PSI-issues in FTU

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OUTLINE

1. Liquid Lithium Limiter Experiment
2. Disruption mitigation by ECRH
3. Dust measurement
4. Manufacturing and characterisation of Rhodium coated molybdenum mirrors

1. Liquid Lithium Limiter Experiment

PHYSICAL ISSUES

- **Wall Conditioning**
  Lithization of vacuum vessel shot by shot

- **Effects on plasma discharges**
  Z_{eff}, Recycling, Density limit, P_{rad},etc

TECHNOLOGICAL ISSUES

- **To study J×B effects on liquid Lithium**

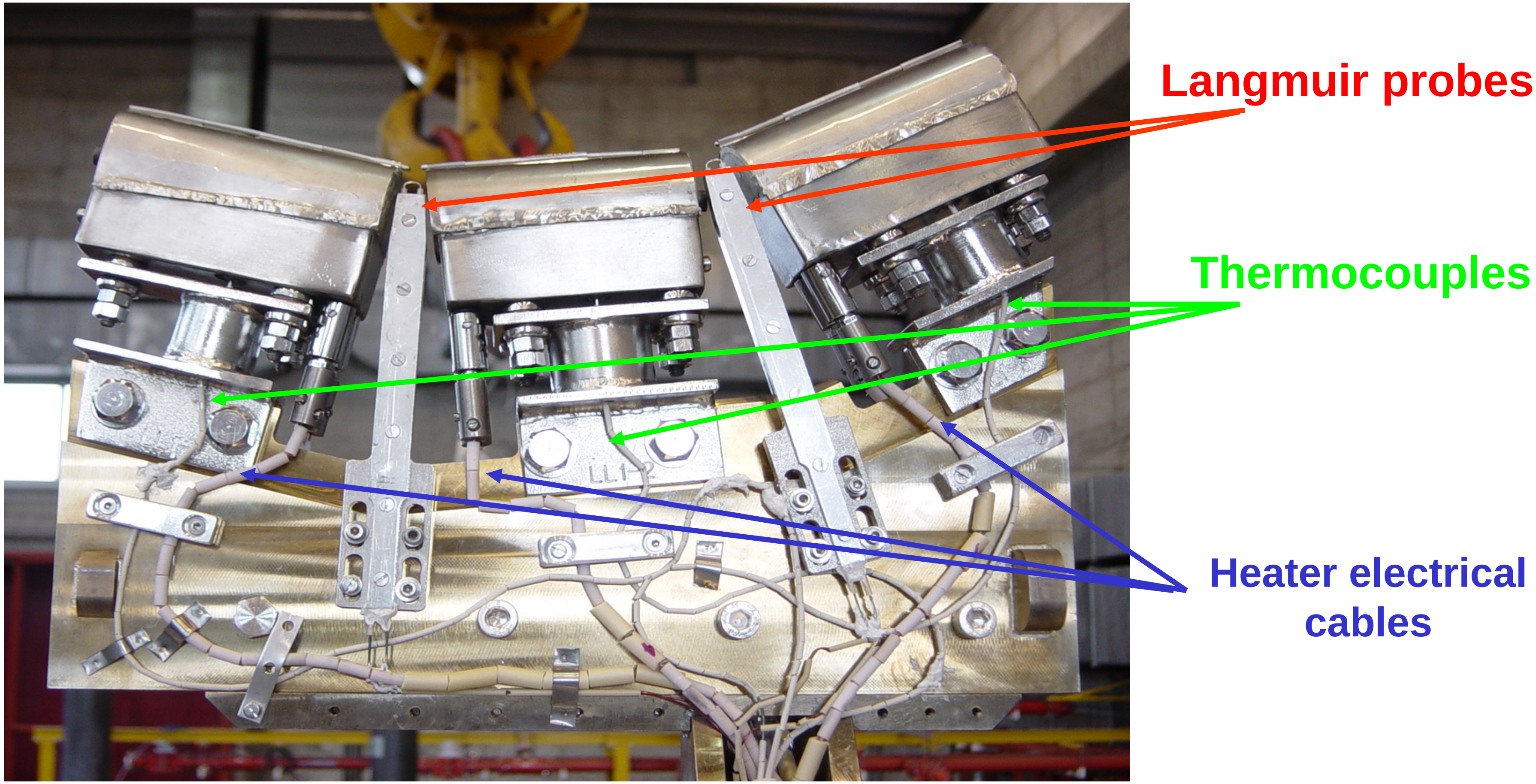
  On DIII-D, J × B forces on liquid lithium caused MHD instabilities on plasma due to a strong influx of Li.

  We have tested the Russian concept to solve this problem

  Capillary Porous System (CPS)

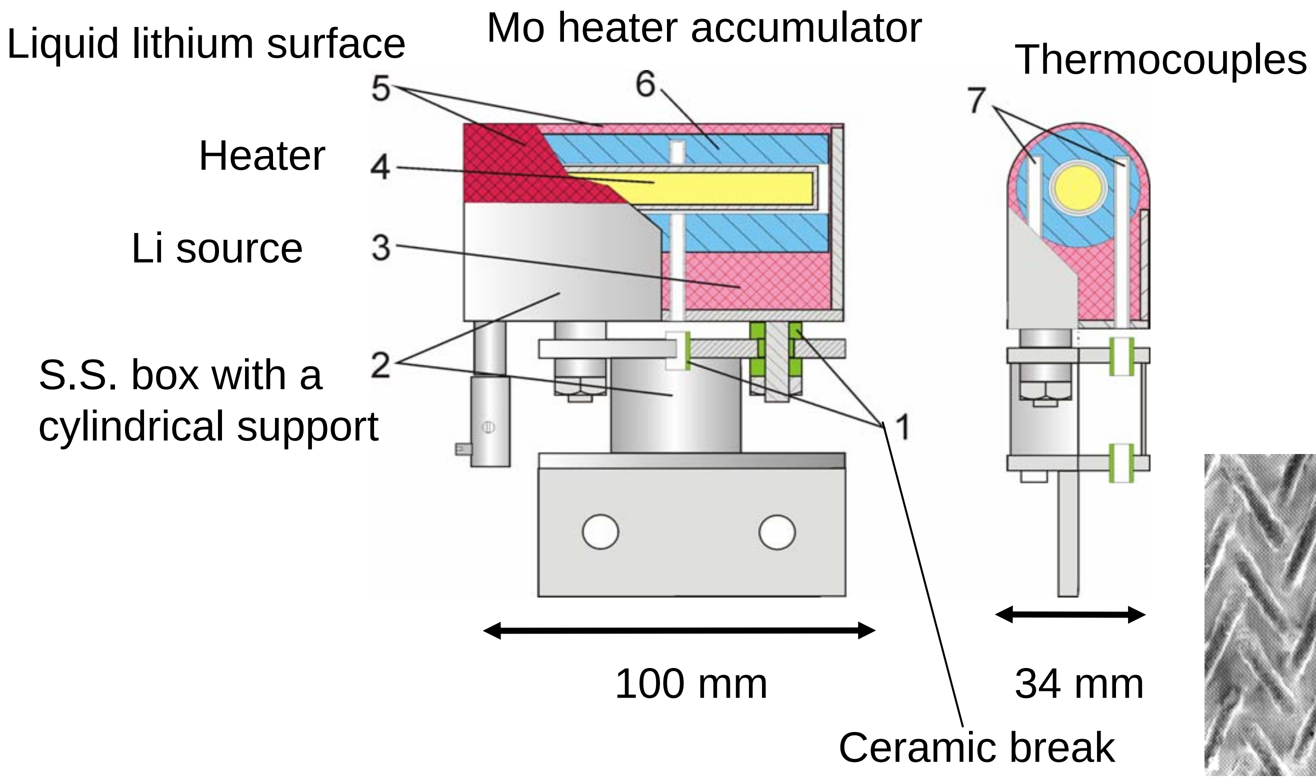
- **To study heat loads, damage of Liquid Lithium Limiter (LLL) in a medium size high field tokamak FTU**

Liquid Lithium Limiter



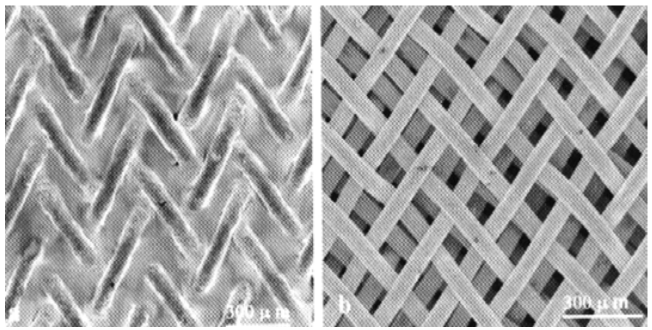
Capillary Porous System (CPS)

➢ The LLL system is composed by three similar units

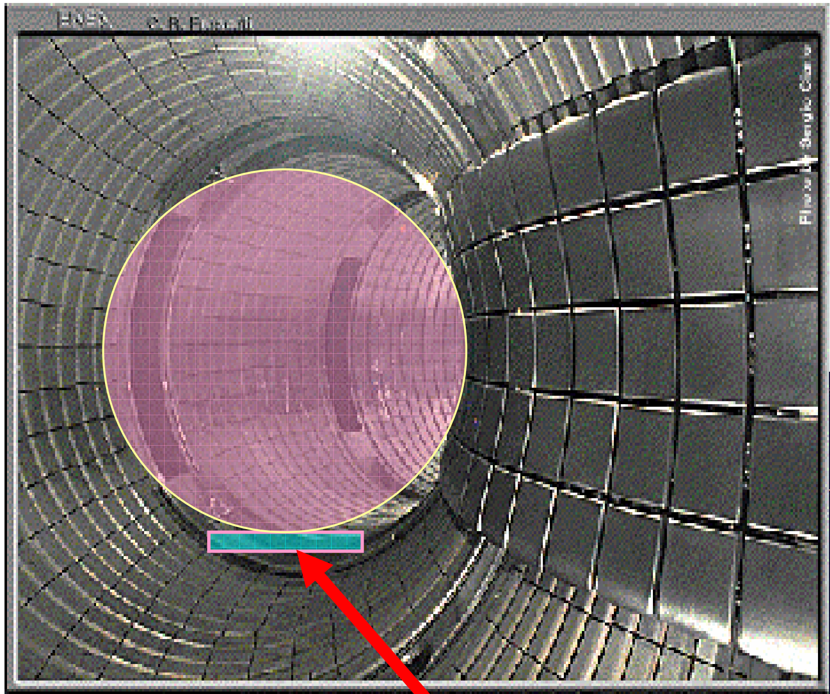


Scheme of fully-equipped lithium limiter unit

CPS is made as a matt from wire meshes with porous radius 15 μm and wire diameter 30 μm Structural material of wires is S.S.

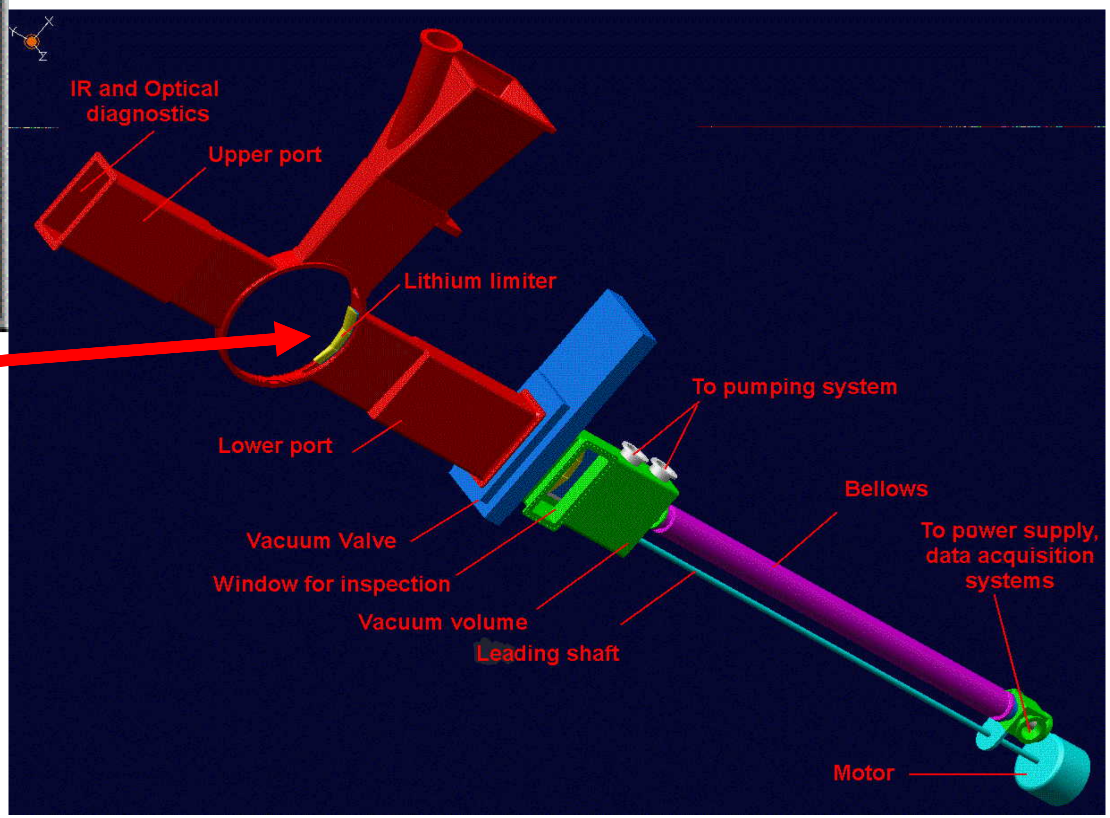


Meshes filled with Li



Total lithium area ~ 170 cm^2
Plasma interacting area ~ 50- 85 cm^2
Total amount of lithium ≅ 80 g
LLL initial temperature > 200^{o}C

Liquid Lithium Limiter



Melting point 180.6 °C
Boiling point 1342 °C

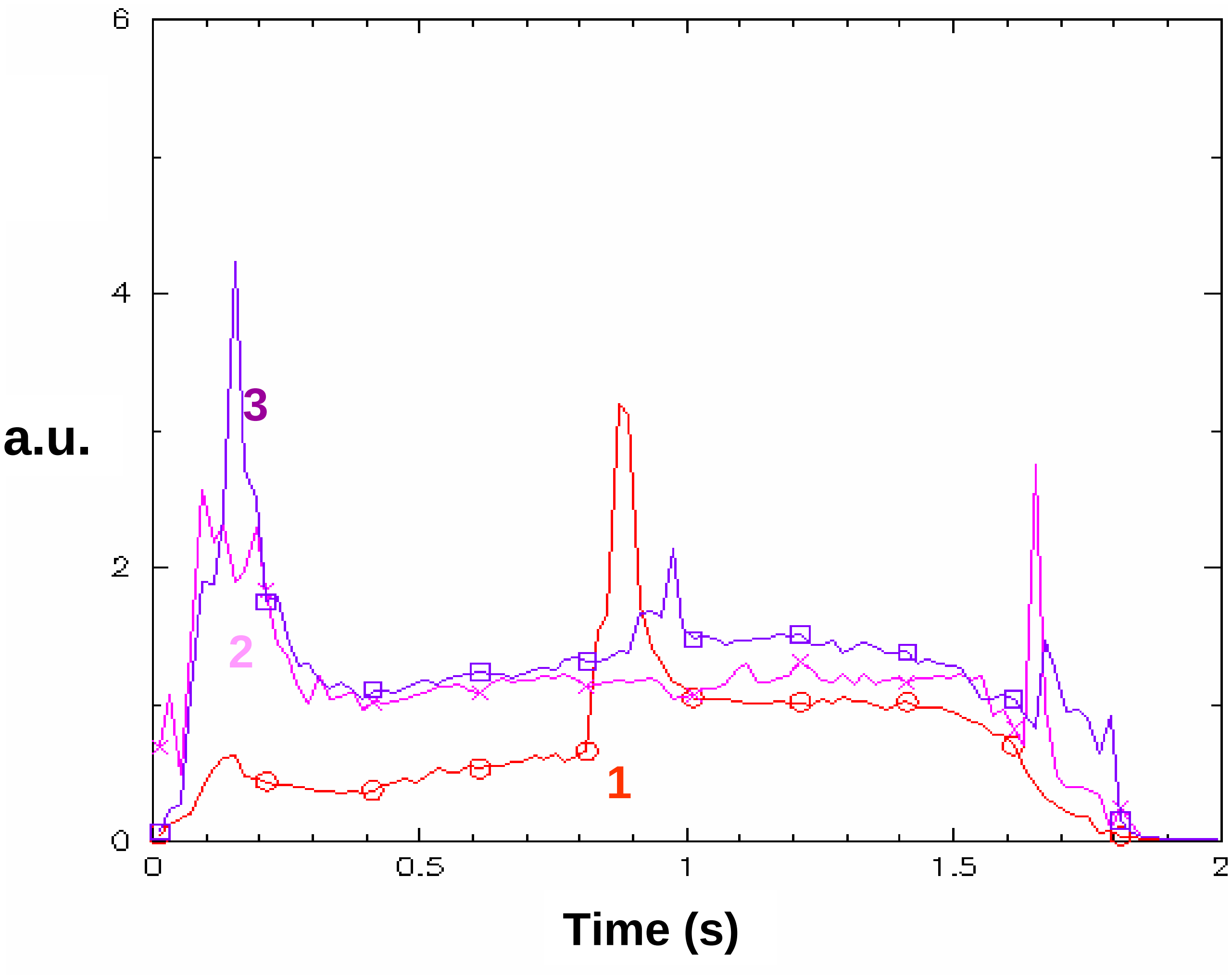
1. Liquid Lithium Limiter Experiment

Discharges without LLL

Lithization Procedure

- Before the insertion on FTU, the lithium limiter is heated up to the liquid phase (210 °C)
- Lithization is performed by doing three equal shots with LLL 2-2.55 cm away from the LCMS and by monitoring the temporal evolution of Li III line intensity in the VUV spectrum
- About $0.5\text{-}1.0\times10^{21}$ Li atoms are produced by physical sputtering plus evaporation (~ 10 monolayers)
- After these shots, the LLL is extracted and the lithization is studied in the following plasma discharges

Lithization Procedure

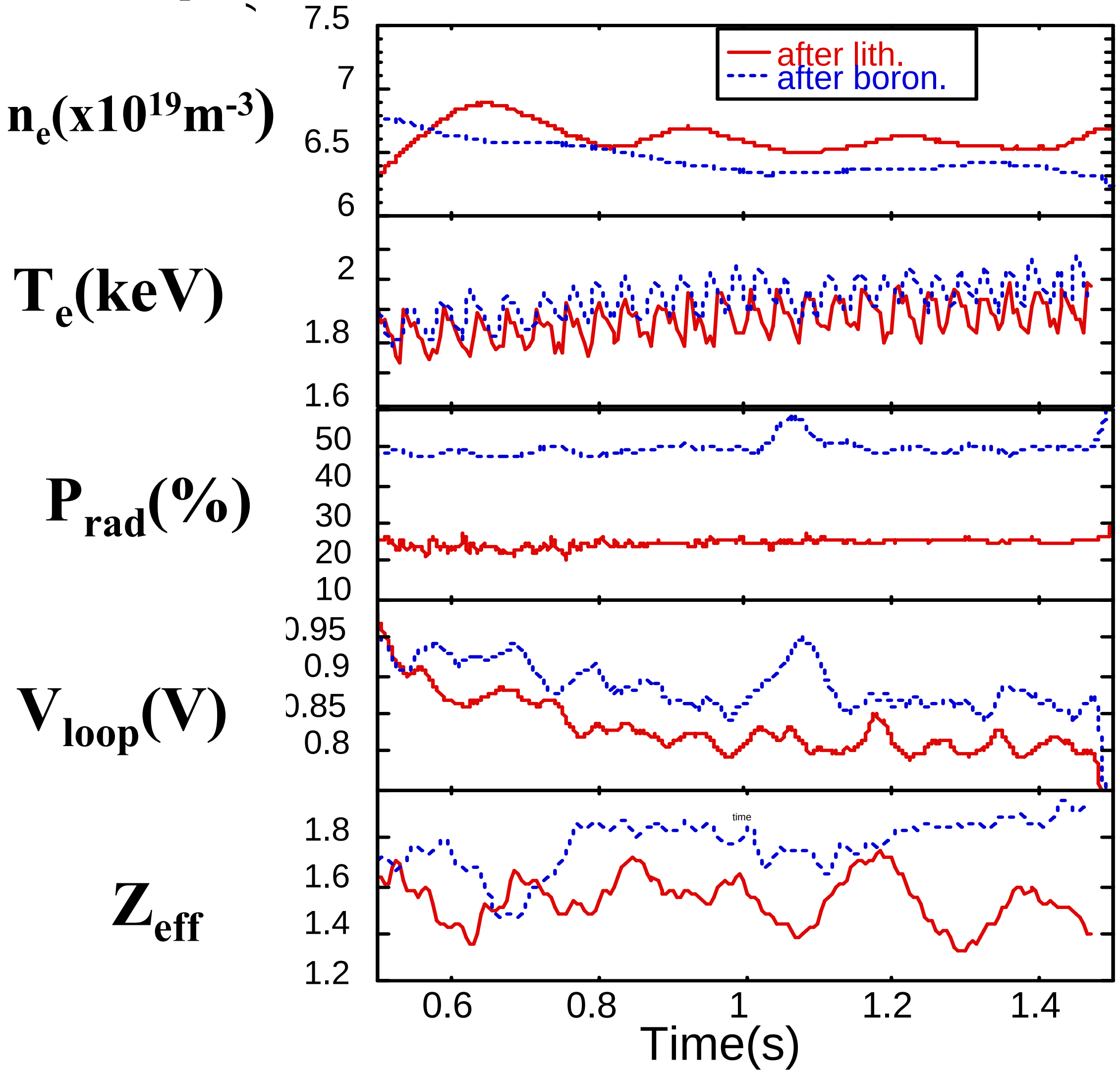


Li III 13.5 nm

Time evolution for three consecutive shots

LLL is 2 cm away from LCMS

Comparison between Lithization and Boronization



Ohmic shots

I_p=0.5MA B_t=6T

The Li effects are similar or even better than those of B

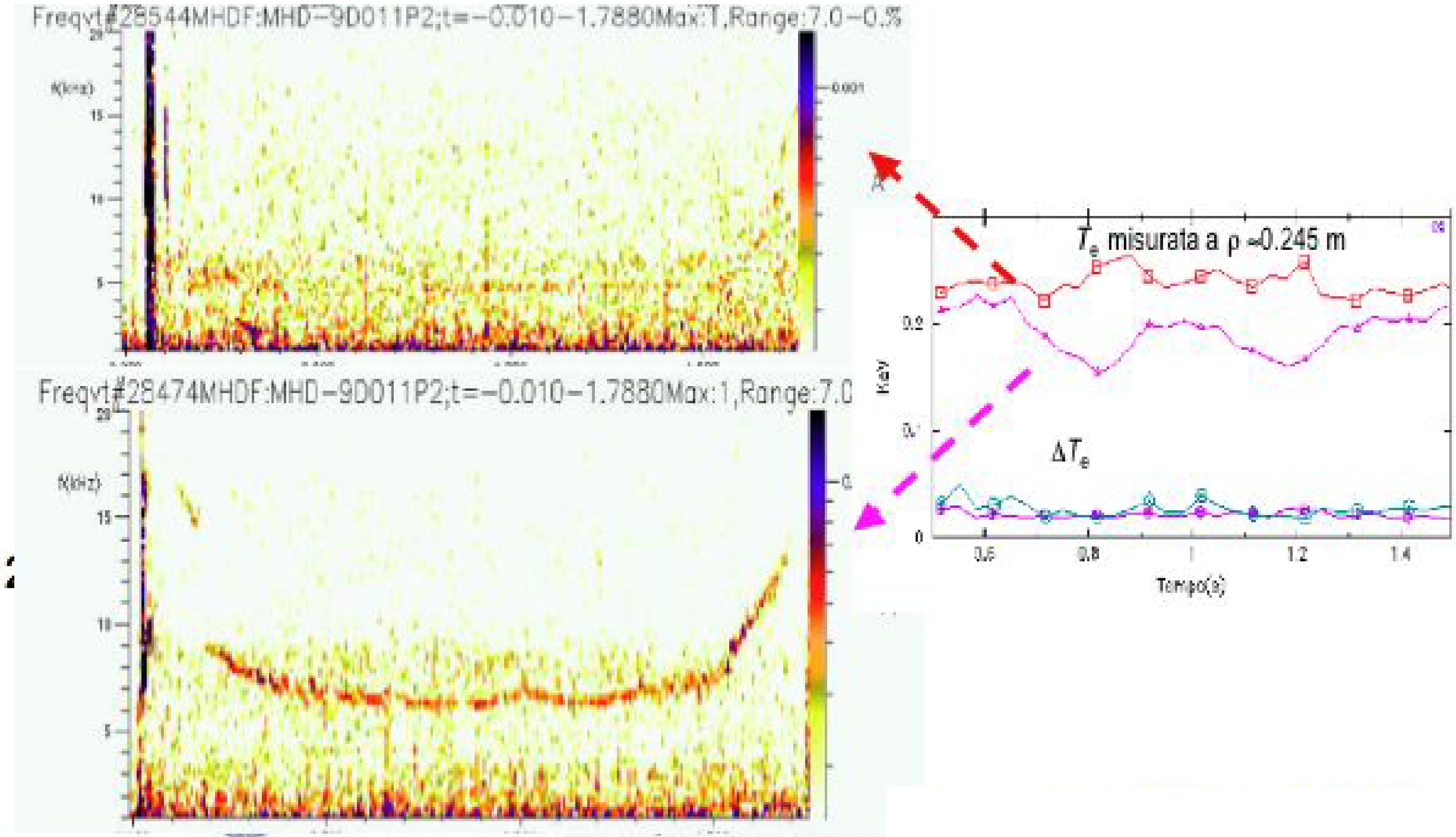
Comparison between Lithization and Boronization

With higher T_e at the edge reduced MHD occurs

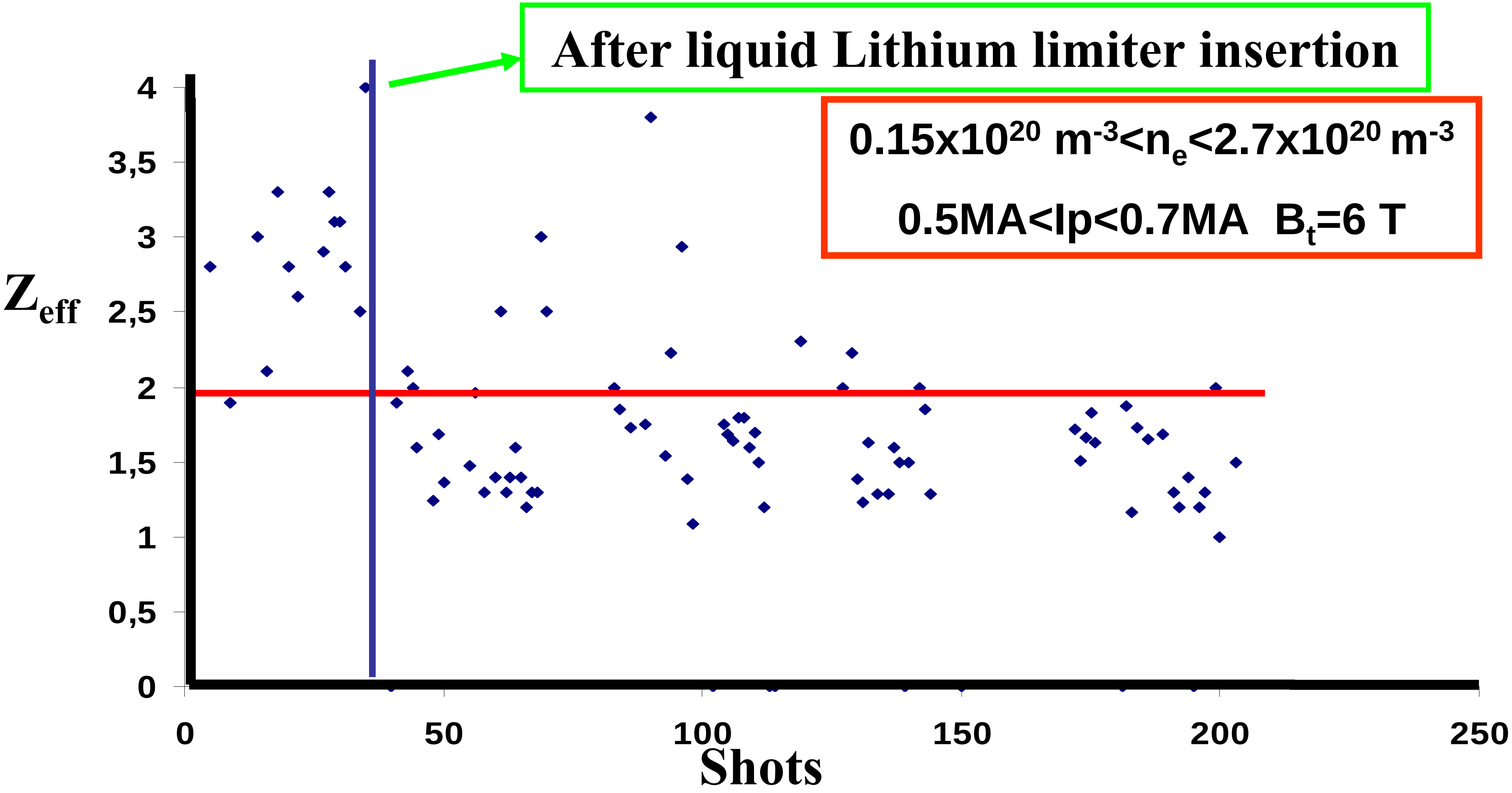
FTU: shots with similar parameters but with vessel:

With Lithium: MHD quasi-quiescent

Boronised: intense MHD (amplitude 5 times higher)

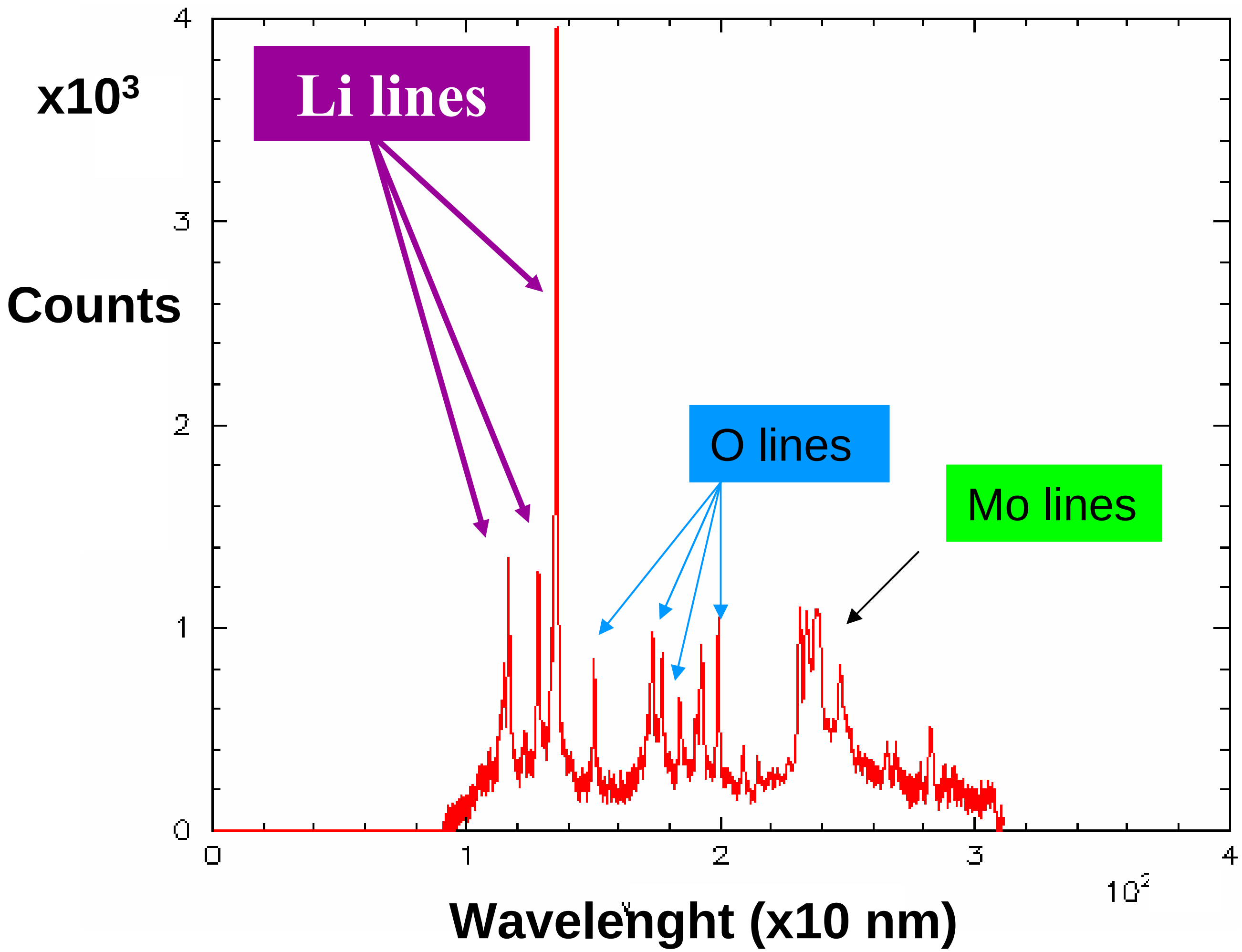


Z_{eff} was well below 2 during all the experimental campaign



Zeff is always well below 2 with lithizated wall

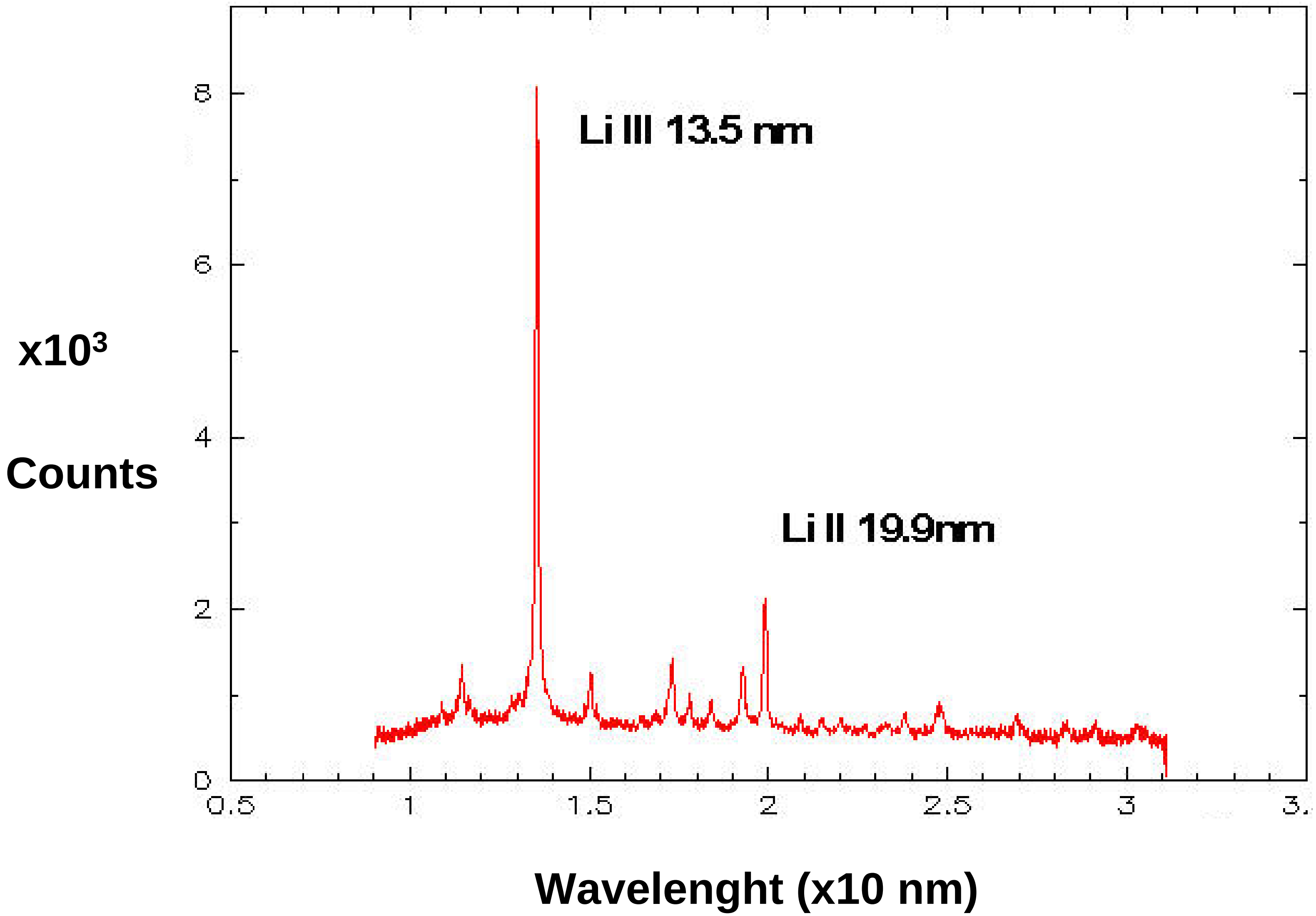
Impurities



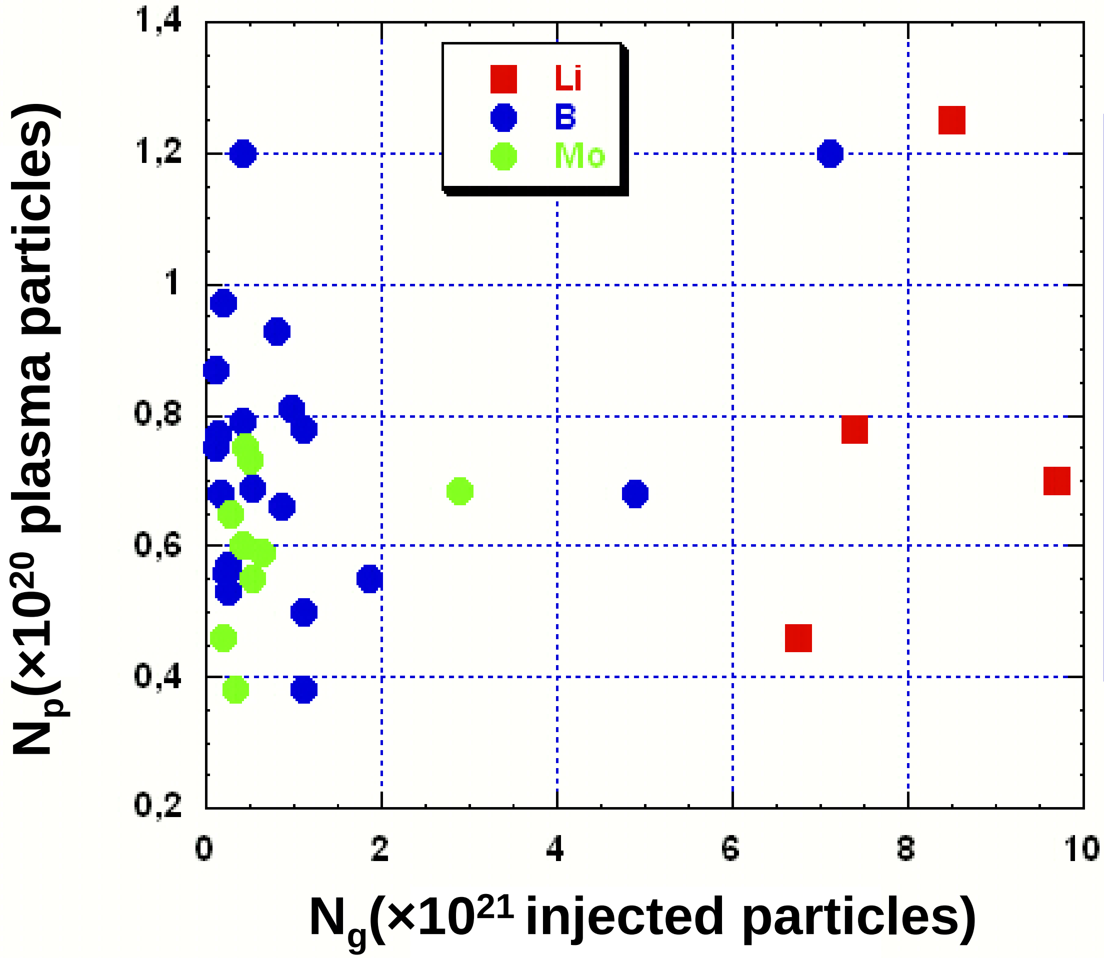
In the VUV spectrum the prominent line is Li III

O, Mo and are strongly reduced respectively by a factor 3.5 and 1.8

Impurities

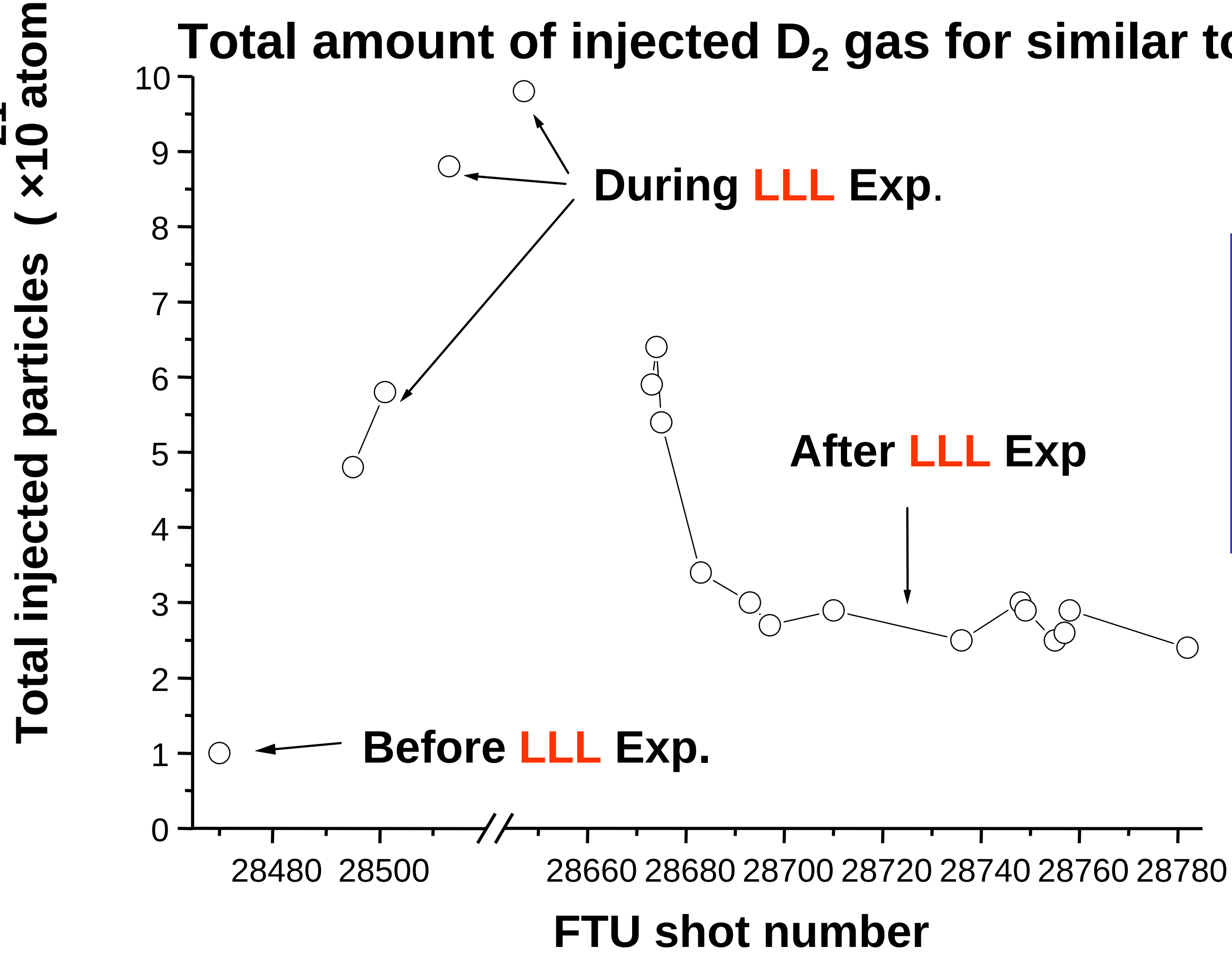

x10³
Counts
8
6
4
2
0
0.5
1
1.5
2
2.5
3
3.
Li III 13.5 nm
Li II 19.9nm
Wavelenght (x10 nm)

Strong D_2 pumping capability



After Lithization much more gas has to be injected to get the same electron density with respect to boronized and fully metallic discharges

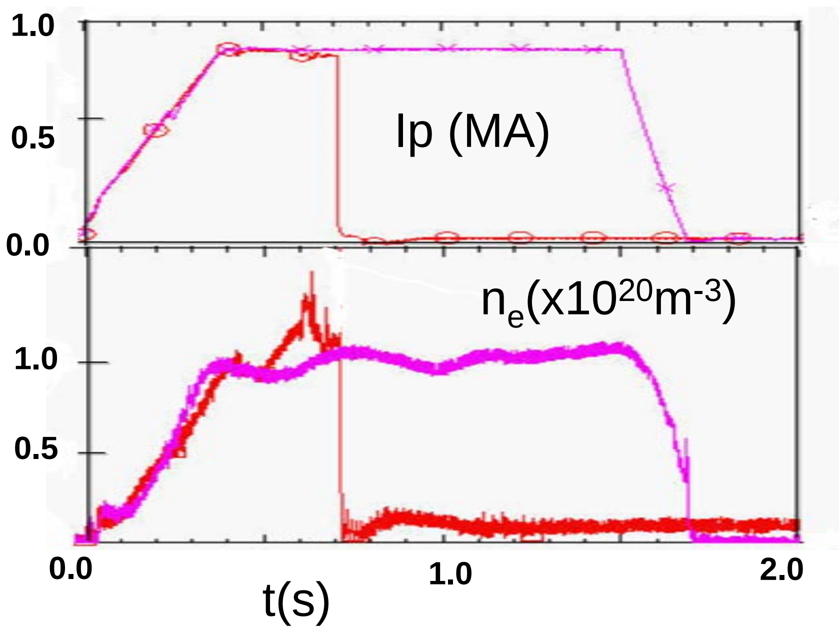
Strong D_2 Pumping Capability



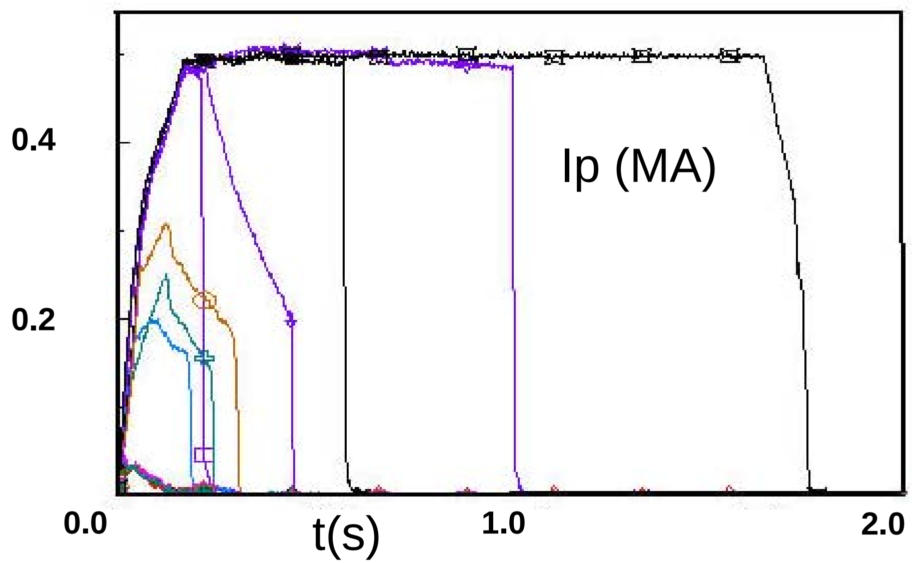
The pumping effect of Lithization lasts for long time

Other effects

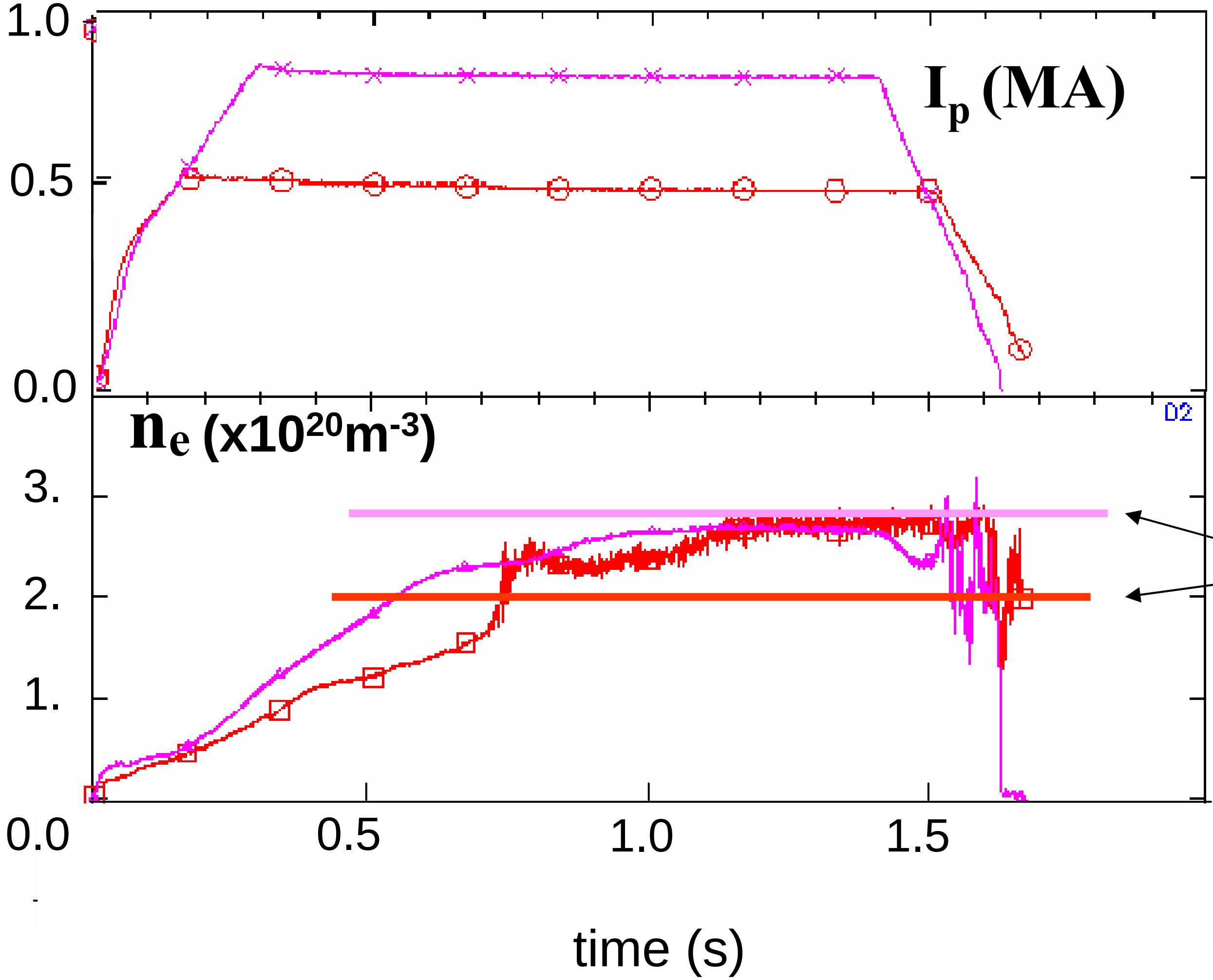
Recovery from disruptions



Plasma Restart



Improved Ohmic Density Limit



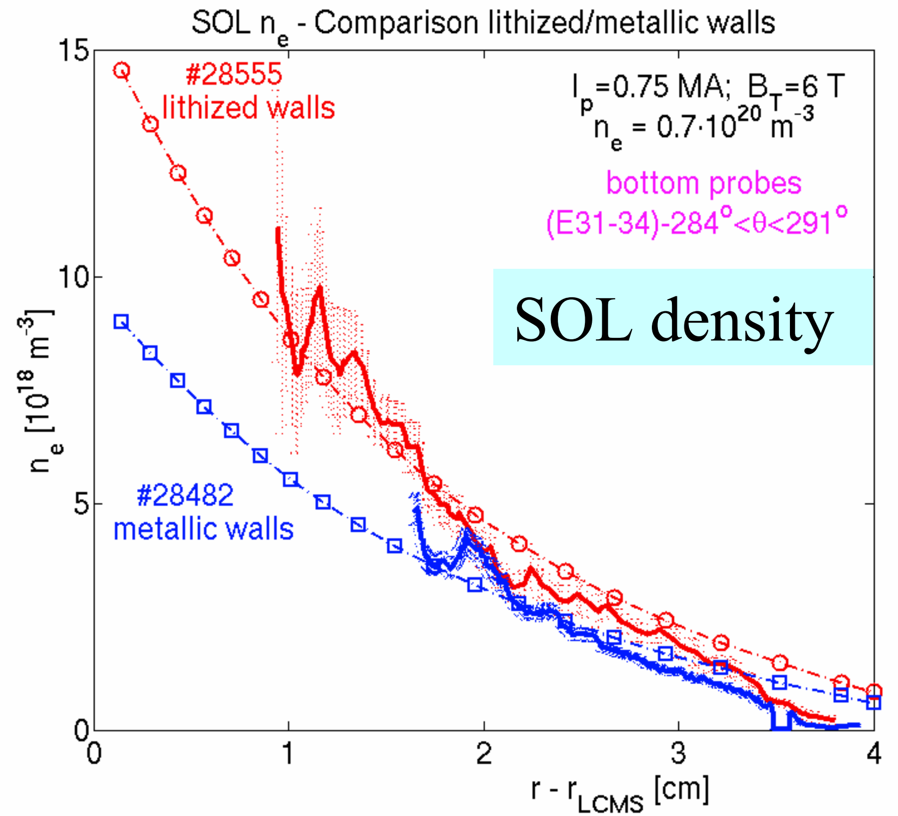
The operations near or beyond the Greenwald limit are easily performed

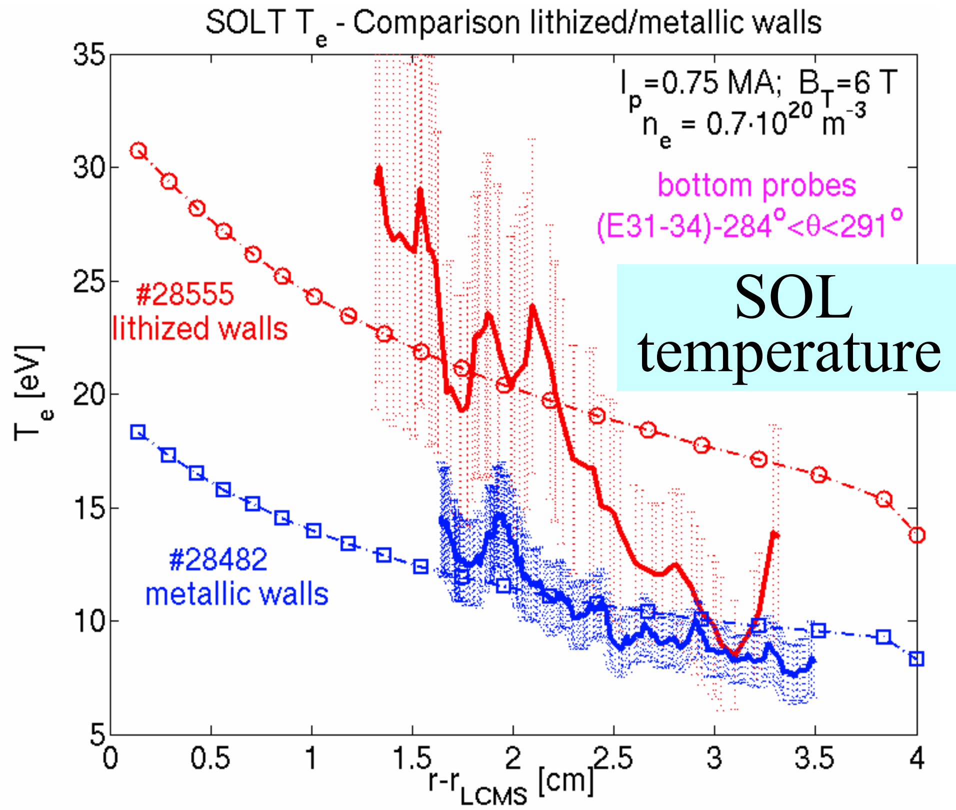
$<n_e>/n_G=1.0$

Greenwald limit

$<n_e>/n_G=1.4$

SOL physics with lithized walls - $n_e(r)$ and $T_e(r)$: experiment and code (TECXY)

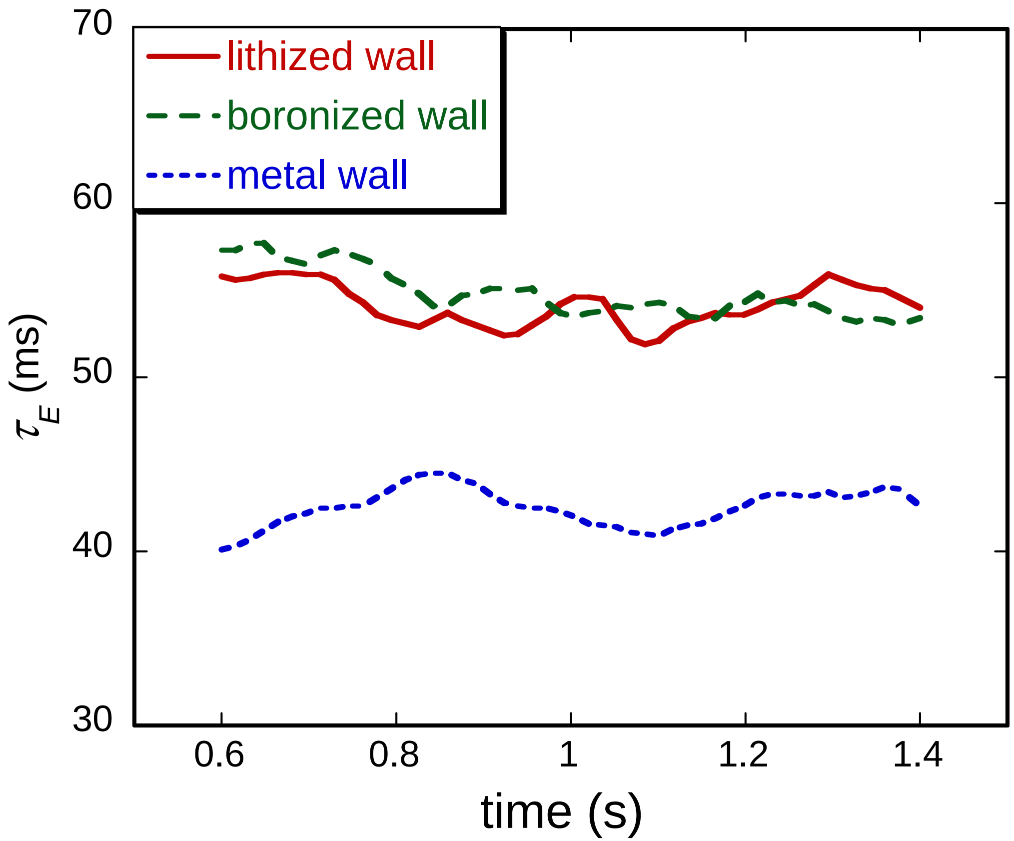




SAME $Q_{inp,SOL}$ YET QUITE HIGH ΔT_e

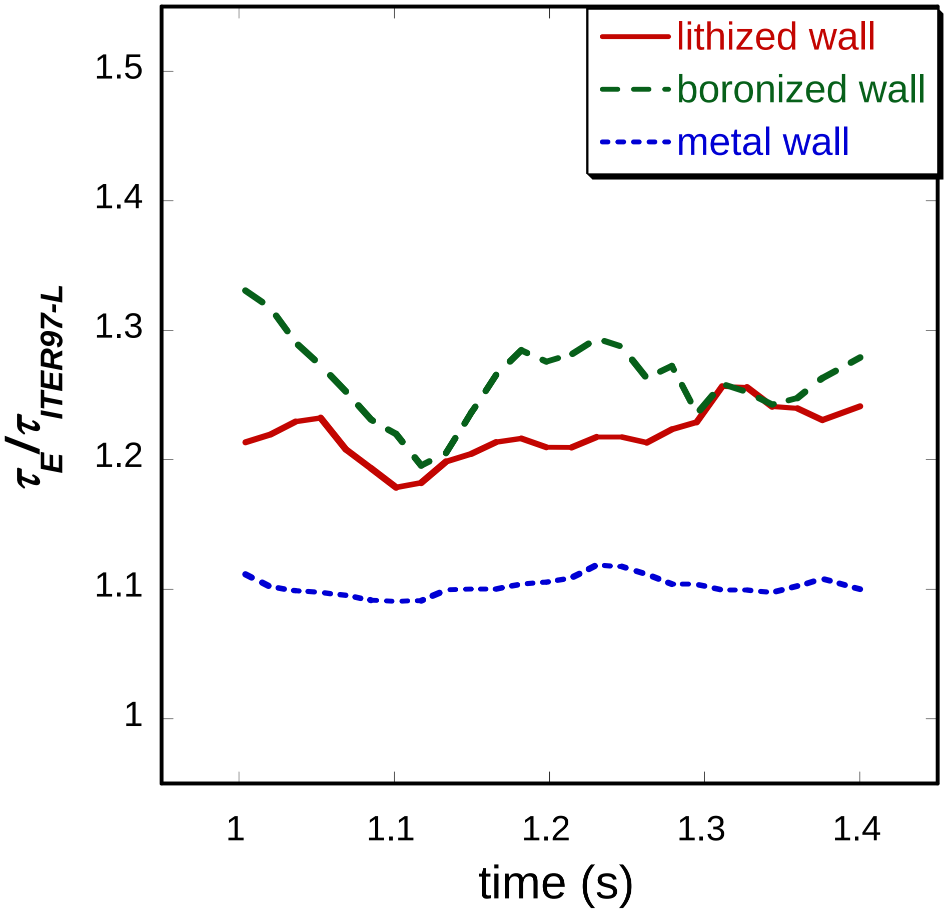
Set of three reciprocating probes at θ~0°, -70° and +70°, each with an array of L-electrodes (overall sampled angle ~70°) + two fixed L-electrodes on the LLL

Energy confinement time



By transport analysis performed with JETTO code [3] the energy confinement time in **lithizated** and **boronized** discharges results higher by a factor of **1.3** with respect to **metallic** discharge.

Energy confinement time and ITER97 L scaling



a) Enhancement of energy confinement time over ITER97 L scaling (H_{97}) up to **1.2 ÷ 1.25** for **lithizated** and **boronized** discharges.

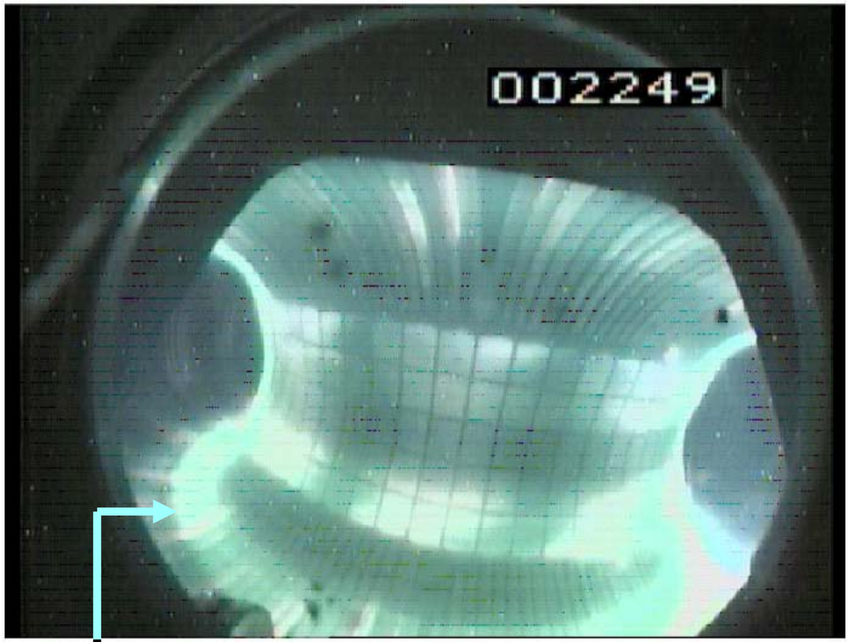
b) For the **metallic** discharge H_{97} is enhanced at a value of about **1.1**, that is higher than the average value of the standard FTU ohmic discharges (H_{97} = **0.92**) [4]

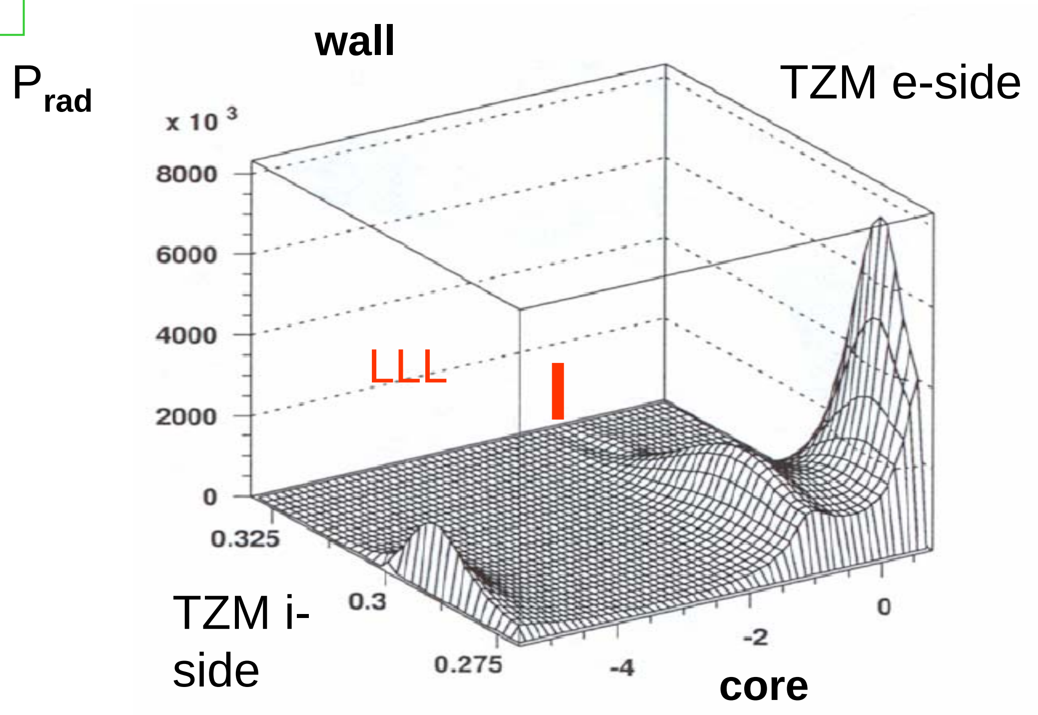
1.Liquid Lithium Limiter Experiment

Discharges with LLL

LLL inserted - modification of SOL parameters

#28568 - I_p=0.5MA,n_e=1.10^{20}m^{-3}, B_t=6T



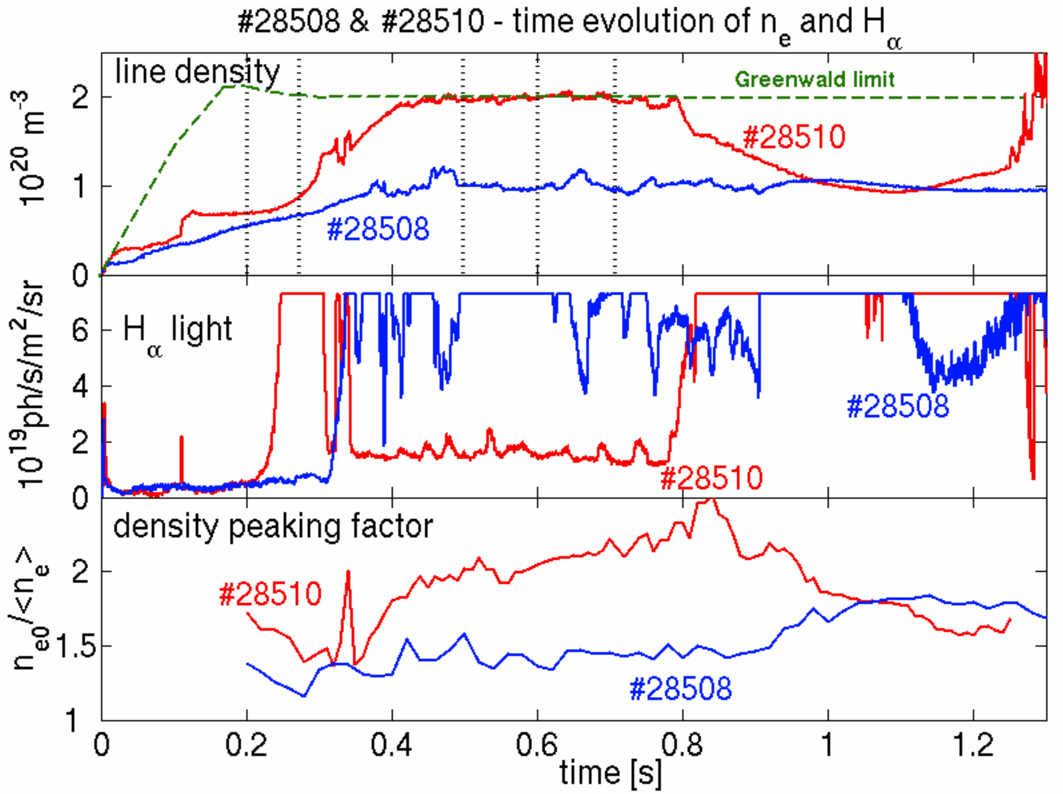


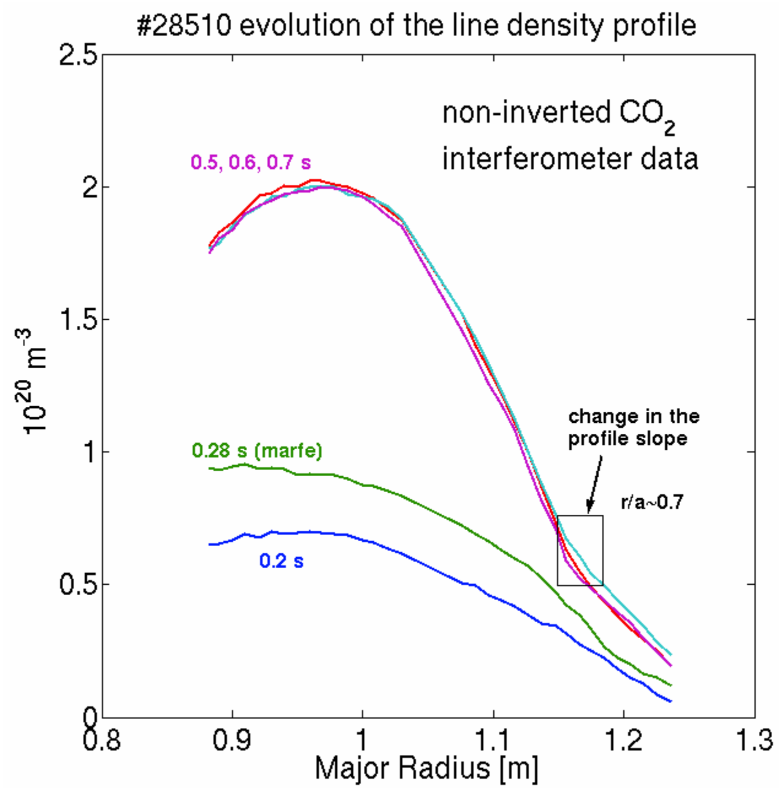
CCD camera view: the bottom brigth annular ring develops just in between LLL and TZM

3D sketch (TECXY) of P_{rad}

Most (60%) Li radiation (not in coronal equilibrium) in between TZM and LLL Strong interaction plasma - LLL => also density peaks in front of LLL => shorter λ_n

LLL inserted - modification of main parameters

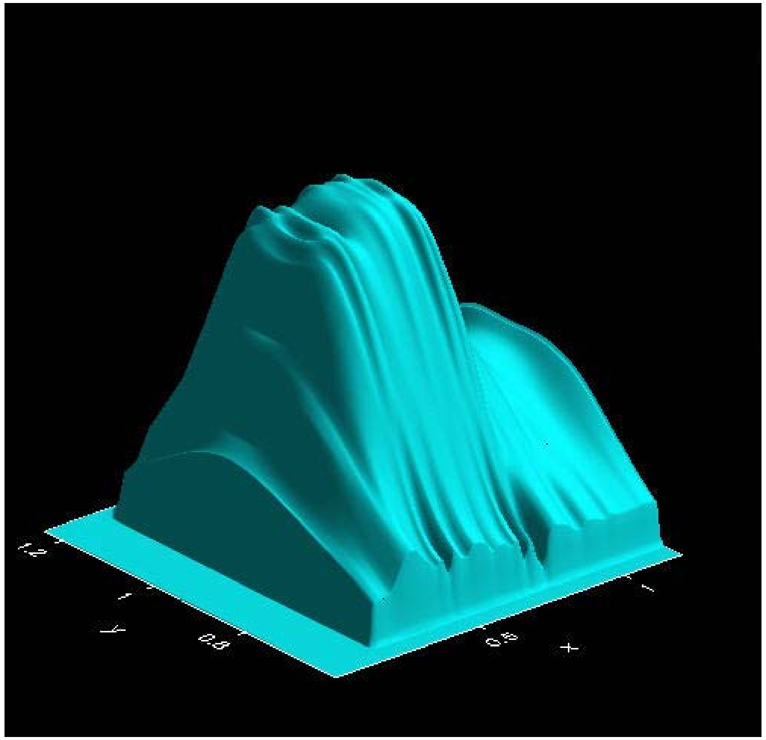




#28510: LLL inserted ~1.4 cm in the SOL:
MARFE desappears at 0.31 s - high particle confinament/high peaked density phase starts
#28508: LLL outside.

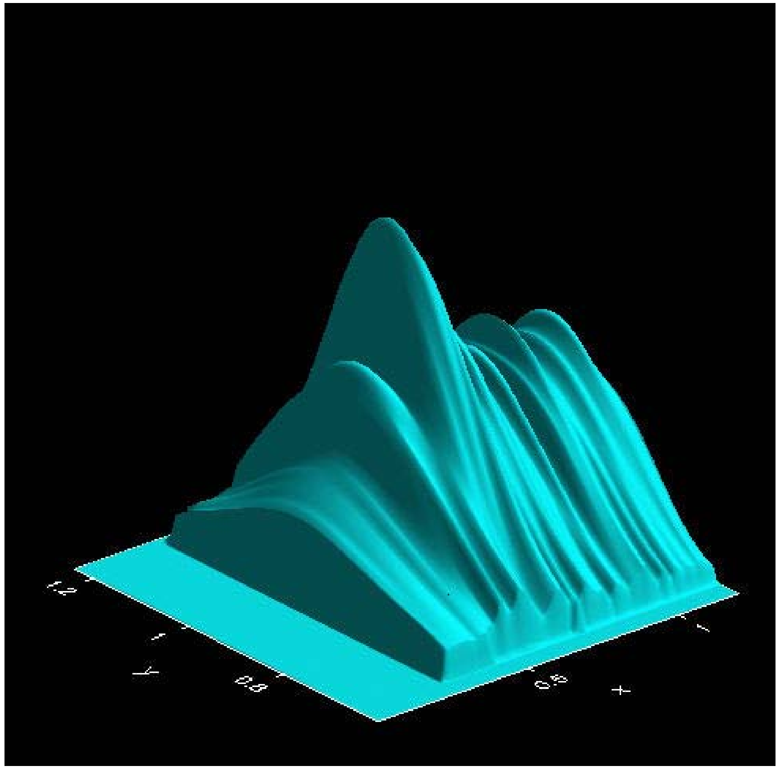
DENSITY BARRIER ??
Time of profiles at the vertical grey lines of the aside plot

Peaked density profiles

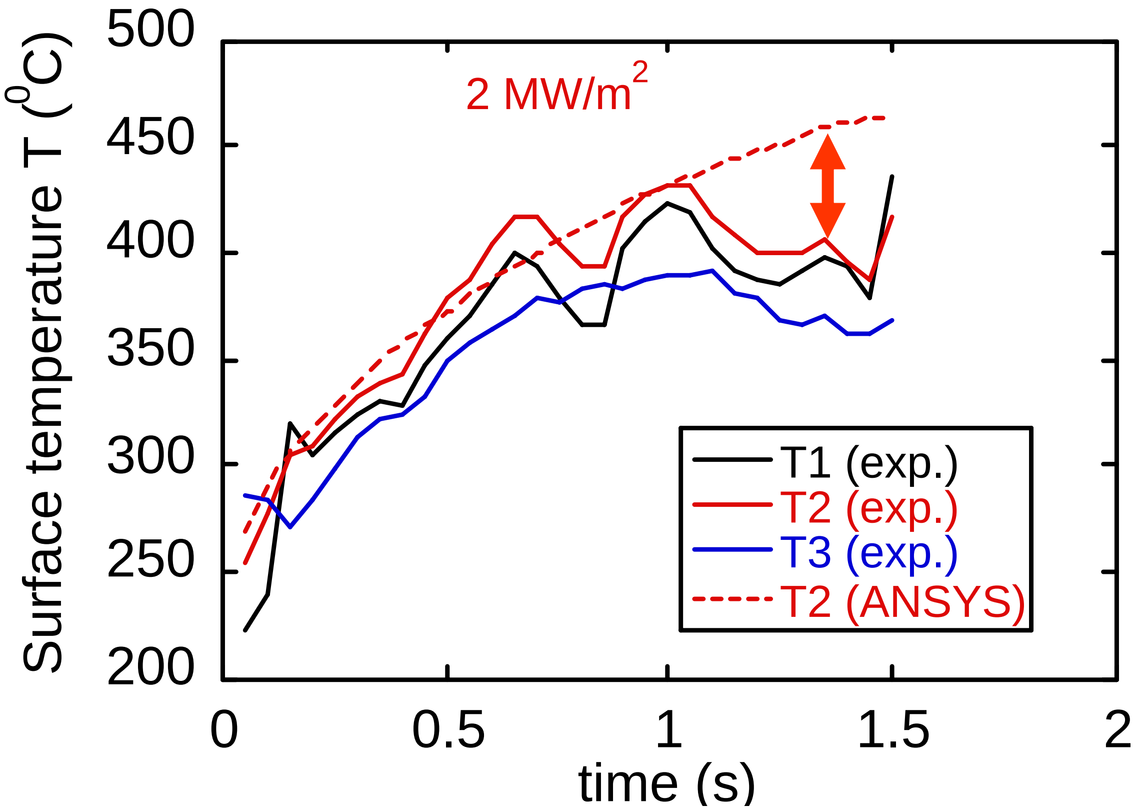


Shot 28510

Shot 30362 15/05/07



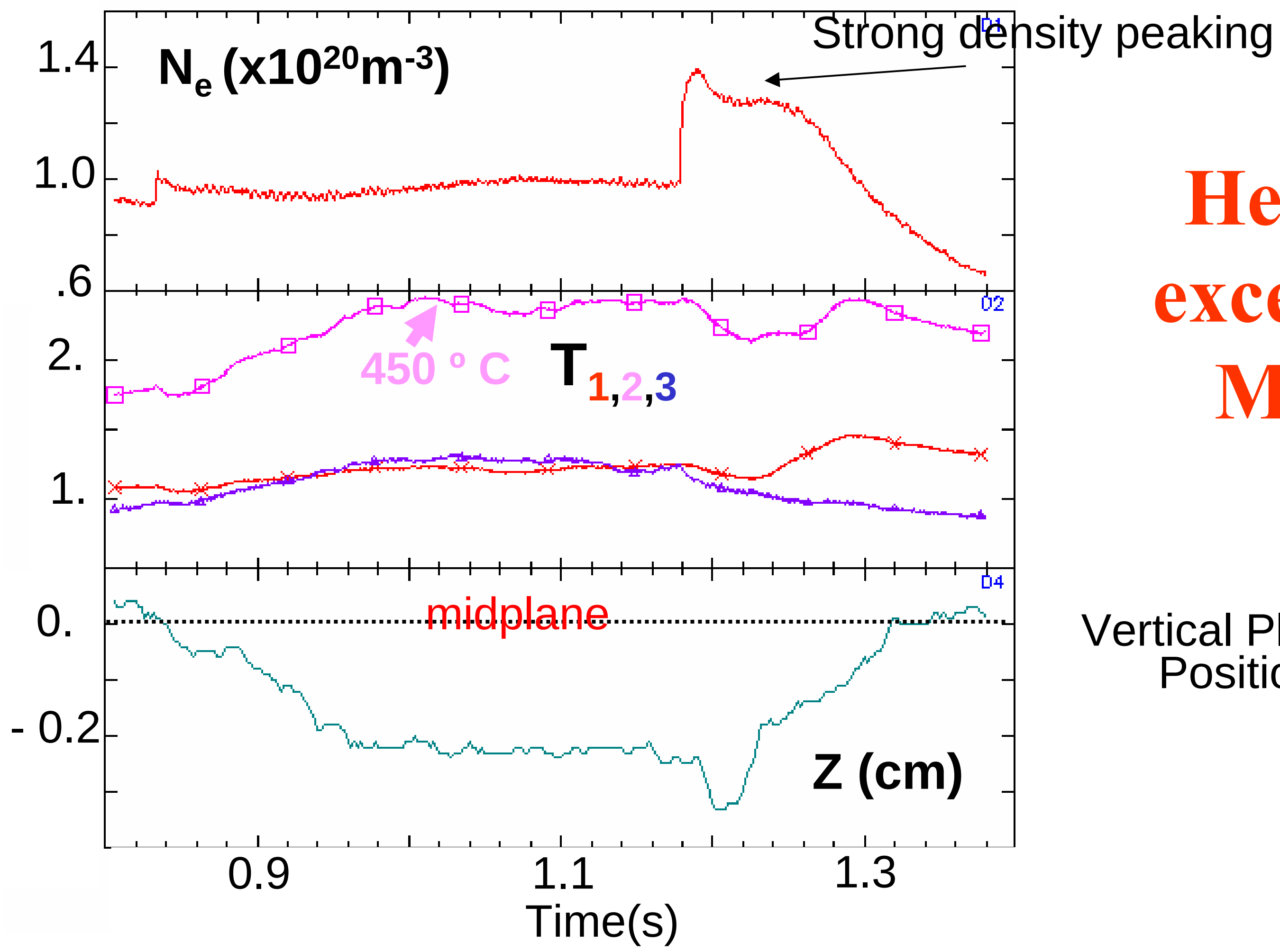
Thermal analysis



Surface temperature deviation from ANSYS calculation at about 1s is probably due to Li radiation in front of the limiter surface.

Calculation with TECXY code support this hypothesis

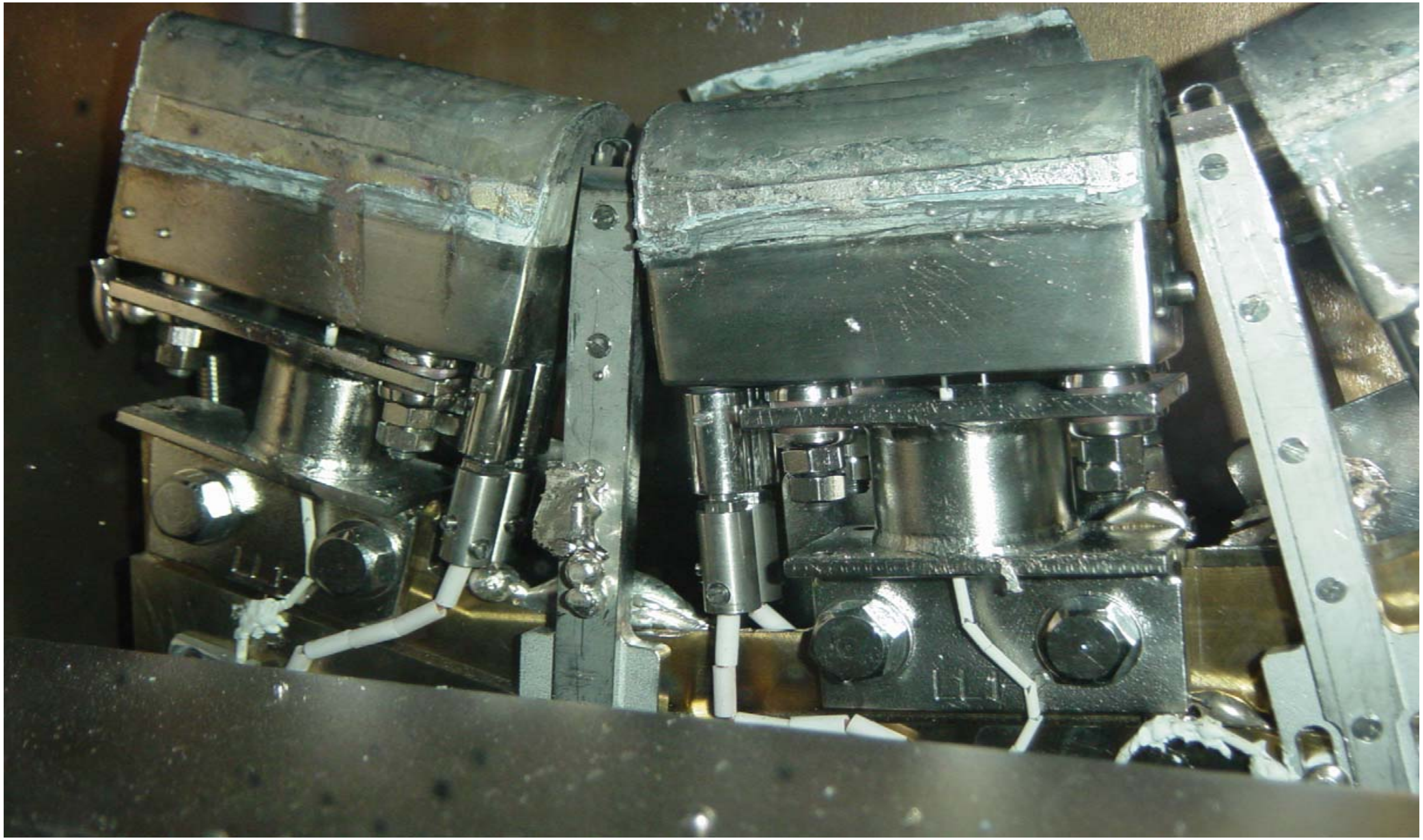
High capability to sustain high thermal loads



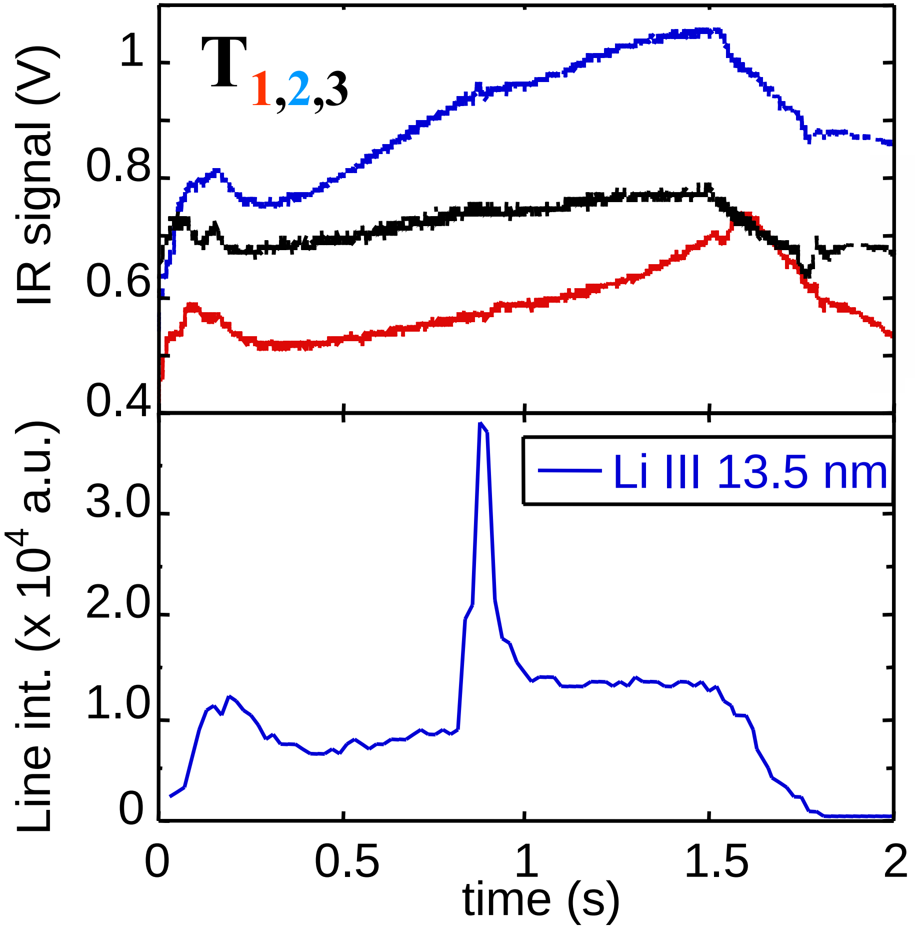
Heat load exceeding 5 MW/m²

Vertical Plasma Position

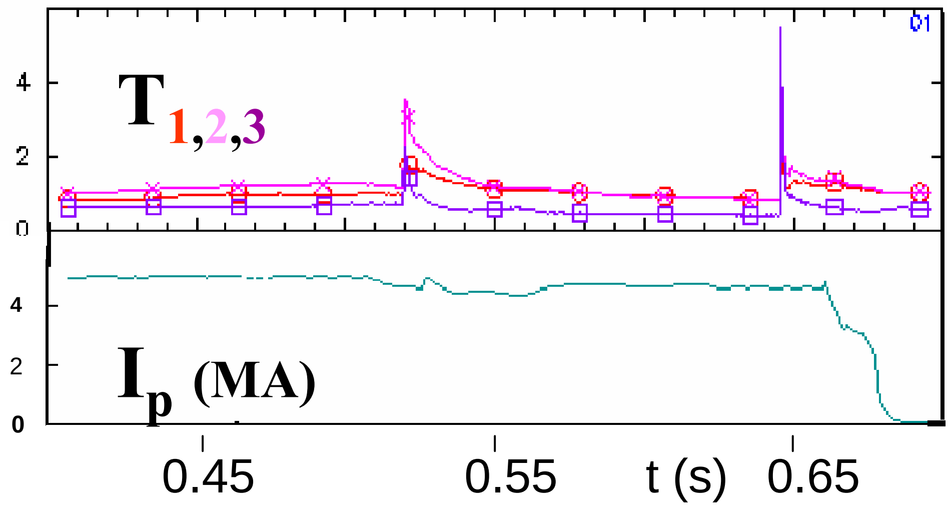
No Surface Damage of CPS Structure



Problems

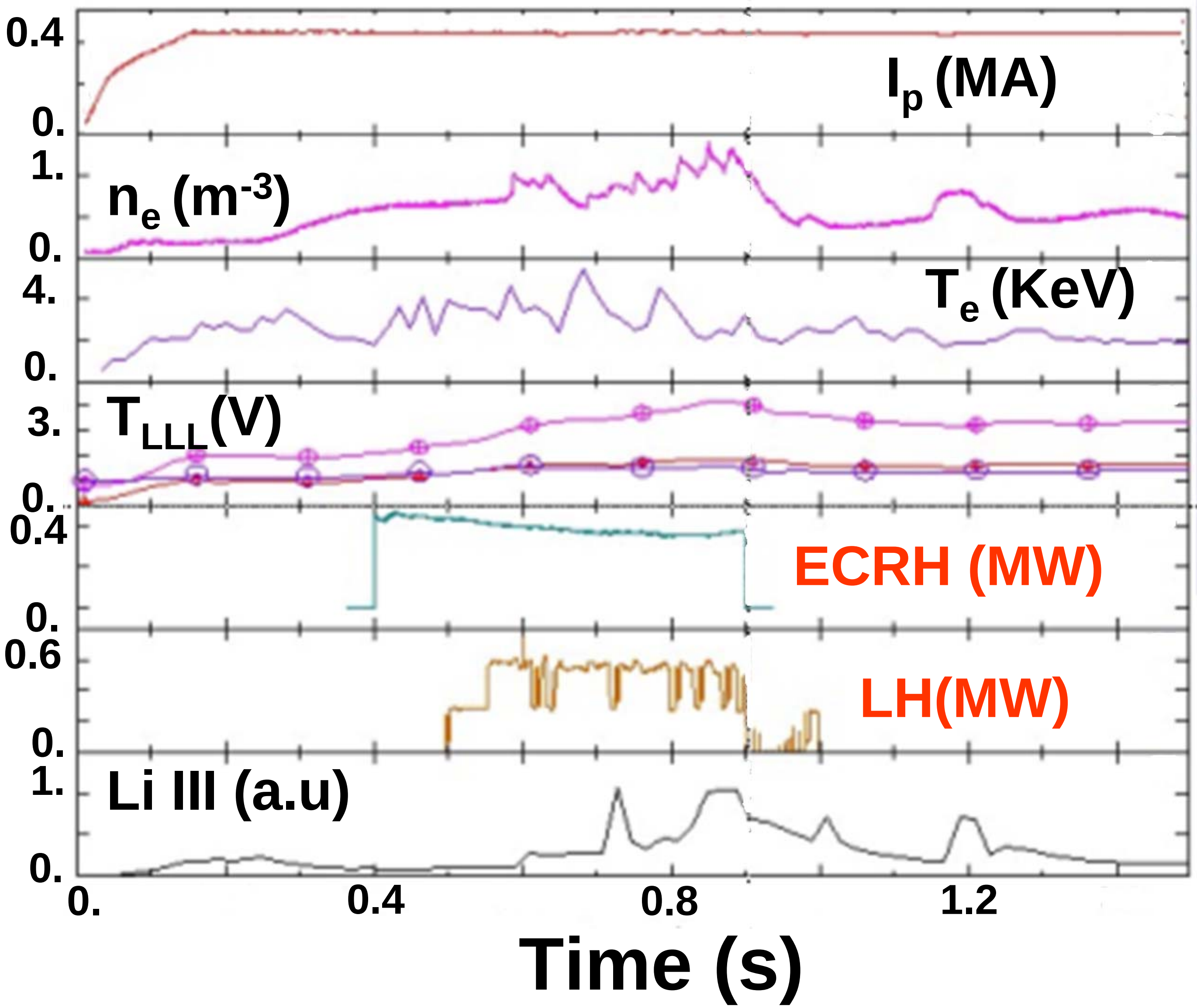


Unipolar arcs ?



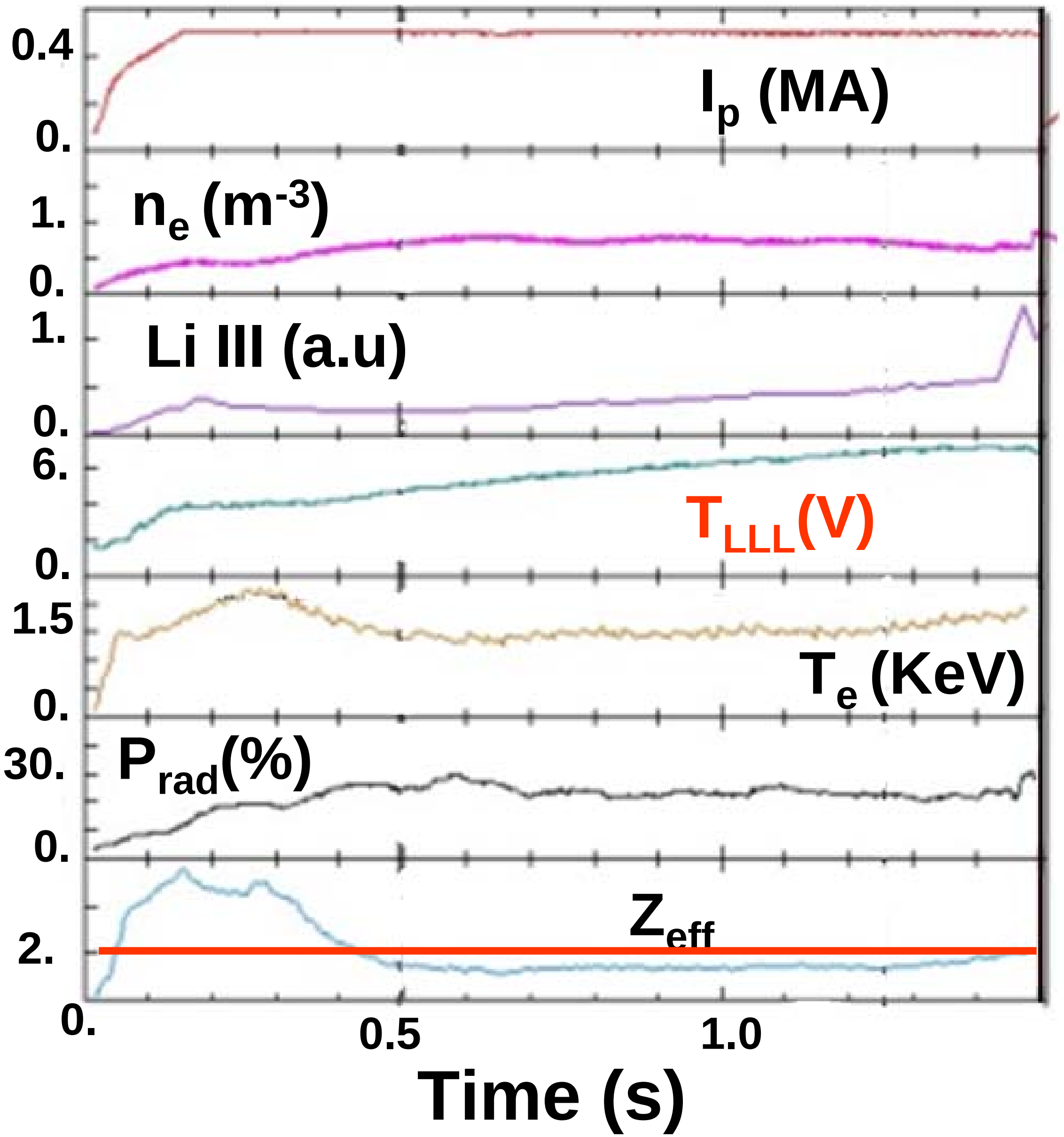
Temperature spikes, followed by a thermal decay, are correlated with plasma instabilities.

Discharge with additional Power



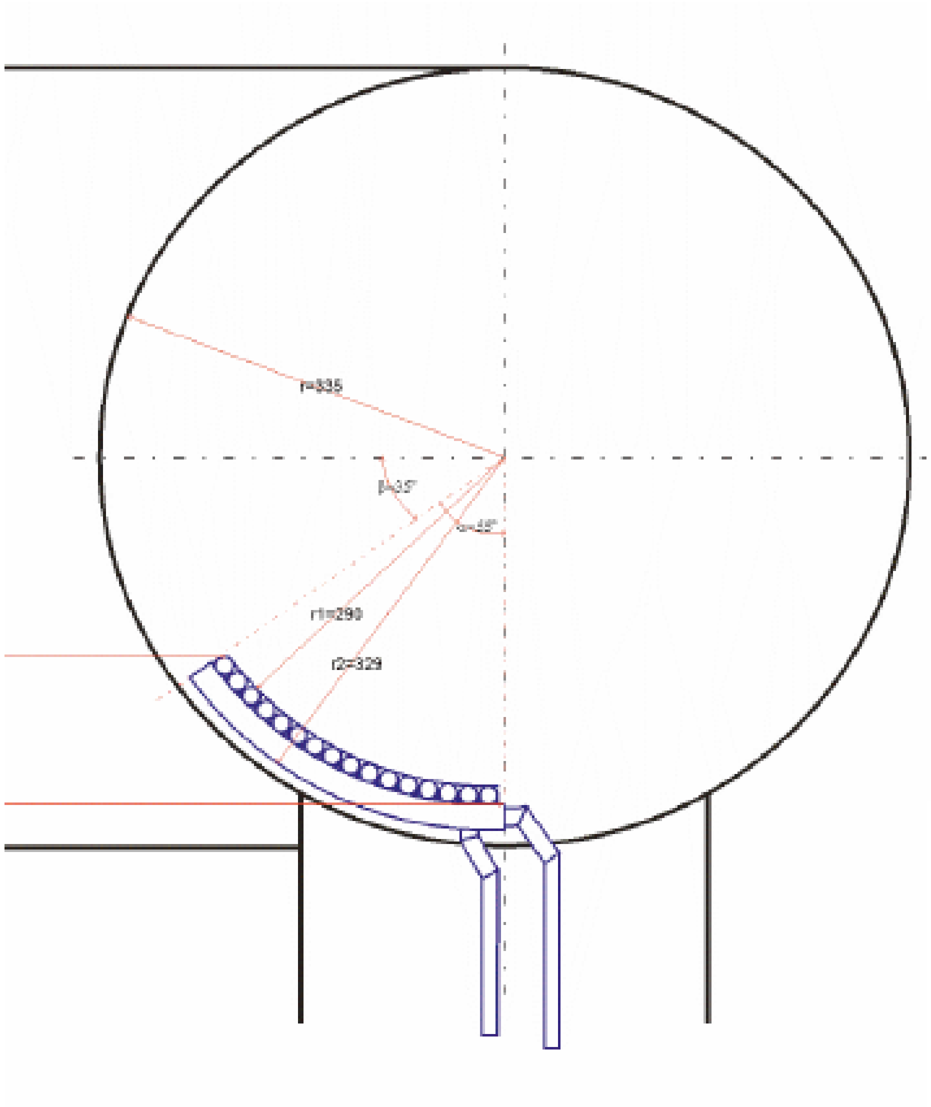
LLL 2cm from LCMS

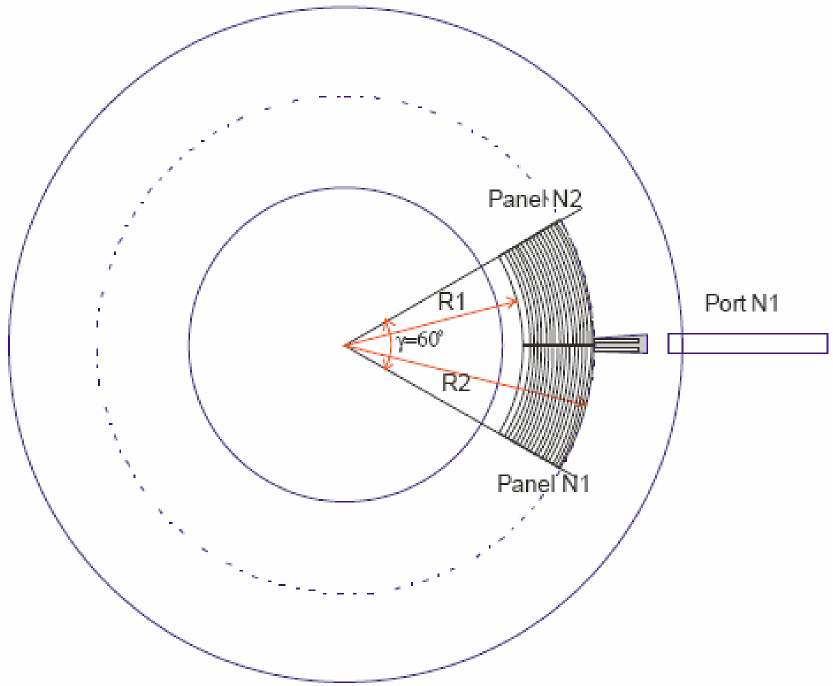
LLL less than 1 cm from LCMS



Max Temperature
LLL ~ 600 °C

Next Step : A new panel type liquid lithium limiter





Preliminary design

CONCLUSIONS

- **Lithization is a very good and effective tool for plasma operations**

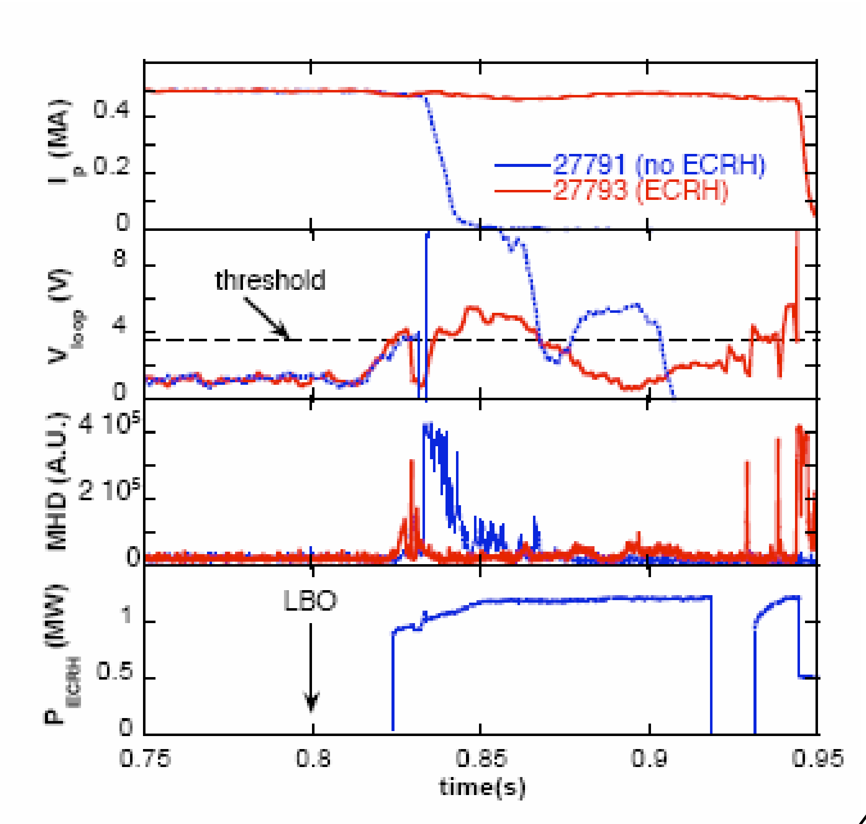
- **Exposition of a liquid surface on tokamak has been done on FTU with very promising results**

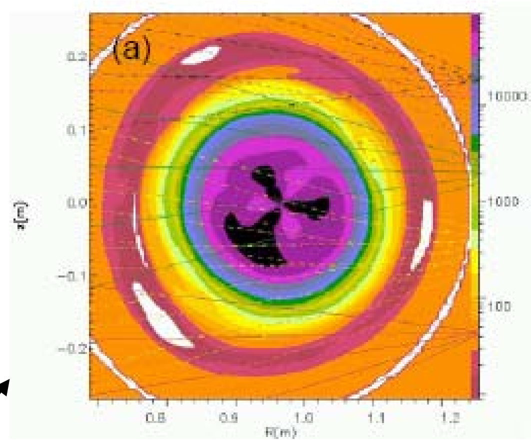
ECRH Disruption Mitigation on FTU

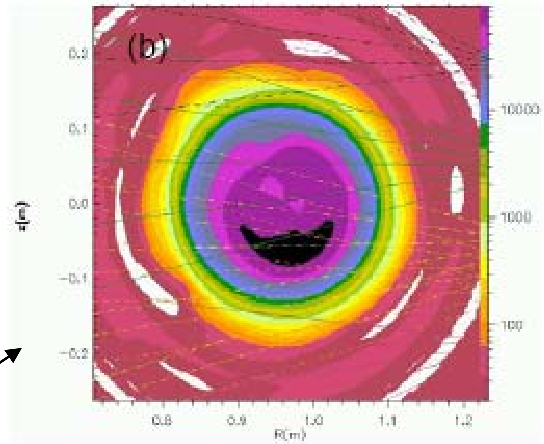
G. Granucci, B. Esposito et al., paper in progress

- **Disruption avoidance in FTU has been obtained by applying ECRH in both Mo injection induced and density limit disruptions.**
- **To avoid disruptions ECRH has to be injected in correspondence of the location of q surfaces q=1-3/2-2 as inferred by MHD analysis**

ECRH Disruption Mitigation on FTU

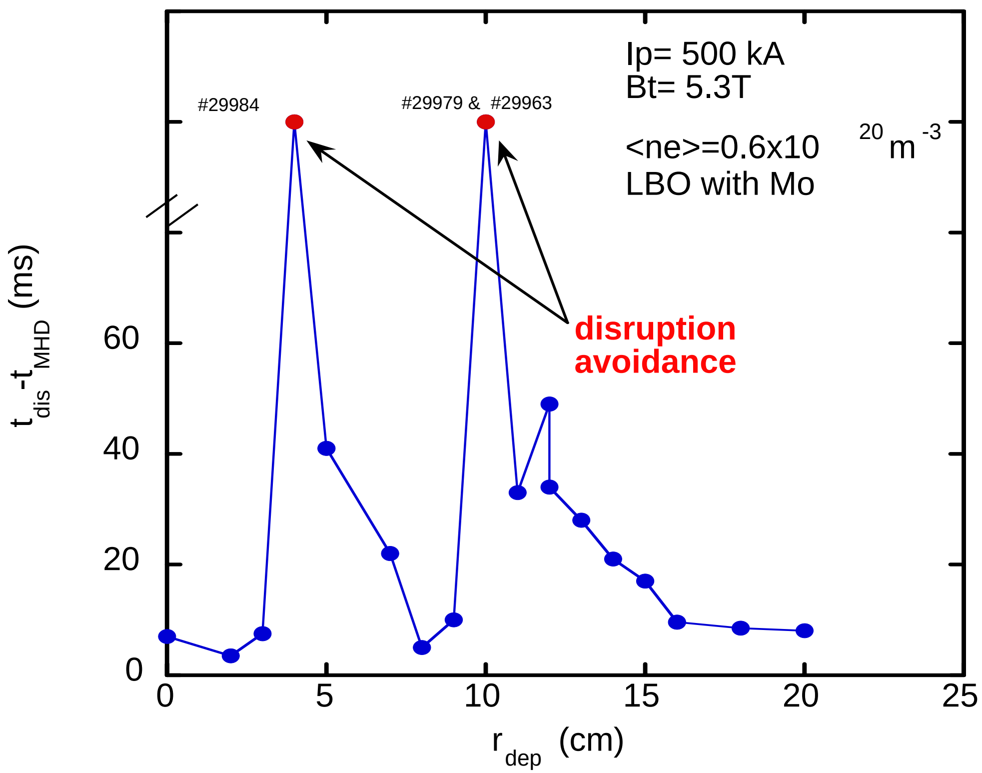






Tomograms: **(a)** #27791 t=0.8308-0.8314;
(b) #27793 t=0.8293-0.8296 s.

ECRH Disruption Mitigation on FTU



Lithized Wall (October 2006)

- **ECRH Deposition scan by poloidal steering**
- **Power from 2 gyrotrons ≈0.75 MW sufficient to stabilize disruptive modes**
- **Disruption avoidance occurs at 2 locations:**
  r_{dep}=4 cm →q=3/2
  r_{dep}=10 cm →q=2
- **Detailed analysis on-going**

Dust measurement by Thomson Scattering in FTU

- **The FTU Thomson scattering diagnostic has been used to measure the density and size of dust particles following plasma disruptions [1].**

- **A dust density of the order of 10^7 m^{-3} has been found.**

- **The Rayleigh approximation was used to determine the particle size, which is of the order of 0.1 μm and less.**

[1] Evidence of dust in FTU from Thomson Scattering diagnostic measurements
E. Giovannozzi, C. Castaldo, G. Maddaluno, Proc. 33rd EPS Conf. (Roma 2006) vol. 30I(ECA) (2006) P-2.093

Dust measurement by Thomson Scattering in FTU

- The detection system consists of 19 polychromators, each of them being provided with 5 spectral channels.
- Four channels are used during the discharges to measure Thomson scattered light; the last one is used for alignment and the spectral transmission of its filter is centred at the laser wavelength.
- Therefore, this channel can be used to detect elastic light scattering, which might be due to the presence of dust particles

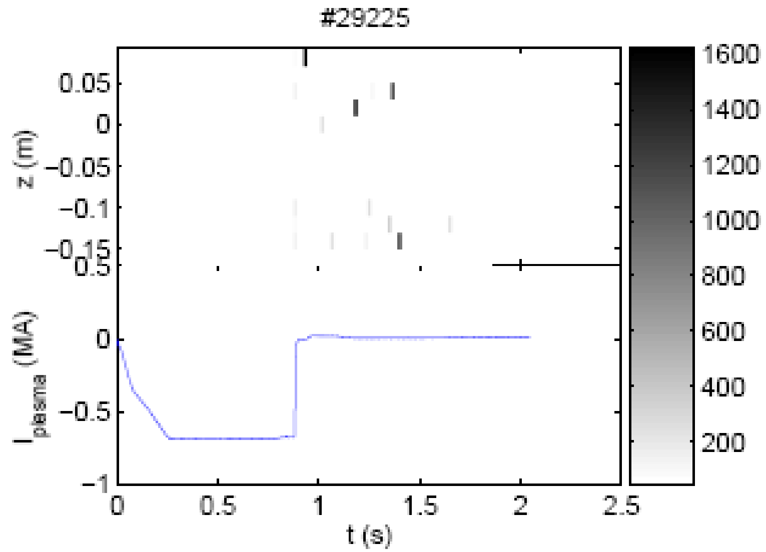


Figure 1: Intensity of the signal in counts from channels at the laser wavelength together with the plasma current signal, showing no dust is present before the disruption.

Dust measurement by Thomson Scattering in FTU

- Only 7% of the examined discharges have not any dust following a disruption, even though for a large majority of the discharges (70%), the dust is detected in less than 10% of the about 30-60 laser pulses following a distruption (Fig. 2).
- The dust content following a disruption is decreasing with time (see the number of dust particles in the first 0.5 s and and between 0.5 s and 1.0 s after a disruption).

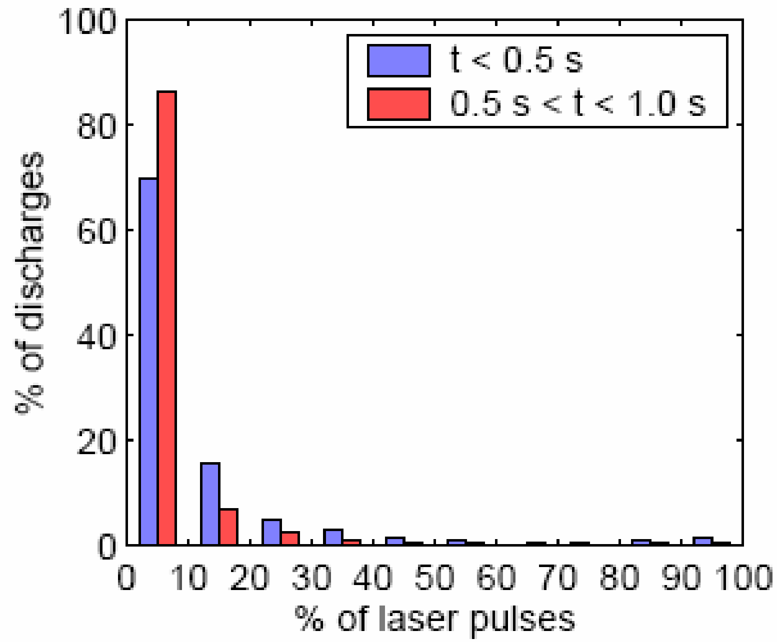
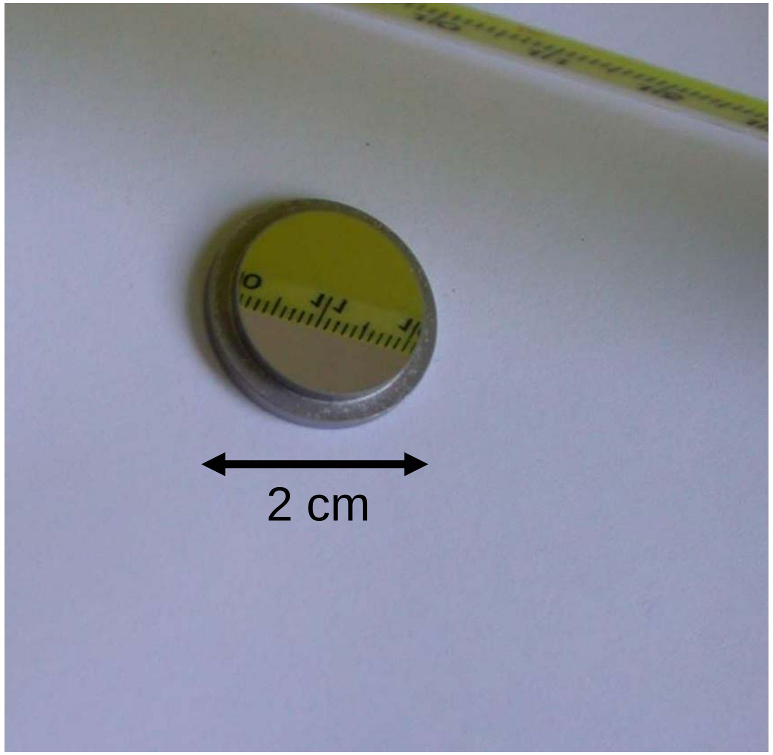


Figure 2: Percentage of discharges versus percentage of laser pulses detecting a dust particle

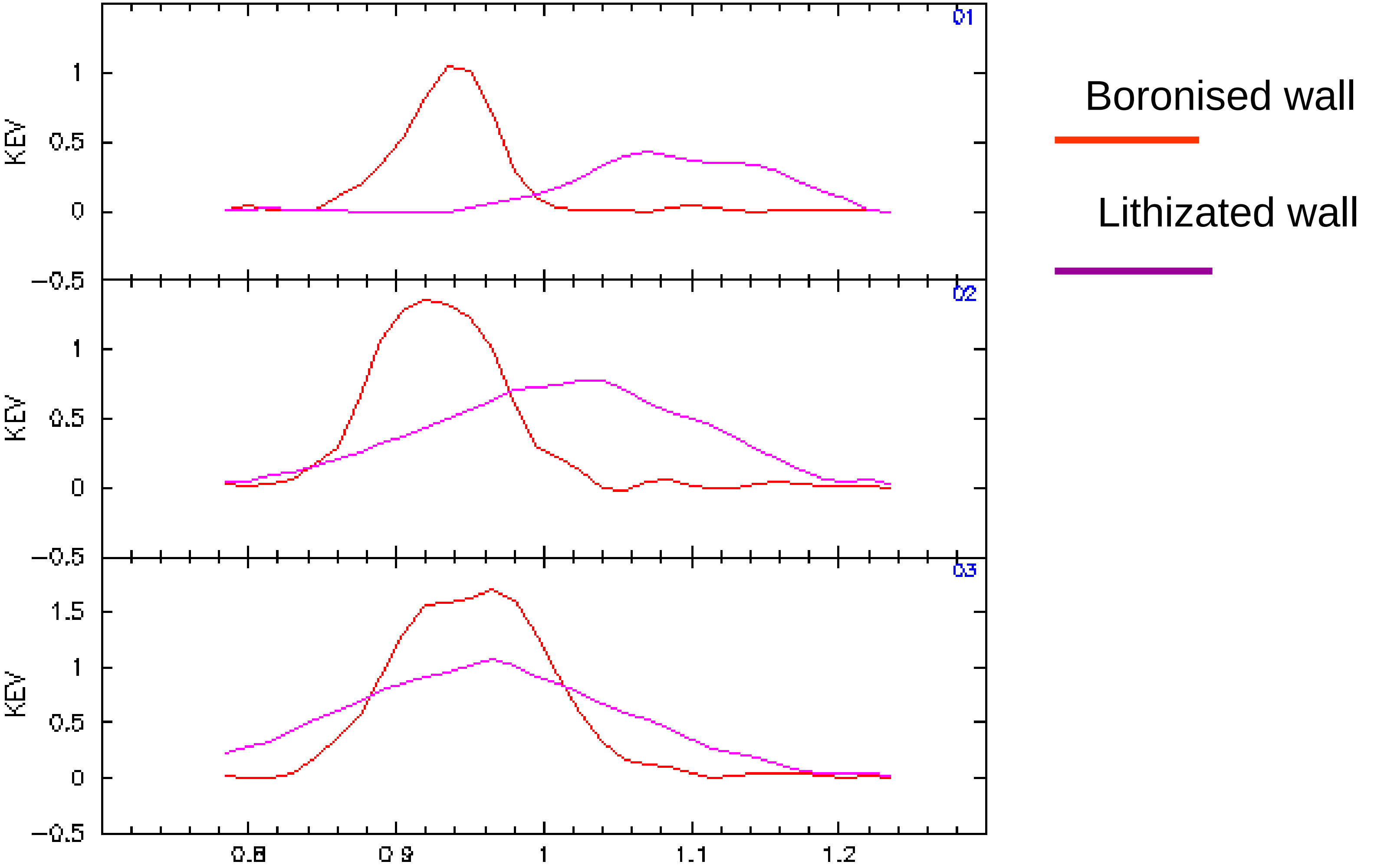
Rh-coated Mo mirrors

- In the framework of TW5-TPDS-DIADEV EFDA Task, Rhodium mirrors with Molybdenum substrate have been produced by using electrodeposition.
- Thick coating of Rh (> 1μ) was obtained
- Surface as well optical characterization has been done.
- The mirror(s) will be exposed in the TEXTOR scrape-off layer for monitoring the changes of optical properties under plasma flux.




011294
Thank you for your attention

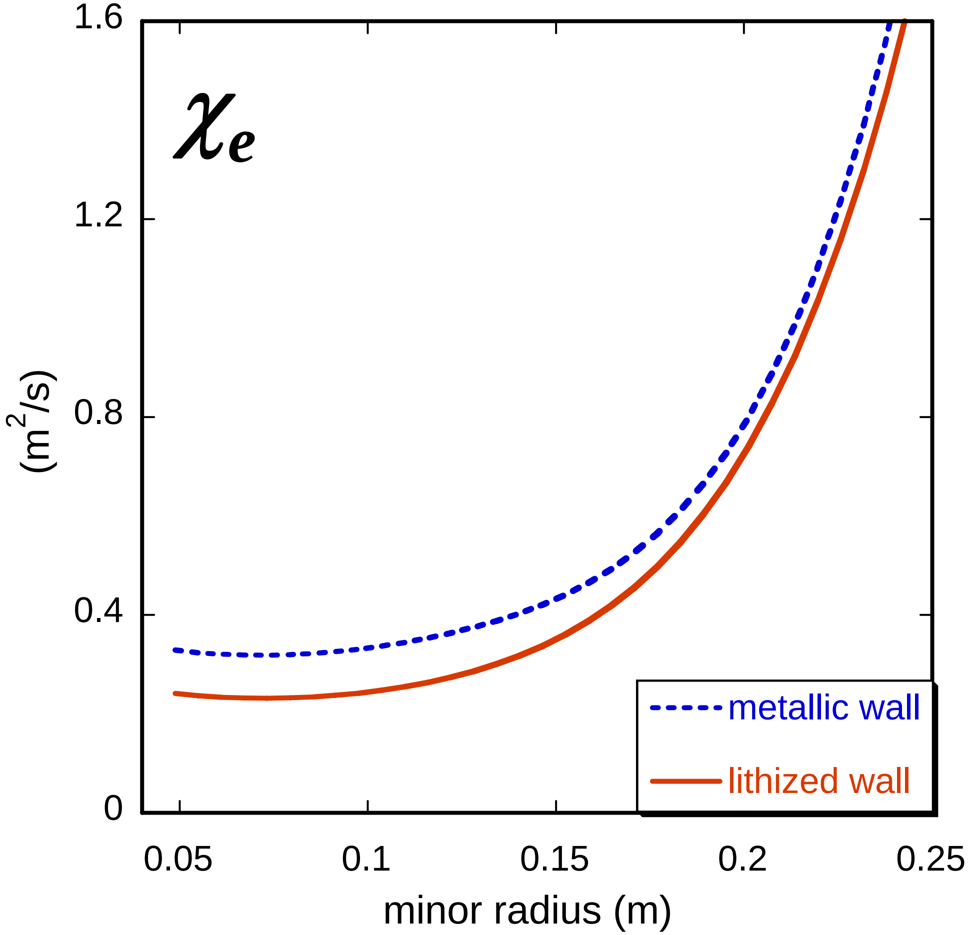
Broader temperature profile at the start-up



Improved Ohmic Density Limit

I_{p}, B_t Greenwald limit	0.5MA, 6T $1.9x10^{20}$ m^{-3}	0.7MA,6T $2.6x10^{20}$ m^{-3}	1.1MA, 7.2T $4.1x10^{20}$ m^{-3}
With B Coating	$2.0x10^{20}$	$2.0x10^{20}$	$3.2x10^{20}$
Metallic Wall TZM+SS	$2.0x10^{20}$	$2.4x10^{20}$	$3.2x10^{20}$
With Li coating	$2.7x10^{20}$	$2.7x10^{20}$	Next Campaign

Electron thermal diffusivity



Electron thermal diffusivity is significantly lower for the **lithizated** discharge with respect to the **metallic** one

Lithium

- Isotopic Abundances

  ^{6}Li 7.59%

  ^{7}Li 92.41%
- Melting point

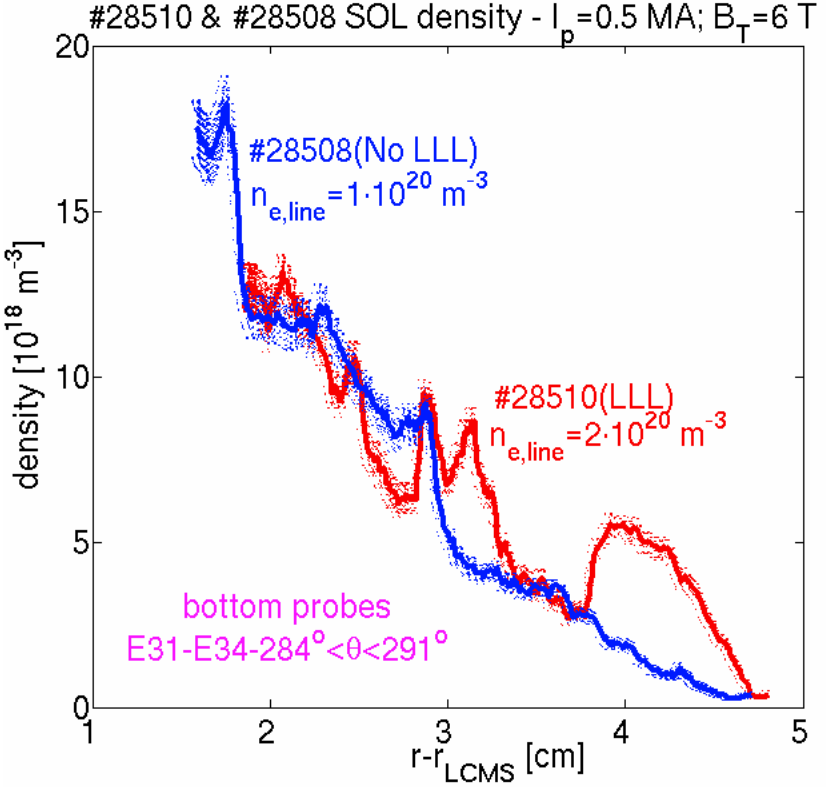
  180.54 ° C
- Boiling point

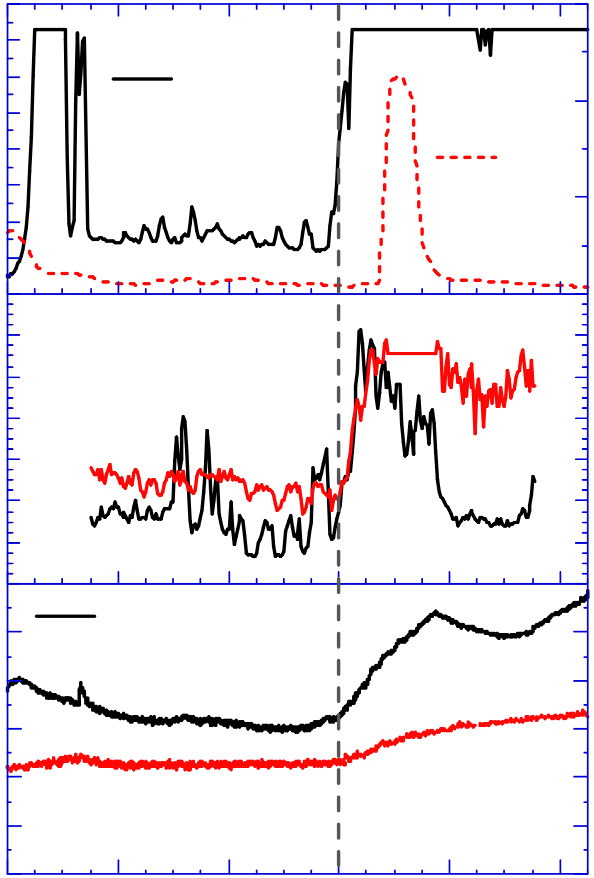
  1342 ° C
- Nuclear Reactions

  $^{6}Li + n \rightarrow T + \alpha + 4.8$ MeV

  $^{7}Li + n \rightarrow T + \alpha + n' - 2.87$ MeV

LLL inserted - modification of SOL parameters





Despite the large change in $\bar{n}_e$ (~2× in #28510) $n_{e,SOL}$ is little affected due to much reduced recycling and in turn of the transport. Also $T_e(r)$ are very similar

$$\mathbf{n_{e,SOL} \propto (\bar{n}_e/f_{pk})^{1.36} \sim 1.7}$$

High confinement termination

LITHIUM DETECTION

LITHIUM REACTS WITH WATER GIVING A BASIC SOLUTION:

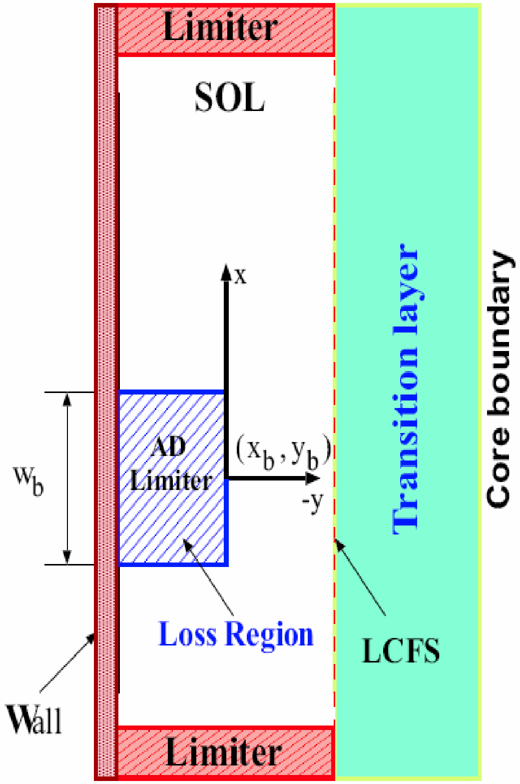
$$2Li(s,l,g) + 2H_2O(l,g) \rightarrow 2LiOH(aq,g) + H_2\ (g)$$

USING A A WHITE CLOTH IMBUED WITH A SOLUTION OF PHENOLPHTHALEIN (ACID-BASE INDICATOR) WE CAN DETECT LITHIUM DROPS BECAUSE THE SOLUTION TURNS FROM COLORLESS(ACID-NEUTRAL SOLUTION) TO RED (BASIC SOLUTION) IN PRESENCE OF LITHIUM.

The TECXY code (shortly)

TECXY: 2D multifluid code, extension of EPIT

- *Background plasma*: Braginskij-like equations
- *Impurity ions*: rate equations - all Z states ($T_{Z,all}=T_i \neq T_e$)
- *Neutrals (cold and CX)*: analytical description of recycling and sputtering and self-sputteringat the limiter surface
- *Drift motions and currents* considered self-consistently
- *Real curvilinear geometry* of the boundary layer
- *Global ambipolarity* of the radial electric current in the transition layer inside LCMS ensured
- *Parallel transport*: classical, coefficients from 21-momen Grad approx.
- *Radial transport*: anomalous, assigned coeff. ($\sim D_{bohm}$)



Latest modifications: possibility to treat simultaneously few different impurity species (e.g. Mo+Li) (but without drifts)

TECXY modeling

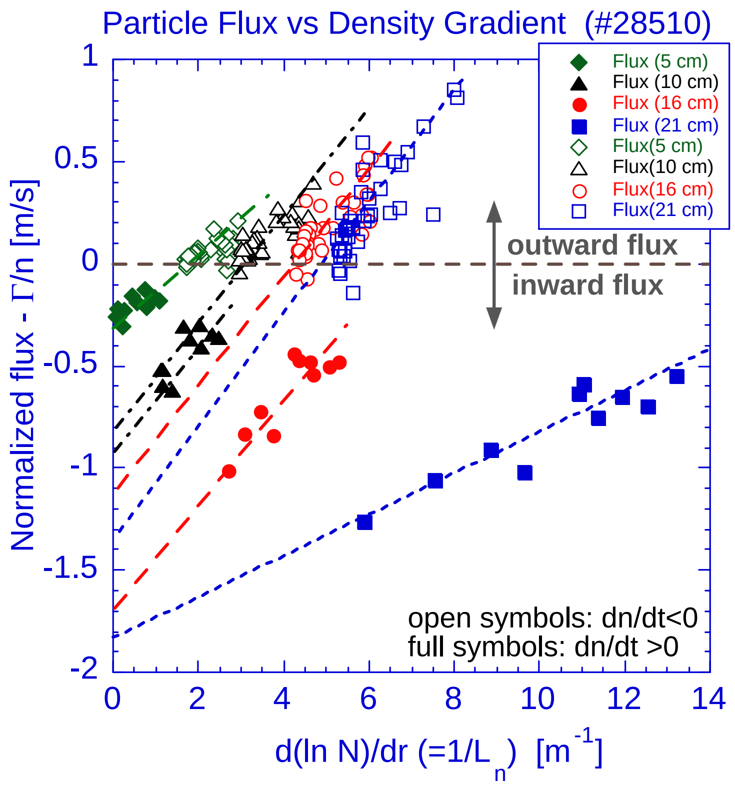
Metallic walls - very good agreement

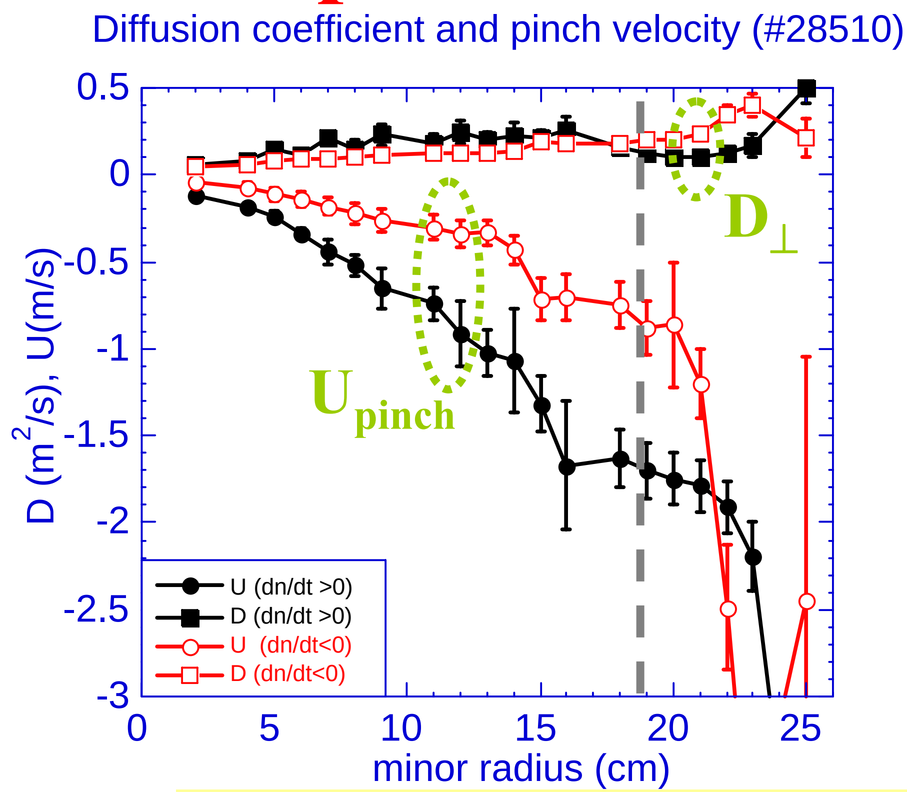
$D_\perp$=0.5 m^2/s, R(recycling coeff) =0.75 , typical for FTU; input particle flux, $\Gamma_{inp}=1.1\cdot10^{21}\ s^{-1}$, consistent with FTU-SELF code (0D core model+two-points edge model). T_e maintained quite low by the high cooling rate of the sputtered Mo ions

Lithized walls - agreement: $n_e(r)$ very good, $T_e(r)$ good at LCMS

Essential: i) highly reducing recycling (R=0.02), due to the strong pumping of the Li film; ii) retaining a small Mo content (not fully coated TZM limiter) otherwise T_e too high. $D_\perp$=0.5 m^2/s (unchnaged); $\Gamma_{inp}=5\cdot10^{21}\ s^{-1}$. $\chi_{e\perp}$ little affects T_e profiles mainly determined by $\chi_{e||}$ and R.

LLL inserted - modification of the edge particle transport

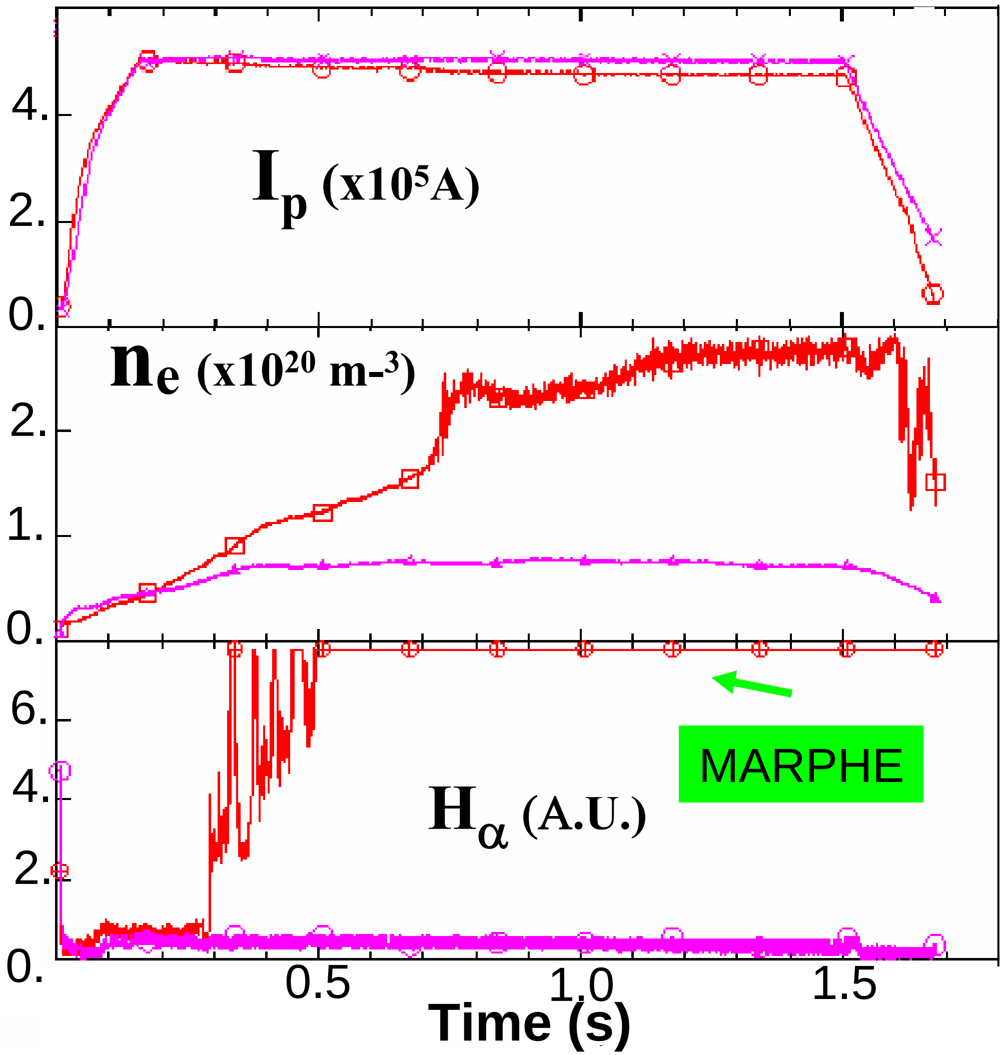




$$\partial N_r/\partial t = -\Gamma_r \implies$$
$$\partial N_r/\partial t = (D_\perp \cdot \partial n(r)/\partial r - n(r)\cdot U)\cdot \Sigma_r$$

Only in the outer region, where the $n_e(r)$ slope suddenly changes (fig. 6) the two quantities both vary towards reducing outward transport

Strong D_2 pumping capability



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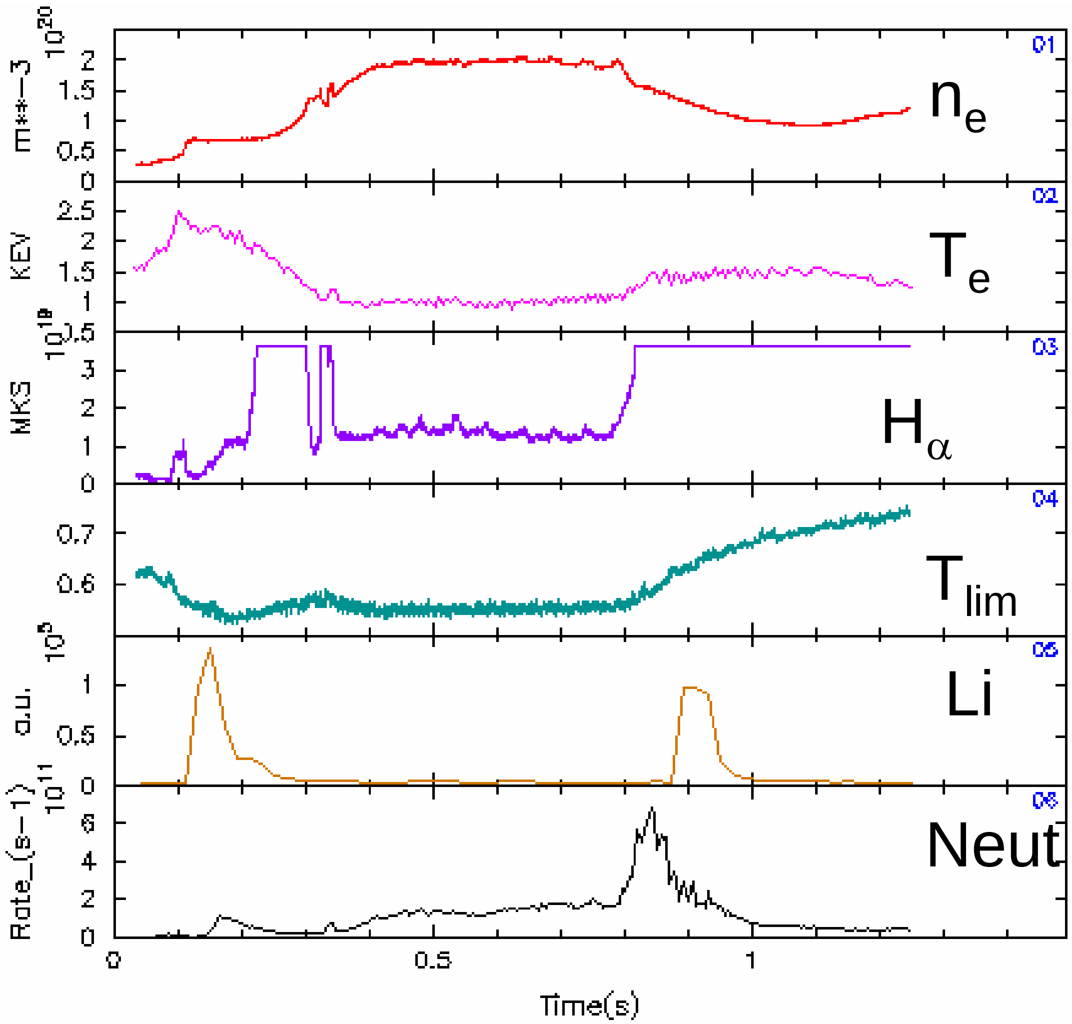
Very good density control was obtained

Stable operations at very low density ($0.15 \times 10^{20} m^{-3}$), never reached before on FTU, were performed

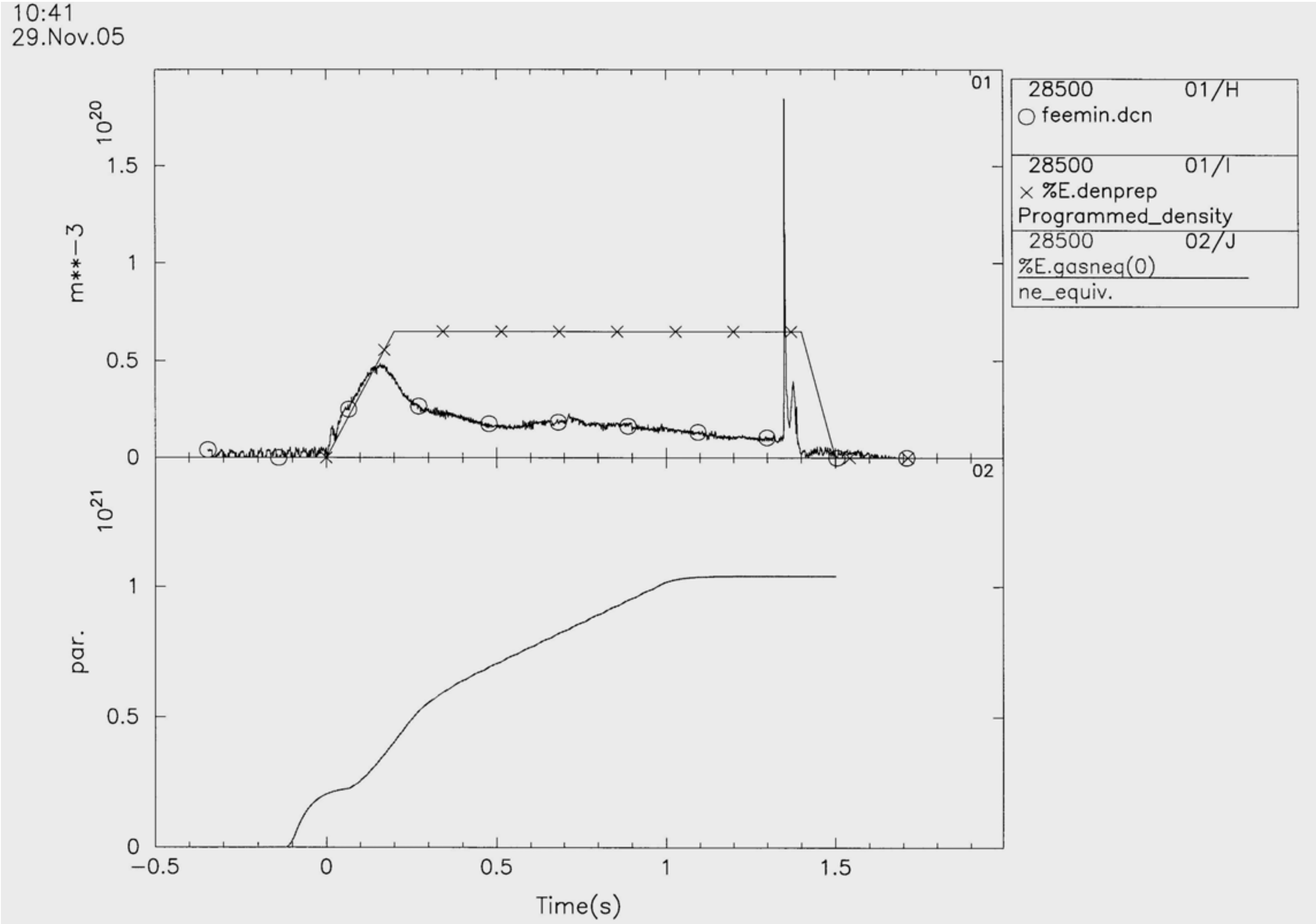
Peculiar discharge

Ip=0.5MA, BT=6T
28510
limiter Li at + 1.0cm

Electron density profile is peaked and H emission is strongly reduced at the edge



Plasma density behavior without density feedback



Main parameters for Li limiter

• Total area of Li surface	~100 cm^2
• Effective plasma interaction	~ 50-60 cm^2
• Li volume in limiter	~170 cm^3
• Li weight	~80 g
• Capillary pressure	~ 10^5 Pa
• Relative mass change on one shot	~10^{-4}

Dust measurement by Thomson Scattering in FTU

- The Mie Scattering theory is used for analyzing the particle size; the perpendicular scattering cross section for a small particle is:

$$\sigma = \left(\frac{2\pi}{\lambda}\right)^4 a^6 \frac{n^2-1}{n^2+2} \cong \left(\frac{2\pi}{\lambda}\right)^4 a^6$$

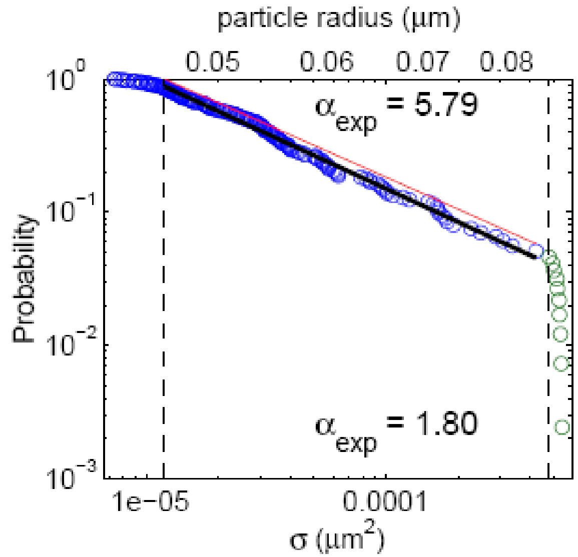


Figure 3: Experimental cumulative distribution function of the particle cross sections and radii using the Rayleigh approximation in the central spectrometer.