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

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Motivation (I)

- Stationary temperature profiles on short time scales ($\tau_{eq} << \Delta t_{\text{Discharge}}$)
- Typical heat fluxes $q = 10-20$ MW/m$^2$.
- 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.

Actively cooled target

\[ q \downarrow \]

\[ \Delta T \]

\[ T_{\text{max}} \quad (10 \text{ MW/m}^2) \]

- CFC
- AMC® Cu
- CuCrZr

Heat resistance:

\[ \alpha^{-1} = \frac{\Delta T}{q} \approx 100 \frac{K}{\text{MW/m}^2} \]
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)

• 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

- 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:
Surface temperature evolution – EK 98

- 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.

\[
\Delta T_{1D} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{kpc}} \sqrt{t} \ q_s
\]

\[
\Delta t = 500 \mu s
\]

\[
\Delta T = 20 K
\]

\[
qu = 4.2 MW / m^2
\]

\[
\sqrt{kpc} = 10.5 \ s^{0.5} kW/(m^2 K)
\]

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

\[
\Delta T_{FGG} \approx 4 - 8 \frac{K}{MW / m^2} q_s
\]
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:
CFC structure effects

• 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/m².
- Heat conductivity of the fiber adjusted to get the ‘averaged’ CFC data.

\[ \kappa_{\text{fiber}} \approx 4.5 \kappa_{\text{filler}} \approx 500 \frac{W}{m \, K} \]

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

\[ a_{\text{CFC}} \approx \frac{\kappa_{\text{Fibre}}}{\rho c_{\text{Fibre}}} f_V \]

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 $\sqrt{t}$ dependence.
- The surface temperature difference is given by the thermal parameters:
  \[
  \sim \sqrt{\frac{\kappa_{\text{Fibre}} \rho c_{\text{Fibre}}}{\kappa_{\text{Filler}} \rho c_{\text{Filler}}}} \approx 3
  \]
- ‘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/m²)
- 710μs time resolution

![CFC Image](image)

- 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/m².
- 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

- 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

Uniform heat load
10 MW/m², Δt = 3ms

Top layer: 30 μm
contact layer (no heat capacity)
q = α ΔT

bulk
200 μm (stationary case)
2 mm (transient case)

T = const (actively cooled)

• 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/m³/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/m².

\[ \Delta q = \alpha \Delta T = \alpha \frac{d_l}{\kappa_l} q_s \]

- 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
  \[ \Delta T_{\text{FGG}} \approx 4 - 8 \frac{K}{MW/m^2} \]
- 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).