Surface temperature measurement and heat load estimation for targets with plasma contact and machine protection

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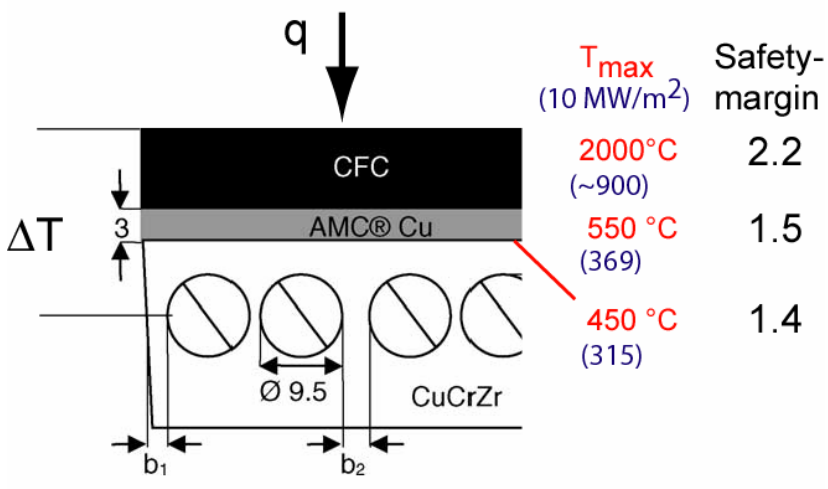
Motivation (I)

Actively cooled target



W7-X target tile (cross section)

Heat resistance:

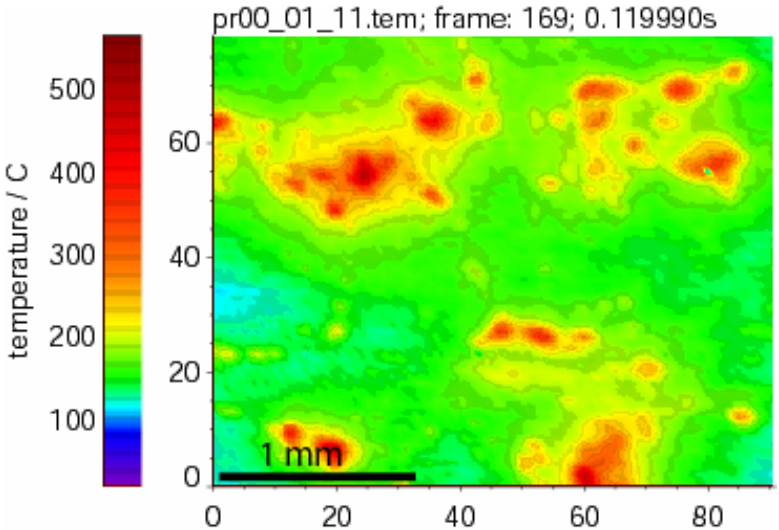
$$\alpha^{-1} = \frac{\Delta T}{q} \approx 100 \frac{K}{MW/m^2}$$

- Stationary temperature profiles on short time scales ($\tau_{eq} << \Delta t_{Discharge}$)
- Typical heat fluxes q = 10-20 MW/m².
- Safety margin about 40% (CuCrZr)
- The sensitive component is inside the target …
- But the surface temperature is measured.
- Correlation to the temperature inside the bulk by solving the heat conduction equation.
- The machine protection is as good as
  - the temperature measurement and
  - the thermal model of the target.

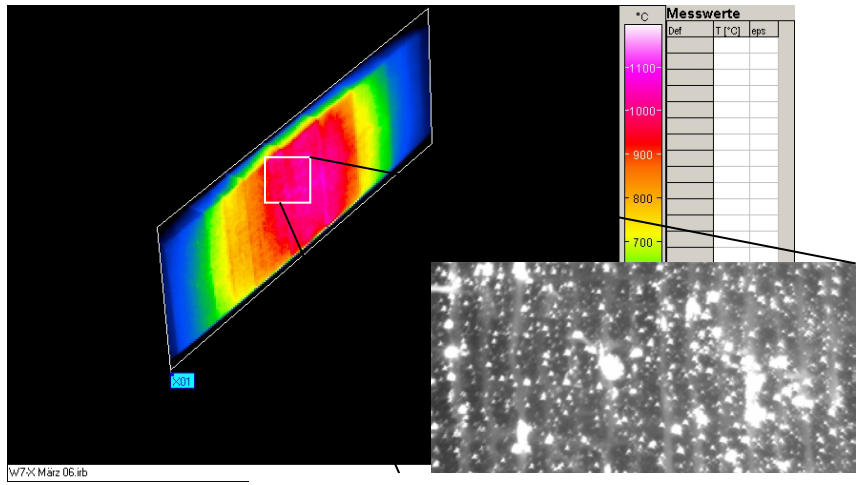
Motivation (II) – Real life

Surface temperature distribution on CFC NB 31

Pulsed experiments (10J, 1 ms)
Sub-millimeter temperature pattern
30 µm spatial resolution, MWIR.



Gladis - high heat flux tests
(LWIR, visible)



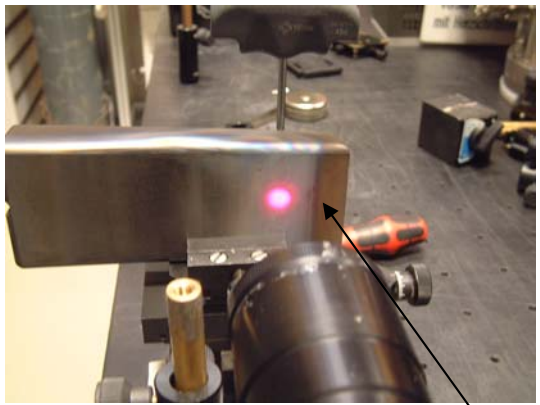
Remote distance microscope
CCD – image, Δ x ≈ 100µm

- What is the temporal behavior of the surface temperature under heat load?
- How effects the microscale (few 10 µm) temperature distribution the macroscale (mm) measurements?

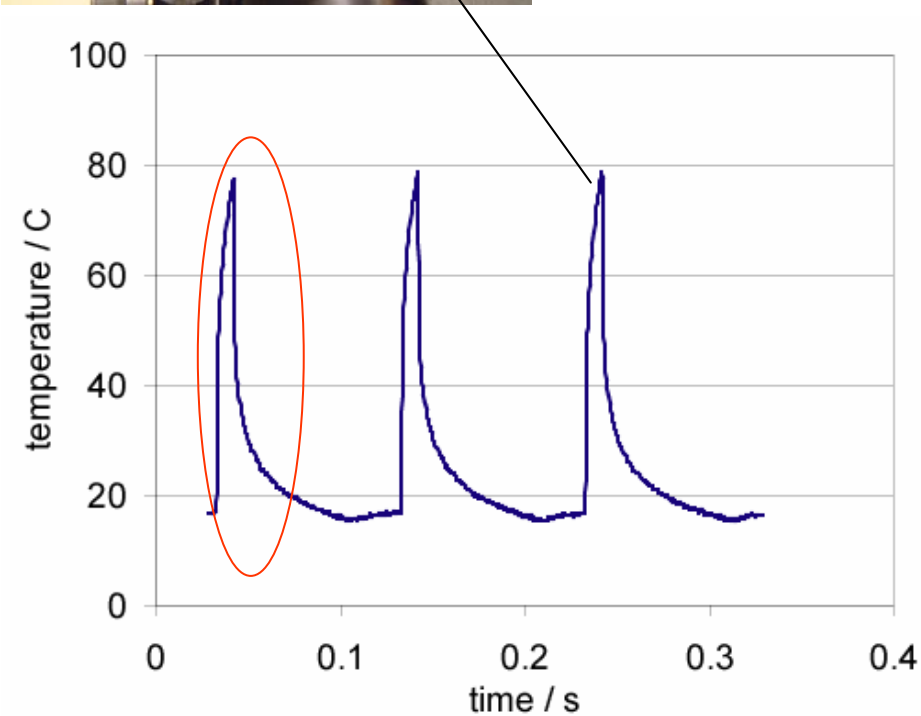
Outline

- Surface temperature distribution and heat flux
  - Fine grain graphite (FGG) - the ‚simple‘ case
  - Carbon fiber composite (CFC) – intrinsic structured
  - layer effects (due to plasma interaction)
- Conclusions

Surface effects are detected by response on heat loads



AUG S8, A1



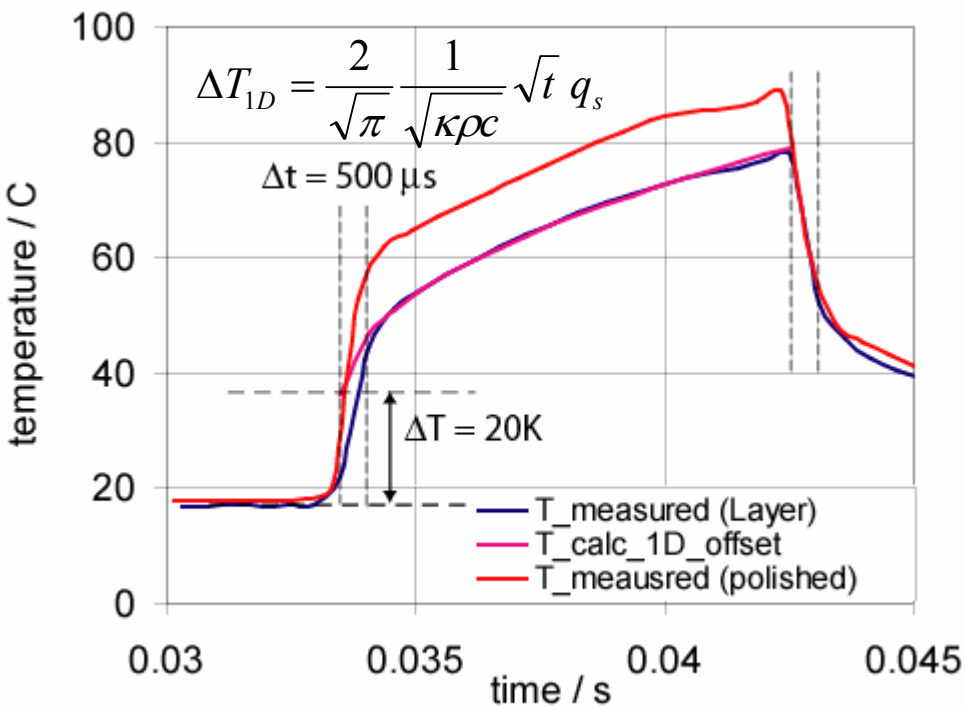
- Pulsed heat load:
  - ELMs, disruptions
  - laser pulse (welding laser)
- Probes
  - AUG target tile Upper divertor (FGG)
  - NB 31 – W7-X

To do:

- Compare measured and expected (analytical solution) T-evolution.
- Calculate the heat flux (2D, THEODOR).

Experimental details:
Herrmann, A., et al., *Investigation of infrared emission from carbon microstructure on a 30 micron spatial scale.* Physica Scripta, 2004. **T 111**

Surface temperature evolution – EK 98



$$q_s = 4.2 MW/m^2$$

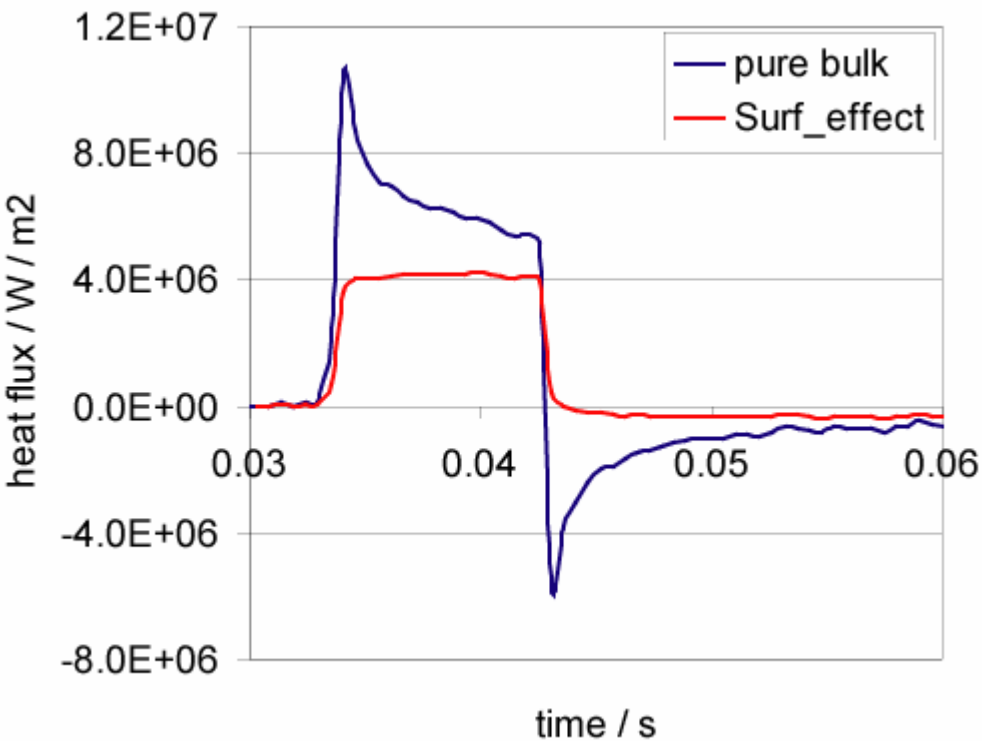
$$\sqrt{\kappa\rho c} = 10.5\ s^{0.5} kW/(m^2\ K)$$

$$\alpha^{-1} = \frac{\Delta T}{q} \approx 4 \frac{K}{MW/m^2}$$

- Instantaneous temperature jump ($\Delta T \sim q_s$).
- The shifted analytic solution fits well to the measured T evolution.
- Qualitatively the same behavior with and without plasma exposure.
- Sophisticated polishing can reduce the surface effect (Hildebrandt PSI 2006).
- The contribution of the initial T-jump is more and more negligible as the surface temperature increases.

$$\Delta T_{FGG} \approx 4 - 8 \frac{K}{MW/m^2} q_s$$

Thermal model for heat flux calculation



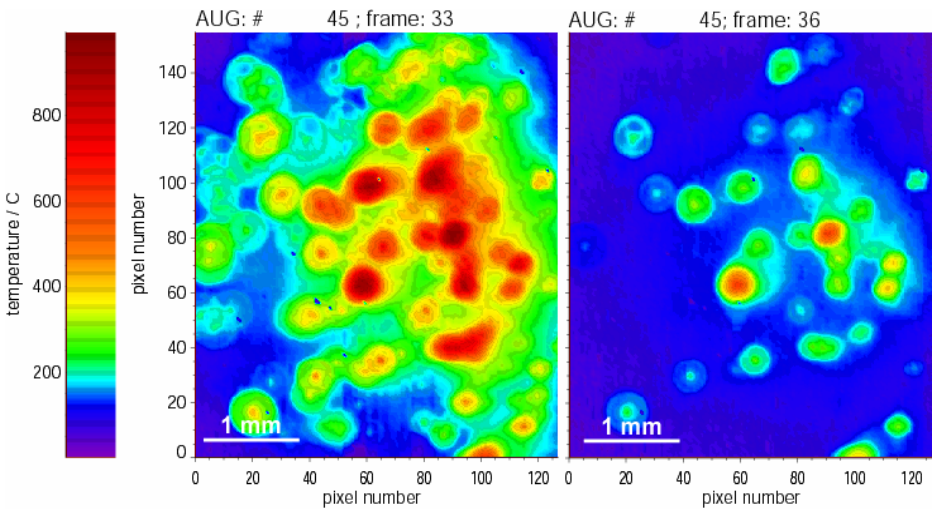
- The calculated heat flux depends on the thermal model.
- Pure bulk thermal data:
  - Overestimation of the heat flux on short time scales.
  - Compensated by negative heat flux at the end.
- Calculated energy is o.k.

More details:

Herrmann, A., *Limitations for Divertor Heat Flux Calculations of Fast Events in Tokamaks.* EPS 2001
Andrew, P., et al., *Thermal effects of surface layers on divertor target plates.* JNM, 2003. **313**.

CFC structure effects

Carbon fibre composite

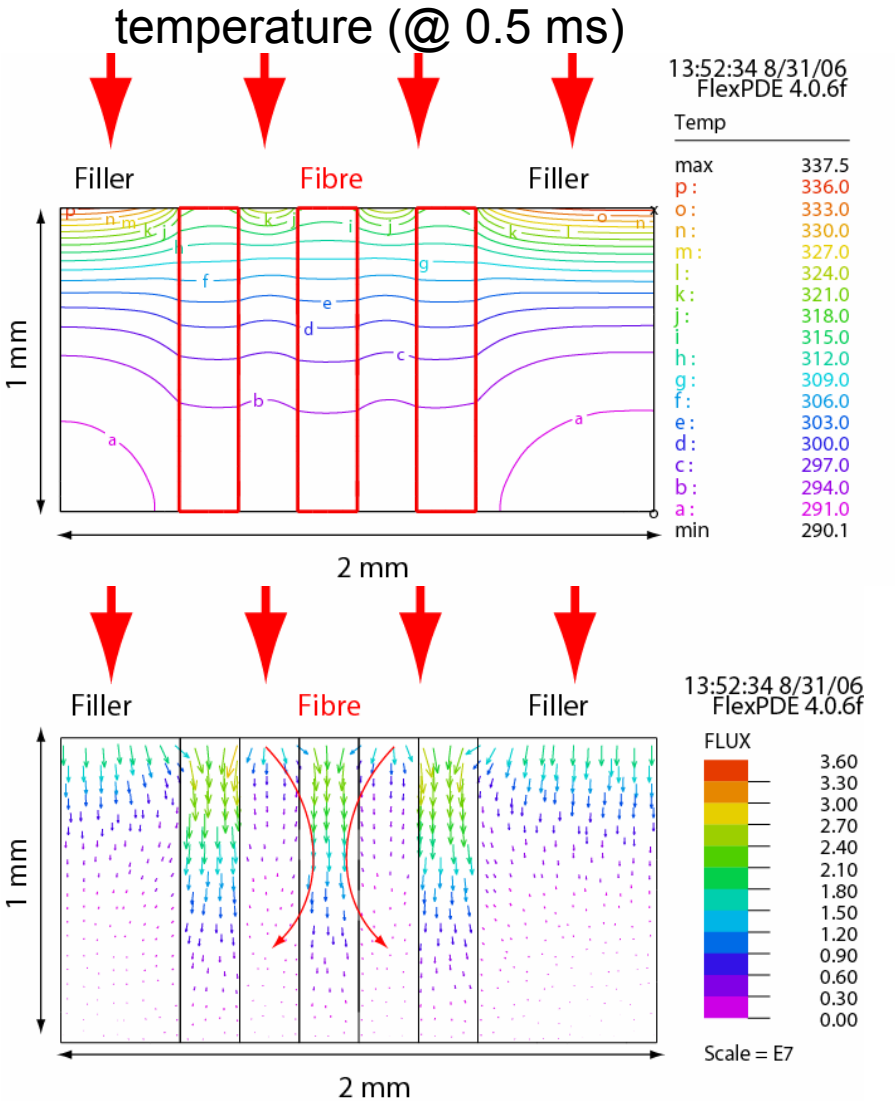


During After - heat pulse

- The thermal behavior of CFC is expected to be more complicated.
- Two or more thermal components (depending on CFC structure).
- Typical dimensions are in the sub millimeter range (fiber bundle size).
- Hot spots are observed.
- The hot spot pattern is fixed (over a number (~100) of load cycles; H. Greuner et. al, SOFT 2006).

- What is the expected (intrinsic) surface temperature variation?
- What is the effect of the small scale hot spots on large scale temperature measurements?

Intrinsic temperature modulation on CFC



- Fiber embedded in carbon (FGG) - filler
- Volume fraction 50% (NB31 30% for pitch fibers).
- Heat capacity of the fiber equal to filler.
- Heat pulse 1 ms 20 MW/m^2.
- Heat conductivity of the fiber adjusted to get the 'averaged' CFC data.

$$\kappa_{fiber} \approx 4.5\,\kappa_{filler} \approx 500\,\frac{W}{m\,K}$$

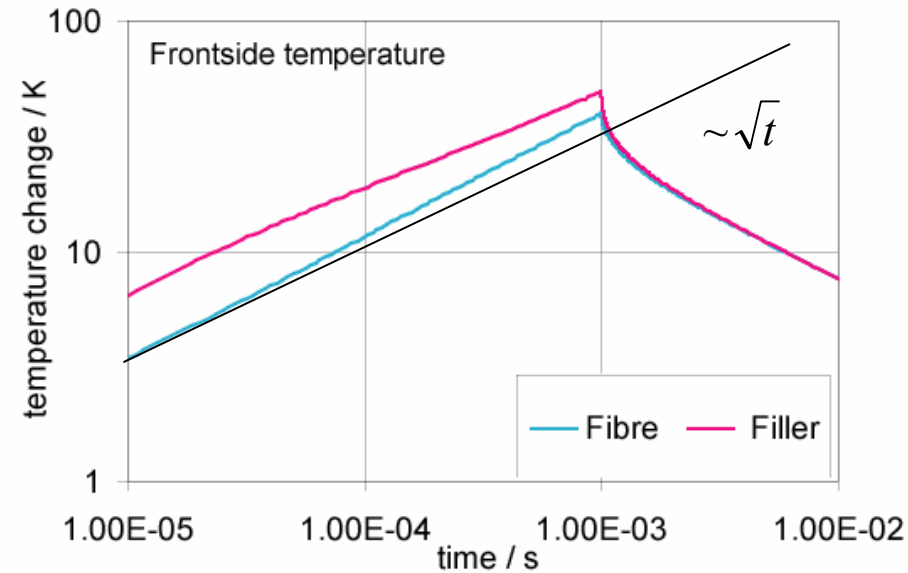
- The heat is transported by the fiber.
- CFC heat diffusivity:

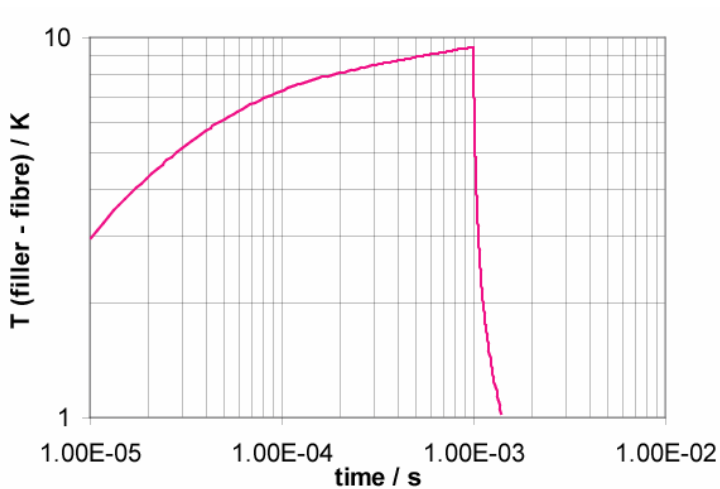
$$a_{CFC} \approx \frac{\kappa_{Fibre}}{\rho c_{Fibre}} f_V$$

$$with\ \ f_V - Volume\ \ fraction\ \ of\ \ Fibres$$

For more sophisticated models see PEGASUS, PHEMOBRID, S. Pestchanyi, B. Bazylev)

Surface temperature difference





- Filler and fiber follows √t dependence.
- The surface temperature difference is given by the thermal parameters:

$$\sim \frac{\sqrt{\kappa_{Fibre}\rho c_{Fibre}}}{\sqrt{\kappa_{Filler}\rho c_{Filler}}} \approx 3$$

- 'Late' during the heat pulse: the temperature difference becomes smaller. Limit when the lateral heat flux becomes comparable to the heat flux to the surface:

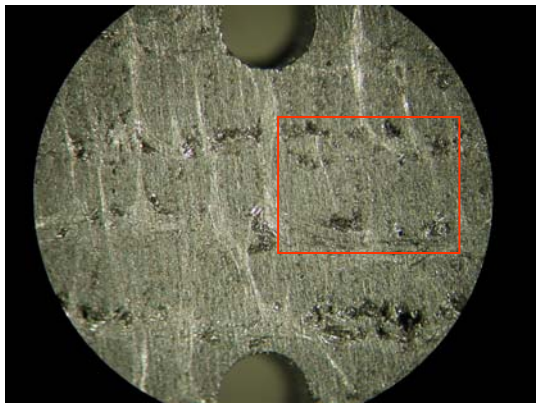
$$\kappa_l \frac{\Delta T_L}{\Delta y} \leq \kappa \frac{\partial T}{\partial x} = -q_s$$

$$\Delta T_l \approx 100\,\mu m / 110\,W/m\,K\,/ \approx 1 \frac{K}{MW/m^2} = 20\,K$$

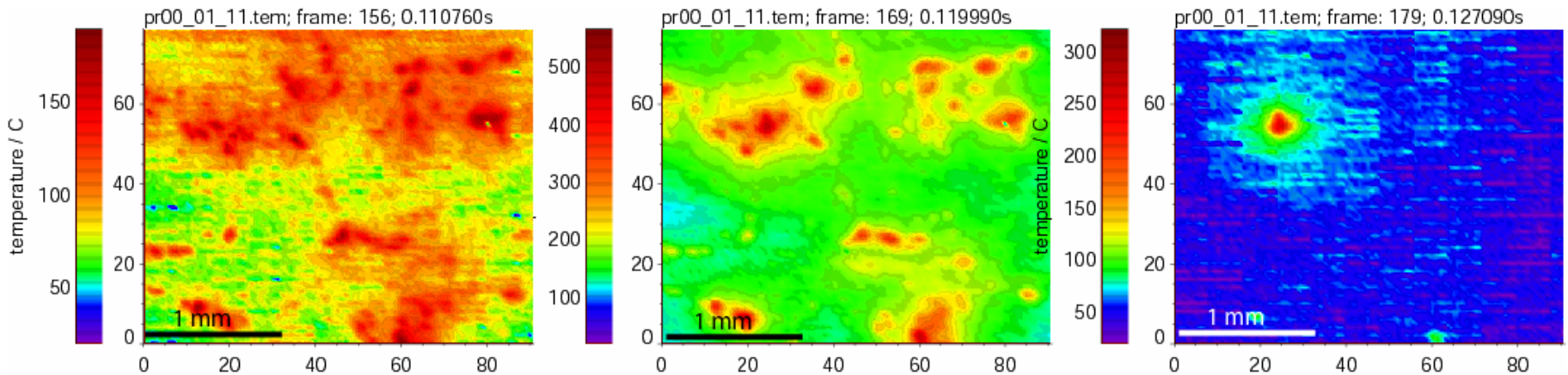
- Same temporal decay after the end of the heat pulse.

CFC in reality (no plasma effect)

CFC (NB31)

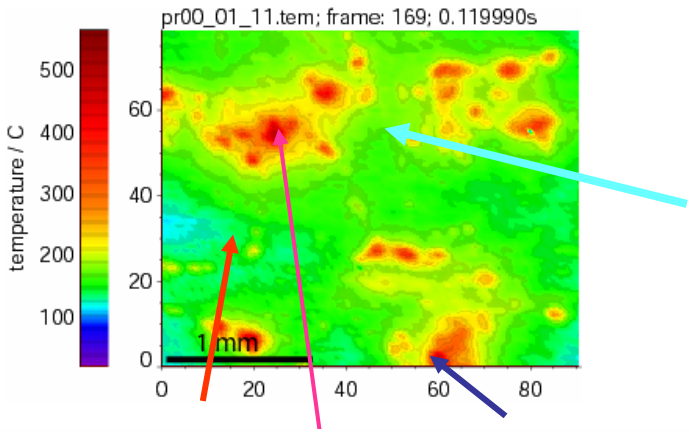


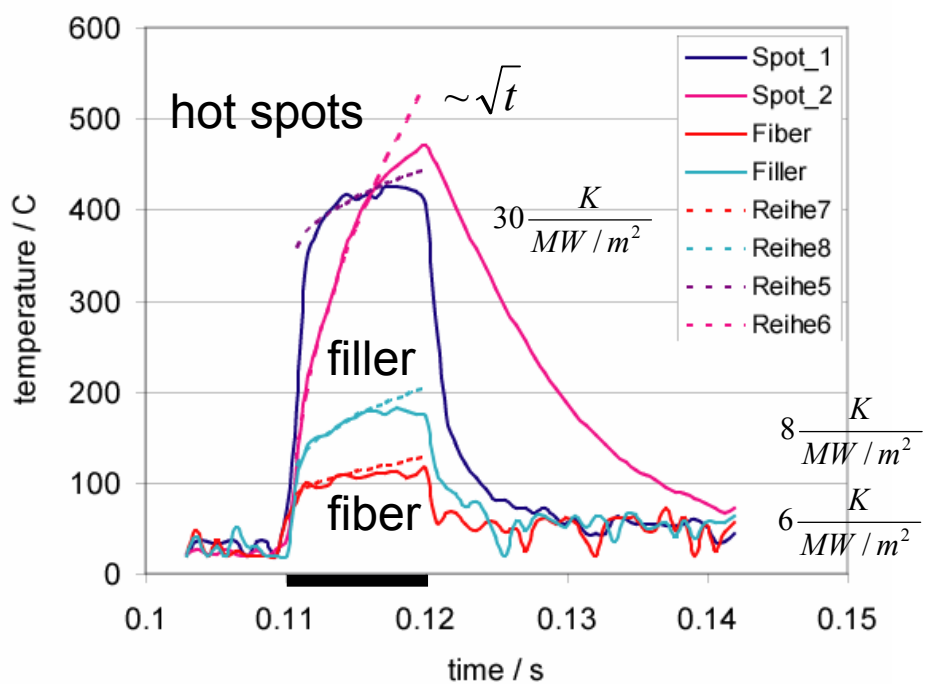
- Laser flash experiments
- 10 ms – 30 J (10 MW/m^2)
- 710µs time resolution



start end 7 ms after

Temperature evolution at different CFC parts

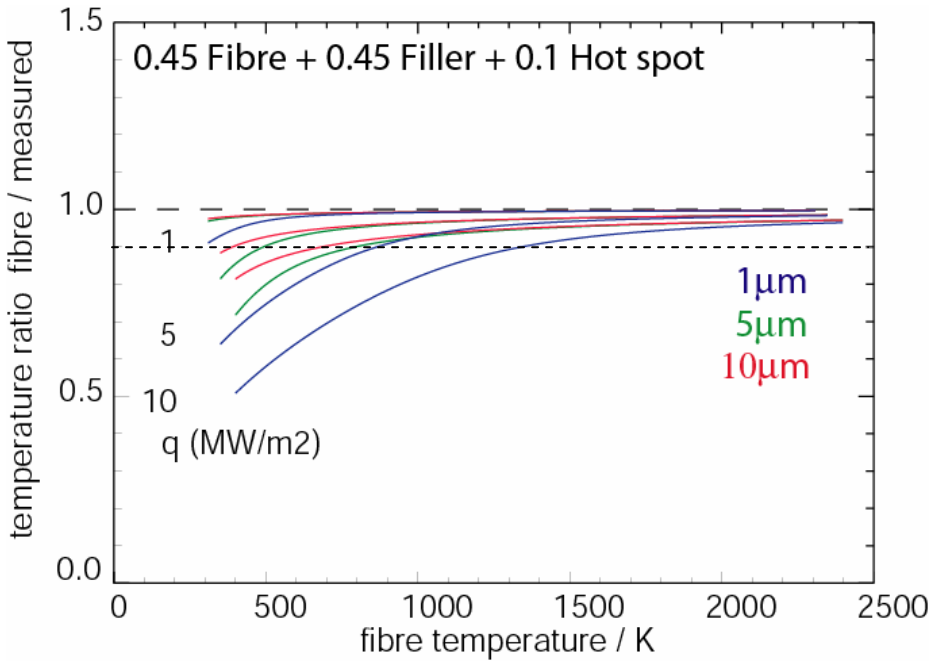




- CFC temperature pattern is more complex than expected from two components.
- Filler and fiber shows the T-jump at the start of the heating.
- Additional components with bad heat contact are found.
- Different types of hot spots are found.
  - thermally equilibrated. Dominated by heat transmission to the bulk.
  - Not yet in equilibration after 10 ms. Slow temperature decay.
  - The filling factor is 2-10%
- Heat flux calculation for the filler and fiber results in 10MW/m^2.
- The hot spot temperature is limited by heat conduction not by radiation!

Structure effect on measured temperature

Compare the real fiber temperature with the measured (mixed) temperature

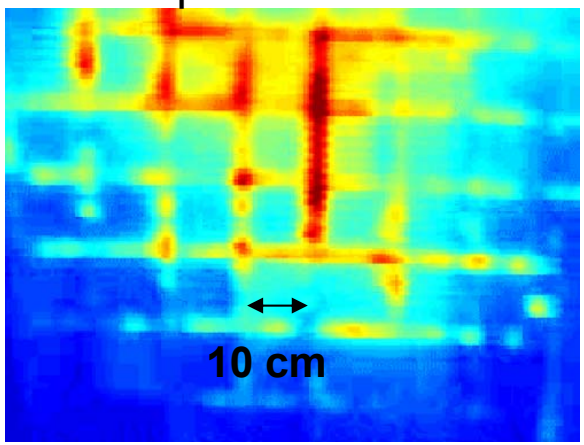


- CFC consists of minimum 3 components.
- Fiber, filler, hot spots
- The hot spot fraction is 10 %
- Volume fraction 50 %
- The filler and hot spot contribution is heat flux dependent:
  - Fiber : $\Delta T / q_s = 6\ K / MWm^{-2}$
  - Filler : $\Delta T / q_s = 8\ K / MWm^{-2}$
  - Hot spot: $\Delta T / q_s = 50\ K / MWm^{-2}$

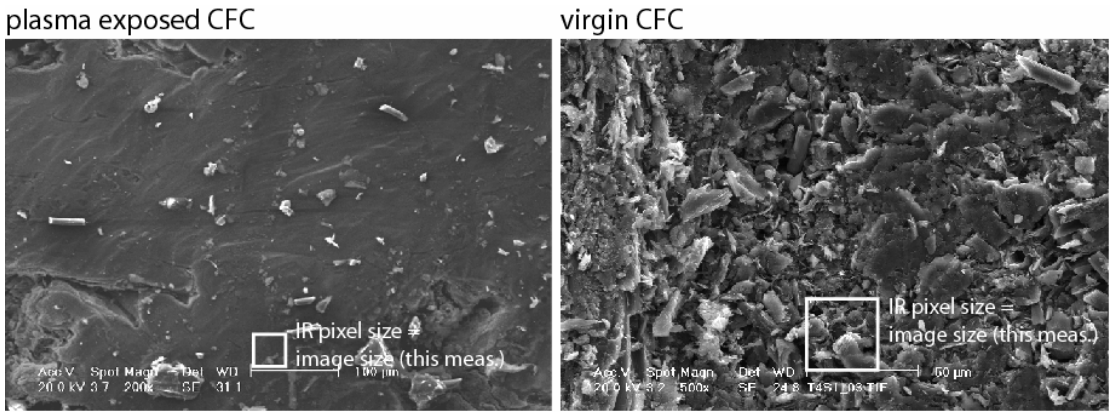
- Measurement error increases with:
  - Heat flux.
  - Decreasing wavelength.
- CFC structure is stable in time and can be characterized.
- T correction possible.
- The temperature is overestimated.

Plasma effects

ToreSupra limiter

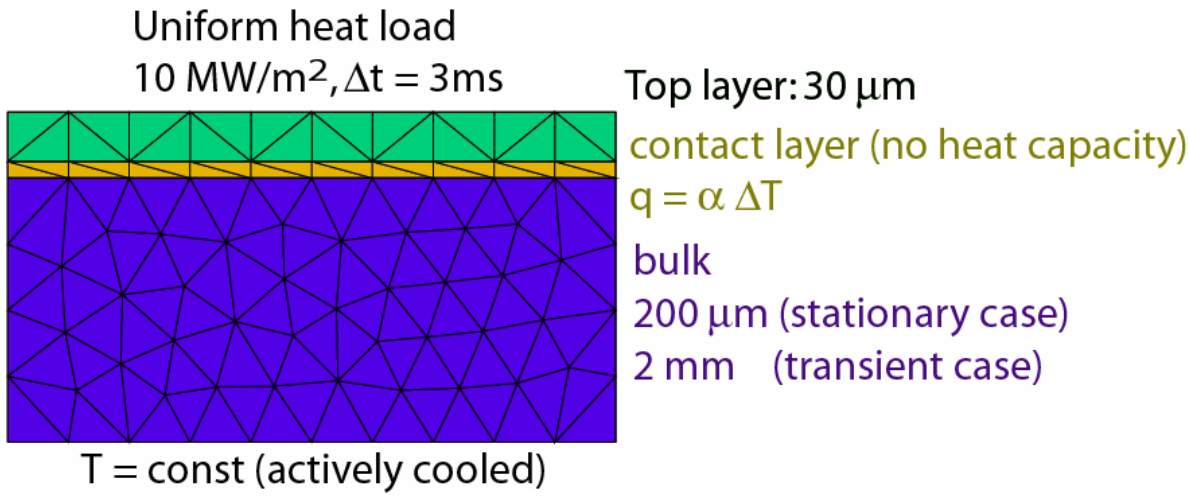


ASDEX Upgrade divertor tile (outer SP) - SEM



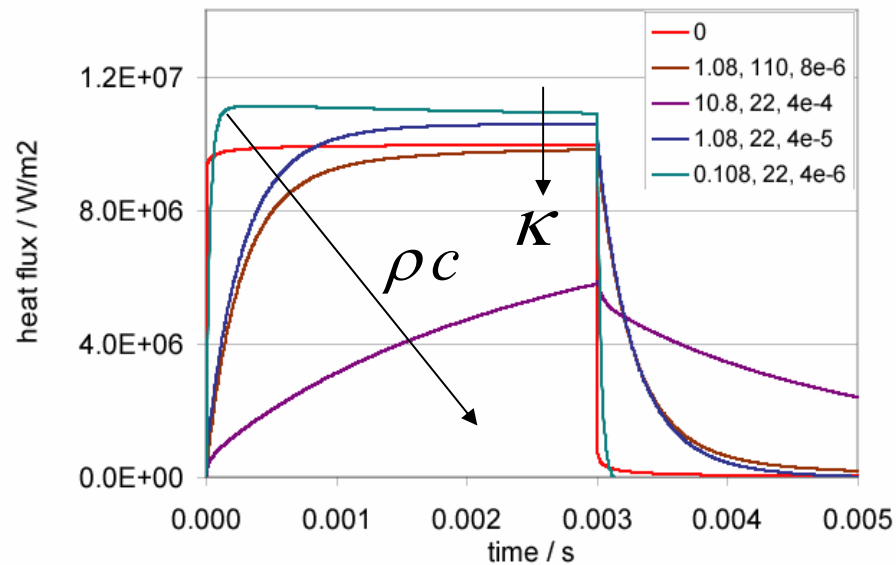
- Plasma effects?
  - Modification of the bulk surface by particle implantation/redeposition.
  - Layer deposition.
- Can changes of the thermal properties of the system target cooling structure be detected?
- Can we learn something on surface effects?

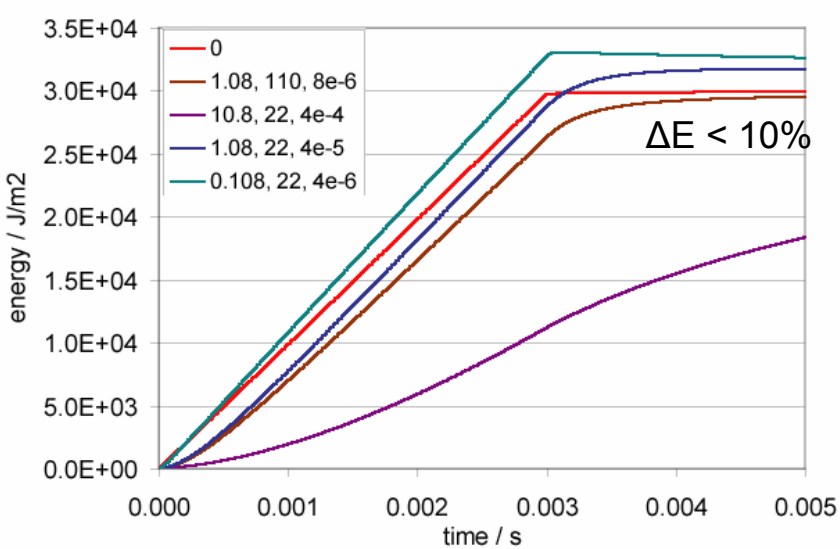
Plasma effects – simple model



- Thermal model for the target (bulk with surface effects)
- Add a layer on it.
- Calculate the surface temperature evolution for different thermal parameter sets (κ = 110 – 22 W/m/K; ρc = 0.1, 1, 10 MJ/m^3/K, α^{-1} =).
- Calculate the heat flux with the standard model (thermal model for the target).

Layer in good contact



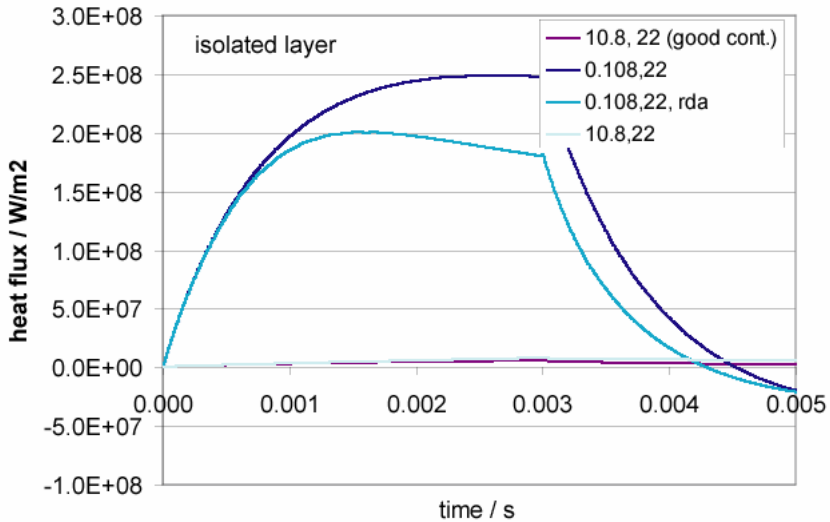


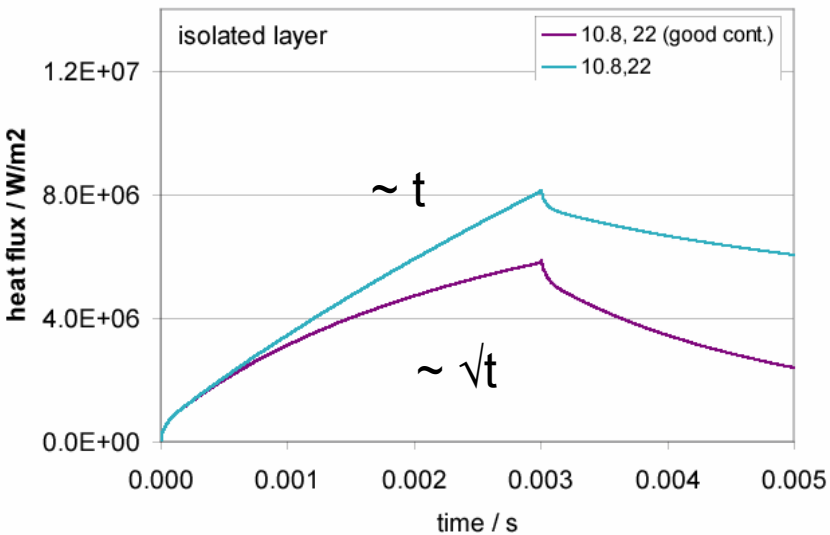
- Heat capacity varied by a factor of 100.
- Heat conductivity by a factor of 5.
- Main effect is in the rise time.
- The layer results in a temperature increase in addition to the T-jump.
- The heat flux is overestimated by about 1 MW/m^2.

$$\Delta q = \alpha \, \Delta T_l = \alpha \frac{d_l}{\kappa_l} q_s$$

- The more probable case of a layer with reduced heat conduction and lower heat capacity has the lowest impact on the calculation.

Layer with bad heat contact (Flakes ?)





- Bad heat contact results in an over estimation of the heat load.
- Make use from power balance estimations.
- Use power steps to identify thin isolated layers.

- See the talk of X. Courtois

Conclusions

- All effects overestimate the surface temperature!!!
- Detection of surface modifications needs additional information:
  - Temporal behavior (load changes)
  - Power balance (input – radiation)
- Carbon materials show an intrinsic temperature increase of about

$$\Delta T_{FGG} \approx 4-8\,\frac{K}{MW/m^2}$$

- Temperature at the CFC surface is more structured:
  - Filler and fiber with moderate temperature difference.
  - Hot spots with large temperature excursions (but small size)
- The effect on the measured temperature is about 10% and can be corrected.
- Layers as found in the high heat load region (AUG, JET) have a small impact on the temperature increase.
- Isolated layers may result in significant errors (heat flux).