PWIE annual meeting, March 24-27, 2025

Plans for the Work Package Tokamak Exploitation in 2025 and links with WP PWIE

E. Tsitrone for WP TE TFL

E. Tsitrone, N. Vianello, M. Baruzzo, A. Hakola, V. Igochine, D. Keeling, B. Labit

With many thanks to RT06 RTC : Y. Corre, K. Krieger, A. Widdowson and RT06 team

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Outline

- How does WP TE work ?
- Recent selected highlights
- Plans for 2025
- Summary and prospects for 26-27

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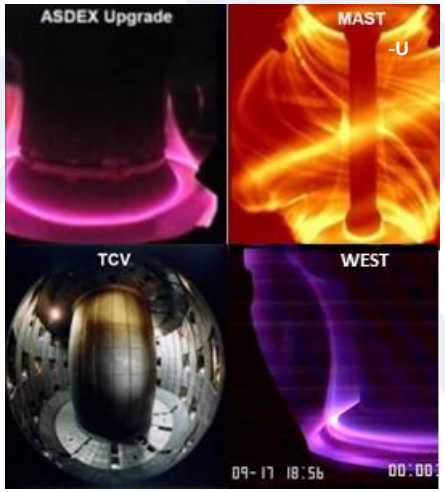
WP TE : coordinating the programme of EU tokamaks

Overarching goals of WP TE :

- Prepare ITER operation
- Provide physics basis for guiding DEMO design

  while building a pan European team for the scientific exploitation of fusion devices

(cross-device program with > 600 participants from > 20 labs ➔ EU contribution to JT-60SA, ITER)

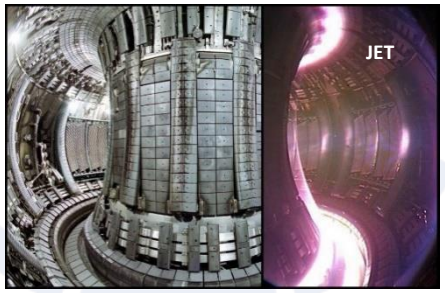


WP TE addresses primarily the following missions of the EUROfusion roadmap:

- Mission 1 (Plasma Regimes of Operation)
- Mission 2 (Heat exhaust System)

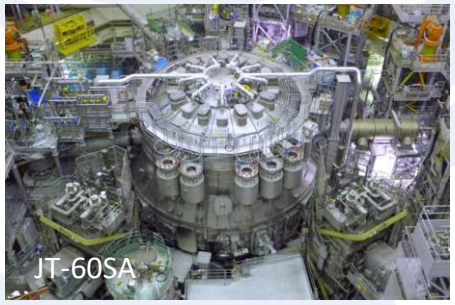
WP TE coordinates the scientific programme of complementary EU tokamaks :

- Running the TE share of experimental time on AUG, MAST-U, TCV and WEST
- Analysing data from past JET campaigns
- Preparing the scientific exploitation of JT-60SA (since 2024)

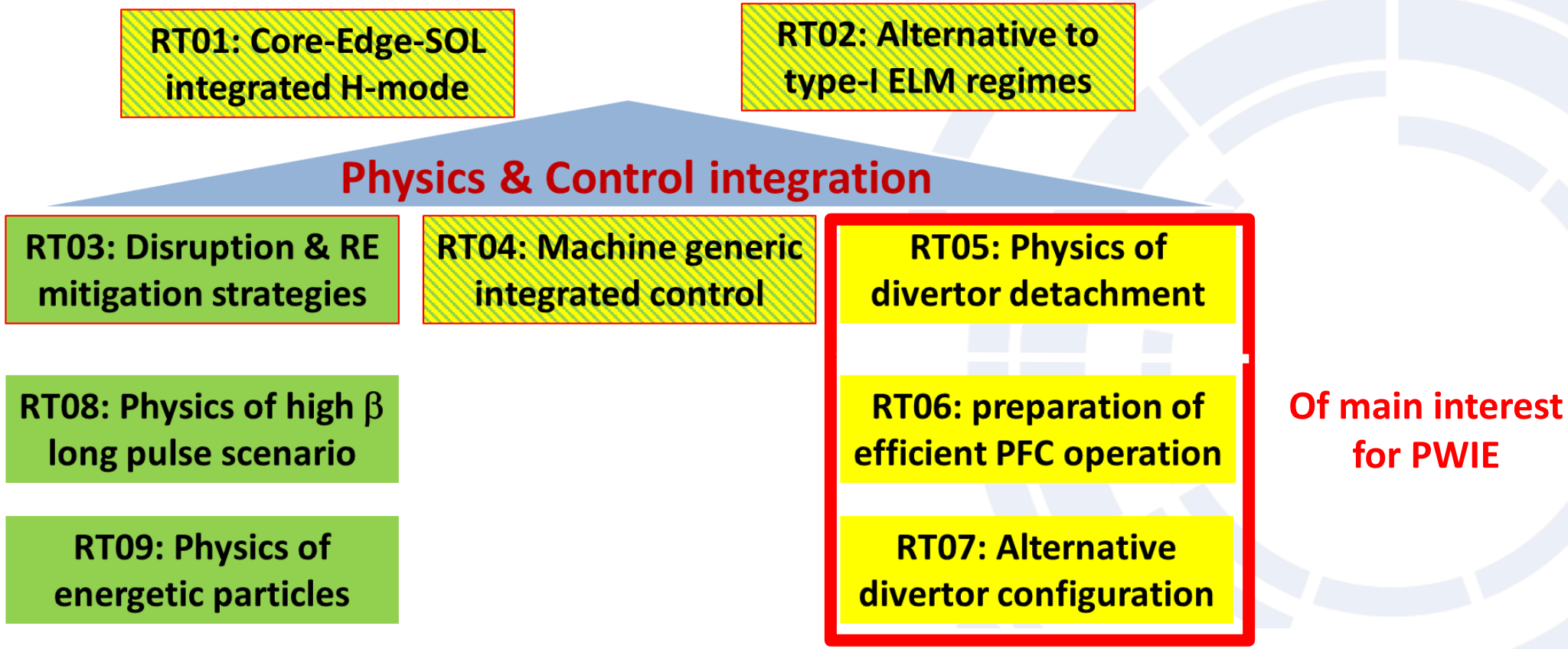


WP TE also involved in :

- International collaboration (US : no ELM scenarios, KSTAR, EAST)
- Support to TE devices enhancements
- AI projects



WP TE is organized in 9 programmatic Research Topics



JET RT :

RT10 : JET data validation

RT11 : experiments run before 2023

Mission 1 | Mission 2

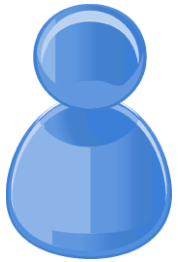
JT-60SA RT :

RT12 to RT18, reflecting the structure of the EU-JA Experimental Team (RT17 : Divertor, Scrape Off Layer and Plasma-Material Interaction)

WP TE is run by a collegium of Task Force Leaders …

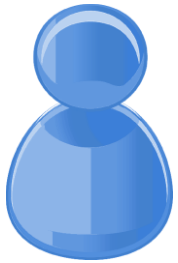
E. Tsitrone / CEA
TFL

N. Vianello / ENEA
TFL



M. Baruzzo/ ENEA
DTFL

A. Hakola / VTT
DTFL



V. Igochine / MPG
DTFL

D. Keeling / CCFE
DTFL

B. Labit / EPFL
DTFL

J. Garcia / CEA
DTFL – JT-60SA ETL

… and a large team of Research Topic coordinators

Research Topics	Research Topic Coordinators	Ref TFLs
RT-01: Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER	Carine Giroud, Lorenzo Frassinetti, Sven Wiesen, Damian King	Nicola Vianello, Benoît Labit
RT-02: Physics understanding of alternatives to Type-I ELM regime	Mike Dunne, Michael Faitsch, Olivier Sauter and Eleonora Viezzer	Benoît Labit, David Keeling
RT-03: Strategies for disruption and run-away mitigation	Ondrej Ficker, Cedric Reux, Umar Sheikh	**Valentin Igochine**, Antti Hakola
RT-04: Physics-based machine generic systems for an integrated control of plasma discharge	Adriano Mele, Lidia Piron, Charles Vincent	Matteo Baruzzo, **Valentin Igochine**
RT-05: Physics of divertor detachment and its control for ITER, DEMO and HELIAS operation	Matthias Bernert, Holger Reimerdes, Nicolas Fedorczak, Stuart Henderson	Nicola Vianello, Emmanuelle Tsitrone
RT-06: Preparation of efficient Plasma Facing Components (PFC) operation for ITER, DEMO and HELIAS	Yann Corre, Karl Krieger, Anna Widdowson	Emmanuelle Tsitrone, Antti Hakola
RT-07: Physics understanding of alternative divertor configurations as risk mitigation for DEMO	Dominik Brida, Christian Theiler, Kevin Verhaegh	Antti Hakola, **Benoît Labit**
RT-08: Physics and operational basis for high beta long pulse scenarios	Fulvio Auriemma, Alexander Bock, Chiara Piron	Matteo Baruzzo, **Valentin Igochine**
RT-09: Physics understanding of energetics particles confinement and their interplay with thermal plasma	Yevgen Kazakov, Joaquin Galdon, Anton Jansen van Vuuren, Roman Ochoukov	David Keeling, Matteo Baruzzo
RT-11:Analysis and modelling of DTE2 related experiment on JET		David Keeling, Matteo Baruzzo

Contact TFL for PWIE : E. Tsitrone, A. Hakola

RT06 RTC : Y. Corre, K. Krieger, A. Widdowson

For more information : check the WP TE wiki
https://wiki.euro-fusion.org/wiki/WPTE_wikipages:_Tokamak_Exploitation_Work_Package

Building the WP TE programme : yearly cycle of calls

Year n

Call for experimental proposals for year n+1

- Review meeting : mid year status of progress (RTC)
- Call for experimental proposals : early fall (TFL)
- General Planning Meeting : priority for proposals received and shot allocation within % of experimental time allocated to WP TE on each device as defined by EUROfusion GA (TFL)

Call for participation for year n+1

- Call for participation (TFL) : late fall
- Staffing selection before Xmas (TFL)

Year n+1

Experimental Campaign year n+1

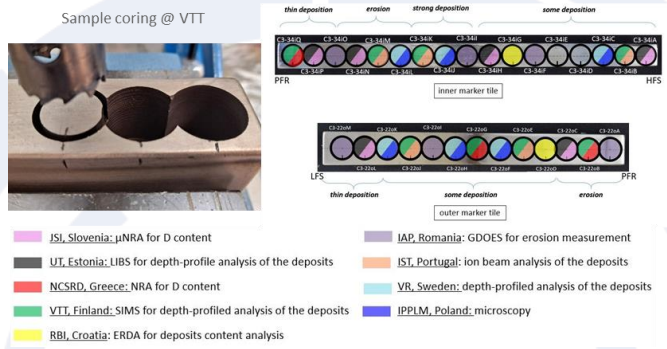
- Strategy meeting : early year (RTC)

Strong links between WP TE and WP PWIE

Post mortem analysis of components exposed in tokamaks (SPA, SPB, SPC)

- Key for understanding material migration / fuel retention and recovery / PFC ageing in tokamaks …
- WP TE (RT06) : components exposure / dedicated experiments in tokamaks
- WP PWIE : pre/post exposure components analysis, in particular from metallic machines AUG, JET, WEST (SPB, SPE) + comparison with experiments in linear devices/HHF facilities (SPA)

Plan for WEST samples analysis (SPB)



PWI modelling (SPD)

- WP TE (RT06, RT05, RT07 …) : dedicated PWI or plasma exhaust experiments, associated plasma background modelling (SOLEDGE, SOLPS, PIC modelling …)
- WP PWIE (SPD) : PWI modelling (ERO2.0, MEMOS-U, WallDYN …) using WP TE plasma background

NB : has to be adjusted at best, given available resources in TE/PWIE

Specific topics of common interest (SPX, SPF)

- Alternative Divertor Configurations (ADC) in the past (now RT07)
- Laser based diagnostics at JET : LID-QMS under TE, LIBS under PWIE
- Topics for ITER new baseline : boronisation (WP TE metallic fusion devices versus WP PWIE test devices)

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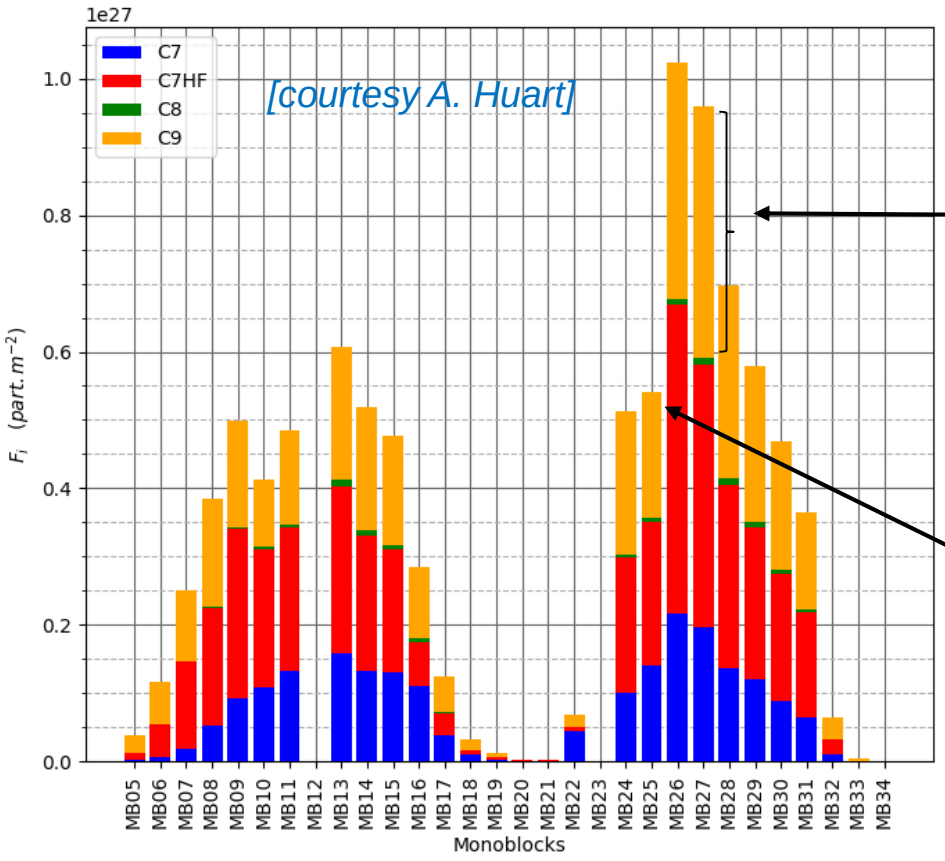
Not shown today :

- RT05 : XPR demonstrated in all TE devices (incl JET), work on impurity mix (N_2 ➔ Ne, Ar), reduced model for divertor re-attachment
- RT07 : continuation of exploration of ADC (MAST-U, TCV) showing continuum from SN to ADC, DN in WEST, AUG new upper divertor from 2025
- RT01/RT02 : modelling of the wall sources (JET high current seeded scenario ➔ ITER baseline)

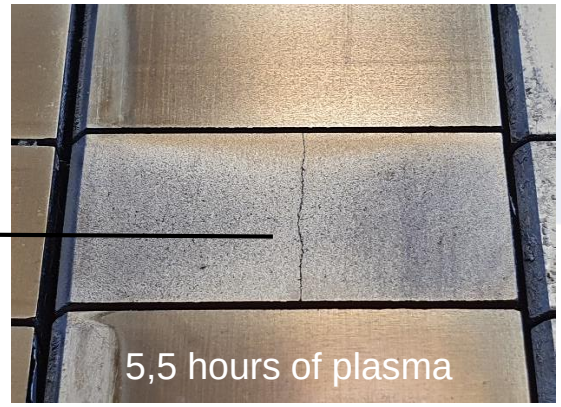
Exposure of pre damaged components (WEST)

Damage evolution under tokamak conditions (combined heat/particle loads, disruptions, etc …) ➔ ITER divertor lifetime and failure mechanisms

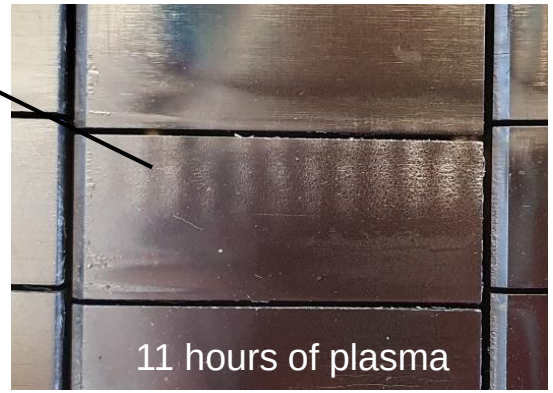
WEST cumulated fluence on each monoblock



Pre-dam#3 (C8-C9)



Pre-dam#2 (C7-C9)



- **Components pre-damaged at JUDITH**
  - Pre-dam#2 : crack network (transients)
  - Pre-dam#3 : macro cracks (steady state > 20 mW/m²)

JÜLICH FORSCHUNGSZENTRUM

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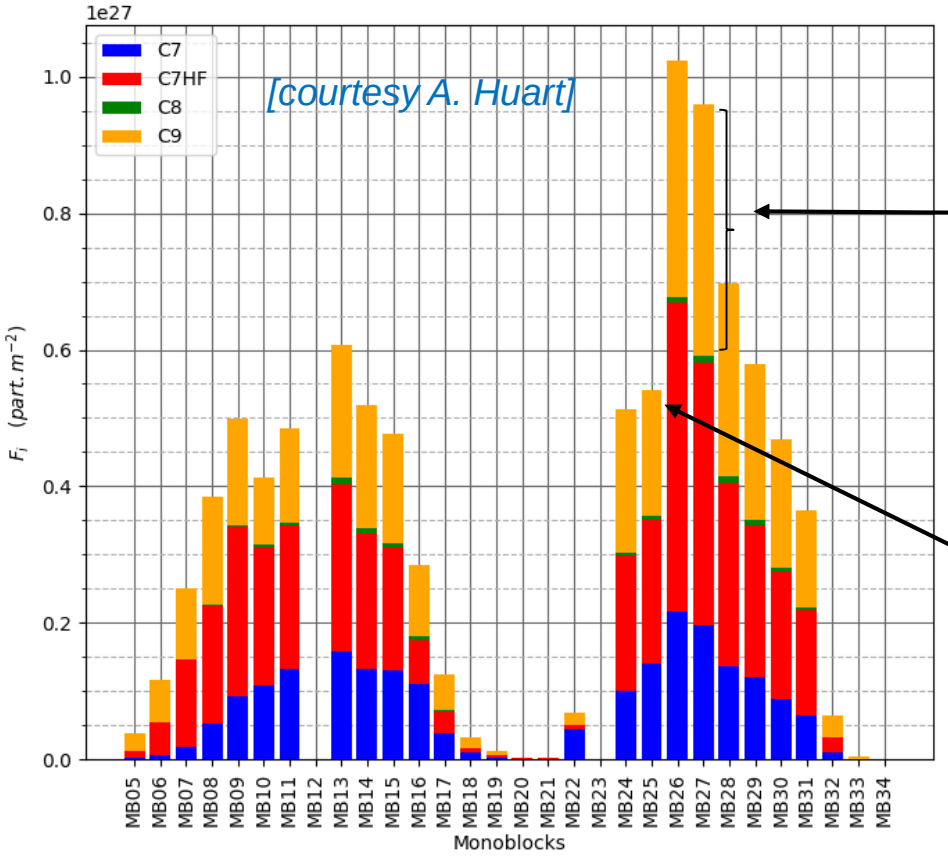

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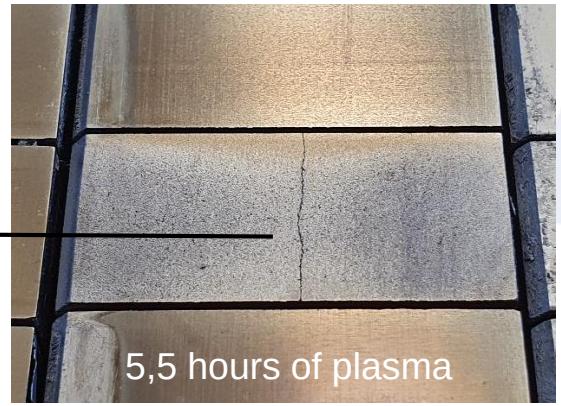

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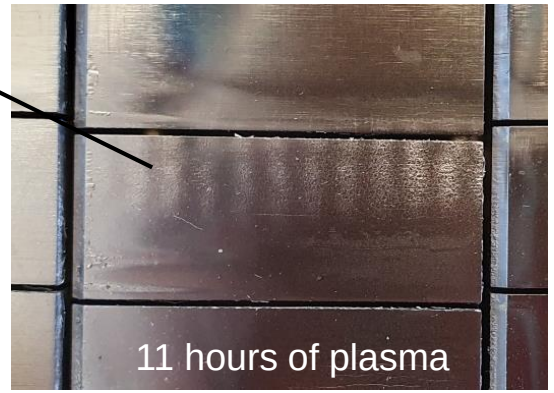
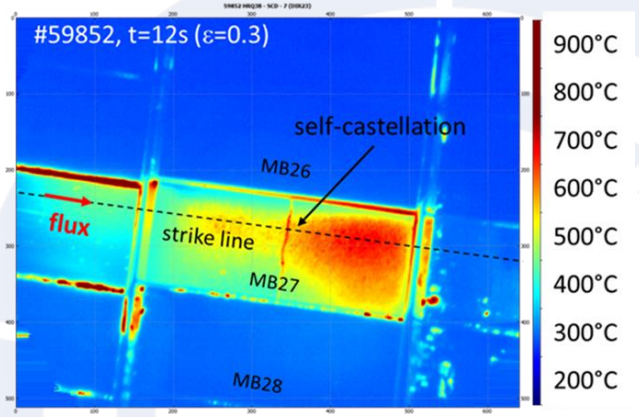




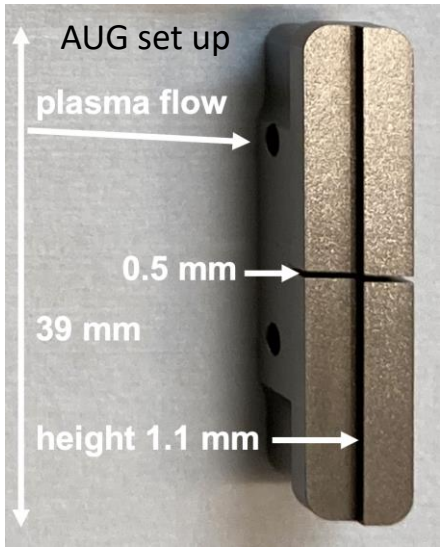
VHR IR data (0.1mm/pixel)

- **Exposure to hours of plasma in WEST**
  - > 1000 pulses, high fluence (~ ITER PFPO), max heat load 11 MW/m²
  - No degradation of heat exhaust capability
  - Components still in WEST for further exposure

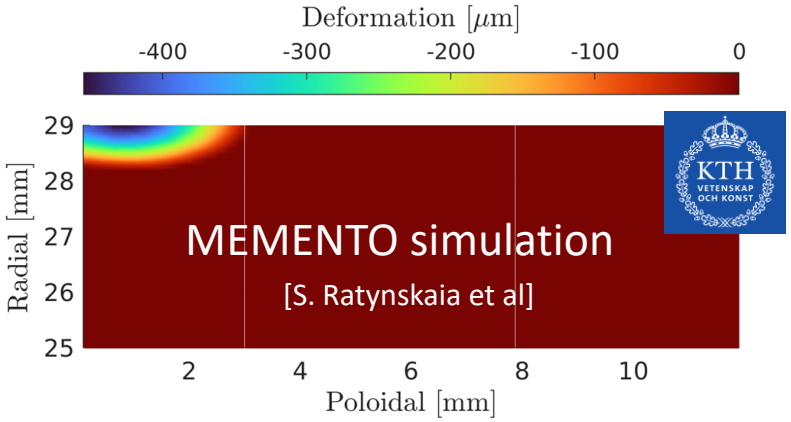
➔ Comparison of W monoblocks behavior in HHF facilities versus tokamak

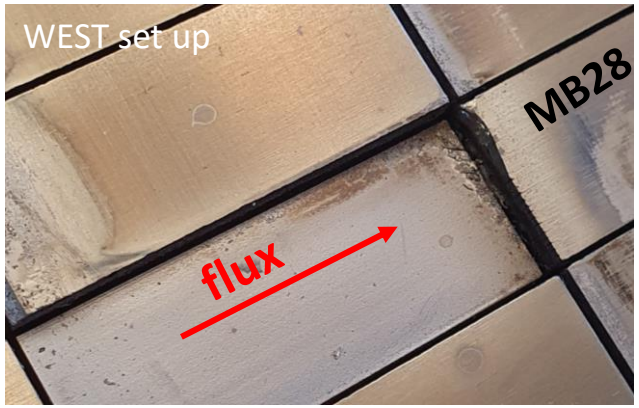
W melting experiments (AUG/WEST)

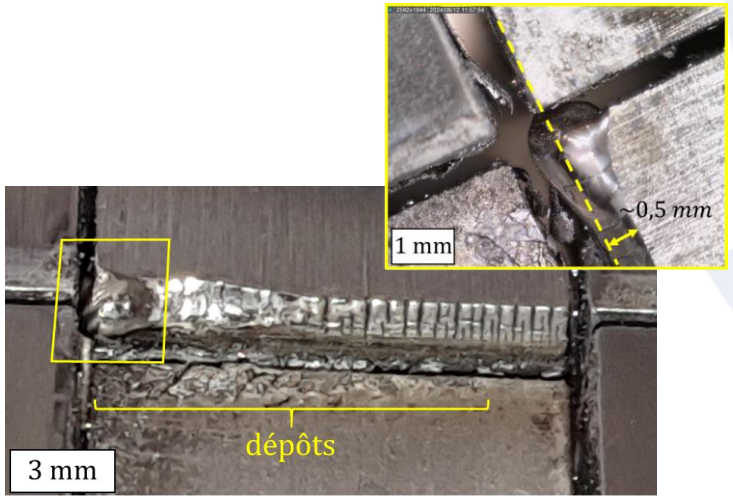
Gap bridging or infiltrating between monoblocks under steady state W melting (impact of currents flowing in subsequent disruptions ?) + validation of codes used to predict melt layer motion in ITER



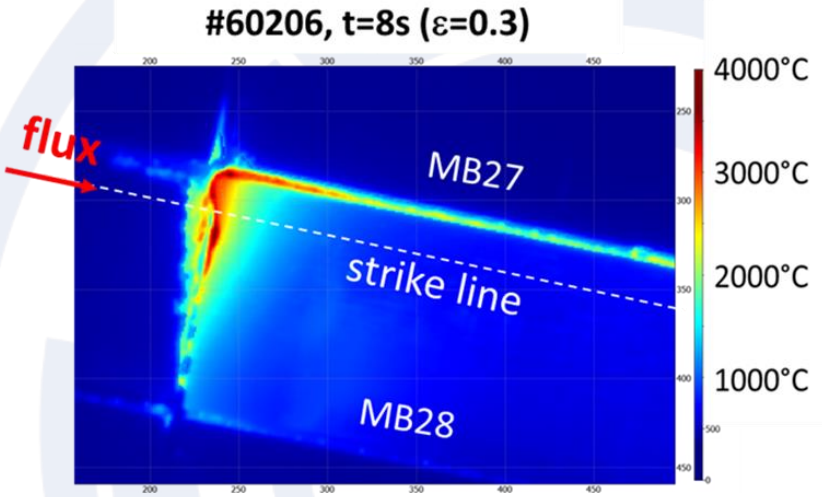
Experiment to come soon







[Y. Corre, ITPA DivSOL, October 2024]



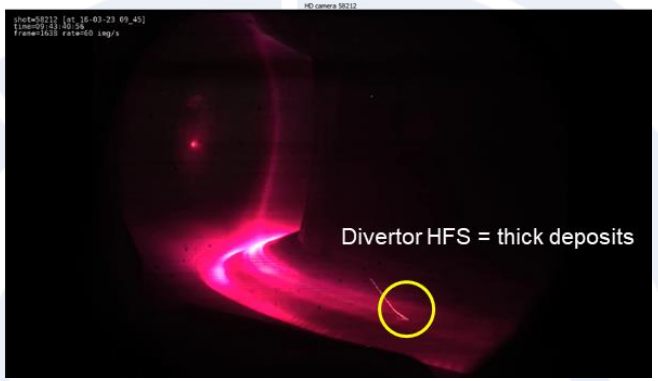
➔ Gap bridging observed under WEST conditions, like in AUG previous experiments

➔Further validation of the MEMENTO code (used for ITER)

Preparing the next high fluence campaign (WEST)

Testing ITER divertor under tokamak conditions : Plasma ⇄ Divertor

- **First High Fluence campaign carried out under attached divertor conditions**
  - ~ ITER PFPO shot particle fluence cumulated over ~1 month of long pulse operation
  - Prone to W erosion ➔ thick deposited layers on the HFS (+ shadowed MB bevel areas)
  - UFOs (or TIEs) hampering plasma operation ➔ laser cleaning developed



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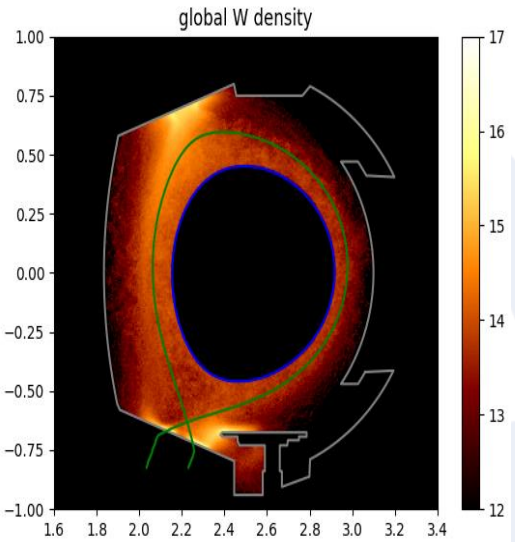
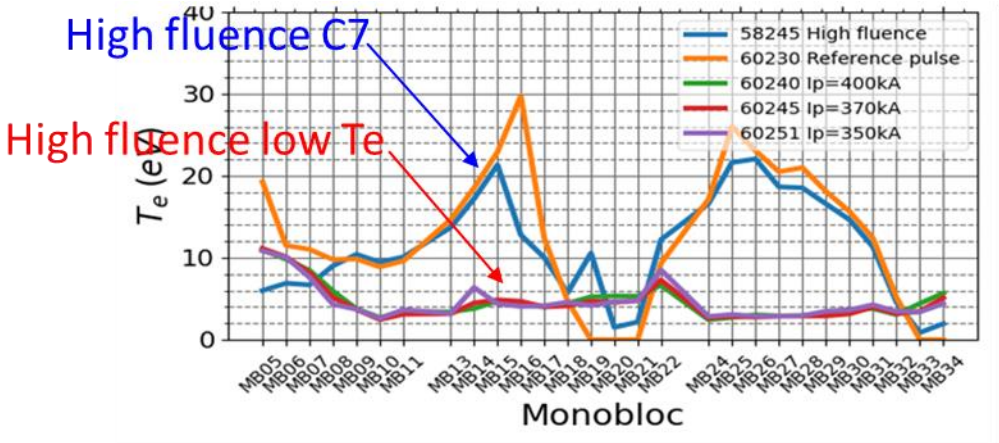
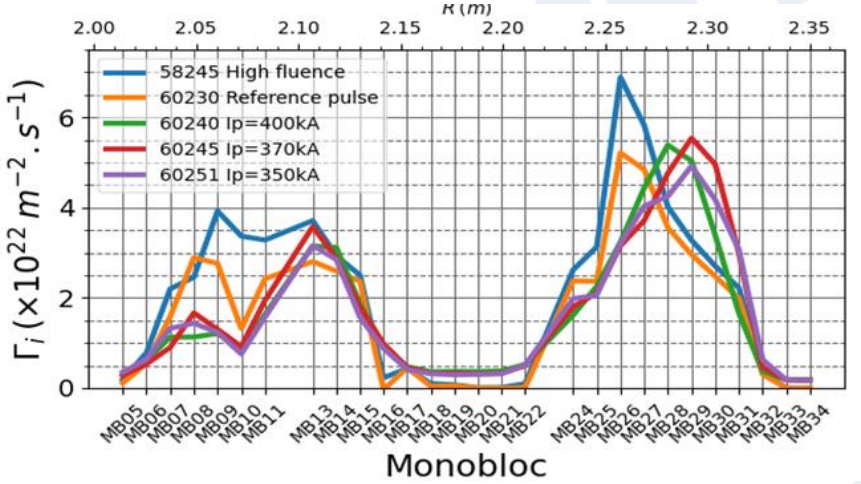
  - Prone to W erosion ➔ thick deposited layers on the HFS (+ shadowed MB bevel areas)
  - UFOs (or TIEs) hampering plasma operation ➔ laser cleaning developed
- **Second High Fluence planned in 2025 under cold divertor conditions**
  - Scenario developed (based on X Point Radiator with N_2 injection), under consolidation
  - Divertor laser cleaning planned this summer
  - High Fluence campaign planned in fall 2025

W-tracing by ERO2.0



[PhD A. Huart]

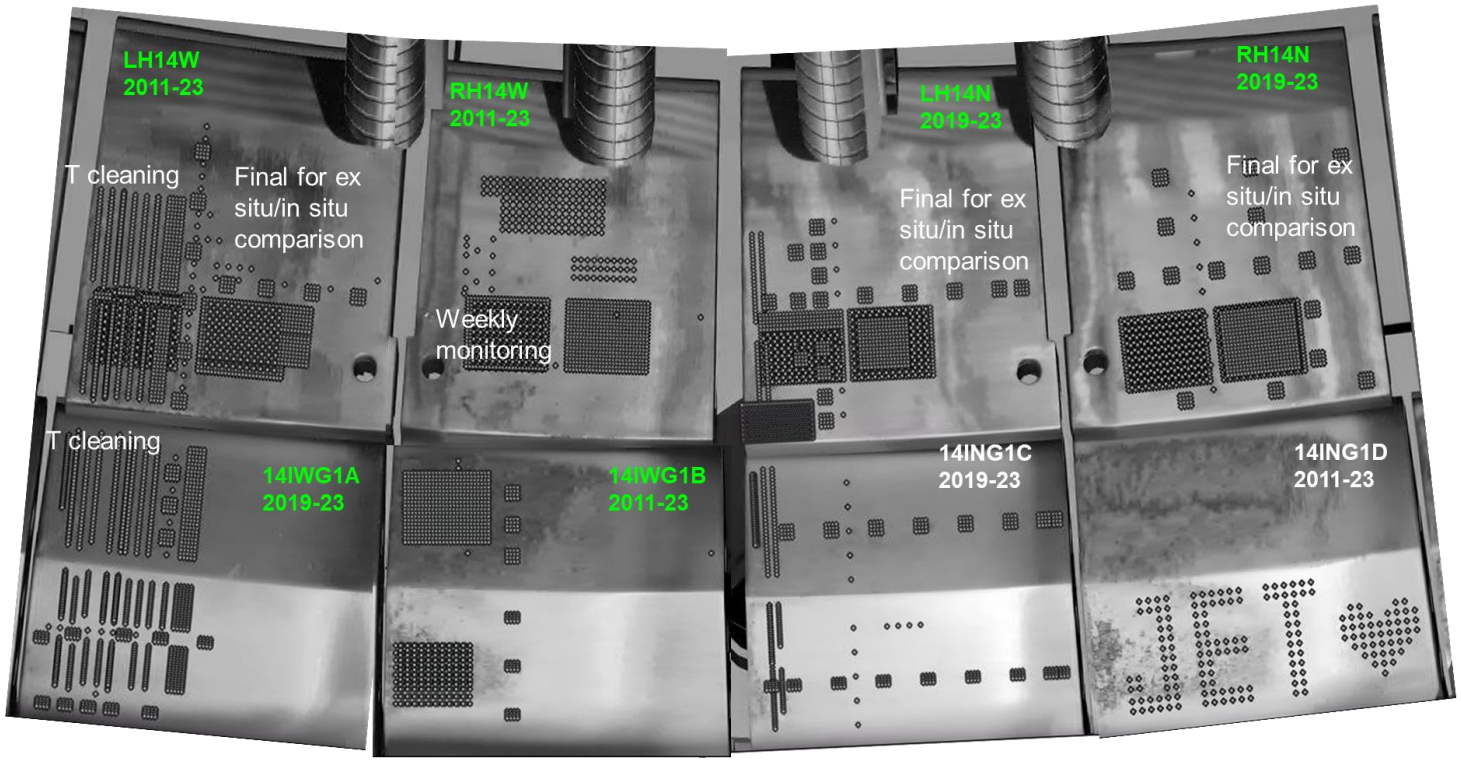


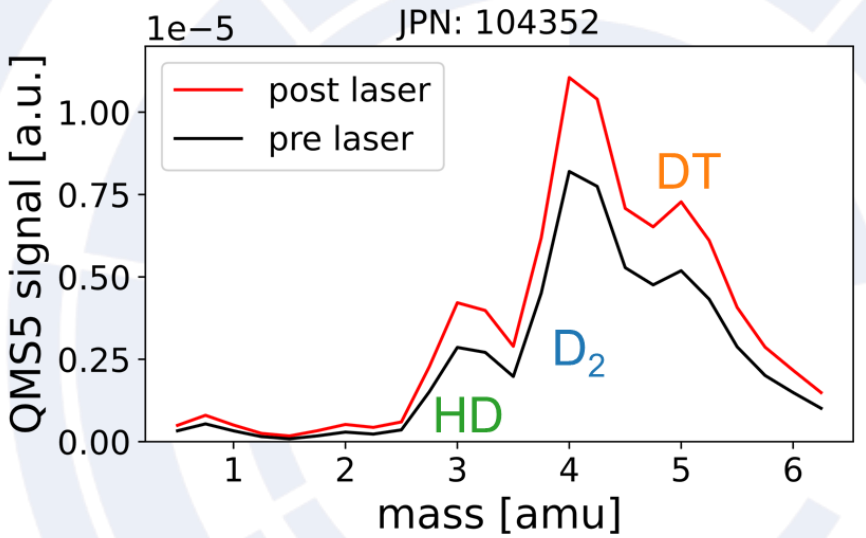


➔ **Experiment ongoing in Magnum to better understand thick "WEST like" deposited layers flaking + IAP**

In situ measurements of fuel retention with laser based diags (JET)

Use of laser based diags in situ assessment of for fuel retention in ITER : demonstration under tokamak environment





- **Extensive use of LID-QMS in JET DTE3 and subsequent clean up**
  - First demonstration of in situ tritium measurements
  - Quantitative analysis ongoing

[M. Zlobinski, FEC2023, A. Widdowson, PSI 2024]

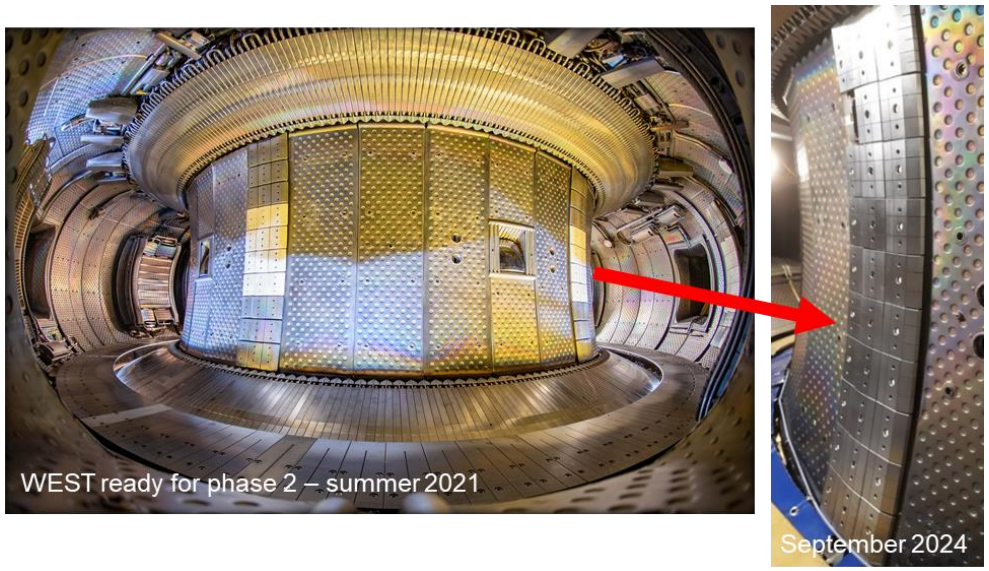
➔ **Comparison of LID-QMS (WP TE), LIBS and post exposure analysis of JET tiles (WP PWIE)**

Uniform versus non uniform boronisation studies (AUG/WEST)

New focus as required for full W ITER configuration : Optimize boronisation parameters for ITER (electrodes, injection points, wall temperature etc ➔ design) and assess frequency required (conservative IO estimate : up to once every 2 weeks)

Similar restart plan for both AUG/WEST

- **Test (briefly) start up without boronisation**
  - WEST : new bulk W inner bumper tiles
  - AUG : new upper divertor, first restart after long shutdown and B cleaning
  - ➔ In both machines, start up w/o boronisation very slow and challenging (RE generation in AUG)



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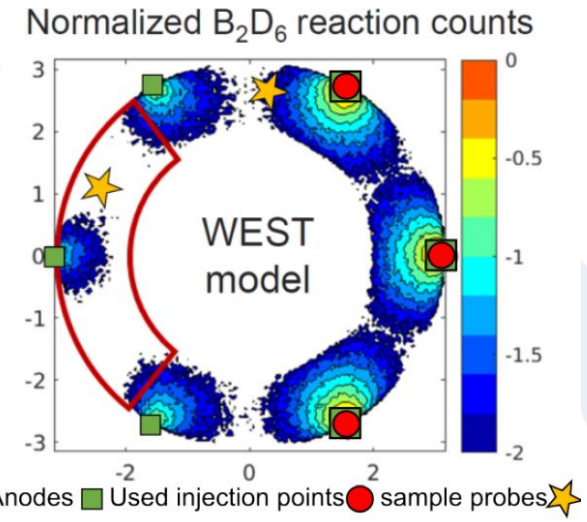


[Courtesy T. Wauters, E. Geulin, FEC 2025]

Similar restart plan for both AUG/WEST

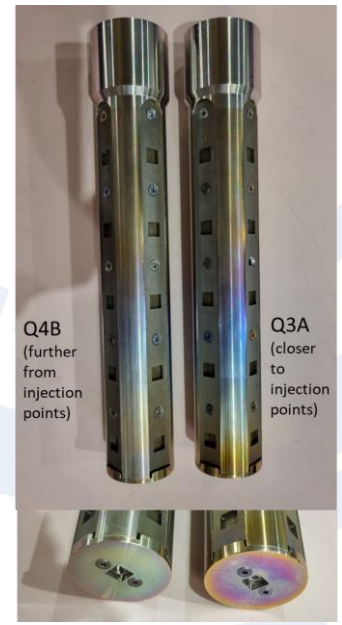
- **Test (briefly) start up without boronisation**
  - WEST : new bulk W inner bumper tiles
  - AUG : new upper divertor, first restart after long shutdown and B cleaning
- **Perform non toroidally uniform boronisation**
  - WEST : 3 of 6 injection points, ITER ref temperature (70°C), no collector probe available in 2024 (repeated recently with collector probe, exposing W and SS samples), LTS
  - AUG : 2 of 4 anodes, room temperature, samples exposed in manipulators + LTS + new QMB

➔After non uniform boronisation :
Start up much easier in both machines (WEST operated for ~1 month)

- **Perform uniform boronisation**

➔Sample / QMB data analysis performed in AUG :
Preliminary results indicate inconsistencies between QMB/samples, under consolidation
➔ Samples from WEST now also available for analysis

[V. Rohde, K. Krieger, S. Han, PFMC 2025]



[Courtesy M. Diez]

➔ **Comparison of B layers from tokamaks / PWIE devices**

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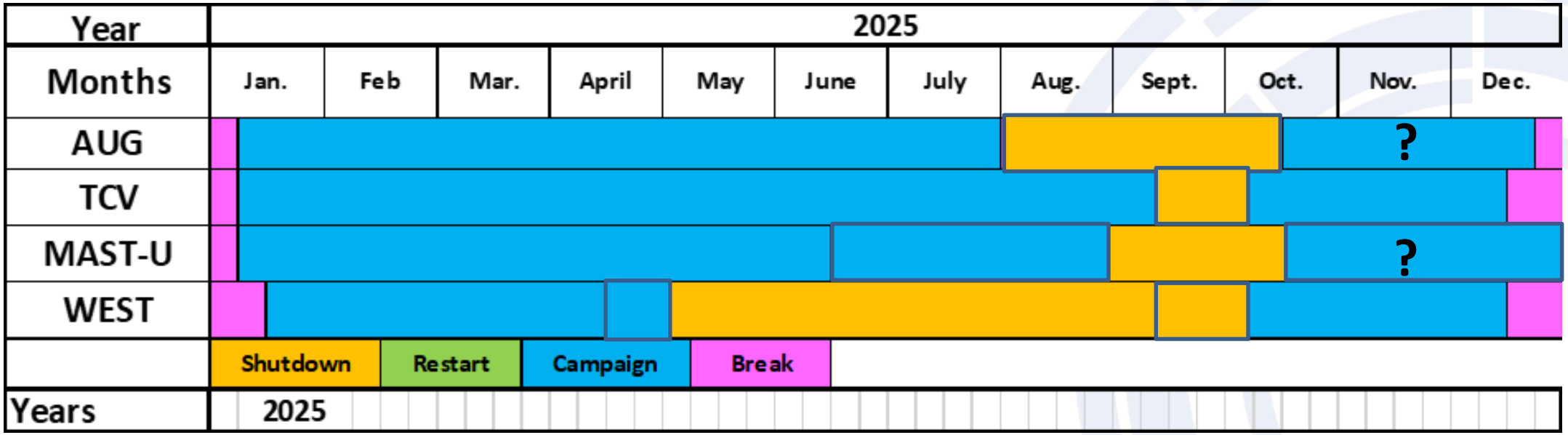
WPTE 2025 program definition

High Level Objectives

- Address urgent issues related to ITER full W using TE metallic devices (AUG, WEST + JET) : far SOL loads, W sources, screening and transport in pedestal, start up on W limiters, RE on W first wall, boronisation …
- Exploit the PEX upgrade of AUG towards qualifications of ADCs at high P/R
- Modelling effort for extrapolation of results from TE devices to ITER / DEMO (e.g. ADC for DEMO, impurity mix for ITER …)
- Prepare JT-60SA scientific exploitation (OP2 campaign end 2026, transition to W)

Planned device availability for 2025



- Busy year for WP TE with 4 devices running in early 2025
- New features : upper divertor AUG, ECRH on WEST, MAST-U cryopump

	TE fraction	Shot budget
AUG	50 %	584 (+ fall)
MAST-U	~35 %	346 (tbc)
TCV	40 %	1320
WEST	40 %	384

Experiments of interest for PWIE (RT06)

PFC evolution / damage under plasma exposure
(2025 focus : high fluence II, impact of RE on first wall)

Fuel retention / recovery and vessel conditioning
(2025 focus : boronisation, ICWC)

	AUG	# shots	WEST	# shots	
First part of 2025	Multi-scale melt dynamics across PFC gaps	10	Operation with actively cooled ITER-like PFU with crack network and self-castellation	20	First part of 2025
	W PFC damage induced by runaway electron incidence	10	W PFC damage induced by runaway electron incidence	10	
	Efficiency and lifetime of boronisation	7	Effect of spatially (non-)uniform boronization on plasma parameters, wall retention	25	
	Particle balance in AUG as a measure of global D retention following fresh GDB	3	Isotope wall changeover with ICWC	30	
Fall campaign 2025	PSI characterization on Mo-coated antenna limiter tiles	4 (tbc)	ITER grade divertor behavior under high particle fluence campaign low Te div. regime	95	Fall campaign 2025
	W erosion sources and global transport in Ne-seeded D2 plasma	10 (tbc)			

Material migration (2025 focus : W first wall)

[Y. Corre and RT06 RTC, WP TE strategy meeting, Jan 2025]

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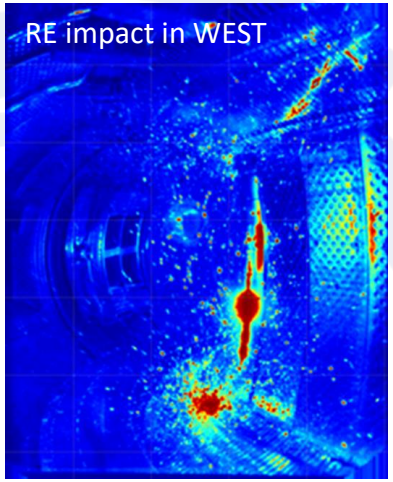
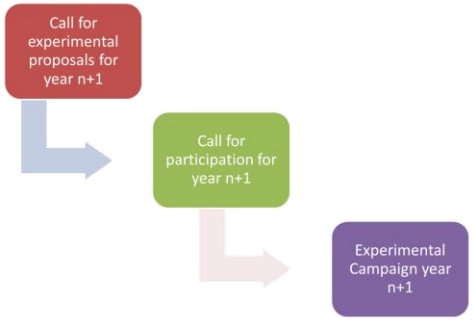
In summary …

- Strong links between WP TE and PWIE :
  - Post mortem analysis of samples exposed in tokamaks
  - Comparison of components behaviour under tokamak conditions versus HHF and linear devices
  - Modelling of material migration / W melting and RE impact under tokamak conditions
  - Boronisation (coordination between RT06 and SP F)

  ➔ Exciting experiments coming ahead in AUG/WEST, wealth of data available from JET



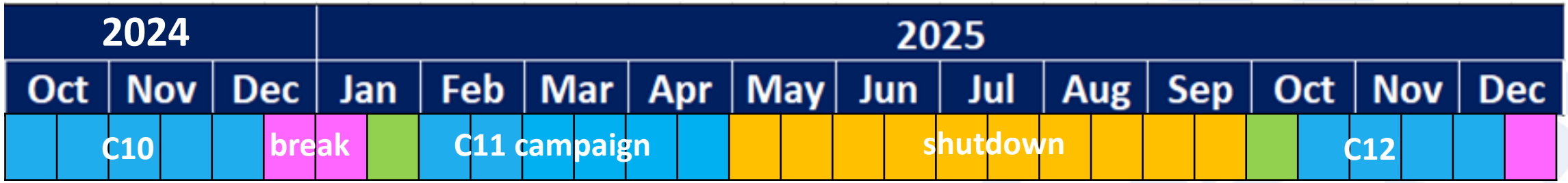
- Prospects for 2026-2027 :
  - WP TE facing strong budget cuts (machine operation, manpower for campaign participation …)
  - BUT focus on ITER urgent R&D issues for the full W baseline : boronisation, W wall sources, screening, transport, start up on W limiters, impact of RE on W walls …
  - Usual WP TE call for proposals / participation to be launched in the fall, covering 2026-2027 :



You are welcome to participate !

Back up slides

Summary RT06 experiments in WEST and AUG for 2025



- Exposure of predamaged PFUs (VHR IR) #15+5
- Wall isotope changeover with ICWC #15+15
- Boronization studies (col. probes + efficiency + ret. + CAPS) #10+15
- Impact of RE beam (fast IR camera WA view) #10
- Scenario development HF2 #15

- Divertor laser cleaning
- Remove RE damaged PFCs

WEST #100 in C11

- High fluence campaign low Te plasma (with fully cleaned div.) #80
- Boronization studies WP TE samples (collector probes) #0

WEST #80 in C12

Multi-scale melting exp.

- Multiscale melting exp. #10
- Boro. studies + particle balance + CAPS + mirror exp. #10
- Impact of RE beam #10

AUG: #30

- W erosion sources in Ne-seeded plasma #6
- ICRH with Mo-coated antenna limiter #4

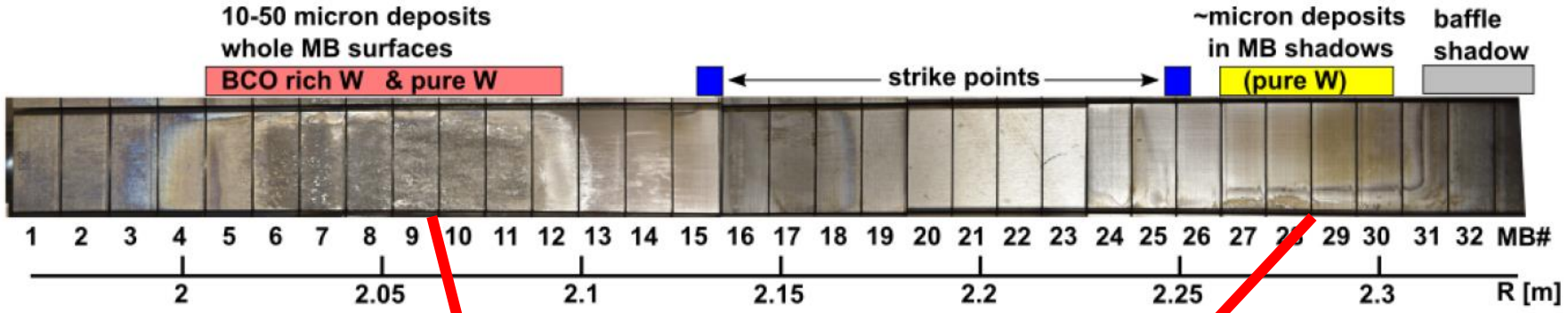
pending on available budget for RT06 and AUG operation (?)

Option 2: if RE beam no feasible

- Multiscale-melting exp. #10
- Boronization studies + particle balance + CAPS #10
- W erosion sources in Ne-seeded plasma #6
- ICRH with Mo-coated antenna limiter #4

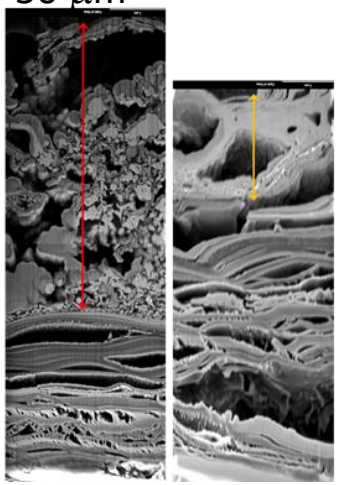
Experimental observations after C7

Picture of a single plasma facing unit of WEST after C7 campaign



- **Two kinds of deposits**
- **Simulations are performed to try to understand their causes**

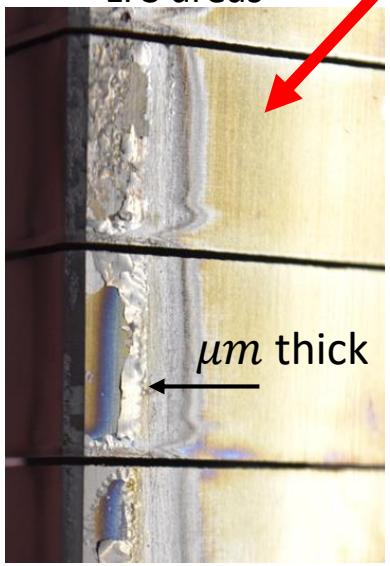
Layer cross section
~50 µm

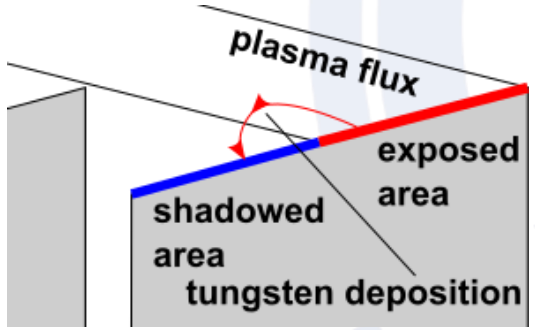


MB8 MB9

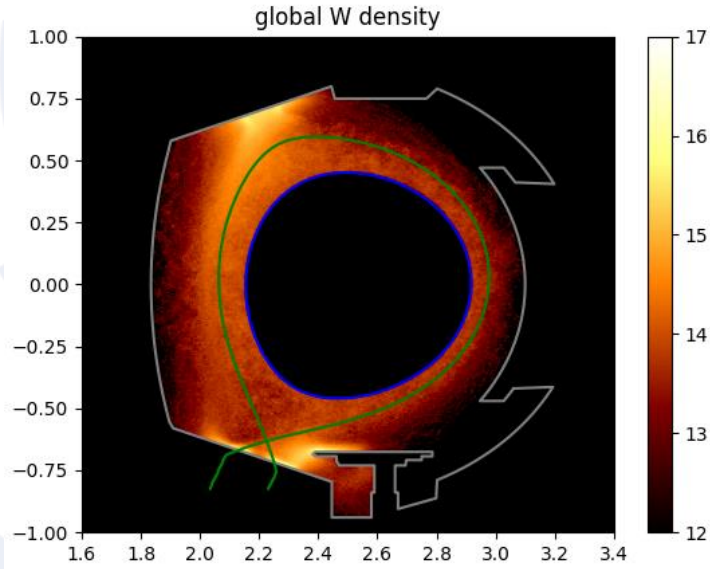
HFS areas

LFS areas



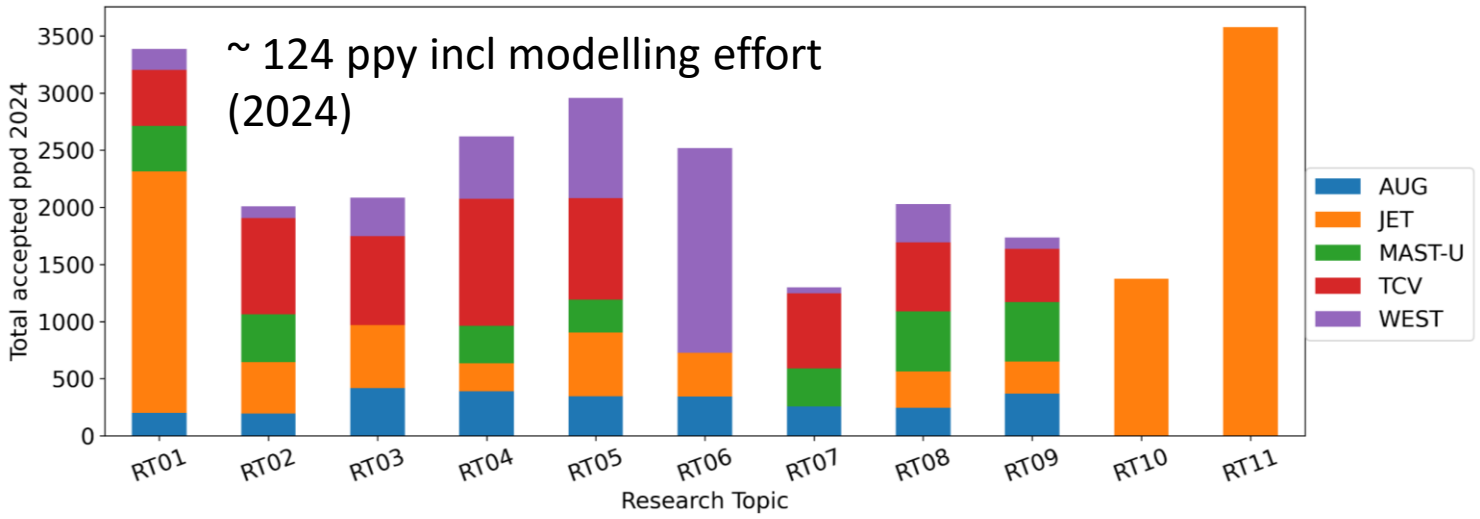


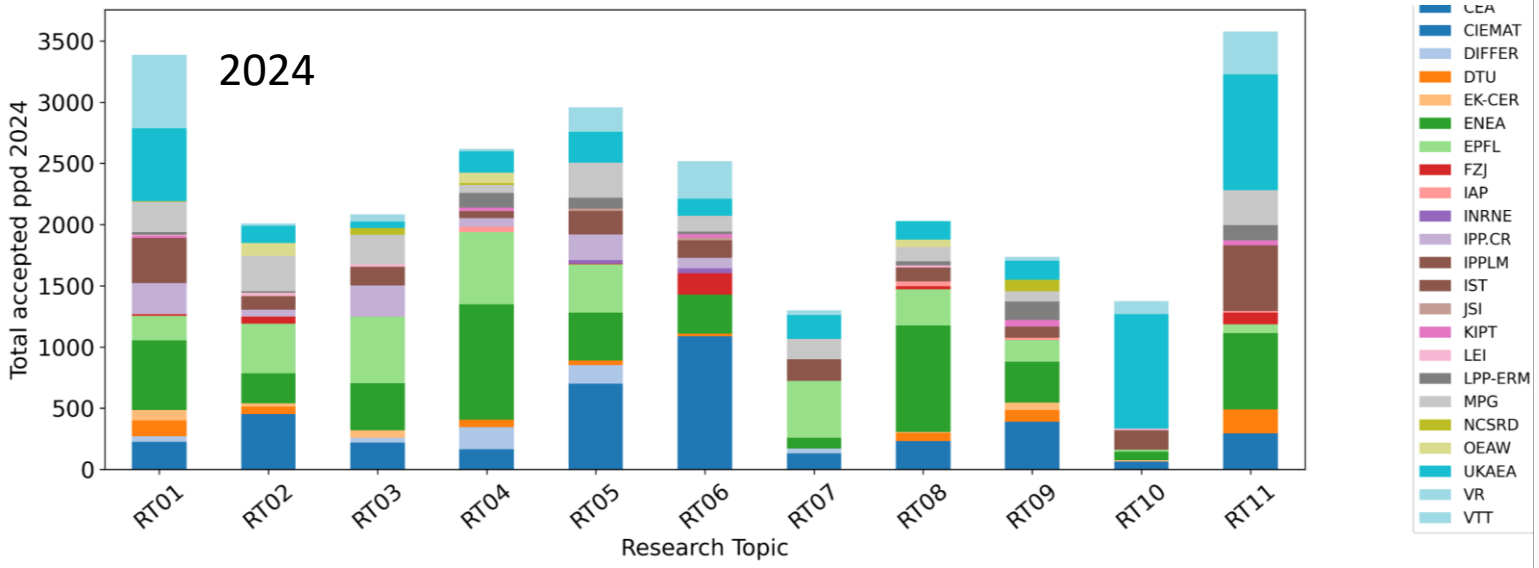
W-tracing by ERO2.0



[PHD A. Huart]

WP TE in figures





- WPTE : cross-device program with strong contribution by EUROfusion beneficiaries (> 600 participants from > 20 labs)
- JET data validation/modelling/scientific exploitation still essential in WPTE strategy (significant backlog for data validation)
- Additional effort on modelling (interpretative + extrapolation to ITER/DEMO) started in 2024-2025
- In addition, ~10 ppy devoted to JT-60SA (RT12 to RT18) in 2024, rising in 2025