28th IAEA Fusion Energy Conference,10 - 15 May 2021 – Virtual event

OV/2-1

Operating a Full Tungsten Actively Cooled Tokamak: Overview of WEST First Phase of Operation

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*http://west.cea.fr/WESTteam

Tore Supra transformed to WEST (2013-2016)

Tore Supra
Carbon Limiter
Long Pulse Ops

In Support of ITER Operation and DEMO conceptual activities

- ❑ **Divertor Configuration** (up-down symmetric divertors)
- ❑ **ITER-grade Divertor Plasma Facing Components**

Worldwide fusion labs involved WEST construction/exploitation (CN, EU, IN, JA, KO, US)

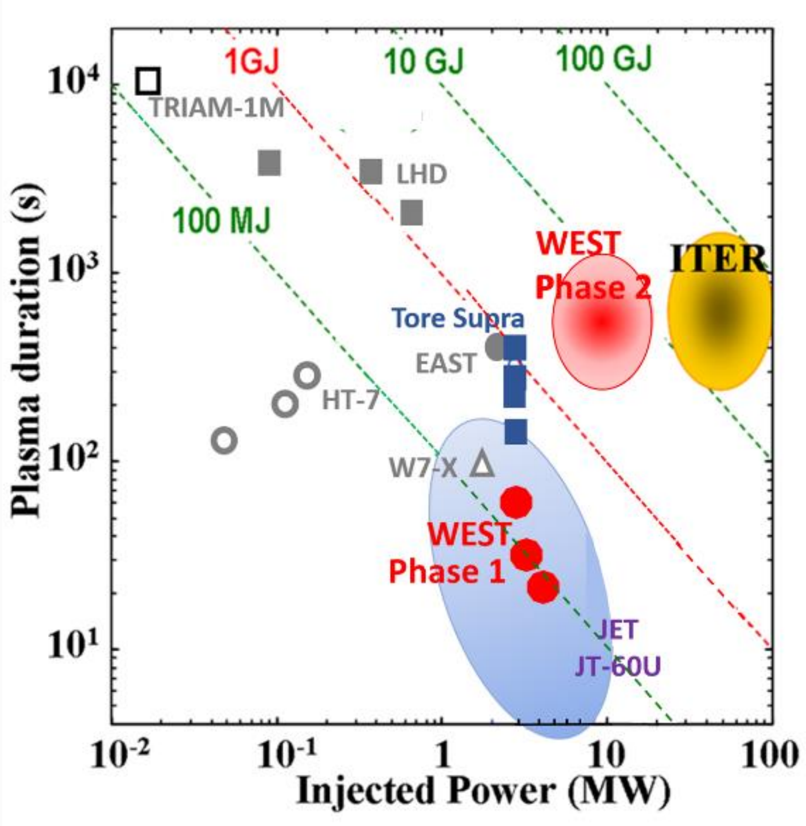
- **Missions and Research plan**
- **WEST Capability**
  - Heating and current drive systems
  - Specific diagnostics
- **Overview of phase I**
  - Development of scenarios towards steady-state operation
  - Plasma Wall Interaction
  - Tests of ITER-grade Plasma Facing Unit prototypes
- **Prospects for phase II**
  - Fully actively cooled ITER-grade divertor

First phase of operation 2017-2020: a set of ITER-grade prototypes complemented by tungsten coated PFC

- Testing prototypes of ITER-grade Plasma Facing Unit (PFU) from 6 suppliers (via F4E, JADA and ASIPP)
- Development of long pulse scenarios towards steady-state operations

Second phase of operation 2021+: full ITER-grade lower divertor, 1000 s pulse duration capability

- Preparation of ITER operation
  - ✓ Test et Validate ITER plasma facing components
  - ✓ Towards long pulse H-mode plasmas
  - ✓ Study plasma-surface interaction at high particle fluences
- Explore innovative PFCs for DEMO



Bucalossi J., Fus. Eng. Design 2014
Bourdelle C., Nucl. Fusion 2015

- Missions and Research plan
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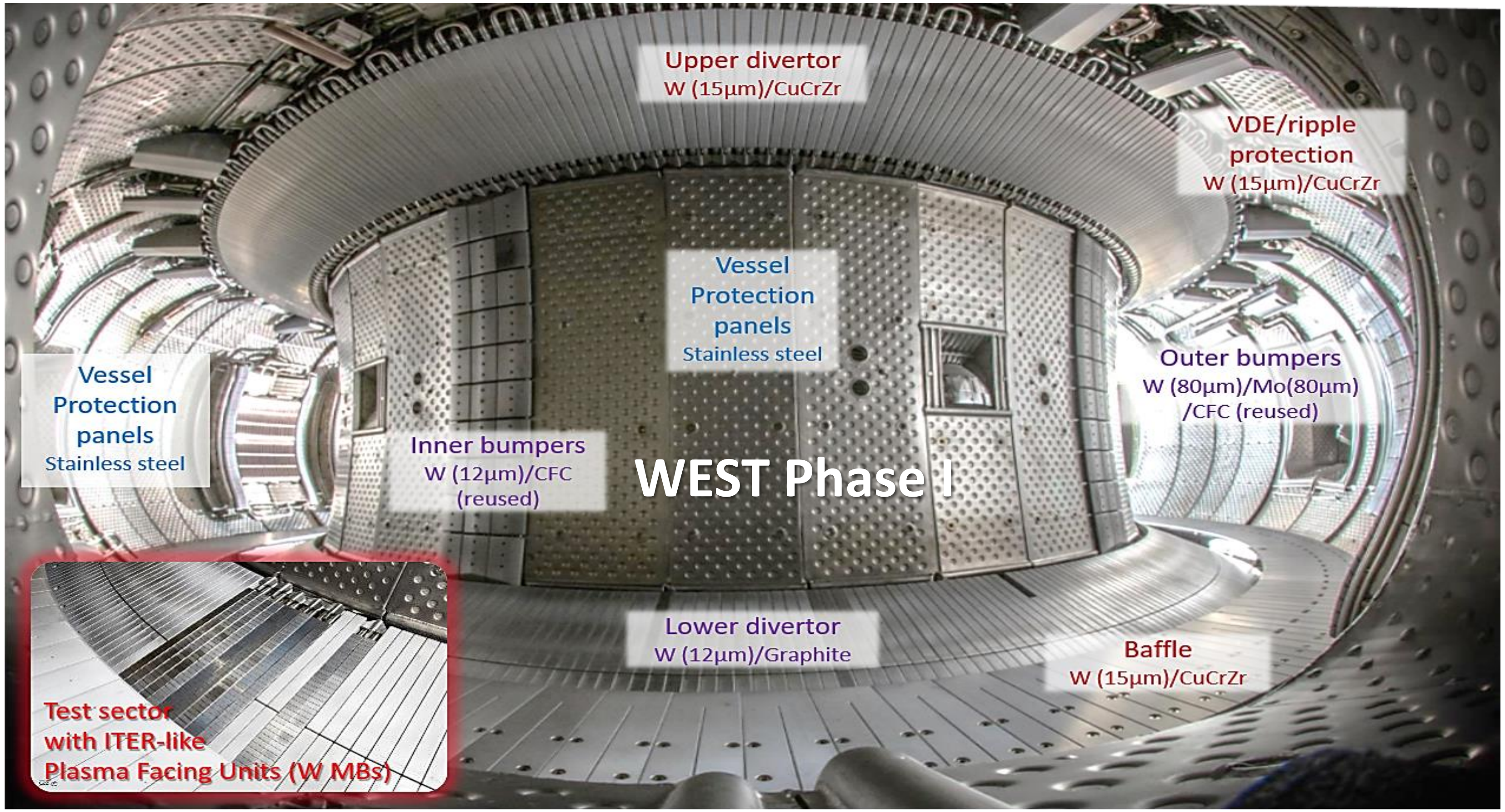
- **Superconducting tokamak with all tungsten PFCs**

B	I_p	R	A	V_p	κ / δ	P_{RH}	Magnetic conf.
3.7 T	1 MA	2.5 m	5-6	15 m^3	1.4 / 0.5	16 MW	LSN, USN, DN

- **Upper divertor**
  - ✓ W-coated copper (actively cooled)
  - ✓ Long pulse capability

- **Lower divertor**
  - ✓ A set of actively cooled ITER-grade PFUs
  - ✓ W-coated carbon (inertially cooled)



Multi-megawatt RF heating and current drive systems for long pulses

LIANG EX/P5-2, HILLAIRET TECH/3-5Ra

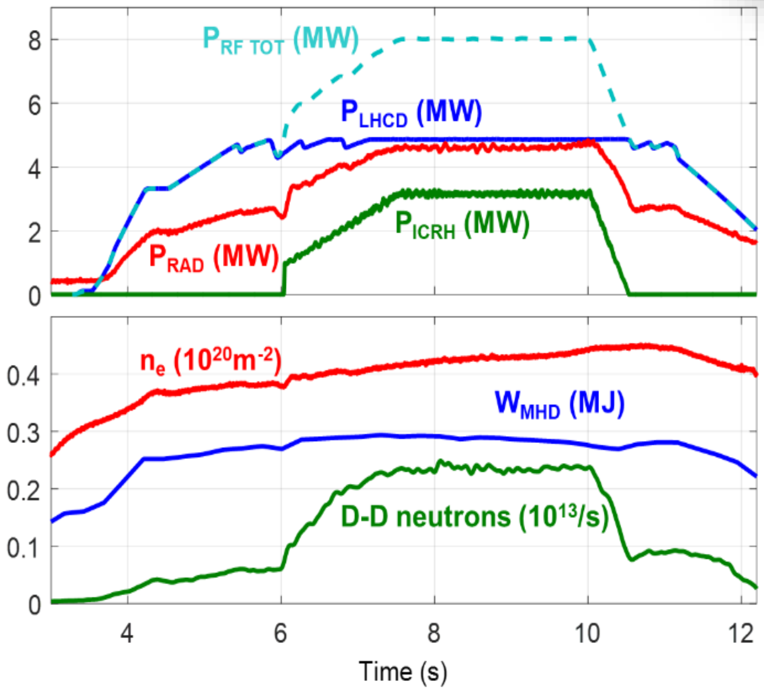
16 MW of Radio Frequency power

- **9 MW of Ion Cyclotron Resonance Frequency (ICRF) power**
  - ✓ Three actively cooled ELM-resilient antennas
  - ✓ 5.7 MW coupled to plasma
- **7 MW of CW Lower Hybrid Frequency power @ 3.7 GHz**
  - ✓ Two actively cooled launchers (Fully Active Multi-junction – FAM and Passive Active Multi-junction – PAM)
  - ✓ 5.3 MW coupled to plasma

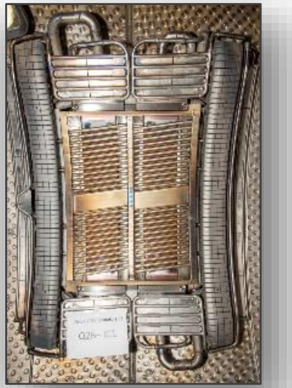
Up to 9 MW of combined ICRF/LHCD power coupled to plasmas

Long duration RF heated plasmas routinely performed, 30 s – 1 min

WEST # 55799

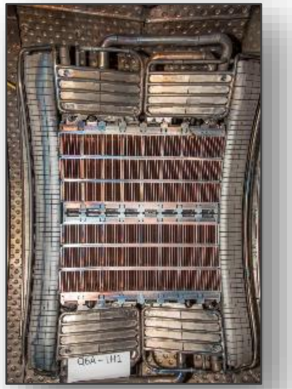


IC2-Q1B



IC1-Q2B

IC3-Q4B



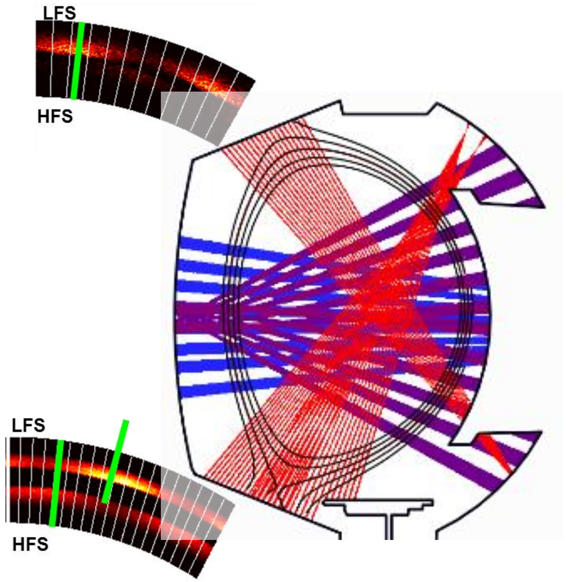
LH1-Q6A

LH2-Q6B

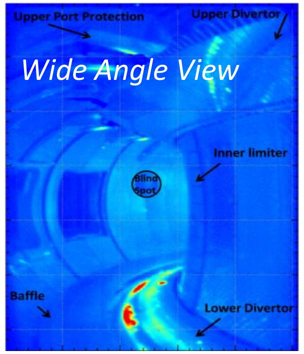
Delpech L., Fus. Eng. Design 2015
Bernard J.M., Fus. Eng. Design 2017

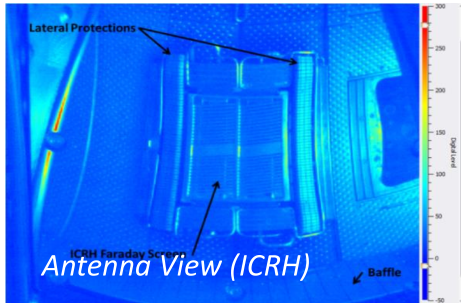
Monitoring and inspection of plasma facing components

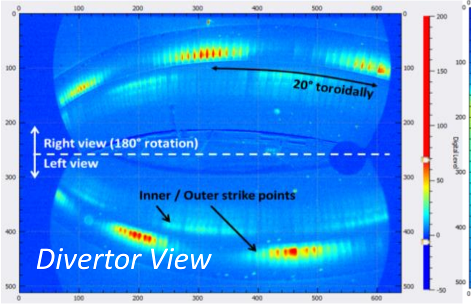
Visible spectroscopy + VUV

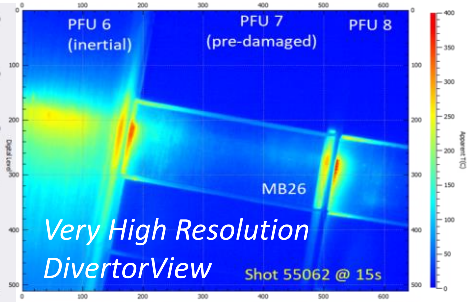


Extensive IR coverage

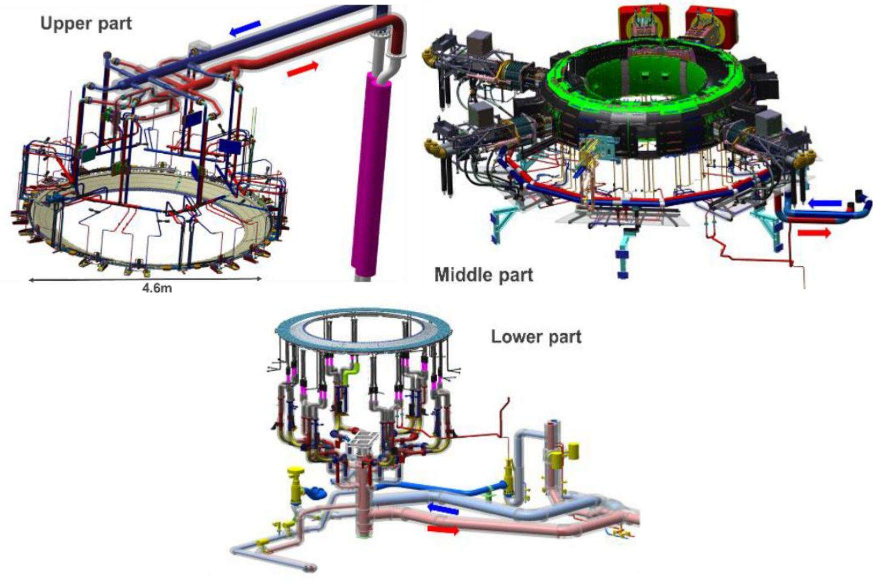




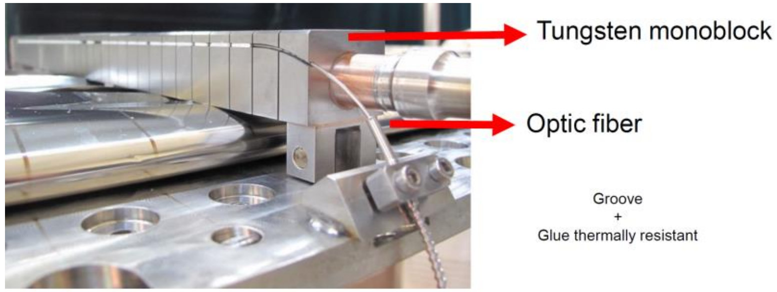




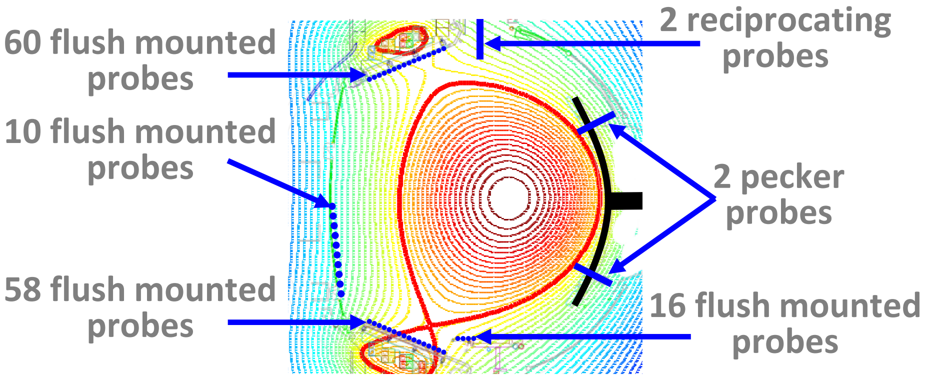
200+ calorimetry sensors in PFC



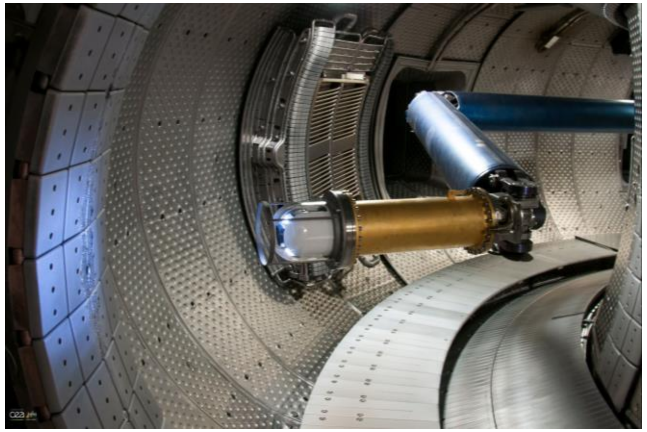
Fibber Bragg Grating in divertor



Wide array of Langmuir probes

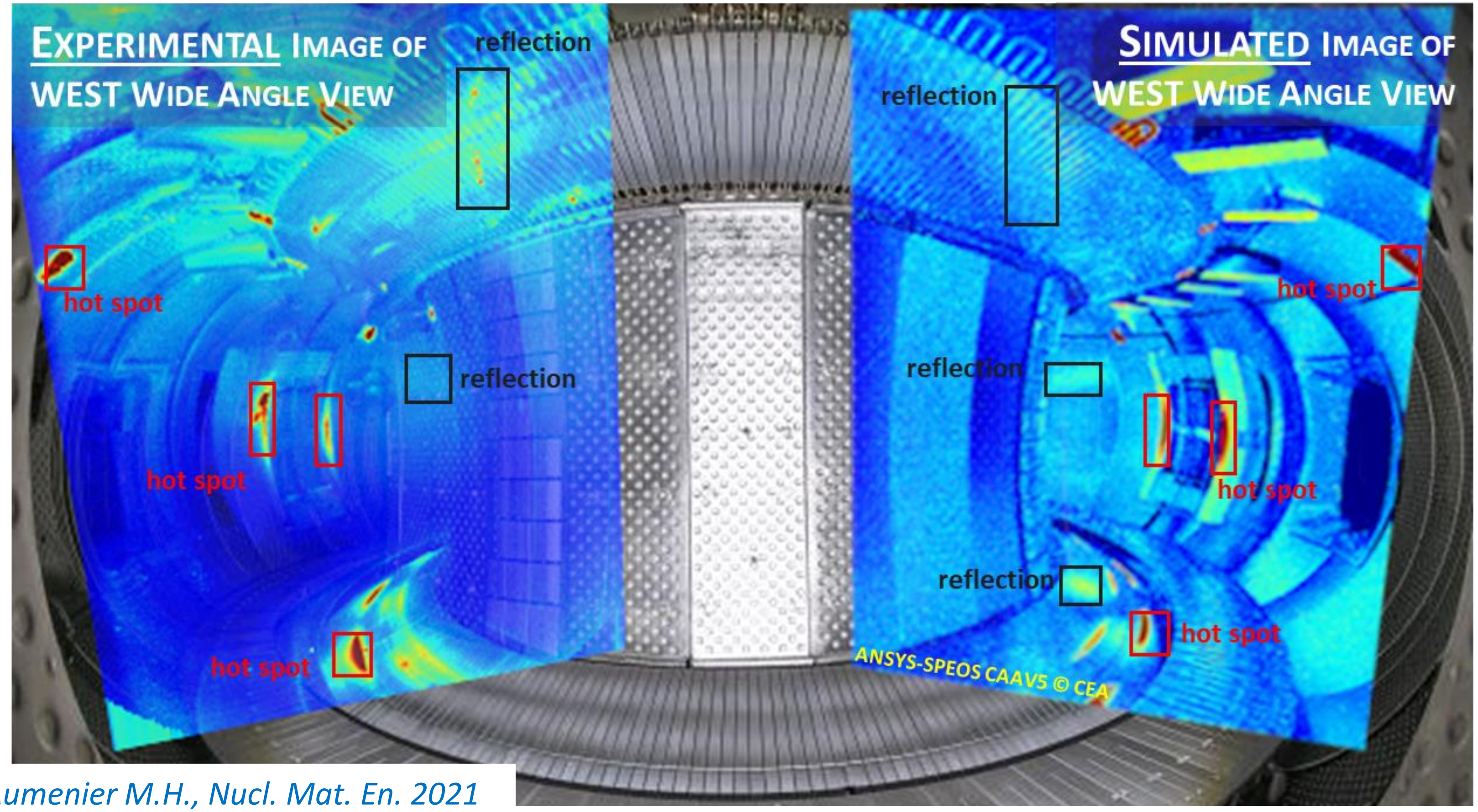


Articulated Inspection Arm

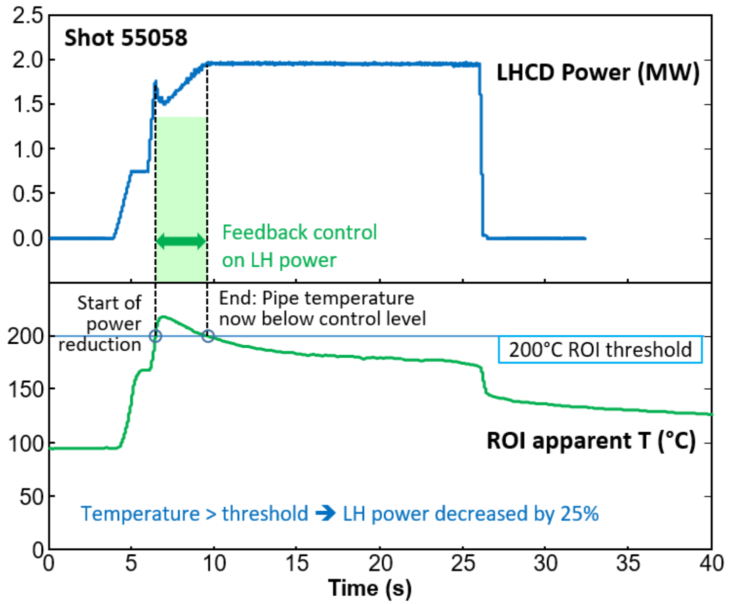


COURTOIS TECH/P8-18

- Multi diagnostics Wall Monitoring System (IR, spectro., calorimetry, Langmuir probes, …)
- Real time image processing, thermal events detection (machine learning, scene simulation)
- Various real time feedback control strategies implemented (32+ Region Of Interests)



Aumenier M.H., Nucl. Mat. En. 2021



Real-time feedback control of the LHCD power, using IR system, to avoid the overheat of PFCs

Crucial for safe operation in ITER metallic environment

- Missions and Research plan
- WEST Capability
  - Heating and current drive systems
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Core W radiation issues during current/power ramp up

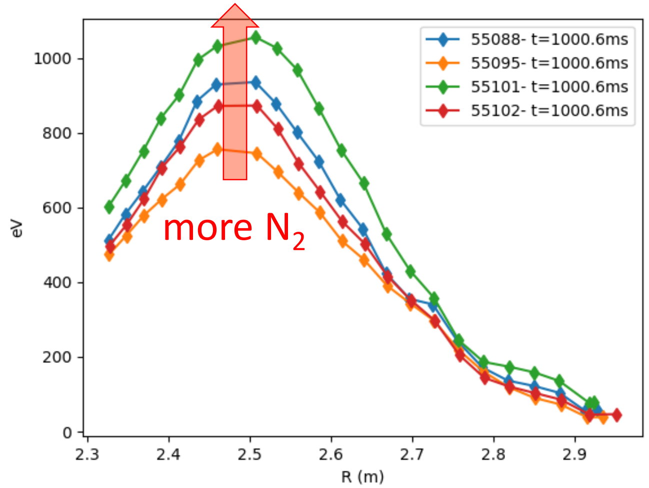
- **Core W radiation triggers MHD**
  - ✓ T_e central cooling → flat/hollow current density profile
  - ✓ 2/1 tearing mode
  - ✓ Possible locked mode → disruption
- **Similar observation in JET ITER-like wall experiments**

Challis C., NF 2020

- **Early N_2 injection during the current ramp-up avoided MHD**
  - ✓ Faster resistive current diffusion (increasing plasma inductance li) → Higher core temperature

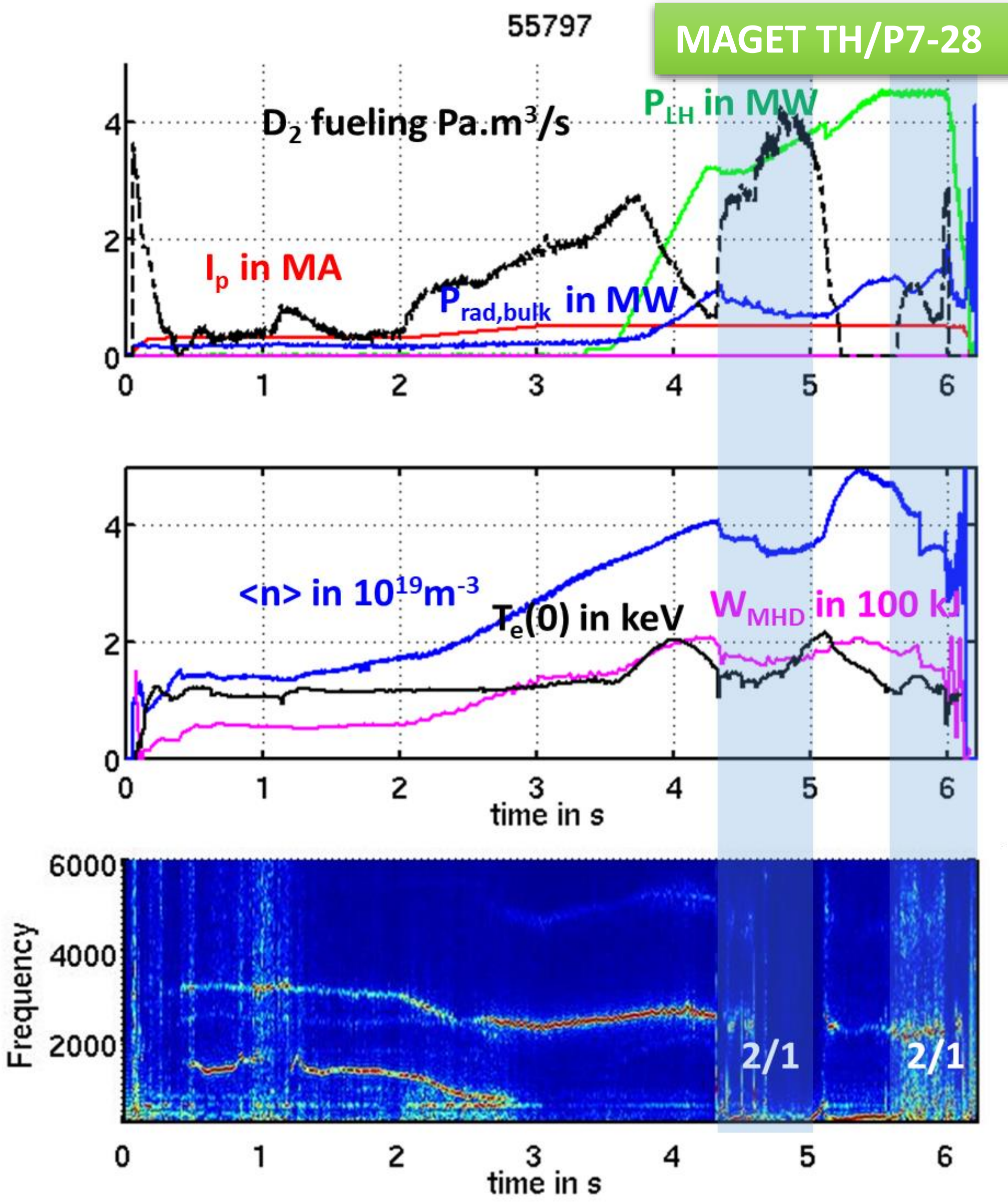
Impact of N injection during the ramp-up phase

Maget P., EPS 2020

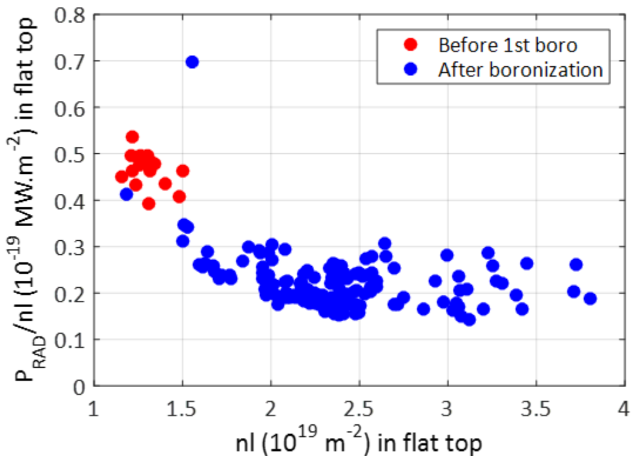


Challenge for MHD-stable scenario in a full W environment

MAGET TH/P7-28

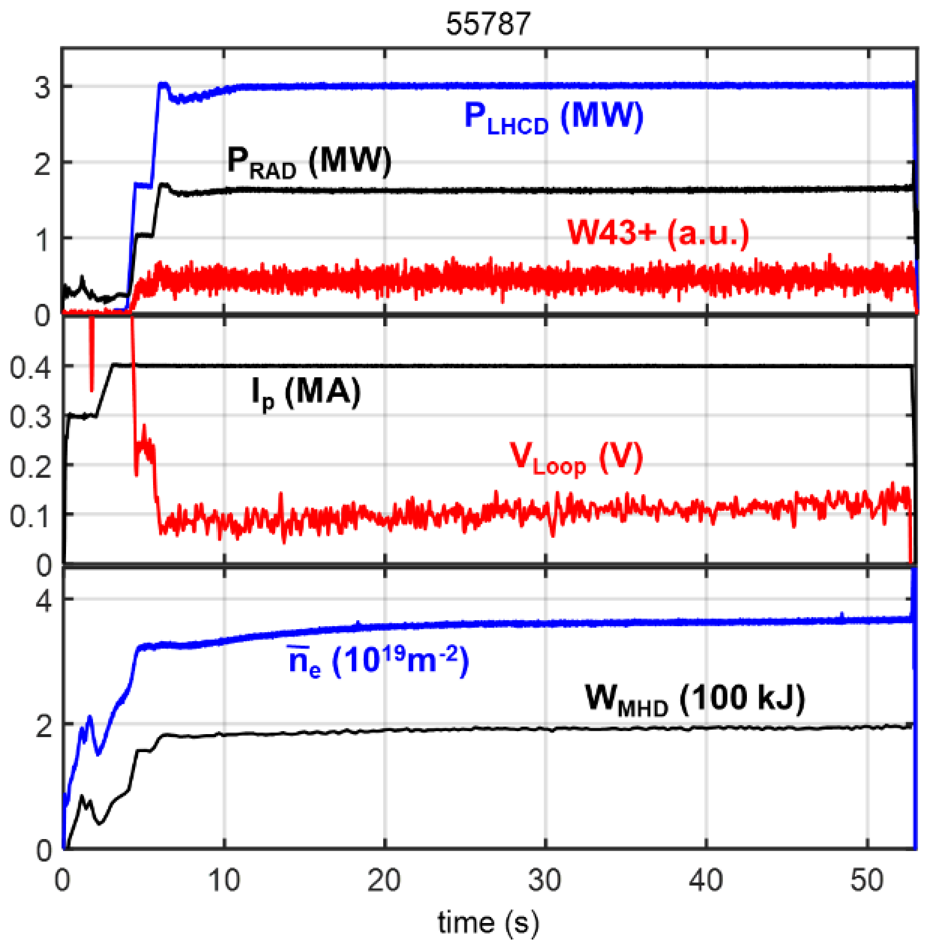


Long pulse discharges maintained up to one minute in USN



- **Boronization needed to open the operational domain**
  - ✓ Strong reduction of light impurities (oxygen): improved breakdown conditions and higher density achievable

GONICHE EX/P5-11, LOARER EX/P5-6



- **Radiation power fraction generally 50-55%**
  - ✓ Dominated by tungsten: concentration $n_W/n_e \leq 3 \times 10^{-4}$
  - ✓ Similar for LHCD and/or ICRF heated discharges
- **No tungsten accumulation despite peaked electron density profiles**
  - ✓ Peaked density profile unfavorable for neoclassical W transport
  - ✓ Could be explained by low torque plasma (V_ϕ ~ 0-15 km/s)
  - ✓ Good news for low torque plasma in ITER?

Yang et al., Nucl. Fusion 2020

Ekedahl A., APS 2019

Good L-mode confinement at large aspect ratio

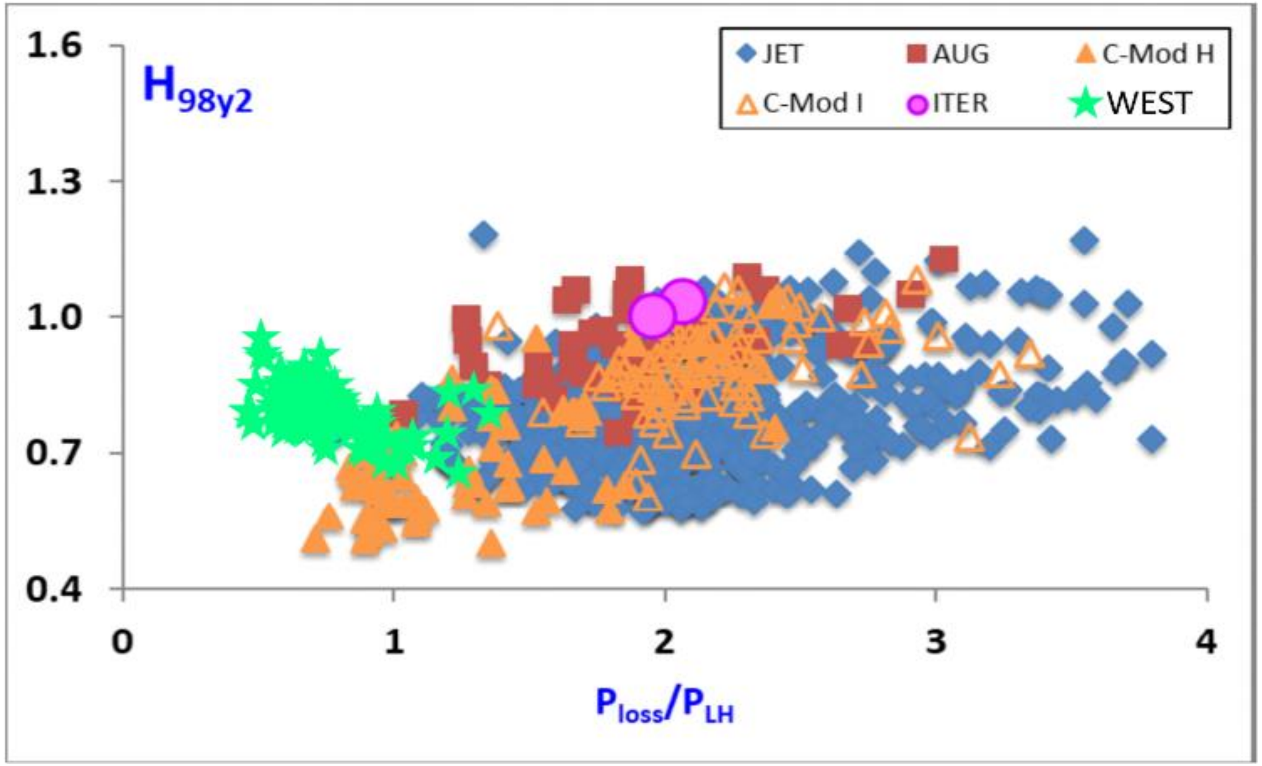
SARAZIN TH/P5-20

- **L-mode discharges exhibits H_{98} ~ 0.8**
  - ✓ Similar confinement time prediction using L96 or H98
  - ✓ Weak aspect ratio dependence of L96 confirmed (adding 1000+ WEST entries modifies exponent in L96 from 0.04 to 0)

Ostuni V., ITPA TC 2020

- **Close to H-mode in metallic machines and I-modes in C-Mod**
  - ✓ Disagreement between scaling laws: H98 reports a degradation with A while DS03 a benefit

Petty C.C., PoP 2004



From A.C.C. Sips et al 2018 Nucl. Fusion 58 126010

Need to explore H-mode confinement at large aspect ratio (WEST A~5-6)

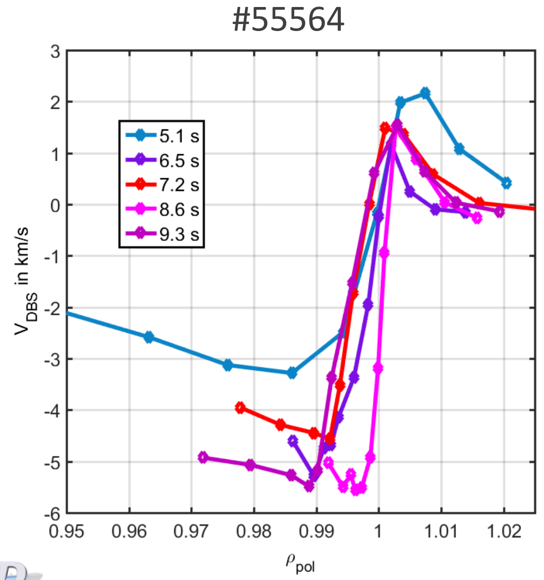
H-mode access: oscillating transition due to W radiation

VERMARE EX/P5-4

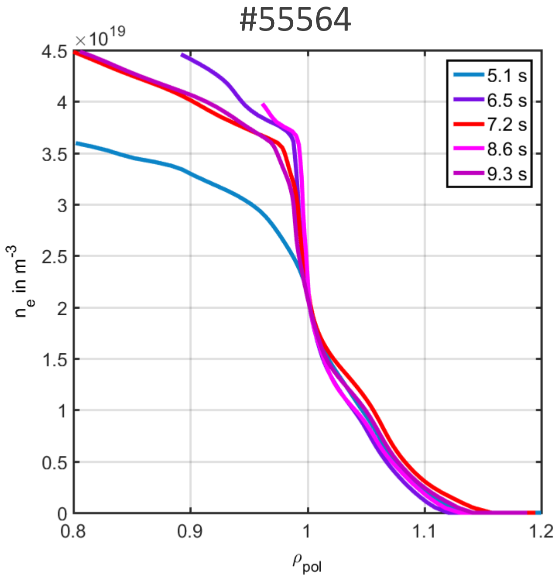
- **Coupled RF power in phase 1 → operation close to the expected L-H threshold**
  - ✓ P_{L-H} around 3-4 MW at 3.7 T

Martin Y., J. Phys. Conf. 2008

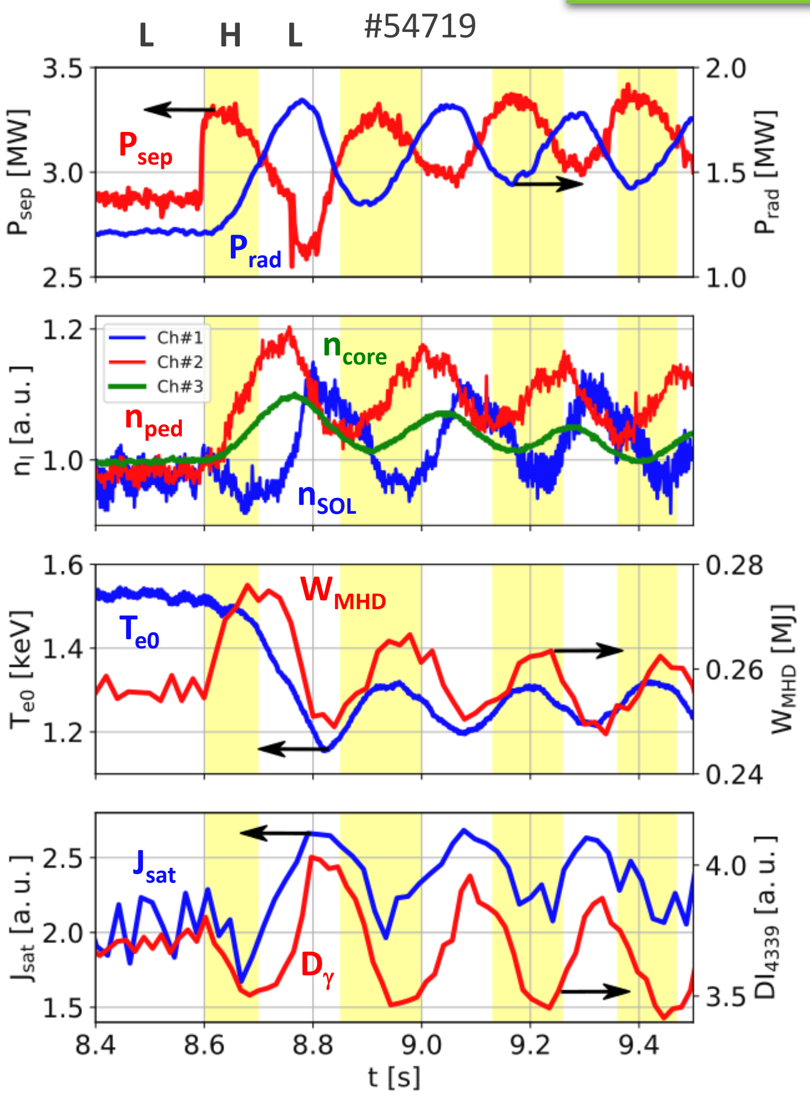
- **L-H transition not sustained due to bulk radiation increase**
  - ✓ Density increase ↗ bulk radiation ↗ separatrix power ↘
- **Radial electric field profile exhibits a well inside the separatrix at L-H transition onset**



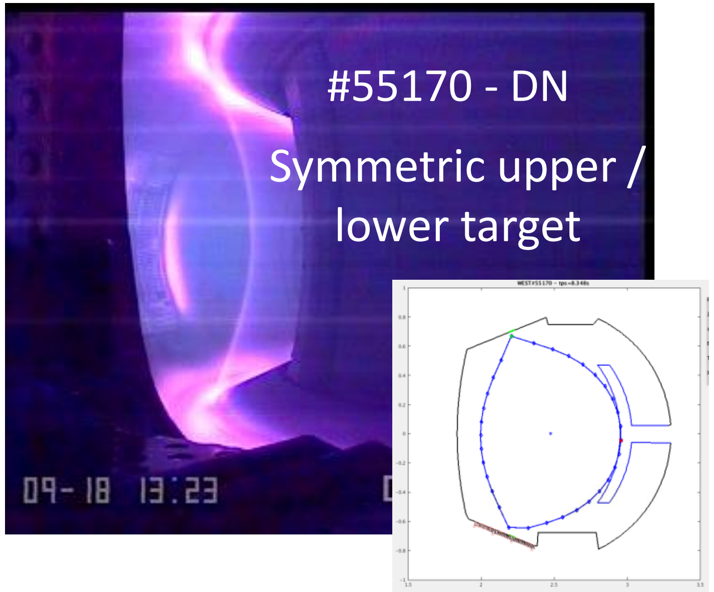
ExB velocity profile

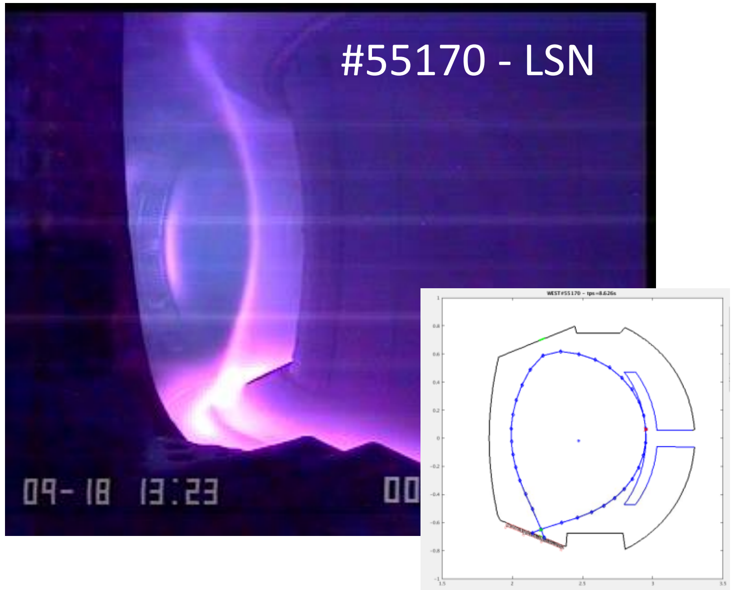


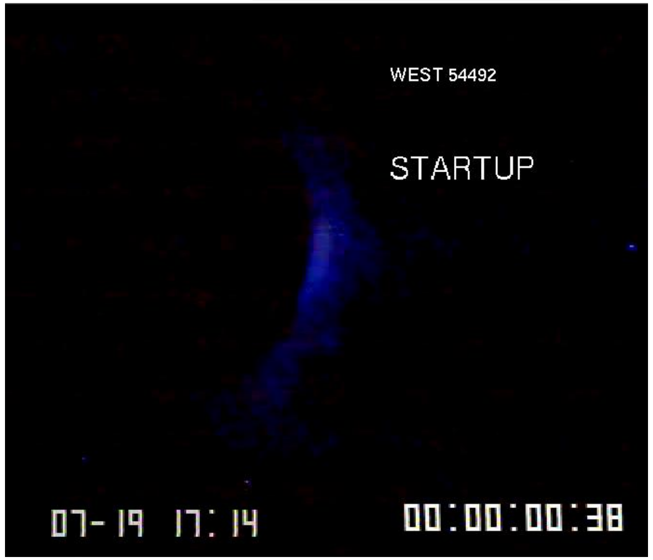
Density profile evolution

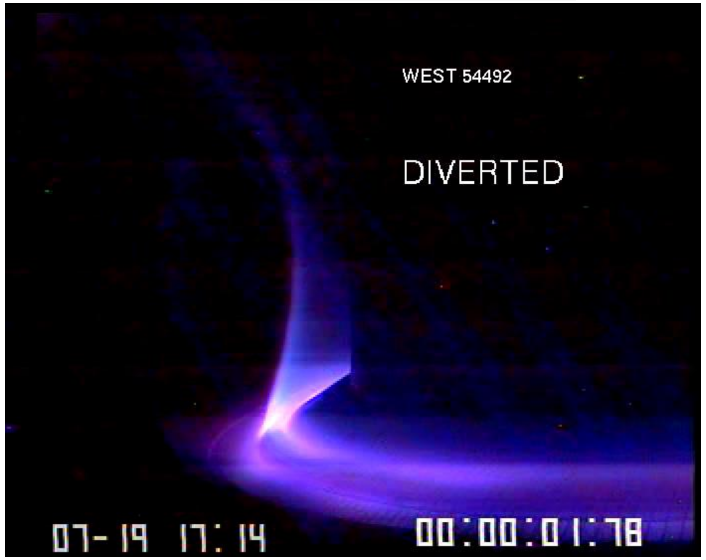


Exploration of double null operation & divertor detachment started

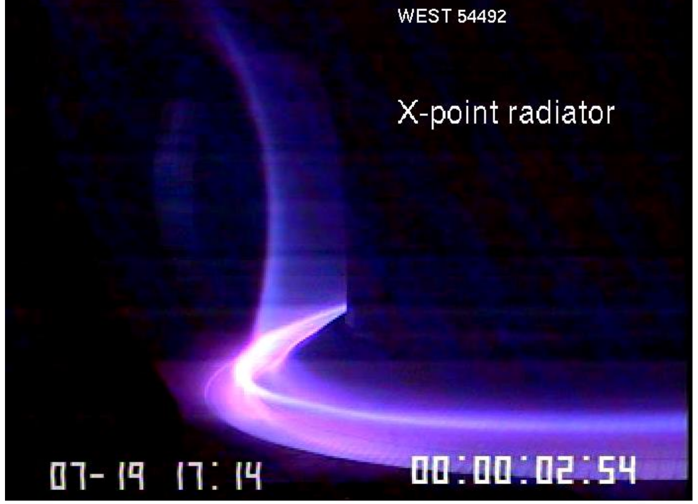








Stable X point radiation regime



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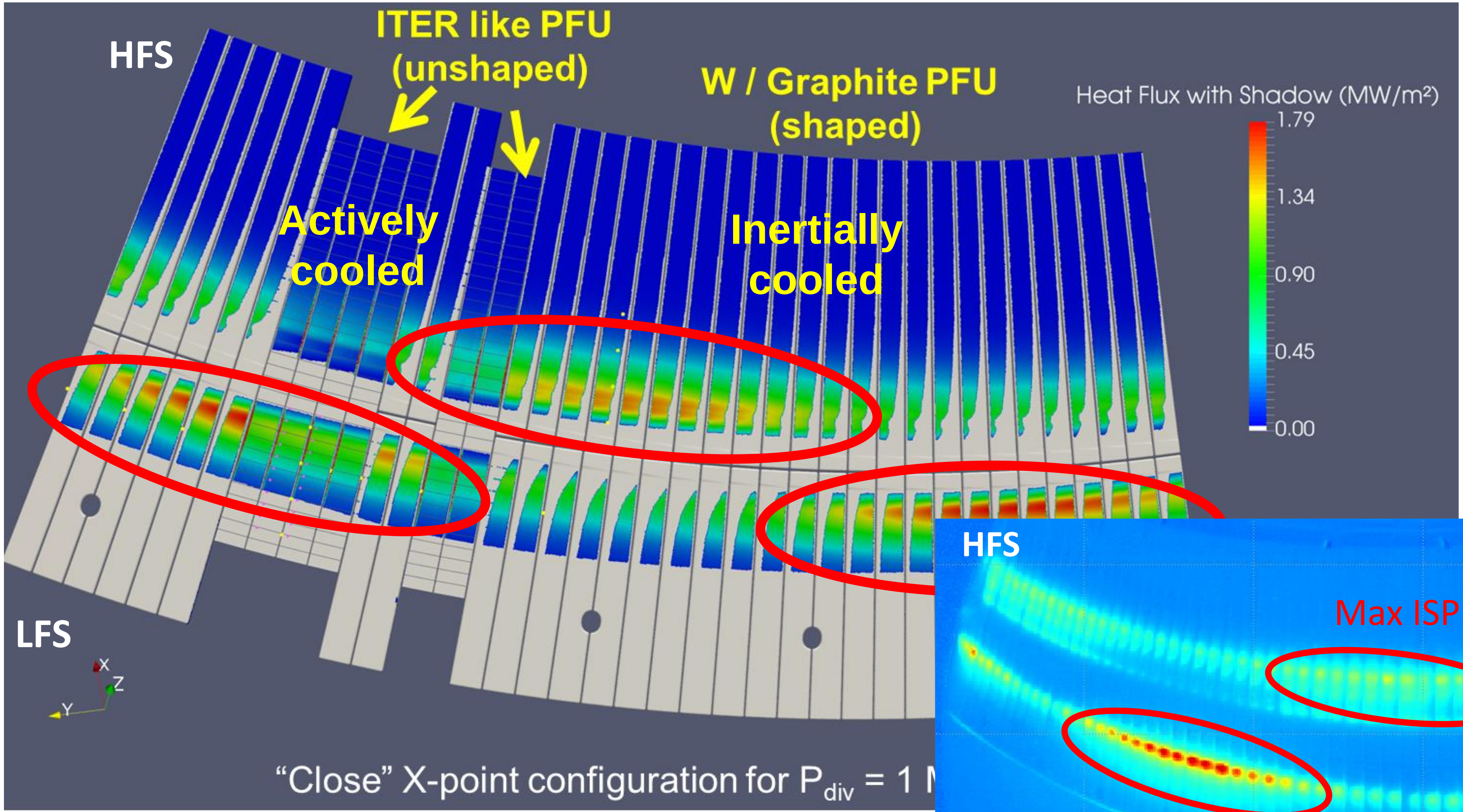
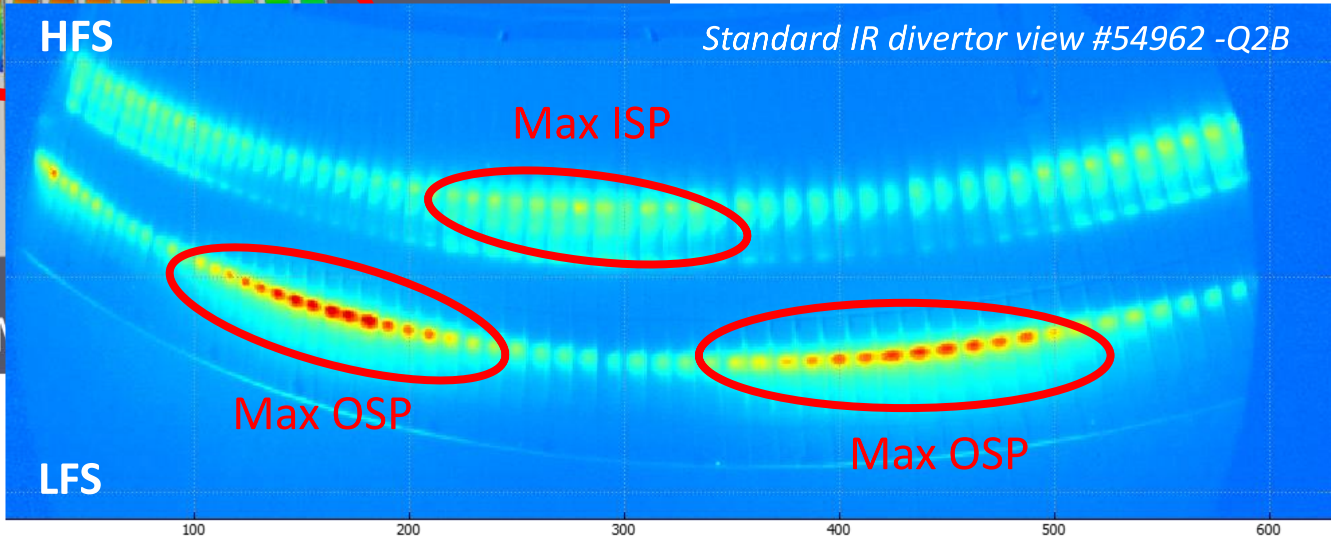
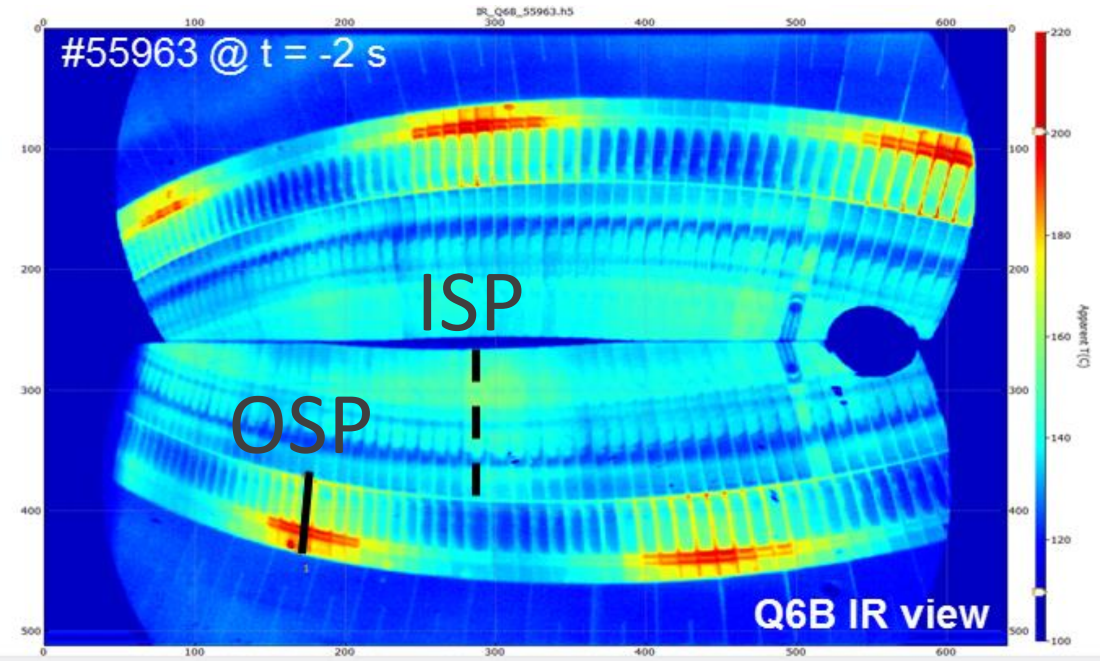




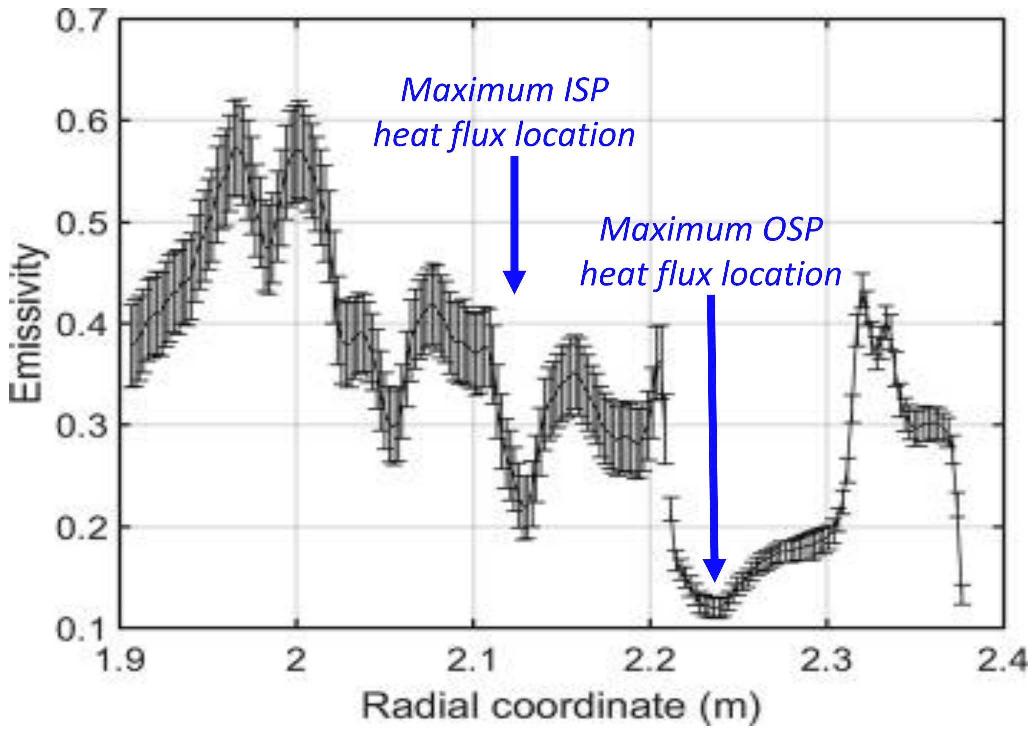
- Field line incidence angle varies toroidally (18 TF coils)
  - ✓ ≤ 3° at strike point
- Incidence angle in the ITER range

W emissivity correlated with erosion/redeposition pattern

- **W emissivity sensitive to surface state → complex pattern along the PFU**
  - ✓ ~0.12 and ~constant in OSP region (consistent with pristine inertial PFU)
- **Evolves significantly over the campaign**
- **In-situ emissivity profile from IR measurements between pulses after PFU thermalisation**



Apparent temperature map between pulses (with homogeneous PFU temperature)



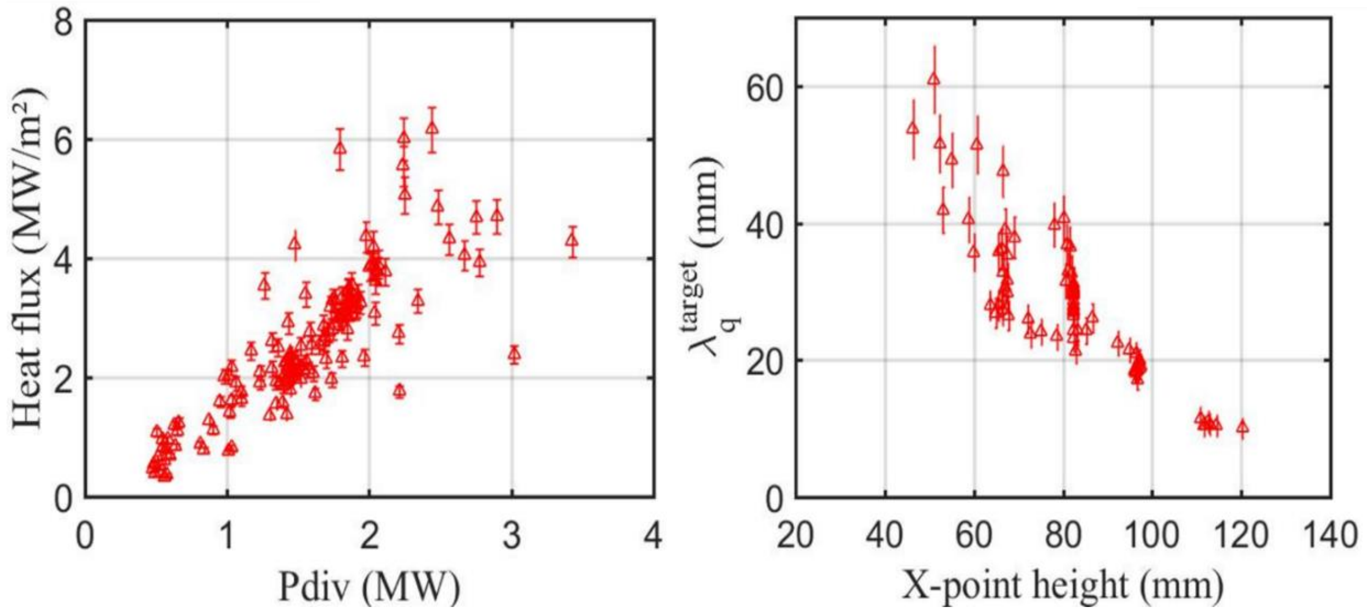
Gaspar J., Nucl. Mat. En. 2020

Divertor peak heat flux: towards 10 MW/m² in steady-state

GASPAR EX/P5-10

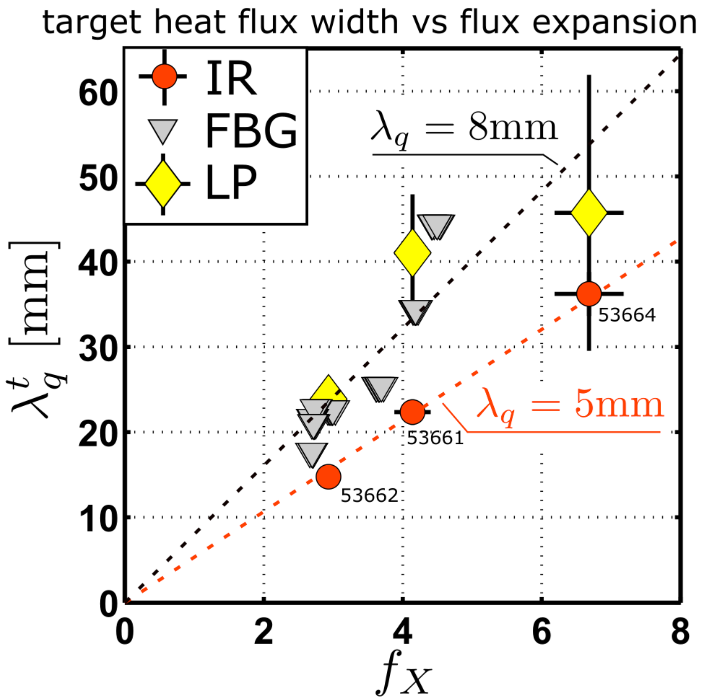
▶ Divertor peak heat flux ~ 6 MW/m² for P_{LHCD} = 4 MW

- ✓ Asymmetry between inner and outer divertor (1/4 vs 3/4)
- ✓ Fine tuning by adjusting X point height
- ✓ 10-20 MW/m² achievable in phase 2



▶ Discrepancy in SOL width estimates

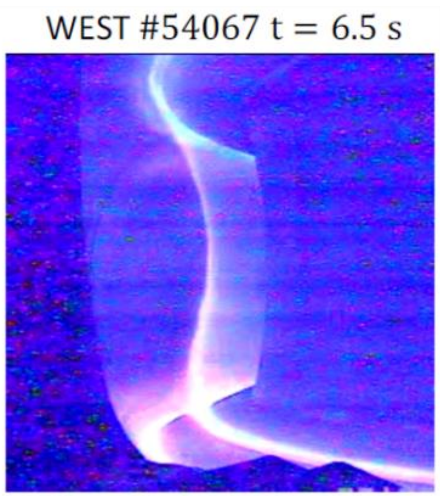
- ✓ IR analysis in line with L-mode scaling with λ_q ~2.8 mm (L-mode scaling: 2.9-3.7 mm)
- ✓ Fibber Bragg Grating/Thermocouples and Langmuir probes gives λ_q x2-3

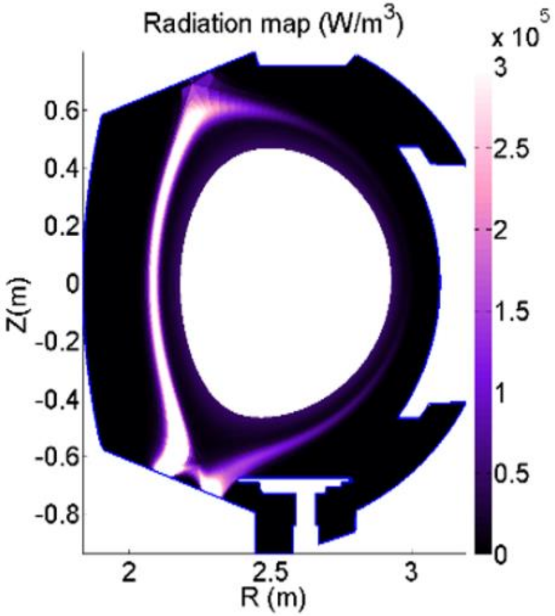


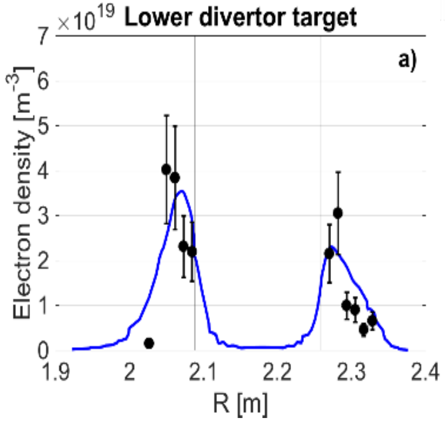
Fedorczak N., Phys. Scr. 2020

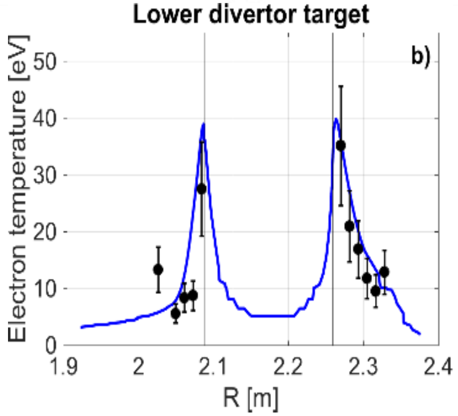
A test bed for validating plasma boundary codes

CIRAOLO TH/P4-12

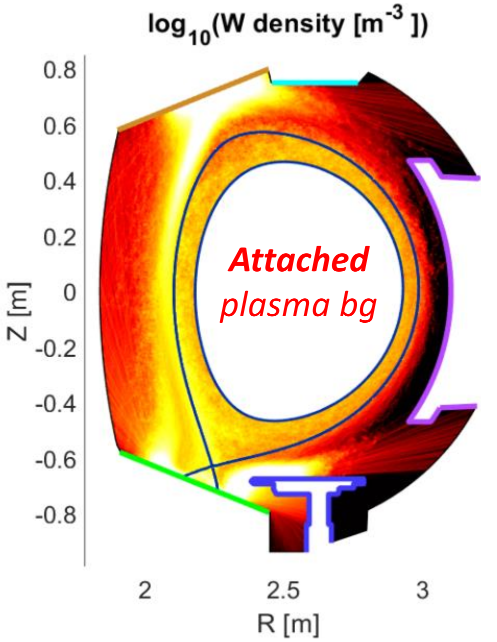


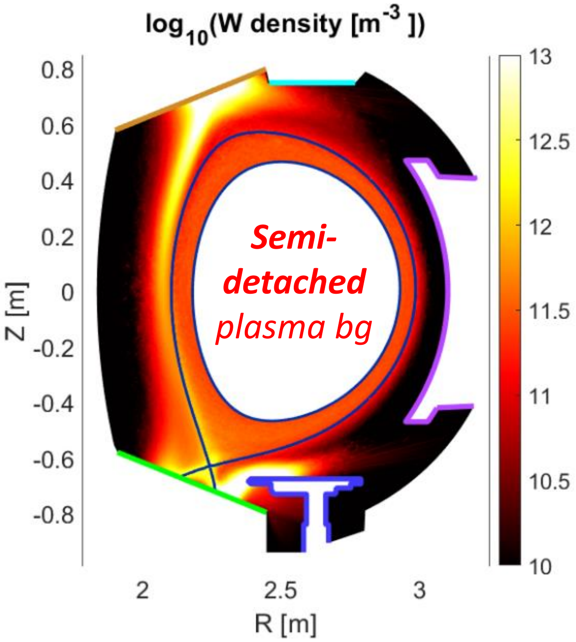






- **Plasma background: impurities included**
  - ✓ Zhdanov multi-fluid collisional closure implemented in SolEdge2D-Eirene
  - ✓ Good agreement with LP and bolometry measurements
  - ✓ In/out asymmetries reproduced
- **First simulations of W sources with ERO2.0**
  - ✓ Simulation of poloidal W density map using S2DE plasma backgrounds



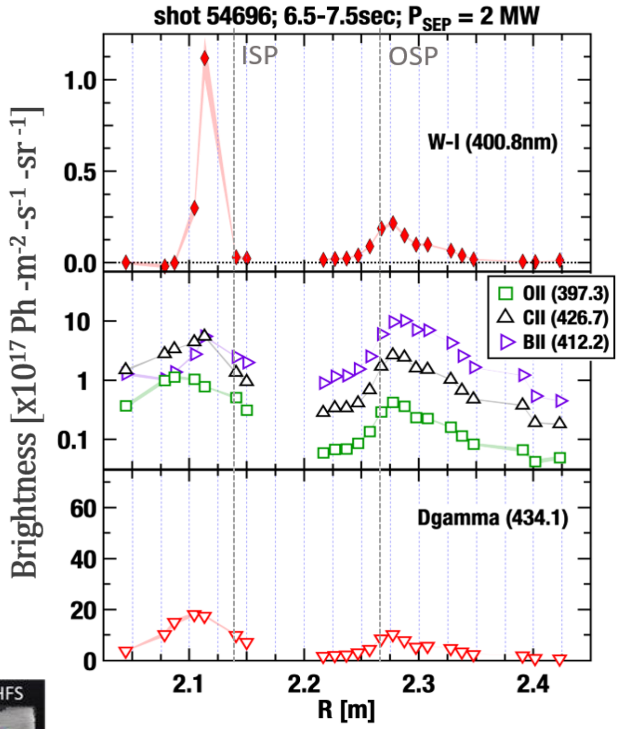


With its well diagnosed divertor WEST provides a test bed to progress in divertor physics understanding

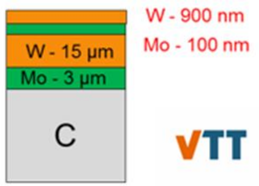
Gallo A., Nucl. Fus. 2020, Di Genova S., in preparation

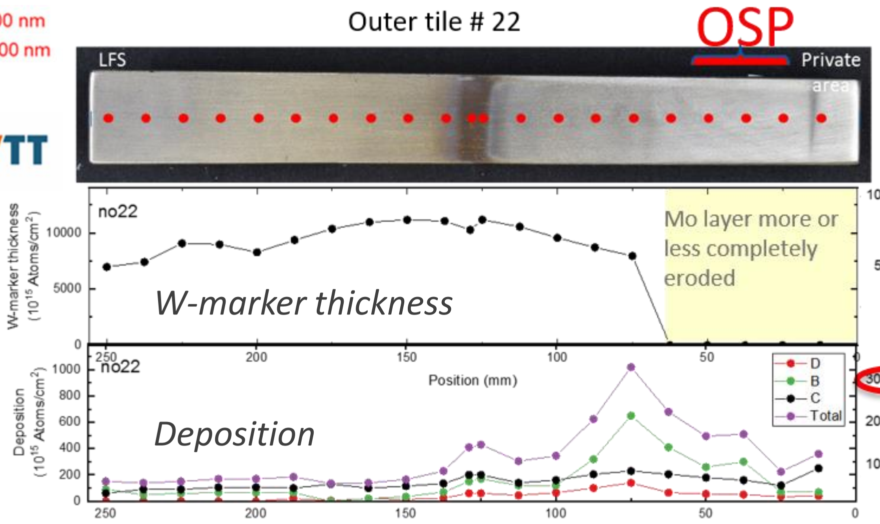
- **In/out asymmetries in divertor emission profiles**
  - ✓ Significant in / out asymmetry in WI brightness @ low power, more balanced at higher power
  - ✓ Sputtering dominated by light impurities, consistent with ~3% of O and/or C (ohmic conditions @ ISP)

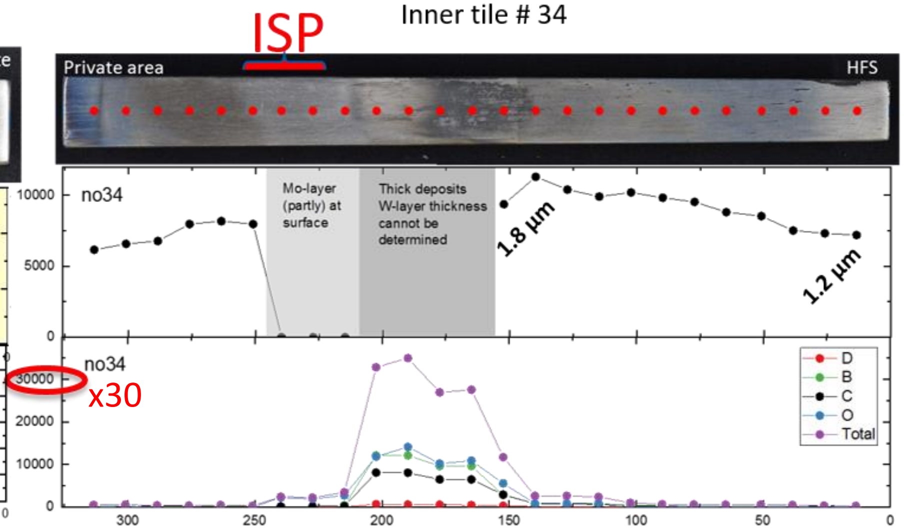
- **Net erosion @ ISP/OSP, more pronounced @ OSP**
  - ✓ OSP: net erosion ≥ 1 µm. C3 campaign averaged net erosion rate ≥ 0.1 nm/s
  - ✓ Moderate redeposition close to OSP. Thick redeposited layers (> 10 µm) close to ISP
  - ✓ Transition strong-erosion/thick deposition very sharp



Klepper C. et al., APS 2019
Unterberg Z., ANS-TOFE 2020
Van Rooij G., Phys. Scr. 2020





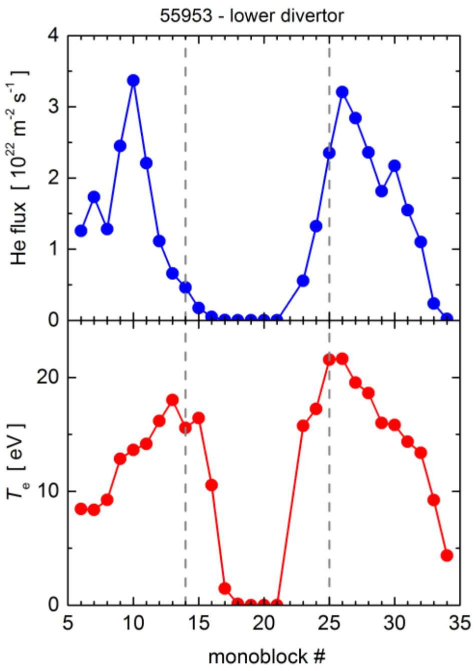


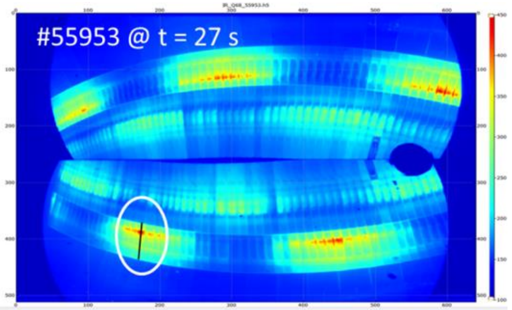
Balden M., PFMC 2021

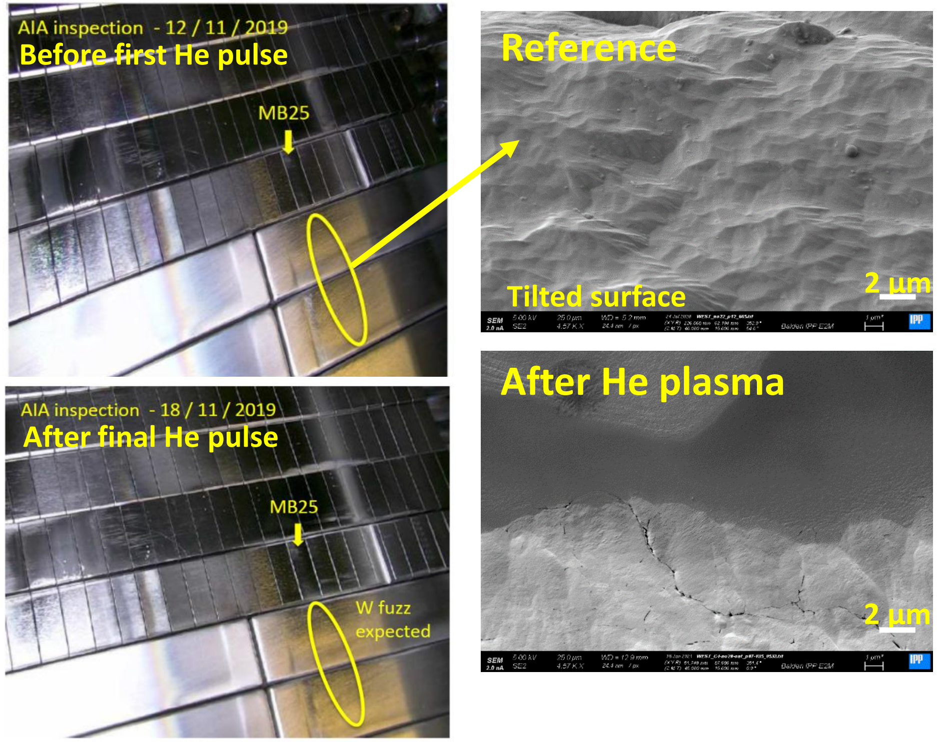
Long pulse He experiments: no W fuzz observed on W-coated PFUs

TSITRONE EX/P5-7

- **Repetitive 20-30 s pulses over 1 week of operation: 4.4GJ of injected energy, ~2000 s of He plasma exposure**
  - ✓ Incident energy > 100 eV (competition with erosion at OSP ?)
  - ✓ T_{surf} over 700°C at max OSP on inertial PFUs for a significant time
  - ✓ Fluence at max OSP ~4 10^{25} He/m^2
- **Post mortem analysis of W PFUs**
  - ✓ No W fuzz observed in WEST W-coated PFUs
  - ✓ No visible change of reflection properties
  - ✓ No evidence of W nanostructures in Scanning Electron Microscopy (SEM)
- **Does W erosion dominate over W fuzz formation?**
  - ✓ Role of W coatings?
  - ✓ Role of prompt re-deposition at 3.7 T?







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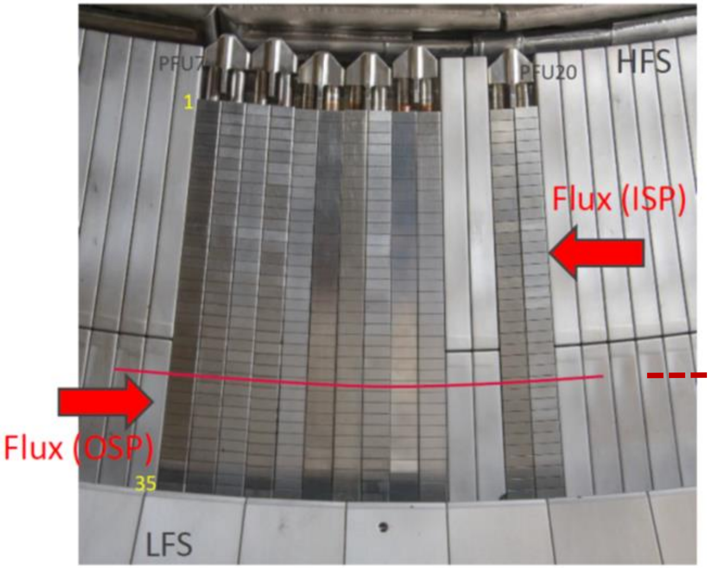
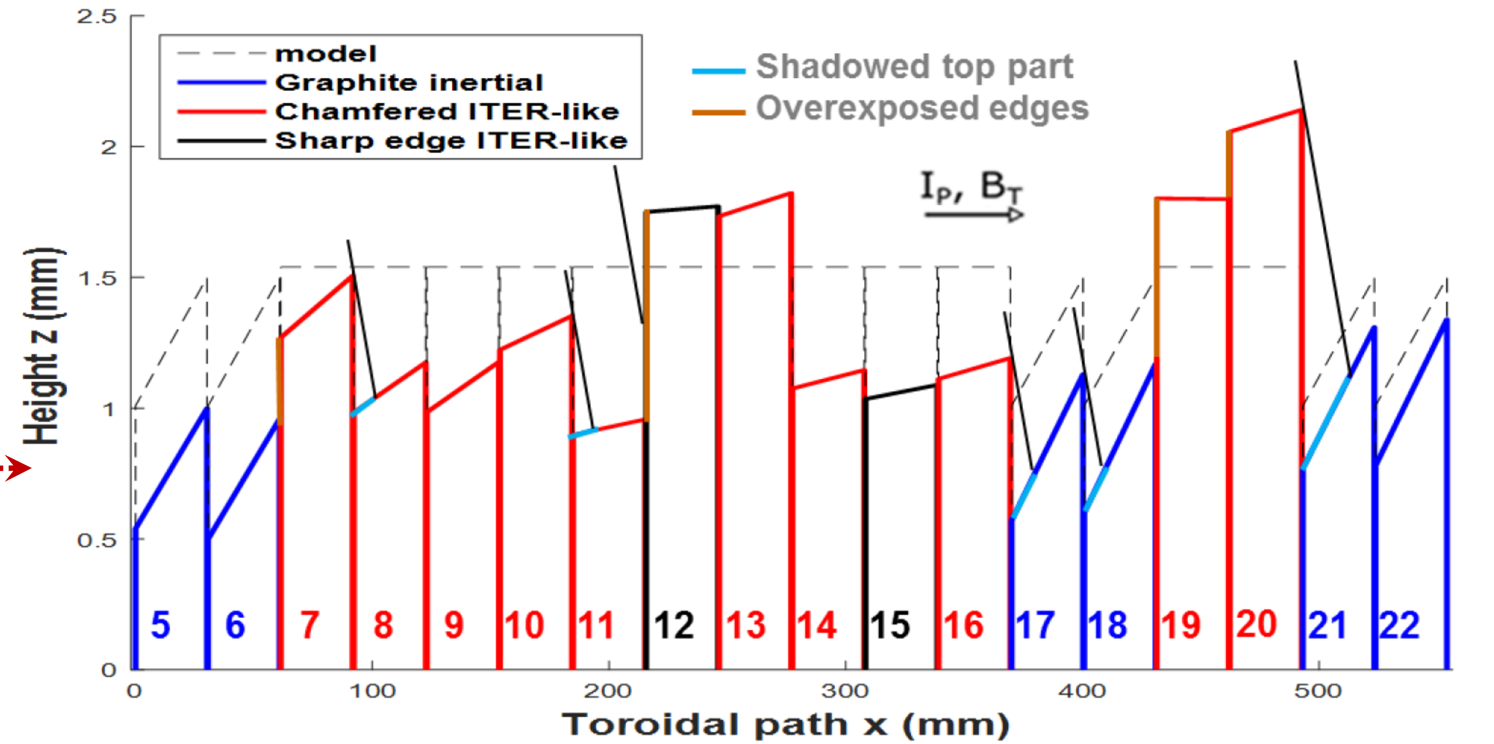
  - Plasma Wall Interaction
  - **Tests of ITER-grade Plasma Facing Unit prototypes**
- Prospects for phase II
  - Fully actively cooled ITER-grade divertor

A set of ITER-grade PFUs prototypes exposed to tokamak plasma

- No shaping on W monoblocks, sharp and chamfered edges (bevel on W-coated PFUs)
- Three relatively misaligned PFUs at OSP during C3 campaign



C3 campaign PFUs layout



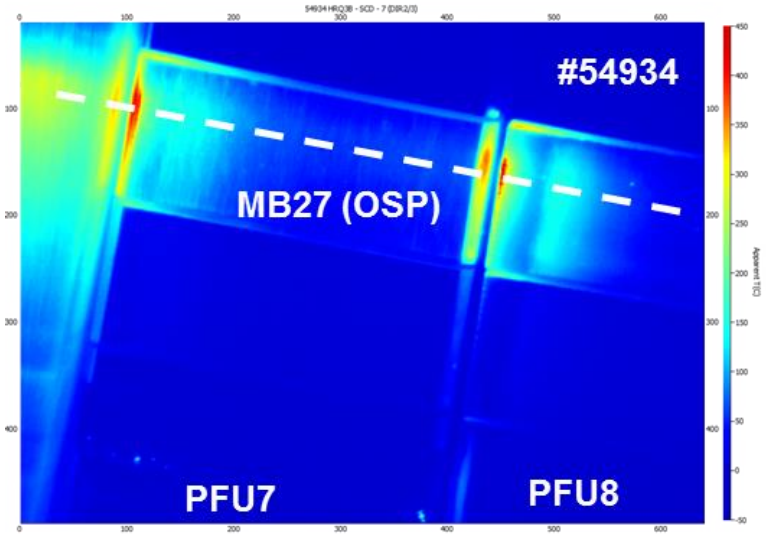
Misaligned PFUs at OSP. PFU#7: 0.31 mm; PFU#12: 0.79 mm; PFU#19: 0.63 mm

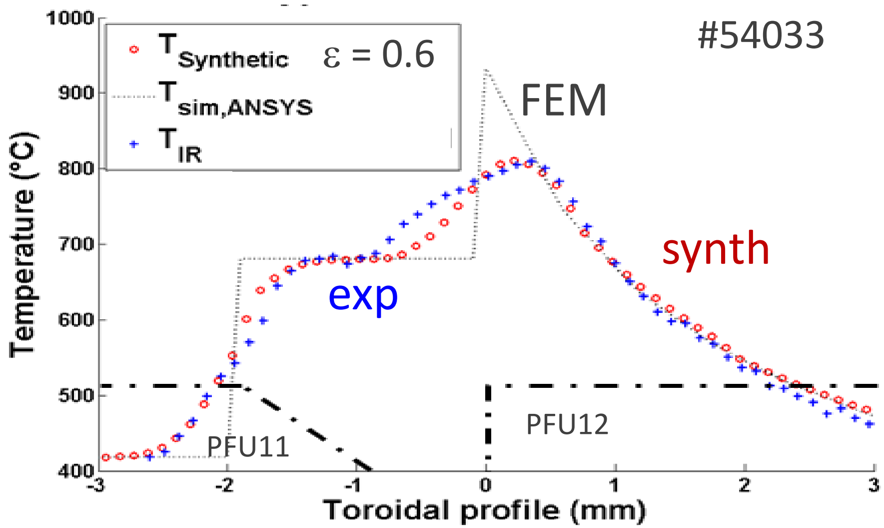
- **2.5 hours of plasmas with 5 GJ of injected energy in C3**
  - ✓ Up to 5 MW of LH heating, with high radiation fraction (0.5 to 0.8)
  - ✓ Moderate parallel heat flux at OSP: 20 to 50 MW/m^2 → 1 to 2.5 MW/m^2 on the divertor target

New insights on PFU gap heat loads with the very high resolution IR view

▶ Heat loads on misaligned PFUs in agreement with Optical Approximation

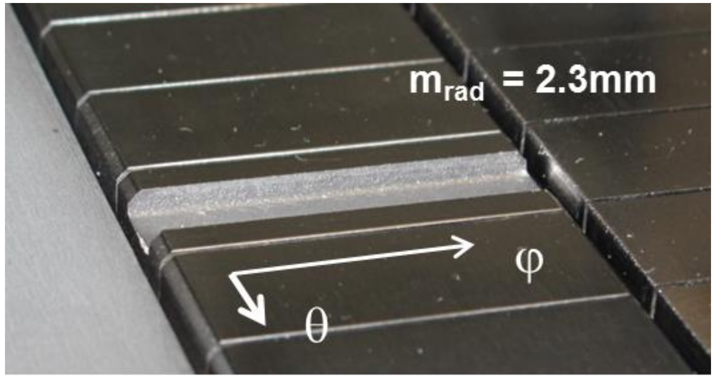
Grosjean A., Nucl Mat Energy 2021
Grosjean A., Fus. Eng. Design 2021

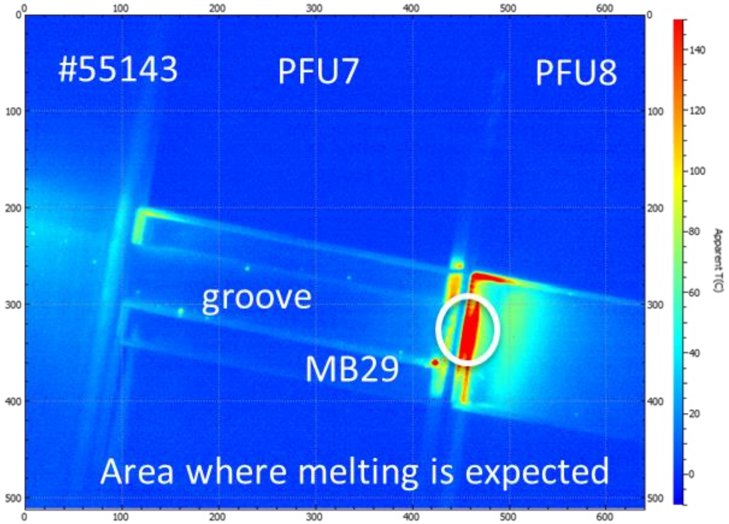


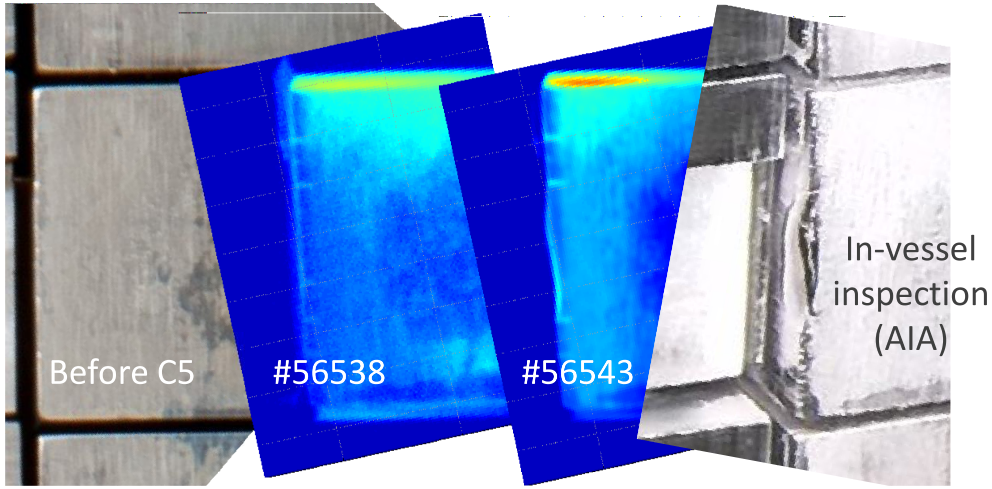


▶ PFU melting experiment performed

Corre Y., PFMC 2021





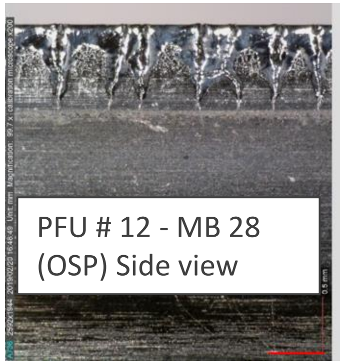


No failure but first evidence of damages on ITER-grade PFUs

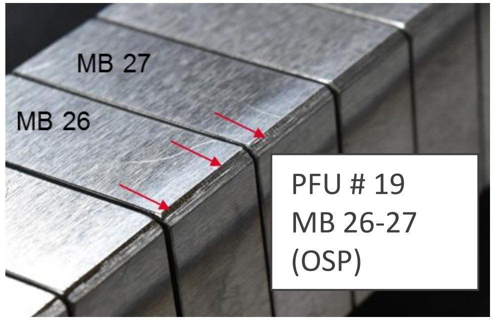
DIEZ TECH/P7-5

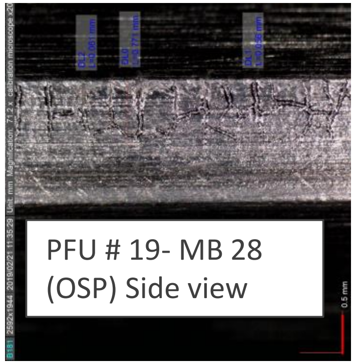
- **Cracks and local melting observed on misaligned PFUs side (both for sharp and chamfered), even outside peak heat flux area**

Misalignment ~ 0.8 mm

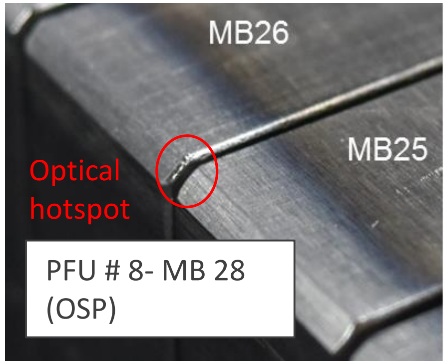


Misaligned / sharp





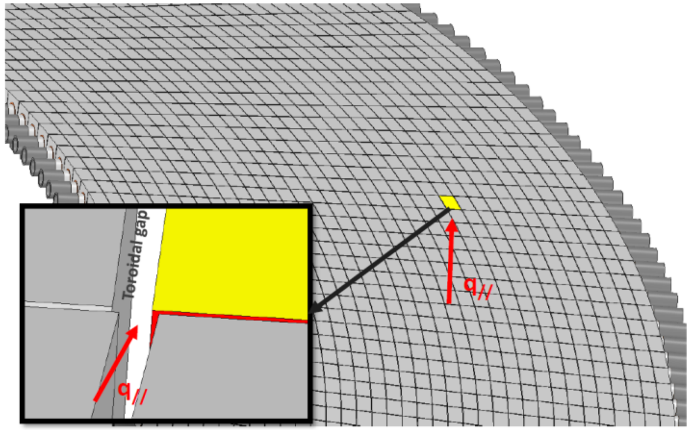
Misaligned / chamfered

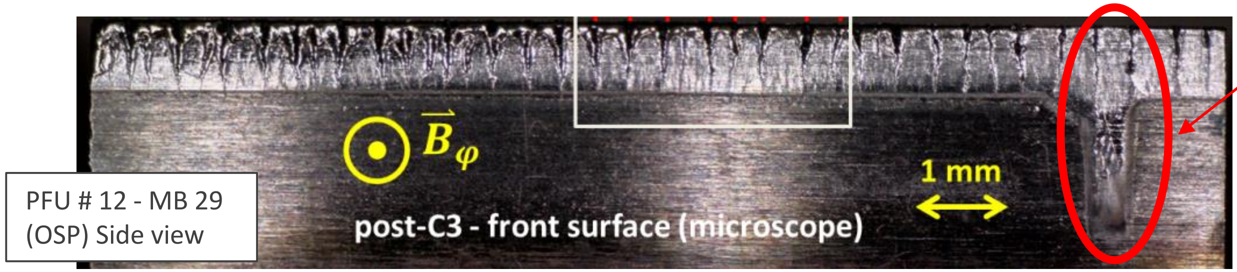


Aligned / chamfered

M. Diez, PFMC2019
M. Firdaouss, Divconcepts2019

- **Optical hot spots evidenced even for PFUs aligned within specs (local melting / cracks)**





Optical hot spot

M. Diez, Nuc. Fus. 2020
J. Gunn, Nucl. Mat. En. 2021

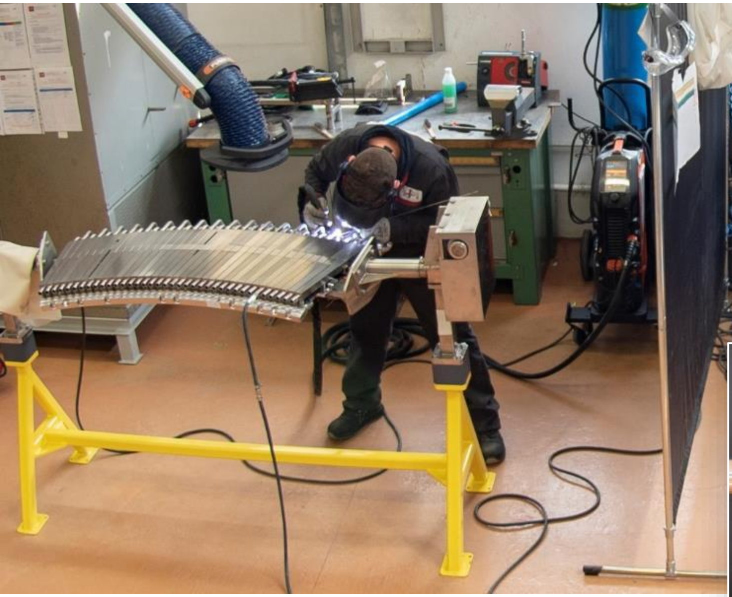
- ✓ Predicted to happen in ITER — J. Gunn, Nuc. Fus. 2017 and 2019
- ✓ Possibly combination of transients + steady state)

Damage propagation study and impact on plasma operation in phase 2

- **Missions and Research plan**
- **WEST Capability**
  - Heating and current drive systems
  - Specific diagnostics
- **Overview of phase I**
  - Development of scenarios towards steady-state operation
  - Plasma Wall Interaction
  - Tests of ITER-grade Plasma Facing Unit prototypes
- **Prospects for phase II**
  - Fully actively cooled ITER-grade divertor

Extending plasma duration to 1000s towards high duty, high fluence operation

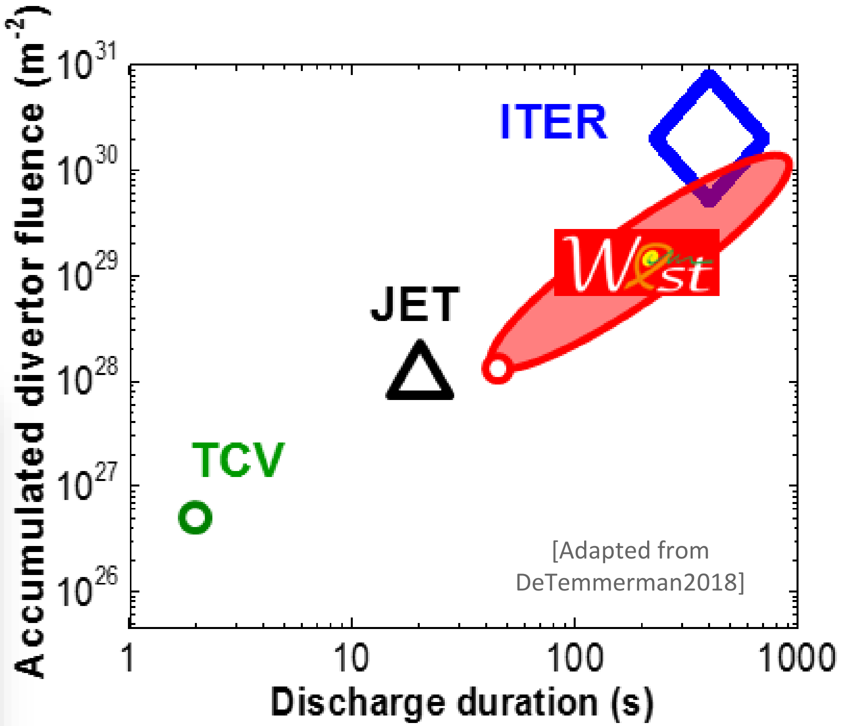
- **Installations of the full actively cooled ITER-grade divertor ongoing**
  - ✓ 456 PFUs received and qualified
- **Phase 2 operation to start in summer 2021**
- **ECRF heating system upgrade towards 3 MW/CW**
  - ✓ Ready in 2023



Dedicated workshop for the preparation of the 30° degree-sectors

A 30 degree-sector of divertor composed of 38 ITER-grade PFUs

Accumulated over 5000 discharges

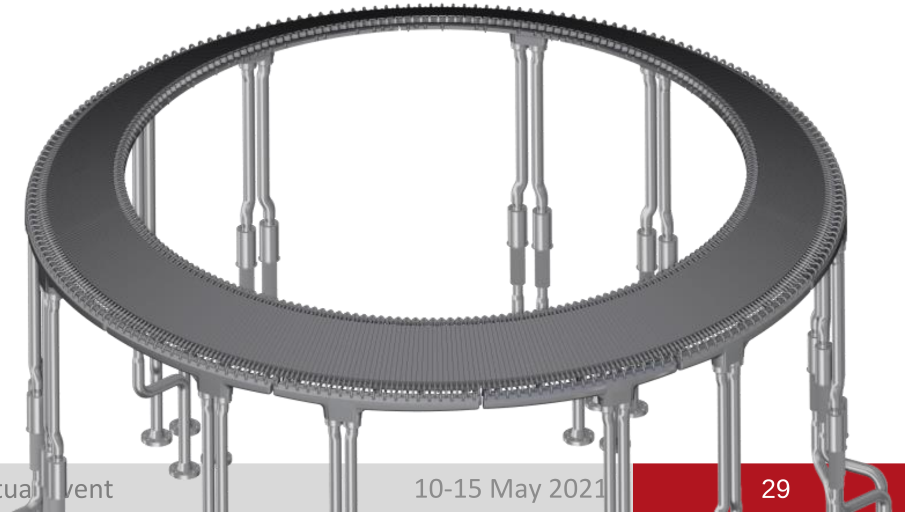


Long pulse discharges with duration 30 s – 1 min have been routinely performed in Phase I

- **9 MW of combined ICRF/LHCD power coupled to plasmas, without W accumulation**
- **Wall monitoring system for RT metallic PFC protection implemented**
- **No failure on ITER-grade PFU prototypes (from CN, EU and JPN) but evidence of damages**
  - ✓ Optical hot spot observed for the first time as predicted by modeling
  - ✓ Cracks and local melting observed at moderate heat flux on misaligned PFUs from 0.3mm - 0.8mm
    → crucial issues for safe operation in ITER and divertor lifetime

Phase II towards plasma duration of 1000s to start in summer 2021

- **Combined high heat flux/high particle fluences**
- **Towards steady-state H-mode operation in full W device**



Thank you for your attention

WEST.CEA.FR

WEST at This Conference

EX/P5-2 LIANG Optimization of lower hybrid wave coupling for the WEST LHCD launchers
EX/P5-4 VERMARE Formation of the radial electric field profile in WEST tokamak
EX/P5-5 REUX Toroidal field coil quench caused by runaway electrons on the WEST tokamak
EX/P5-6 LOARER Long discharges in steady state with D2 and N2 on the actively cooled tungsten upper divertor in WEST
EX/P5-7 TSITRONE Investigation of plasma wall interactions between tungsten plasma facing components and helium plasmas in the WEST tokamak
EX/P5-10 GASPAR Power load measurement on WEST lower divertor: results obtained with W-coated graphite components along the WEST phase 1
EX/P5-11 GONICHE Developing high performance RF heating scenarios on the WEST tokamak
TECH/3-5Ra HILLAIRET WEST Actively Cooled Load Resilient Ion Cyclotron Resonance Heating Results
TECH/P7-5 DIEZ Observation of tungsten plasma-facing components after the first phase of operation of the WEST tokamak
TECH/P8-18 COURTOIS Exploitation of infrared thermography for WEST Plasma Facing Components protection during 2019 campaign
TH/P4-12 CIRAOLO Interpretative modeling of impurity transport and tungsten sources in WEST boundary plasma
TH/P5-20 SARAZIN Impact of aspect ratio on tokamak confinement: nonlinear gyrokinetic evidence, WEST results and implications for DEMO
TH/P7-28 MAGET Collisional transport and poloidal asymmetry distribution of impurities in tokamak plasmas, with application to WEST