EUROfusion

Joint WP TE and WP PWIE Technical Meeting on Plasma Wall Interactions in full W devices

High Heat Flux devices capabilities for W damage studies

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KIPT
Kharkov Institute of Physics and Technology
UKRAINE

cea
The French Alternative Energies and Atomic Energy Commission
FRANCE

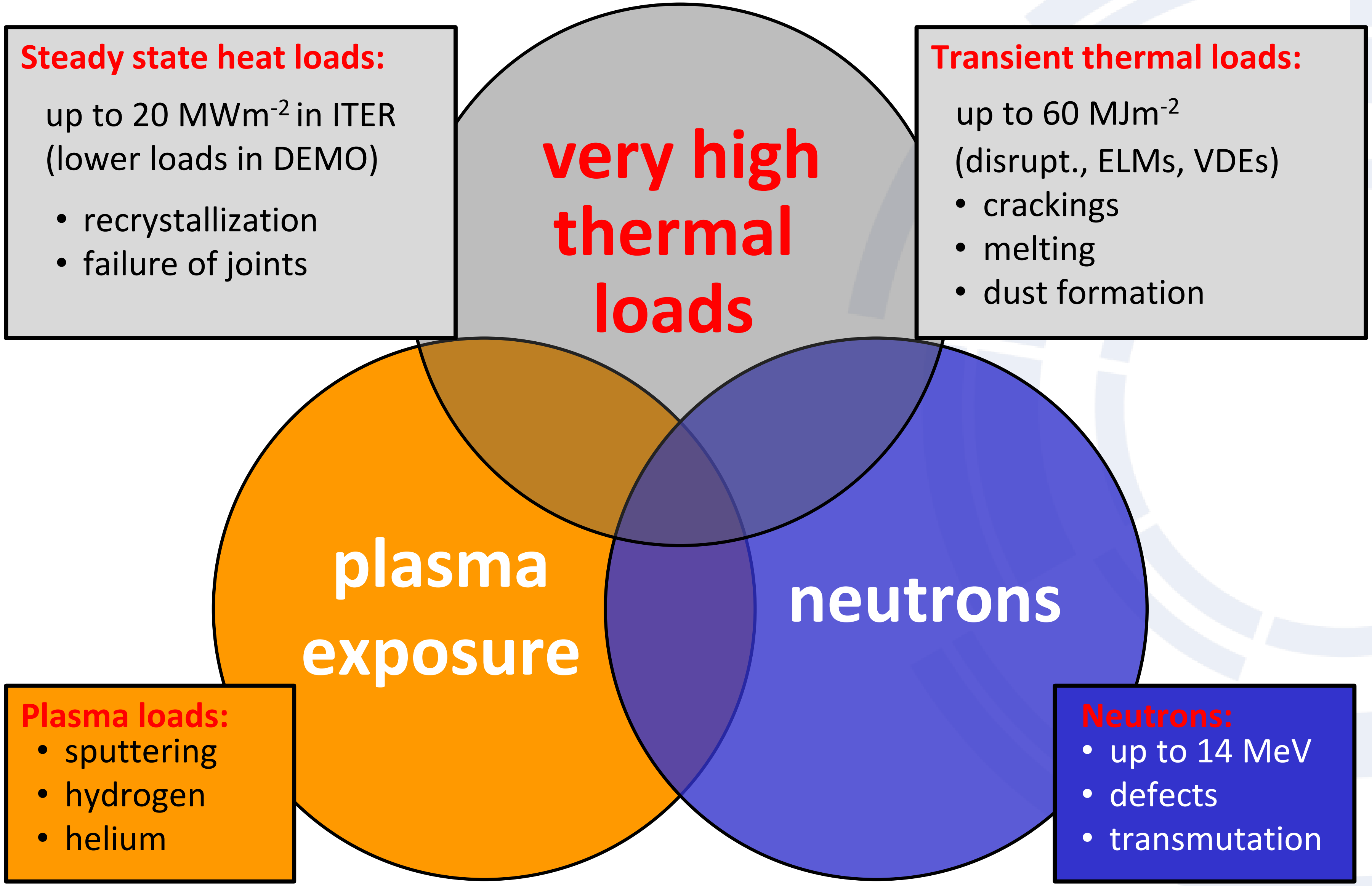
JÜLICH
Forschungszentrum
GERMANY

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
GERMANY

DIFFER
The Netherlands

Laboratorio Nacional de Fusión
Ciemat
Centre for Energy, Environment And Technology Research
SPAIN

Environmental conditions



Steady state heat loads:

up to 20 MWm^{-2} in ITER
(lower loads in DEMO)

- recrystallization
- failure of joints

very high thermal loads

Transient thermal loads:

up to 60 MJm^{-2}
(disrupt., ELMs, VDEs)

- crackings
- melting
- dust formation

plasma exposure

neutrons

Plasma loads:

- sputtering
- hydrogen
- helium

Neutrons:

- up to 14 MeV
- defects
- transmutation

Outline

QSPA

HADES

JUDITH 2

PSI-2

GLADIS

MAGNUM-PSI

OLMAT

JUDITH 3 (under construction)

JULE-PSI (under construction)

KIPT: QSPA

Energy density [MJ/m^2]	(0.5-30)
Pulse duration [ms]	0.25
Magnetic field [T]	0.54
Plasma pressure [MPa]	(0.3-1.8)
Particle flux [ions×(m^{-2}s^{-1})]	up to 10^{27}
Diameter of the plasma stream [cm]	18 cm

S.S. Herashchenko et al. 2023 Fus. Eng. & Des. 190 113527

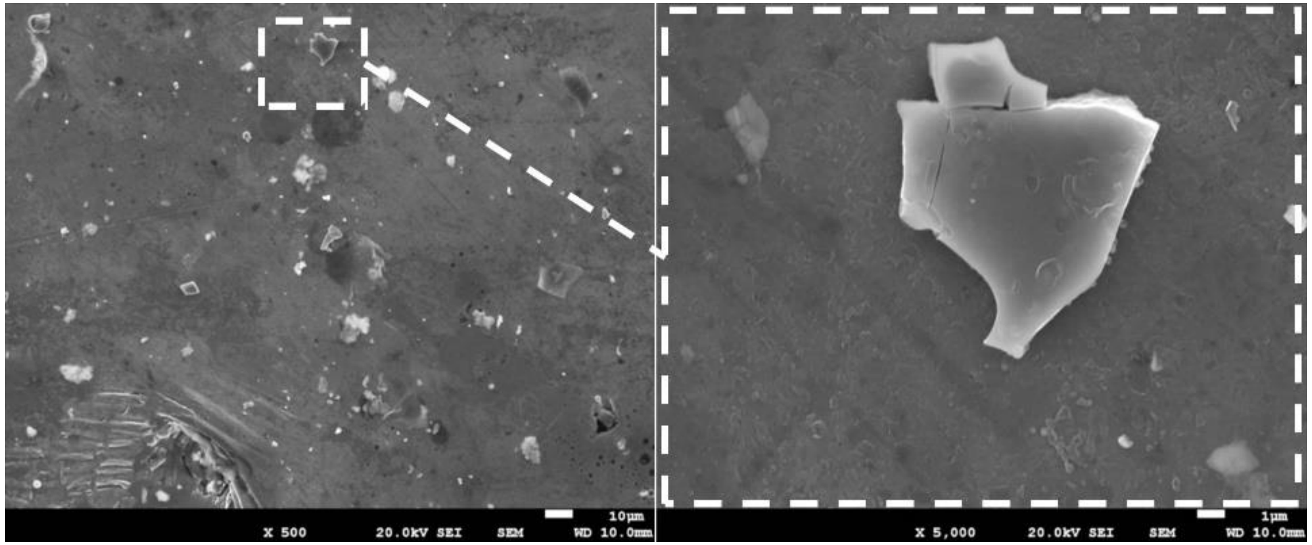
Energy density [MJ/m^2]	(0.3-1)
Pulse duration [ms]	0.10
Magnetic field [T]	up to 1
Plasma pressure [MPa]	0.3
Particle flux [ions×(m^{-2}s^{-1})]	(0.5-2)10^{26}
Diameter of the plasma stream [cm]	6 cm

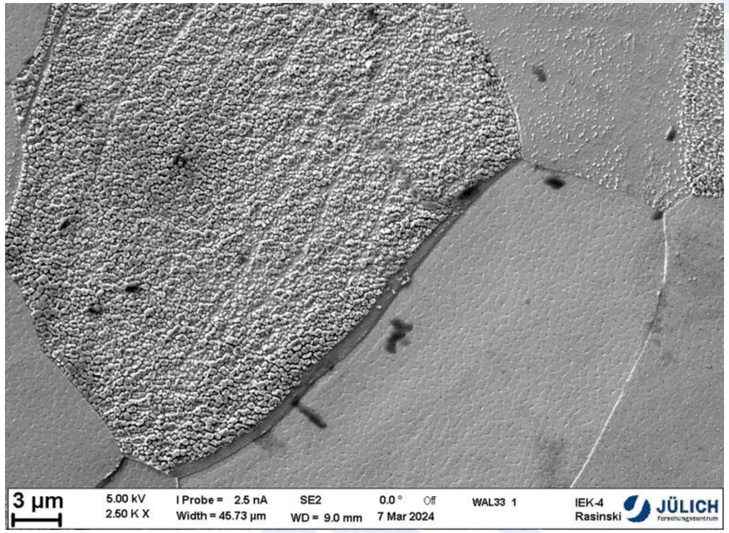
I.E. Garkusha et al 2024 Nucl. Fusion 64 056010

Capable reproducing disruptions and ELM loads both in terms of energy and particle fluxes!

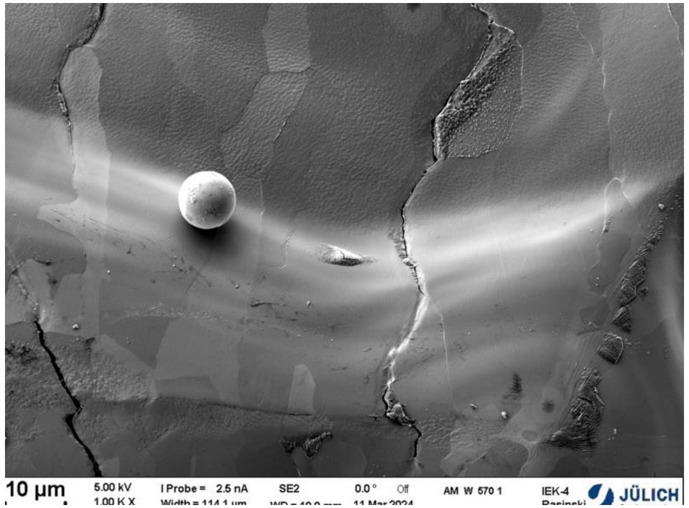
KIPT: QSPA

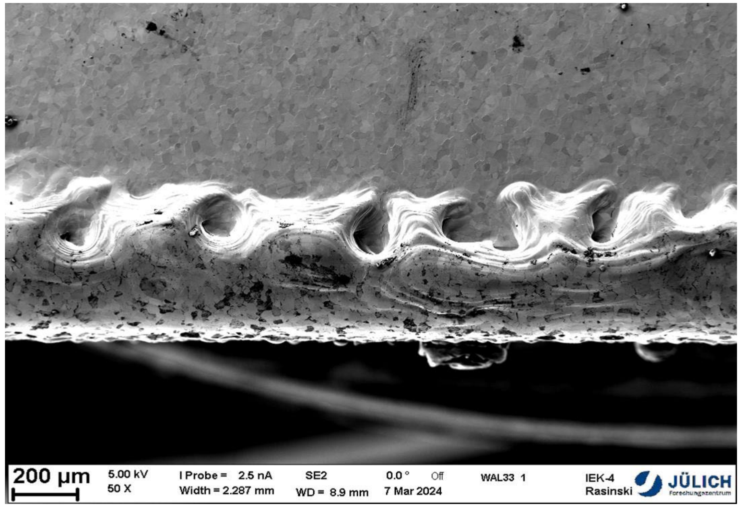
Studies of erosion mechanisms: evaporation and melt motion, droplets and W dust generation. Surface modification effects induced





SEM images of dust and droplets with different magnification, collaboration with FZJ





Both the re-solidified droplets as well as the dust particles have been collected.

Solid dust is overwhelming majority of the particles ejected from castellated tungsten surfaces. It is mainly attributed to the cracking during the surface cooling.

V.A. Makhlai et. al. Phys. Scr. 96 (2021) 124043

KIPT: QSPA

After a 2.5 year break, QSPA is producing plasma again!

More than one month of successful plasma operation during the summer 2024

CEA: HADES

Electron Beam Gun

Power = 10 - **150 kW**
Steady state mode / Pulse mode
Thermal flux = up to **a few 10 MW/m^2** (stationary)
up to 1GW/m^2 (transient)
Beam deflection angle = ±25°, sweeping frequency = 10kHz
Minimum beam diameter = ~10 mm @ 45kV

Water cooling loop

Pressure = 0.8 – **3.5 MPa**
Temperature = 50 - **220°C**
Max water flow = **6kg/s**

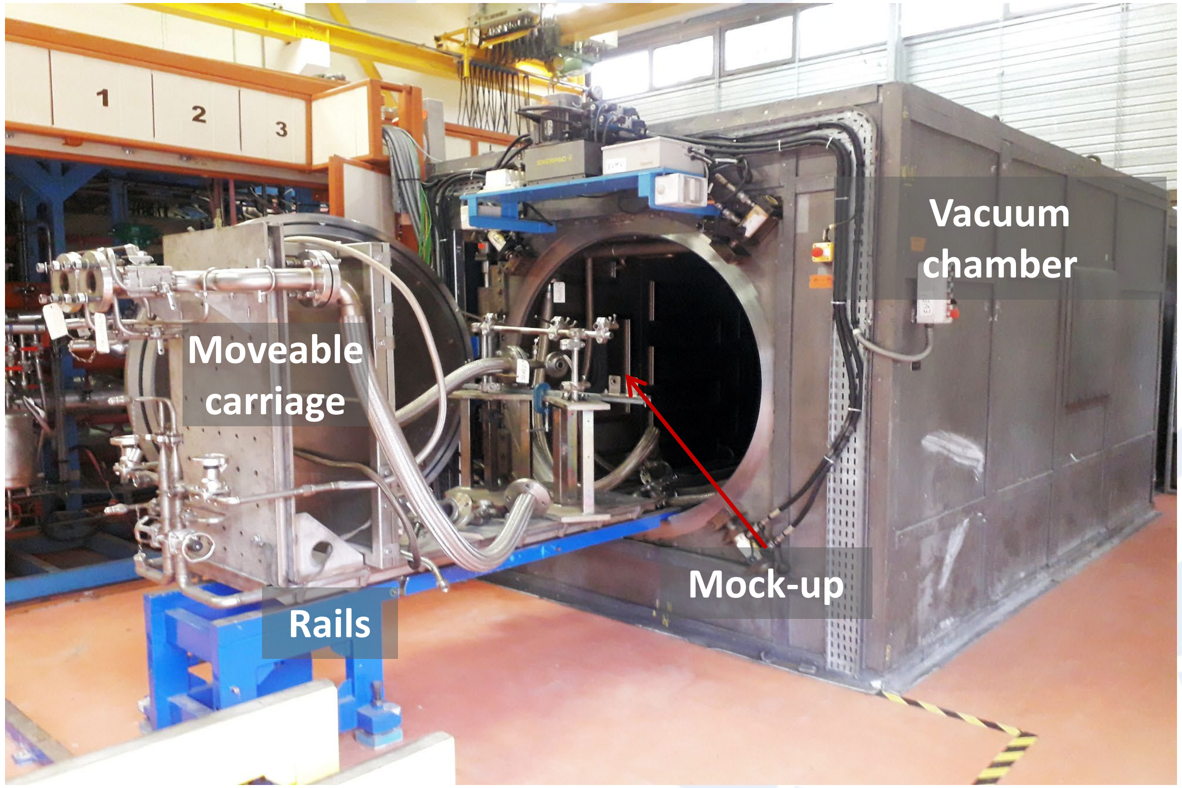
Vacuum chamber

Volume ~**8m^3**
Door diameter ~**1.3m**
Mock-up – gun distance = 1 – 2m
Inner panels cooled
Pressure ~ 10^{-3} Pa

Thermal flux (MW/m^2) @150kW (max EB power)	Max loaded area (mm^2)
Material	W
Absorption coefficient	~0.55
5	~100 x 160
10	~100 x 80
20	~100 x 40
40	~100 x 20

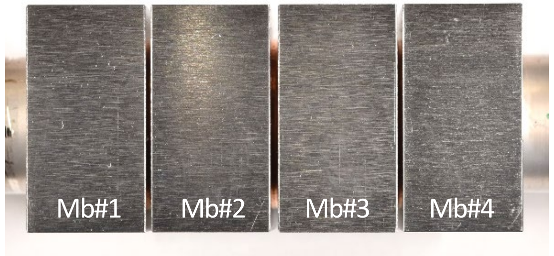
Diagnostics

IR camera (1.5-5.5µm), 30-1500°C @ ε = 1
Visible CCD camera
Thermocouples: calorimetry, embedded
In-situ ε measurement @low temperature

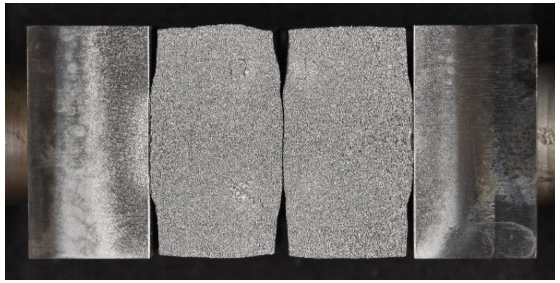


CEA: HADES

EXPERIMENTAL CAMPAIGN	TASK
Extra fatigue test, 500 cycles @25MW/m², 4 W blocks (23 x 13mm²), 2 blocks loaded	2021 - DIV-2.8.3-T003
Fatigue tests, 2000cycles @20MW/m², 4 W blocks (23 x 12mm²), 2 blocks loaded **Illustrated bellow ↓**	**2021 - DIV-2.8.3-T005**



BEFORE



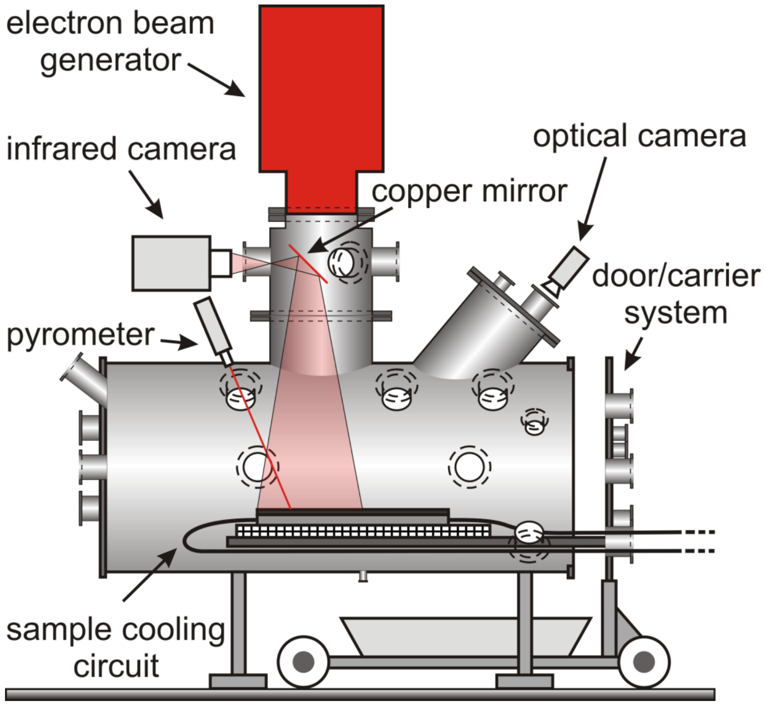
AFTER

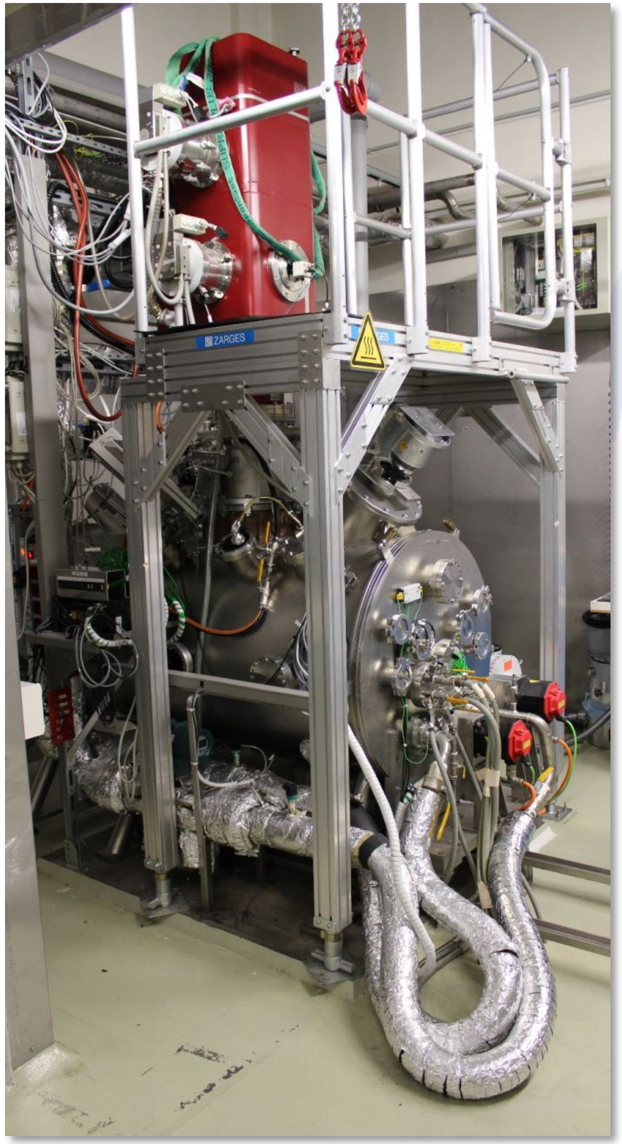
- No serious defect occurred during thermal cycling.
- No (evident) damaging of the heat extraction capacity after thermal cycling.
- Noticeable change in the surface condition, and surface roughening during 20 MW/m² cycling, in particular during the first 800 cycles.
- Strong deformation of Mb#2 and Mb#3 is observed particularly along the cooling tube.
- Gaps are completely obstructed by the swelling at the top surface along the cooling tube.
- Localized cracks on two W monoblock occurred during 20 MW/m² cycling, beginning after 1600 cycles.
- Micro cracks appeared on Mb#1 and Mb#4 visible with a binocular microscopy.

FZJ: JUDITH 2

JUDITH 2 – machine parameters

max. beam power:	200 kW
acceleration voltage:	40 – 60 kV
irradiation area:	40 x 40 cm^2
power density:	≤ 2 GWm^{-2}
pulse length:	5 µs – cont.
beam diameter:	> 3 mm





suited for toxic materials, e.g. Be

JUDITH 2 – cooling circuit

temperature:	RT – 120 °C
pressure:	≤ 4 MPa
flow rate:	≤ 200 l/min

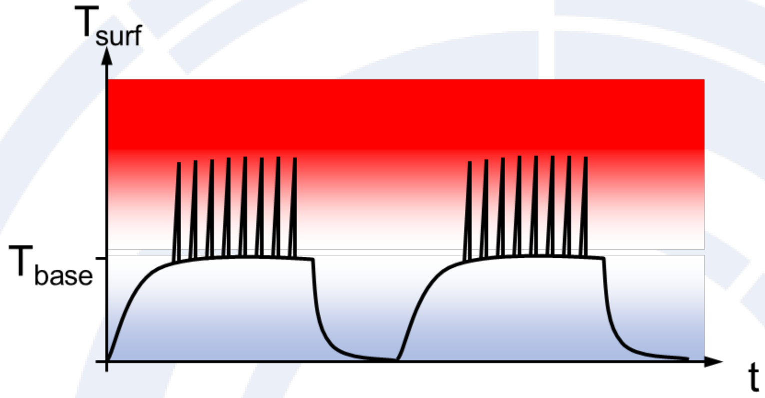
in-situ high purity control

conductivity:	< 0.3 µS/cm
oxygen content:	< 0.04 mg/l

FZJ: JUDITH 2

Definition of standard testing procedure (benchmarking tests):

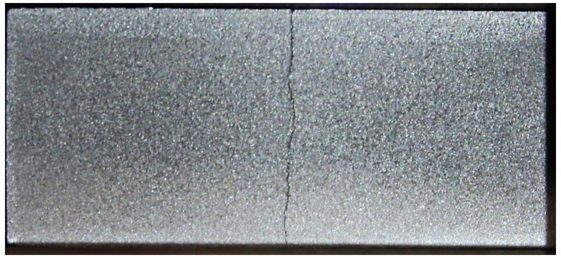
300 cycles at 20 MW/m^2 (10s/10s), continuation to 1000 cycles on survival, long hold time test (creep) at 10 MW/m^2 (e.g. 10 × 400 s loading), continue with 20 MW/m^2



Generation of macro cracks within the WEST PFU MBs

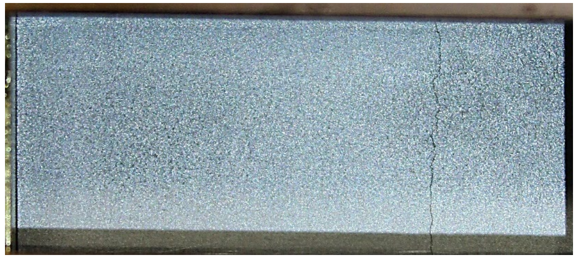
MB 27: @ 24 MW/m²

Cycle: 1 - 20



MB 32: @ 20 MW/m²

Cycle: 21 – 40

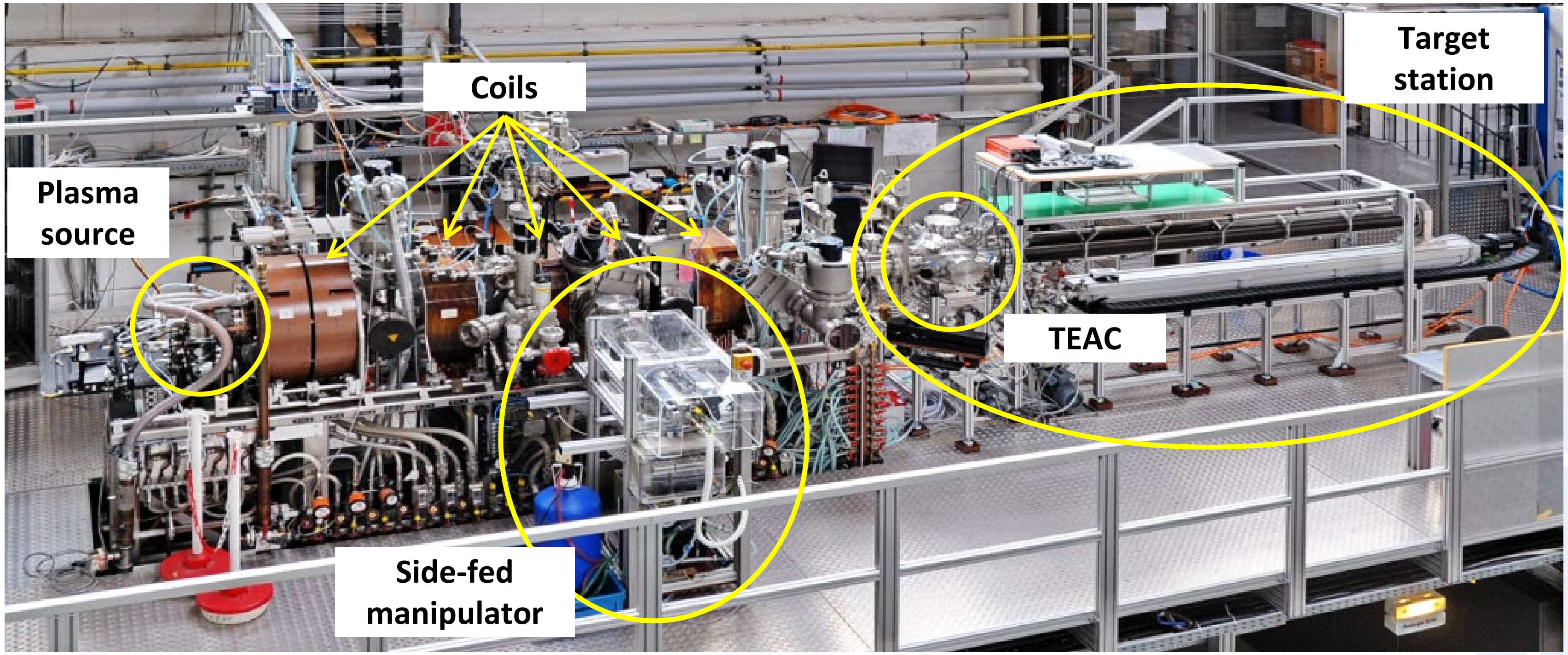


MB width has influence on the power density/stresses needed to generate a macro crack

Influence of thermal shock cracks on the macro-crack formation during stationary heat loads in ITER

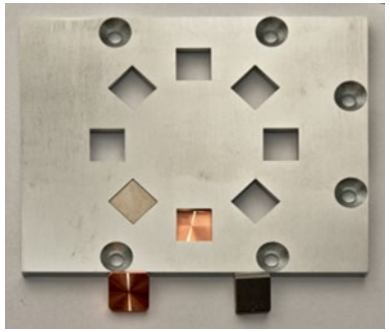
Surface cracks seem to have no influence on initiation macro cracks (≤ 1000 @ 20 MW/m²).
However, surface damages become more pronounced and sever plastic deformation (creep) of the MB occurs.

FZJ: PSI-2



Target Exchange and Analysis Chamber (TEAC):

- **E**nergy-**D**ispersive **X**-ray **Sp**. (EDX)
- **L**aser **I**nduced **B**reakdown **Sp**. (LIBS)
- **L**aser **I**nduced **D**esorption-QMS (plan)

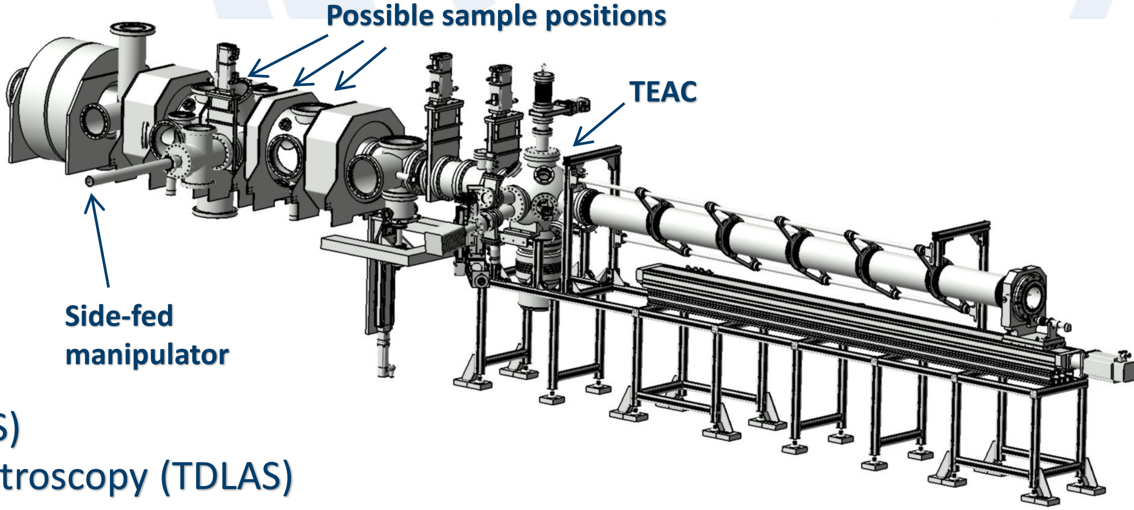


Steady-state

- D, He, Ar plasma
- plasma column diameter 60 mm
- ion flux ≤ 1023 m-2s-1
- incident ion energy (bias) 10 – 300 eV

Plasma chamber:

- Langmuir probe
- Nd:YAG laser (1064 nm, 32 J)
- Infrared (IR) camera
- **O**ptical **E**mission **S**pectroscopy (OES)
- **Q**uartz **M**icro **B**alance (QMB)
- **Q**uadrupole **M**ass **S**pectroscopy (QMS)
- **T**unable **D**iode **L**aser **A**bsorption **S**pectroscopy (TDLAS)



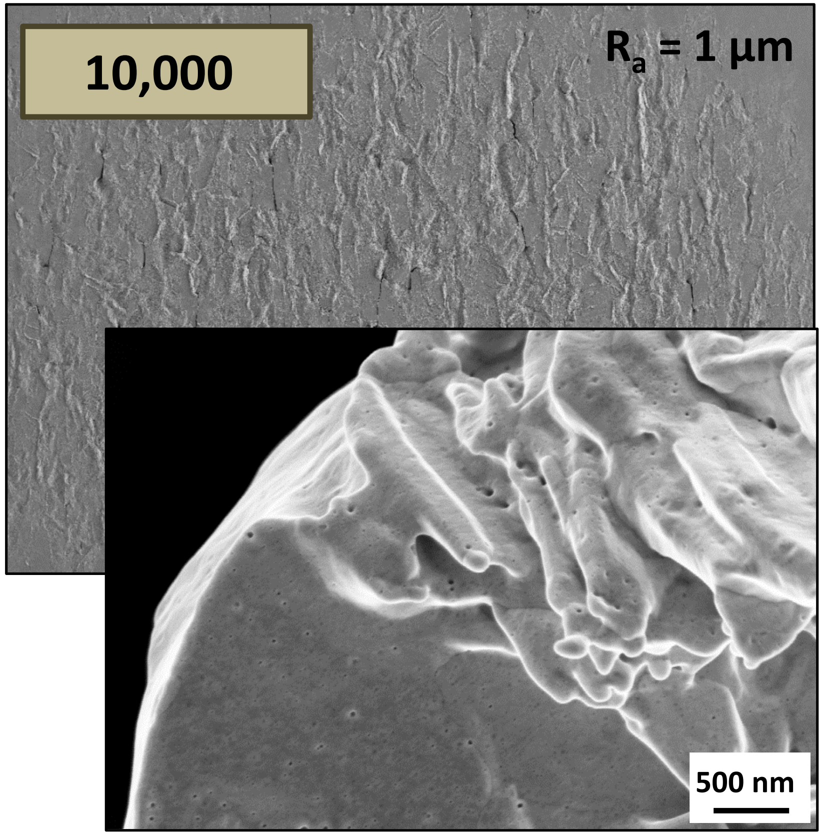
FZJ: PSI-2

Laser beam

ELM-like heat loads at 730 °C

absorbed power density: 0.38 GW/m^2

pulse duration: 0.5 ms (f = 10 Hz)

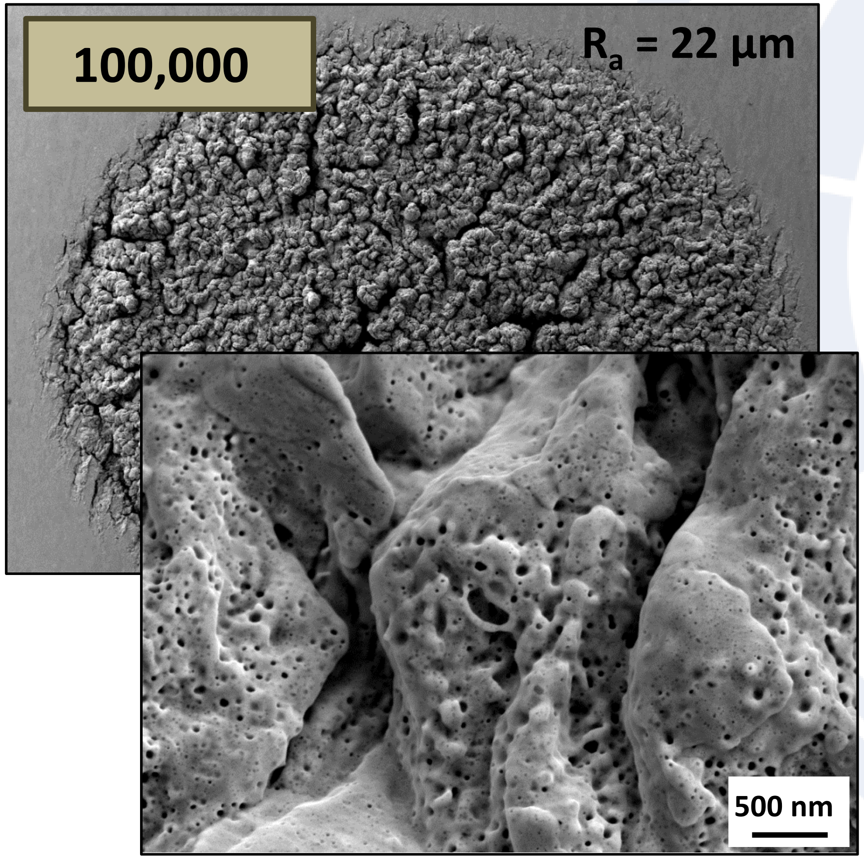


H/He (6 %) - Plasma

particle energy ≈ 35 eV

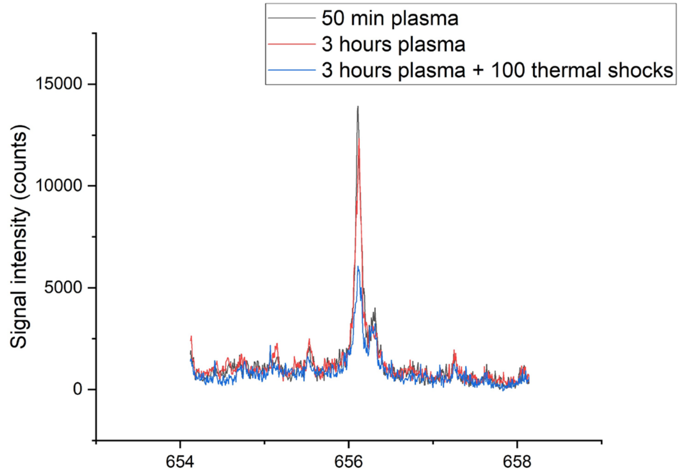
plasma flux ≈ 6.0×10^{21} $m^{-2}s^{-1}$

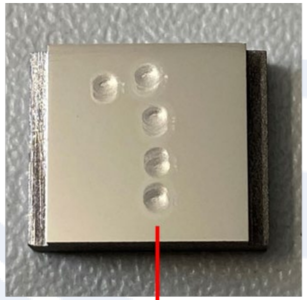
fluence ≈ 9.0×10^{24} m^{-2} / 6.0×10^{25} m^{-2}



Measurement of deuterium retention *in-situ* via laser-induced breakdown spectroscopy (LIBS).

Enables measurement of dynamic deuterium retention at different times, also after thermal shock tests



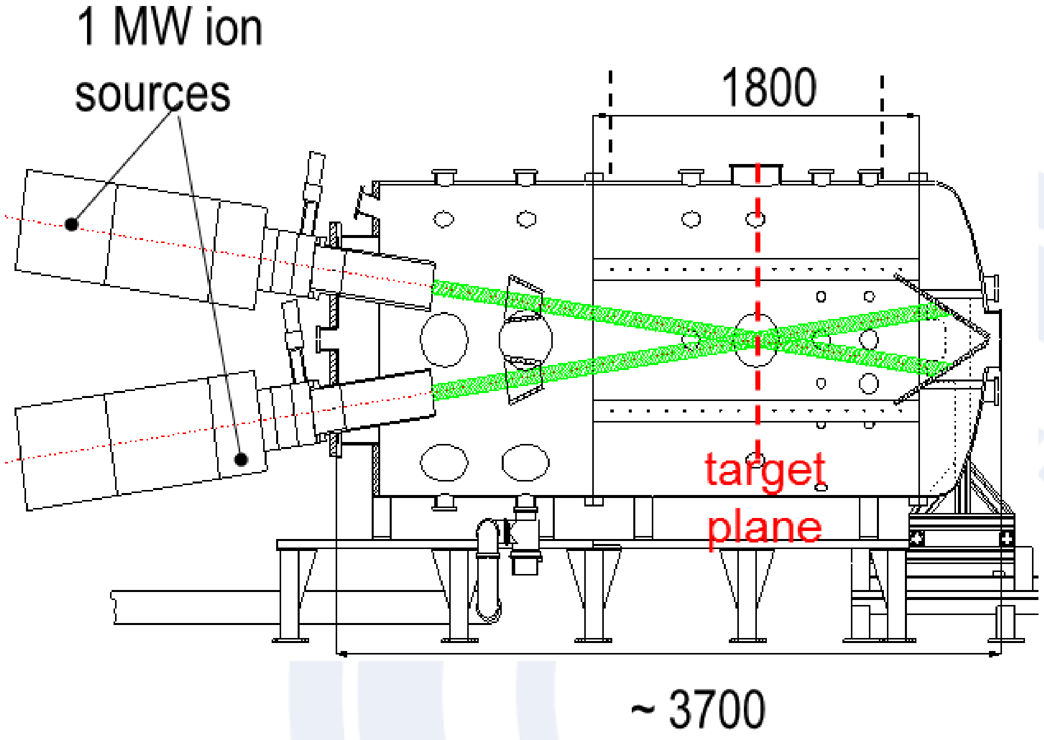


Laser ablation spots

IPP: GLADIS

- Power 2 x 1 MW ion source
- Capability to operate with H/ He
- U_{ex} 15 – 55 kV
- Heat flux 3 - 45 MW/m^2 p. source
- Beam ∅ 7 cm (80% of q'_{max})
- Pulse length 1 ms - 45 s
- Cycle rate 80 - 100 /h
- Target dim. cm size up to 2 m
- Target cooling: < 8 l/s, 10 – 25 bar

Simultaneous loading with high heat AND H/He particle flux



Nucl. Fusion **57** (2017) 092012

IPP: GLADIS

- Mock-up “Optimized”: optimized honeycomb structure with attached W tiles (grains perpendicular to surface)
- Mock-up “Heuristic”: standard honeycomb structure on building plate (grains parallel to surface), optimised infiltration
- Design and manufacturing details shown by R. Lürbke

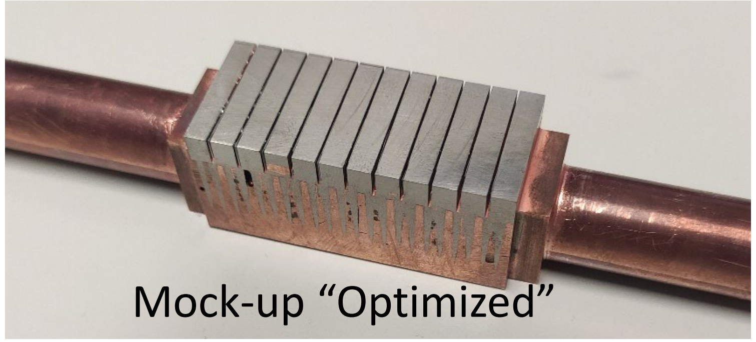
Performed tests:

cold water cooling, T_{in}= 15 – 27 °C, p= 10 bar, 12 m/s

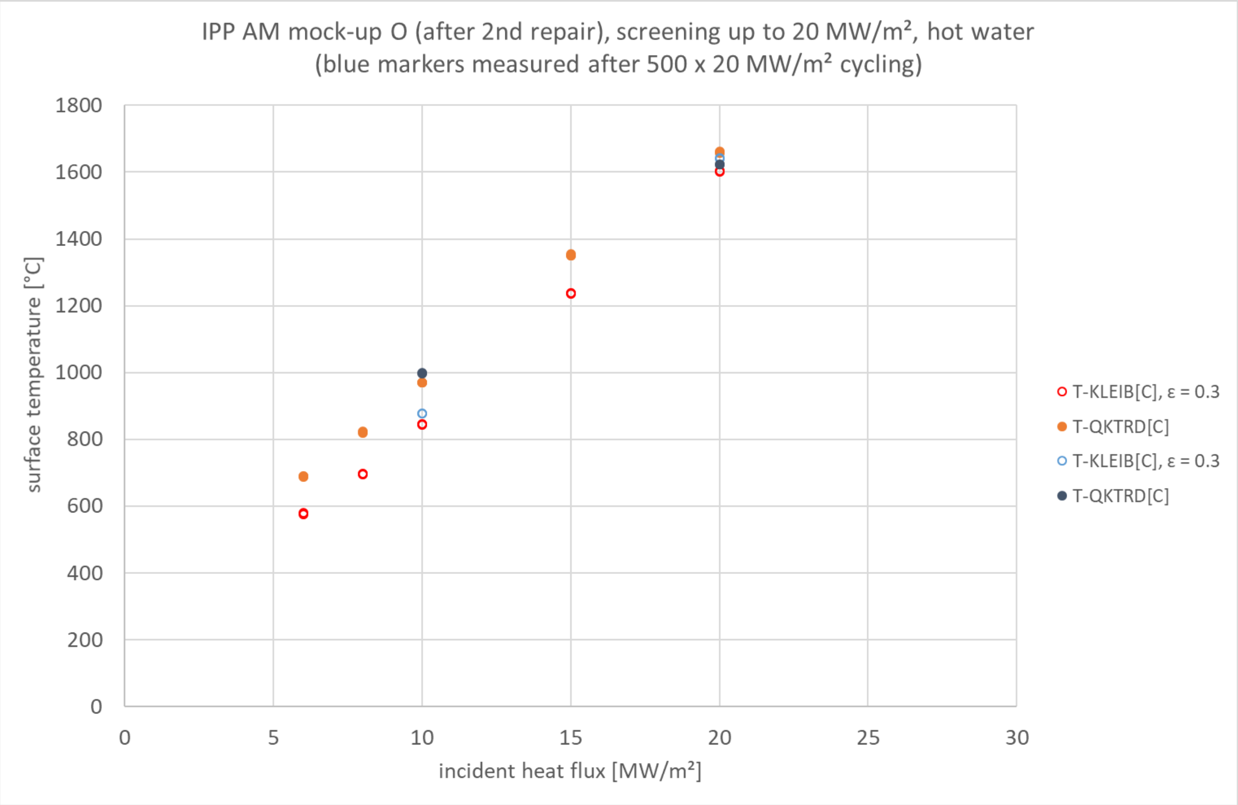
1. Screening up to 25 MW/m²
2. Cyclic loading: 100 pulses @ 10 MW/m² , 10 sec.

hot water cooling, T_{in}= 130 °C, p= 40 bar, 16 m/s

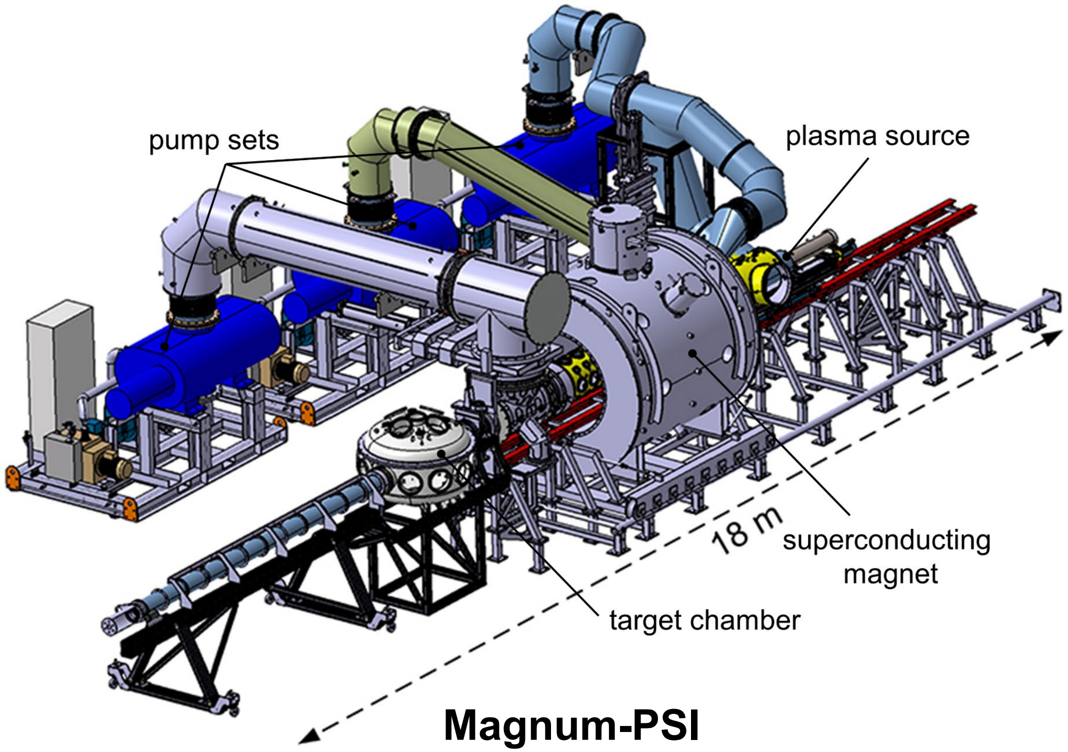
1. Screening up to 20 MW/m²
2. Cyclic loading: 500 pulses @ 20 MW/m² , 10 sec.



Mock-up “Optimized”

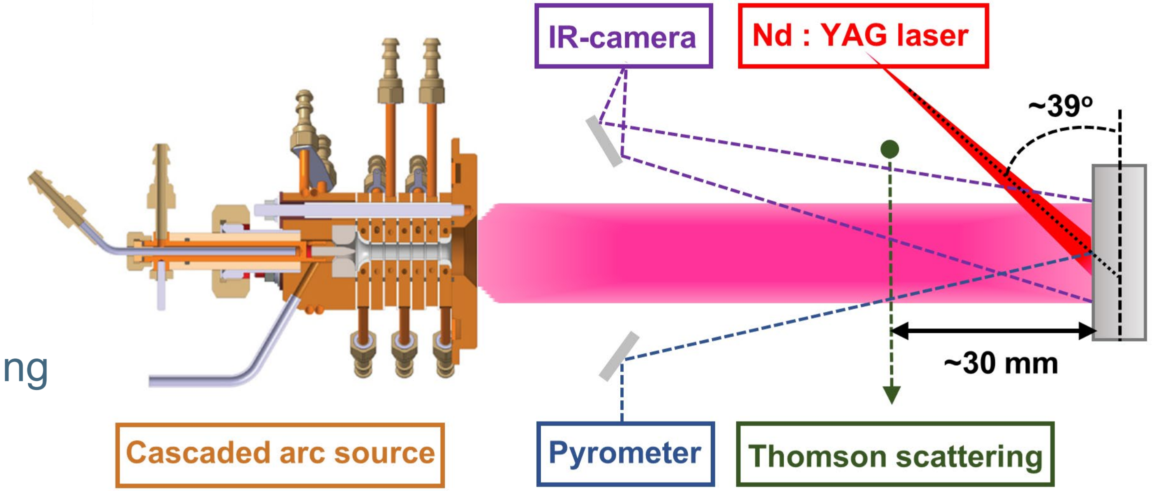


DIFFER: MAGNUM-PSI



Magnum-PSI

Property	Typical values
Electron density (n_e)	10^{19} - 10^{21} m^{-3}
Electron temperature (T_e)	0.1 – 5 eV
Particle flux density (Γ)	10^{23} - 10^{25} m^{-2} s^{-1}
Heat flux density (q)	1 – 50 MW m^{-2}
Magnetic field (B)	0 – 2.5 T
Pulse length (s)	continuous



Use Magnum-PSI to recreate aspects of slow-transient loading and high-power laser for ELM-like loading:
good fidelity simulation of divertor plasma conditions

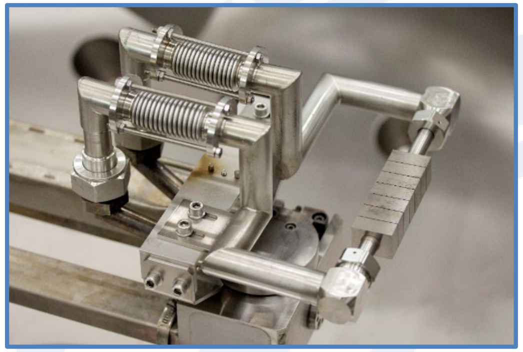
DIFFER: MAGNUM-PSI

Increasing base temperature leads to decrease in fatigue cracking threshold (H plasma, 4.0×10^5 pulses)

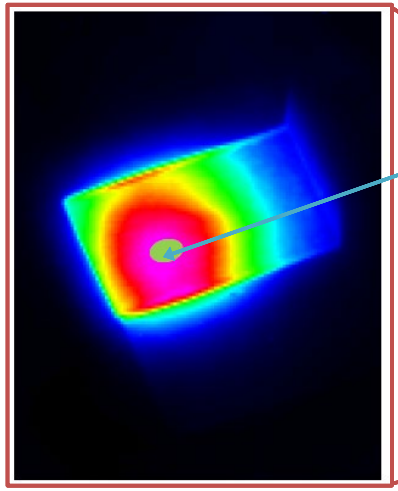
Take advantage of steady-state operations of Magnum-PSI with superconducting magnet

Use a high-power welding laser to recreate up to 10^6 ELM-like loading events (1 ms)

ITER monoblock mock-up chain mounted in Magnum-PSI

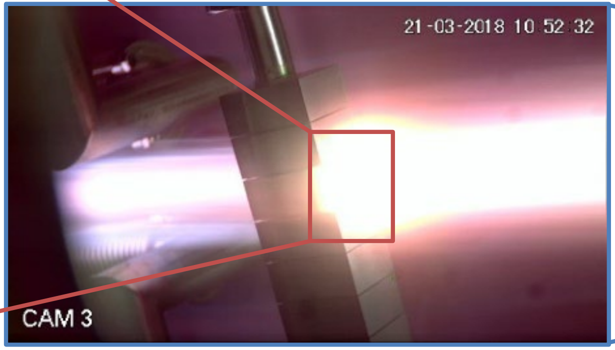


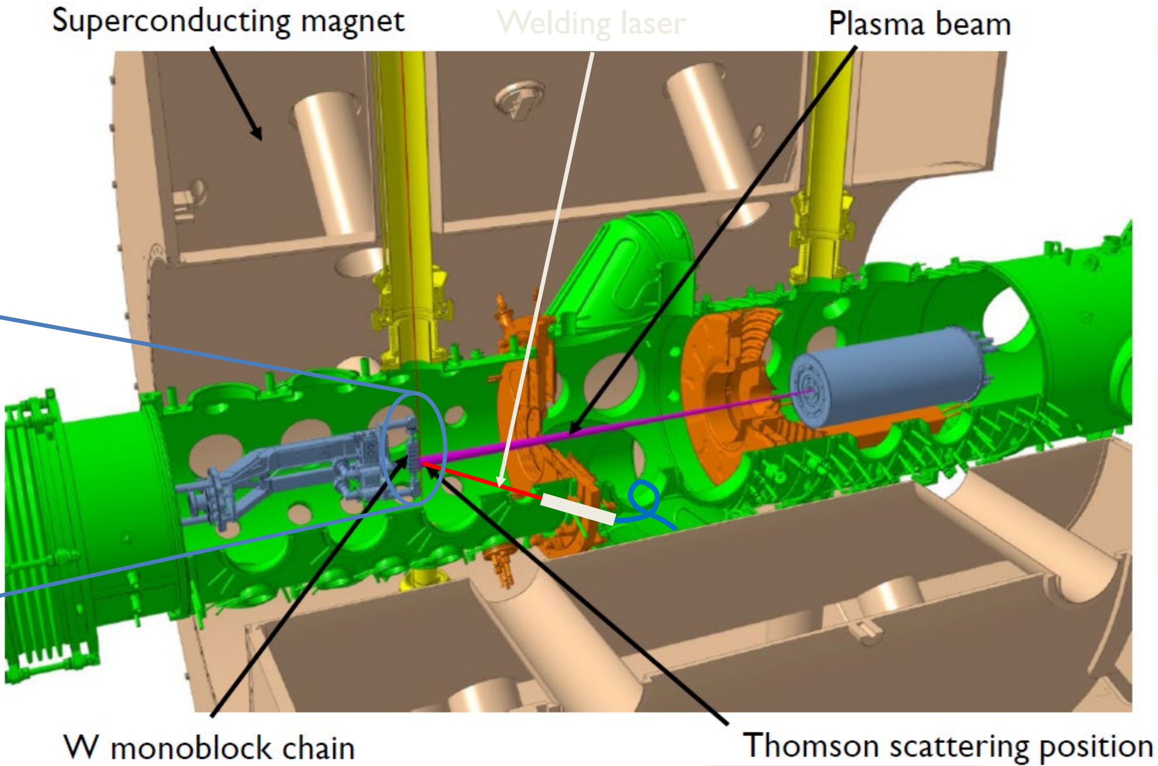
Typical IR-cam image



Laser spot dimensions (~4 × 2 mm)

T.W. Morgan et al., *Phys. Scr.* (2020)





CIEMAT: OLMAT

NBI BEAM

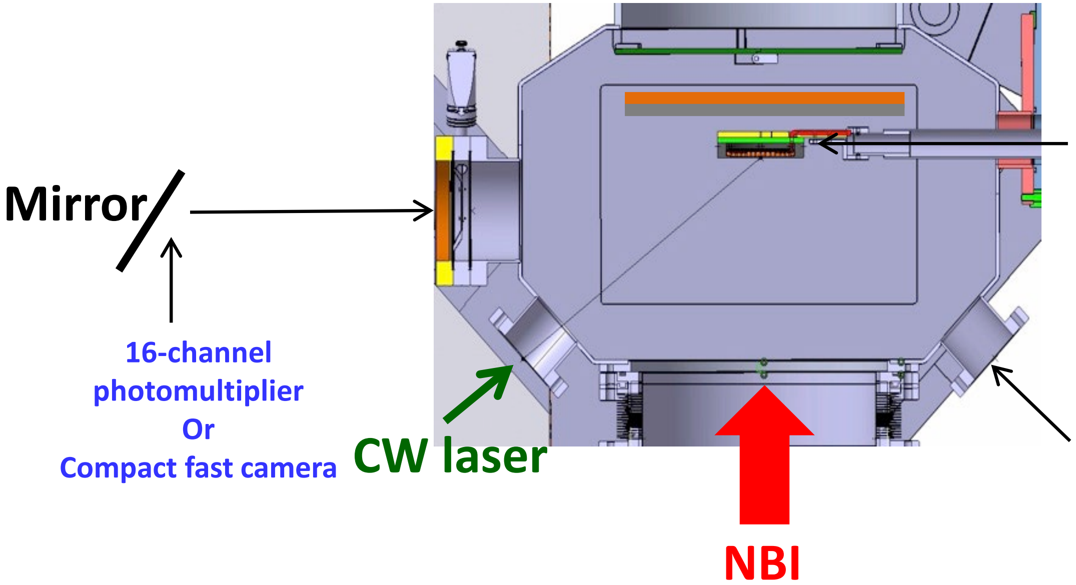
For steady state and slow transients simulation

- **Beam power:** 705 kW; **8 ± 2 to 40 ± 5 MW/m^2**
- **H^+ energy:** 8-40 keV. H^+ flux : $1.7\cdot10^{22}$ 1/m^{2}s.
- **Wide beam:** gaussian with 1/e **width of 20 cm.**
- **Pulse duration:** up to **150 ms.** Every 30-120 s.

LASER

Simulate steady state to few GW/m^2 disruptions.

- **Y fiber CW laser from IPG. Spot at focus: 0.67 mm**
- **Power: 930 W continuous; 9300 W pulsed.**
- **Pulses: 0.2-10 ms; 90 J energy; 1-2000 Hz**
  - ➢**Spot size** (defocusing) **and laser power** (software) to control **power density.**
  - ➢But then laser beam is **Gaussian**: **complex interpretation**



16-channel photomultiplier
Or
Compact fast camera

Manipulator:

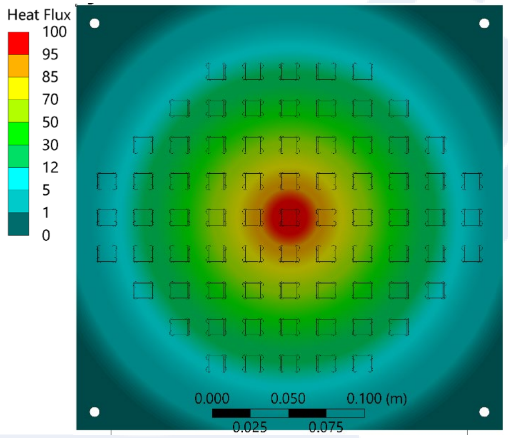
- 2 thermocouples
- Langmuir probe
- V float and I sat

3 of:

- 2 Pyrometers
- IR camera
- OES
- Fast camera

Large holder (new):

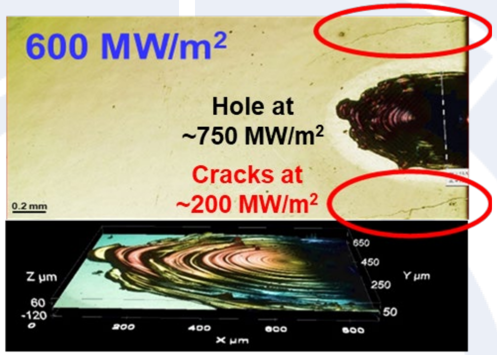
- **Refrigerated:** but no heating
- **90º** irradiation angle.
- **75 samples** by 200 mm beam.
- **Gaussian power distribution**



CIEMAT: OLMAT

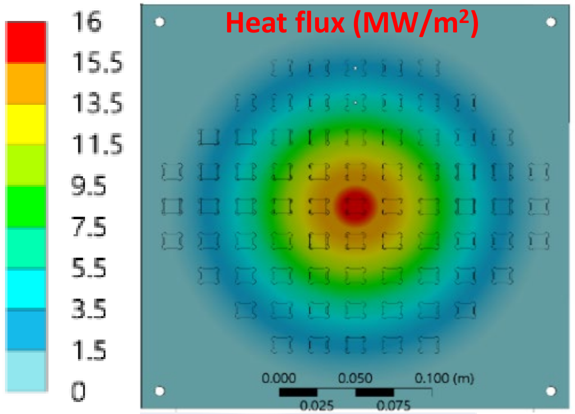
LASER: TRANSIENT SIMULATION ON W

- Past experiments suffered thermal ablation at center by <u>Gaussian beam shape</u> (2x mean energy). <u>No realistic!</u>
- After careful beam profiling we learned laser had <u>flat profile at focus point</u>.
- Future: <u>use fibers of larger diameter</u> to have larger spots at focus point.
- We are also trying to <u>simulate DEMO mitigated ELMs</u> 0.1 MJ/m^2: 7·10^8 pulses in armor lifetime. At our laser up to ~6·10^7 pulses/day



NBI: SIMULATION OF FATIGUE BY STEADY STATE LOADS

- <u>Successful experiments in the past</u>, but only 4 samples at the same time.
- <u>Now up to 75 cooled samples at the same time</u>! Gaussian NBI power shape allow for a power distribution along the samples (divertor to main wall)
- But <u>difficult assembling</u>: only one operation day, and inefficient cooling.
- We expect to solve these issues in October campaign.



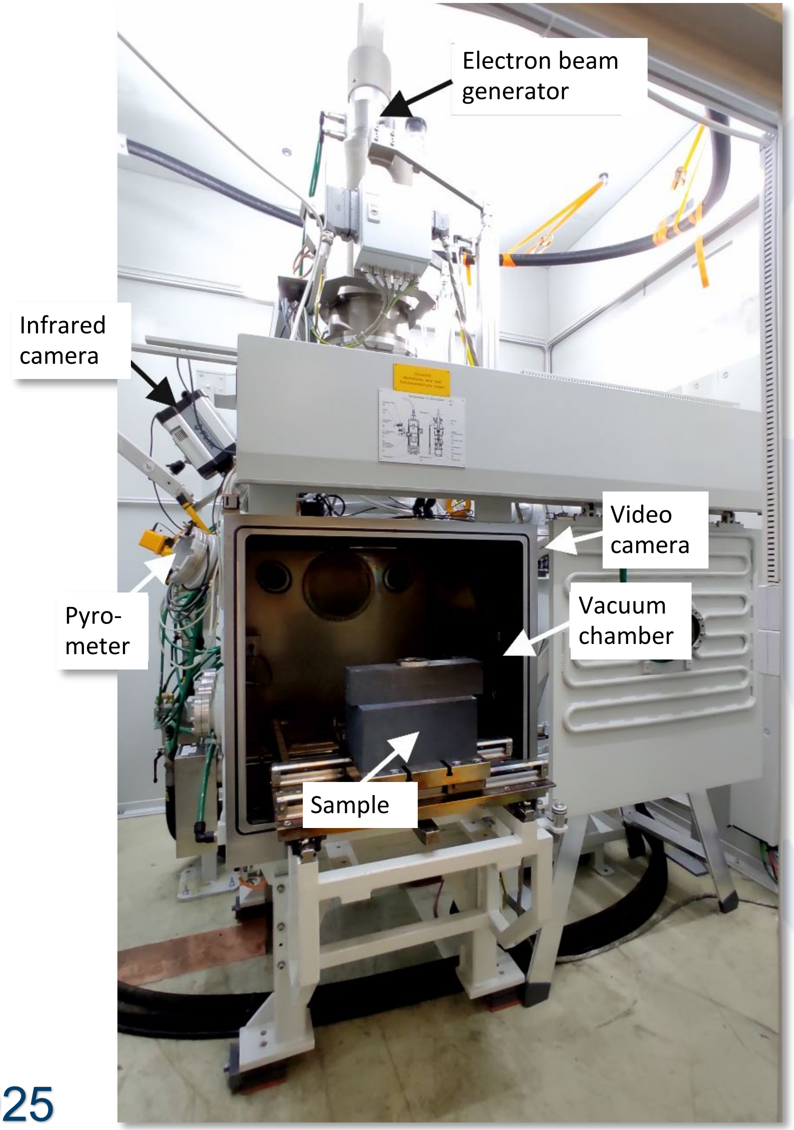
Under construction FZJ: JUDITH 3

JUDITH 3 – machine parameters

max. beam power:	60 kW
acceleration voltage:	≤ 150 kV
irradiation area:	15 x 15 cm^2
power density:	≤ 2 GWm^{-2}
pulse length:	5 µs – cont.
beam diameter:	~1 mm FWHM

Provisional set-up in controlled area

To be installed in new hot-cell until 2025



JUDITH 3 – cooling circuit

(to be installed in 2023)

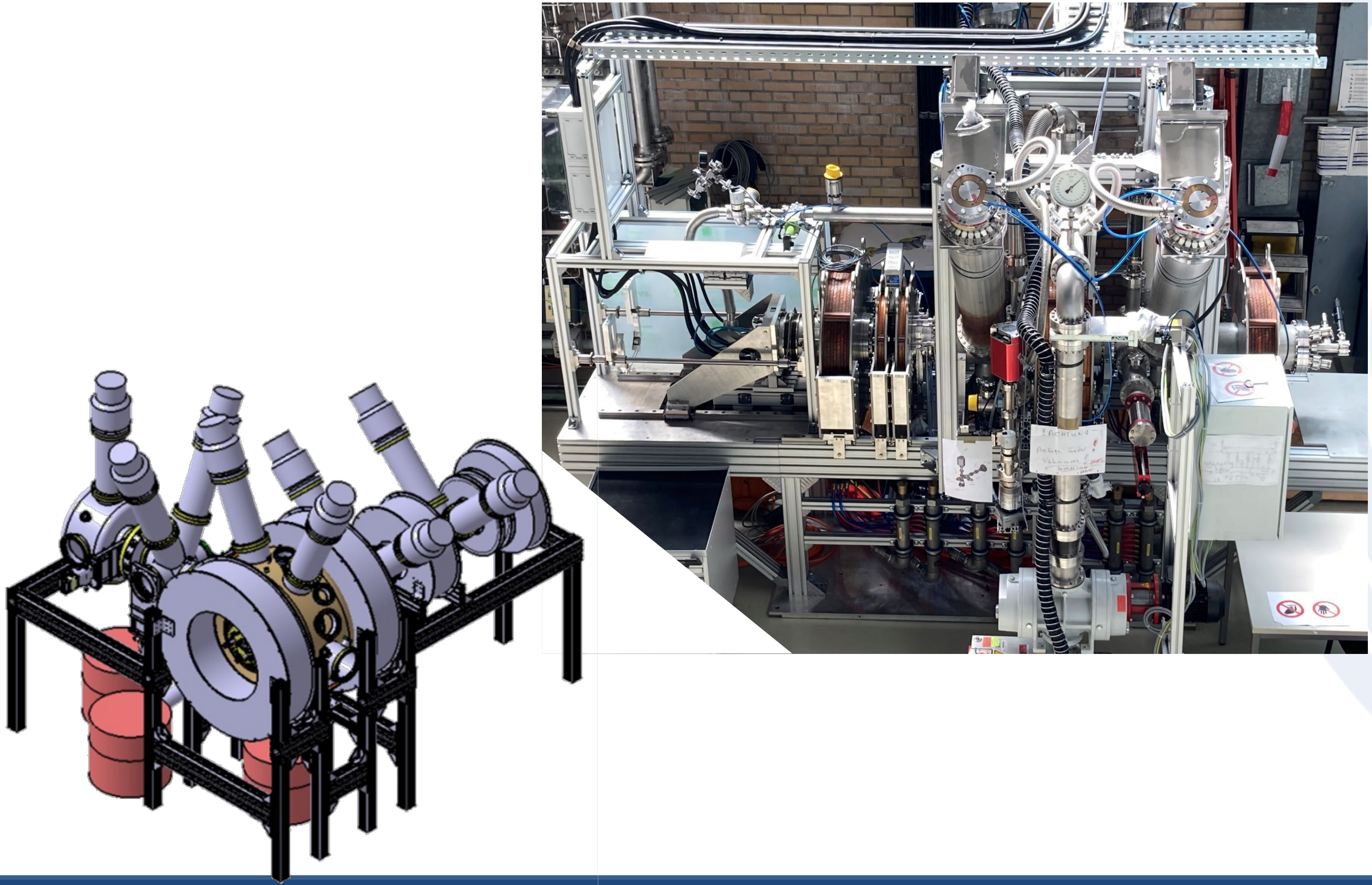
temperature:	RT – 120 °C
pressure:	≤ 4 MPa
flow rate:	≤ 80-100 l/min

in-situ high purity control

conductivity:	< 0.3 µS/cm
oxygen content:	< 0.04 mg/l

Under construction FZJ: JULE-PSI

Linear plasma device (under construction for implementation in a hot cell)

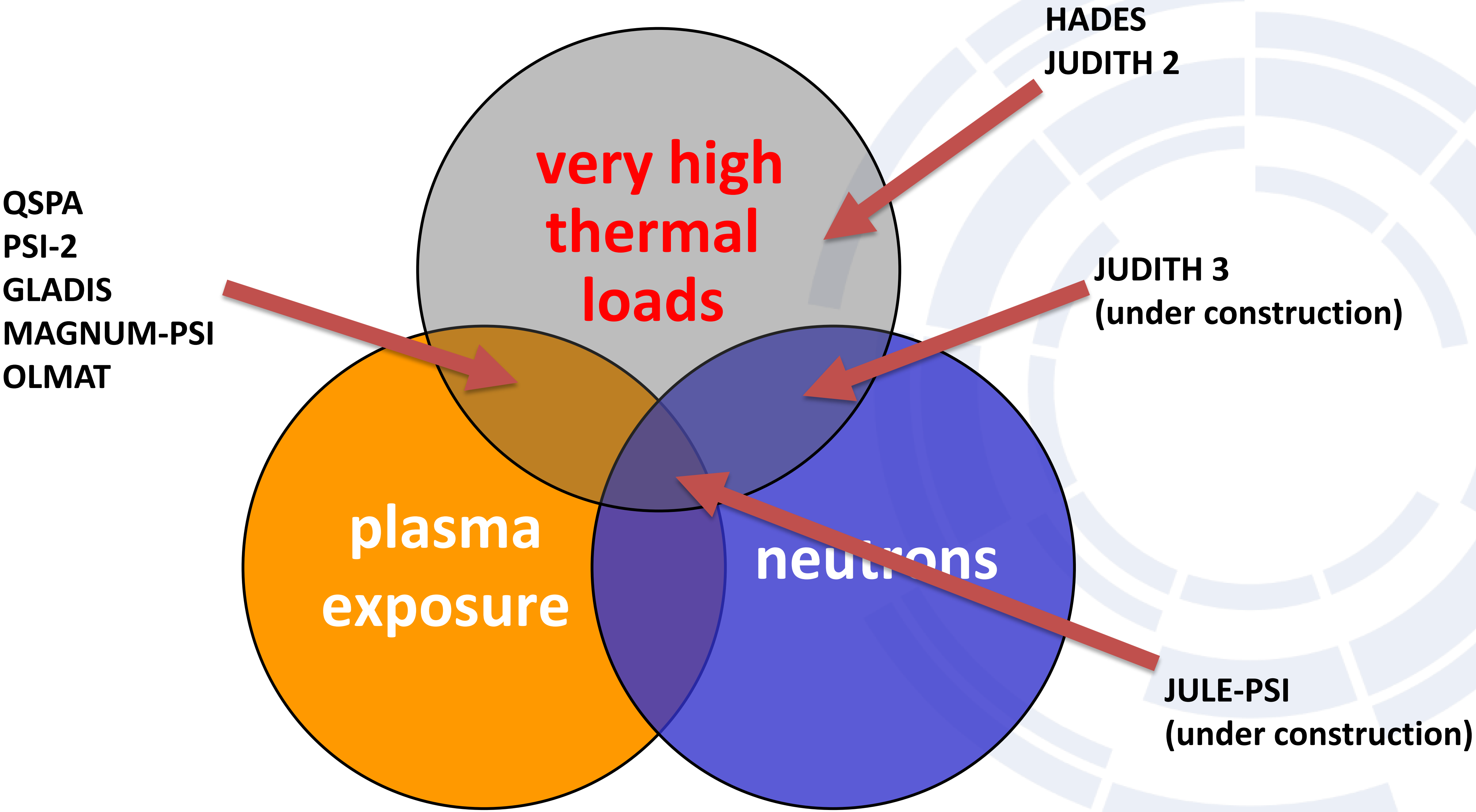


Similar options planned as for PSI-2:

- Langmuir probe
- **I**nf**r**a**r**ed (IR) camera
- **T**unable **D**iode **L**aser
  Absorption **S**pectroscopy (TDLAS)
- **O**ptical **E**mission **S**pectroscopy (OES)
- **Q**uartz **M**icro **B**alance (QMB)
- **Q**uadrupole **M**ass **S**pectroscopy (QMS)

- **E**nergy-**D**ispersive **X**-ray Sp. (EDX)
- **L**aser **I**nduced **B**reakdown **S**p. (LIBS)
- **L**aser **I**nduced **D**esorption-QMS (LIDS)

Summary & Conclusion



Summary & Conclusion

	Stationary heat loads	Number of cycles	Transient heat loads	Number of pulses	Synergistic loads (heat/particles)	Components size	Activly cooled	Neutrons/ activated samples
QSPA	🟩	$>10^3$	🟩	$>10^3$	🟩	several cm	🟥	🟥
HADES	🟩	$>10^3$	🟩	$>10^6$	🟥	>1 m, up to ITER divertor full scale	🟩	🟥
JUDITH 2	🟩	$>10^3$	🟩	$>10^6$	🟥	up to 1 m	🟩	🟥
PSI-2	🟩	-	🟩	$>10^6$	🟩	several mm up to cm	▨	🟥
GLADIS	🟩	$>10^3$	🟥	-	🟩	up to 1m	🟩	🟥
MAGNUM-PSI	🟩	$>10^3$	🟩	$>10^6$	🟩	up to ~20 cm	🟩	🟥
OLMAT	🟩	$>10^3$	🟩	~100/day	🟩	up to 28 cm	▨	🟥
JUDITH 3	🟩	$>10^3$	🟩	$>10^6$	🟥	?	🟩	🟩
JULE-PSI	🟩	?	🟩	$>10^6$	🟩	?	▨	🟩