Association EURATOM – FZJ

Radiation induced degradation of tungsten grades under thermal and plasma exposure and development of advanced tungsten materials

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Outline:

- A Loads on plasma facing components
- B Simulation of steady state and transient thermal loads
- C Material degradation by energetic neutrons
- D Fusion specific loading conditions – unique set of test devices in Jülich
- E Development of new advanced tungsten materials

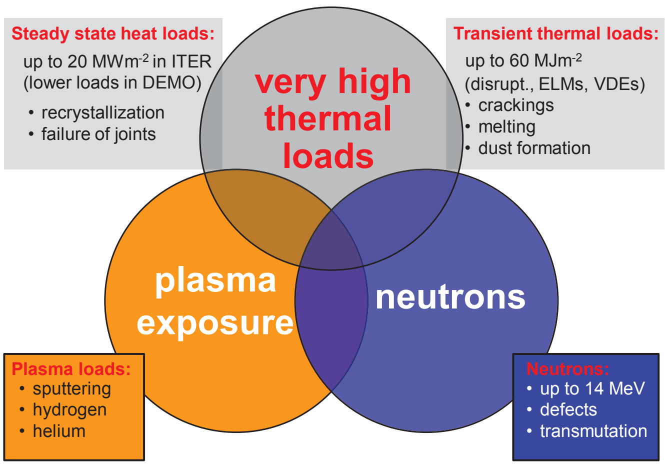
Scope of activities

- Thermal shock behavior of un-irradiated and irradiated W grades
- Synergistic effects of particle and transient heat loads on thermal shock performance of W grades
- Modification of W surface morphology under high flux / high fluency bombardment by H and He and subsequent W erosion
- Fuel retention in pre-damaged W: impact of impurities (He, N, Ne, Ar) on fuel retention
- Isotope exchange in damaged W
- Impact of W surface contamination with oxygen on hydrogen retention
- Development of advanced tungsten materials with improved micro-structure

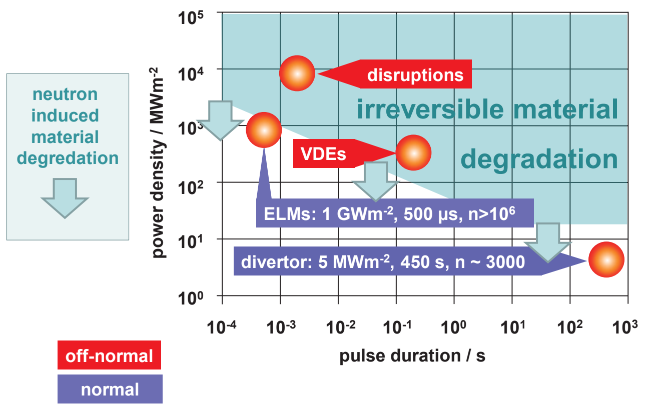
A

Loads on plasma facing components

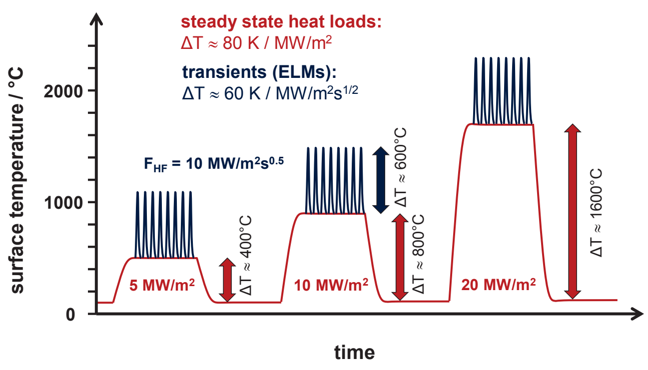
Loads on plasma facing components



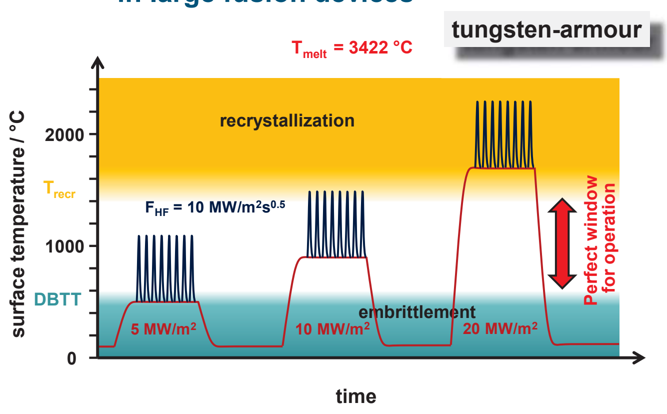
Wall loads on plasma facing components in ITER



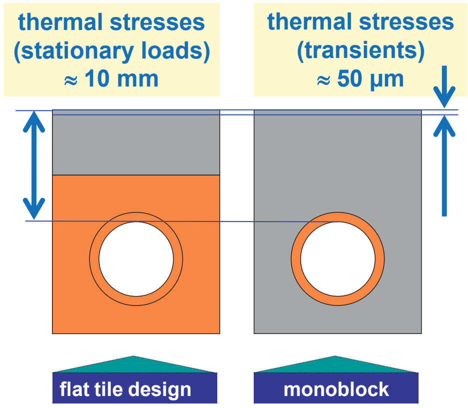
Thermal loads during divertor operation in large fusion devices



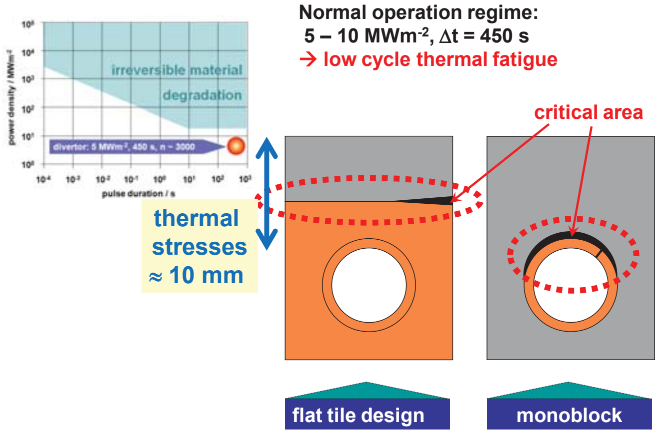
Thermal loads during divertor operation in large fusion devices



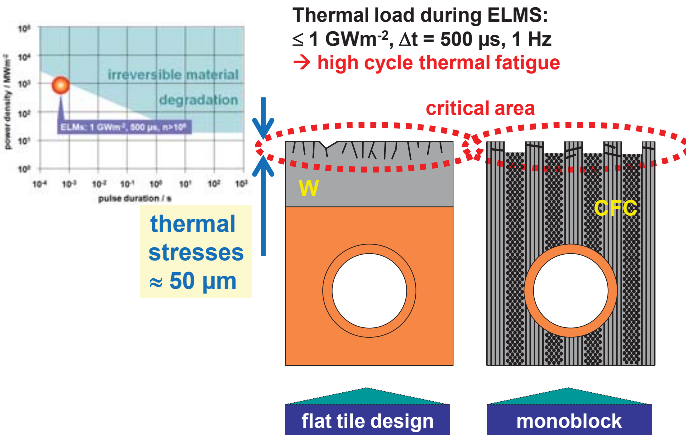
Wall loads on plasma facing components in ITER



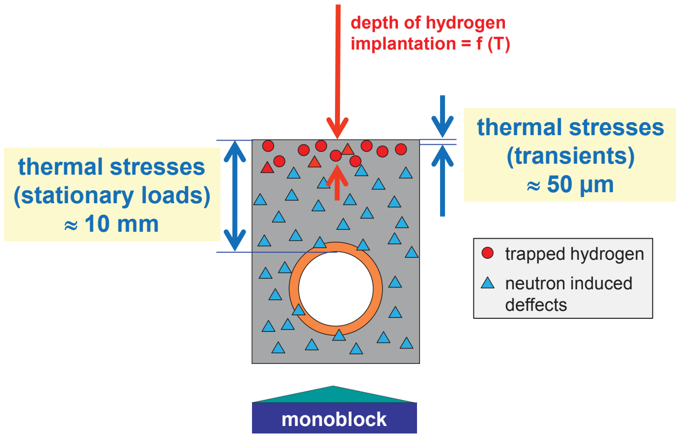
Wall loads on plasma facing components in ITER



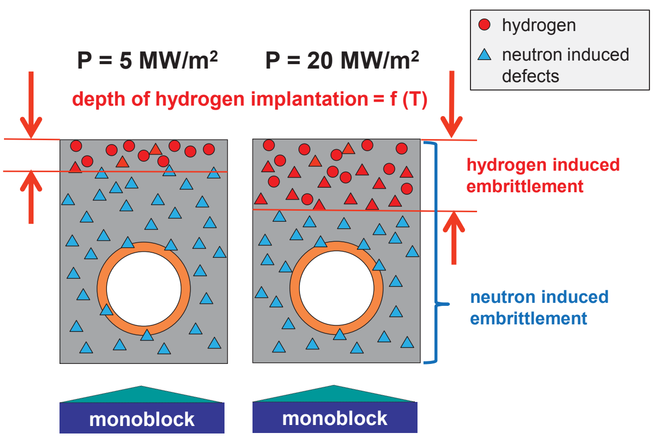
Wall loads on plasma facing components in ITER



Wall loads on plasma facing components in ITER



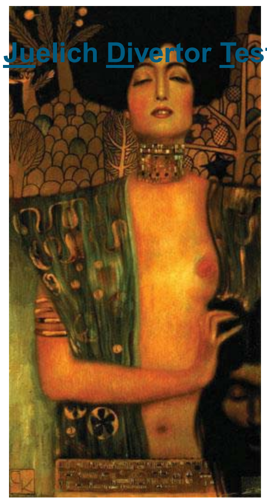
Wall loads on plasma facing components in ITER



B

Simulation of steady state and transient thermal loads

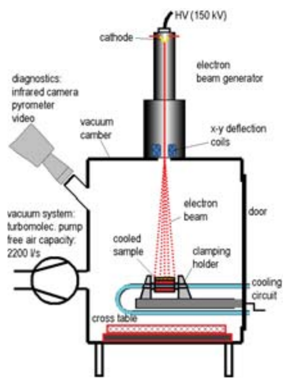
Juelich Divertor Test Facility Hot Cells (JUDITH)

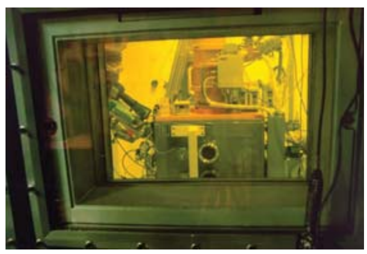


Judith was an Old Testament Jewish heroine. In the Apocryphal 'Book of Judith', she is portrayed as a widow who made her way into the tent of Holofernes, general of Nebuchadrezzar, cut off his head, and so saved her native town of Bethulia.

Gustav Klimt, Judith I, 1901

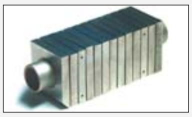
Juelich Divertor Test Facility Hot Cells (JUDITH)



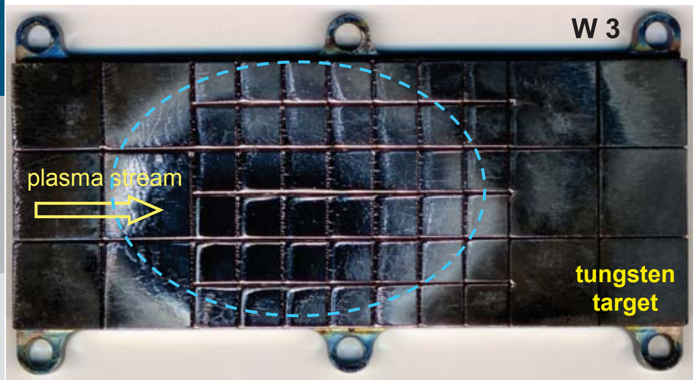


total power:	60 kW
acceleration voltage:	≤ 150 kV
power density:	≤ 15 GWm⁻²
loaded area:	4 mm² … 100 cm²
pulse duration:	1 ms to continuous

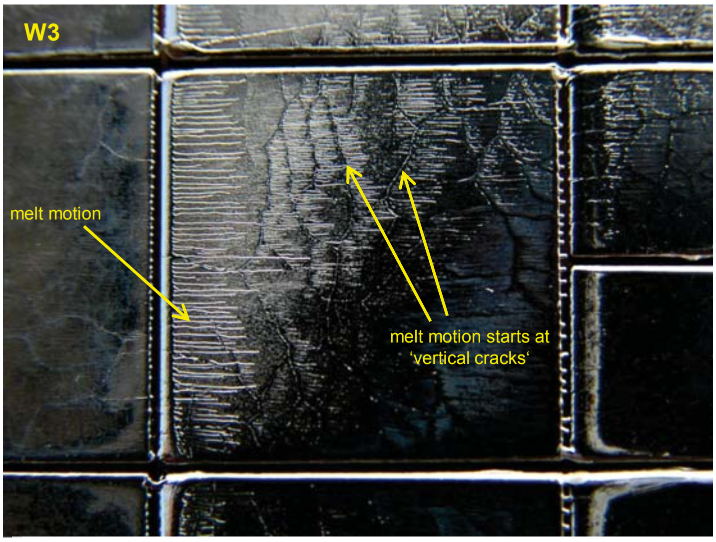
Fatigue testing on PFCs for ITER

	CFC armour	tungsten armour
flat tile design	 **CFC flat tile** Silicon doped CFC NS31, active metal casting, e-beam welding to CuCrZr heat sink **1000 cycles @ 19 MWm^{-2}**	 **W macrobrush** coating of WLa_2O_3 tiles with OFHC-Cu, e-beam welding to CuCrZr heat sink **1000 cycles @ 18 MWm^{-2}**
monoblock design	 **CFC monoblock** drilling of CFC tiles (NB31), active metal casting (AMC®) low temperature HIPing **1000 cycles @ 25 MWm^{-2}**	 **W monoblock** lamellae technique, drilling of WLa_2O_3 blocks, casting with OFHC-Cu, HIPing **1000 cycles @ 20 MWm^{-2}**

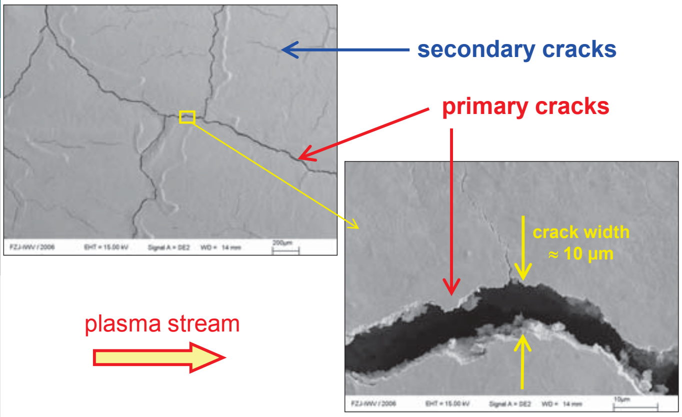
Simulation of ELMs in QSPA



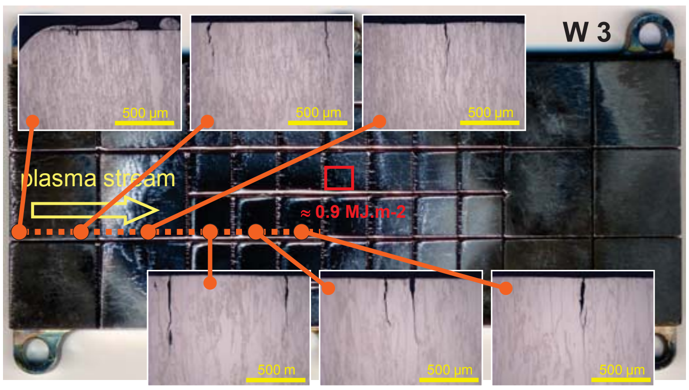
E = 1.0 MJm^{-2} Δt = 500 μs 100 pulses T_0 = 500°C



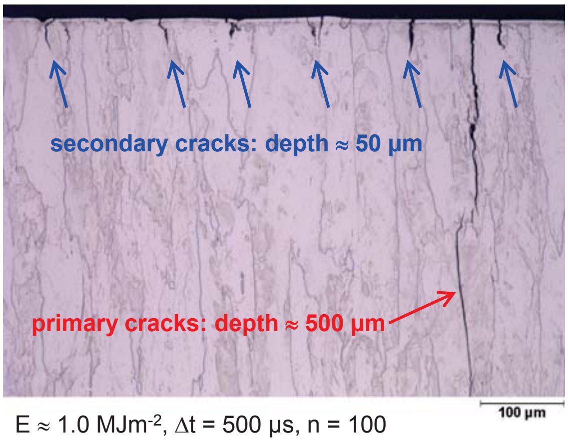
Crack formation on tungsten in QSPA
(energy density E = 0.9 MJ/m² @ 500 μs)



Crack formation on tungsten in QSPA

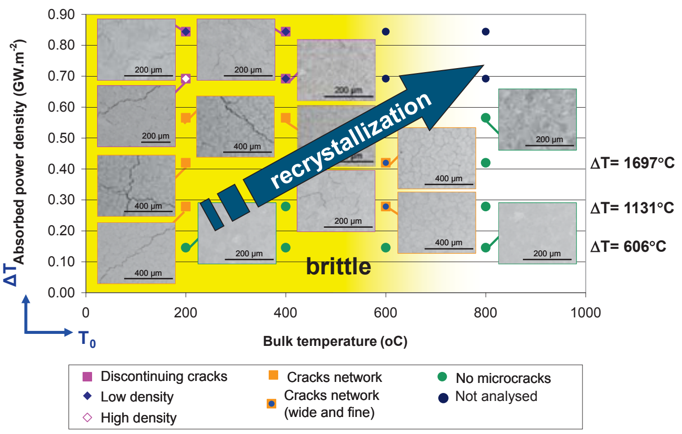


Crack formation at the melting threshold

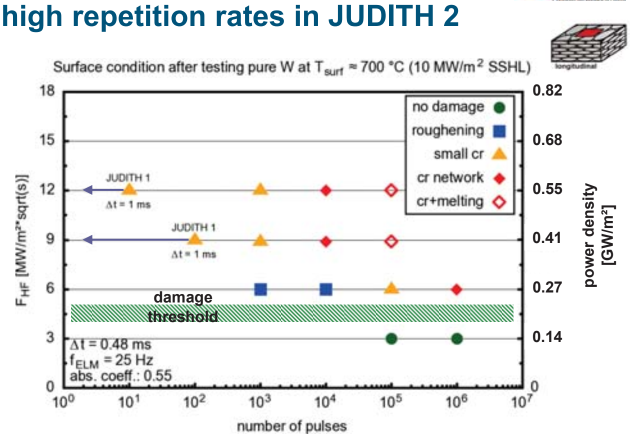


E ≈ 1.0 MJm^{-2}, Δt = 500 μs, n = 100

Surface modification of tungsten
transient thermal loads (Δt = 5 ms) in JUDITH

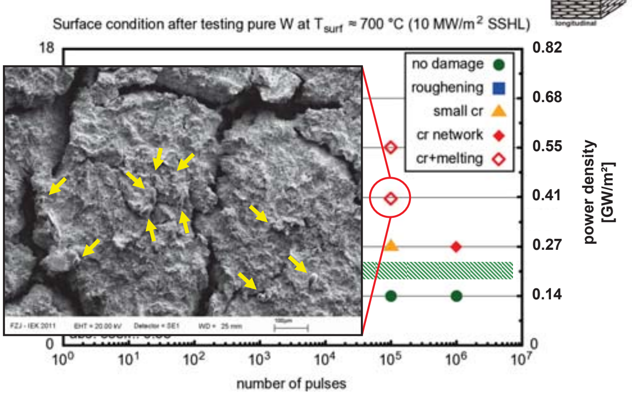


ELM simulation using e-beams with high repetition rates in JUDITH 2



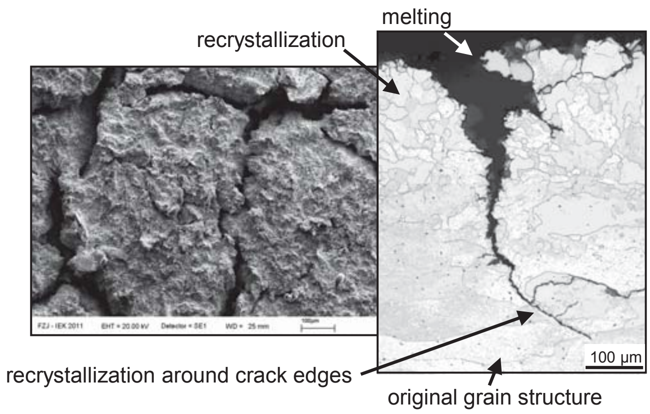
Th. Loewenhoff et al., Physica Scripta T145 (2011) 014057

ELM simulation using e-beams with high repetition rates in JUDITH 2



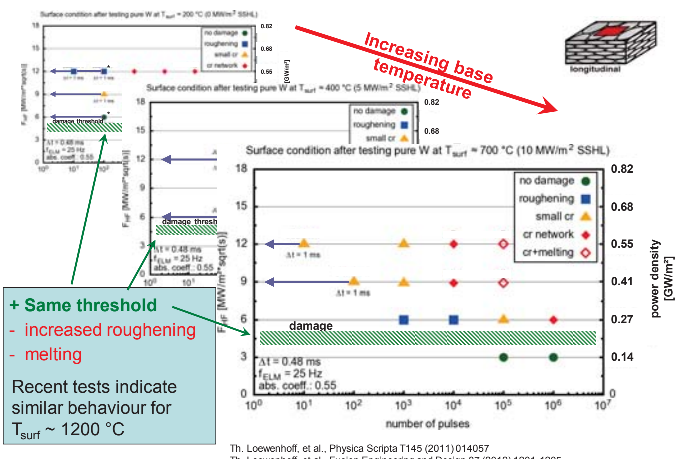
Th. Loewenhoff et al., Physica Scripta T145 (2011) 014057

ELM simulation using e-beams with high repetition rates in JUDITH 2



Th. Loewenhoff, et al., Fusion Engineering and Design 87 (2012) 1201-1205

High pulse number thermal shock

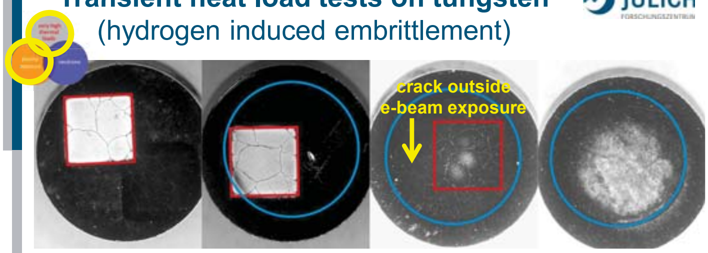


+ Same threshold
- increased roughening
- melting

Recent tests indicate similar behaviour for T_{surf} ~ 1200 °C

Th. Loewenhoff, et al., Physica Scripta T145 (2011) 014057
Th. Loewenhoff, et al., Fusion Engineering and Design 87 (2012) 1201-1205
*G. Pintsuk et al., Journal of Nuclear Materials 417 (2011) 481-486

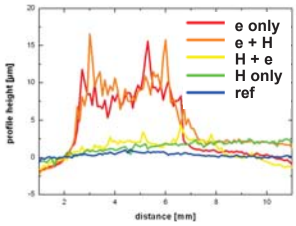
Transient heat load tests on tungsten
(hydrogen induced embrittlement)



e-beam only | e- + H-beam | H- + e-beam | H-beam only

right: surface profile of polished tungsten samples after different loading scenarios
- e-beam (thermal shock)
- H-beam (hydrogen loading)

e-beam: P_{abs} = 2.1 MJm^{-2}, Δt = 5 ms, n = 100
H-beam: F ≈ 10^{24} m^{-3}, T_e ≤ 5 eV, T = 800 – 1000 K



C
neutron induced material degradation

Neutron-induced material degradation
(experimental options)

today

heavy ions:
- shallow penetration
- mainly suitable for plasma wall interaction studies, *but excluding* approach to synergistic effects with heat and particle loads, quantitative differences with respect to fuel retention

materials test reactor:
- volumetric loading
- mainly dpa-damage
- moderate dose rate (few dpa/y)
- relatively large irradiation rigs
- irradiation of test samples (thermal, mech. properties, transient heat loads) and small scale components

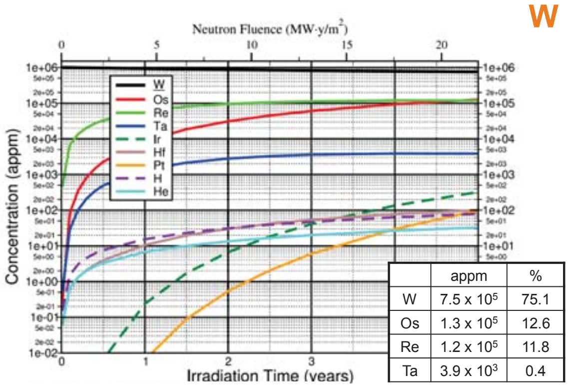
future

IFMIF:
- 14 MeV neutrons → realistic He/dpa ratio
- very high dose rates (up to 20 dpa/y)
- limited sample dimensions
- transmutation effects

moderate activation | severe activation

Transmutation of tungsten
DEMO first wall – 5 years full power operation

W



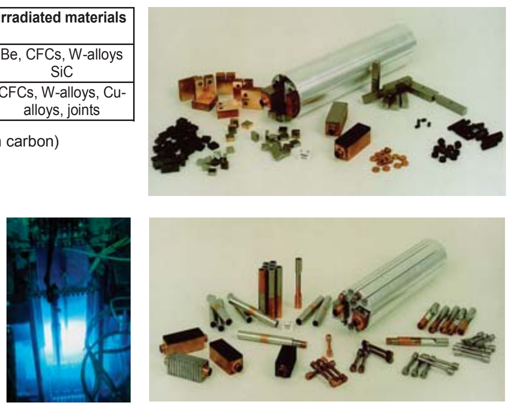
	appm	%
W	7.5 x 10^5	75.1
Os	1.3 x 10^5	12.6
Re	1.2 x 10^5	11.8
Ta	3.9 x 10^3	0.4

source: Mark Gilbert, CCFE Fusion association

Neutron Irradiation Experiments
PARIDE 3 and PARIDE 4

	T_{irr} [°C]	fluence [dpa]	irradiated materials
#1	350	0.35	Be, CFCs, W-alloys SiC
#2	700	0.35	
#3	200	0.2	CFCs, W-alloys, Cu-alloys, joints
#4	200	1.0	

(all dpa's in carbon)



High Flux Reactor (HFR)
Petten, The Netherlands

Fatigue testing on PFCs for ITER

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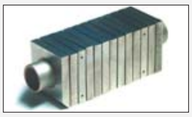
flat tile design



CFC armour	tungsten armour
CFC flat tile 0 dpa: 1000 cycles @ 19 MWm^{-2} **1 dpa: 1000 cycles @ 15 MWm^{-2}** (no degradation)	W macrobrush 0 dpa: 1000 cycles @ 18 MWm^{-2} **0.6 dpa: 1000 cycles @ 10 MWm^{-2}** (increasing of T_{surf})
CFC monoblock 0 dpa: 1000 cycles @ 25 MWm^{-2} **1 dpa: 1000 cycles @ 12 MWm-2** (substancial evaporation @ 14 MWm^{-2})	W monoblock 0 dpa: 1000 cycles @ 20 MWm^{-2} **0.6 dpa: 1000 cycles @ 18 MWm^{-2}** (no degradation)

monoblock design

Neutron irradiation effect of tungsten and carbon on thermal conductivity

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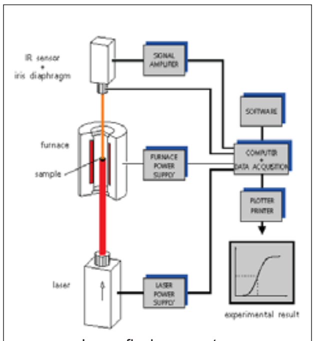
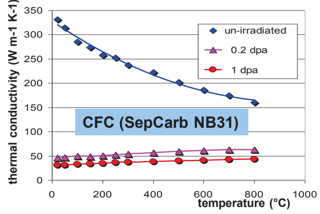
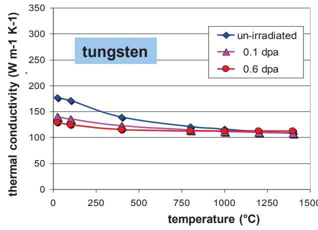


Laser-flash-apparatus
(schematic diagram)





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D

Fusion specific loading conditions – unique set of test devices in Jülich

A new laboratory for plasma facing materials under extreme loads

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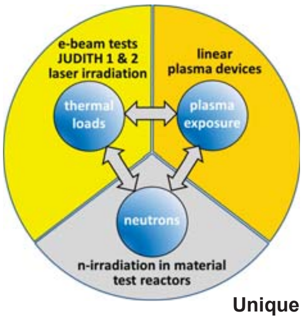
Synergistic effects govern behaviour of PFMs.



Hot Material Laboratory: controlled area, Hot Cells

Unique features at FZJ

Existing and planned facilities in the Hot Material Laboratory at FZJ

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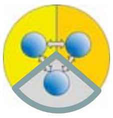
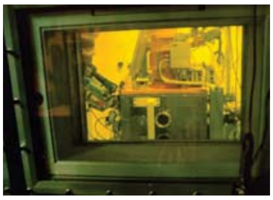
Hot Cell capabilities to handle irradiated materials

Hot Cells existing inside HML, under comissioning for future heat load tests



Hot Cell operational with heat load test facility JUDITH-1 (other building)



Additional Hot Cell for has been planned for a new linear plasma device (currently under design review), shielding available.

Existing and planned facilities in the Hot Material Laboratory at FZJ

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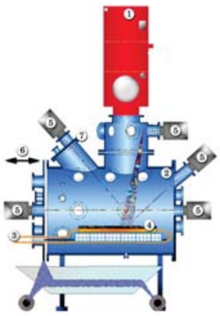
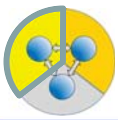
Heat load test facilities



JUDITH-2



Machine parameters

electron energy	30 - 60 keV
beam power:	200 kW
irradiation area:	50 x 50 cm²
power density:	up to 10 GWm^{-2}
pulse length:	1.5 µs ... cont. beam
beam scanning:	digital mode

e-beam test facilities JUDITH-1 (inside Hot Cell, operational) / JUDITH-1 upgrade (planned) and JUDITH-2 (inside controlled area, operational)

Laser irradiation facilities

Existing and planned facilities in the Hot Material Laboratory at FZJ

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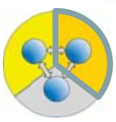
Plasma facility

- Steady-state linear plasma generator (B=0.2 T)
- Loading conditions (deuterium plasmas), with target biasing
  - q = 0.1 -2 MW m^{-2}, simulation of transients by laser irradiation (40 J / 1ms)
  - $n_e = 10^{17} - 10^{20}$ m^{-3}
  - T_e up to 20 eV ($T_i \sim 0.5\ T_e$)
  - E_{ion} = 10-200 eV (biasing)
  - $\Gamma_{ion} = 10^{21} - 10^{23}$ m^{-2}s^{-1}
  - F = 10^{27} m^{-2} in 4 h
  - $\Delta_{flow\ channel}$ ~ 6 cm

Pilot experiment PSI-2



Linear plasma device JULE-PSI (inside Hot Cell) with integrated target analysis and exchange chamber (laser based surface diagnostics), operational 2016

PSI-2 – a test bed for JULE-PSI

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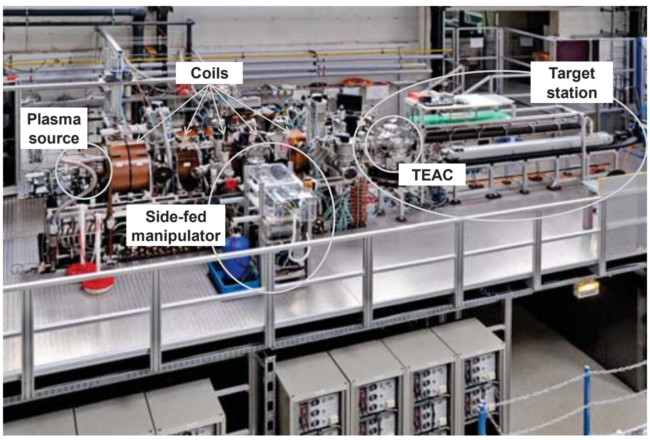
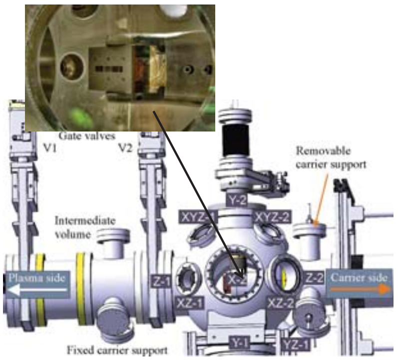
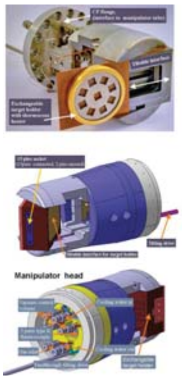


Coupling of laser beam to simulate transient heat loads

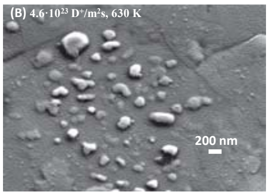
Flexible target station at PSI-2





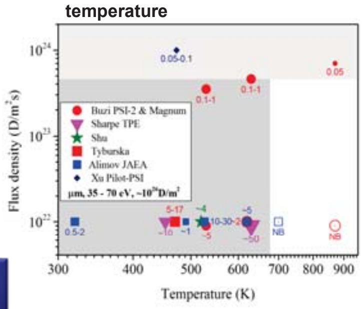
Coupling of laser beam to simulate transient heat loads

Modification of W surface morphology under high flux / high fluency bombardment by H and He and subsequent W erosion



L. Buzi et al, ICFRM 2013, Beijing

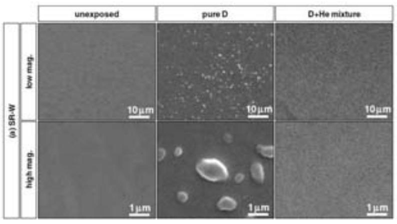
Formation of blisters as a function of particle flux density and temperature



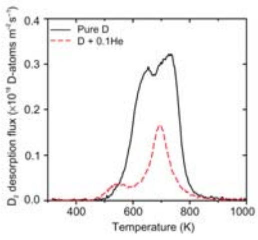
Correlation of blister formation to fuel retention observed.
Next: Impact of transient heat loads onto surface structure.

Fuel retention in pre-damaged W: impact of impurities (He, N, Ne, Ar) on fuel retention

Previous results



"Observations of suppressed retention and blistering for tungsten exposed to deuterium–helium mixture plasmas"
M. Miyamoto et al, Nucl. Fusion 49 065035 (2009)



„Fuel retention in carbon materials under ITER-relevant mixed species plasma conditions", A. Kreter et al, Phys. Scr. T138, 014012 (2009)

Impurities → impact on surface morphology / damage to material structure?
Impurities → impact on release mechanisms?

Initial exposures in PSI-2

Tungsten samples specifications:

- ITER-grade Tungsten
- grain elongation perpendicular to target surface
- surface area (front): 13x13 mm
- cutting by spark eroding
- mechanically polished
- annealed for 2 h at 1000 °C

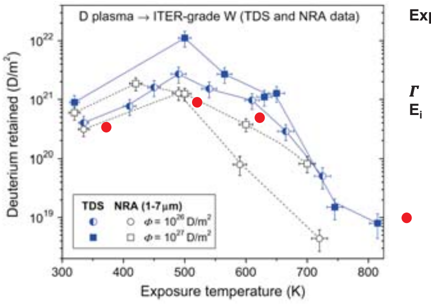
Plasma exposure parameters:

- Ion flux 0.7-1.0·10^{22} $m^{-2}s^{-1}$
- fluence 1·10^{26} m^{-2}
- ion energy 30 eV/D
- surface temperature 370 K
- variation of impurity concentrations:
  - pure D2 plasma
  - 1%, 5% Helium seeding
  - 1%, 5% Argon seeding

Sample for the PSI-2 side manipulator

Target holder + sample in the plasma

Initial step: Comparison to existing data from literature



V. Kh. Alimov et al, Temperature dependence of surface morphology and deuterium retention in polycrystalline ITER-grade tungsten exposed to low-energy, high-flux D plasma, Journal of Nuclear Materials, Volume 420, Issues 1–3, January 2012, Pages 519–524

Exposure parameters:

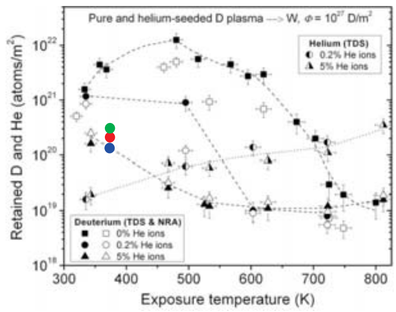
	PSI-2	JAEA
Γ	1·10^{22} $m^{-2}s^{-1}$	1·10^{22} $m^{-2}s^{-1}$
E_i	30 eV/D	38 eV/D

Total retention in a pure D_2 plasma in PSI-2:

370 K: 3.1·10^{20} D/m²

530 K: 9.0·10^{20} D/m²
630 K: 5.8·10^{20} D/m²
870 K: 1.0·10^{19} D/m²

Initial step: Comparison to existing data from literature



V. Kh. Alimov et al, Surface morphology and deuterium retention in tungsten exposed to low-energy, high flux pure and helium-seeded deuterium plasmas , Phys. Scr. T138 (2009) 014048 (5pp)

Exposure parameters:

	PSI-2	JAEA
ϕ	1·10^{26} m^{-2}	1·10^{27} m^{-2}
Γ	1·10^{22} $m^{-2}s^{-1}$	1·10^{22} $m^{-2}s^{-1}$
E_i	30 eV/D	30 eV/D

Total retention in a mixed D_2/He plasma

0% He: 3.1·10^{20} D/m²
1% He: 1.9·10^{20} D/m²
5% He: 1.2·10^{20} D/m²

E

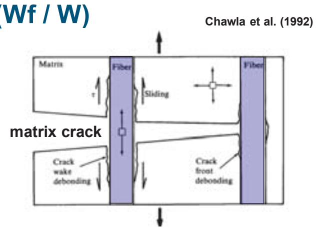
Development of new advanced tungsten materials

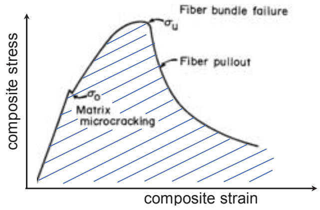
Development of advanced tungsten materials with improved micro-structure: Fiber- reinforced tungsten (Wf / W)

Mechanical toughening mechanism

- engineered fiber/matrix interface:
  → controlled crack deflection
- interfacial debonding/friction:
  → internal energy dissipation
- mechanical effect:
  → less influence of operational embrittlement (recrystallization, neutron damage)

Chawla et al. (1992)

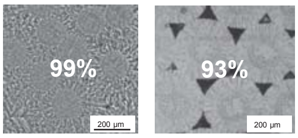




Fiber- reinforced tungsten (Wf / W) Status and plans

Proof-of principle (J. Riesch et al, IPP Garching)

- Development of dense Wf/ W composites via hot pressing / chemical vapor infiltration
- Bending tests, analysis of crack formation



CVI HP

Exploration at FZJ

- Systematic comparison of HP/ CVI route (HP at IEK-1, installation of CVI device at IEK-4
- Analysis of mechanical properties
- Exposure to synergistic heat and plasma loads at PSI-2

Development of advanced tungsten materials with improved micro-structure: Self- passivating W alloys

Surface composition automatically adjusts to the requested property

Normal operation (600°C):
Formation of tungsten surface by depletion of alloying element(s) due to preferential sputtering

Accidental conditions:
(air ingress, up to 1200 °C)
Formation of protective barrier layer

Self-passivating W alloys Status and plans

Proof of principle (F. Koch et al., IPP Garching)

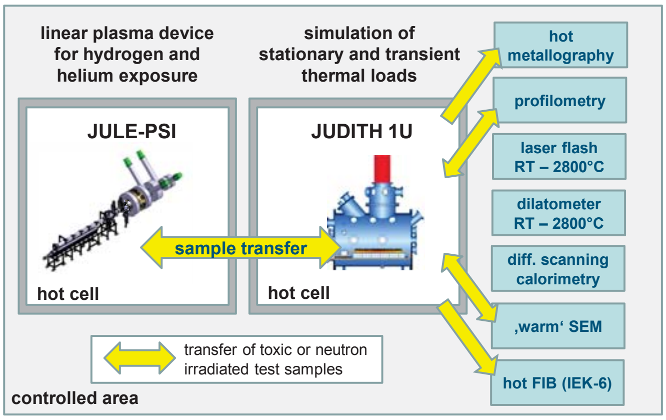
- Self-passivating demonstrated for a number of model systems (e.g., W-Cr-Ti, W-Cr-Zr-Y)
- W enrichment under normal operation conditions (preferential sputtering)
- Oxidation rates reduced by 3-5 orders of magnitude
- No formation of volatile WO_3

Exploration at FZJ

- Characterization of model systems: optimization of elemental composition
- Exposure to PSI-2 plasma, characterization under high fluence plasma impact, transient loads, studies on preferential sputtering and fuel retention

Hot Materials Laboratory (HML)

plasma wall interaction processes in future fusion devices



Future fusion materials research in