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ューム
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)

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

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W melt-experiments in ASDEX Upgrade and TEXTOR

J.W. Coenen[(1*)], Karl Krieger[(2)] and Contributors

(*) EFDA Fusion Researcher Fellowship
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(2)Max-Planck Institut fuer Plasma Physik, Garchingen Germany

ITPA 2012 - Juelich

Part of DSOL-25

ITER

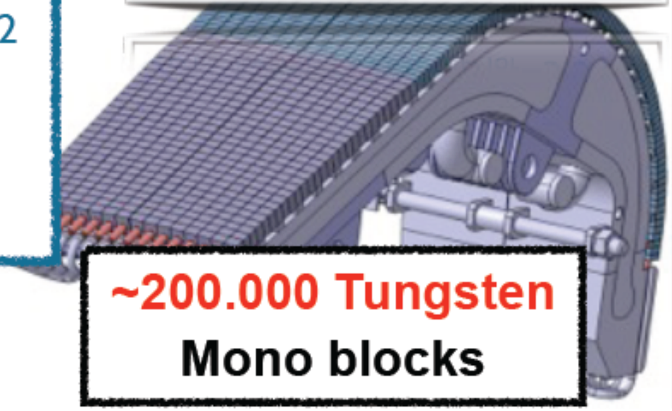
ITER Standard Scenario
$Q_{DT}=10$, $I_P=15MA$, $B_{Tor}=5.3T$

Steady-state heat loads $q_{\perp}\sim$ 10-20MW/m²

Transient heat loads ~GW/m²

ELMs: $\tau_{rise}\sim0.5ms$, 2.1 MJ/m²

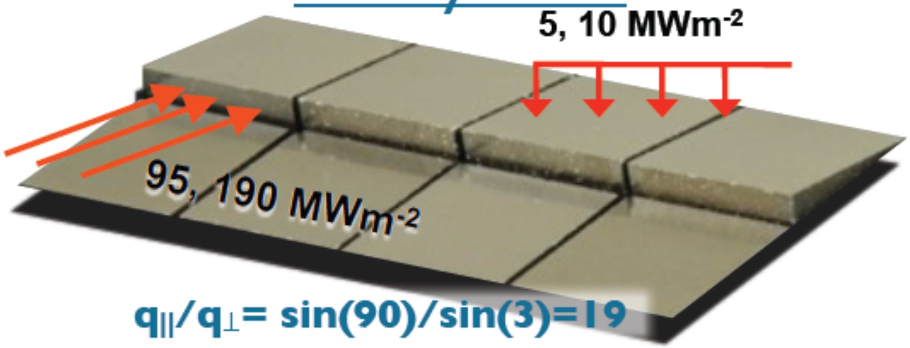
Disruptions: $\tau_{rise}\sim2.5ms$, >2 MJ/m²



~200.000 Tungsten Mono blocks

$\alpha = 3°$

Steady State



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

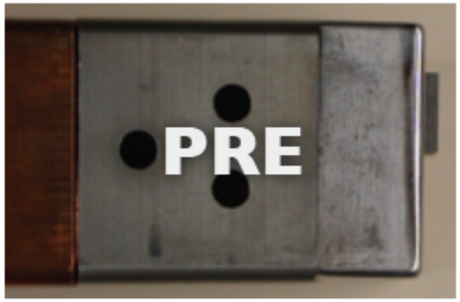
Monoblocks can tolerate 0.3 mm offsets at 10MW/m²

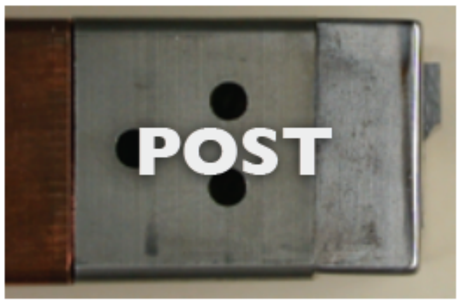
Tolerances: Neighbouring blocks < 0.3mm

Transients

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

Melting





PRE

POST

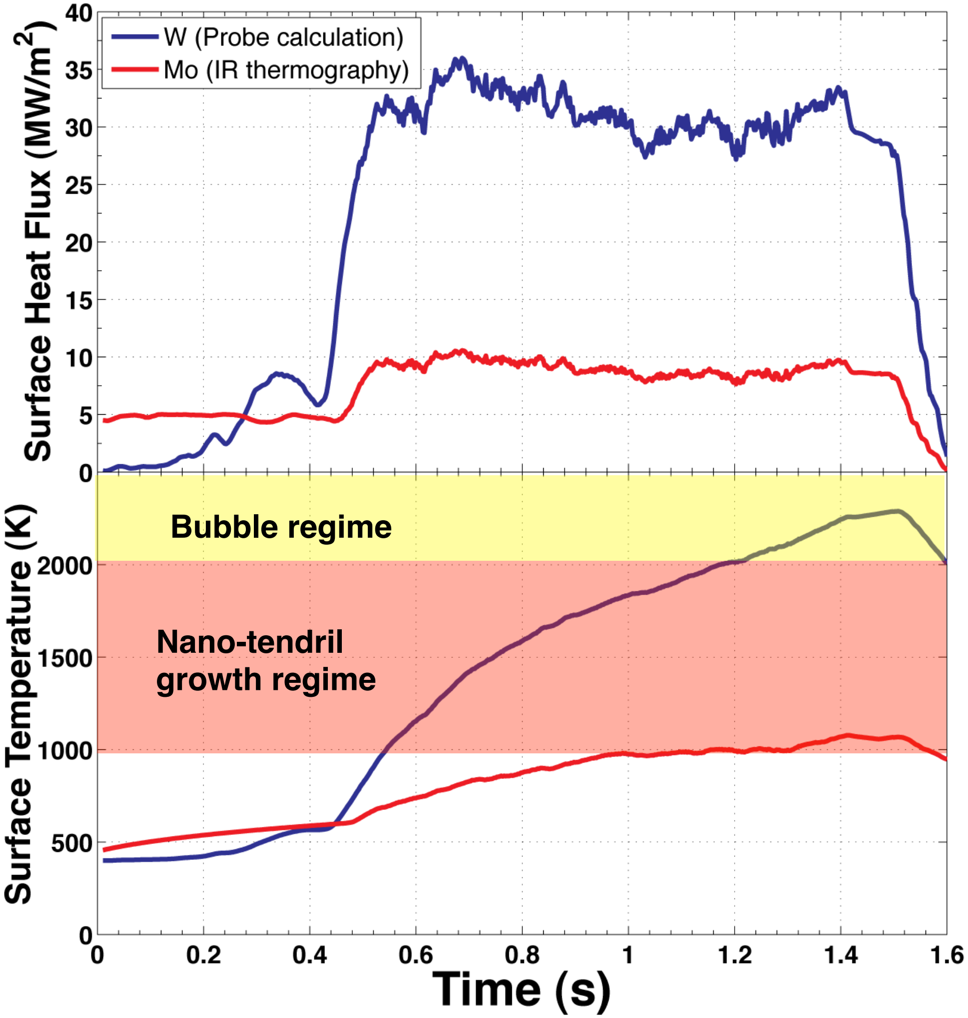
- Melt is flowing following jxB down into the Divertor
- Leading edge is not smoothed but persists
- Molten material is now impacted by $q_{||}$ in subsequent shots – responsible for discharge terminations ?

Tungsten nano-tendril 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



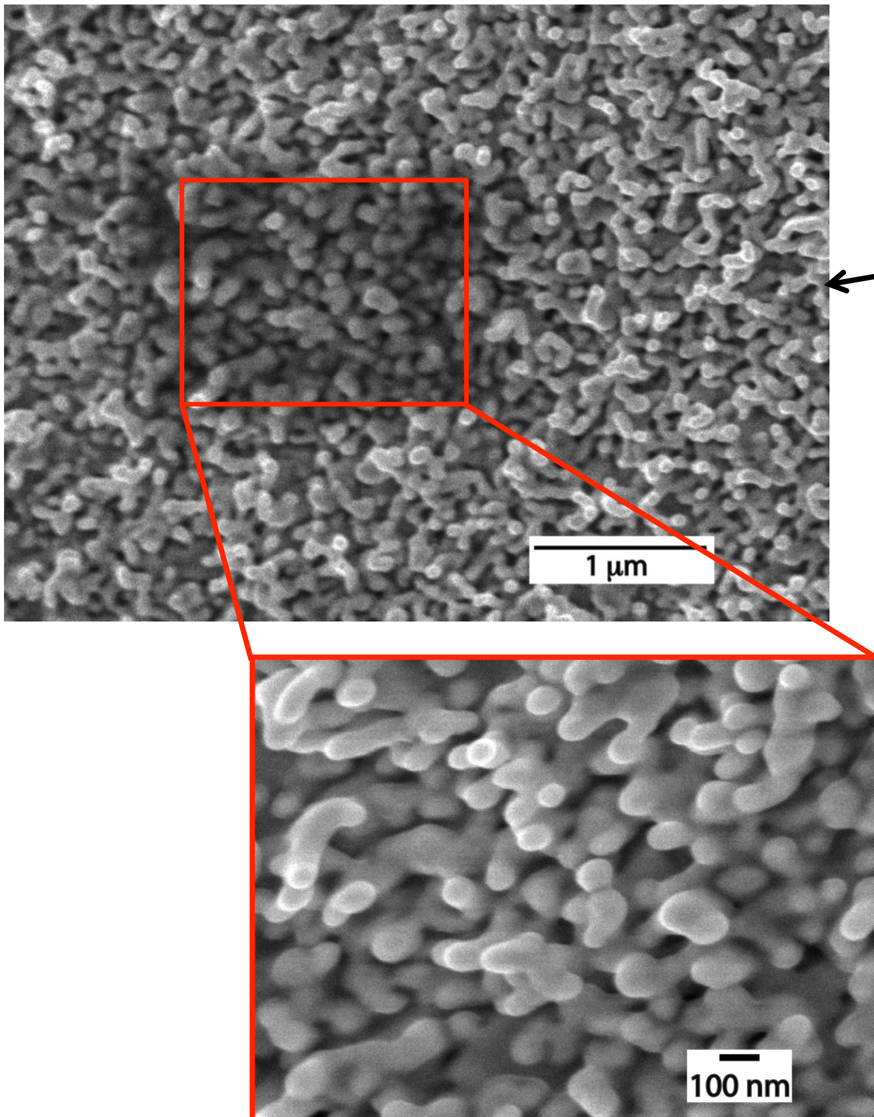
W probe ramped ~11^o into parallel heat flux and is electrically/thermally isolated. Mo tiles are grounded and ramped at ~2^o

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

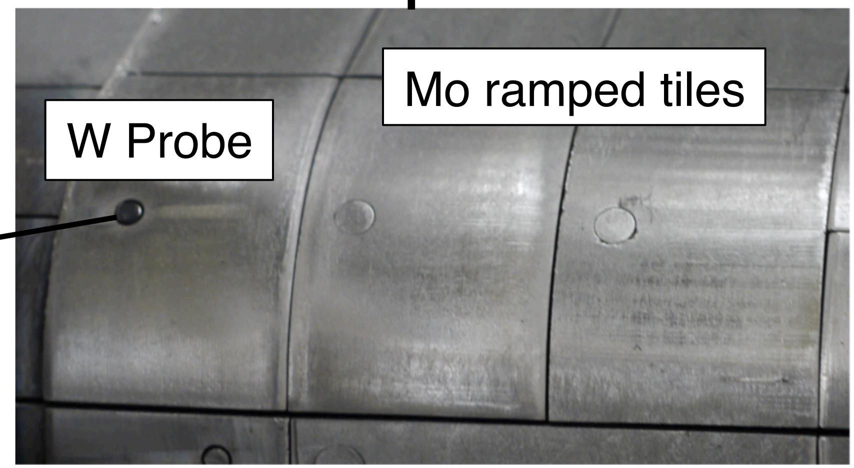
Surface heat flux is obtained directly from probe measurements. W probe T_{surf} is determined from 1-D heat flux modeling. Mo tiles T_{surf} determined with IR thermography

Note: Surface continues to be modified at T_{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^2



After exposure



Thickness of individual tendril 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

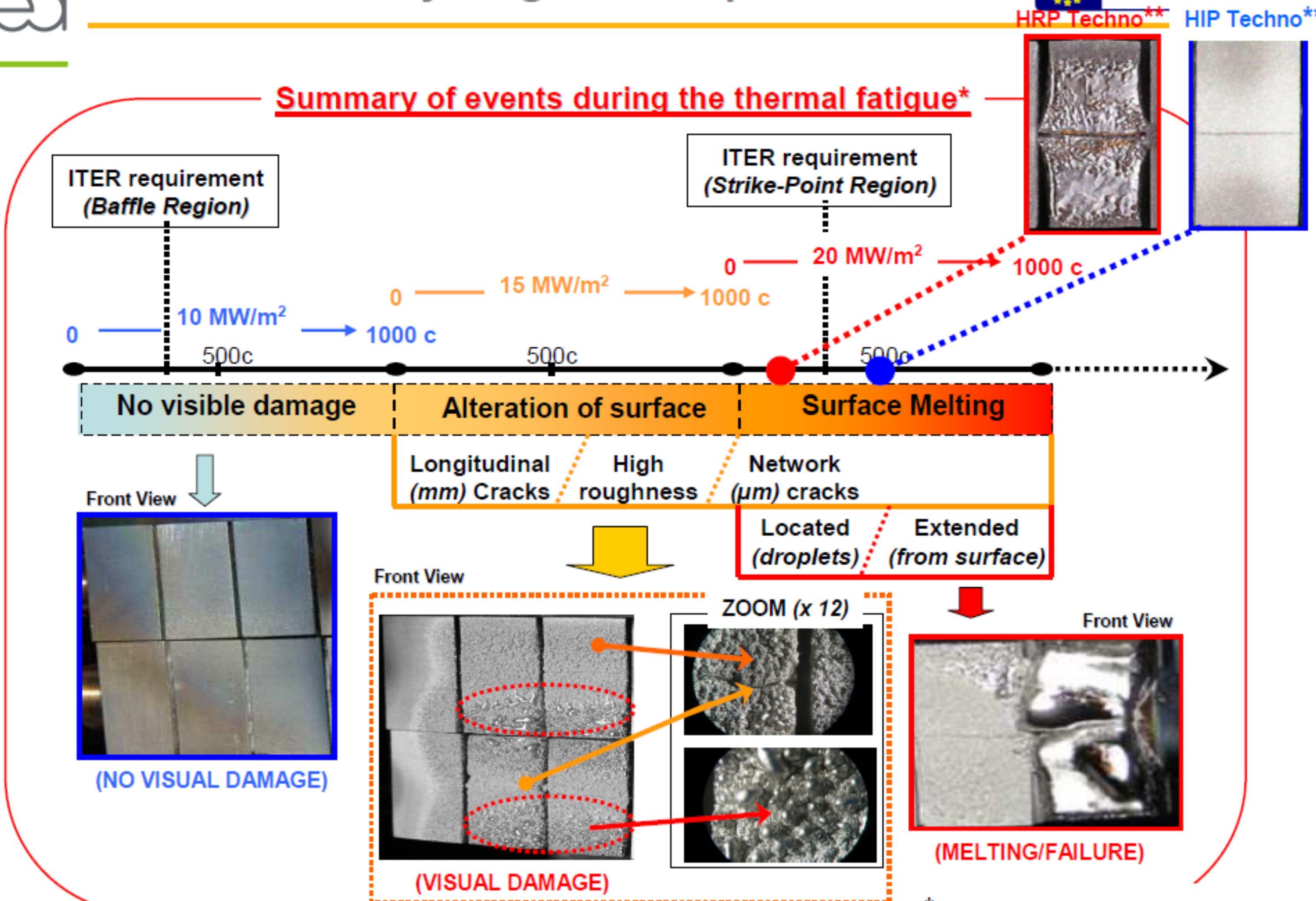
E. Tsitrone on behalf of M. Missirlian

- **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

Thermal cycling : W components



*Ref. P. Gavila (SOFT-2010)

**Ref. M. Richou (SOFT-2010)

Summary & Conclusion

- **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/m²)* in steady state**

ITER REQUIREMENT *(normal operation)*

- **Phase 1: "Mixed CFC / W"**

  Target *(strike-point region)* / **CFC armour**:
  10 MW/m² steady state, 3000 pulses; → **Good** *(thermomechanical)* **behaviour**
  20 MW/m² during 10 seconds, 300 pulses → **Slight** *(located)* **erosion phenomenon** in surface after 500 cycles *(with a low heat transfer degradation)*

  Target *(baffle region)* / **W armour**:
  5 MW/m² steady state, 3000 pulses
  10 MW/m² during 2 seconds, 300 pulses
  → **Good** *(thermomechanical)* **behaviour**

↓

- **Phase 2: "Full W"**
  - ↳ *W up to 20 MW/m² in steady state !* →
    - **Start of embrittlement in surface at 15 MW/m²**
    - **Spread of embrittlement in surface at 20 MW/m²**
      - ↳ significant altered surface *(cracks, located surface melting)*
    - ⇨ repairing process validated *(up to 500 cycles)* for HIP techno. and a few cycles for HRP technology

Tungsten damage under simultaneous steady-state and transient loading

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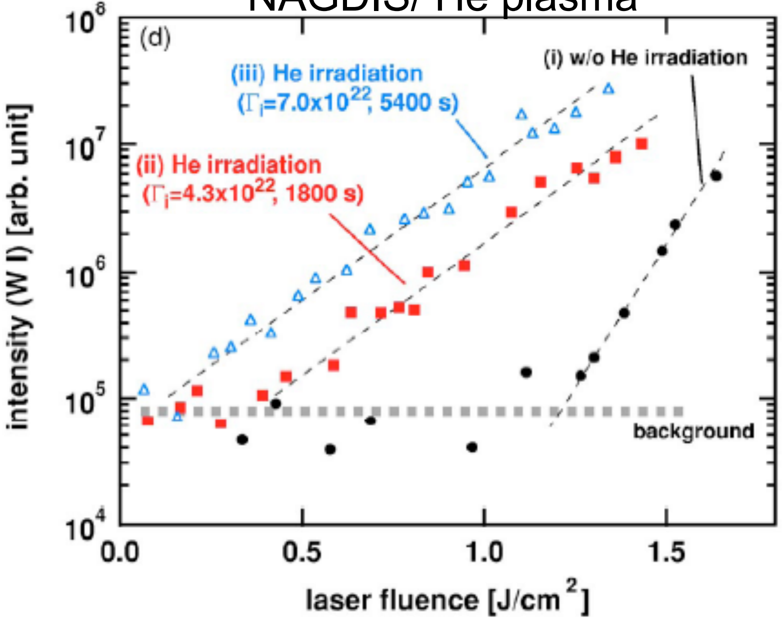
DIFFER
Dutch Institute for Fundamental Energy Research

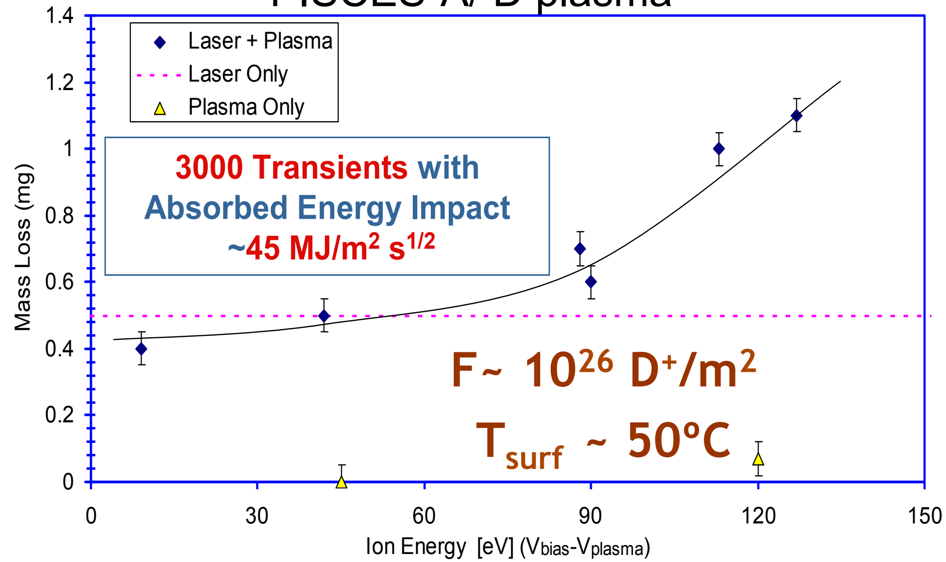
Motivation (2/2)

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

NAGDIS/ He plasma



PISCES-A/ D plasma

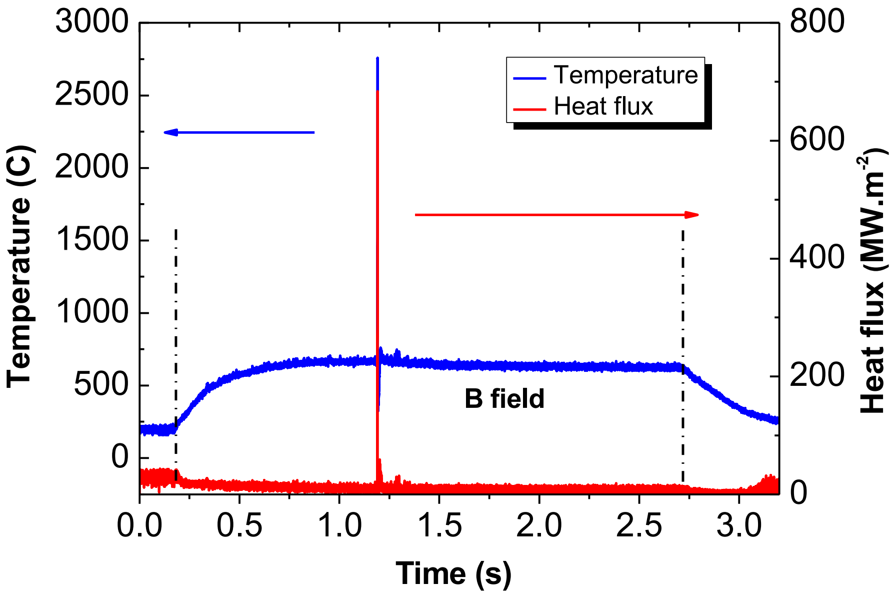


- Need to investigate what happens at higher flux densities
- An ELM is accompanied by significant ion flux (not included in those experiments)

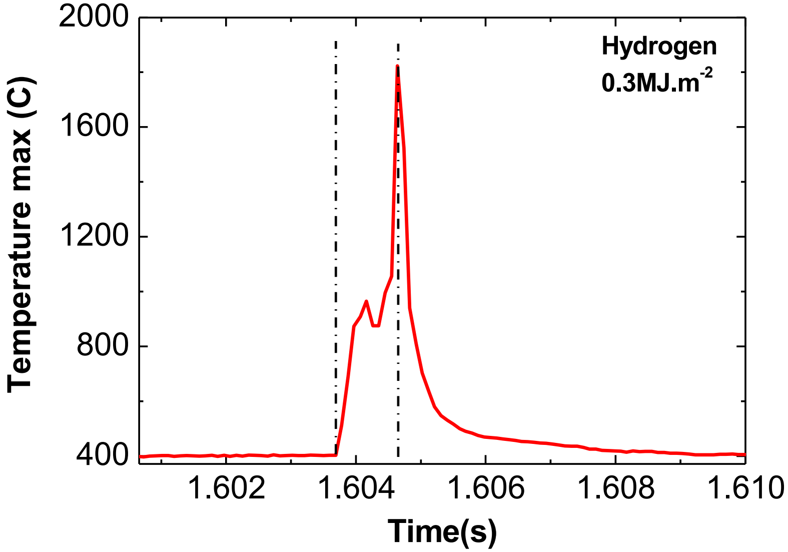
[2] S. Kajita et al, Appl. Phys. Lett. 91 (2007), [3] K. Umstadter et al, Phys. Scr. T138 (2009)

Experimental procedure

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



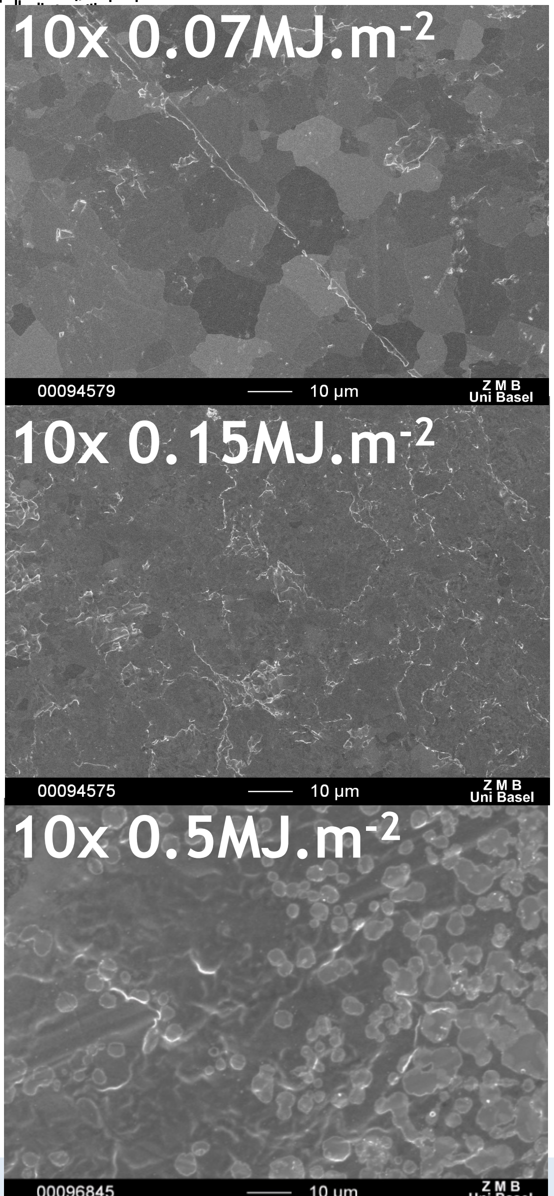
Peak surface temperature



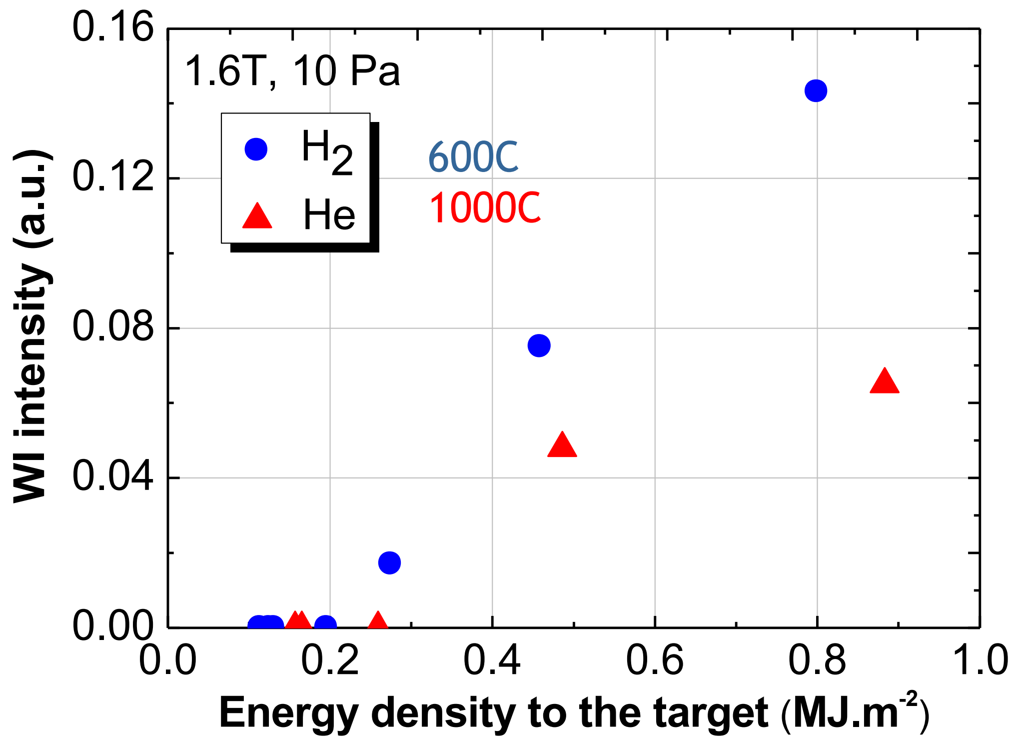
Temperature risetime: 0.5-1ms relevant for Type-I ELM

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

Plasma-enhanced surface damage



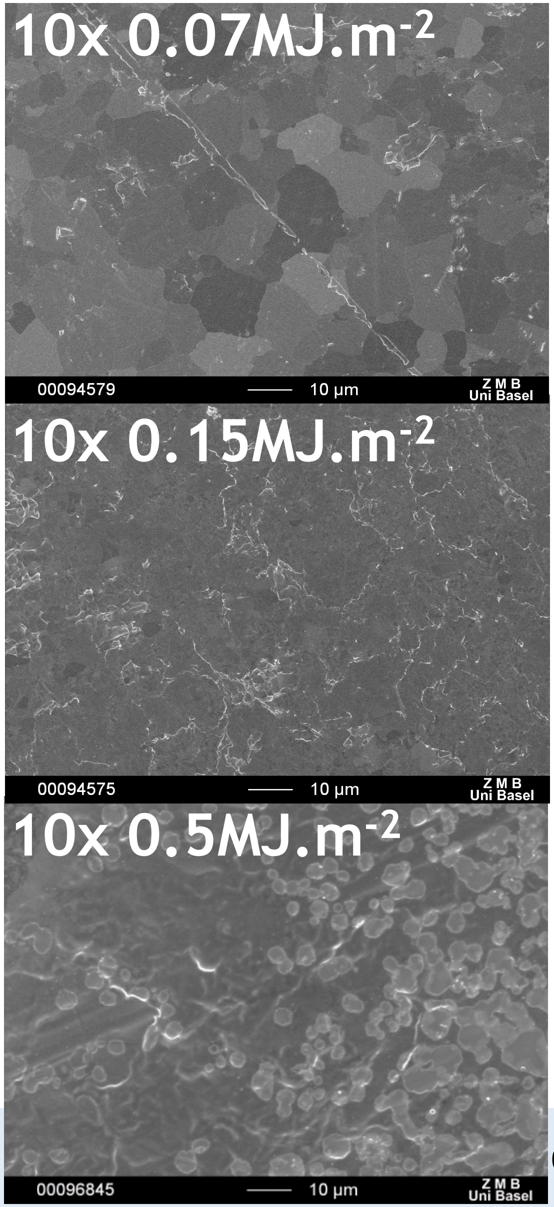
- Measured ablation threshold much lower than expected



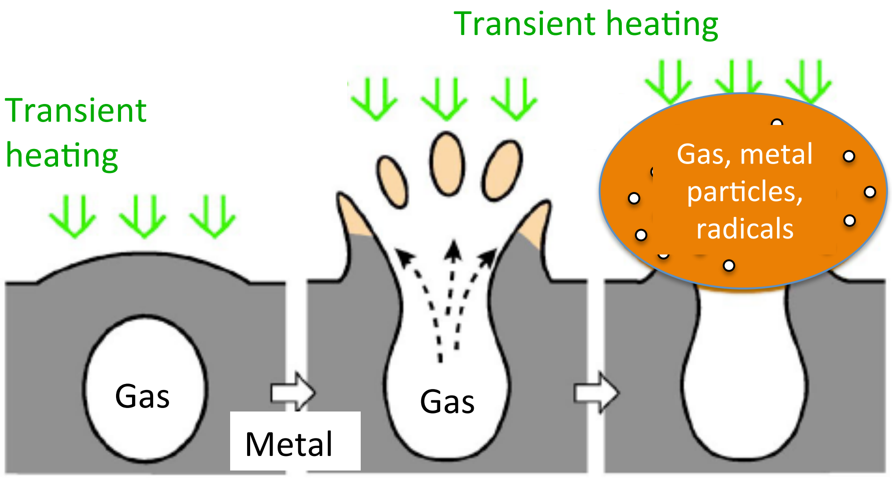
Plasma enhanced surface ablation

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 densitites in ITER might be necessary

G. De Temmerman et al, IAEA FEC, 2010