ELM simulation experiments under ITER-like conditions in a linear plasma device

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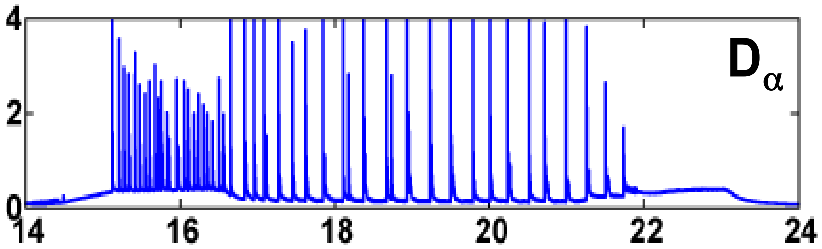
Motivation (1/2)

- Edge Localized Modes (ELM)
  - Plasma instability occurring in enhanced confinement mode (H-mode)
  - Rapid expulsion of energy and particles from edge plasma

Peak energy density on divertor surfaces: 5-10MJ.m^{-2} for 0.2-1ms

Significant threat for material lifetime

- Maximum tolerable ELM size determined from plasma gun experiments
  - Energy density to be kept below 0.5MJ.m^{-2}
- How does it look in reality?



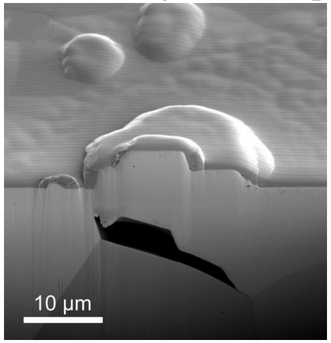
Inter-ELM: 10^{24}m^{-2}s^{-1}

During ELMs: transient heat **AND** particle pulse

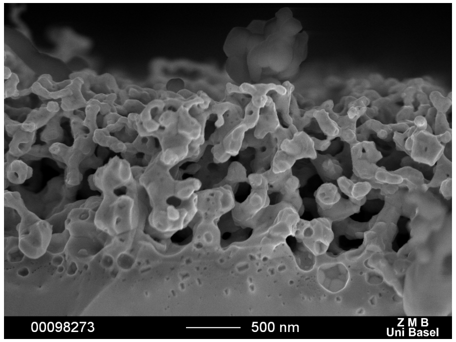
Motivation (2/2)

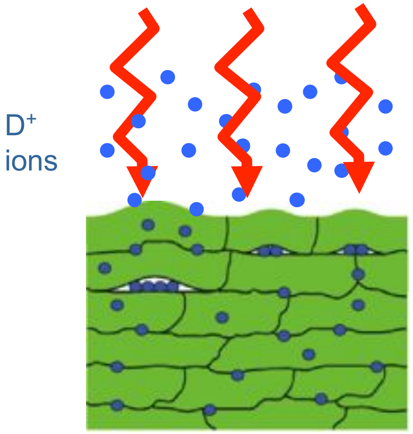
- In ITER, an ELM will interact with a plasma exposed/modified surface

Blister/ D plasma [1]



'Fuzz'/ He plasma





Synergistic effects?

Decrease of damage threshold

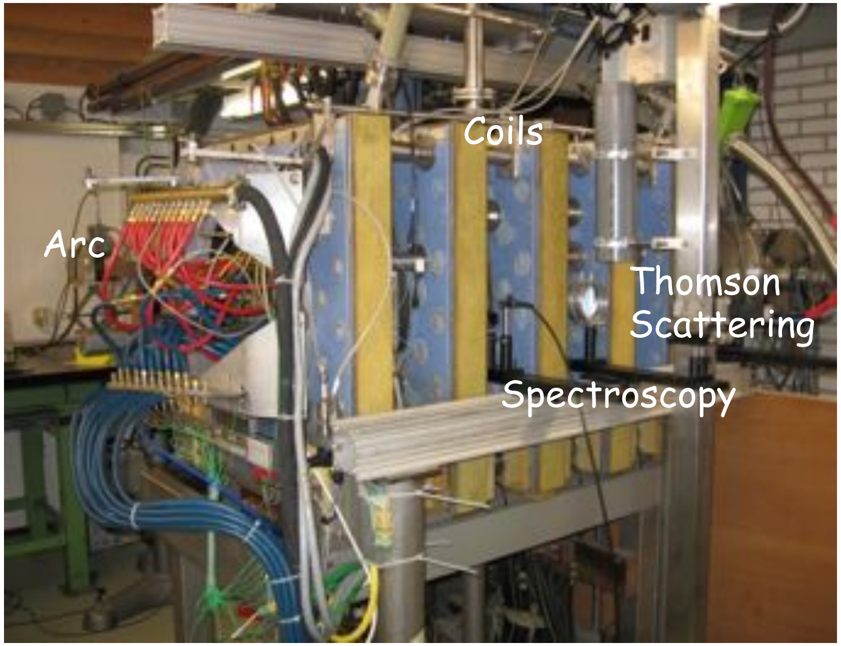
- Some hints of synergistic effects observed in NAGDIS/PISCES [2,3]
  - High-flux plasma+transient laser surface heating
  - Increased surface damage under simultaneous irradiation conditions
  - No transient particle flux

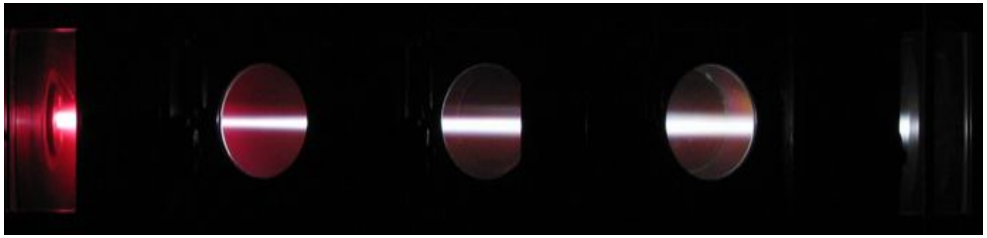
➡ **Combination of divertor relevant steady-state plasma and transient heat/particle pulse needed: this talk**

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

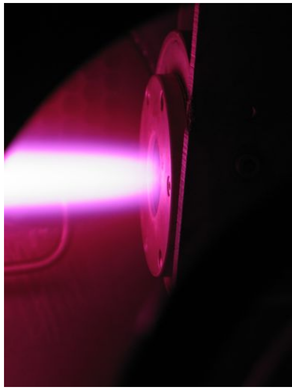
Pilot-PSI

- Linear plasma device producing ITER-like divertor plasma conditions





Hydrogen plasma in Pilot-PSI



Typical parameters of Ar and H plasmas

$n_e = 10^{19}$-10^{21} m^{-3}

$T_e = 0.1$-3 eV

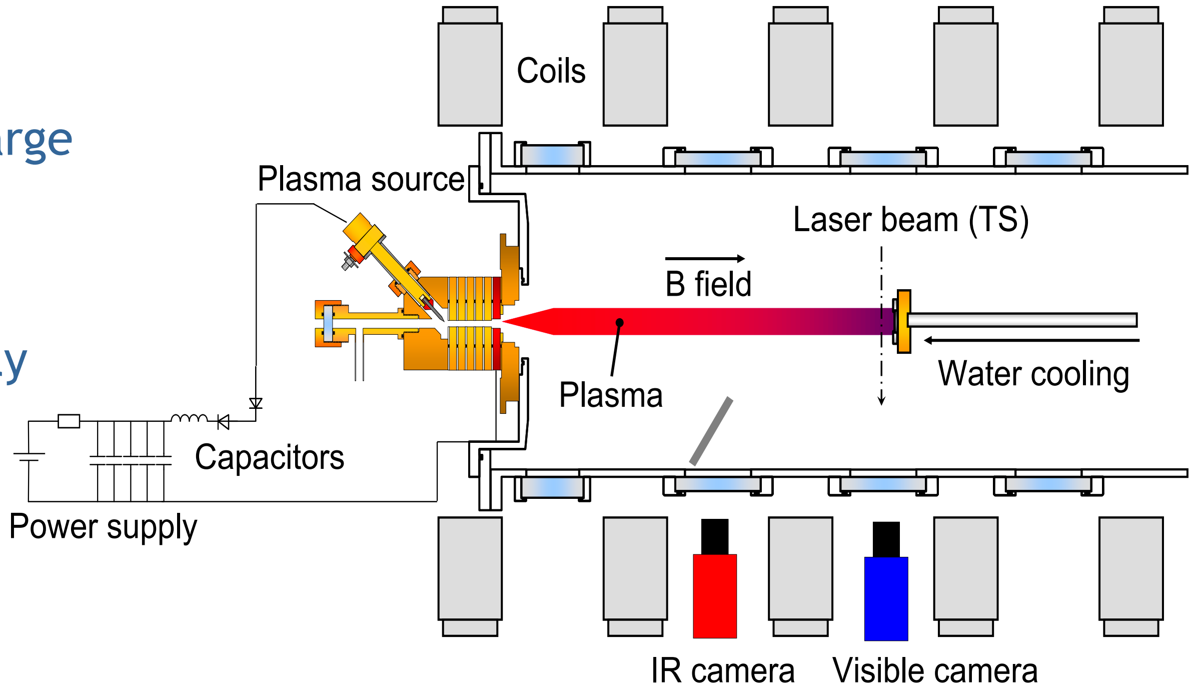
Pulsed device (4-160s depending on B)

Reproduces conditions expected in the ITER divertor (first 5cm of ITER strike point)

Ref: G.J. van Rooij, App. Phys. Lett., 90 (2007)

Transient heat/particle pulses in Pilot-PSI

- **Pulsed plasma source system installed on Pilot-PSI [4]**
  - Modified plasma source (large channel, single cathode)
  - Capacitor bank parallel coupled to DC power supply
  - Mo source in preparation

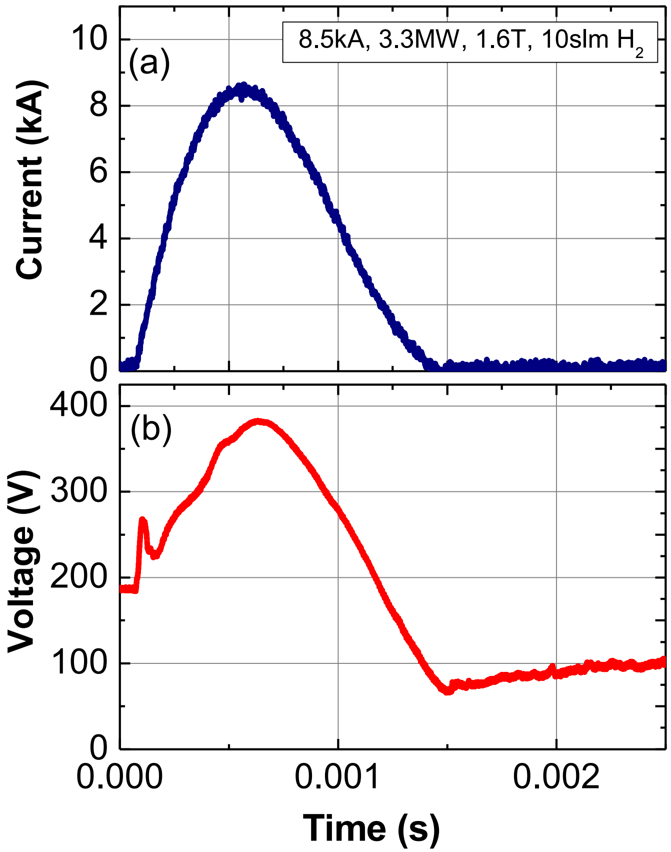


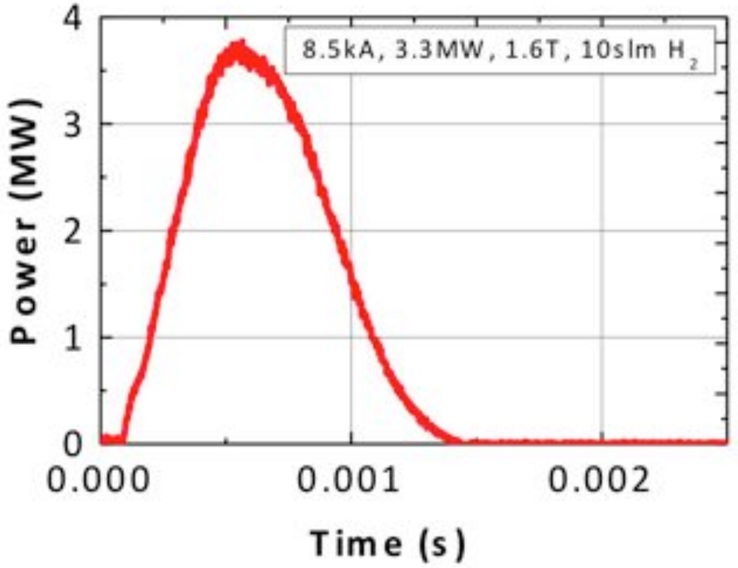
- **System can operate in various gases (or mixtures): H, He, Ar, N**
- **Currently no repetition rate (old capacitor system, limited B field-on time)**
- **Comprehensive set of diagnostics: IR, VIS cameras, Thomson scattering, Calorimetry**

[4] G. De Temmerman et al, Appl. Phys. Lett, 97 (2010) 081502

Experimental procedure

- Capacitor bank discharged into plasma source
- Transient increase of voltage and current



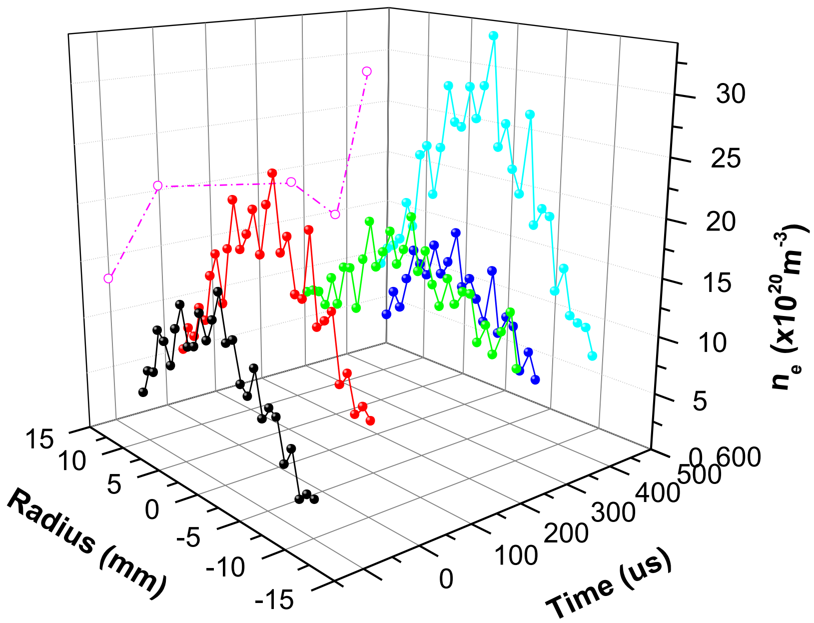


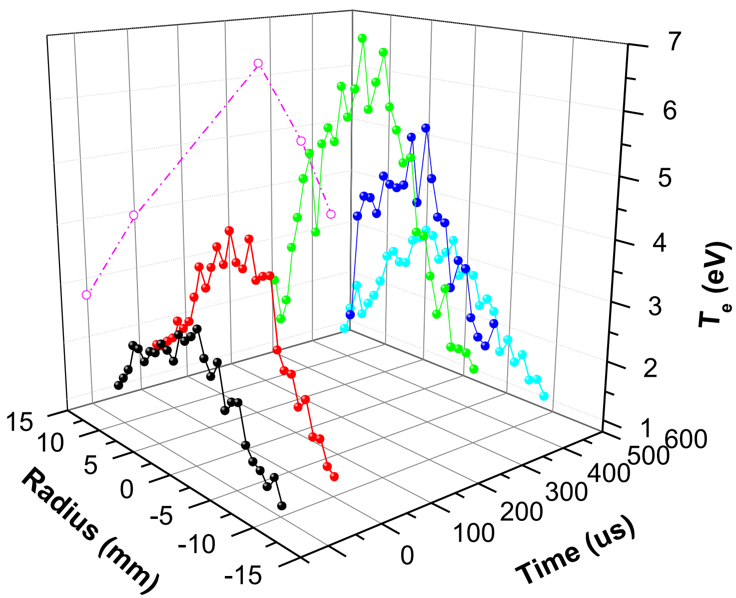
Pulse duration 1-1.5ms (tunable)

Maximum input power of 5.5MW

Plasma parameters during pulse

- Trigger for pulsed plasma synchronized with Thomson scattering system
- Variable delay between both systems to study the time evolution of plasma parameters



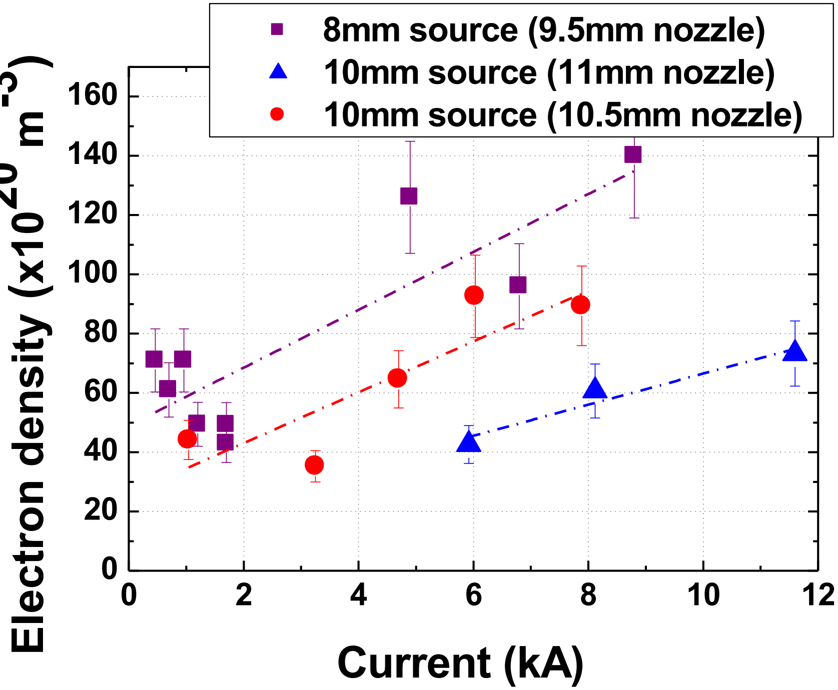


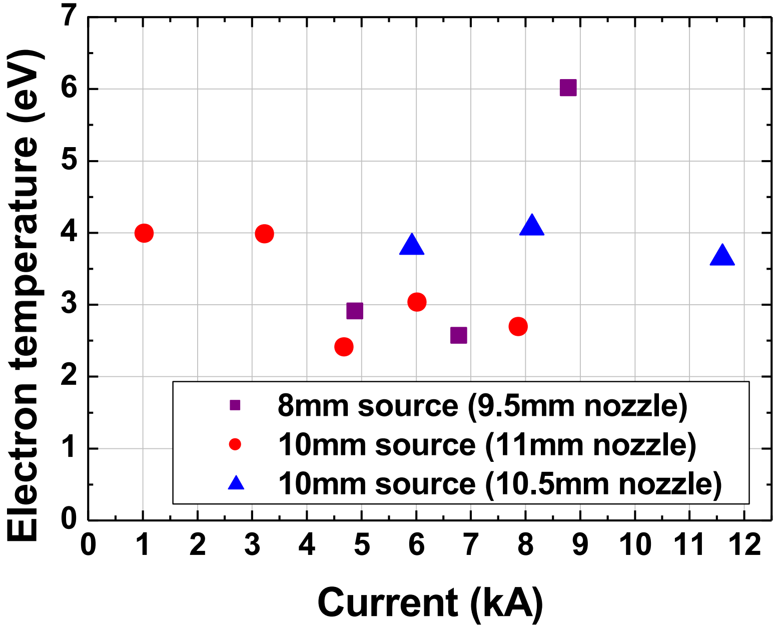
Beam broadening during pulsed plasma (around 2cm FWHM)

Radial decay similar to what is observed during tokamak ELMs

Plasma parameters during pulse

- Plasma parameters during pulsed depend on input power, gas flow and magnetic field



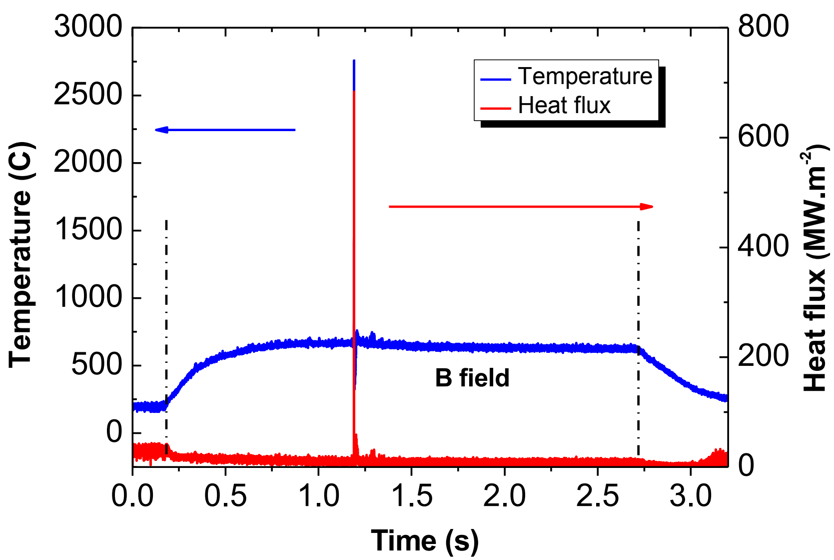


Electron temperature remains low (max 6eV): low ion energy

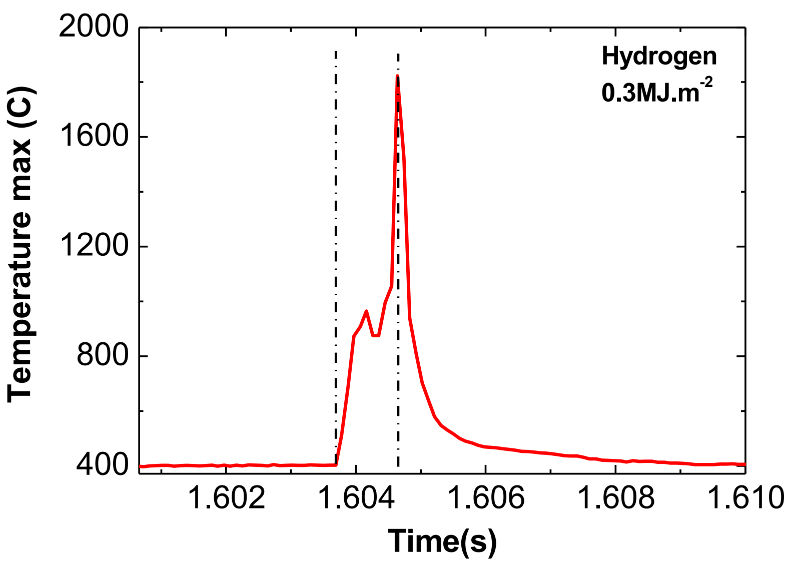
Ion energy can be controlled through biasing

Experimental procedure

- Magnetic field triggered for 2s at 1.6T
- Plasma pulsed triggered at t=1s



Peak surface temperature



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

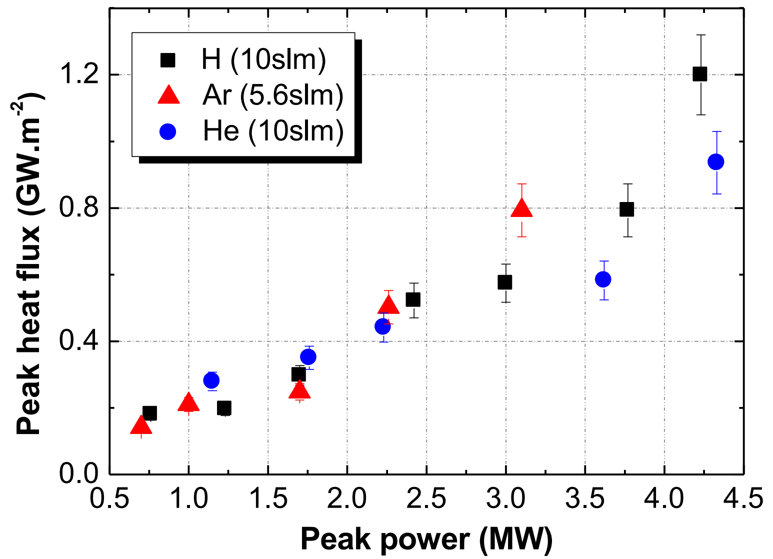
For the first time, superimposition of divertor relevant steady-state plasma and transient heat/particle pulse

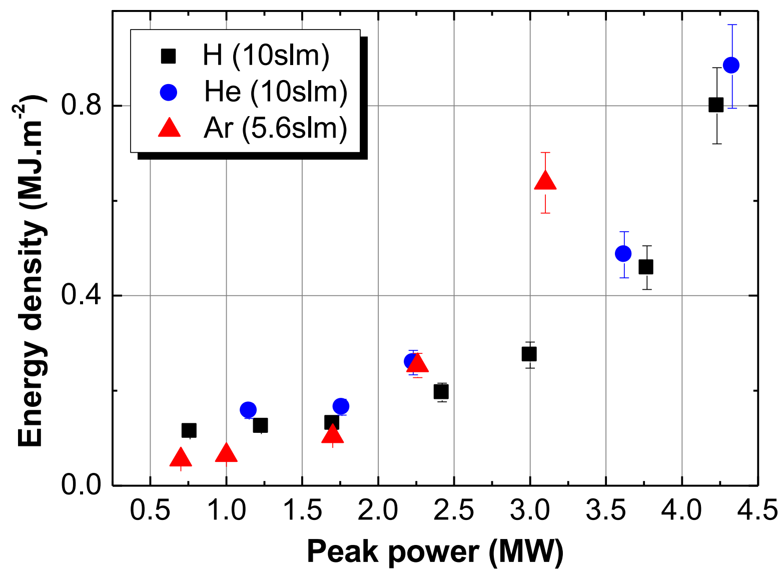
System output

- Target heat flux determined by IR thermography, using the THEODOR code
- Peak heat flux and energy density increase with input power
- Similar energy densities can be reached with different gases
- Peak energy density limited by pumping capability of the machine

Heat loads in excess of 1GW.m^{-2}

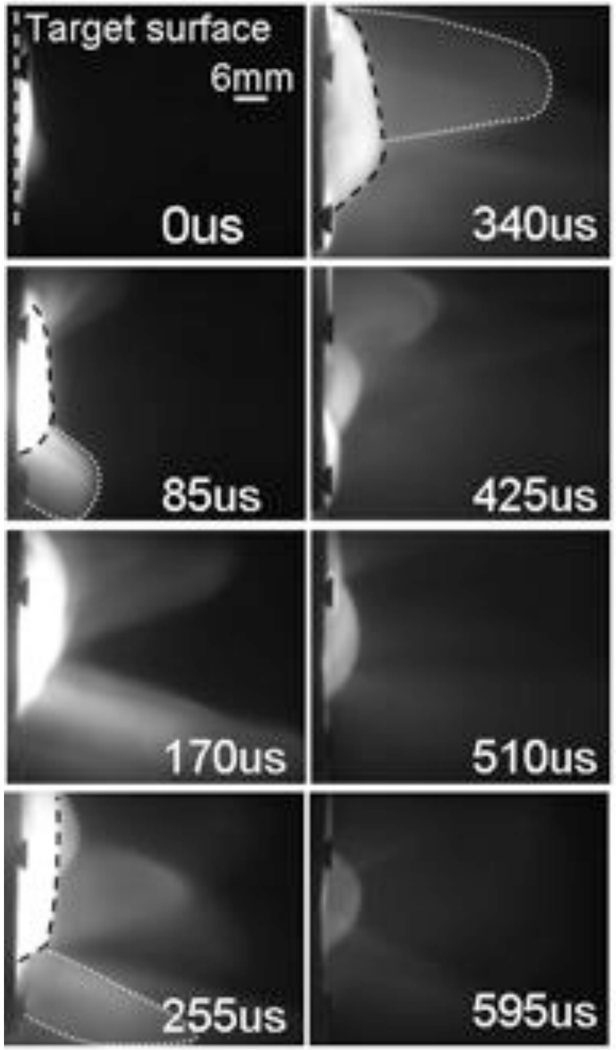
Properties of pulsed and steady-state plasma can be tuned independently

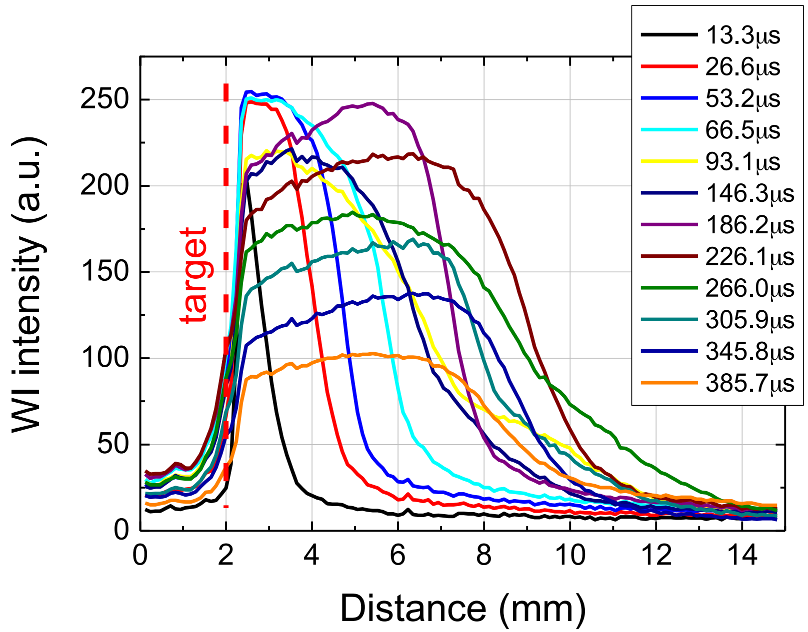




Tungsten surface exposed to high heat flux

- Tungsten target (1mm thick) exposed to $0.8 MJ.m^{-2}$ (hydrogen plasma)

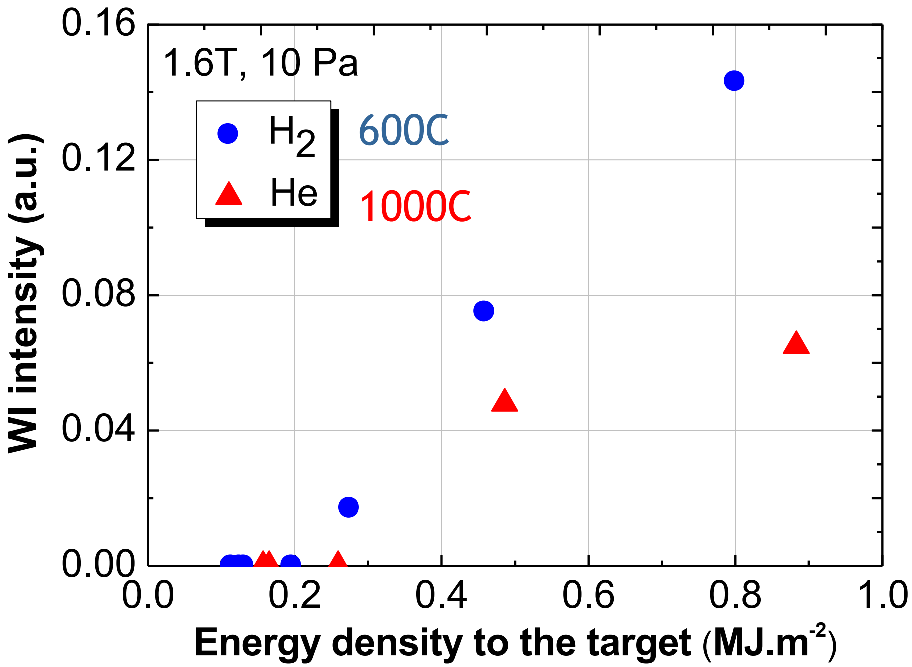




- Tungsten release (neutrals) observed from the target
- WI emission front moves upstream to a distance lower than 1.5cm
- Velocity is about $100 m.s^{-1}$

Tungsten release

- Simultaneous observations with Fast visible and IR camera



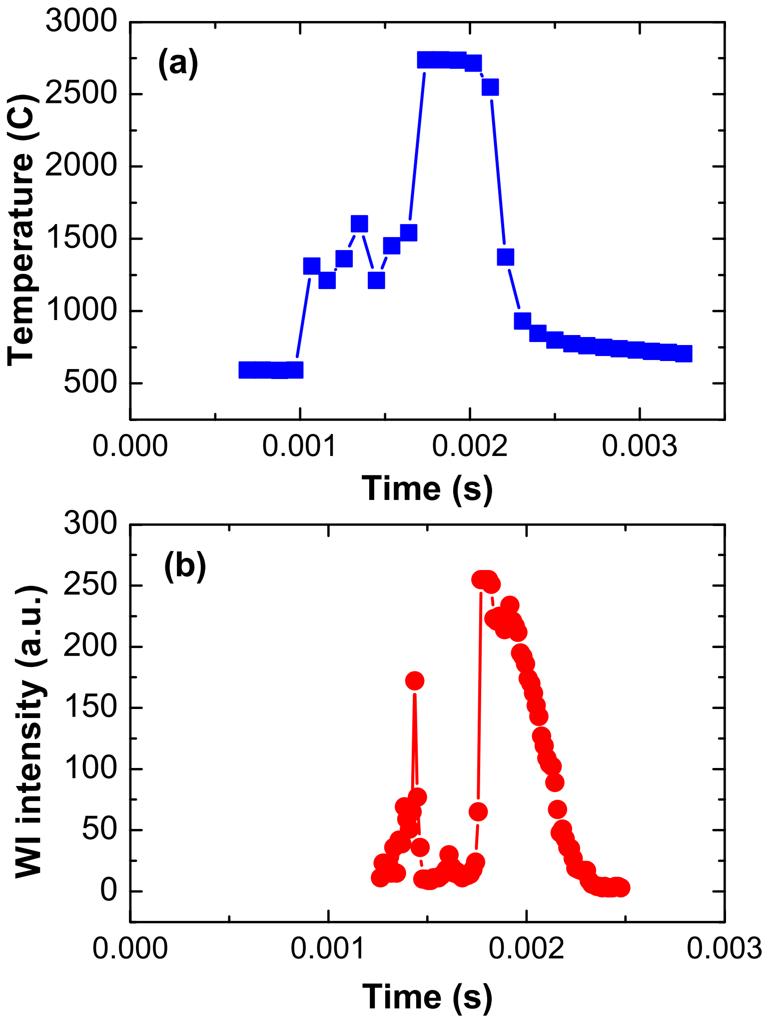
- Clear threshold effect
- WI signal during He pulses lower than during H pulses (different base temperatures)

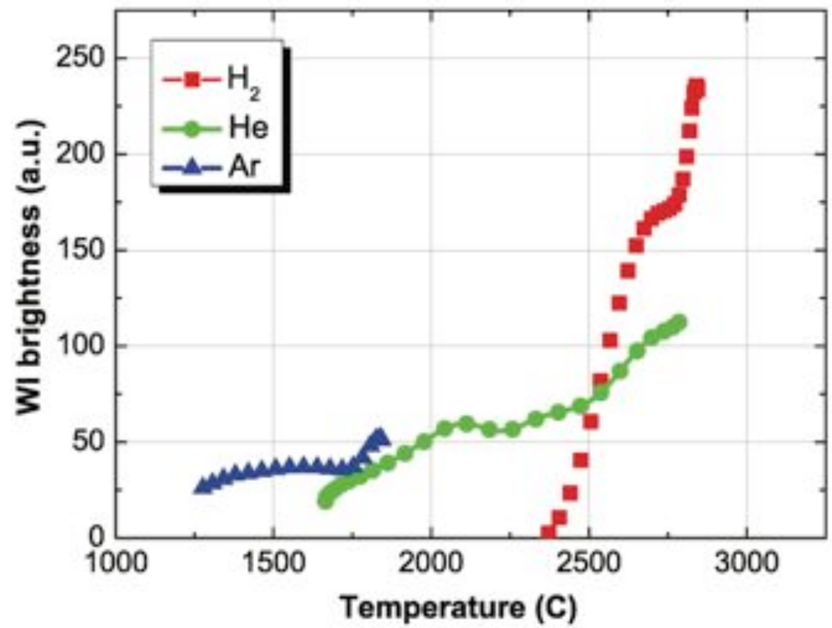
Influence of the base temperature (and near-surface gas content) on damage threshold needs to be investigated in details

At what temperature does WI emission start?

Tungsten release vs temperature

- Simultaneous observations with Fast visible and IR camera





Tungsten release observed already when evaporation is negligible

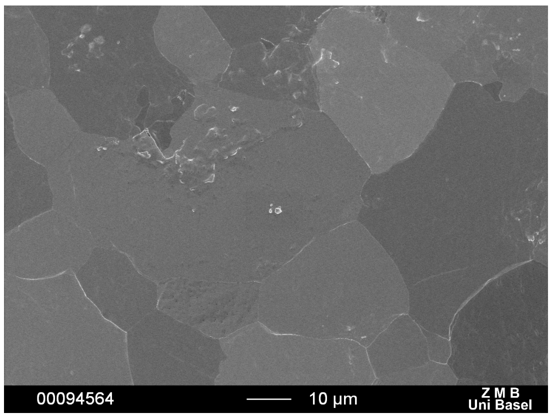
Damage mechanism?

Surface damage/ H plasma

- Surface damage observed by post-mortem SEM

W target/ H plasma

400 C, 40 s, 4s/shot



Surface roughening observed, increases with energy density and pulse number

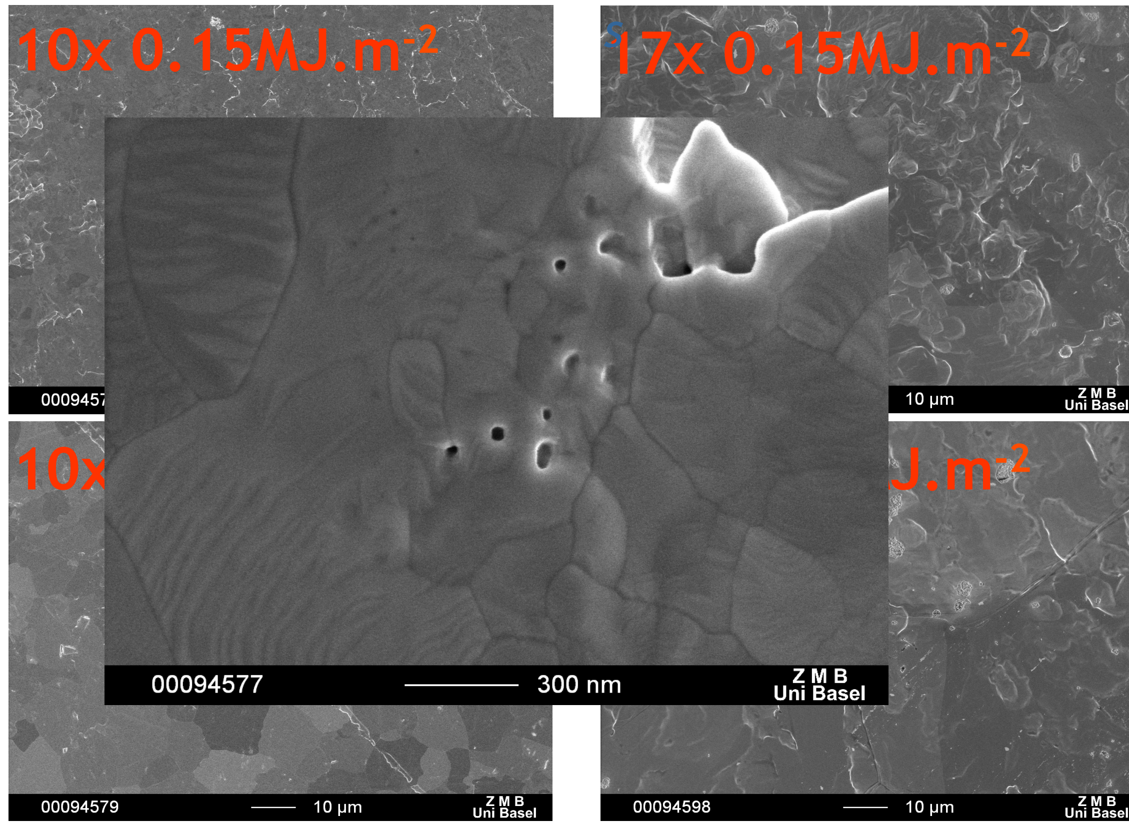
Occurs at very low energy density

W target

400 C (steady-state), 40 s

W target

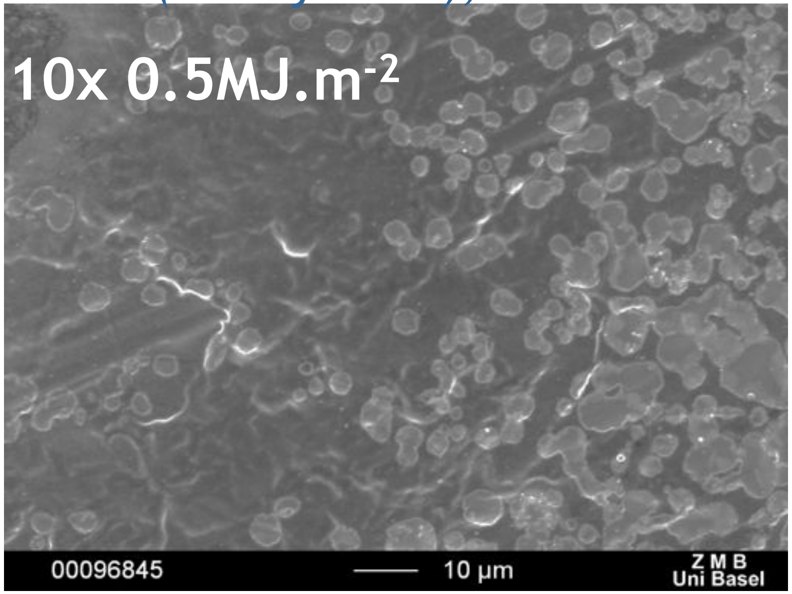
400 C (steady-state), 68

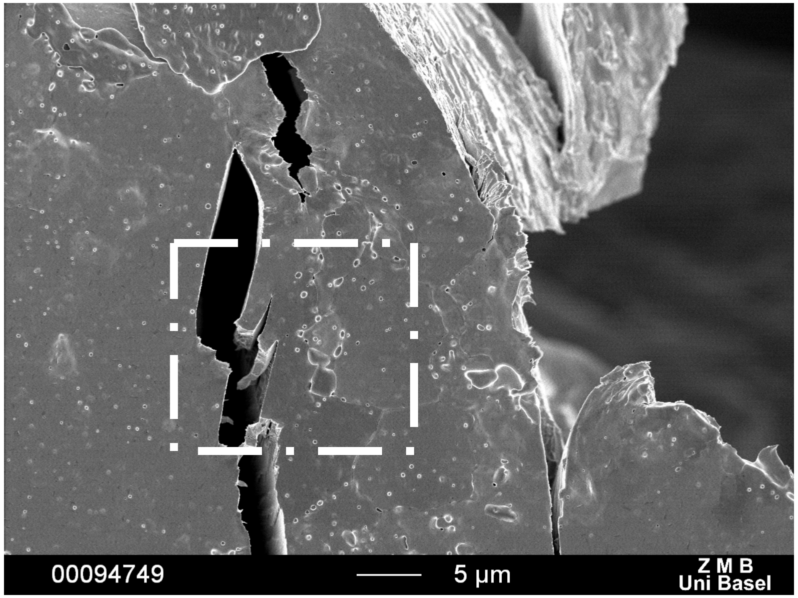


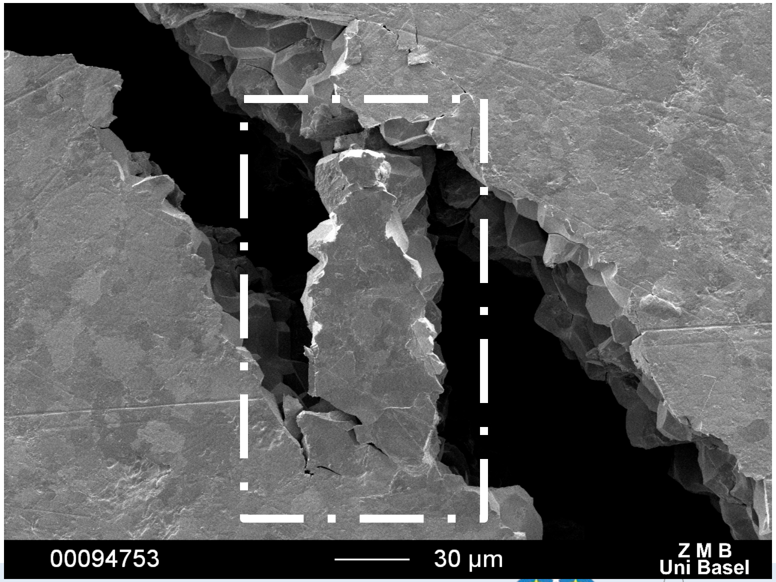
Surface damage/ H plasma

W target

600 C (steady-state), 40 s







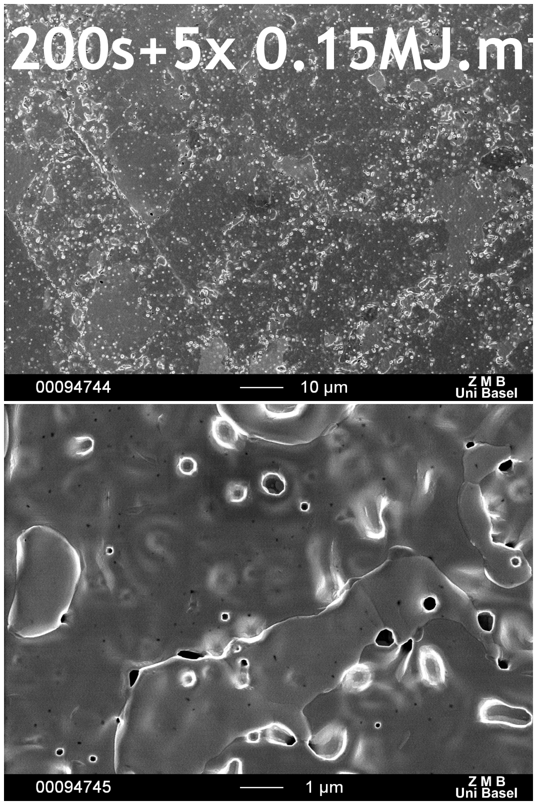
Observation of burst blister caps

Also, loosely bound particles observed along cracked surface: source of dust?

Surface damage/ He plasma

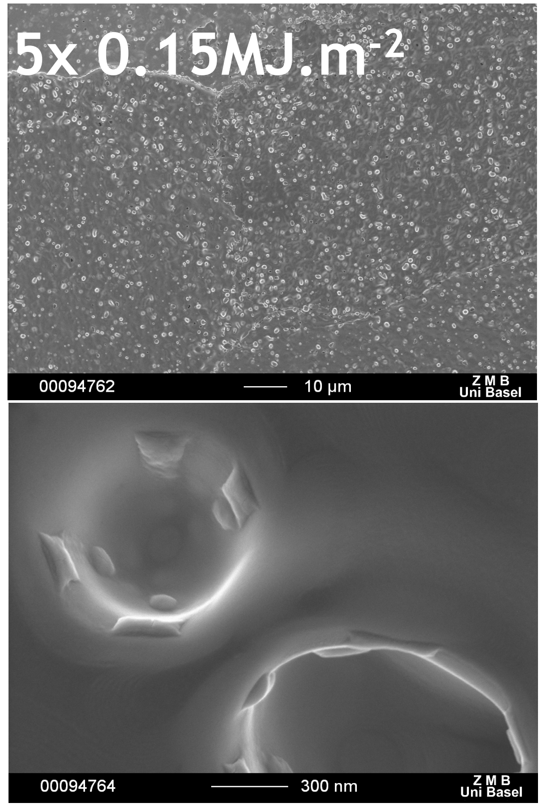
W target pre-exposed

1800 C, 220 s, 4s/shot+pulse



No pre-exposure

1800 C, 20 s, 4s/shot+pulse



- Formation of pinholes on the surface typical of He plasma exposure
- Some holes present blistered sides…

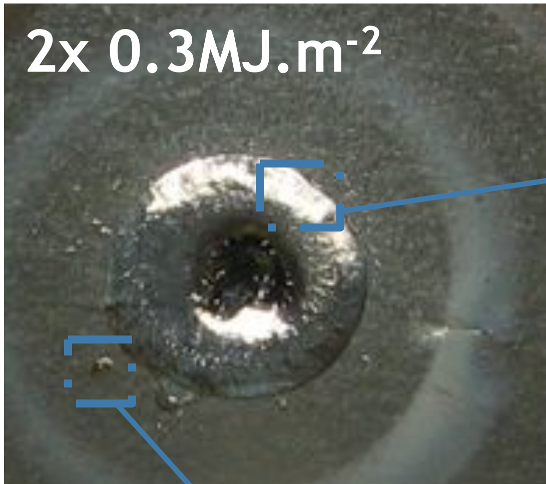
Pre-irradiation increases surface roughening but hole formation observed already with pulsed plasma

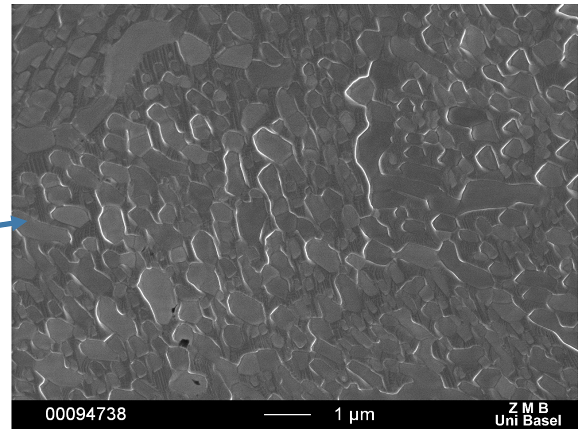
Effect of He pre-exposure on damage

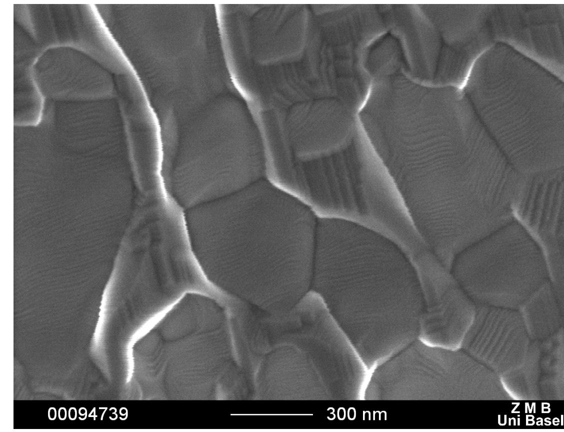
- **Helium pre-exposure strongly increases the likelihood of arcing/melting**

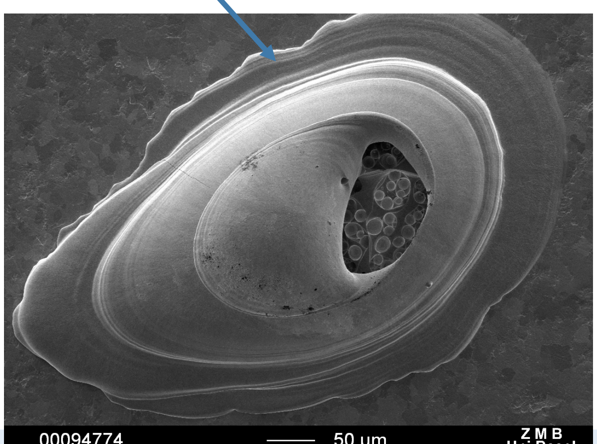
W target pre-exposed

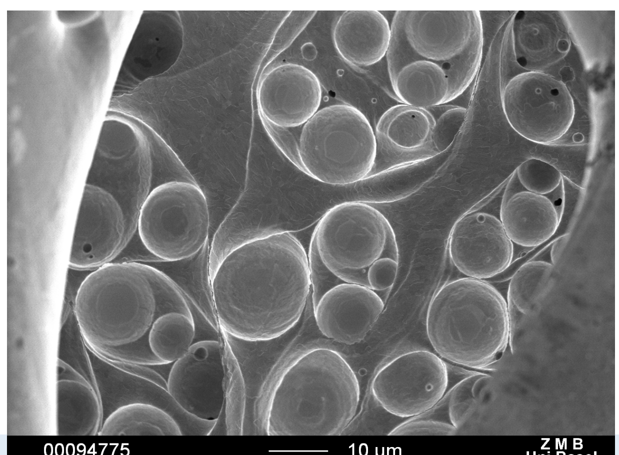
1800 C, 200 s











Reason for such significant melting not totally clear

Consistent observation, biasing increases the probability of melting

Summary/ perspectives

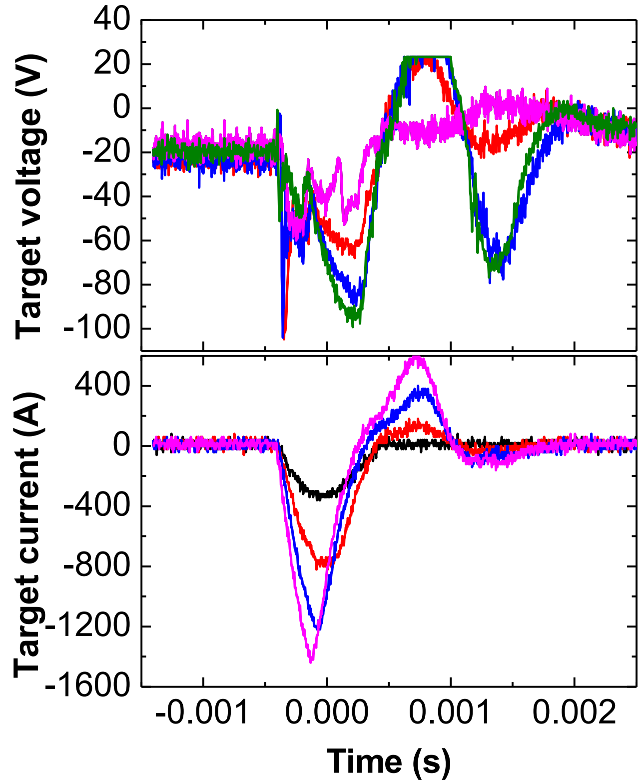
- Pulsed source system developed on Pilot to 'mimic' ITER conditions
  - Generation of high heat fluxes with relevant timescales
  - Independent control of steady-state and transient plasmas
  - Active bias for ion energy control (presently up to 0.1keV)

- First experiments on damage by simultaneous steady/pulsed plasma
  - Surface roughening observed for H at 0.15MJ.m^{-2} (very low value)
  - Helium-induced morphology changes make surface prone to strong melting
  - Studies at higher energy densities ongoing

- Combined exposure to steady-state/transient conditions could call for re-defining the maximum tolerable energy densities

Future developments

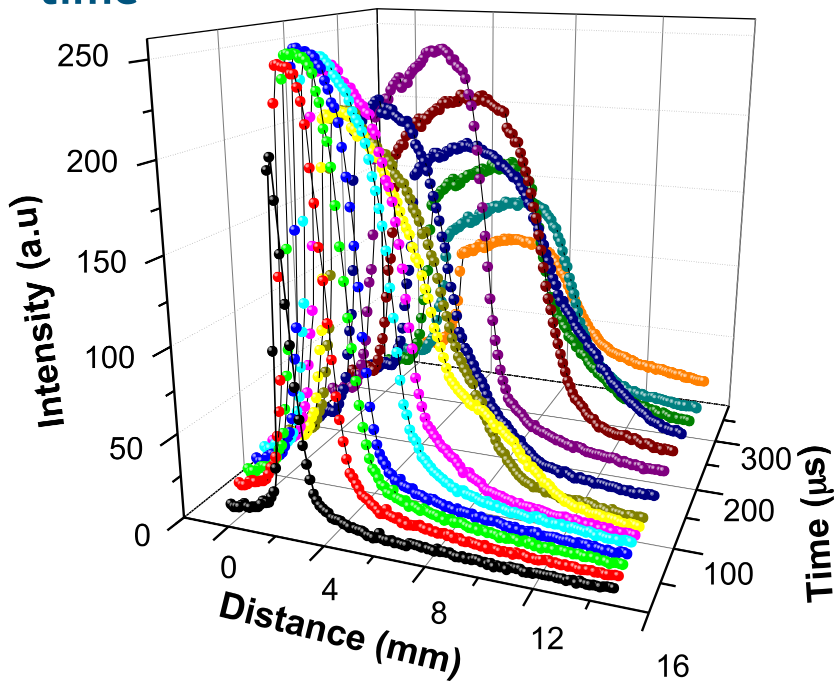
- **Pulsed bias**
  - Need to increase (and vary) ion energy during pulse
  - DC bias possible (max~ -100V)
  - Preliminary tests with capacitor bank on target successful (NB: problem with voltage measurement)

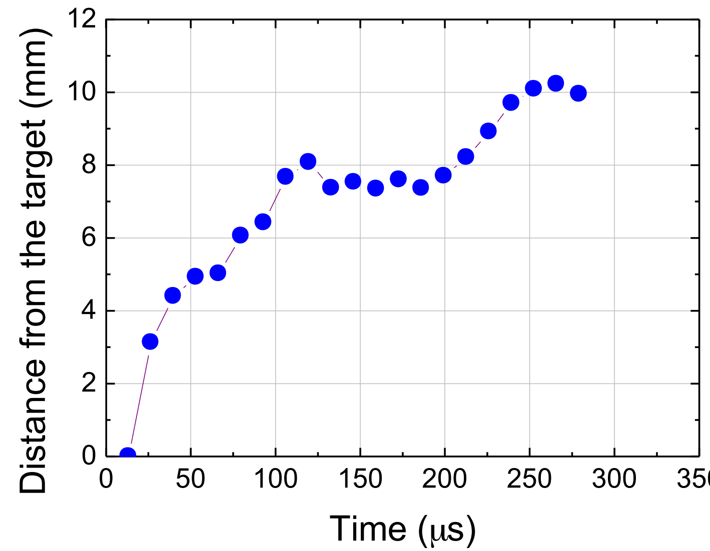


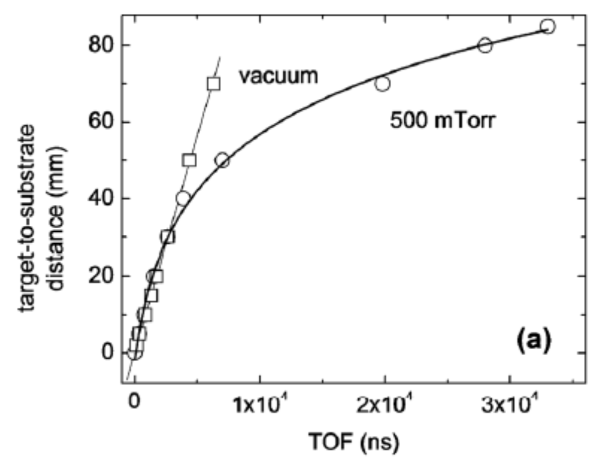
- **Magnum ELM Simulation System (MESS)**
  - Designed for 10Hz at 1-2GW.m^{-2} /up to 70Hz for currents up to 2kA
  - Funding agreed, under construction (completion date 09/11)
  - Pulsed bias not included: additional funds to be identified

Tungsten surface exposed to high heat flux

- Evolution of the from of the emission cloud vs time







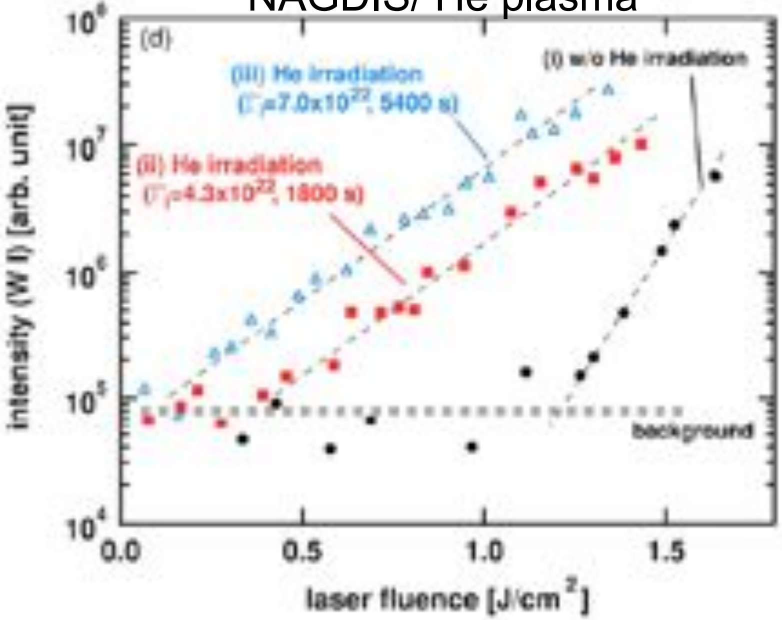
Motion of the emission front shows similarities with observations from laser ablation with high background pressure

[6] Riabinina, J. Appl. Phys., 108 (2010) 034322

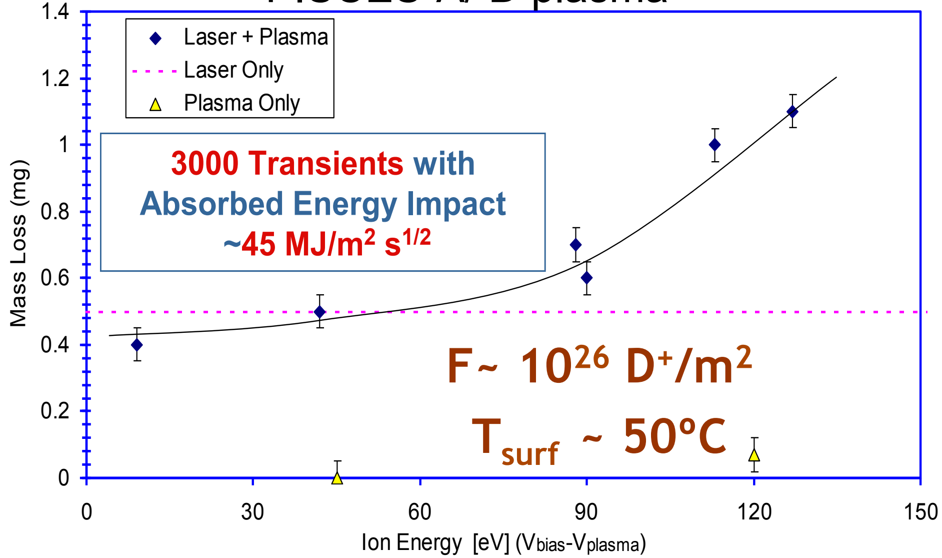
Motivation (2/2)

- 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)