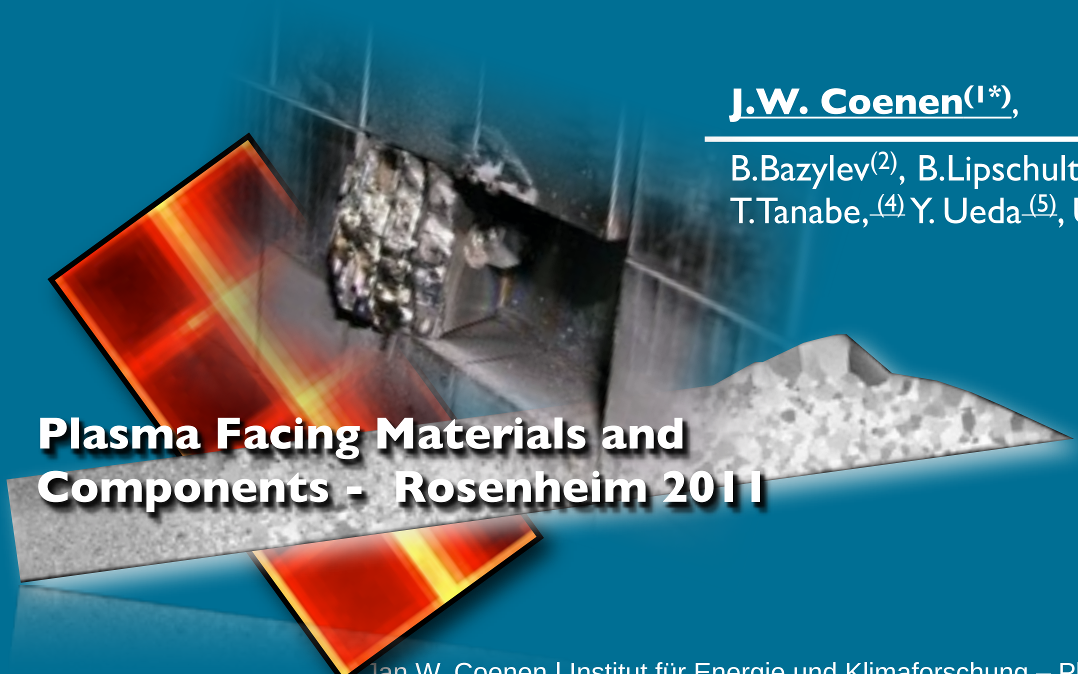
Mitglied der Helmholtz-Gemeinschaft

TEC TRILATERAL EUREGIO CLUSTER

JÜLICH FORSCHUNGSZENTRUM

Analysis of Structural Changes and High-Heat-Flux Tests on pre-damaged Tungsten from Tokamak Melt Experiments



Plasma Facing Materials and Components - Rosenheim 2011

J.W. Coenen[1*],

B.Bazylev[2], B.Lipschultz[3], G.Pintsuk[1], V. Philipps[1], S. Brezinsek[1], M. Laengner[1], T.Tanabe,[4] Y. Ueda[5], U.Samm[1] and the TEXTOR-Team

(*) EFDA Fusion Researcher Fellowship

(1)Institut fuer Energie und Klimaforschung - Forschungszentrum Juelich GmbH, Germany

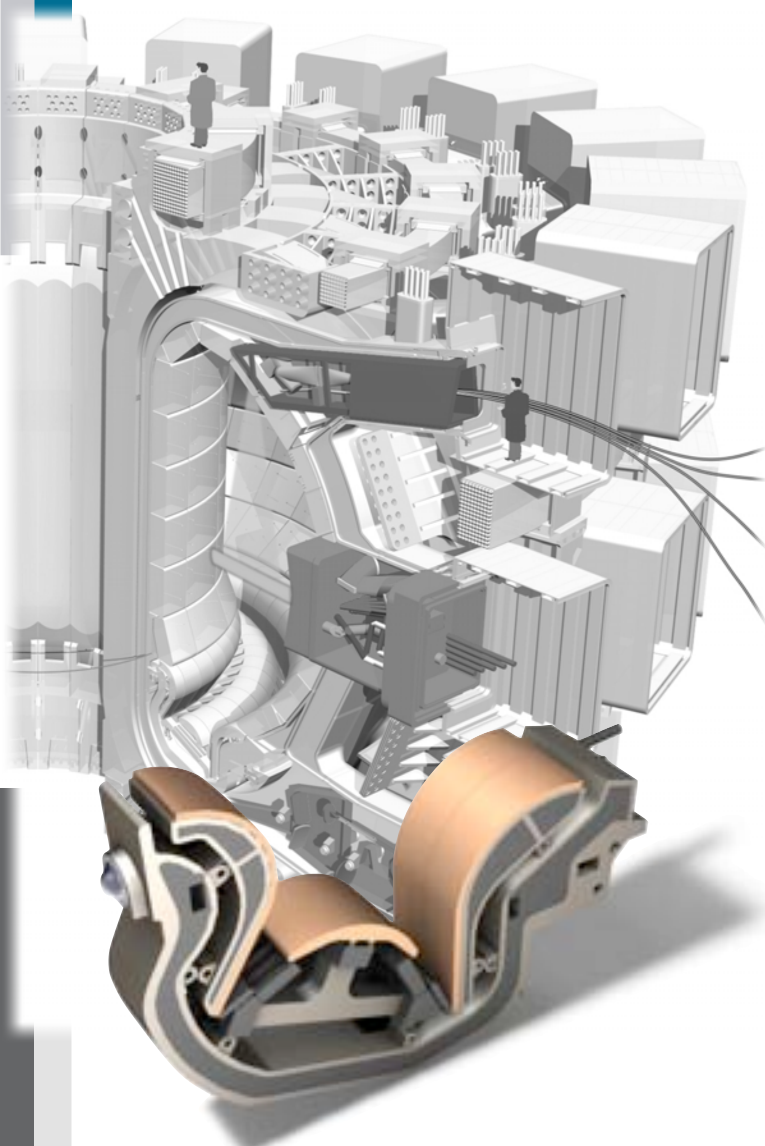
(2)Institut fuer Hochleistungsimpuls und Mikrowellentechnik, Forschungszentrum Karlsruhe , Germany

(3) Massachusetts Institute of Technology, PSFC, Cambridge, USA

(4)Interdisciplinary Graduate School of Engineering Science, Kyushu , Japan

(5)Graduate School of Engineering, Osaka University, , Japan

Overview



Introduction

1. Melting and Melt Layer Motion
2. Power-handling
3. Material Loss & Splashing
4. Re-solidification and Material Structure
5. Transient Heat-Flux Tests
6. Accidental Melting

Summary and Conclusions

TRILATERAL
EUREGIO CLUSTER

FORSCHUNGSZENTRUM

Introduction

Conditions

ITER

Power into Scrape Off Layer

$P_{SOL,\,ITER} = 100MW$

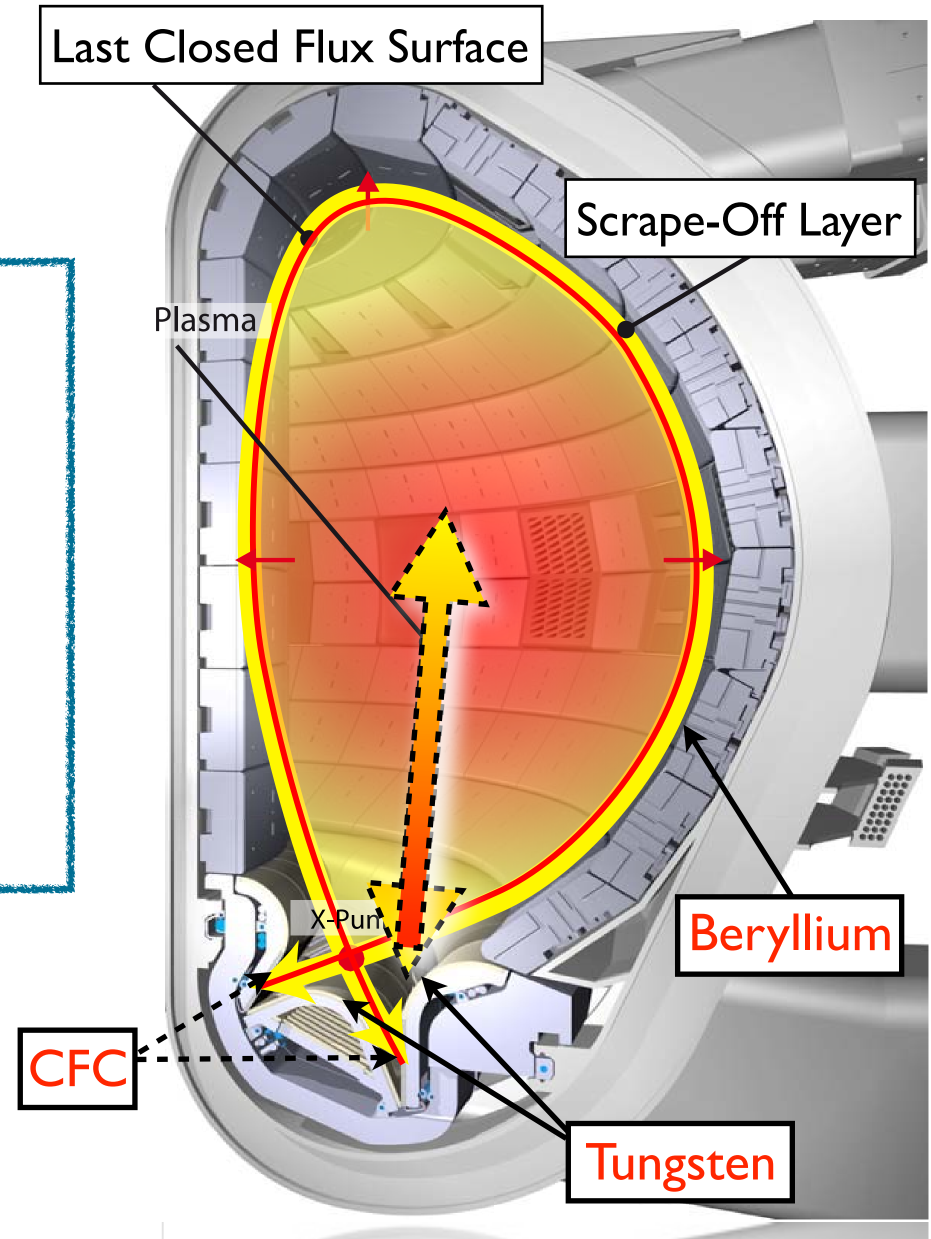
Radiated Power (Divertor)

$P_{rad,div}=0,7*P_{Sol}$ ($P_{rad,div}=0,2*P_{Sol}$)

Heat Flux

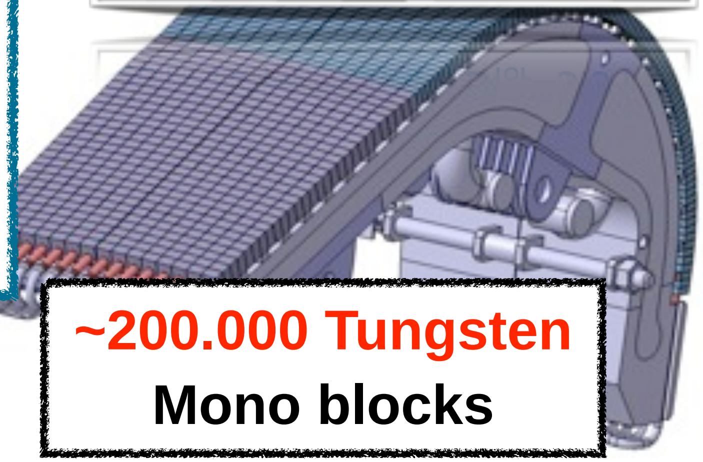
$q_{||,div}\sim 200MW/m^2$ ($q_{||,div}\sim 900MW/m^2$)

Pitts PSI2010



ITER

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



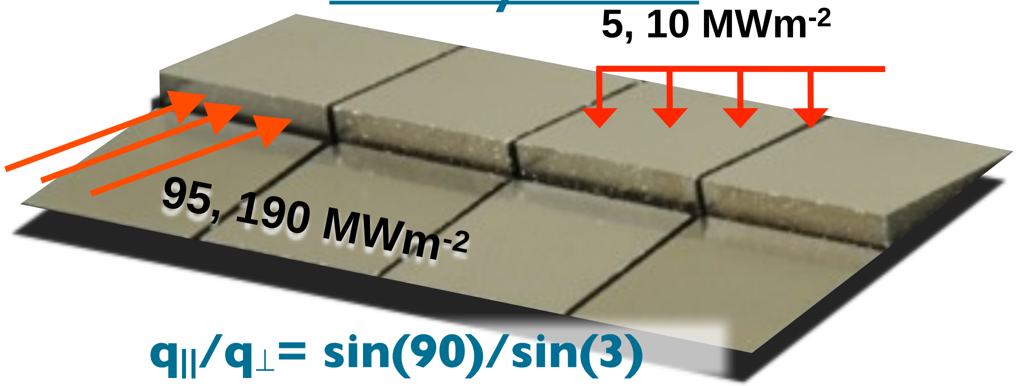
Steady-state heat loads $q_{\perp}\sim$ 10-20MW/m^2
Transient heat loads ~GW/m^2
ELMs: τ_{rise}~0.5ms, 2.1 MJ/m^2
Disruptions: τ_{rise}~2.5ms , >2 MJ/m^2

J.Linke Monday - Tutorial
M.Missirlian Tuesday I-04

~200.000 Tungsten
Mono blocks

Steady State

α = 3°



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

Monoblocks can tolerate 0.3 mm offsets at 10MW/m^2

Tolerances: Neighbouring blocks < 0.3mm

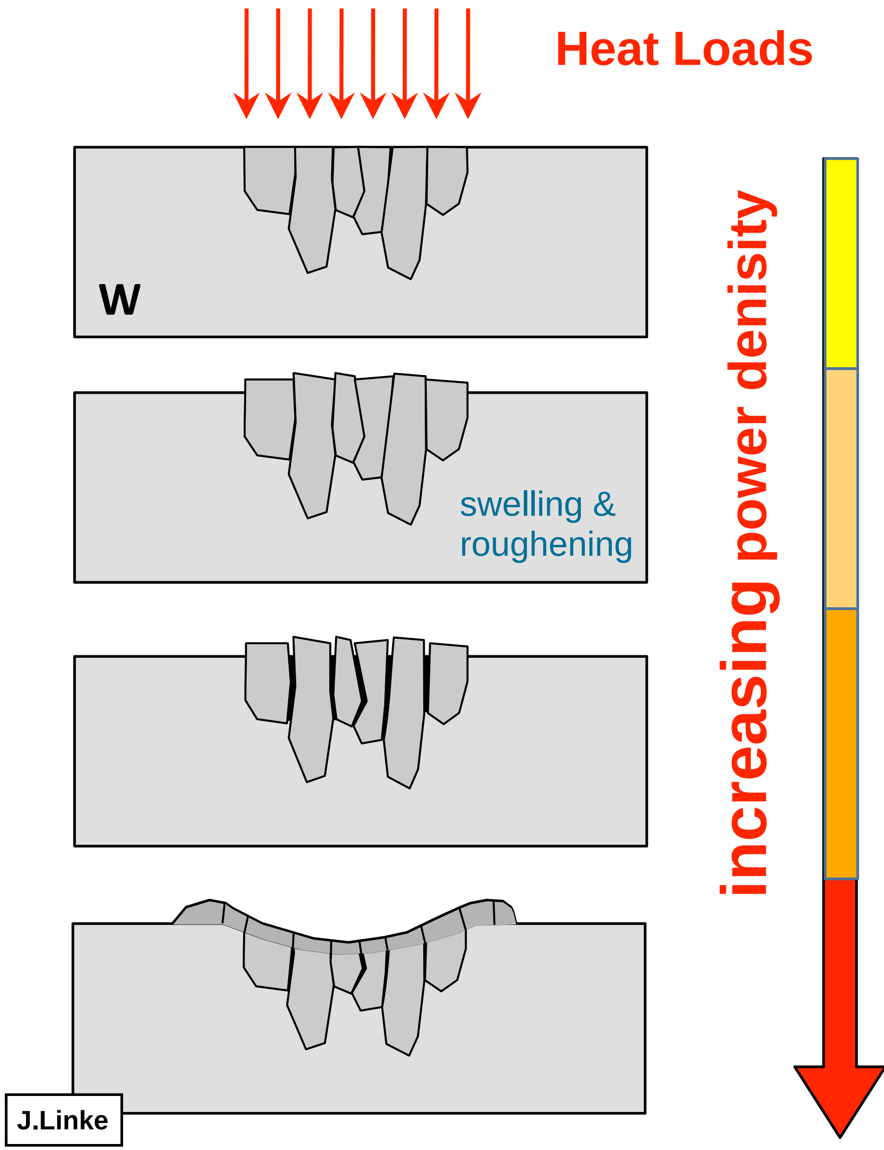
T.Hirai Monday - Tutorial

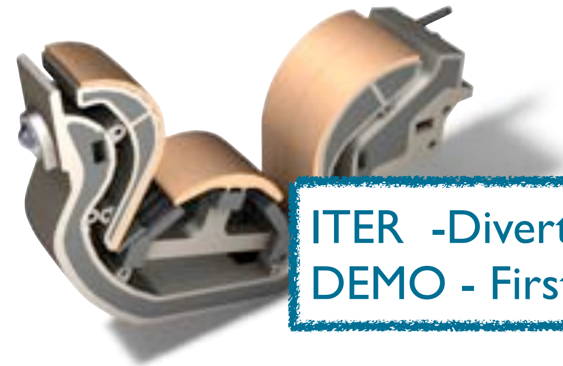
Transients

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

Pitts PSI2010

High Heat Loads





ITER -Divertor
DEMO - First-wall

damage threshold

thermal expansion of heat affected grains
→ plastic deformation when T > DBTT

cracking threshold

contraction during cool-down:
→ cracking along grain boundaries

melting threshold

What happens under extreme heat loads ?

Issues

Powerhandling Limits & Melt Damage

Melt Layer Motion and Splashing

Material Structure

Performance of Re-solidified Components

PFC Lifetime
Impact on Machine Operation

Transfer Knowledge to **Real** Conditions

Mitglied der Helmholtz-Gemeinschaft

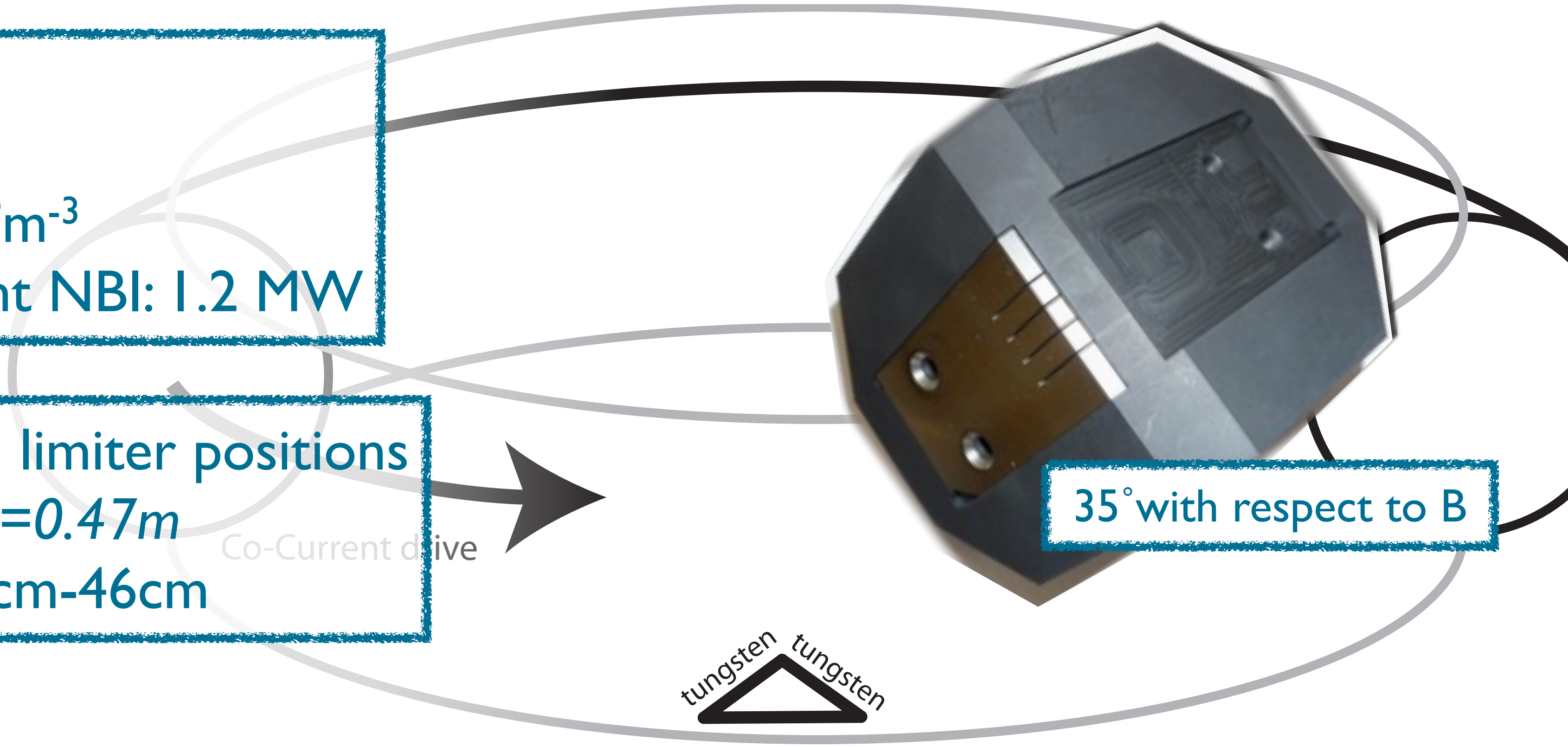
Experimental Setup

Tokamak Exposures

TEXTOR Setup

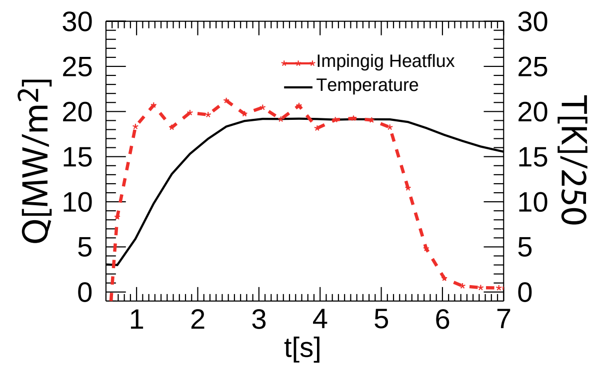
B_T=2.25 T
I_P=350kA
n_e=3.5 $10^{19}m^{-3}$
Co-Current NBI: 1.2 MW

Plasma and limiter positions
R=1.75m a=0.47m
Limiter 49cm-46cm



35°with respect to B

Typical heat-flux ~20MWm²
Temperatures > 4500 °C

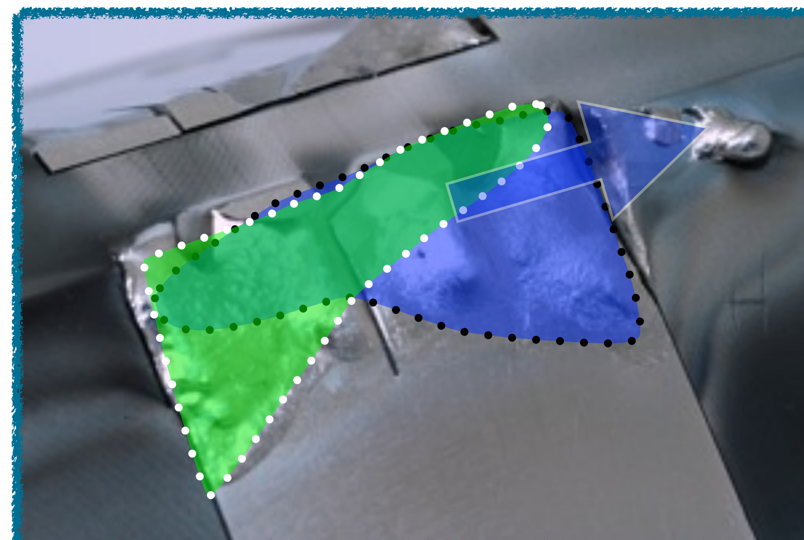


TRILATERAL
EUREGIO CLUSTER

1. Melting and Melt Layer Motion

Phenomenology

7 melt exposures (3-5s)
Significant melting
and bridging

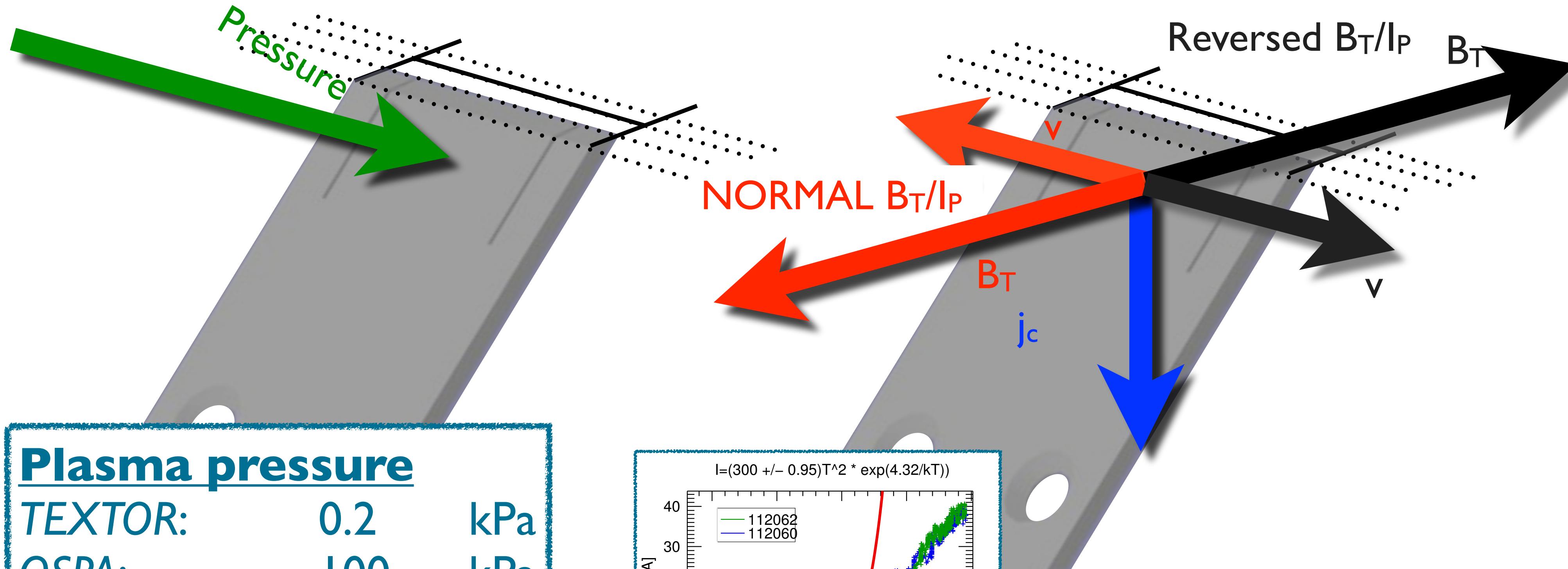


Motion due to acting forces

Forces

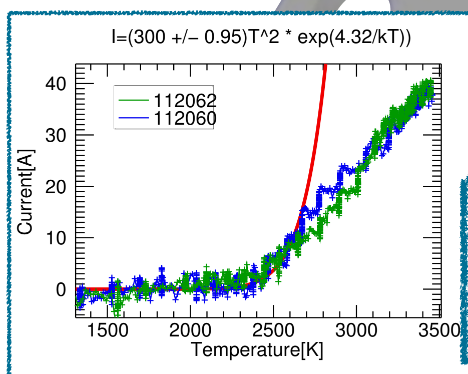
Pressure , jxB , ...

Forces



Plasma pressure

TEXTOR:	0.2	kPa
QSPA:	100	kPa
ITER(ELM):	5-10	kPa



Thermo-electric emission

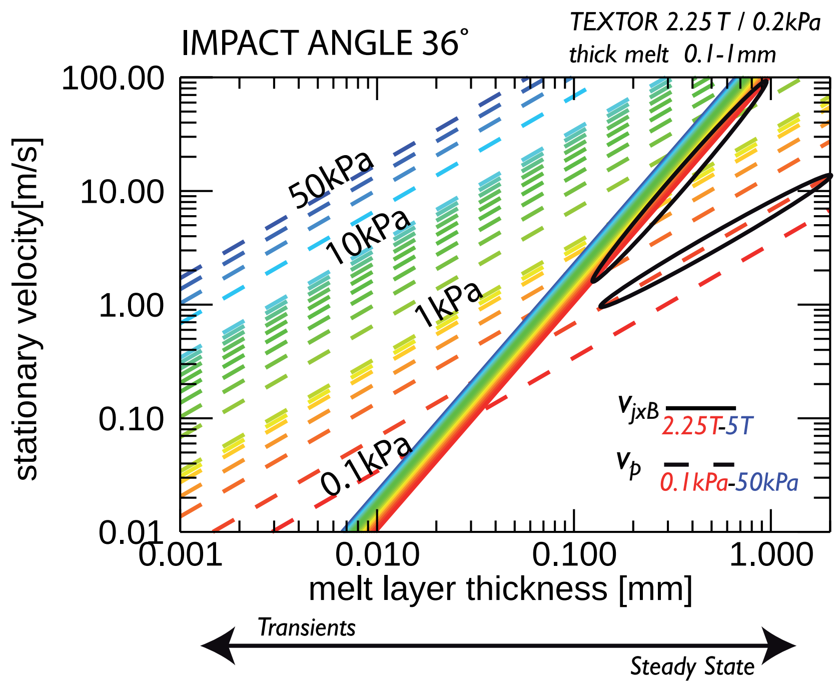
~3-4 cm^2 Emission-surface

Melting on both samples

jxB: 0.2-1mm melt ➠ ~600-4500 N/m^2

Dominant force under TEXTOR conditions is jxB

Velocities



TEXTOR *(steady state)*

Melt motion is dominated by F_{jxB}

Ratio depends strongly on melt layer thickness

All relevant forces are included in the MEMOS modeling

Bazylev, B. et al. ***Journal of Nuclear Materials*****, 2009, 390-391, 810-813**
Experimental validation of 3D simulations of tungsten melt erosion under ITER-like transient loads

Mitglied der Helmholtz-Gemeinschaft

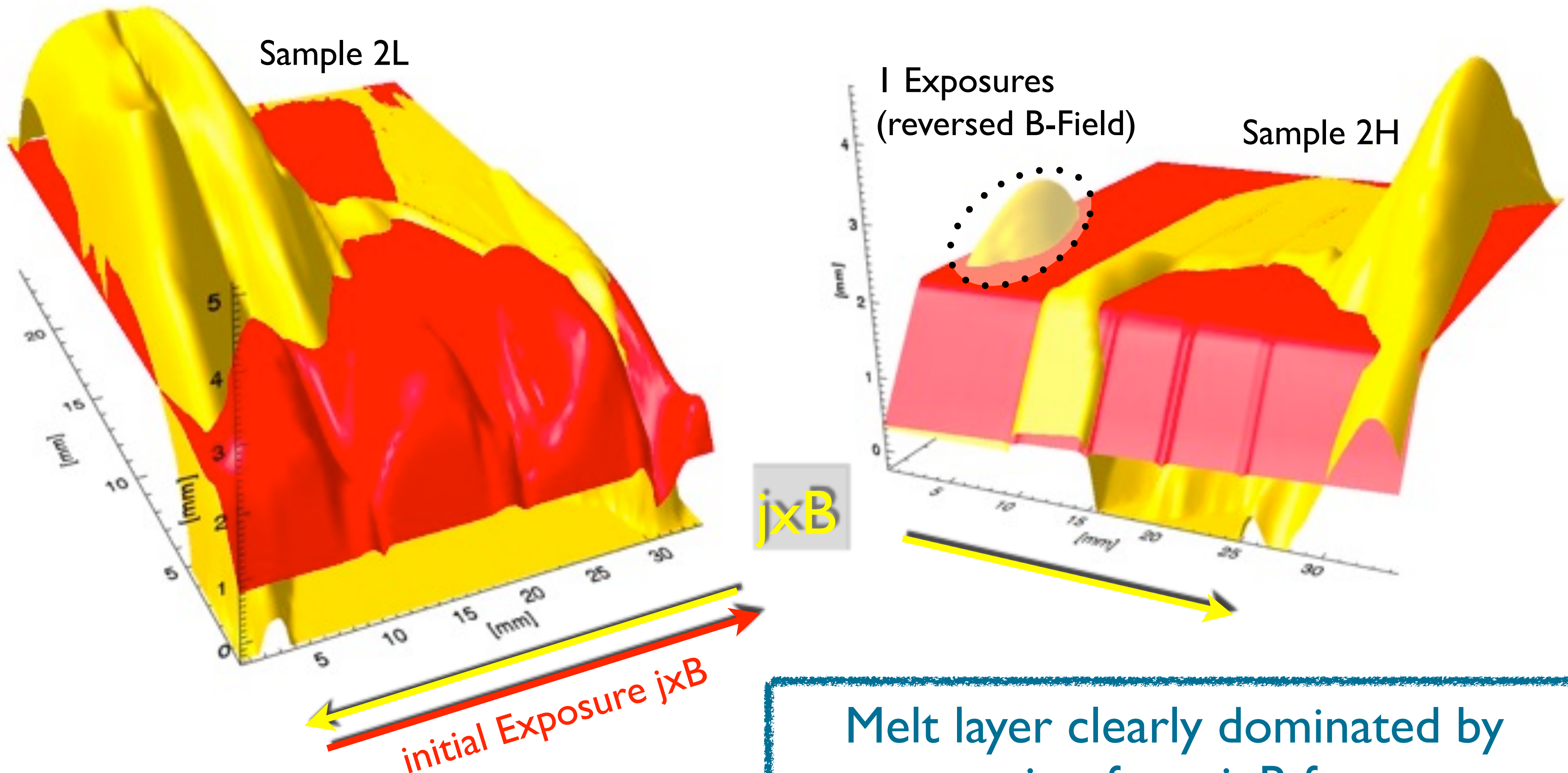
TRILATERAL EUREGIO CLUSTER

JÜLICH FORSCHUNGSZENTRUM

Topology

Material redistribution

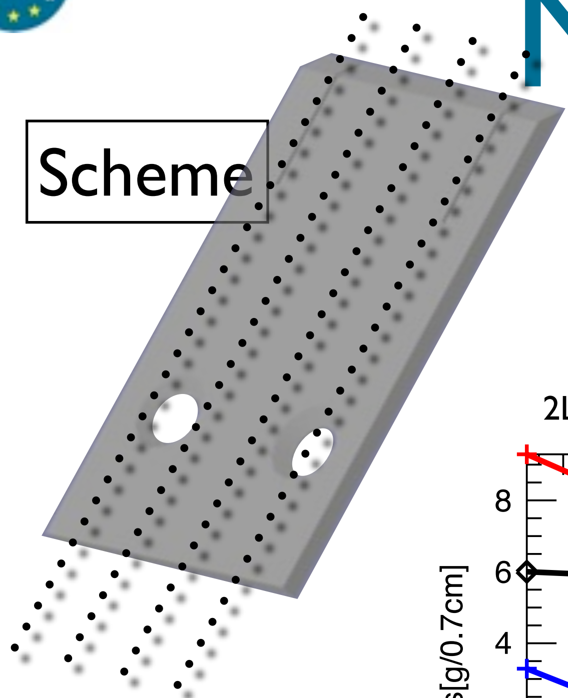
Topology



Melt layer clearly dominated by motion from jxB force

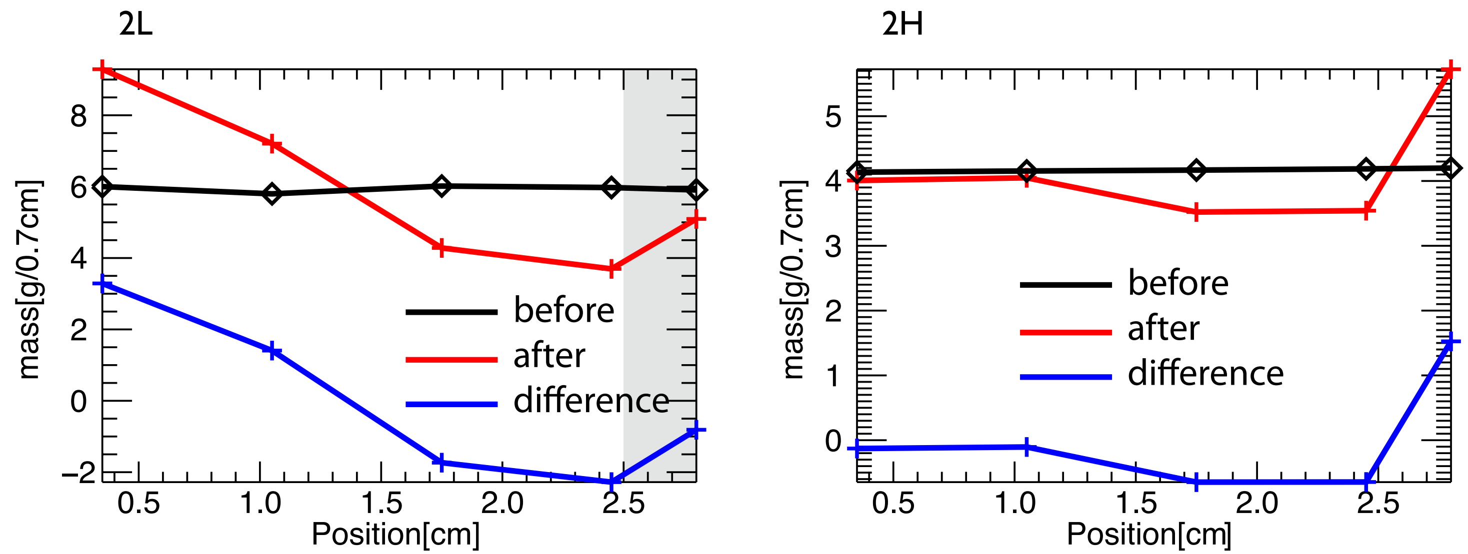
Multiple exposures lead to bridging and strong hill formation (> 2+3mm)

Mass Motion



Up to 4g of tungsten are redistributed

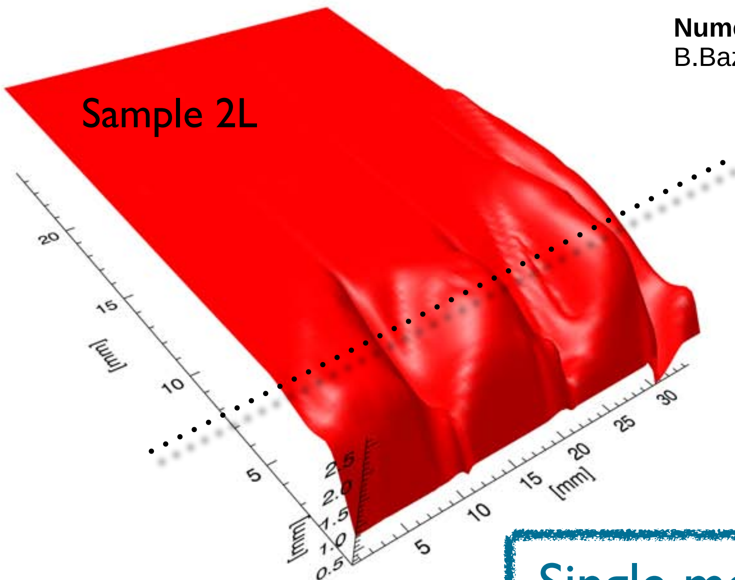
30 % of affected material is moved



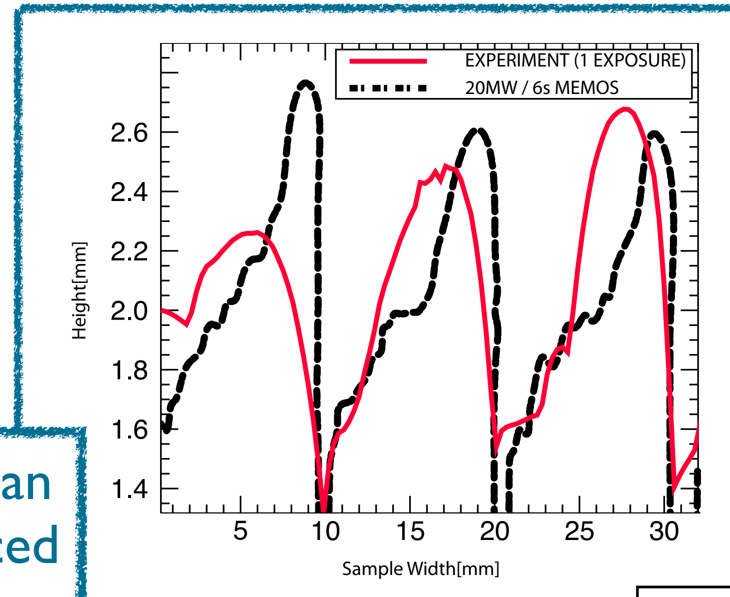
Changing direction of B can move mass segments back

Shape does not recover into a beneficial state

Modeling



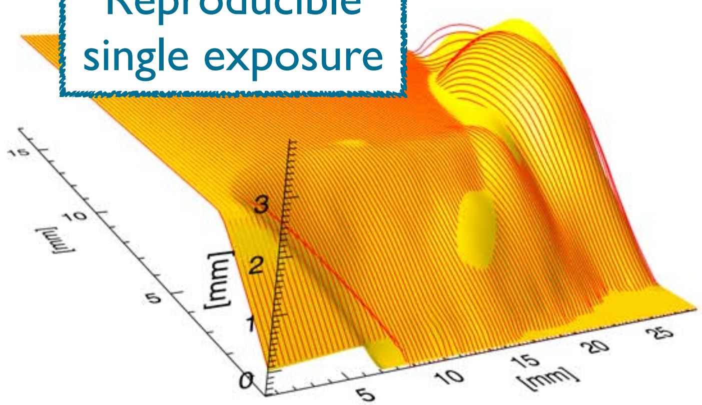
Numerical Simulation of Tungsten Melt Layer Erosion caused by JxB force at TEXTOR
B.Bazylev et al



B. Bazylev

Single melt exposure can be accurately reproduced with 2D simulations.

Reproducible single exposure



<u>3D-Code in preparation to model 3D topology from single and multiple melt exposures</u>

TRILATERAL
EUREGIO CLUSTER

2. Power-handling

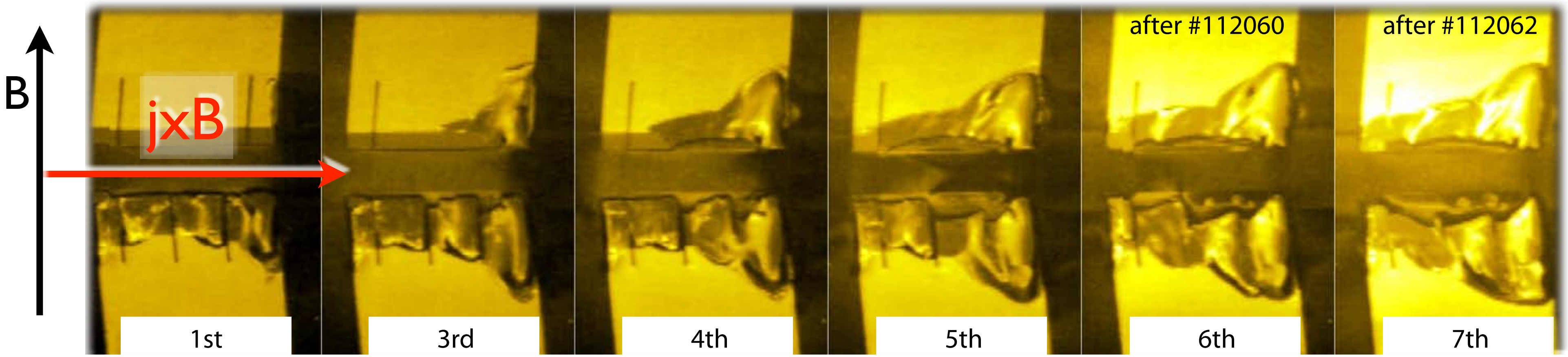
Evolution

- SHOT BY SHOT -

Plasma Illuminated Plates

(r=48cm)

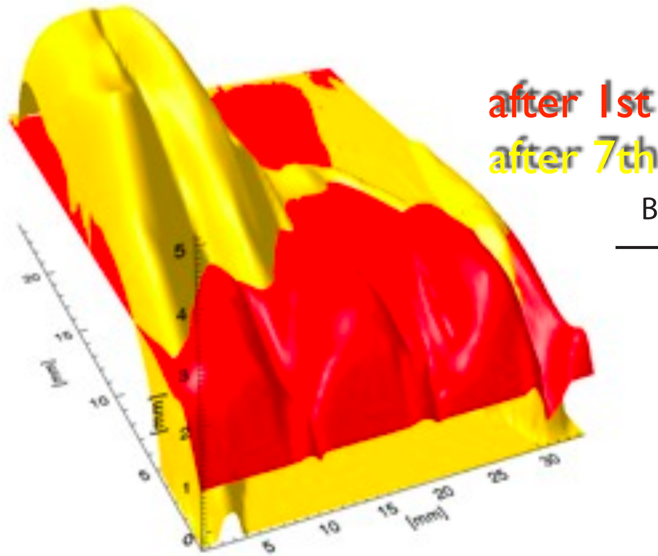
sample W

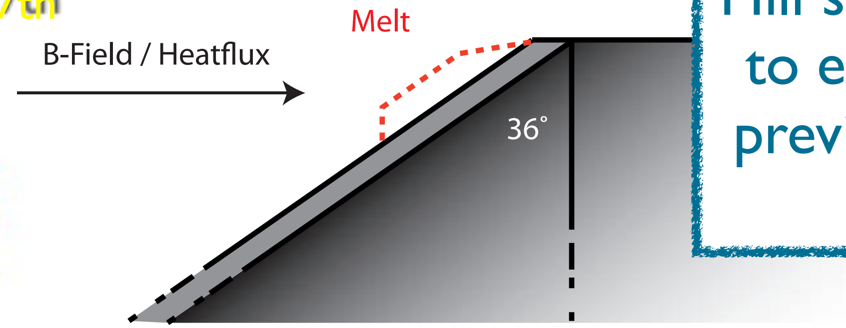


sample 2L

Strong Shaping - Hill Structures & Edges

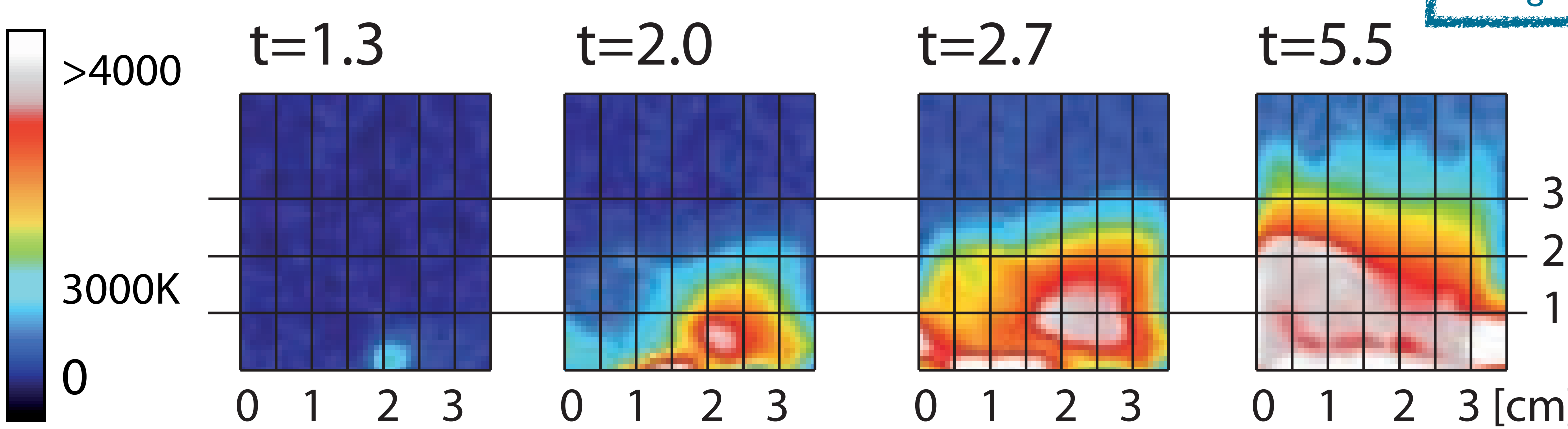
Powerhandling





Hill structure can lead to exposed edges in previously unaffected regions.

during 7th exposure



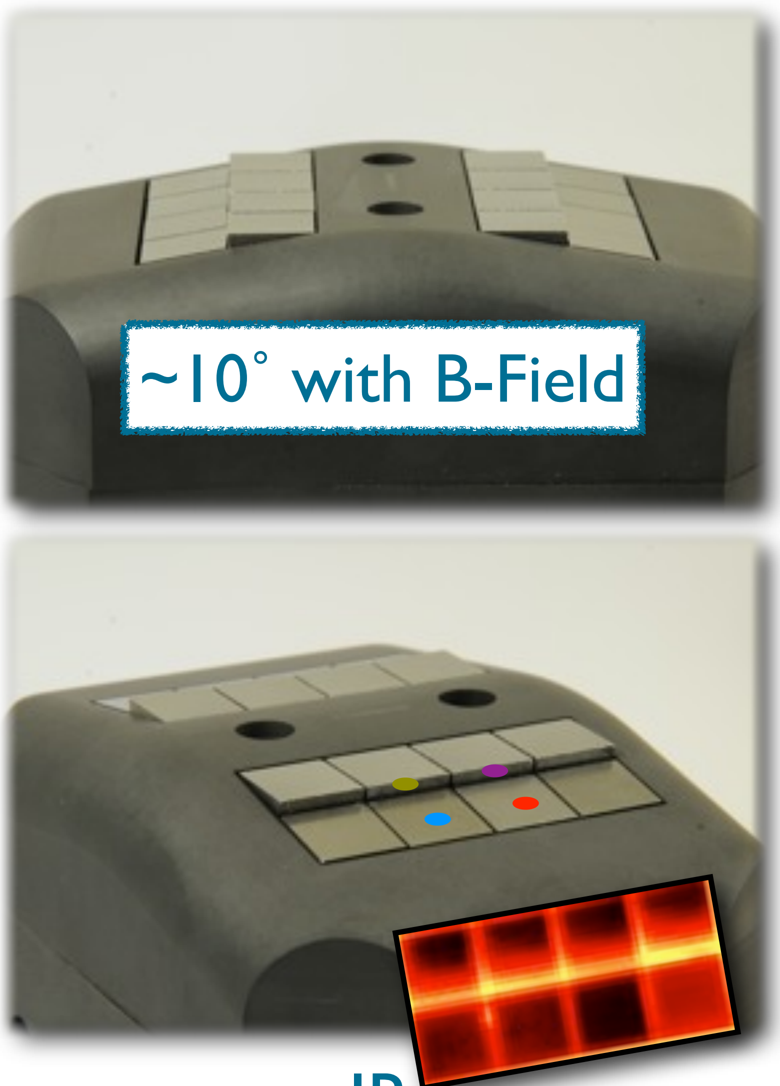
ITER: $q_{||}/q_{\perp} = \sin(90)/\sin(3) = 19$

Leading Edges

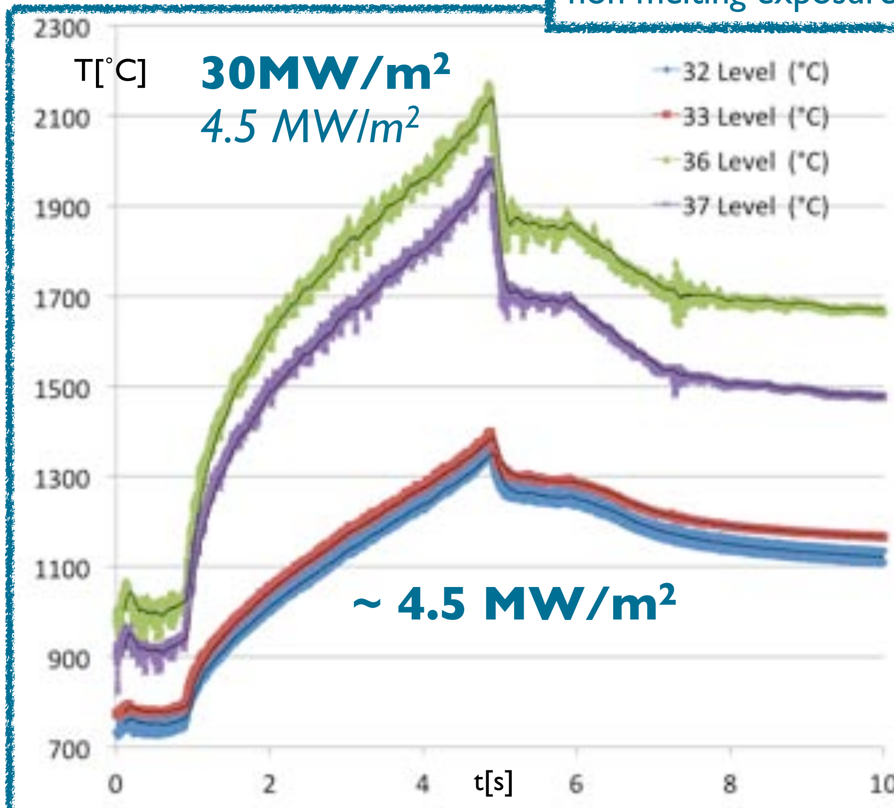
by Design

Leading Edges

(12x12x15) mm^3 Tungsten blocks
2mm leading edges

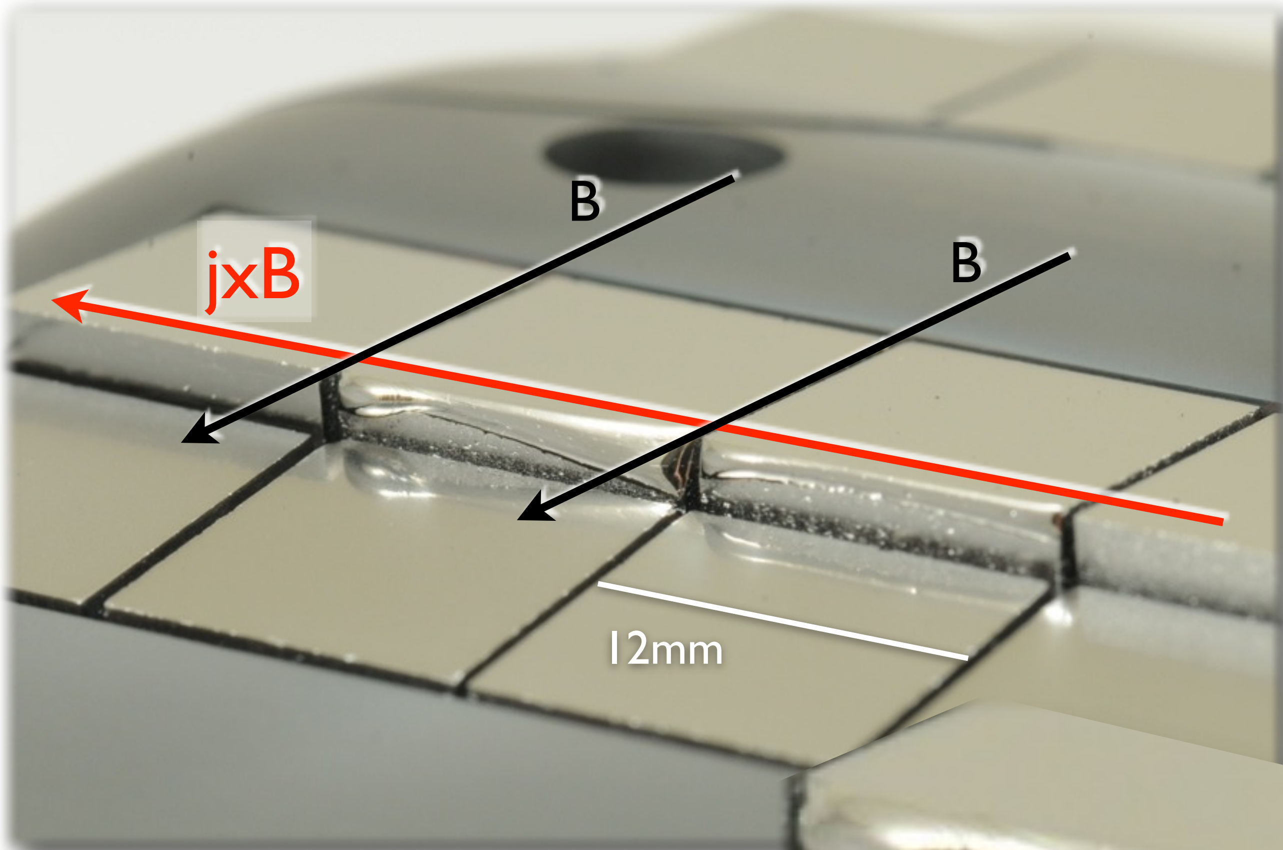


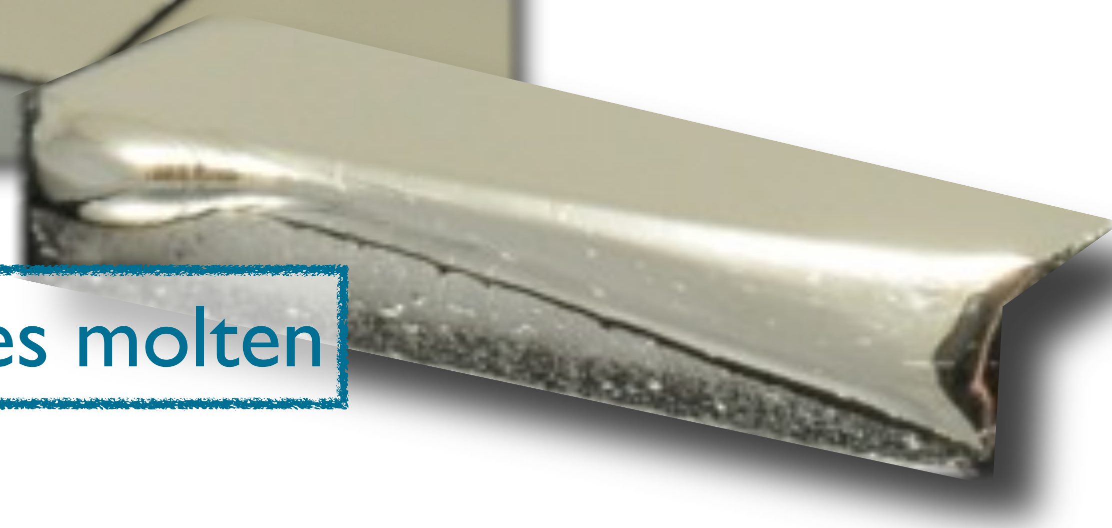
non melting exposure



q_{edge}/q_{top} = sin(90)/sin(10) ~ 6

Melting





Only front surfaces molten

Mitglied der Helmholtz-Gemeinschaft

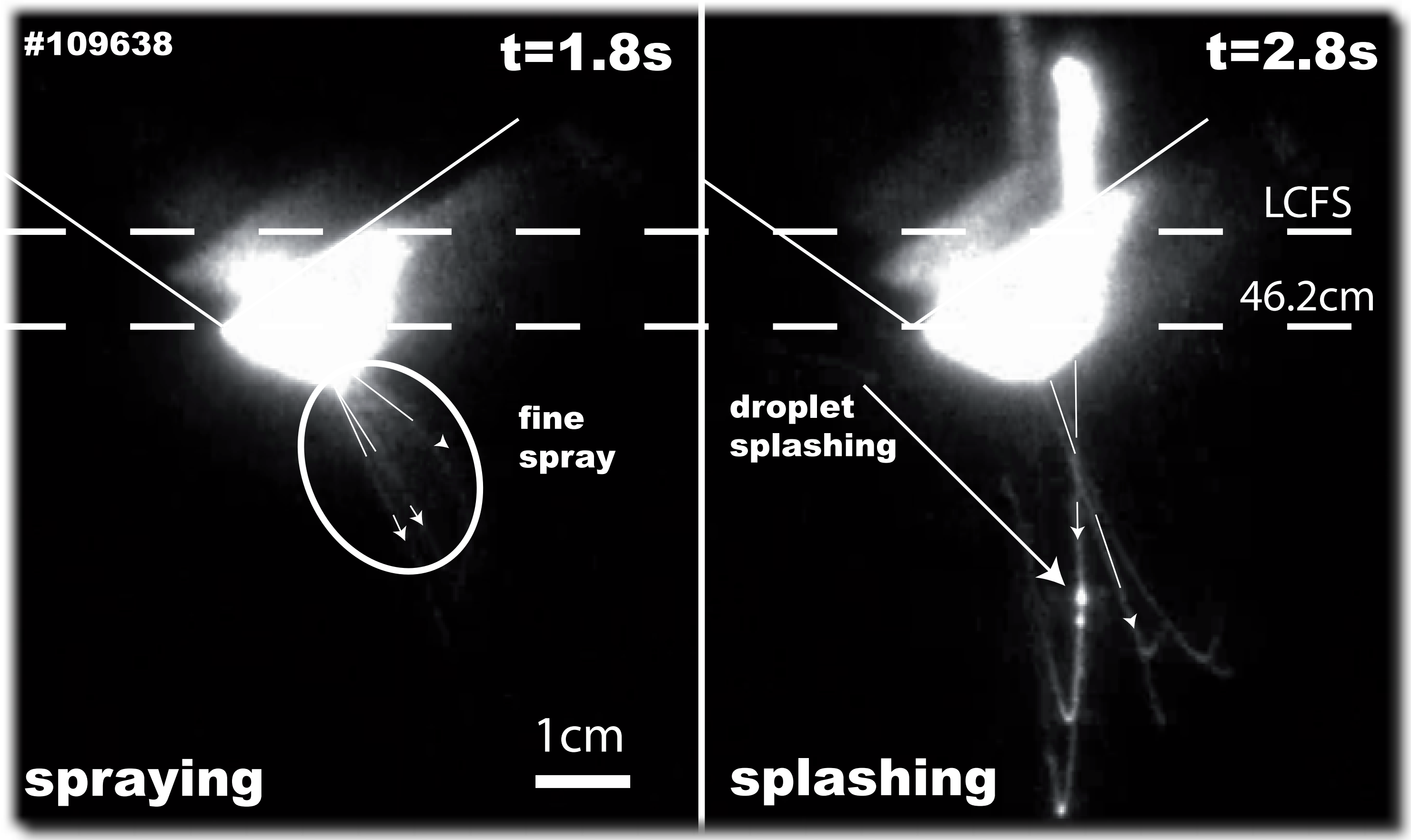
TEC
TRILATERAL
EUREGIO CLUSTER

JÜLICH
FORSCHUNGSZENTRUM

3. Material Loss and Splashing

Transport and screening of ejected tungsten in controlled melt experiments at ASDEX Upgrade
Karl Krieger

Spraying & Splashing

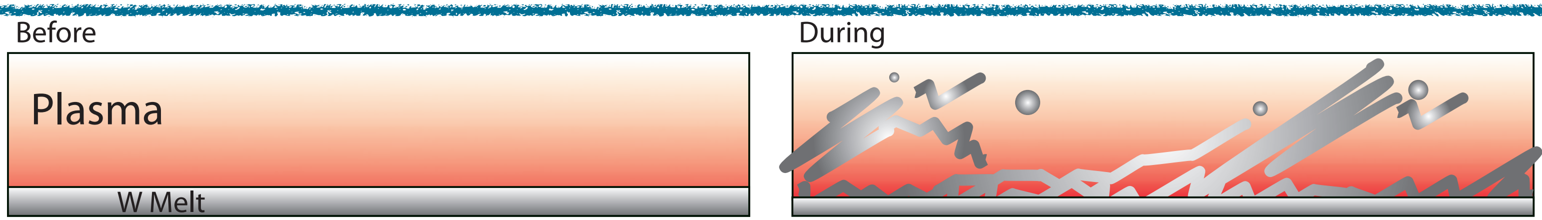


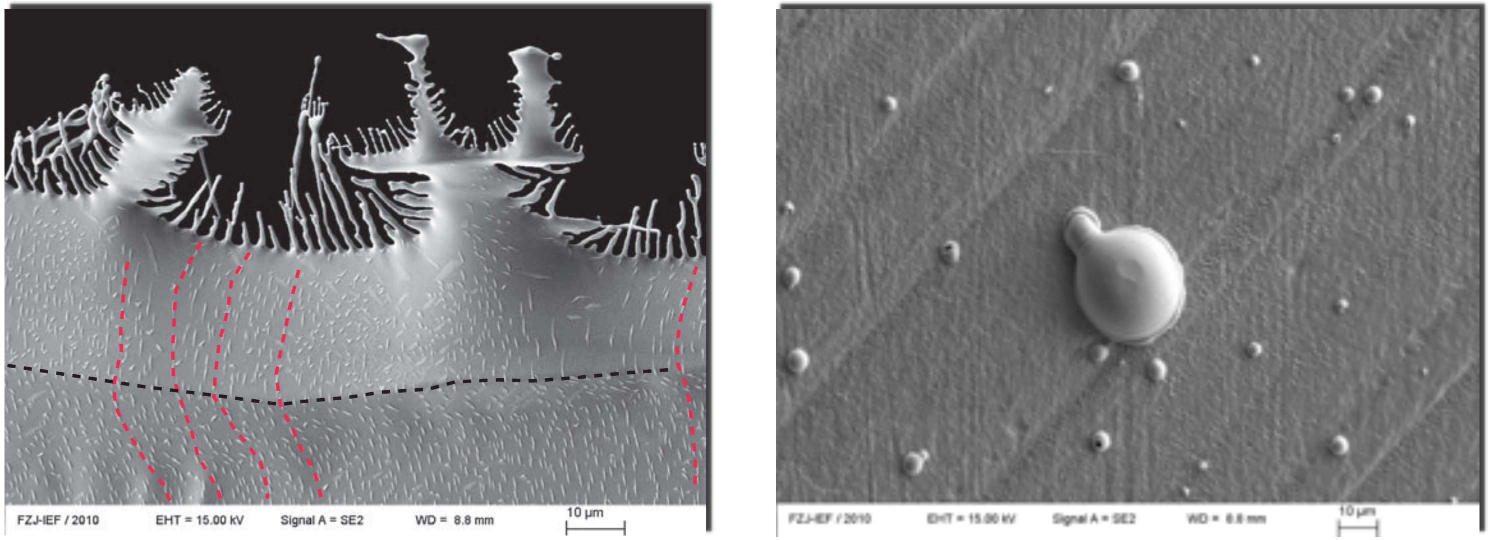
Droplet Production

The most promising explanation for splashing seems a Kelvin-Helmholtz instability incorporating linear stability analysis and non linear modeling

Bazylev, B. et al. Fusion Engineering and Design, 2009, 84, 441-445
Experimental and theoretical investigation of droplet emission from tungsten melt layer

Miloshevsky, G. et al, *accepted by Nuclear Fusion,* 2010
Modelling of Kelvin-Helmholtz instability and splashing of melt layers from plasma facing components in tokamaks under plasma impact





Spraying and Splashing

e.g. Droplets

Plasma Impact

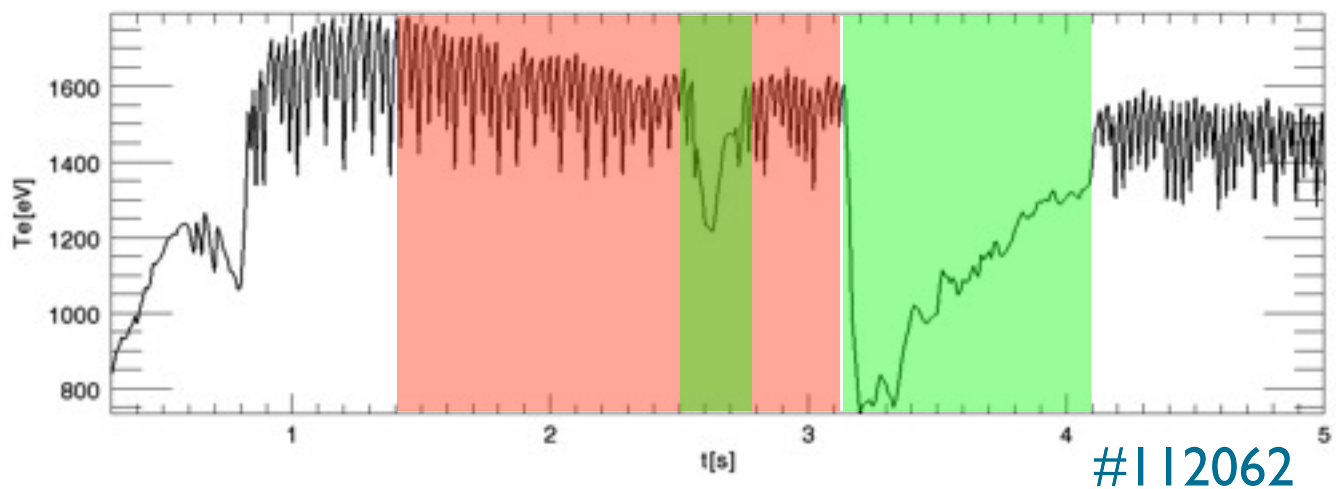
Spraying
Does not necessarily lead to a disruption

Feedback between spraying, W accumulation and temperature.

Splashing
Droplet can extinguish the plasma

Clear drop in core temperature

Can induce a disruption



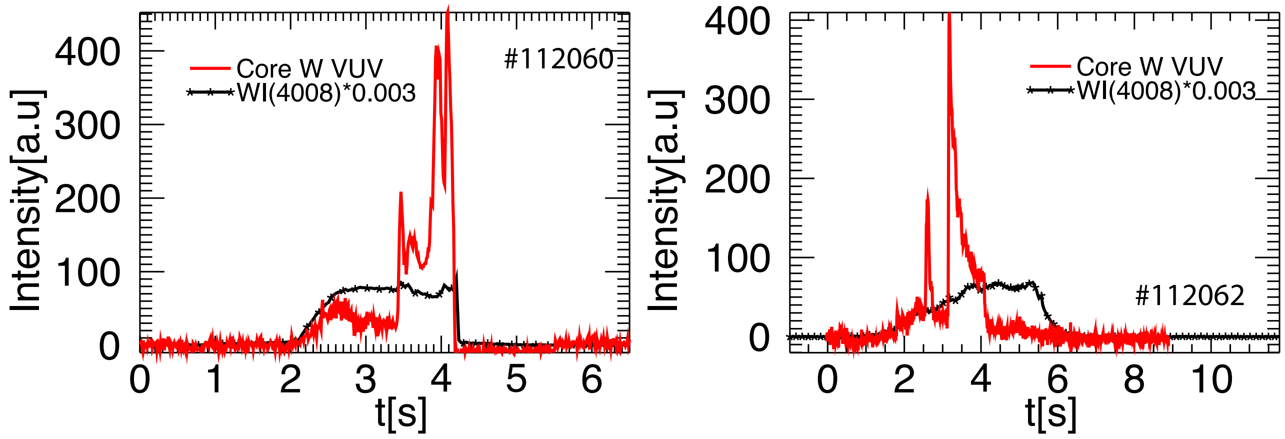
#112062

Mitglied der Helmholtz-Gemeinschaft

Tungsten source

Limiter source & Core

Droplets



Local W source consistent with evaporation

Local boiling may explain Spraying

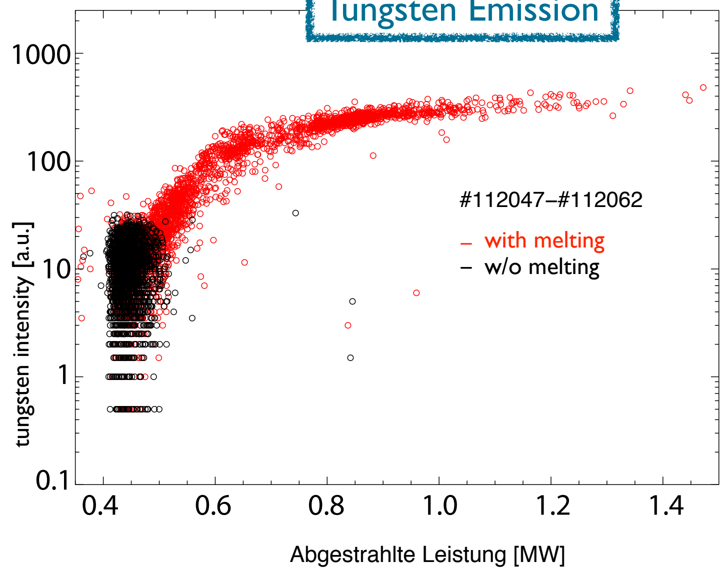
Droplets emitted from the surface can penetrate deeplydue to their lifetime and thus contribute strongly to the accumulation and radition in the core

Tungsten emission can lead to radiation collapse

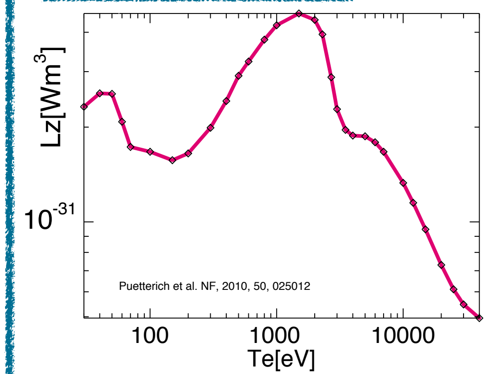
Transport and screening of ejected tungsten in controlled melt experiments at ASDEX Upgrade
Karl Krieger

Radiated Power

Tungsten Emission



Cooling Factor



Max. 1MW radiated power from W source

T_e=1100 eV
n_e=4.2 10^{19}m^{-3}

Splashes >200kW per droplet ⇒ 5.8 10^{16} m^{-3}

Spray 50-200kW ⇒ (0.29 - 1.16) 10^{16} m^{-3}

c_W=~10^{-3}, 10^{-4}

Consistent with transport modeling of spray source, including feedback between plasma and spraying

M.Tokar , FZJ

TRILATERAL
EUREGIO CLUSTER

4. Re-solidification and Material Structure

Thermal shock response of fine and ultra fine grained tungsten based materials
G.Pintsuk

TRILATERAL
EUREGIO CLUSTER

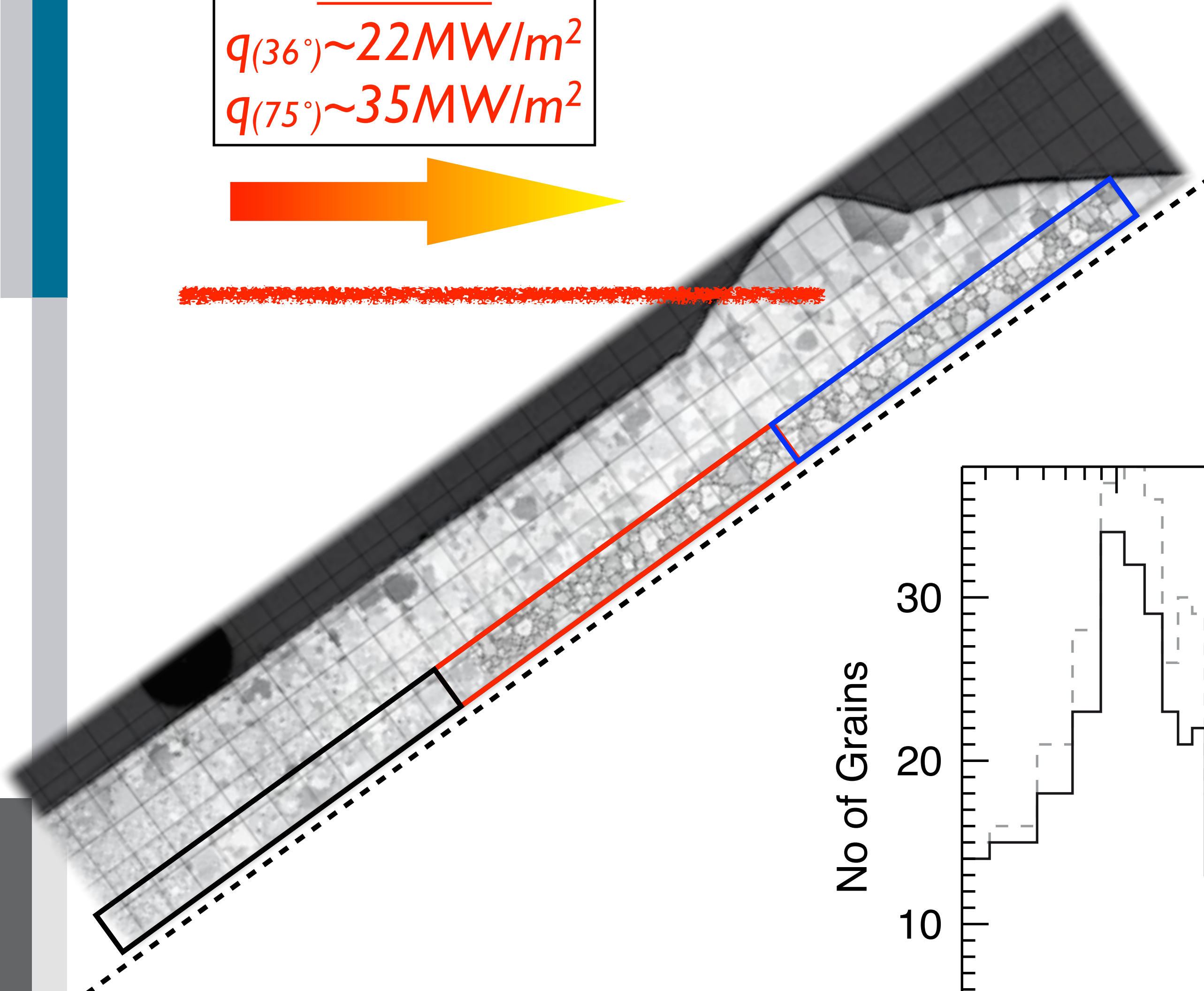
FORSCHUNGSZENTRUM

Grain Growth

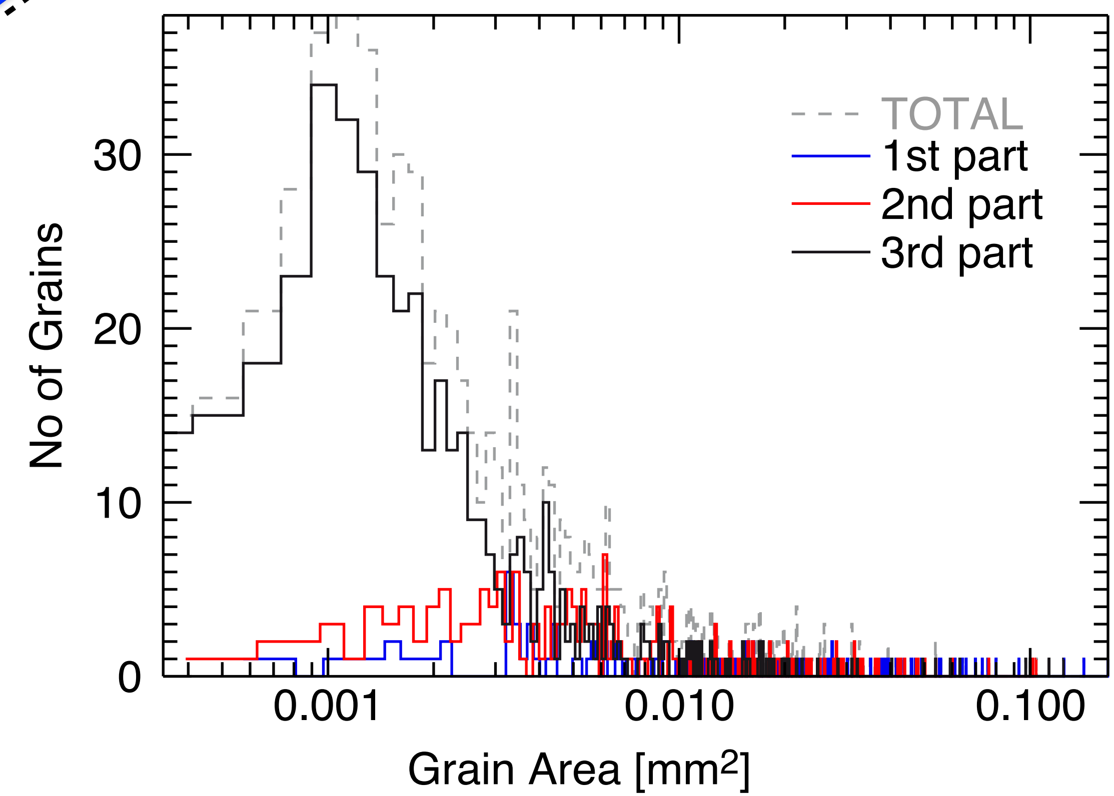
Re-crystallization

Grain Size

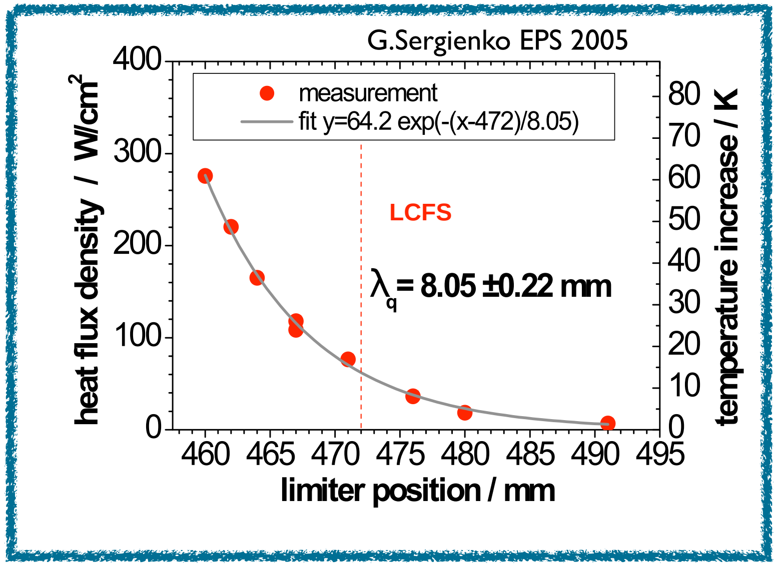
PLASMA
$q_{(36^\circ)} \sim 22 MW/m^2$
$q_{(75^\circ)} \sim 35 MW/m^2$



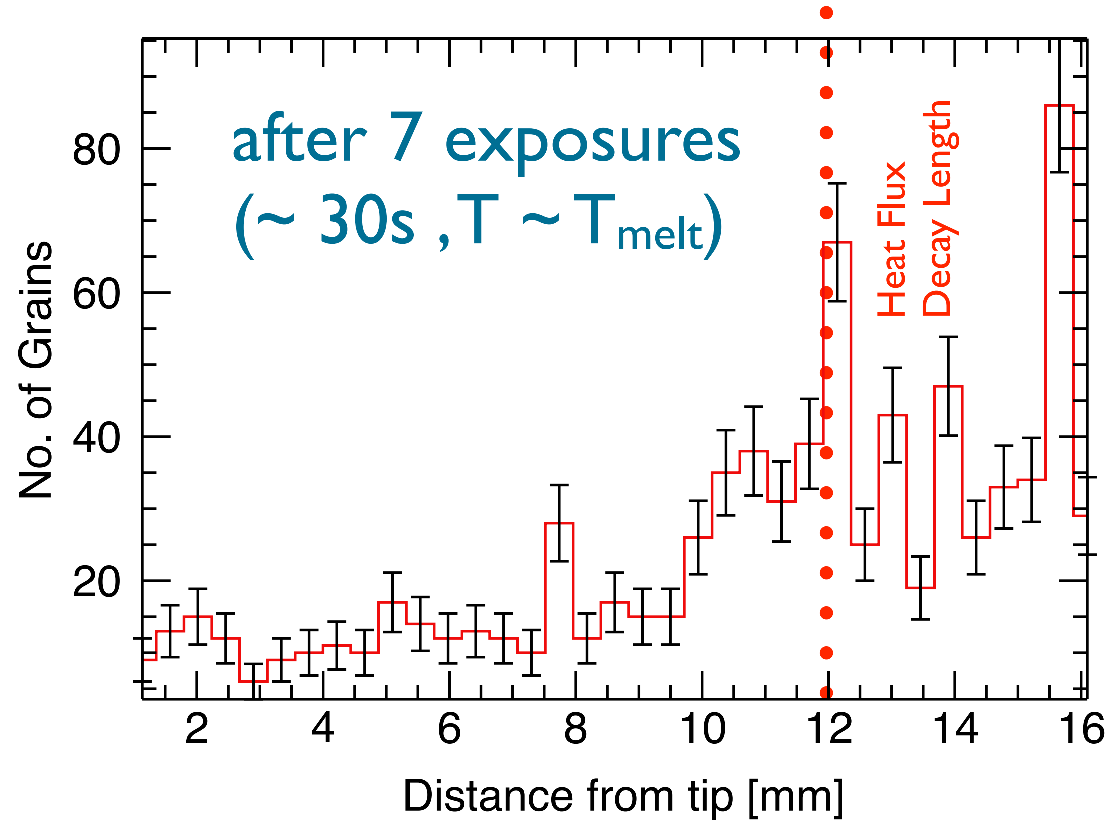
Strong recrystallization along the sample



Grains



Amount of grains along sample



The re-crystallization is directly connected to the amount of impinging heatflux (temperature)

Mitglied der Helmholtz-Gemeinschaft

TRILATERAL EUREGIO CLUSTER

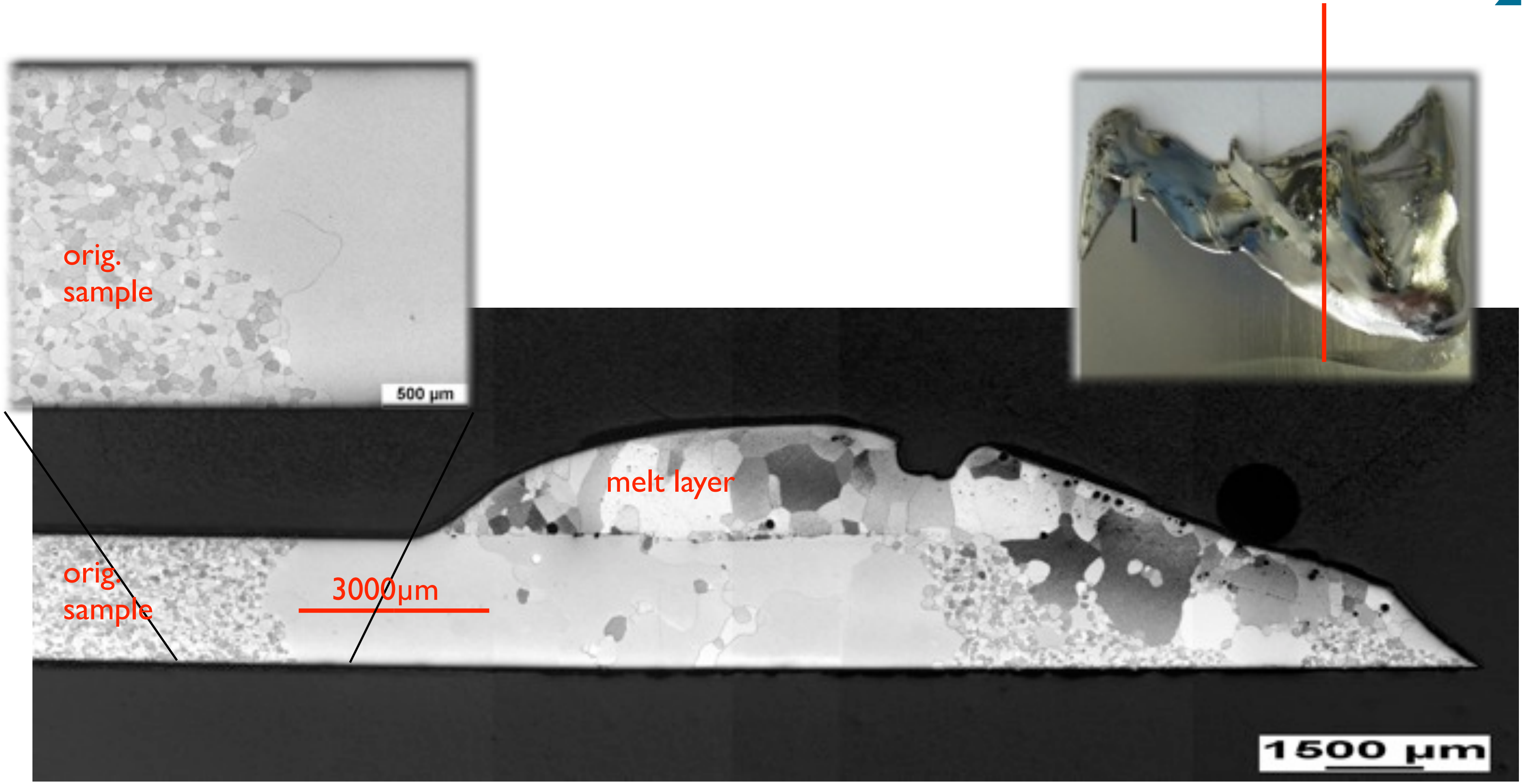
FORSCHUNGSZENTRUM

Melt Layers

After Multiple Exposures

Melt Layer Structure

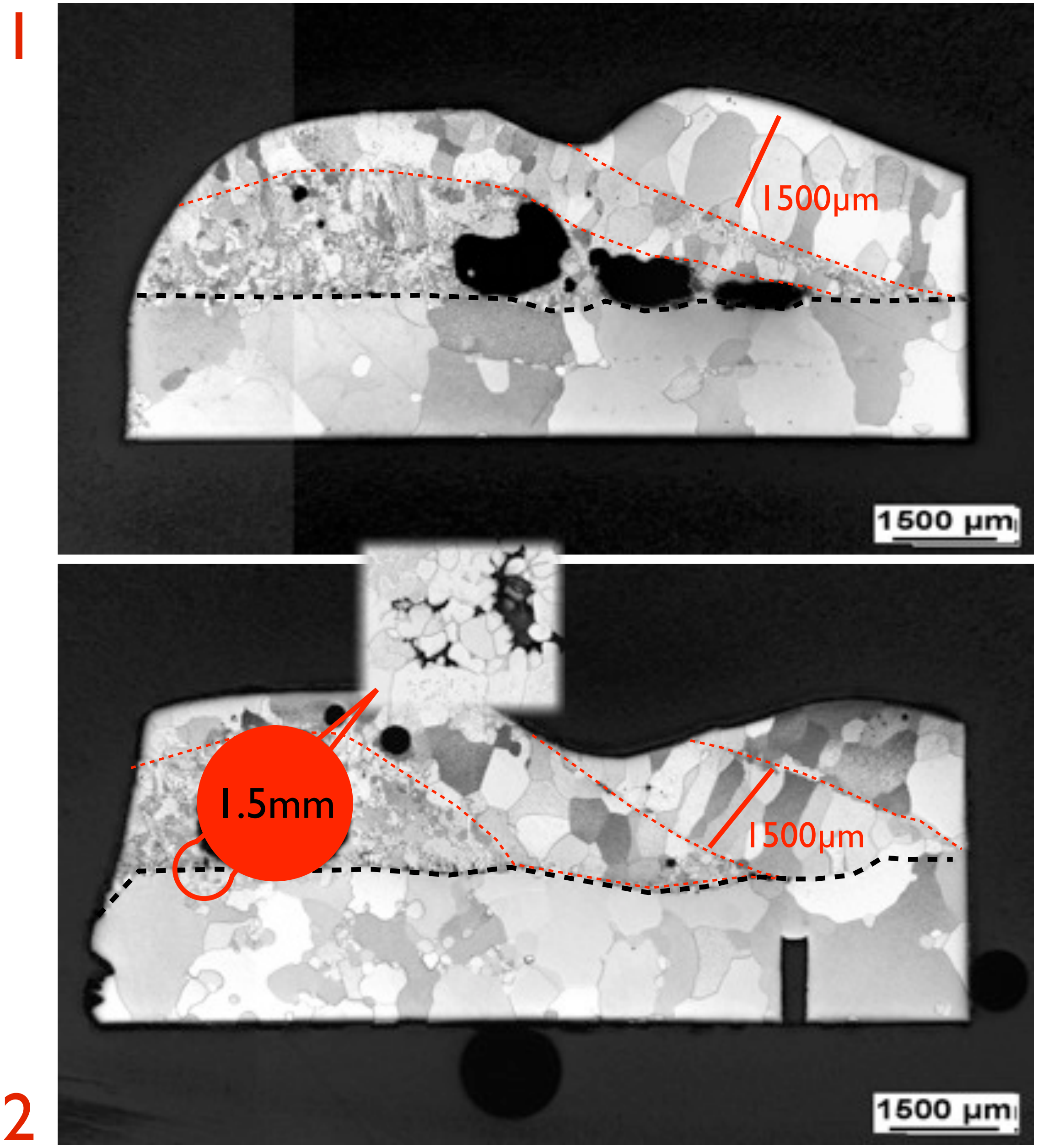
2010

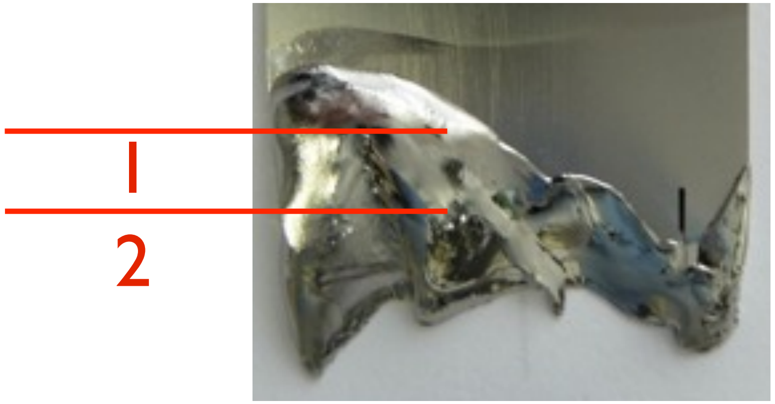


Strong re-crystalisation in both molten and un-molten material

Power-handling capability significantly degraded

Melt Layer Structure

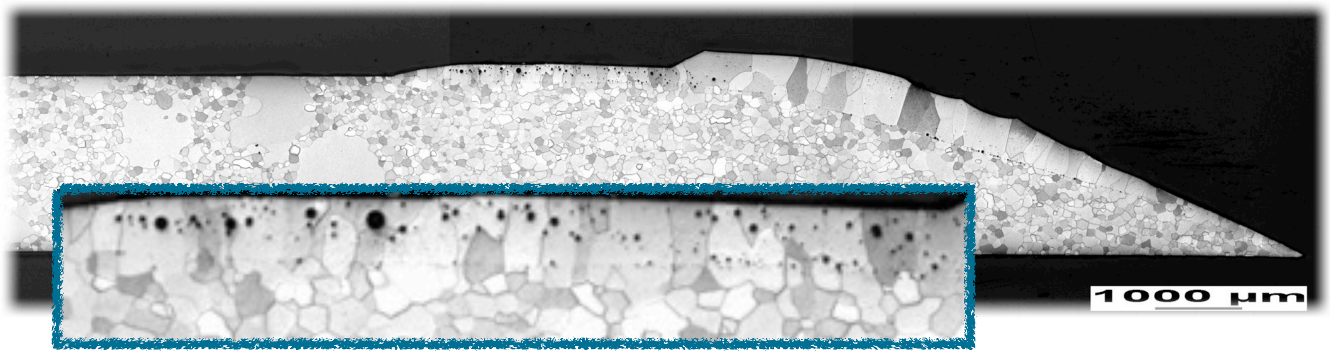


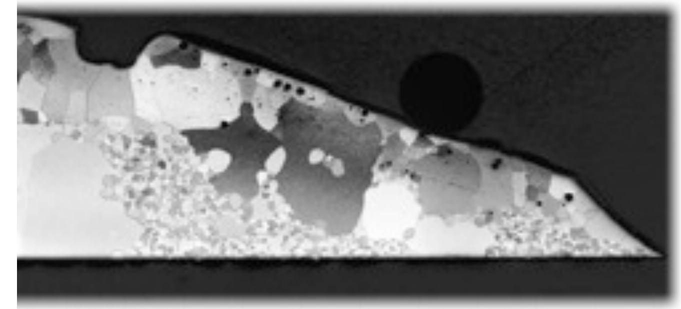


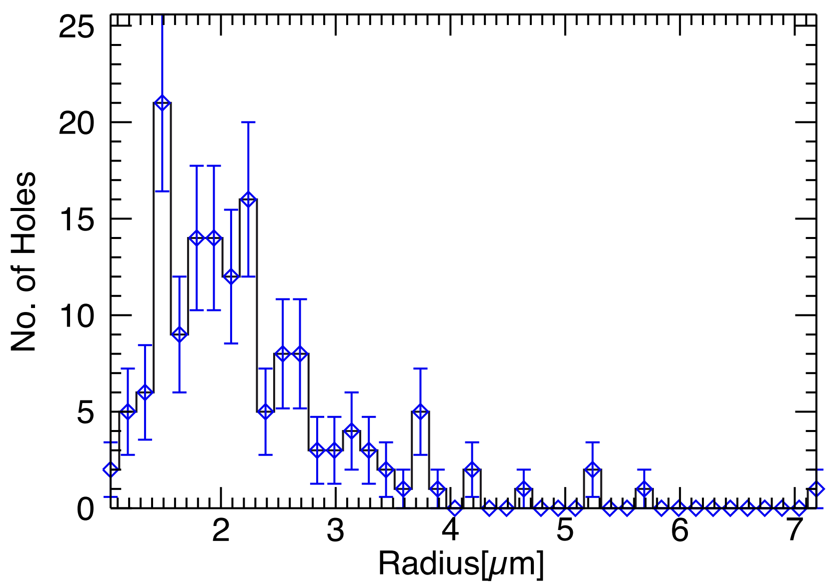
Melt layer thickness can reach up to 1.5 mm

Power-handling capability significantly degraded

Bubble-like Structures







Total Bubble / Area Total
Area: (2986/ 31643) µm²

Volume fraction~ 10%

Origin and content

TRILATERAL
EUREGIO CLUSTER

FORSCHUNGSZENTRUM

5. Transient Heat Flux Tests

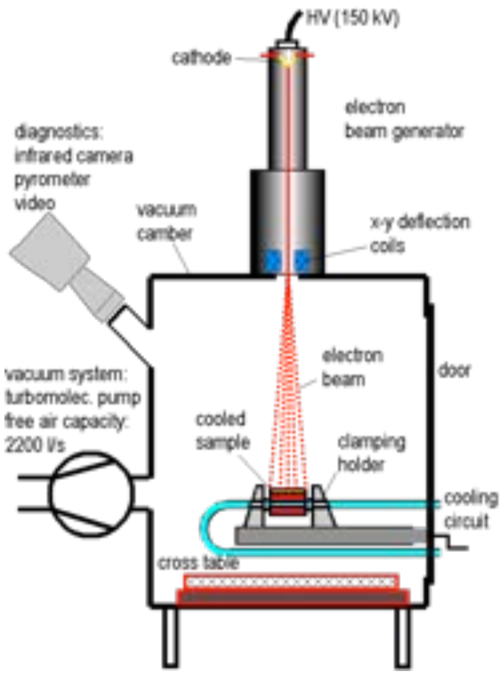
Judith I

Thermal shock response of fine and ultra fine grained tungsten based materials
G.Pintsuk

ELM-simulation experiments under ITER-like conditions
Gregory de Temmerman

E-beam Tests

JUDITH 1

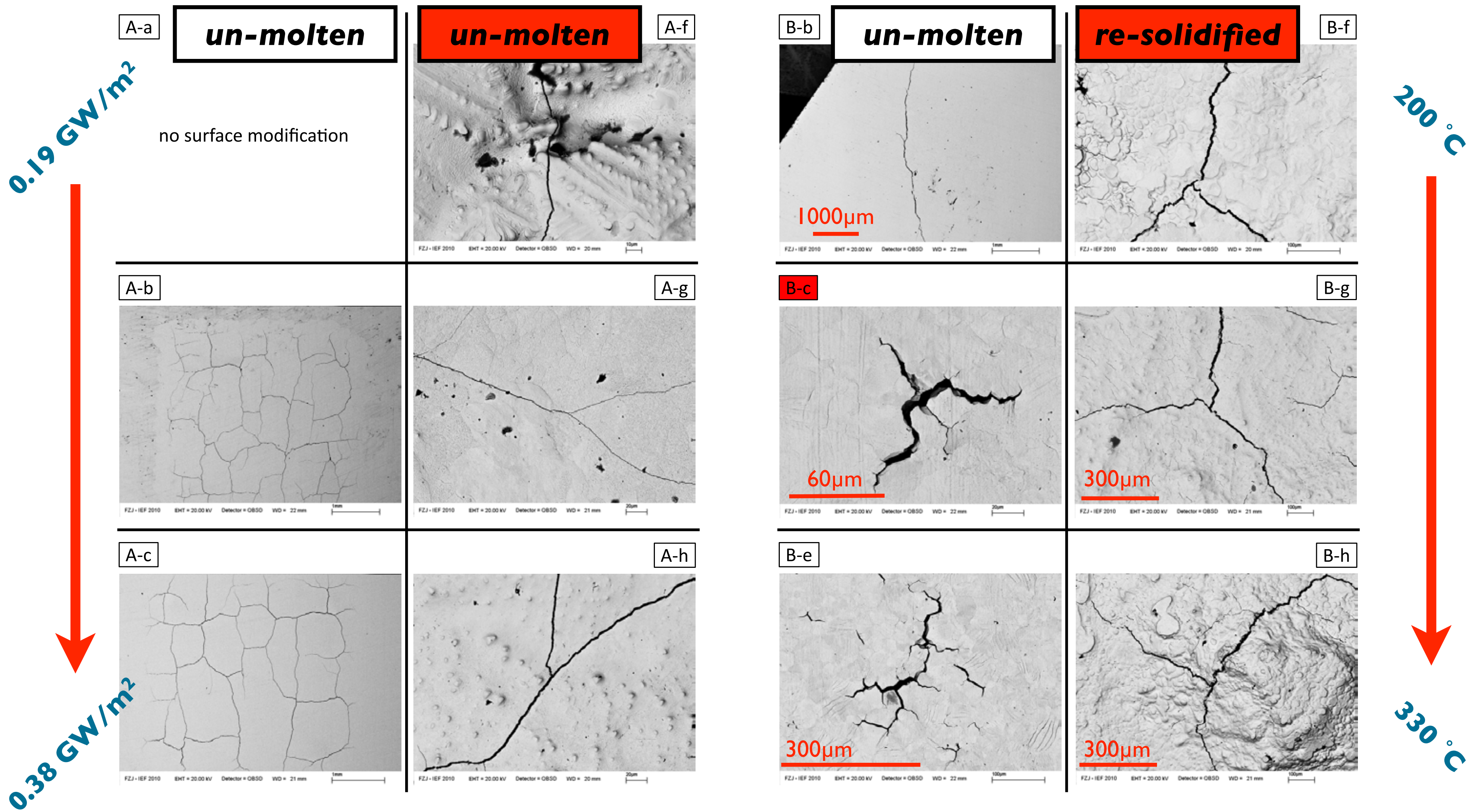


Electron beam power:	60 kW
Acceleration voltage:	120 - 150 kV
Electron beam diameter:	~ 1 mm
Power density:	< 15 GW/m²
Pulse duration:	> 1 ms
Scanning frequency:	100 kHz
max. scanning area:	100 x 100 mm²

	A-a	A-b	A-c	A-d	A-e	A-f	A-g	A-h
Base Temperature [$^\circ C$]	RT	RT	RT	RT	RT	RT	RT	RT
Heat Flux [GW/m^2]	0.19	0.28	0.38	0.57	1.13	0.19	0.28	0.38
Energy impact [$\frac{MJ\sqrt{s}}{m^2\cdot\sqrt{s}}$]	6	9	12	18	36	6	9	12

	B-a	B-b	B-c	B-d	B-e	B-f	B-g	B-h
Base Temperature [$^\circ C$]	150-175	200-240	250-280	250-280	330	200-240	250-280	330
Heat Flux [$\frac{GW}{m^2}$]	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Energy impact [$\frac{MJ\sqrt{s}}{m^2}$]	36	36	36	36	36	36	36	36

Cracks



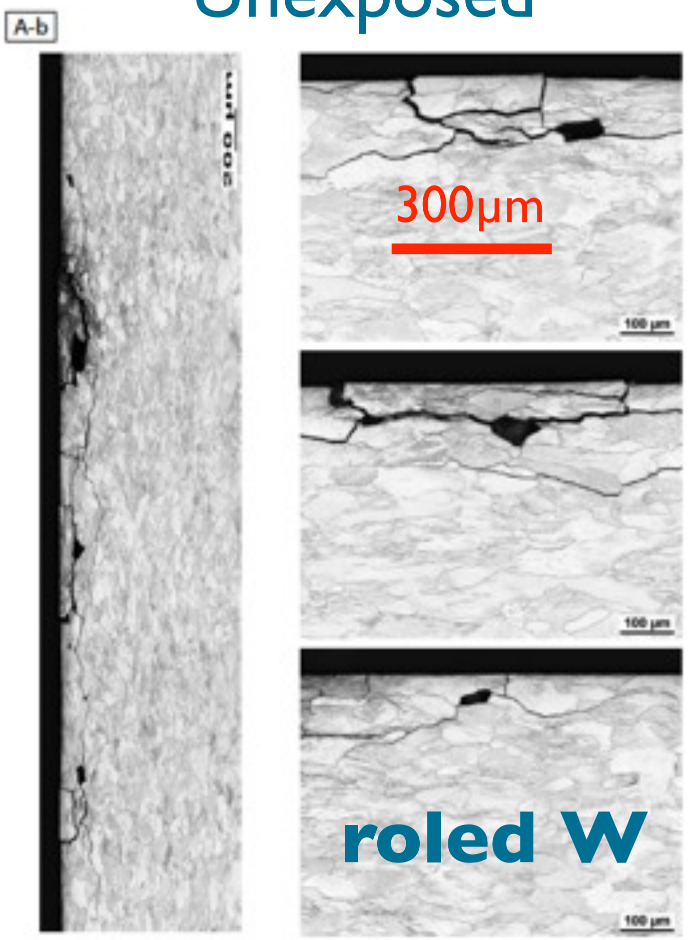
Room Temperature

$1.13\ GW/m^2$

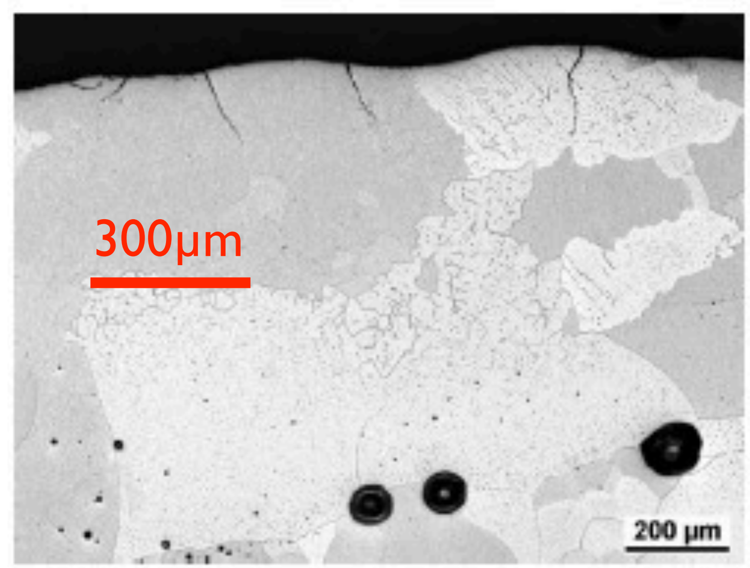
Material Properties

Bad News : Exposed material is much more brittle

Unexposed



Exposed

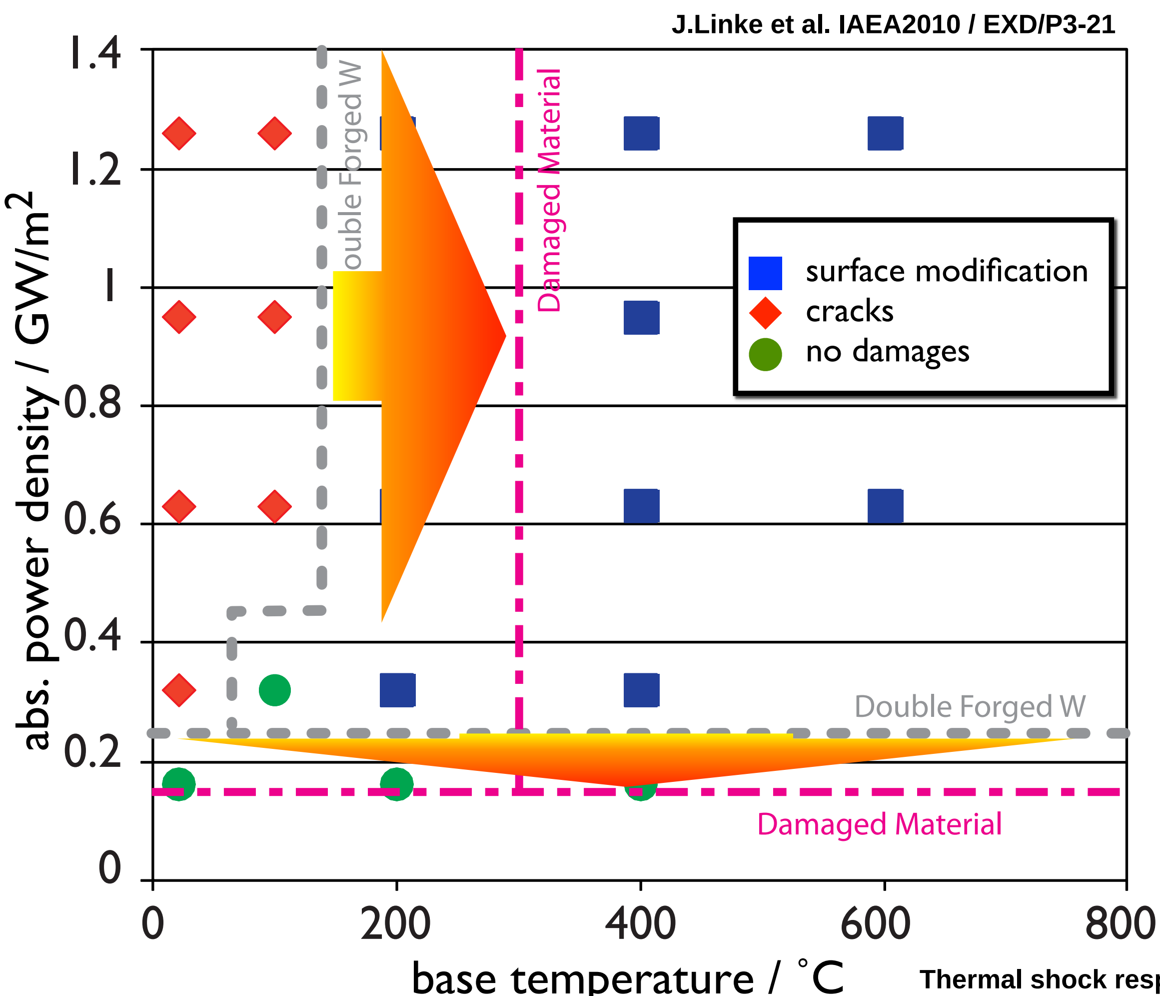


Crack behavior under transients seems more benevolent

Result

(M190): test matrix

<u>electron beam test facility</u>
JUDITH 1: Δt = 1 ms; n = 100 cycles
Boundary conditions: $P_{abs} / P_{inc} = 0.46$



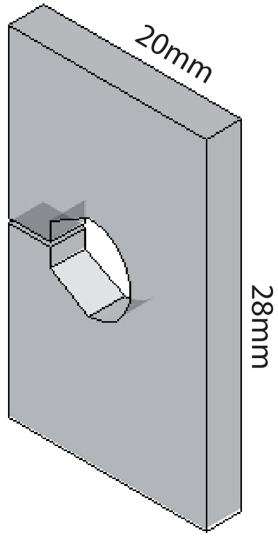
Melting leads to deterioration of material properties during high-heat flux tests

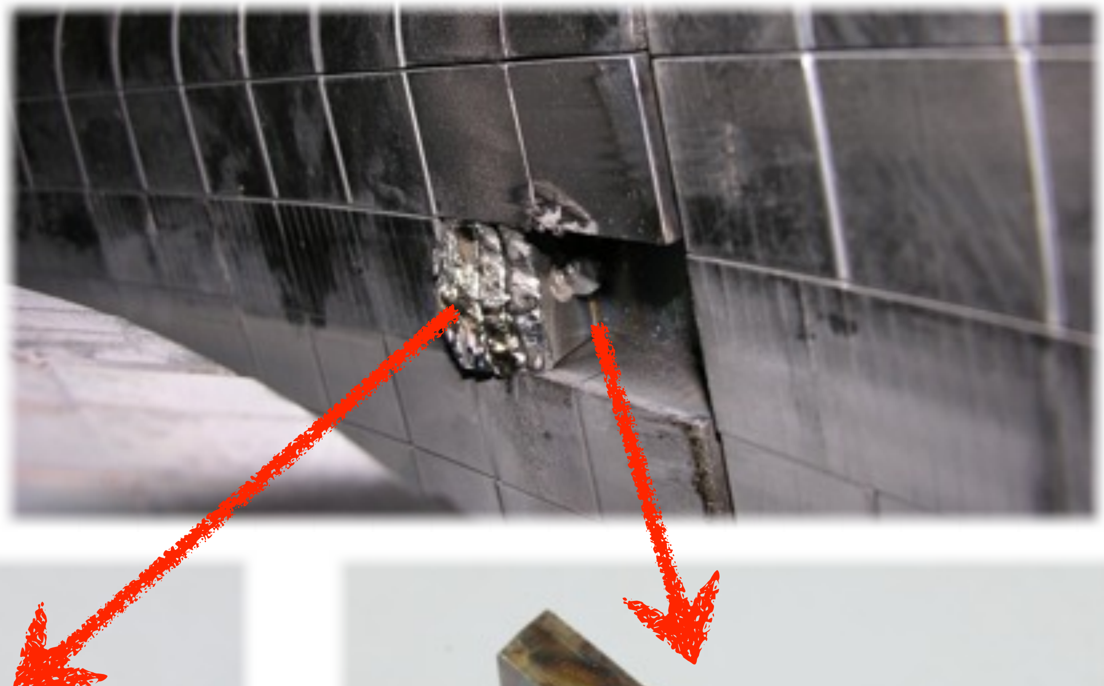
Thermal shock response of fine and ultra fine grained tungsten based materials
G.Pintsuk

6. Accidental Melting

Alcator C-Mod

Lamellae



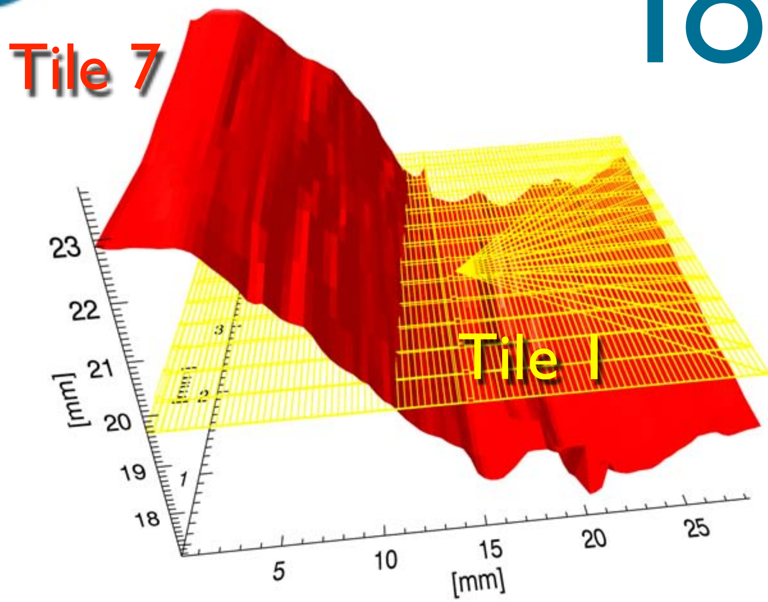


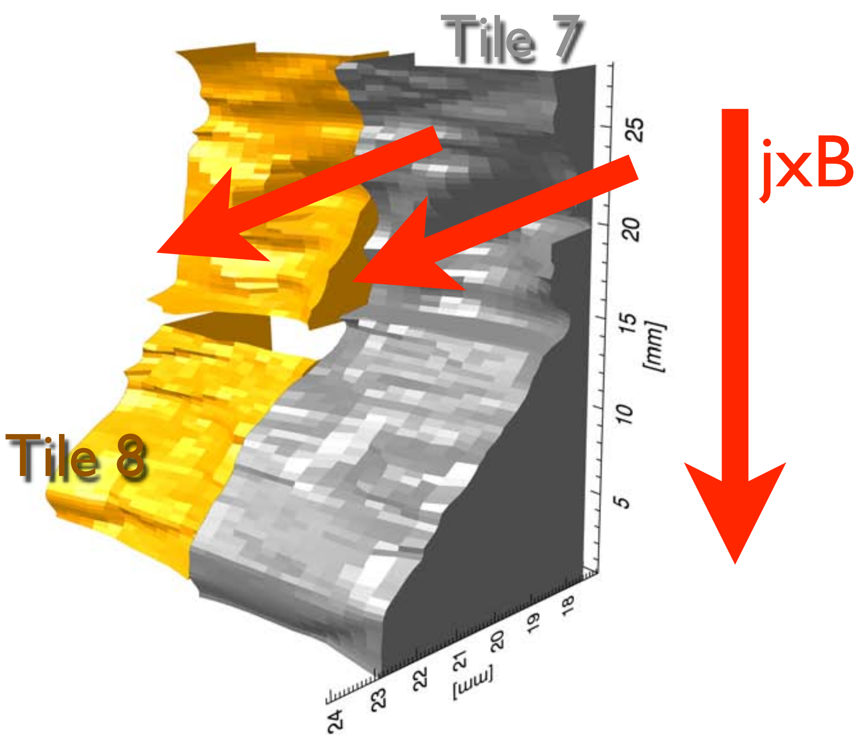
Damaged parts prohibits H-Mode operation on Tungsten row

Results

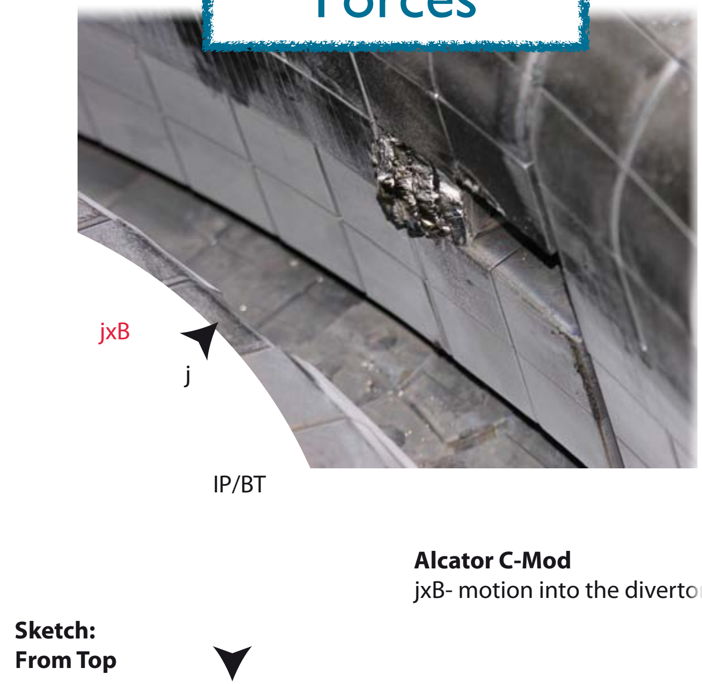
Analysis ongoing

Topology





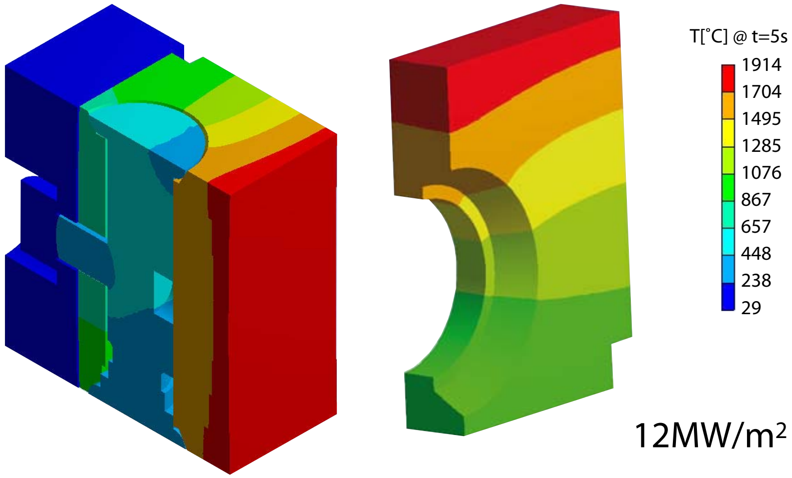
Forces

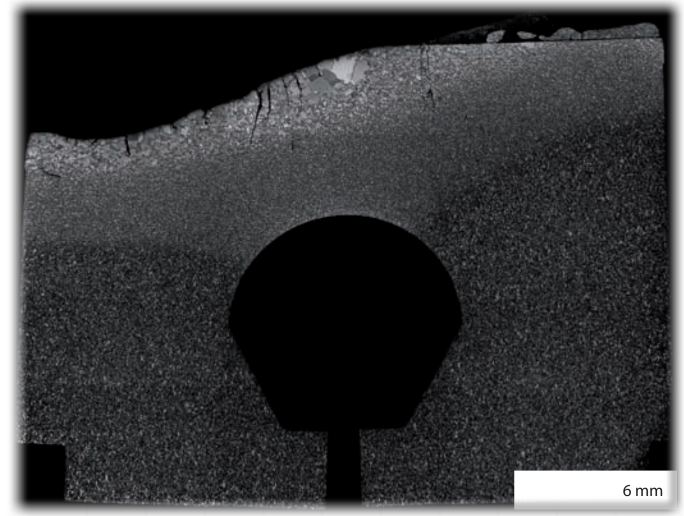


Material moved predominantly following jxB forces and gravity

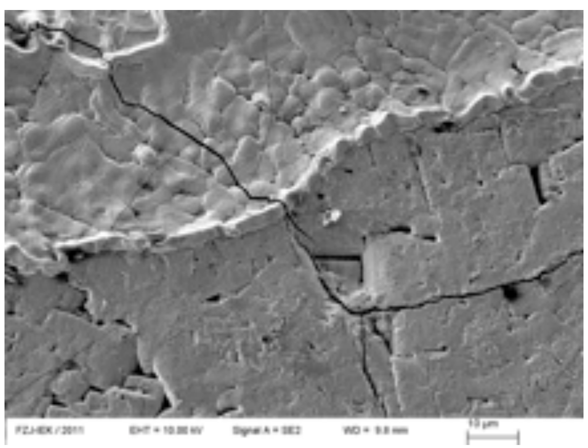
Indentations hint at additional pressure driven motion

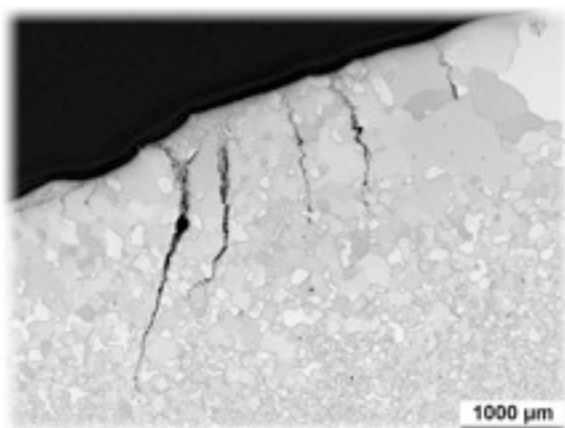
Material

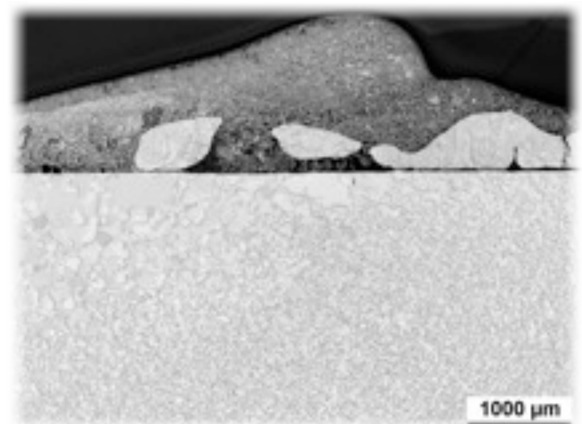




Grain growth and re-crsytallization follow the temperature profile

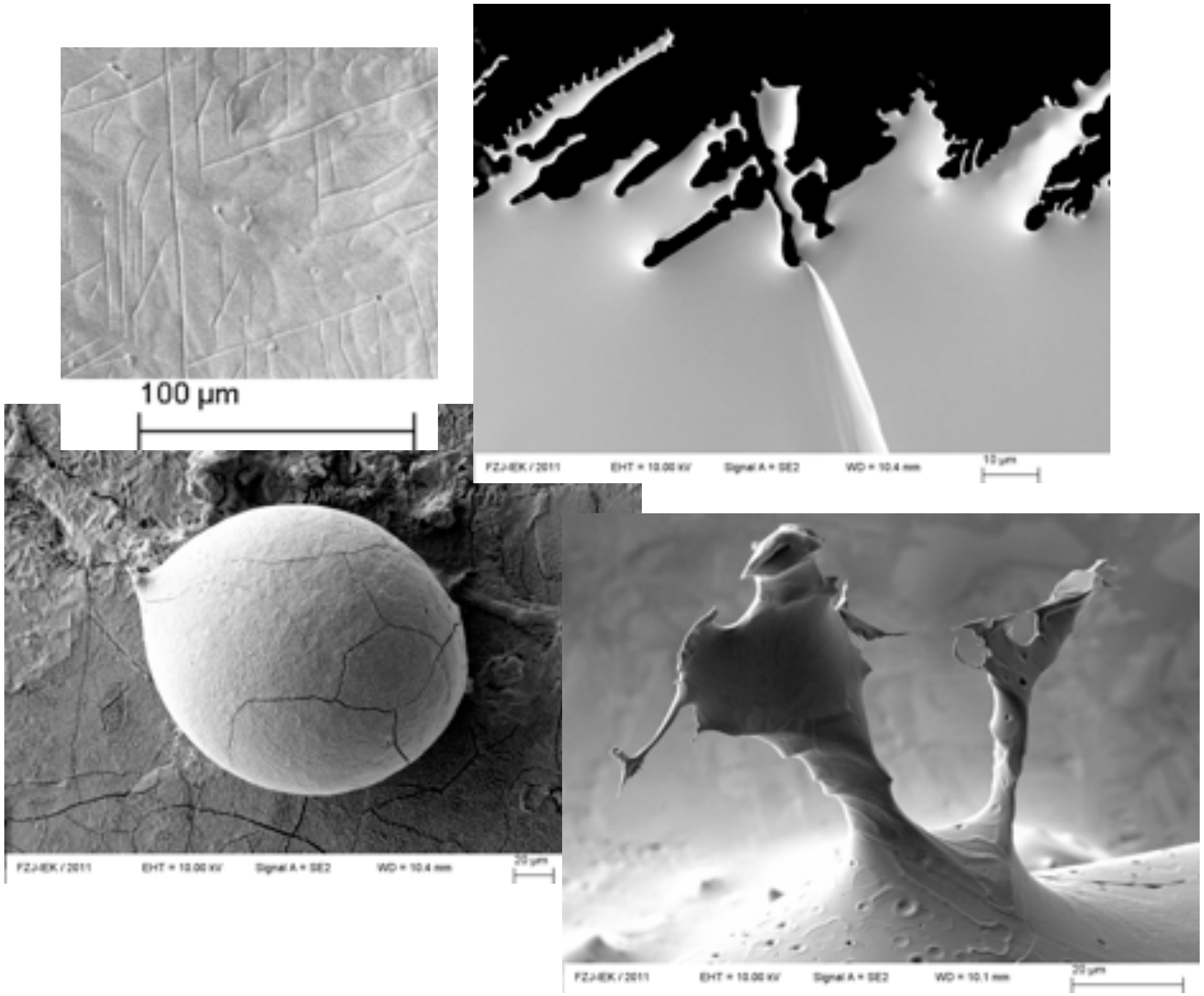






Strong , deep cracking and layer formation

Material Loss ?



Surface structures are similar to melt experiments

Melt Layer loss mechanisms probable

Mitglied der Helmholtz-Gemeinschaft

TRILATERAL
EUREGIO CLUSTER

Summary

Summary

Power handling with a metal wall is a severe issue
Resolidified materials decrease tolerable limits

Melt motion significantly worsens the situations
Forces include pressure and jxB (melt thickness , timescale)

Material structure departs strongly from design values
Additional transient heat flux is less tolerable (brittle)

Material suffers severly and material loss can significantly impact machine and plasma operation

‚Real' melt damage and modeling confirm experimental results

Do we need new Concepts when going beyond ITER ?

certainly more and new experiments and modeling (*ITPA DSOL-25*)

TRILATERAL EUREGIO CLUSTER

JÜLICH FORSCHUNGSZENTRUM

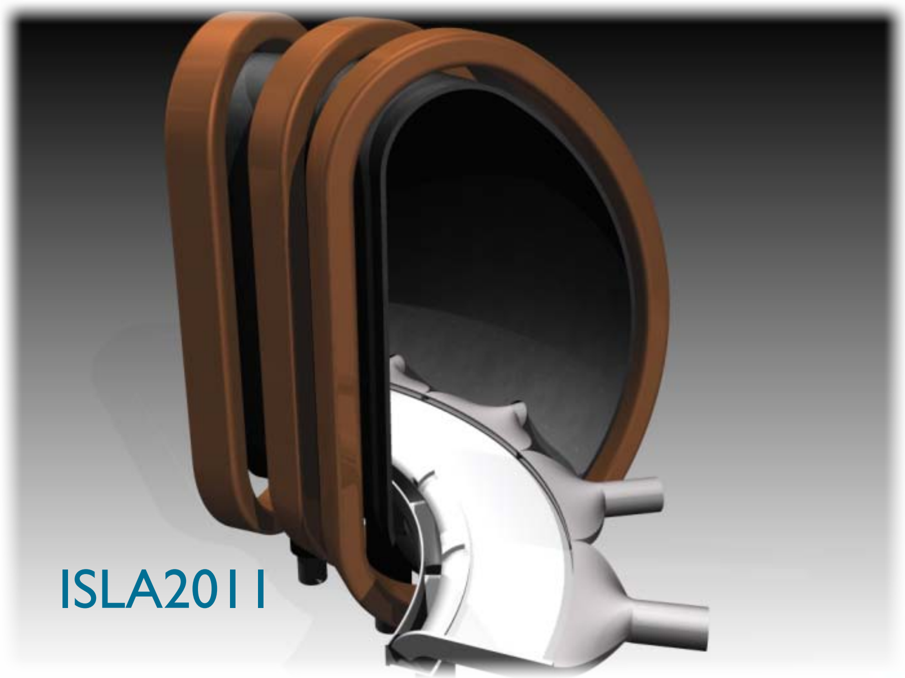
Thank You

- Melting and material degradation have to be avoided -

A strategy has to be devised for dealing with the degraded components and their power-handling capabilities should the observed effects be present in future devices.

This work, supported by the European Communities under the contract of Association between EURATOM/FZJ, was carried out within the framework of the EFDA Task Force on Plasma-Wall Interactions. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Supported under the IEA Implementing Agreement ‚Plasma Wall Interaction in TEXTOR'

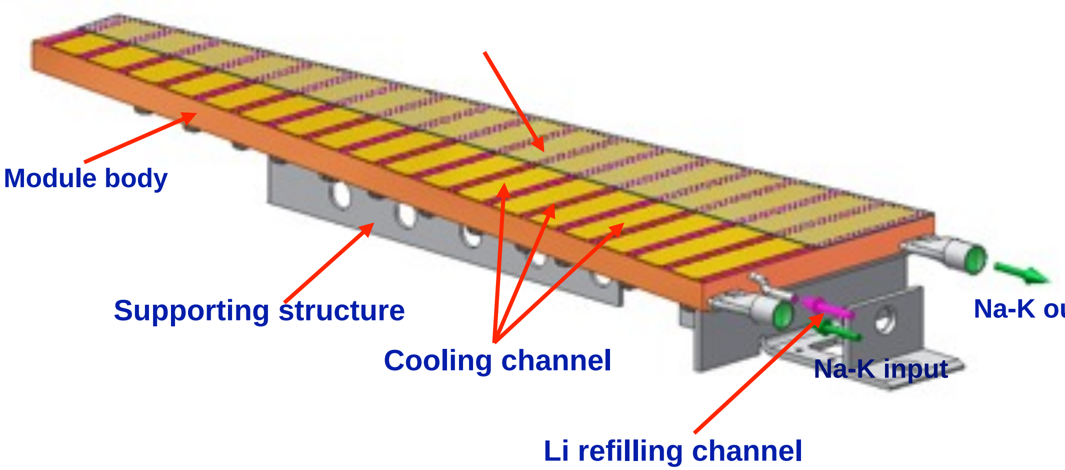
Outside the Box



New Wall concepts ?

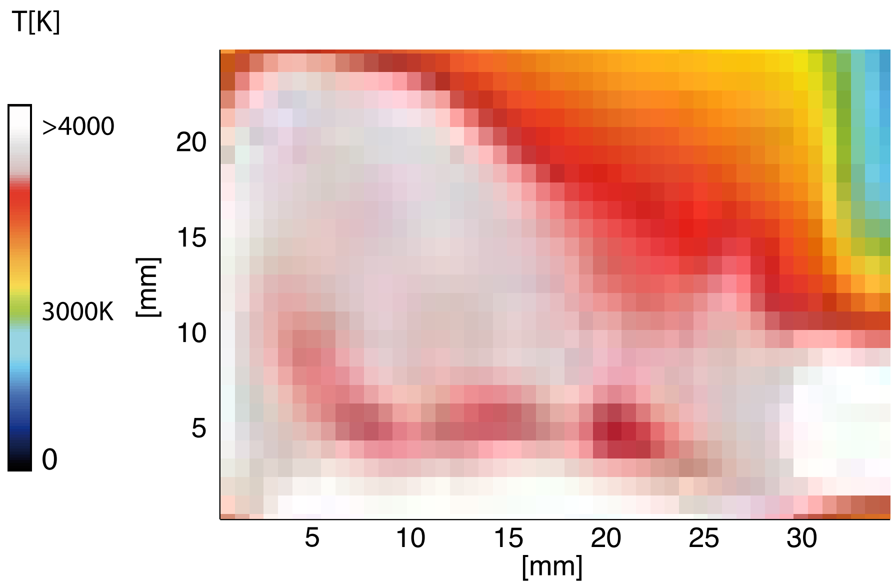
Flowing Liquid Wall?

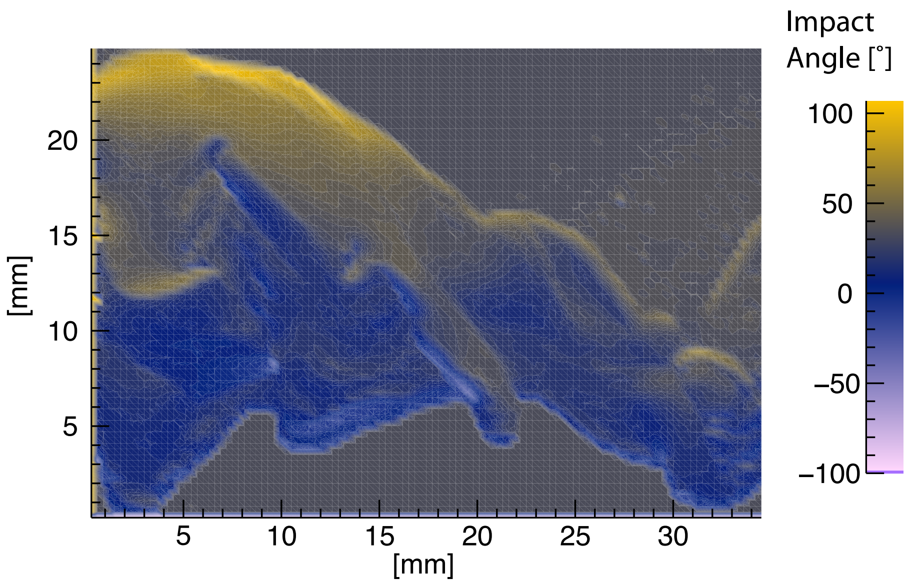
Static Liquid Wall ?



Lithium filled Capillary Pourus System tested in SPRUT-4 up to 25MW/m^2 steady state

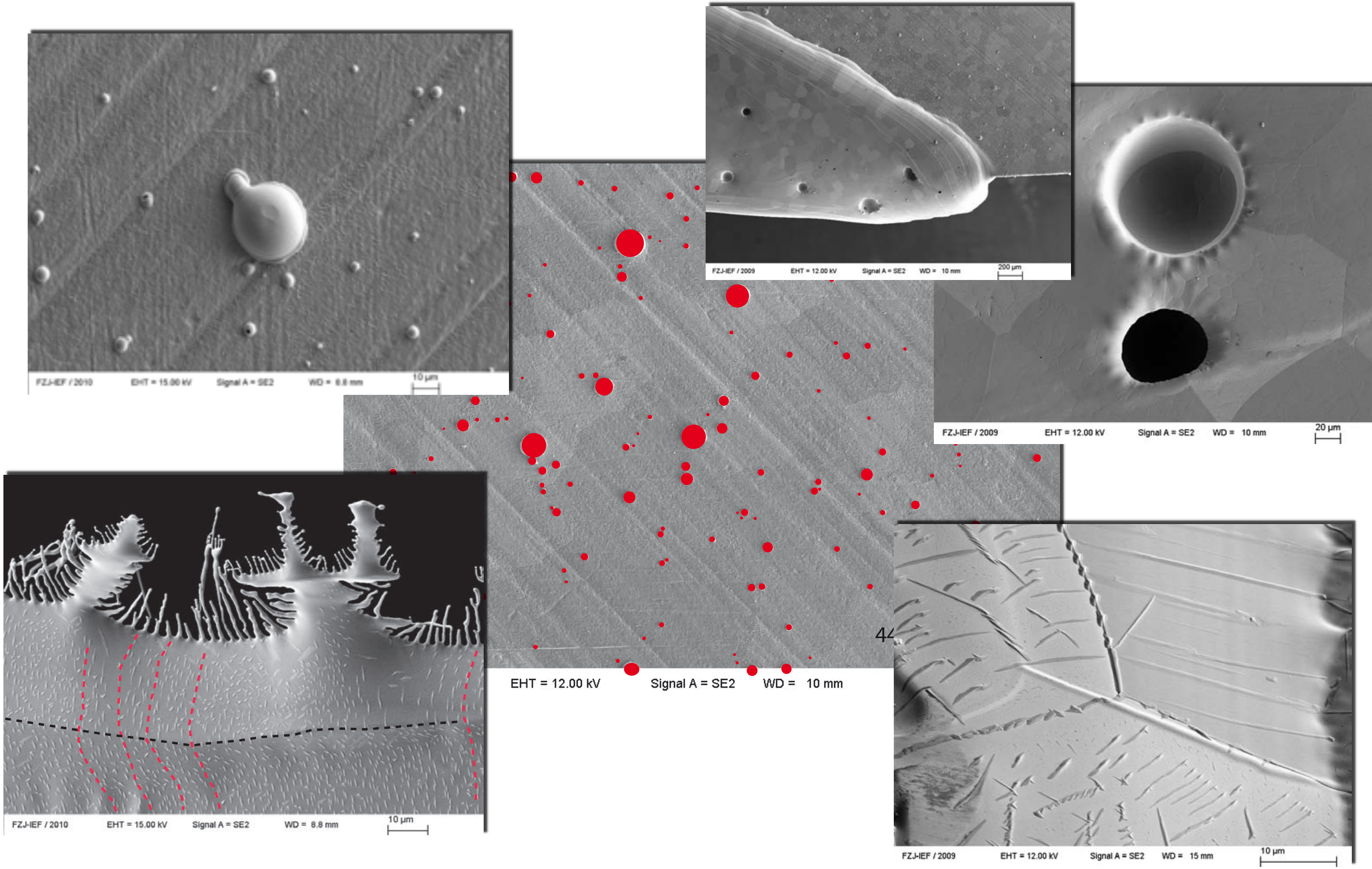
Impact Angle



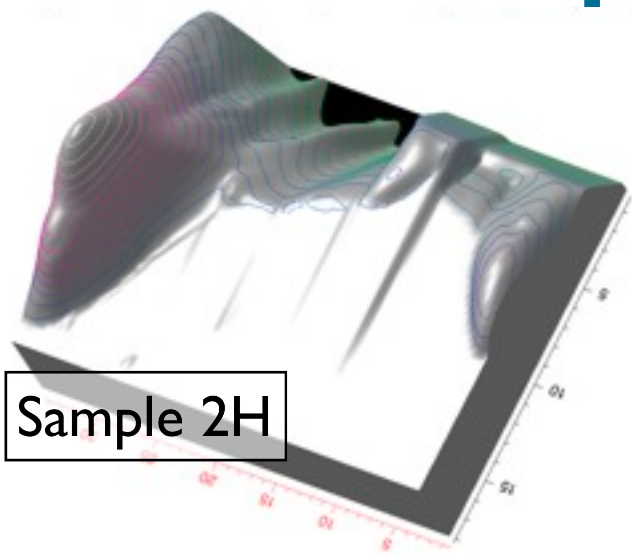


Leading edge can receive up to 40 MW/m^2

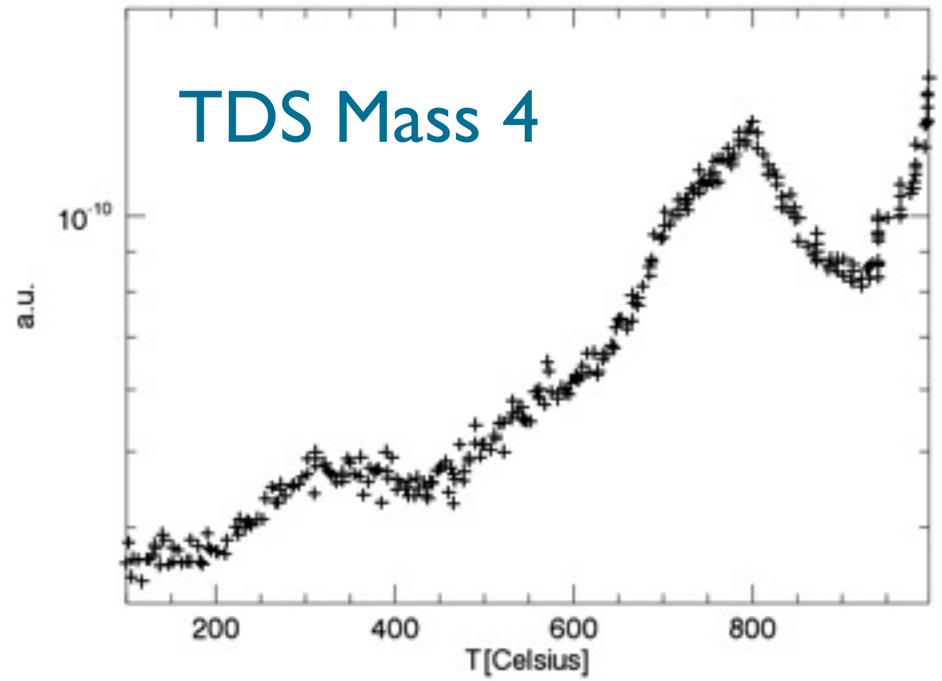
Droplets & Ligaments



Retention



4 melt exposures



Total amount released:

D:1.33E+19 at/m^2

H:1.29E+20 at/m^2

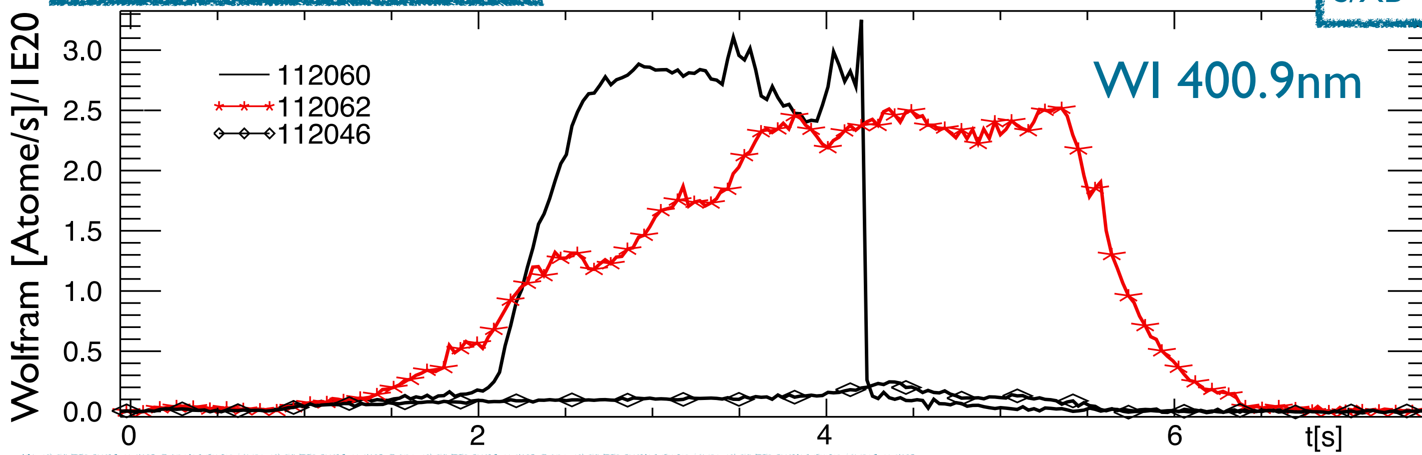
Melting depleated the sample ?
Except for bubbles and voids ?

T > 1000°C

Local W Source

Tungsten Flux

S/XB=100

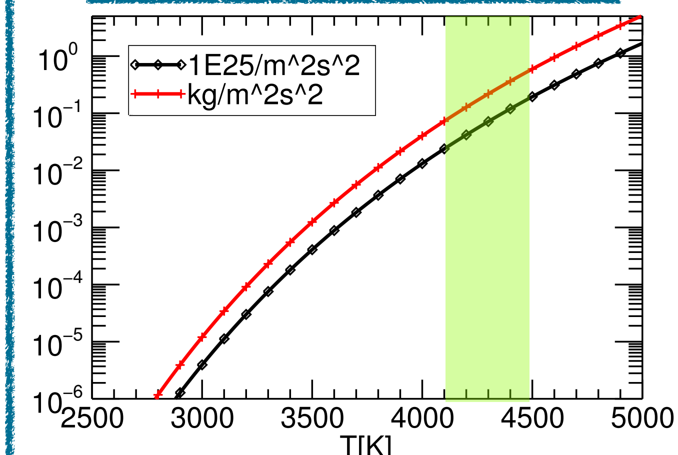


W Source 100 times stronger then from sputtering

$4cm^2 \;\; => \;\; \sim 1x10^{24}$ Atoms/m^2s^1

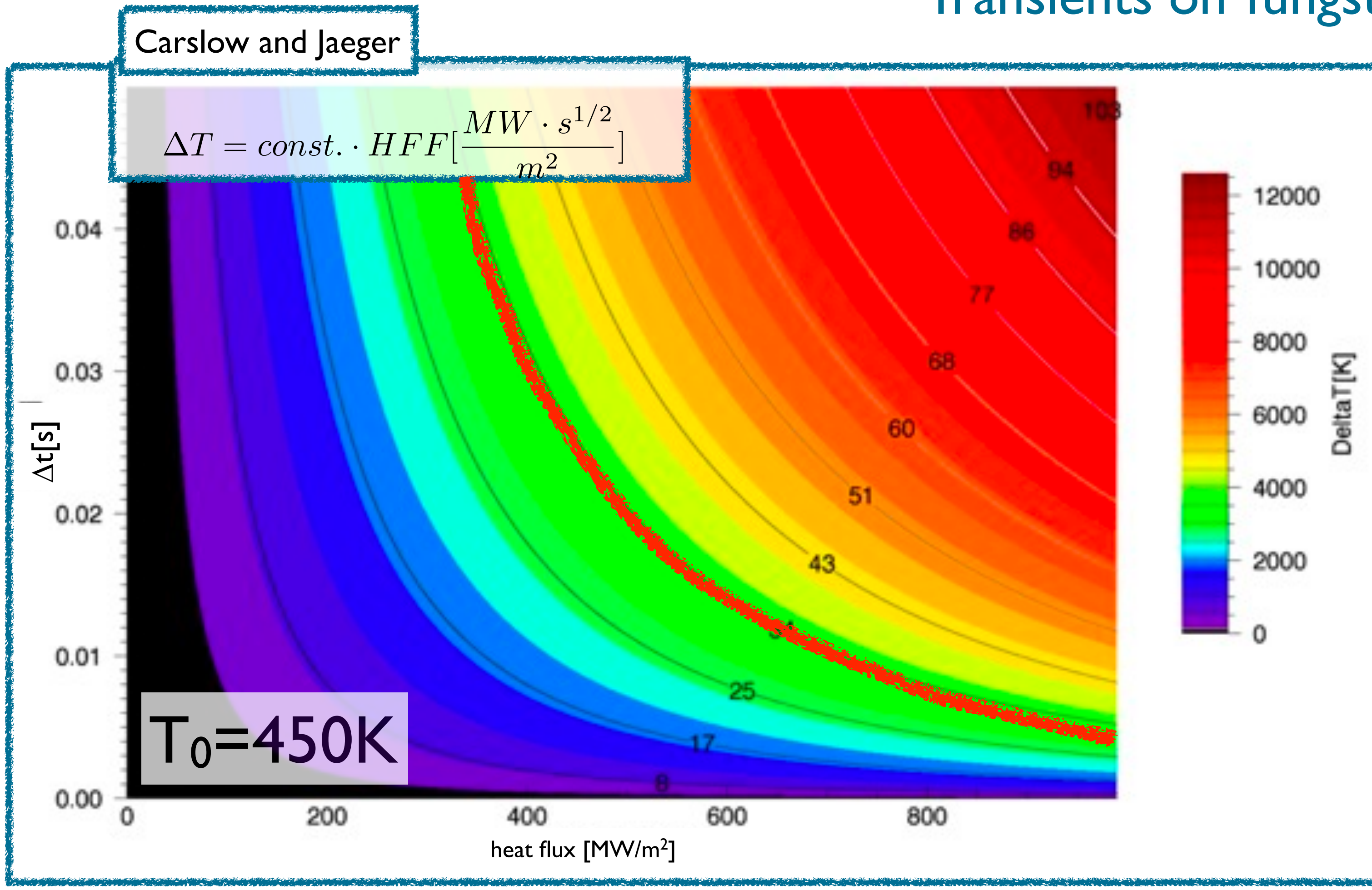
W influx consistent with evaporation

Tungsten Evaporation



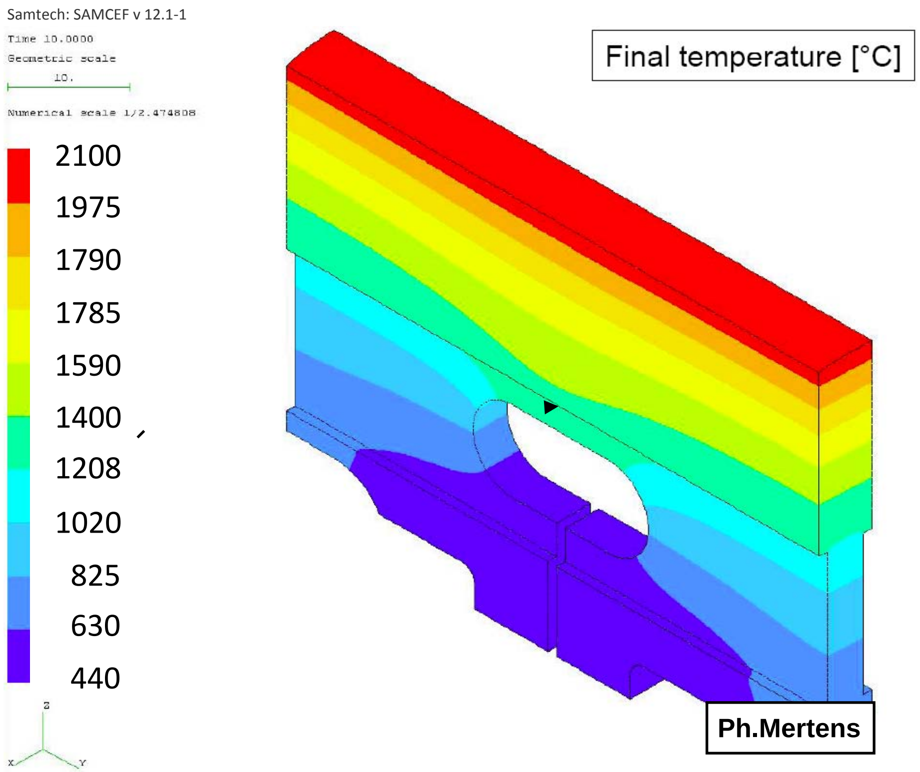
Energy Impact

Transients on Tungsten



The Factor describes the impact of impinging transient heat flux to the surface

JET



9MW/m^2

Additional material data after next JET campagins (2012)

Melt Experiments 2013?

Detailed Design of a Solid Tungsten Divertor Row for JET in Relation to the Physics Goals
Philippe Mertens