INSTITUT FRESNEL MARSEILLE

High power CW laser heating for the study of materials at very high temperature

L. Gallais*
Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel

G. Kermouche
Mines Saint-Etienne, Univ Lyon, CNRS, Laboratoire Georges Friedel

M. Minissale
Aix Marseille Univ, CNRS, PIIM

Y. Pontillon
CEA, DES, IRESNE, DEC, Cadarache

M. Richou
CEA, IRFM, Cadarache

J.L. Rullier
CEA CESTA

PhD & Post-docs

T. Doualle, A. Durif,
M. Reymond, T. Vidal

*laurent.gallais@fresnel.fr

Introduction

Positioning of our work

Super-high temperature*

> 5000 K

Ultra-high temperature

- 2700 K

High temperature

- 1500 K

Elevated

- 700 K

Moderate

- 300 K

Ambient

- 200 K

Cryogenic

Different applications and fundamental research require to reach this range

- Steady state or transient
- Long duration (> s)
- Large scales (> cm)

=> Can be reached with « low cost » high power CW lasers

*I. L. Shabalin, Ultra-High Temperature Materials (Springer), 2014.

Outline

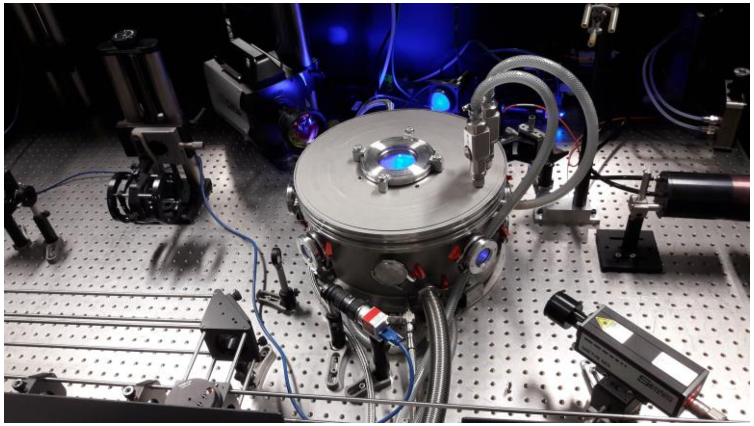
- ChauCoLase platform
  => Chauffage Contrôlé par Laser
- Graphite
  => Controlled laser heating up to 4000 K
- Tungsten
  => Recrystallisation kinetics at high temperature
- UO_2
  => Laser simulated accidental thermal transients on nuclear fuels
- Conclusions

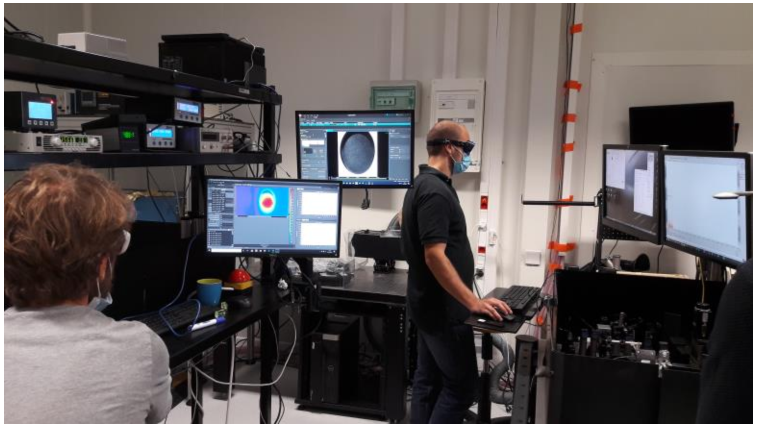
ChauCoLase platform

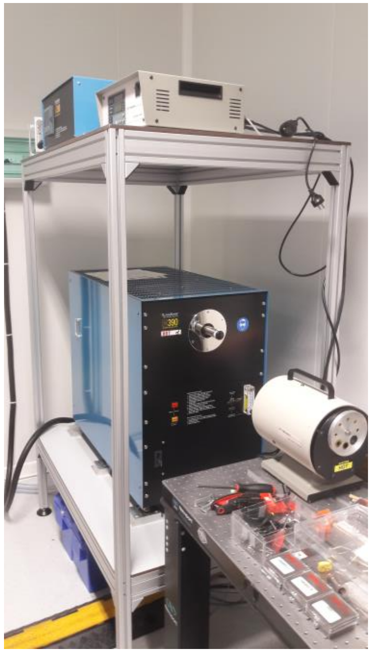
Chauffage Contrôlé par laser

A laser-based facility at Institut Fresnel, shared with CEA

- kW Ytterbium fiber lasers
- Vacuum chambers
- High speed thermal camera
- Pyrometers
- Spectrometers
- High temperature black body







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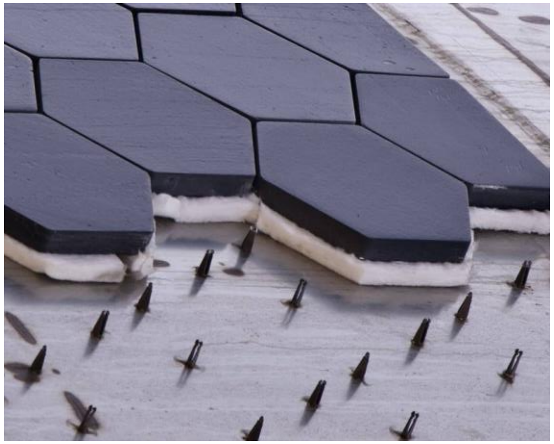
Graphite

Context of the study

- Graphite for scientific and industrial applications:



Thermal protection systems for reentry vehicles (Space X)

Graphite tiles in a Stellarator (Max Planck IPP)

- Application developments require knowledge of material properties at very high temperatures
- Objectives of our work on graphite:
    - Controlled laser heating of graphite samples up to 4000K for laser shock

Graphite

Properties

Samples:

- polycrystalline graphite produced by sintering

Optical properties

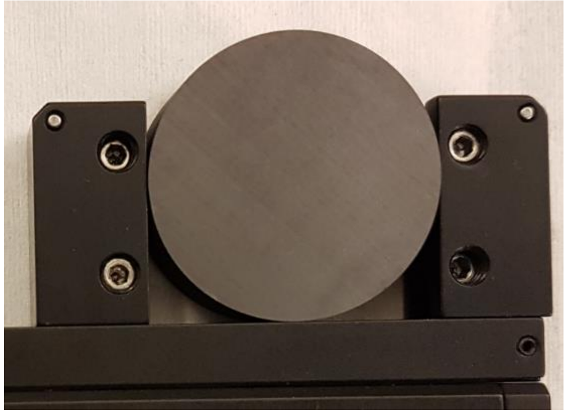
- Opaque material
- Dependent on surface state

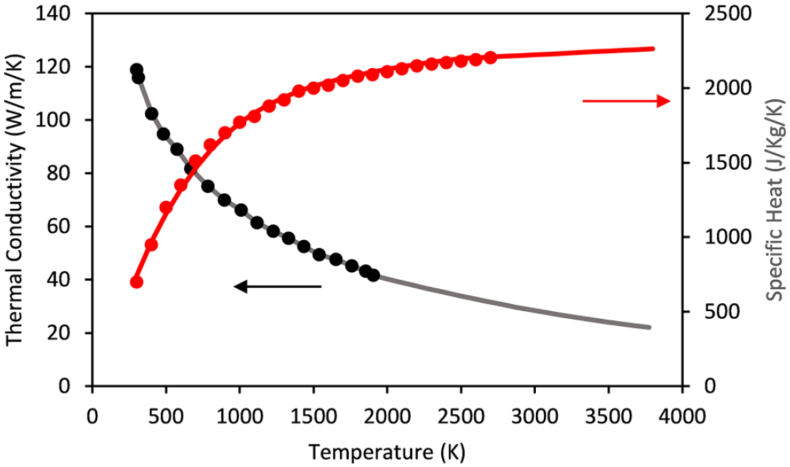
Thermal properties

- Decrease of thermal conductivity with T
- Increase of heat capacity with T

Thermodynamic properties:

- Graphite sublimates at a temperature close to 4200 K*

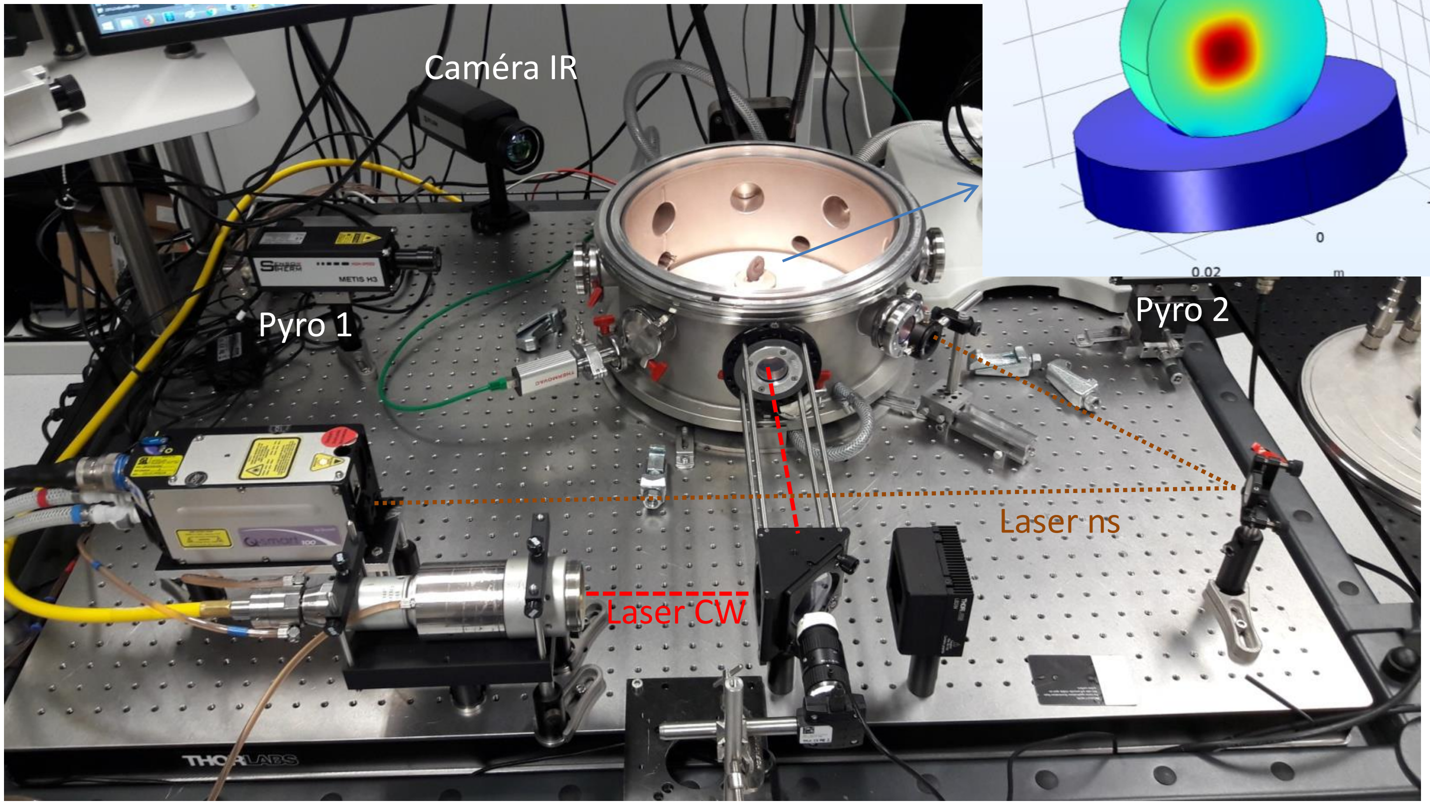


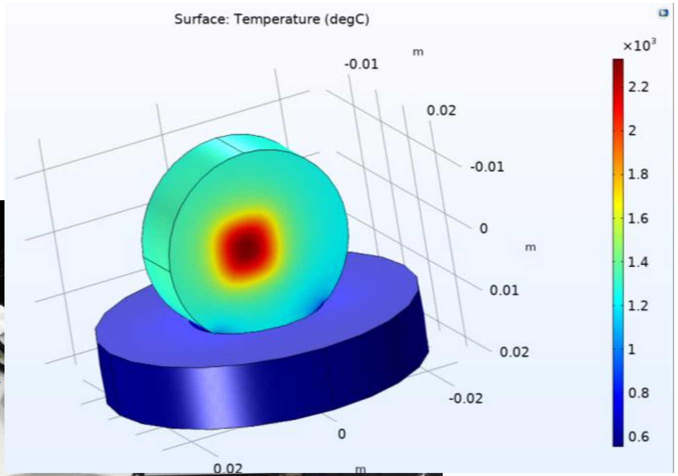


**F. P. Bundy, "Pressure-temperature phase diagram of elemental carbon," Phys. A 156, 169 (1989).*

Graphite

Experimental configuration

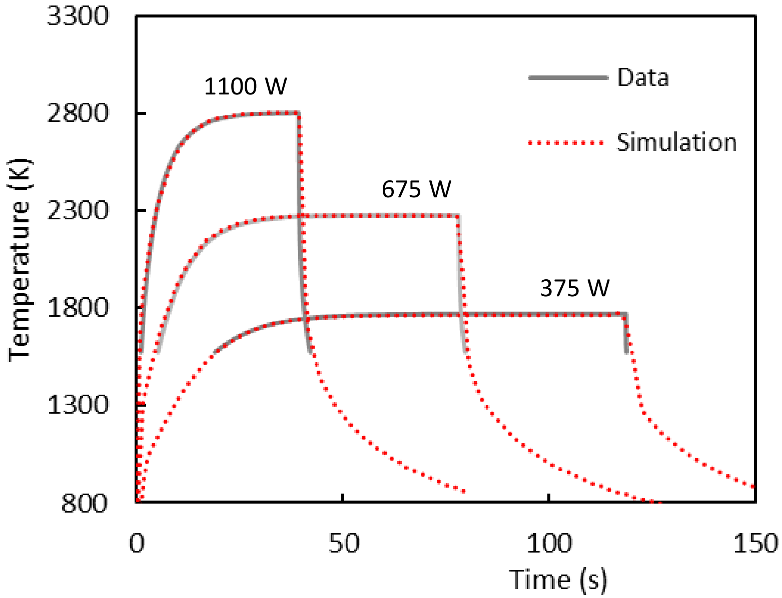




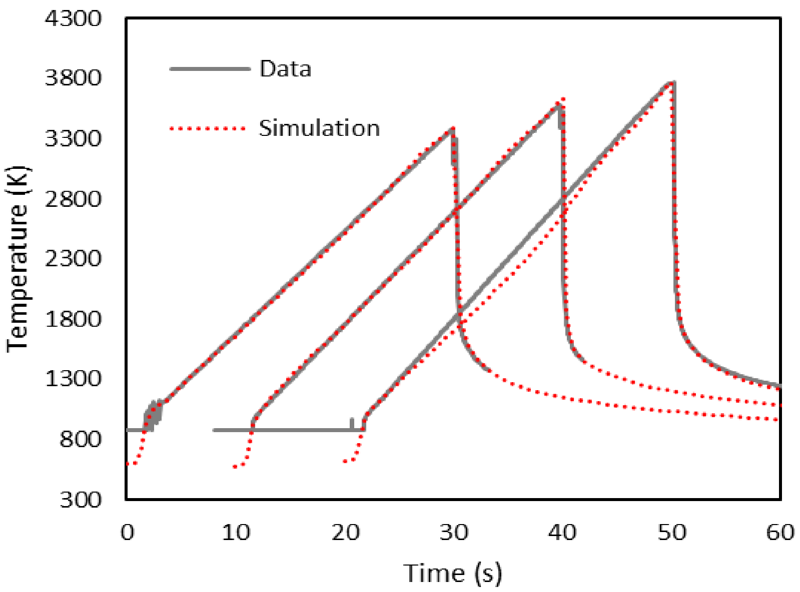
Graphite

Results

CW laser heating with 13 mm diameter beam and comparison with simulations.



Linear heating rate experiments** up and their comparison with simulations.

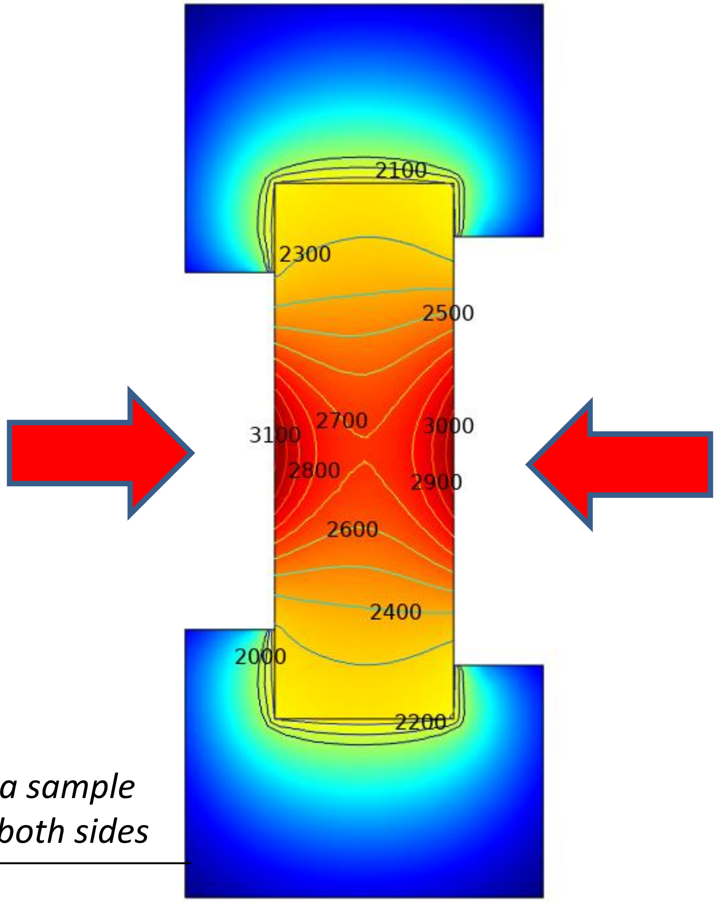


**Obtained at the GCLT facility (Générateur de Chocs Laser Transportable) located at the CEA-DIF

Graphite

Summary & perspectives

- Demonstration of controlled heating on graphite up to 3800 K with tunable heating rates, associated to a numerical model*
- Next step: coupling laser heating and laser shock



Temperature distribution in a sample heated with 2 kW lasers on both sides

*L. Gallais, T. Vidal, E. Lescoute, Y. Pontillon, and J. L. Rullier, « High power continuous wave laser heating of graphite in a high temperature range up to 3800 K", J. Appl. Phys. 129, 043102 (2021)

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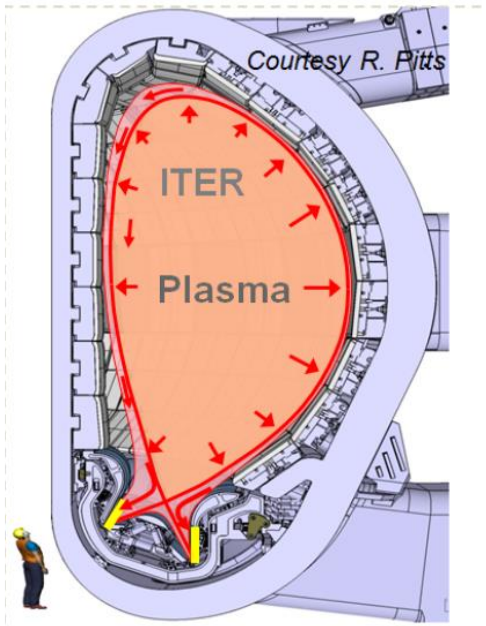
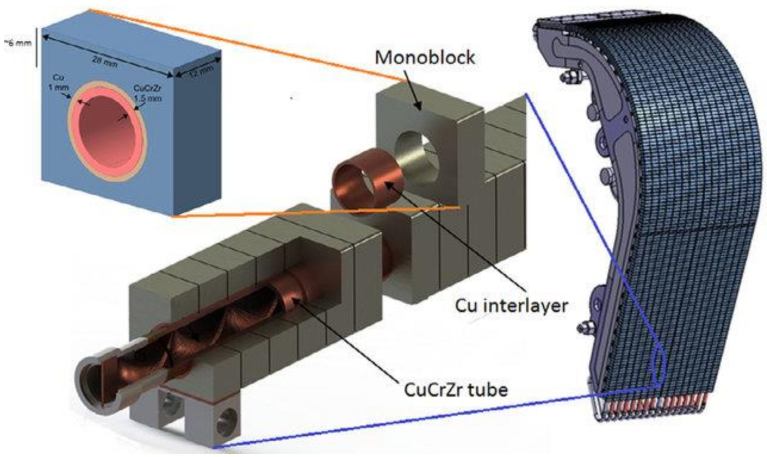
Tungsten - W

Context of the study: ITER

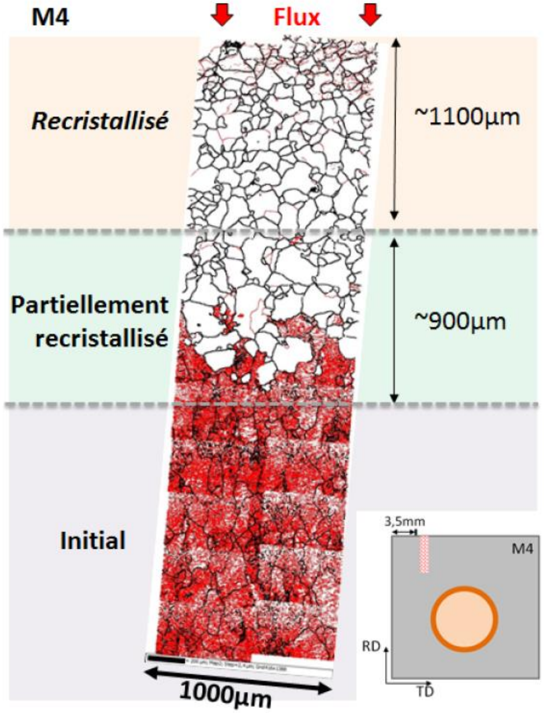
- Some of ITER plasma facing components will be made of W
- They will be submitted to high heat flux (up to GW/m^2)
- Mechanical properties changes linked with recrystallization, can strongly affect the W thermal shock resistance



ITER Tokamak section



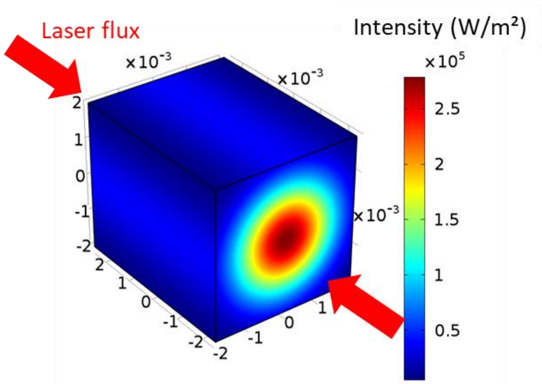
ITER W monoblock

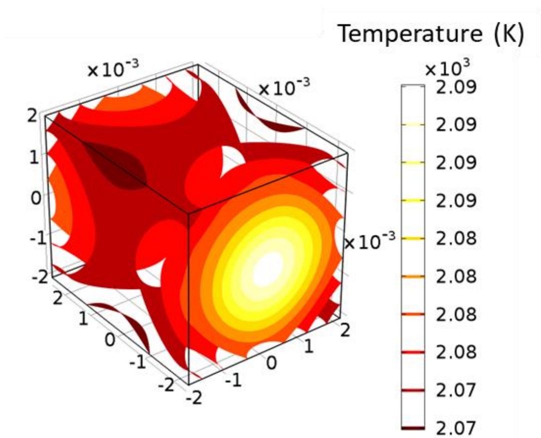


Tungsten - W

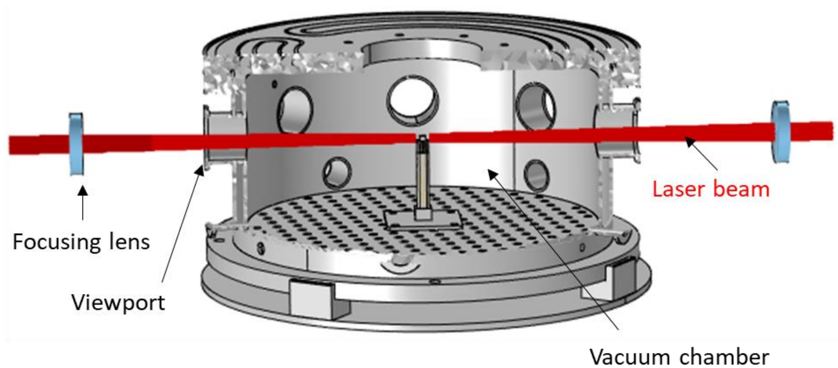
Laser experiments – isothermal annealing

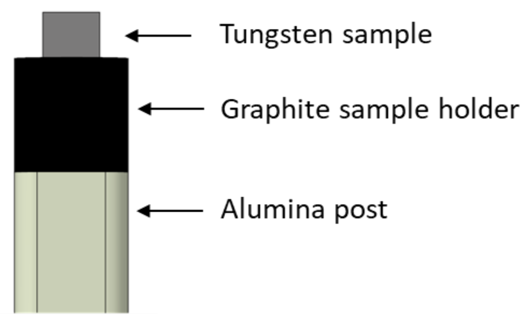
Laser heat load and thermal gradients

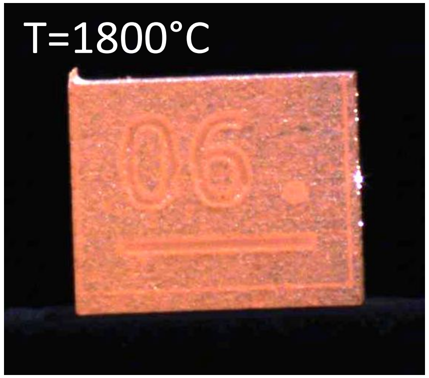




Experimental configuration

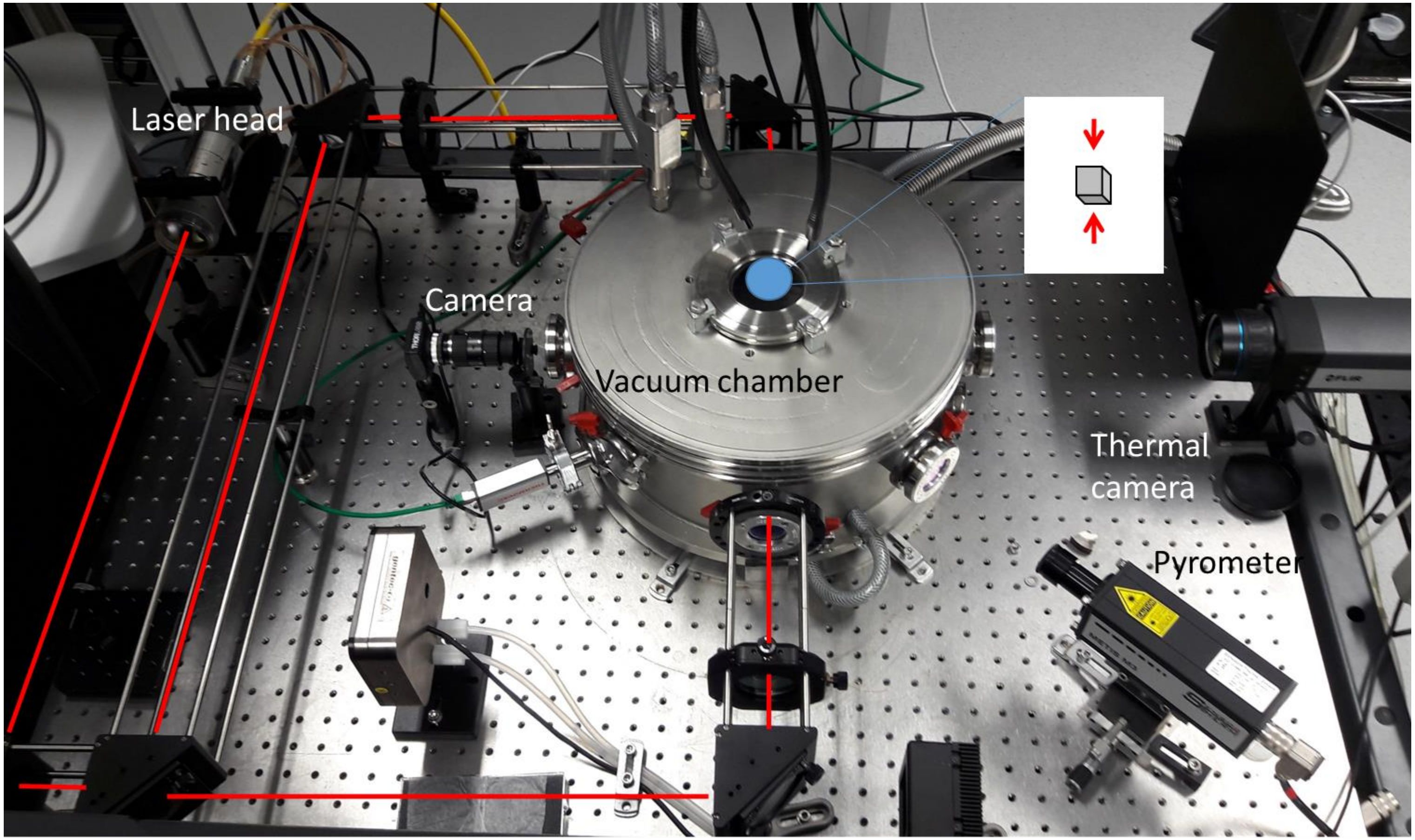






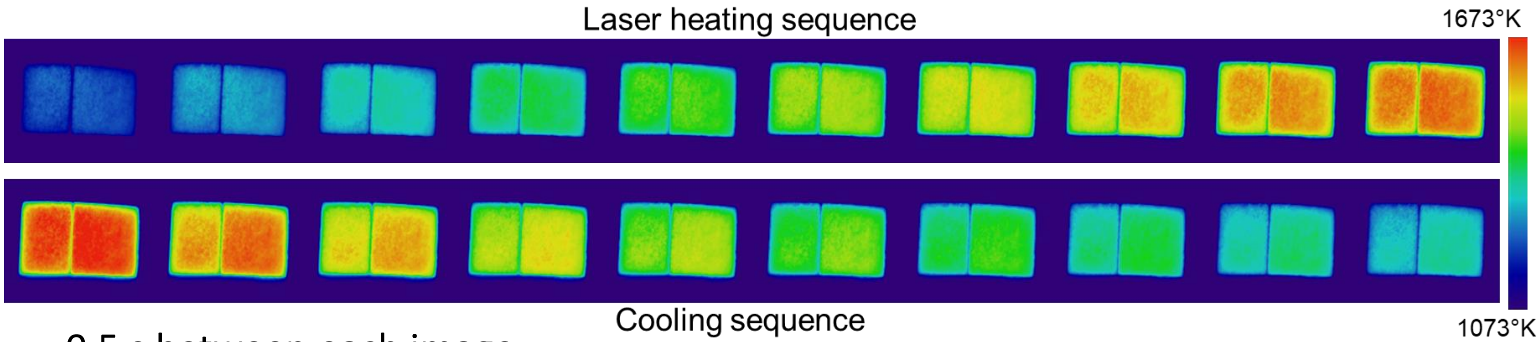
Tungsten - W

Experiments

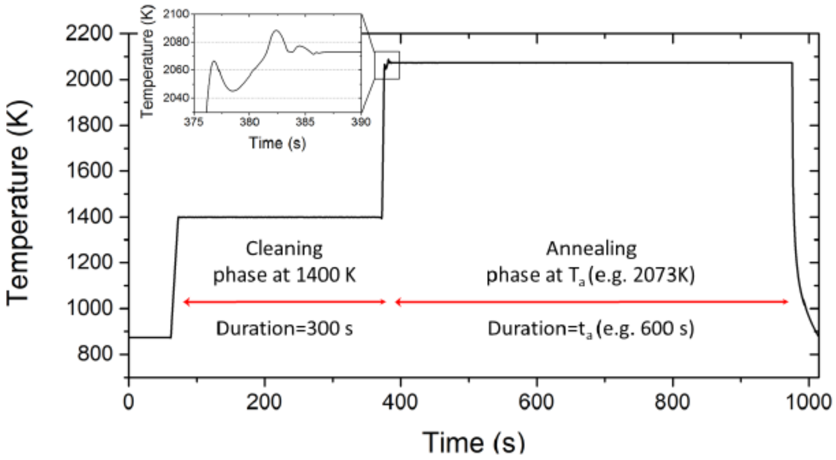


Tungsten - W

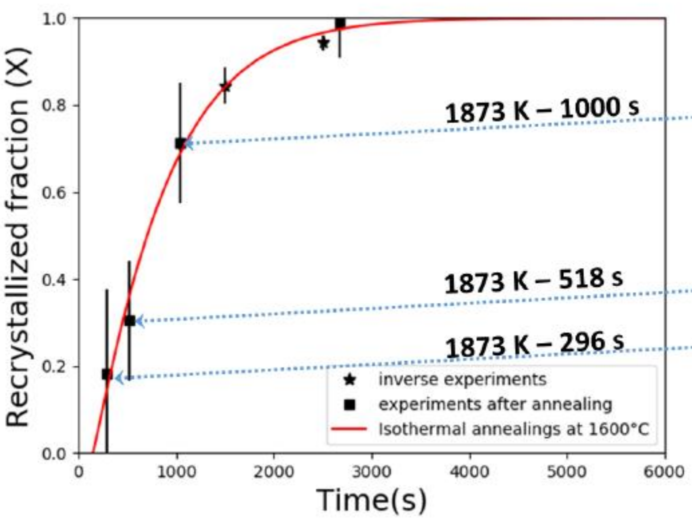
Measurements



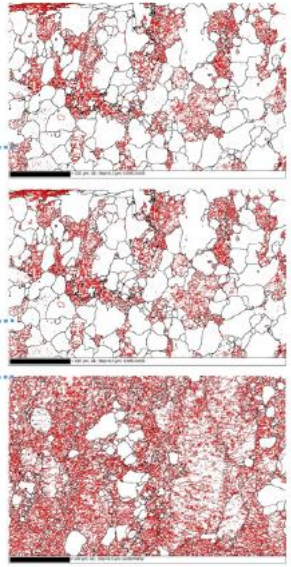
0.5 s between each image



Measured temperature during a laser heating sequence



Recrystallisation kinetics

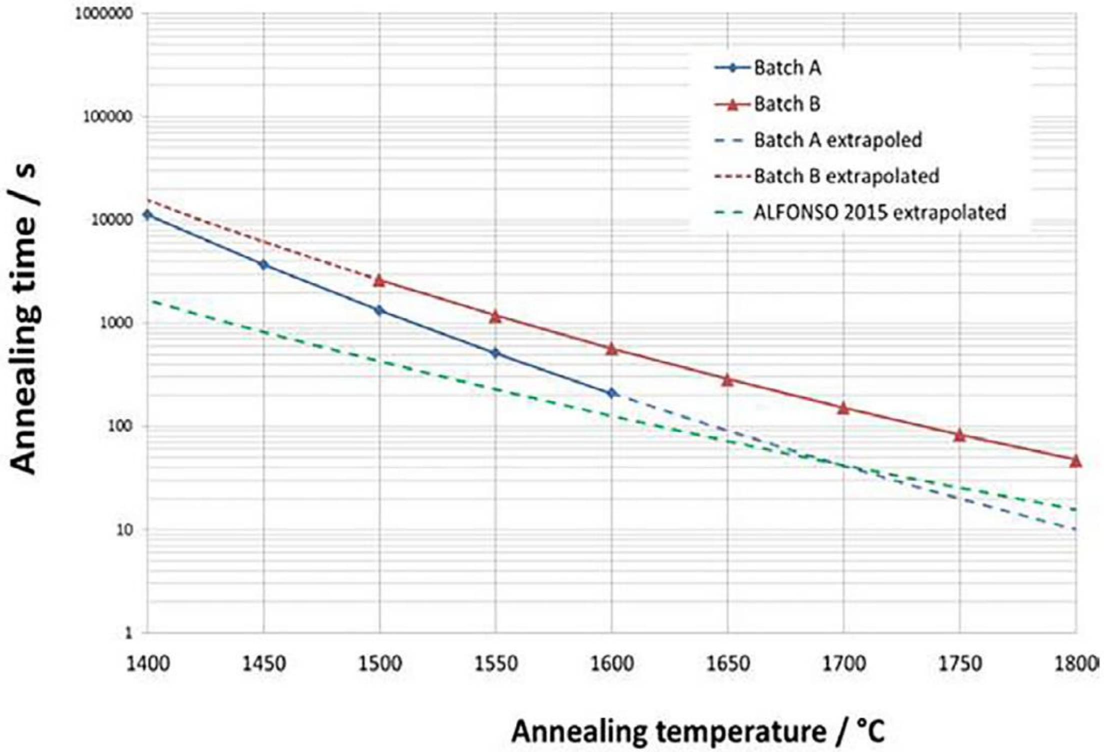


Analyses EBSD (Electron BackScattered Diffraction)

Tungsten - W

Results

Annealing time to achieve 50% recrystallization fraction for batches from 2 ITER suppliers



M. Richou, A. Durif, M. Lenci, M. Mondon, M. Minissale, L. Gallais, G. Kermouche, G. De Temmerman, ‘Recrystallization at high temperature of two tungsten materials complying with the ITER specifications’, Journal of Nuclear Materials 542, 152418 (2020)

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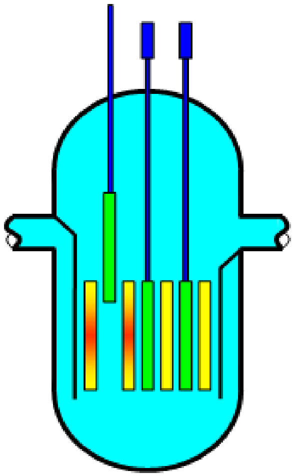
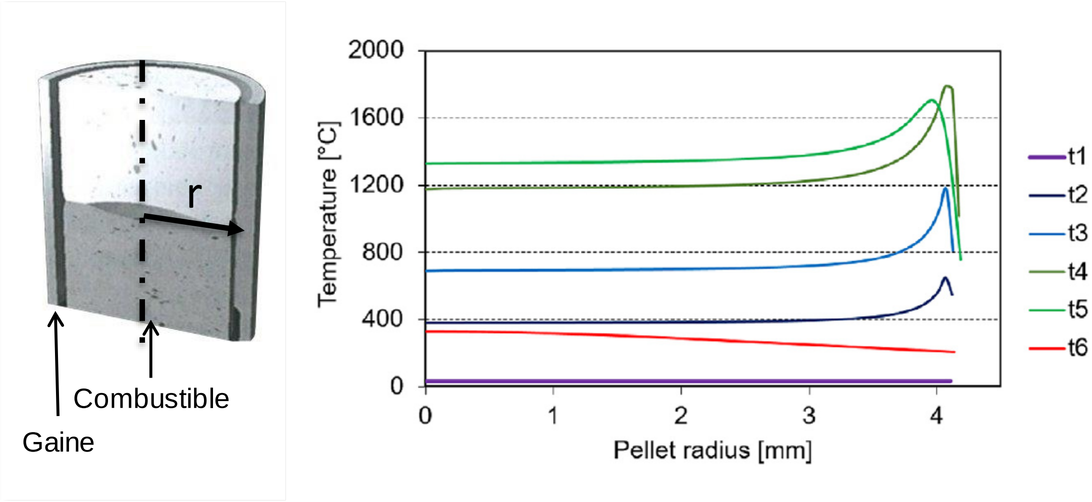
UO_2
Context of the study

- Knowledge of nuclear fuel behavior during nominal operation or accidental conditions, is of paramount importance
- Some thermal conditions, for instance Reactivity Initiated Accident (RIA), can only be reached in integral experiments



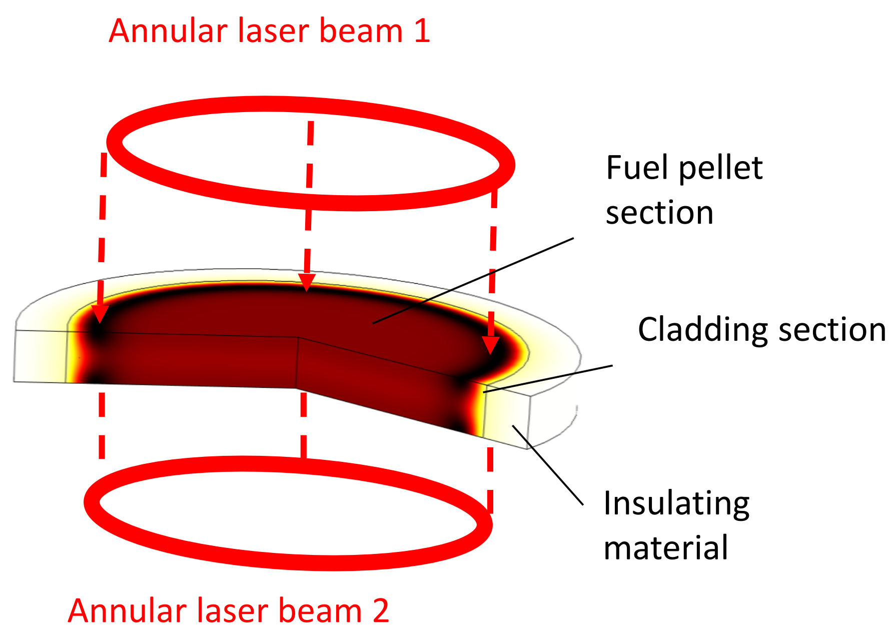
Ejection of a control rod leading to a fast rise of nuclear power and of temperature in the fuel.



Simulations of a RIA event with ALCYONE(2), a fuel performance code developed by the CEA, EDF and FRAMATOME.

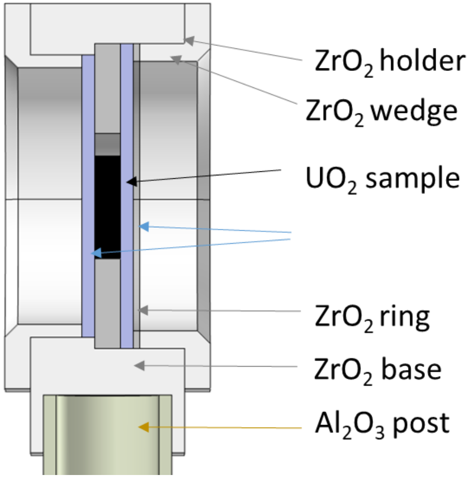
UO_2

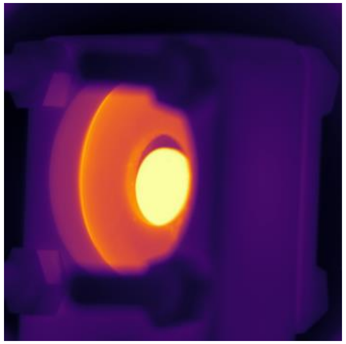
Concept of a thermal transient induced by laser



UO_2
« RIA » Experiment

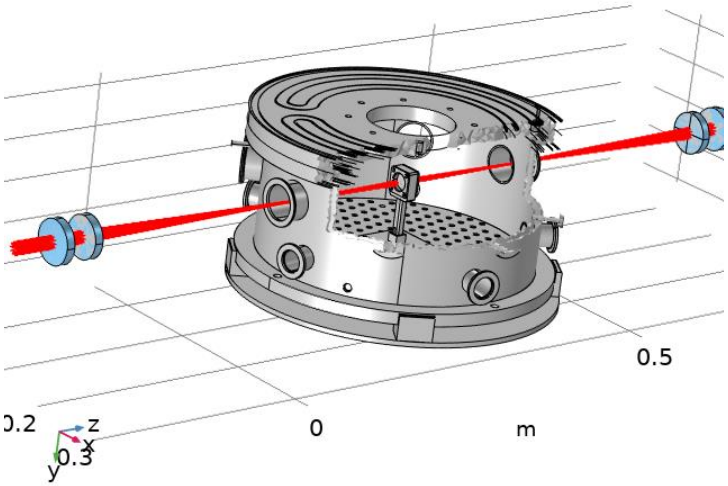
Sample holder



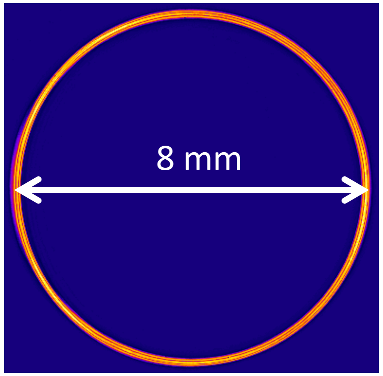


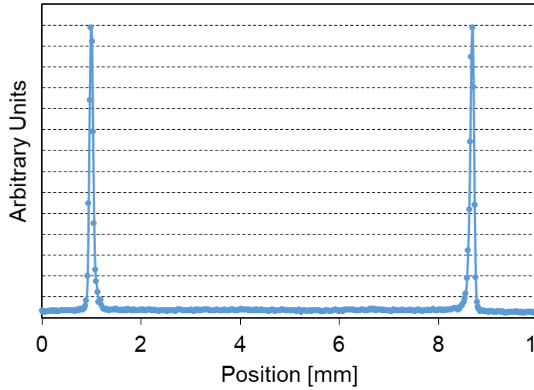
UO_2 sample at 800°C

Experimental configuration



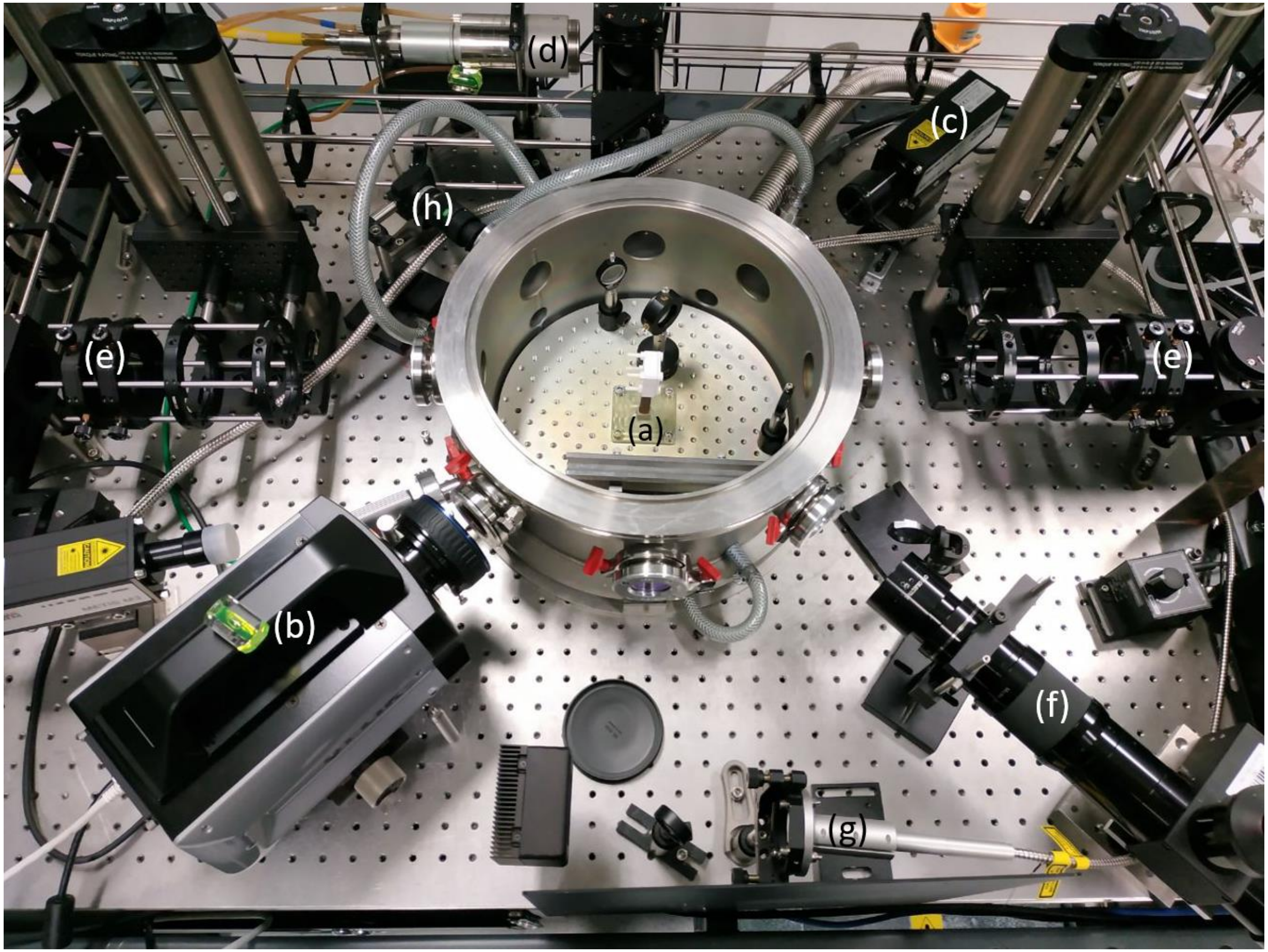
Beam shaping





UO_2

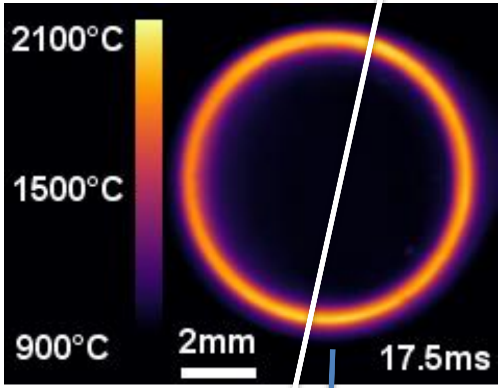
« RIA » Experiment

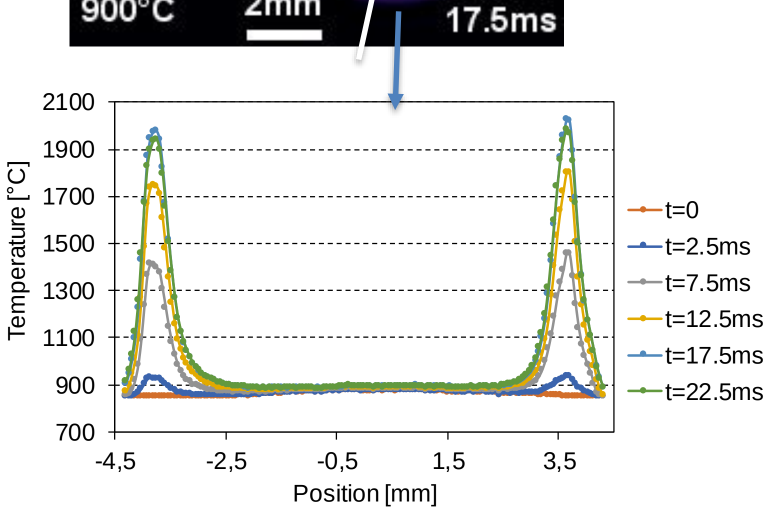


UO_2

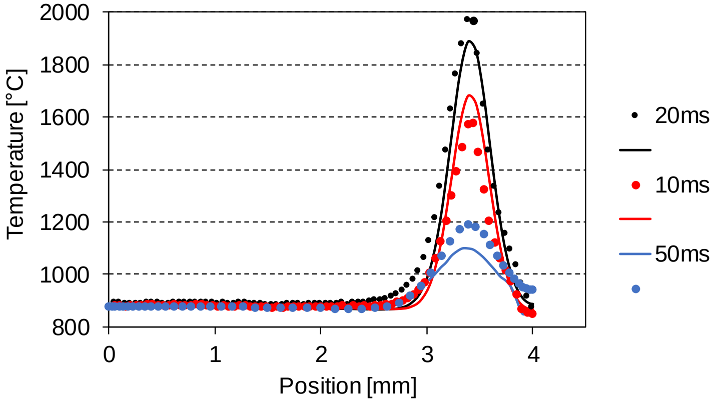
« RIA » Experiments - Results

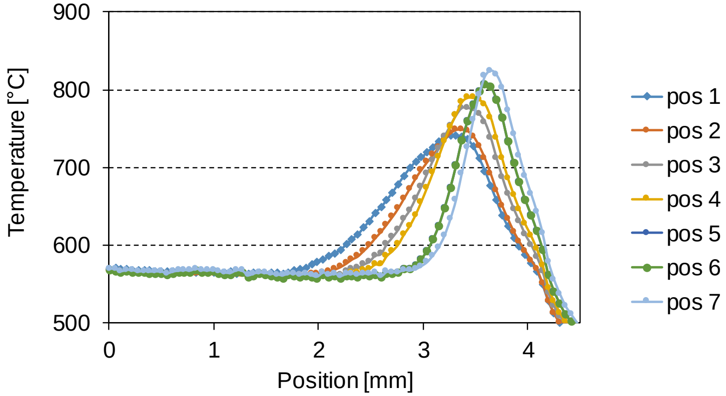
UO_2 sample submitted to a 470 W annular beam irradiation during 20 ms on both sides.





Comparison simulation / experiments





T. Vidal, et al, 'Simulation of reactivity initiated accident thermal transients on nuclear fuels with laser remote heating', Journal of Nuclear Materials 530, 151944 (2020)

UO_2

Perspectives

CHARTREUSE Laser Platform at CEA Cadarache

Laser experiments on irradiated fuels in hot laboratory

Conclusions & Perspectives

- Laser remote heating is an efficient and simple solution for studies of materials at very high temperatures

- The laser material interactions must be well controlled and understood for a correct interpretation, which can be challenging at high temperature

- Perpectives of this work should be the measurement of optical and thermal properties at high temperature