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High density and high neutral particle pressure in the divertor for steady state operation in LHD

Second Technical Meeting on Long-Pulse Operation of Fusion Devices

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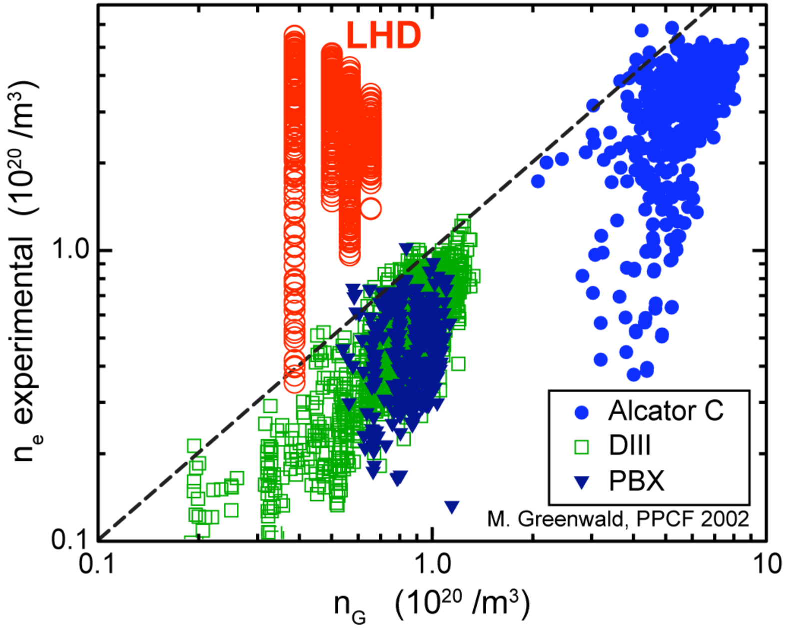
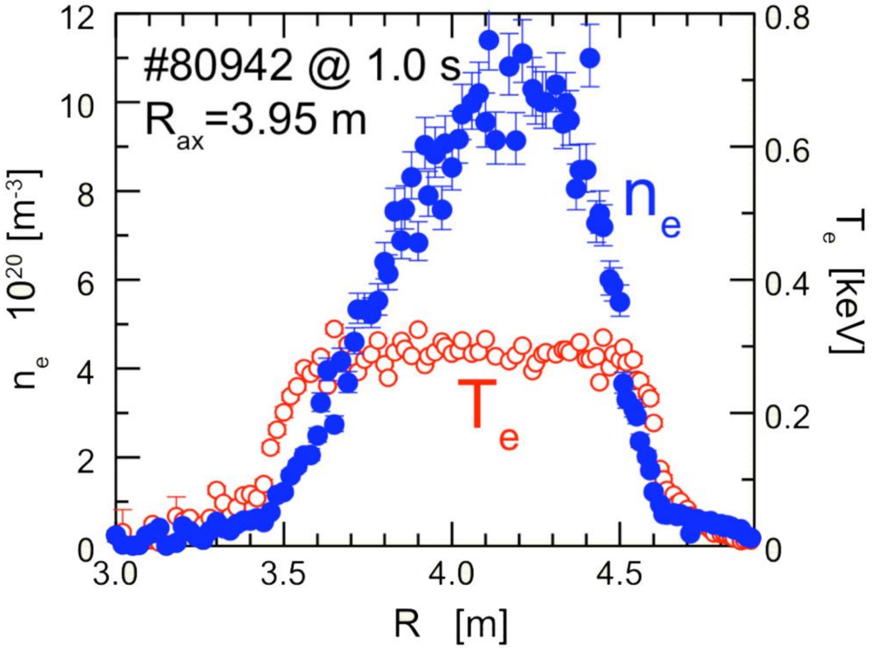
Stellrartor/Heliotron devices can be operated in much higher density regime than tokamaks

Super Dense Core (SDC): High-density improvement mode in LHD

M. Greenwald, PPCF 2002



N. Ohyabu+, Phys. Rev. Lett. **97** 055002 (2006).



- The maximum attained central density is > 1×10^{21} m^{-3}.
- Central pressure exceeds atmospheric pressure.
- Low density mantle plasma prevents radiation collapse
- Attainable density is restricted as follows.
  - Lack of central heating power due to high density
  - Pellet cannot ablate effectively at low temperature plasma (<300 eV)

High density in LHD

Actuator

Mag. config.

Fueling

Boron powder

Physics

Thermal Instability

Turbulence

MHD Instability

Fast ion

Results

Radiative collapse

Core Density Collapse

Associated

Neutral compression

Hα measurement

Introduction

Why are high sub-divertor pressures important?

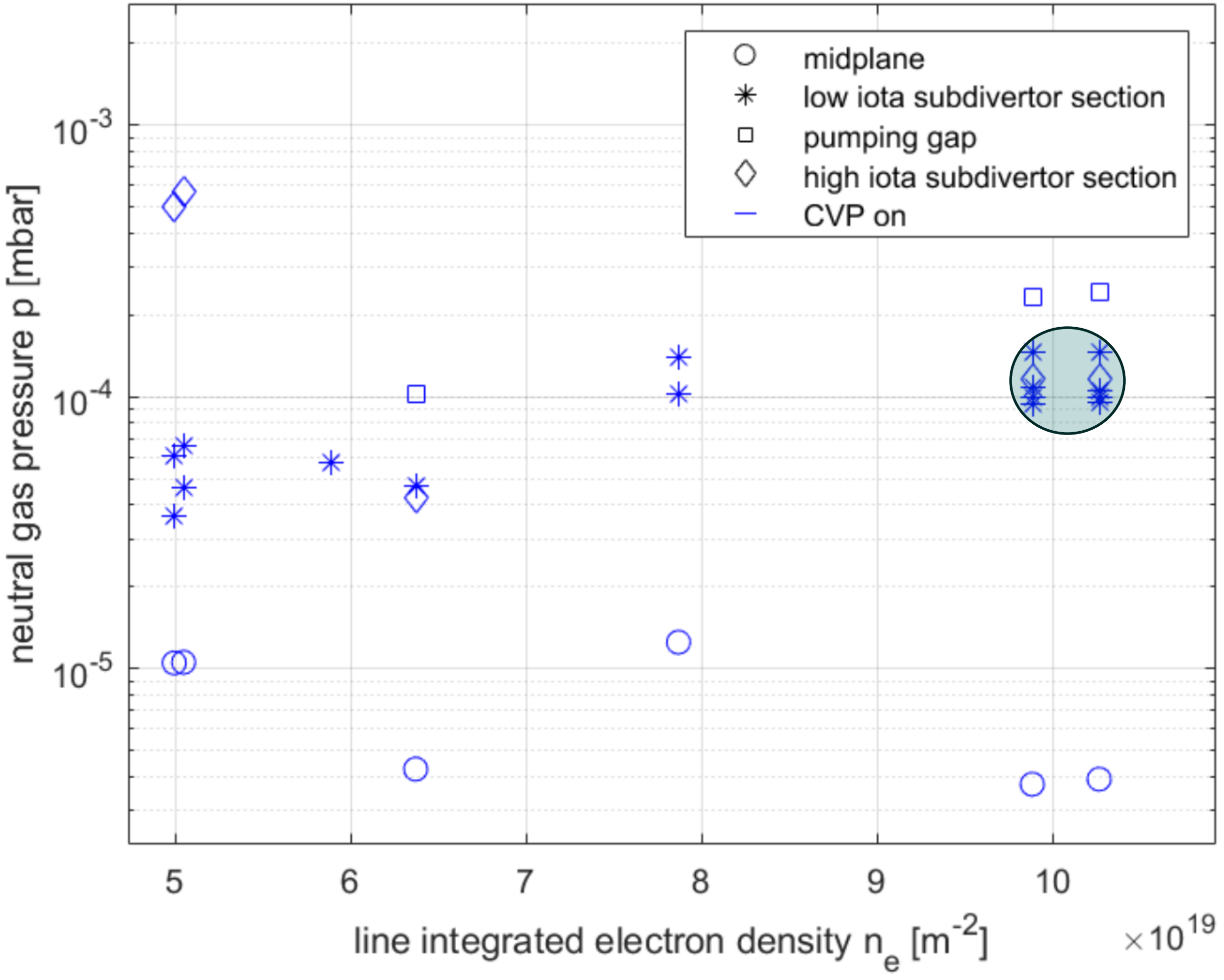
1) One needs high divertor pressures for good particle exhaust which is **S_{eff} * p_{div}.**

2) In general, stellarators have only low pressures. In Wendelstein 7-X about 0.01 Pa in the last campaign (see the stars in the figure).

3) Tokamaks are superior in this respect. In ASDEX Upgrade up to 5 Pa was obtained, for ITER up to 20 Pa is predicted.

Therefore, it is important to understand how to obtain high sub-divertor neutral pressures and good particle exhaust in stellarator divertors.

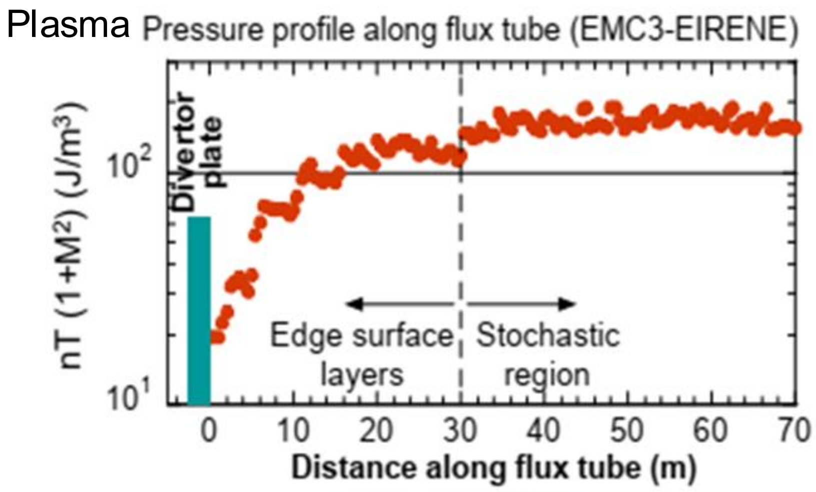
Wendelstein 7-X

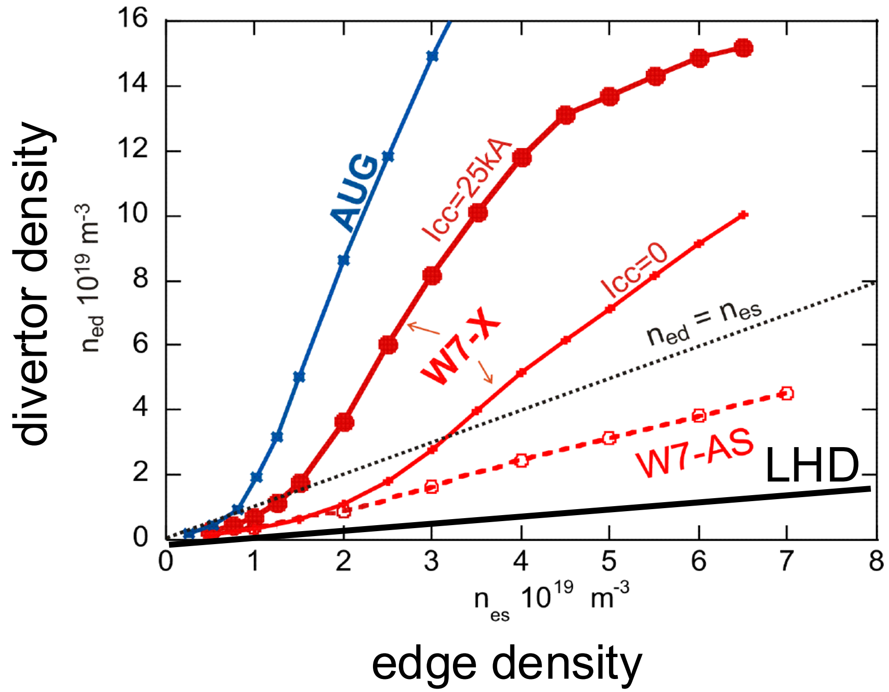


V. Haak et al., FED 2024

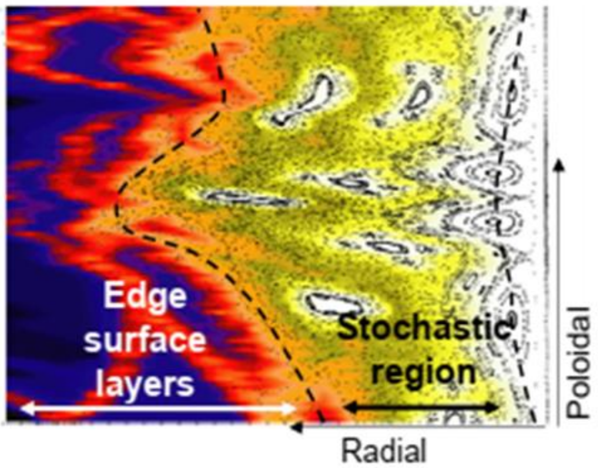
Why low neutral pressures in a stellarator divertor?

The rather low sub-divertor pressure (0.01-0.1 Pa) is **due to low divertor density** (absence of high recycling regime) ← loss of pressure conservation along flux tubes due to enhanced cross-field transport (3D effect) (M. Kobayashi 2019).

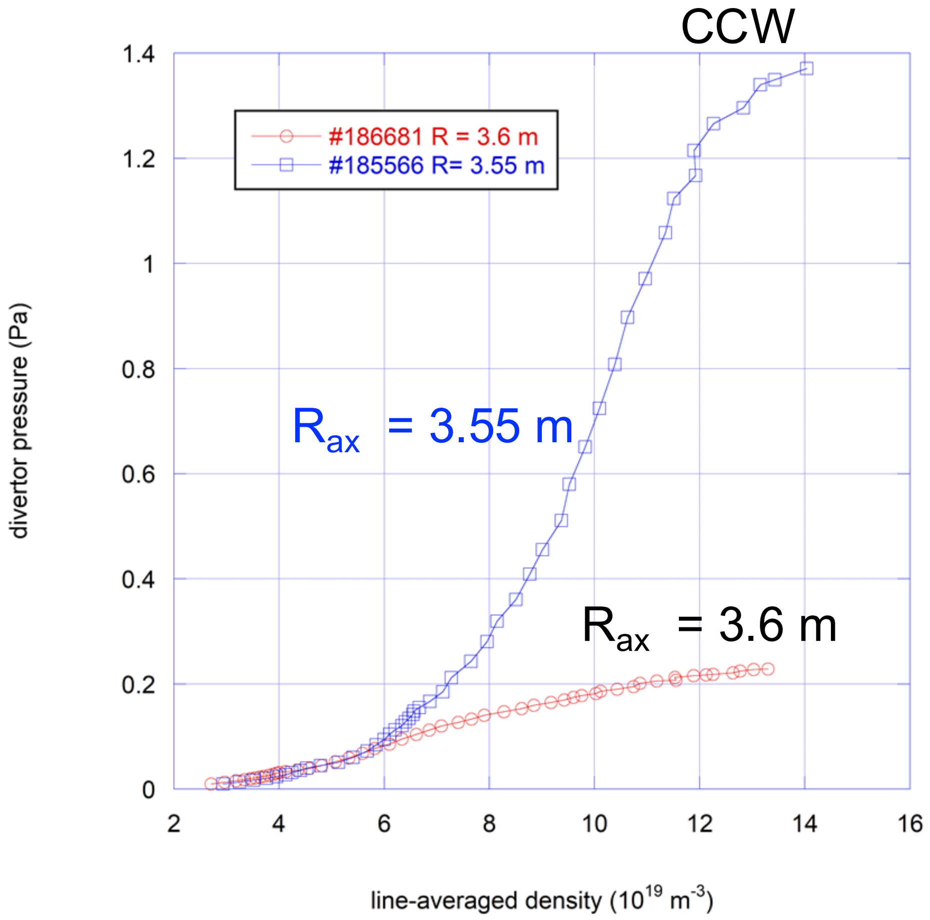




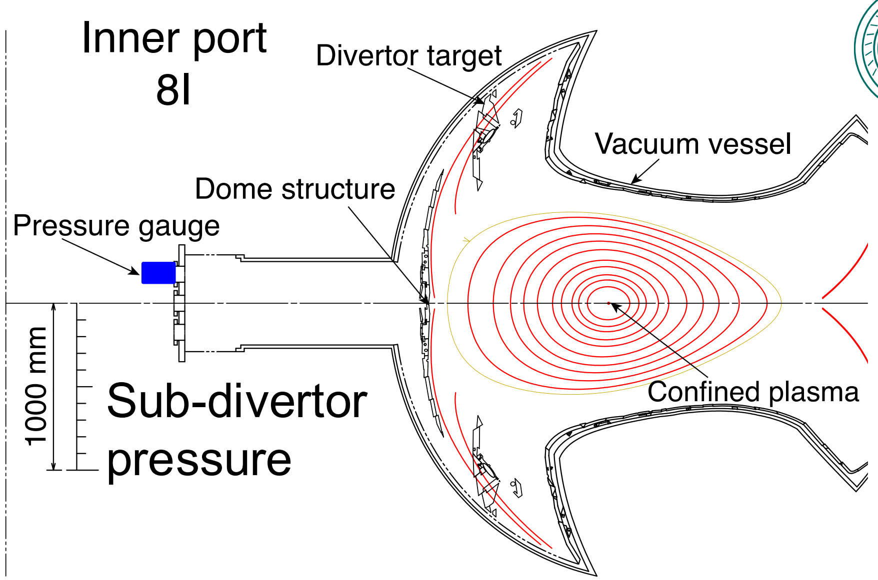
The huge differences of the divertor densities cause the huge differences of the sub-divertor neutral pressures between tokamaks and stellarators.



Scaling of divertor pressure in LHD



Up to 1.4 Pa



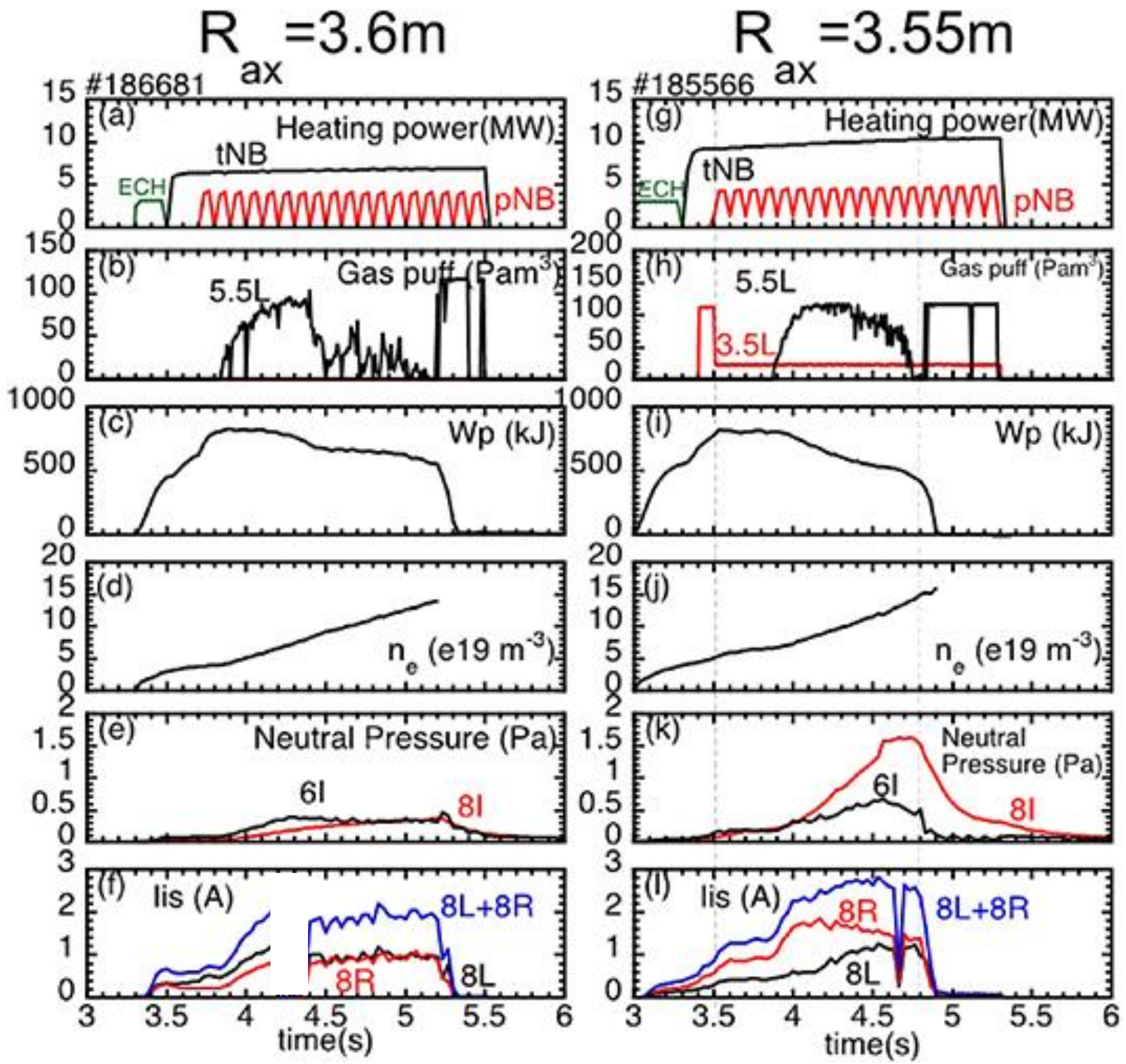
U. Wenzel et al 2024 Nucl. Fusion 64 034002

The divertor density drives the neutral sub-divertor pressure. Therefore, an almost linear scaling is expected, which is true for the R_{ax} = 3.6 m configuration with counter-clockwise field (CCW).

In the **R_{ax} = 3.55** m configuration, **more than 1.4 Pa of sub-divertor pressure was obtained**. **The scaling is quite different for densities** larger than 6e19m^{-3}.

Above this density threshold, there must be another physical process.

Scaling of divertor pressure in LHD

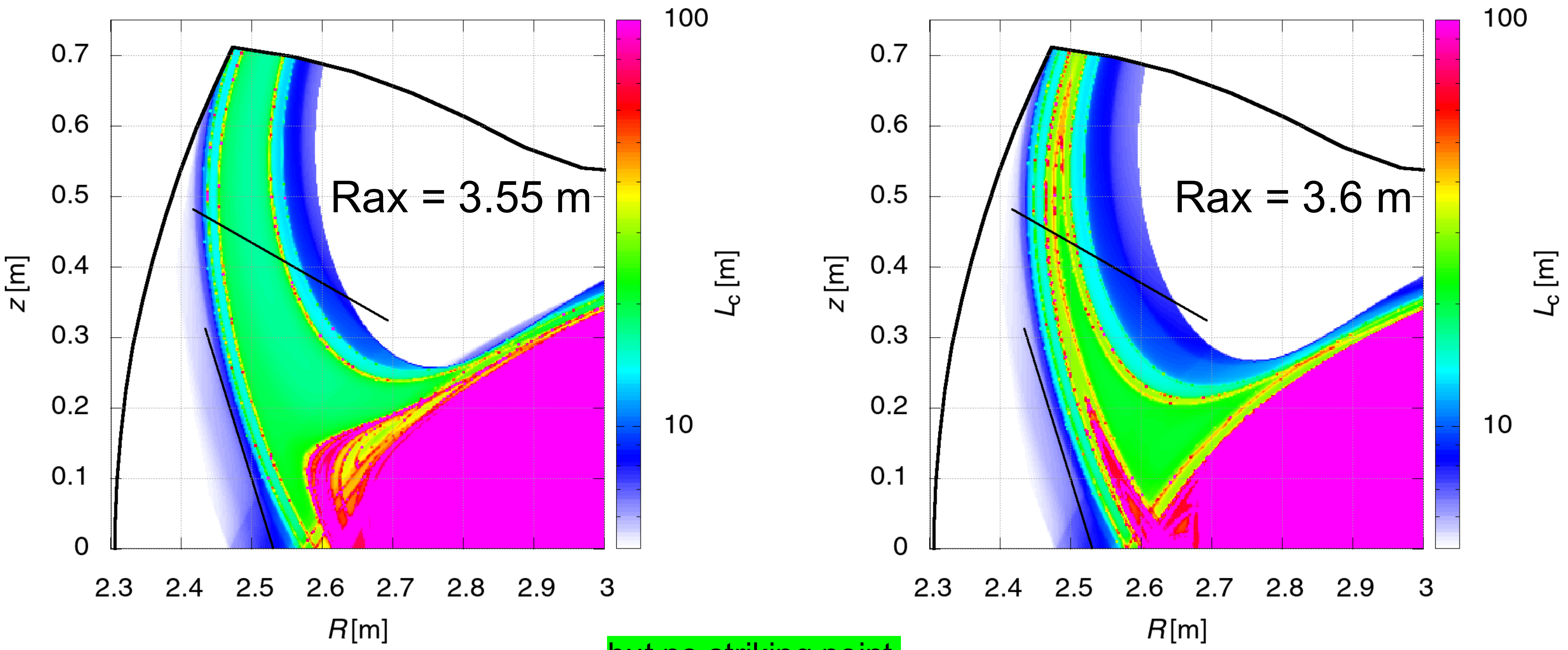


Data are from density ramp-up shots.

An almost linear pressure scaling is expected, which is true for the 3.6 m configuration. In the 3.55 m configuration, the scaling is quite different after 3.5 s.

Particle fluxes initially rise and flatten or even decrease.
They do not cause the high neutral pressures directly.

Comparison of the configurations – target strike point

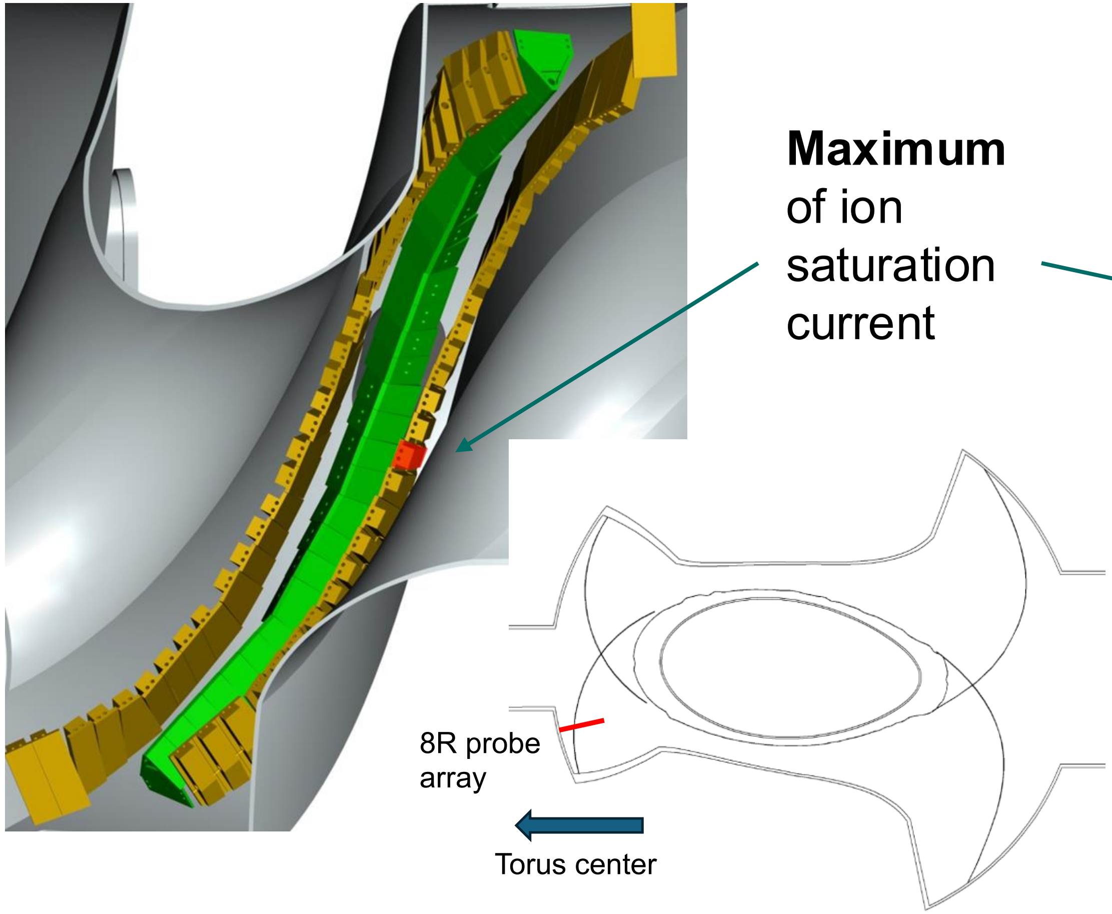


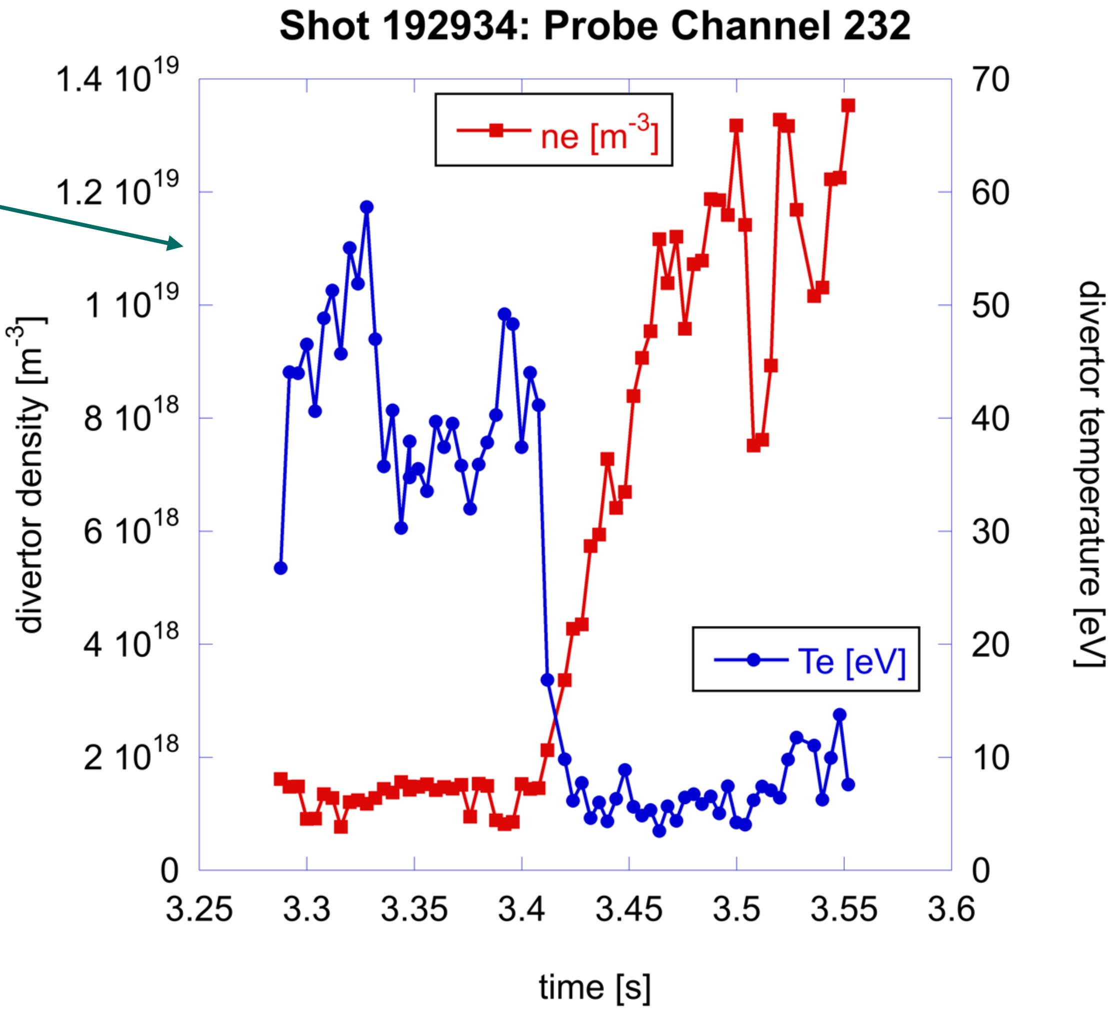
2 strike points in a larger distance

but no striking point differences in particle flux

3 strike points in a smaller distance

Divertor temperature drops at the transition in R_{ax} = 3.55m

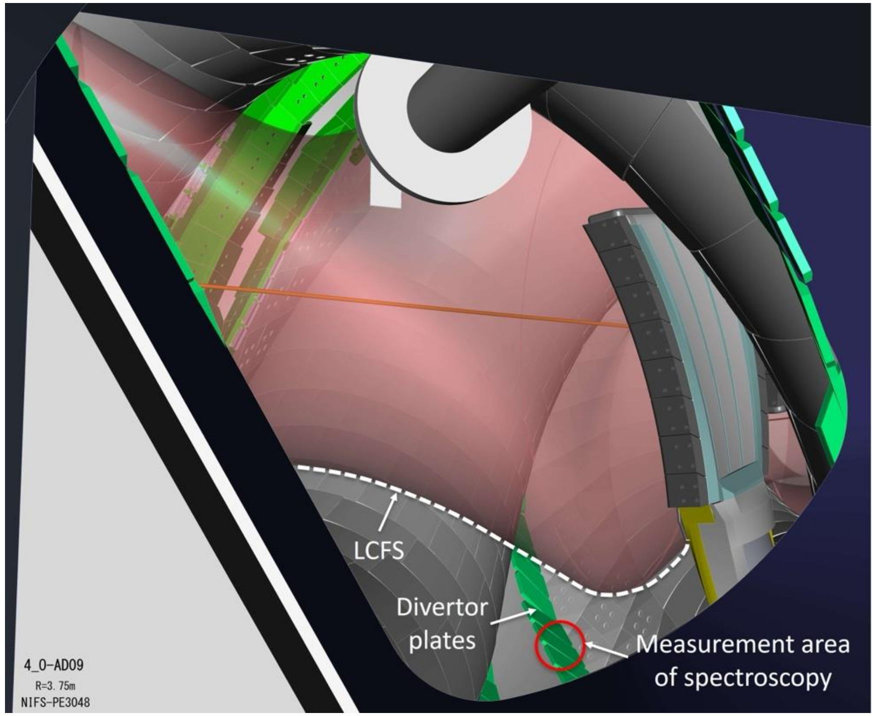


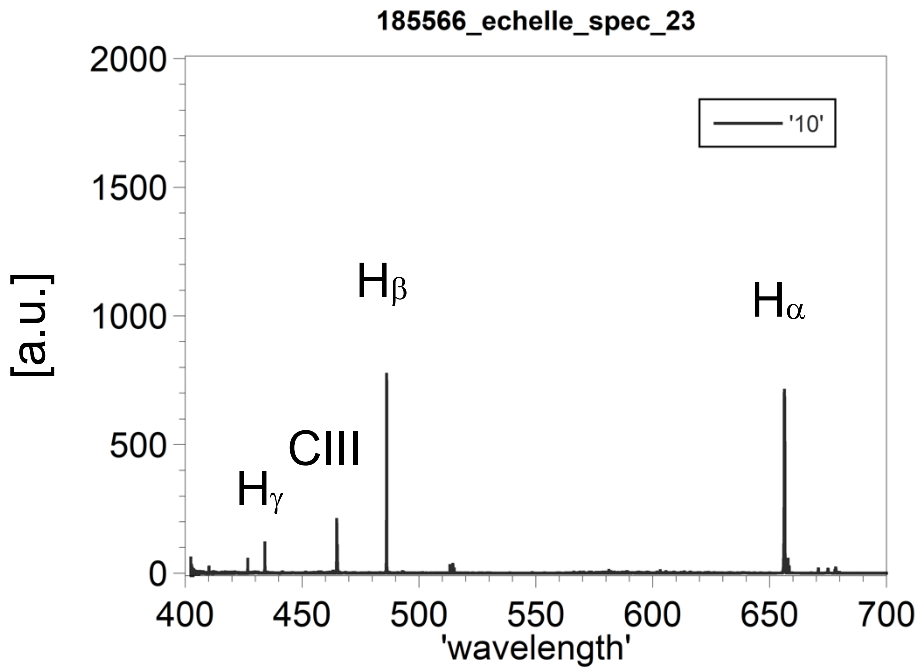


For R_{ax} = 3.55 m, the Langmuir probe data show a drop of temperature from 40 to about 5 eV at the transition. By this temperature drop the carbon radiation **moves away from the divertor target** (which is also called “detachment“).

Spectroscopic data confirm the detachment

Direct view of the divertor without crossing the main plasma (M. Kobayashi)



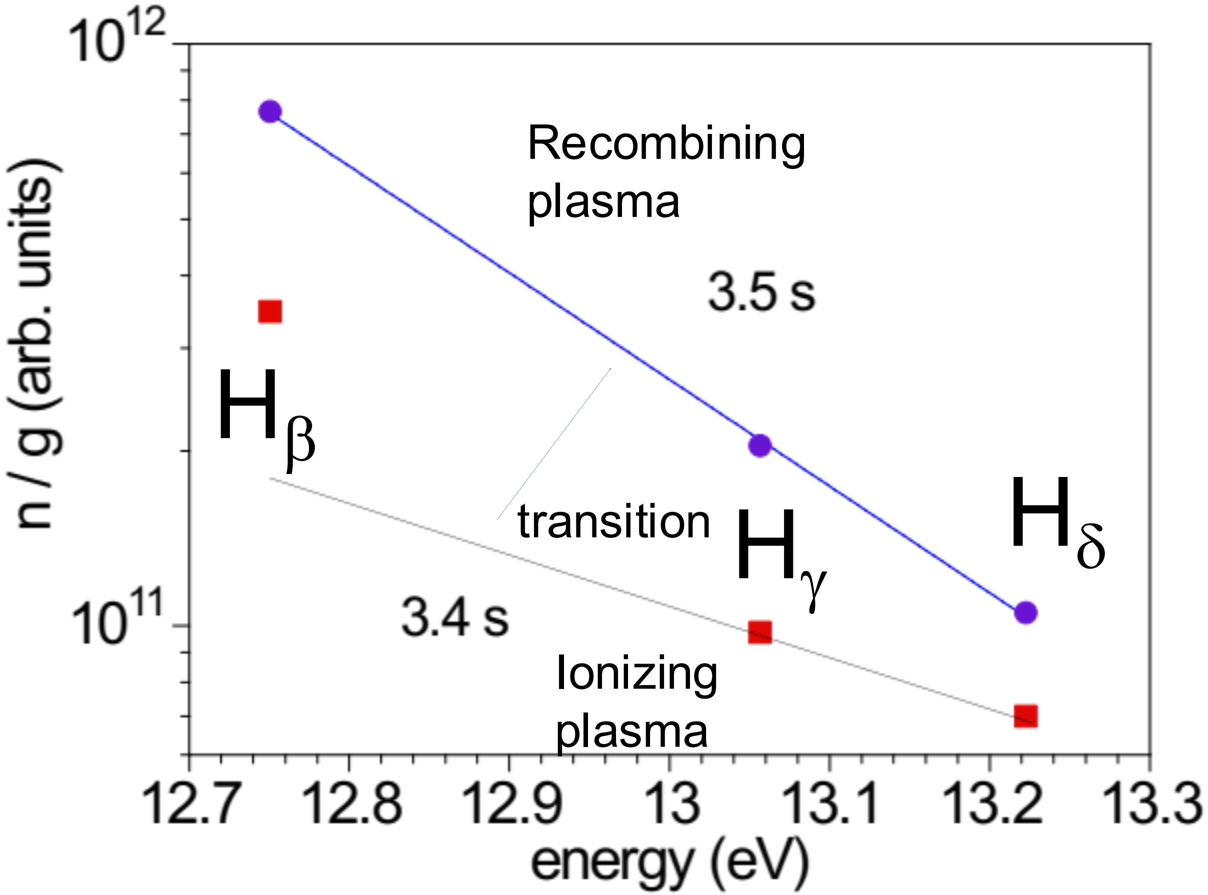


Carbon line (CIII) shows the radiation in the divertor

Hydrogen Balmer lines give the electron temperature in the divertor

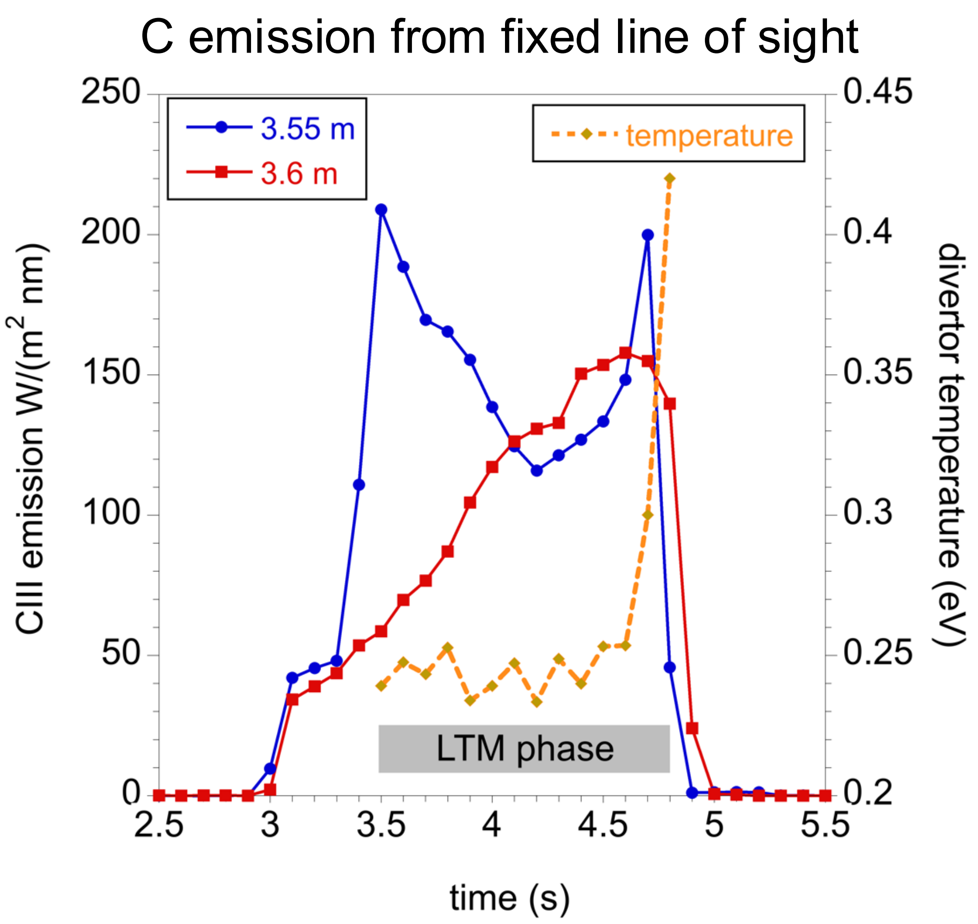
Hydrogen radiation analysis

After the transition, hydrogen atoms are populated differently. They follow a Boltzmann distribution which give very low temperatures below **1 eV**. This suggests volume recombination in the helical divertor.

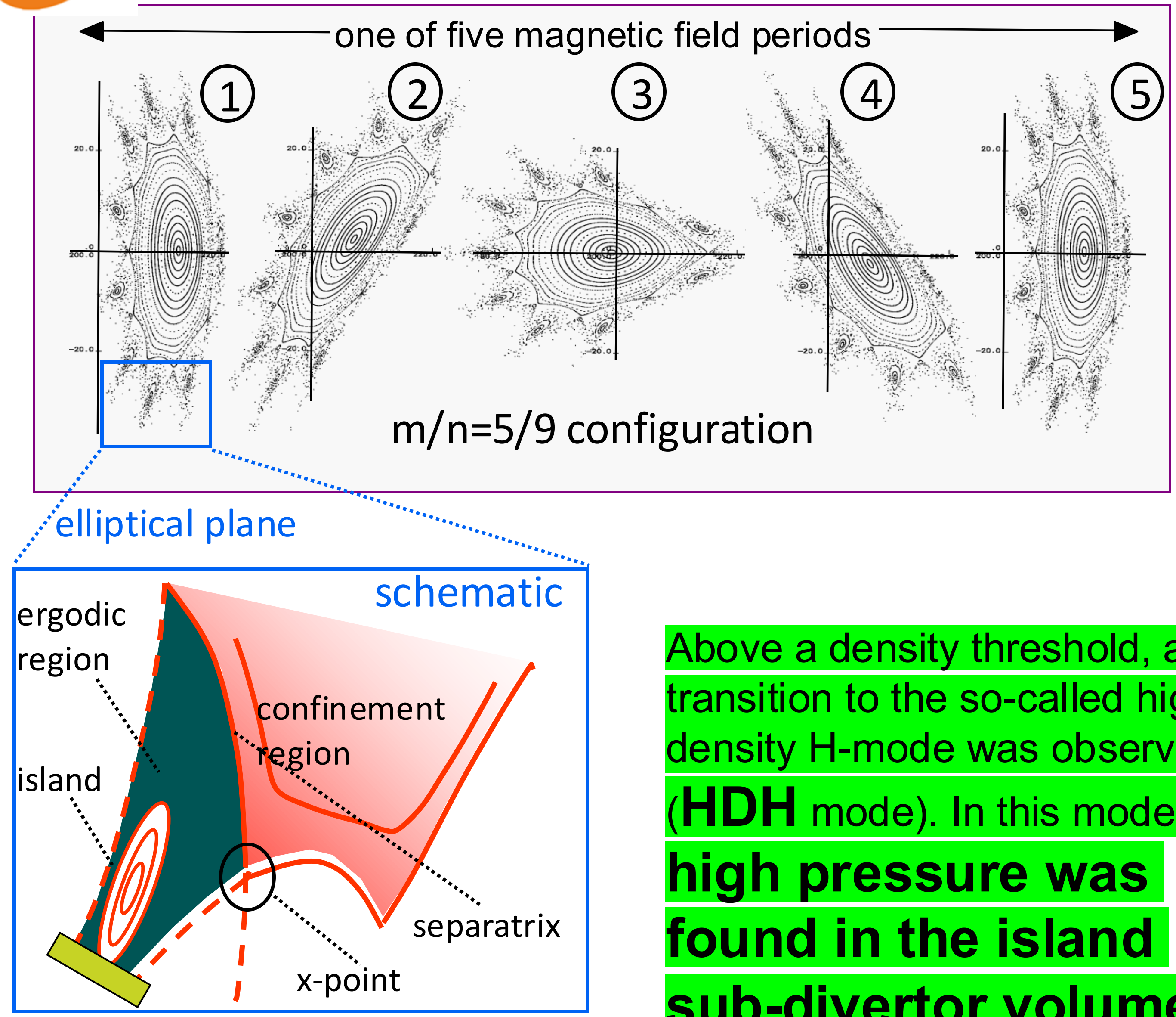


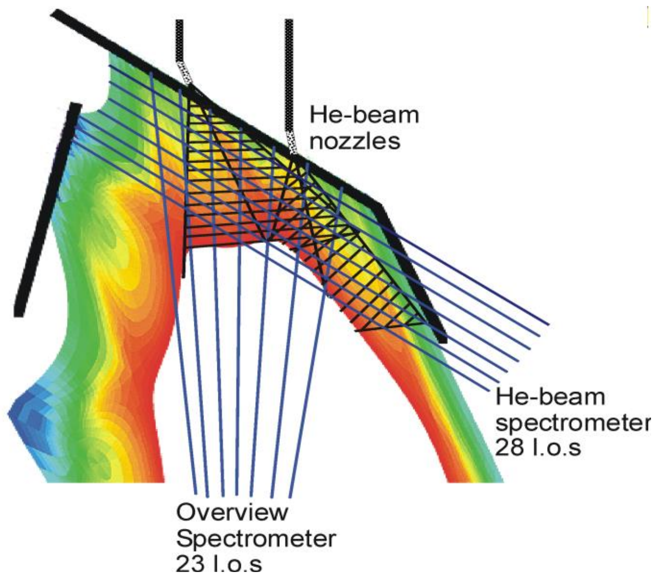
Carbon radiation detaches from the target

- ✓ In the Rax = 3.6 m configuration, the carbon emission follows appr. density.
- ✓ In the Rax = 3.55 m configuration, the carbon emission rises steeply and moves away from the target.
  From 3.5 s on there is a low temperature mode of the divertor (LTM).
- ✓ Temperature data are obtained from the evaluation of the hydrogen emission.



What causes the high pressure in LHD? Looking back to W7-AS

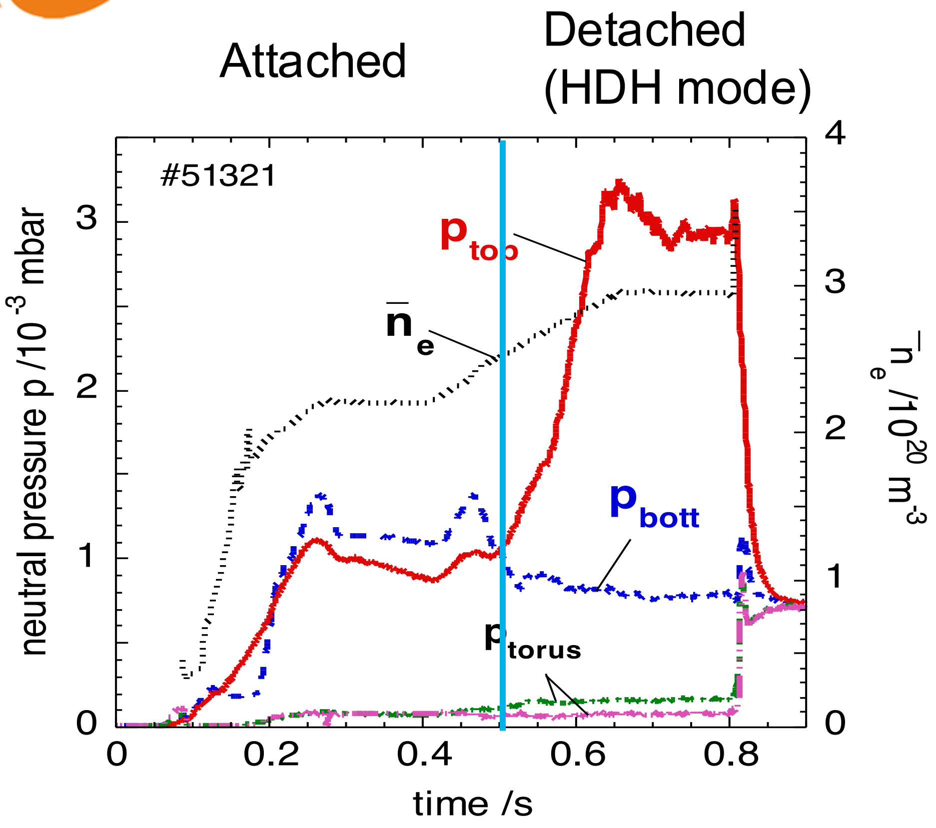




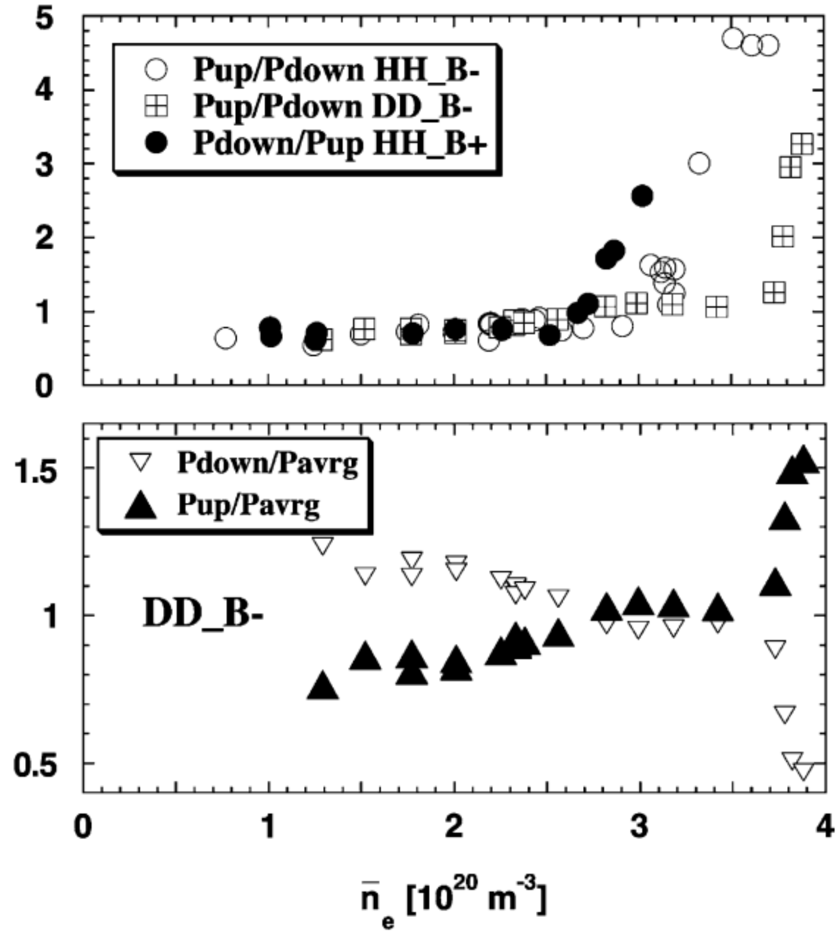
Above a density threshold, a transition to the so-called high-density H-mode was observed (**HDH** mode). In this mode, a **high pressure was found in the island sub-divertor volume**.

By spectroscopy, **volume recombination was identified** as the cause of the enhanced sub-divertor pressure.

Ultra-high divertor pressure in W7-AS

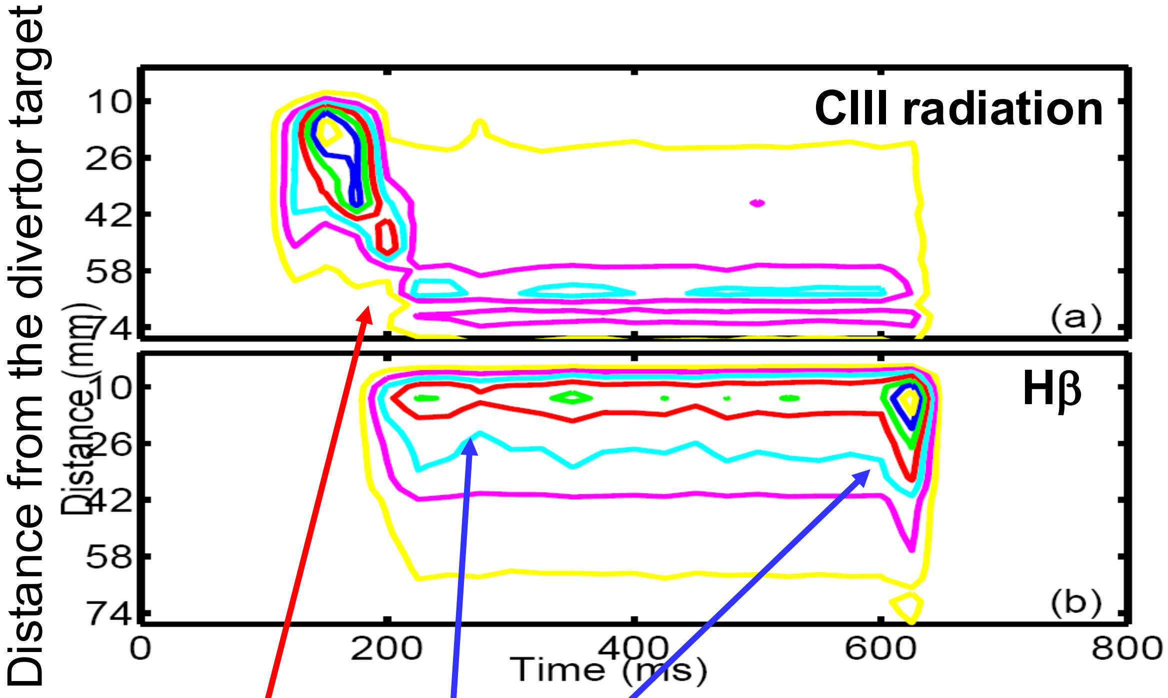


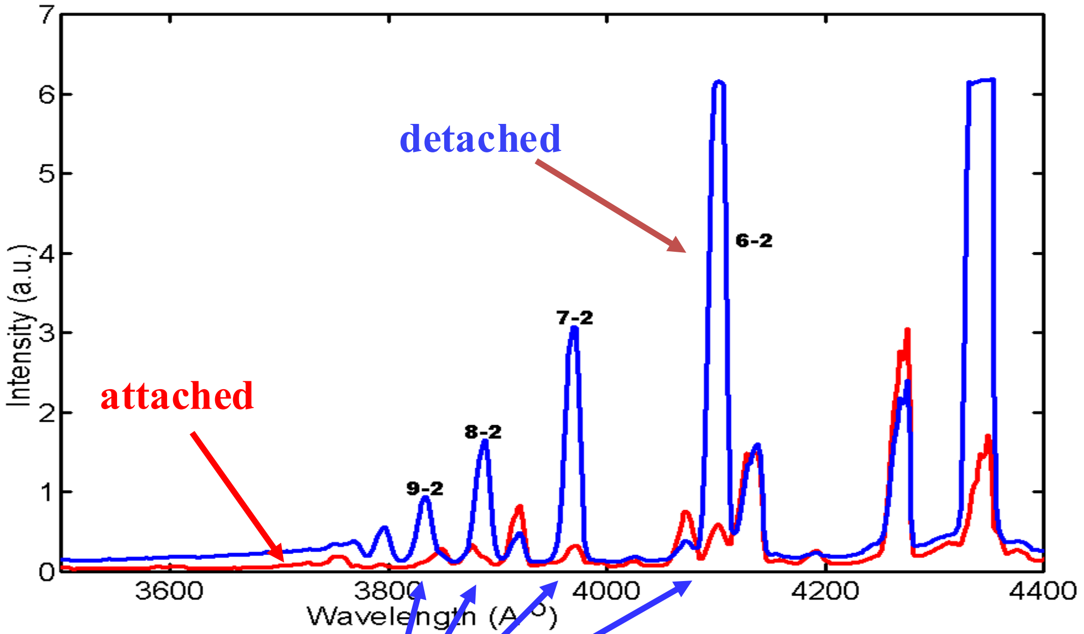
At 0.48 s there was a **sudden transition** to a state with a high sub-divertor pressure on **top** of W7-AS.



With **reversal of the magnetic field**, the high divertor pressure was observed at **bottom** after the transition.

High-density zone in W7-AS





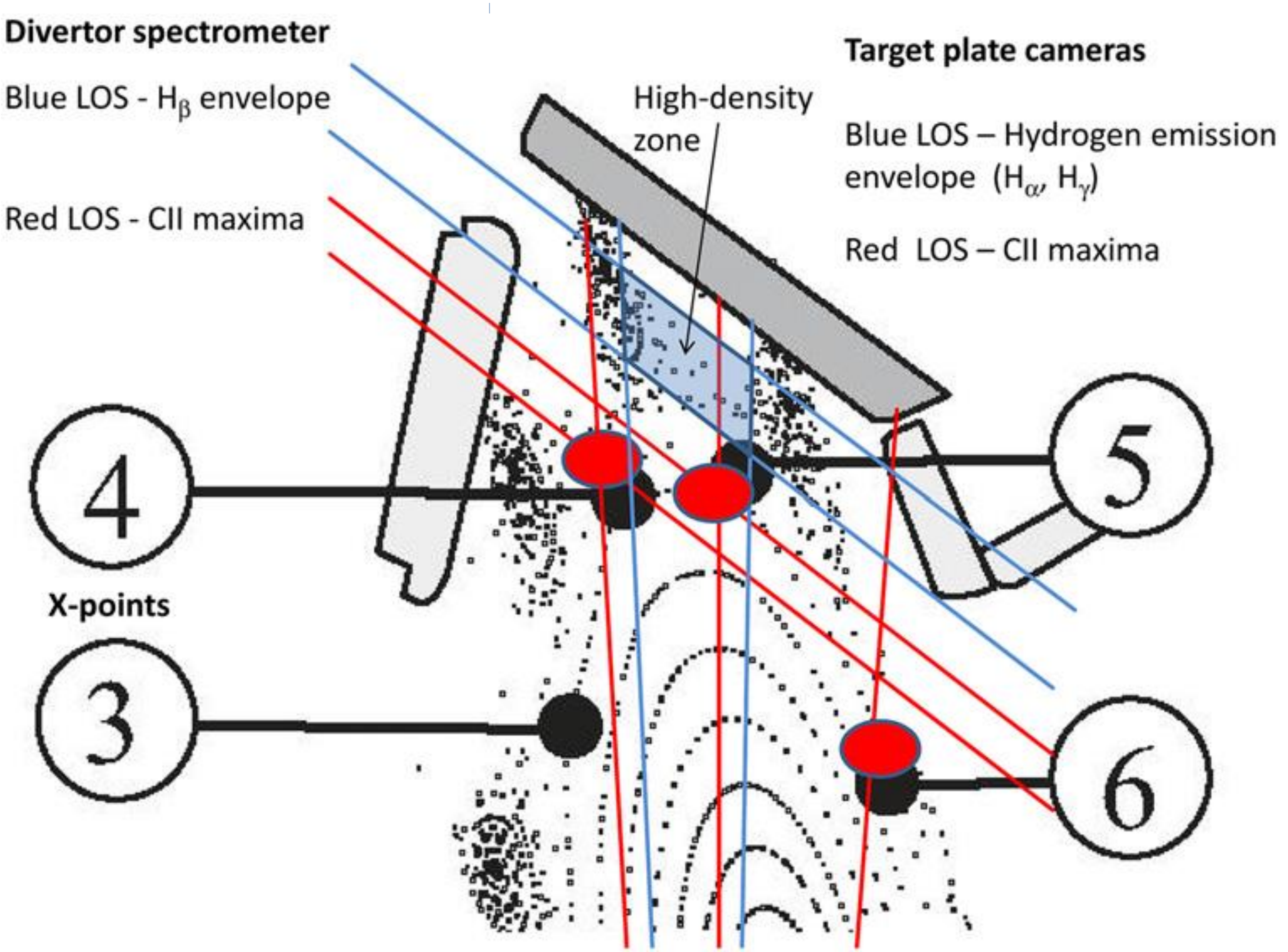
Detachment followed by a phase with **strong volume recombination** → High-n Balmer lines show up

Stark broadening of n-n'=8-2 Balmer line: $n_e \sim 2 - 8 \times 10^{20}$ m^{-3}

Boltzmann plot: $T_e \sim 0.1 - 0.3$ eV

N. Ramasubramanian et al.
2004 Nucl. Fusion 44 992

High-density zone in W7-AS (heuristic tomography)



N. Ramasubramanian et al.
2004 Nucl. Fusion 44 992

The sequence was as follows

1. Sudden movement of the thermal front (carbon radiation) to the X-points
2. A cool, dense divertor plasma region developed
3. Volume recombination by the low temperature in the high-density zone
4. High sub-divertor pressures driven by the neutrals generated by 3-body recombination

Physical cause of ultra-high sub-divertor pressures in LHD

Hypothesis:

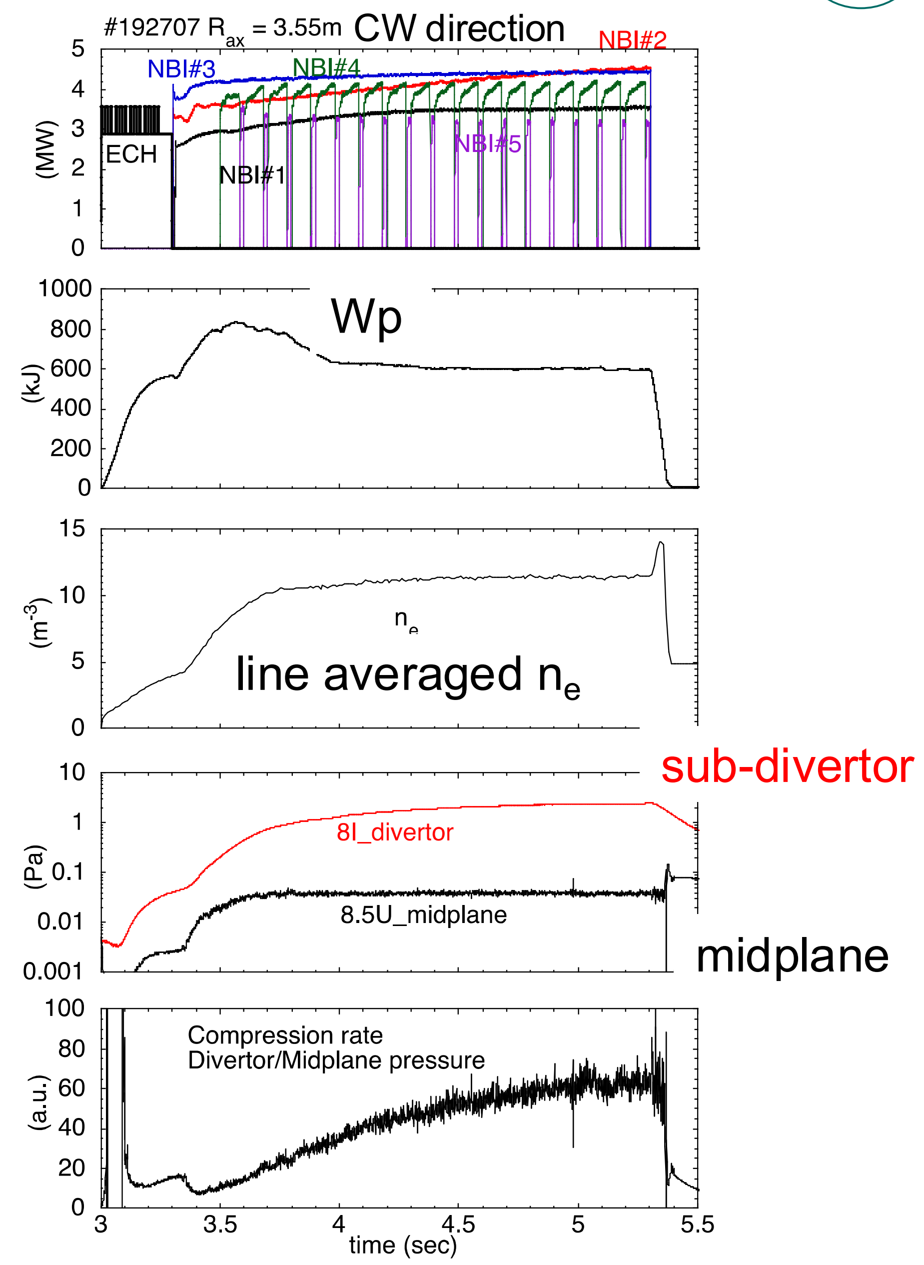
Ultra-high pressures in W7-AS and LHD have the same physical cause.

1. Sudden movement of the thermal front (carbon radiation) to the X-points
2. A cool divertor plasma region developes
3. 3-body recombination
4. Ultra-high sub-divertor pressures

Some details are different:

i. Behaviour at field reversal. Up/down asymmetry of the ultra-high pressure in W7-AS. With field reversal the asymmetry reversed, too. In LHD, this was not observed. Sub-divertor pressures up to 2 Pa were obtained in clockwise field (CW) direction as well. →

ii. 3-body recombination not yet directly detected by the Balmer series limit



Possible Explanation – Wall (or Hydrogen) Marfe

Samm 1999 Textor tokamak

a) Standard (thin) Marfe

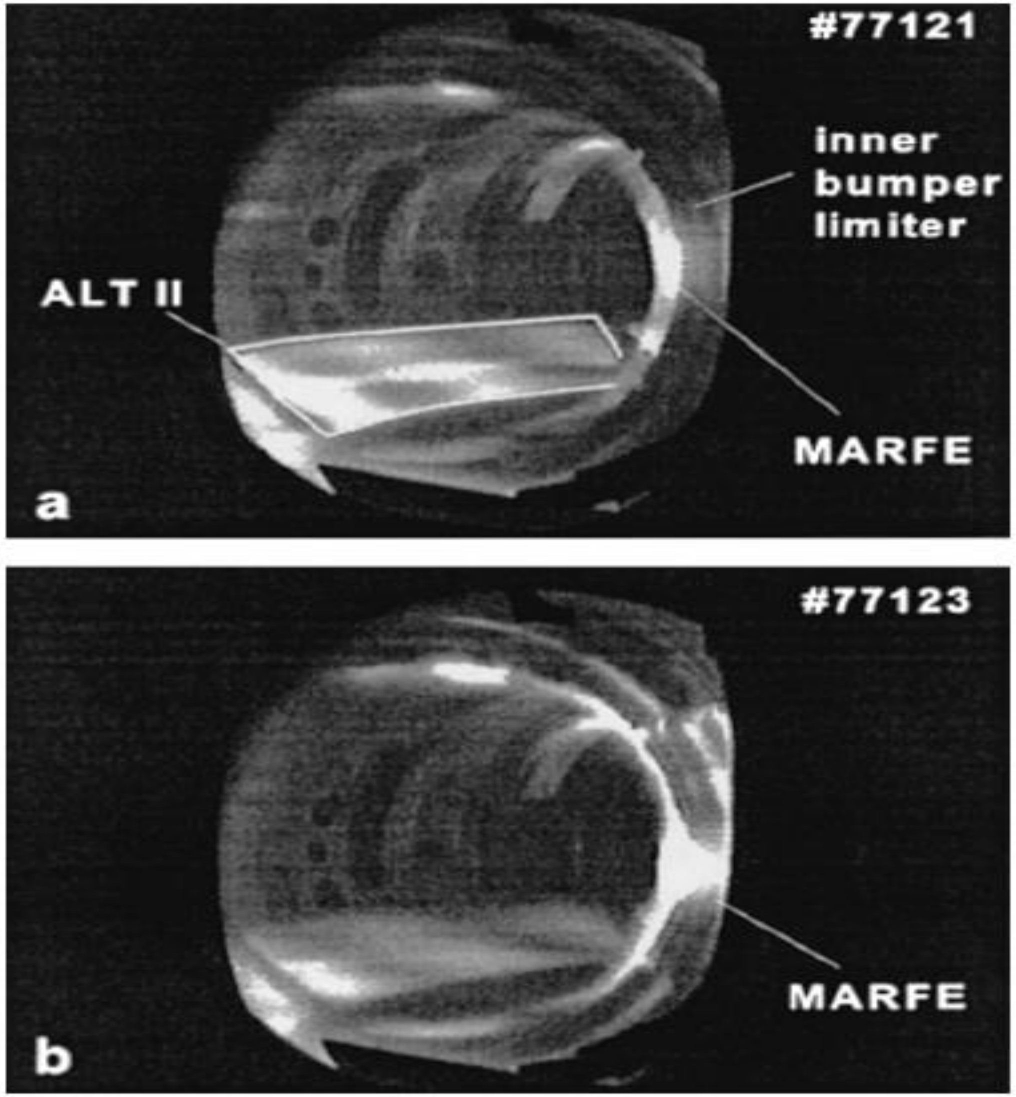
Large distance to the wall. Density increase by gas puffing possible (beyond the Greenwald limit).

b) Wall (fat) Marfe

Small Distance to the wall. Density is clamped. Gas puffing results in an increasing size of the Marfe

Tokar 1999 Localized recycling as a trigger of MARFE

Center of a Marfe can be recombining and a neutral particle source (virtual target or limiter).



Summary

There are striking similarities between W7-AS and LHD resulting in ultra-high sub-divertor neutral pressures above a density threshold. Maximum pressure in LHD is more than **2 Pa** which is the same as for an H-mode discharge in ASDEX Upgrade.

In both devices only low pressures are predicted by the modeling. Predicted scaling over density is approximately linear while we found $p_{div} \sim n^{3.6}$ for $R_{ax} = 3.55$ m.

Most probable explanation is the formation of a hydrogen Marfe (or wall Marfe) when the distance between the X-point and the wall becomes small.

Conclusion and outlook

The question is "Do the ultra-high sub-divertor pressures solve the exhaust problem of a stellarator?"

We think "**yes**".

Steady-state operation is possible for inward shifted plasmas with more than 1 Pa in LHD →

but the phenomenon has not been studied in sufficient detail to be used in reactor design studies!
Not predicted by modeling.