SURFACE TEMPERATURE MEASUREMENT ON PLASMA FACING COMPONENTS IN FUSION DEVICES

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OUTLINE

• Introduction

• Monitoring surface temperature in tokamak
  ➢ Carbon on Tore Supra
  ➢ Be and W on JET

• Challenge of PFC control in ITER

• WEST project

• Lab development on metallic PFC Ts monitoring
  - Bicolor camera
  - Active IR thermography

• Conclusion
What is fusion?

The energy of the stars …
Fusion on earth: the magnetic trap

- Tokamak:
  - external coils $\Rightarrow$ toroidal field
  - plasma current $I_p$ $\Rightarrow$ poloidal field
Edge plasma:

- exhaust heat fluxes (~ 10 MW/m²)
- exhaust the reaction ashes (He)
- without perturbing core plasma performance (impurities)
PFCs MONITORING on TORE SUPRA

Endoscopes and IR cameras
(3-5µm – τ=20ms – 10mm)

- Actively cooled Toroidal Pumped Limiter
- 3 ICRH antennae
- 2 LHCD launchers

RT control required/mandatory for PFCs protection
REAL TIME CONTROL ON ICRH POWER

1. Before plasma discharge
   • Definition of region of interest (ROI)
   • Temperature threshold for each ROI

2. Real Time
   • Extraction of $T_{\text{max}}$ in each ROI
   • If $T_{\text{max}} > T_{\text{threshold}}$ → Warning to RTC system

Accurate $T$ measurements for
Protection of PFCs and scenario development
Routinely operated in Tore Supra
IR cameras demonstrated to be robust
First wall:
Be
Surface temperature < 900°C

Divertor:
W coating on CFC
Surface temperature < 1200°C

Bulk W
Surface temperature < 3400°C

Inertial PFCs.
RT protection required for avoiding damages
Safety system based on 3 systems

- **Thermocouples**

- **8 bicolor pyrometers** (IMPAC: IGAR 12-LO)
  
  1.52 and 1.64 µm
  
  Temperature range 400°C - 1277°C

- **13 CCD Cameras** equipped with filters
  
  \( \lambda = 981\text{nm} \); \( \Delta \lambda = 10\text{nm} \)
  
  \( \lambda = 1016\text{nm} \); \( \Delta \lambda = 80\text{nm} \)
Defining ROI

Excluded area

ROI with 3 different areas

Ex: View of the divertor KL1
Pulse 80455  
T = 61.17 s

From Camera (DL) ➔ Real Time treatment ➔ Warning VTM ➔ Actuator (Plasma moved)

E. GAUTHIER
SFT, Paris 13 Février 2014
- However...limits/thresholds not always detected

- Local melting due to off-normal events and prolonged heated limiter tests (high elongation limiter plasmas at low $q_{95}$ with $P_{IN}=5$MW for 7.5s)
HIGH HEAT FLUX TESTS ON BE TILE

P : 2 - 7 MW/m²
t : 0-5s
To : 20 - 400°C
#207071

ε = 0,25

To = 370°C

P = 5.2MW/m²

Δt = 1.7s
IR IMAGE ON BE TILE

#207179
ε = 0,25
To = 470°C
P = 7.5 MW/m²
Δt = 3.3s

melting ?

2λ pyrometry
DEDICATED W MELTING EXPERIMENT

Exposed edge 2.4mm

Angle to surface 2.5°

Exposed edge 0.25mm

One expose lamella
Ydimension 5.9 mm
Xdimension 58 mm
DATA PROCESSING ON THE REFERENCE LAMELLAS

Field of view of KL9A (L-mode, JPN 84514)

Flat lamellas (#10 - #13)

Shaped lamellas (#15 - #22...)

Wetted area
Temperature evolution on the special Lamella for three different durations. The two longest exposures showed signs of melting.
Melting experiment successful... BUT

$T^\circ \text{measured by IR} \sim 2300^\circ C$

$T^\circ \text{corner} \sim 3250^\circ C$ (inter-ELM, close to melting point)

$T^\circ \sim 3400^\circ C$ (reached during ELM and melting point reached)
Materials for ITER

First wall: Be (700 m²)
- Moderate heat flux
- Low Z, oxygen getter: control of impurity content
  ⇒ plasma performance

Divertor: W (150 m²)
- High heat flux
- High erosion threshold
  ⇒ life time + T retention
440 Blanket modules

**WEST : risk minimisation in support of ITER divertor strategy**

 spoiler

**Keys figures for ITER divertor risk analysis**

- Cost > 100 M€
- Manufacturing: ~ 6 to 8 years
- Installation and commissioning: ~1 year

R. Pitts, SWIP CFS, March 2013
WEST: in support to the ITER divertor strategy

- WEST: scale 1 of high heat flux flat part of ITER divertor target
- >15 000 W monoblocks (~14 % ITER)

First integrated test in tokamak environment

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<th>WEST vs ITER</th>
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<td>Monoblock geometry and shape</td>
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<td>Assembling technology</td>
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WEST Plasma Facing Components: full metallic actively cooled environment

- Water cooled Stainless steel panel
- Upper target W-coating
- Ripple/VDE protection W-coating
- Bumper W-coating
- Water cooled Stainless steel panel
- Lower target W-coating
- Baffle W-coating
- ITER Divertor Technology

**ITER requirement:**

- * 10 MW/m² in steady state
- 20 MW/m² in slow transient (< 10s)
Filtering the electrical signal

\[ S_{\lambda} \propto \varepsilon_{\lambda} L_{\lambda}^o (T_o) + (1 - \varepsilon_{\lambda}^\prime) \varepsilon_{\lambda} L_{\lambda}^o (T_s) + Brem_{\lambda} (Plasma) + \dot{\varepsilon}_{\lambda} \frac{\partial L_{\lambda}^o}{\partial T} (T_o) \Delta T(t) \]

\[ \text{Emission} \quad \text{Reflexions} \quad \text{Parasitic} \]

\[ \text{Cst} \]

\[ \text{Filtering the electrical signal} \rightarrow \text{Separation of emission } f(t) \quad \text{reflection (Cst)} \]
How to deduce $T_0$?

$$S_\lambda(t) = D_\lambda \varepsilon_\lambda \Delta \Omega \tau_\lambda \Delta \lambda \frac{\partial L_o^\lambda}{\partial T}(T_o) \Delta T(t)$$

Measurement at two $\lambda$ and ratio:
- $\Delta T$ “disappears”
- $\varepsilon_{\lambda 1}/\varepsilon_{\lambda 2}$ known

$$\frac{S_{\lambda_1}}{S_{\lambda_2}} = \frac{D_{\lambda_1} \tau_{\lambda_1} \Delta \lambda_{1}}{D_{\lambda_2} \tau_{\lambda_2} \Delta \lambda_{2}} \frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_2}} \frac{\partial L_o^{\lambda_1}}{\partial T}(T_o) \frac{\partial L_o^{\lambda_2}}{\partial T}(T_o)$$

- Constant value $\Rightarrow R = f(T_o)$
- $\lambda_1, \lambda_2 \Rightarrow T$ detection range
IR ACTIVE PYROMETRY BENCH

Vacuum vessel

IR source

2D IR camera
$\lambda = 3.97 - 4.01 \, \mu m$
IR ACTIVE PYROMETRY BENCH

YAG laser

D2
\( \lambda = 2.35 \text{ \(\mu\)m} \)

D1
\( \lambda = 3.42 \text{ \(\mu\)m} \)

IR detectors
Objectif: Demonstrate active thermography unaffected by reflected flux

Material: Aluminium (polished)

Standard thermography IR camera, **bicolor measurements** and **active thermography measurements**

Active 2-wavelength thermography **unaffected** by reflected flux
So far, Real Time control of PFC in tokamaks performed by standard IR thermography, but

- Occasional melting of Be
- Large uncertainties on surface temperature on W
- Control of PFC in ITER is very challenging
- R&D needs on accurate temperature measurement on W & Be in tokamak environment