Temperature measurement and heat load estimation in fusion experiments

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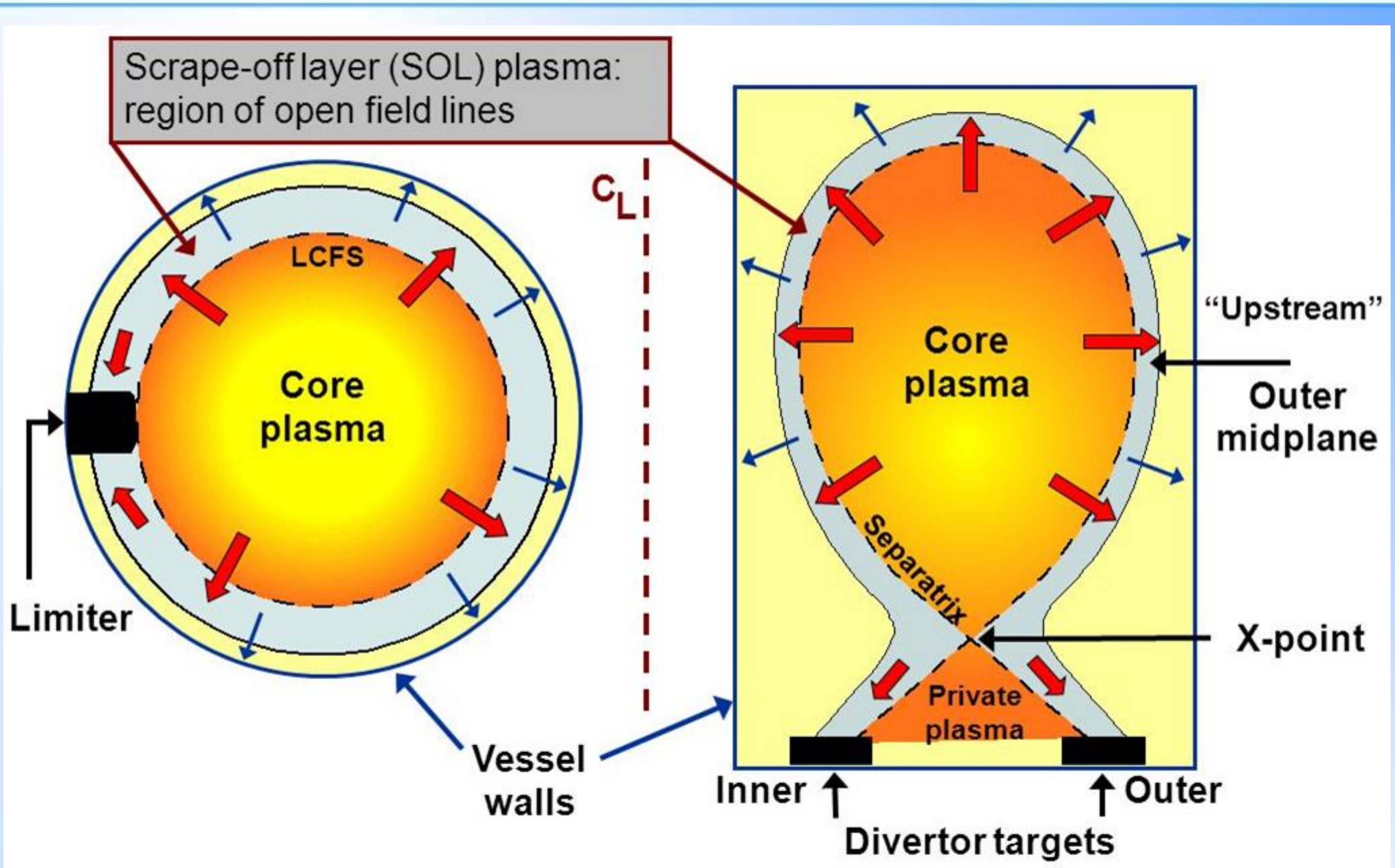
MEPhI summer school 2020

Outline

- Why heat load measurements?
- Thermography @ ASDEX Upgrade
- Thermography basics
- Heat load calculation
- Summary

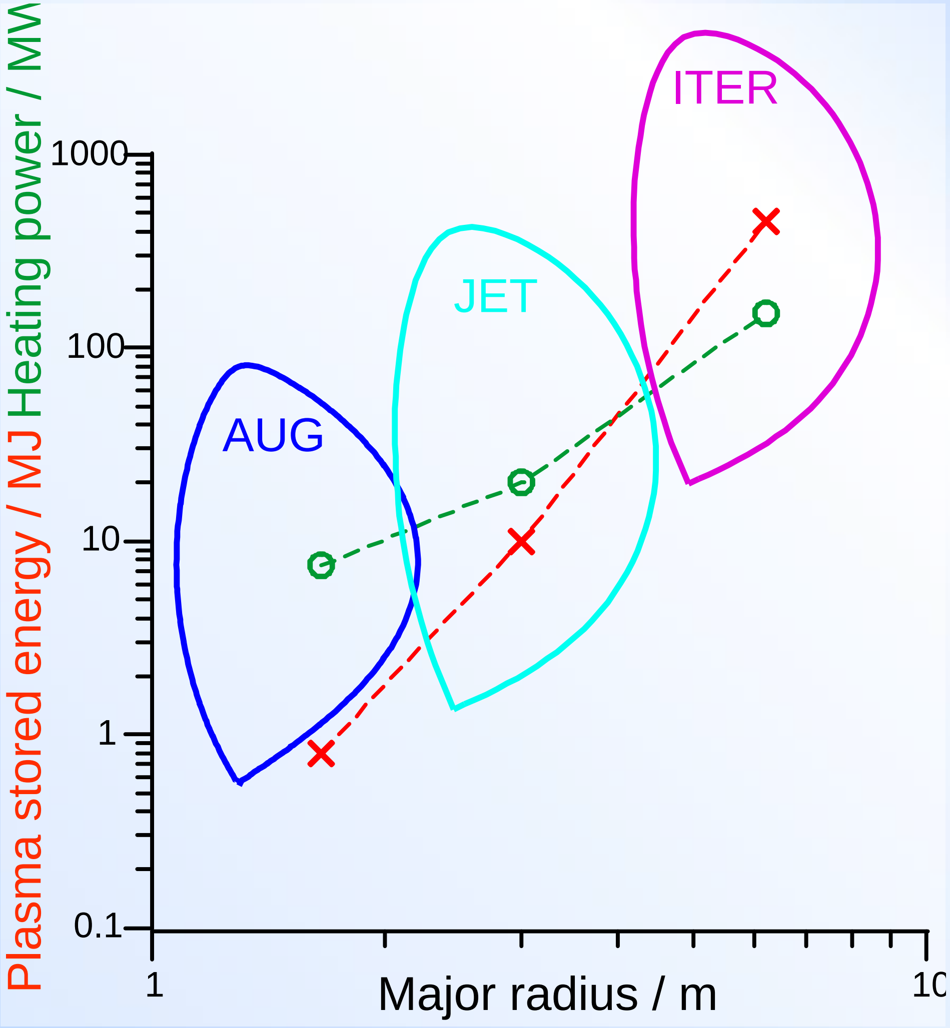
Why is heat load measurement and control such a serious topic?

Limiter vs. Divertor



- Heat load exhaust as general problem in fusion devices
- 1990th change from limiter to divertor configurations.
- Disentangling plasma core (performance) and heat exhaust

Larger devices – higher divertor heat load



Heating power increases with about

$$P_{Heat} \sim R^2$$

Plasma stored energy increases stronger than with R^3

$$W_{mhd} \sim \beta_t \, B_t^2 \, R^3$$

Surface to be loaded with radiation:

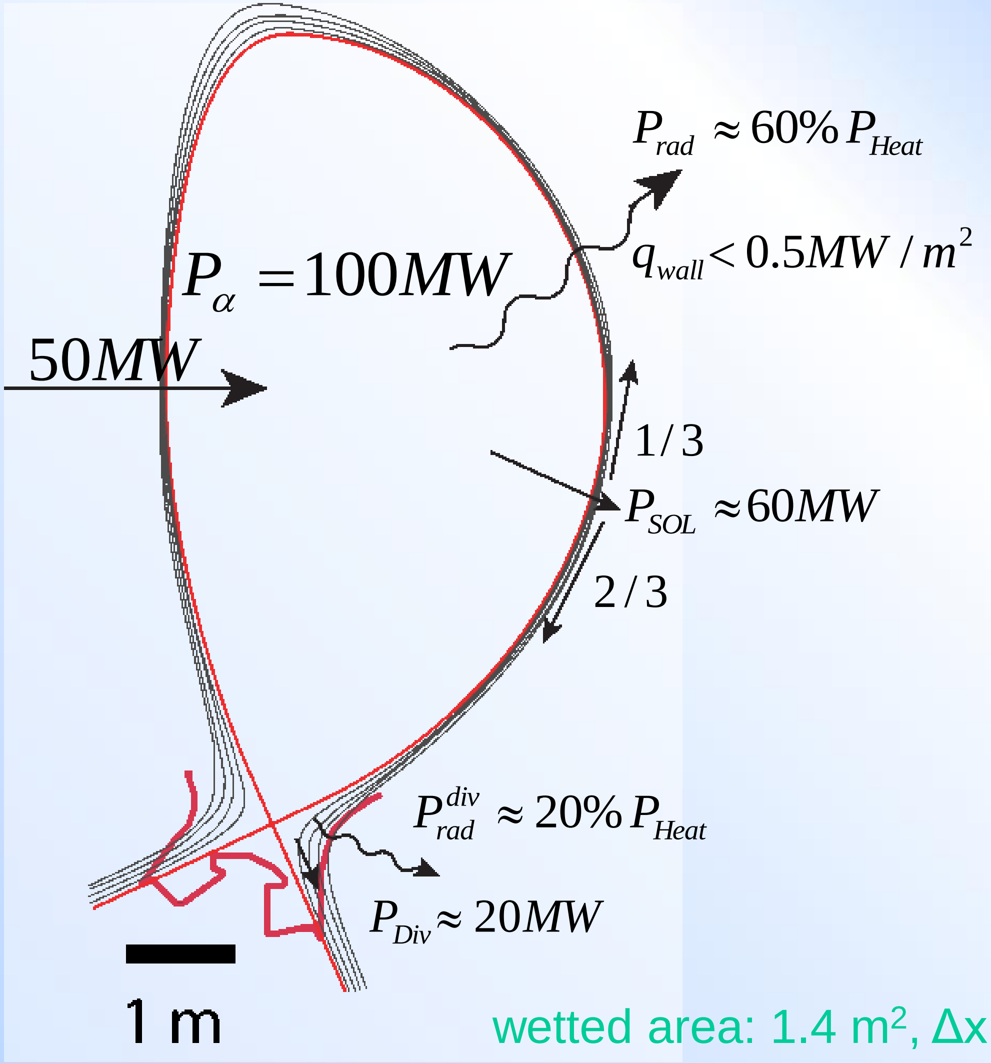
$$A_{Vessel} \sim R^2$$

Wetted area of the divertor:

$$A_{Div} \sim R \times \Delta x^{\boxed{\gamma}} \quad ?$$

Δx - Extrapolation to ITER

ITER – loss channels



$P_{rad} \approx 60\% P_{Heat}$

$q_{wall} < 0.5 MW / m^2$

$P_\alpha = 100 MW$

$50 MW$

$1/3$

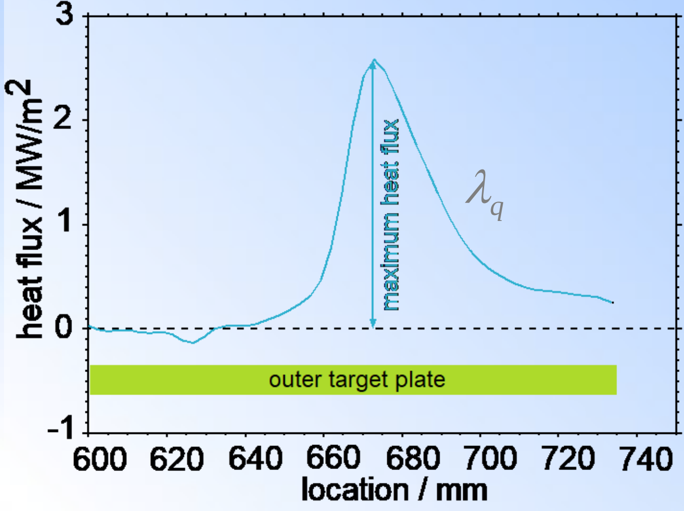
$P_{SOL} \approx 60 MW$

$2/3$

$P_{rad}^{div} \approx 20\% P_{Heat}$

$P_{Div} \approx 20 MW$

Wetted area in present experiments?



Thermography (AUG, JET)

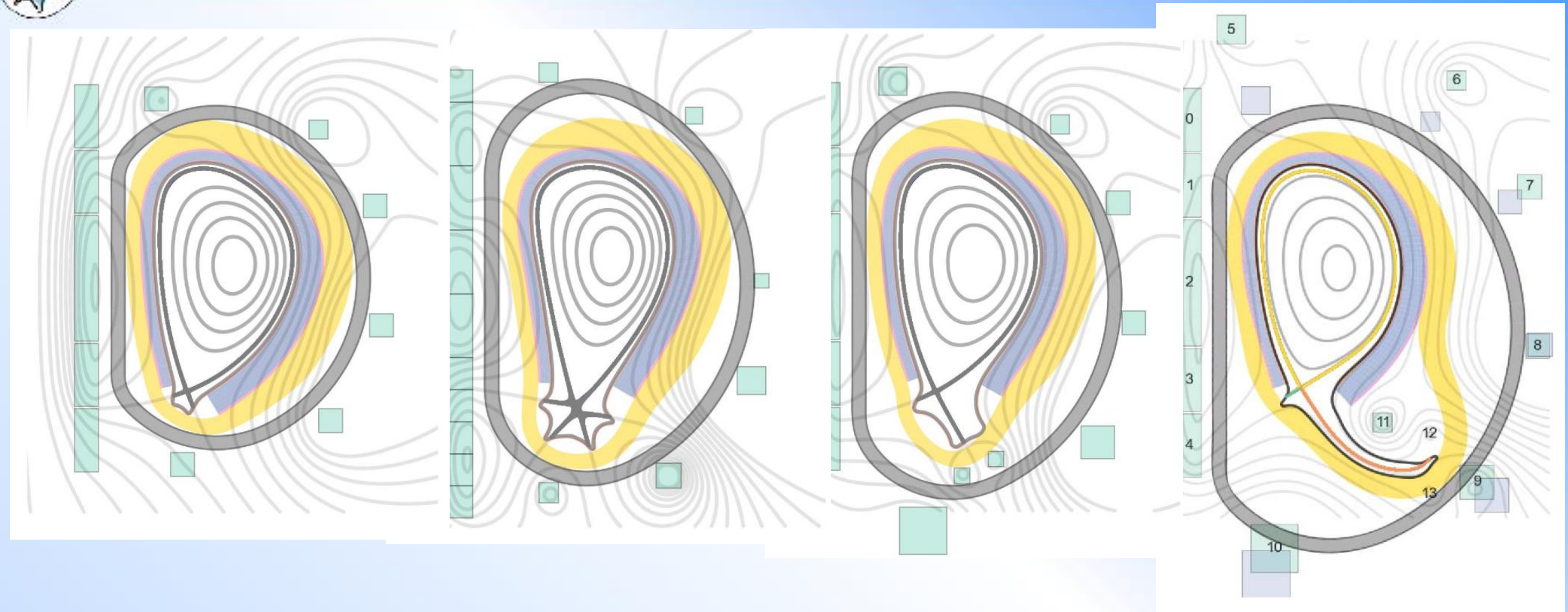
$$\lambda_q \sim P_{Plate}^{-0.1} \, \overline{n}_e^{0.6} \qquad \approx 5\, cm$$

Langmuir probes (JET)

$$\lambda_q \sim P_{Plate}^{-0.5} \, \overline{n}_{e,u}^{0.1} \qquad \approx 3.5\, cm$$

wetted area: 1.4 m², Δx = 3.6 cm

Increase of the wetted area – alternative magnetic configurations



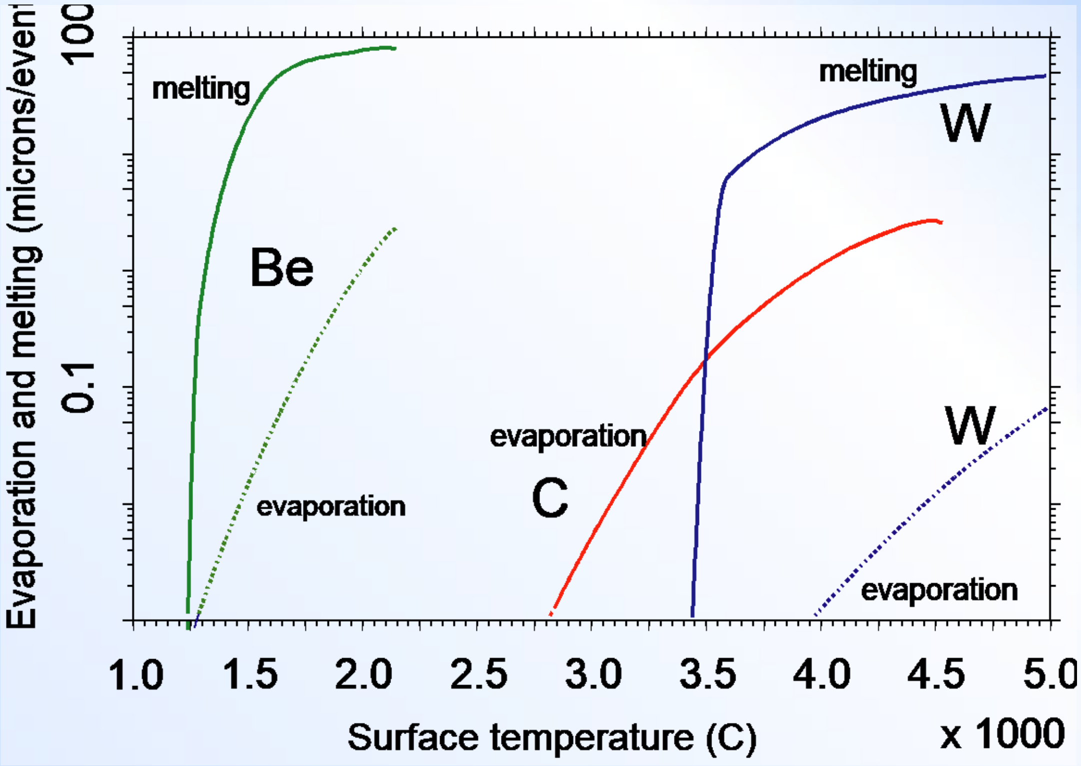
- All configurations are in principle technically feasible (forces, shielding)
- The cost-to-benefit ratio has not been assessed so far!

Zohm 2015, Adapted from H. Reimerdes et al.,
1st IAEA TM on divertor concepts, 2015

- Target heat loads are no concern for presently running fusion experiments.
- But are a serious concern for future larger fusion reactors.
  - Higher heat load (MW/m^2)
  - Material degradation due to Neutrons
  - Smaller temperature operation range for actively cooled targets

Surface temperature limitations

Federici et al., PPCF **45** (2003) 1523

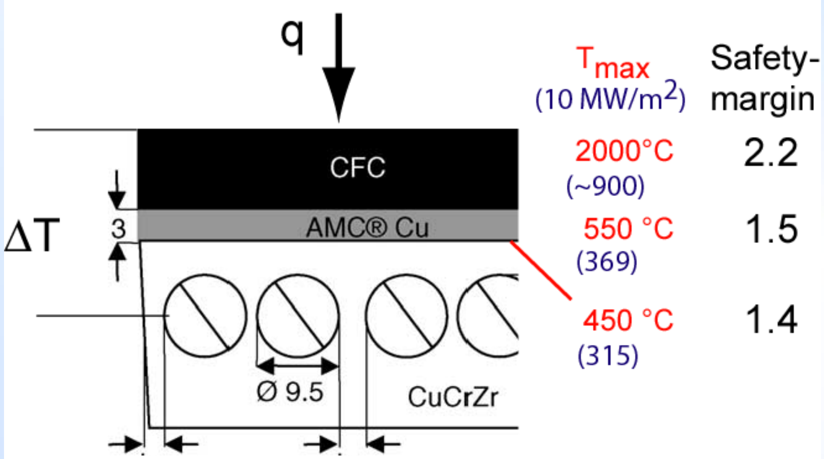


- Sputtering and erosion during 'normal' plasma wall interaction:
  - Impurity concentration
  - Life time
- Catastrophic increase of released material above a critical temperature:
  - Strong life time reduction
  - Damages
- The threshold temperature depends on the material.

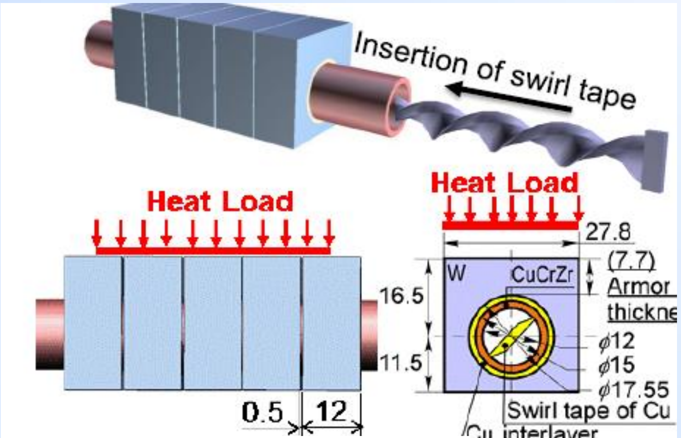
Establish plasma operation resulting in PFC temperatures below the threshold.

Interface limitations

Actively cooled targets



W7-X target tile (cross section)

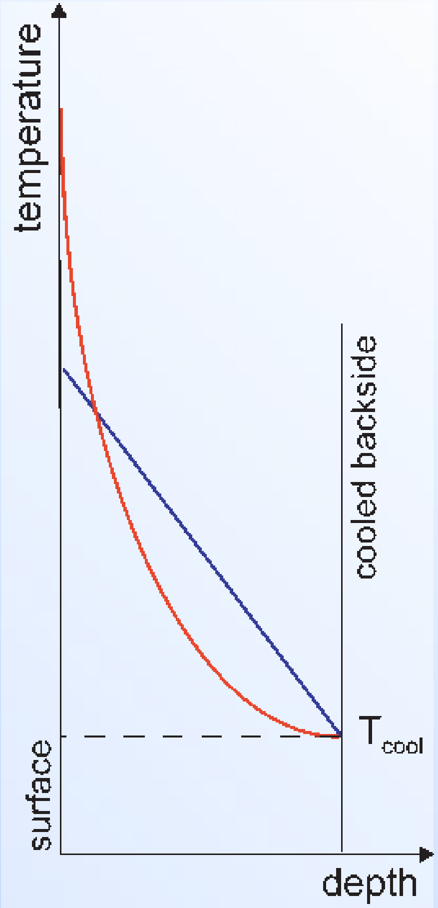


Y. Seki et al., FIP/1-1, IAEA FEC 2014, 13th Oct. 2014

- Stationary case: 10 MW/m^2
- The sensitive component is inside the target …
- Safety issue:
  - The surface temperature is measured.
  - Correlation to the temperature inside the bulk.
  - Thermal model
- Situation might be opposite for pulse like events (ELMs, Disruptions)
  - Surface temperature limits will be exceeded.

Tolerable heat load?

Relation between material and (plasma) heat deposition



steady state:

$$\Delta T_s = (T_s - T_{cool}) = \frac{q_s}{\kappa} d$$

actuator: profile shape

transient (short vs. transition time (a few seconds)):

$$\Delta T_t = (T_t - T_s) = \frac{2}{\sqrt{\pi}} \frac{\boxed{q_t \sqrt{\Delta t}}}{\sqrt{\kappa \rho c}}$$

actuator: profile shape
temporal evolution

- minimum thickness
  - life time
  - transients

$$q_s^{\max} \leq 15 MW / m^2$$

$$P = 2\pi R \int q(x) dx$$

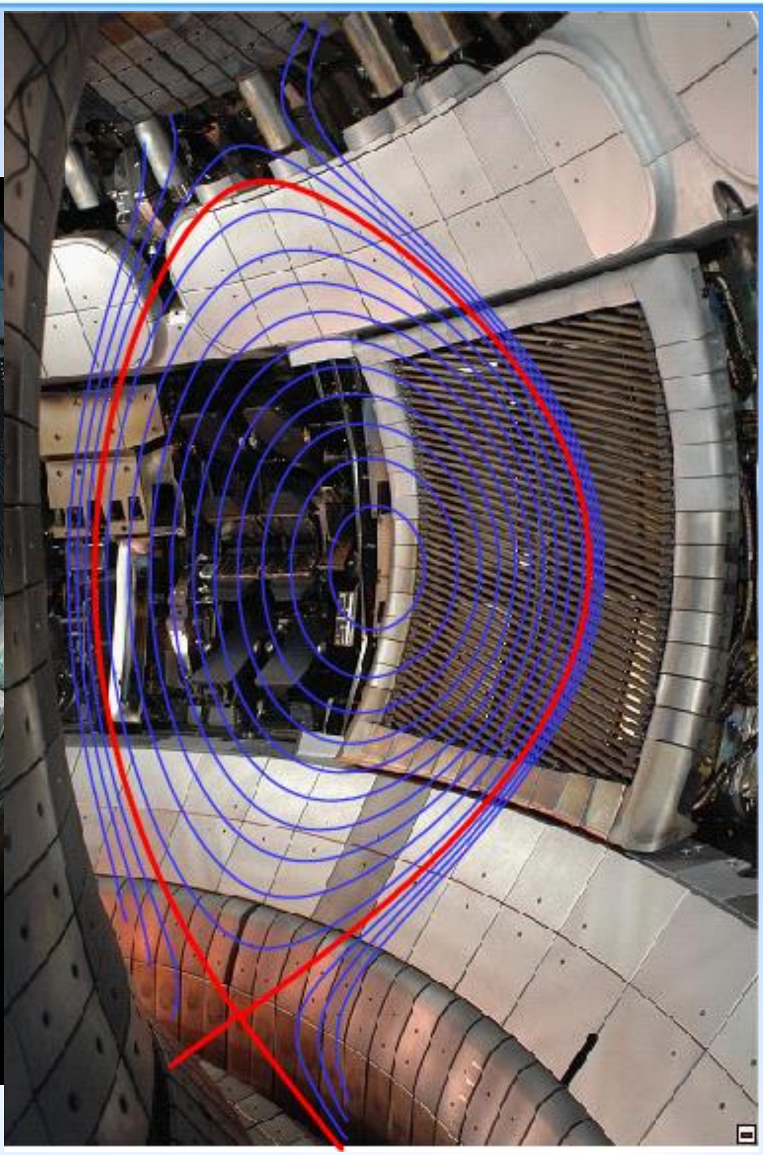
$$Tungsten: \approx 40 \frac{MJ}{m^2 \sqrt{s}}$$

$$Graphite: \approx 20 \frac{MJ}{m^2 \sqrt{s}}$$

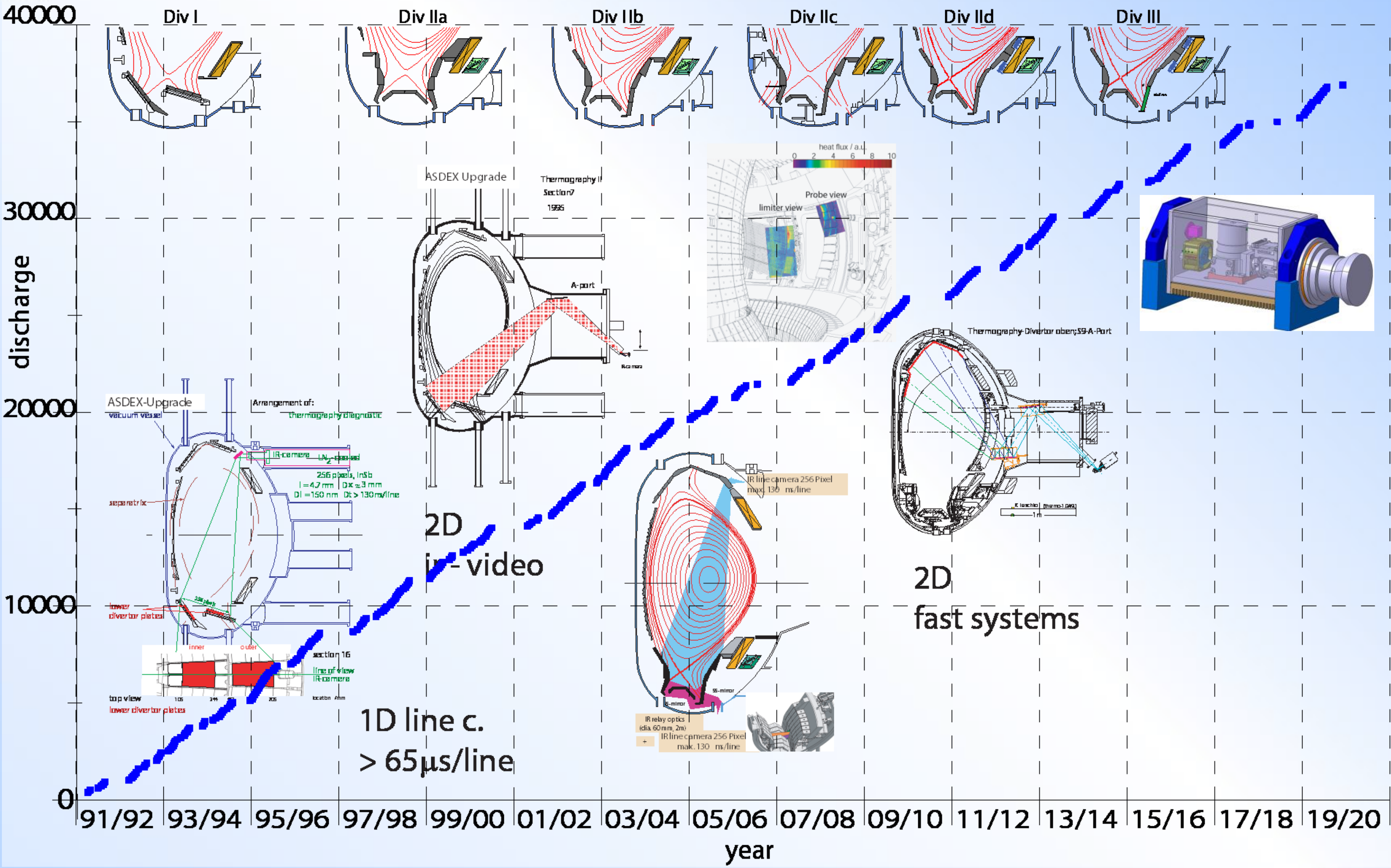
See the talk by Aleksey Arakcheev

Thermography at ASDEX Upgrade

ASDEX Upgrade - vessel view



Thermography @ ASDEX Upgrade



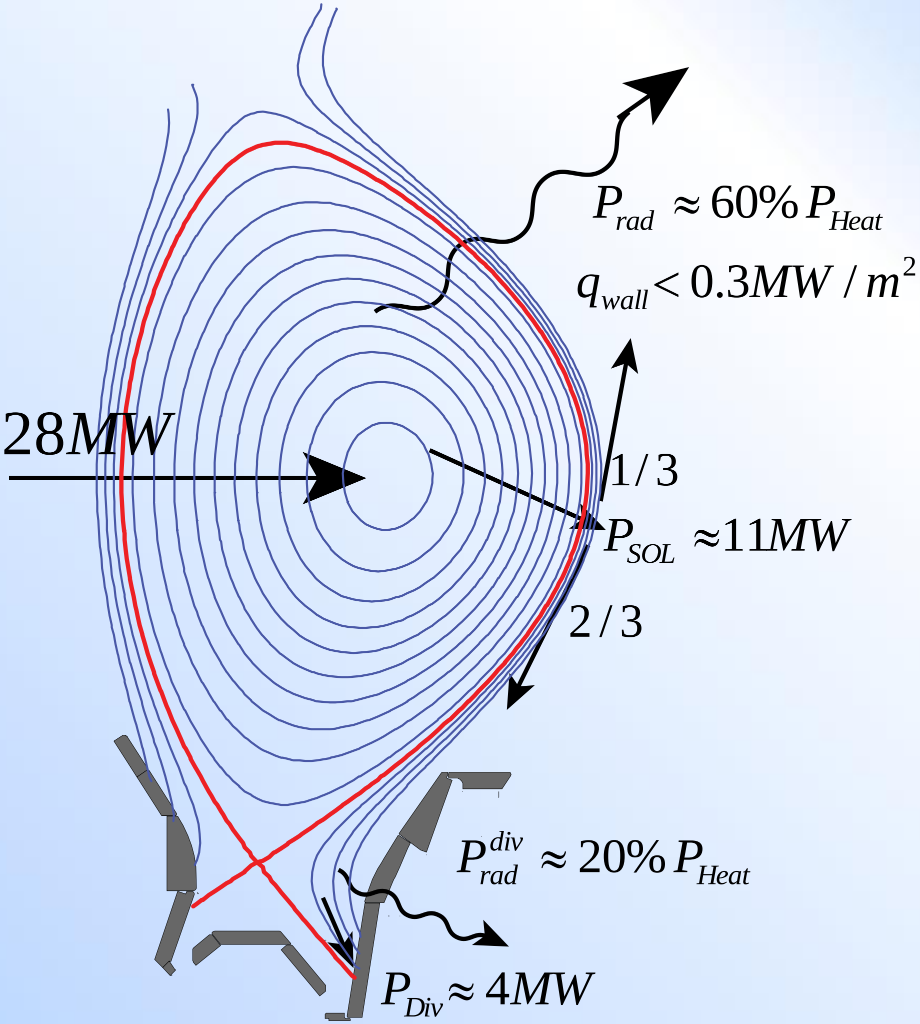
1D line c.
> 65µs/line

2D
ir - video

2D
fast systems

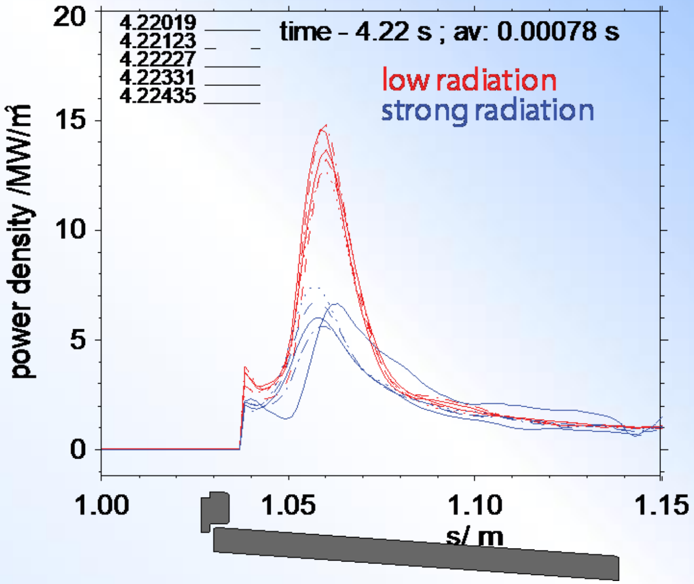
How thermography is used?

ASDEX Upgrade power loss channels



Machine protection

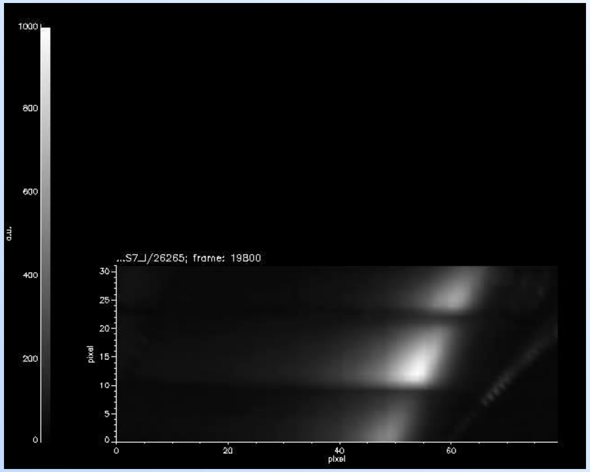
Physics investigation



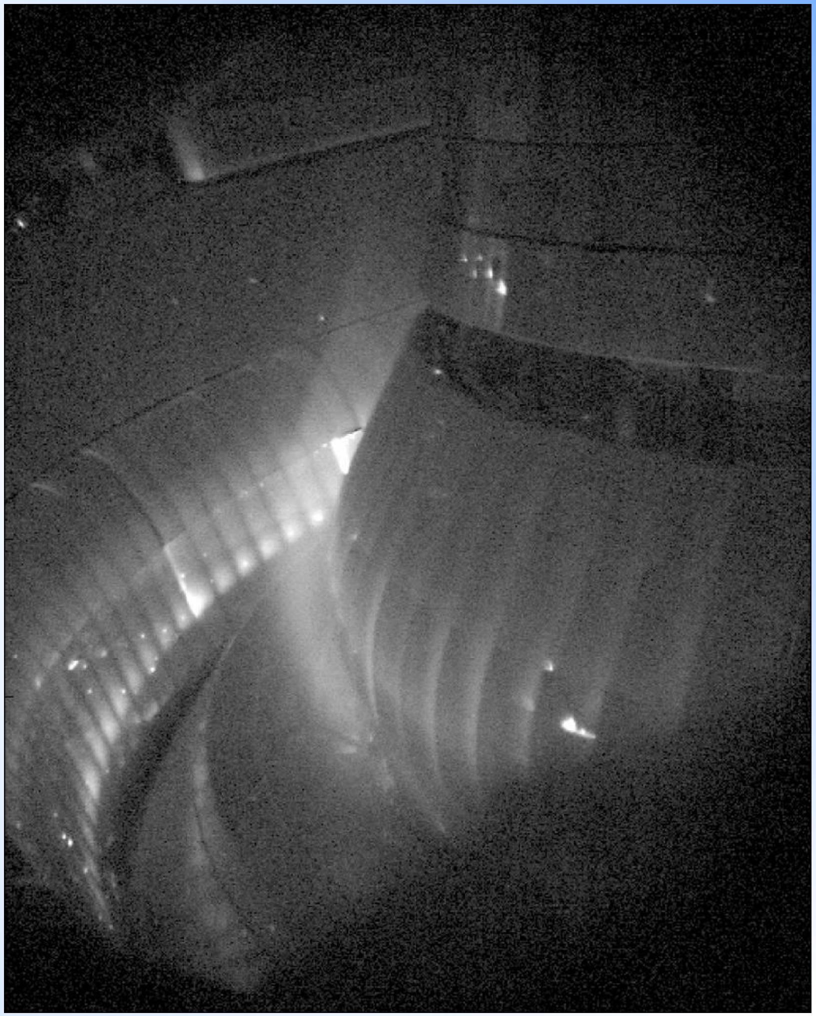
Examples

Arcs

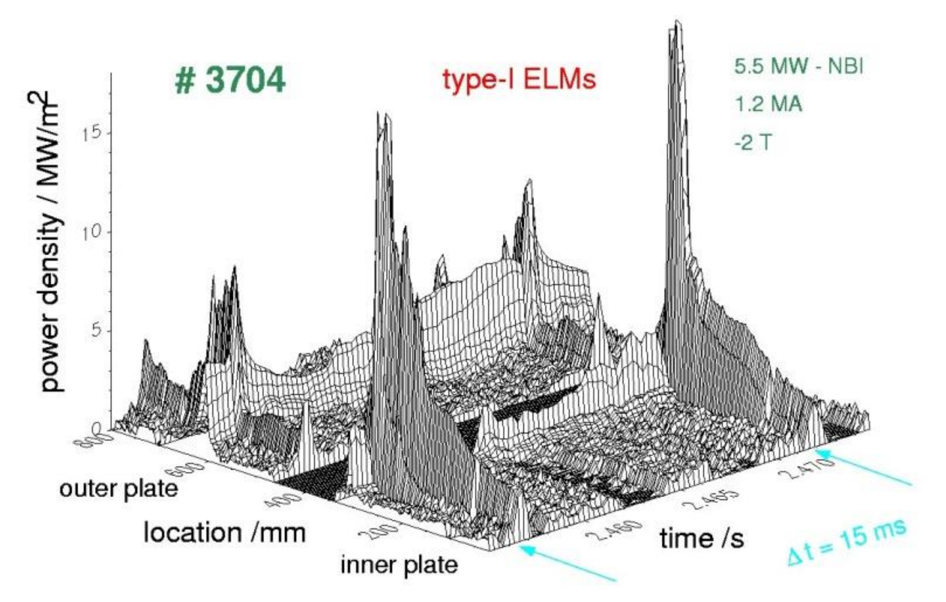
Dust



Bremsstrahlung/Reflections

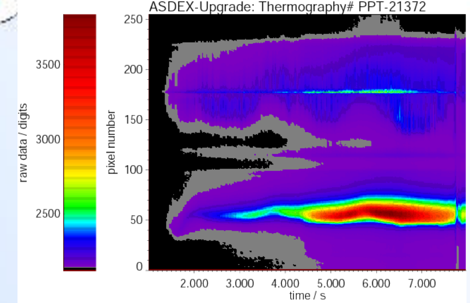


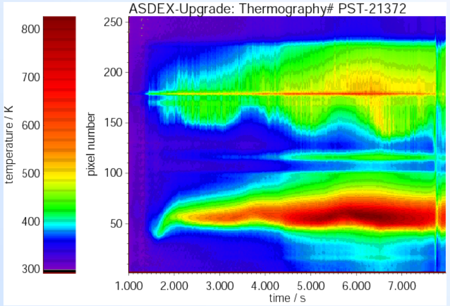
Physics investigation - ELMs

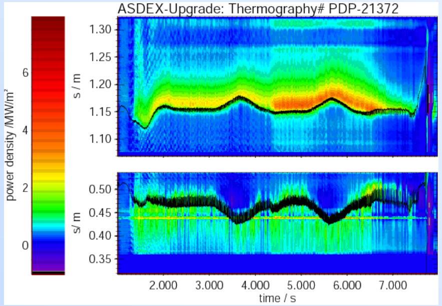


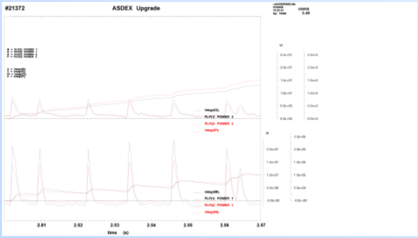
- 1992 – Type-I ELMs measured with a fast IR line camera
  - 256 pixel
  - LN_2 cooled
- Since then – thermography is a standard diagnostic at AUG

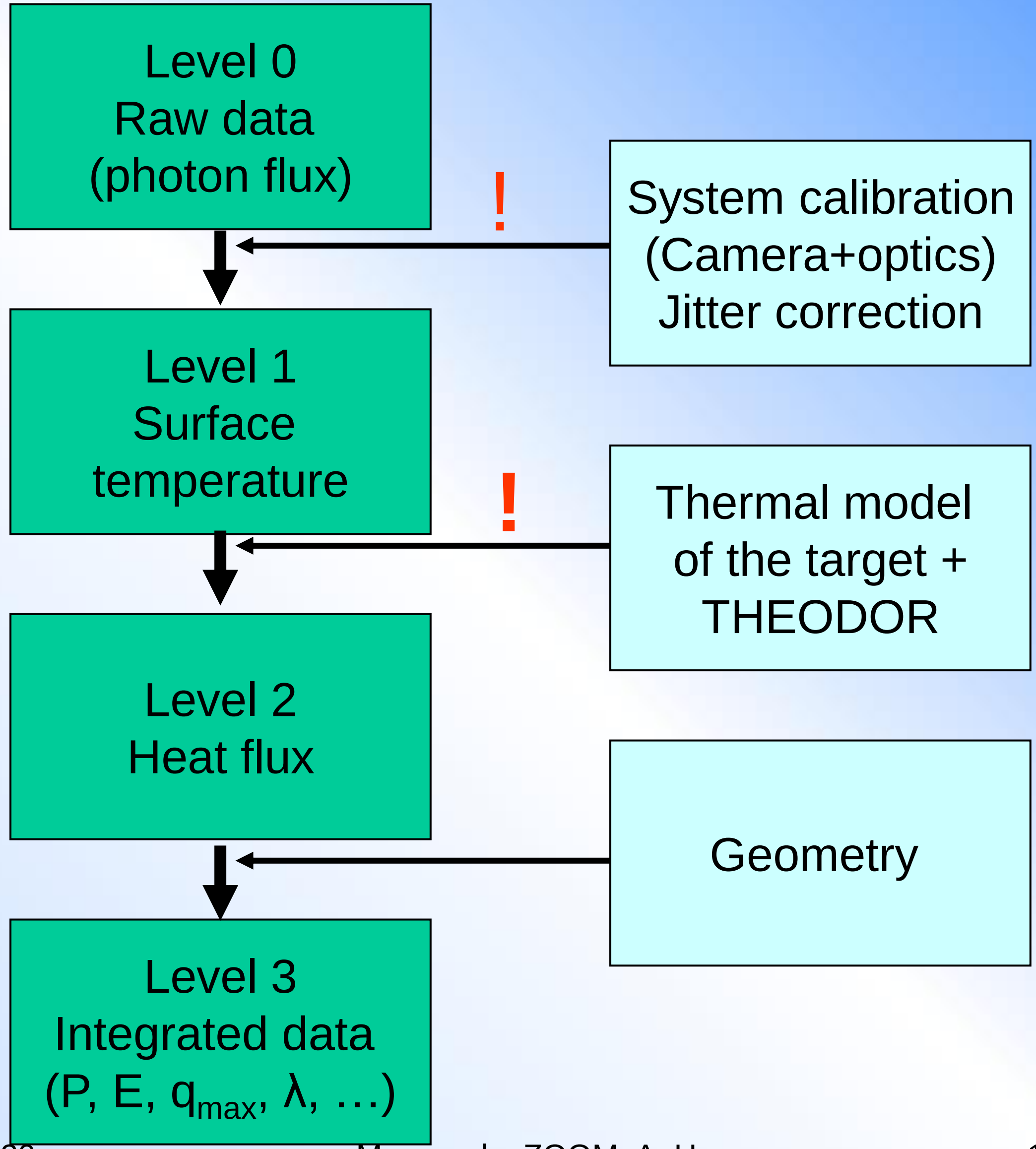
From photons to heat load


ASDEX-Upgrade: Thermography# PPT-21372


ASDEX-Upgrade: Thermography# PST-21372


ASDEX-Upgrade: Thermography# PDP-21372





Level 0
Raw data
(photon flux)

Level 1
Surface
temperature

Level 2
Heat flux

Level 3
Integrated data
(P, E, q_{max}, λ, …)

!

System calibration
(Camera+optics)
Jitter correction

!

Thermal model
of the target +
THEODOR

Geometry

(optical) temperature measurement

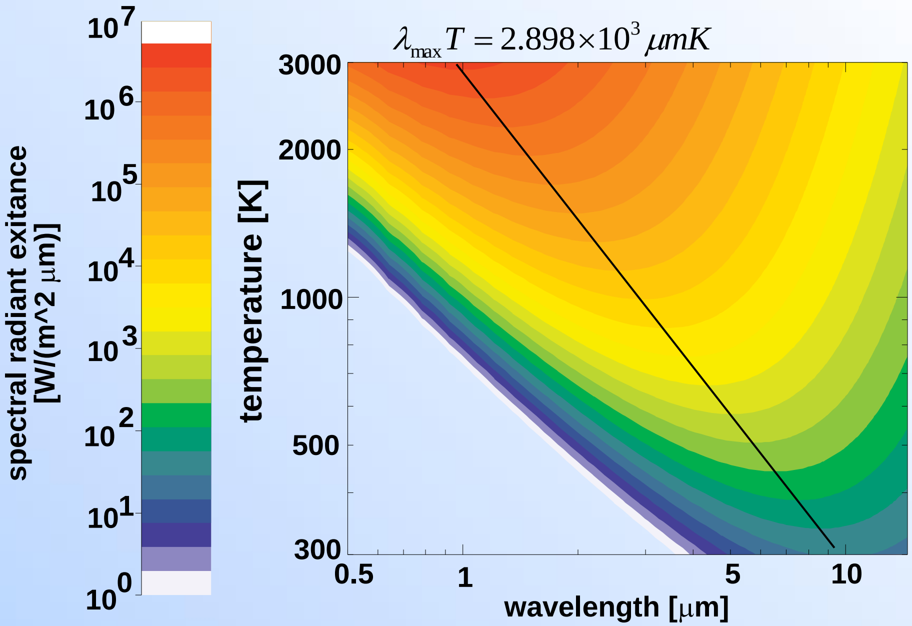
- How to measure surface temperatures?
- How to optimize the measurement according the task?
  - Physics
  - Machine protection
  - Temperature range and sensitivity

Planck's law – correlation between photon flux (power flux) and temperature

Planck's formulae for radiation from a black body into the half space

$$M_e(T,\lambda) = \frac{c_1}{\lambda^5}\frac{1}{\exp(\frac{c_2}{\lambda T})-1} \qquad [M_e] = \frac{W}{m^2 \mu m}$$

$$c_1 = 2\pi hc^2 = 3{,}741\times10^{-16}\,Wm^2 \qquad c_2 = \frac{ch}{k} = 1.438\times10^4\,\mu mK$$



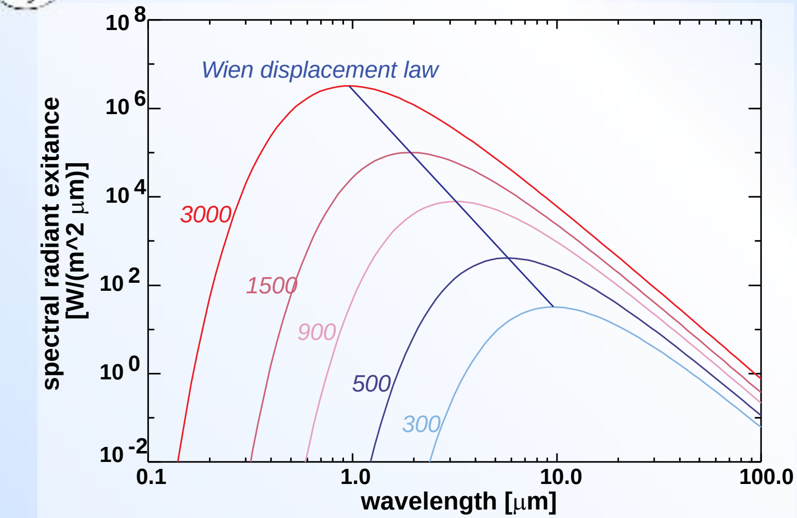
$$\lambda_{\max} T = 2.898\times10^3\,\mu mK$$

- Planck's law
  - Strong non-linear
  - Unique relation between radiation/photon emission of a body and temperature.
  - Depends on the wave length (broad band radiation).

- Select an optimum wavelength:
  - Temperature range.
  - Environment (vacuum, air).
  - Available detectors (costs).

Wien's displacement law
Relation between λ_{max} and T

Planck's formulae - approximated

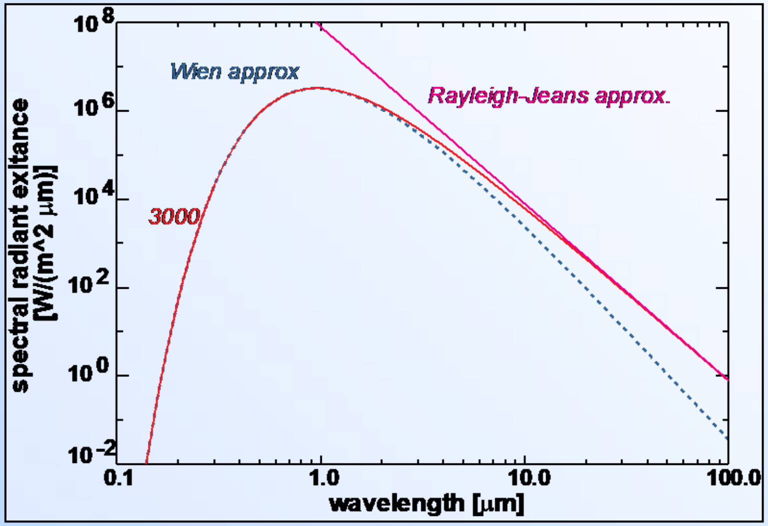


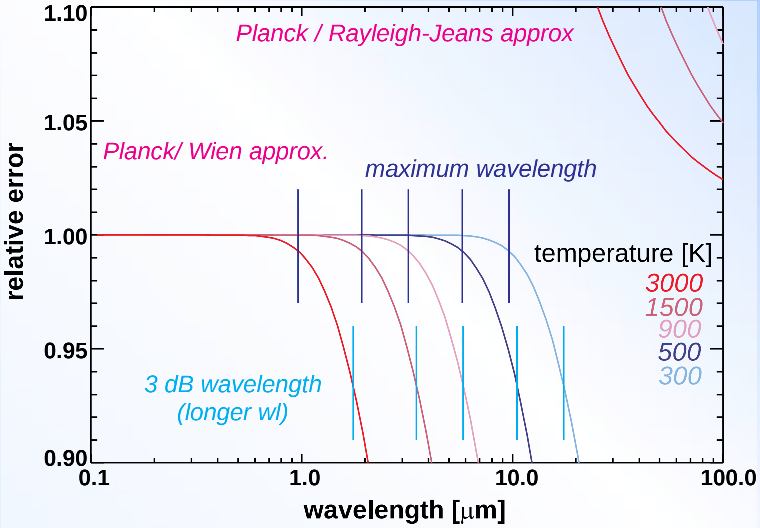
Approximations

$$M_e(T,\lambda) = \frac{c_1}{\lambda^5}\frac{1}{\exp(\frac{c_2}{\lambda T})-1}$$

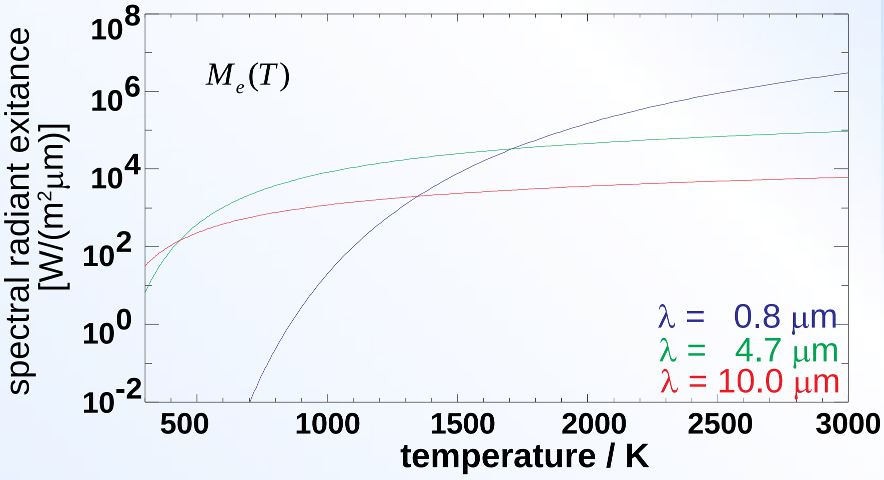
1. $\frac{c_2}{\lambda T} >> 1$ $$M_e^w(T,\lambda) = \frac{c_1}{\lambda^5}\exp(-\frac{c_2}{\lambda T})$$ Wien

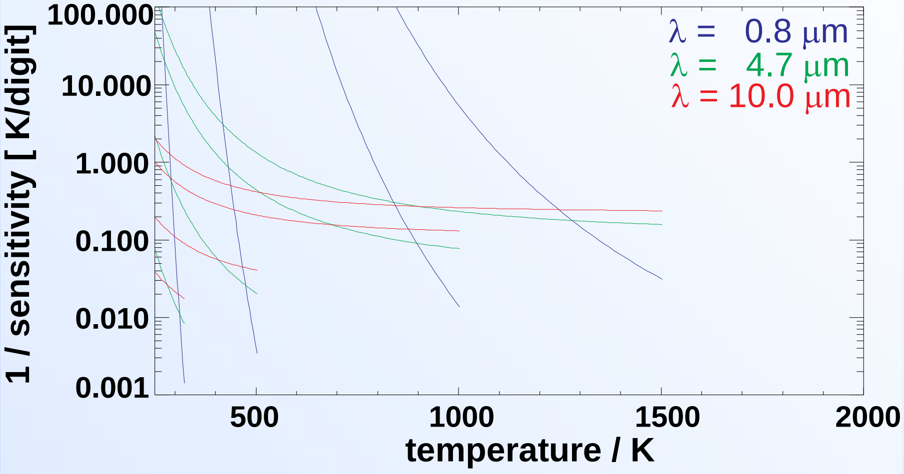
2. $\frac{c_2}{\lambda T} \approx 0$ $$M_e^{RJ}(T,\lambda) = \frac{c_1}{c_2}\frac{T}{\lambda^4}$$ Rayleigh-Jeans





Dynamic range and sensitivity can’t be selected independently





4 settings for the dynamic range

Representative wavelength:

- 0.8 μm – NIR (Near Infra Red)
- 4.7 μm – MWIR (Mid Wave IR)
- 10.0 μm – LWIR (Long Wave IR)

Strong non linear behaviour:

- The dynamic range/sensitivity can be changed
  - **optically**
    - Filter (gray, wavelength)
    - diaphragm (1/f)
  - **in the detection system**
    - integration time
    - integration capacity
    - detector characteristics
- Preferences for the wavelength selection
  - (higher λ for low temperature)

Temperature error increases with wavelength and temperature

The measured signal consists of the temperature information and a background signal (fixed and small wavelength window)

$$S([digits]) = K\varepsilon\tau\frac{1}{\exp(\frac{c_2}{\lambda T})-1} + S_{Bck}(T_{Bck})$$

K - calibration factor
ε - emissivity of the object
τ - transmission of the optical system
S_{Bck} - background radiation (the background temperature(s) is constant in time scale of the signal change)

temperature of the object:

$$T = \frac{c_2}{\lambda}\frac{1}{\ln(\frac{K\varepsilon\tau}{S-S_{Bck}}+1)}$$

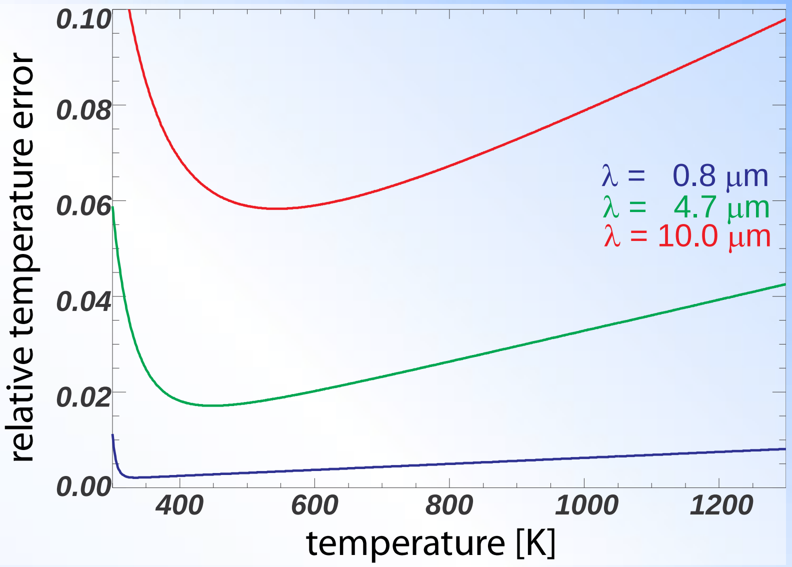
measuring error ?

$$dT = \frac{\partial T}{\partial K}dK + \frac{\partial T}{\partial \varepsilon}d\varepsilon + \frac{\partial T}{\partial \tau}d\tau + \frac{\partial T}{\partial S_{Bck}}dS_{Bck}$$

$$\frac{\Delta T}{T} = \boxed{\frac{\lambda T}{c_2}}\frac{\exp(\frac{c_2}{\lambda T})-1}{\exp(\frac{c_2}{\lambda T})}\left(\frac{\Delta K}{K}+\frac{\Delta\varepsilon}{\varepsilon}+\frac{\Delta\tau}{\tau}+\frac{\frac{S_{Bck}}{K\varepsilon\tau}}{\exp(\frac{c_2}{\lambda T})-1}\frac{\Delta S_{Bck}}{S_{Bck}}\right)$$

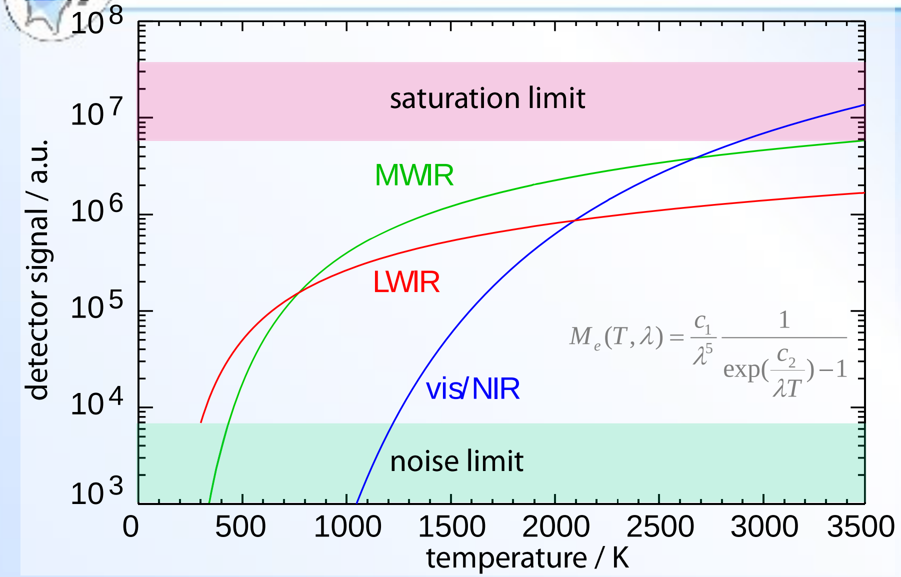
<1 ≈1 >> 1 for $T \sim T_{Bck}$

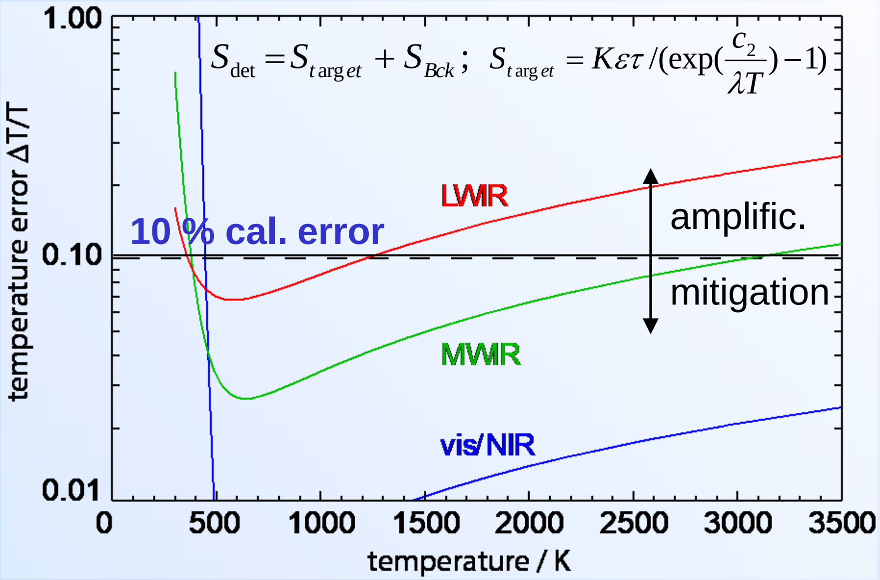
$$c_2 = 1.438\times10^4\,\mu mK$$



$$(\frac{\Delta K}{K}+\frac{\Delta\varepsilon}{\varepsilon}+\frac{\Delta\tau}{\tau}) = 0.1$$

Summary – Wavelength detection





- Typical wavelengths regions for T measurement:
  - Vis/near infrared (vis/NIR, ~ 1 µm)
  - Mid wave infrared (MWIR, ~ 5 µm)
  - Long wave infrared (LWIR, ~ 10 µm)
- MWIR and LWIR cover temperature range from 500 to 3500 K.
- Vis/NIR covers a ‘small’ T-range.
- T measurement error:

$$\frac{\Delta T}{T}=\frac{\lambda T}{c_2}\left(\boxed{\frac{\Delta K}{K}+\frac{\Delta\varepsilon}{\varepsilon}+\frac{\Delta\tau}{\tau}+}\frac{S_{Bck}}{S_{target}}\frac{\Delta S_{Bck}}{S_{Bck}}\right)$$

- Strong error mitigation in the vis/NIR wavelength region:
  - Comparator like behaviour.
  - robustness against change of system parameters (emissivity).

Properly designed thermography system

- **Adapted to the measuring requirements**
- **Calibrated**

Are a prerequisite for heat load calculation.

Heat load calculation

Power flux

$$\vec{q} = -\kappa \, grad \, T \qquad ; \left[\frac{W}{m^2} \right]$$

$$\kappa - heat\ conduction\ coefficient$$

- No direct power measurement.
- Power is calculated from a temperature change

Temperature response – heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = div(\kappa \, grad \, T) + S$$

$$\rho c_p - heat\ capacity$$

$$a = \frac{\kappa}{\rho c_p} - heat\ diffusivity$$

- Heat conduction equation.
- Relation between temperature change and heat flux.
- Solve for appropriate thermal model.

Time constant (Fourier number)

$$F_0 = \frac{a\,t}{d^2}$$

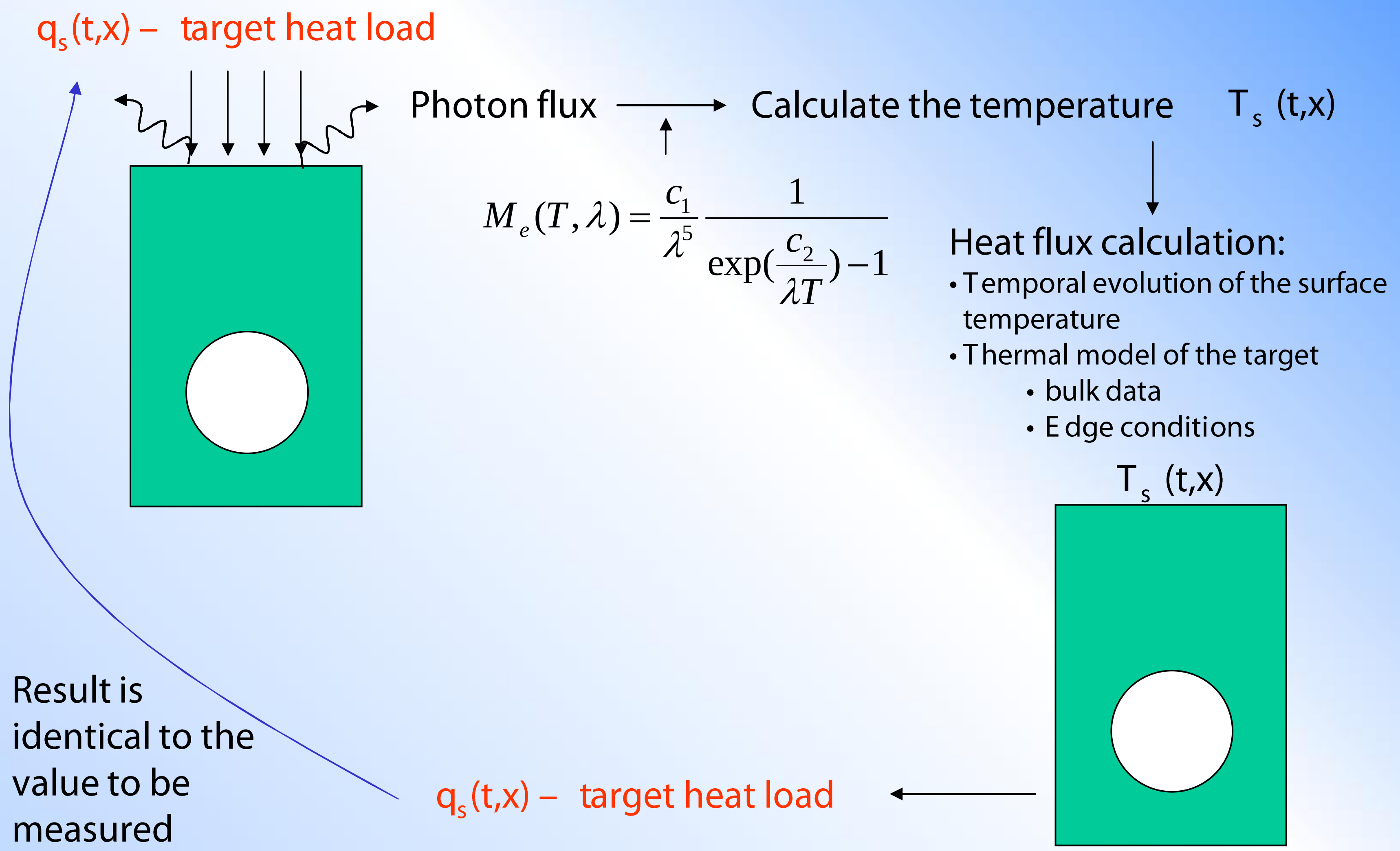
$F_0 < 1/\pi$ – semi infinit

$$\tau = \frac{d^2}{\pi \, a}$$

Time to penetrate into depth d

$$\tau_{CFC} = \frac{d^2}{\pi \, a} = \frac{(2cm)^2}{\pi \, 2cm^2 / s} \approx 0.7s$$

From photon flux to heat flux



$q_s(t,x)$ – target heat load

Photon flux → Calculate the temperature $T_s(t,x)$

$$M_e(T,\lambda) = \frac{c_1}{\lambda^5}\frac{1}{\exp(\frac{c_2}{\lambda T})-1}$$

Heat flux calculation:

- Temporal evolution of the surface temperature
- Thermal model of the target
  - bulk data
  - Edge conditions

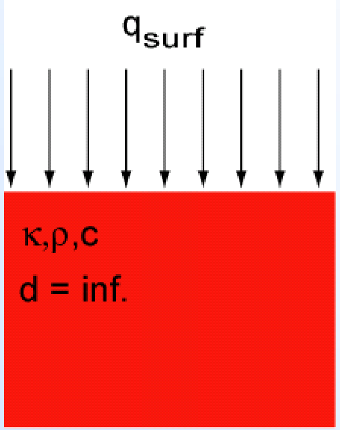
$T_s(t,x)$

$q_s(t,x)$ – target heat load

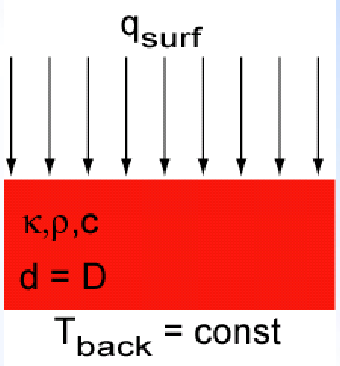
Result is identical to the value to be measured

Basic (text book) solutions

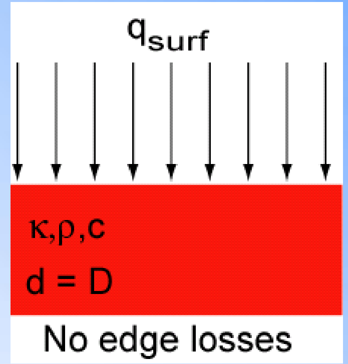
Semi infinite target



Stationary, backside cooled



Floating target



$$\Delta T_s(t) = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{\kappa \rho c}} q_s \sqrt{\Delta t}$$

$$T_s - T_{back} = \frac{d}{\kappa} q_s$$

$$\Delta T_s = \rho c d \, q_s \, \Delta t$$

Transients
- ELMs, disruptions

Depends on:
- product of Heat capacity and heat conductivity

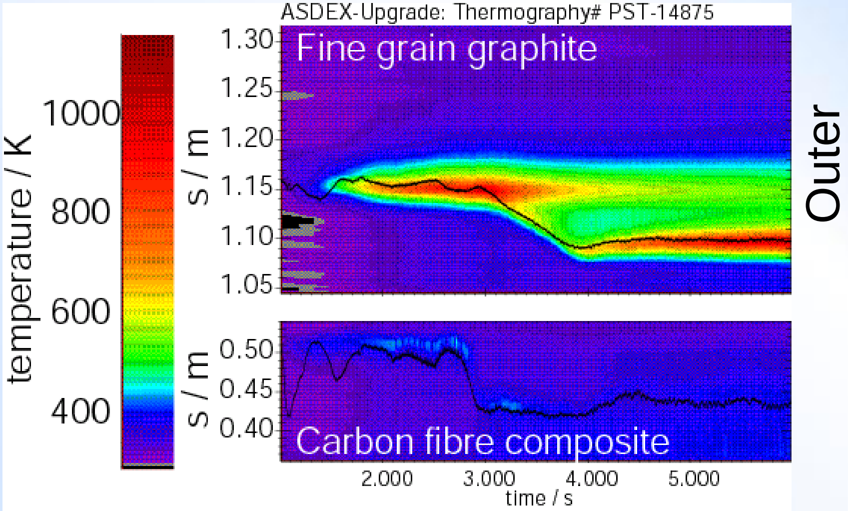
Stationary
- Actively cooled target

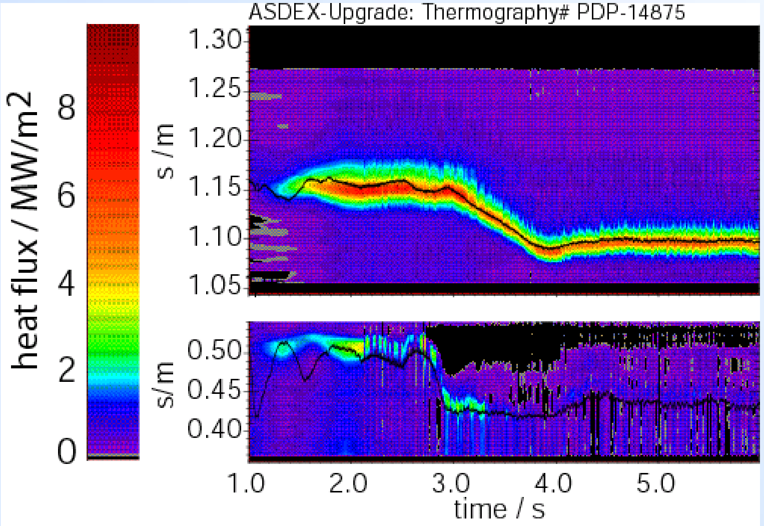
Depends on:
- Heat conductivity

Stationary
- Thin layer with bad thermal contact

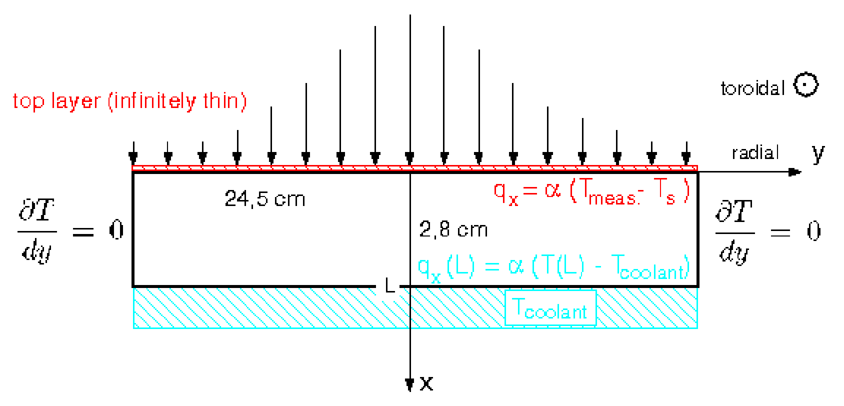
Depends on:
- heat capacity

Numerical - heat load calculation



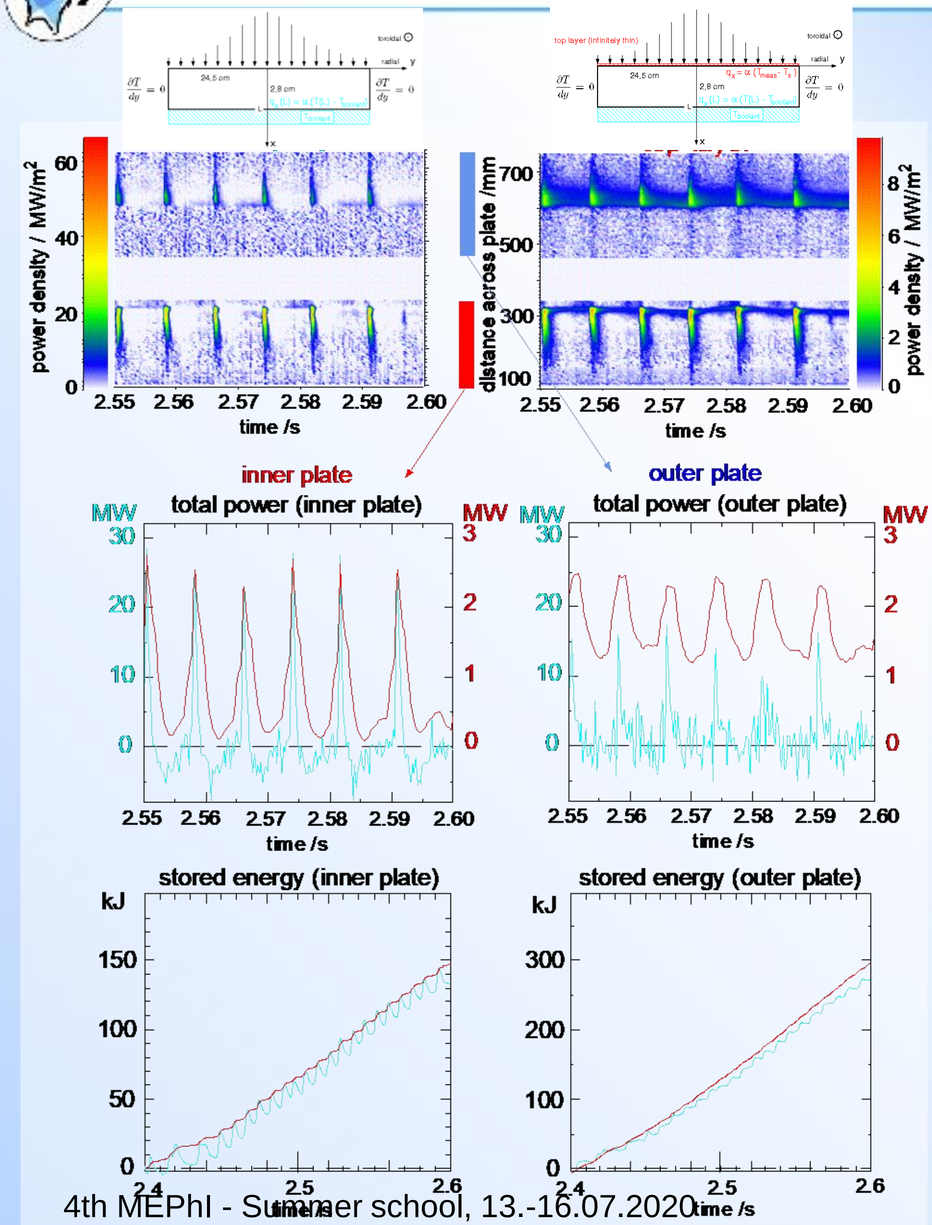


- 2D heat flux equation (THEODOR)
- Numerical solved (FTCS, explicit)



- Thermal model with heat transfer edge condition on top and bottom.
- Bottom: clamped to the cooling structure
- Top: to consider surface effects (transients)

Surface effects



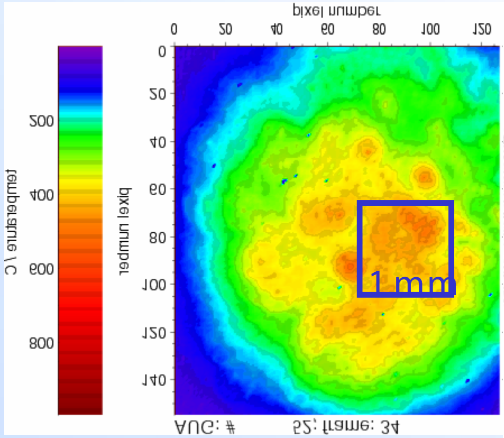
- Same T(t) as input
- … but different thermal models
- One order of magnitude difference in the heat flux (transients).
- No difference in the calculation of the accumulated energy at the target!

- Thermal model and surface conditions
  - Micro structures as pseudo layers
  - Layers
- Wavelength selection

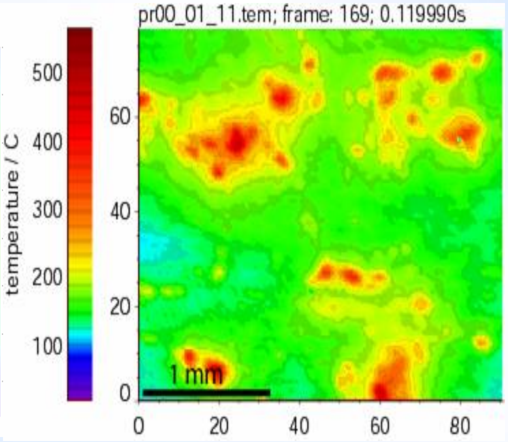
Surface effects – micro thermography

- Overestimation of the bulk temperature due to:
  - Surface morphology
  - Deposits/layers.

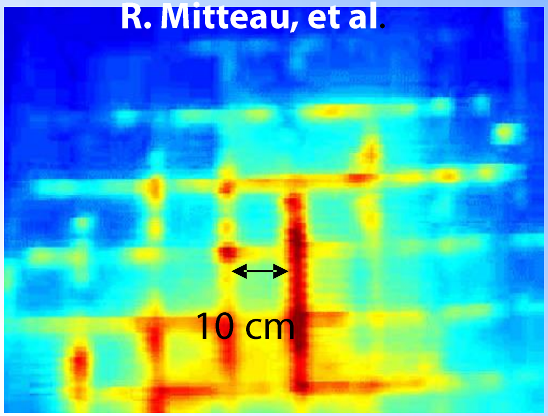
Fine Grain Graphite (FGG)



Carbon Fibre composite (CFC)



ToreSupra limiter

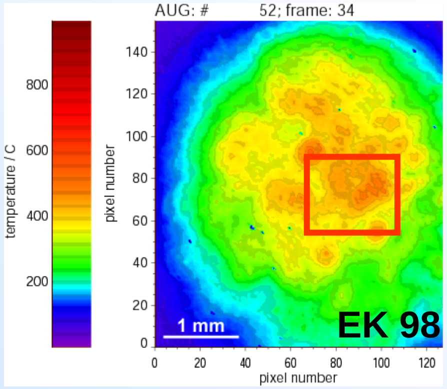

R. Mitteau, et al.

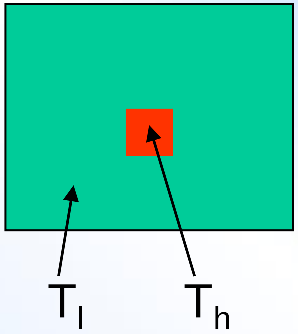
Laser beam heating, 5 MW/m^2

- During surface heating micro spots (a few 10µm) are detected at the surface.
- Detected for plasma exposed and unexposed materials.
- Pattern is constant over at least a few hundred load cycles.

- Layers in deposition areas are hotter compared to the bulk material.
- For the same heat flux!

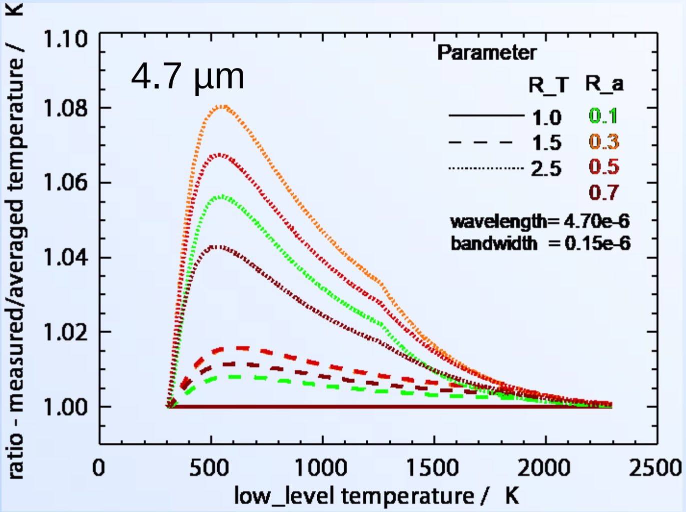
Hot spots result in an artificial temperature increase

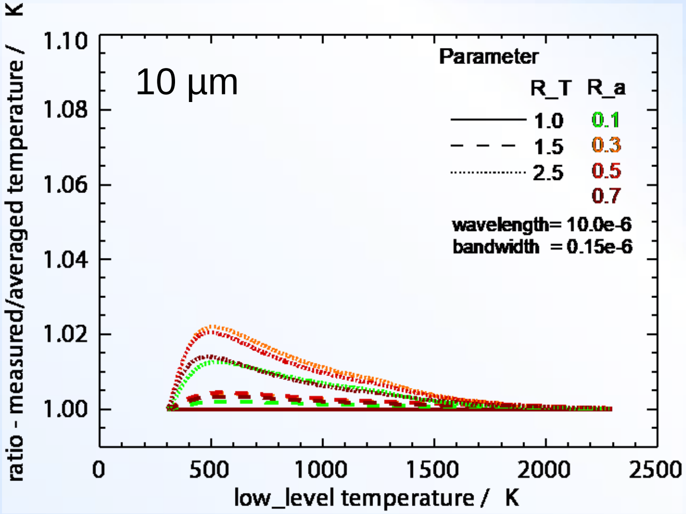




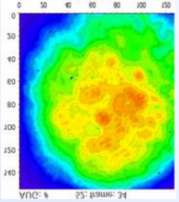
- The measured temperature is calculated from the photons belonging to two (ore more) temperatures.
- The microscopic temperature patterns are fixed over many heating cycles.

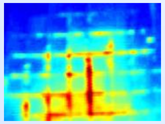
R_T – temperature ratio hot spot/bulk
R_a – area ratio hot_spot/total area

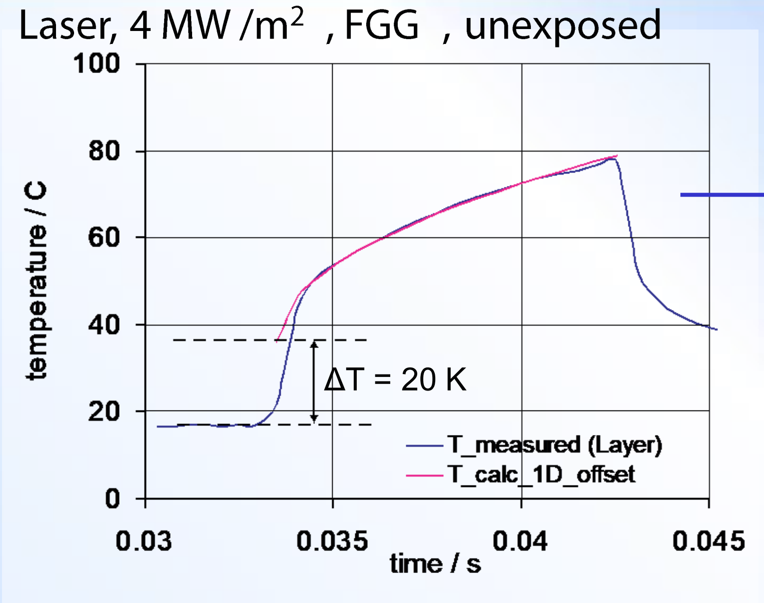


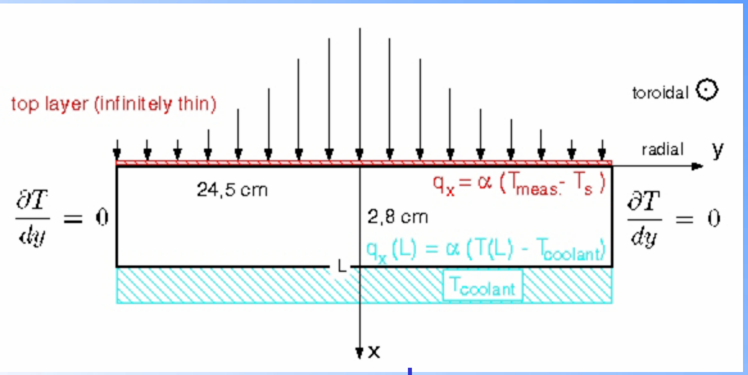


Layer effects





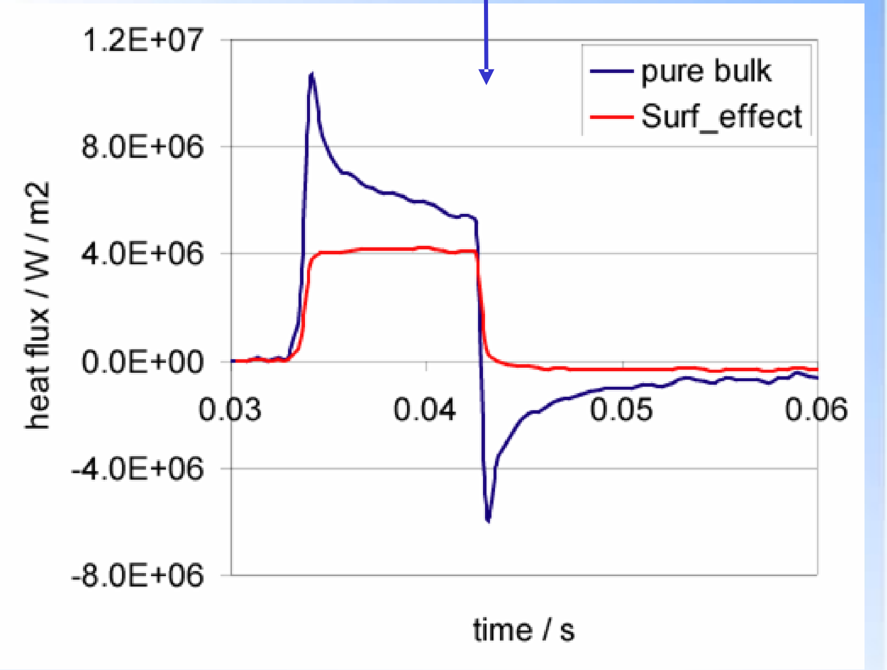

Laser, 4 MW /m^2 , FGG , unexposed



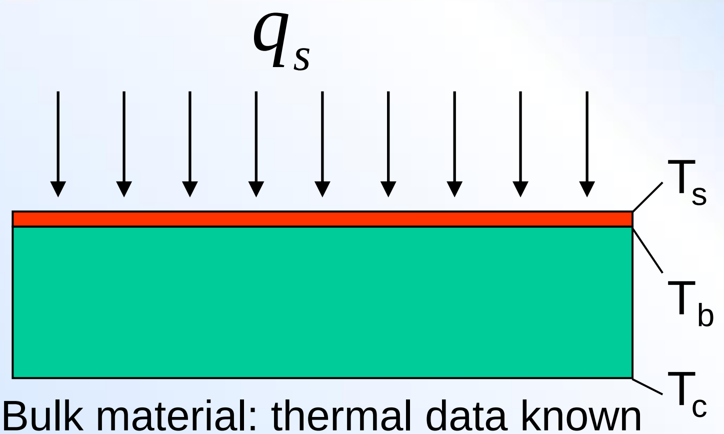
$$\Delta T_{meas} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{\kappa\rho c}} \sqrt{t}\, q_s + \frac{q_s}{\alpha}$$

‘wrong surface properties’:

- Temperature jump results in a strong heat pulse (positive and negative).
- The integral signal gives the deposited energy.
- Correction of top layer effects on time scales longer then the pulse length (energy conservation)



Thermal model



Bulk material: thermal data known

Numerical:

$$d = 50\,\mu m \qquad \kappa_b = 100\,\frac{W}{m\ K} \qquad \kappa_l = 1/10\,\kappa_b$$

The additional ΔT is 45 K/MWm^{-2}

The time constant for such a thin region is short.

$$\tau = \frac{d^2}{\pi\, a} \approx 50\,\mu s$$

After this time the time behaviour of the surface temperature follows the heating of the bulk.

Temperature gradient in top of the bulk

$$\Delta T_{layer} = T_s - T_b = \frac{d_l}{\kappa_l}\, q_s$$

1. $\kappa_l = \kappa_b$

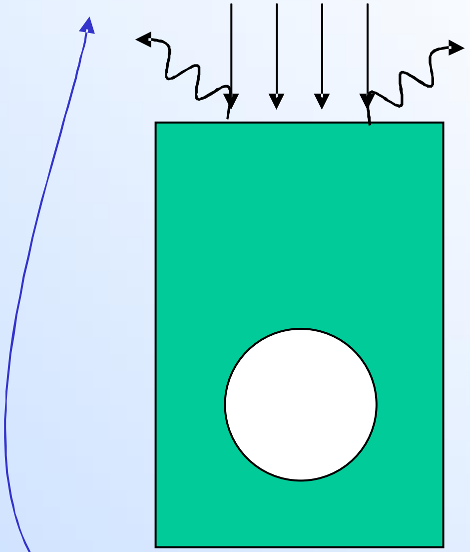
   (Nearly) no effect on the measured surface temperature

2. $\kappa_l < \kappa_b$

   The surface temperature is increased
   The derived heat flux is too large if the surface effect is not considered.

Surface effects

$q_s(t,x)$ – target heat load



$$M_{detector} = \frac{(A_0 - A_1)}{A_0} * M_e(T_l) + \frac{A_1}{A_0} * M_e(T_h)$$

Photon flux $\longrightarrow$ Calculate the temperature $T_s(t,x)$

$$M_e(T,\lambda) = \frac{c_1}{\lambda^5} \frac{1}{\exp(\frac{c_2}{\lambda T}) - 1}$$

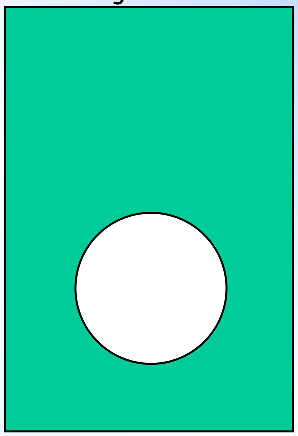
Heat flux calculation:

- Temporal evolution of the surface temperature
- Thermal model of the target
  - bulk data
  - Edge conditions

Contributions to the photon flux that are not considered in the thermal model

- Radiation from the plasma (Marfe)
- Hot spots on top of the bulk.
- Layers with 'bad' thermal properties.

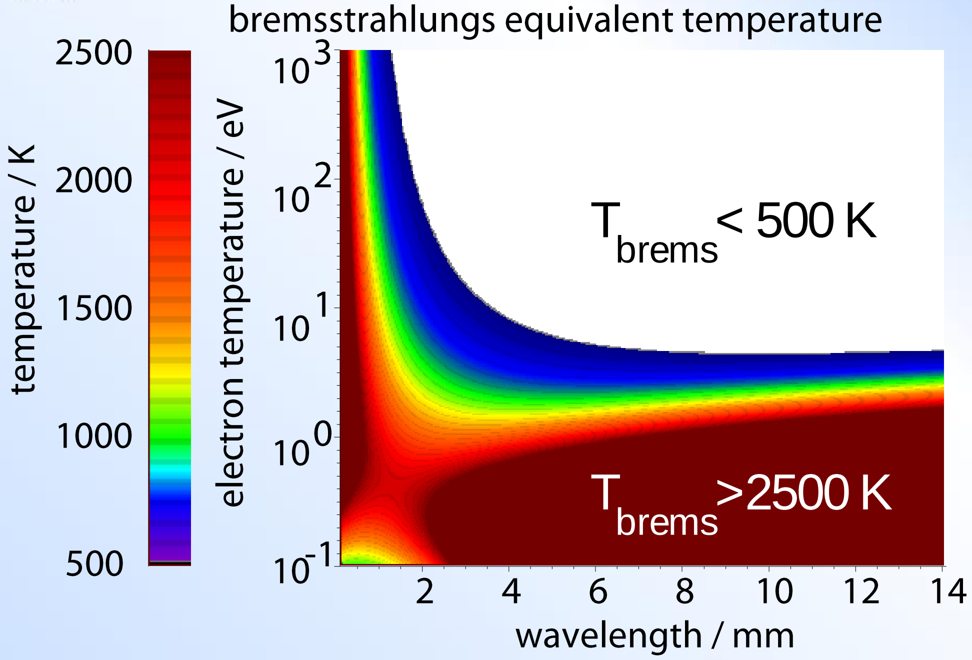
$T_s(t,x)$



$q_s(t,x)$ – target heat load

Result is NOT identical to the quantity to be measured.

Bremsstrahlung



Temperature equivalent for Bremsstrahlung.
A constant pressure of $n_e T_e = 1\times10^{22}$ eVm^{-3} is assumed.

- Bremsstrahlung is emitted from a dense plasma in the SOL and divertor region.
- Strong decrease of Bremsstrahlung contribution between 1 and 5 µm ($1/\lambda^2$).
- Optimum wavelength – 5 µm
- Cold and dense plasmas contribute to Bremsstrahlung.
- Reduced target load due to divertor detachment.

$$\frac{dW_B}{d\lambda\, dV} = const \frac{1}{\lambda^2} \frac{Z_{eff} n_e^2}{(T_e)^{1/2}} G_{ff} Exp\left[-\frac{hc}{\lambda T_e}\right]$$

Summary

- Heat dissipation is a serious task for the design of a fusion reactor and is a main topic in present research activities.
- Thermography is a powerful tool for safety and physics investigations.
- Compared to infrared systems, video cameras have a smaller measurement range but are 5 -10 times more robust against changes of the optical system including emissivity and transmission.
- Heat flux = Temperature + thermal model
  - Temperature measurements needs careful interpretation
  - Transients are dominated by surface effects
  - Long lasting events are dominated by the bulk (robust energy conservation)
- The non linearity of Planck’s law pronounces hot spots at low temperatures and low wavelengths).
- Heat load calculation is energy conserving
  - As long as the thermal model for the bulk is correct, ‘wrong’ transient effects will be corrected