OLMAT as a HHF Facility for Testing ITER & DEMO Divertor Armor Materials

2022/2023 3rd project meeting

D.Alegre, E. Oyarzabal, F. Tabares, A. de Castro, D. Tafalla and the OLMAT team.

Fusion National Laboratory. CIEMAT. Madrid. Spain

Laboratorio Nacional de Fusión

Ciemat

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

INDEX

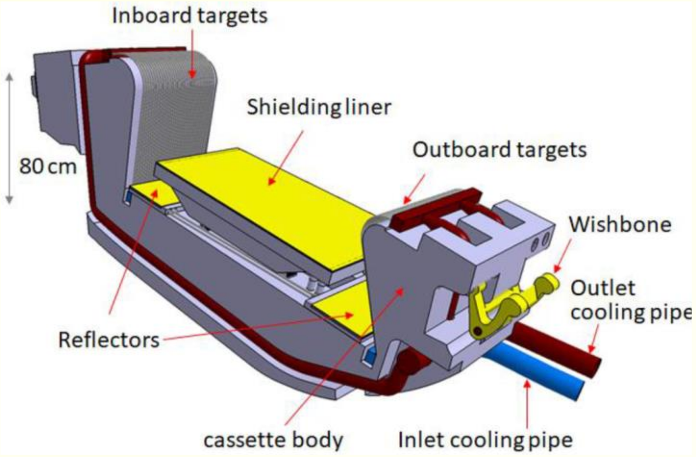
DEMO: power loads

Challenging conditions for a nuclear fusion reactor.

- ✓ **Large, energetic (14 MeV) neutron loading of walls**
- ✓ **Large heat and particle loads:** plasma exhaust at divertor region
- ✓ **Try to simulate them in OLMAT**

Typical heat loads [1]

- **Steady state:**
  - ➢ Normal: ~10 MW/m^2 *(ΔT_s ~800 K)*
  - ➢ Slow tran.: ~20-70 MW/m^2 (ΔT_s ~1600-4200 K)



[1] J.H. You et al., Fus. Eng. Des. 175 (2022) 113010.

DEMO: power loads

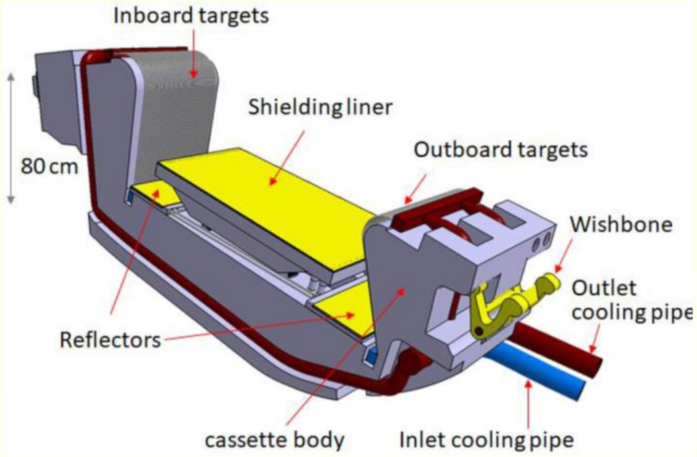
OLMAT | 2021-2 REPORT | 2023 PLAN | SUMMARY

Challenging conditions for a nuclear fusion reactor.

- ✓ **Large, energetic (14 MeV) neutron loading of walls**
- ✓ **Large heat and particle loads:** plasma exhaust at divertor region
- ✓ **Try to simulate them in OLMAT**

Typical heat loads [1]

- **Steady state:**
  - Normal: ~10 MW/m^2 *(ΔT_s ~800 K)*
  - Slow tran.: ~20-70 MW/m^2 *(ΔT_s ~1600-4200 K)*
- **Transients (off-normal):**
  - ELMs (mitigated): ~20 MW/m^2 0.5 ms *(ΔT_s ~150 K)*
  - ELMs: ~150-500 MW/m^2 1 ms. *(ΔT_s ~1,100-3,600 K)*
  - Disruptions: 80-110 GW/m^2 1-4 ms. *(ΔT_s ~600,000 K)*

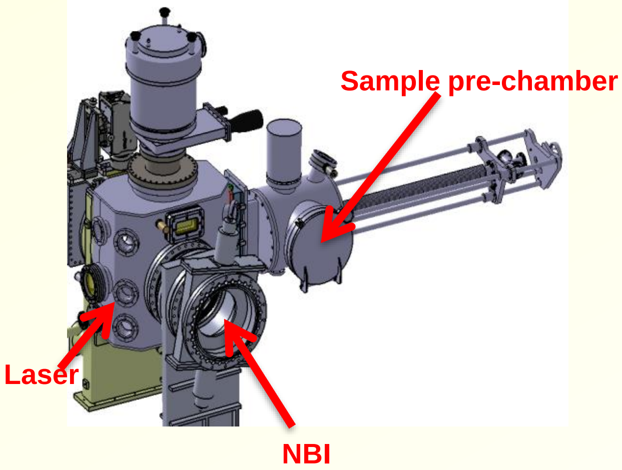


[1] J.H. You et al., Fus. Eng. Des. **175** (2022) 113010.

OLMAT: NBI BEAM

Heating a target with the NBI beam from TJ-II stellarator [2-3]

- **Devoted exposure chamber and pre-chamber with independent vacuum system.**
- **Beam power: 705 kW; H^+ energy: 8-40 keV. H^+ flux : $1.7 \cdot 10^{22}$ $1/m^2s$.**
- **Wide beam:** gaussian beam with 1/e width of **20 cm.**

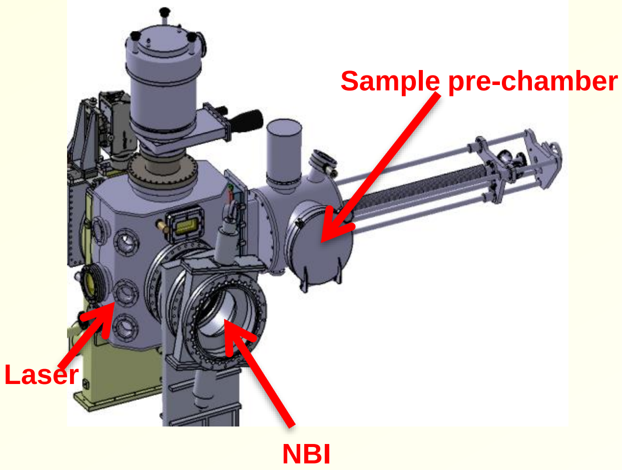


[2] D. Alegre,et al. J Fus. Ener. **39** (2020) 411–420.
[3] F.L. Tabarés et al., Fus. Eng. Des. **187** (2023) 113373

OLMAT: NBI BEAM

Heating a target with the NBI beam from TJ-II stellarator [2-3]

- Devoted exposure chamber and pre-chamber with independent vacuum system.
- Beam power: 705 kW; H^+ energy: 8-40 keV. H^+ flux : $1.7 \cdot 10^{22}$ $1/m^2s$.
- **Wide beam:** gaussian beam with 1/e width of **20 cm.**
- **Power density between 8±2 to 55±15 MW/m^2.**
- **Pulse duration up to 150 ms.**
- **Repetition rate:** pulse every **30-120 s** depending on power
  - More oriented to **fatigue testing**.
  - 800 pulses per day achievable.

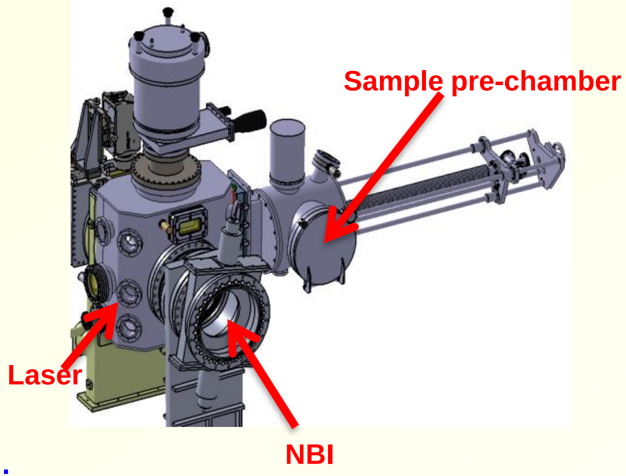


[2] D. Alegre,et al. J Fus. Ener. **39** (2020) 411–420.
[3] F.L. Tabarés et al., Fus. Eng. Des. **187** (2023) 113373

OLMAT: NBI BEAM

Heating a target with the NBI beam from TJ-II stellarator [2-3]

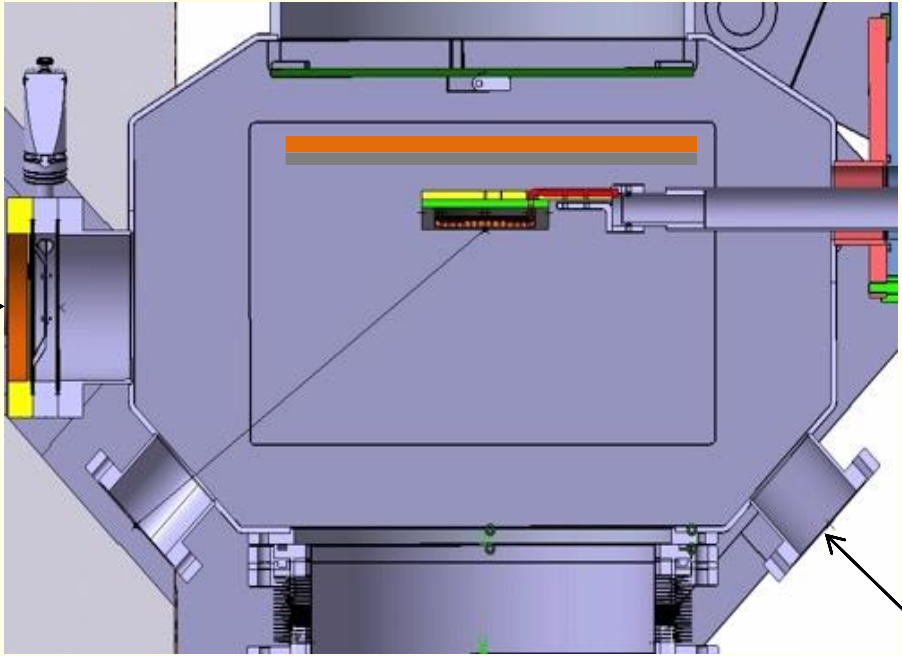
- Devoted exposure chamber and pre-chamber with independent vacuum system.
- Beam power: 705 kW; H^+ energy: 8-40 keV. H^+ flux : $1.7 \cdot 10^{22}$ $1/m^2s$.
- **Wide beam:** gaussian beam with 1/e width of **20 cm.**
- Power density between 8±2 to 55±15 MW/m^2.
- Pulse duration up to 150 ms.
- **Repetition rate:** pulse every **30-120 s** depending on power
  - More oriented to **fatigue testing**.
  - 800 pulses per day achievable.
- **Developed plasma: T_e: ~2 eV; n_e: 10^{18} m^{-3}** (OES and probe).
- **Equipped with a large variety of diagnostics.**



[2] D. Alegre,et al. J Fus. Ener. **39** (2020) 411–420.
[3] F.L. Tabarés et al., Fus. Eng. Des. **187** (2023) 113373

OLMAT: DIAGNOSTICS

Mirror



16-channel photomultiplier
Or
Compact fast camera

3 of:

- **2 Pyrometers**
- **IR camera**
- **OES**
- **(C. Fast camera)**

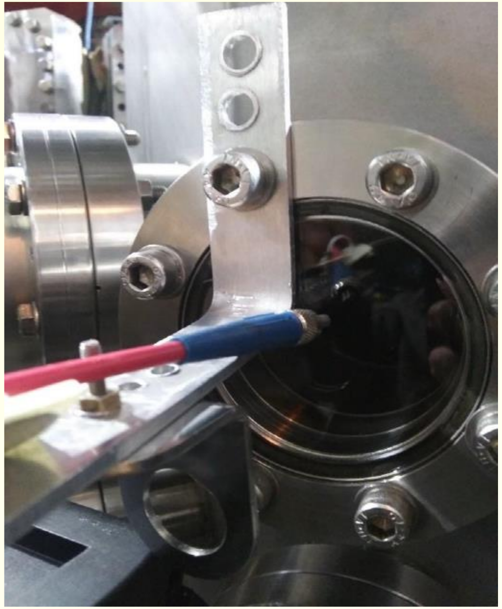
OLMAT: DIAGNOSTICS

16-channel photomultiplier

Compact fast camera

IR camera and pyrometers

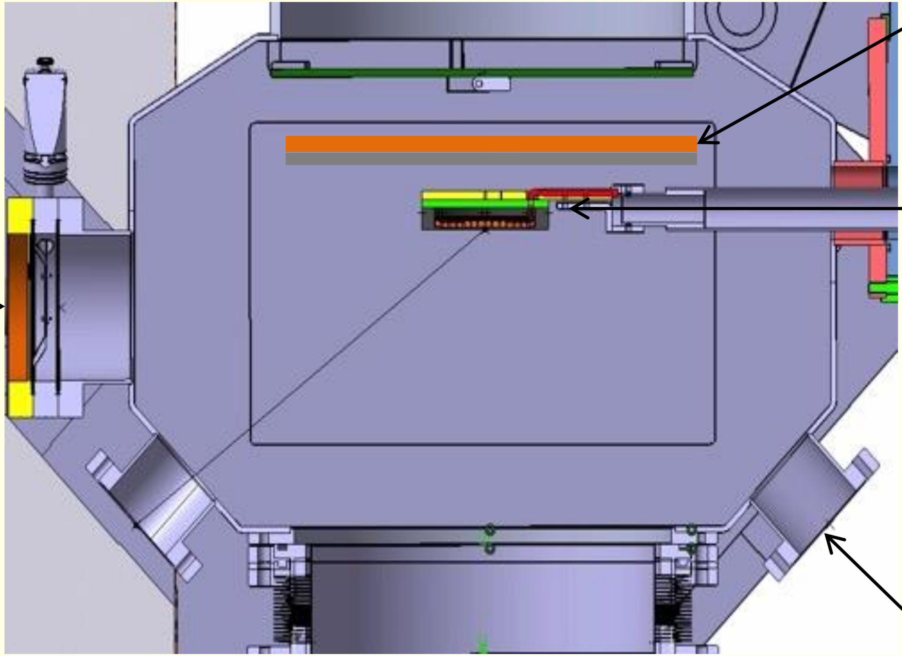
CMOS OES



OLMAT: MANIPULATOR

Mirror

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**

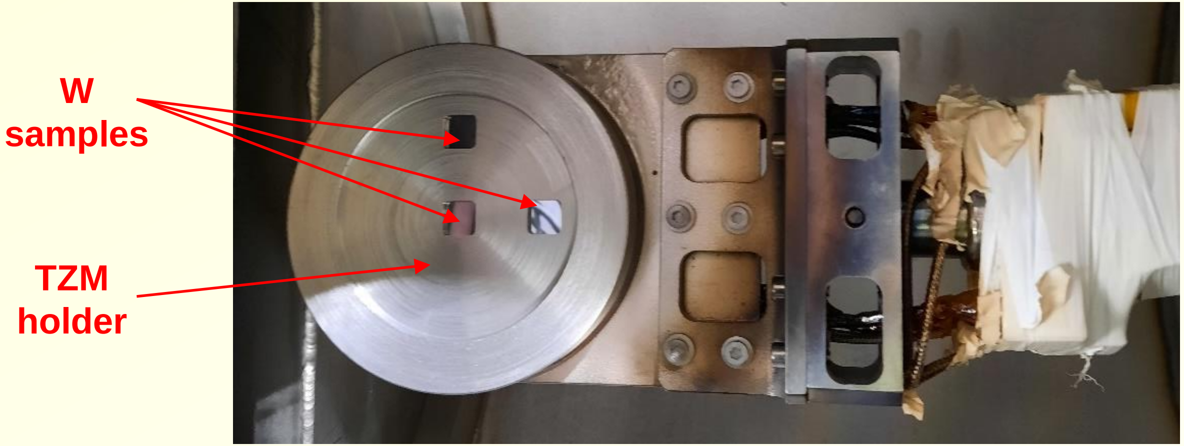
OLMAT: MANIPULATOR

Manipulator:

- **Loading of samples in <u>pre-chamber</u>:** heat treatment under vacuum, TDS analysis …
- **<u>Heating</u> until about 500 ºC. But no refrigeration!** plateau at 600 ºC after 10-30 pulses
- **<u>Turntable</u> to change irradiation angle to 60º or more.**

Manipulator:

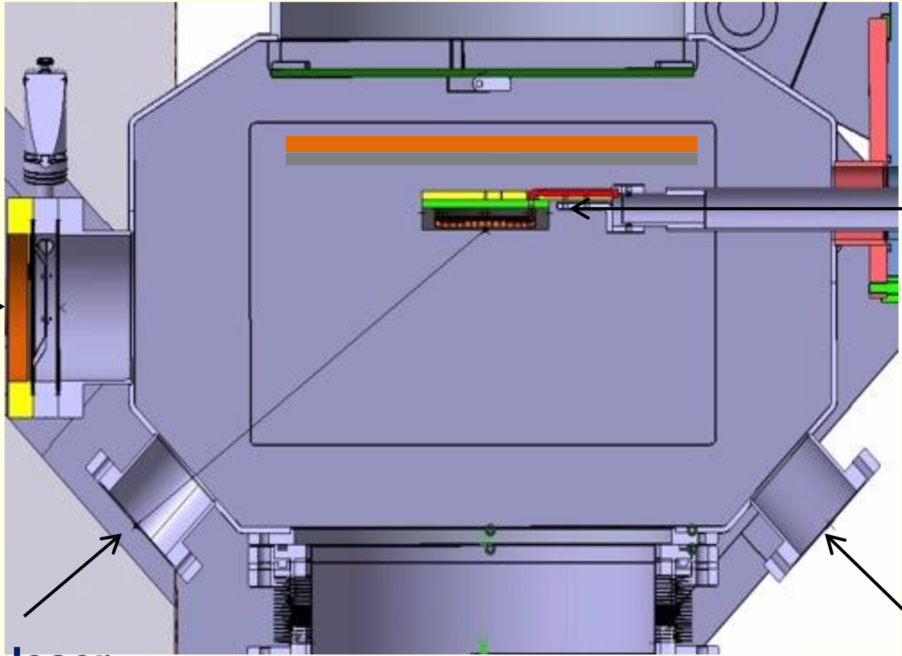
- **Loading of samples in <u>pre-chamber</u>:** heat treatment under vacuum, TDS analysis …
- **<u>Heating</u> until about 500 ºC. But no refrigeration!** plateau at 600 ºC after 10-30 pulses
- **<u>Turntable</u> to change irradiation angle to 60º or more.**
- **Sample <u>holder size limited to about 100 mm diameter and 40 mm thick</u>:**
  - Usually much smaller to irradiate many at the same time



OLMAT: CW LASER

Mirror

16-channel photomultiplier
Or
Compact fast camera



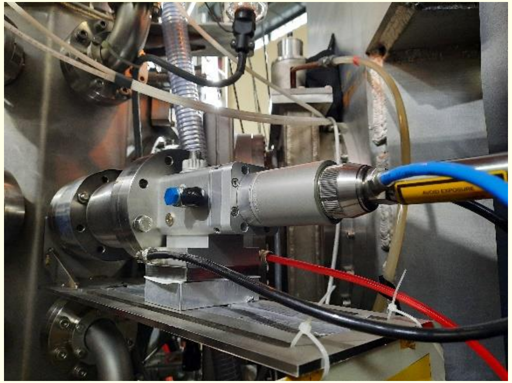
CW laser

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

3 of:
- 2 Pyrometers
- IR camera
- OES
- Fast camera

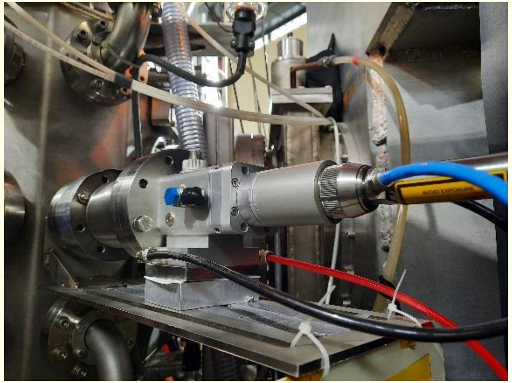
OLMAT: CW LASER

- **Power: 930 W continuous; 9300 W pulsed.**
- **Pulses: 0.2-10 ms; 90 J energy; 10-2000 Hz**
- **NBI 55±15 MW/m^2. Synergies laser+beam**
  - **Ellipsoidal spot due to 52 deg angle irradiation**
  - **Slow installation of a industrial laser in a laboratory:** safety, integration, vacuum systems…
  - **Bellow to allow laser positioning on sample.**



OLMAT: CW LASER

- **Power: 930 W continuous; 9300 W pulsed.**
- **Pulses: 0.2-10 ms; 90 J energy; 10-2000 Hz**
- **NBI 55±15 MW/m^2. Synergies laser+beam**
  - Ellipsoidal spot due to 52 deg angle irradiation
  - Slow installation of a industrial laser in a laboratory
  - Bellow to allow laser positioning on sample.

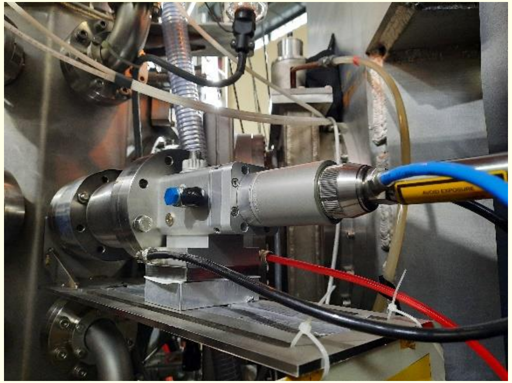


Continuous mode:

- **ITER (or DEMO) steady state:**
  - 10 MW/m^2 in 33 mm^2 area. Few seconds until steady state is reached.
- **Slow transients:**
  - 20-70 MW/m^2 in 17-4 mm^2 area.

OLMAT: CW LASER

- **Power: 930 W continuous; 9300 W pulsed.**
- **Pulses: 0.2-10 ms; 90 J energy; 10-2000 Hz**
- **NBI 55±15 MW/m^2. Synergies laser+beam**
  - **Ellipsoidal spot due to 52 deg angle irradiation**
  - **Slow installation of a industrial laser in a laboratory**
  - **Bellow to allow laser positioning on sample.**



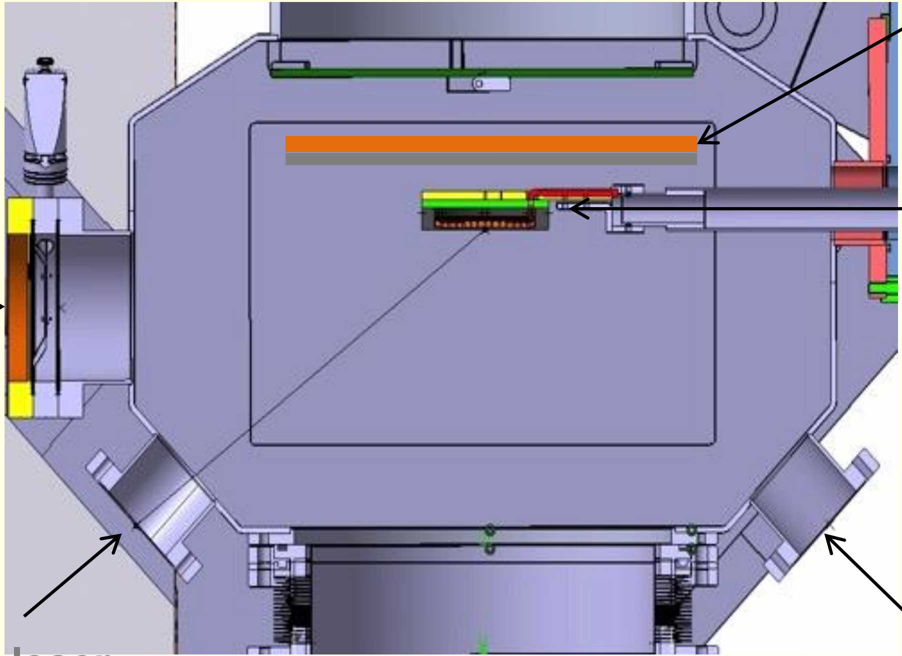
Continuous mode:

- **ITER (or DEMO) steady state:** 10 MW/m^2 in 33 mm^2 area.
- **Slow transients:** 20-70 MW/m^2 in 17-4 mm^2 area.

Pulsed mode:

- **Mitigated ELMs**:
  - 20 MW/m^2 for 0.5 ms in 130 mm^2 area. 2000 Hz. Quite important fatigue
- **Disruptions**:
  - 1-6.5 GW/m^2 for 2 ms in 3.3-0.5 mm^2 area.

OLMAT: BEAM DUMP



Mirror

16-channel photomultiplier
Or
Compact fast camera

CW laser

Beam dump

- **Lg. sample holder**
- **3 thermocouples**

Manipulator:

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

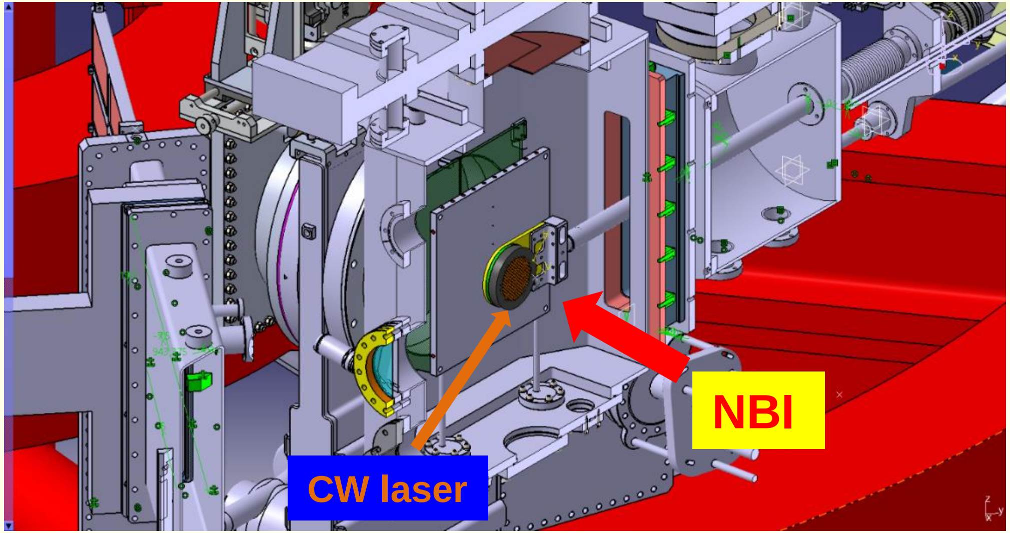
3 of:

- **2 Pyrometers**
- **IR camera**
- **OES**
- **Fast camera**

UPGRADES: beam dump

Install actively-cooled copper beam dump.

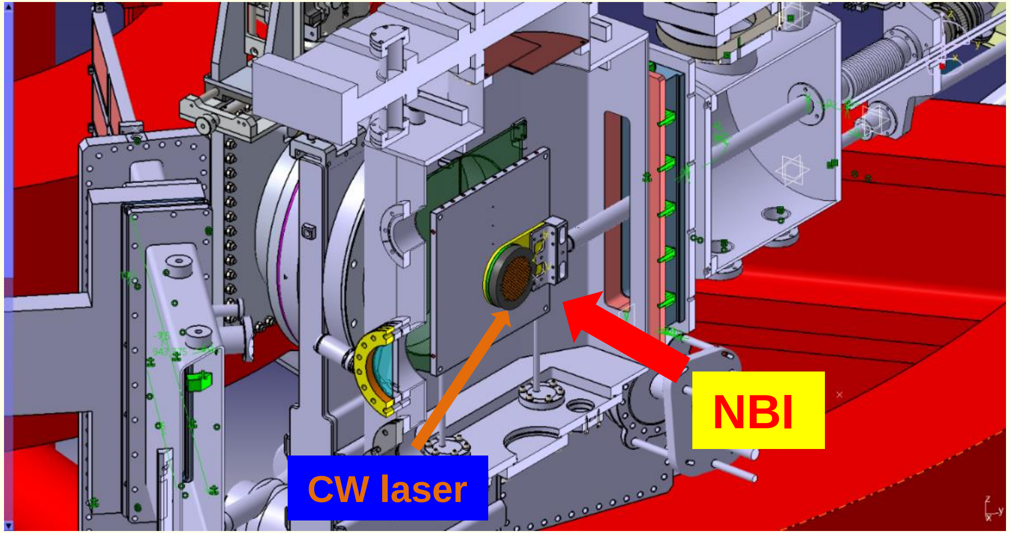
- Better protection of valves and experimental time increased.
- Place a large (280x280 mm) sample holder.



UPGRADES: beam dump

Install actively-cooled copper beam dump.

- Better protection of valves and experimental time increased.
- Place a large (280x280 mm) sample holder.
- Fabrication of copper plate failed (water leaks), so delay until autumn 2023



INDEX

OLMAT
2021-2 REPORT
2023 PLAN
SUMMARY

OLMAT

1.- Introduction
2.- CW laser
3.- Beam dump

2021-2 REPORT

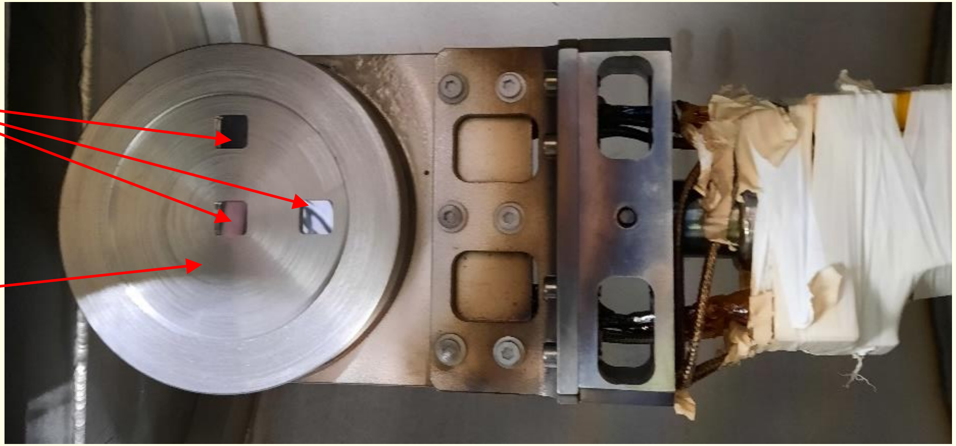
1.- ITER-like W
2.- WfW

2023 PLANNING

1.- Disruption-like pulses (cracking at WEST)
2.- Large holder: testing >50 samples

SUMMARY

ITER-like W samples at 600-700 ºC with ΔT = 200-350 ºC:

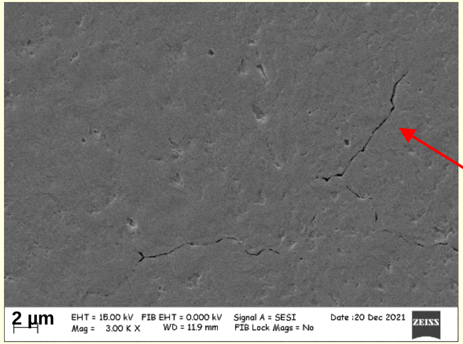


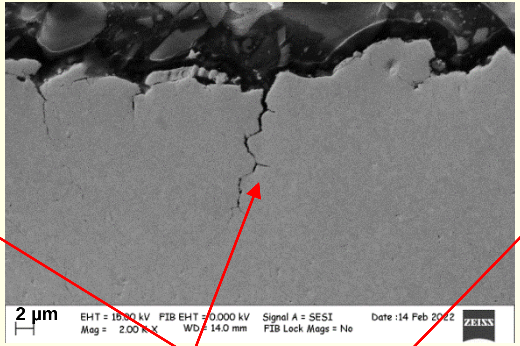
12x12x5 mm, polished, ITER-like W samples provided by FZJ

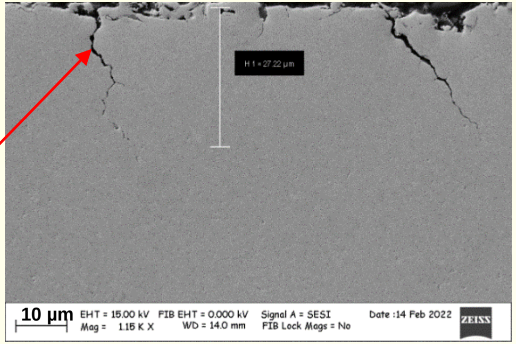
[4] M. Wirtz, et al, Nucl Mat. Ener. **12** (2017) 148

ITER-like W samples at 600-700 ºC with ΔT = 200-350 ºC:

- **641 pulses of 15±5 MW/m^2 every 45s: F_{HF} = 4.7±1.6 MW/m^{2}s$^{0.5}$**
- **Particle flux 0.62 ·10^{22} m^{-2}s^{-1}.** OLMAT range: 0.28-1.45 ·10^{22} m^{-2}s^{-1}







Small cracks

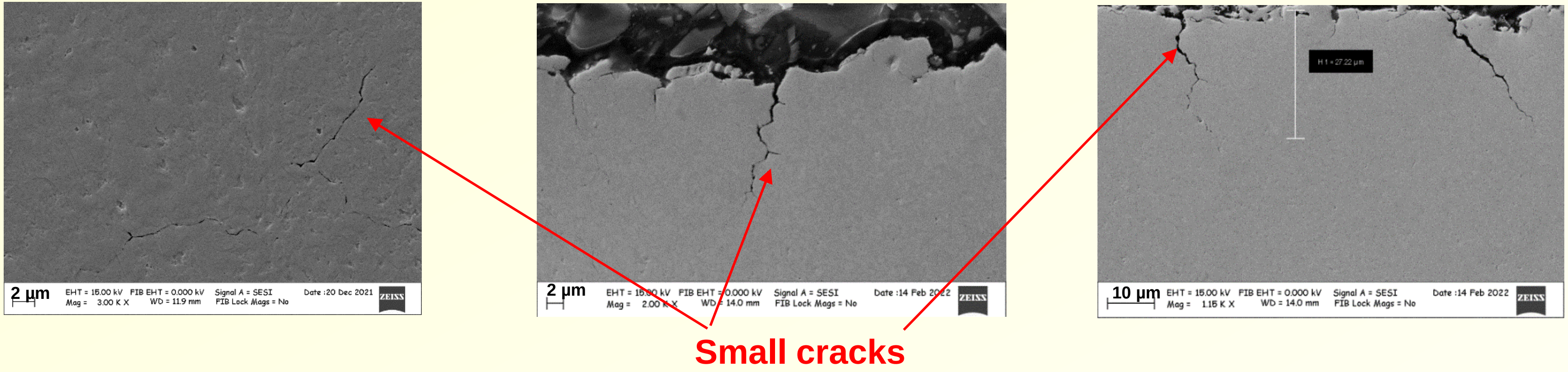
Damage has only been found at F_{HF} =4.7 MW/m^{2}s$^{0.5}$ (tested F_{HF} = 1.8-4)

[4] M. Wirtz, et al, Nucl Mat. Ener. **12** (2017) 148

REPORT: ITER-like W

ITER-like W samples at 600-700 ºC with ΔT = 200-350 ºC:

- 641 pulses of 15±5 MW/m^2 every 45s: F_{HF} = 4.7±1.6 MW/m^{2}s$^{0.5}$
- Particle flux 0.62 ·10^{22} m^{-2}s^{-1}. OLMAT range: 0.28-1.45 ·10^{22} m^{-2}s^{-1}



Damage has only been found at F_{HF} =4.7 MW/m^{2}s$^{0.5}$ (tested F_{HF} = 1.8-4)

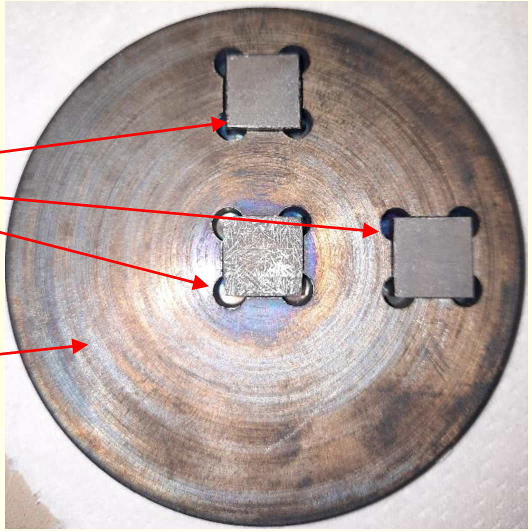
- No measurable erosion (<1 mg)
- Intergranular cracking of up to 20-30 µm deep.
- Relatively small number of pulses. But results from JUDITH2 reproduced [4]!

[4] M. Wirtz, et al, Nucl Mat. Ener. **12** (2017) 148

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

[5] Y. Mao et al., Nucl. Fusion. **62** (2022) 106029.

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:



12x12x4 mm, <u>rough</u>, PoMa- WfW samples provided by FZJ [5]. 85% por., 150 μm, 2-3 mm long fibers

<u>Samples should have been polished, but no warning due to bad luck.</u>

[5] Y. Mao et al., Nucl. Fusion. **62** (2022) 106029.

REPORT: WfW

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

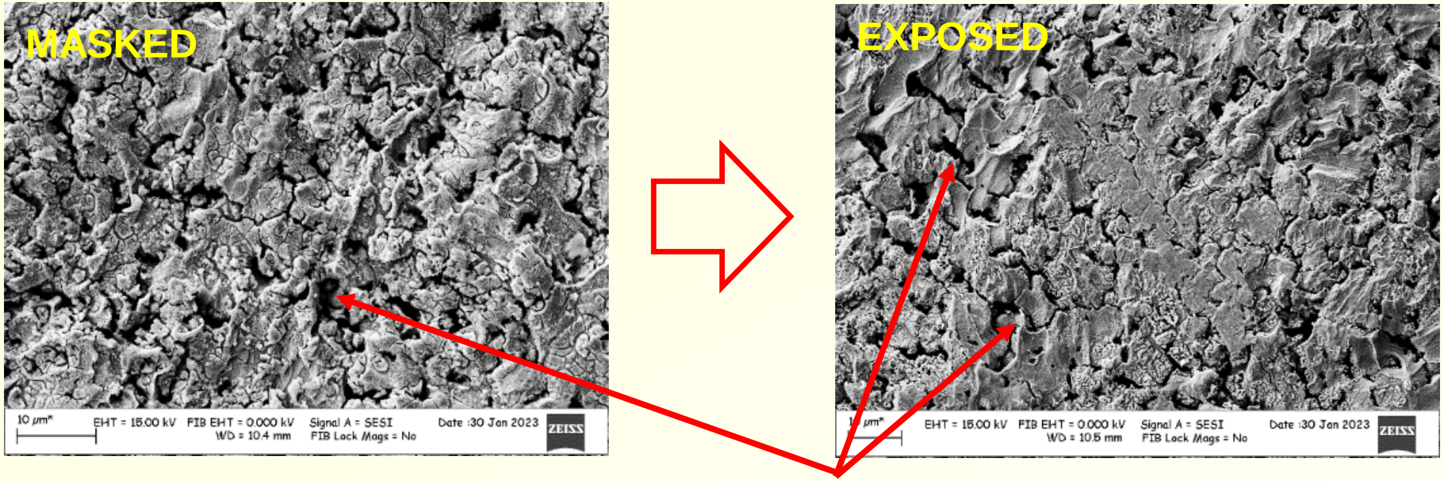
- **934 pulses of 12-15±5 MW/m^2 every 45s: F_{HF} = 3.8-4.7±1.6 $MW/m^2s^{0.5}$**
- **Particle flux 0.62 $\cdot 10^{22}$ $m^{-2}s^{-1}$.** OLMAT range: 0.28-1.45 $\cdot 10^{22}$ $m^{-2}s^{-1}$

OLMAT
2021-2 REPORT
2023 PLAN
SUMMARY

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

- 934 pulses of 12-15±5 MW/m^2 every 45s: F_{HF} = 3.8-4.7±1.6 MW/m^{2}s$^{0.5}$
- **Particle flux 0.62 ·10^{22} m^{-2}s^{-1}.** OLMAT range: 0.28-1.45 ·10^{22} m^{-2}s^{-1}

Complex analysis due to so a high roughness (tens µm)



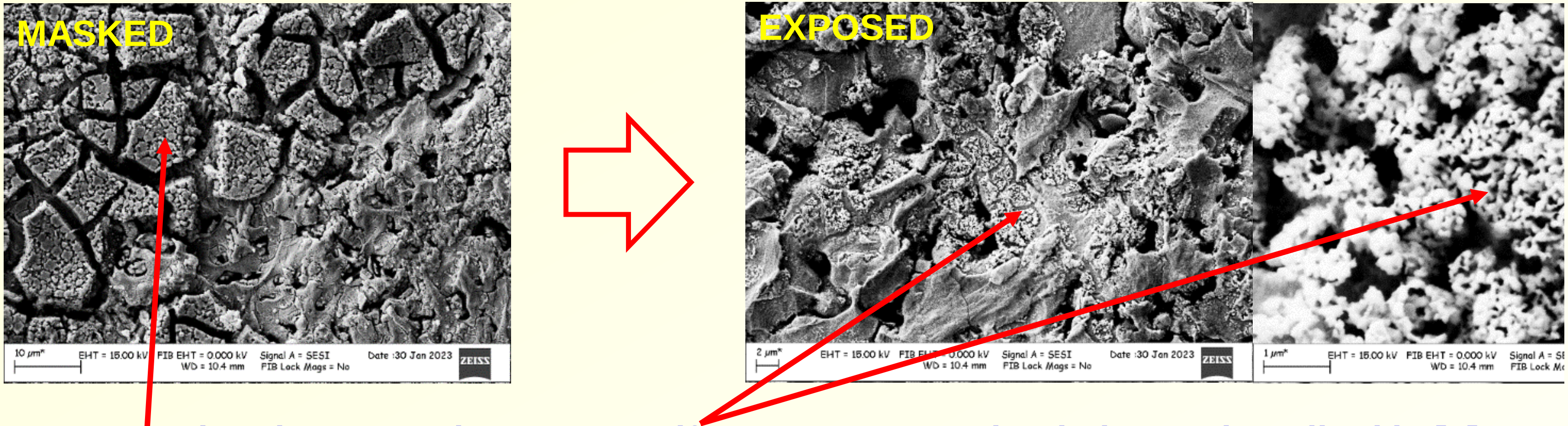
Rough surface with flat and granulated grains. Pores and gaps between grains are evident

REPORT: WfW

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

- **934 pulses of 12-15±5 MW/m² every 45s: F_{HF} = 3.8-4.7±1.6 MW/m²s$^{0.5}$**
- **Particle flux 0.62 ·10^{22} m^{-2}s^{-1}.** OLMAT range: 0.28-1.45 ·10^{22} m^{-2}s^{-1}

Complex analysis due to so a high roughness (tens µm)



Granulated grains caused a large cauliflower-type growth. Similar to described in [5].

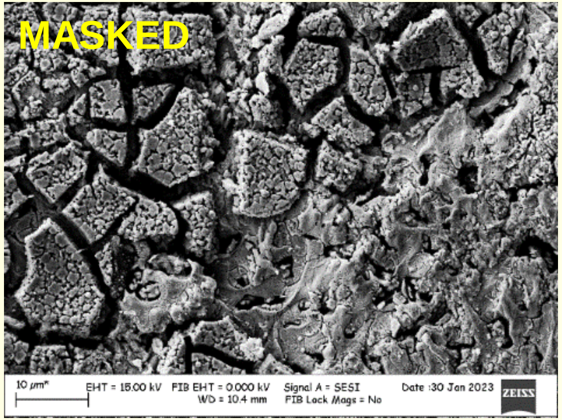
[5] Y. Mao et al., Nucl. Fusion. **62** (2022) 106029.

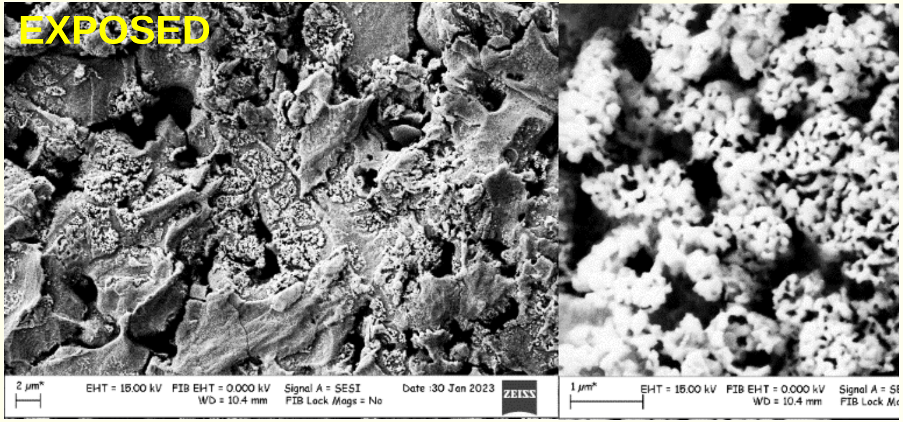
REPORT: WfW

PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

- **934 pulses of 12-15±5 MW/m^2 every 45s: F_{HF} = 3.8-4.7±1.6 MW/m^{2}s$^{0.5}$**
- **Particle flux 0.62 ·10^{22} m^{-2}s^{-1}.** OLMAT range: 0.28-1.45 ·10^{22} m^{-2}s^{-1}

Complex analysis due to so a high roughness (tens µm)





Some erosion, but likely due to loose grains (10-20 mg). No evident particle emission observed by fast camera. **This is due to not being polished, as in [5] less erosion than ITER-like W.** But this is an issue for a real reactor, need to polish all WfW surface?

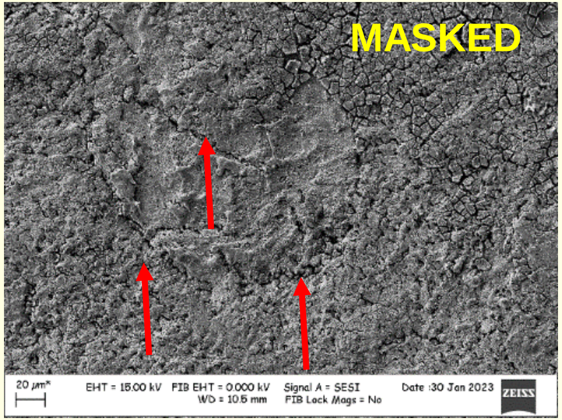
[5] Y. Mao et al., Nucl. Fusion. **62** (2022) 106029.

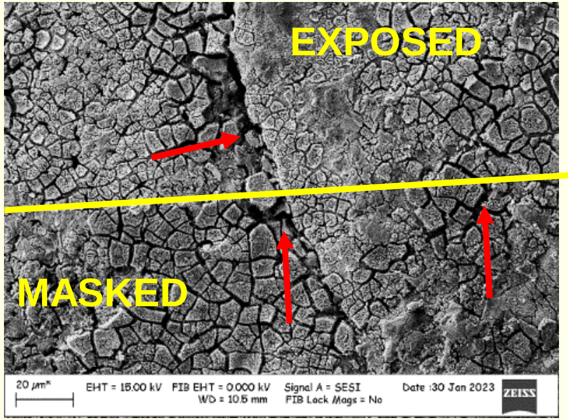
REPORT: WfW

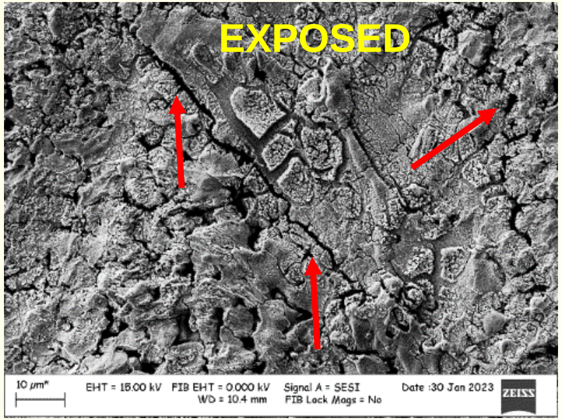
PoMa- WfW samples at 600-700 ºC with ΔT = 200-350 ºC:

- **934 pulses of 12-15±5 MW/m² every 45s: F_{HF} = 3.8-4.7±1.6 MW/m²s$^{0.5}$**
- **Particle flux 0.62 ·10²² m⁻²s⁻¹.** OLMAT range: 0.28-1.45 ·10²² m⁻²s⁻¹

Complex analysis due to so a high roughness (tens μm)







Some cracks appear but difficult to confirm, as they are also in masked part. Fabrication?

Appears more resilient than ITER-like W. Repeat at higher pulses and polished samples.

INDEX

OLMAT

1.- Introduction
2.- CW laser
3.- Beam dump

2021-2 REPORT

1.- ITER-like W
2.- WfW

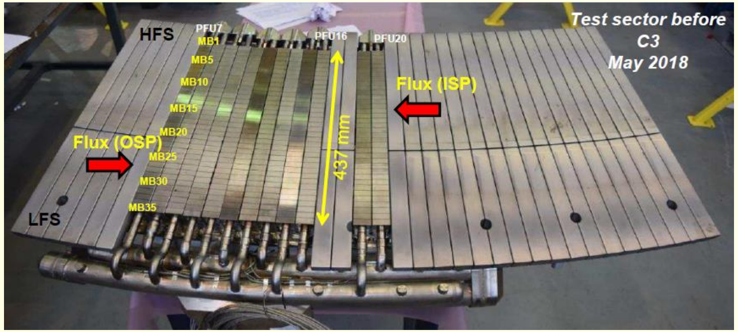
2023 PLANNING

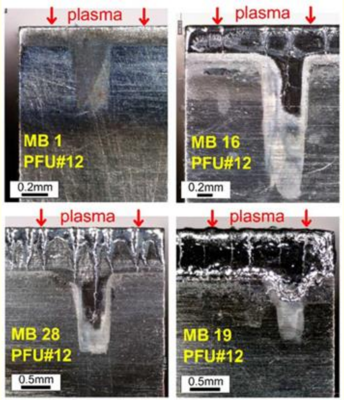
1.- Disruption-like pulses (cracking at WEST)
2.- Large holder: testing >50 samples

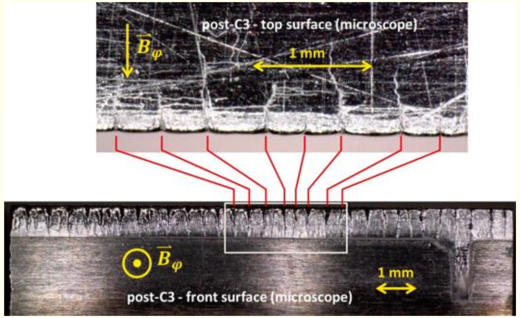
SUMMARY

WEST ITER-like tiles, actively cooled [6]:

- Cracking and melting of exposed surfaces over full poloidal extent of divertor, even on areas with no steady state heat flux.





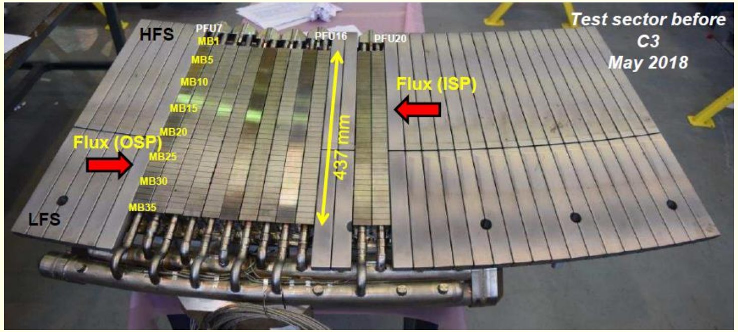


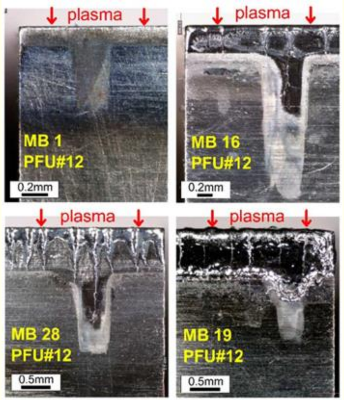
[6] J.P. Gunn et al., *Nucl. Mat. Ener* **27** (2021) 100920

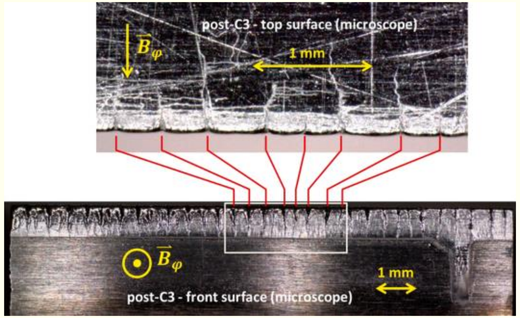
DISRUPTION CRACKING AT WEST

WEST ITER-like tiles, actively cooled [6]:

- Cracking and melting of exposed surfaces over full poloidal extent of divertor, even on areas with no steady state heat flux.
- **Brittle cracking or ductile failure of W due to disruptions of 600 MW/m^2 [7]:**
  - Just one-two disruptions are enough to cracking and prompt failure.
  - But if previously steady state heat load (45 MW/m^2) almost no damage: **more realistic**
- **Consistent with cracking threshold determined in JUDITH2 [4] F_{HF} = 6 MW/m^{2}s$^{0.5}$**







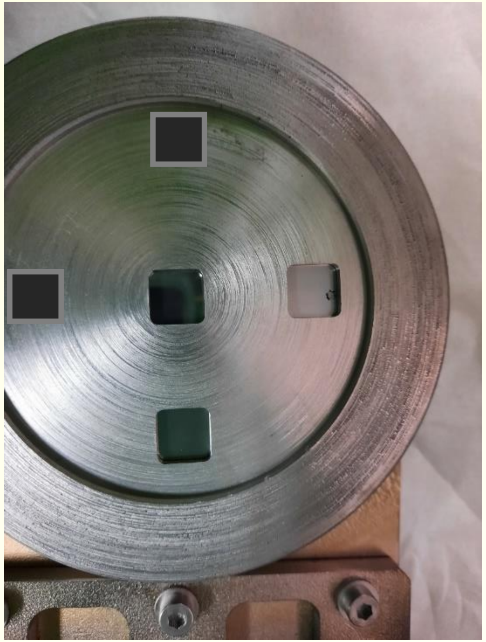
[4] M. Wirtz, et al, Nucl Mat. Ener. **12** (2017) 148
[6] J.P. Gunn et al., *Nucl. Mat. Ener* **27** (2021) 100920
[7] A. Durif, et al., Phys. Scr. 97 (2022) 074004.

EXPERIMENTS: laser

Laboratorio Nacional de Fusión Ciemat

Test WEST disruptions conditions with our CW laser [6-7] in March

- Laser irradiation at edges and at 52 deg.
- Power 600 MW/m^2 for 2 ms (in DEMO 10-110 GW/m^2 1-4 ms)

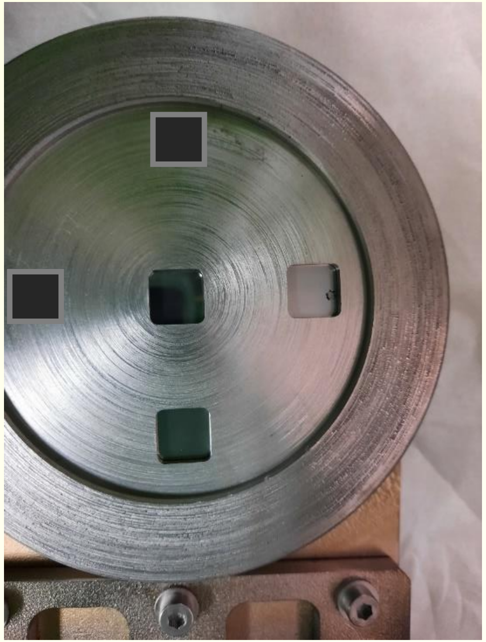


[6] J.P. Gunn et al., *Nucl. Mat. Ener* **27** (2021) 100920
[7] A. Durif, et al., Phys. Scr. 97 (2022) 074004.

EXPERIMENTS: laser

Test WEST disruptions conditions with our CW laser [6-7] in March

- Laser irradiation at edges and at 52 deg.
- Power 600 MW/m^2 for 2 ms (in DEMO 10-110 GW/m^2 1-4 ms)
- **Make use of laser flexibility: look for damage threshold**
  - Just 1-2 pulses should cause cracking [6-7]. Test 1, 2, 4, 10...
  - Cracking threshold at different powers: 150, 300, 1000 MW/m^2
  - Same but with 45 MW/m^2 in continuous just before disruption.
  - Heat up samples at 600 ºC: > DBTT

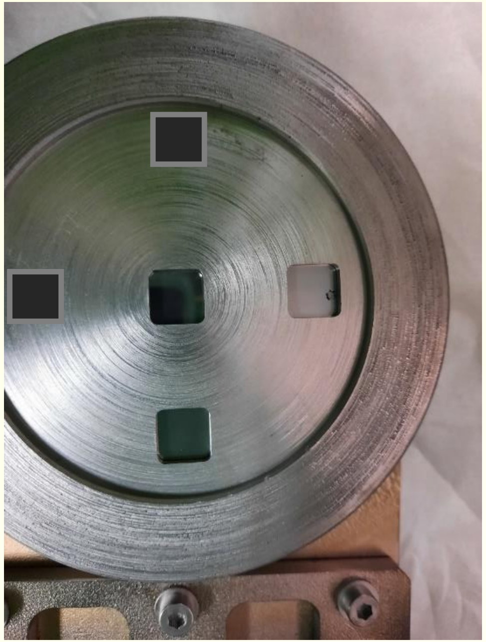


[6] J.P. Gunn et al., *Nucl. Mat. Ener* **27** (2021) 100920
[7] A. Durif, et al., Phys. Scr. 97 (2022) 074004.

EXPERIMENTS: laser

Test WEST disruptions conditions with our CW laser [6-7] in March

- Laser irradiation at edges and at 52 deg.
- Power 600 MW/m^2 for 2 ms (in DEMO 10-110 GW/m^2 1-4 ms)
- Make use of laser flexibility: look for damage threshold
  - Just 1-2 pulses should cause cracking [6-7]. Test 1, 2, 4, 10...
  - Cracking threshold at different powers: 150, 300, 1000 MW/m^2
  - Same but with 45 MW/m^2 in continuous just before disruption.
  - Heat up samples at 600 ºC: > DBTT
- Mainly ITER-like W, but also PoMa-WfW



[6] J.P. Gunn et al., *Nucl. Mat. Ener* **27** (2021) 100920
[7] A. Durif, et al., Phys. Scr. 97 (2022) 074004.

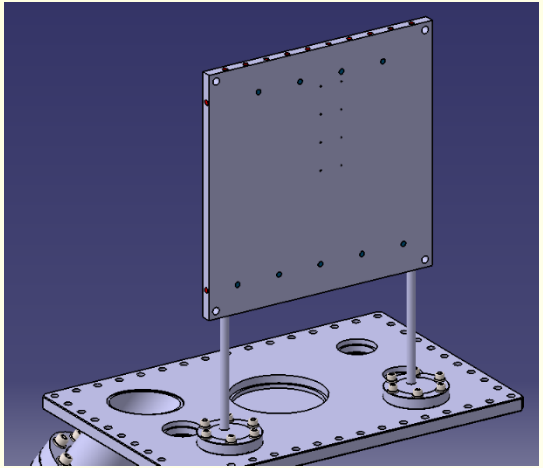
EXPERIMENTS: large holder

At beam dump: different materials at a power density distribution: late 2023

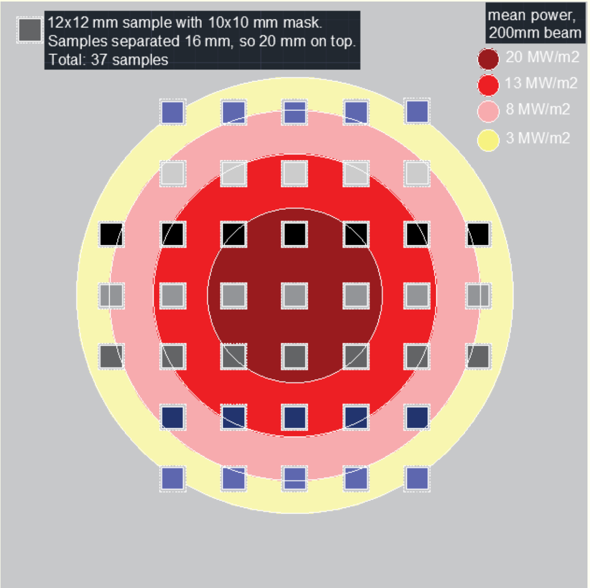
EXPERIMENTS: large holder

At beam dump: different materials at a power density distribution: late 2023

- **Use the whole OLMAT beam (20 cm) to have a <u>power distribution</u>** (here just an idea)
- **Changed daily to have a <u>distribution of number of pulses</u>: 1000, 2000, 5000, etc.**



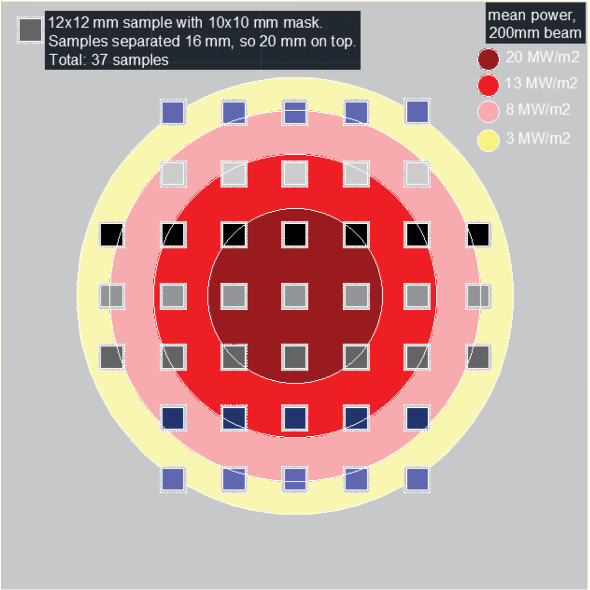
280x280 mm TZM mask



EXPERIMENTS: large holder

At beam dump: different materials at a power density distribution: late 2023

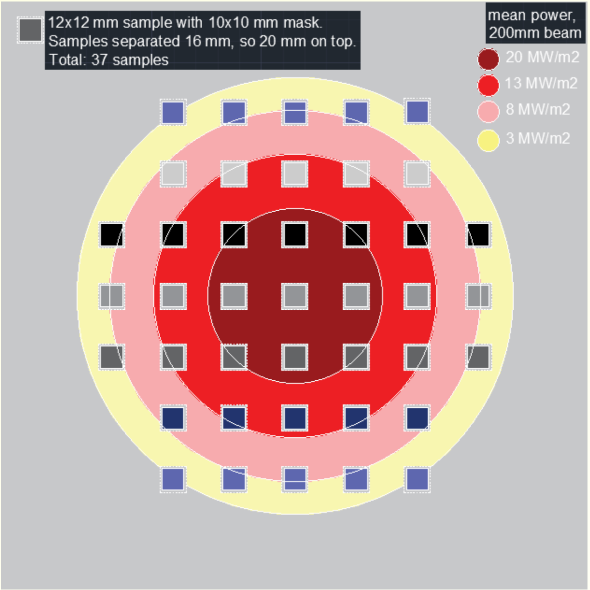
- **Different samples irradiated at the same time *to compare its fatigue resilience*. Represented by colors in the picture:**
  - **Yet to be defined** the total number of samples



EXPERIMENTS: large holder

At beam dump: different materials at a power density distribution: late 2023

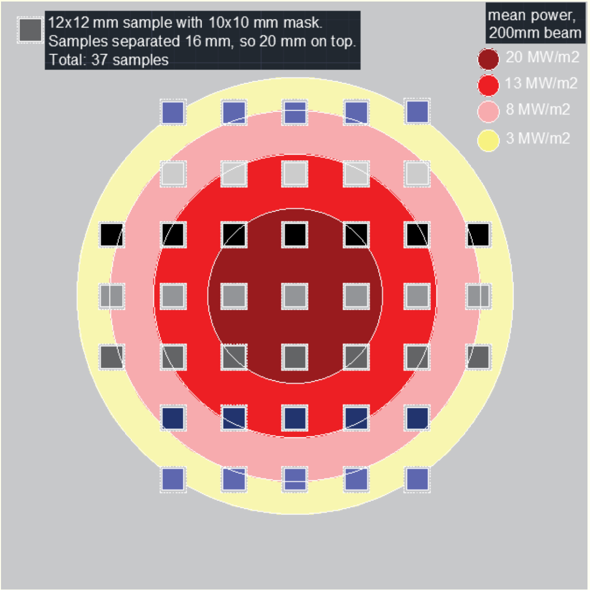
- Different samples irradiated at the same time *to compare its fatigue resilience*. Represented by colors in the picture:
  - **Yet to be defined** the total number of samples
  - **High power, Divertor:** ITER-like W, WfW.
  - **Low power, main wall:** SMART-W+Zr, Eurofer.



EXPERIMENTS: large holder

At beam dump: different materials at a power density distribution: late 2023

- **Different samples irradiated at the same time *to compare its fatigue resilience*. Represented by colors in the picture:**
  - **Yet to be defined** the total number of samples.
  - **High power, Divertor:** ITER-like W, WfW.
  - **Low power, main wall:** SMART-W+Zr, Eurofer.
- **One sample may be irradiated by the CW laser:**
  - Pulsed: to simulate transients (0.5-10 GW/m^2)
  - Heated continuously to T > DBTT to avoid brittle fatigue.



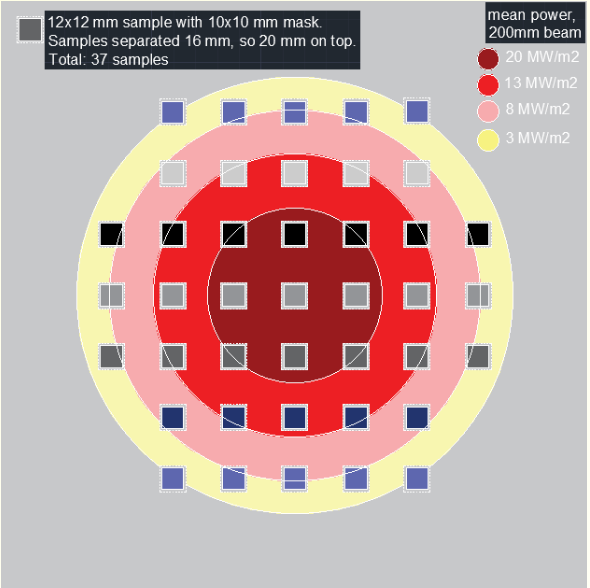
EXPERIMENTS: large holder

Laboratorio Nacional de Fusión Ciemat

OLMAT | 2021-2 REPORT | **2023 PLAN** | SUMMARY

At beam dump: different materials at a power density distribution: late 2023

- **Different samples irradiated at the same time *to compare its fatigue resilience*. Represented by colors in the picture:**
  - **Yet to be defined** the total number of samples
  - **High power, Divertor:** ITER-like W, WfW.
  - **Low power, main wall:** SMART-W+Zr, Eurofer.
- **One sample may be irradiated by the CW laser:**
  - Pulsed: to simulate transients (0.5-10 GW/m^2)
  - Heated continuously to T > DBTT to avoid brittle fatigue.
- **Future:** W nanostructured, composites, variety of 3D-print structures (collaboration with private company), etc.
- **Open to more collaborators**



INDEX

OLMAT

1.- Introduction

2.- CW laser

3.- Beam dump

2021-2 REPORT

1.- ITER-like W

2.- WfW

2023 PLANNING

1.- Disruption-like pulses (cracking at WEST)

2.- Large holder: testing >50 samples

SUMMARY

SUMMARY

- Initial experiments of OLMAT gives interesting results.
- PoMa-WfW seems to be more resilient against fatigue cracking than ITER-like W. But we need to polish and repeat experiments.

2023 plans (6 days)

- Use the new, flexible CW laser to study disruptions on edges like in WEST. ~3 operation days in March.
- Install actively-cooled beam dump in summer.
- Better characterize OLMAT beam power distribution (need cooling).
- Large sample holder to compare different materials at different powers and number of pulses. ~3 operation days in late 2023

RESERVE SLIDES

CW laser for OLMAT: characteristics

Laboratorio Nacional de Fusión Ciemat

PREVIOUS | UPGRADES | EXPERIMENTS | SUMMARY

- **Power: 930 W continuous; 9300 W pulsed.**
- **Pulses: 0.2-10 ms; 90J energy; 10-2000 Hz**

1. Optical characteristics

N	Characteristics	Test conditions	Symbol	Min.	Typ.	Max.	Unit
1	Operation Mode			CW / pulsed			
2	Polarization			Random			
3	CW Nominal Power		P_{nom}	900			W
4	Pulsed Nominal Power			9000			W
5	Pulse duration			0.2		10	msec
6	Pulse energy	Duty cycle 10 %, PRR = 10 Hz, Maximum power		90			J
7	Duty Cycle*	Pulsed mode				50*	%
8	Output Power Tuning Range	Pulsed mode		10		105	%
9	Emission Wavelength	Output power: 900 W	λ		1070		nm
10	Emission Linewidth	Output power: 900 W	$\Delta\lambda$		3	6	nm
11	Switching ON/OFF Time	Output power: 900 W			100	150	µs
12	Maximum Modulation Frequency	CW & Pulsed modes Output power: 900 W		2000			Hz
13	Output Power Instability	Output power: 900 W Time interval: 8 hrs (T=Constant)			±1	±2	%
14	Red Guide Laser Power				0.4	0.5	mW

**Maximum duty cycle limit is inversely proportional to peak power: 10% for 9000W, 15% for 6000 W,........, 50% for 1800W and lower*