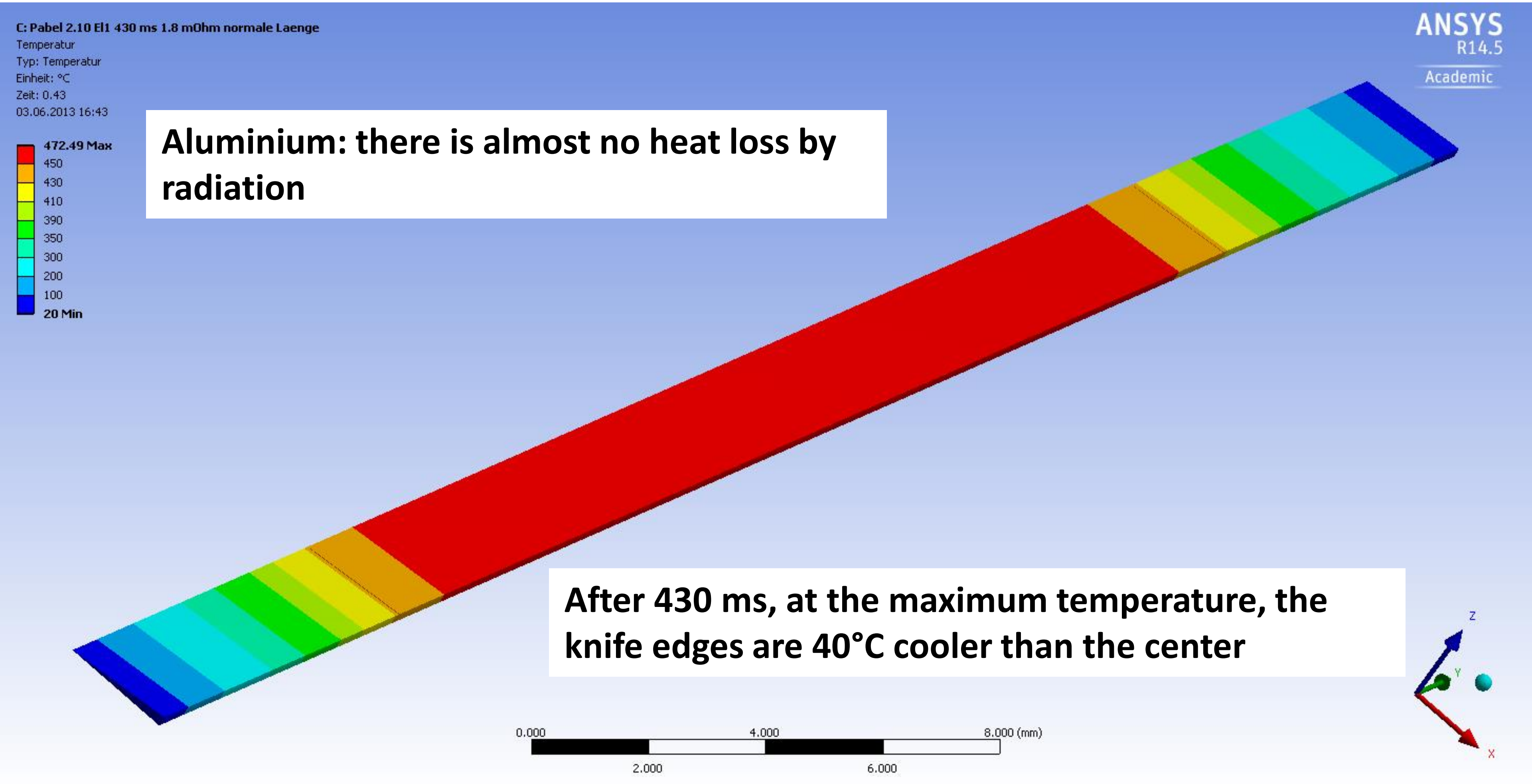
Simulation of millisecond pulse-heating



Simulation of millisecond pulse-heating



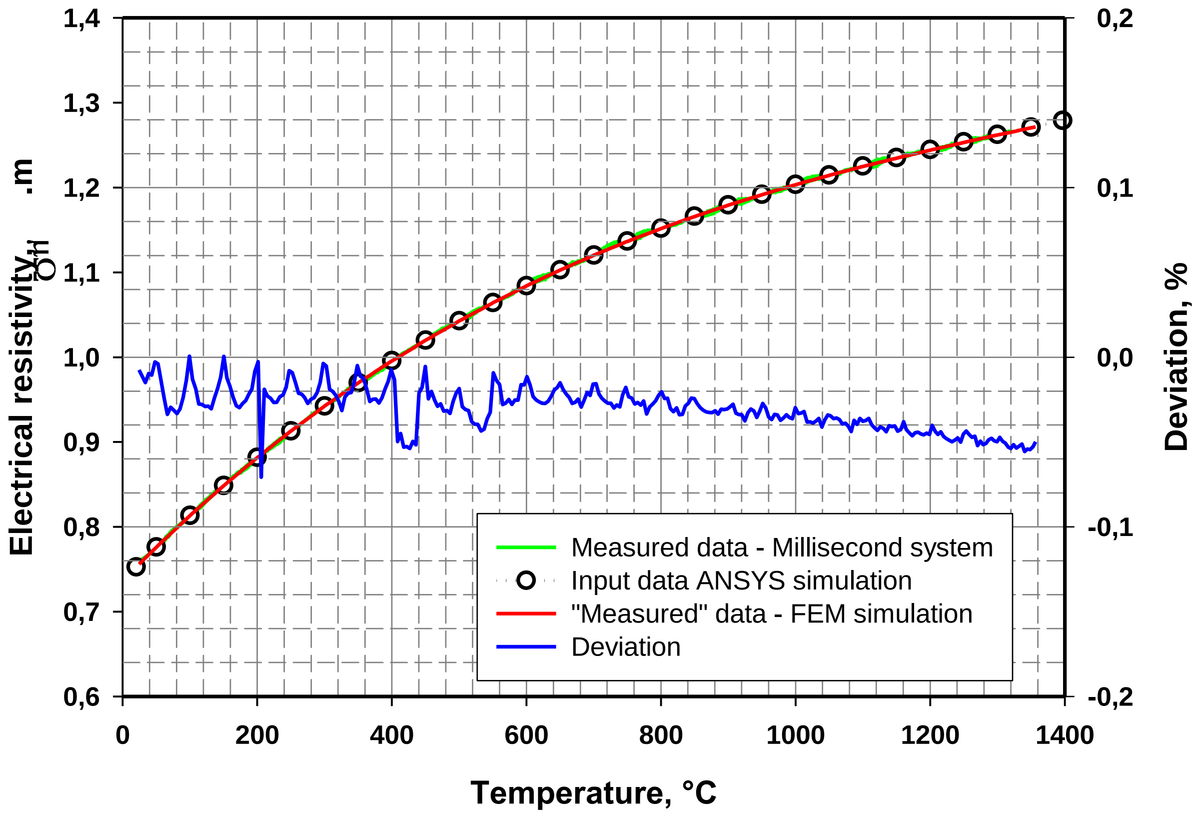
Simulation of millisecond pulse-heating



Aluminium: there is almost no heat loss by radiation

After 430 ms, at the maximum temperature, the knife edges are 40°C cooler than the center

Simulation of millisecond pulse-heating



Worst case scenario

Calculation thermal conductivity - electrical resistivity

- **Thermal conductivity λ as a function of temperature T is calculated from electrical resistivity ρ_{el} ; the Sommerfeld-value of the Lorenz number L_0 (2.445 x 10^{-8} V^2/K^2), the phonon contribution of thermal conductivity λ_G, and A, a factor to consider scattering at solute atoms and :**

$$Wiedemann - Franz\colon \lambda(T) = \frac{L_0\, T}{\rho_{el}}$$

$$Smith - Palmer\colon \lambda(T) = \frac{A\, L_0\, T}{\rho_{el}} + \lambda_G$$

Smith-Palmer-Plot

- **Thermal conductivity λ as a function of temperature T is calculated from electrical resistivity ρ_{el} ; the Sommerfeld-value of the Lorenz number L_0 (2.445 x 10^{-8} V^2/K^2), the phonon contribution of thermal conductivity λ_G, and A, a factor to consider scattering at solute atoms and :**

$$\lambda(T) = \frac{A\, L_0\, T}{\rho_{el}} + \lambda_G$$

Variable

Smith-Palmer-Plot

- **Thermal conductivity λ as a function of temperature T is calculated from electrical resistivity ρ_{el} ; the Sommerfeld-value of the Lorenz number L_0 (2.445 x 10^{-8} V^2/K^2), the phonon contribution of thermal conductivity λ_G, and A, a factor to consider scattering at solute atoms and :**

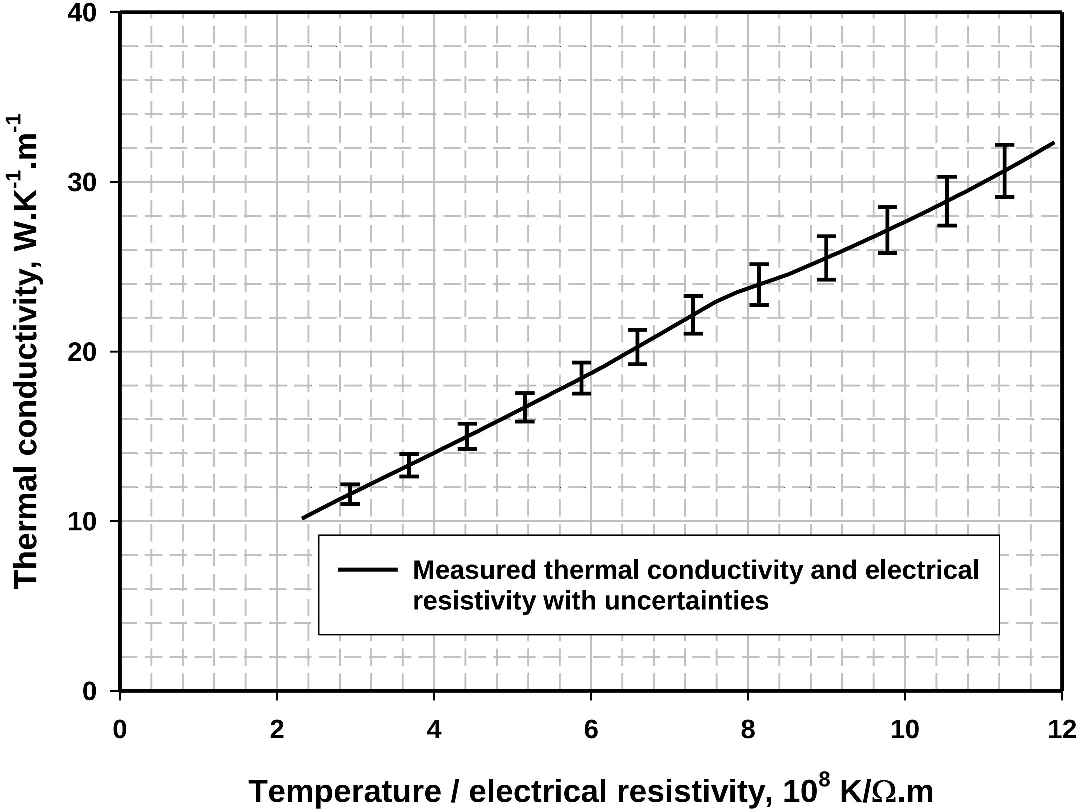
$$\lambda(T) = \frac{A\ L_0\ T}{\rho_{el}} + \lambda_G$$

Slope

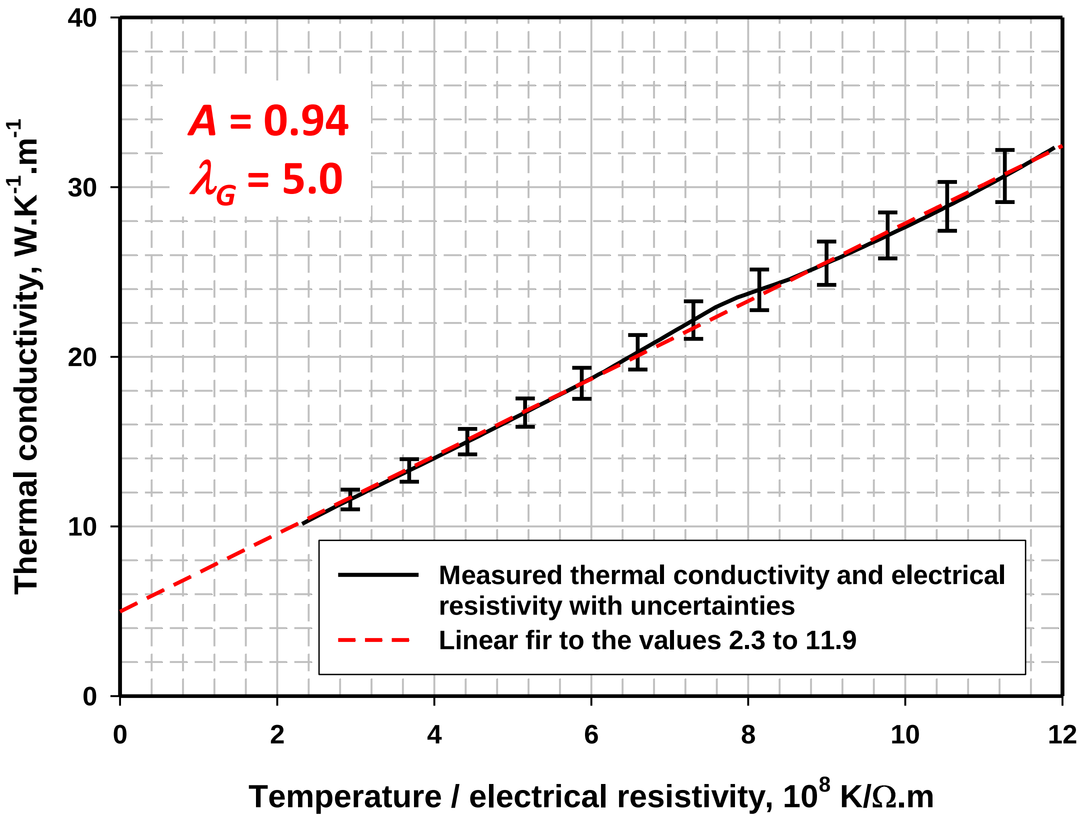
Variable

Intercept

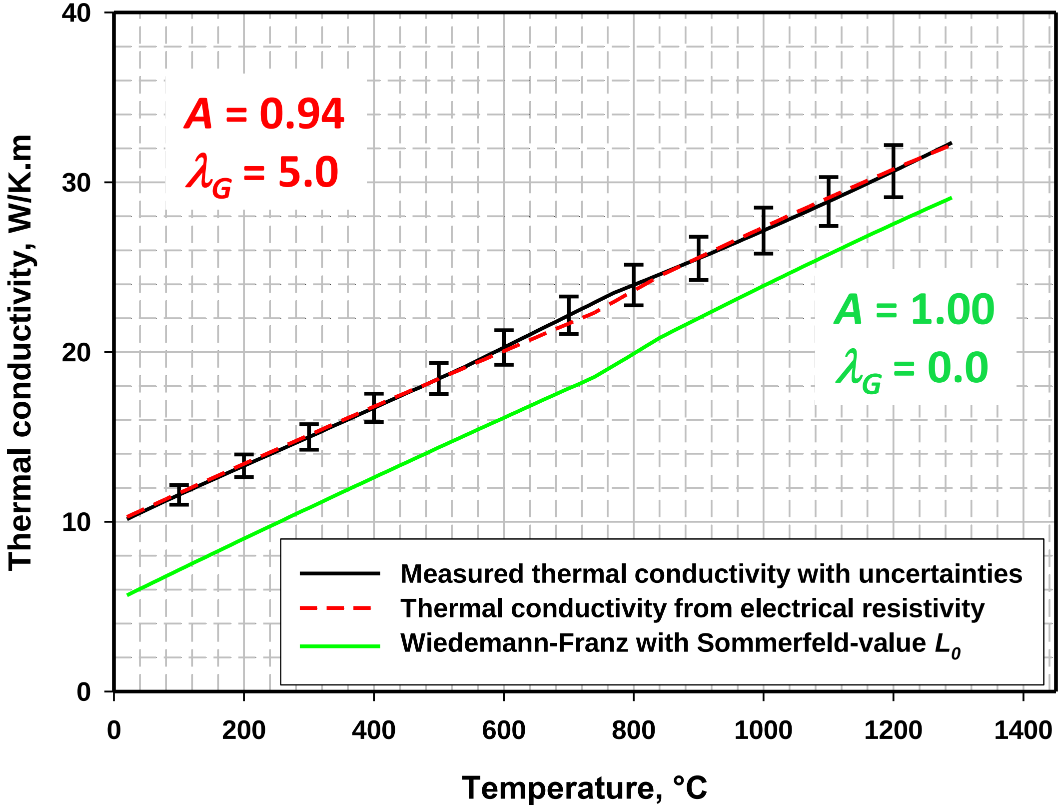
Smith-Palmer-Plot: Inconel 625



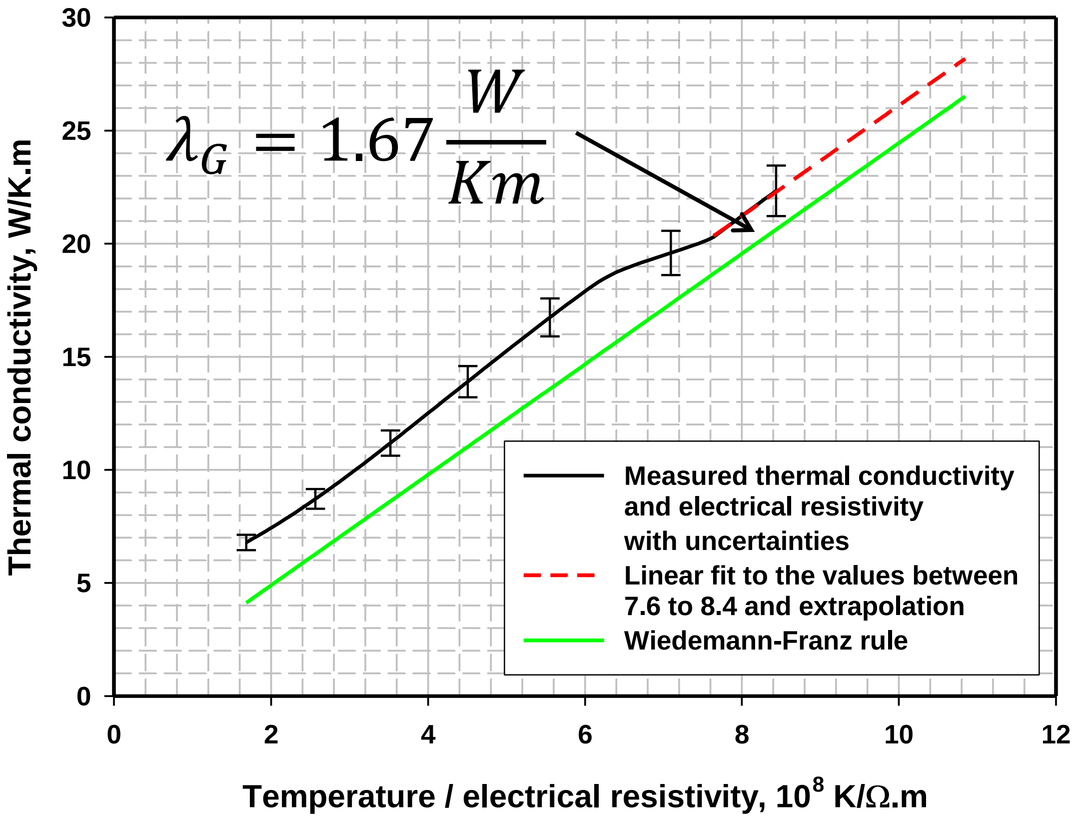
Smith-Palmer-Plot: Inconel 625



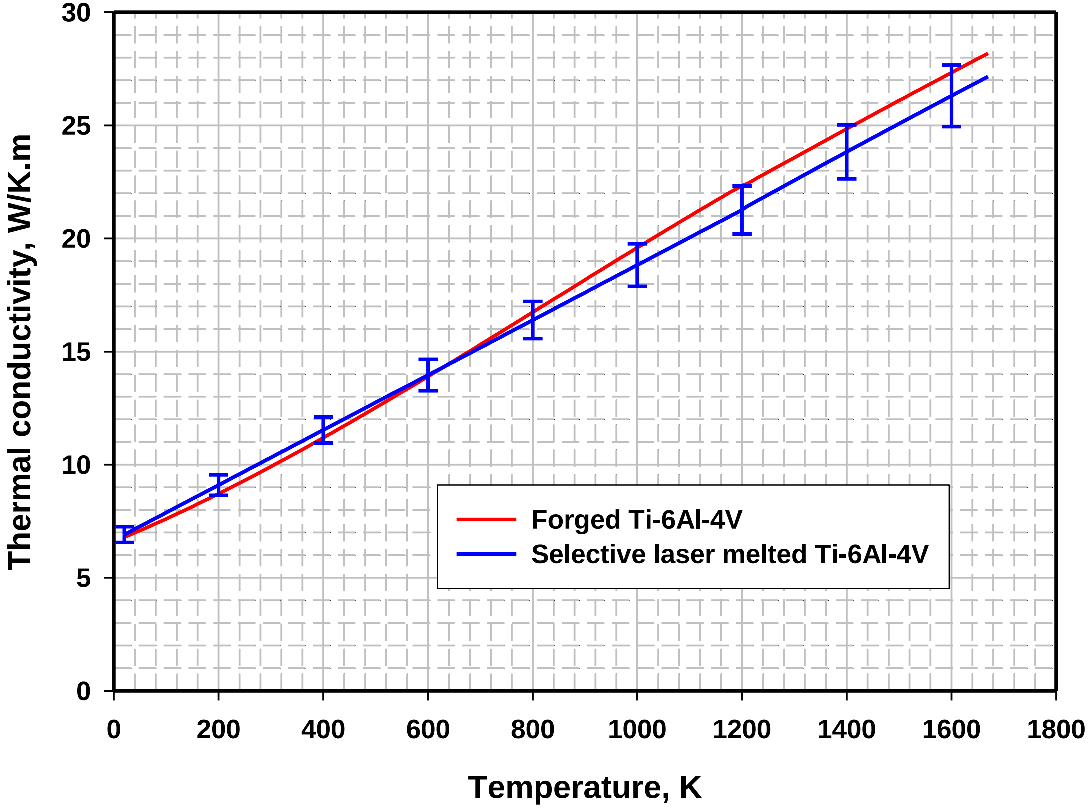
Thermal conductivity as a function of temperature: Inconel 625



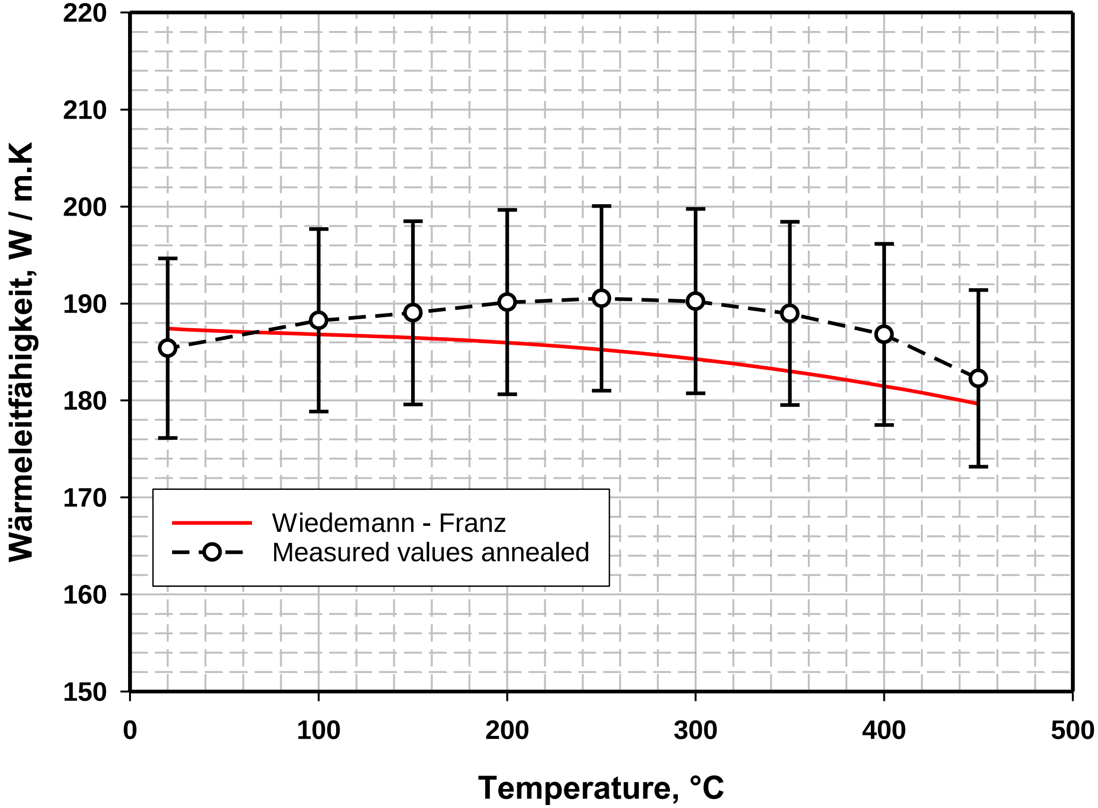
Smith-Palmer-Plot (forged Ti-6Al-4V):



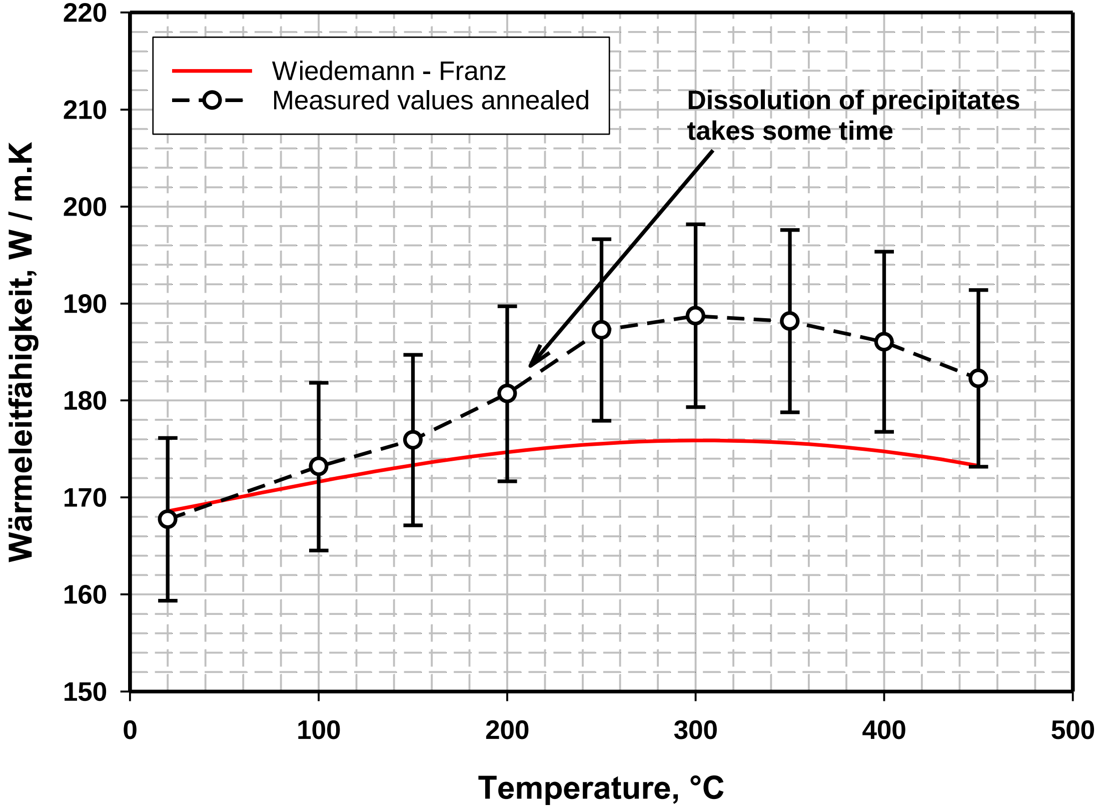
Results of thermal conductivity (both types of Ti-6Al-4V):



Thermal conductivity as a function of temperature: AlSi7Mg - annealed



Thermal conductivity as a function of temperature: AlSi7Mg – as cast



Conclusions

- A full set of thermophysical properties in the range room temperature to melting was measured to characterise aerospace alloys:
  - Electrical resistivity
  - Specific heat capacity
  - Density and linear thermal expansion
  - Thermal diffusivity – thermal conductivity

- Electrical resistivity can be measured precisely by millisecond pulse heating, heat losses are negligible

- Only a modified Wiedemann-Franz law can be used to calculate thermal conductivity from electrical resistivity - especially when the lattice contribution is relatively high

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