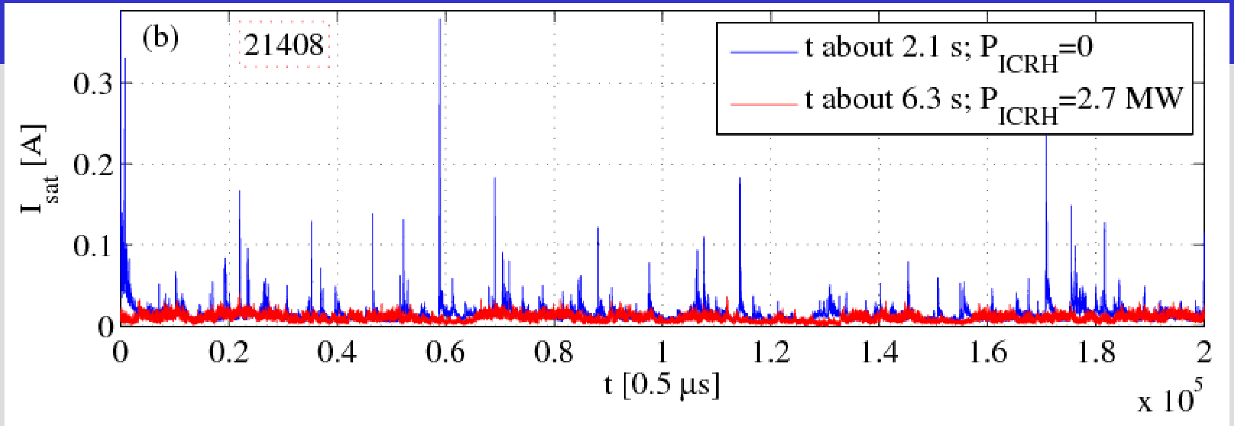
# Scrape-off Layer Turbulence L-mode, NBI-driven H-mode and ICRH H-mode





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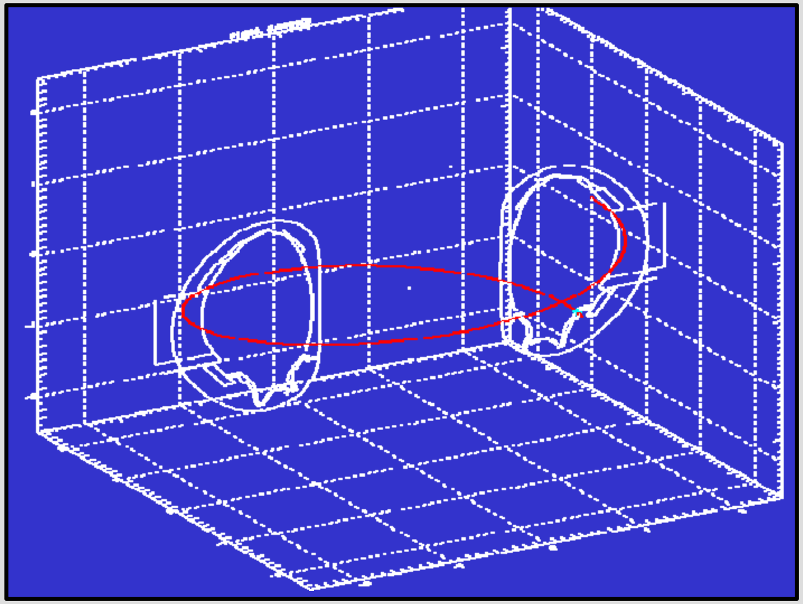
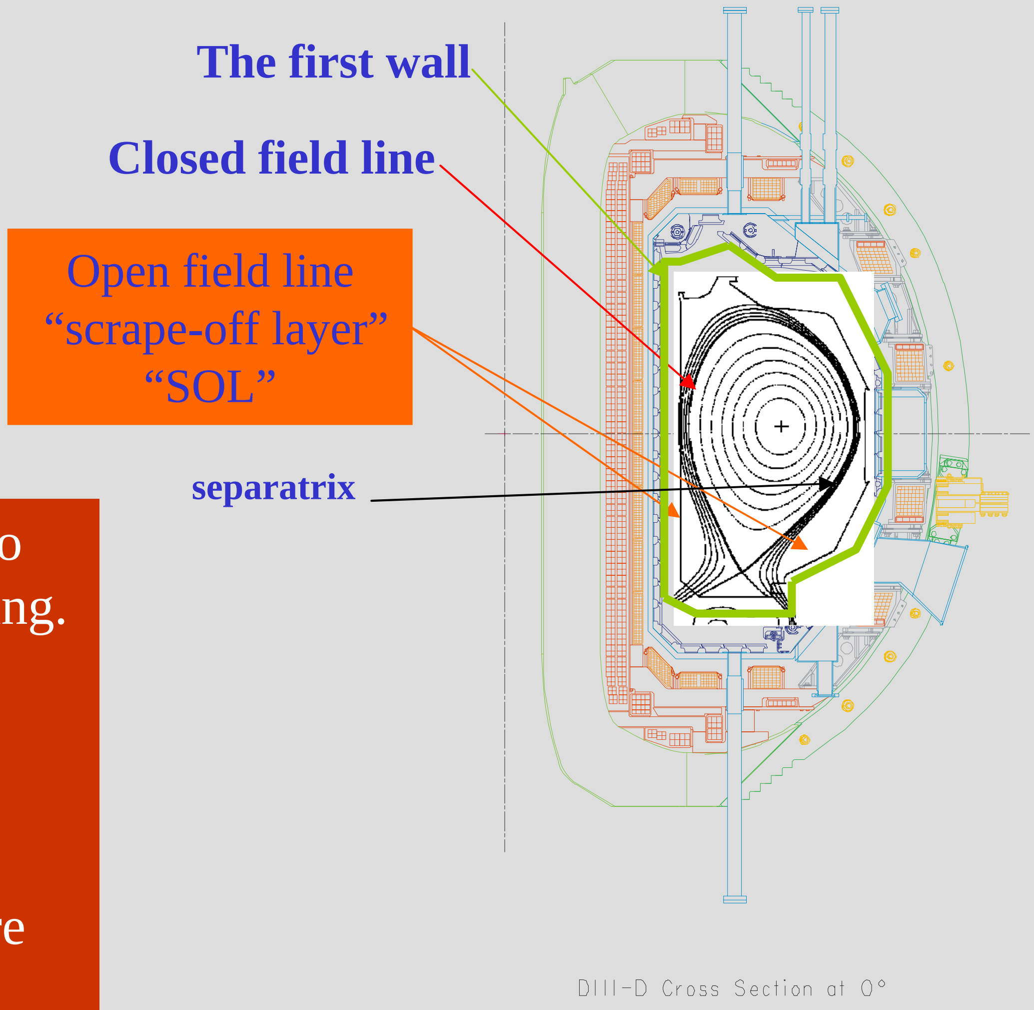
# OUTLINE

- A short introduction to the Scrape-off layer physics and the origin of plasma and turbulence in this region
- Short review of (recent) advances in understanding the SOL in L-mode plasmas
- Turbulence in the SOL for NBI-driven H-mode [G. Antar et al PPCF 2008]
- Turbulence in the SOL with ICRH and the ‘real’ suppression of turbulence
- Conclusion

# The scrape-off layer is a region where field lines are open, hence, connected to the vessel walls in contrast to 'closed' field lines in the plasma that lies inside the separatrix



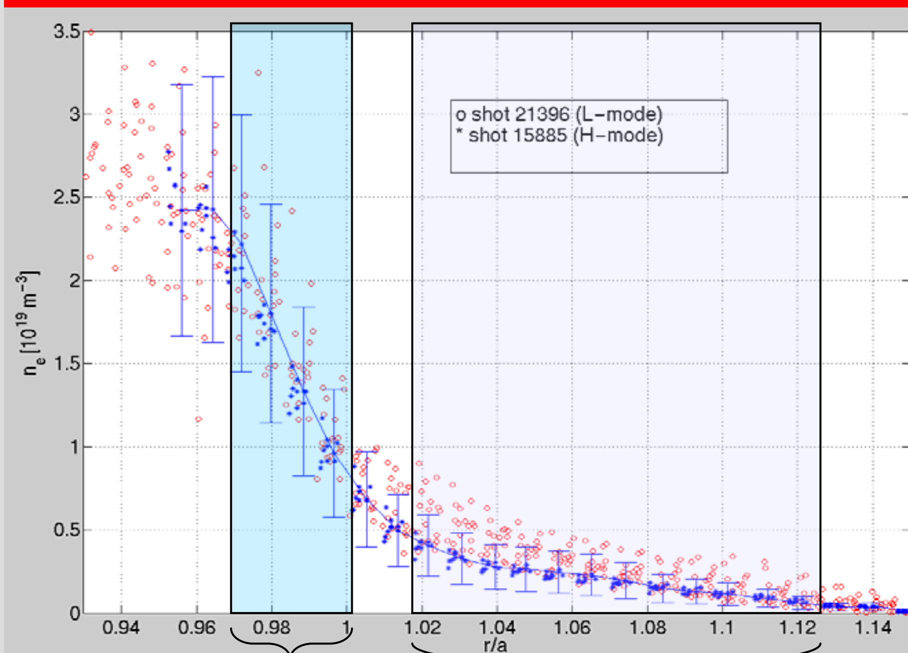



- The plasma-wall interactions leads to the first wall deterioration via sputtering. This limits the life-time of the confinement device.

- Impurities that come from the wall finds its way back into the plasma core and deteriorate the confinement.

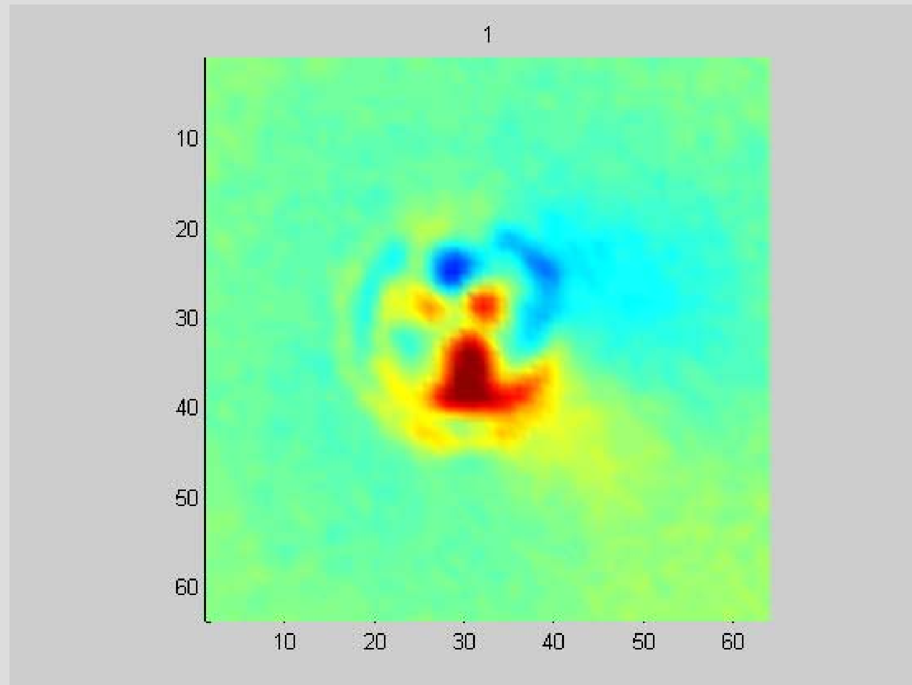
# Turbulence inside the separatrix is the main (only) source of plasma in the SOL.
# => Turbulence increase/reduction around the separatrix
# =
# Plasma increase/decrease in the SOL

**Because this where the gradients are the steepest, turbulence around the separatrix is the main cause of turbulence in the SOL**




Steep profile => source of instabilities and turbulence

Rather flat plasma profile



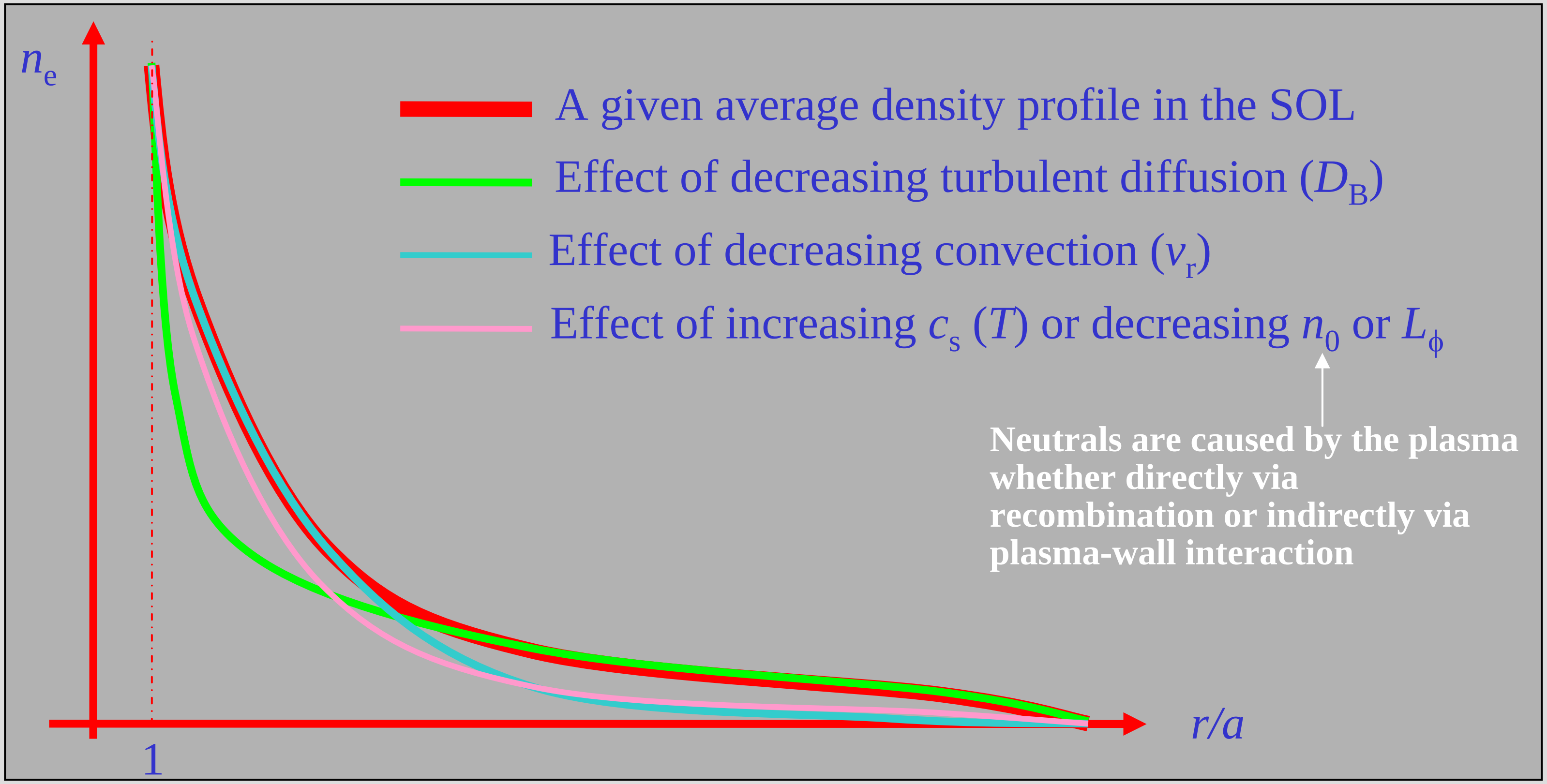

CSDX linear plasma device: Plasma in the far SOL exists because of an *m*=1 instability inside the main plasma column.

# Parameters affecting the average density profile in the SOL viewed by the continuity equation

An approximate form of the continuity equation

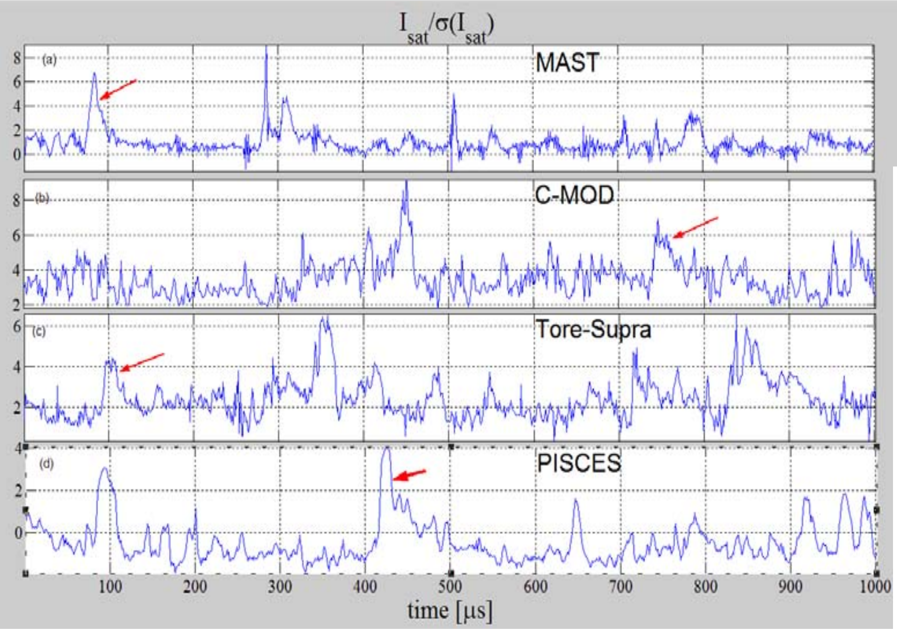
$$\frac{1}{r}\partial_r(D_B\partial_r(rn) + nv_r) = -\frac{nc_s}{L_\phi} + n(n_0\sigma_i(T) - n\sigma_r(T))$$

| Turbulent diffusion | Convection | Open Field lines | Neutrals acting as source and/or sink. |
|---|---|---|---|

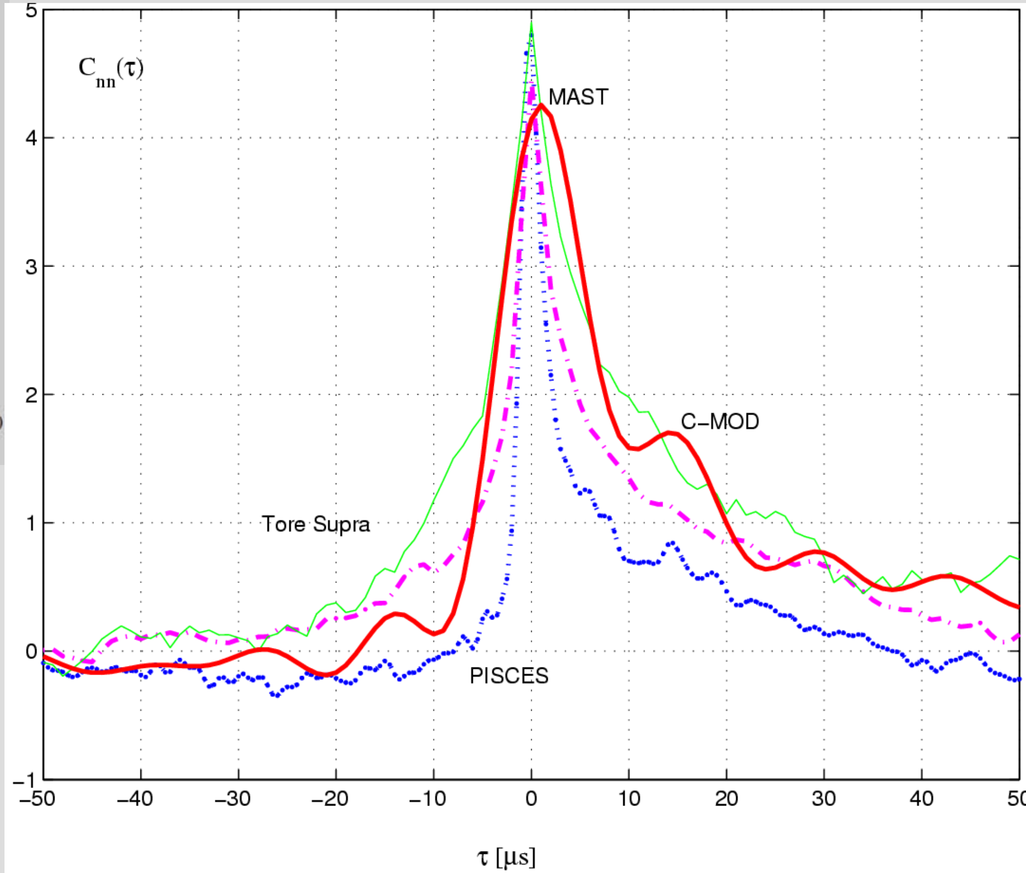


# Recall the L-mode Results

# Magnetic fusion devices are 'leaking' by, (1), radial transport of incoherent eddies, and (2), by large-scale structures with large radial velocities that are called avaloids (or more loosely blobs).

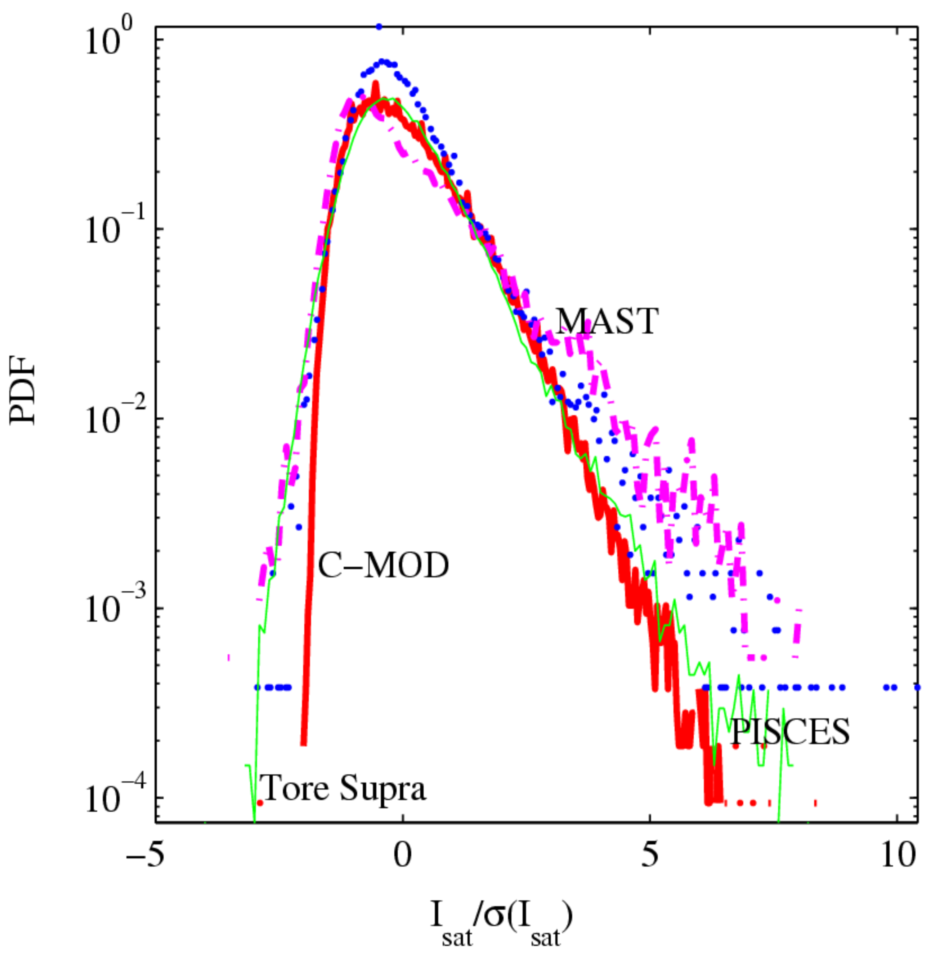



The auto-conditional average represents a typical 'spike' in the Isat signals

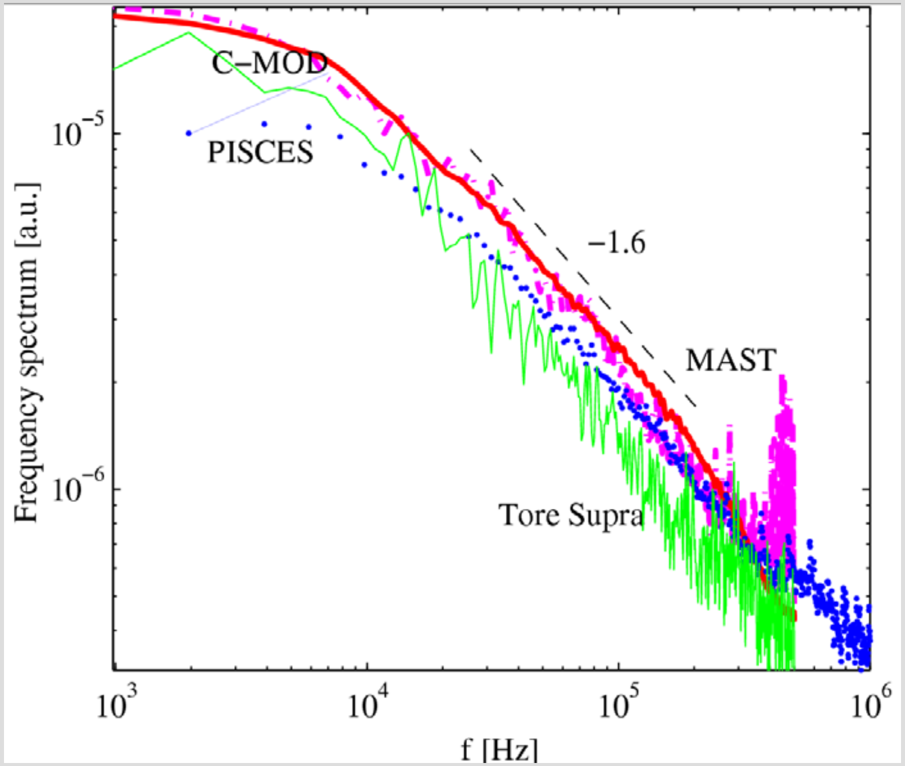


# Universality: Avaloids have the same properties on different magnetic fusion devices.

Similarity of the PDF of $I_{sat}$ fluctuations
- Gaussian for negative fluctuations
- Strongly Skewed (~exponential) for positive fluctuations




Similarity of the power spectra of $I_{sat}$
- One scaling region
- approximately the same scaling exponent -1.6



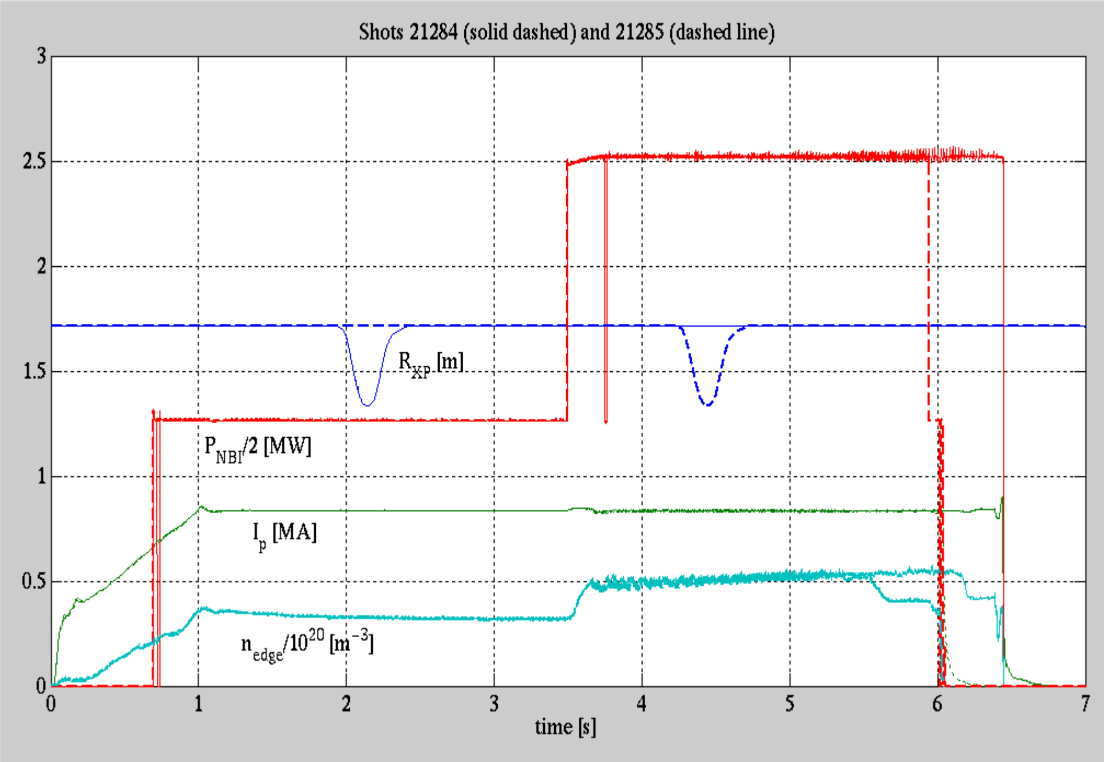
**- So, what happens in H-mode? Do any of the above results apply? Is is worth doing L-mode studies?**

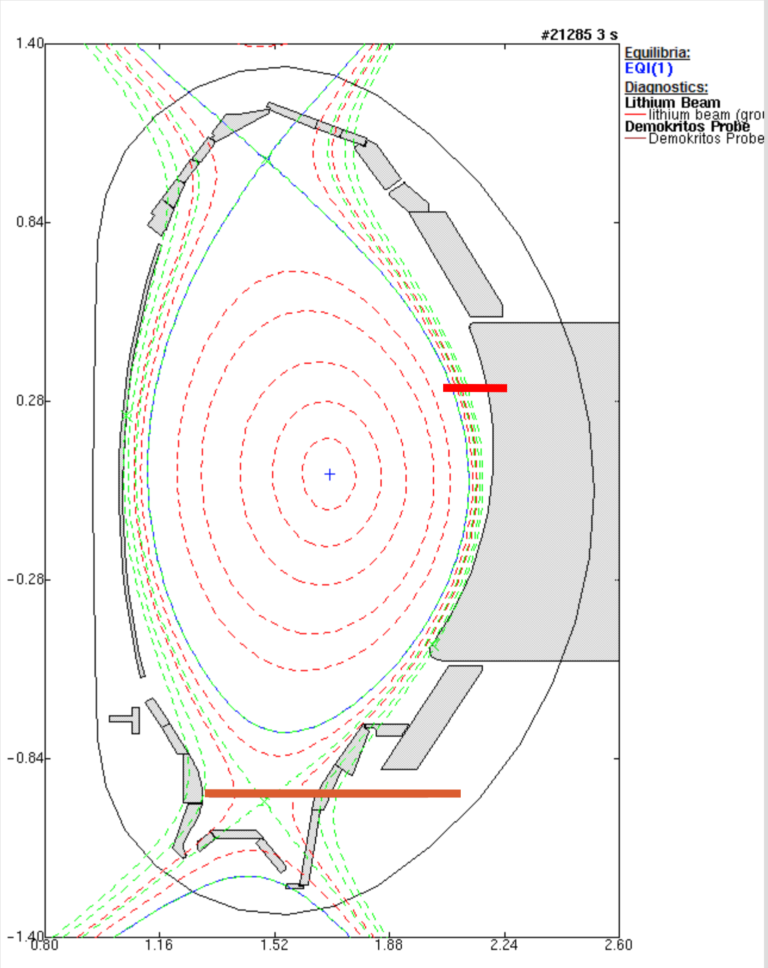
**- What is the plasma flux on the walls in H-mode?**

**- What is the role of turbulence in H-mode plasmas? And how come turbulence codes cannot simulate H-modes in a self-consistent fashion?**

# SOL Turbulence in L and NBI-driven H-mode or The *search* of turbulence decrease

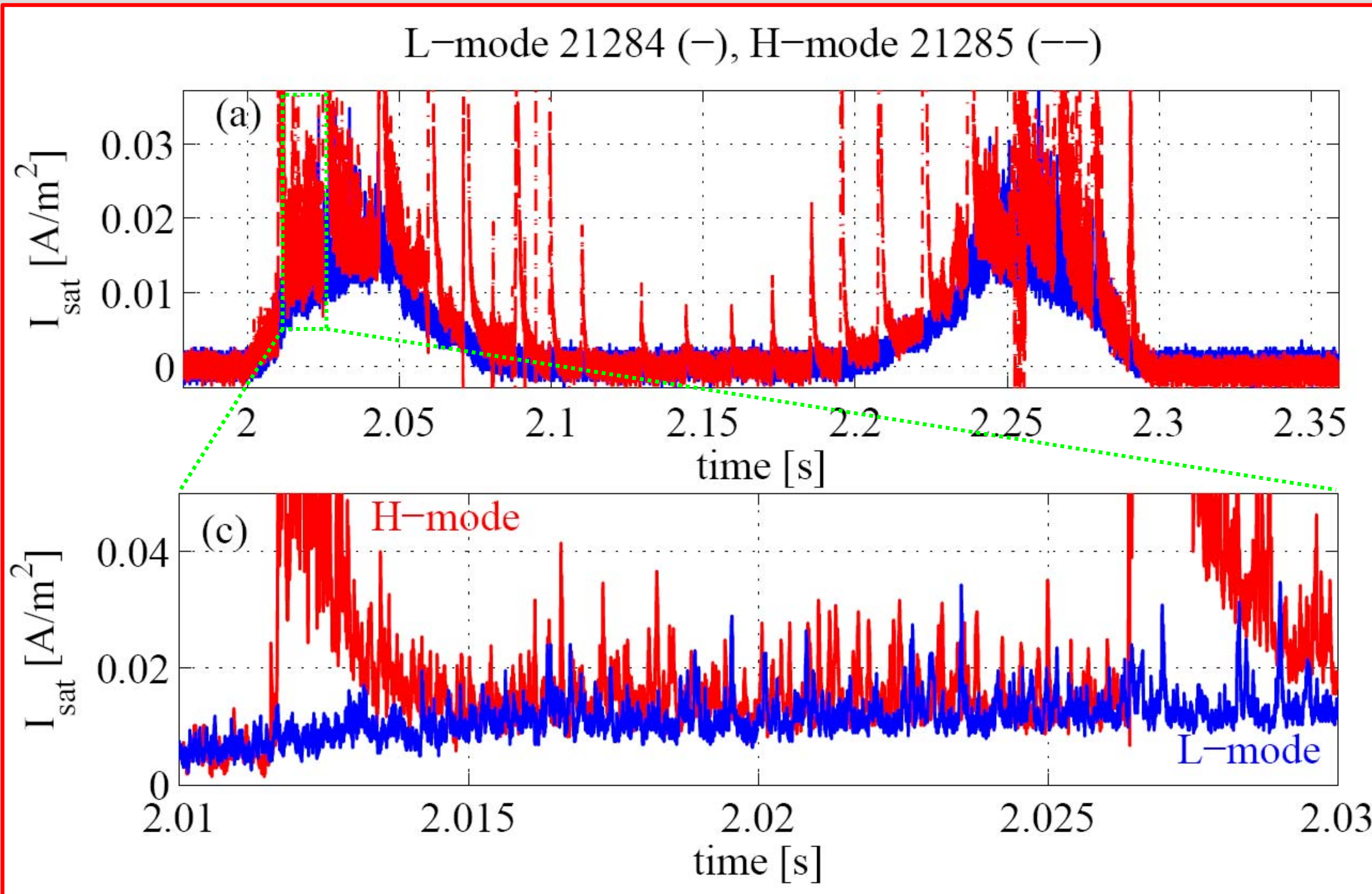
# Plasma Scenario I: Low density H-mode leading to type-I ELMs with relatively long time in-between the ELMs crash

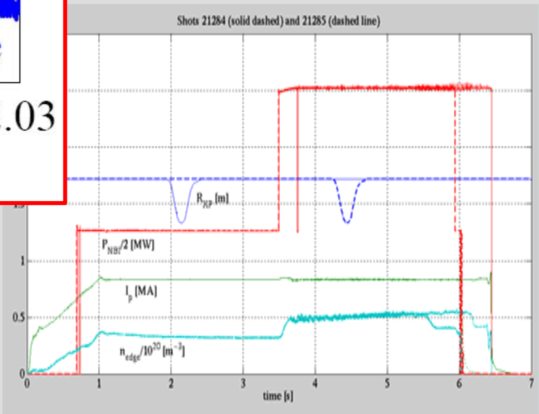


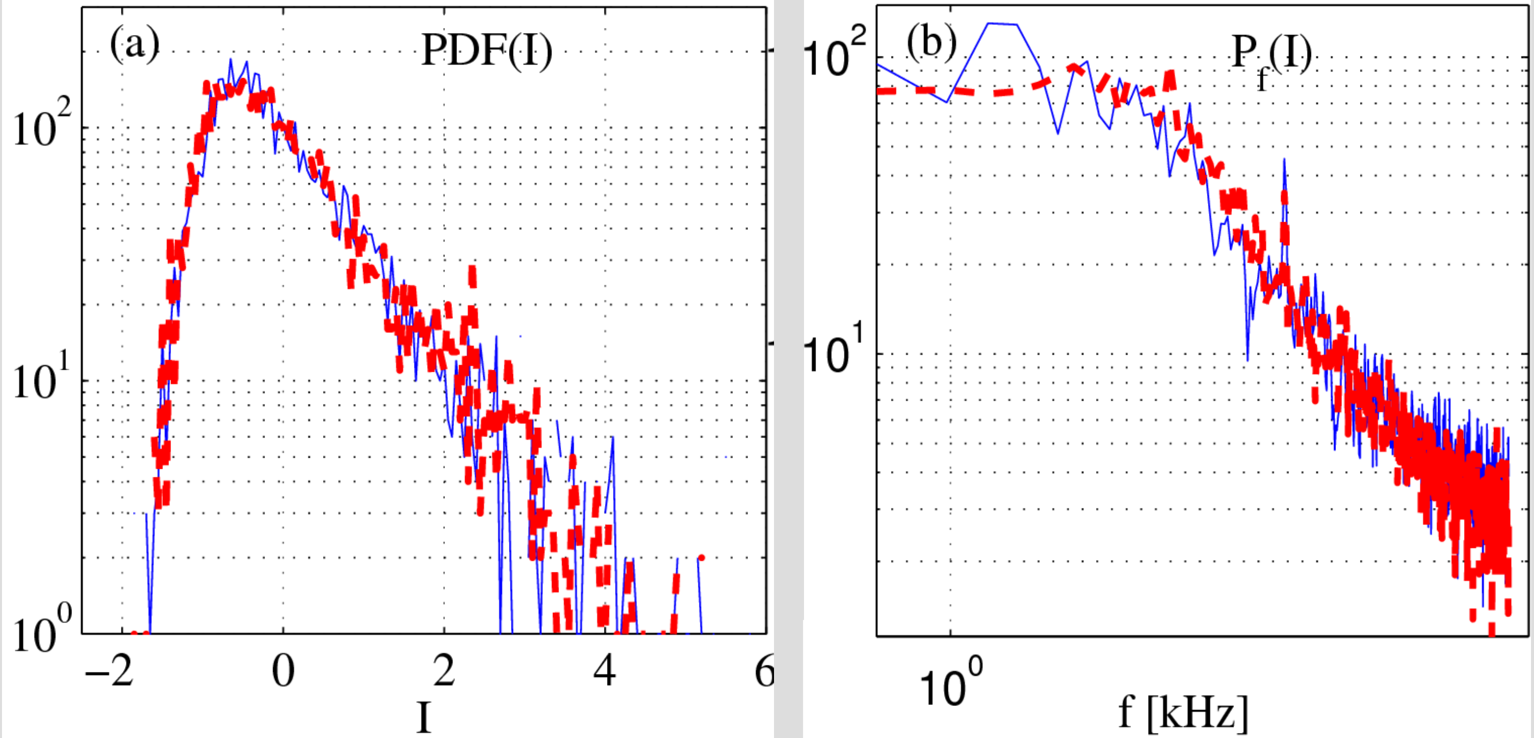



# RED-> H-mode; BLUE-> L-mode

# The statistical properties of turbulence in L and H-modes are not different !!!



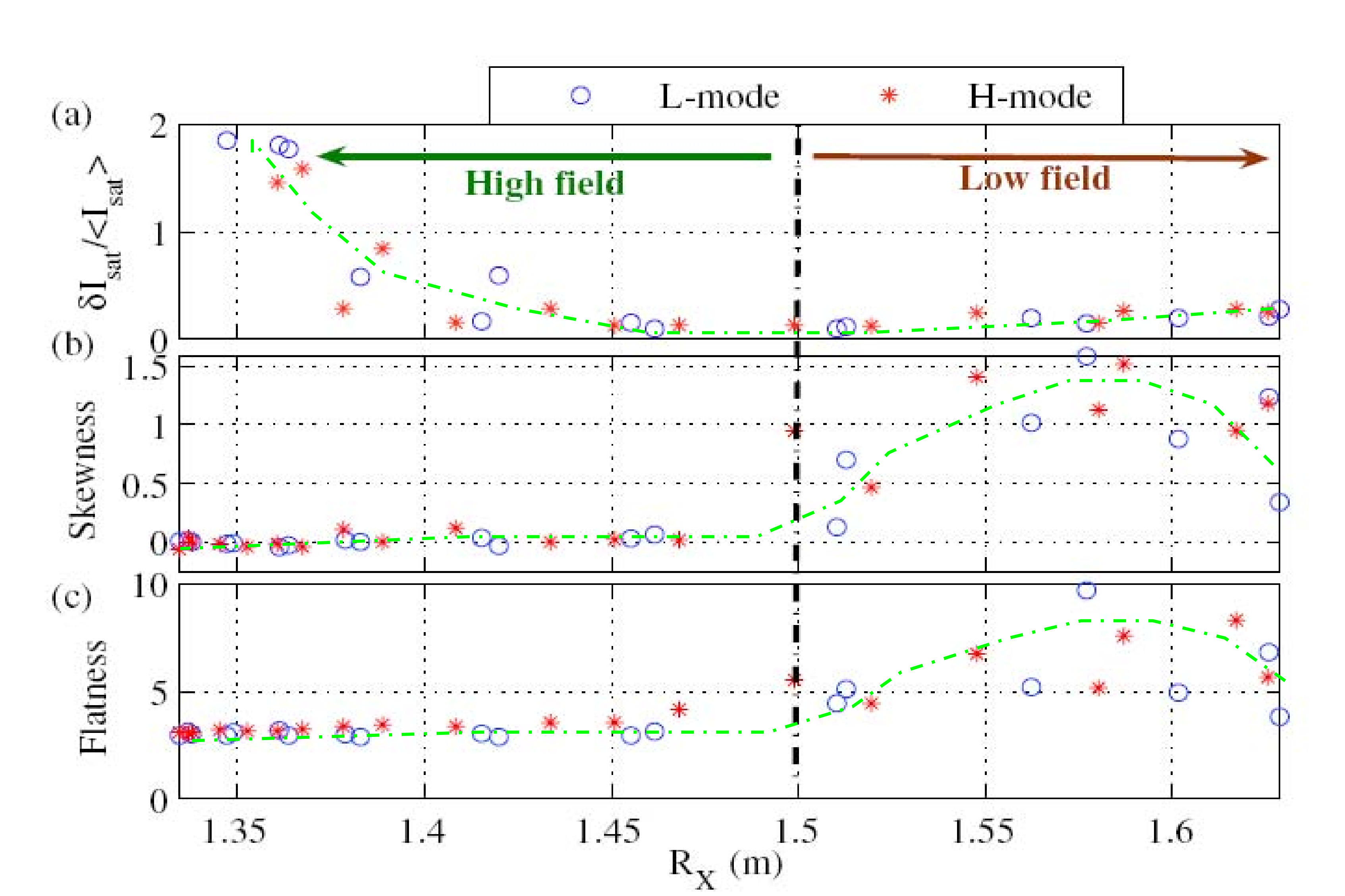



•The similarity of the PDF indicates that neither the relative amplitude (with respect to the standard deviation) nor the frequency of occurrence of turbulent events are modified in the L to H transition.

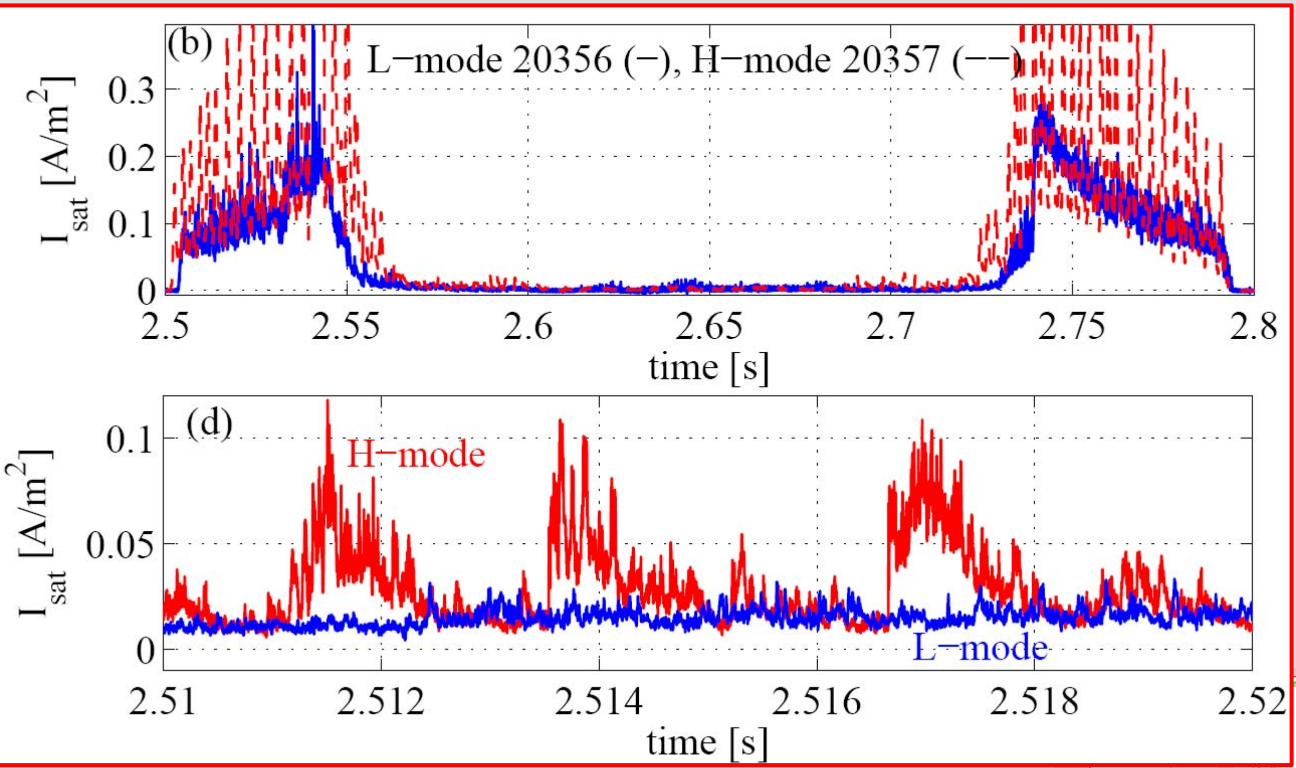
* One can deduce that if turbulence is affected in the L to H transition it is not *via* the transport mechanisms, that are, diffusive and convective.

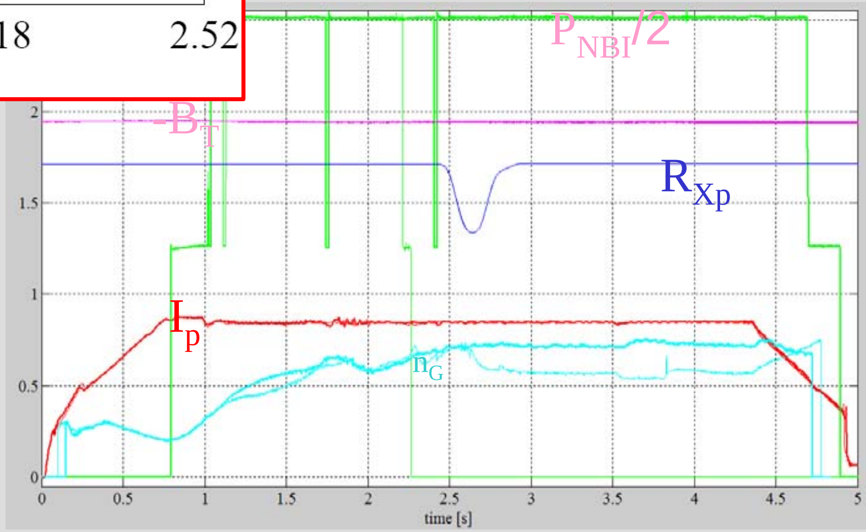
* The transition from L to H mode is **not** done via a modification of the distribution of the power among the turbulent scales

# The non-modification of the turbulence properties in the SOL extends is valid not only on the high field side but also on the low field one

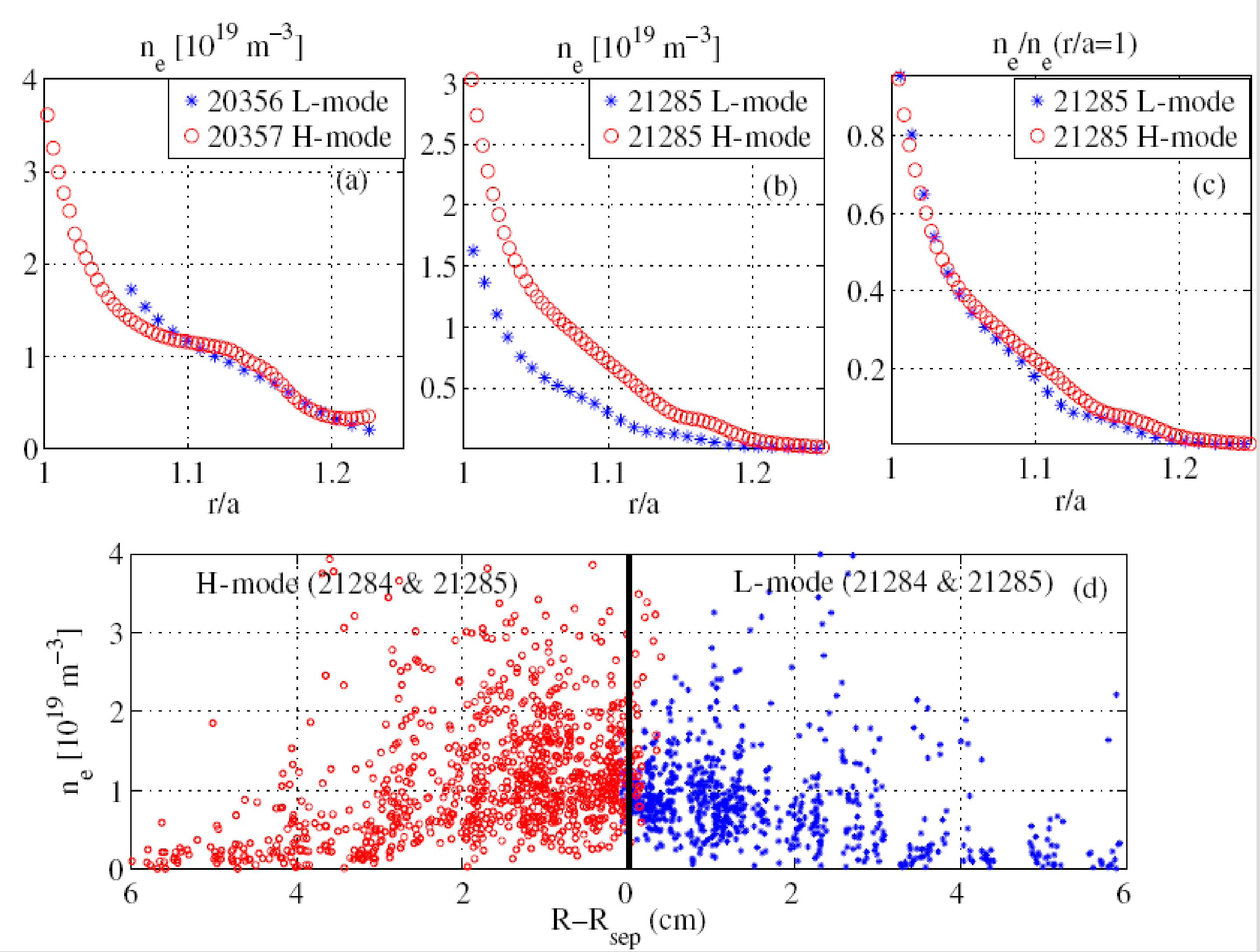


# One can check this with a different scenario with the same plasma density (shots 20356 20357)



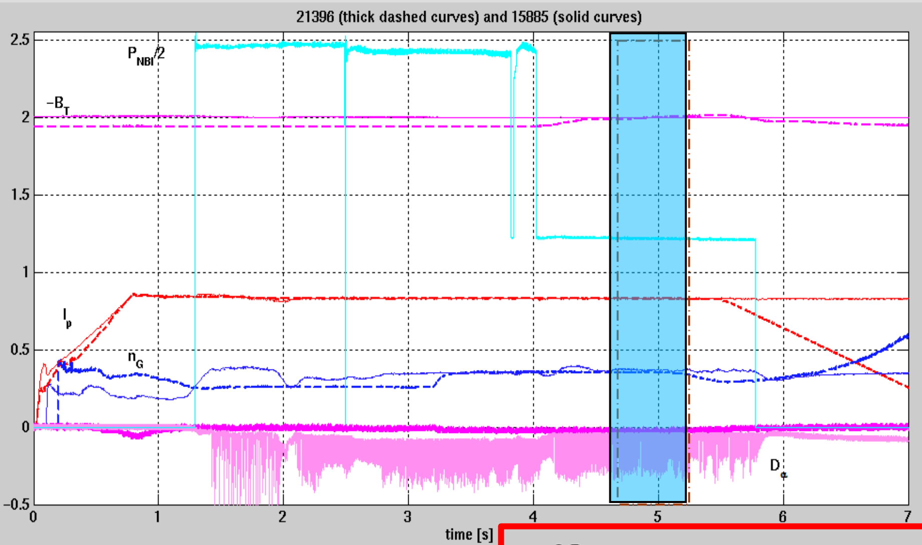
# The profiles of density measured by the Lithium beam at the mid-plane are not different this means the convective and diffusive transport are not modified

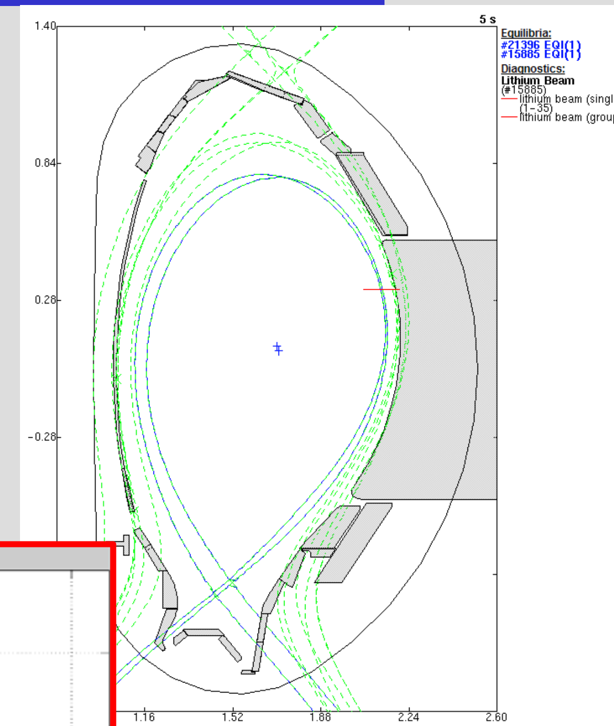


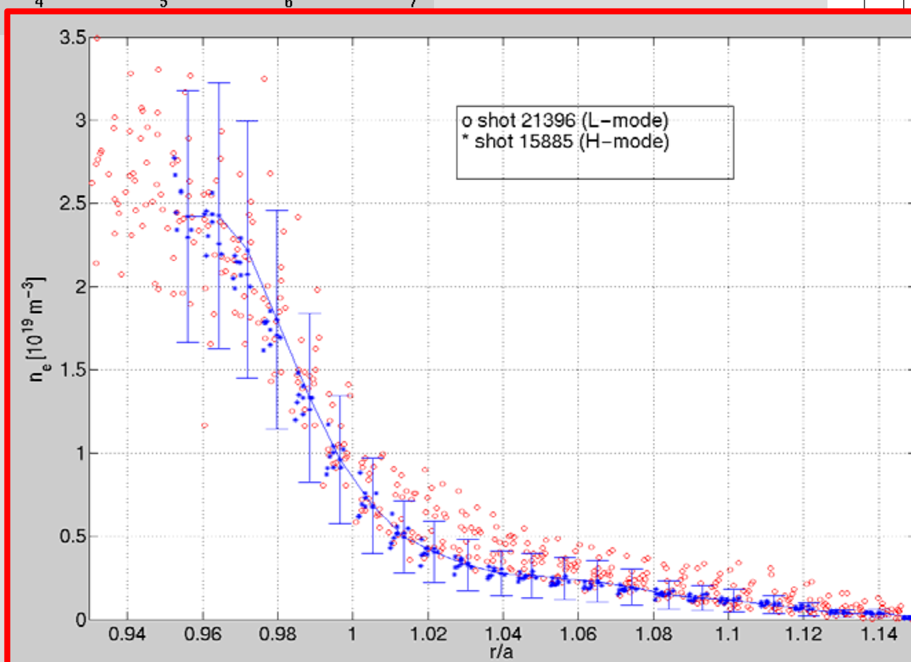

SOL time-averaged radial profiles from the lithium beam diagnostic

SOL radial profiles from the Thomson scattering diagnostic

# A lower single null case: with the same plasma parameters but one in L-mode (21396) and the other in H-mode (15885) with 2.5 MW of NBI



# Conclusion about NBI-driven H-mode SOL when compared to L-mode

1. The L to H transition by NBI does not affect the non-linear processes, turbulent diffusion and convection, that are leading to radial transport from inside the confinement zone into the SOL.

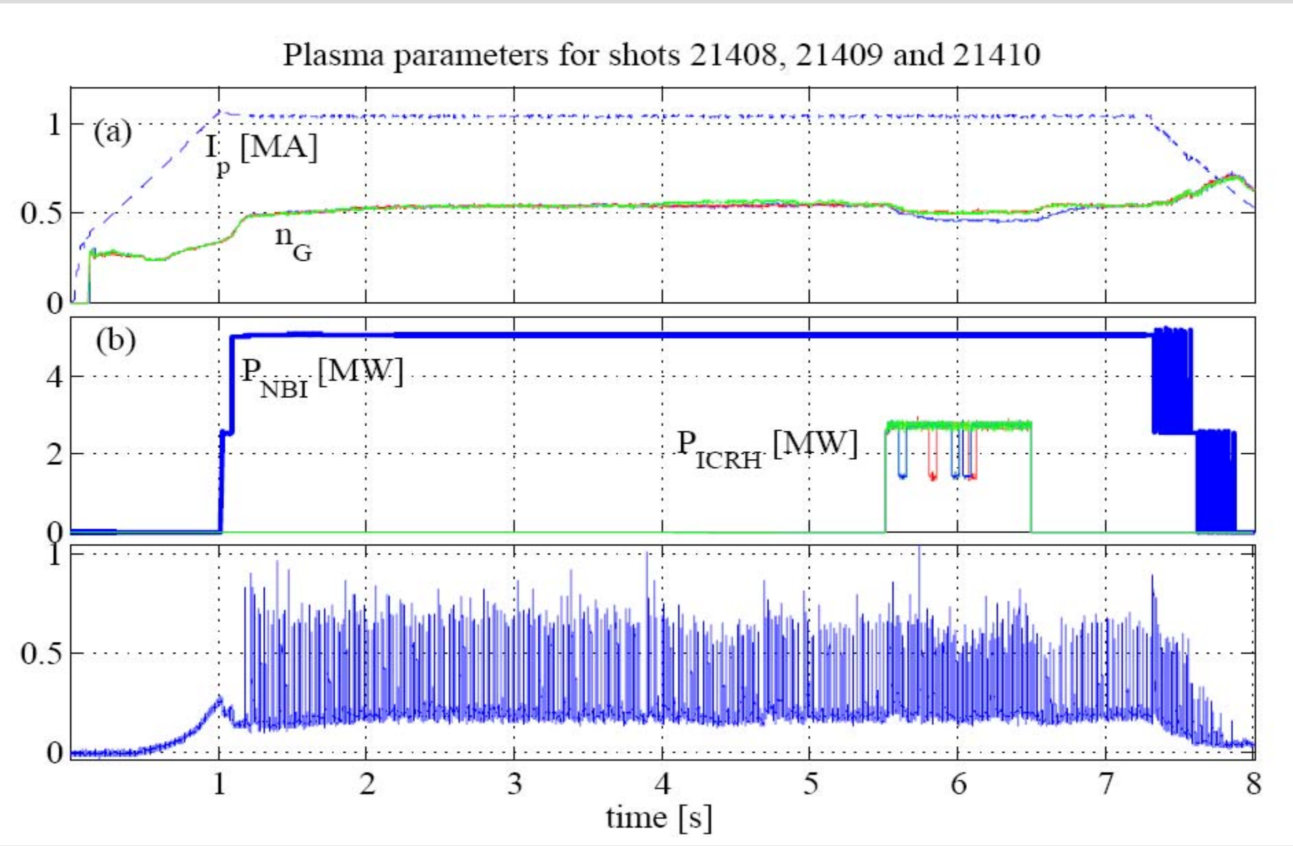
2. The L to H transition by NBI is not modifying the power distribution among the turbulent scales.

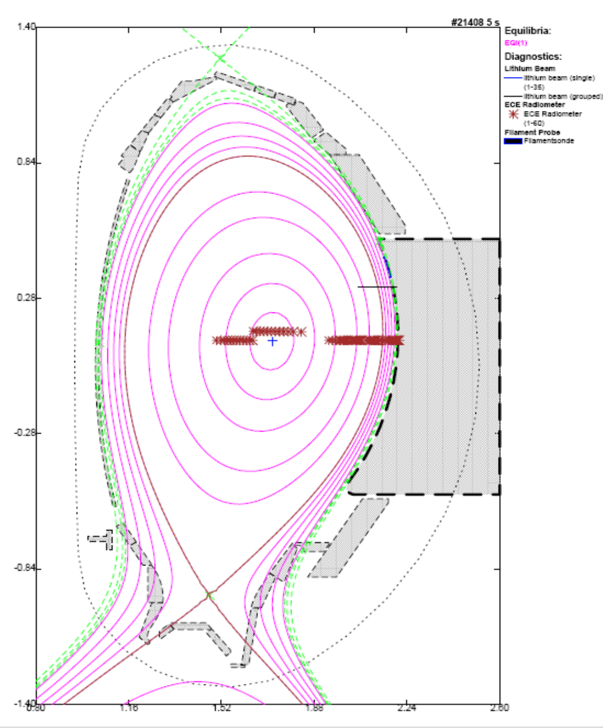
3. The L to H by NBI transition is not modifying the relative level of fluctuations.

4. The L to H transition by NBI is not modifying the profiles shape in the SOL.

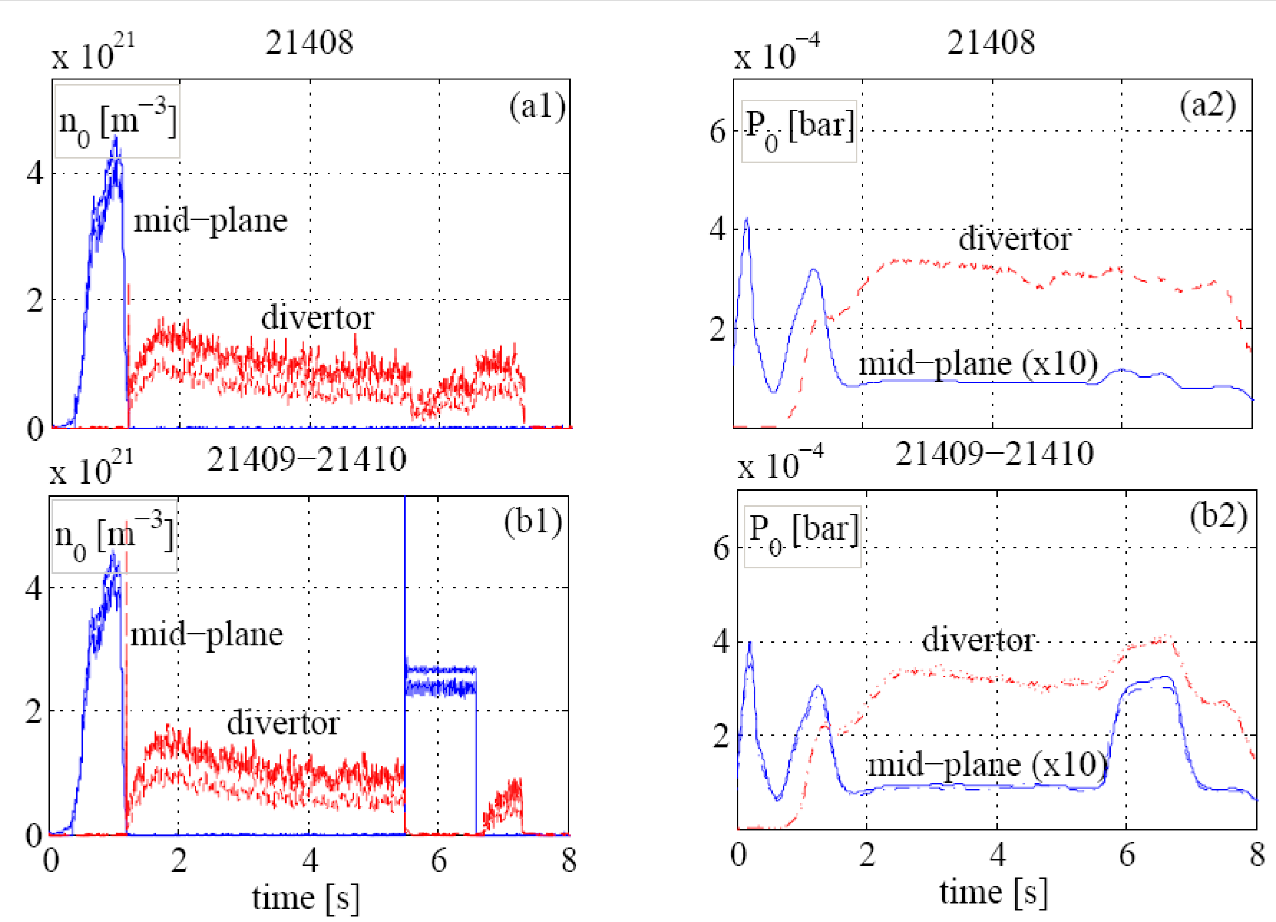
# ‘Real’ Turbulence Suppression in the SOL Using Ion Cyclotron Resonance Heating

# The Plasma Scenario
# We compare the SOL in NBI H-mode to [NBI-ICRH] H-mode



# Neutral gas injection




During the shot, only the valves in the divertor were open [CFDU1X CFDU5X and CFDU13X]

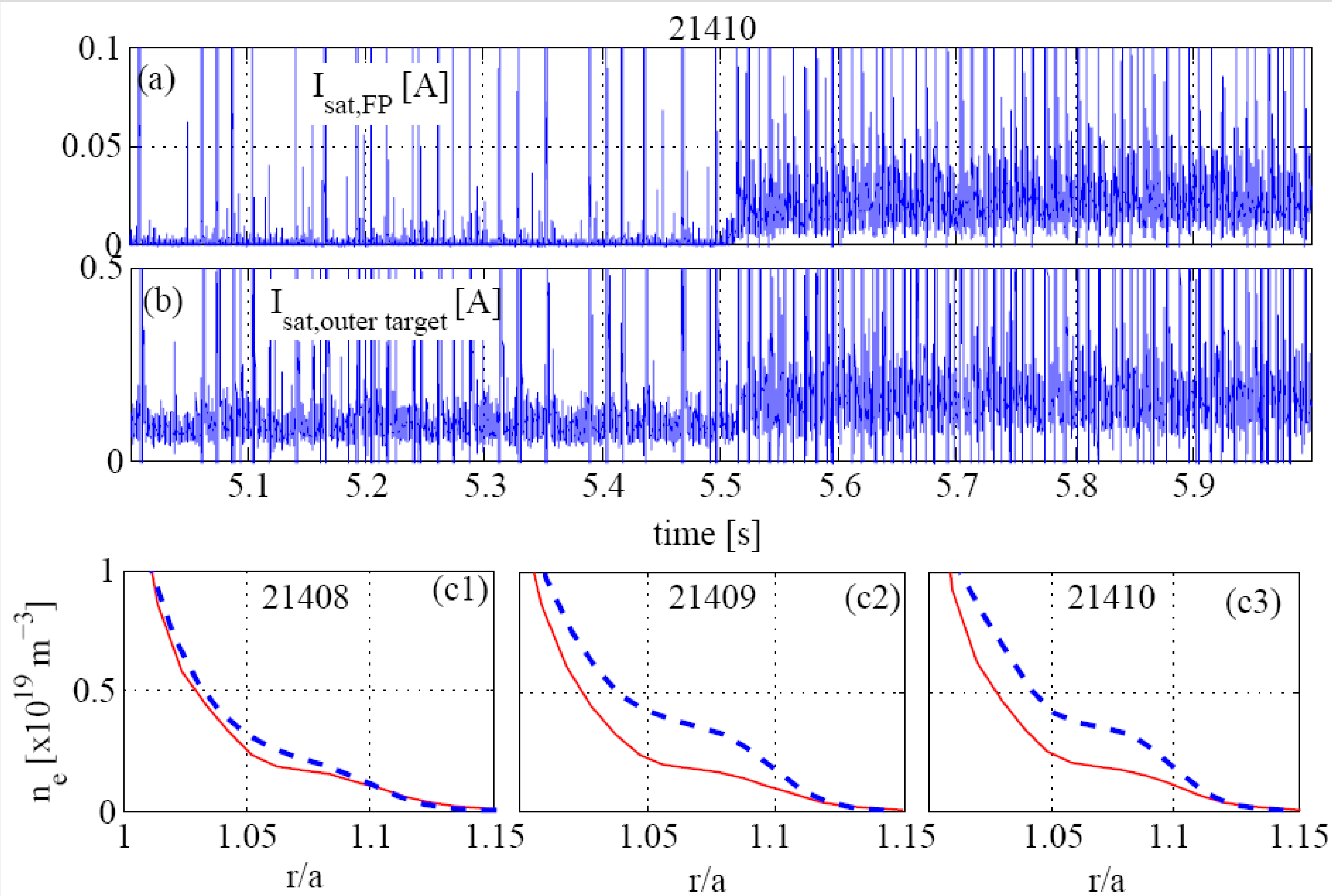
Mid-plane valves were opened while the divertor valves were shot down [CFDU1X CFDU5X and CFDU13X (red curves) and CFA1II and CFA13II (blue curves)]

**During the ICRH, the neutral gas pressure at the mid-plane is:**

**unchanged in 21408**

**whereas it increases by a factor of 3 in 21409 and 21410**

# The SOL density increases during the ICRH in 21409 and 21410 but not in 21408 (no neutrals no plasma!)

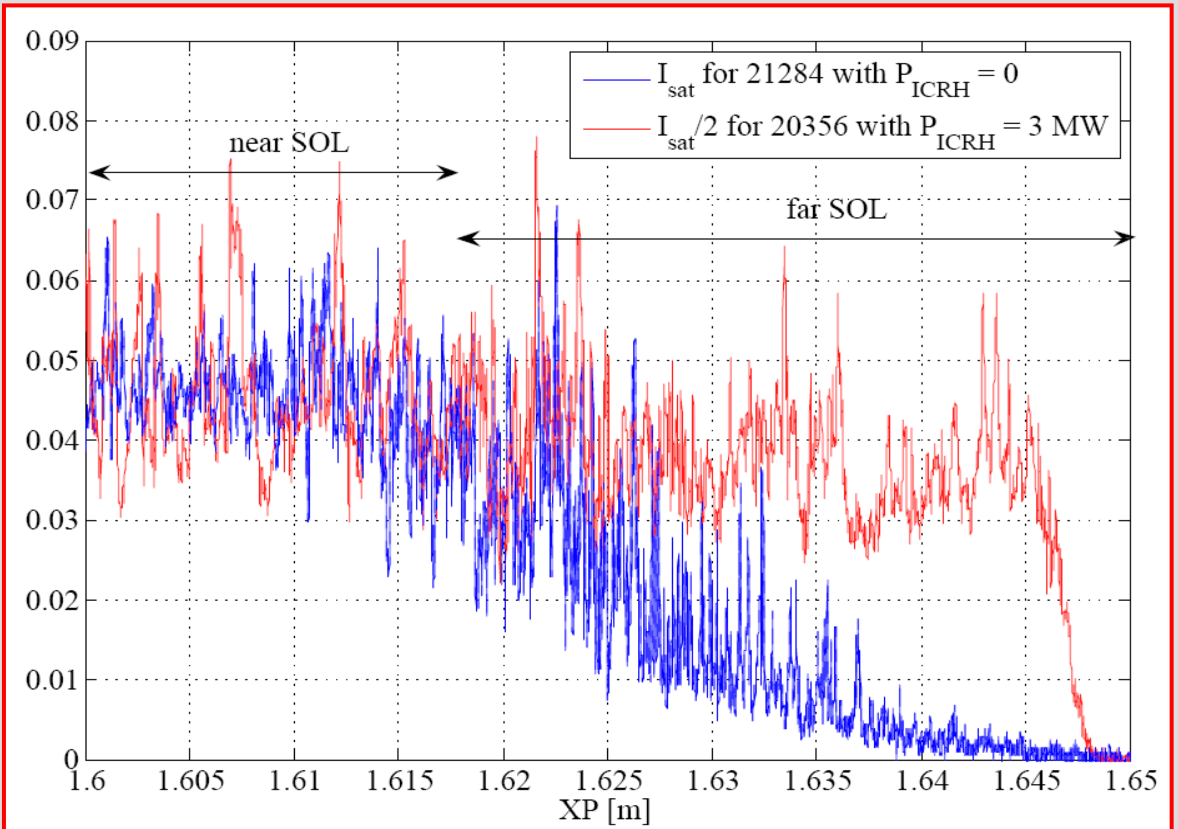


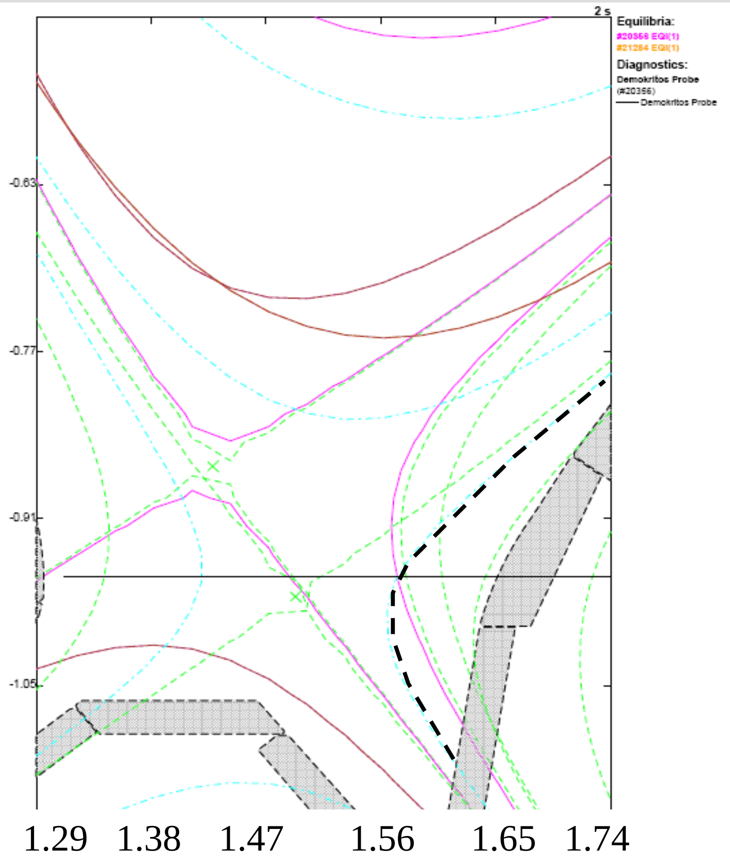

The filament probe at the mid-plane

and the target probe on the outer divertor

Using the Lithium beam diagnostic (ELM-free) Red and blue

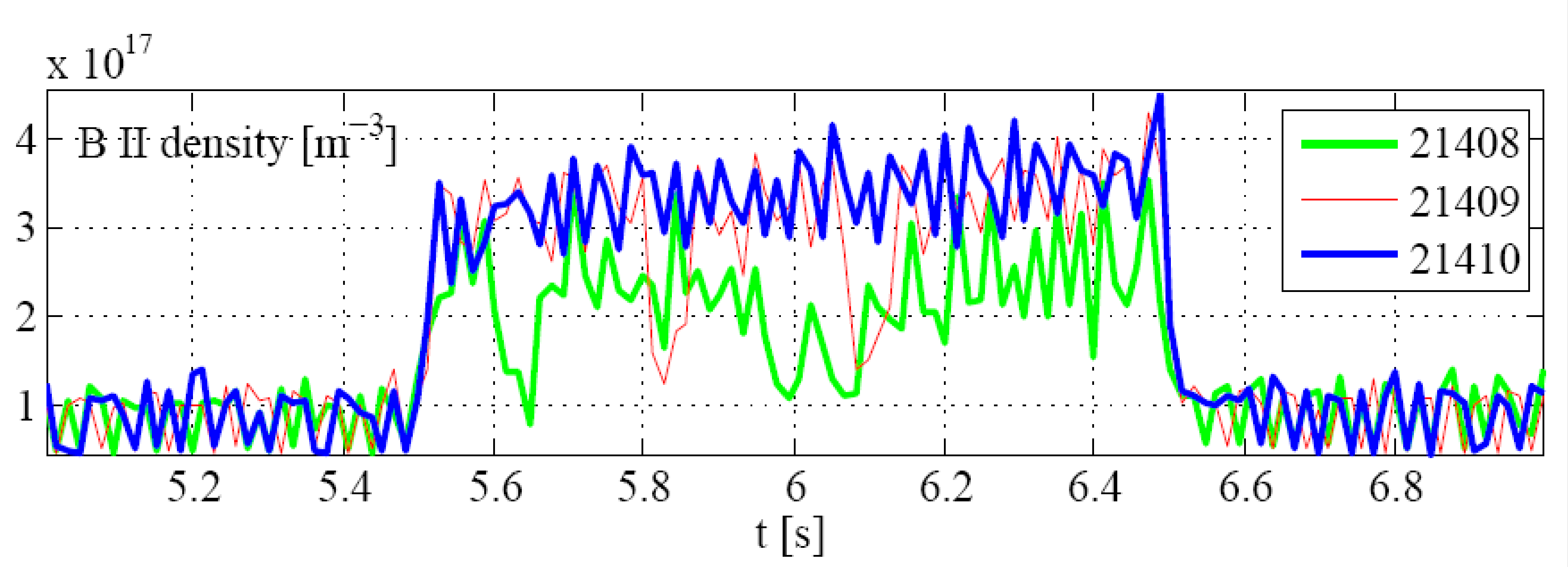
# From the Demokritos Divertor probe in L-mode upper single null magnetic configuration [20356 and 21284] we deduce that **the plasma density increase is recorded up to the vessel wall**



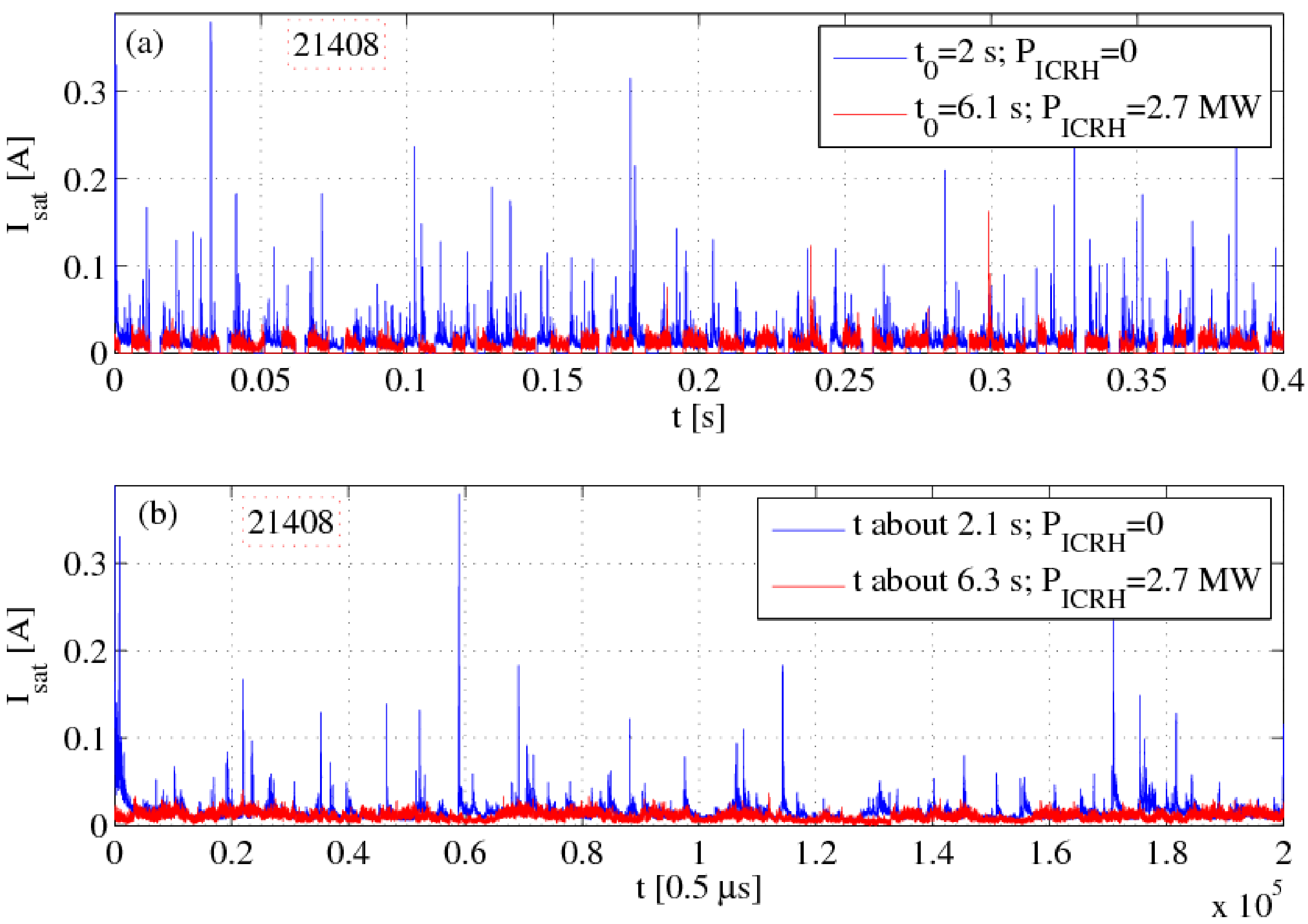




This means relatively large densities are facing the Faraday cage leading to more sputtering. The signals are less intermittent in the far SOL with ICRH

- Since these shots came just after boronization, no modification in WI and in HI lines were observed.
- An enhancement in the BII line clearly indicates the (usual) effect of the ICRH on the Boron layer.
- More Boron is observed to be generated in 21409 and 21410 then in 21408



# SOL turbulence as seen by the 'Filament Probe' at the mid-plane is observed to be dramatically modified where the intermittent bursts almost completely suppressed and they disappear from the signal.



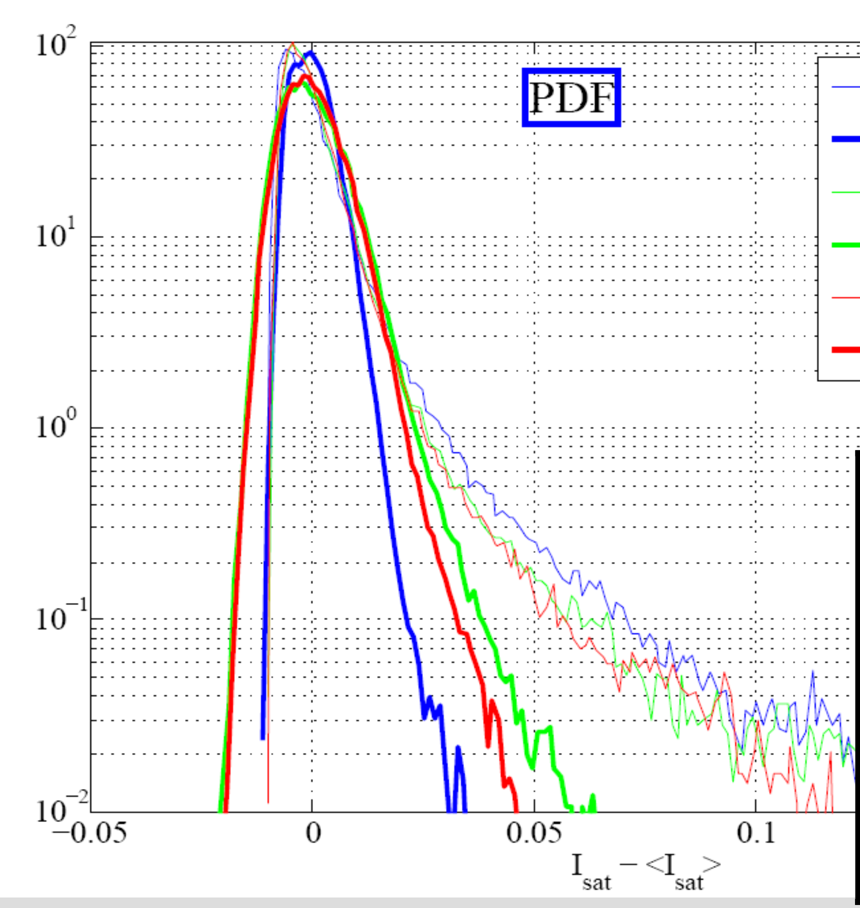

(a) The empty spots are caused by:
1- positive biasing of the probe and,
2- ELMs as they were removed to study the inter-ELM phase.

(b) Shows Isat after the empty lapses are removed.

# Modification of the SOL Plasma Properties showing the decrease of the plasma level of fluctuations

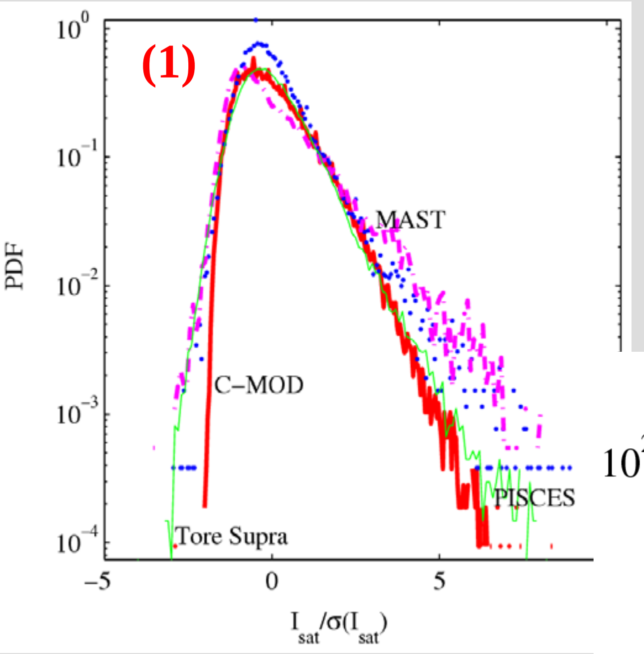
| | 21408 | | 21409 | | 21410 | |
|---|---|---|---|---|---|---|
| PICRH [MW] | 0 | 2.7 | 0 | 2.7 | 0 | 2.7 |
| <Isat> [A] | 0.015 | 0.017 | 0.015 | 0.022 | 0.015 | 0.021 |
| δIsat [A] | 0.01 | 0.006 | 0.01 | 0.007 | 0.009 | 0.065 |
| δIsat/ <Isat> | 70% | 30% | 67% | 32% | 60% | 32% |
| **Turbulence reduction** | **57%** | | **50%** | | **48%** | |

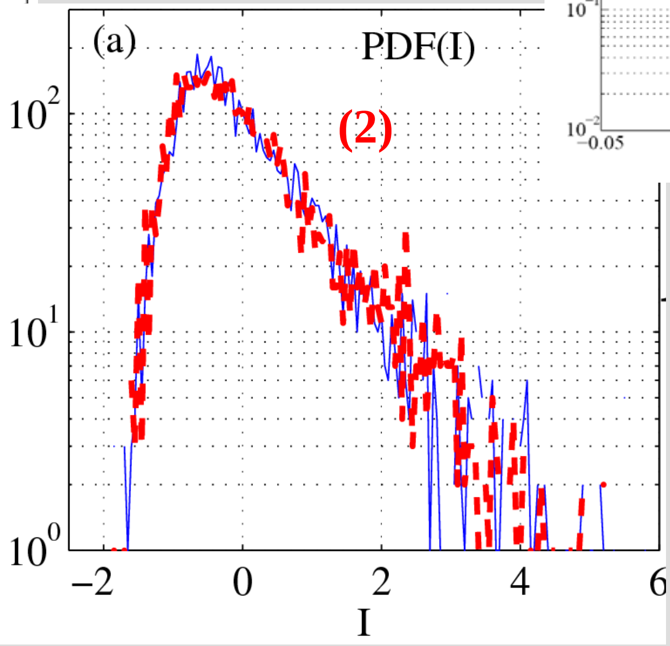
The probability Distribution Function (PDF) of Isat indicates a radical modification of the PDF positive side.
* The signals become much closer to Gaussian reflecting the suppression of the intermittent bursts.
* This suppression is stronger in 21408 then in 21409-21410

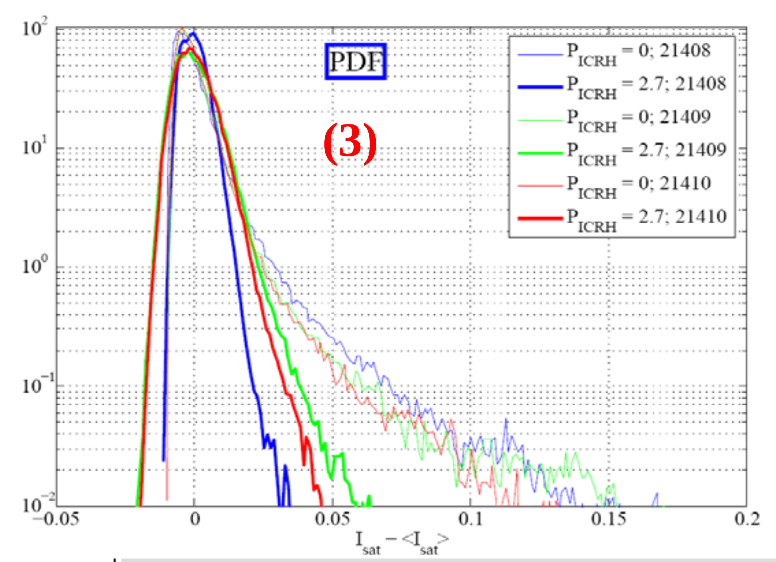



| | 21408 | | 21409 | | 21410 | |
|---|---|---|---|---|---|---|
| PICRH [MW] | 0 | 2.7 | 0 | 2.7 | 0 | 2.7 |
| Skewness | 7.6 | 0.8 | 12 | 1 | 7 | 0.8 |
| Flatness | 65 | 5.6 | 105 | 15 | 55 | 5 |

# Recall the PDF behavior
# (1)- in L-mode plasmas
# (2)- in NBI-driven H-mode when compared to L-mode
# (3)- In NBI-driven H-mode with and without ICRH

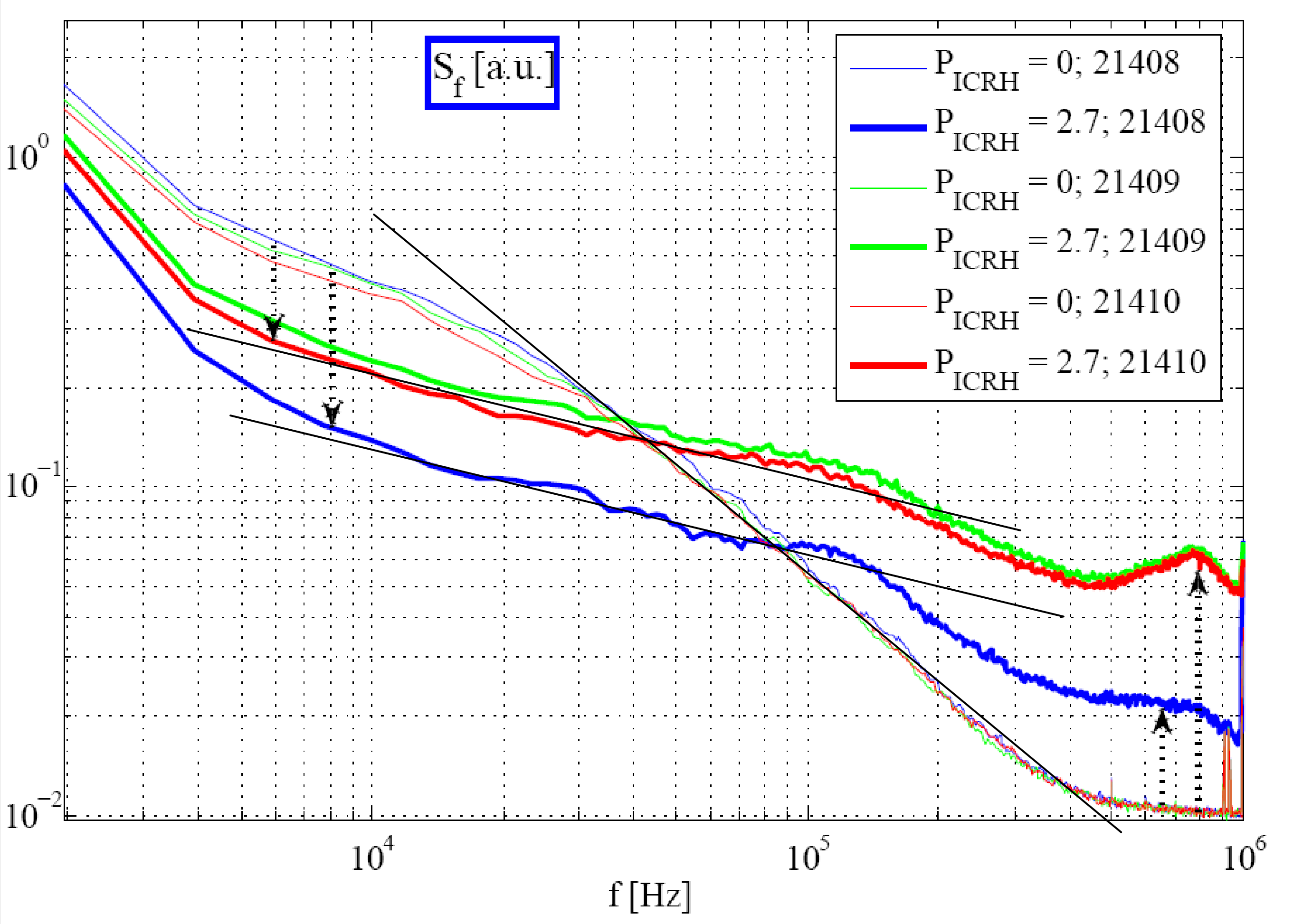


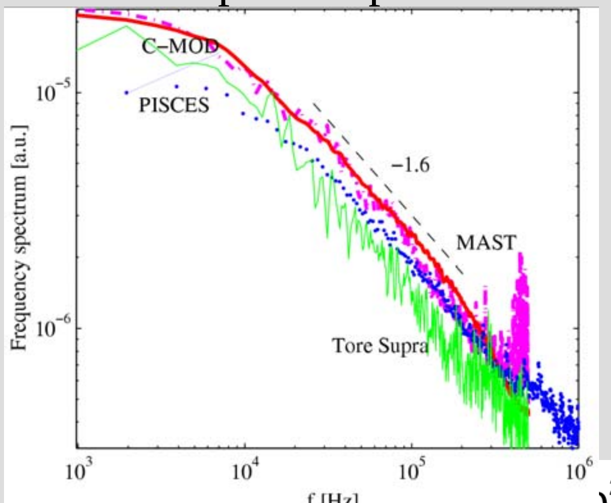
The Power spectrum of Isat reflects the distribution of the fluctuation power among the scales indicates:

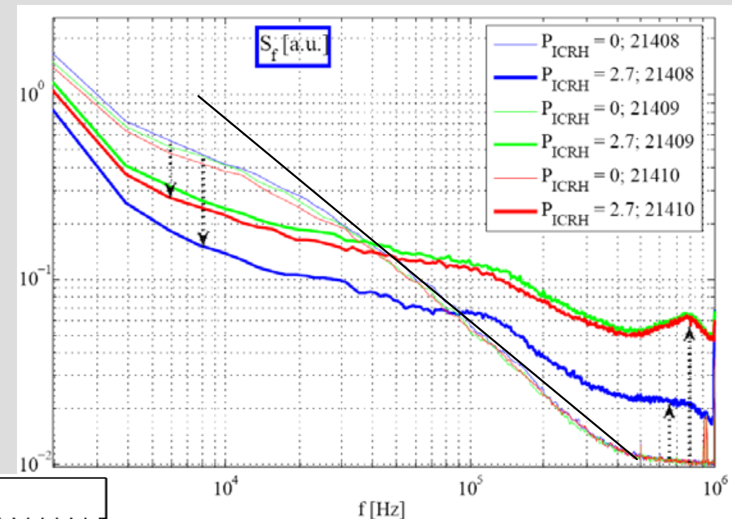
* The low frequencies (large-scale fluctuations) are suppressed by about a factor of 3 in 21408. The high frequency (small-scale fluctuations) are enhanced by a factor of 2 in 21408
* In 21409-21410 the large-scale suppression is less important (/2) and there are more small-scale fluctuations (x6)



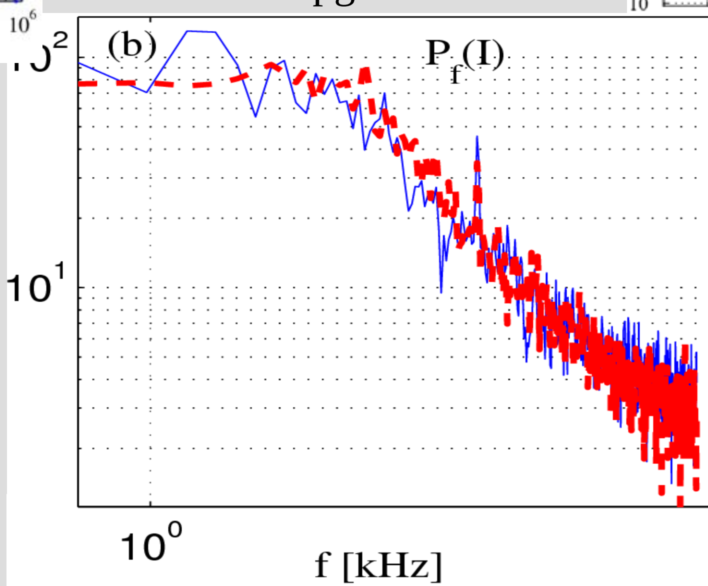
# In contrast to a NBI-driven H-mode where no modifications of the turbulent fluctuations among the scales was observed. In the presence of ICRH, a net modifications of turbulence is detected.

L-mode power spectra

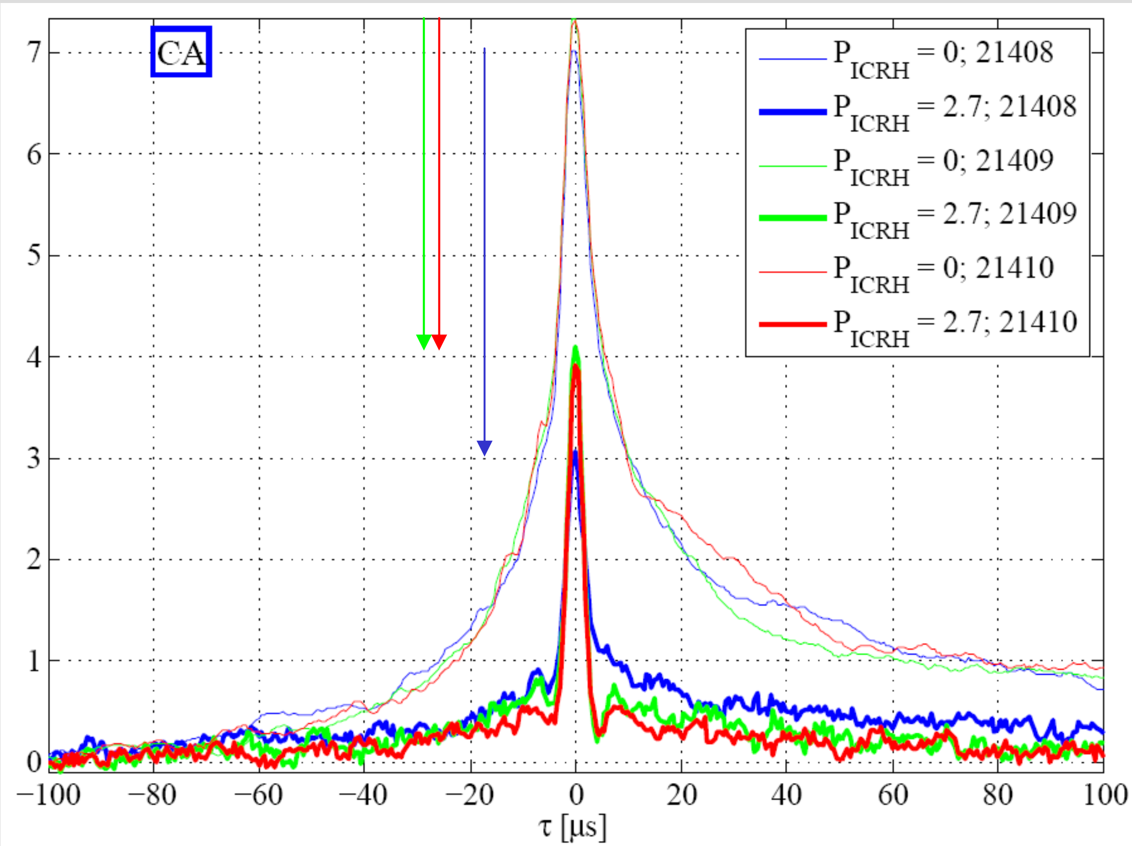


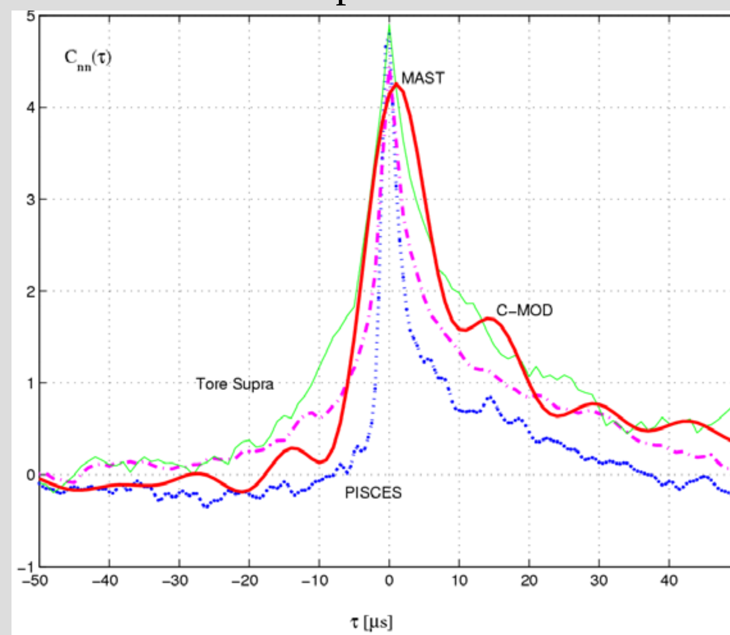

Comparing the power spectra in L and NBI-driven H-mode on ASDEX-Upgrade



# As one would have expected from the raw Isat signals, the amount of particles transported by the most intense spikes is reduced dramatically in the presence of ICRH.

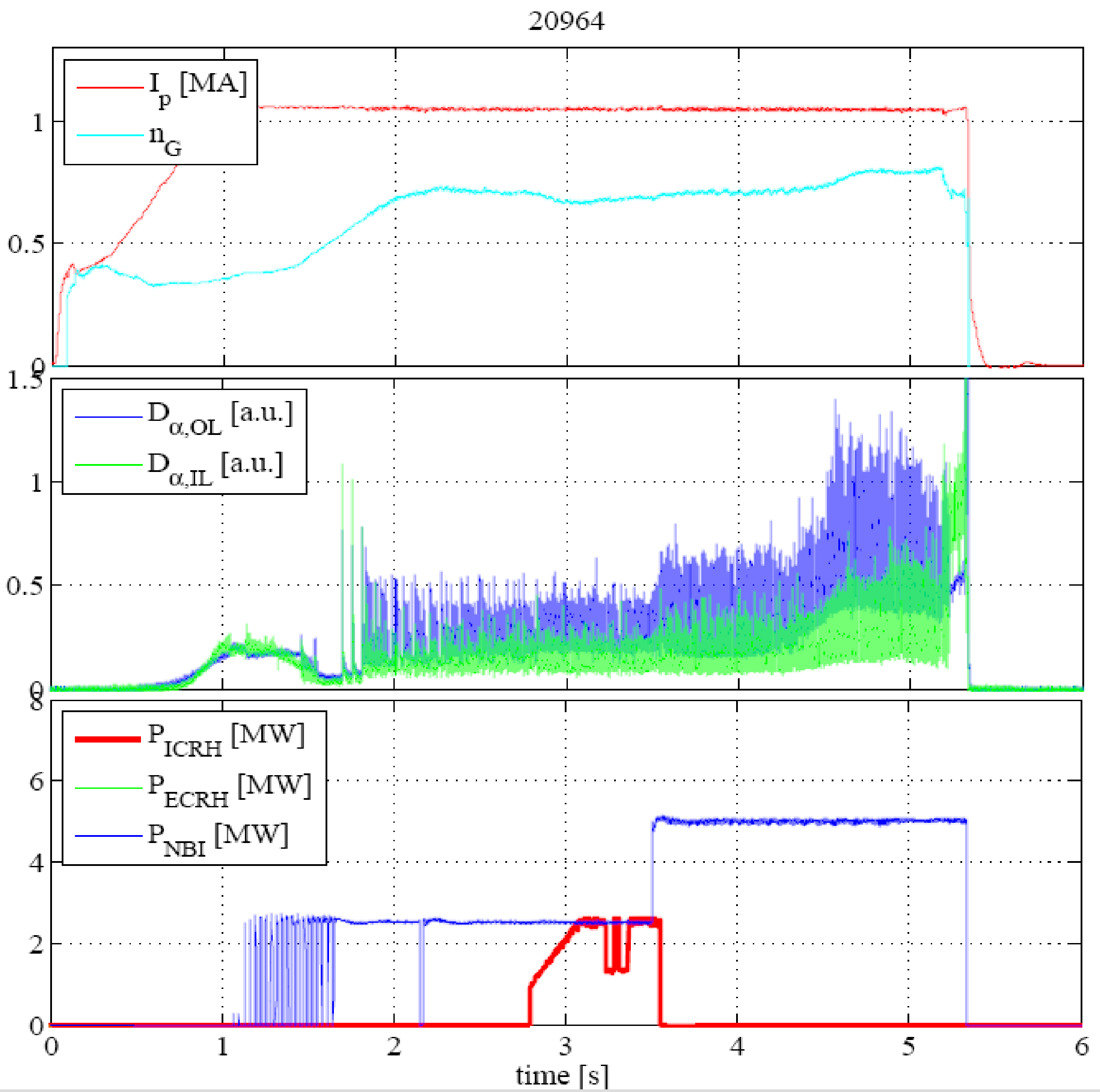



L-mode CA on Tore Supra, Alcator C-MOD, MAST tokamaks and PISCES linear plasma device

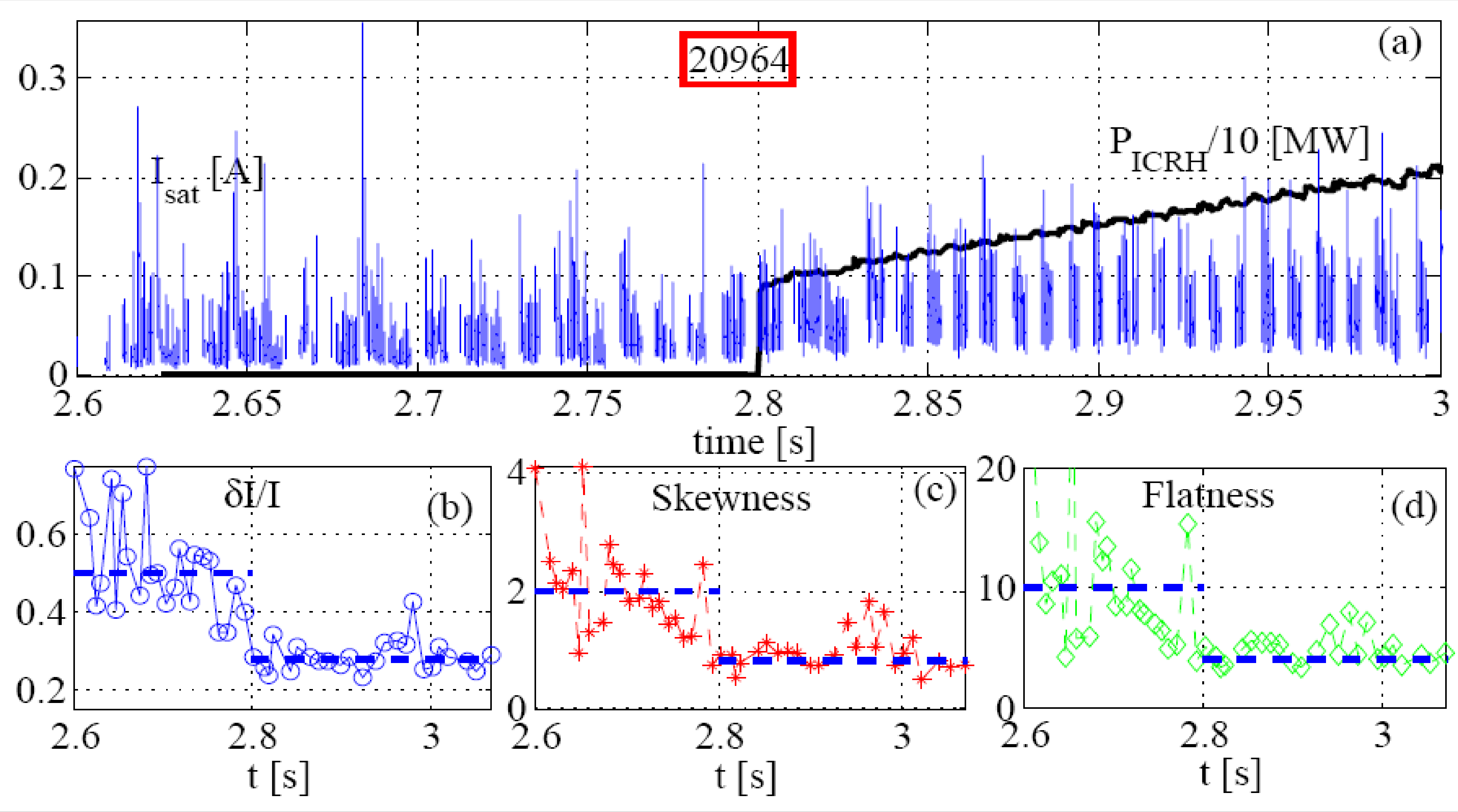



Conditional averaging, denoted by CA, is applied by selecting maxima above a threshold (=2.5 times the standard deviation) and average all the spikes within a time frame between -100 to +100 µs. The signals are normalized to their standard deviation.

# Shot 20964 for confirmation without previous boronization

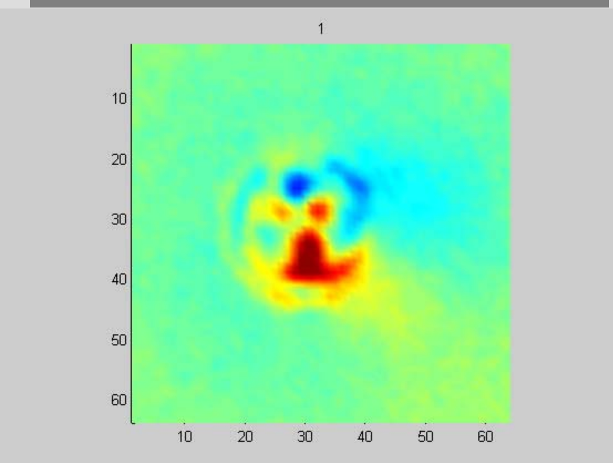


# Shot 20694 main statistical Properties show the change:
# δI/I from 0.5 to 0.25
# Skewness from 2 to 1 (0 is the Gaussian value)
# Flatness from 10 to 5 (3 is the Gaussian value)

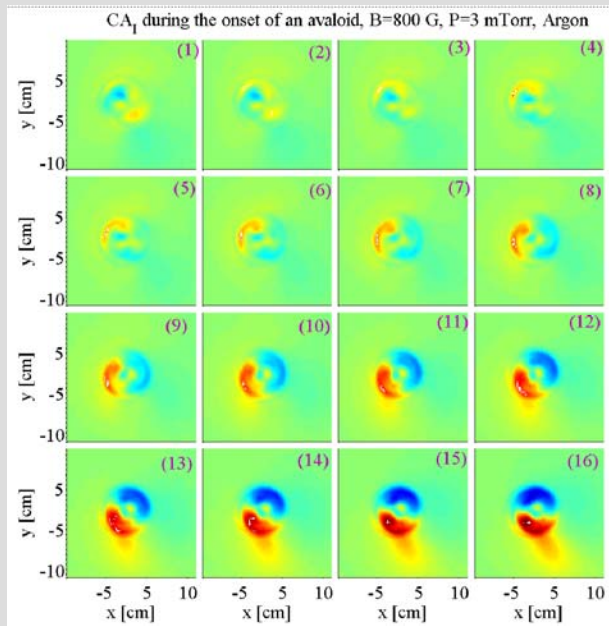


# One Possible Explanation: ICRH forces the plasma at the edge with high frequency fluctuations, hence, the large-scale fluctuations cannot grow and are thus suppressed

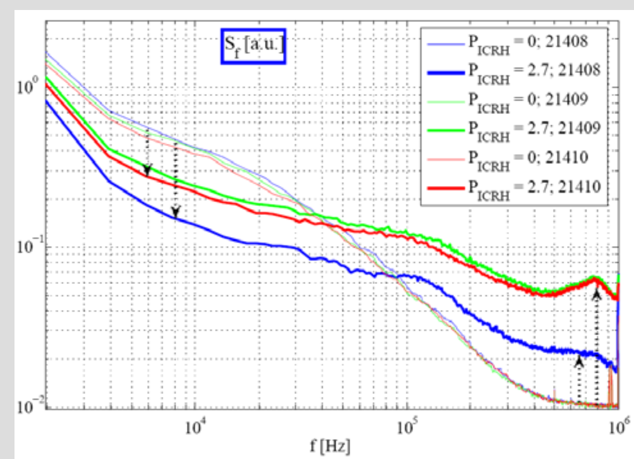
In CSDX the system sustain **many** poloidal mode numbers and transit from to the other after some period of time



The onset of large-scale intermittency in the SOL is associated with the non-linear evolution of **low** poloidal numbers instabilities.

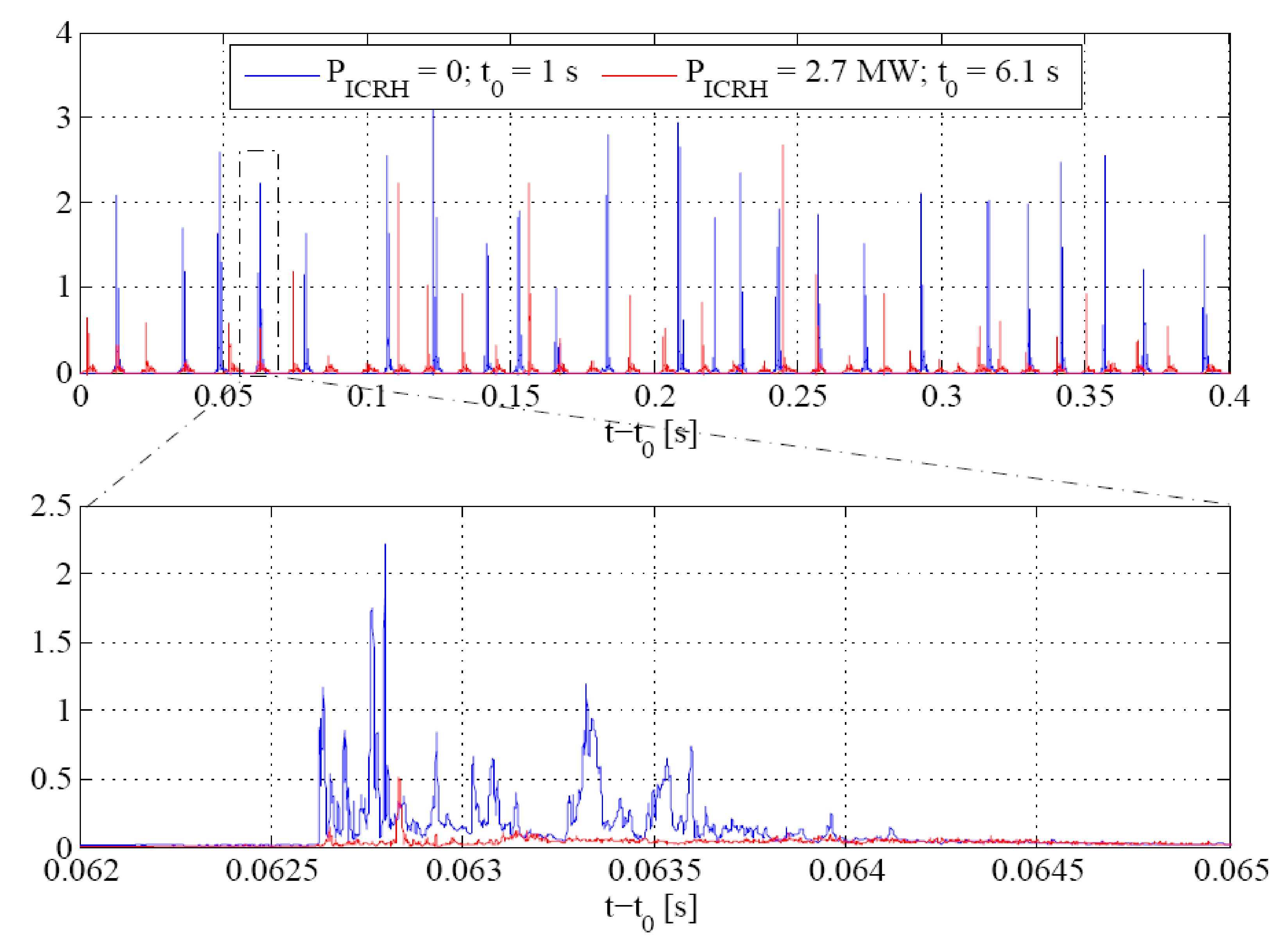



**The ICRH applies a high frequency forcing of the fluctuations, hence, not allowing large-scale events, mainly avaloids, to grow leading to their suppression**

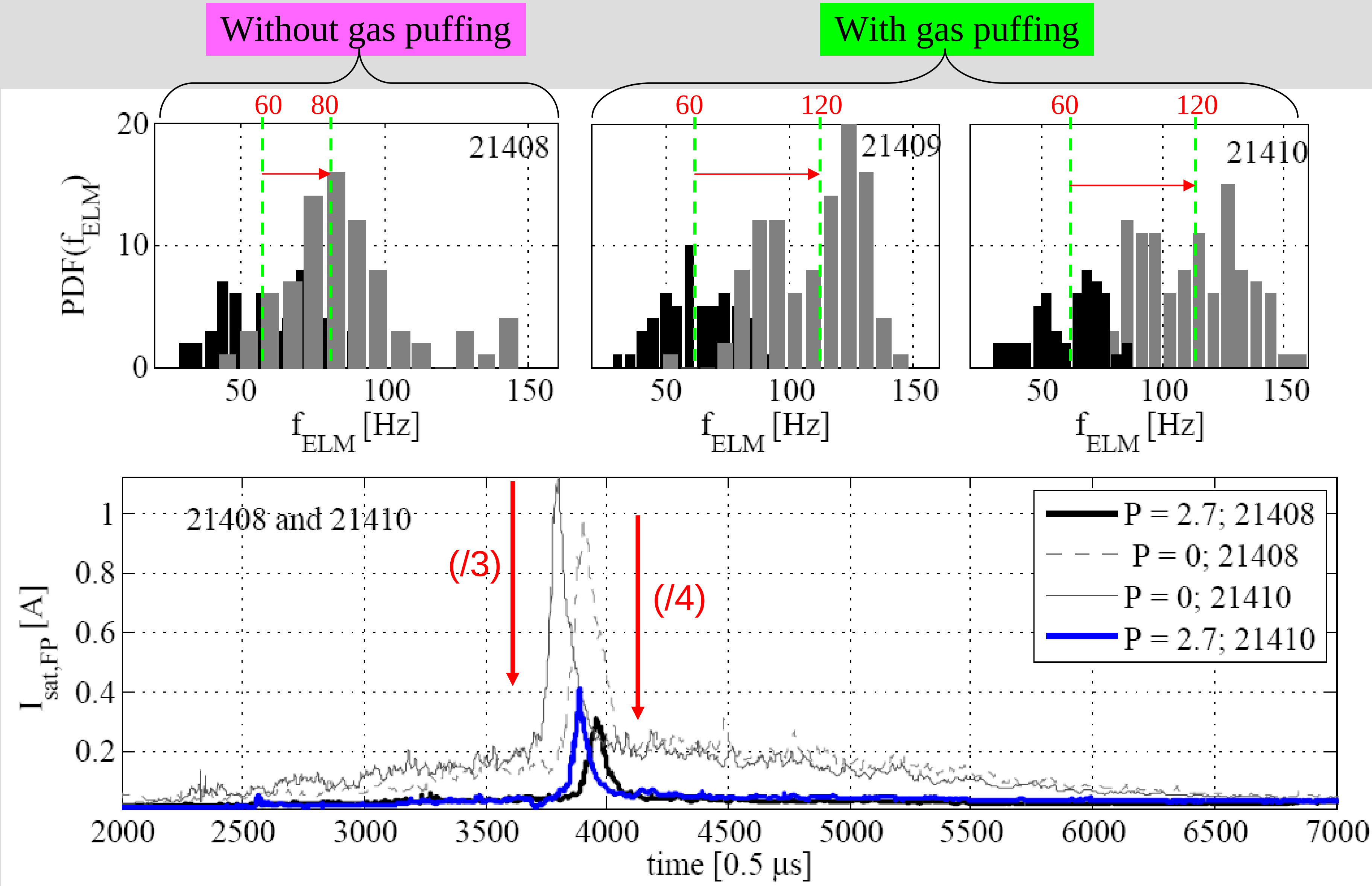


How About ELMs behavior with and without ICRH???

# ELMs behavior during shot 21408



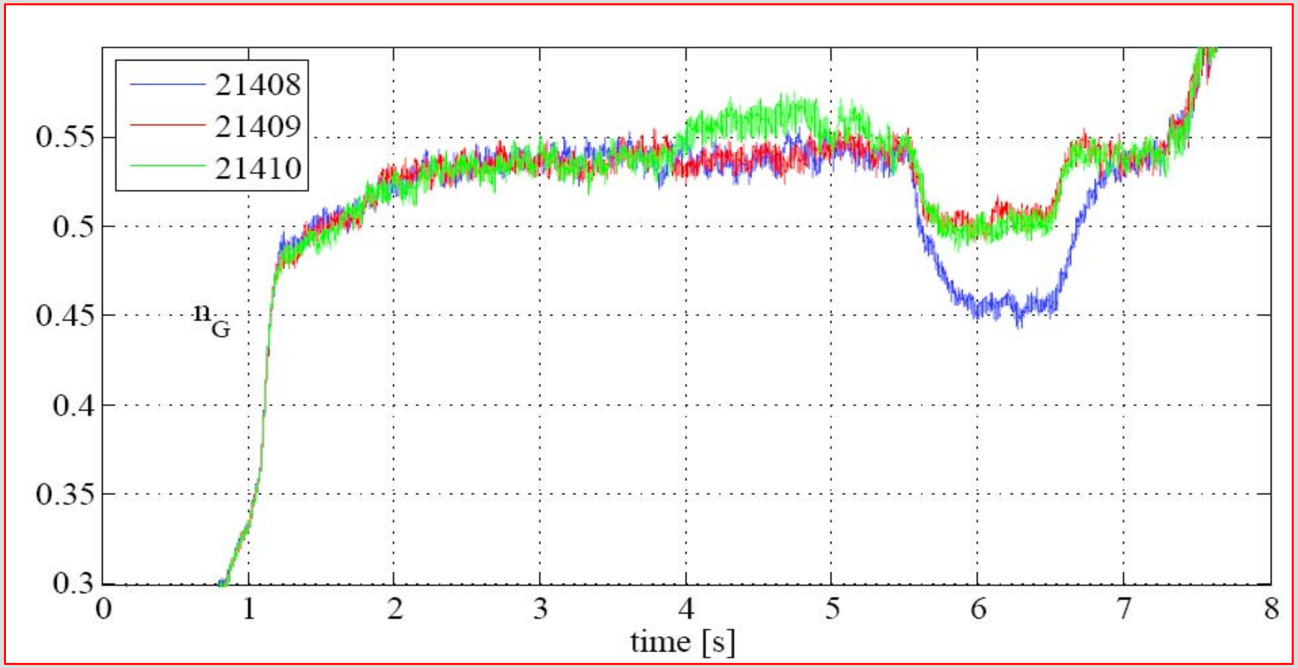
# The conditional averaging technique is applied here for ELMs revealing the decrease of the amplitude and duration (despite the decrease of the average density)

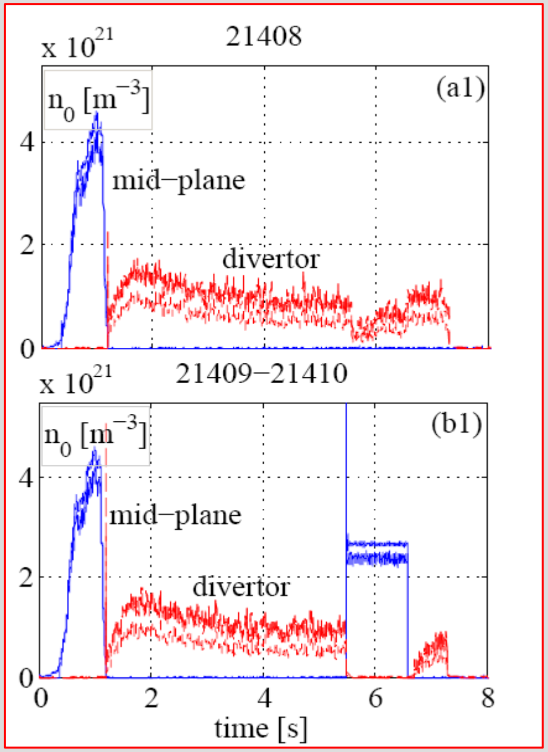


# ELMs results

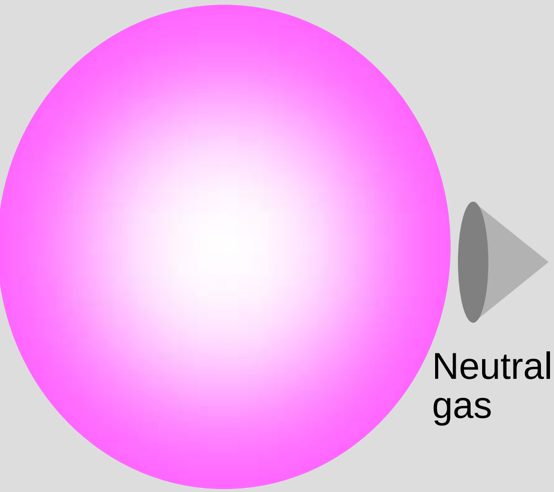
- The best effect on ELMs is obtained where no gas puffing is done. The ELMs frequency is increased by 40% where as the amplitude is divided by 4!
- When gas puffing occurs, the decrease of the ELMs amplitude is lesser, only a factor of 3, but the frequency of the ELMs is now doubled.

# Why does the plasma density decreases during ICRH despite of massive gas jet increase at the mid-plane?

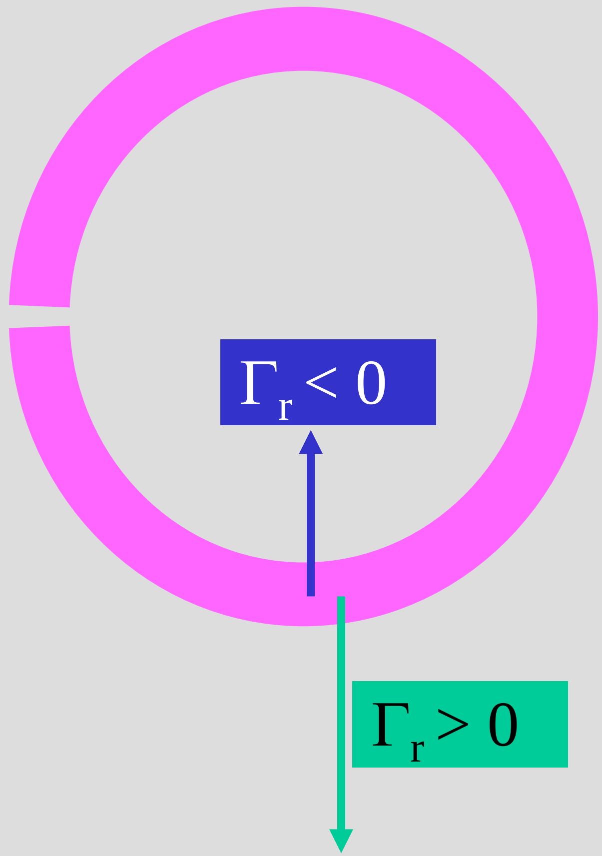


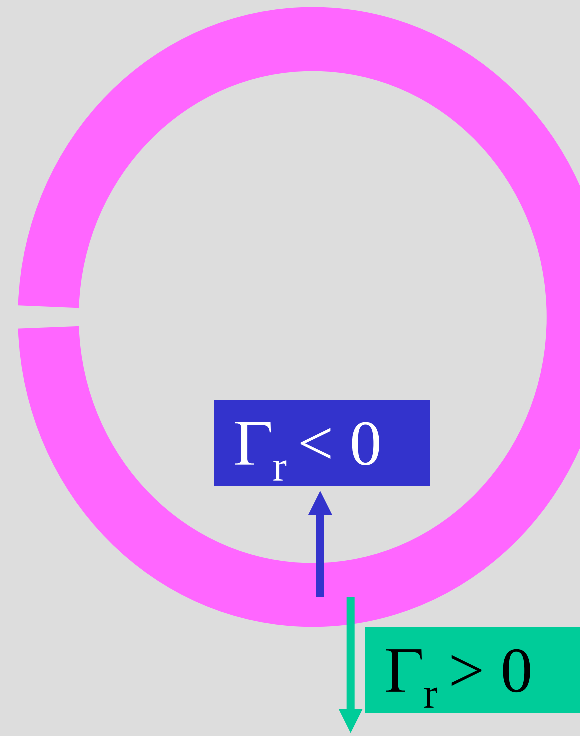
# The suppression of turbulence at the edge leads to less fueling of the plasma core




The open valves feed the plasma with neutrals which are ionized at the plasma edge




Edge radial transport leads to part of the plasma going back into the SOL and the other going inside to increase the core plasma density

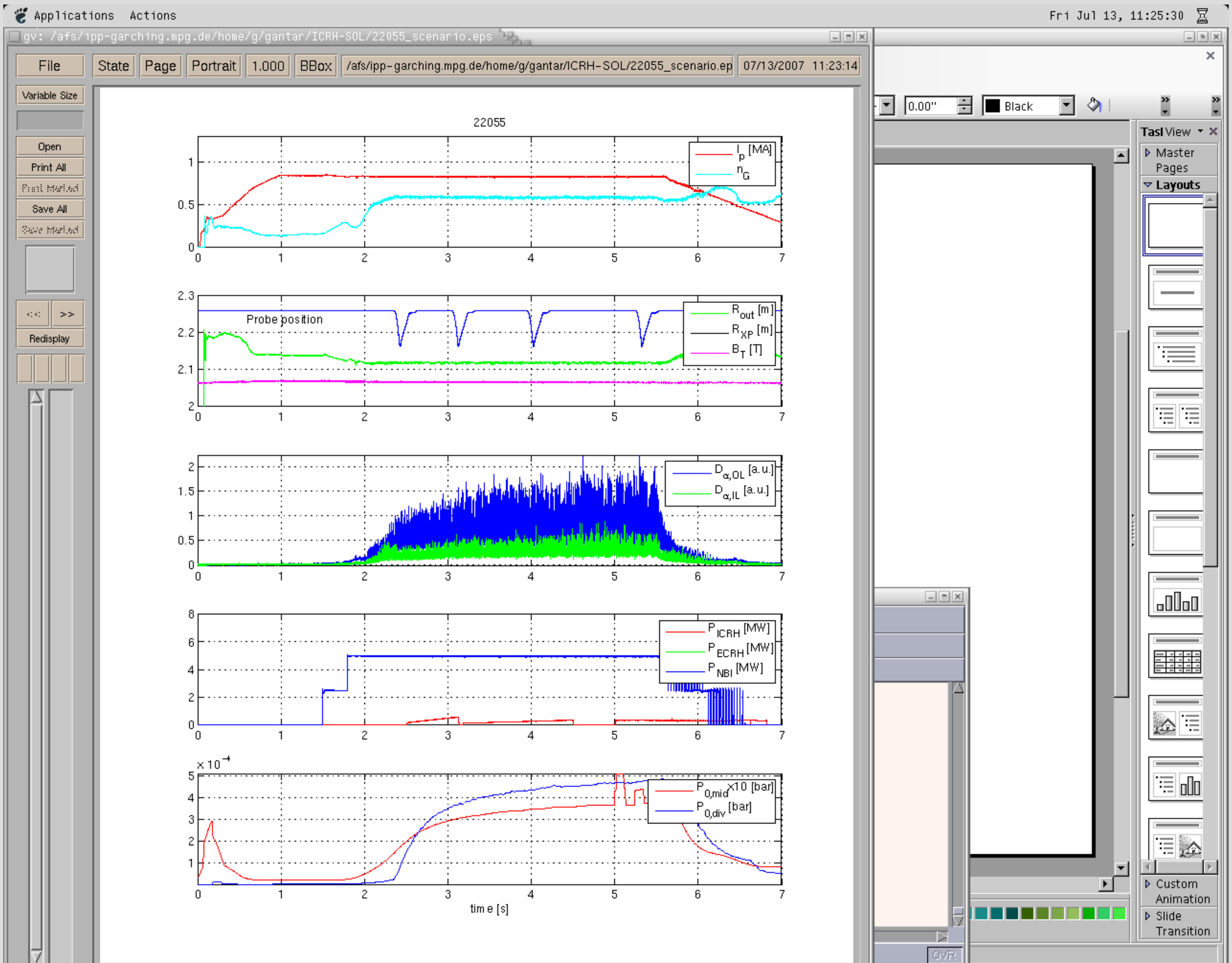



When edge radial transport is reduced not only the SOL have less plasma but also there less fueling of the core. This explains the disability to increase the plasma density despite a large gas puffing.

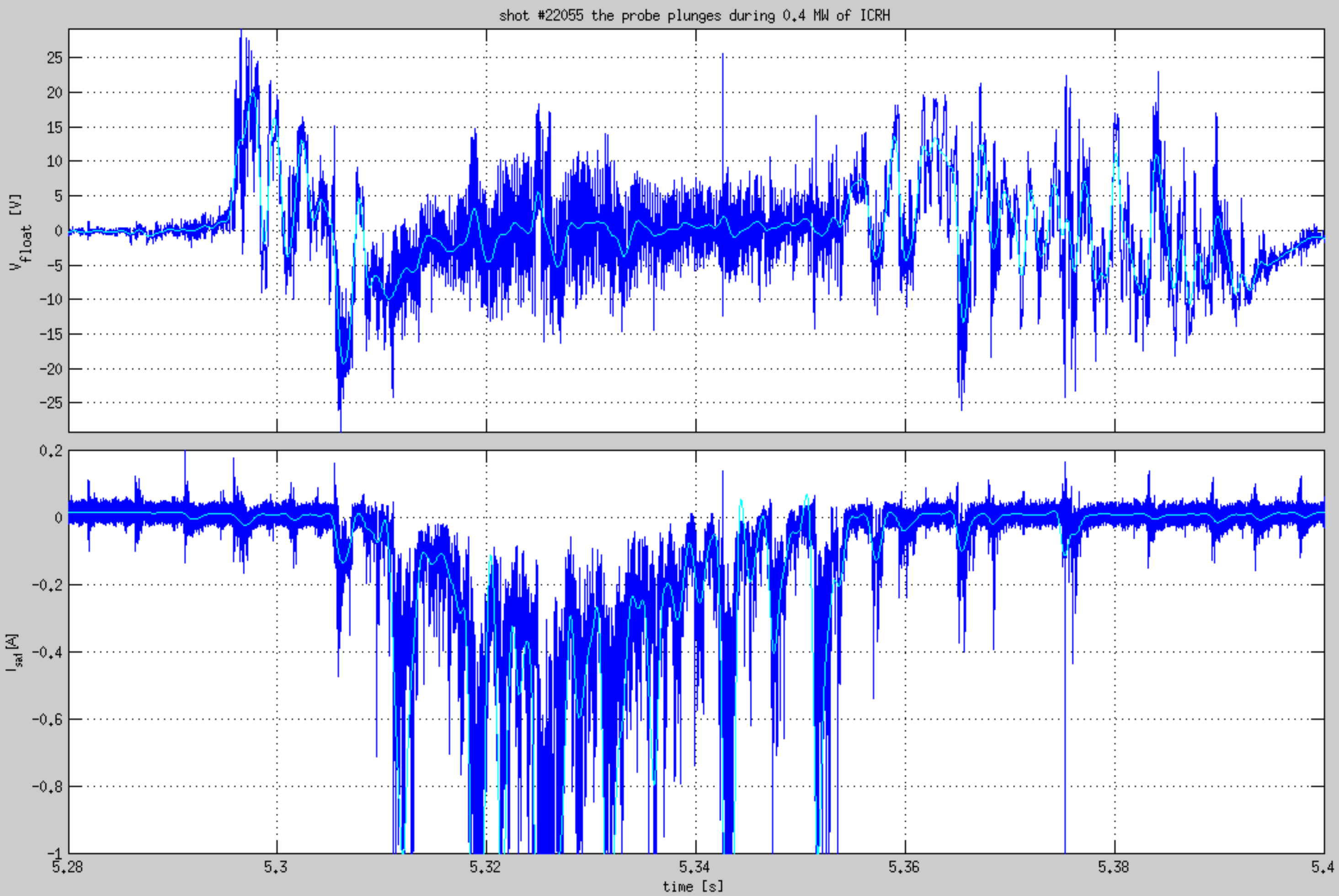
# Conclusions

- ICRH is an effective mean to suppress turbulence transport into the SOL.
- Turbulence in the SOL was found to be Gaussian because of the suppression of large-scale structures namely the convective part; the high-frequency component is observed to increase.
- As the neutrals density increases, either naturally from the vessel walls or by gas puffing, the efficiency of plasma suppression decreases and more energy goes to ionization.
- ELMs are also strongly affected by ICRH in terms of their amplitude and the amount of plasma transported into the SOL. The frequency of the ELMs is seen on the other hand to increase by 50% (good news for ITER).
- As neutral density increases, the effect on the ELMs is lesser but still important but the frequency of the ELMS is doubled.
- The decrease in radial transport may be the origin of the core density decrease during ICRH often called pump-out

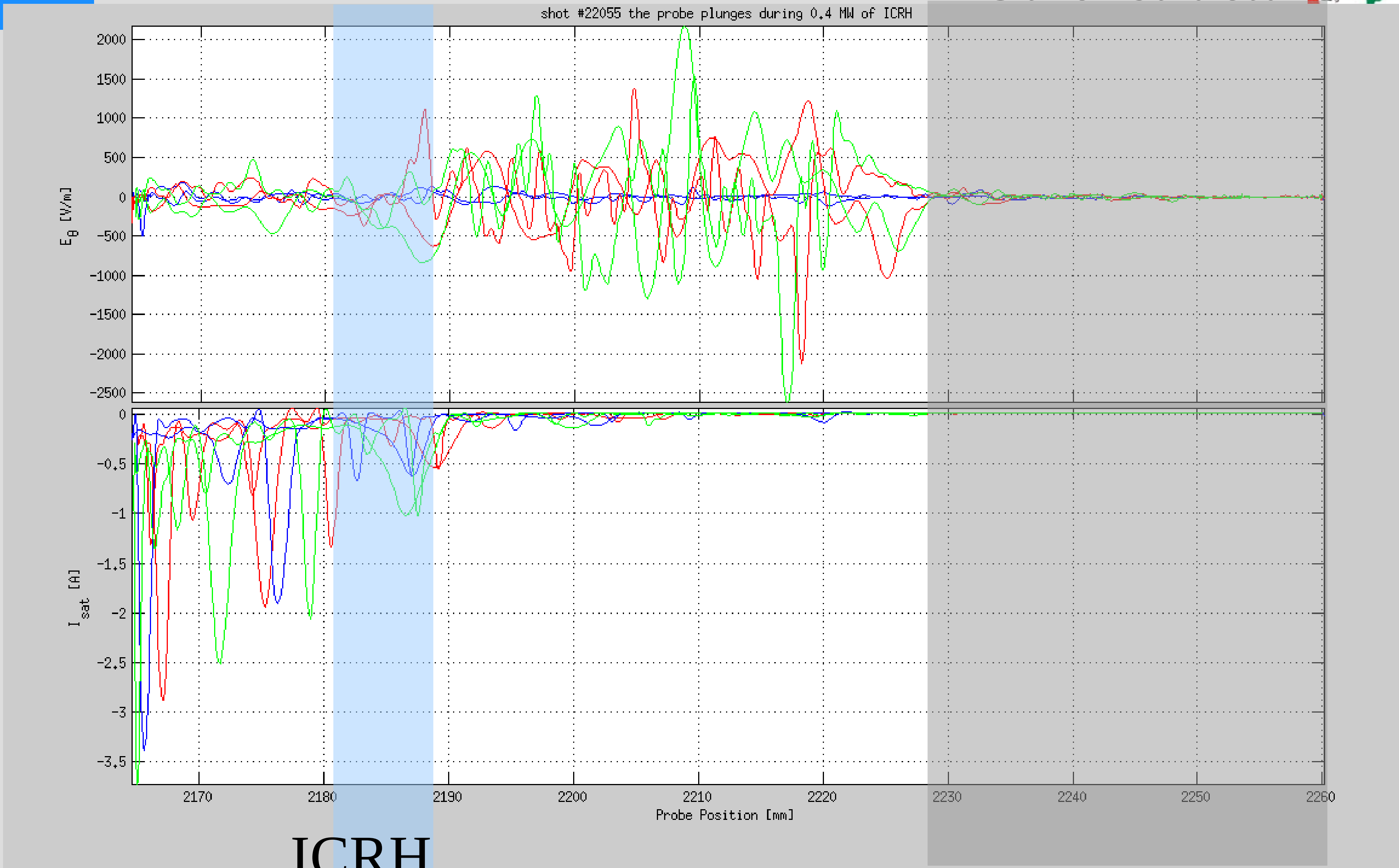
# ICRH-SOL Interaction Experiment (1 shot out of 6!!)



# During ICRH, the floating potential of the probe records strong fluctuations as the probe moves towards the plasma while the ion saturation signal is unchanged



# Other structure

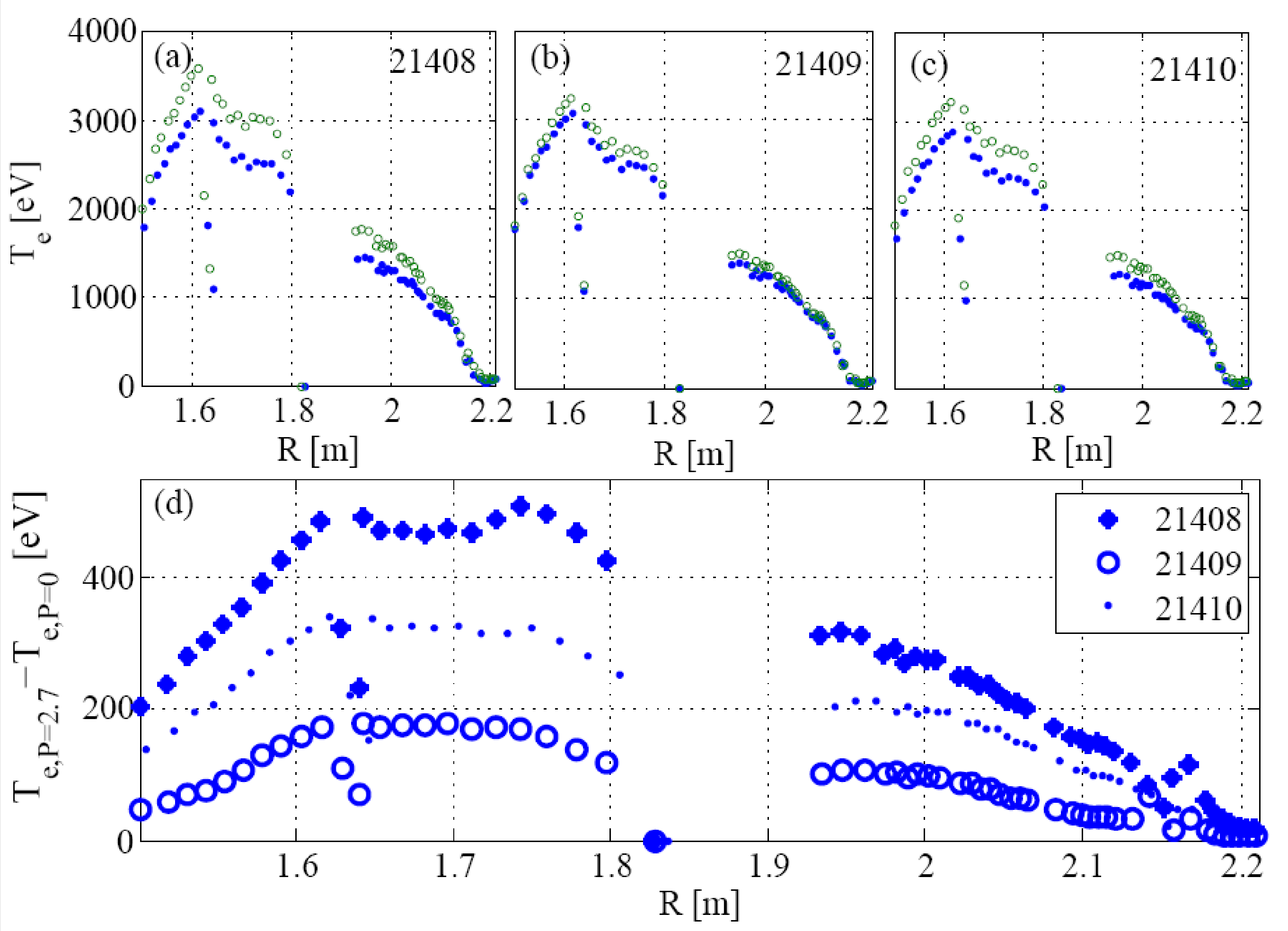



ICRH Limiter

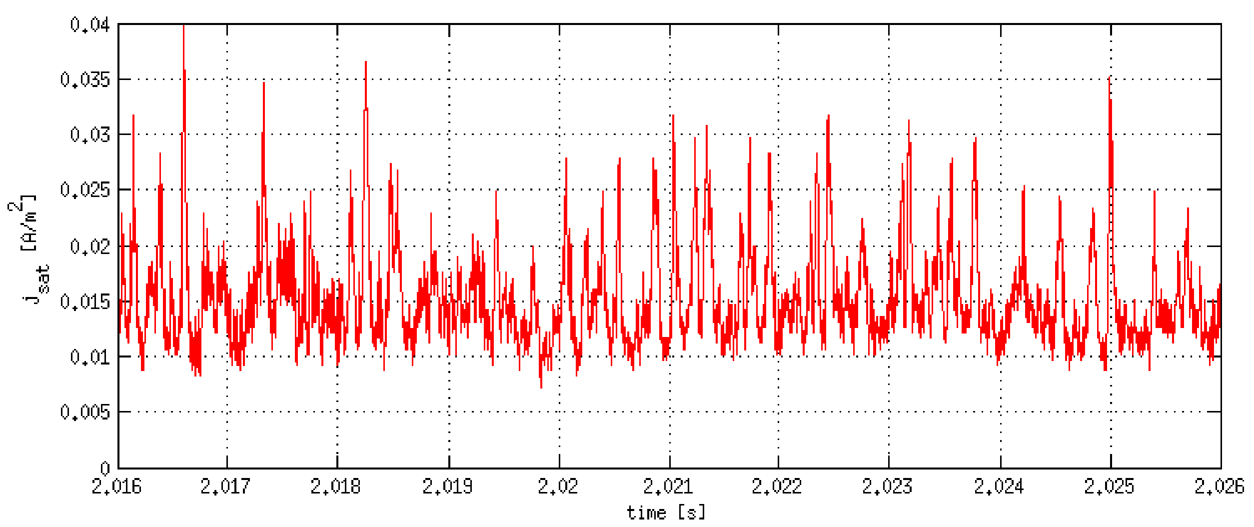
SOL

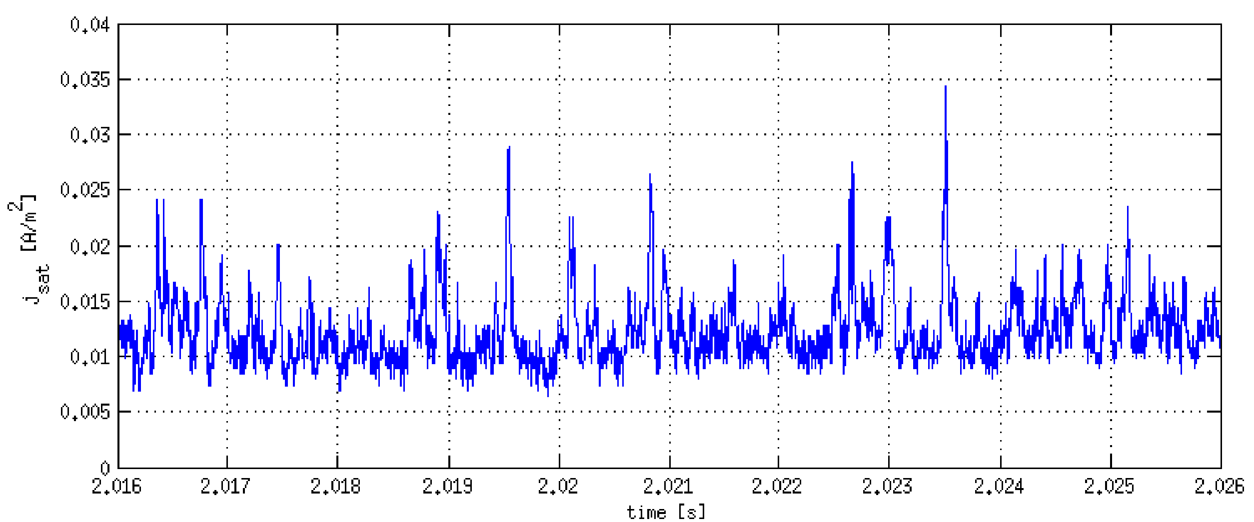
Behind the ICRH limiter

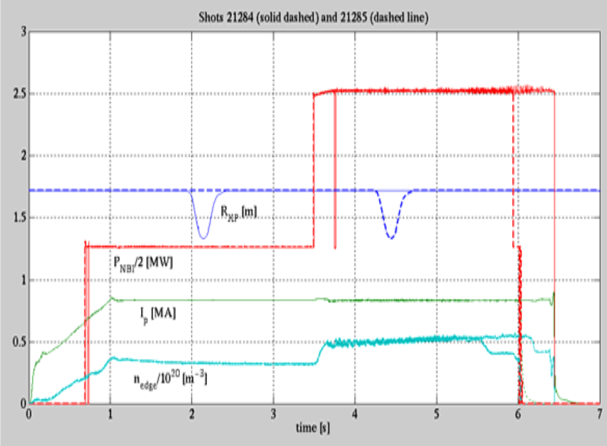
# The temperature increase due to ICRH as observed using the ECE indicates that:
# * the change in the temperature is occurring mainly in the center.
# * More temperature increase is recorded for 21408 then for 21409 and 21410 by a factor of 2!



Two signals taken at the same location in the low-field SOL
one is in H-mode and the other is in L-mode
Make a guess, which of the curves is in H-mode and which is in L-mode ?

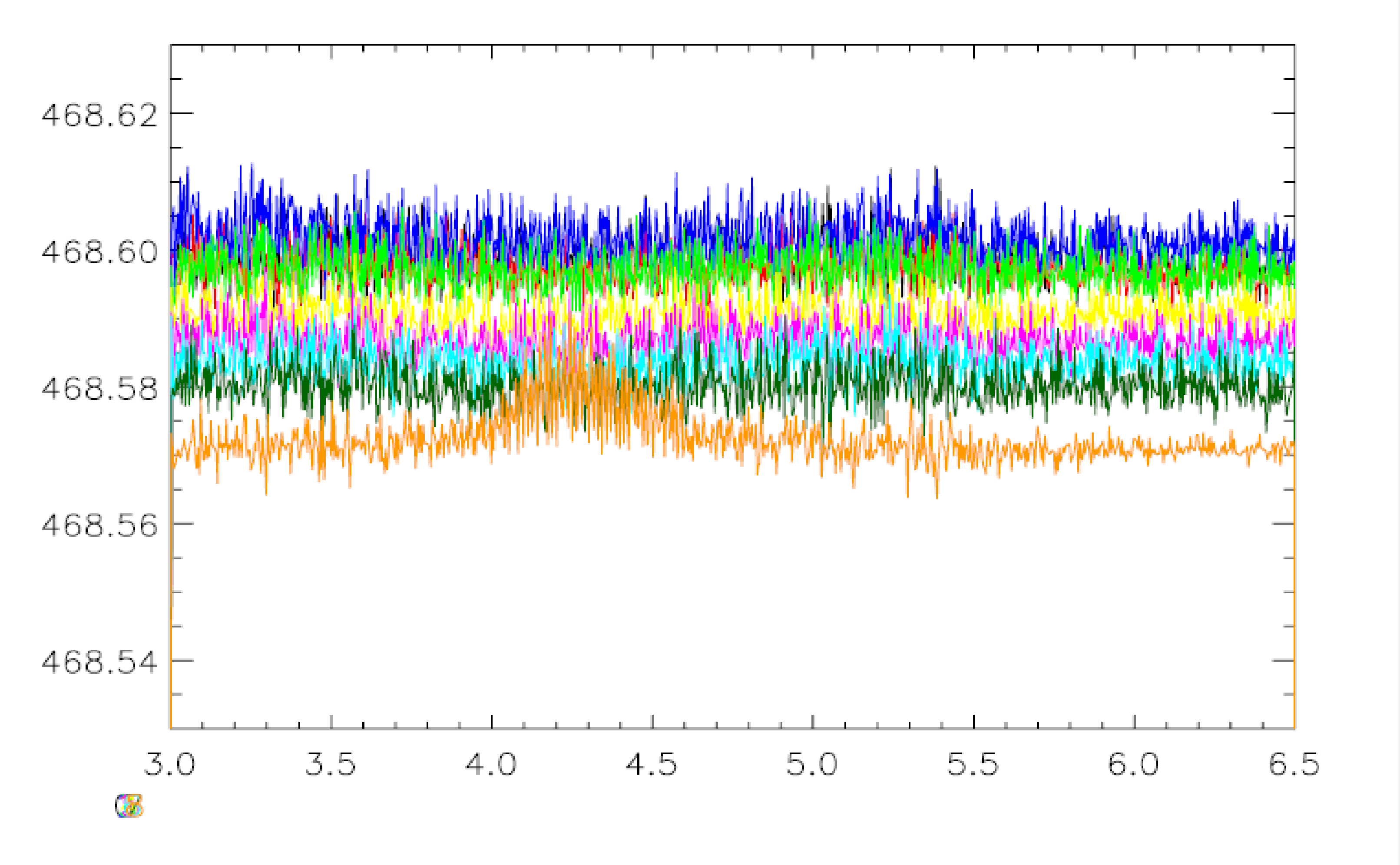


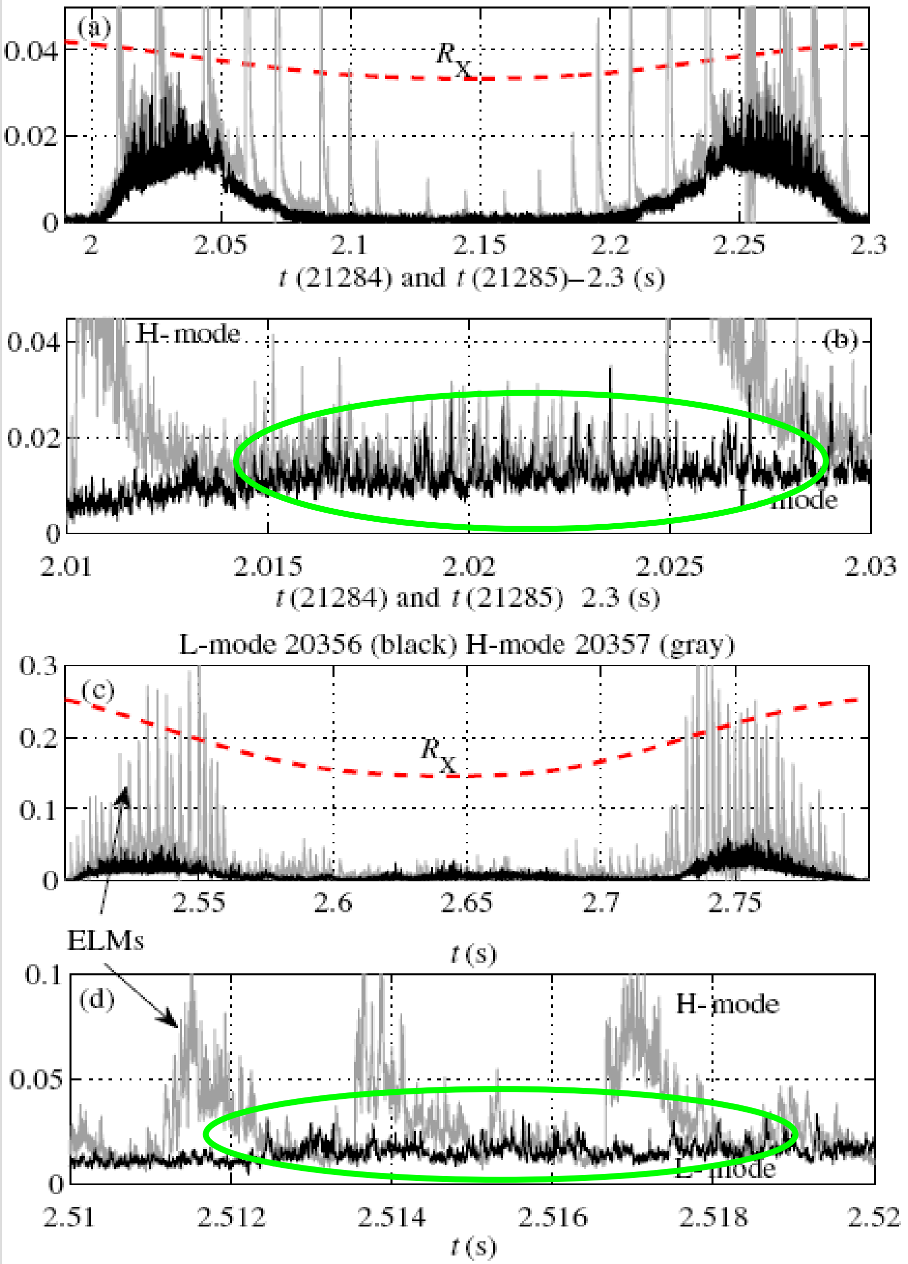



# We use the He II lines giving an idea about the radial electric modification during ICRH (21410)

**No modification above the experimental error is observed**



# Where did all this started???

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