MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS

AUG CAPABILITIES FOR W DAMAGE STUDIES

CURRENT KNOWLEDGE ON W DAMAGE FROM TE DEVICES AND FUTURE PLANS FOR STUDIES IN 2024-2025

K. Krieger

BACKGROUND

- ITER design now with full-W 1st wall armour
- ITER divertor has to survive >10 years, from APO (H, He, D) until far into FPO (D,T)
- Open issues requiring urgent experimental assessment:
  - Prediction of PFC damage by runaway electrons
  - Prediction of PFC damage by accidental excessive plasma loads
- Additional studies for assessment of PFC armour long term performance:
  - Crack formation and evolution and influence of recrystallisation

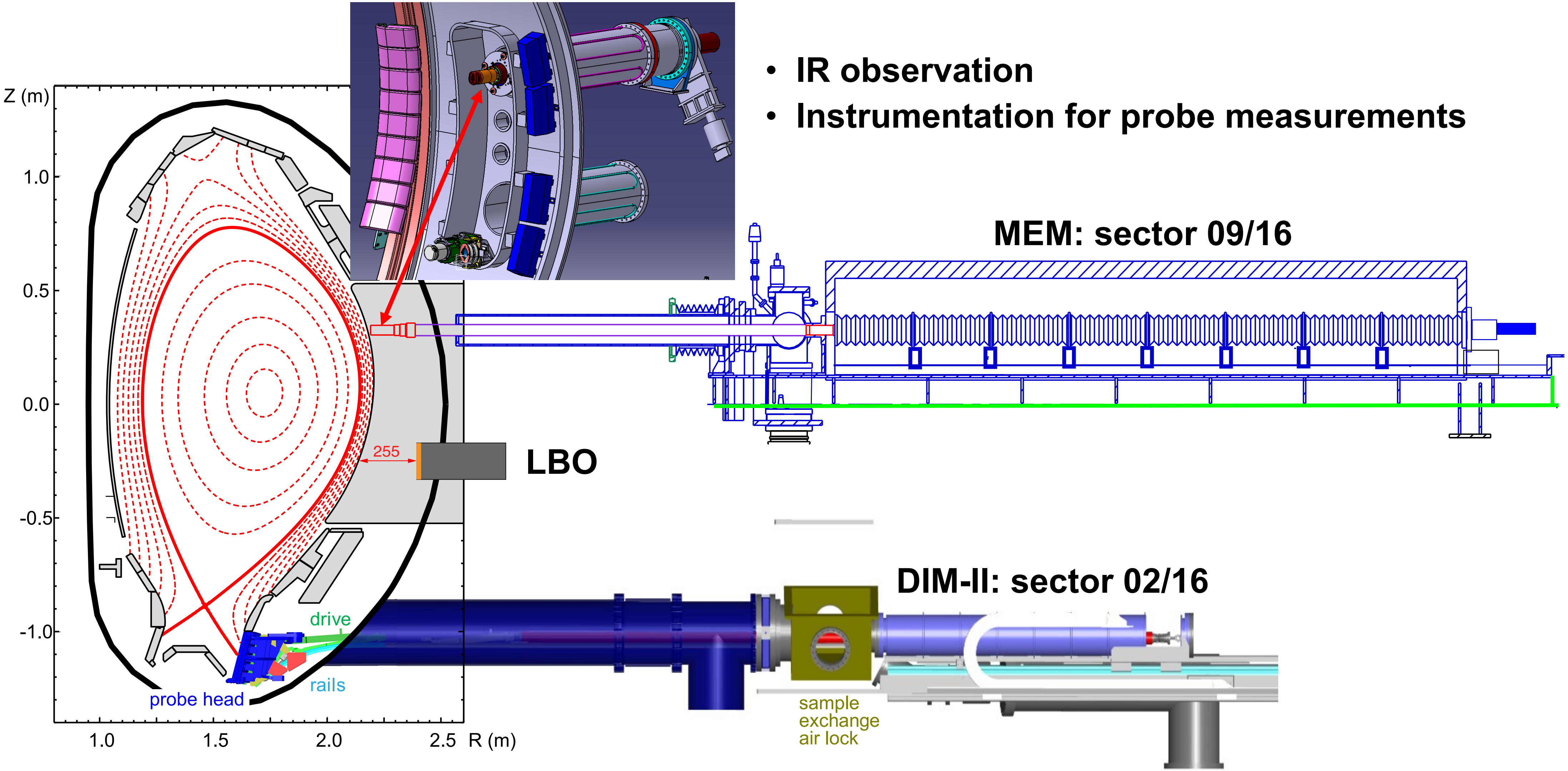
OVERVIEW

- **Experimental capabilities of ASDEX Upgrade for studying W damage processes**
- **Recent WP TE studies on W-damage processes and current near-term plans**

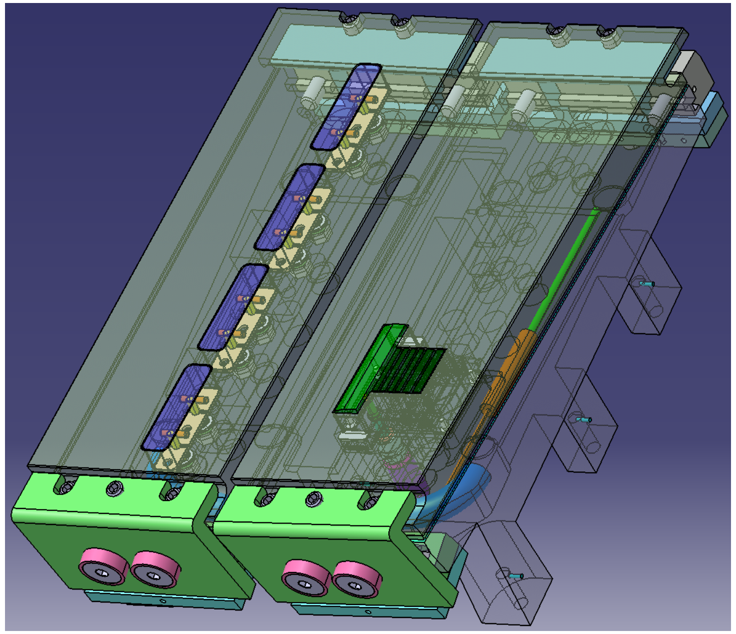
AUG CAPABILITIES FOR W DAMAGE STUDIES

MANIPULATORS WITH AIR LOCKS FOR SAMPLE EXPOSURE

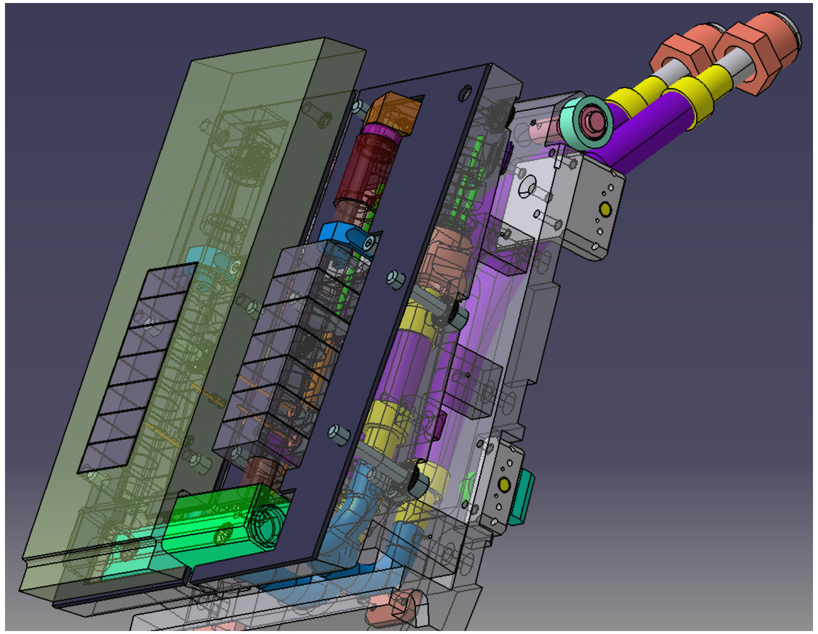
- **IR observation**
- **Instrumentation for probe measurements**



DIM-II PROBE HEADS FOR HIGH POWER FLUX EXPOSURES



Standard: inertially cooled tiles

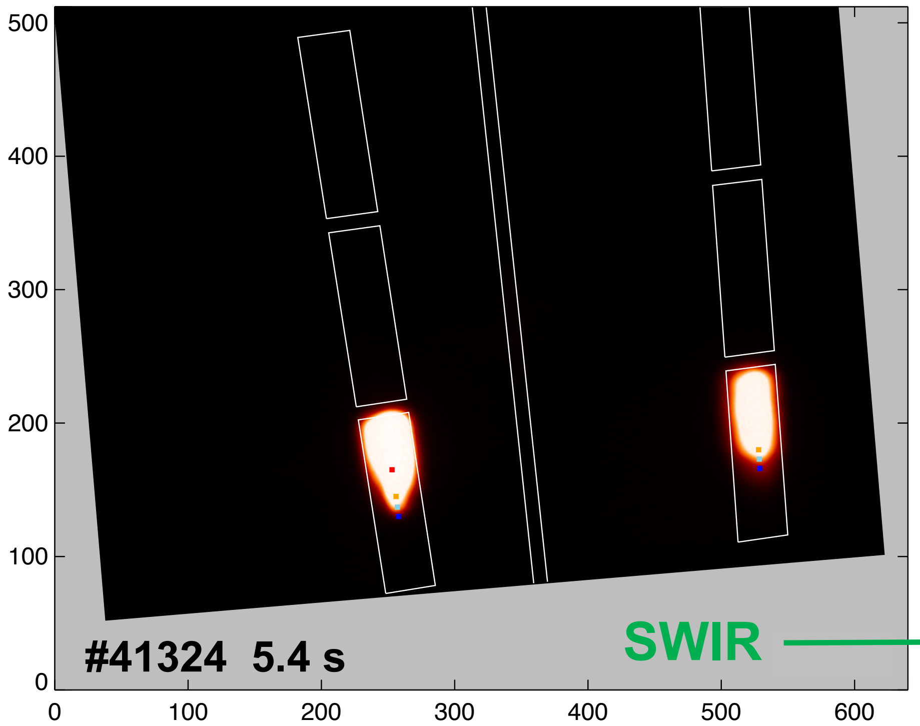


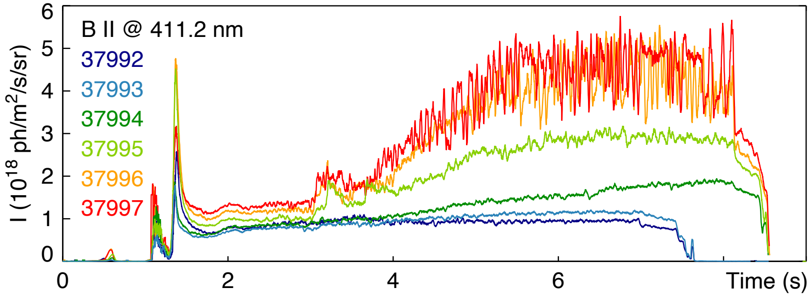
Actively cooled components

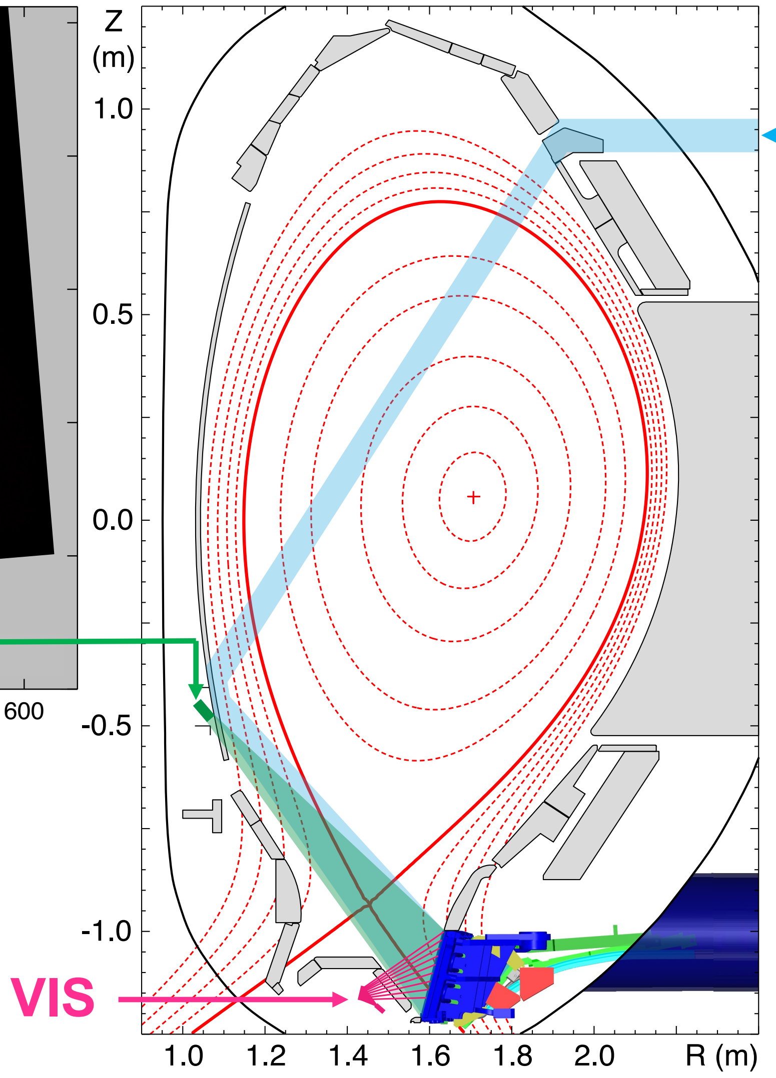
- Electrical connection for instrumentation by 4 feedthroughs with 5 pins each
- Currently only one inertially cooled probe head unit for flexible use

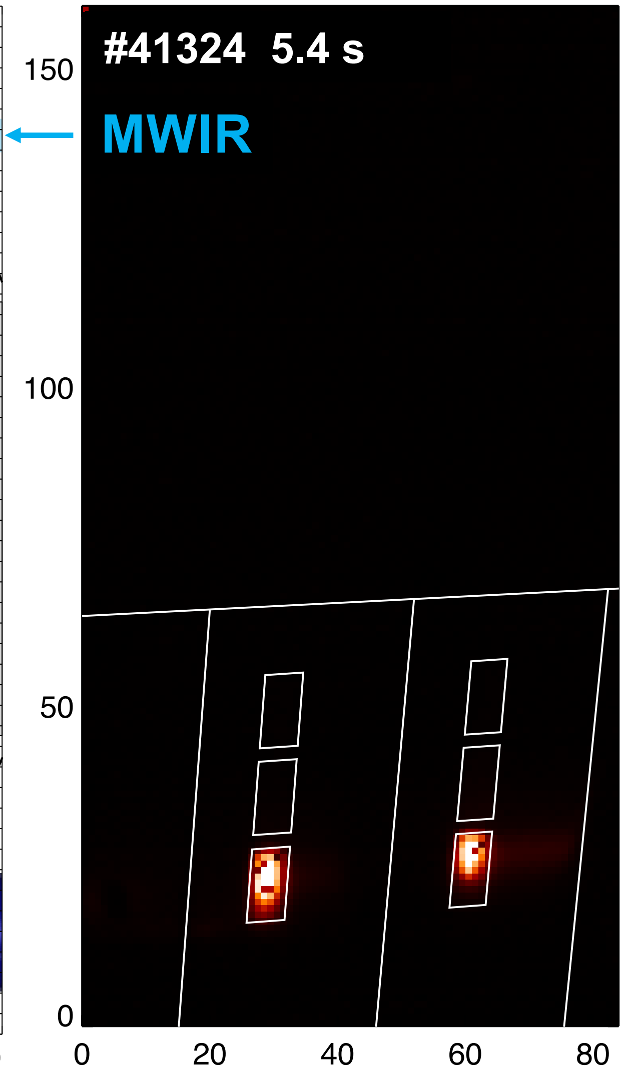
→ New unit currently in manufacturing, ready in early 2025

LOCAL OPTICAL DIAGNOSTICS AT DIM-II



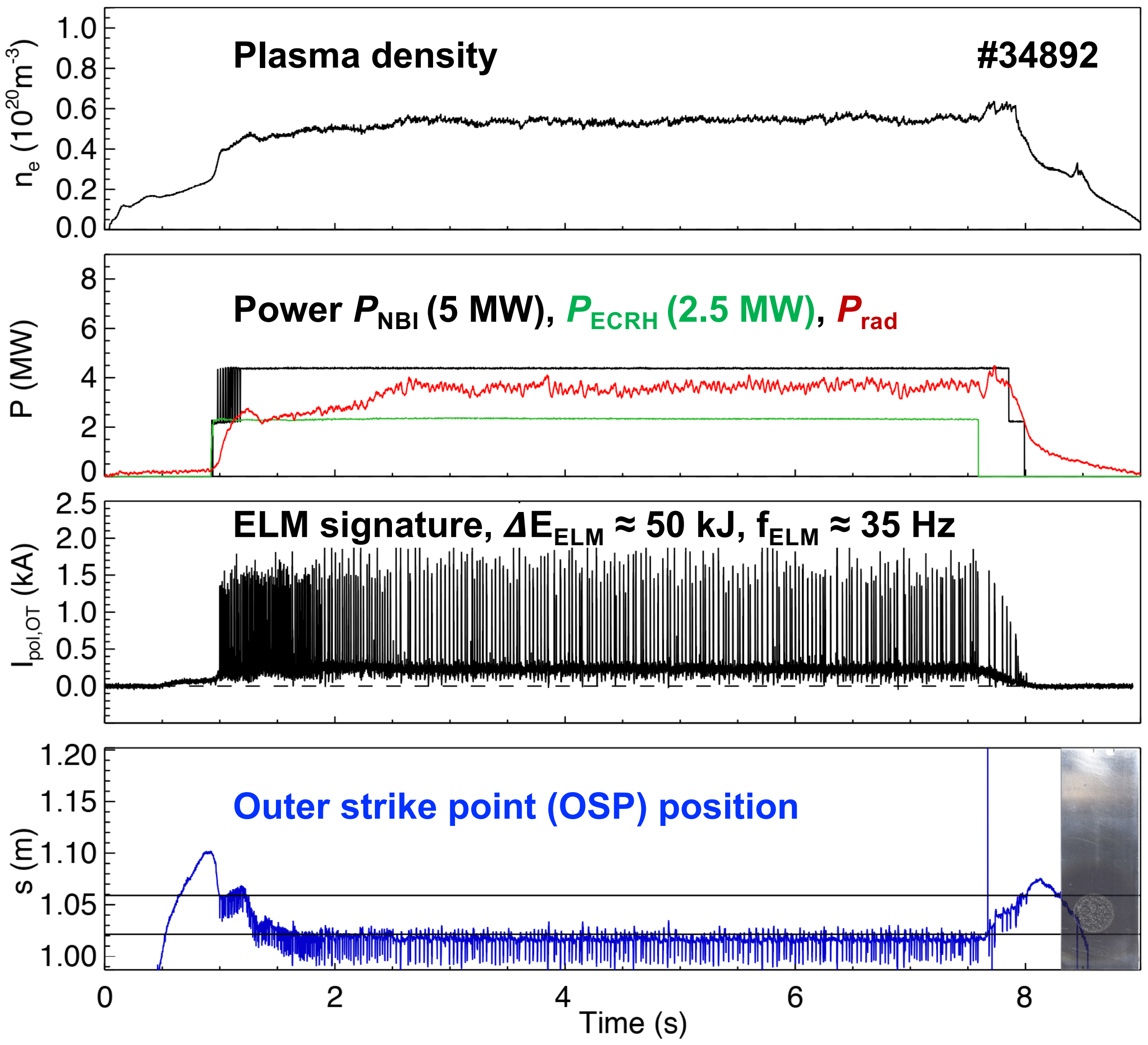






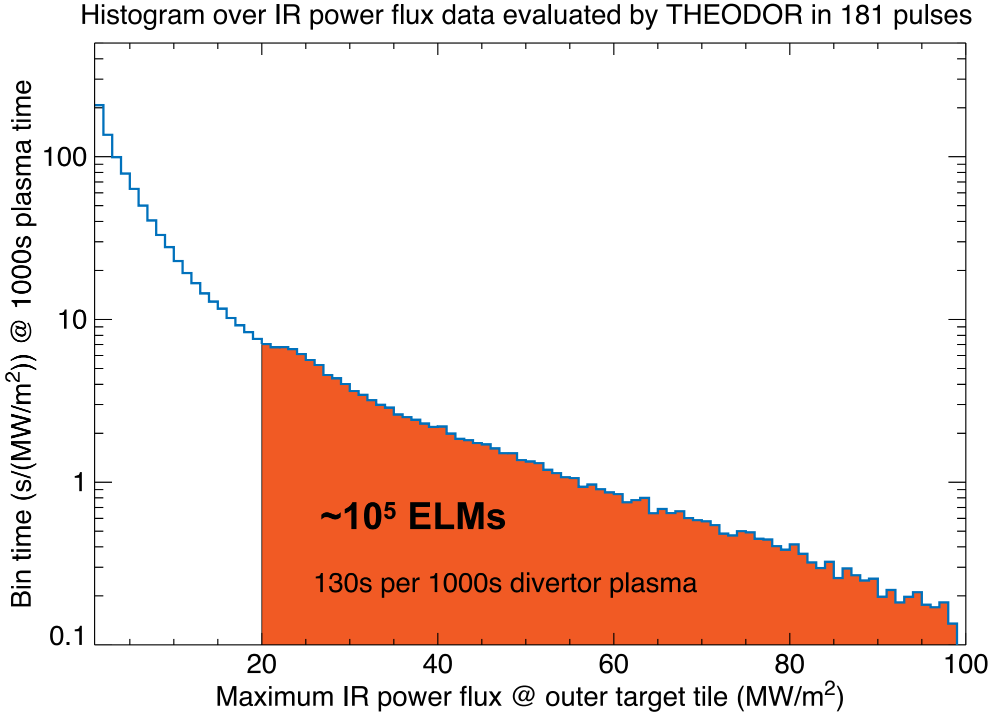
ACHIEVABLE POWER FLUX AND PARTICLE FLUENCE – I

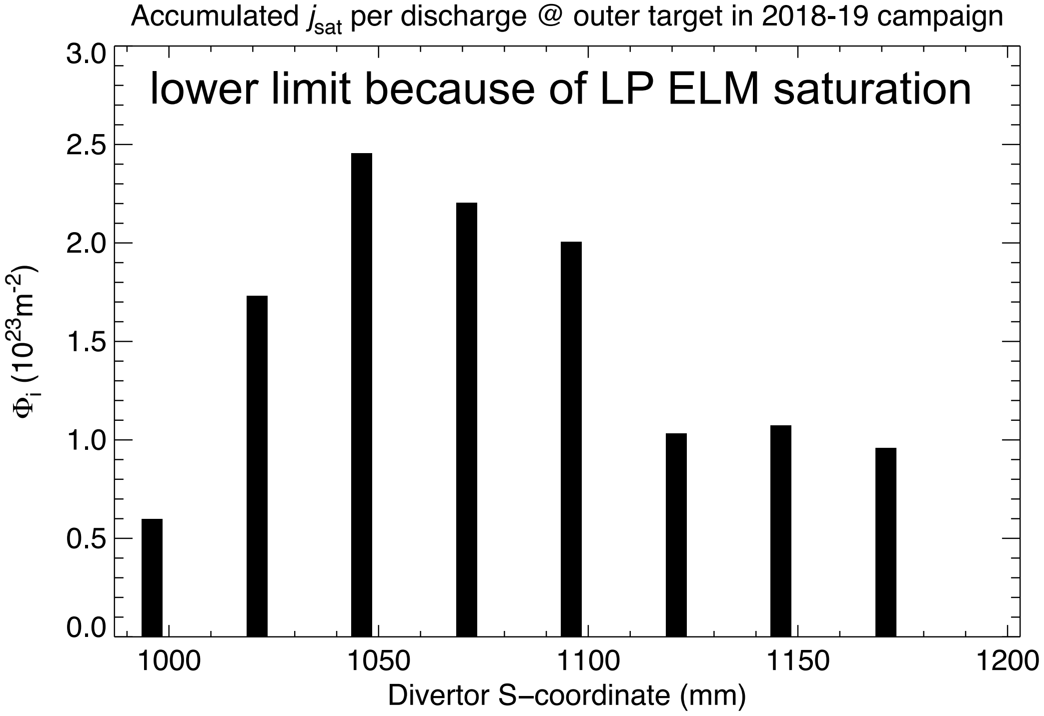
- **AUG discharges limited to ~ 7s flat-top**
- **Experiment day ~ 25 discharges**
- **High q_{div} ⟹ always in H-mode**



ACHIEVABLE POWER FLUX AND PARTICLE FLUENCE – II

- **Transient ELM power flux $q_\perp$ up to 100 MW/m^2 (100 kJ/m^2) $\Longrightarrow$ to reach ITER type-I ELM energy density, dedicated sample designs with steeper surface angle required**
- **Fluence / experiment day $\lesssim 6\times10^{24}$/m^2**





CURRENT KNOWLEDGE ON W DAMAGE FROM TE DEVICES AND FUTURE PLANS FOR STUDIES IN 2024-2025

CURRENT STATUS OF MODELLING FOR W-DAMAGE ISSUES

Predictive modelling of surface evolution during melt events

→ **Available code workflow (KTH) mature and validated against many exposure scenarios and several metal species (Be, W, Nb, Ir). Further experiments aiming at validating models for small scale effects (gap bridging, melt ejection).**

Predictive modelling of RE damage

→ **Code workflow is still in its infancy. Current focus on validating GEANT4 RE power deposition model** ***Pitts NME 2024 (subm), Ratynskaia NF 2024 (subm)*** **and interpretative models for deriving RE energy spectrum. Dedicated experiments required for validating these and subsequent model steps predicting primary material damage, debris ejection and connected secondary damage.**

Predictive modelling of crack formation and growth (PFC health monitoring)

→ **New code T-REX validated against two experiments: self-castellation created in JUDITH2 e-beam facility and in WEST on the leading edge of a W-block exposed to repeated excessive heatloads (plasma + MHD crashes)** ***Durif 2022 JNM & 2022 PS, Tichit 2023 NME*****.**

→ **Additional validation against tile cracking in AUG (standard vs slim tiles)**

MELT DYNAMICS

Extensive validation of predictive codes MEMOS-U / MEMENTO / ANSYS by experiments in JET, AUG and WEST

Thoren PS 2017 & NF 2018 & NME 2018, Ratynskaia PS 2021, Vignitchouk NME 2020 & NF 2023, Paschalidis NME 2023

- **JET (W transient melting by ELMs, Be melting by VDE/disruptions)**

  Coenen NF 2015 & JNM 2015 & PS 2017, Jepu et al. NF 2019, Ratynskaia NF 2020, Vignitchouk NF 2022

- **AUG (W transient melting by ELMs)**

  Krieger PS 2017 & NF 2018, Ratynskaia NF 2020 & NME 2022 & NF 2024

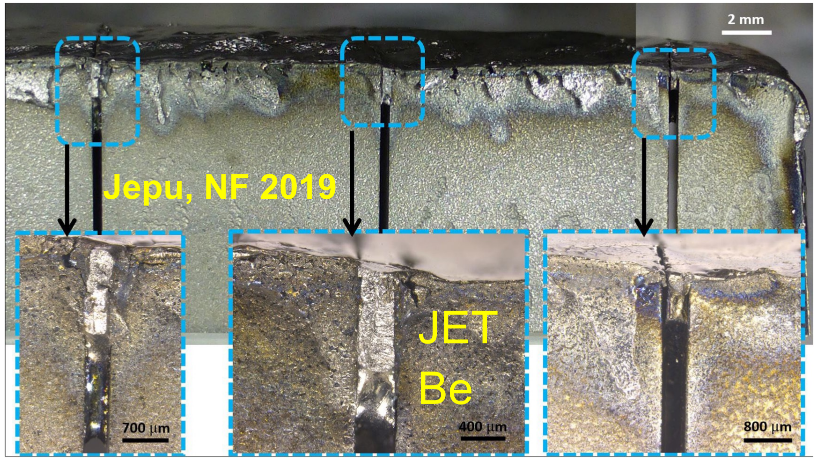
- **WEST (W sustained melting)**

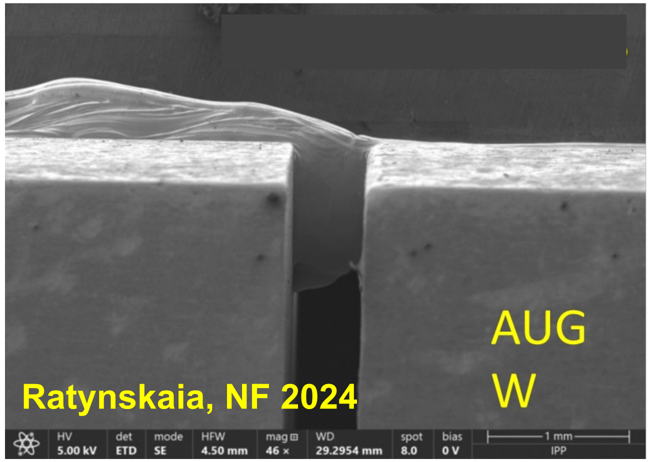
  Corre PS 2021, Ratynskaia NME 2022 & NF 2024

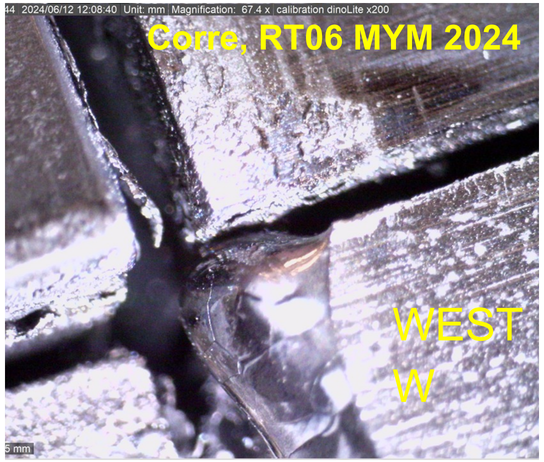
Experiments in 2024/25 focused on open details → <u>melt flow across monoblock gaps</u>

EXPERIMENTS ON MELT BRIDGING OR INFILTRATING GAPS

- **W-melt dynamics → gap infiltration vs gap bridging**
- **Be sustained melting**   **W transient melting**   **W sustained melting**



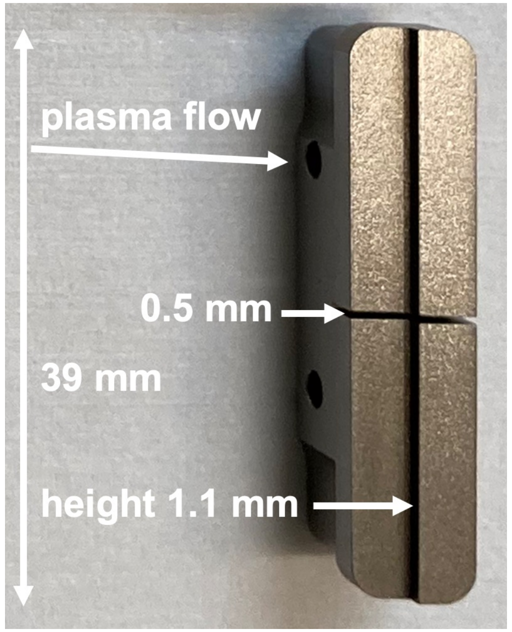


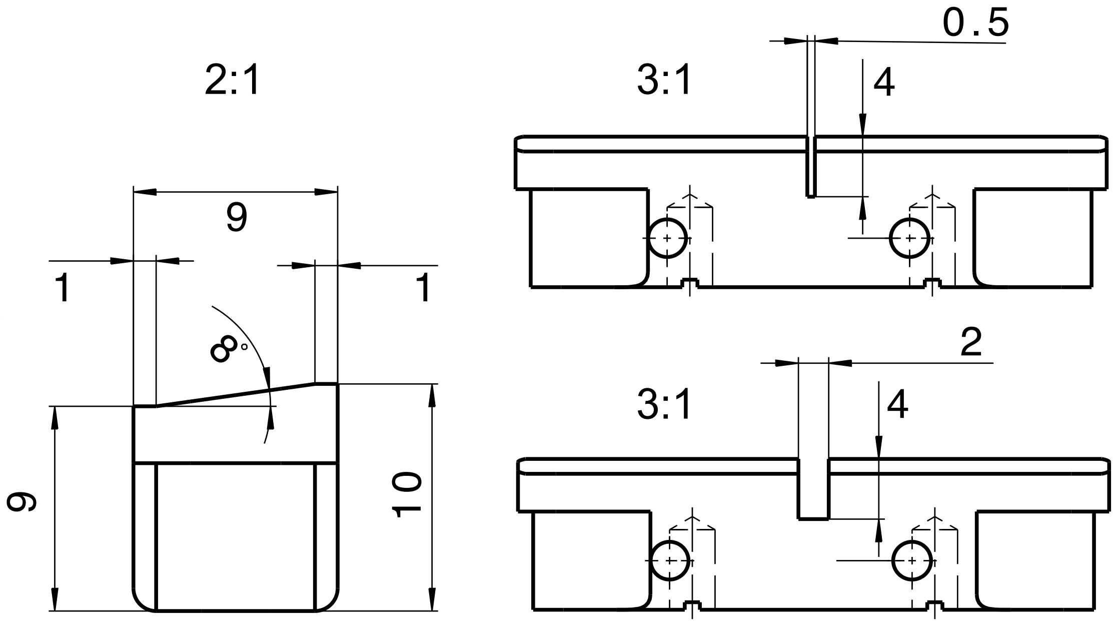


- **AUG 2024/25 and WEST C10/C11 campaigns:**
  investigate influence of gap width and B-field to surface ∡

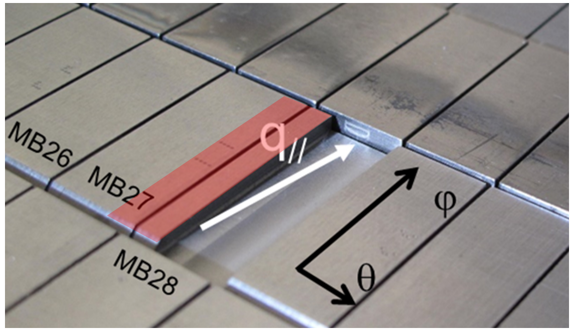
EXPERIMENTS ON MELT BRIDGING OR INFILTRATING GAPS

- **AUG → adapted standard bulk-W melt sample design with 8° slope angle (≈3.6×$q_{\perp}$)**





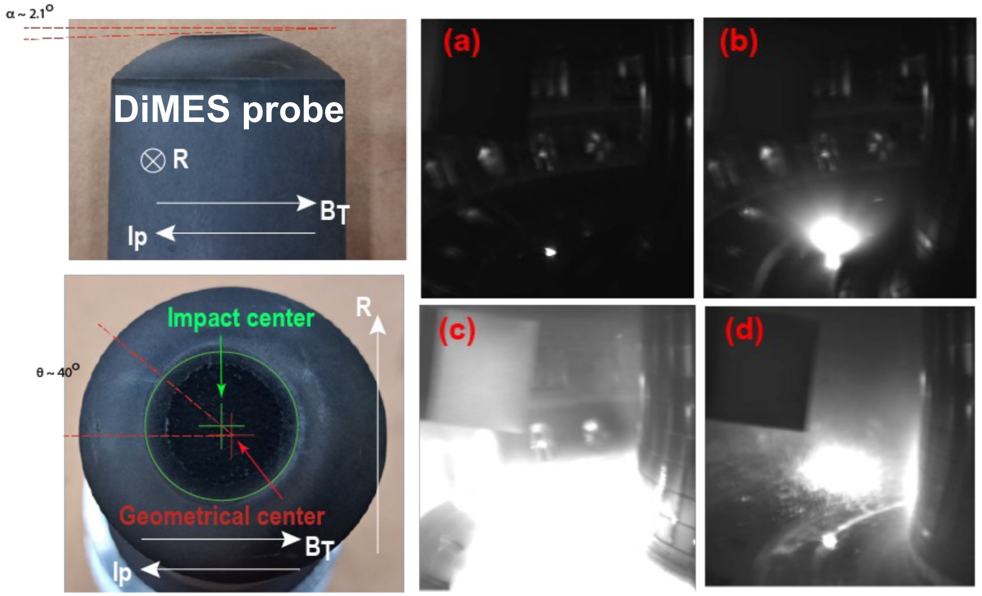
- **WEST → monoblock geometry with larger gap melt surface?**



RUNAWAY ELECTRON DAMAGE

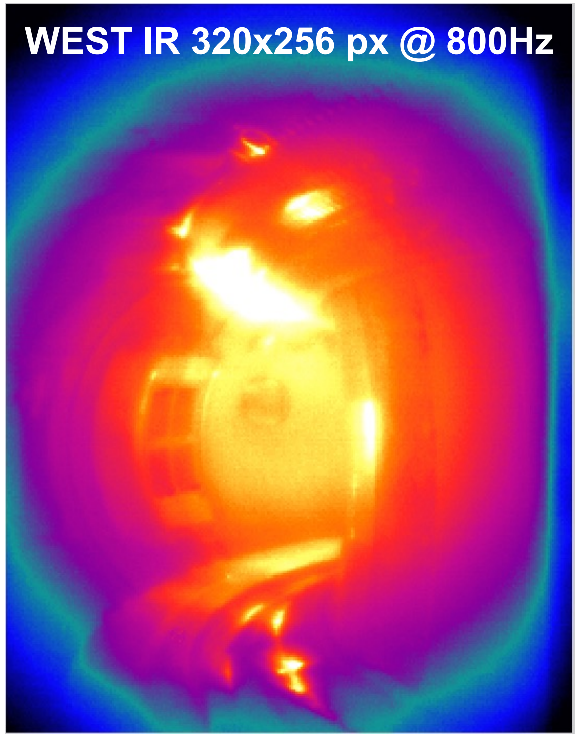
Recent studies of RE damage under controlled conditions in DIII-D …

- Low-Z RE beam intentionally impacted onto graphite dome limiter.
- Scaled MARS-F used to estimate MHD dB.
- KORC used to estimate RE orbits for different assumptions of energy, pitch.
- GEANT4 + COMSOL used to estimate resulting damage.
- Dust explosion after ~1ms



Hollmann, ITPA DivSOL, Kyoto, 2024

Hollmann, PPCF 2024 (subm)



… and in WEST C9 (WPTE RT-03)

Controlled RE impact on inner (BN) and outer (W) bumper tile

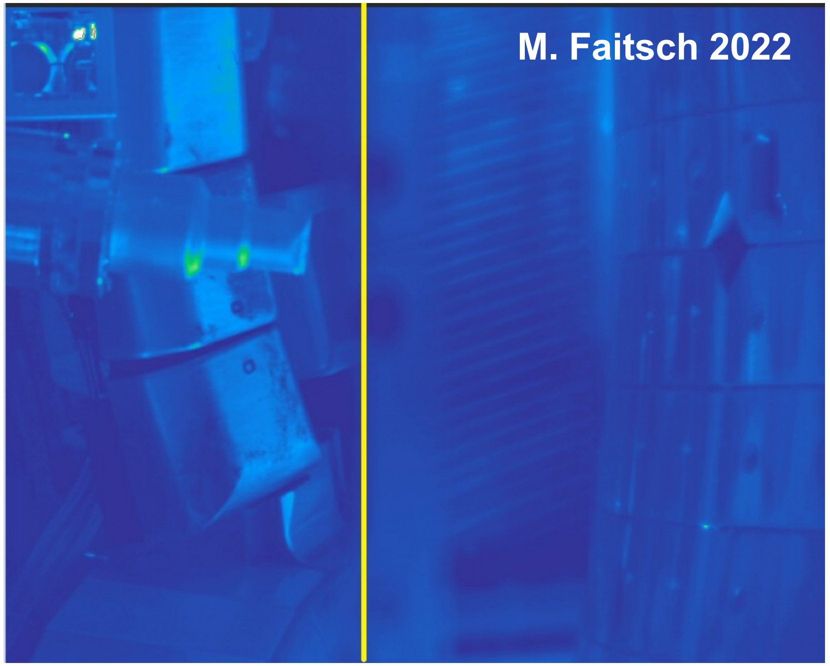
→ Fast IR data with 8 spectral filters, ***Gauthier 2024 GP3***

Both experiments provided first data for GEANT4 validation

RUNAWAY ELECTRON DAMAGE

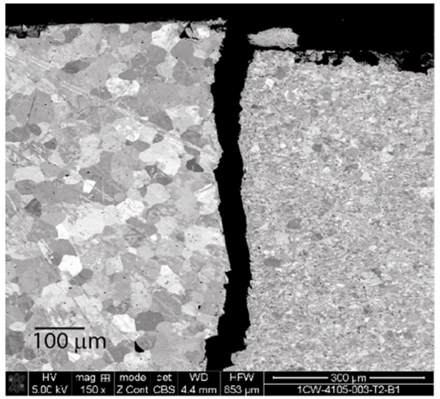
Experiments in 2024/25 focused on validation of RE power deposition model

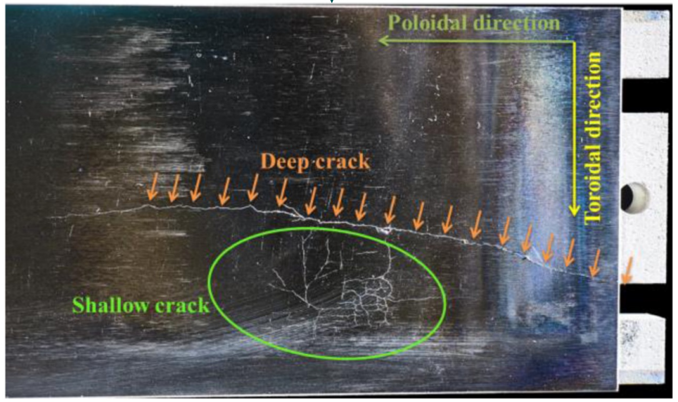
- **WEST:** installed instrumented inner bumper W tile with two TCs to be exposed to controlled RE beam
- **AUG:** dedicated instrumented sample to be exposed by MEM (07/2025) depending on positive outcome of safety analysis (EM forces on MEM manipulator arm)
  Local diagnostics:
  TCs, IR observation,
  shunt resistor for RE current,
  γ-counter.



W DAMAGE IN AUG – GENERAL OBSERVATIONS

- For standard full-W PFC, only one relevant scenario → macro cracking of outer target flat W tiles in <100 pulses
- No melting but local over-heating
- <u>No tile parts dislodged requiring vent</u>

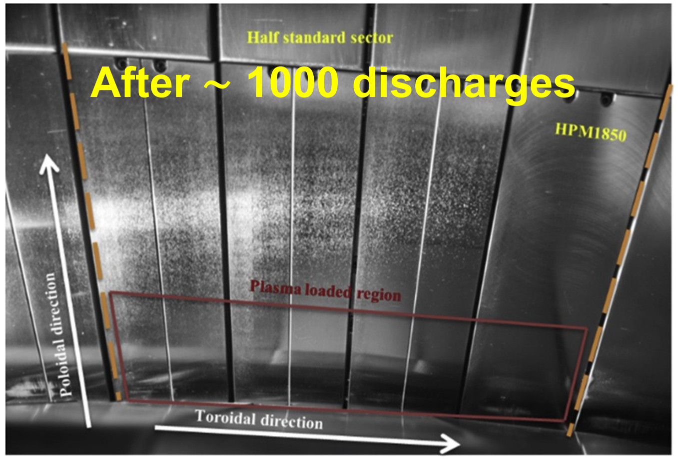




- Avoidance by optimised design (castellation or split in 2 narrow tiles) and softer mounting clamps (SS→Ti)

  Zammuto et al., FED 2018 & FED 2019, Rohde et al., NME 2023

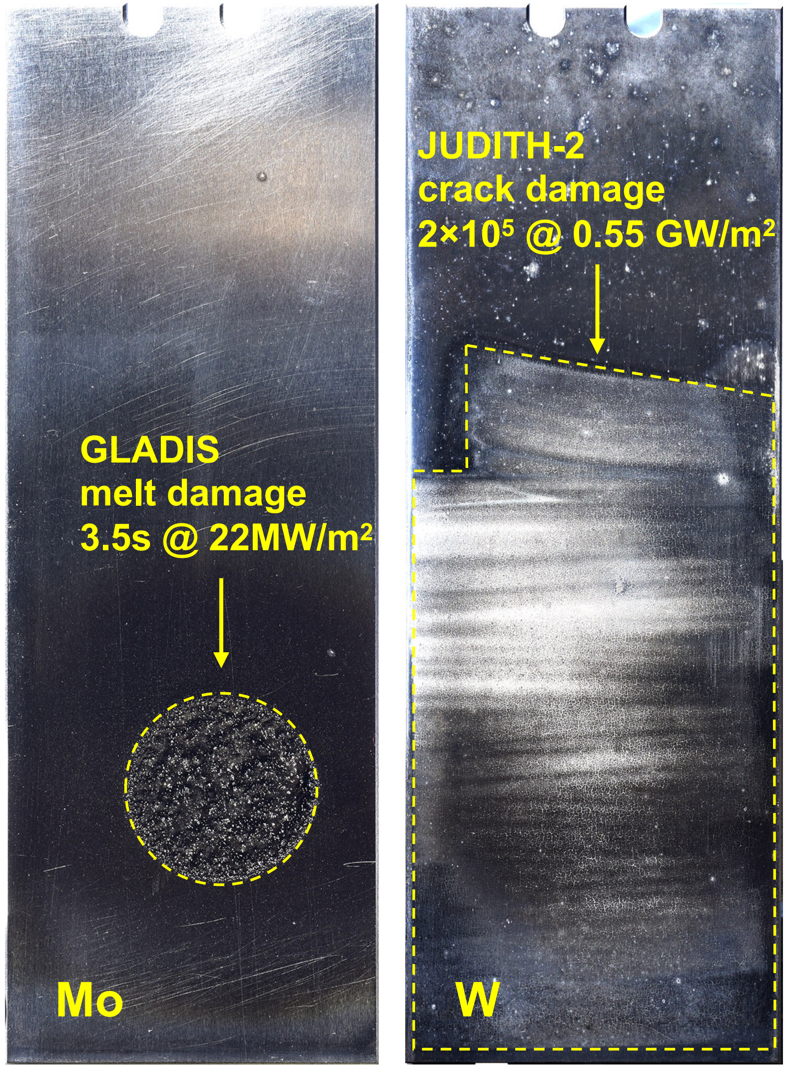
- Not relevant to ITER but provides data set for code validation (ANSYS, T-REX, ...)
- Other damage scenarios require dedicated experiments



CRACK FORMATION AND GROWTH – AUG

- **Series of 15 identical H-mode discharges with large type-I ELMs**
- **Total divertor time ≈ 90 s**
  ≈ 3200 ELMs
- **No signs of melting during exposures**
- **No signs of crack propagation**
- **Increased erosion rate @ corrugated surface**
- **Deposition inside cracks**

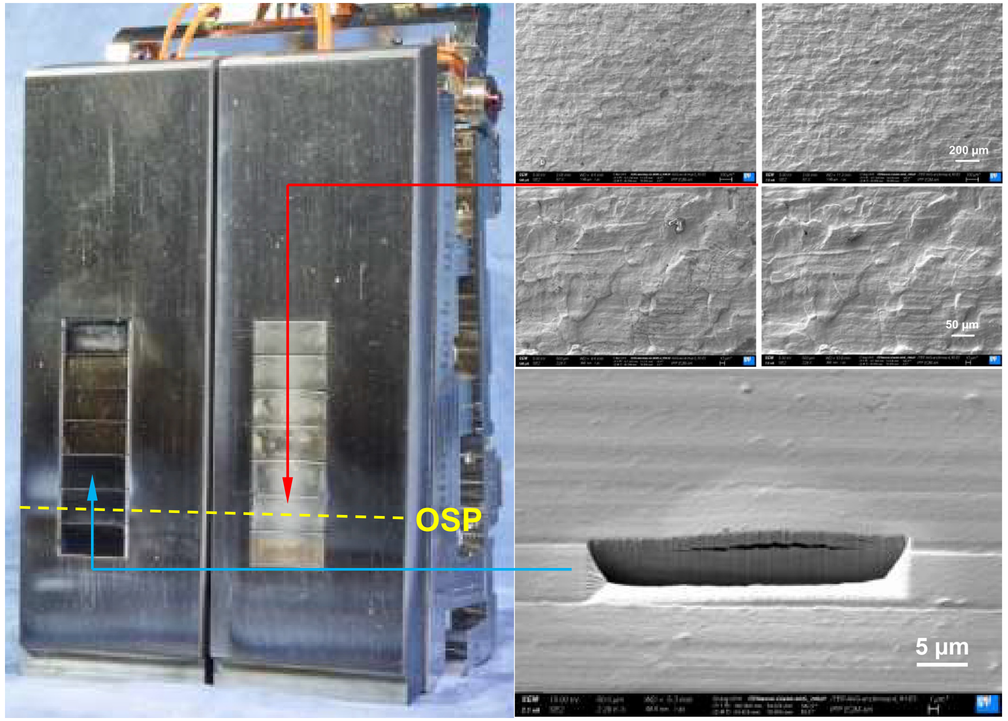
Krieger PS 2020

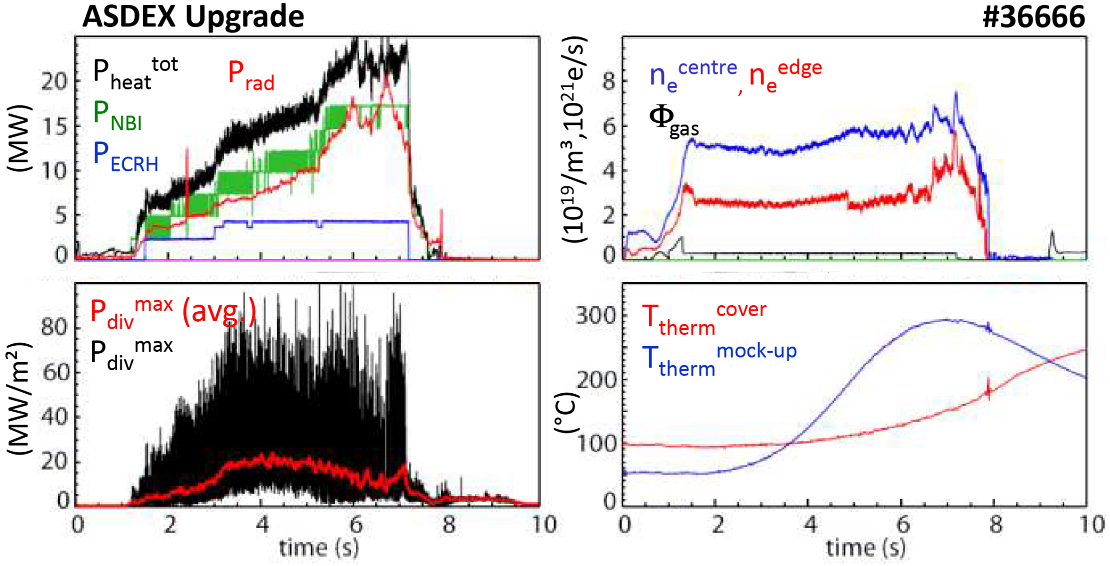


CRACK FORMATION AND GROWTH – AUG

- **W monoblock stacks with ITER geometry and active cooling parameters (70°C, 1 l/s) exposed to 40 H-mode discharges, $\langle q_{\perp} \rangle$ up to 20 MW/m^2, $10^4 \times q_{\perp,ELM}$ up to 100 MW/m^2**
- **Minor roughening at grain boundaries and blisters after ~10^{25} D/m^2 but <u>no cracking</u>**

Neu 2018 PSI & 2019 ISFNT

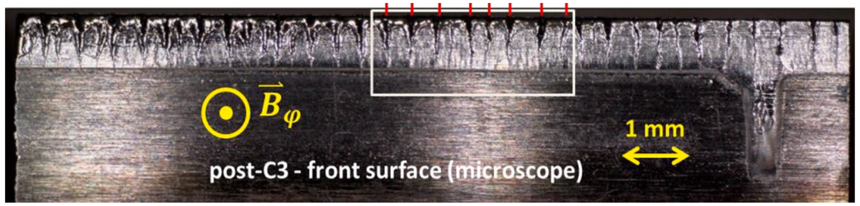


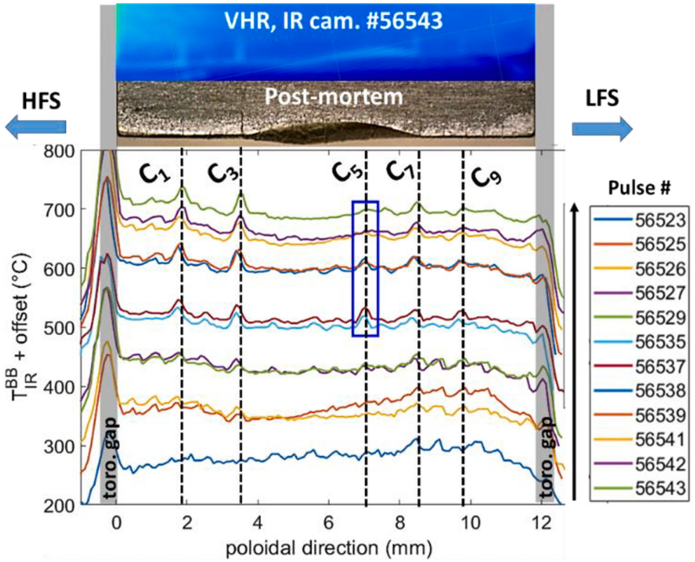


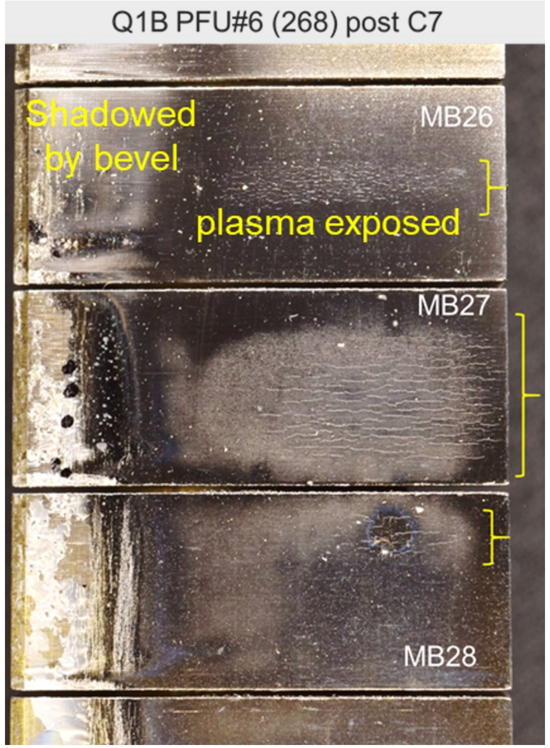
W DAMAGE IN WEST – GENERAL OBSERVATIONS

- **Full campaign exposure of actively cooled W PFU up to C4 → no noticeable cracking at MB flat surface but cracks developed at leading and trailing edges → <u>brittle cracking of cold W due to disruptions</u>. New data from C7: also on flat surface**

Gunn 2021 NME, Diez 2023 NME, Corre 2023 NME ***Diez 2024***





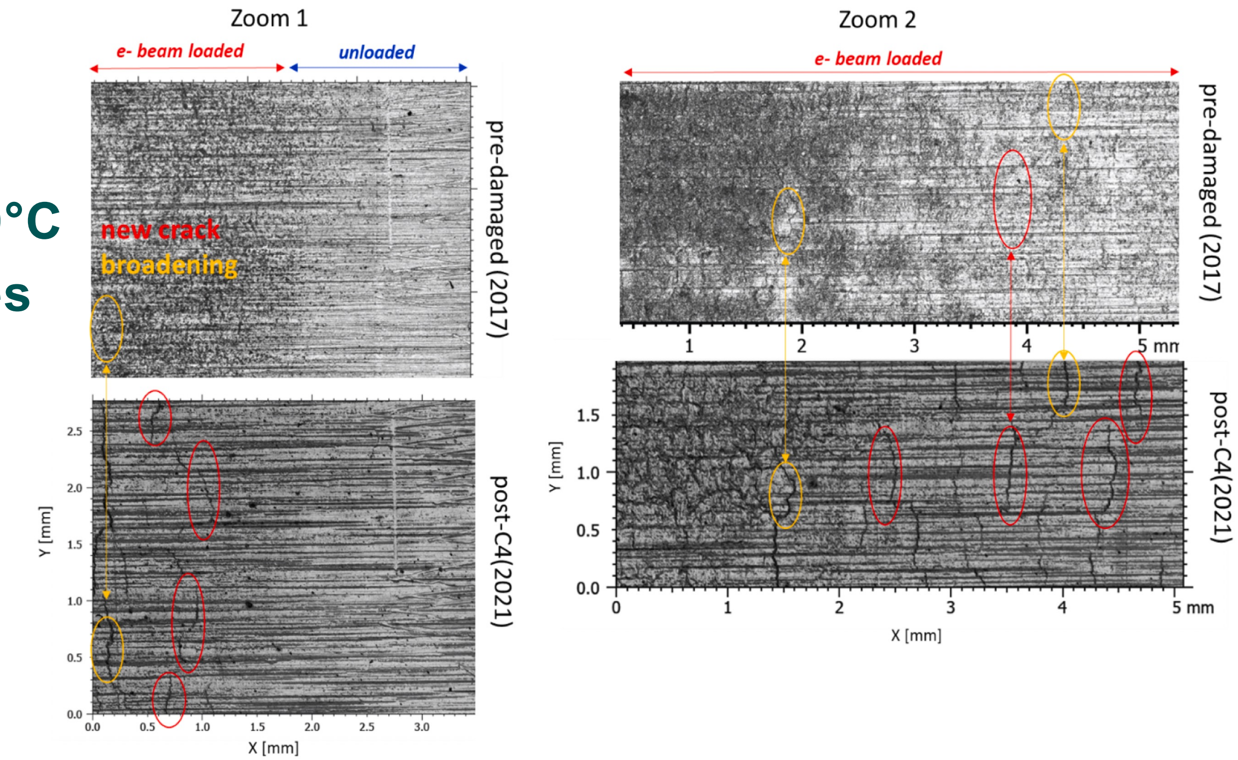


- **Crack formation observed in-situ by high resolution IR camera during LE melt experiment and modelled by T-REX → <u>ductile failure by thermal cycling</u>**

Tichit 2023 NME

CRACK FORMATION AND GROWTH – WEST C3-C4

- **PFU with pre-damaged monoblocks created by ELM-like transients in JUDITH-2**
- **Damage variation by varying power density 0.14-0.55 GW/m^2 and pulse-# 10^4-10^6**
- **C3: $q_\perp$ < 0.5 MW/m^2, T_s < 300°C**
  ⇒ no noticeable damage detected
  Richou 2022 NF
- **C4: 30# @ $q_\perp$ < 2.4 MW/m^2, T_s < 400°C**
  ⇒ new cracks in pre-damaged zones
  Corre 2023 NME



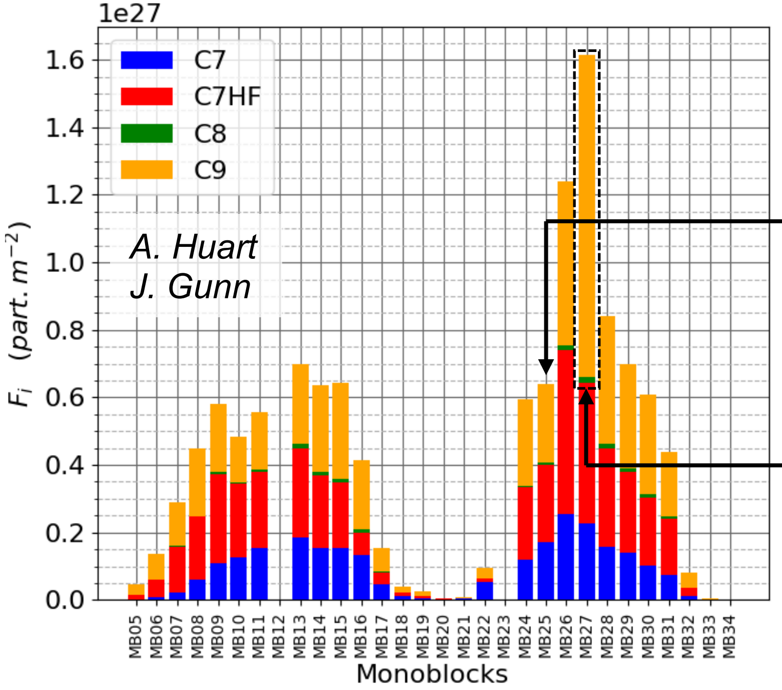
CRACK FORMATION AND GROWTH – WEST C7-C9

- **RT22-06, RT-06: Pre-damaged W monoblocks exposed for entire campaigns**

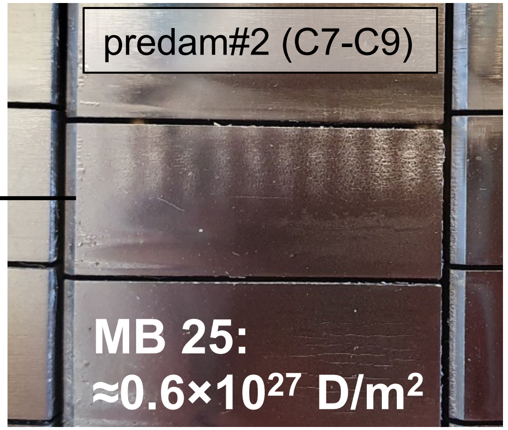
  (A. Durif, M. Richou, M. Diez, M. Firdaouss, Y. Corre, M. Wirtz)

- **ITER relevant fluence reached, up to 1.6×10^{27} D/m^2 ~10 pulses, T_{surf} up to 700°C**

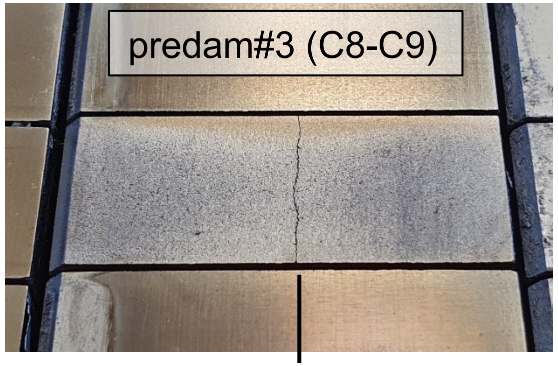
WEST cumulated fluence for each monoblocks over C7-C9



Crack network by ELM-like transients



Deep crack to cooling tube by repeated steady state cycling



MB 27: ≈1×10^{27} D/m^2

- **No noticeable impact on plasma operation**
- **Stack uninstalled after C9 for surface analysis**
- **Follow-up exposure in next campaign**

SUMMARY

- **For W-damage studies WP TE has two devices with complementary capabilities**

  AUG: – H-mode scenarios $\langle q_\perp \rangle$ <20 MW/m^2, $q_{\perp,ELM}$ <100 MW/m^2 (≈100 kJ/m^2)
  – Manipulator systems DIM-II & MEM for exposure in well-defined conditions
  – Actively cooled divertor target sample studies possible on DIM-II
  – Limited particle fluence practically achievable within one experiment day

  WEST: – Campaign integrated fluence of ~10 ITER pulses achievable (~10^{27}/m^2)
  – Actively cooled divertor target with ITER technology and geometry
  – Very high spatial resolution IR system and in-situ vessel inspection camera
  – Long discharges limited to L-mode at power loads <10 MW/m^2
  – Only campaign integrated exposure of divertor target samples

- **Upcoming experiments mainly focused on ITER new baseline R&D requirements**
  – PFC damage by runaway electron impact
  – Damage of divertor W-monoblocks by cracking and melting