DE LA RECHERCHE À L'INDUSTRIE

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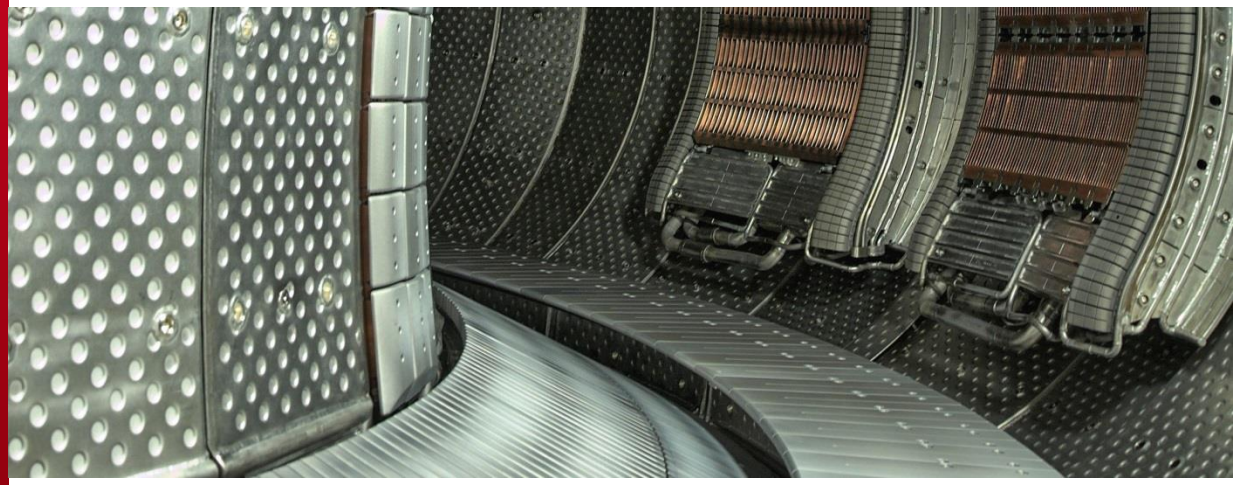
ACHIEVEMENTS OF THE C3 CAMPAIGN

AND

OUTLOOK OF THE C4 CAMPAIGN

TASK FORCE WEST 2

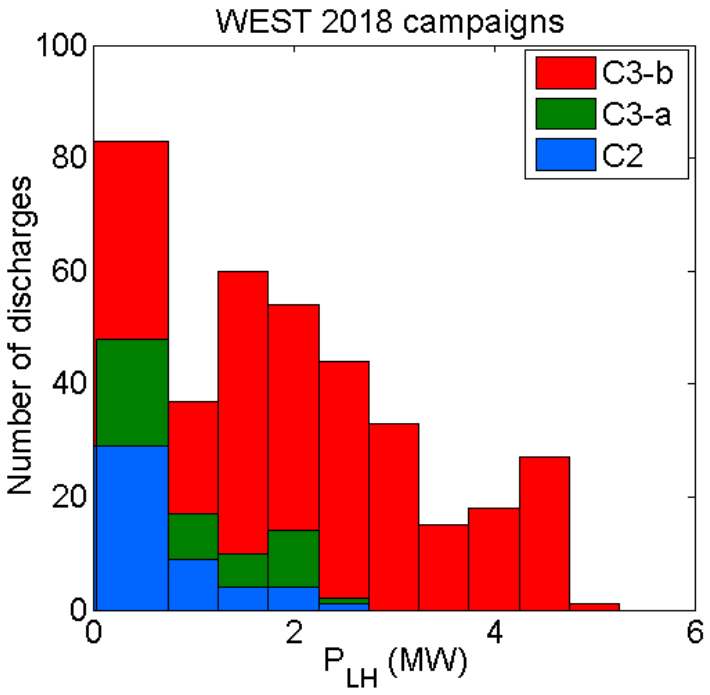


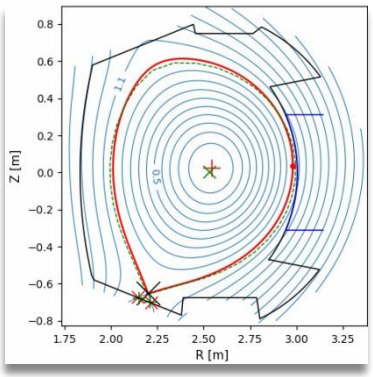
6th WEST Governing Board May 17th, 2019 | C. Bourdelle, N. Fedorczak and the WEST team

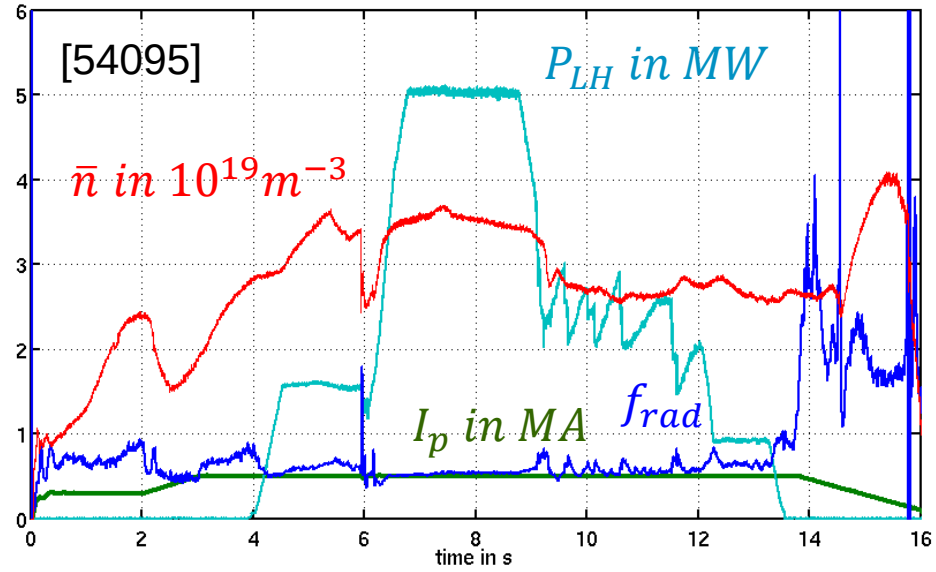
TOWARDS LONG PULSE H MODE AND STEADY STATE OPERATION

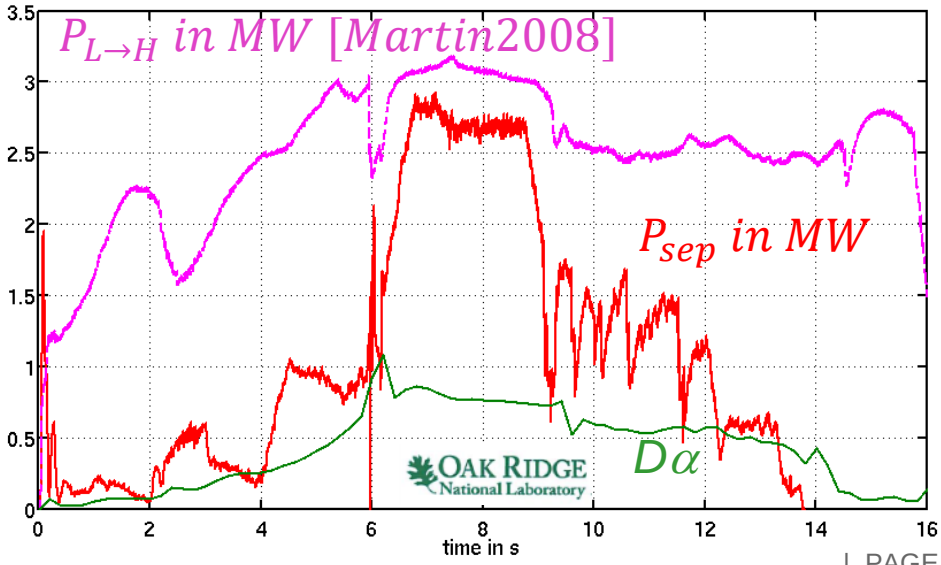
- **C3 Power ramp up**
- C3 Long pulse operation
- C4 strategy for H mode

UP TO 5 MW OF LH POWER COUPLED TO DIVERTED PLASMA





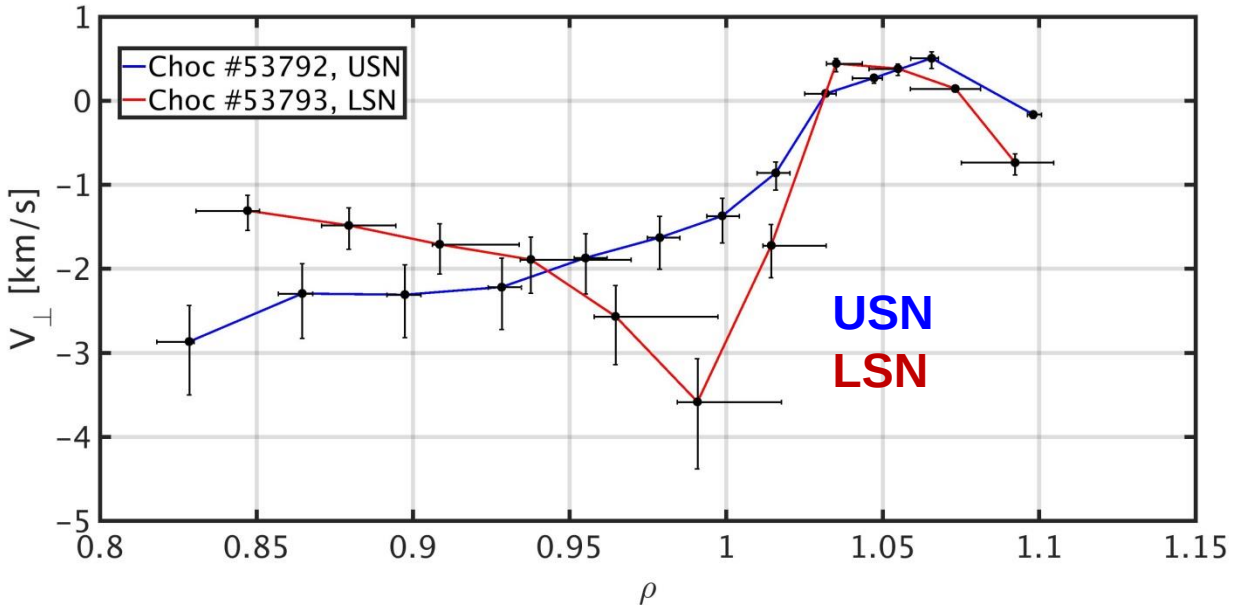




SHEARED E_r

∇E_r measured by Doppler reflectometer

Larger sheared Er in LSN than USN, H mode access easier for Bx∇B drift towards X pt as expected

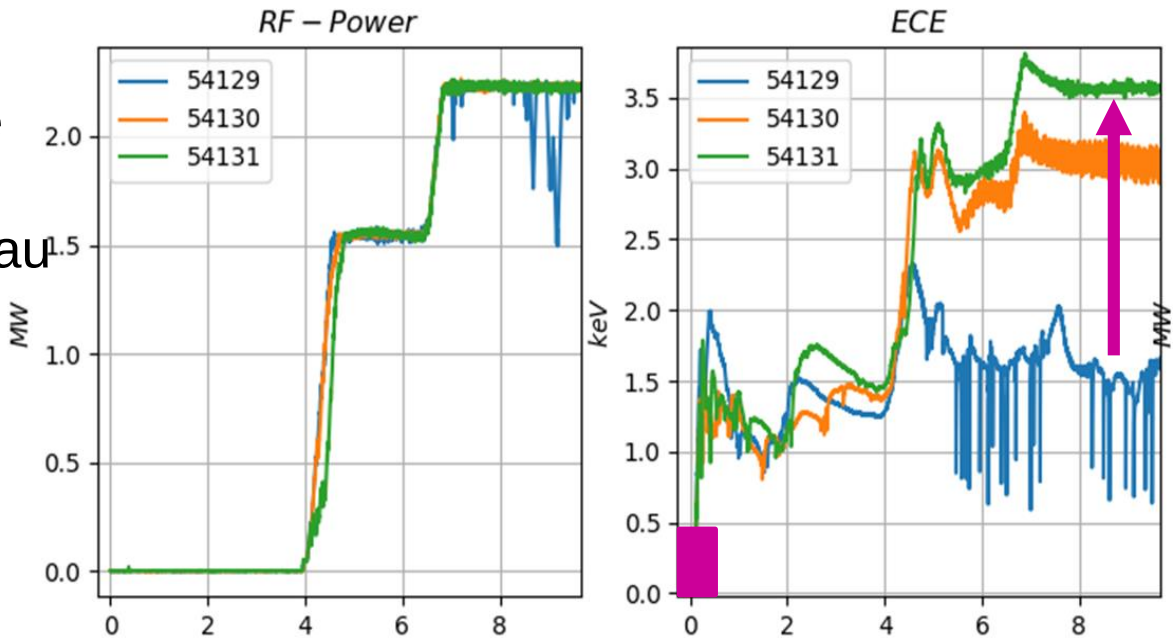


(2,1) MHD AVOIDANCE THANKS TO CURRENT PREFORMING

Need to improve margin to reversed q profiles leading to deleterious (2,1) double tearing modes

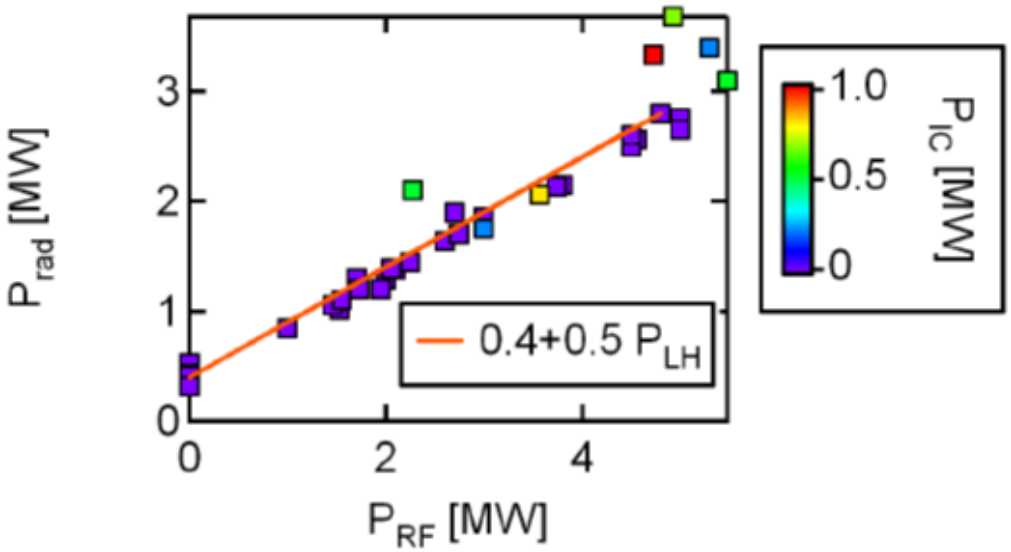
Tested in C3:
- Early N_2 to increase edge resistivity and peak j
- Timing of Ip and LH plateau

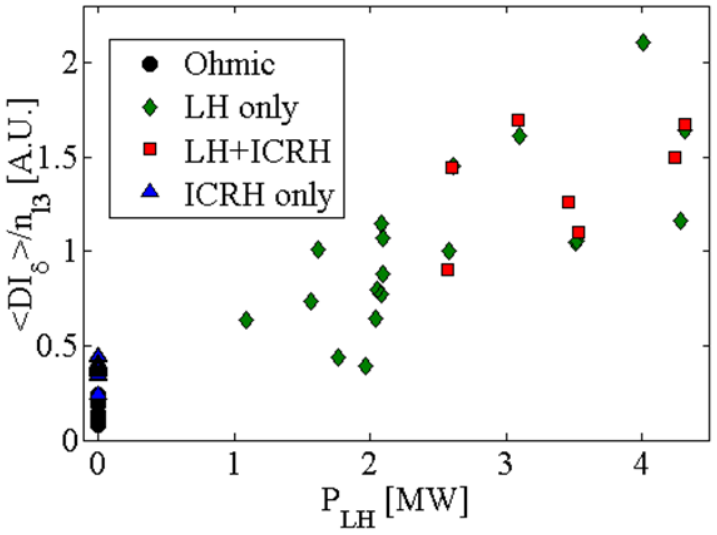
To be explored in C4 :
- Early RF application
- Ip modulation
- timing of RF
- RF ramp rate



HIGH RADIATED POWER FRACTION

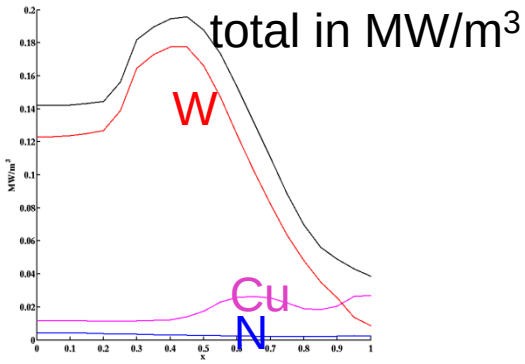
1st boronisation opened density domain,
but did not reduce **f_{rad} = 50% of LH power** from 1 to 5MW
Probably due to SOL D flux increase with P_{LH}





W dominates radiation

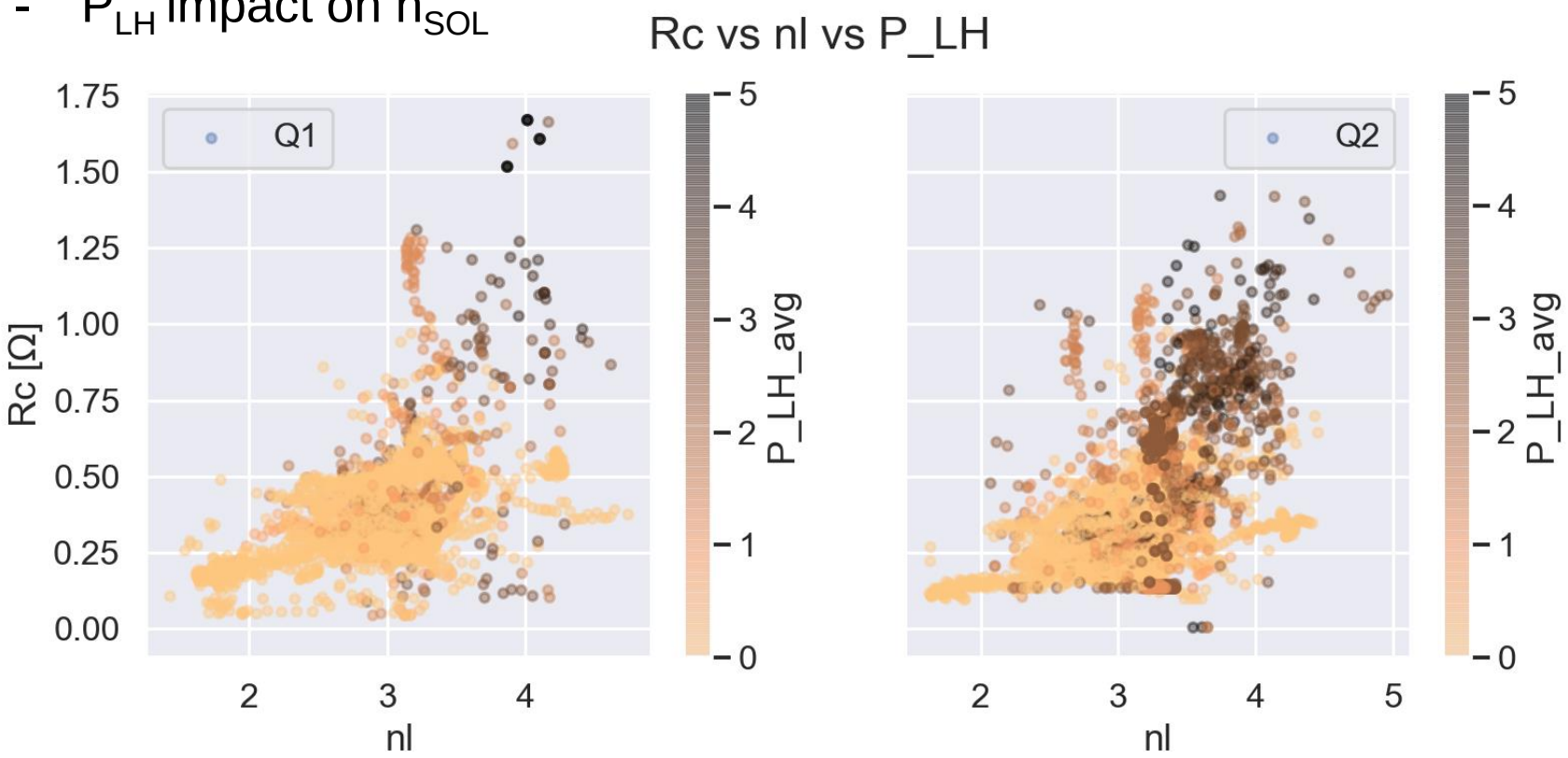
Here a METIS impurity mix estimate
54178 at 8s
Iterations on-going using synthetic diag
(SXR/bolo/brem and UV)



1ST ICRH MW INJECTED WITH 2 ANTENNAS

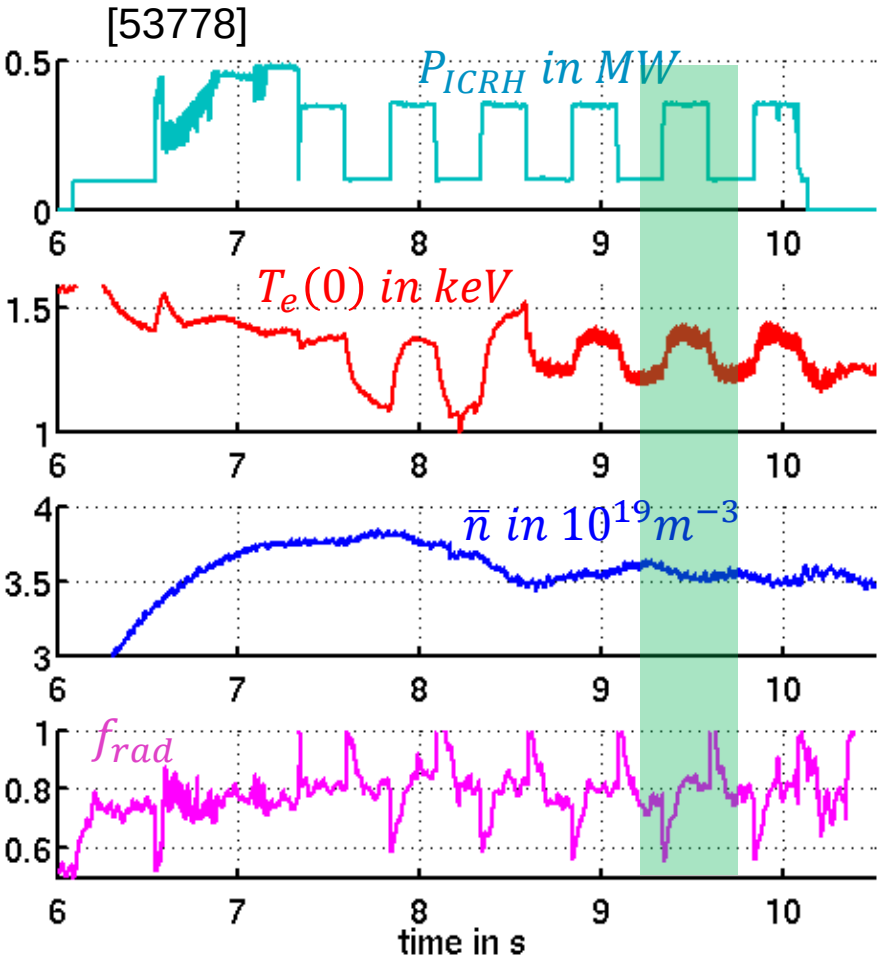
During C3 **ICRH coupling improved** thanks to

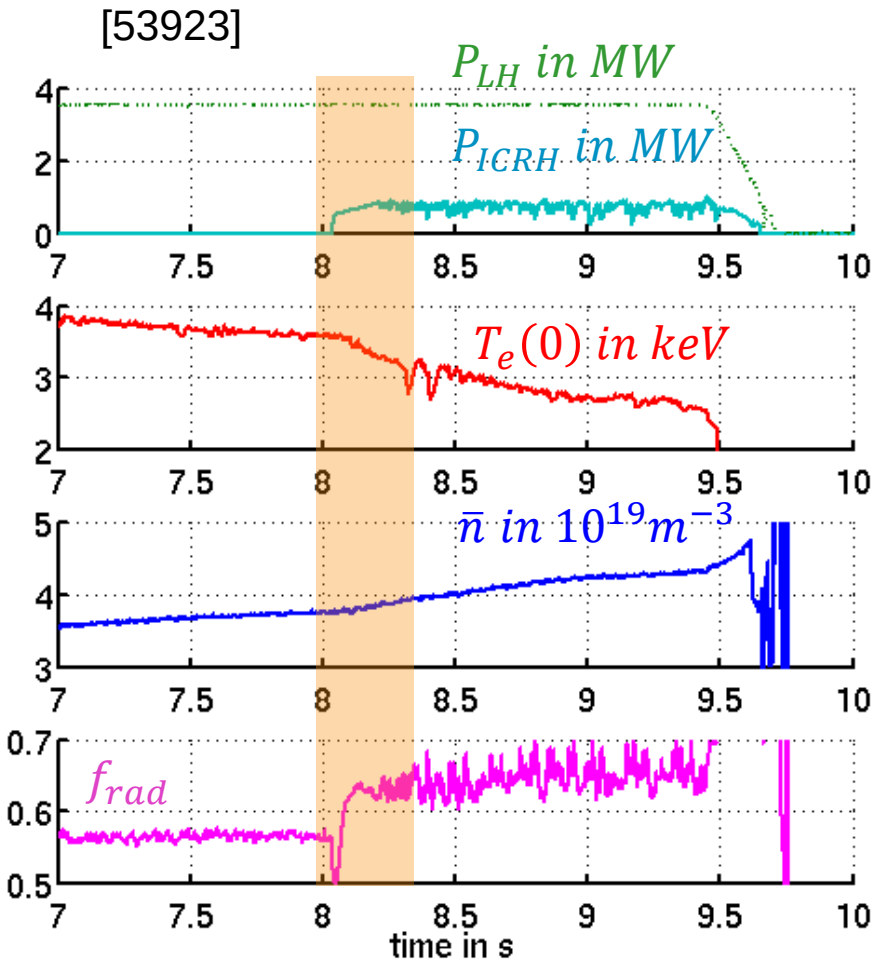
- controlled gap
- fuelling by IC antenna
- larger density
- P_{LH} impact on n_{SOL}



compatible with ~2 MW per antenna

ICRH IMPACT ON PLASMA





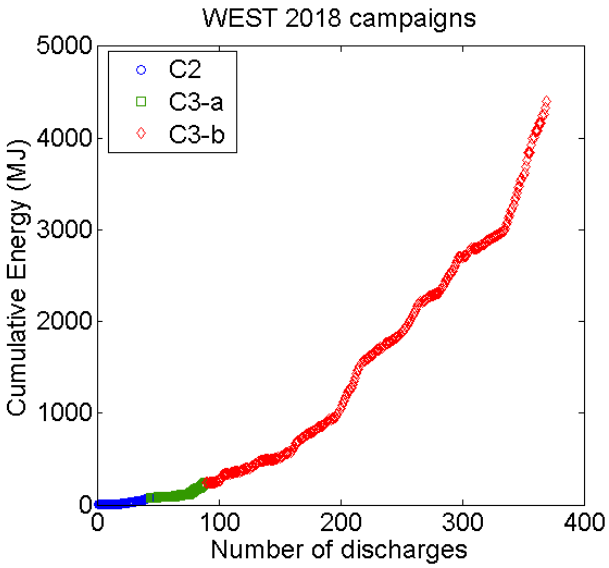
In some cases ICRH lead to steady f_{rad}, in others to an increase of f_{rad}

Role of W sources, RF potential, LHCD: under investigation

TOWARDS LONG PULSE H MODE AND STEADY STATE OPERATION

- C3 Power ramp up
- **C3 Long pulse operation**
- C4 strategy for H mode

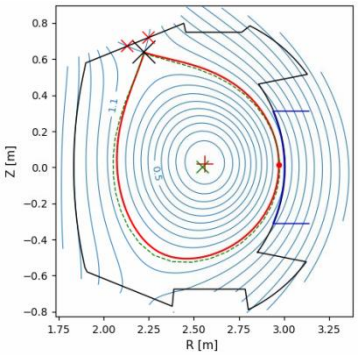
UP TO 35 s L MODE PLASMAS WITHOUT W ACCUMULATION

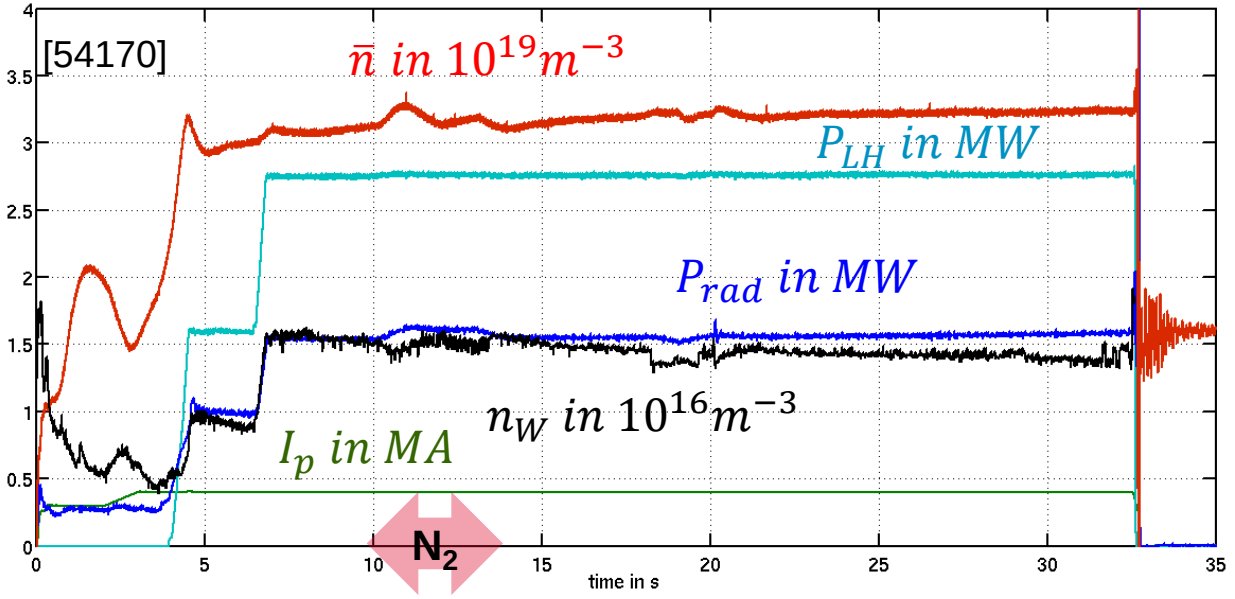


~ 20 minutes of plasma over 2 days
On actively cooled upper divertor

W <u>estimate</u> using Z_{eff} resistive and P_{rad}

$$n_W/n_e \sim 5.10^{-4}$$





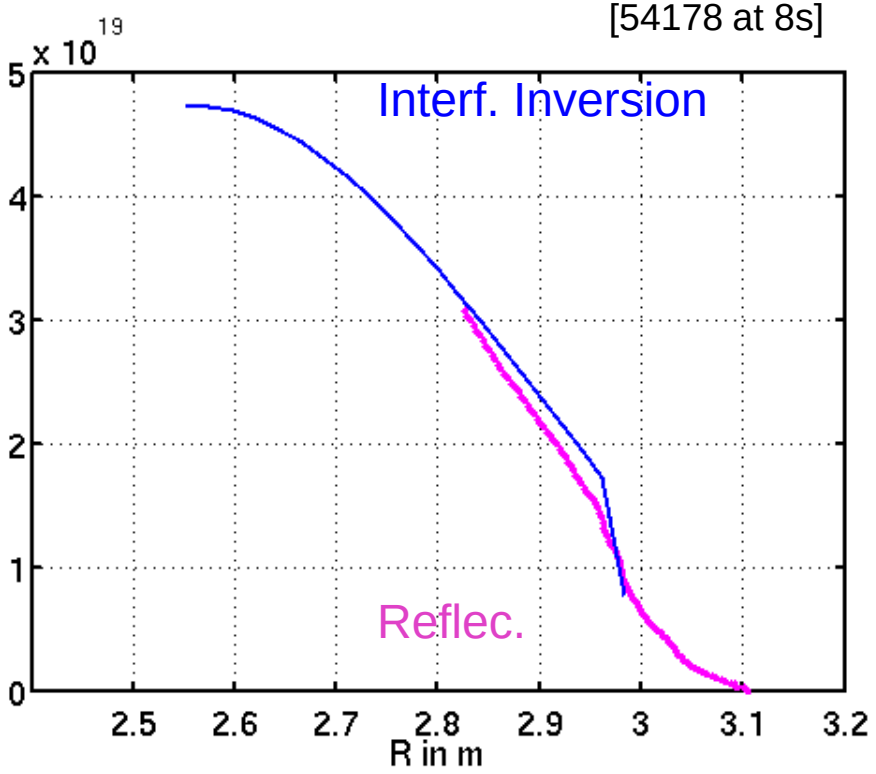
DESPITE PEAKED DENSITY PROFILES, NO W ACCUMULATION IN L MODE

Peaked n_e:

A priori a challenge for W neoclassical transport

$$V_{W,neoclassical} \propto \frac{\nabla n}{n} - 0.5\frac{\nabla T_i}{T_i}$$

[54178 at 8s]



But, unlike JET and AUG in WEST no torque, W neoclassical transport < turbulent W transport

→ a very different operational domain

More at EPS by X. Yang and P. Manas EUROfusion AUG/WEST researcher Grant

TOWARDS LONG PULSE H MODE AND STEADY STATE OPERATION

- C3 Power ramp up
- C3 Long pulse operation
- **C4 strategy for H mode**

C4 GOAL: 10 MW COUPLED

Developements of experiments at 3.7T, dedicated sessions on:

- MHD (2,1) mode avoidance
- ICRH, 3 antennas, up to 4 MW
- Fuelling rate and location on W sources
- LHCD up to 6 MW

Integration in « high confinement » sessions:

- Best of (2,1) avoidance, best fuelling, and ramp up ICRH and LHCD simultenaously up to 10 MW
- If no H mode, reduce B to 2T and apply LHCD only

As soon as H mode achieved, dedicated sessions on:

- L-H power threshold
- ELM regime
- H mode confinement

Other sessions on:

- I mode access on USN at 3.7T
- Ohmic and L mode confinement

CONFERENCES RELATED TO TF WEST 2 ANALYSIS WORK

- RF topical:

- *ICRH coupling optimization and impurity behavior in EAST and WEST* G. Urbanczyk

- *First Lower Hybrid Current Drive experiments on the WEST tokamak* M. Goniche

- *First Ion Cyclotron Resonant Heating and Cooling experiments on the WEST tokamak* L. Colas

- PFMC:

- *Long pulse experiments with the actively cooled divertor in WEST*, T. Loarer

- EPS:

- *Long pulse L mode operation compatible with a full W environment*, C. Bourdelle

- *W transport in WEST long L mode pulses*, X. Yang

- *MHD interplay with W from a modelling perspective*, P. Maget

- APS:

- *First results of long pulse experiments with the actively cooled W-divertor in WEST* A. Ekedahl

- IAEA SSO: *2 talks on PWI and RF scenarios*

HEADING TOWARDS A SUCCESSFUL C4!

A challenging, hence interesting, C4 ahead:

- Study routes to avoid MHD (2,1) modes
- Optimize trade-off btw W sources and RF coupling (antenna positions, fuelling rate/location, etc)
- Maximize RF absorption, work at high density to limit ripple losses
- Reduce V_{loop}, reach a minute pulse in a full W envt
- W transport in torque free, electron dominated plasma
- Impact of L-H transition on RF coupling, on W sources and transport
- ELM regime at large A

WEST contributting to the step-ladder approach towards JT-60SA, ITER and DEMO

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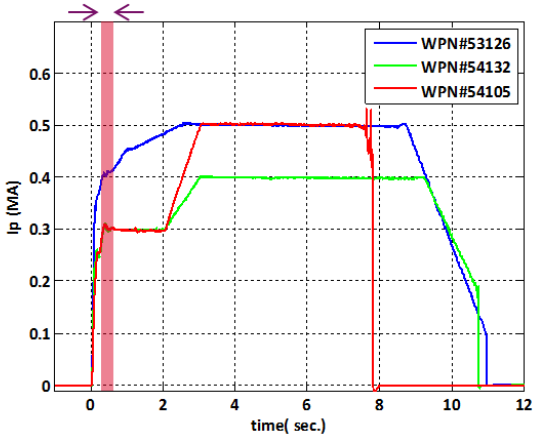
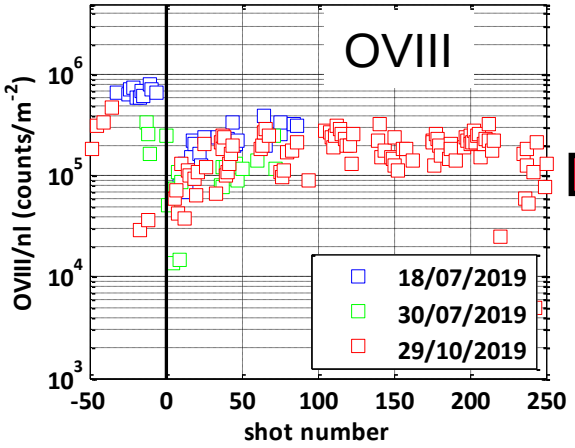
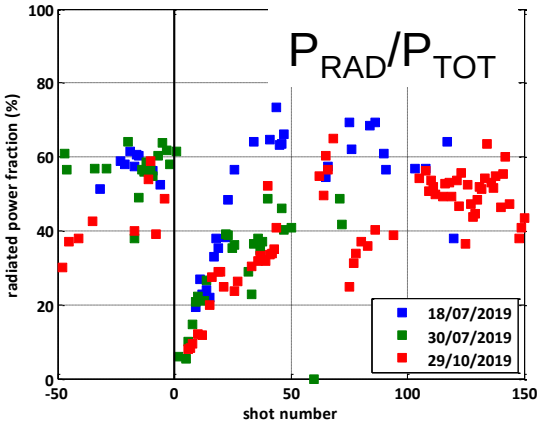
Duration of boronization effect

Ohmic

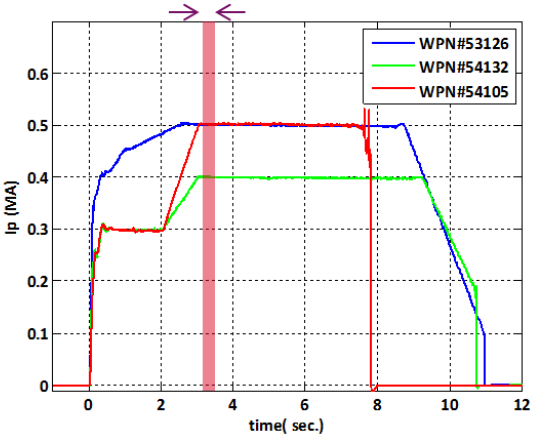
0,3 sec.

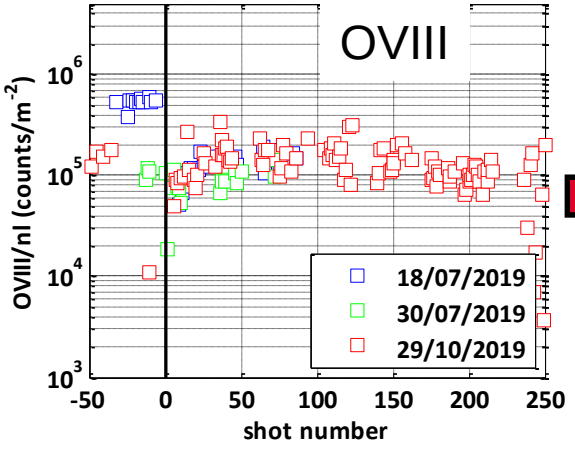




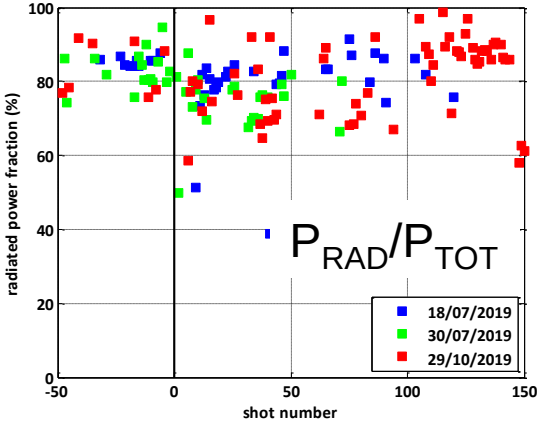


0,5 sec.





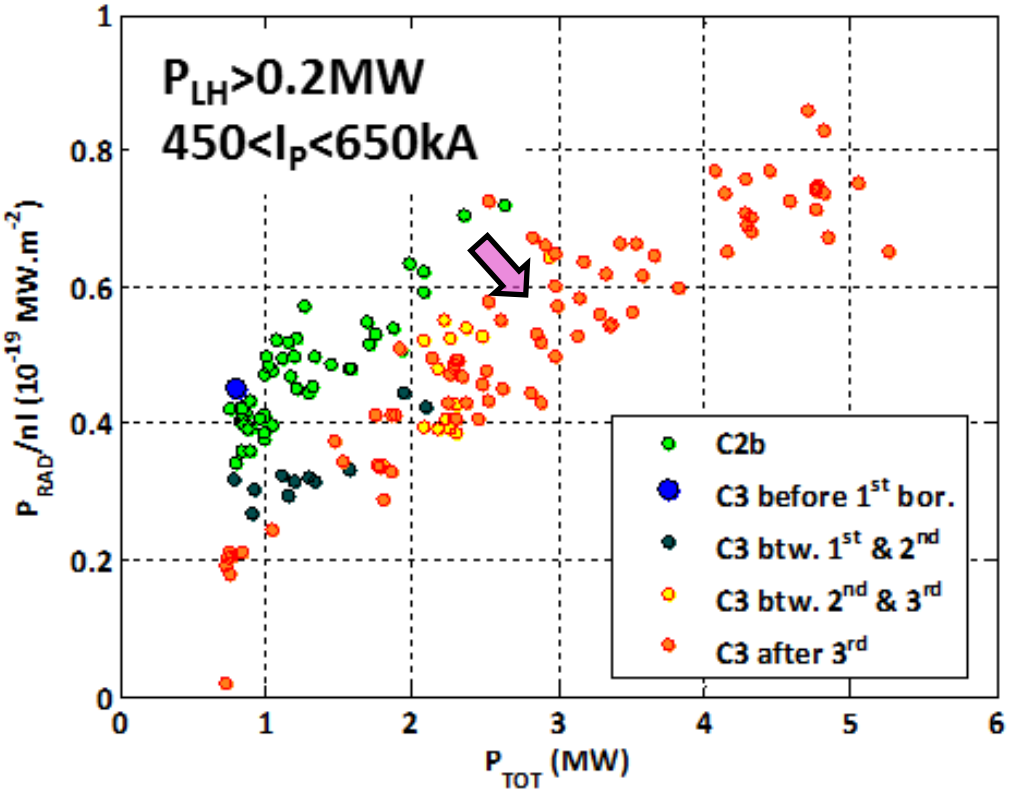
?



Seems to confirm W becomes the main radiator after boronization

3 boronizations performed in C3

- First in WEST since last boronization in Tore Supra (2010)

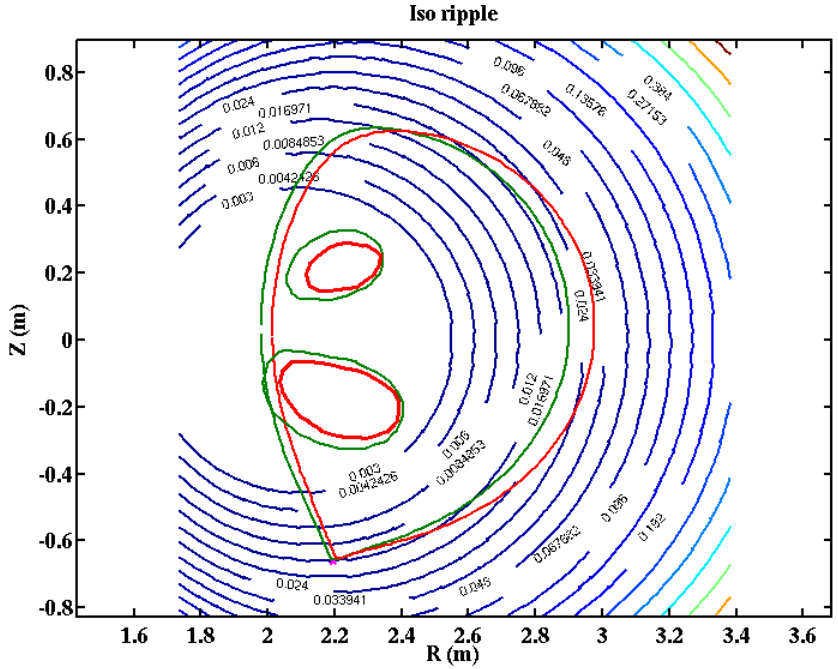


→ enlarged the operational domain in density and power

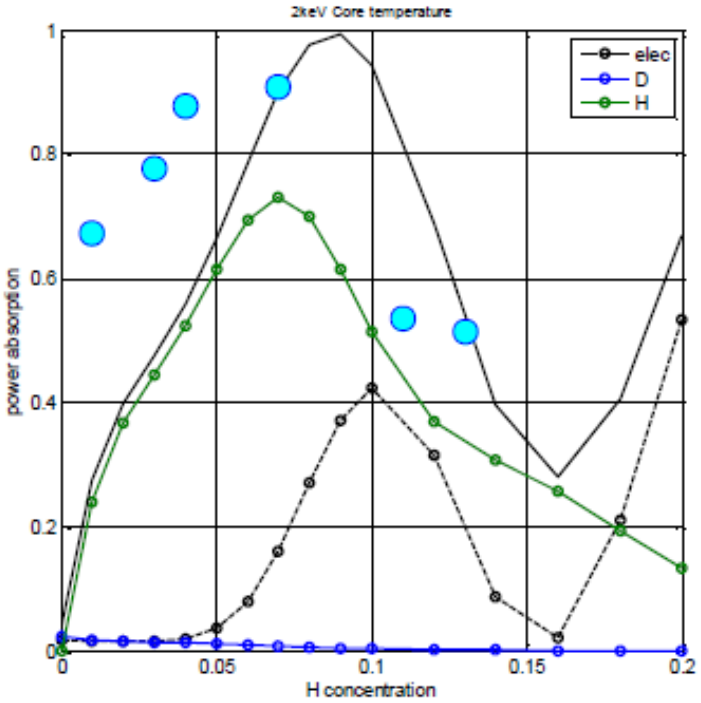
- He-15%B_2H_6 mixture used

ICRH ABSORPTION

Reducing Rext for a larger good confinement zone



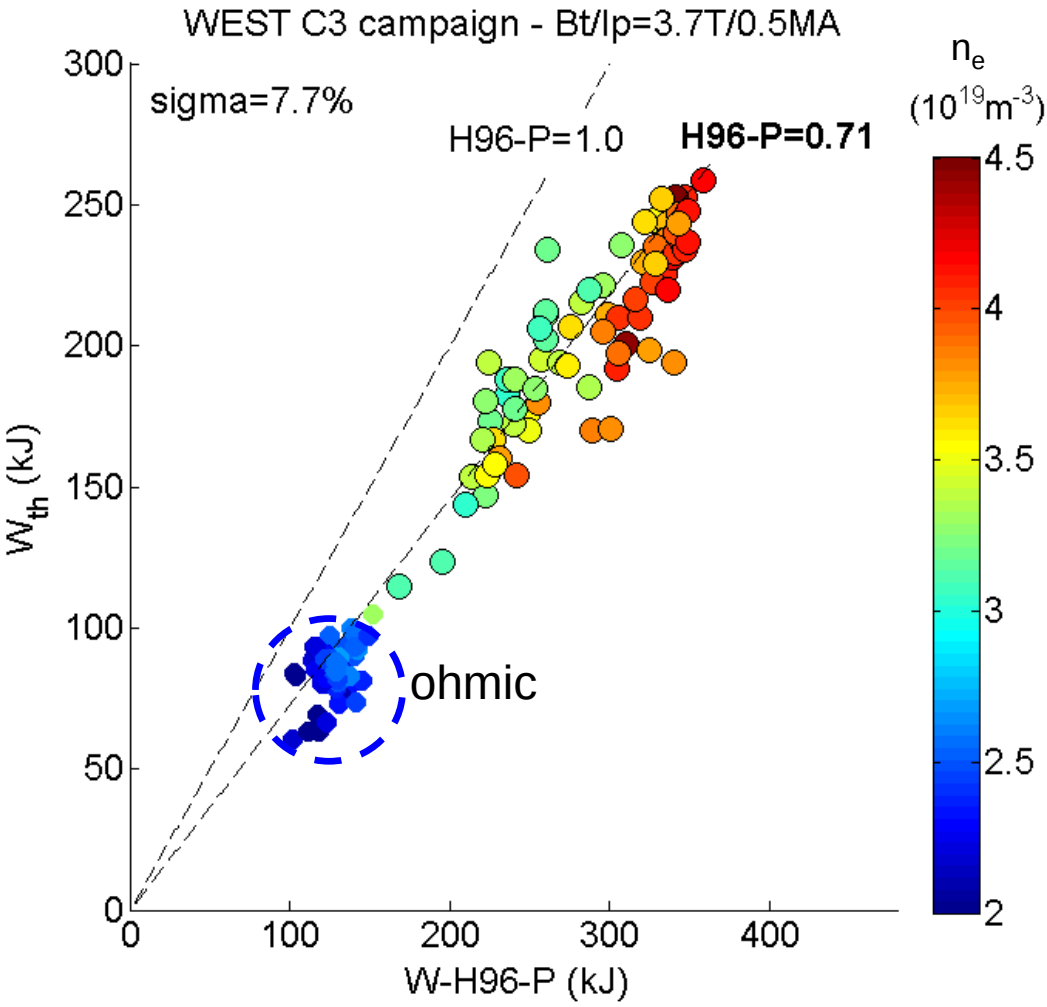
Absorption at 48 MHz,



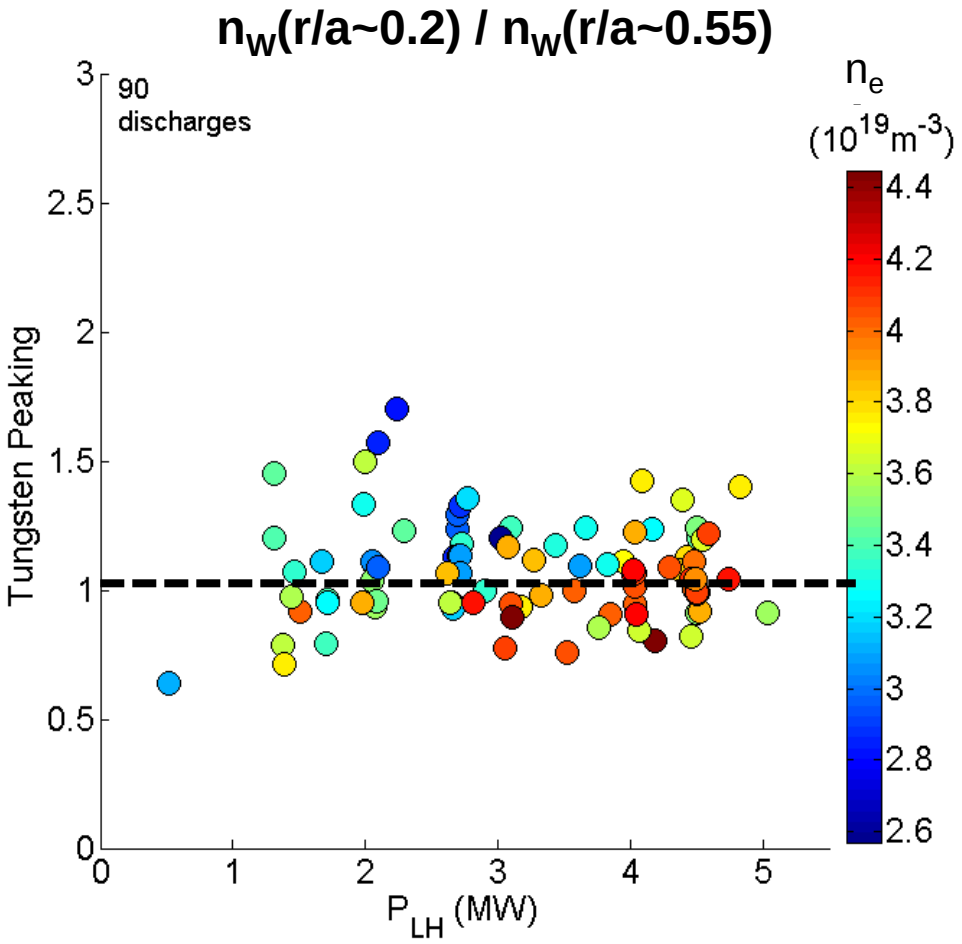
STORED ENERGY SCALES WITH H96-P SCALING LAW

- *W_{ion} derived from neutrons yield and plasma dilution (➔ METIS code)*
- ***$P_{loss} = P_{in}$***

- High density (n_e > 4) plasmas have highest stored energy
  - ➢ $W \sim n_e^{0.4}$ (scaling laws)
  - ➢ W_i/W_e increases with n_e
- Most of discharges with high W_{th} (>200kJ) have sawteeth
- $P_{loss} = P_{in} - P_{rad,bulk}$ would lead to H96-P=0.95



NO TUNGSTEN ACCUMULATION IN THE PLASMA CORE

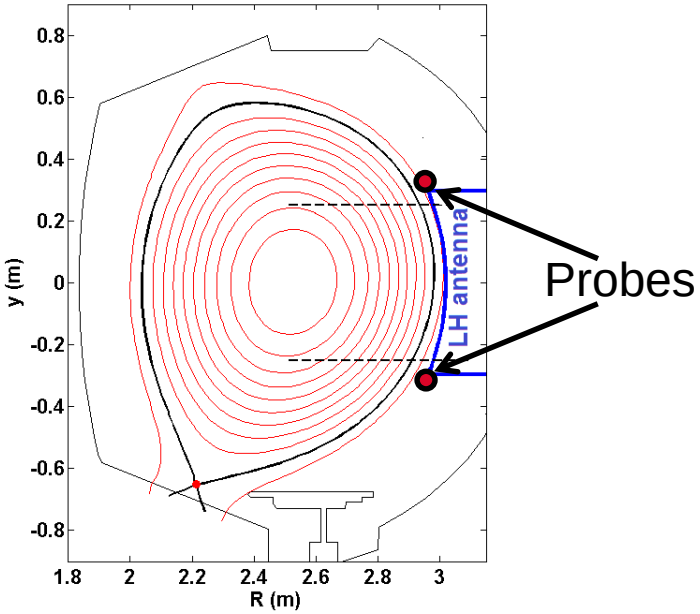


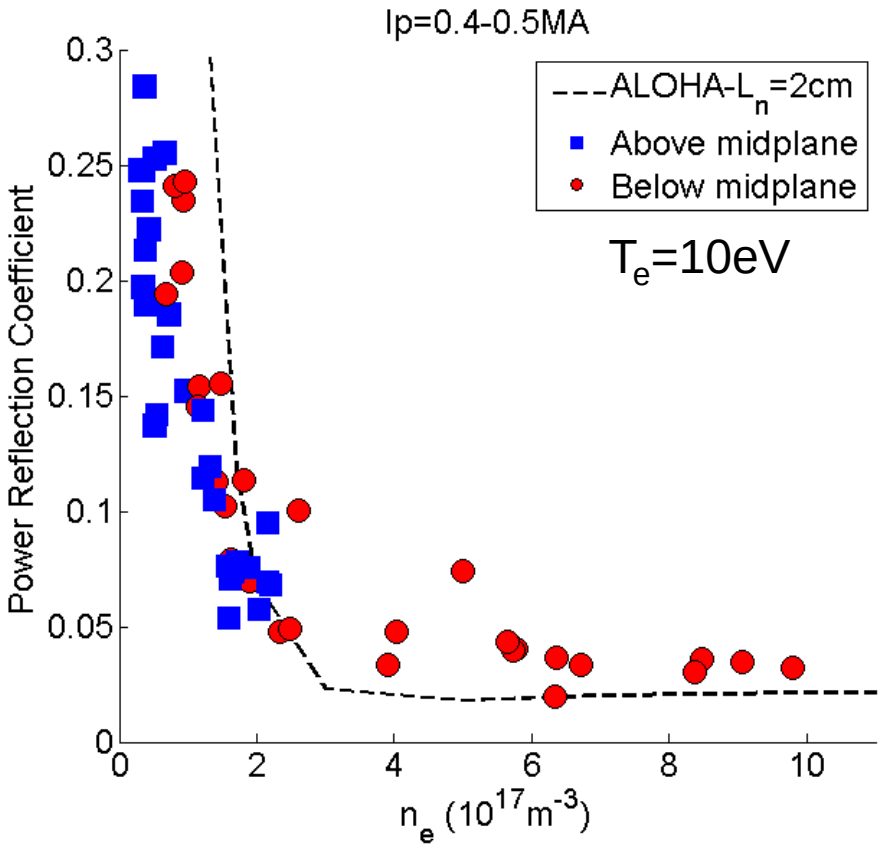
- Tungsten density profile remains flat
- No dependence on LH power

More on W-transport at EPS 2019 (C. Bourdelle & X.D. Yang)

REFLECTION COEFFICIENT IS CONSISTENT WITH DENSITY MEASURED AT ANTENNA FRONT

- $RC_{upperWGs}$ vs. n_e (z=+30cm)
- $RC_{lowerWGs}$ vs. n_e (z=-30cm)





- T_e over-estimated for low n_e discharges
- Measurements agree with ALOHA modelling

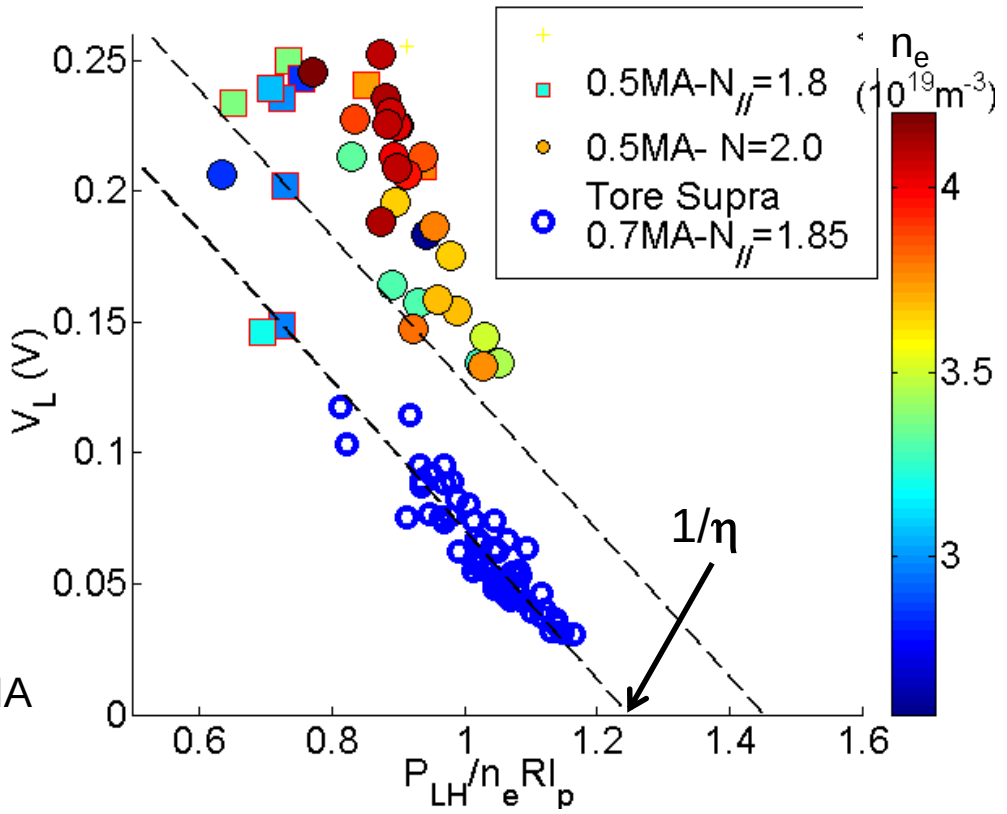
LHCD EFFICIENCY DECREASES WITH DENSITY

LHCD efficiency η *estimated from the slope* V_L *vs* $P_{norm}=P_{LH}/n_e R I_p$

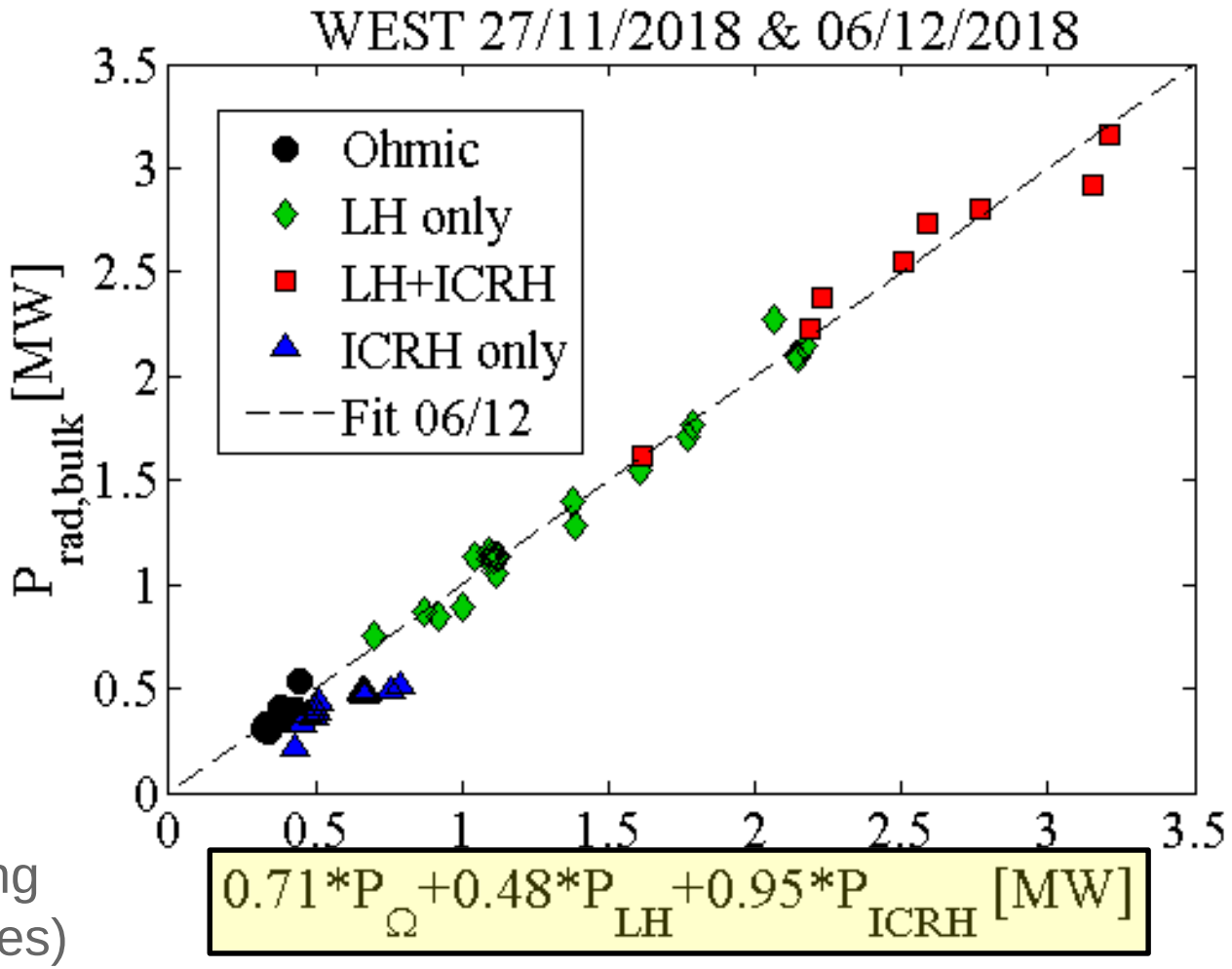
$$V_L = \frac{V_0}{\rho}\frac{\eta}{1+\eta_h/\eta}\left(\frac{1}{\eta}-P_{norm}\right)$$

$$(Z_{LH}/Z_{OH})\,(T_{e,LH}/T_{e,OH})^{-3/2}$$

- LHCD efficiency decreases with density
- No clear effect of N// as launched
- $\eta_{WEST,0.5MA} \sim 0.85\eta_{Tore\text{-}Supra,0.7MA}$ ($<n_e>\sim 3\times10^{19}m^{-3}$)



Nearly all P_{ICRH} goes into extra radiation on high performance plasmas



- Empirical scaling (high-perf. pulses)
- ICRH-only discharges (*e.g.* #53778) are below scaling (ΔP_{rad}~0,6*P_{ICRH}).

Several causes of W source increase

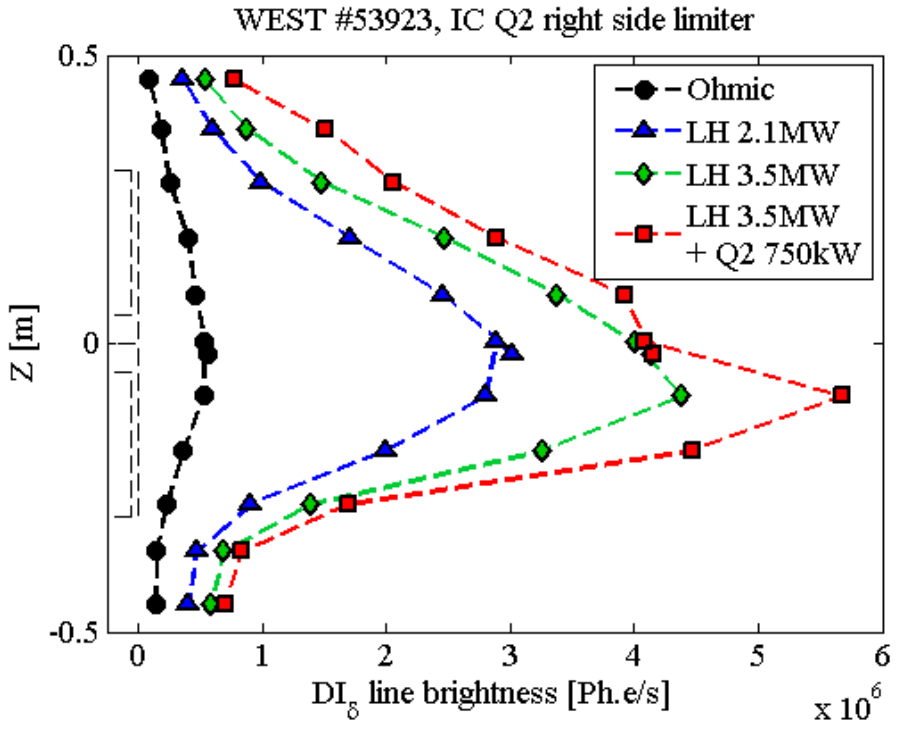
$$\Gamma_W = \Gamma_D Y_{eff}$$

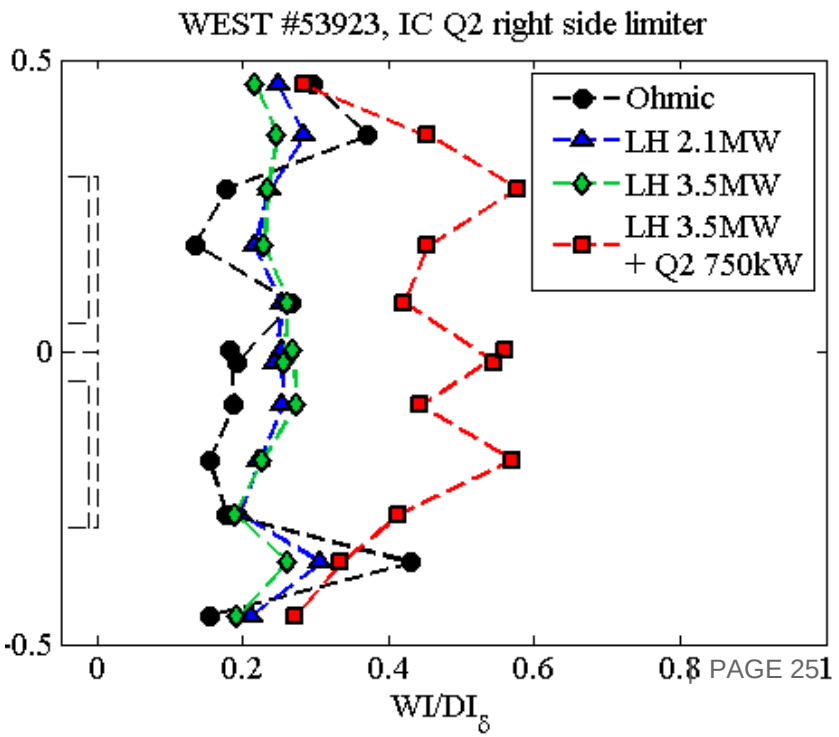
Γ_D

- Proxy: DI_δ brightness on ant. limiter
- Main cause of variation from ohmic to LH-only phases
- Occurs on all observed objects
- Including LH1 grill limiter & divertor

Y_{eff}

- Proxy: line ratio WI/ DI_δ
- Main cause of variation when adding ICRH
- On IC ant. limiter, APL, divertor
- NOT on LH1 grill limiter





Temptative parametric dependance

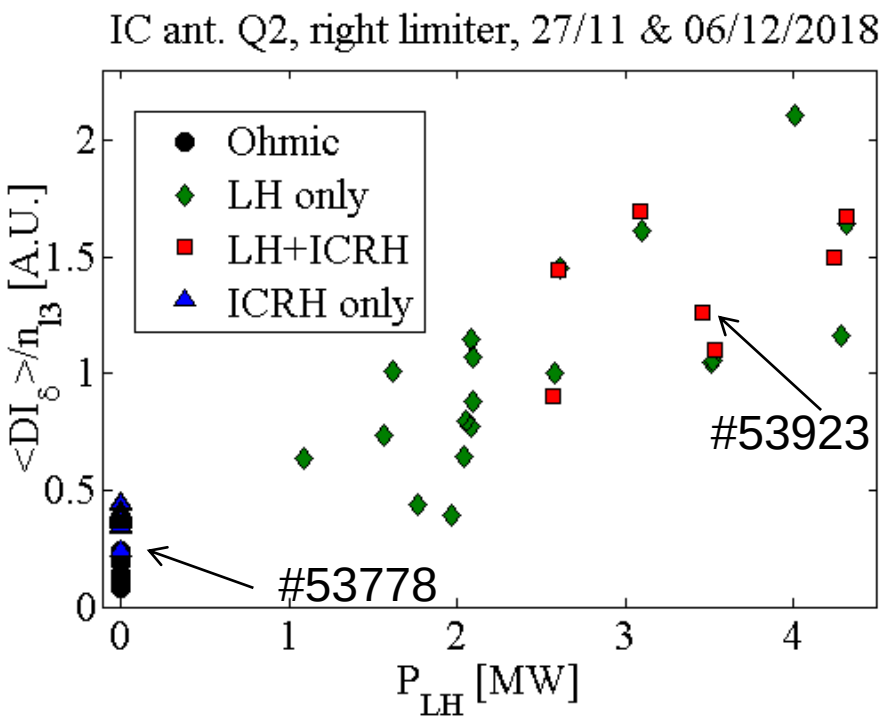
$$\Gamma_W = \Gamma_D Y_{eff}$$

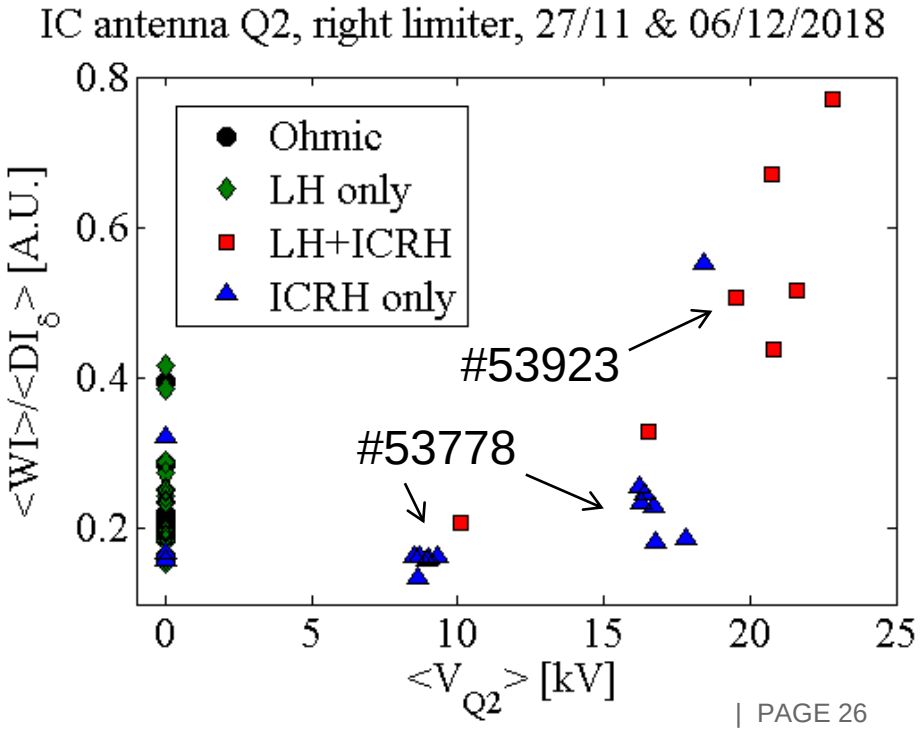
Γ_D=f(n_l, P_{LH})

Y_{eff}=g(T_e,V_{Q2})

- Proxy: DI_δ brightness on ant. limiter
- Larger at high density ⇔ IC coupling
- Increases faster than n_l with P_{LH}
- W penetration also evoloves with n_l

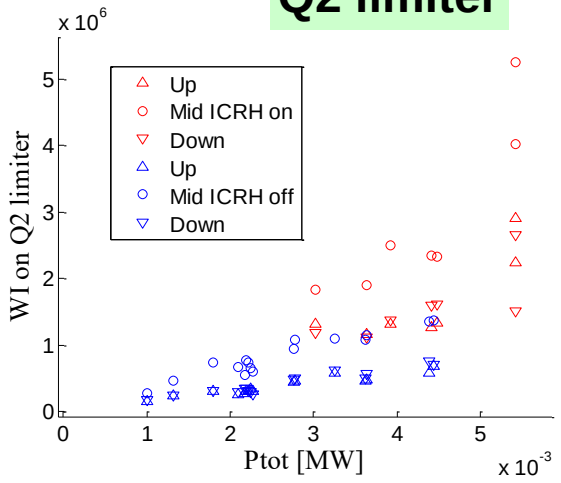
- Proxy for Y_{eff}: line ratio WI/ DI_δ
- Proxy for IC near field amplitudes: V_{Q2}



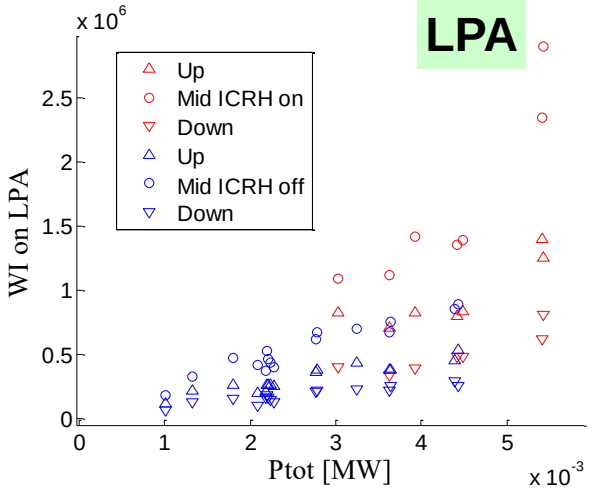


WI evolution with power on different objects [Ph/s]

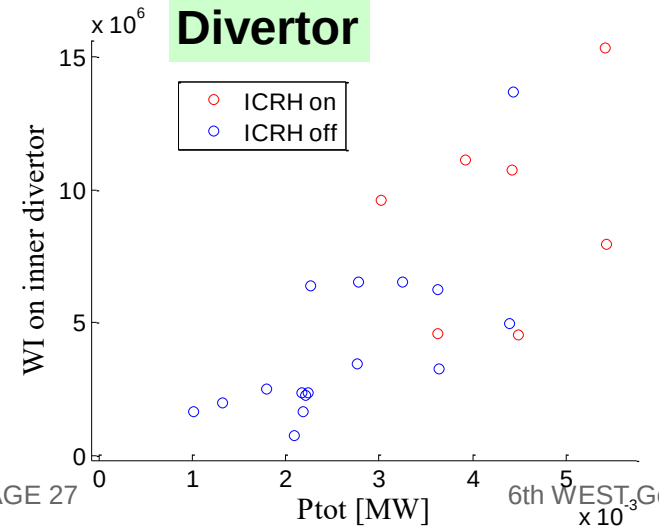
Q2 limiter



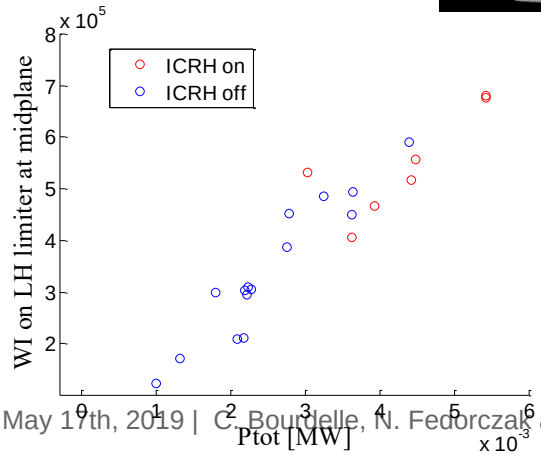
LPA

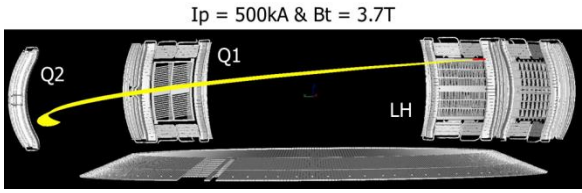


Divertor



LH limiter

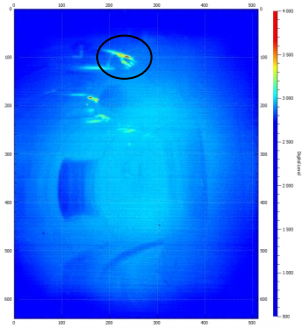


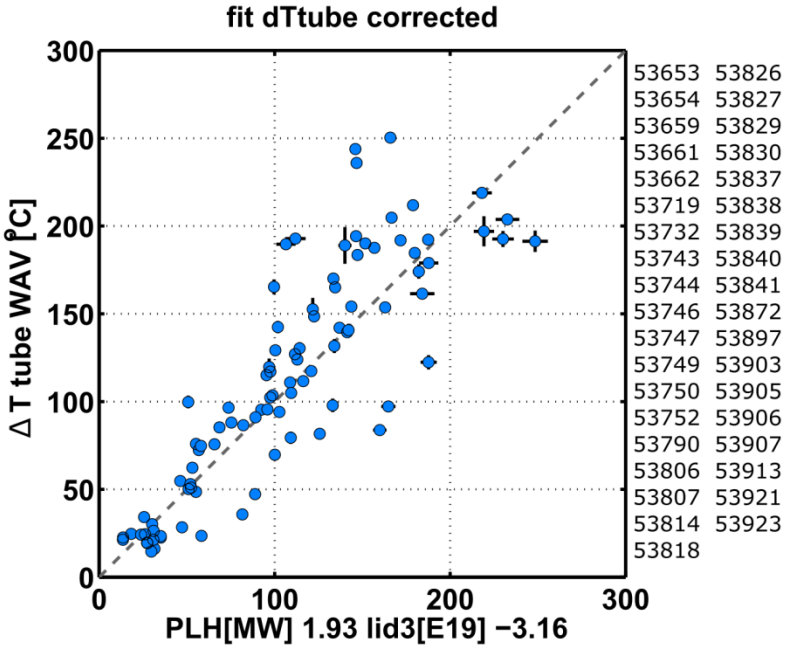


LH - Q2
Not magnetically connected

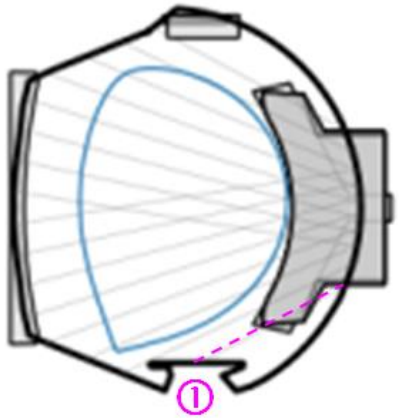
RIPPLE LOSSES: REDUCED AT LARGER DENSITY

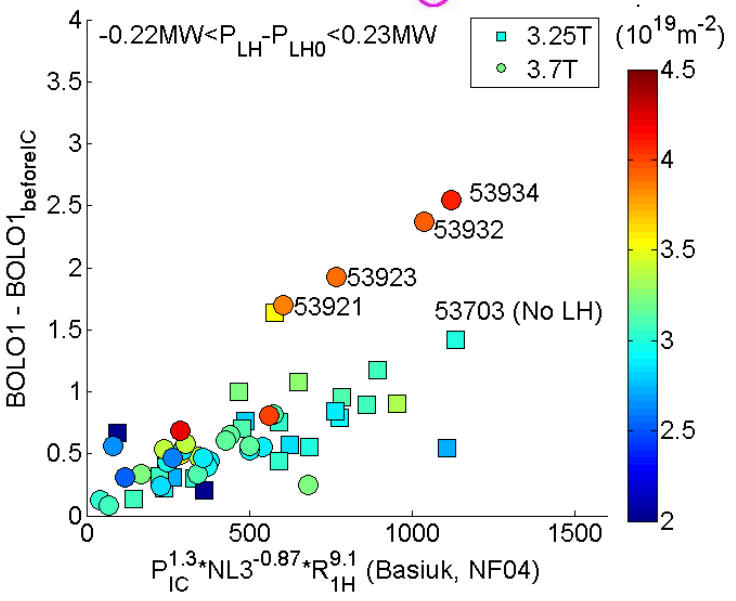
During LHCD on upper part of vessel (IR ΔT on div. cooling pipe)





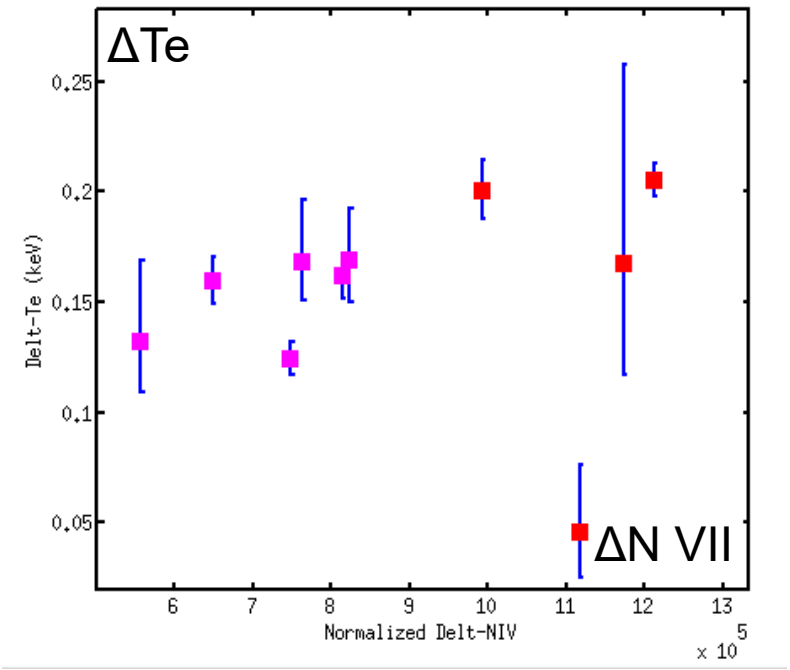
During ICRH on baffle (chord 1 bolometer)

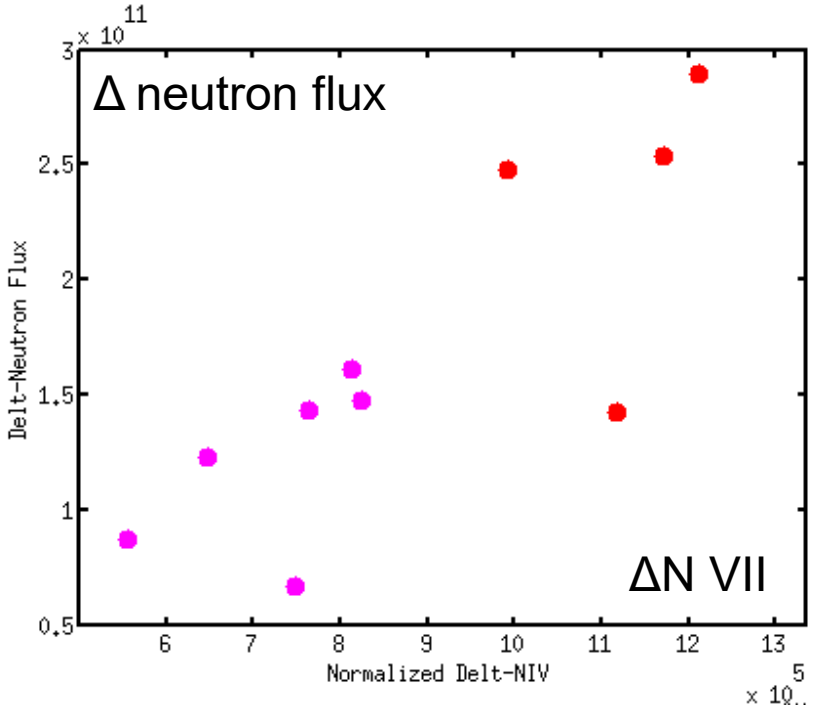




N_2 INJECTION: POSITIVE IMPACT ON ENERGY CONTENT

N_2 from upper divertor
N_2 from outer bumper





Also seen on W_{dia} (for the moment uncorrected from induced currents)

« HIGH CONFINEMENT » SCENARIO DEVT, C4 STRATEGY

1. **10 MW. P_martin atteint avec xx 7MW & 50% rad**
2. **Low B**

MHD: **increase margin to 2-1 modes** before RF application

ICRH:
Maximize coupled power
Maximize absorbed power
Minimize radiated power

Radiation:
Conditionning (boro, baking etc) impact on **low Z, csqces for W**

"HIGH CONFINEMENT" scenario development

LHCD:
Maximize LHCD coupling
In particular when H mode
Minimize ripple losses

When H mode:
L-H threshold, ELMs regime, H mode conft
w/o H mode: I mode exploration, confinement in ohmic and L mode

CONFERENCES RELATED TO TF WEST 2 ANALYSIS WORK

- RF topical:

- *ICRH coupling optimization and impurity behavior in EAST and WEST* G. Urbanczyk

- *First Lower Hybrid Current Drive experiments on the WEST tokamak* M. Goniche

- *First Ion Cyclotron Resonant Heating and Cooling experiments on the WEST tokamak* L. Colas

- PFMC:

- *Long pulse experiments with the actively cooled divertor in WEST*, T. Loarer

- EPS:

- *Long pulse L mode operation compatible with a full W environment*, C. Bourdelle

- *W transport in WEST long L mode pulses*, X. Yang

- *MHD interplay with W from a modelling perspective*, P. Maget

- APS:

- *First results of long pulse experiments with the actively cooled W-divertor in WEST* A. Ekedahl

- IAEA SSO: *2 talks on PWI and RF scenarios*