LONG PULSE OPERATION IN A TUNGSTEN ENVIRONMENT : ACHIEVEMENTS AND WORK PLAN FOR WEST

P. Maget on behalf of the WEST Team

Special thanks to P. Manas, Y. Corre, J. Gaspar, J. Gunn, as well as C. Bourdelle, A. Ekedahl, M. Goniche, J. Hillairet, X. Litaudon, Th. Loarer, Y. Peysson, E. Tsitrone

Technical Meeting on Long-Pulse Operation of Fusion Devices
Vienna, November 14-16th, 2022

A comprehensive workplan for ITER PFU characterisation and the way to long pulse operation in a metallic environment

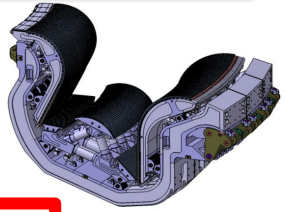
Manufacturing & validation of ITER Plasma Facing Units (PFU)
[talk by M. Firdaouss on Wednesday]

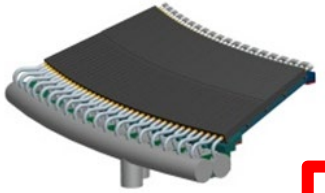
WEST
W Environment in
Steady-state **T**okamak

ITER PFU under operational constraints

ITER divertor cassette

WEST ITER-like divertor





Ageing & structure evolution
[talk by E. Bernard on Wednesday]

Scenario developments for Long Pulse Operation

Control and protection challenges
[talk by Ph. Moreau on Tuesday]

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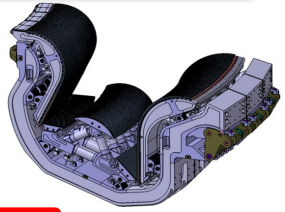

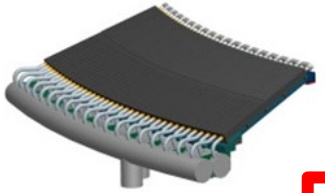

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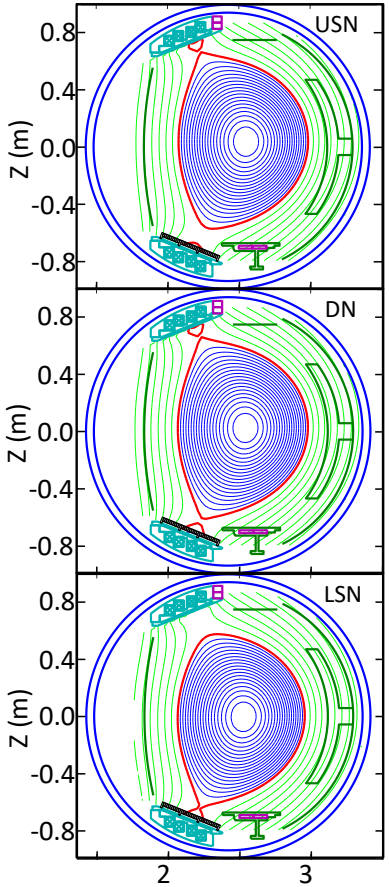
WEST: a MA class superconducting tokamak



I_p (q_{95}~2.5)	1.0 MA
B_φ	3.7 T
R	2.5 m
a	0.5 m
A	5-6
Max κ	1.35
δ	Up to 0.5
V_p	15 m^3
P_{ICRH}	9 MW
P_{LHCD}	7 MW
P_{ECCD}	*3 MW*

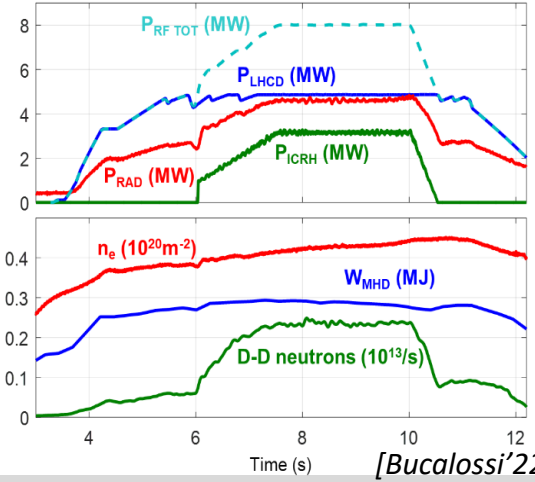
- Actively cooled superconducting tokamak
- Flexible magnetic configuration (LSN, USN, DN)
- Large current drive capability
- **Long pulse operation ➔ 1000 s**

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

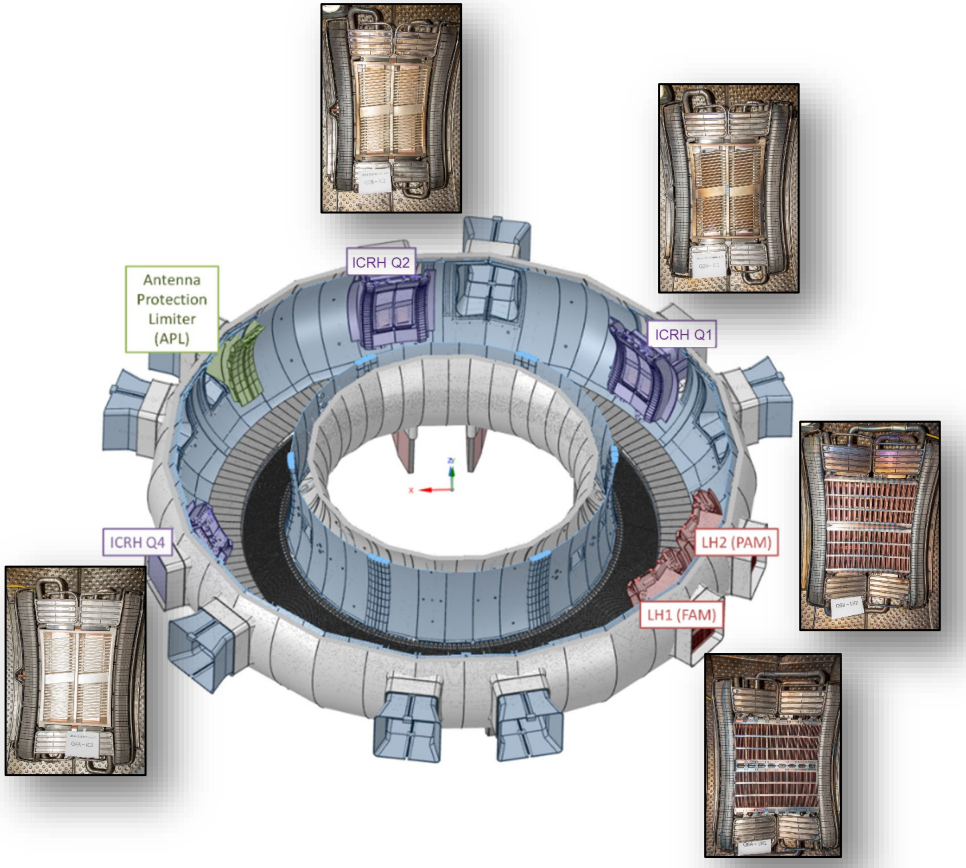
16 MW of Radio Frequency power

- **9 MW/30s of ICRH power, or 3 MW/1000s**
  - ✓ Three actively cooled ELM-resilient antennas
- **7 MW of LHCD power @ 3.7 GHz - 1000s**
  - ✓ Two actively cooled launchers
    - LH1 (FAM) - Fully Active Multi-junction
    - LH2 (PAM) - Passive Active Multi-junction
- ***3 MW of ECCD power @ 105 GHz- 1000s***
  - *Staged installation from 2023*

8 MW RF power coupled to plasmas in W environment



[Bucalossi'22]

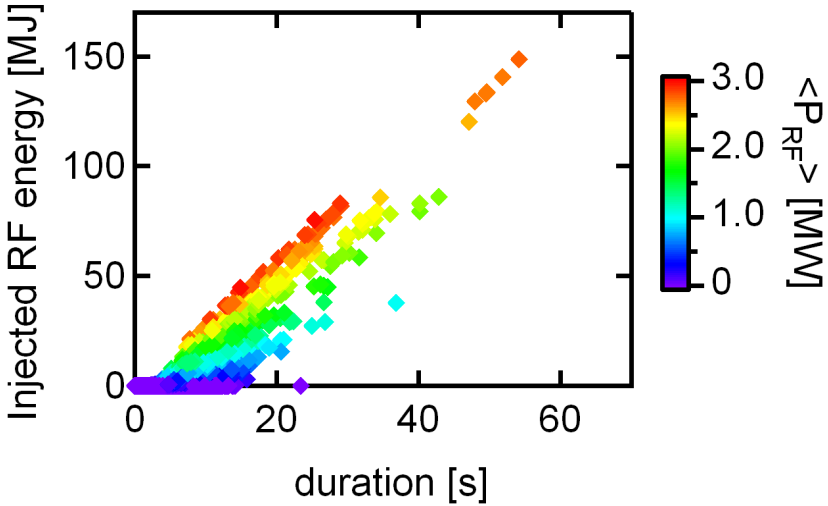


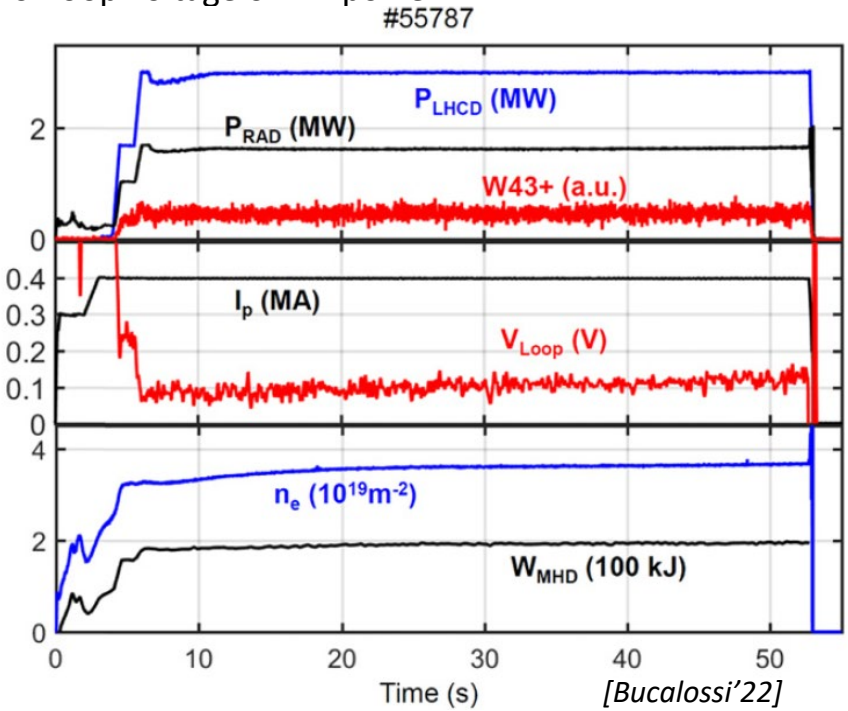
Scenario developments for Long Pulse Operation

Pulse duration and injected energy

- **Pulse length extended to ~ 1 min**
  - Steady-state obtained on most quantities (slow drift of loop voltage associated with density landing to reference)
  - Next step : Coil current optimization & feedback control of loop voltage on LH power

- **Injected energy up to 150 MJ**
  - With ~3 MW of LH power on average





[Bucalossi'22]

Scenario developments for Long Pulse Operation

Non-inductive operation

$$\left(I_p^2 f_{Gr}\right)^{max} \sim \eta_{CD} P_{tot}^{max} / \left(1 - f_{bs}\right)$$

CD efficiency

Access larger I_p & f_{Gr}

MHD avoidance

Current profile control

Impurity control

Minimize W radiation

Power to PFU & H-mode regime

Address PFU limits

Machine protection

Remain within safety constraints

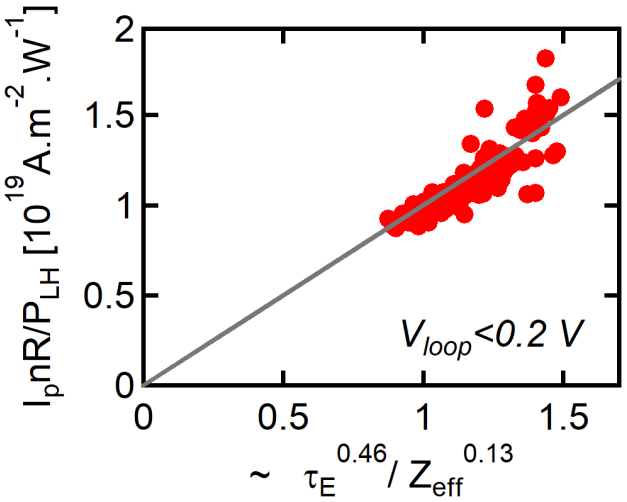
Overview based on actual WEST database & 0D integrated simulations with METIS*

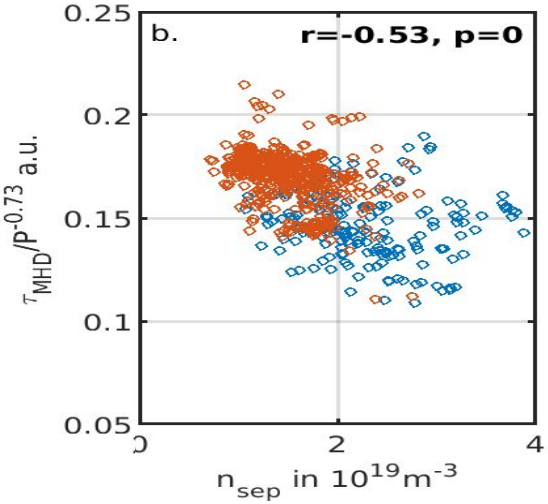
** [Artaud'18]*

Scenario developments for Long Pulse Operation : CD efficiency

Current Drive efficiency

- **Understanding the physics of LH CD efficiency is a key research area**
  - Estimated at η_{CD}~ 0.7 x10^{19} A.m^{-2}.W^{-1} in L-mode
  - An empirical scaling in $\tau_E^{0.46}$ [Goniche'05] is consistent with measurements on WEST
- **Correlations between edge & core quantities tends to hide physics mechanisms involved at the edge**
  - Confinement time is also connected to SOL physics [Ryter'21, Bourdelle'22]
  - Evidences that LH coupling & CD is impacted by SOL physics [Wallace'10, Pericoli-Ridolfini'11, Madi'15, Baeck'20]



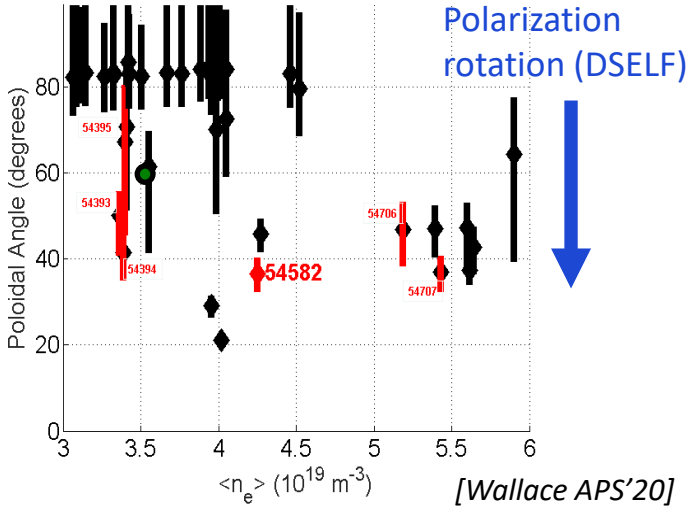


(courtesy C. Bourdelle)

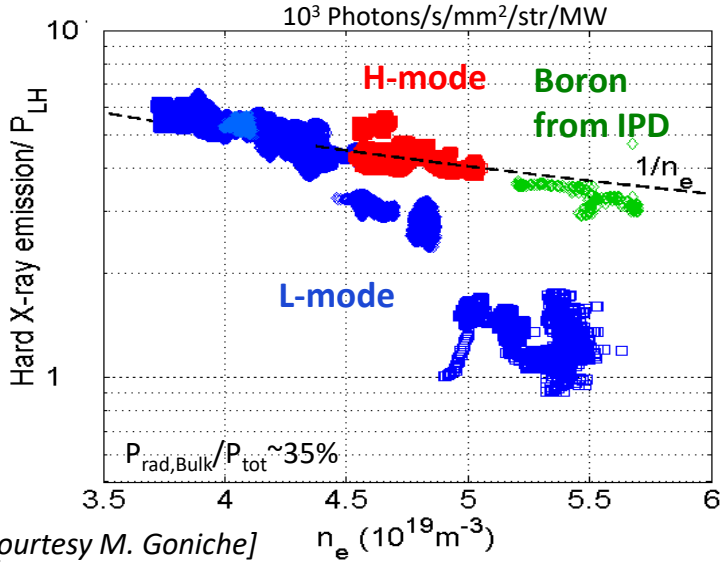
Scenario developments for Long Pulse Operation : CD efficiency

Current Drive efficiency

- **Indications of degraded CD efficiency at high density from spectroscopy & HXR measurements**
  - Spectroscopy in the SOL (DSELF, ORNL): rotation of the wave vector at high density *[Martin'19, Lau APS'21]*
  - Consistent with the fall of HXR signals
- **Preliminary investigations suggest actuators for improved CD efficiency**
  - in H-mode η_{CD} ~ 0.75 x10^{19} A.m^{-2}.W^{-1} (+ 7%) & with light impurity seeding via IPD (PPPL)
  - Similar observations on EAST with Lithium coating *[Goniche'17]*



[Wallace APS'20]

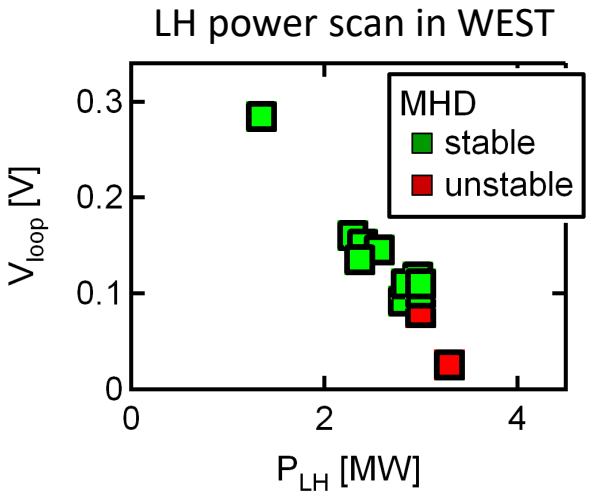


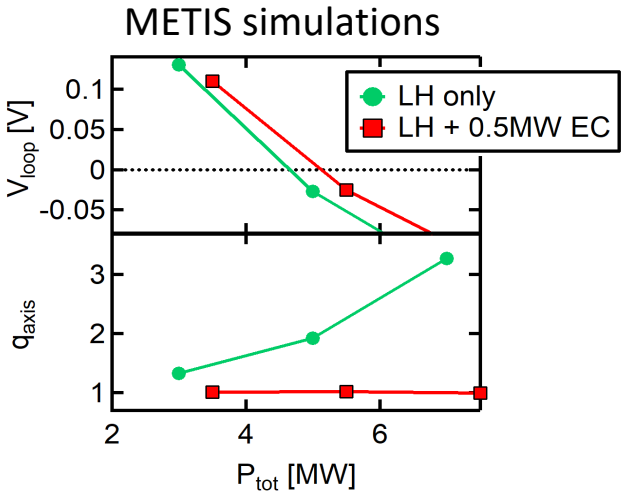
[Courtesy M. Goniche]

Scenario developments for Long Pulse Operation : MHD avoidance

Non-inductive current profile prone to MHD limits

- **LHCD deposition is off-axis and drives hollow current profile [Peysson'20, Wongrach'21, Ostuni'22]**
  - MHD instability triggering at low V_{loop}, reminiscent of Double-Tearing Mode issue on Tore Supra [Maget'05]
  - Consistent with q-reversal in integrated simulations with METIS
  - Improved stability expected from ICRH contribution [Dumont'14]
- **A robust (monotonic-q) scenario requires current profile control actuators**
  - Parallel refractive index of LH
  - Co-ECCD in the plasma core : 0.5 MW are sufficient to prevent q-profile inversion

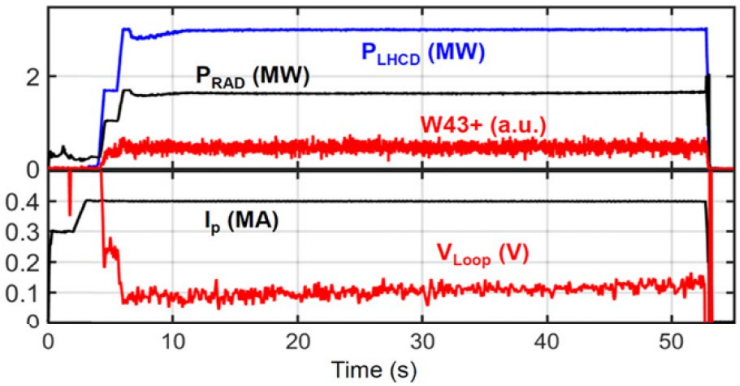




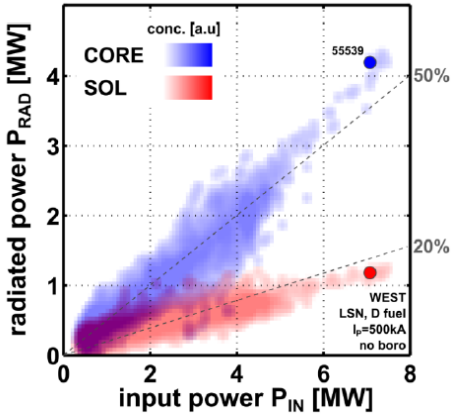
Scenario developments for Long Pulse Operation : W control

Steady tungsten concentration in long pulses

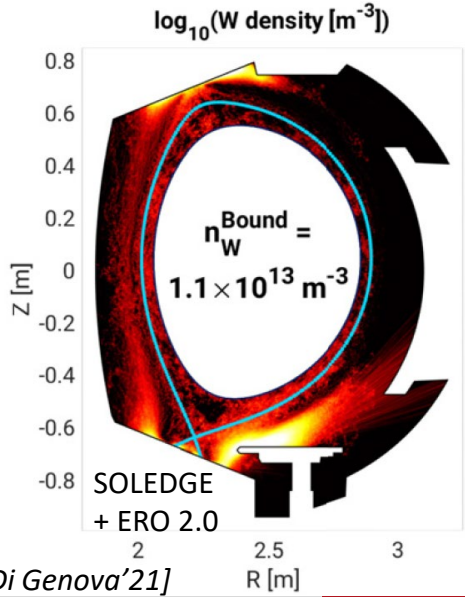
- **No tungsten peaking (except during radiative collapses [Ostuni'22])**
  - Consistent with torque-free plasma condition [Yang'20]
- **Core radiated fraction around 50% far from boronisation**
  - Robust trend independent on density or input power [Fedorczak, PSI'22]
- **Opening the operational space for H-mode access & SOL power increase**
  - Better understand & mitigate W sources [Di Genova'21] : role of vessel conditioning
  - Investigate X-point radiator regime
  - First results on IPD conditioning (PPPL procurement) [Bodner'22, Gallo APS'22]



[Bucalossi NF'22]



[courtesy N. Fedorczak, PSI'22]

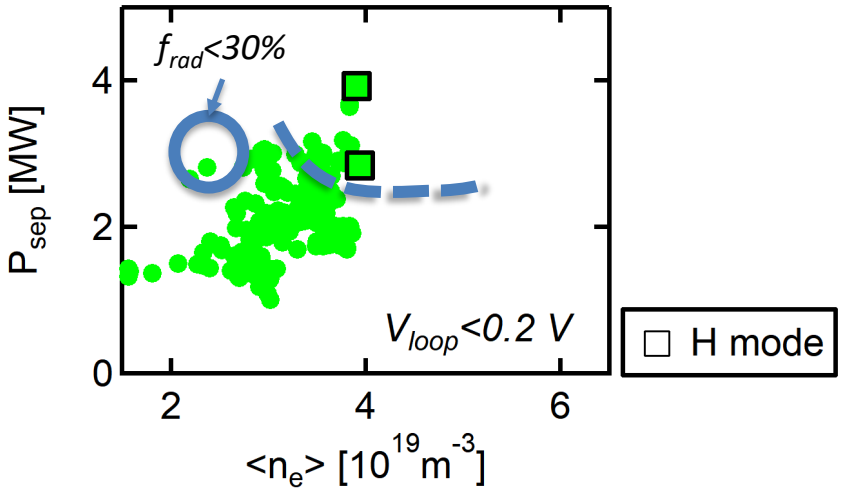


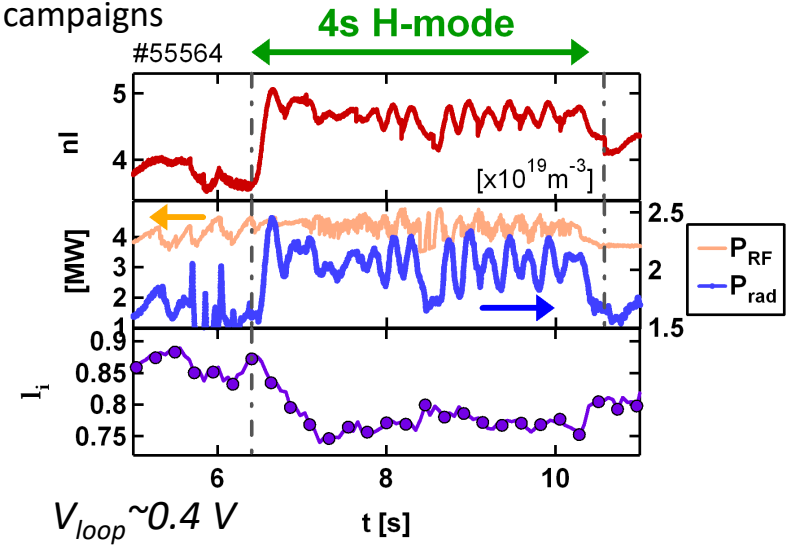
[Di Genova'21]

Scenario developments for Long Pulse Operation : High Power to SOL

PFU testing requires high power transferred to Scrape-Off Layer

- **Power crossing separatrix : up to 4 MW achieved at low V_{loop}**
- **H-mode transition : key for enhancing heat flux on PFUs**
  - Threshold consistent with Martin's scaling *[Martin'08]*
  - Observed only above $\langle n_e \rangle \sim 4\times10^{19} m^{-3}$: reminiscent of low density branch limit *[Ryter'14,Solano'22]*
- **4s H-mode obtained at V_{loop}~0.4 V**
  - Pedestal formation / density increase : more radiative losses and oscillating regime *[Vermare'22]*
  - Exploration of H-mode regime at larger input power in coming campaigns

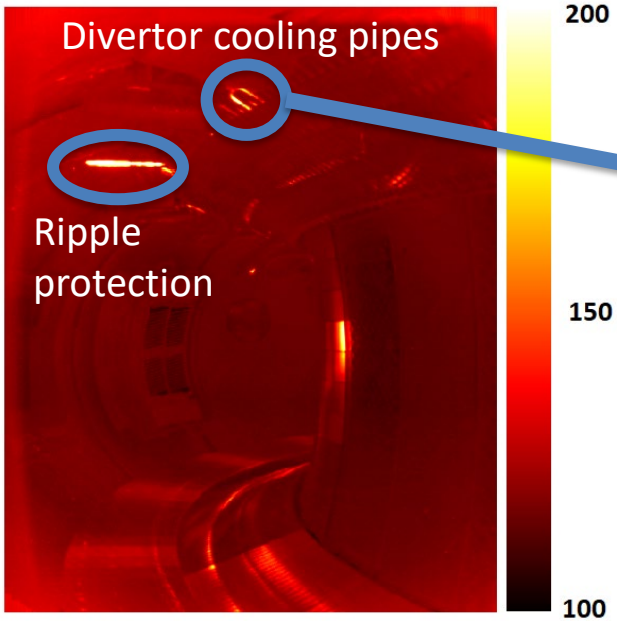


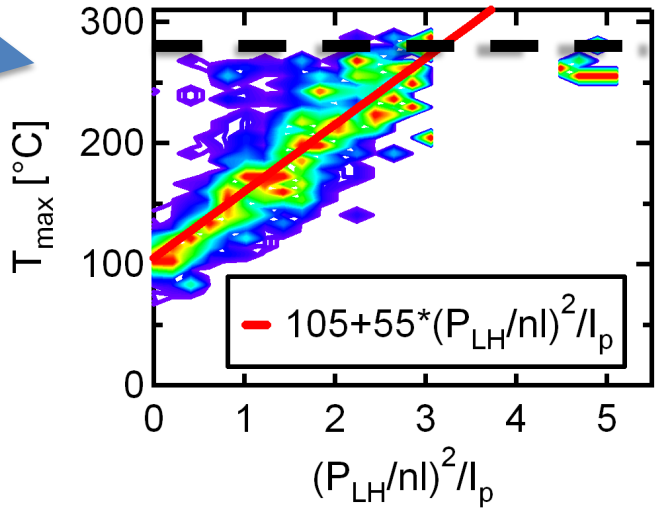


Scenario developments for Long Pulse Operation : machine protection

Real-time Infra Red machine protection (see talk by Ph. Moreau on Tuesday)

- **Vessel protected against electron ripple losses**
  - Limit based on calorimetry evaluation $P_R^{lim} \sim P_{LH}^{1.85}\, n_l^{-2.2}\, I_p^{1.5}$
- **Upper divertor cooling pipes : apparent temperature increases as well with LH power**
  - But different scaling with plasma current, as $T^{max} \sim P_{LH}^{2}\, n_l^{-2}\, I_p^{-1}$: to be refined in high power domain (larger P_{LH})



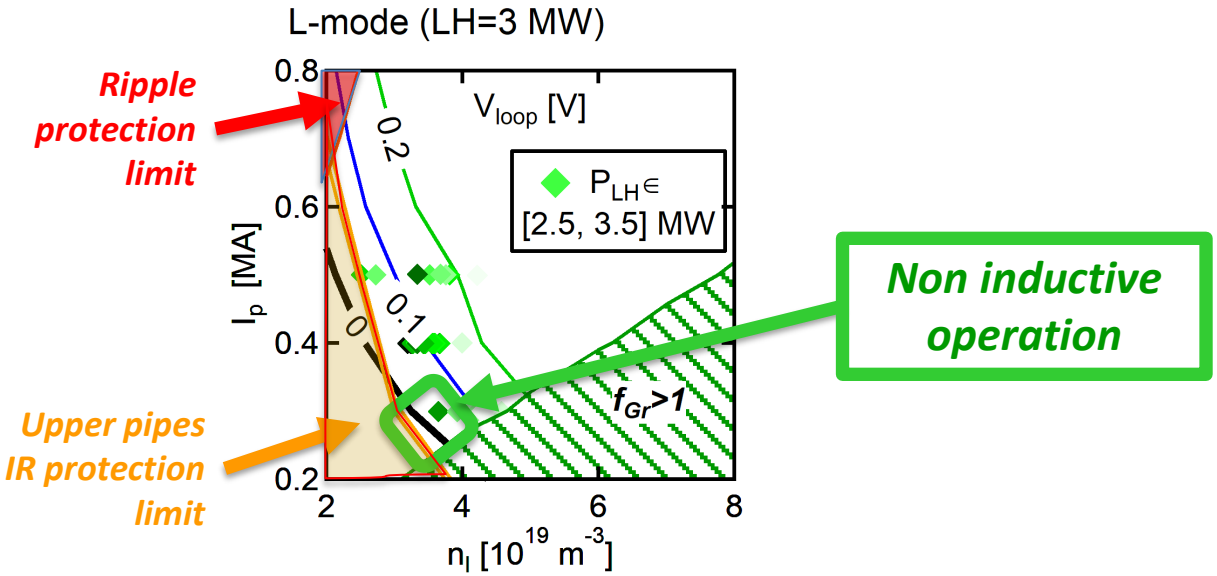


Real-time IR limitation at 275°C (T_{BB}) in place

Scenario developments for Long Pulse Operation : operational space

Integrating all constraints in 0D simulations with METIS at $f_{rad,bulk}$ = 40%

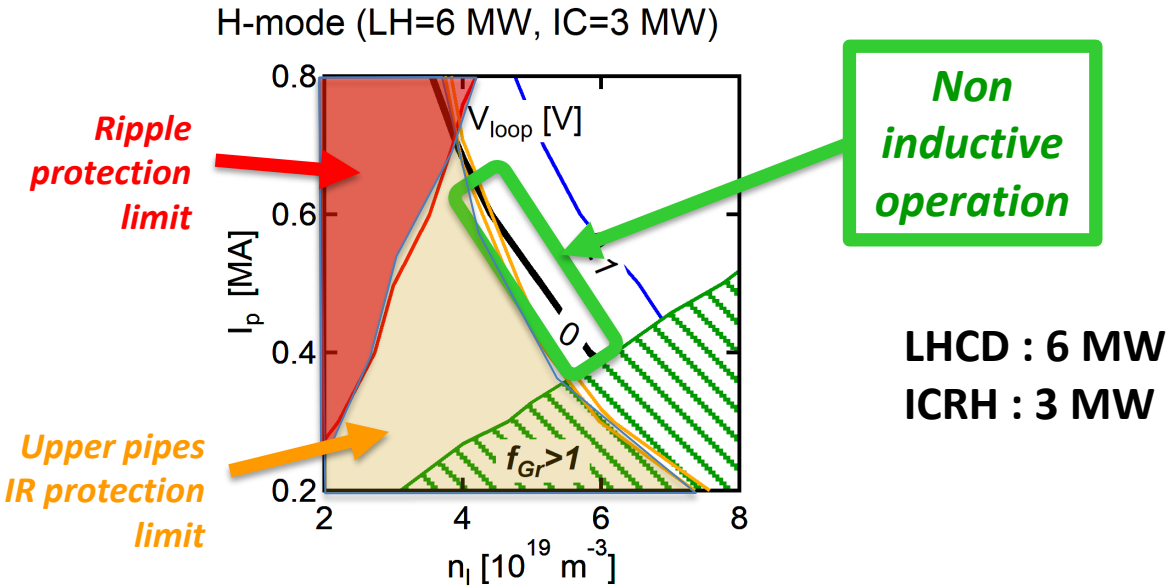
- **Projection in L-mode and H-mode**
- **Non-inductive discharges in L-mode for 3 MW of RF power**
  - Diagram consistent with present WEST data
  - Scaling on upper pipes temperature : density should be above a minimum ~ $3x10^{19}m^{-3}$



Scenario developments for Long Pulse Operation : operational space

Integrating all constraints in 0D simulations with METIS at $f_{rad,bulk}$ = 40%

- **Projection in L-mode and H-mode**
- **Non-inductive discharges in L-mode for 3 MW of RF power**
- **Non-inductive discharges in H-mode for 9 MW of RF power :**
  - Operational window opens in H-mode thanks to bootstrap current (~x2) & CD efficiency increase



LHCD : 6 MW
ICRH : 3 MW

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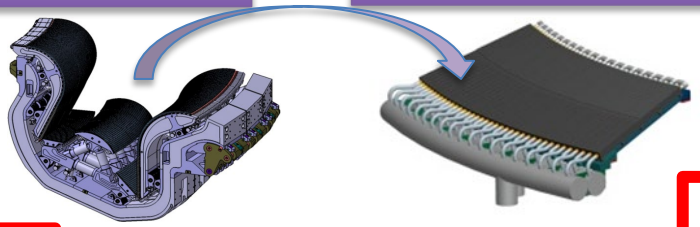

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ITER PFU under operational constraints

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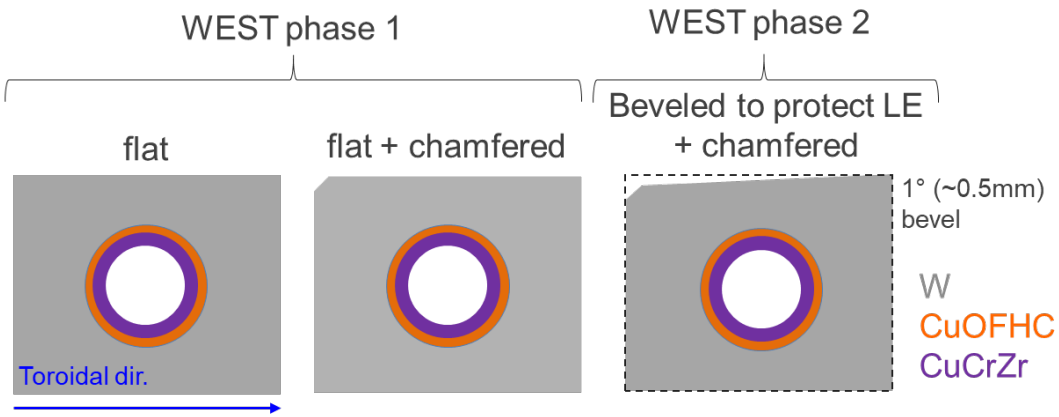
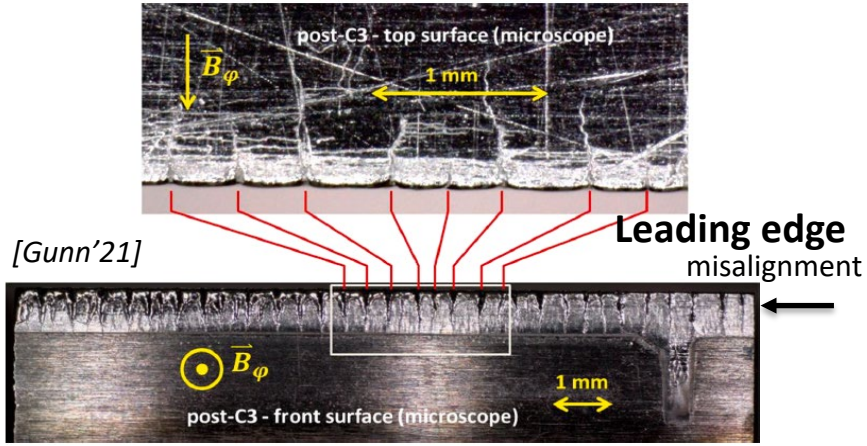
PFU shaping | High heat flux | Melting | High Fluence | Erosion / redeposition



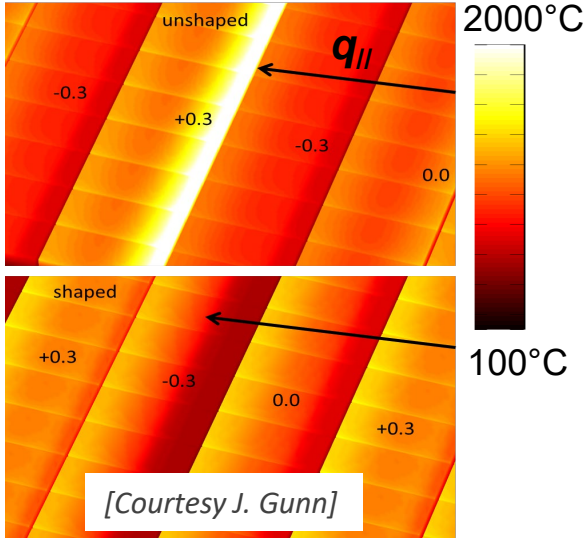
ITER PFU under operational constraints : shaping aspects

ITER PFU design: surface shaping and Optical Hot Spots

- **Shaping : need for beveled PFU in ITER [Gunn'17,Gunn'19]**
  - Cracks on misaligned leading edges : induced by disruption on WEST (thermo-mechanical analysis *[Durif'22]*)
  - Beveled PFU : demonstration of protected leading edges (IR) *[Grosjean'20]* (post-mortem to be done)
- **Optical Hot Spots:**
  - Post-mortem evidence *[Diez'21,Gunn'21]*
  - Risk expected during large ELMs *[Gunn'17]*

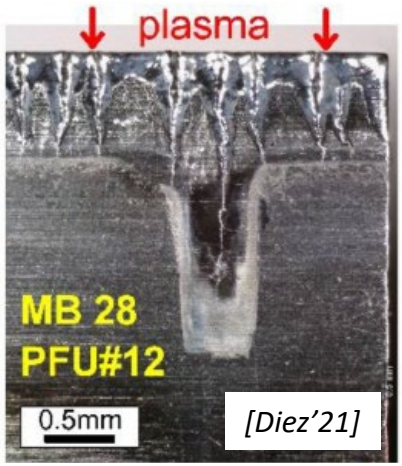


[Gunn'21]



[Courtesy J. Gunn]

OHS (tor. gaps)

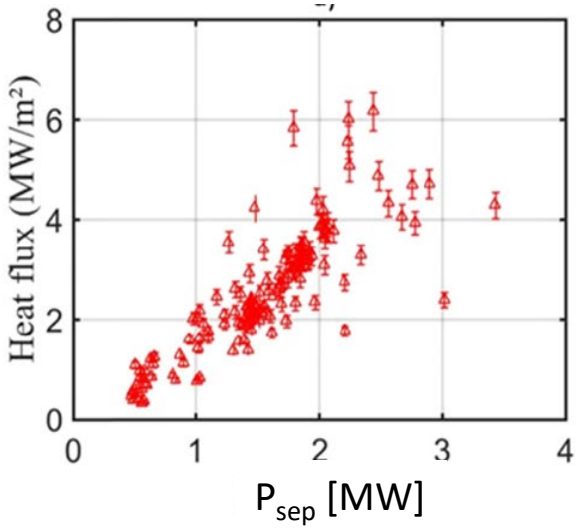


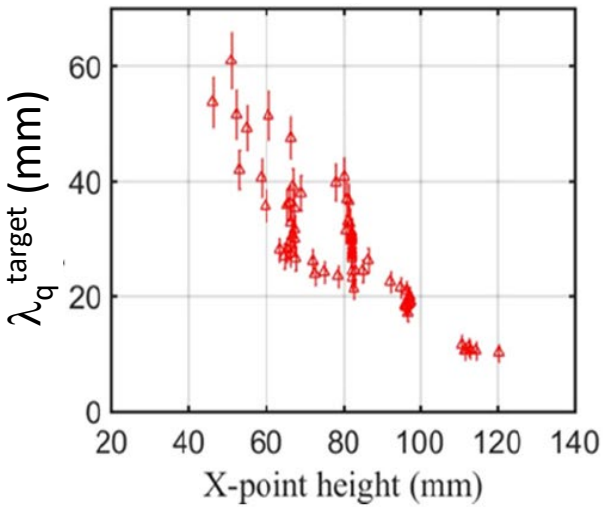
[Diez'21]

ITER PFU under operational constraints : delivering high heat flux

High heat flux on the ITER PFU, controlled by X-point height (magnetic compression)

- **Goal 10 MW/m² (ITER steady-state) at reach:**
  - High X-point height and increased P_{sep} required, H-mode will help (λ_q/2 expected)
- **Scaling law for λ_q at mid-plane from IR measurements**
  - Consistent with existing IR-based L-mode scaling *[Scarabosio'13]*
  - Discrepancy between λ_q obtained from IR and other diagnostics to be understood



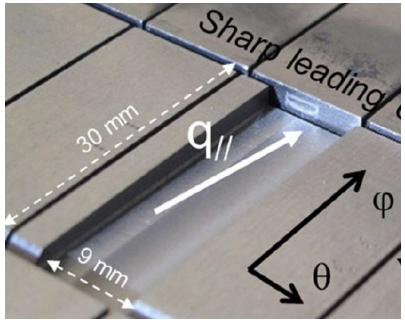


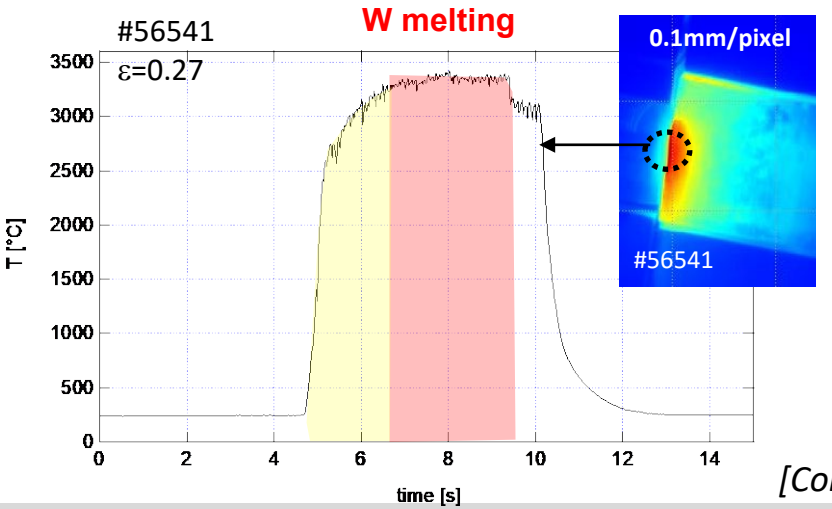
[Gaspar NF'21]
[Bucalossi NF'22]

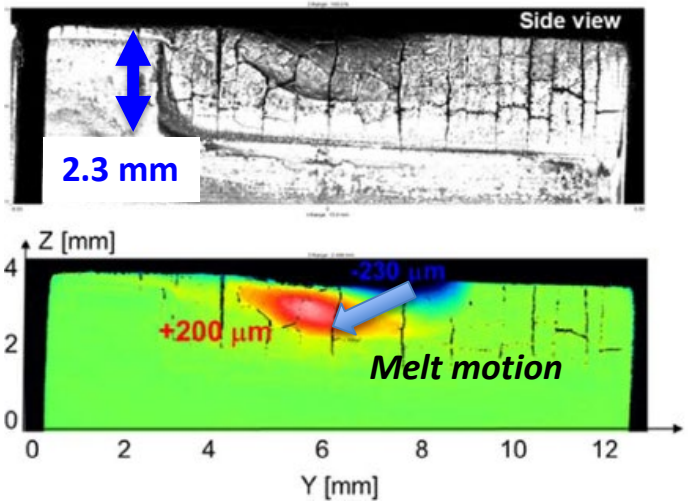
ITER PFU under operational constraints : melting

Melting of actively cooled tungsten monoblocks

- **First sustained melting on actively cooled PFU (5 MW / 5 s of LH power)**
  - High X-point and machined groove at the Outer Strike Point : $q_{//} > 100$ MW/m^2
  - Shallow melting, melt motion (JxB) driven by Thermo-ionic emission
  - Agreement with MEMOS simulation *[Ratynskaia'22]*
- **No impact on radiated fraction & plasma operation**
  - More intense melting experiments in preparation





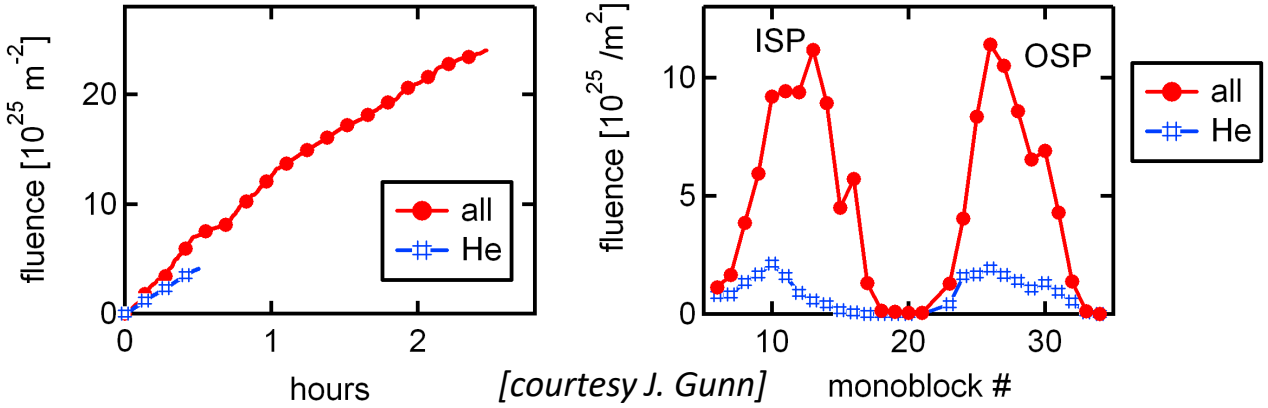


[Corre, Phys. Script. '21]

ITER PFU under operational constraints : high fluence

High cumulated fluence in He and D: investigating W surface modification

- **Helium campaign : a fluence ~ $2x10^{25}m^{-2}$ has been achieved on tungsten inertial PFU (30' of plasma)**
  - No sign of macroscopic W surface modification (fuzz formation conditions reached)
  - Post-mortem analysis on-going (surface, He bubbles)
- **Total fluence (from 1st measurements) ~ $2.5x10^{26}$ m^{-2} (2h 30' of plasma, 7h from 1st WEST plasma)**
  - Represents ~25% of an ITER pulse (~ 10^{27} m^{-2})
  - Symmetric between ISP and OSP : remains to be understood
- **ITER fluence in both He and D are foreseen**
  - Reach the fluence of ~ 1 ITER pulse
  - Pre-characterization and Post-mortem for in-depth ageing studies



[courtesy J. Gunn]

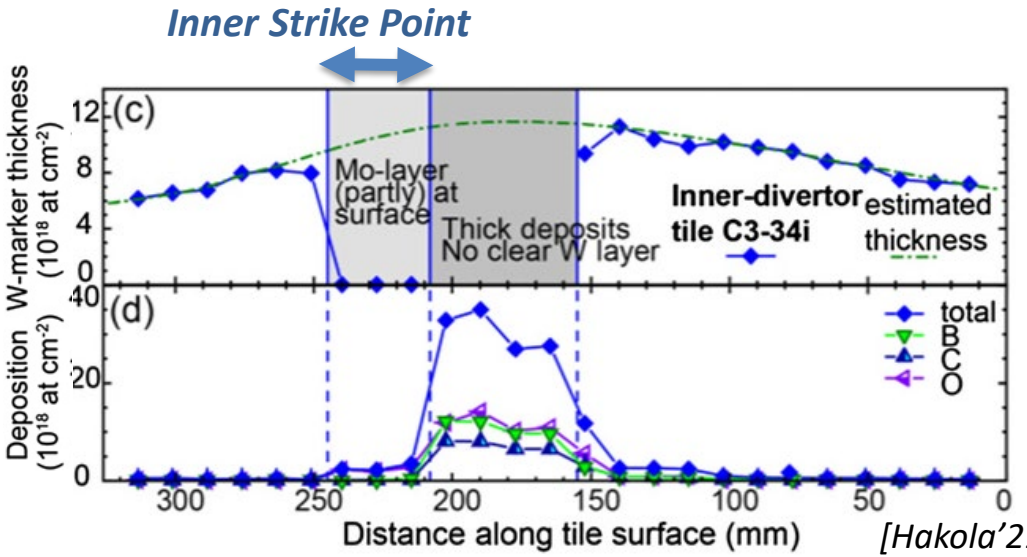
ITER PFU under operational constraints : erosion & redeposition

Erosion / redeposition patterns

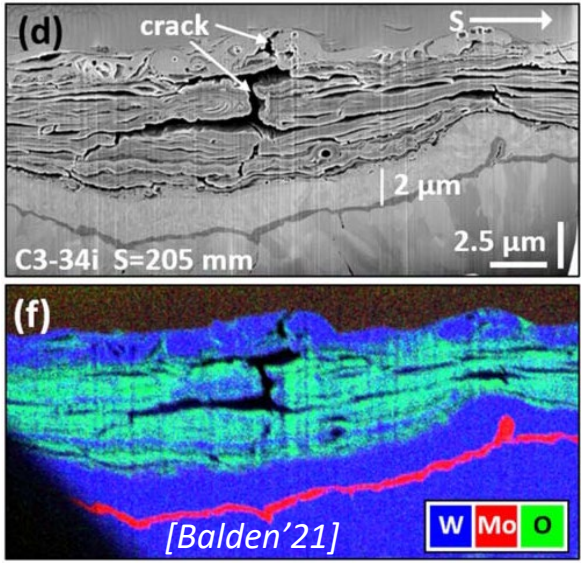
- Erosion evaluated as ~ 0.1 nm/s at Strike Points in L-mode (as in AUG and W7-X) *[Balden'21]*
- Thick deposits (W, B, C, O) outside erosion area *[Hakola'21, Balden'21, Martin'21]*

Perspectives for long pulse operation

- Evolution of deposited layers : flakes formation & ejection ? [Pégourié'09]



[Hakola'21]



[Balden'21]

Summary and conclusion (1/2) – scenario development

First steps towards a suitable scenario for ITER PFU testing on Long Pulse Operation

- **Integrated scenario development towards low loop voltage, high power to SOL**
- **CD efficiency to be probed vs SOL characteristics in H-mode, IPD, low-Z seeding conditions**
- **MHD stability (hollow current profile) can be mitigated with a limited ECCD power**
  - ECCD will be a key player to manage current profile control (installed late 2023)
- **Radiative fraction robustly around 50%**
  - On-going work : Mitigate W sources / Vessel conditioning / Impurity Powder Dropper
  - However H-mode threshold accessible : a domain to be explored in future campaigns
- **Vessel protection limits integrated in the preparation of Long Pulse Operation**
  - Synergy effect between LHCD and ECCD can be exploited to mitigate IR vessel protection
  - H-mode regime opens the operational space

Summary and conclusion (2/2) – ITER PFU under operational constraints

First results on ITER PFU characterization in WEST

- **PFU shaping mandatory to avoid premature W-cracking and damages**
  - → 0.5mm toroidal bevel on ITER
- **Optical Hot Spots : post-mortem evidence in the absence of shaping**
- **Demonstration that large heat flux accessible at high X-point height**
  - 10 MW/m^2 can be reached in WEST even in L-mode
  - Multiple diagnostic evaluation of λ_q : shows differences that remain to be investigated
- **First melting experiments show good agreement with modeling**
  - Shallow melting observed → deeper melting pool foreseen
  - no impact on plasma operation (P_{rad})
- **Helium fluence experiments showed no W fuzz formation**
  - ISP / OSP symmetry is measured
- **Deuterium & He fluence exp. planned to reach ~ITER fluence**
  - evolution of deposited layers is a key aspect to investigate

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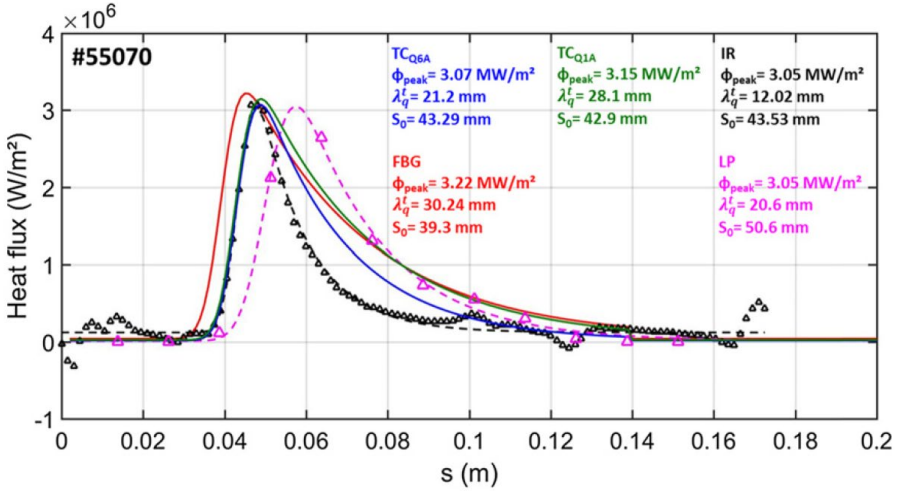
Thank you for your attention

Delivering high heat flux on ITER divertor components : focus λ_q

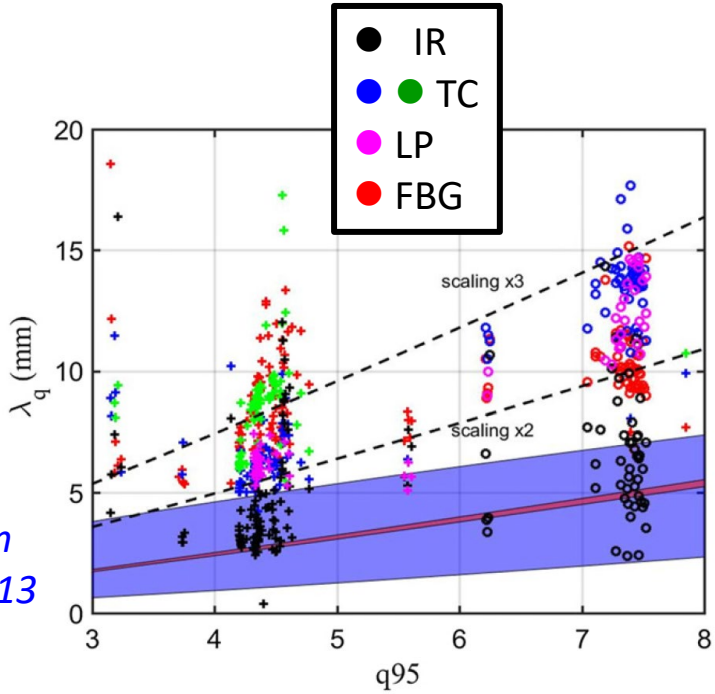
Discrepancy between λ_q evaluation from different diagnostics

- IR, Langmuir probes, Thermocouples, FBG
- IR evaluation consistent with previous IR-based scaling [Scarabosio'13]



[Gaspar NF'21]

Scaling from Scarabosio'13



End back-up slides