An overview of Phase 1 results

Task Force WEST 2

Towards long pulse H mode and steady state operation

P. Maget and J. Hillairet
on behalf of the WEST team#
http://west.cea.fr/WESTteam

Outline

Towards Steady State H-mode Operation in a metallic environment

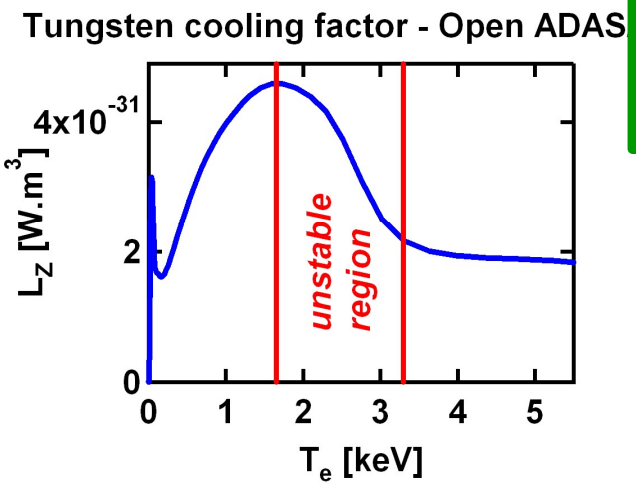
- Plasma ramp-up
- Long Pulse Operation
- Transition to H-mode
- Focus on Physics topics

Summary of scientific results under Task Force WEST 2

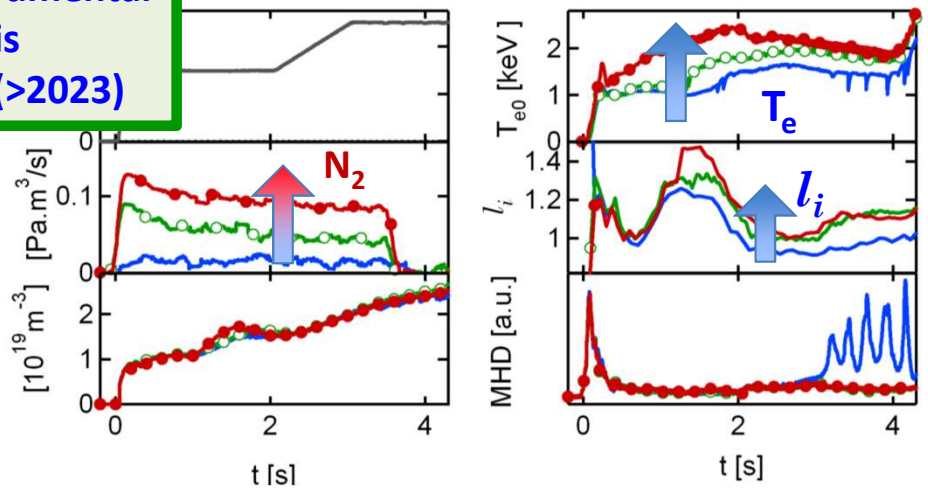
Scenario development: Plasma current ramp-up using Nitrogen seeding

Plasma current ramp-up : a delicate phase with respect to Tungsten contamination

- **A high radiation peak must be crossed**
  - The radiated power goes as $P_{rad} = n_e\, n_W\, L(T_e)$ with $L(T_e)$ maximum around 1.5 keV
  - Low core temperature often leads to MHD activity
- **Some helpful tools have been used**
  - Nitrogen seeding was used in C4 and C5 campaign
  - Plasma ramp up in limiter configuration on Boron Nitride also proved to be a good practical option in C5



ECRH will be instrumental to consolidate this particular phase (>2023)

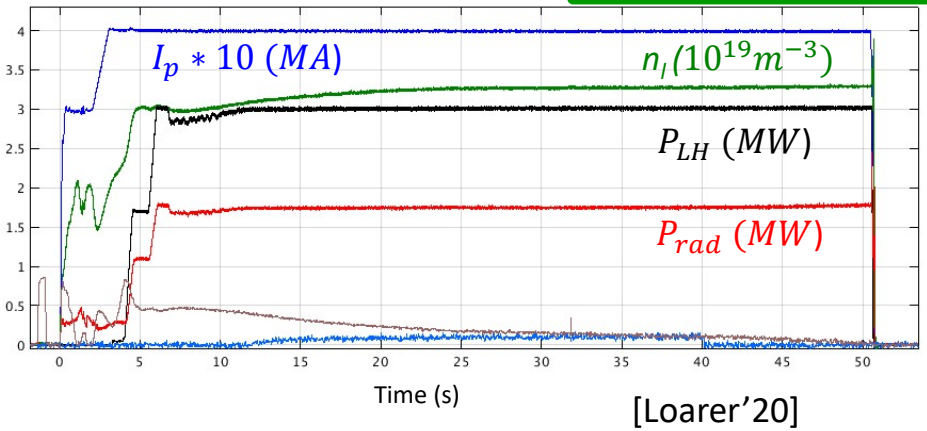


Scenario development for long pulse operation

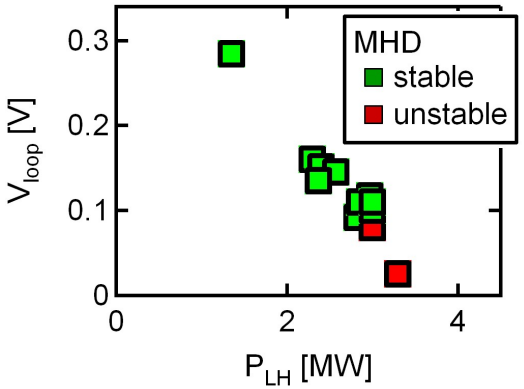
Long pulse scenario development : up to 55s so far (~150 MJ)

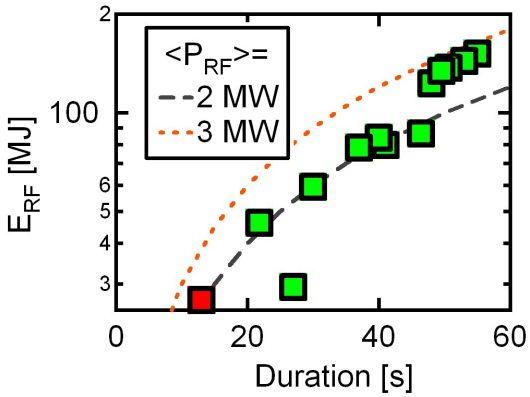
- **Well mastered density control & radiation**
- **More scenario development is required**
  - Avoid MHD at V_{loop}~0: optimize LH deposition & efficiency
  - Initial phase to be adjusted to limit coil currents in steady-state phase

ECRH will be instrumental to facilitate MHD avoidance at low loop voltage (>2023)



[Loarer'20]

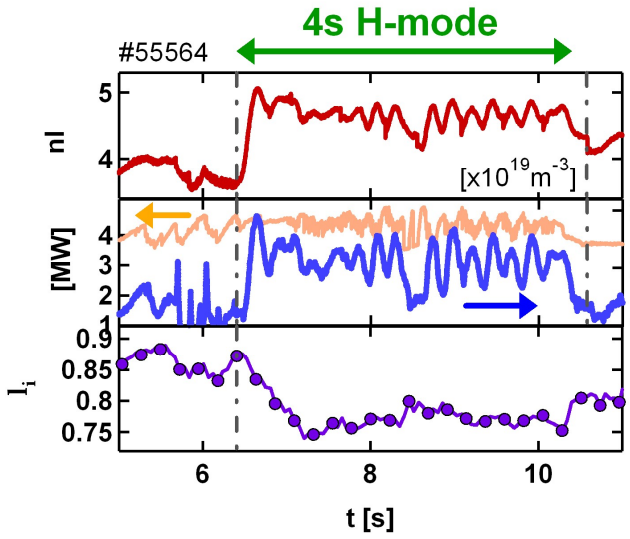




H-mode access in a Tungsten environment

H-mode maintained for 4s with combined LH and ICRH powers

- **Large spontaneous increase of density**
  - With the formation of a pedestal and a drop of internal inductance
  - Deepening of E_r well identified from Doppler Reflectometry
- **Threshold consistent with Martin's scaling law [Martin'08]**
  - H-mode transition in LSN, transitions also observed in USN (H or I)

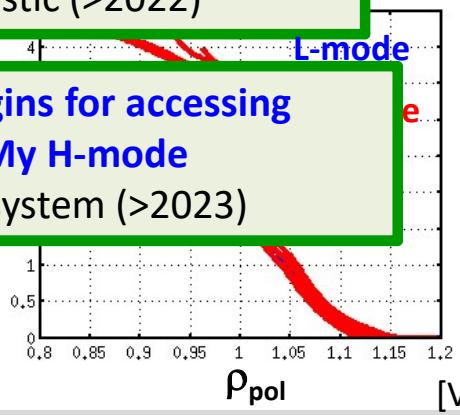


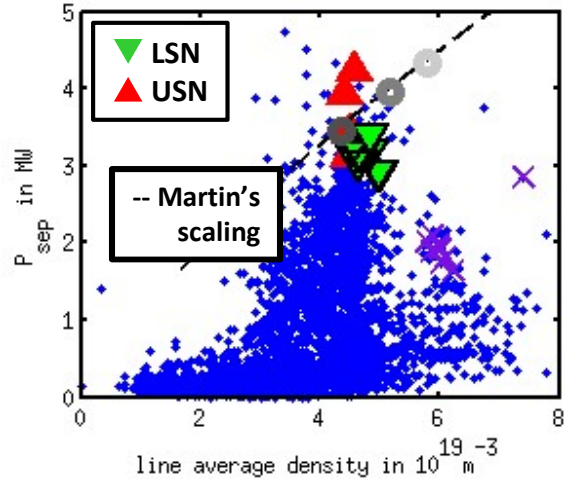
Measure pedestal formation in density & temperature

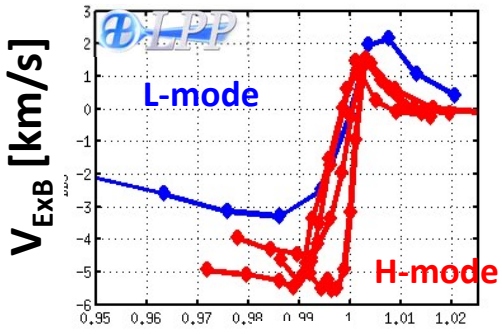
- Thomson scattering diagnostic (>2022)

Gain margins for accessing Type-I ELMy H-mode

- ECRH system (>2023)







[Vermare, IAEA 2021] ρ_{pol}

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- Plasma ramp-up
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  - Mastering Tungsten contamination
  - RF optimization
  - Confinement scaling at high aspect ratio

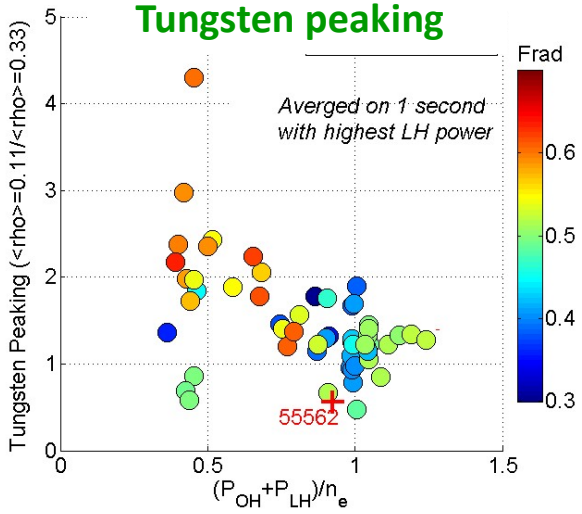
Summary of scientific results under Task Force WEST 2

Focus 1: No Tungsten accumulation issue in WEST

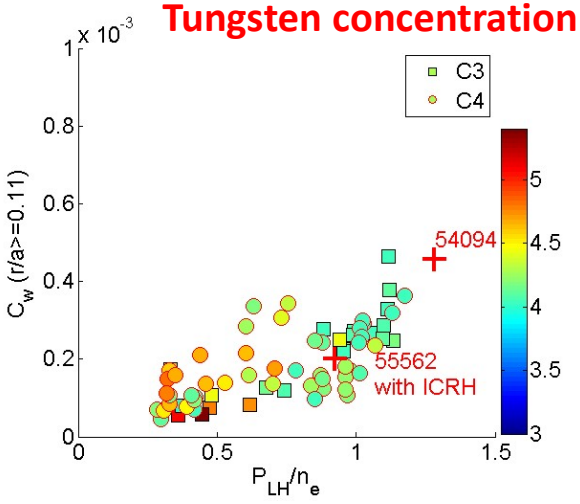
In a low torque tokamak as WEST, turbulent transport dominates over neoclassical pinch

- **Tungsten peaking** is moderate and decreases with LH power
- But its **concentration** increases with RF power
- No systematic issue related with Tungsten accumulation
- A reduction of Tungsten concentration is however required (f_{rad}~50%)

Tungsten peaking



Tungsten concentration



New diagnostics for Phase 2

- SXR-GEM (IPPLM)
- ME-SXR (PPPL)
- CAES (KAIST)
- Vertical bolometer

[Goniche TFM'20]

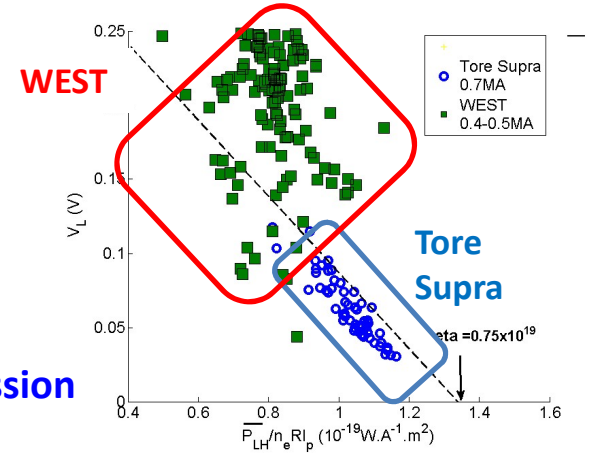
Focus 2: LHCD for Steady State plasma discharges

LH waves provide both electron heating & current drive

- Up to 5.4 MW coupled to WEST plasmas

Current Drive efficiency : an issue for long pulse operation

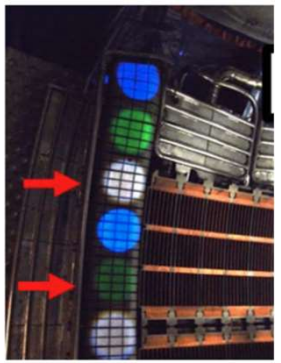
- Large scatter in CD efficiency, can be comparable to that of Tore Supra
- Motivates more data analysis & modelling activities

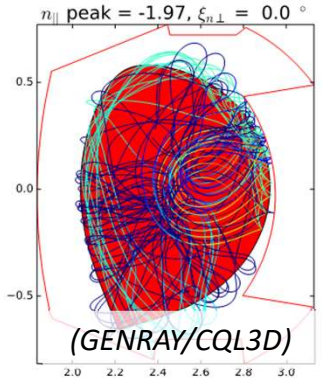


Goniche RF Topical 2020

LHCD modelling: deposition, Current Drive efficiency and HXR emission

- Modelling / experiment comparison
- Fast electron population: signature in the Hard X-Ray (HXR) range
- Impact of LH waves on Scrape-Off Layer : Stark Effect Spectroscopy (ORNL)





(GENRAY/CQL3D)

Wallace APS 2020

LHCD optimization for scenario development in Phase 2

- Find conditions for better CD efficiency
- Understand the physics at play
- New diagnostic : ME-HXR (PPPL)

Focus 3: ICRH, W sputtering & plasma contamination

ICRH : 3 ELM-resilient antennas

- 5.7 MW coupled (peak)

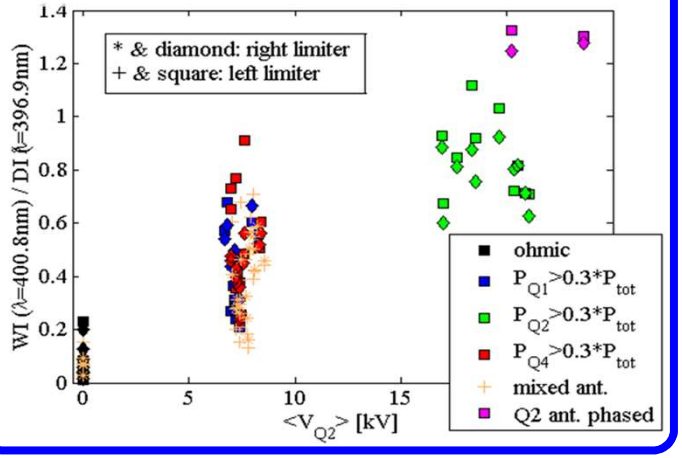
IC-induced W-sources: contamination comparable to LH

- W-sources correlated with RF voltage on local antenna
- **At 180° phasing, radiative fraction not different from LH (f_{rad}~50%)**
- **Modelling effort to connect W sources to plasma contamination**

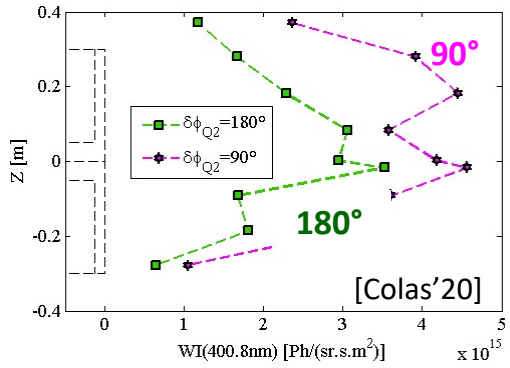
ICRH optimization for phase 2

- RF Modelling: EVE-AQL, ETS, Petra-M
- Impurity sources : SOLEDGE-ERO2.0
- Diagnostics : Visible & UV, RF probe under study (MIT), FILD envisaged

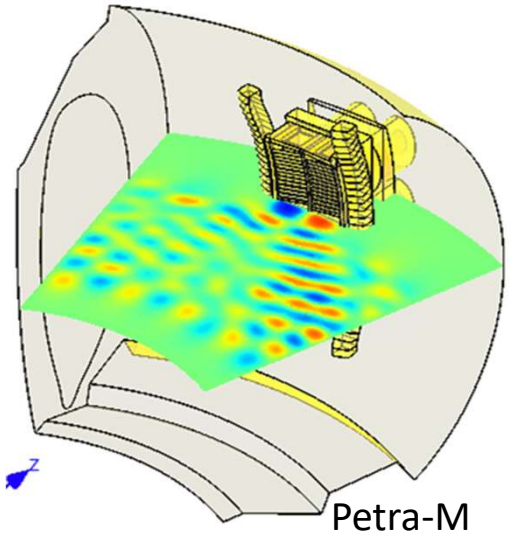
IC antenna voltage drives W sputtering



ICRH phasing: sputtering



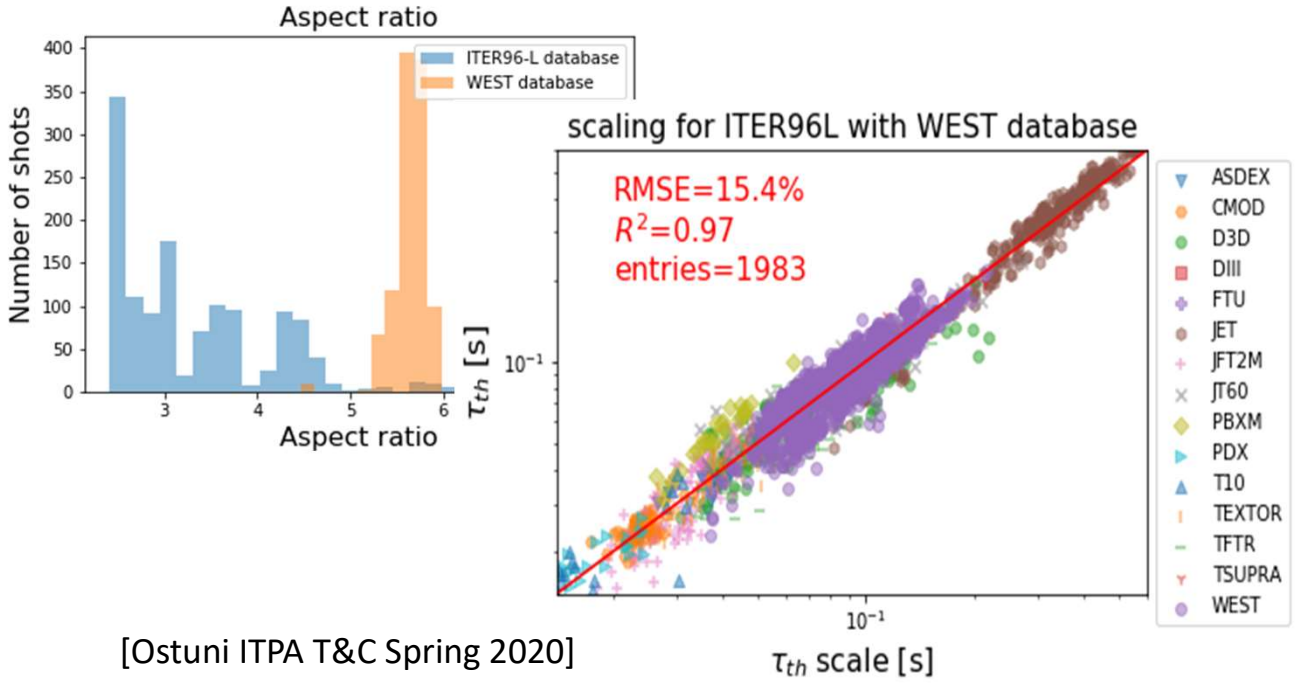
WI visible line on ICRH side limiters



Focus 4: confinement scaling at high aspect ratio

WEST confinement consistent with existing L-mode scaling

- Despite its large aspect ratio A~5
- Provides data in a weakly populated part of the International databases ITER89-P and ITER96-L
- The aspect ratio dependence remains close to zero



[Ostuni ITPA T&C Spring 2020]

Variable	ITER96-L	ITER96-L + WEST
Constant	0.023	0.031
I_P	0.96	1.02
B_T	0.03	0.11
k	0.64	0.55
R	1.83	1.57
R/a	0.06	0.08
n_e	0.40	0.24
M_{eff}	0.20	0.20
P	-0.73	-0.73
entries	1313	2400
WEST	-	1087

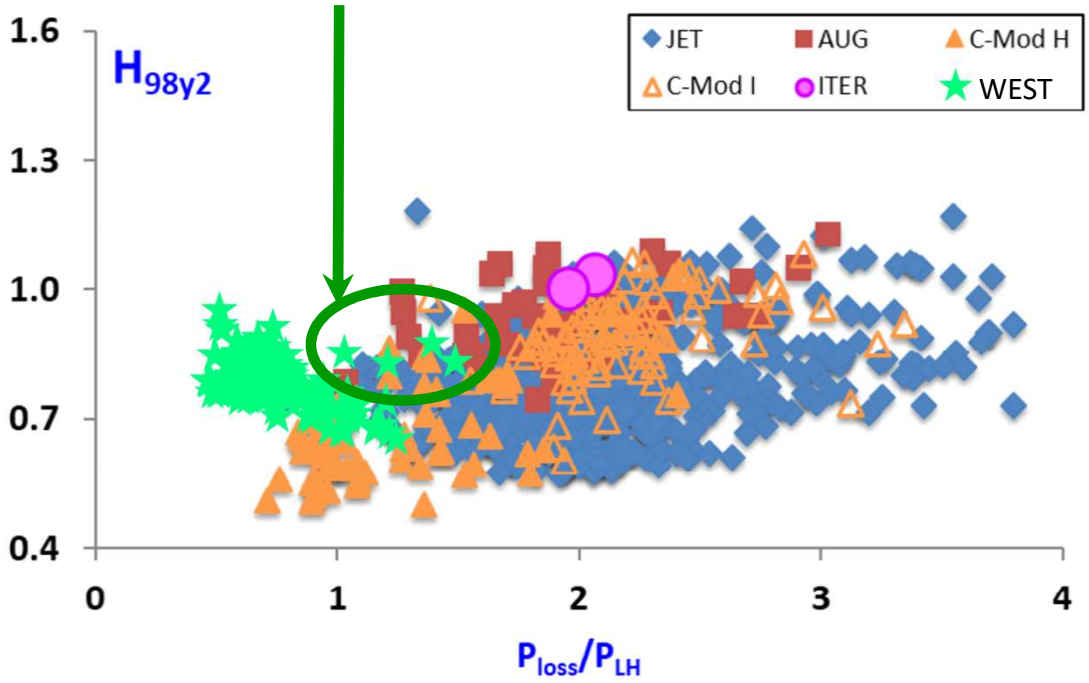
Focus 4: confinement scaling at high aspect ratio

WEST L-mode H factor

- Similar to other machines as L to H mode threshold is crossed (WEST : ★)
- Few points so far in H/I-mode, close to the power threshold

H/I-mode scaling law

- To be further investigated in phase 2



(adapted from Sips NF'18)

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Summary of scientific results under Task Force WEST 2

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WEST program progress towards long pulse H-mode in a Tungsten wall tokamak

- From plasma initiation & conditioning to scenario development
- Plasma ramp-up identified as a critical phase
- Progress towards steady-state operation
- First H-mode transitions
- No limiting Tungsten accumulation problem

Extension to long pulse H-mode to be addressed in coming campaigns

Open questions to be further addressed in C6 campaign

- **Origin of the relatively high radiative fraction f_{rad}~50%?**
- **H mode access : on the low density branch so far ?**
- **Explore favorable vs unfavorable drift direction**
- **Improved confinement with N_2 seeding [Yang NF'20] : similar with Impurity Boron dropper?**
- **Fuelling/pumping impact on core performances**

Perspectives for phase 2

- **New diagnostics**
- **ECRH system to start operation in 2023**

Conference presentations on M1 topics since 2019 GB (1/2)

APS 2020

- Investigation of lower hybrid wave polarization in WEST, G.M. Wallace (MIT)

PSI 2020

- First exploitation results of recently developed SXR GEM-based diagnostics (…), M. Chernyshova (IPPLM)

EPS 2020

- W sources in the long-pulse, all-W wall, RF-heated WEST tokamak environment, C.C. Klepper (ORNL)
- Operating near the L-H power threshold in WEST full tungsten environment, M. Goniche
- Tungsten transport (…): towards real-time kinetic-theory-based plasma performance optimisation, P. Manas
- How Nitrogen seeding securizes plasma ramp-up in the metallic environment of WEST, P. Maget
- Full-wave antenna modeling of LHCD and ICRF antennas on the WEST, S.Shiraiwa (PPPL)
- Impact of partial screening effect on fast electron dynamics in WEST tokamak plasmas (…), K. Kròl (IPPLM)
- Investigation of lower hybrid wave polarization in WEST, G. Wallace (MIT)
- 2D X-Ray spectroscopy on WEST: First data analysis and technical challenges, D. Vézinet
- Gaussian process regression for density profile modeling (…) in WEST tokamak, M. Kozeiha
- From physics to engineering radio-frequency modeling (…), N. Bertelli (PPPL)
- Impact of leakage under divertor baffle on detachment onset in WEST (…), Y. Hao
- Radial electric field profile, pedestal formation and Bx∇B drift direction, L. Vermare

Conference presentations on M1 topics since 2019 GB (2/2)

ITPA Transport and confinement 2020

- W behaviour in WEST and modelling, P. Manas
- L-mode database extension and analysis with WEST data, V. Ostuni

Large International Involvement

- ~30% first authors from WEST partners

IAEA 2020

- Toroidal field coil quench caused by runaway electrons on the WEST tokamak, C. Reux
- Developing high performance RF heating scenarios on the WEST tokamak, M. Goniche
- WEST Actively Cooled Load Resilient Ion Cyclotron Resonance Heating Results, J. Hillairet
- Optimisation of lower hybrid wave coupling for the WEST LHCD launchers, A. Liang (SWIP)
- Impact of aspect ratio on tokamak confinement: nonlinear gyrokinetic evidence, WEST results (…), Y. Sarazin
- The geometry of ICRF – induced wave-SOL interaction: a multi-machine experimental review (…), L. Colas
- Tungsten transport (…): towards real-time kinetic-theory-based plasma performance optimisation, P. Manas
- Collisional transport and poloidal asymmetry distribution of impurities (…), with application to WEST, P. Maget
- Effect of partially ionized high-Z atoms on fast electron dynamics in tokamak plasmas, Y.Peysson
- Towards integrated RF actuator modeling: self-consistent coupling (…), S. Shiraiwa (PPPL)
- Formation of the radial electric field profile in WEST tokamak, L. Vermare

Some references

[Bucalossi'14] Bucalossi at al, The WEST project, Fusion Engineering and Design **86**, 684–688 (2014)
[Bourdelle'15] Bourdelle et al, WEST physics basis, Nuclear Fusion **55**, 063017 (2015)
[Colas'07] Colas et al, Plasma Physics and Controlled Fusion, **49** B35–B45 (2007)
[Goniche'20] Goniche et al, 23rd Topical Conference on Radiofrequency Power in Plasmas (2020)
[Loarer'20] Loarer et al, Nuclear Fusion **60** 126046 (2020)
[Martin'08] Martin et al, J. Phys.: Conf. Ser. **123** 012033 (2008)
[Torre'19] Torre et al, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, 29(5) 4702805 (2019)
[Yang'20] Yang et al, Nucl. Fusion **60** 086012 (2020)

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Combining ICRH and LHCD, a complex SOL problem

Coupling optimization vs W sources

- Up to 9 MW LH+ICRH obtained

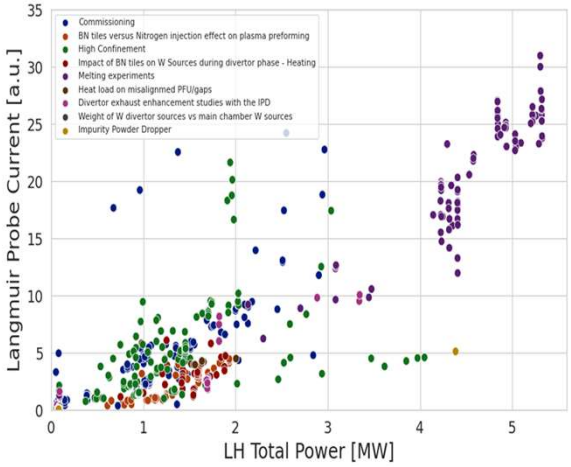
LH & IC modify density profile in the SOL

- Both systems modify density profiles in the SOL
- This can alter the quality of the coupling of both systems
- Magnetic connections between antennas

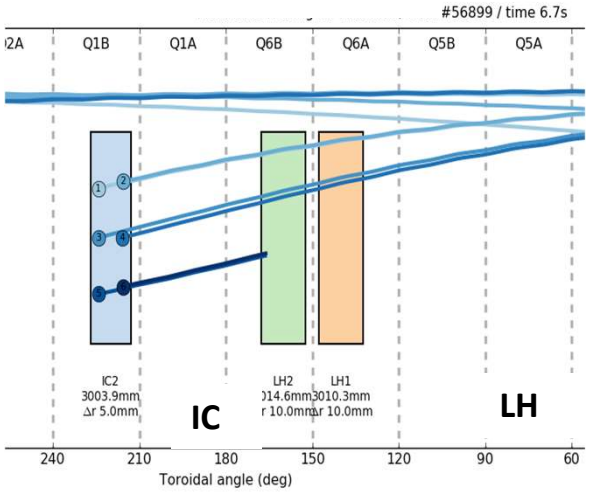
Optimizing combined RF operation

- Density monitoring in the SOL
- Identify best compromise for all systems

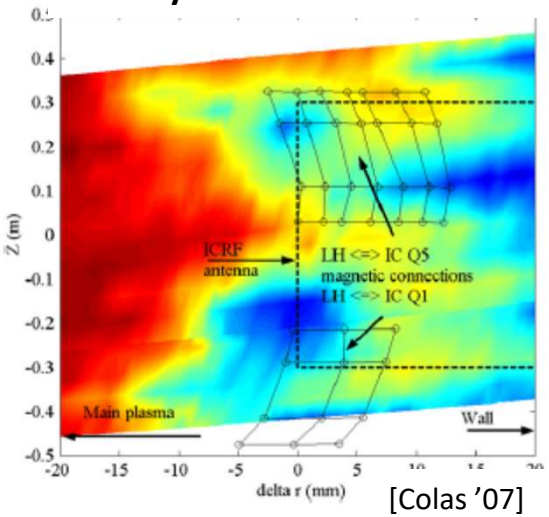
Density increase with LH power



IC-LH connections



Density in front of IC antenna

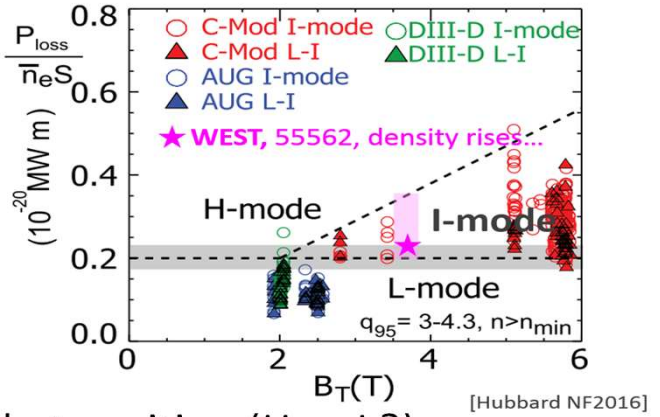


[Colas '07]

H/I-mode access in LSN versus USN

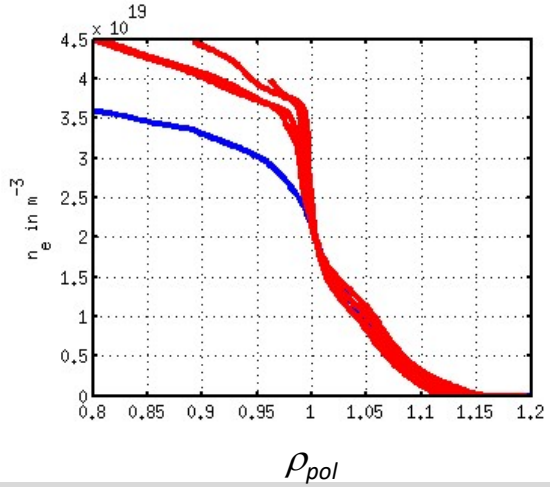
H-mode transition

- **Formation of a pedestal on electron density**
  - As measured by reflectometer
- **In USN, the transition is similar**
  - But some differences in the V_{ExB} dynamics (bursty)

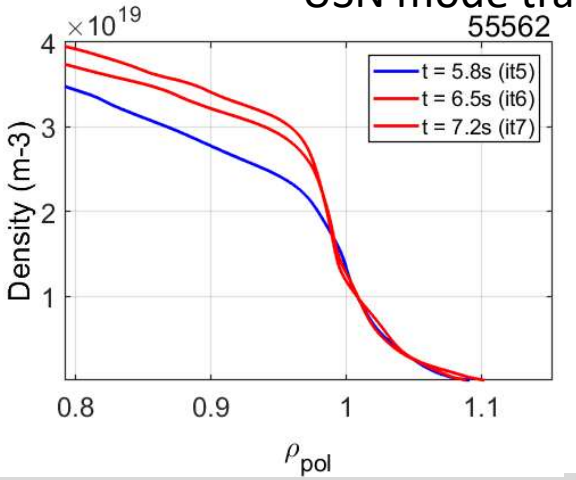


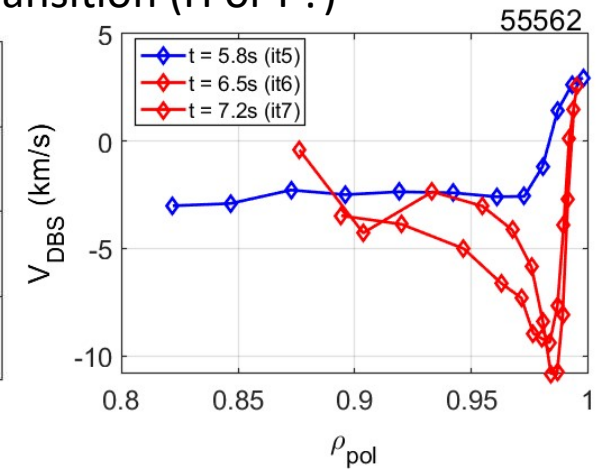
[Hubbard NF2016]

LSN H-mode transition



USN mode transition (H or I ?)





H-mode access in a Tungsten environment

Oscillatory H-mode phases observed

- **Attributed to enhanced radiative losses at transition**
  - Increased density in the edge at pedestal formation (Ch#2)
  - Correlated with increased radiative power losses
  - Inward impurity pinch ?
  - Similar oscillations on ASDEX-U close to L-H threshold [Pütterich, ITPA'20]

- **Mastering impurity contamination mandatory**
  - … for moving well above the L to H power threshold

- **Optimization of coupled RF power mandatory**
  - Conditions on edge density
  - Mastering RF-induced Tungsten sources (see later)

Gain margins for H-mode transition

- Increase combined LH-ICRH input power (9 MW peak so far)
- ECRH project (>2023)