

# 第16回 ITPA (SOL/DIV) の概要

(ITER divertor strategy, W melting,  
W fuzz, W HHF testing)

上田良夫(大阪大学)

PWI 合同研究会  
平成24年 7月23日- 24日

筑波大学プラズマ研究センターシンポジウム  
プラズマ物理クラスター スクレープオフ層とダイバー タ物理サブクラスター(第1回会合)  
炉工学クラスター ブランケット サブクラスター(第2回会合)  
双方向型共同研究会合「ガンマ10装置における炉壁材料の損耗・再堆積の研究と  
そのダイバータ開発戦略における位置づけ」

## January 18 (Wed)-19 (Thu)

|                                     |                |                                                                                     |
|-------------------------------------|----------------|-------------------------------------------------------------------------------------|
| <b>Update on ITER / JET</b>         |                | Chair -E. Tsitrone                                                                  |
|                                     | R. Pitts       | <b>ITER divertor strategy</b>                                                       |
| <b>Tungsten melting experiments</b> |                | Chair A. Kallenbach                                                                 |
|                                     | J. Coenen      | W melt experiments in <b>AUG</b> and <b>Textor</b>                                  |
|                                     | B. Lipschultz  | <b>C-mod</b> results on W melting                                                   |
|                                     | B. Basylev     | <b>Modeling of W melting experiments</b> and extrapolation for <b>ITER</b>          |
| <b>Tungsten fuzz</b>                |                | Chair Y. Ueda                                                                       |
|                                     | G Wright       | W fuzz in <b>Alcator C-Mod</b> and comparison of the role of He with linear devices |
|                                     | G de Temmerman | Behavior of a helium-modified ( <b>fuzzy</b> ) <b>surface</b> during transients     |
| <b>Tungsten HHF testing</b>         |                | Chair Y. Ueda                                                                       |
|                                     | H. Greuner     | <b>Damage studies</b> on different W grades with GLADIS                             |
|                                     | E. Tsitrone    | <b>HHF testing</b> of <b>ITER</b> components                                        |
|                                     | G de Temmerman | Tungsten damage under <b>simultaneous steady-state and transient loads</b>          |
|                                     | J. Linke       | <b>Damage threshold</b> for W under <b>ELM-like</b> thermal loads                   |

# 各セッションのまとめ

---

## □ ITER divertor strategy

- ITERのWダイバータ検討の現状

## □ Tungsten Melting

- TEXTORやAUGでの、リーディングエッジの溶融実験 (後述)
- C-ModにおけるWタイル溶融層の挙動とプラズマへの影響

## □ Tungsten Fuzz

- C-ModにおけるFuzz生成実験→Fuzz様表面が閉じ込め装置で形成された (後述)
- Pilot-PSIによるFuzzの形成とパルス熱負荷影響
  - あるエネルギー以上のELM様熱パルスで消失(W放出なし)

## □ Tungsten HHF Testing

- GLADIS(イオンビーム装置)照射によるWの表面状態変化
- EUが行ったHHFの熱負荷試験の結果 (後述)
- 定常+ELM様プラズマパルスによる異常損耗 (後述)
- 電子ビームによるELM様熱パルス繰り返し照射効果のまとめ



TRILATERAL  
EUREGIO CLUSTER



# W melt-experiments in ASDEX Upgrade and TEXTOR

J.W. Coenen<sup>(1\*)</sup>, Karl Krieger<sup>(2)</sup> and Contributors

(\*) EFDA Fusion Researcher Fellowship

(1) Institut für Energie und Klimaforschung - Forschungszentrum Jülich GmbH, Germany

(2) Max-Planck Institut für Plasma Physik, Garching Germany

**ITPA 2012 - Jülich**

Part of DSOL-25

## ITER Standard Scenario

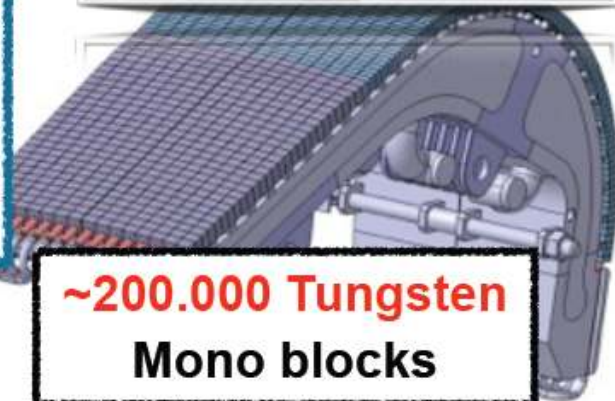
$Q_{DT}=10$  ,  $I_p=15\text{MA}$  ,  $B_{Tor}=5.3\text{T}$

Steady-state heat loads  $q_{\perp} \sim 10\text{-}20\text{MW/m}^2$

Transient heat loads  $\sim \text{GW/m}^2$

ELMs:  $\tau_{\text{rise}} \sim 0.5\text{ms}$  ,  $2.1\text{ MJ/m}^2$

Disruptions:  $\tau_{\text{rise}} \sim 2.5\text{ms}$  ,  $>2\text{ MJ/m}^2$

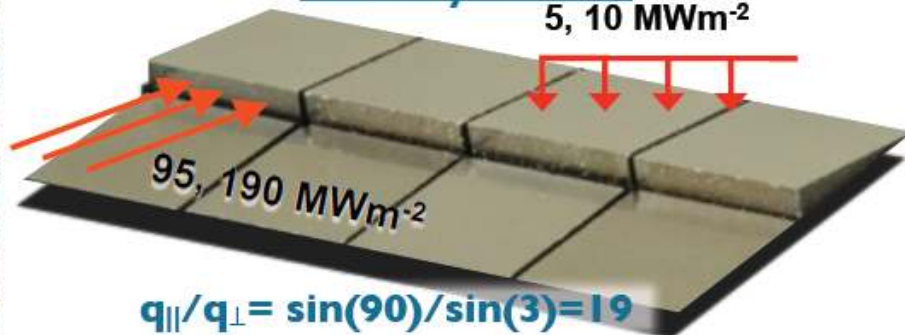


**~200.000 Tungsten  
Mono blocks**

$\alpha = 3^\circ$

Steady State

5, 10  $\text{MWm}^{-2}$



$$q_{\parallel}/q_{\perp} = \sin(90)/\sin(3) = 19$$

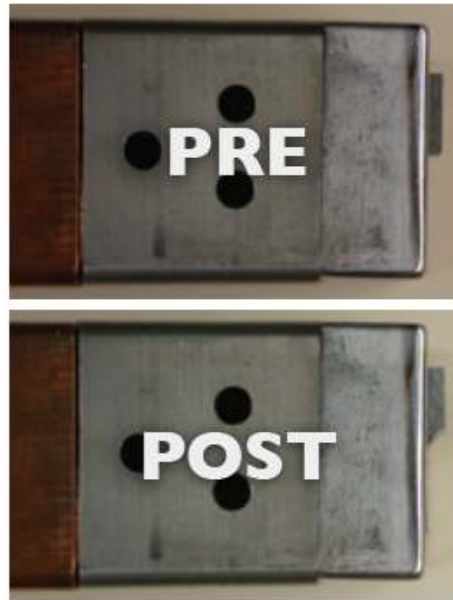
**Monoblocks can tolerate 0.3  
mm offsets at  $10\text{MW/m}^2$**

Tolerances: Neighbouring blocks  $< 0.3\text{mm}$

## Transients

Unmitigated ITER non-active phase ELMs will damage monoblock edges **and** front surfaces

# Melting



PRE



POST

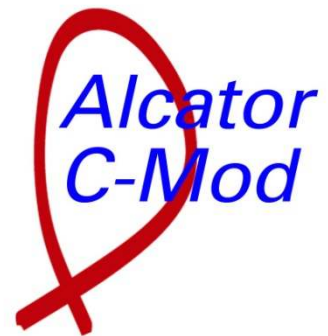


- Melt is flowing following  $j \times B$  down into the Divertor
- Leading edge is not smoothed but persists
- Molten material is now impacted by  $q_{||}$  in subsequent shots – responsible for discharge terminations ?

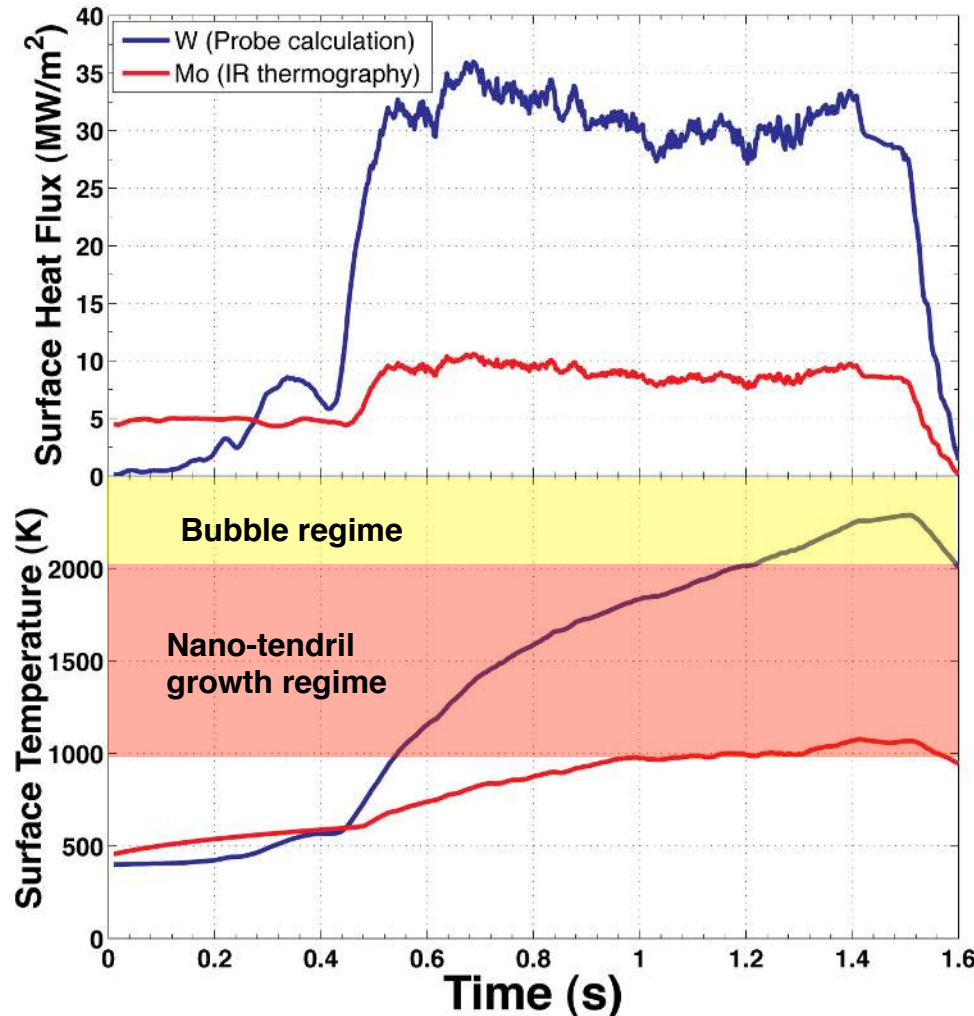
# Tungsten nano-tendrils growth in the Alcator C-Mod Divertor and the role of He

**G.M. Wright**, D. Brunner, B. LaBombard, B. Lipschultz, J.L. Terry,  
and D.G. Whyte

Plasma Science & Fusion Center, MIT, Cambridge USA



# Tungsten probe reached and exceeded surface temperatures required for fuzz growth



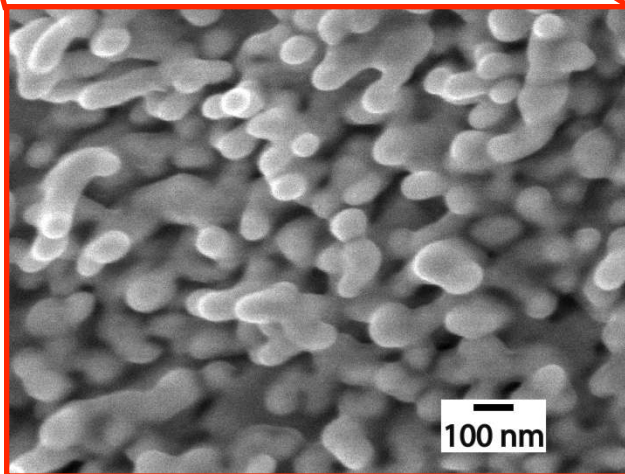
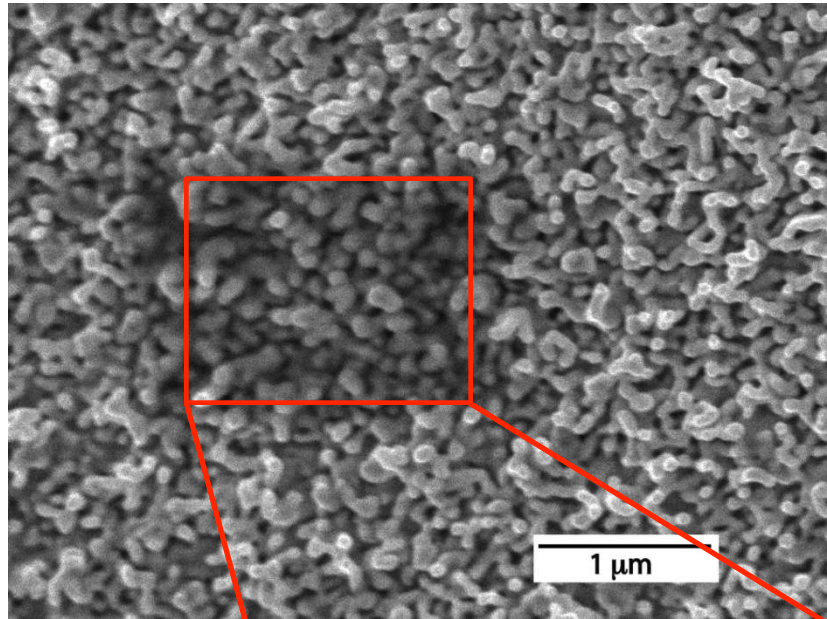
W probe ramped  $\sim 11^\circ$  into parallel heat flux and is electrically/thermally isolated. Mo tiles are grounded and ramped at  $\sim 2^\circ$

→ W probe intercepts significantly more parallel heat flux and *rapidly* reaches **higher surface temperatures**.

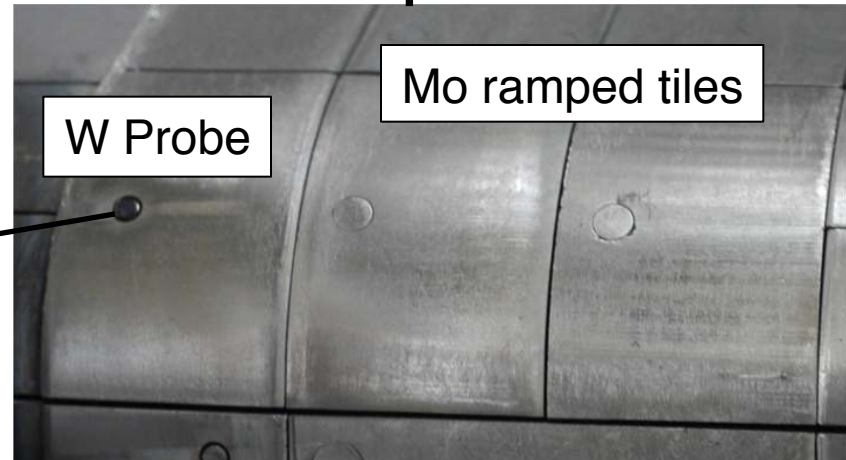
Surface heat flux is obtained directly from probe measurements. W probe  $T_{\text{surf}}$  is determined from 1-D heat flux modeling. Mo tiles  $T_{\text{surf}}$  determined with IR thermography

Note: Surface continues to be modified at  $T_{\text{surf}} > 2000$  K but the morphology changes

# Nano-tendrils are fully formed on surface of the tungsten probe exposed to heat fluxes of 30-40 MW/m<sup>2</sup>



After exposure



Thickness of individual tendrils is 50-100 nm, which is thicker than tendrils grown in linear devices (20-30 nm)

# High Heat Flux Testing of ITER tungsten plasma facing components

E. Tsitrone on behalf of M. Missirlian

- **CEA Cadarache, PFC Team :**  
M. Richou, C. Desgranges, N. Vignal, V. Cantone



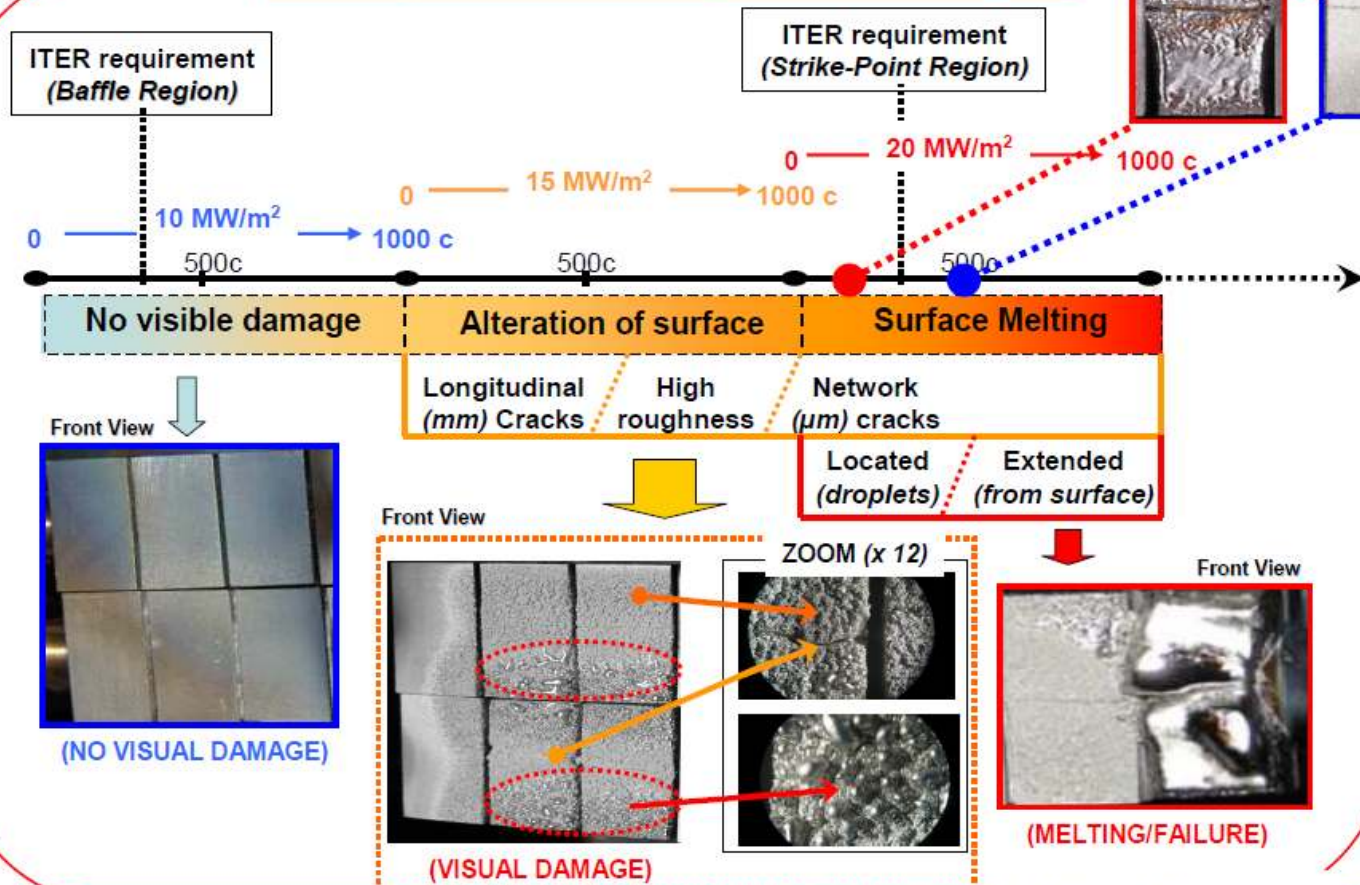
*In collaboration with :*

- **AREVA-NP, FE200 Team** (*Le Creusot, France*)  
S. Constans, I. Bobin, J.L. Jouvelot
- **F4E, Divertor Team** (*Barcelona, Spain*)  
B. Riccardi, P. Gavila



*\*This work was supported by the European Communities under the contract (F4E-2008-GRT-05) between F4E and CEA*

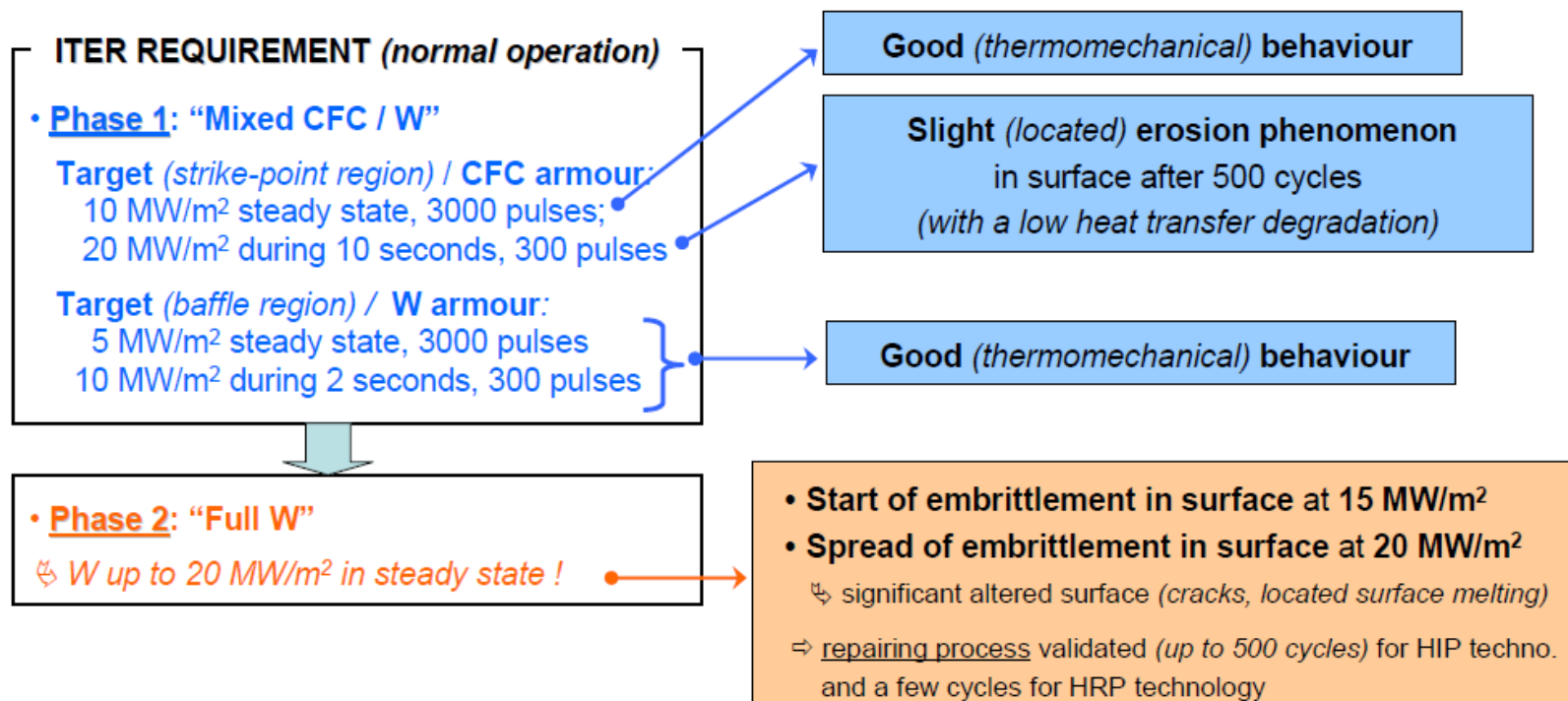
## Summary of events during the thermal fatigue\*



## ♦ Qualification of CFC/W components *after* Manufacturing Phase

↳ **Good bonding quality** of CFC/W armoured components including recent/consolidated (European) development: **Optimization/Reliability of bonding technologies, Repairing process**

## ♦ Damage valuation *after* thermal cycling (up to 20 MW/m<sup>2</sup>) in steady state





# *Tungsten damage under simultaneous steady-state and transient loading*

**G. De Temmerman<sup>1</sup>, B. Hensen<sup>1</sup>, K. Bystrov<sup>1</sup>, L. Marot<sup>2</sup>, H.J. van der Meiden<sup>1</sup>, J.J. Zielinski<sup>1</sup>**

*<sup>1</sup>Dutch Institute For Fundamental Energy Research (formerly FOM Institute for Plasma Physics Rijnhuizen), Ass. EURATOM-FOM, Trilateral Euregio Cluster, Postbus 1207, 3430 BE Nieuwegein, The Netherlands*

*<sup>2</sup>Dept of Physics, University of Basel, Klingelbergstrasse 82, Basel, Switzerland*



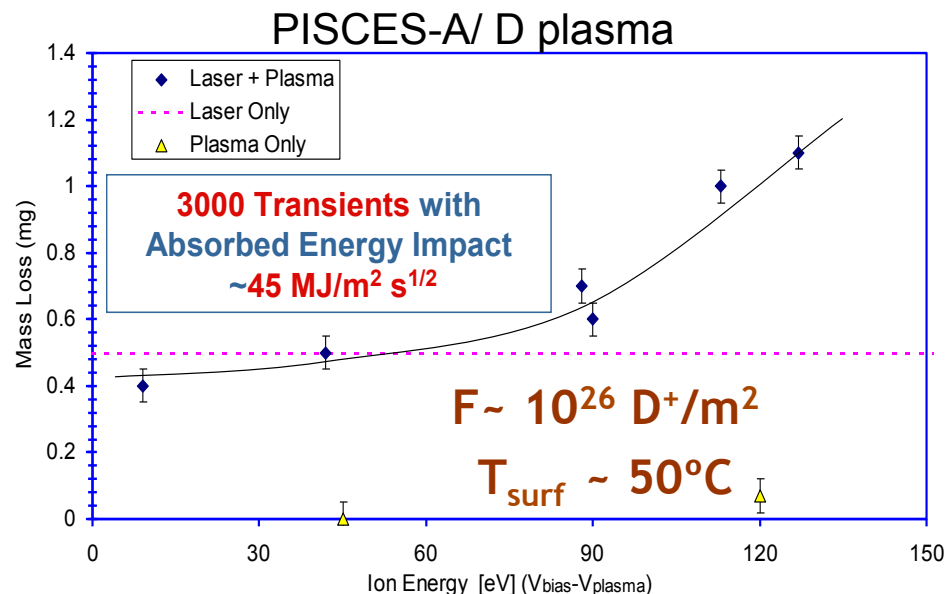
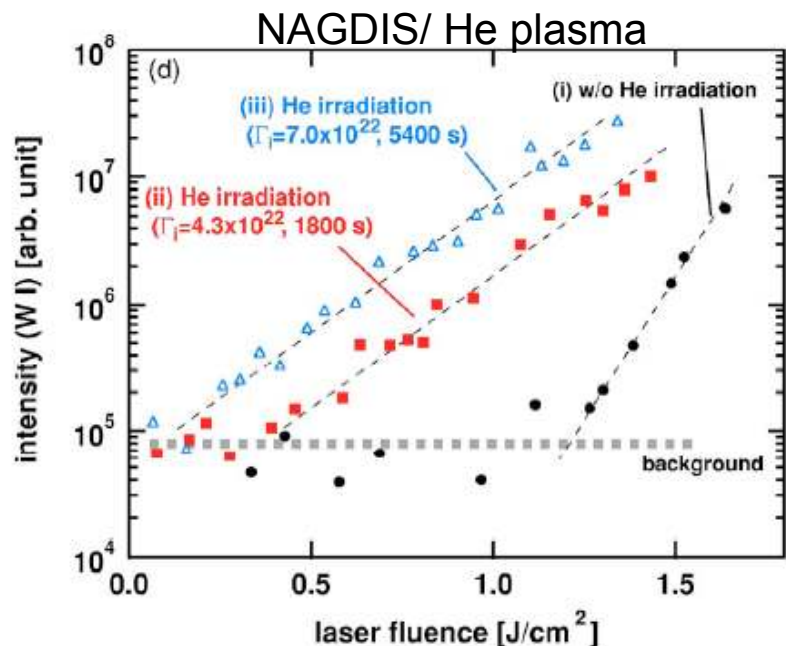
**DIFFER**

Dutch Institute for  
Fundamental Energy Research



# Motivation (2/2)

- Some hints of synergistic effects already observed in NAGDIS/PISCES



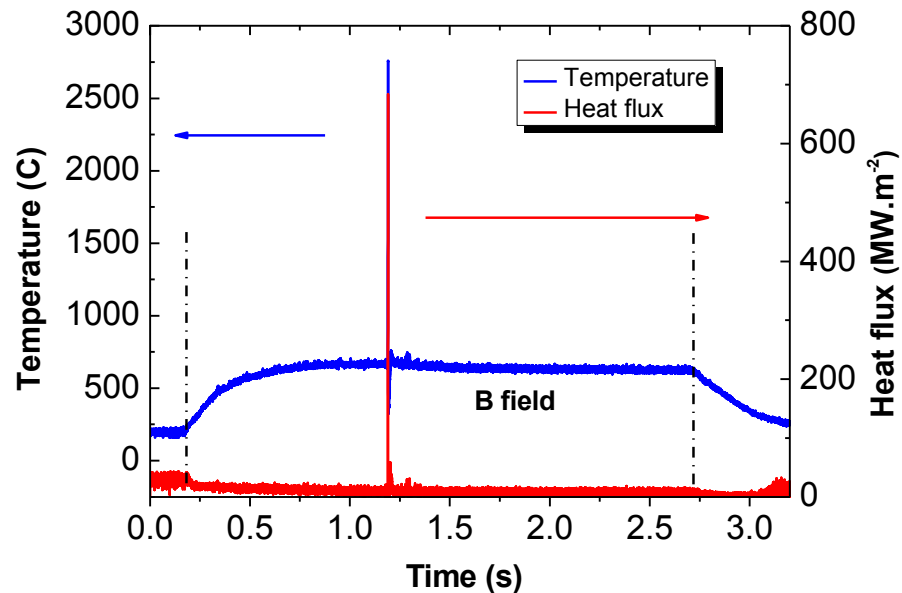
- Need to investigate what happens at higher flux densities
- An ELM is accompanied by significant ion flux (not included in those experiments)

[2] S. Kajita et al, Appl. Phys. Lett. 91 (2007), [3] K. Umstadter et al, Phys. Scr. T138 (2009)

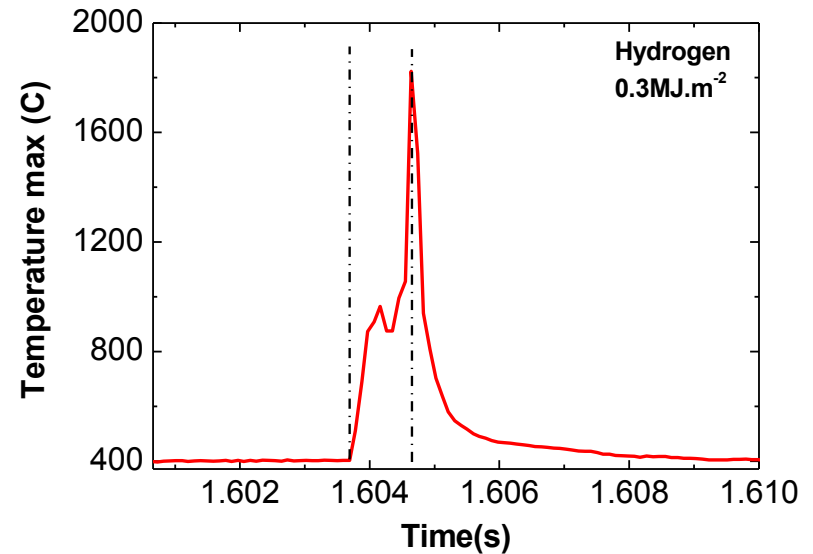


# Experimental procedure

- High speed IR camera (25kHz) to monitor surface temperature



## Peak surface temperature

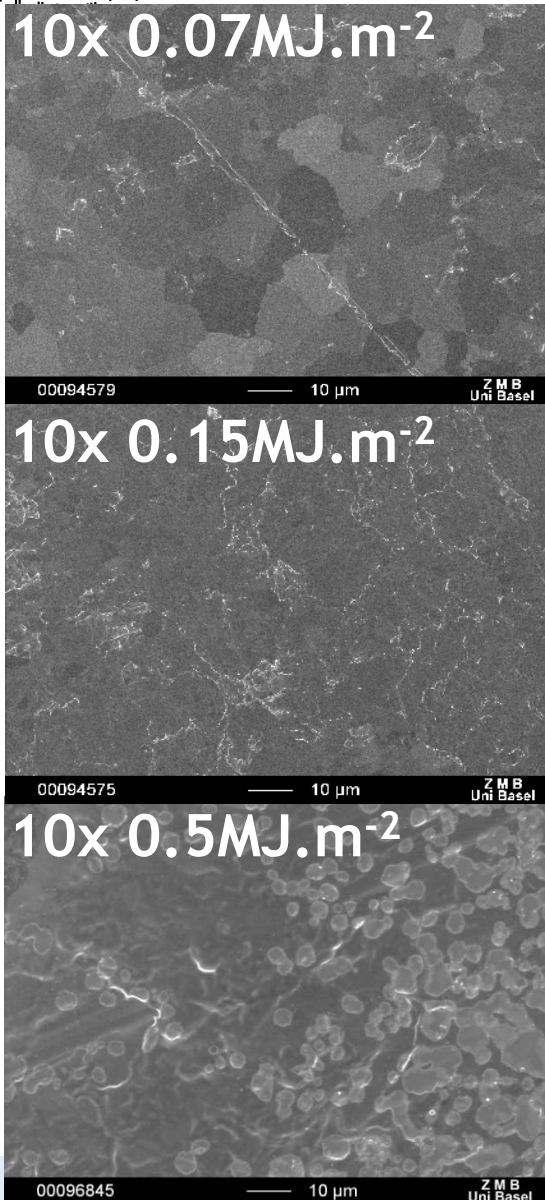


**Temperature risetime: 0.5-1ms relevant for Type-I ELM**

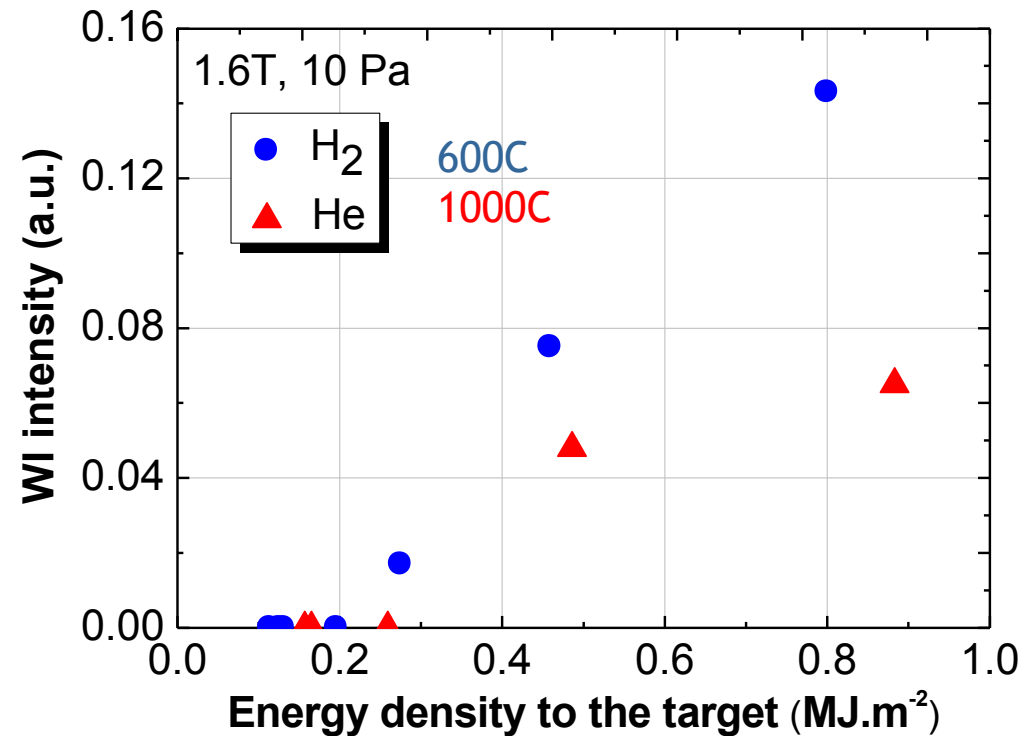
**Superimposition of divertor relevant steady-state plasma and transient heat/particle pulse**



# Plasma-enhanced surface damage



❑ Measured ablation threshold much lower than expected



**Plasma enhanced surface ablation**

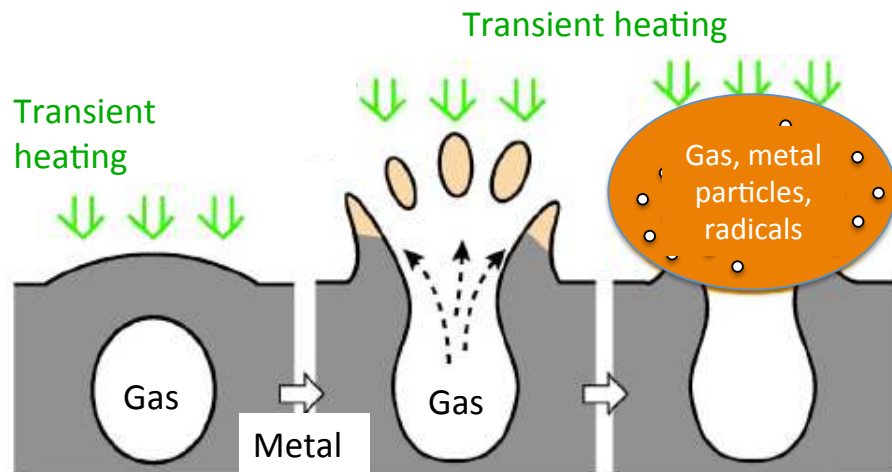
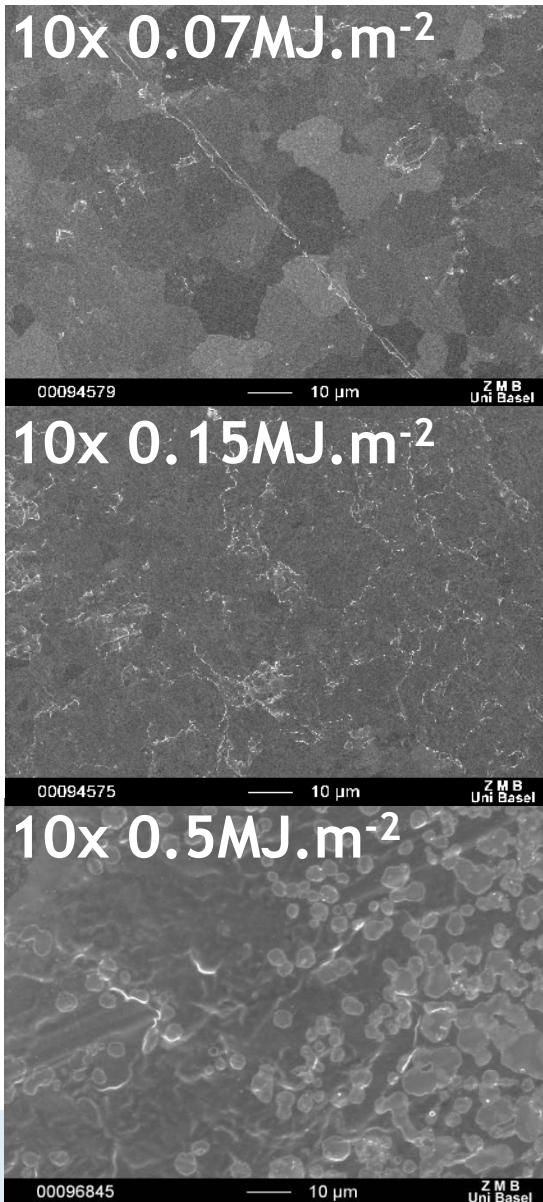
G. De Temmerman et al, IAEA FEC, 2010



# Plasma-enhanced surface damage

## ❑ Synergistic effect:

- ❑ Bubble formation due to high-flux plasma
- ❑ Explosive release of material during transient



**Re-definition of tolerable energy densities in ITER might be necessary**

G. De Temmerman et al, IAEA FEC, 2010