Connecting the edge to the divertor in tokamak plasmas

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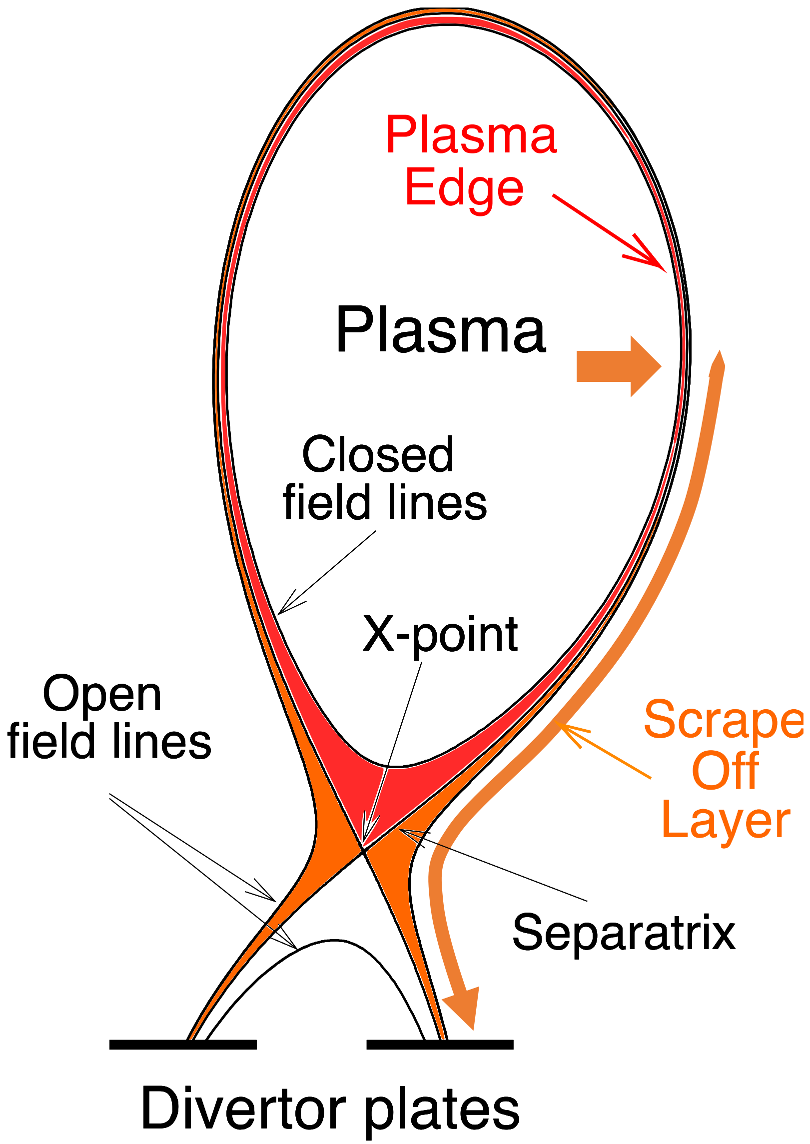
Special thanks to the ASDEX Upgrade, TCV, and the WPTE teams

1° Conferenza Italiana Plasmi (CIP), Frascati, Italy

The importance of the edge and divertor plasmas



Plasma Edge

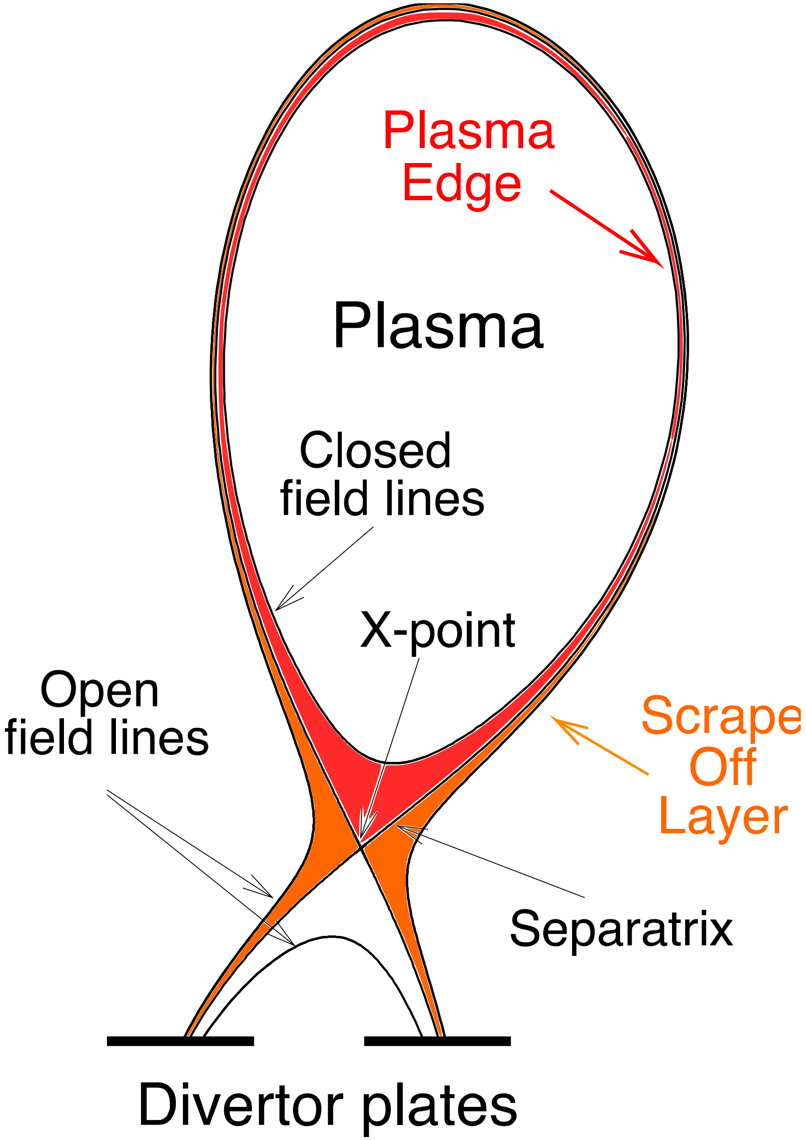
- Interface between confined plasma and the open field line region
- Crucial in defining the overall plasma confinement

Scrape Off Layer (SOL)

- Manage the plasma exhaust
- Manage pumping and helium removal
- …

Outline

- Why does the edge define the confinement?
  - The Low to High confinement mode transition: an interpretation of the power threshold
- Separatrix plasma parameters
  - Role of the ion to the electron temperature ratio
- The plasma exhaust problem
  - Role of deuterium molecules in the divertor of ASDEX Upgrade
  - Transition phenomena: the detachment “cliff”



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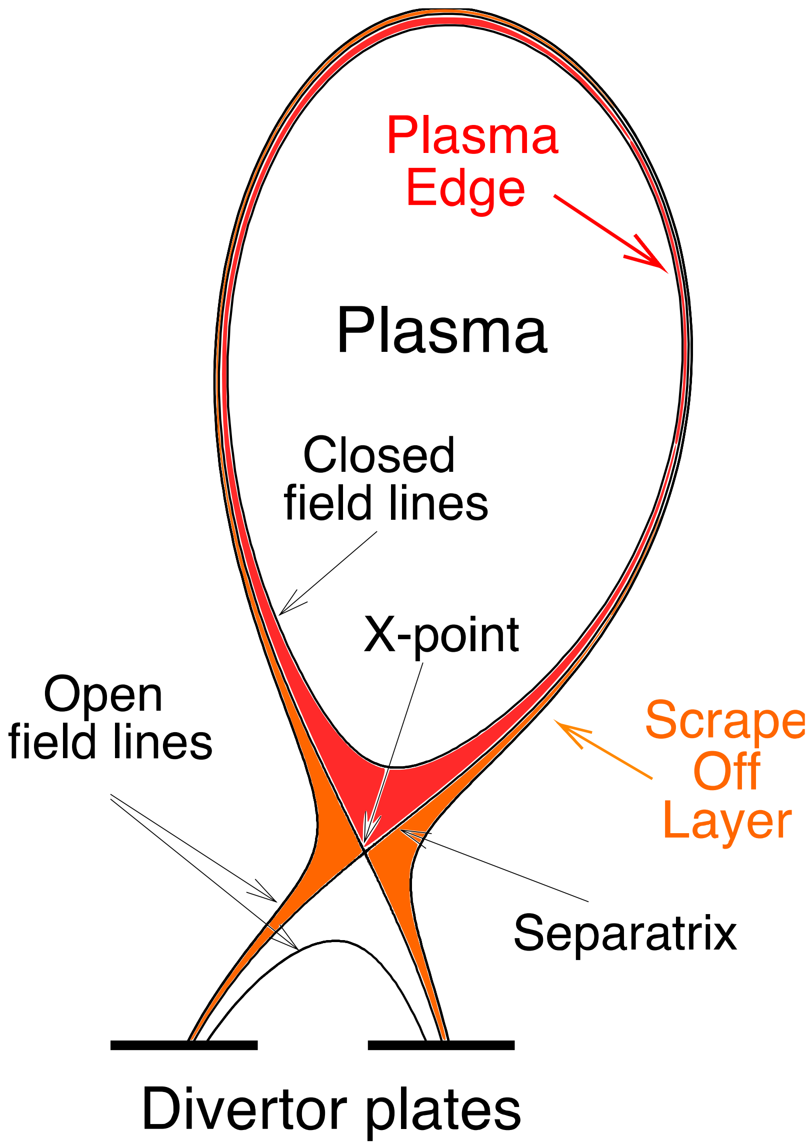


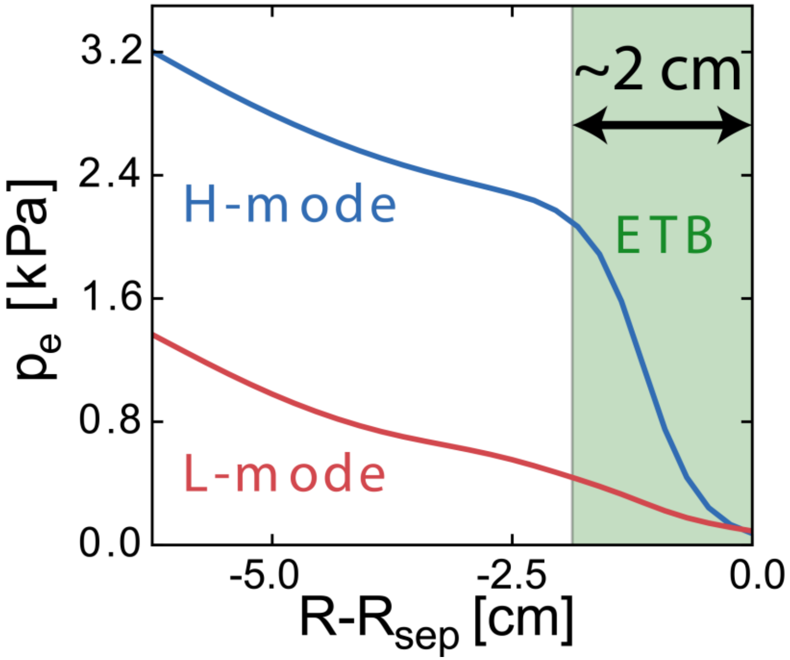
Low (L-) to High (H-) confinement mode transition

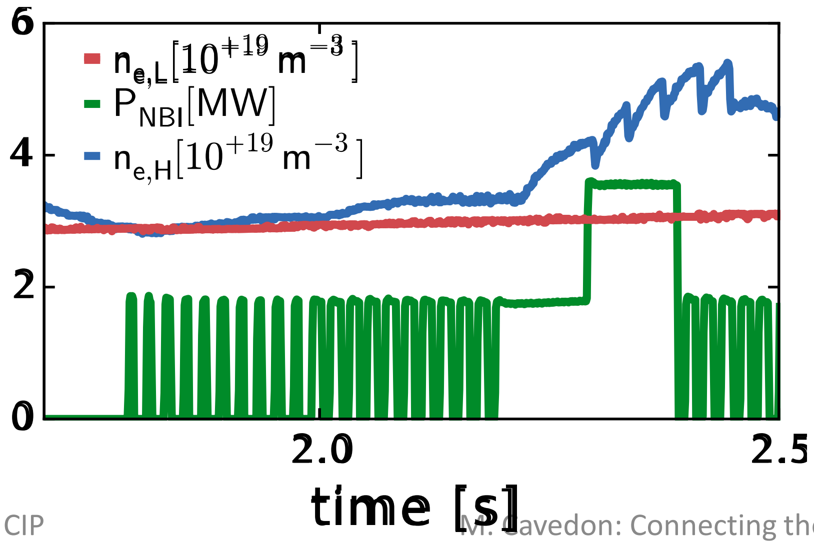
Tokamak plasmas typically show two different confinement regimes [Wagner, PRL 1982]:

- Low confinement mode: L-mode
- High confinement mode: H-mode

$$\tau_{en,H} \approx 2 \cdot \tau_{en,L}$$

H-mode ⟺ Edge Transport Barrier (ETB)





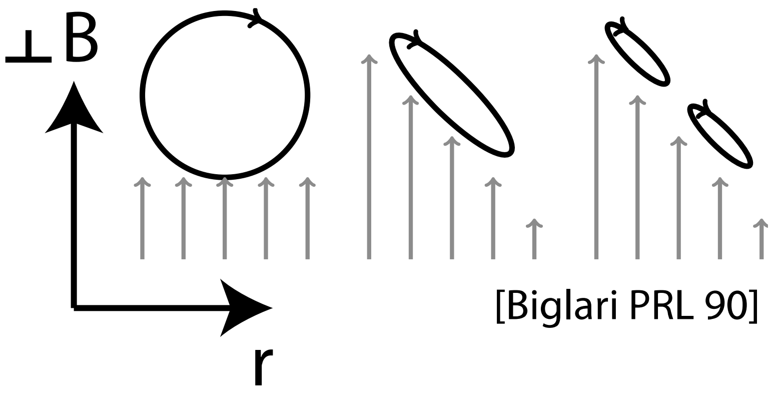
L-H transition reproducible:

$$P_{thr,08} = 0.049\, B_t^{0.8} n_e^{0.72} S^{0.94}$$

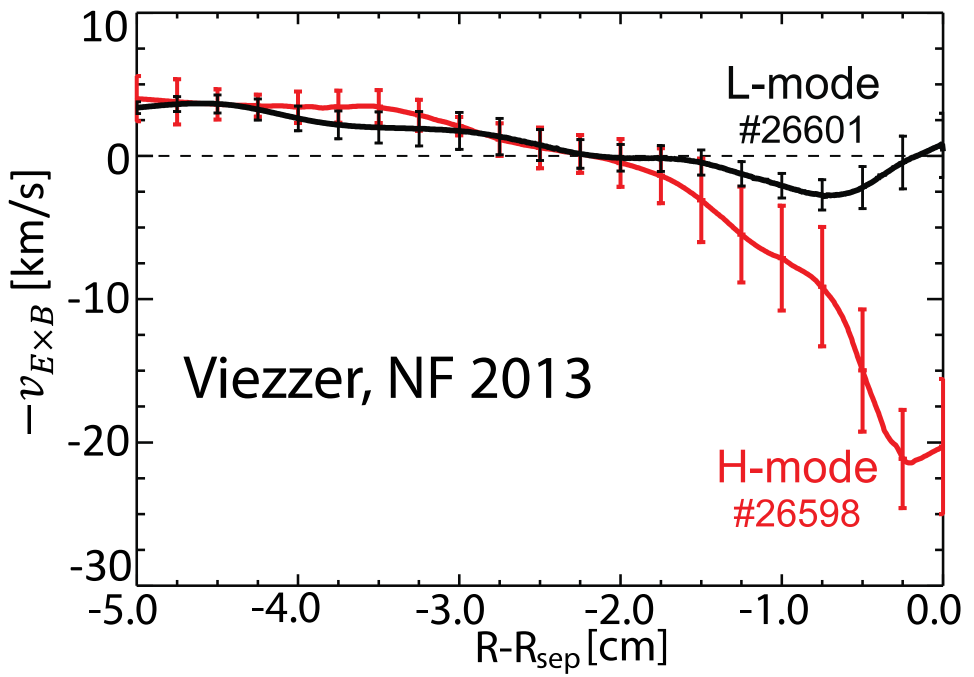
[Martin, JoP, 2008]

Turbulence decorrelation at the L-H transition

Candidate explanation for the L-H transition



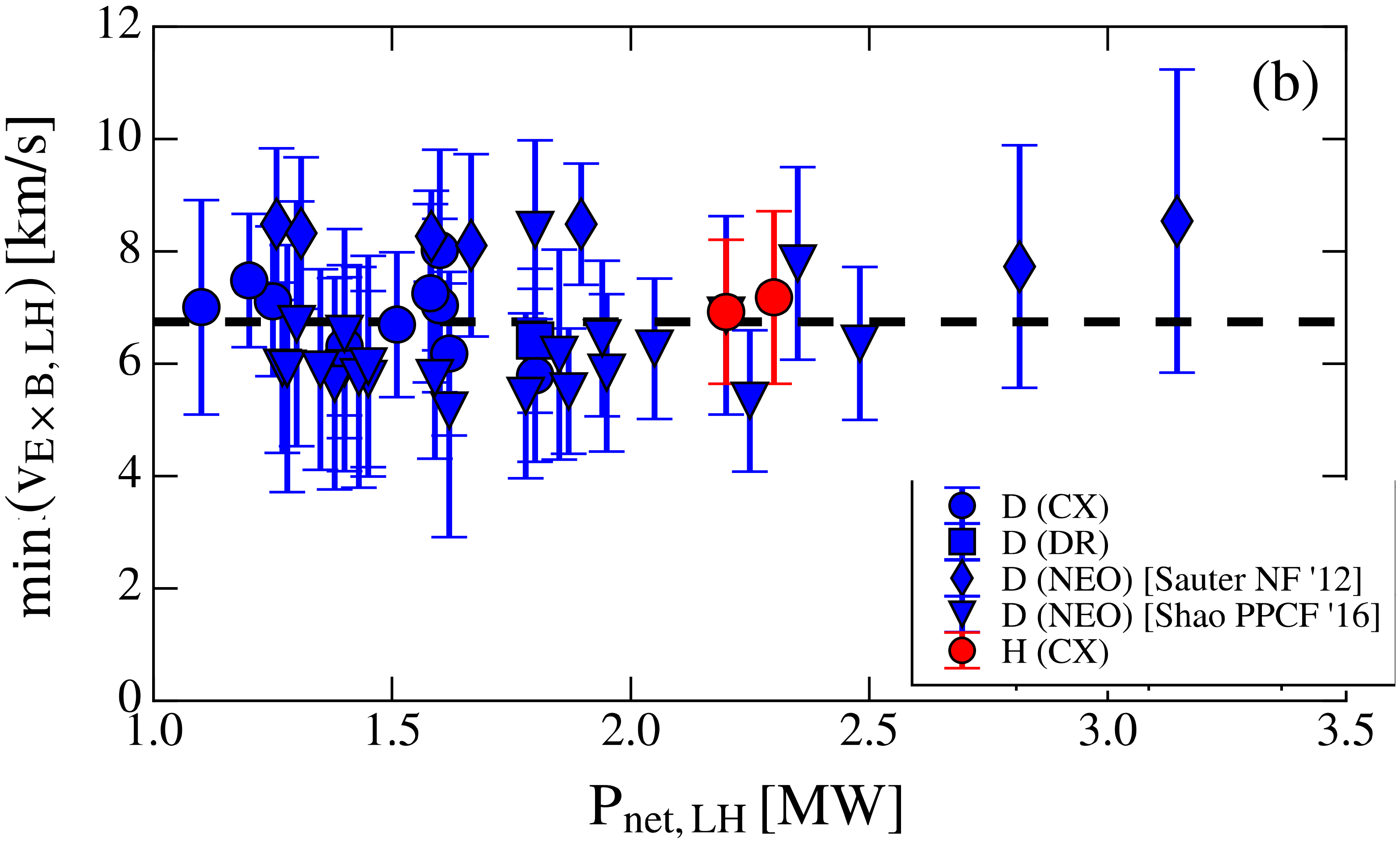
$\nabla v_{E\times B} \gtrsim \gamma_{turb}$
$\Longrightarrow$Turbulence Suppression



Is there a correlation between $P_{thr,08} \propto B_t^{0.8} n_e^{0.72} S^{0.94}$ and the $\nabla v_{E\times B}$ at the L-H transition?

[M. Cavedon et al, RSI 2017]: $v_{E\times B}$ and T_i on 100 μs time scales

$\nabla v_{E\times B} \approx \min v_{E\times B}$ at the L-H transition



$\min v_{E\times B} \approx \nabla v_{E\times B}$ is approximately constant at the L-H transition in AUG

(only B_t and n_e scans in very constant plasma conditions)

[M. Cavedon et al, NF 2020]
[M. Cavedon *et al, PPCF* 2024]

Heuristic Model of P_{thr}

[M. Cavedon et al, NF 2020]
[M. Cavedon *et al*, *PPCF* 2024]

ASDEX Upgrade Experimental Evidences

- $v_{E\times B}^{magic} \approx 6 \text{ km/s}$
- Ions are key for the L-H $\Leftrightarrow v_{E\times B} \approx v_{dia}^{i} = \frac{\nabla(n_i T_i)}{B\, Z_i n_i}$

  [Ryter NF 2014, M. Cavedon NF 2017]

Assumptions

- Only ion transport in equilibrium:
  $$P_{LH} = n_i \chi_{edge} \nabla T_i S$$
- $v_{E\times B} \approx \frac{1}{B}\left[\frac{\nabla \mathrm{T_i}}{e} + \frac{\mathrm{T_i} \nabla n_i}{e\, n_i}\right] \approx 2\frac{\nabla T_i}{Be}$

$$P_{LH} = n_i \chi_{edge} \frac{1}{2} v_{E\times B}^{magic} eBS$$

With $\chi_{edge} = 1\, m^2/s$ and $v_{E\times B}^{magic} \approx 6 \text{ km/s}$:

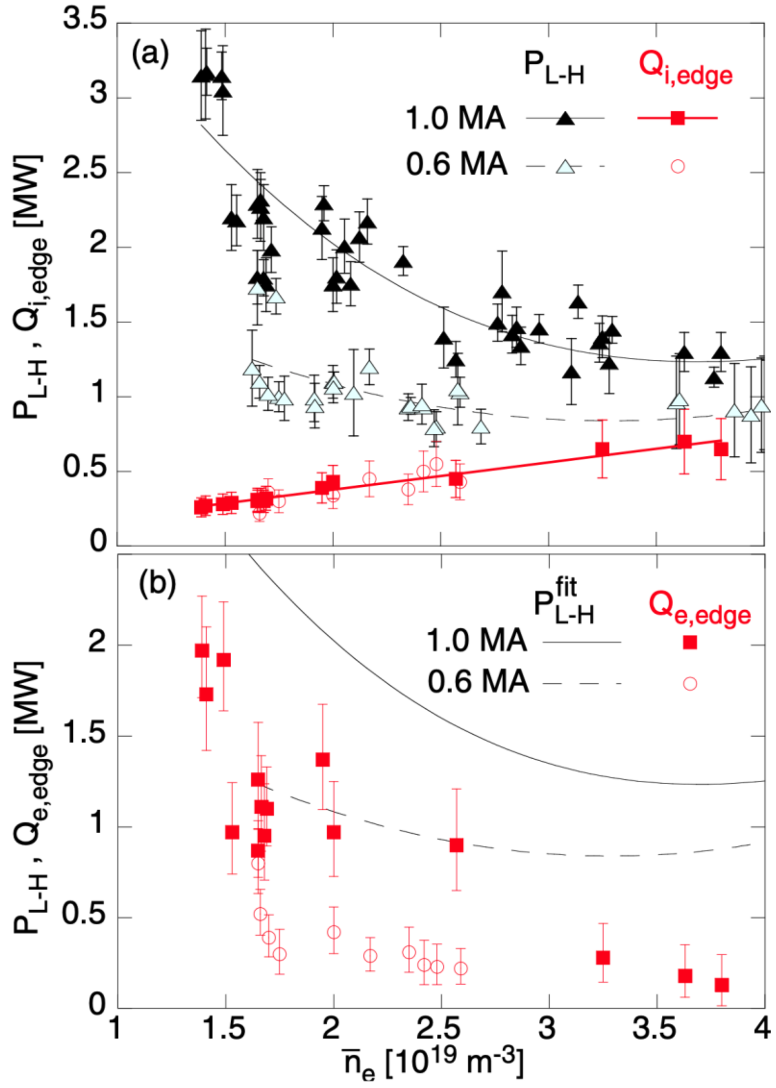
$$P_{LH} = 0.048\, nBS\ [\mathrm{MW}]$$

$$P_{thr,08} = 0.049\, B_t^{0.8} n_e^{0.72} S^{0.94}$$

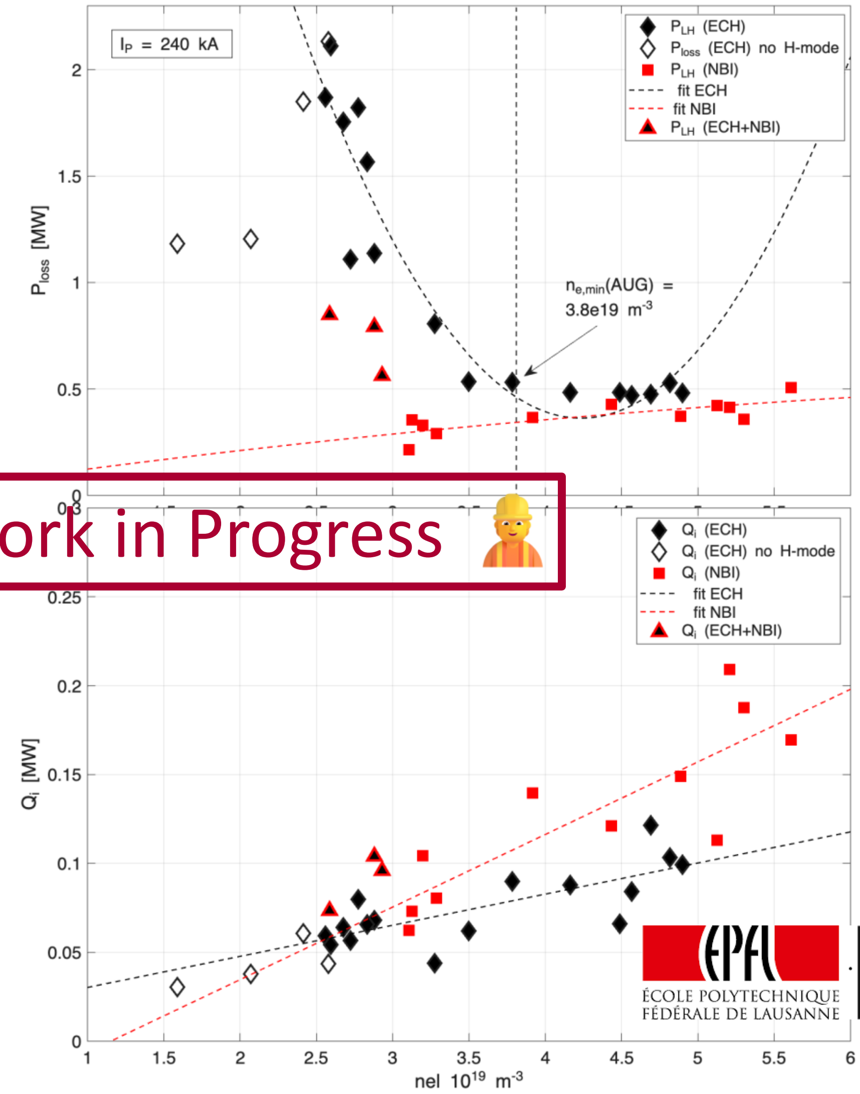
[Martin, JoP, 2008]

[Wagner F. 1994 Workshop on Transport and Fusion Plasmas (Gothenburg, Sweden)]
[Rozhansky V. et al 2002 Nucl. Fusion 42 1110–15]
[R. Bilato *et al* NF, 2020], [U Plank *et al* PPCF 2023]

The edge ion heat flux is a key player in the L-H transition



[F. Ryter et al 2014 Nucl. Fusion 54 083003]



Work in Progress

[L. Aucone, M. Cavedon et al, in preparation]

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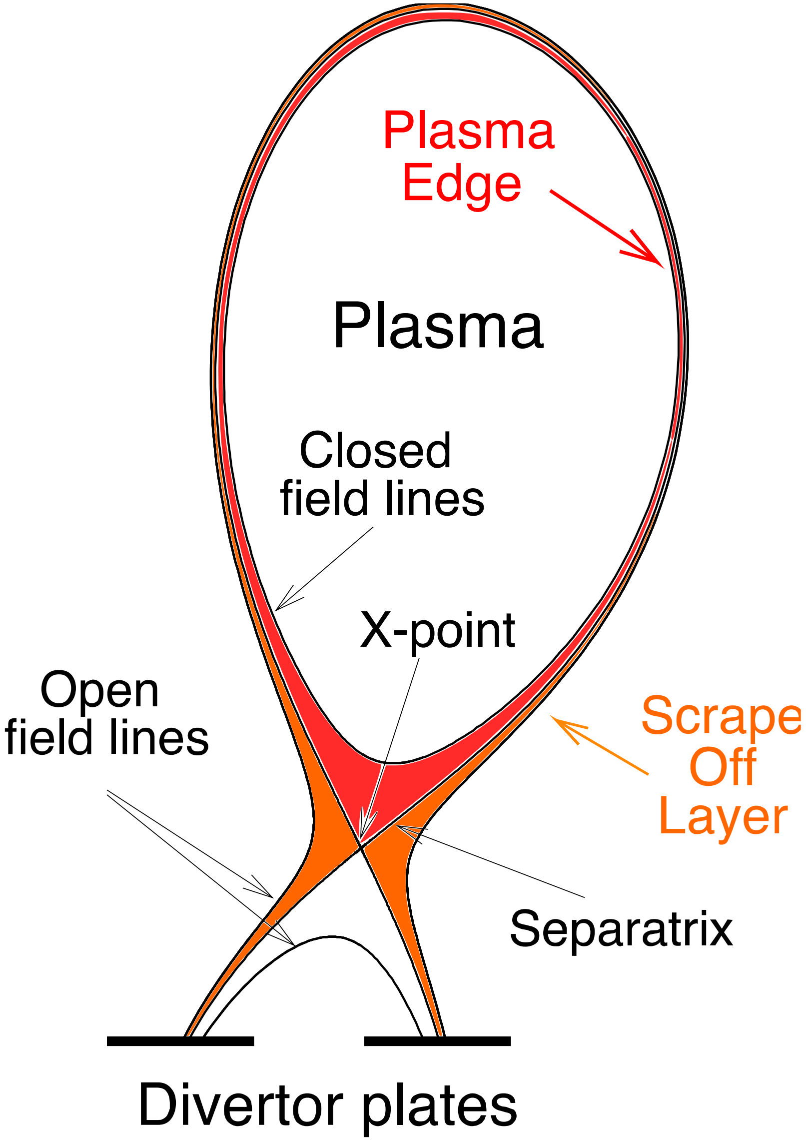
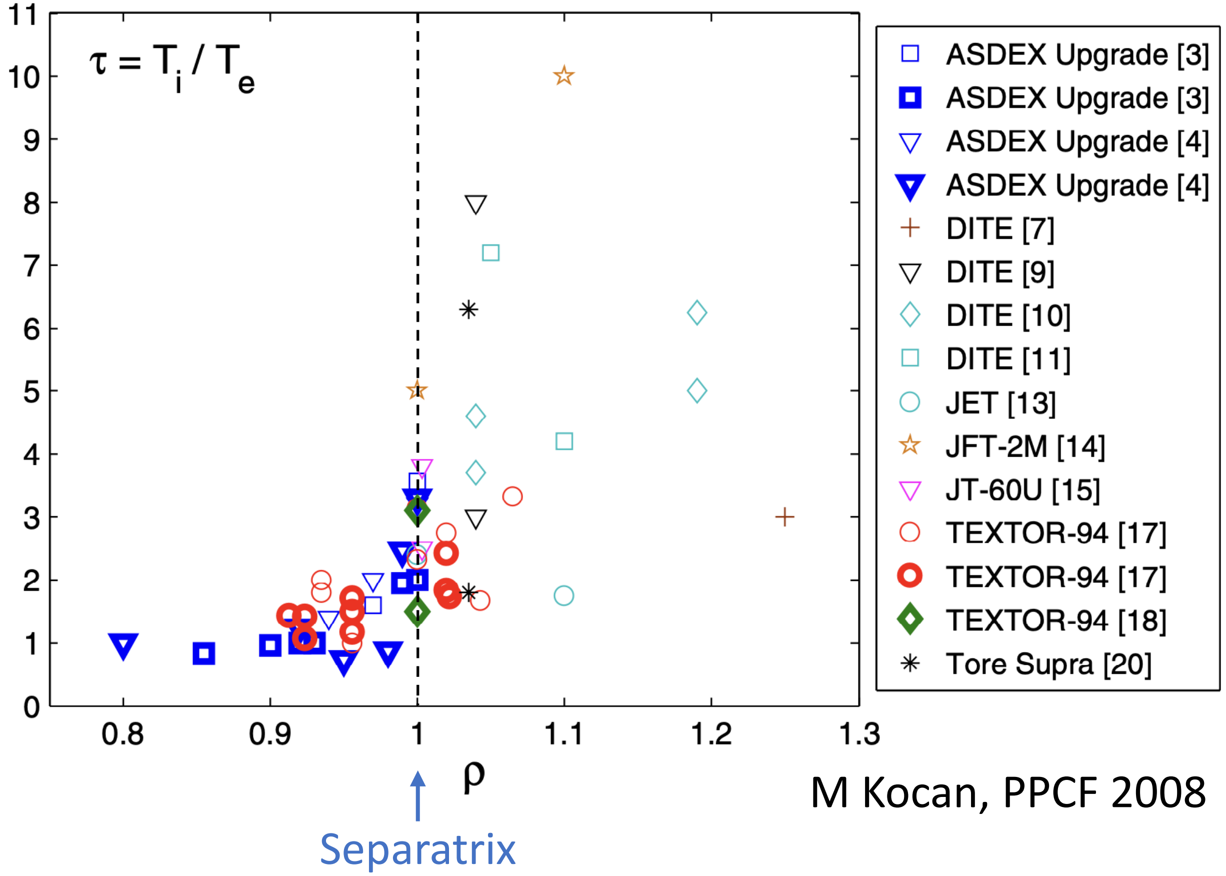


The case of T_i at the separatrix

- In present tokamaks, ions and electrons are coupled in the edge, but they decouple in the SOL due to their different masses such that $T_{i,sep} \geq T_{e,sep}$

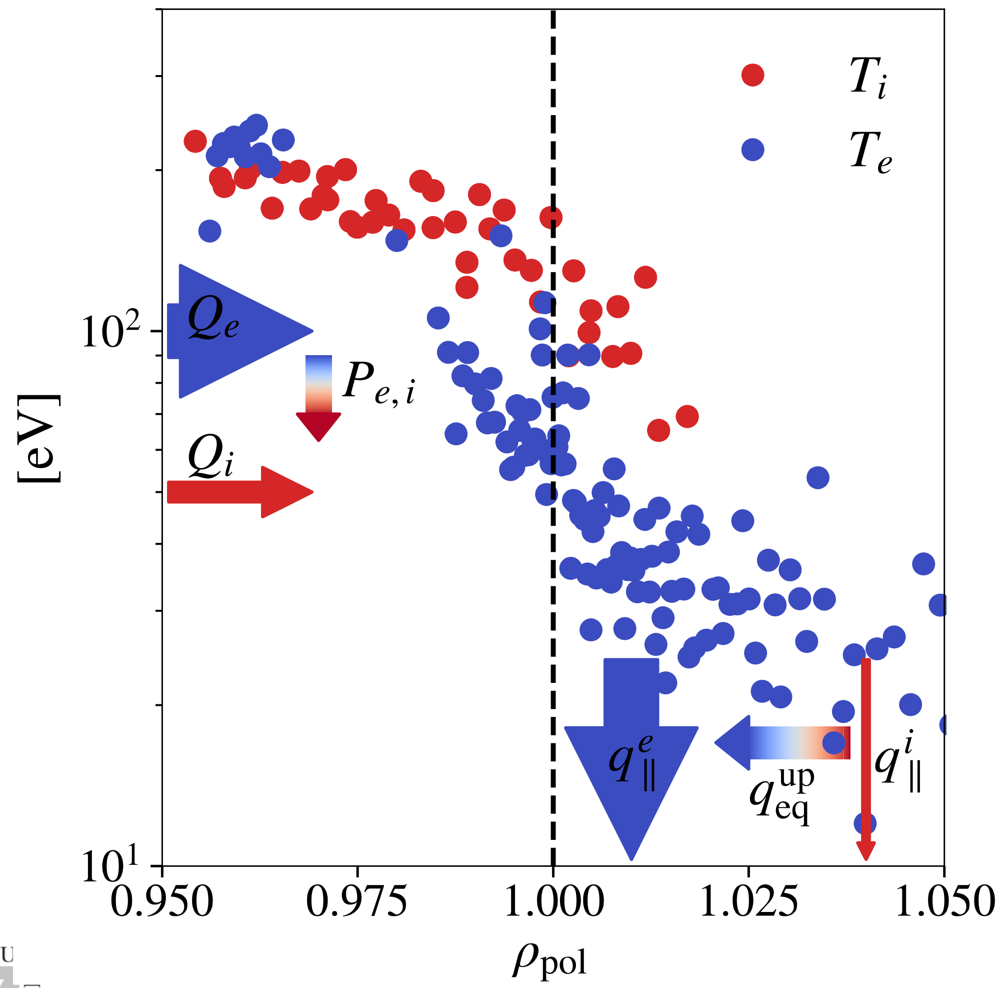
- Important for SOL fluxes
  [Carralero, et al NF 2018, R.J. Goldston NF 2012]
- Sets boundary to predict the confinement
  [T. Luda di Cortemiglia et al NF 2020]
- Determines the edge turbulence
  [P. Manz et al 2020 Nucl. Fusion]



M Kocan, PPCF 2008

[M. Cavedon *et al* 2025 *Nucl. Fusion* **65** 106007]

The physics of T_i / T_e



[M. Cavedon *et al* 2025 *Nucl. Fusion* **65** 106007]

Canonical picture

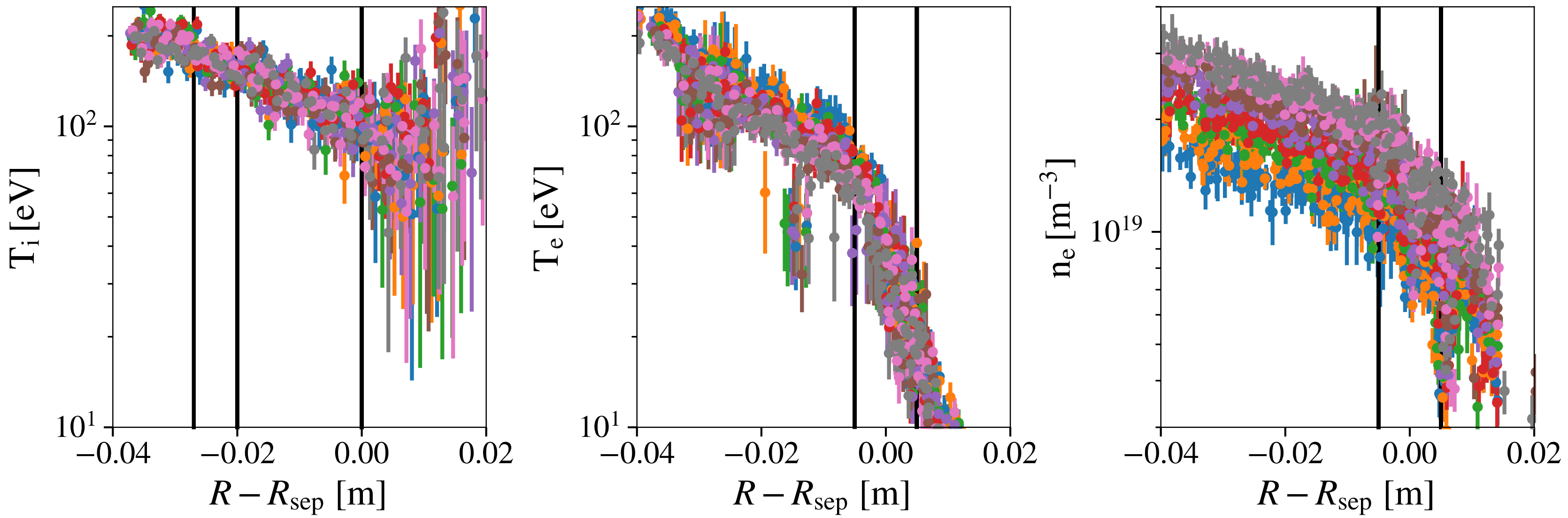
- $q_\parallel^i \ll q_\parallel^e$ due to $m_i \gg m_e$
  $q_{i,e\parallel} \propto \kappa_{i,e}\, T_{i,e}^{7/2} / L$ where $\kappa_e \approx 40\, \kappa_i$
- Ion heat exhausted through electrons

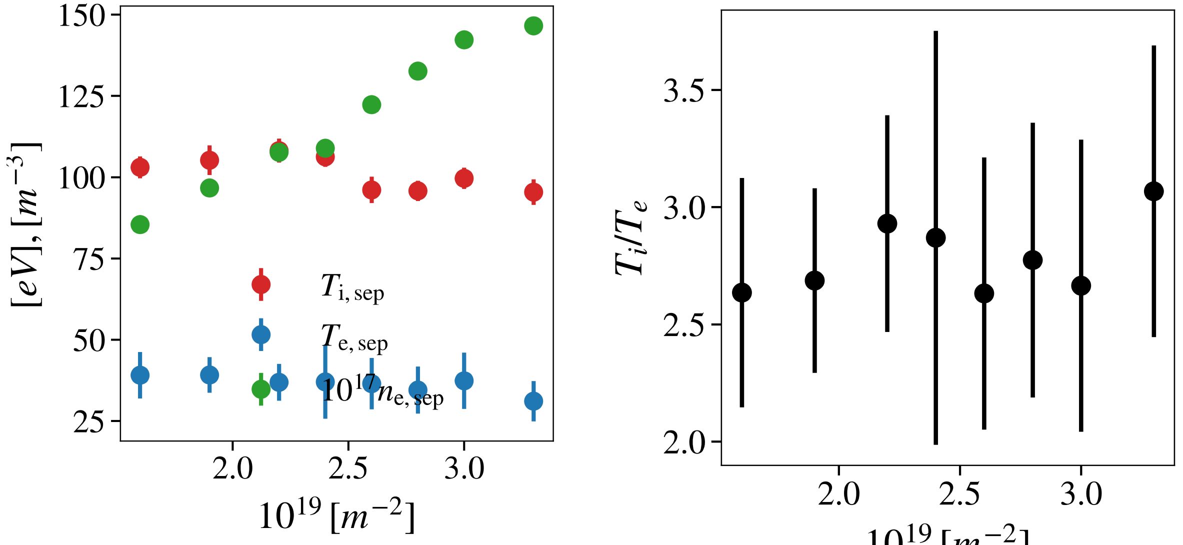
- $q_{eq}^{up} \sim \nu_{SOL}^* \sim \frac{n_e L}{T^2}$
  [Stangeby IoP 2000]

- $P_{e,i} \sim \frac{n_e(T_e - T_i)}{\tau_{e,i}} \sim \frac{n_e^2(T_e - T_i)}{T_e^{3/2}}$

Idea: scan of n_e, B_t, I_p, and power in TCV and ASDEX

Density scan in the TCV tokamak





Within a factor of 2 in n_e there is no change in T_i/T_e

Similar results for ASDEX Upgrade

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[M. Cavedon *et al* 2025 *Nucl. Fusion* **65** 106007]

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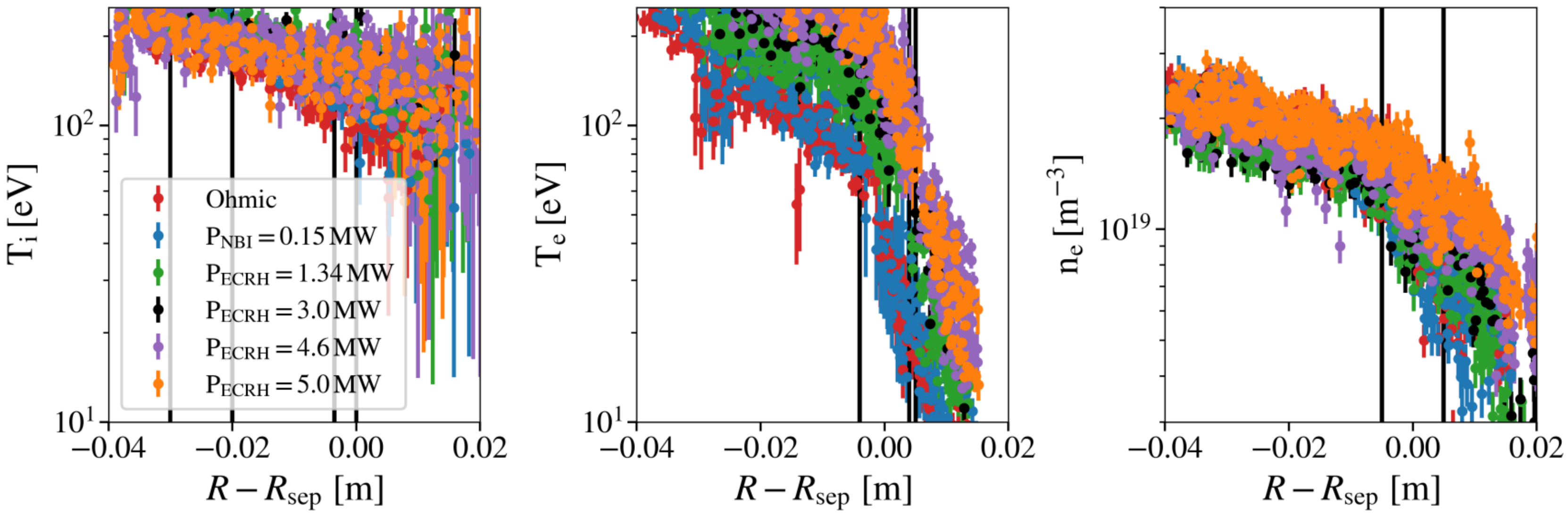
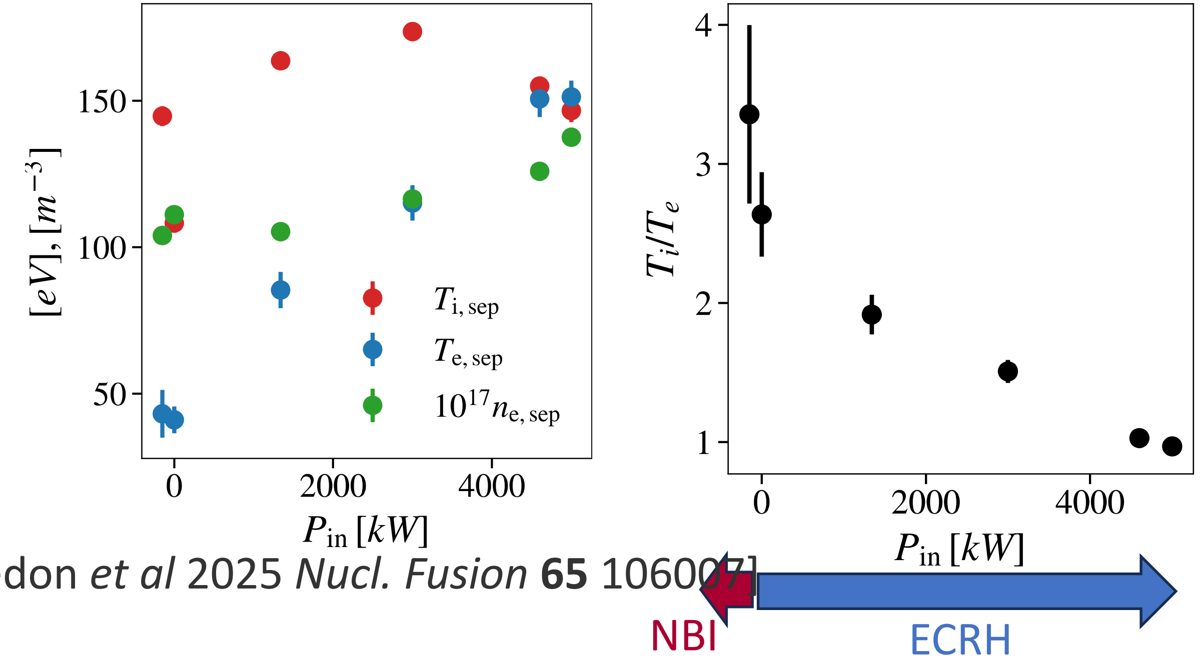
Power scan in TCV



Q_i/Q_e is the dominant factor in determining T_i/T_e



The SOL ion heat flux is not exhausted through $q_{\parallel}^{e}$, or at least this is not the most important mechanism next to the separatrix!

[M. Cavedon *et al* 2025 *Nucl. Fusion* **65** 106007]

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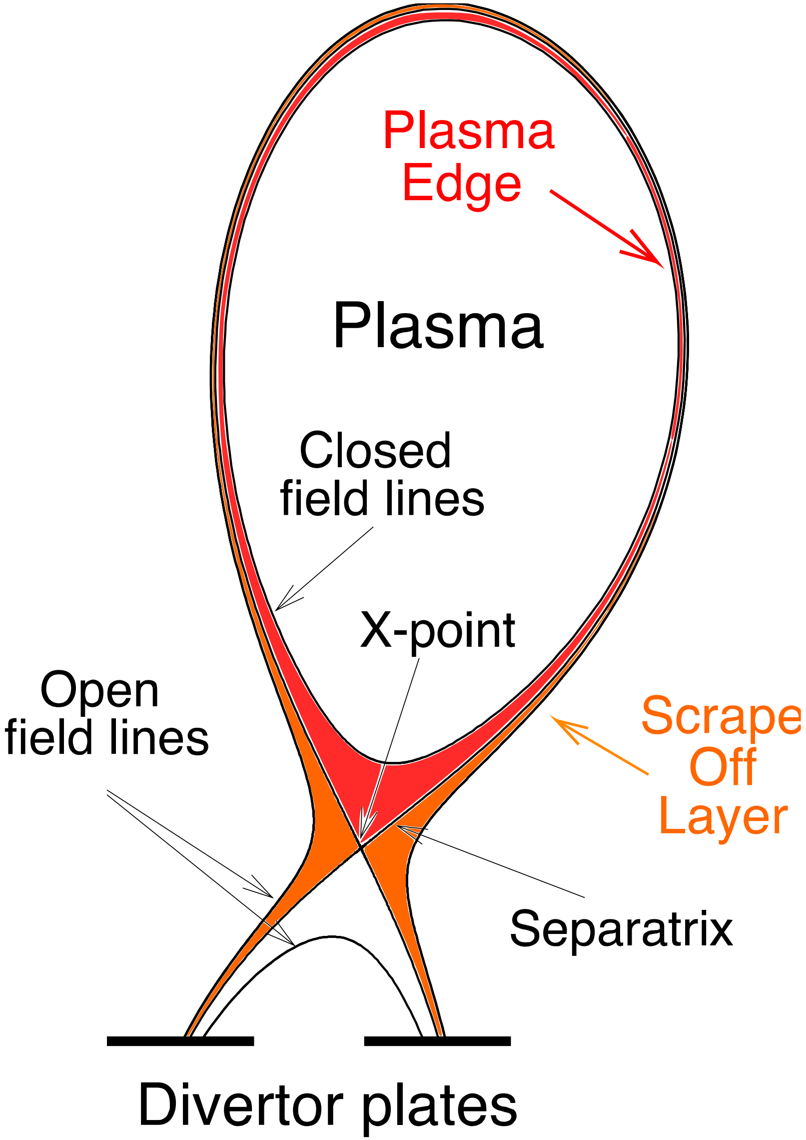
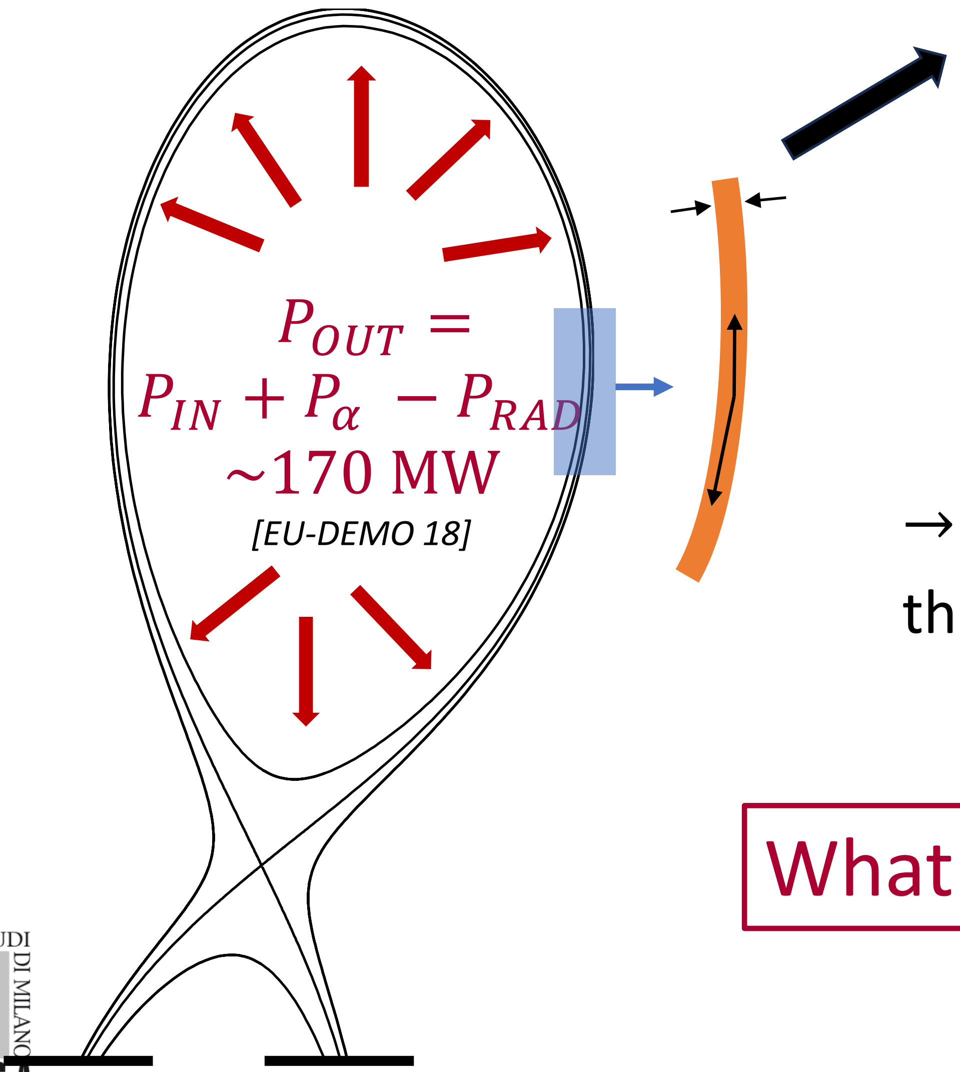


The problem of the plasma exhaust



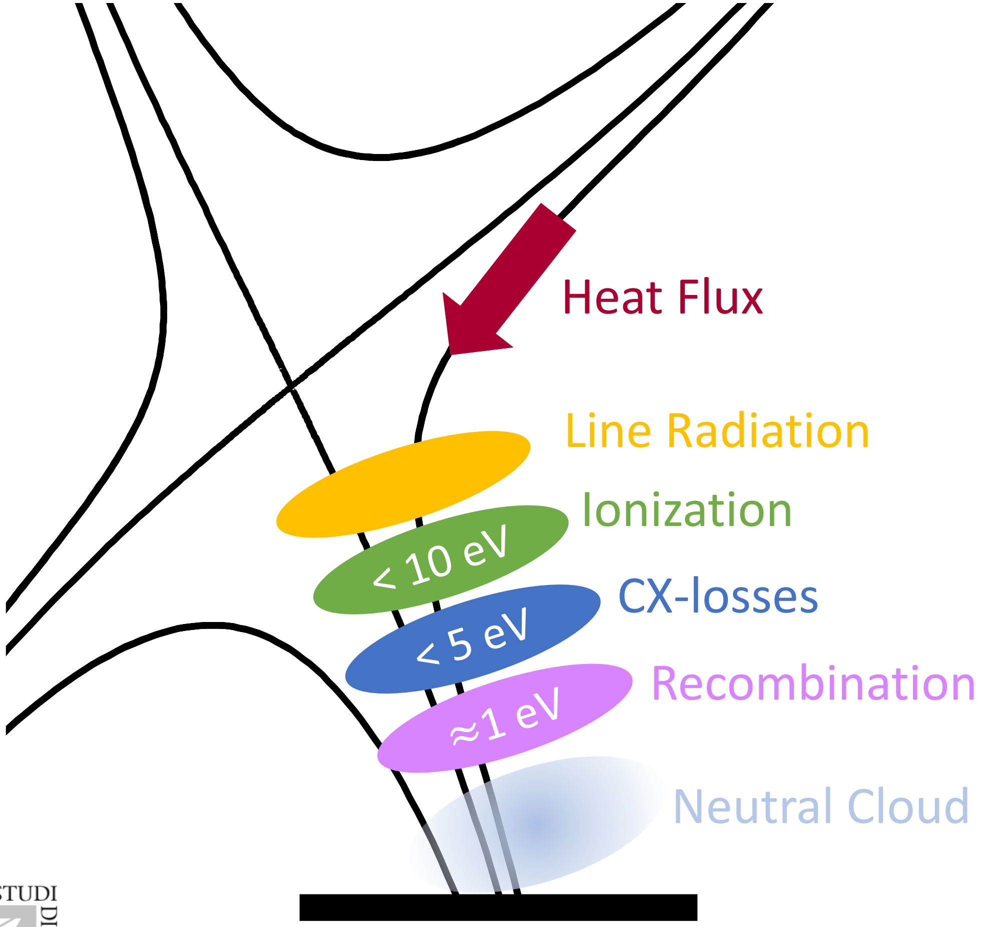
SOL "thickness" of only few mm is expected

$$A_{\mathrm{effective}} \approx 2\ \mathrm{m}^2$$

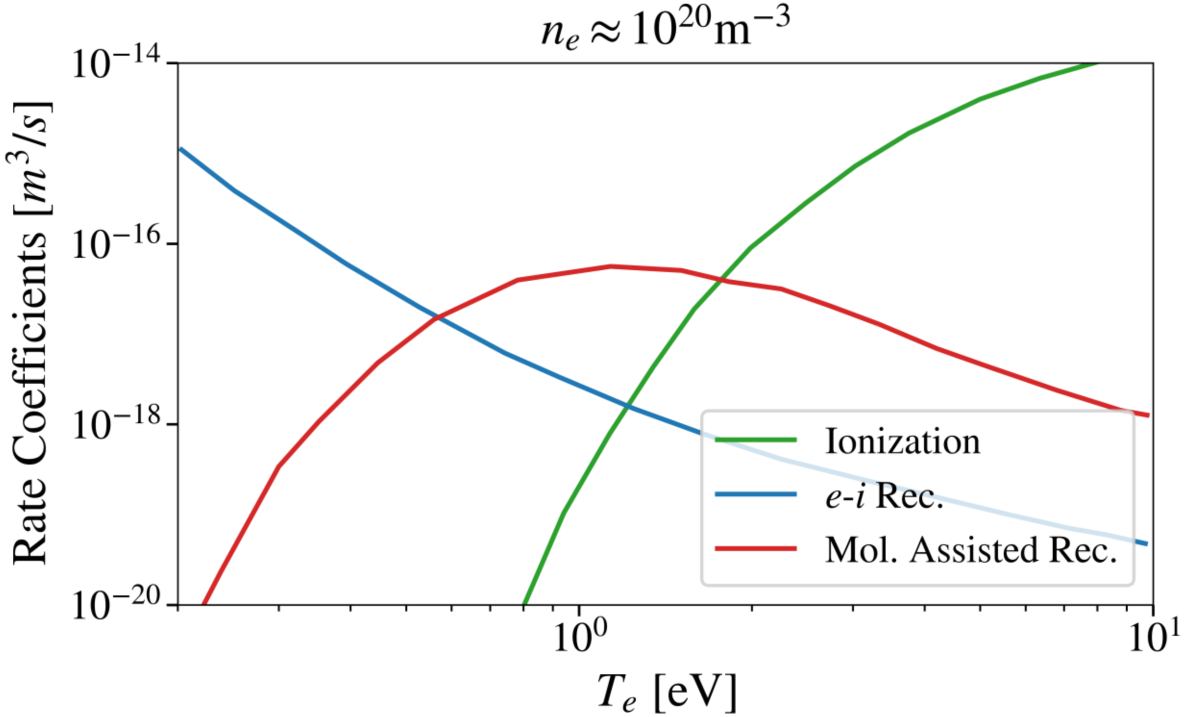
→ $q_{div} \approx 60\ \mathrm{MW/m^2}$ which is like the heat load on the sun surface ($H_{sun} \approx 63\ \mathrm{MW/m^2}$)

What can we do about it?

Plasma Detachment and D_2 molecules



- n_{D_2} is needed for particle balance
- D_2 can play an important role in the recombination region



For a review on the detachment see: A W Leonard PPCF 2018

S I Krasheninnikov 2002 *Phys. Scr.* **2002** 7

Determination n_{D_0} and n_{D_2} from Balmer lines

ASDEX Upgrade

Balmer line emission

$$\epsilon_{D(n)} = n_e\left[PEC_D^n n_D + PEC_{D^+}^n n_e\right] +$$
$$+ n_{D_2} n_e\left[PEC_{D_2}^n + PEC_{D_2^+}^n f_{D_2^+} + PEC_{D_3^+}^n f_{D_3^+} + PEC_{D^-}^n f_{D^-}\right]$$

$n = 3,4,5,6,\ldots$

Depends on

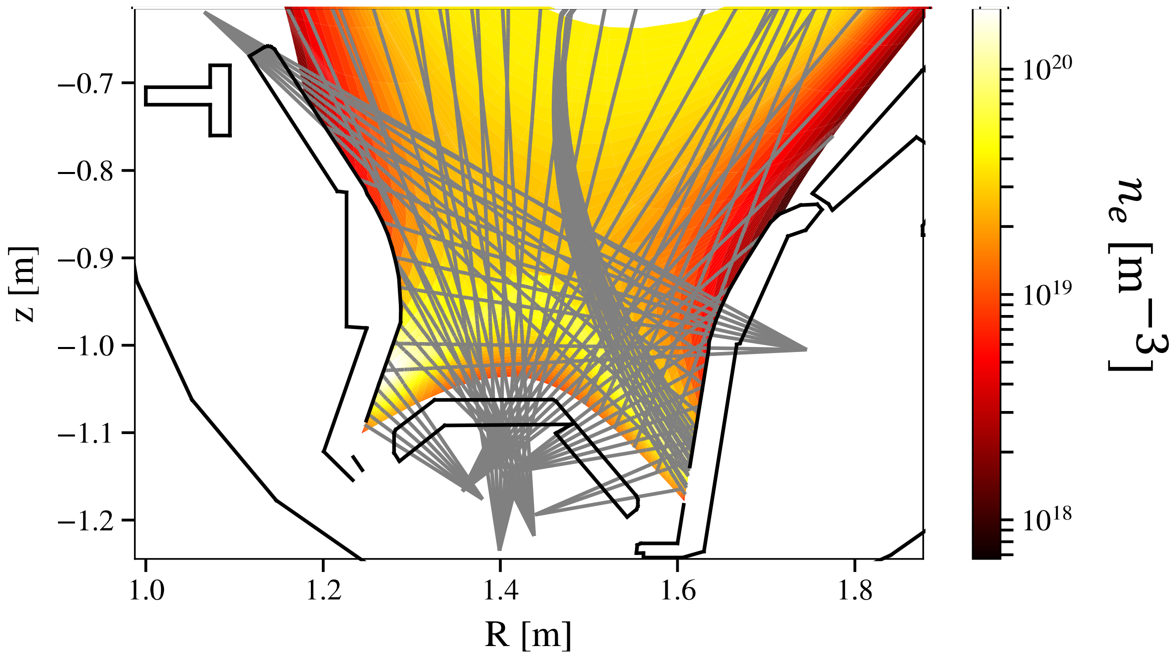
Parameters: n_e, T_e, n_{D_2}, n_D

Approximations:

- 0D approx from AMJUEL => $f_*(n_e, T_e) = n_*/n_{H_2}$
- and $n_{H^+} = n_e$

[K Verhaegh et al, PPCF 2021]

In the divertor, everything is at least 2D!!!



[T Nishizawa, M. Cavedon et al PPCF 2020]
[T Nishizawa, M. Cavedon et al PoP 2021]
[E. Huett, Master’s Thesis, TUM, 2021]

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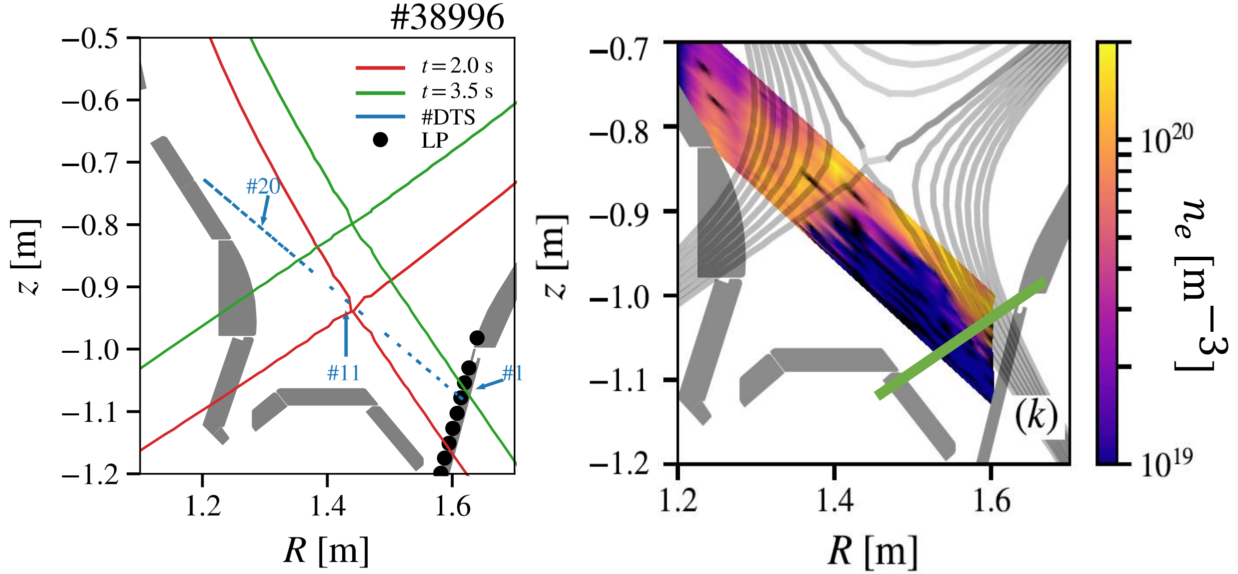
Role of n_{D_0} and n_{D_2} in the detachment

Breakthrough: first 2D n_e and T_e at ASDEX!

DTS: Divertor Thomson Scattering → n_e, T_e



Parameters: n_e, T_e, n_{D_2}, n_D

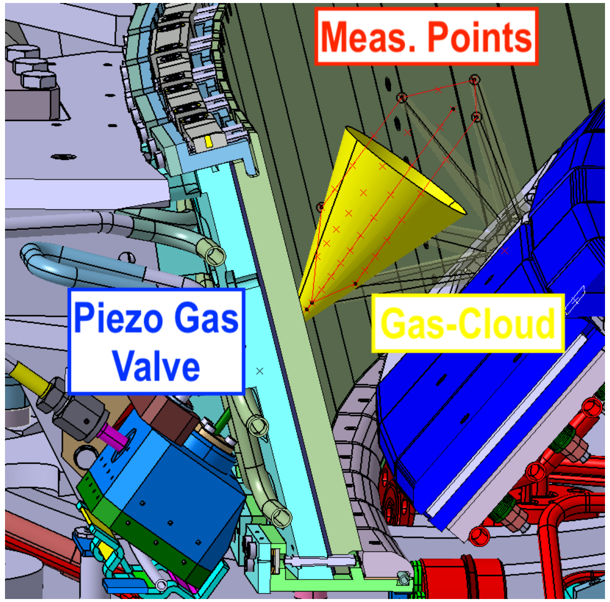
	$< n_e >$ $[m^{-3}]$	$< T_e >$ $[eV]$	$<n_{D_0}/n_e>$	$<n_{D_2}/n_e>$
Attached	$\approx 10^{19}$	9 eV	≈ 0.01	≈ 0
Start of detach.	$1.7\ 10^{20}$	1.8 eV	≈ 0.15	≈ 0
Deep detach.	10^{20}	1.0 eV	≈ 1.0	≈ 0.04

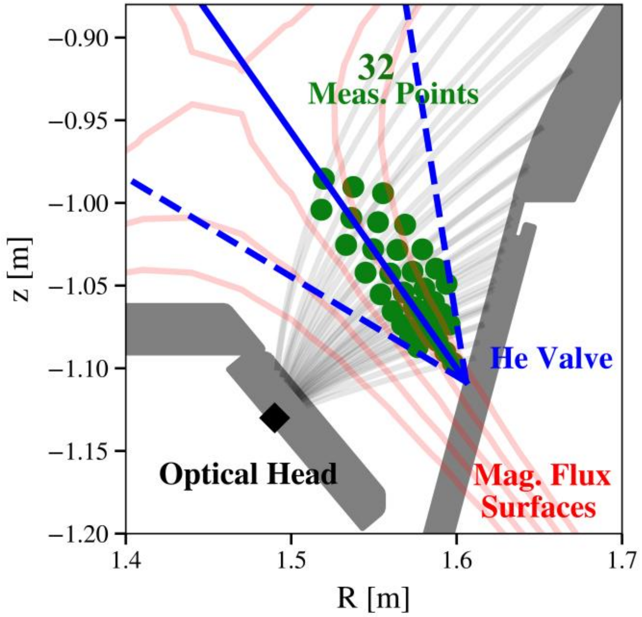
[M. Cavedon et al NF 2022]

Molecule seem to have a minor role in triggering the recombination in ASDEX, while MAR can contribute towards deep detachment

[Fantz, U. *et al.* (2001) *JNM*]

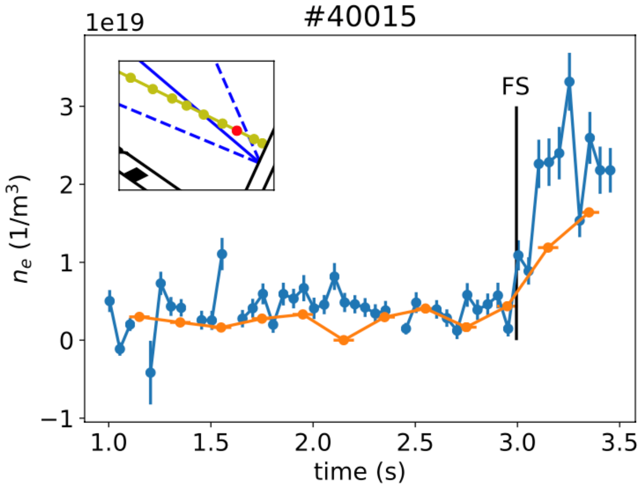
A Divertor Thermal Helium Beam for ASDEX

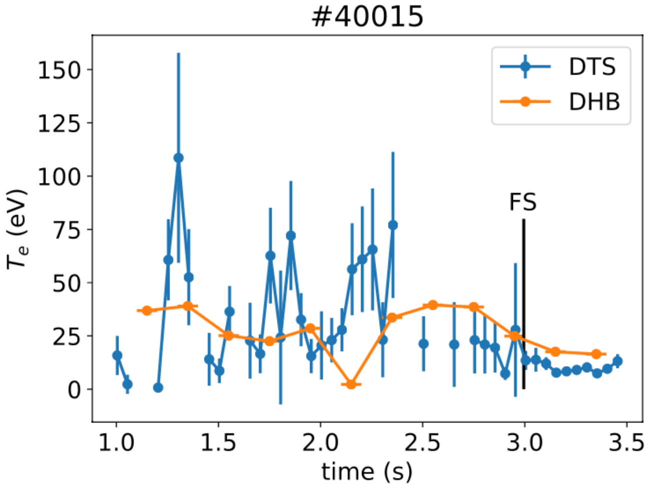




- Continuos 2D measurements of n_e and T_e at the outer divertor
- 900 kHz sampling rate → possibility to investigate turbulence phenomena in the divertor

[S. Hoermann, M. Cavedon et al, RSI (2024)]
[S. Hoermann, M. Cavedon et al, PPCF (2025)]

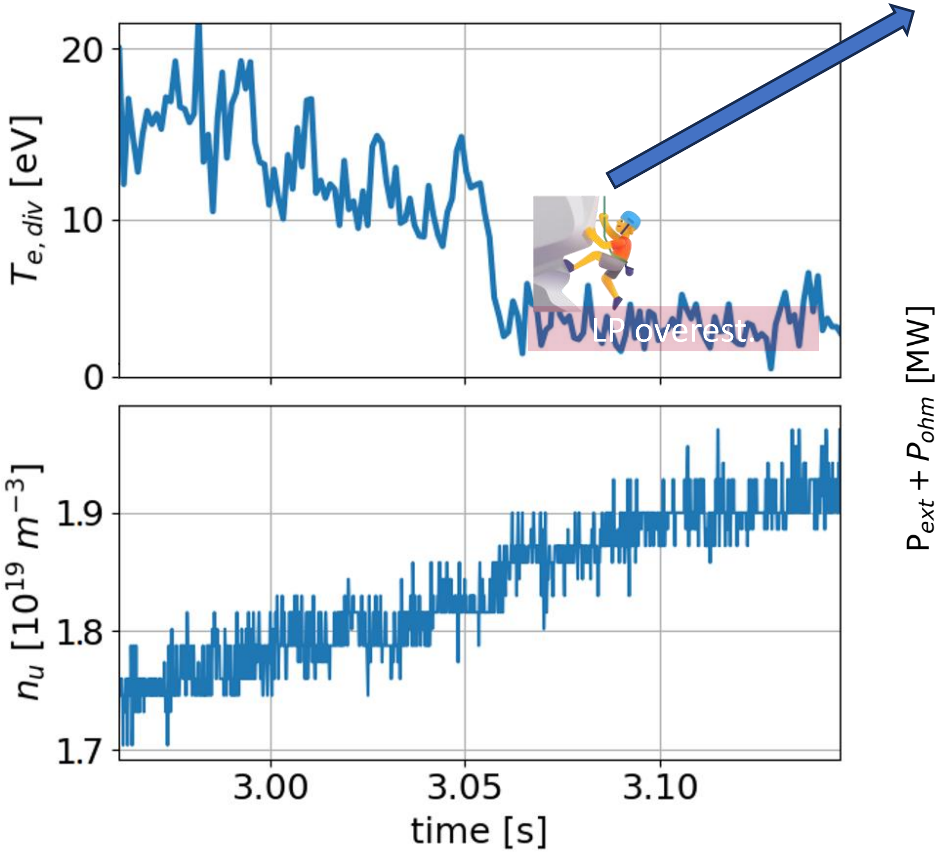


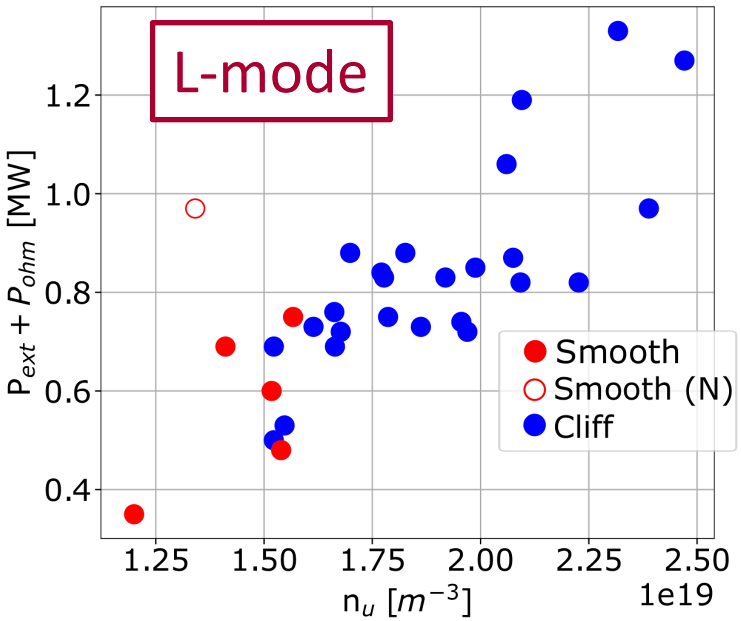


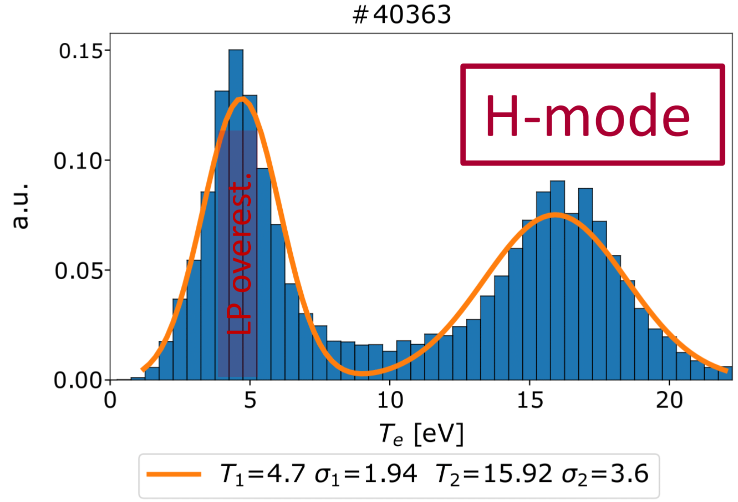
Currently designing the real-time implementation of the spectroscopy diagnostics (T_i, v_{rot}, n_{imp}, …) in AUG
(B. Tosto *et al*)

The detachment "cliff"

- First observed in [McLean et al. JNM 2015] but only in H-mode at DIII-D







[L. Scotti, M. Cavedon et al, PPCF 2025]

→ Physics of detachment (modelling effort ongoing, L. Scotti):
  - Triggering mechanism of the detachment

→ Detachment control:
  - The presence of a transition processes must be known

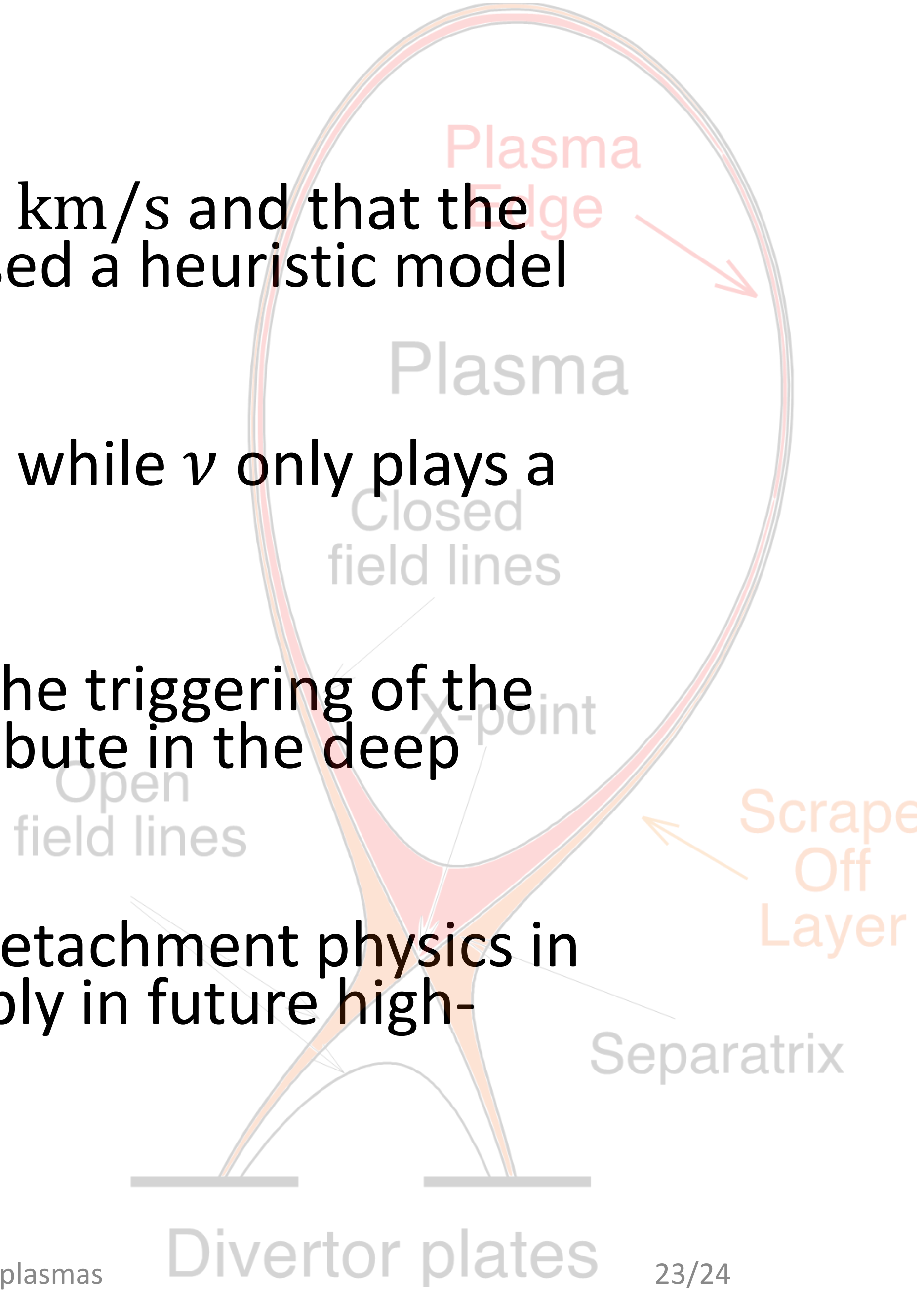
Conclusions

- Using the experimental findings that $v_{E\times B} \approx 6\ \mathrm{km/s}$ and that the ions are key player in L-H transition, we proposed a heuristic model of P_{thr}

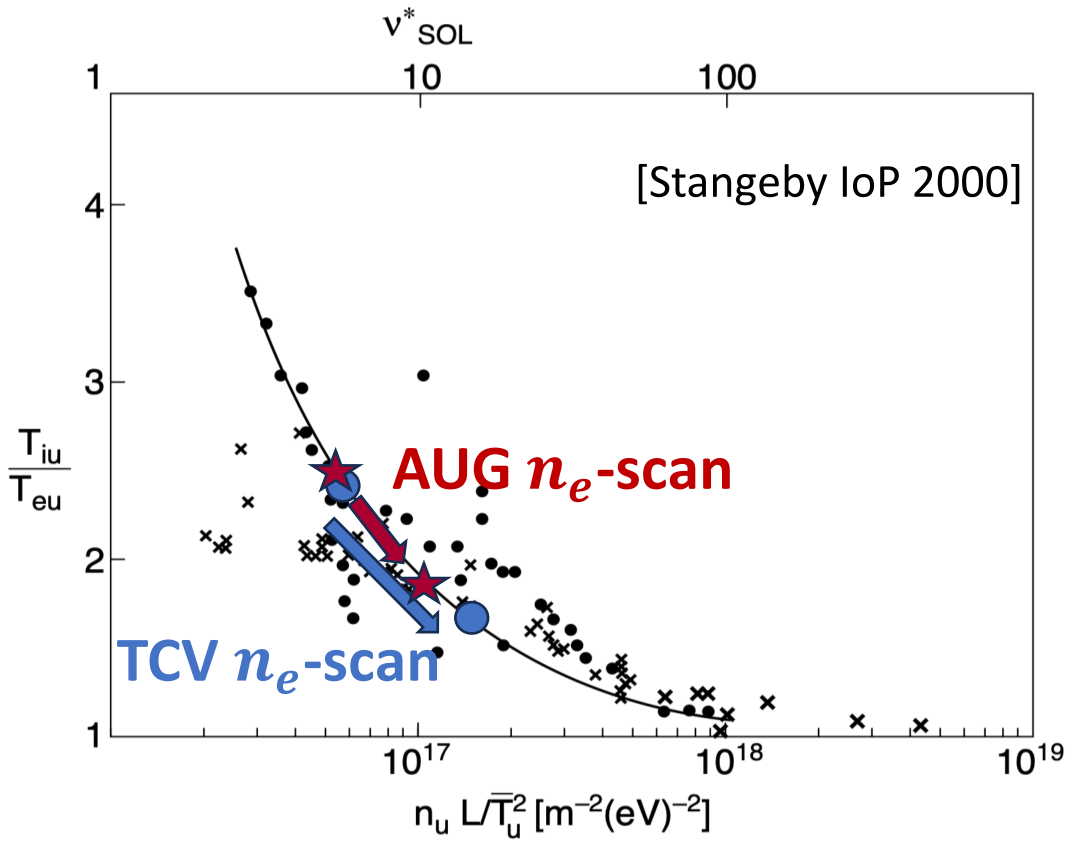
- T_i/T_e at the separatrix is determined by Q_i/Q_e while ν only plays a minor role

- Molecular processes only play a minor role in the triggering of the recombination in ASDEX, while MAR can contribute in the deep detachment

- The detachment “cliff” is a key feature of the detachment physics in ASDEX in both L-mode and H-mode, and possibly in future high-density machines



Are we in the right n_e-range? [Stangeby IoP 2000]

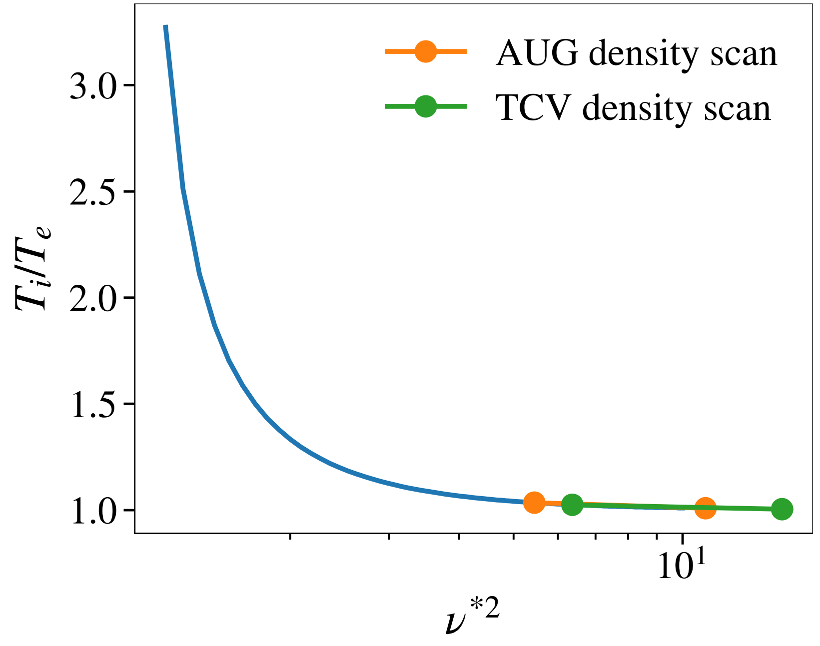


$$\underbrace{\kappa_{i,e}\frac{T_i^{7/2}}{L}}_{q_{i,\parallel}} \propto \underbrace{L\frac{n_e^2(T_i - T_e)}{T_e^{\frac{3}{2}}}}_{q_{i\to e}}$$

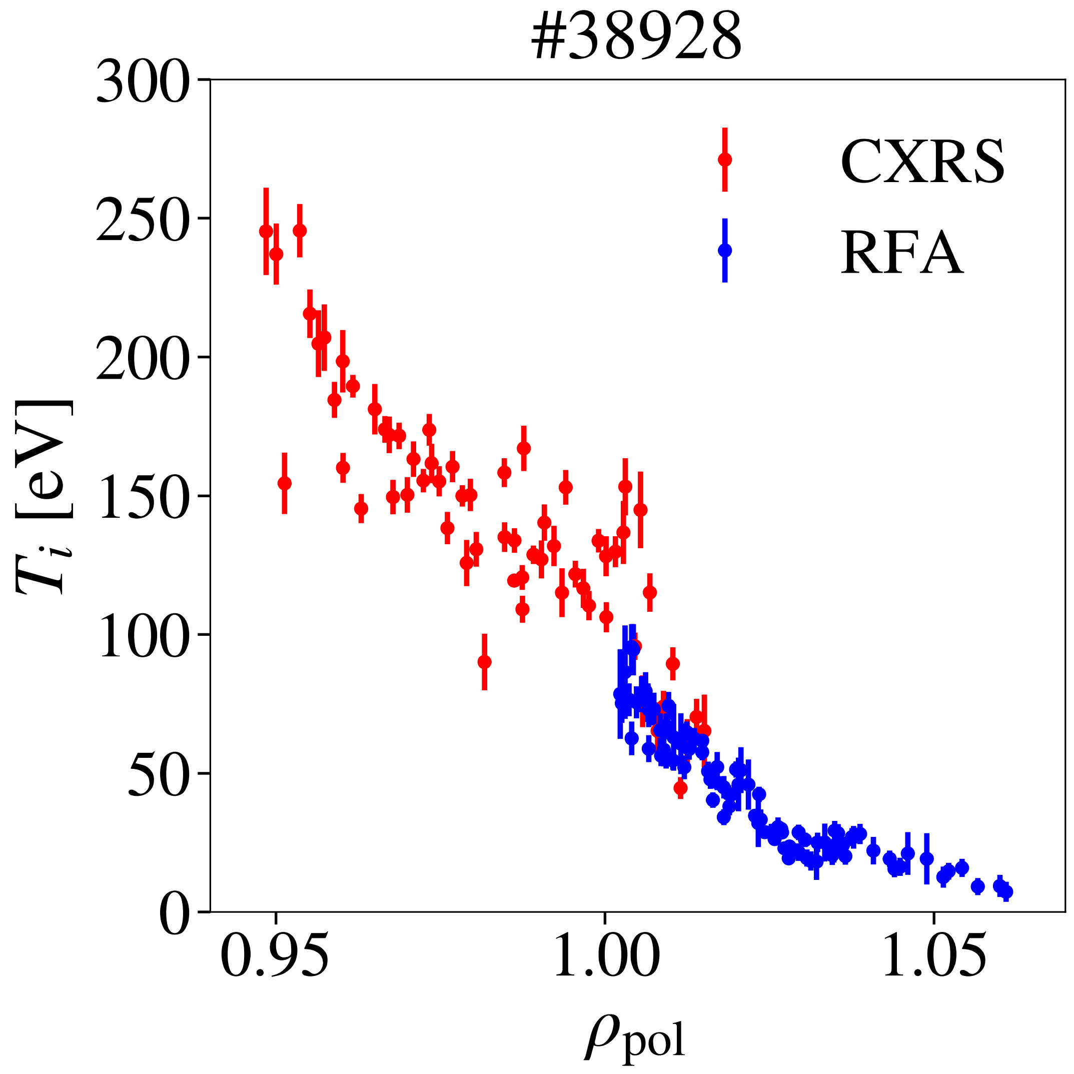
[Brida, E2M seminar, 2023]

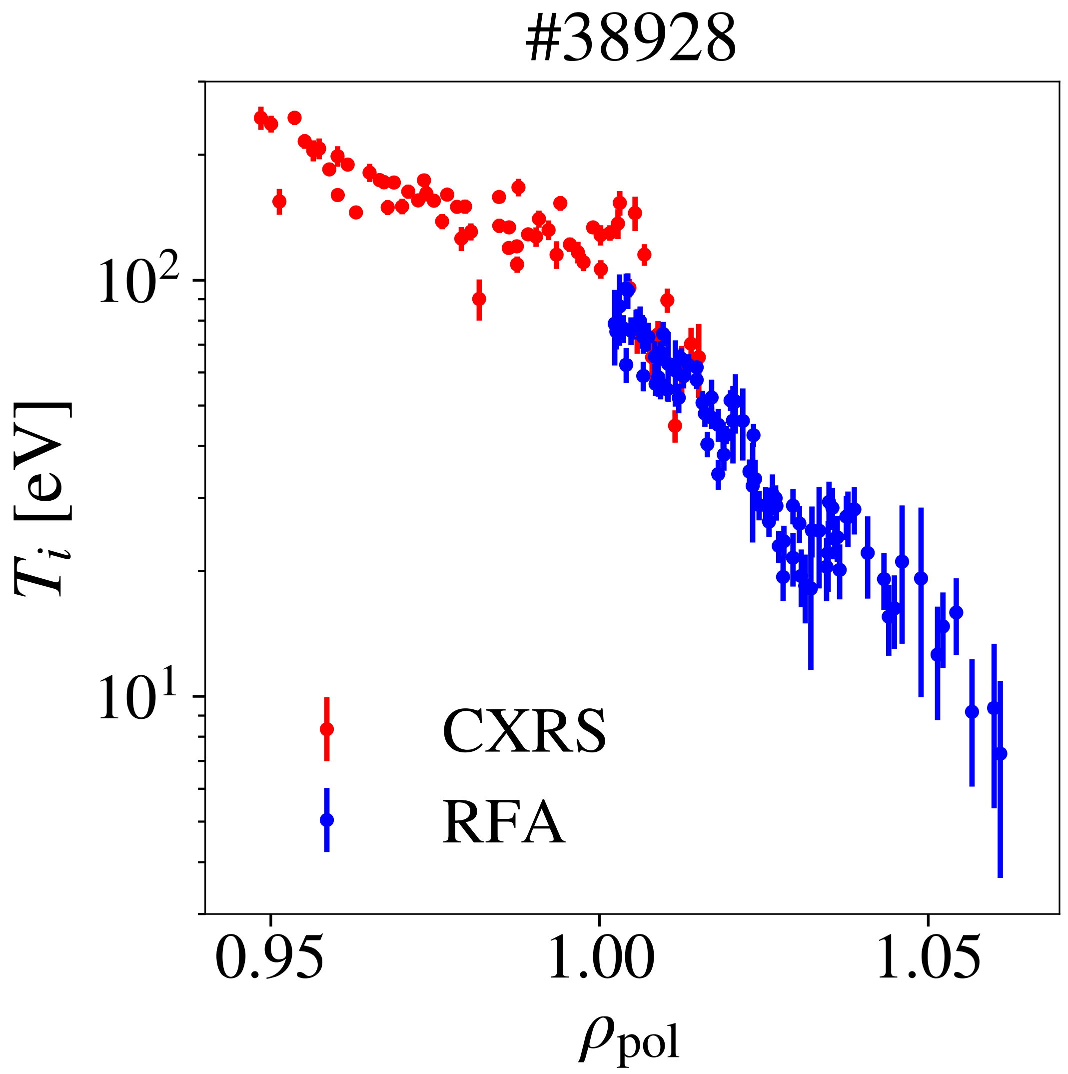
$$\frac{\tau_i}{\tau_i - 1} \propto \frac{L^2 n_e^2}{T_i^{5/2} T_e^{3/2}} \sim \nu^{*2}$$

Collisionality

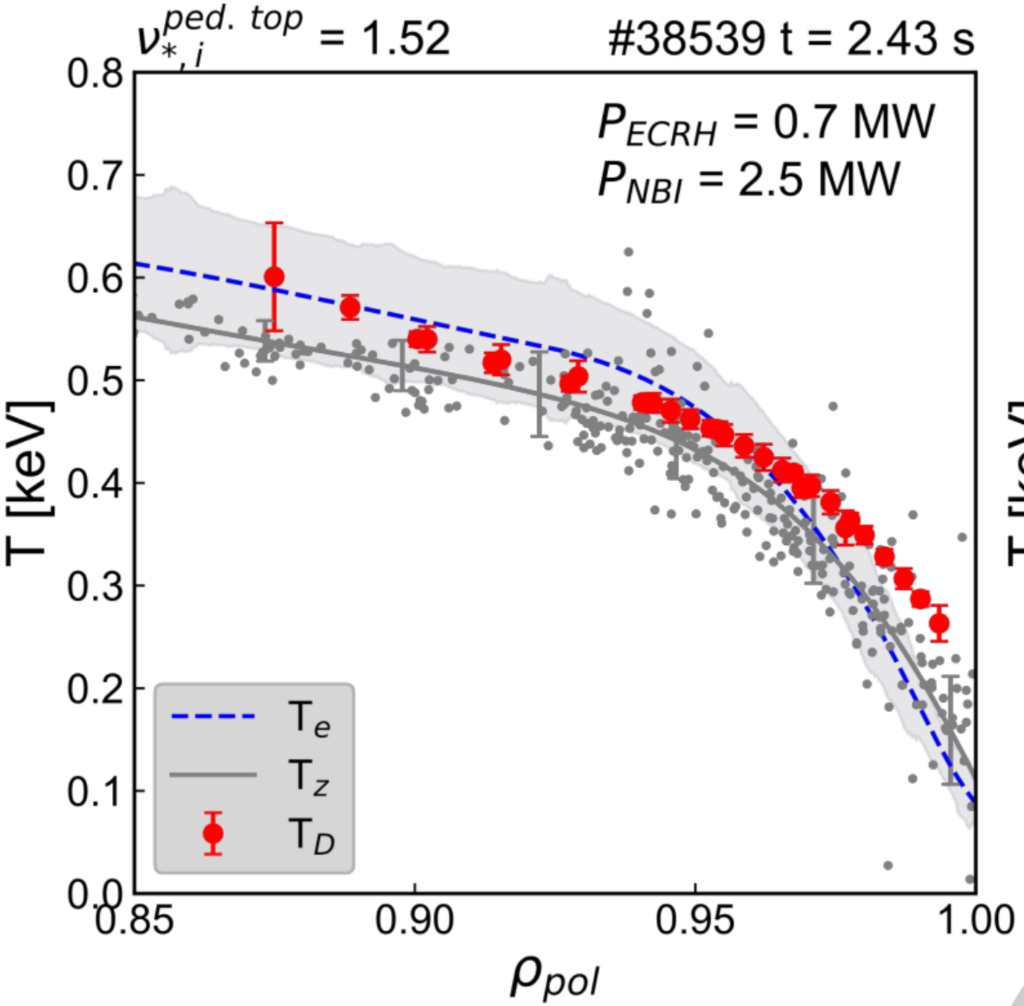


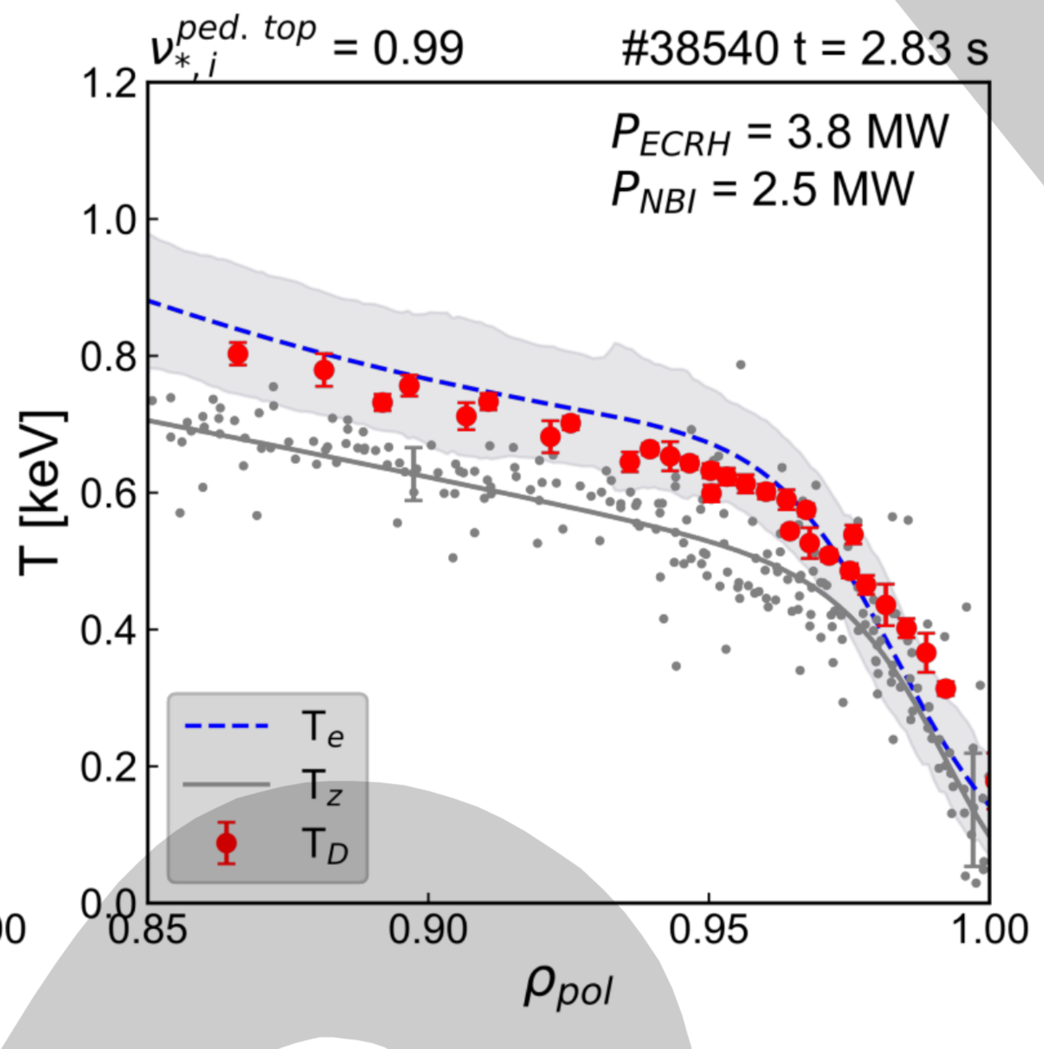
Comparison to RFA



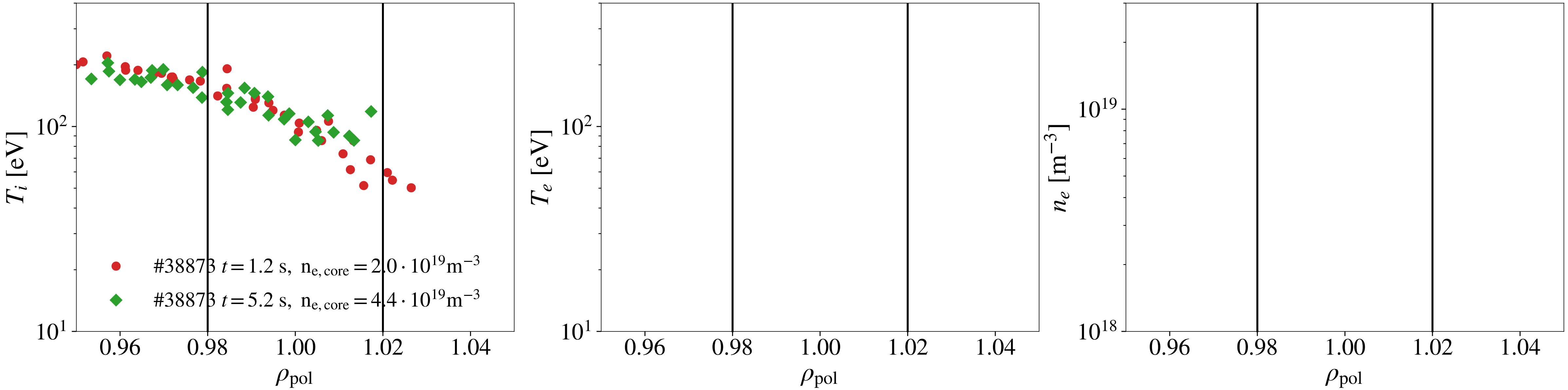


Main Ion CX (P. Cano-Megias et al, upcoming EPS)



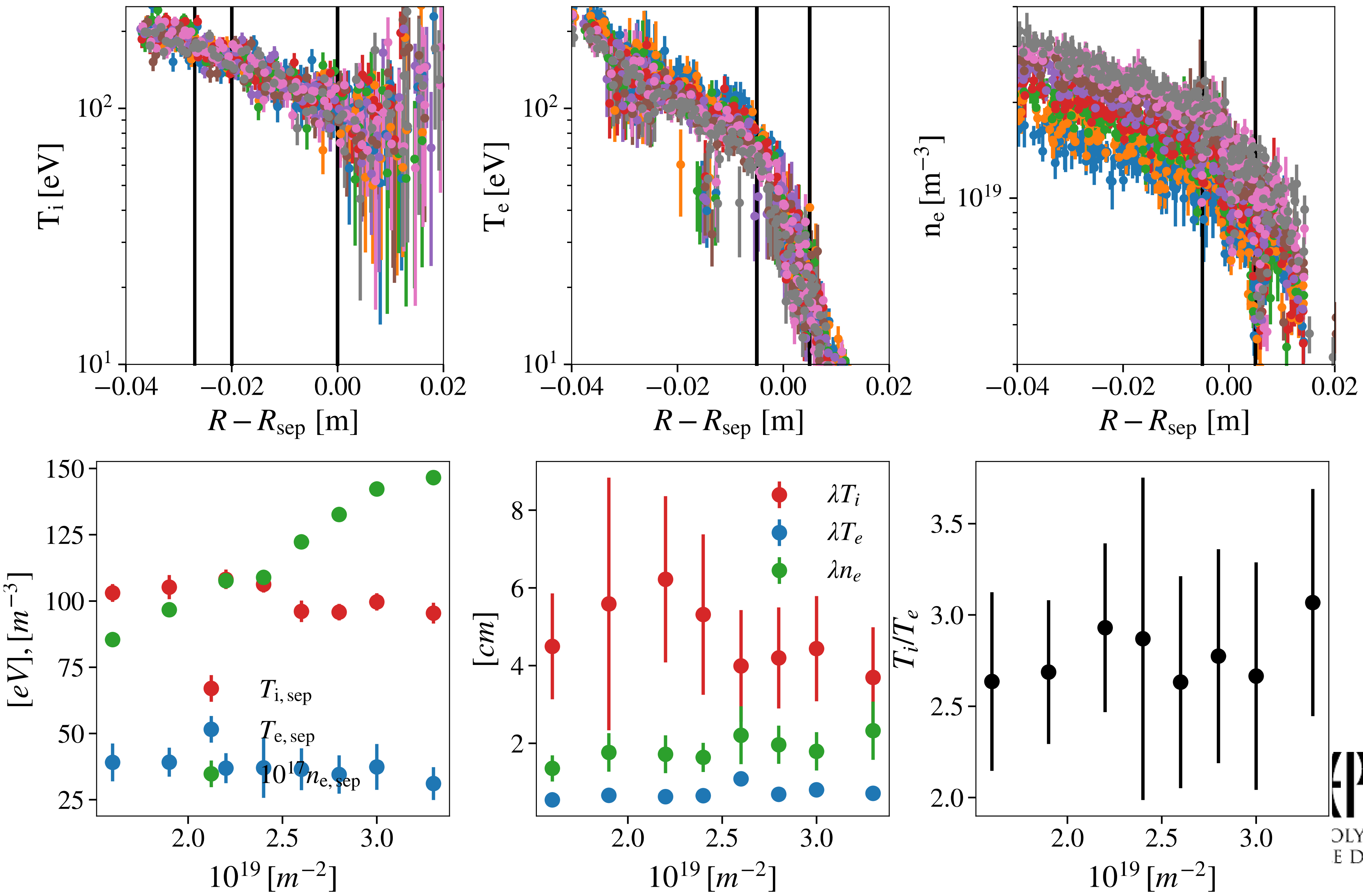


Density Scan



	T_i	T_e	n_e
Sep Value [eV,eV,m^{-3}]	103 ± 23 eV 110 ± 21 eV	43 ± 13 eV 45 ± 8 eV	$7.5 \pm 0.1 \cdot 10^{18}\, m^{-3}$ $1.7 \pm 0.2 \cdot 10^{19}\, m^{-3}$
λ [cm]	2.4 ± 0.4 2.7 ± 0.8	1.5 ± 0.1 1.6 ± 0.2	1.56 ± 0.06 2.48 ± 0.18

$$T_{i,sep} \approx 2.3 \cdot T_{e,sep} \qquad \lambda_{T_i} \approx 1.6\, \lambda_{T_e}$$



$\lambda_{T_i} \approx 2.5\ \lambda_{T_e}$ → is it maybe because I cannot go over the LCFS?

λ_{n_e} increases towards detachment as in AUG

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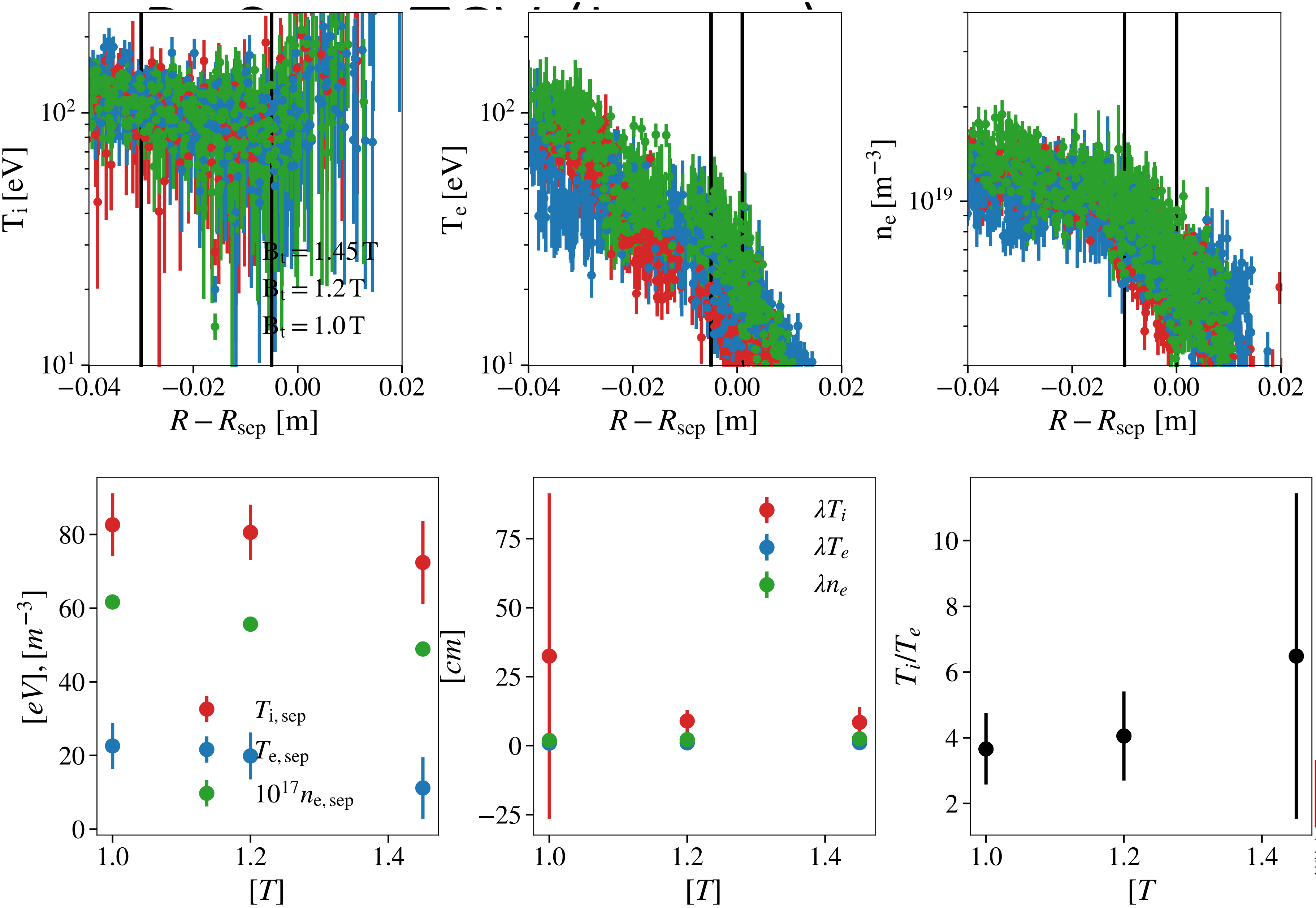

$\lambda_{T_i} \gg \lambda_{T_e}$ → CXRS around LCFS worse

T_i/T_e maybe larger? Difficult to say

Increasing Bt -> decreasing T_{sep} (better confinement?)

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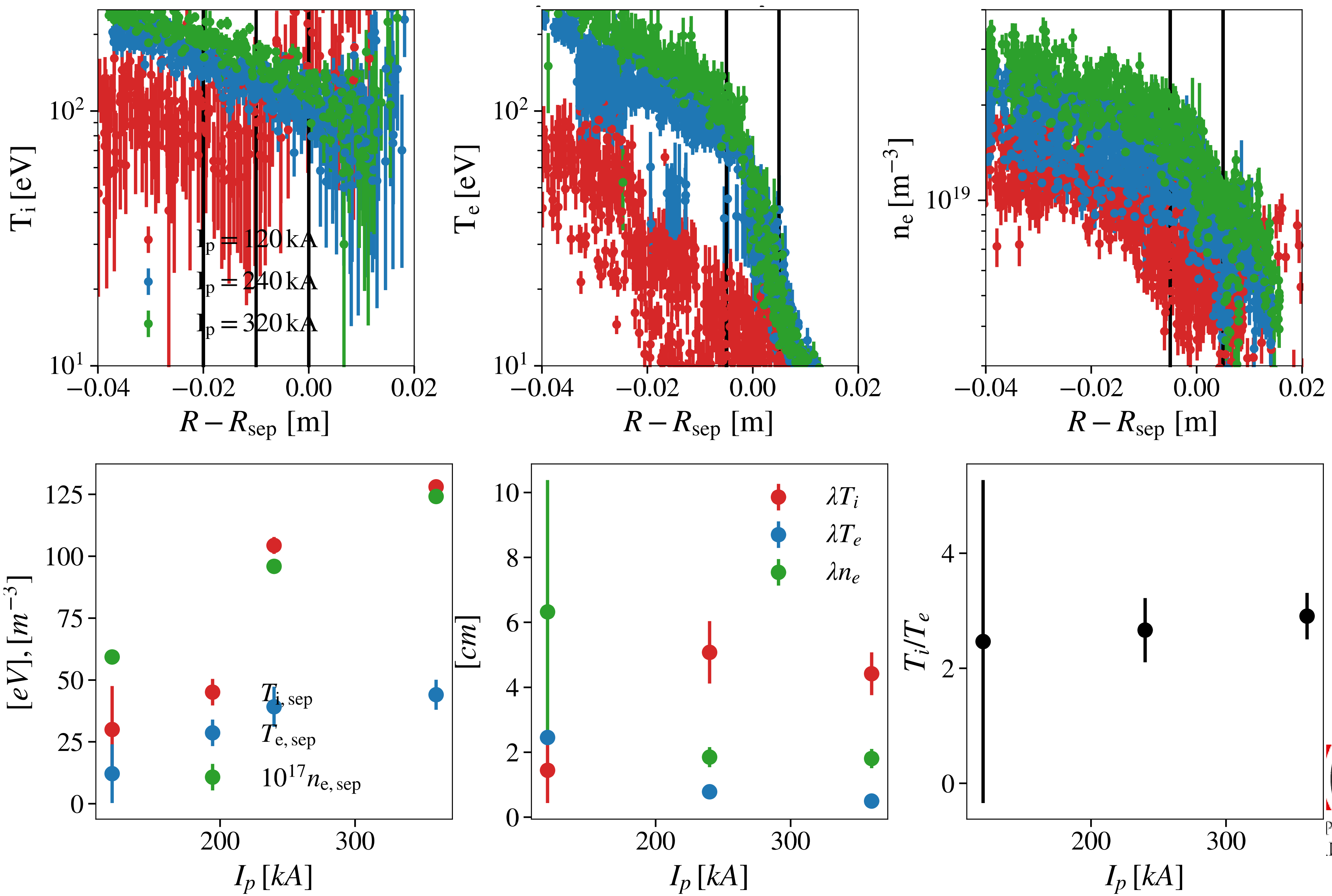
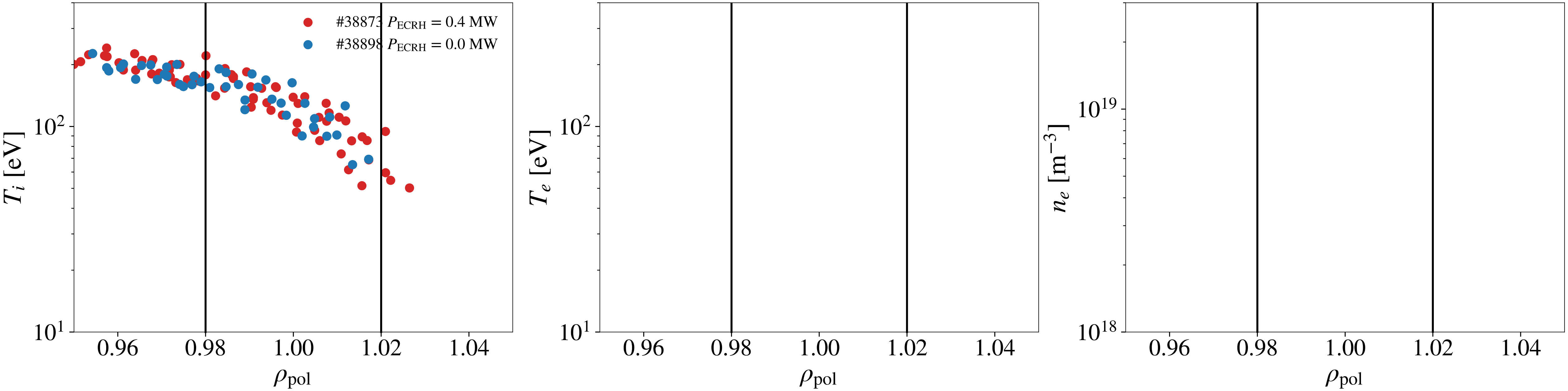


Large changes in all
Terms with Ip, but
Ti/Te remains constant

SWISS PLASMA CENTER

Power scan AUG



Not the best, most of ECRH power lost in radiation

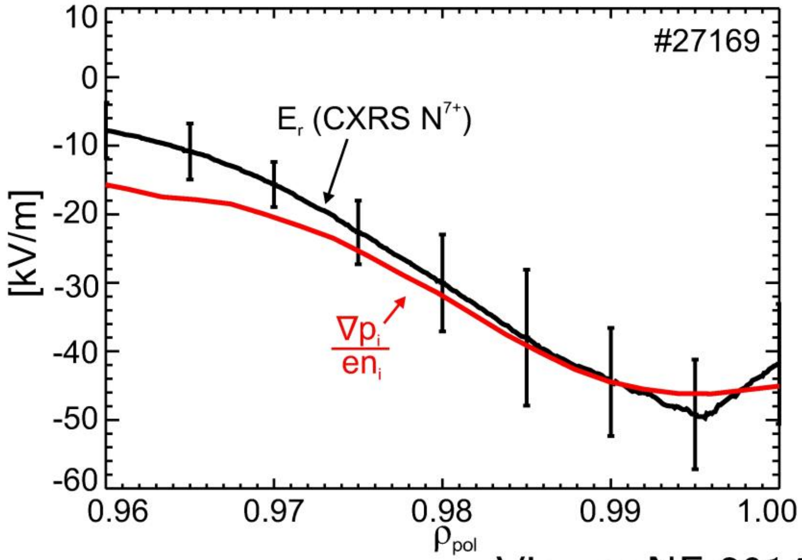
Nature of the radial electric field

Neoclassical theory predicts [1]:

$$E_{r,\text{NEO}} \simeq \frac{\nabla(T_i n_i)}{e n_i} = \frac{v^i_{\text{dia}}}{B}$$

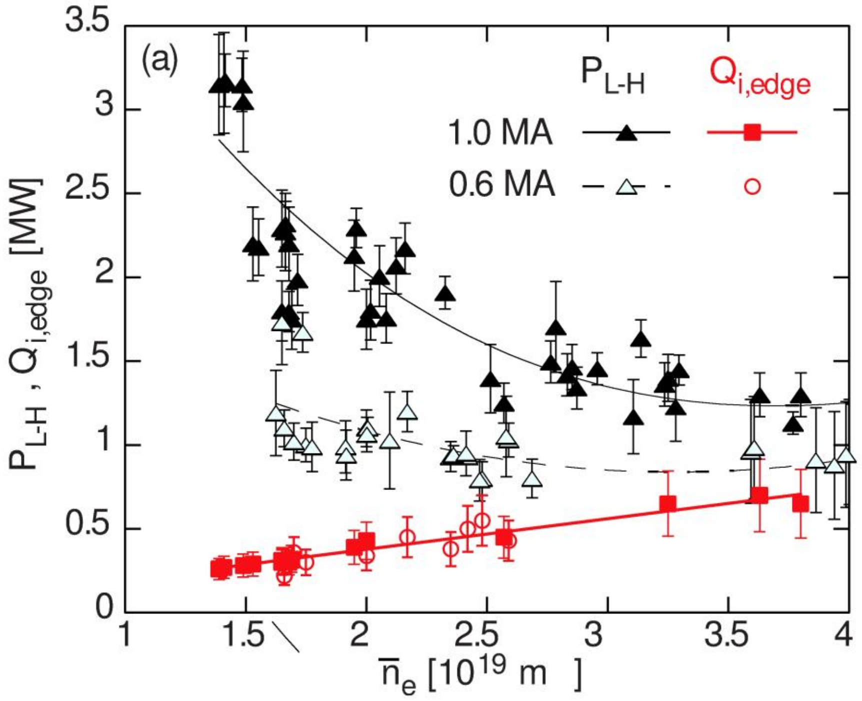
$i =$ main ions

H-mode: $E_r \sim E_{r,\text{NEO}}$



Viezzer NF 2014

Correlation H-mode and Ion Heat Flux



[Ryter NF 2014]

[1] Hinton Rev.Mod.Phys. 1976

Charge eXchange Recombination Spectroscopy

CX spectra contributions:

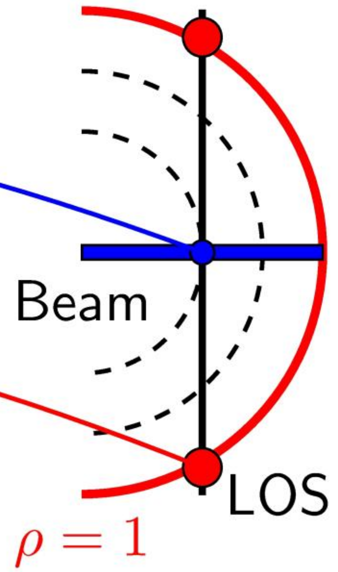
- Active:

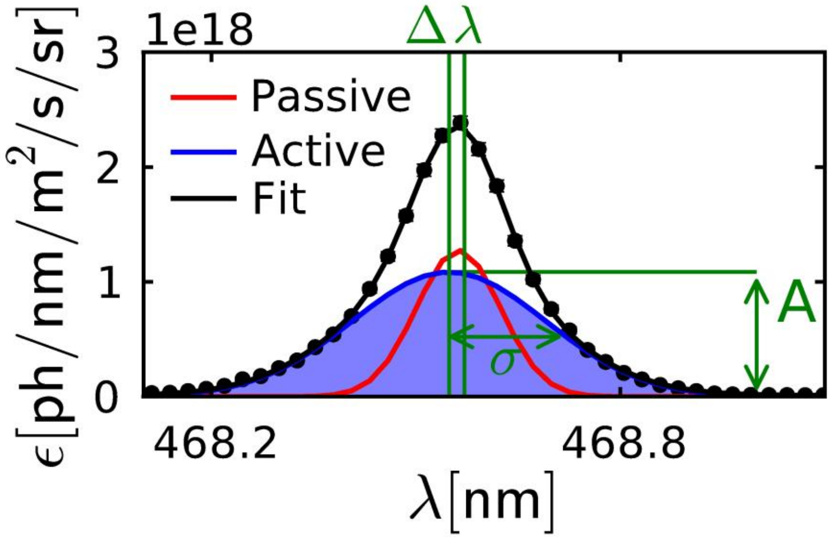
  $\mathcal{A}^{Z+} + D^0_{beam} \rightarrow \mathcal{A}^{(Z-1)+} + h\nu + D^+$

- Passive:

  $\mathcal{A}^{(Z-1)+} + e, i \rightarrow \mathcal{A}^{(Z-1)+} + h\nu + e, i$

  $\mathcal{A}^{Z+} + D^0_{thr} \rightarrow \mathcal{A}^{(Z-1)+} + D^+_{thr} + h\nu$



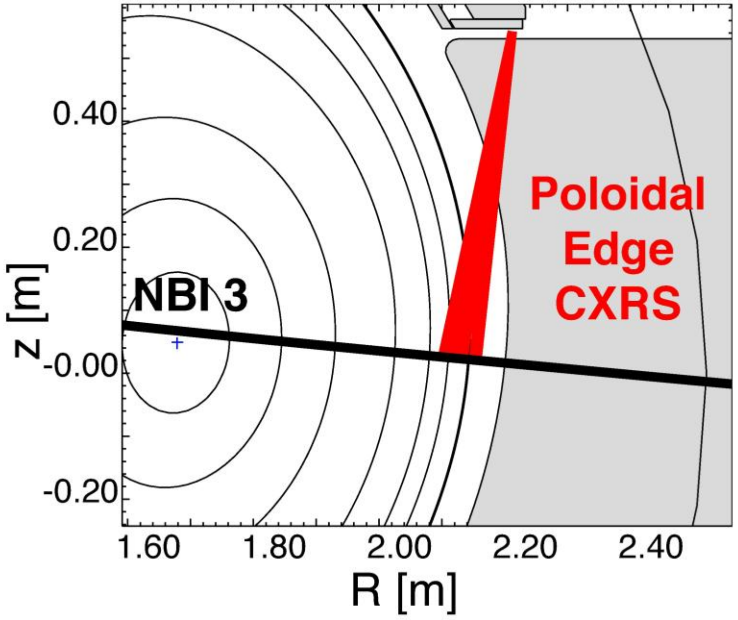


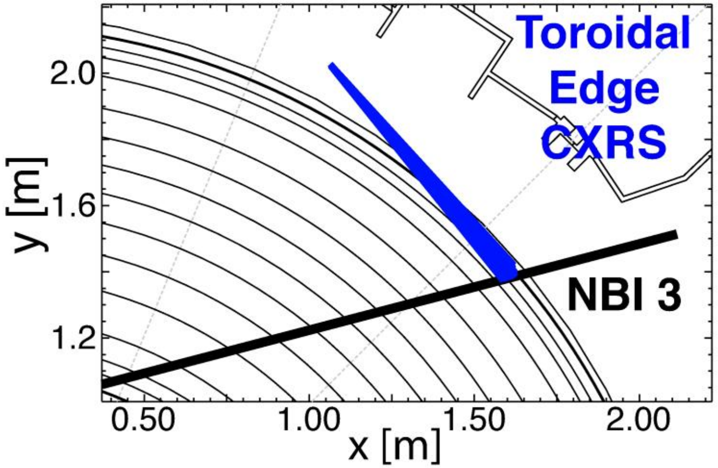
Localized measurements of:

- $\sigma \Rightarrow T_i$
- $A \Rightarrow n_\alpha$
- $\Delta\lambda \Rightarrow v_\alpha$

$$\Rightarrow E_r = \frac{\nabla p_\alpha}{e Z_\alpha n_\alpha} - v_{p,\alpha} B_t + v_{t,\alpha} B_p$$

Edge CXRS at ASDEX Upgrade





- 52 LOS:
  CPR: 21 poloidal (1 head)
  CMR: 31 toroidal (3 heads)

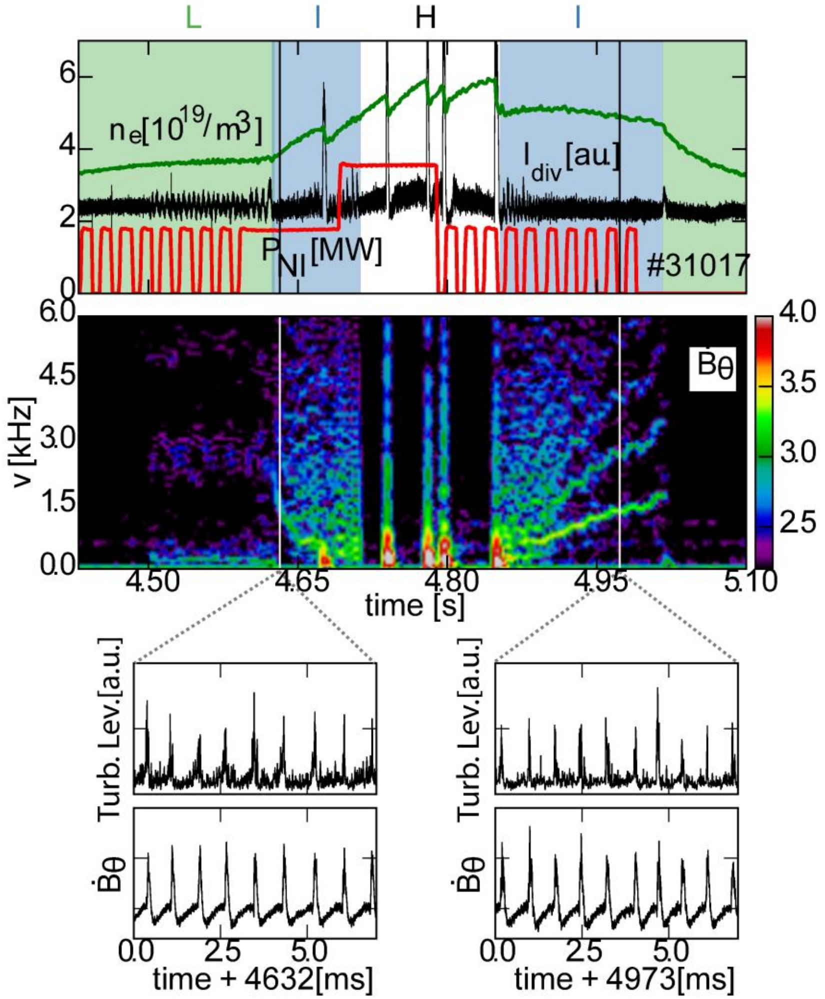
$$E_r = \frac{\nabla p_\alpha}{e Z_\alpha n_\alpha} - v_{\theta,\alpha} B_\phi + v_{\phi,\alpha} B_\theta$$

$$\alpha = \mathrm{He}^{2+}, \mathrm{B}^{6+}, \mathrm{N}^{7+}, \ldots$$

- Radial Coverage and Resolution:
  $R_{maj} \in [2.10, 2.16]$ m, $\Delta r \leq 5$mm
- Temporal Resolution:
  - 35 LOSs@2.3ms (old)
  - 9 LOSs@100μs (new)

[Cavedon et al, RSI 2017]

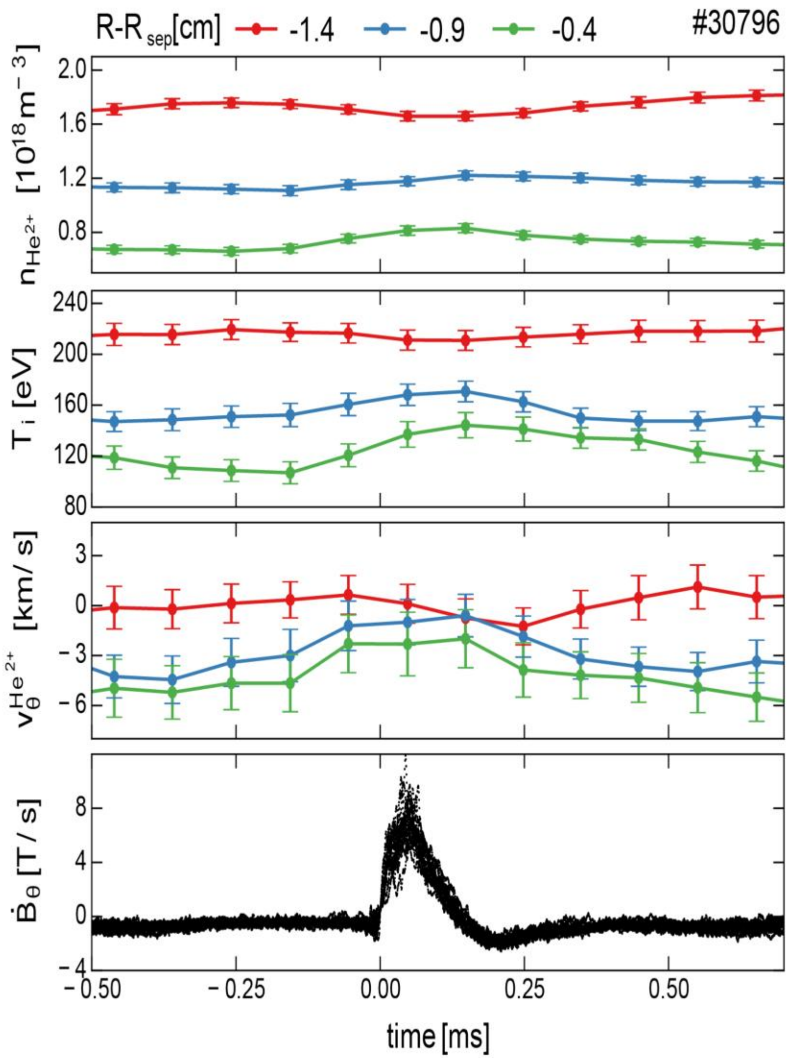
Correlate Macro to Micro: E_r and P_{thr}



- I-phase:
  - present at the L-H and H-L transitions [Zohm PPCF 95, Schmitz NF 14]
  - turbulence bursts A_D correlated with magnetic signal $\dot{B}_\theta$
  - increase of particle and energy confinement (see type-I ELM and H-L transition)

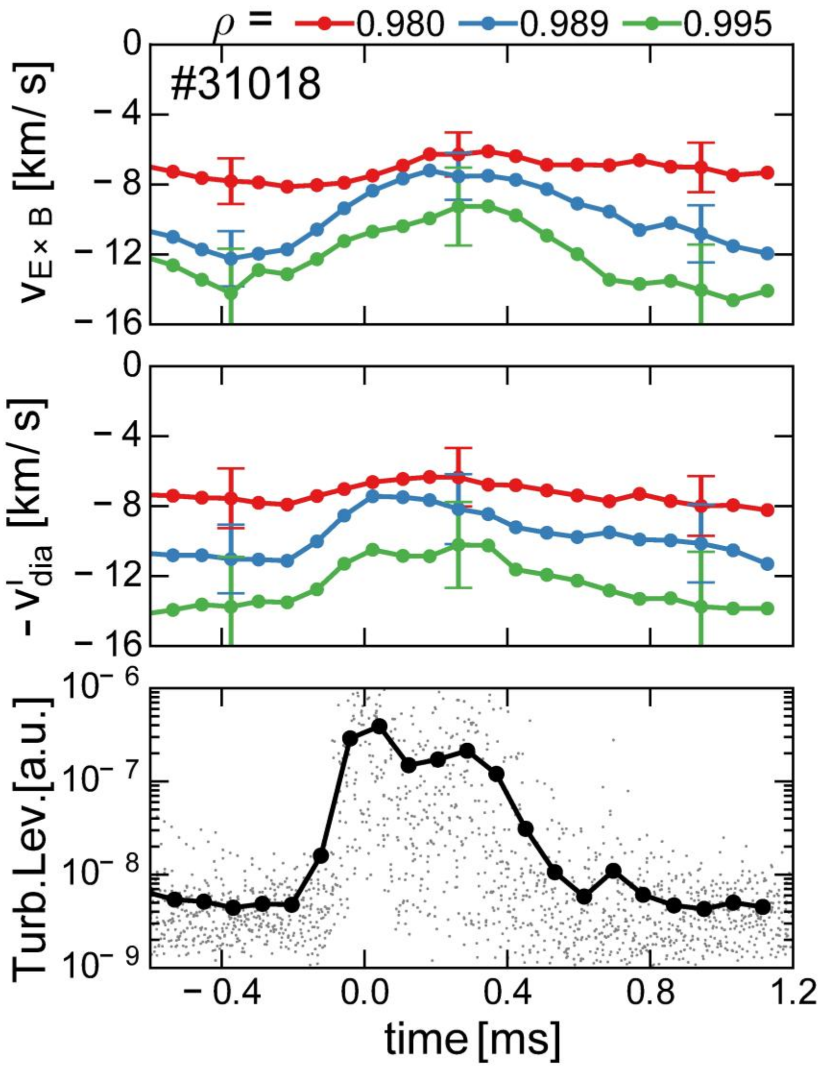
- Compare $\min(E_r)$ and P_{thr}
  - $\min(E_r) \approx \nabla E_r$ [Viezzer NF, 14]
- E_r vs $E_{\mathrm{r,neo}}$ fast dynamics

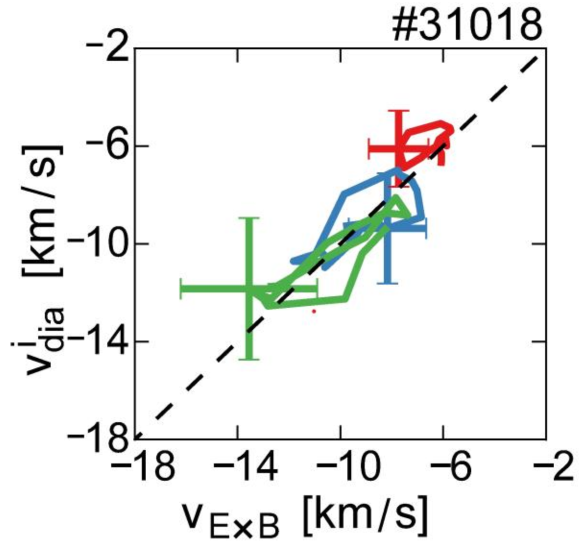
Profile evolution during a stable I-phase



- Reduction of the Edge Profile Gradients at the turbulence onset
- $v^i_{\mathrm{dia}} = \nabla p_i/(eBn_i)$ fluctuates in phase with $v_{\mathrm{E}\times\mathrm{B}}$ during the I-phase [Zohm PPCF 96, Cholchin NF 02]
- Neoclassical flow need to be included in the fast turbulence-flow interaction

E_r vs Neoclassics during constant I-phase





[Cavedon et al, NF, 2017]

$v_{\mathrm{E\times B}} \approx v^i_{\mathrm{dia}}$ within $100\,\mu\mathrm{s}$ time resolution

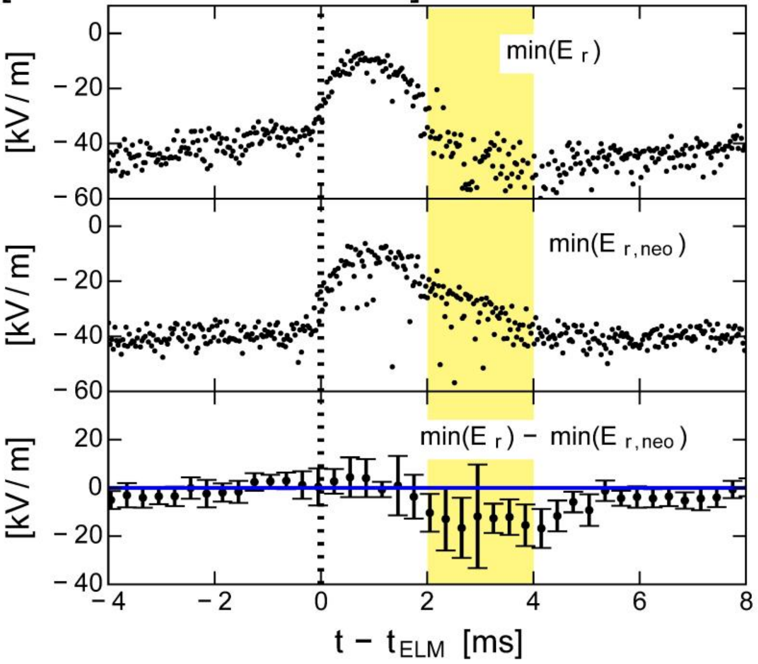
⇒ Other contributions to E_r are small

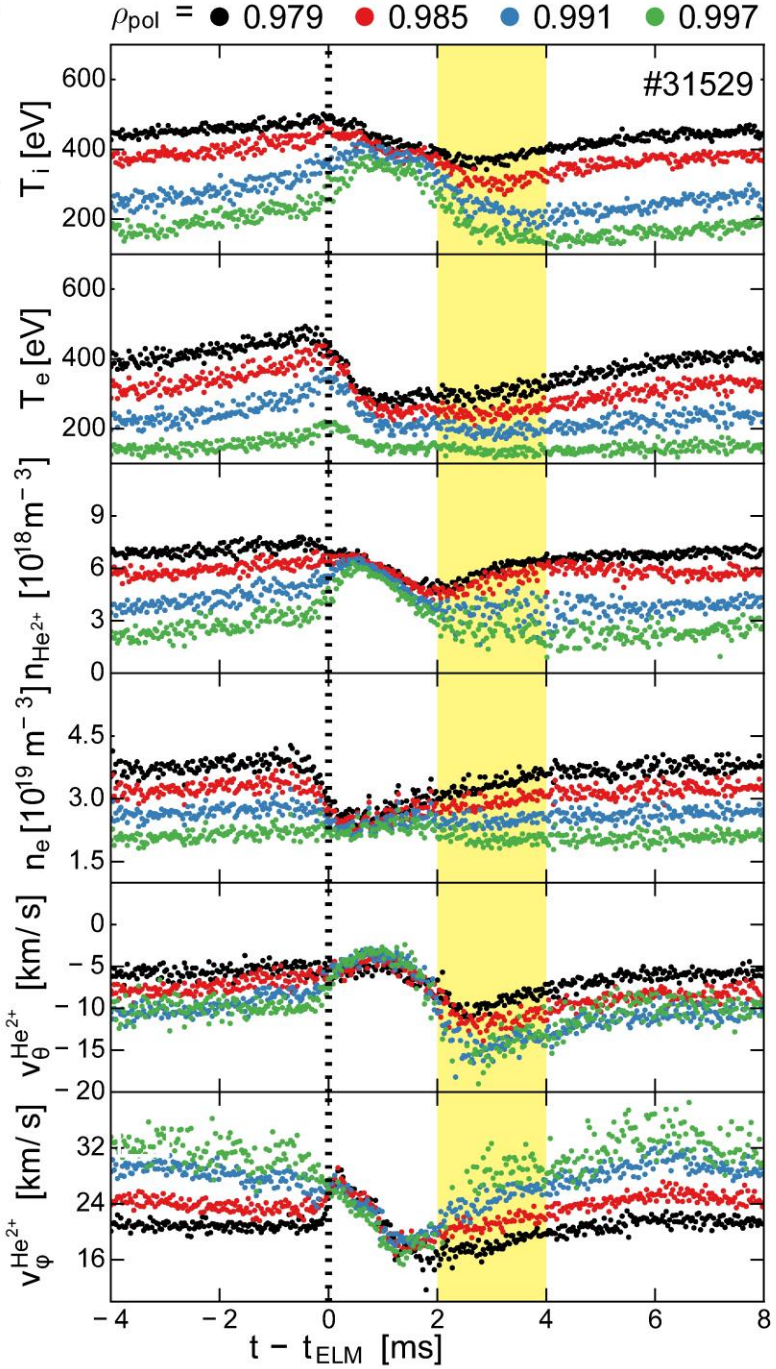
[Kobayashi PRL 13]

Edge E_r evolution during an ELM-cycle

- Difference in E_r in this phase while it consisitent to neoclassical for the rest of the cycle
  [Viezzer NF 14, McDermott PoP 09]
- Between 2 and 4 ms spin-up of the He^{2+} poloidal velocity compare to pre-ELM conditions

[Cavedon PPCF 2017] #31529





γ_{turb}

$$\nabla v_{E\times B} \approx \frac{v_{E\times B}}{\Delta r} \geq \gamma_{turb}$$

$\approx$ constant

[Schneider P, et al 2013 Nucl. Fusion 53 073039]

L-mode confinement weakly depends on B

$$\tau_E^{\mathrm{ITER89\text{-}P}} = 0.048\ \mathrm{M}^{0.5}\ \mathrm{I_p}^{0.85}\ \mathrm{R}^{1.2}\ \mathrm{a}^{0.3}\ \mathrm{k}^{0.5}\ \mathrm{n}^{0.1}\ \mathrm{B}^{0.2}\ \mathrm{P}^{-0.5}$$

P.N. Yushmanov et al 1990 Nucl. Fusion 30 1999

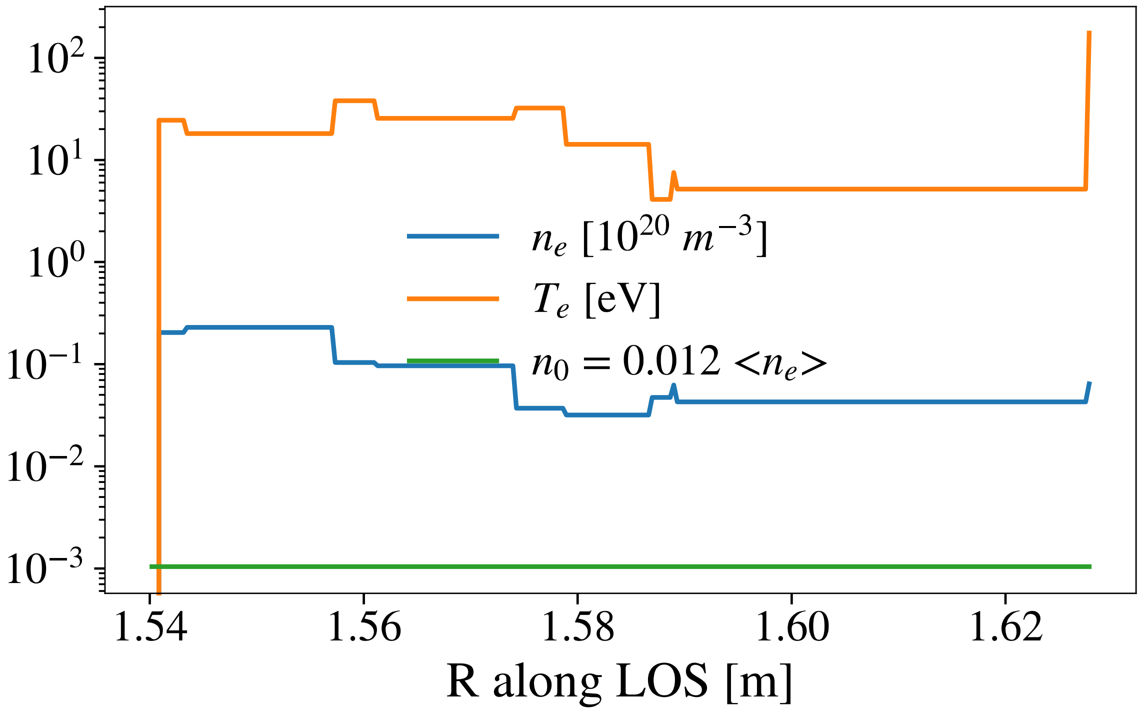
Mass dependence:
See R. Bilato et al 2020 Nucl. Fusion 60 124003

GENE simulations towards the L-H: N. Bonanomi et al, pinboard

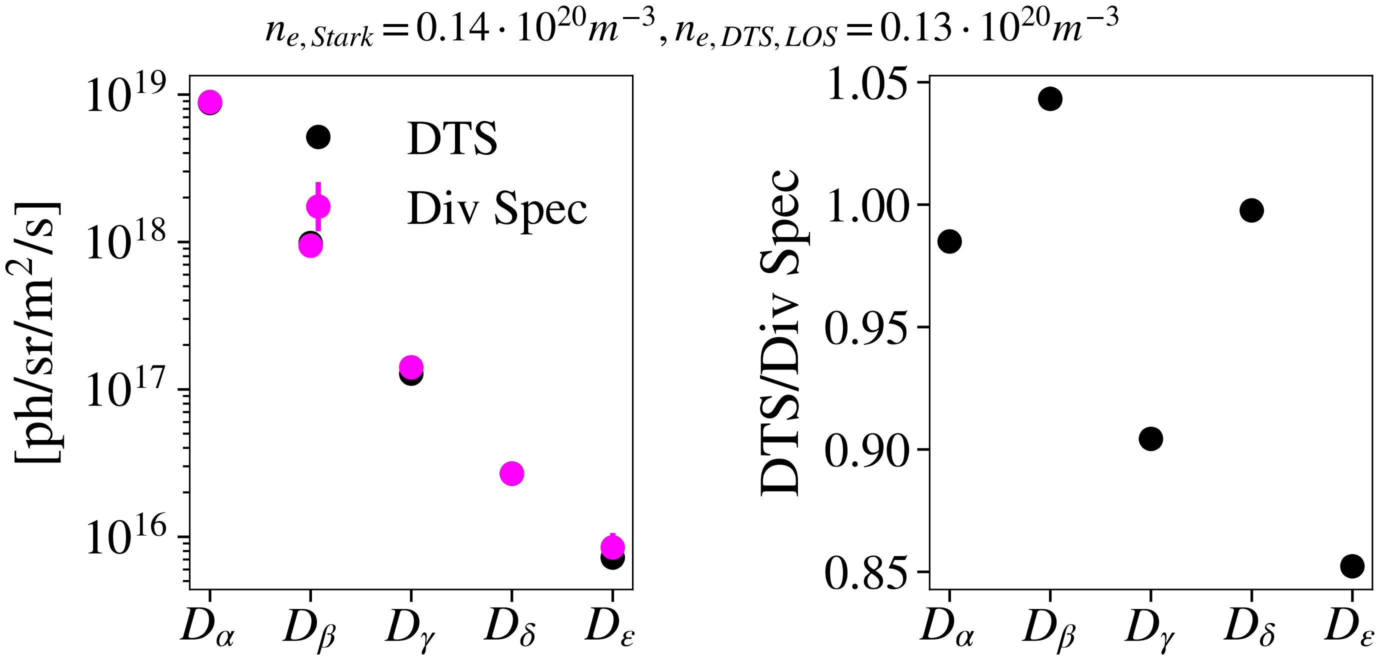
R. Bilato et al 2020 Nucl. Fusion 60 124003

Step 2: HFHD

$$\epsilon_{H(n)} = n_e\left[PEC_H^n n_0 + PEC_{H^+}^n n_e\right]$$

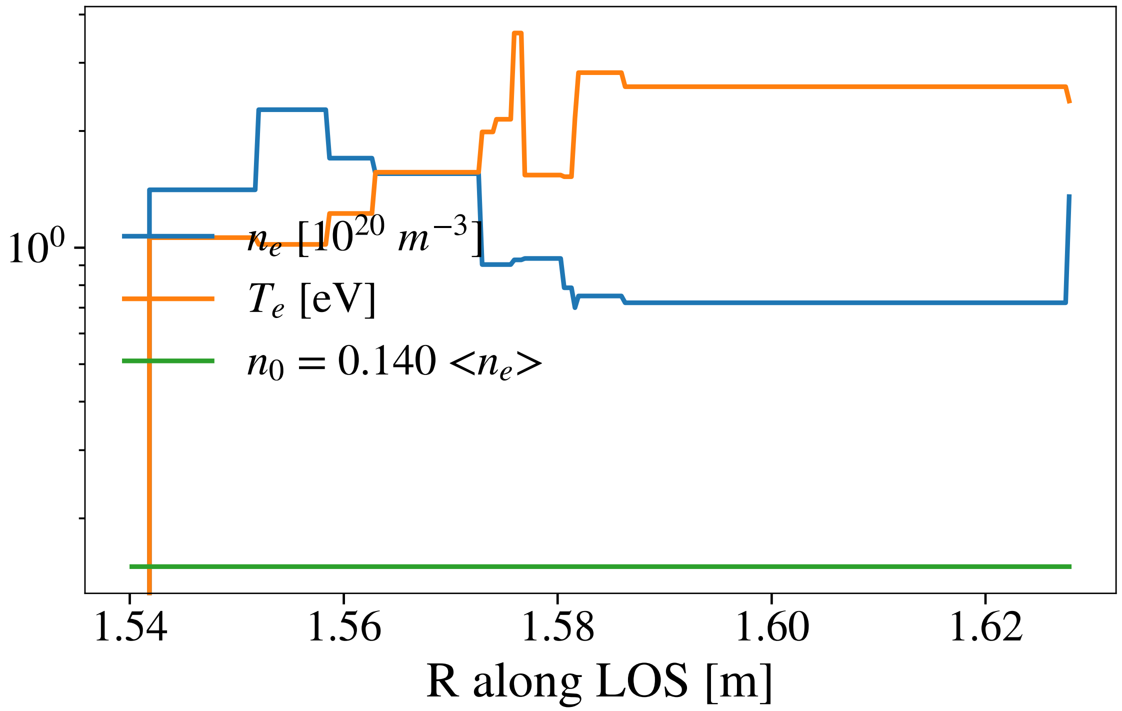


- Very good match DTS and Stark-broadening n_e
- No need of n_{H_2} to explain Balmer signal

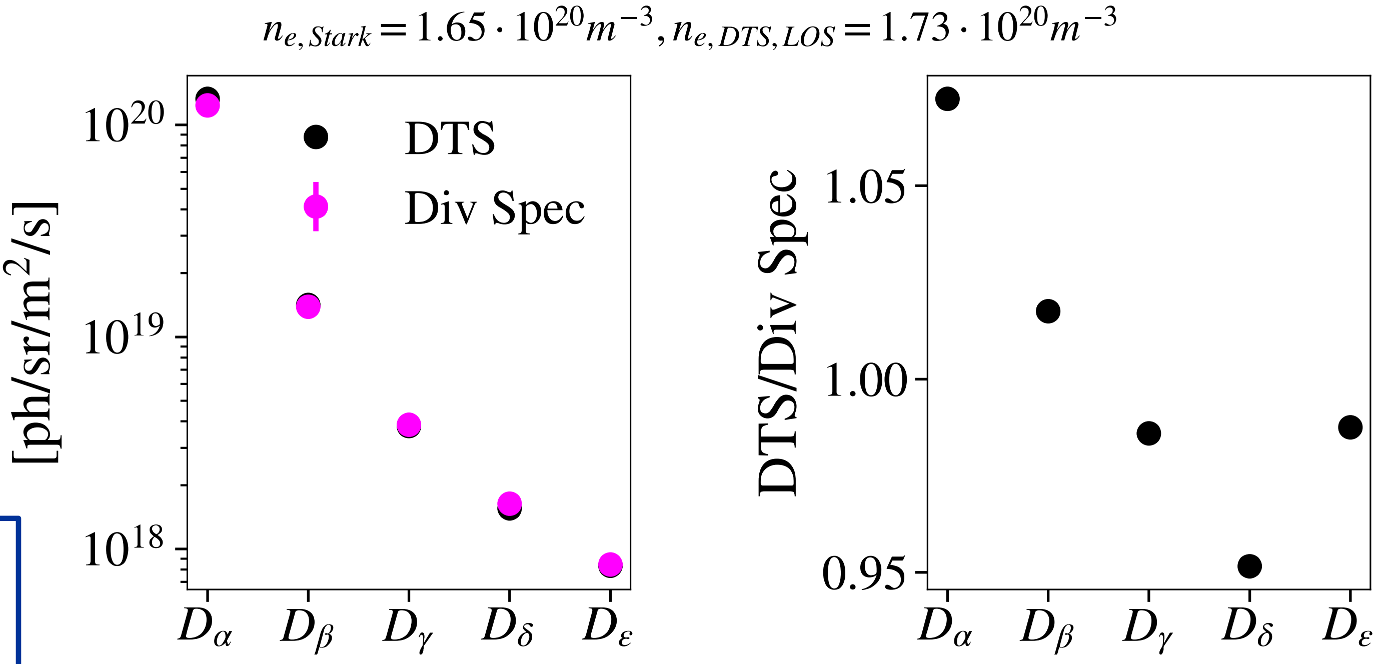


Step 3: Detachment onset

$$\epsilon_{H(n)} = n_e\left[PEC_H^n n_0 + PEC_{H^+}^n n_e\right]$$



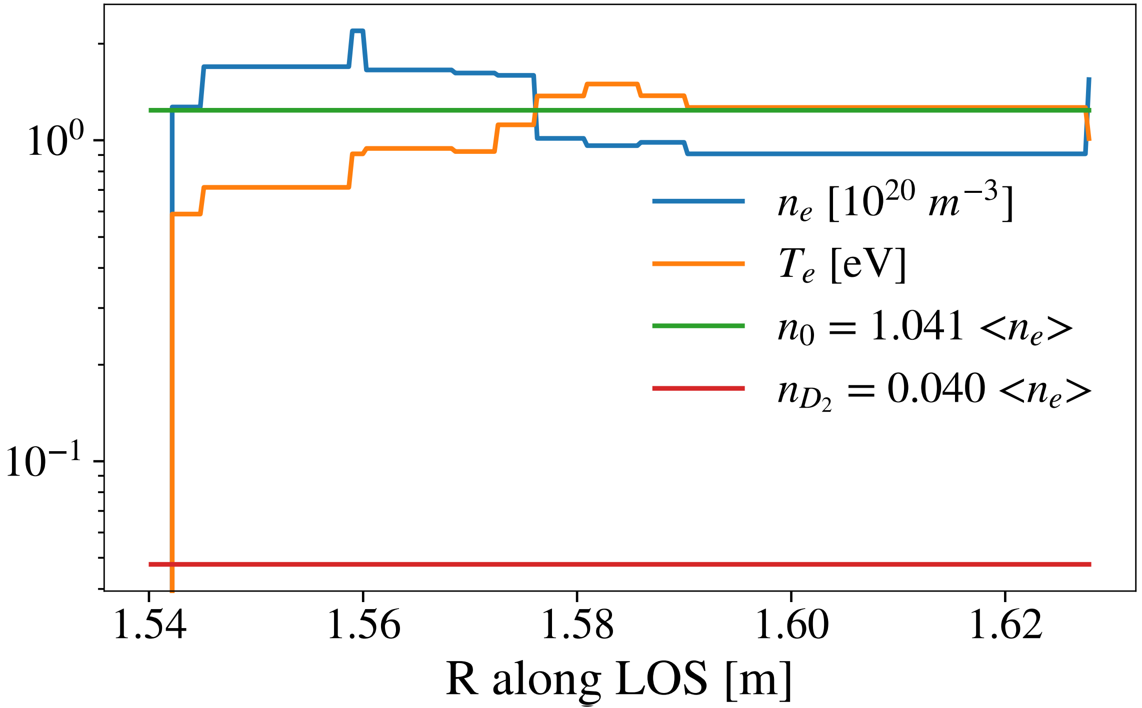
- Very good match DTS and Stark-broadening n_e
- No need of n_{H_2} to explain Balmer signal



Role of MAR seems to be limited in triggering the detachment

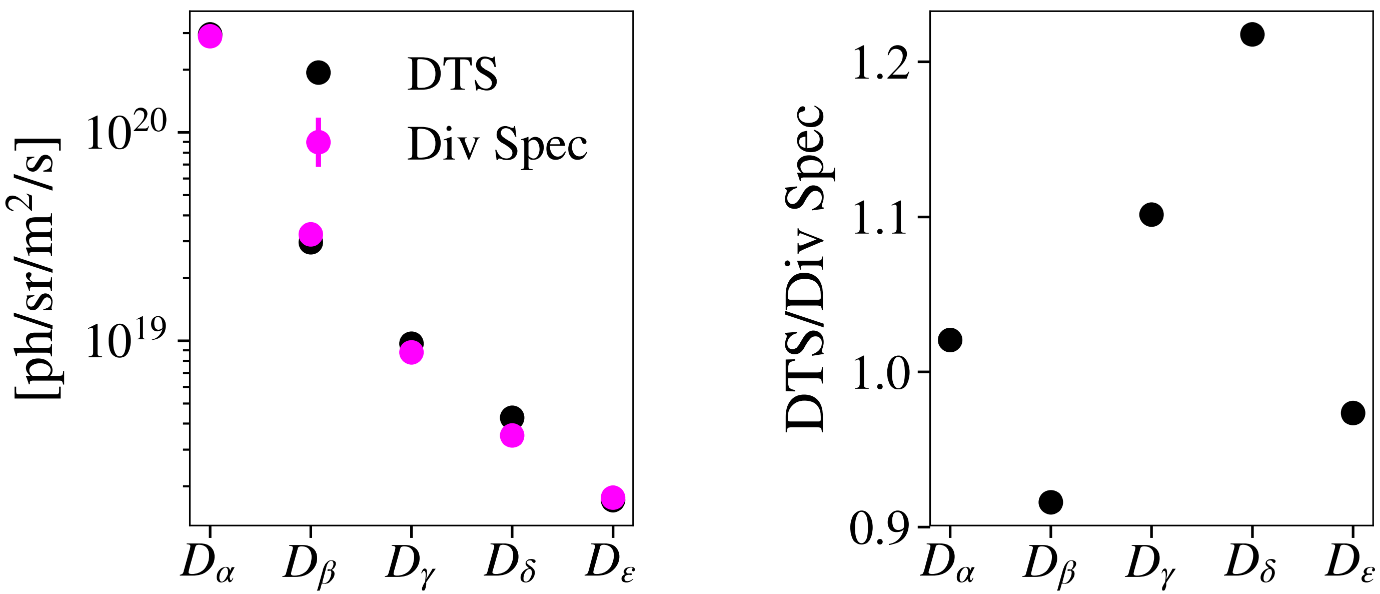
Step 4: Complete Detached L-mode

$$\epsilon_{H(n)} = n_e[PEC_H^n n_0 + PEC_{H^+}^n n_e] + n_{H_2} n_e [PEC_{H_2}^n + PEC_{H_2^+}^n f_{H_2^+} + PEC_{H_3^+}^n f_{H_3^+} + PEC_{H^-}^n f_{H^-}]$$



- Very good match DTS and Stark-broadening n_e
- Mismatch between measured and fitted Balmer emissions

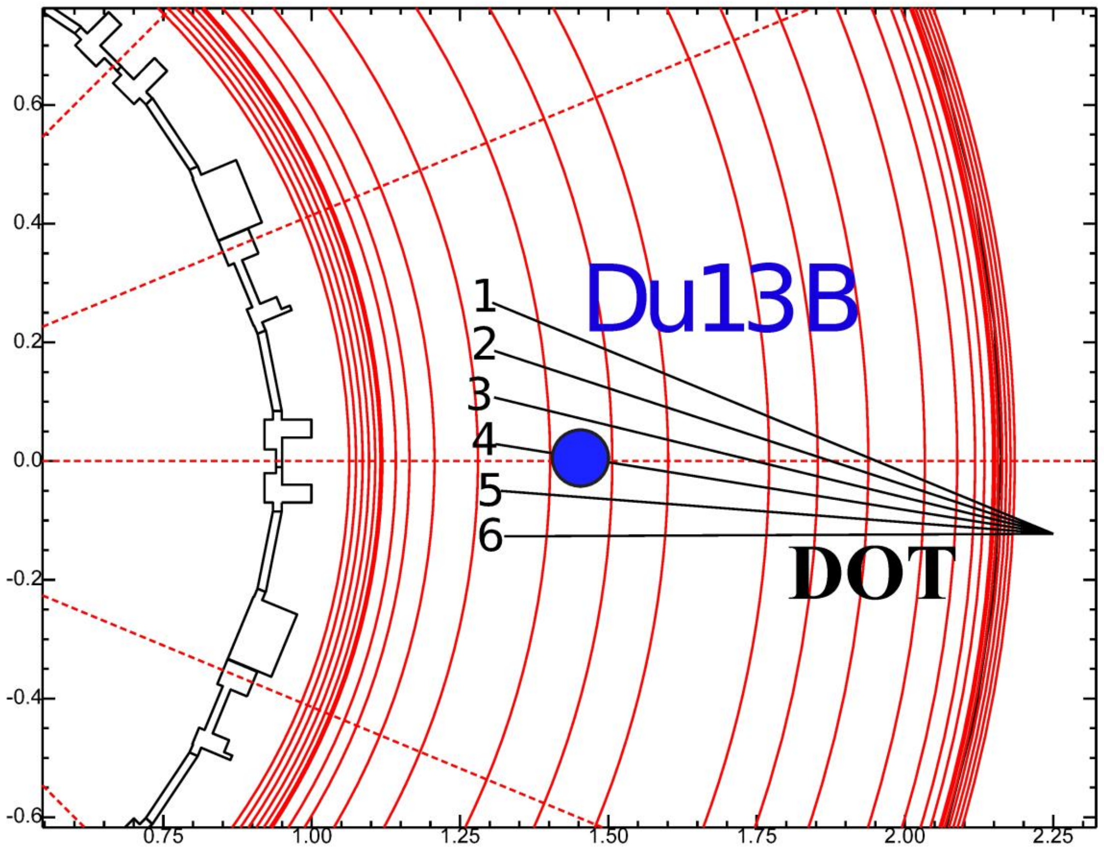
$n_{e,Stark} = 1.66 \cdot 10^{20} m^{-3}, n_{e,DTS,LOS} = 1.54 \cdot 10^{20} m^{-3}$

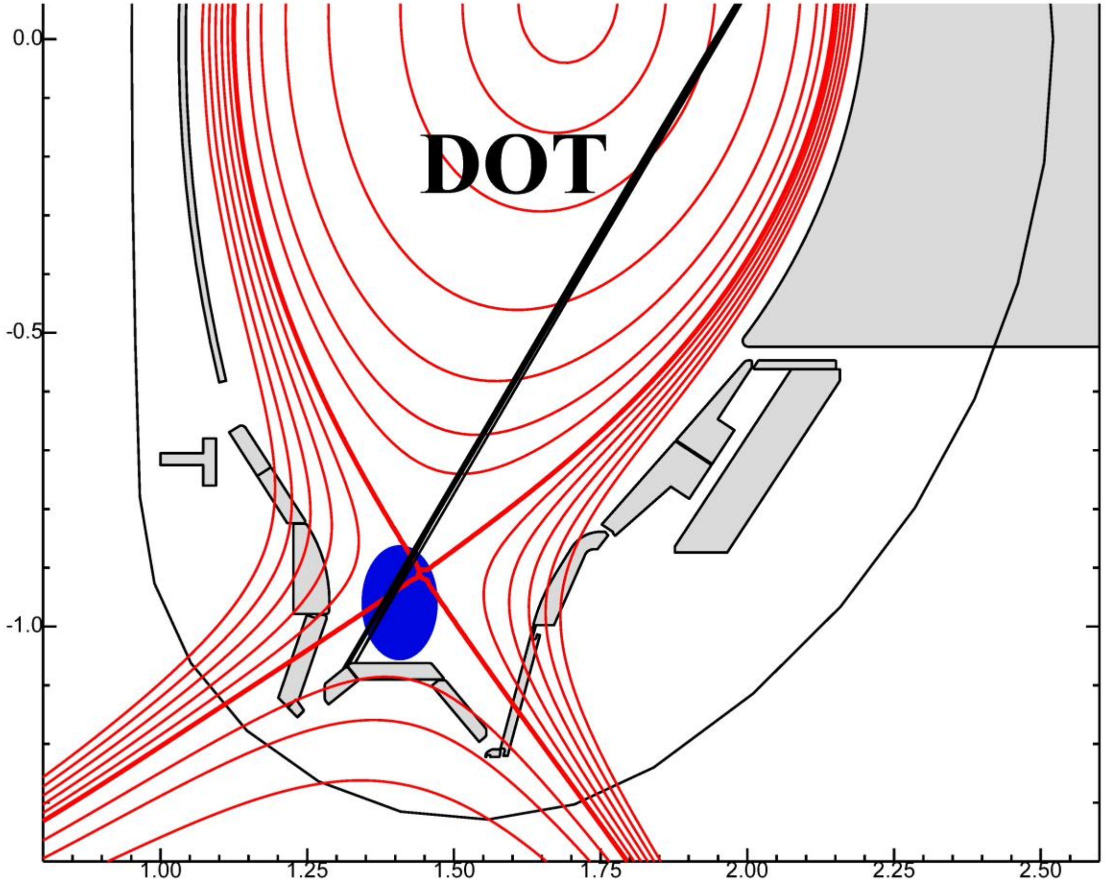


n_{H_2} starts to be important to interpret the B series but n_{H_2} is only few % of n_e or n_H n_0 (consistent to Fantz, U. *et al.* (2001) *JNM)*

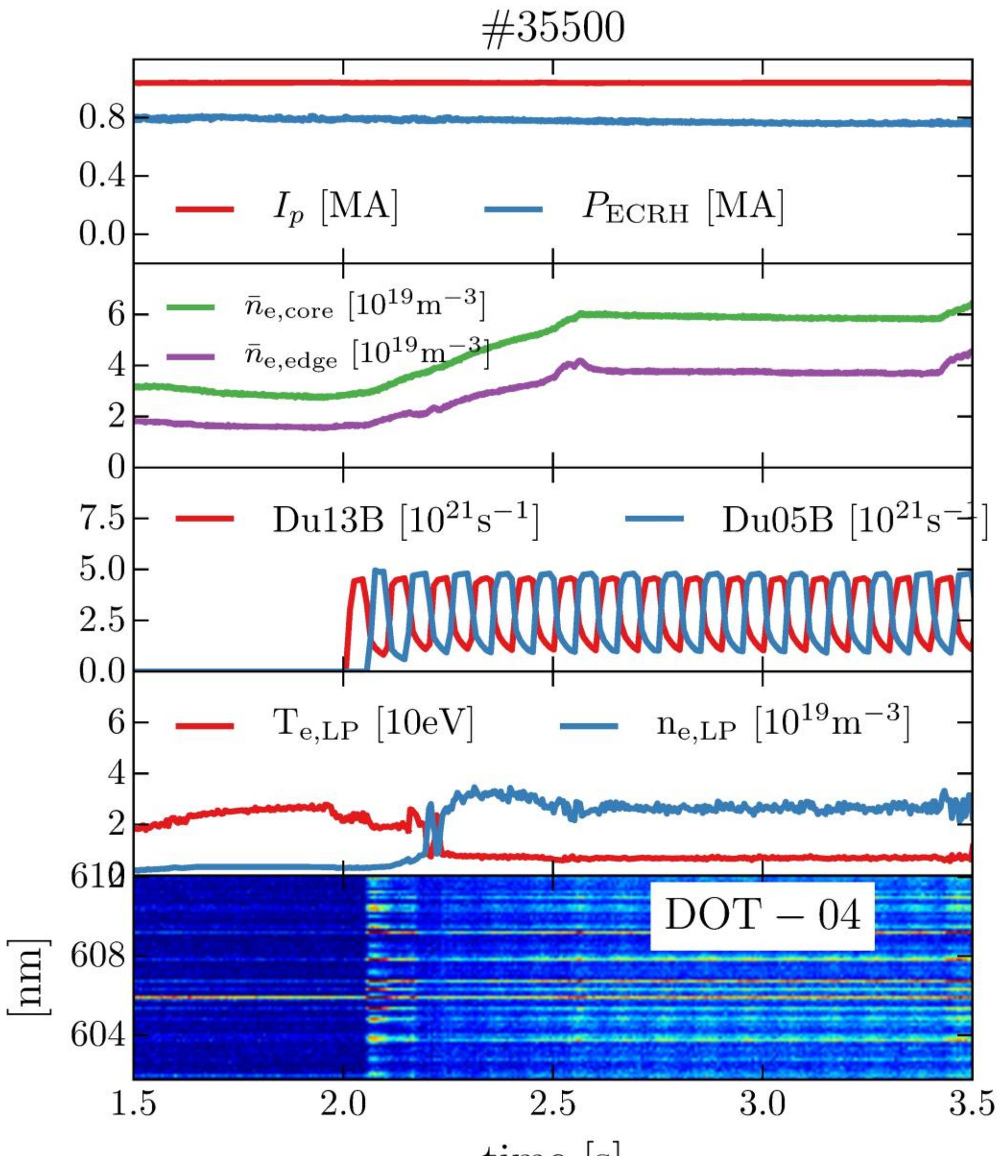
New Head for Fulcher Measuraments in W-AUG

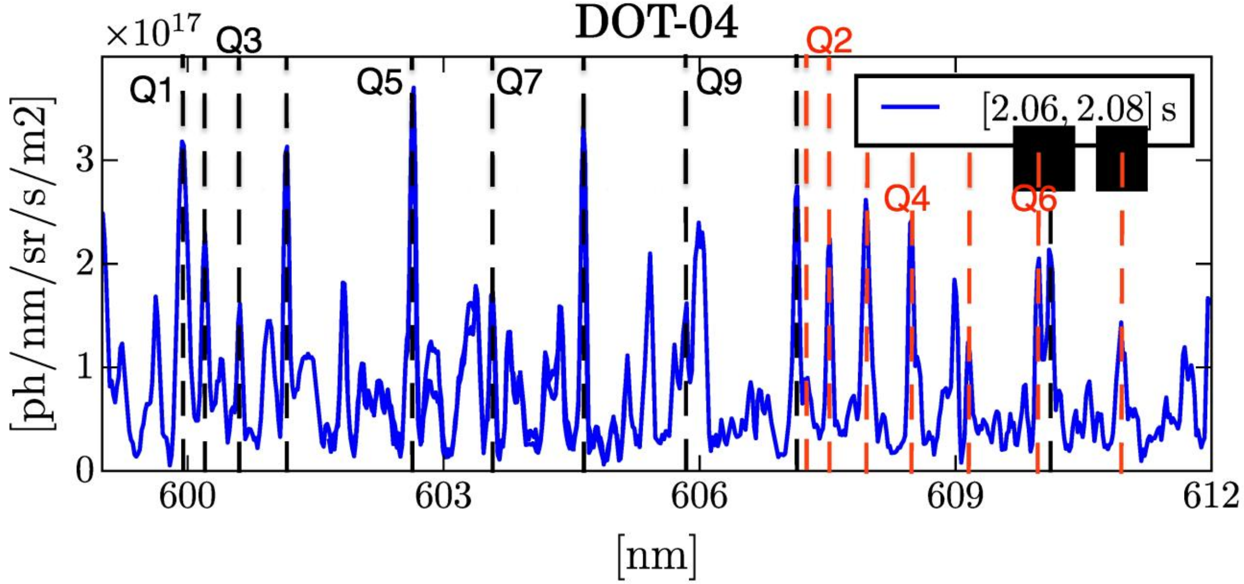
. . . but no clear sign of Fulcher Bands in the 2017 Campaign! New Head!





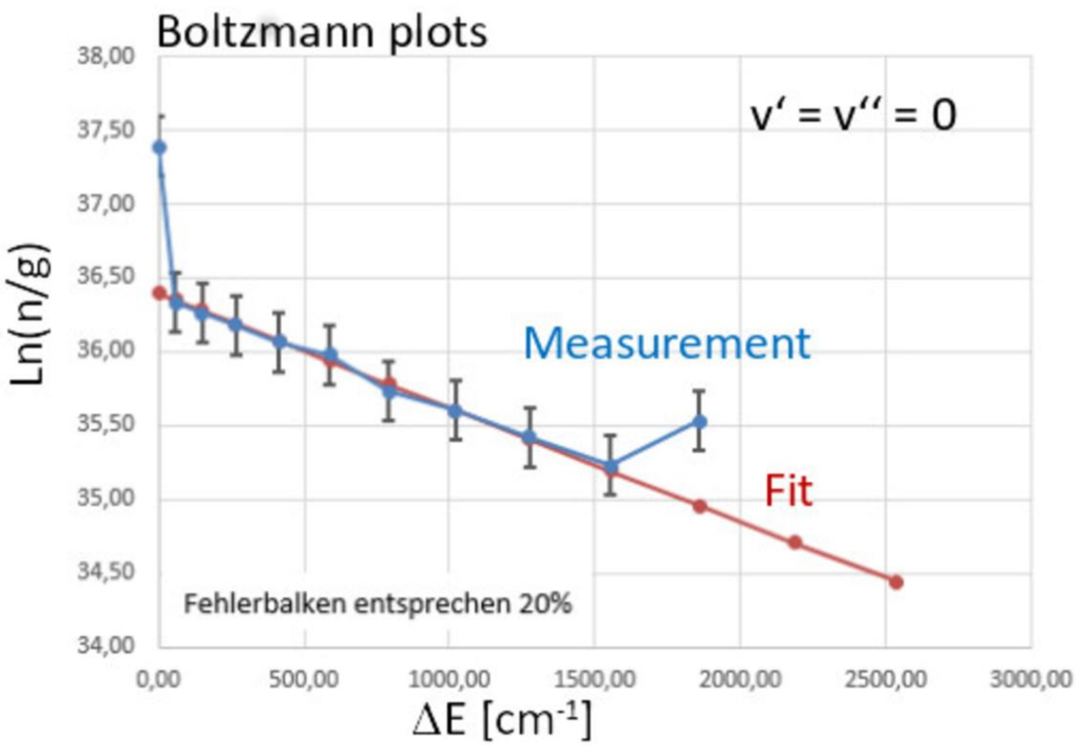
First Measuraments of the Fulcher in W-AUG





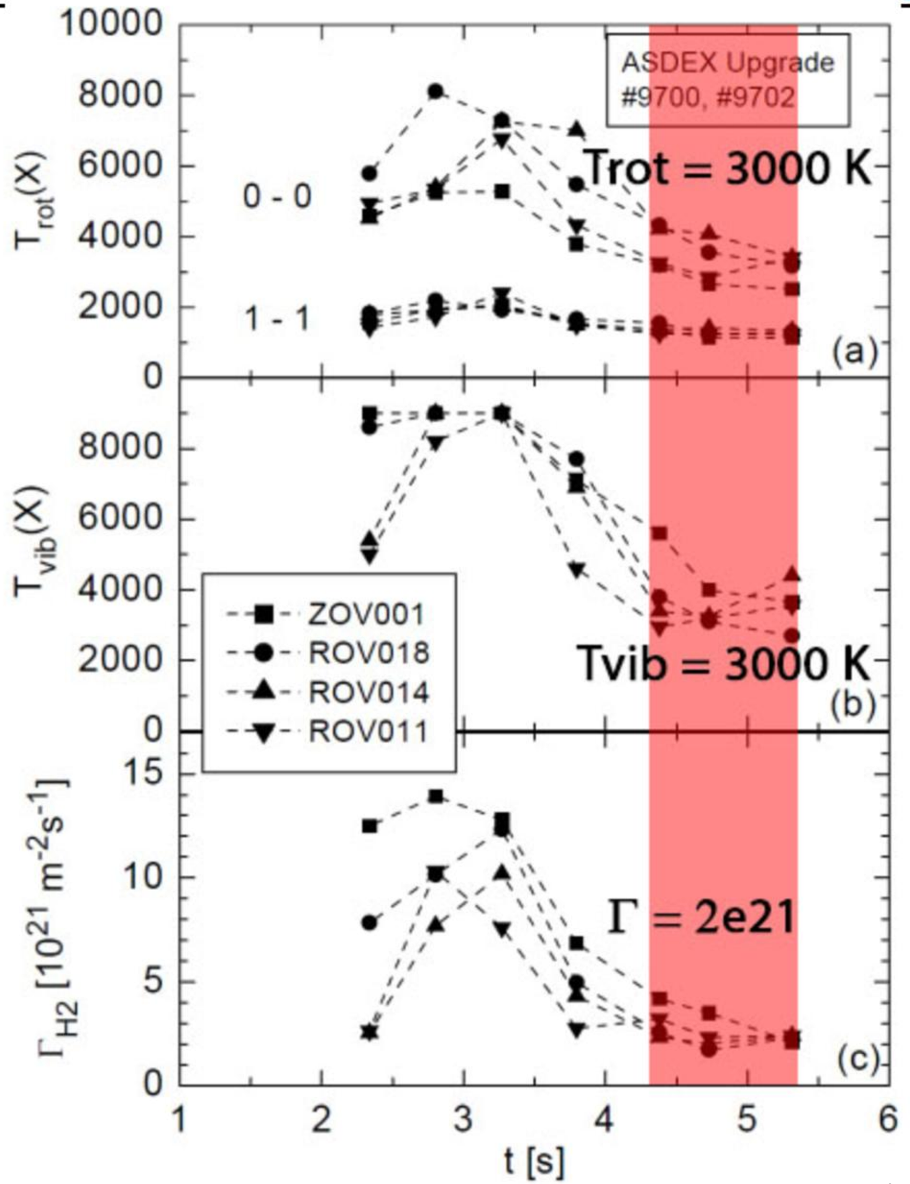
- Clear Fulcher emission for LOS looking directly at the gas valve (DOT-4)
- Two vibrational bands: $0-0$, $1-1$
- Some of the peaks overlap with other lines

D_2 T_{vib} and T_{rot} in W vs C (preliminary)

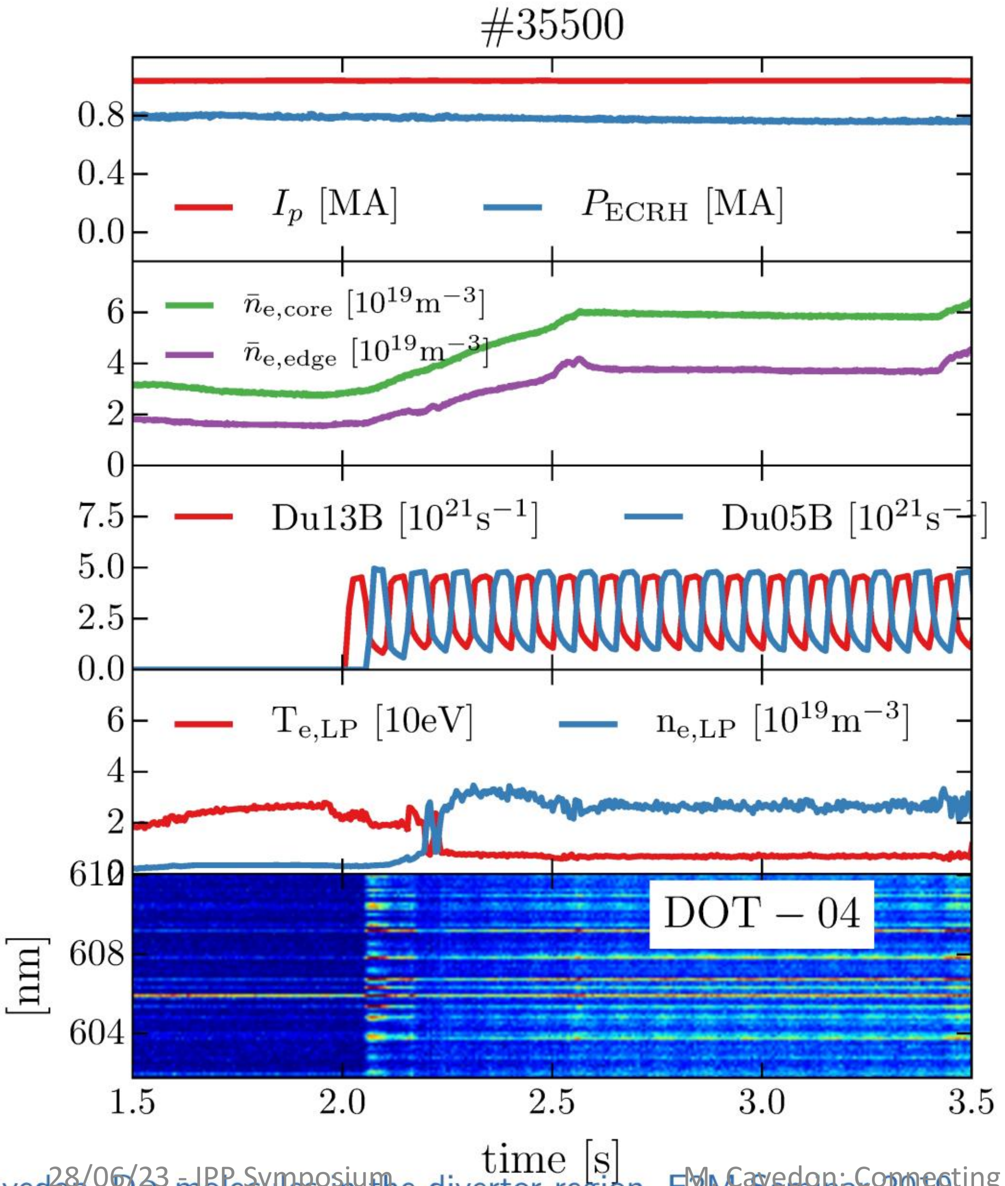


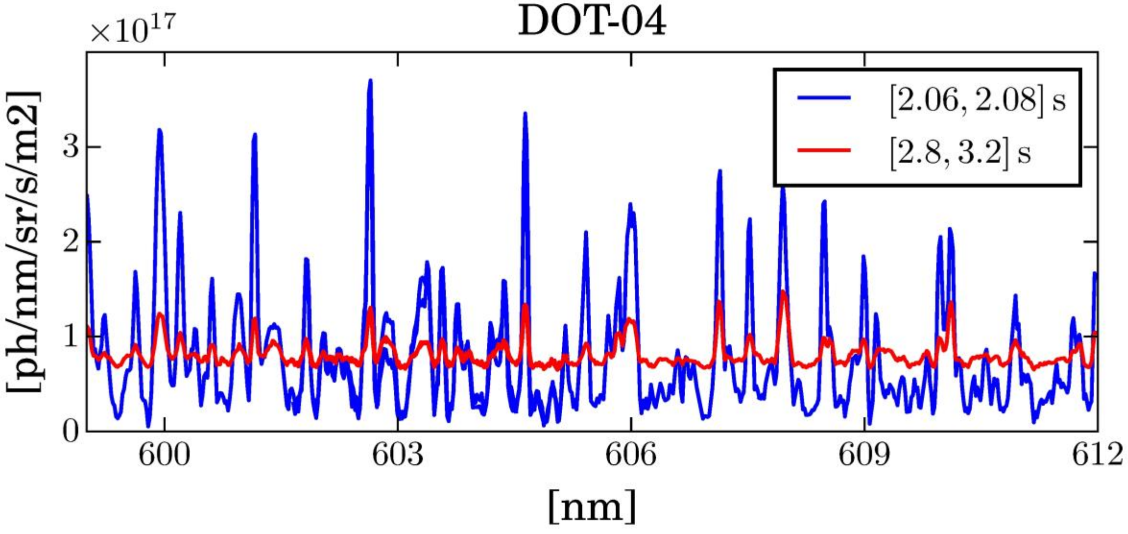
Fantz et al., JNM 266-269 (1999) 490 (old)

- $T_{\mathrm{vib}} = 1700\,\mathrm{K}$
- $T_{\mathrm{rot}} = 3000\,\mathrm{K}$
- $\Gamma_{D_2} \simeq 1 \times 10^{21}\mathrm{p/s/m}^2$

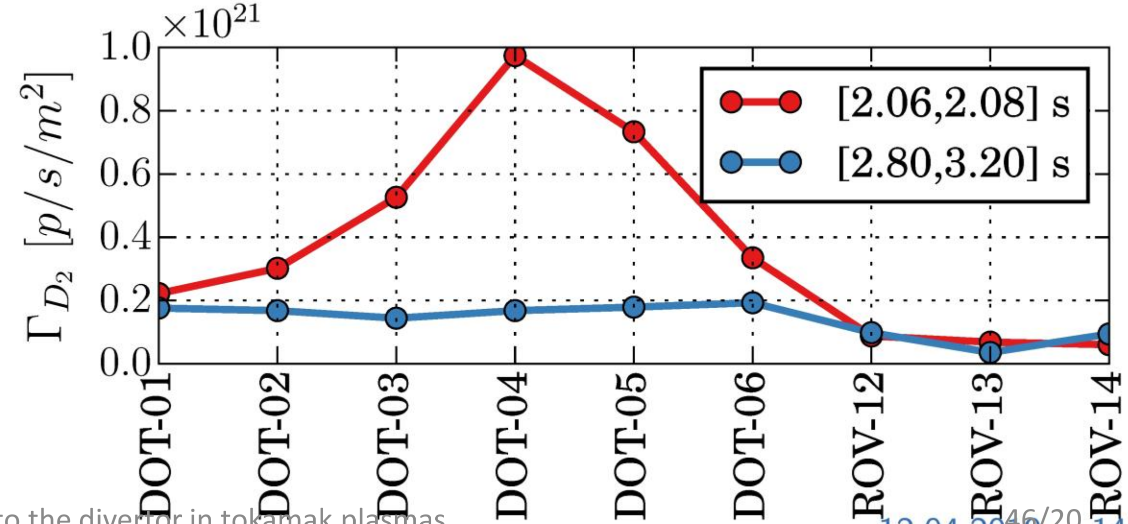


Time evolution of the D_2 emission during density ramp



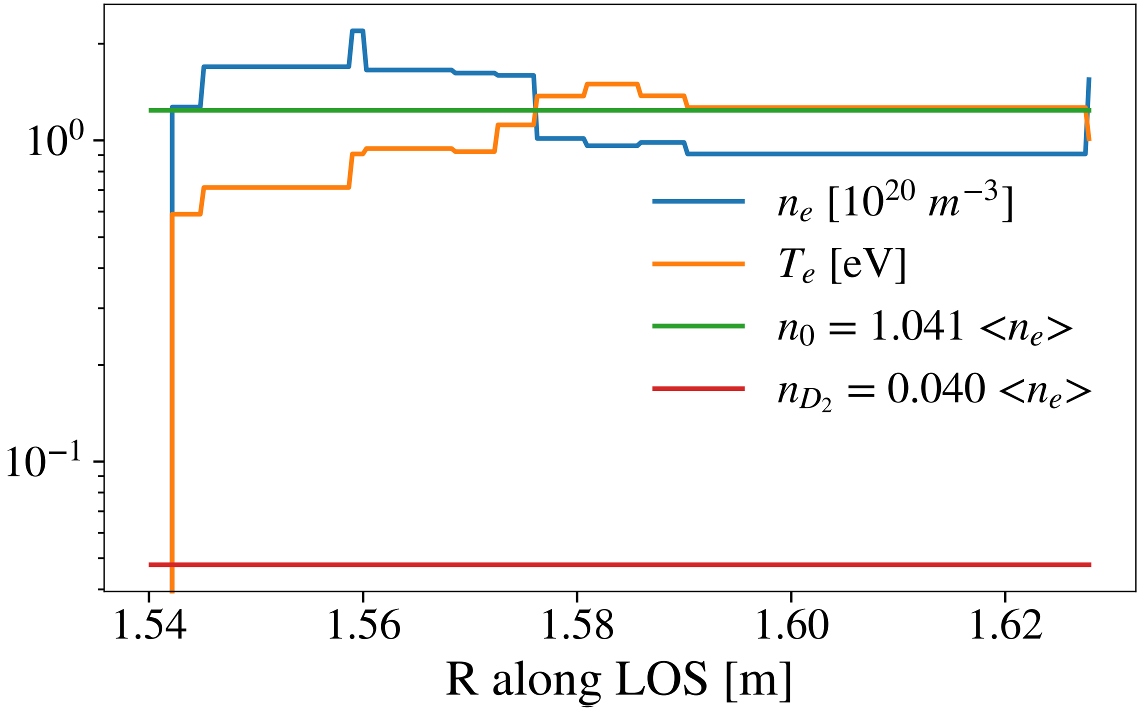


- T_{vib} and T_{rot} constant within errorbars

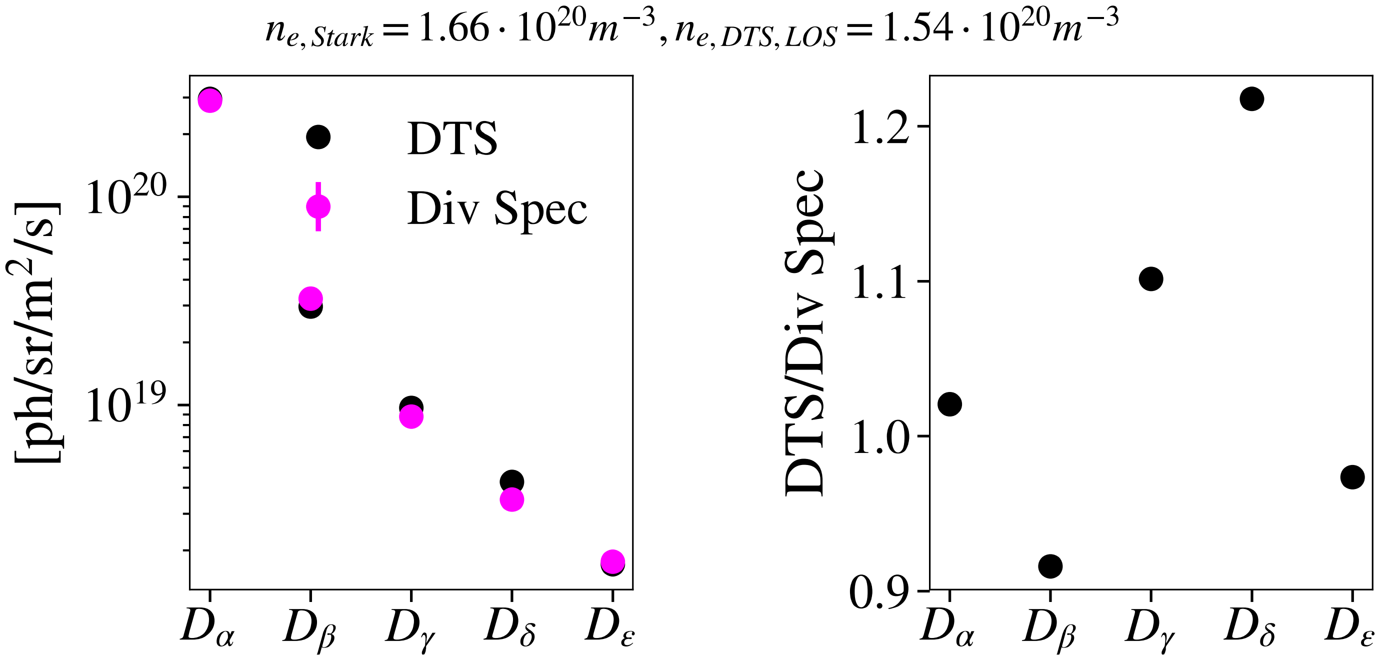


Step 4: Complete Detached L-mode

$$\epsilon_{H(n)} = n_e\left[PEC_H^n n_0 + PEC_{H^+}^n n_e\right] + n_{H_2} n_e\left[PEC_{H_2}^n + PEC_{H_2^+}^n f_{H_2^+} + PEC_{H_3^+}^n f_{H_3^+} + PEC_{H^-}^n f_{H^-}\right]$$



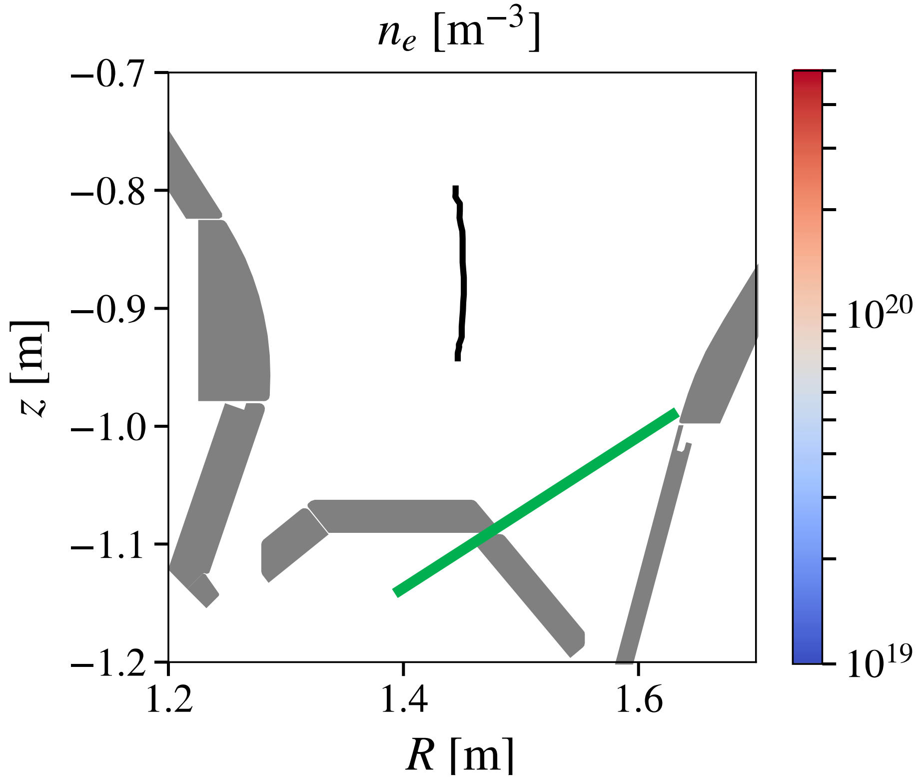
- Very good match DTS and Stark-broadening n_e
- Mismatch between measured and fitted Balmer emissions



n_{H_2} starts to be important to interpret the B series but n_{H_2} is only few % of n_e or n_H n_0 (consistent to Fantz, U. *et al.* (2001) *JNM)*

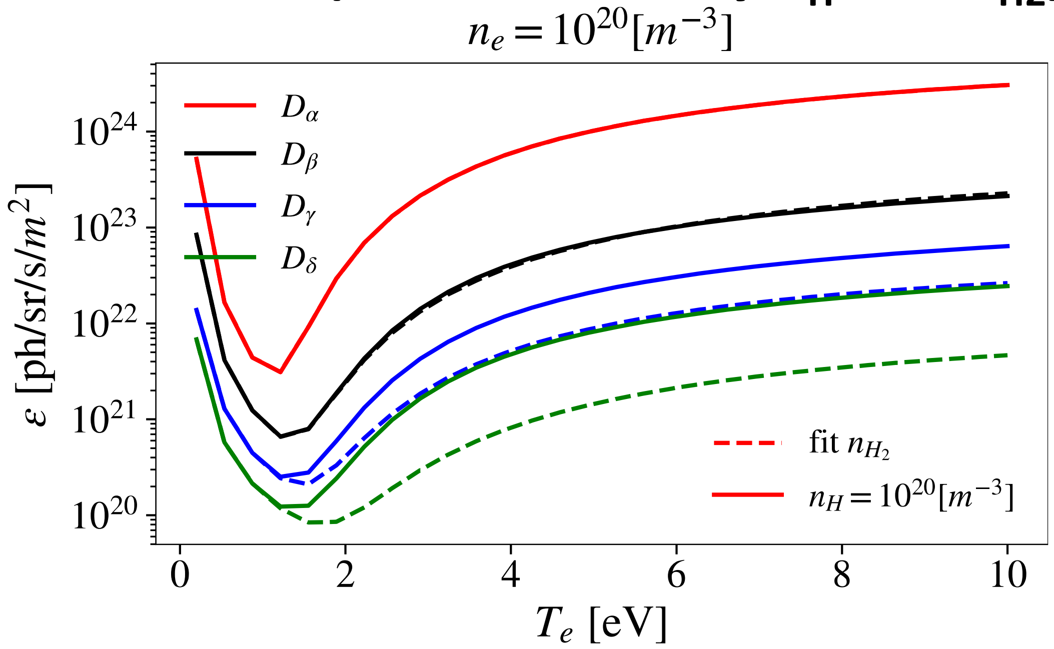
Determination n_{D0} and n_{D2} from Balmer lines

Problem 1: Spectroscopy Line Integration



Unprecedented advantage of 2D (n_e, T_e)

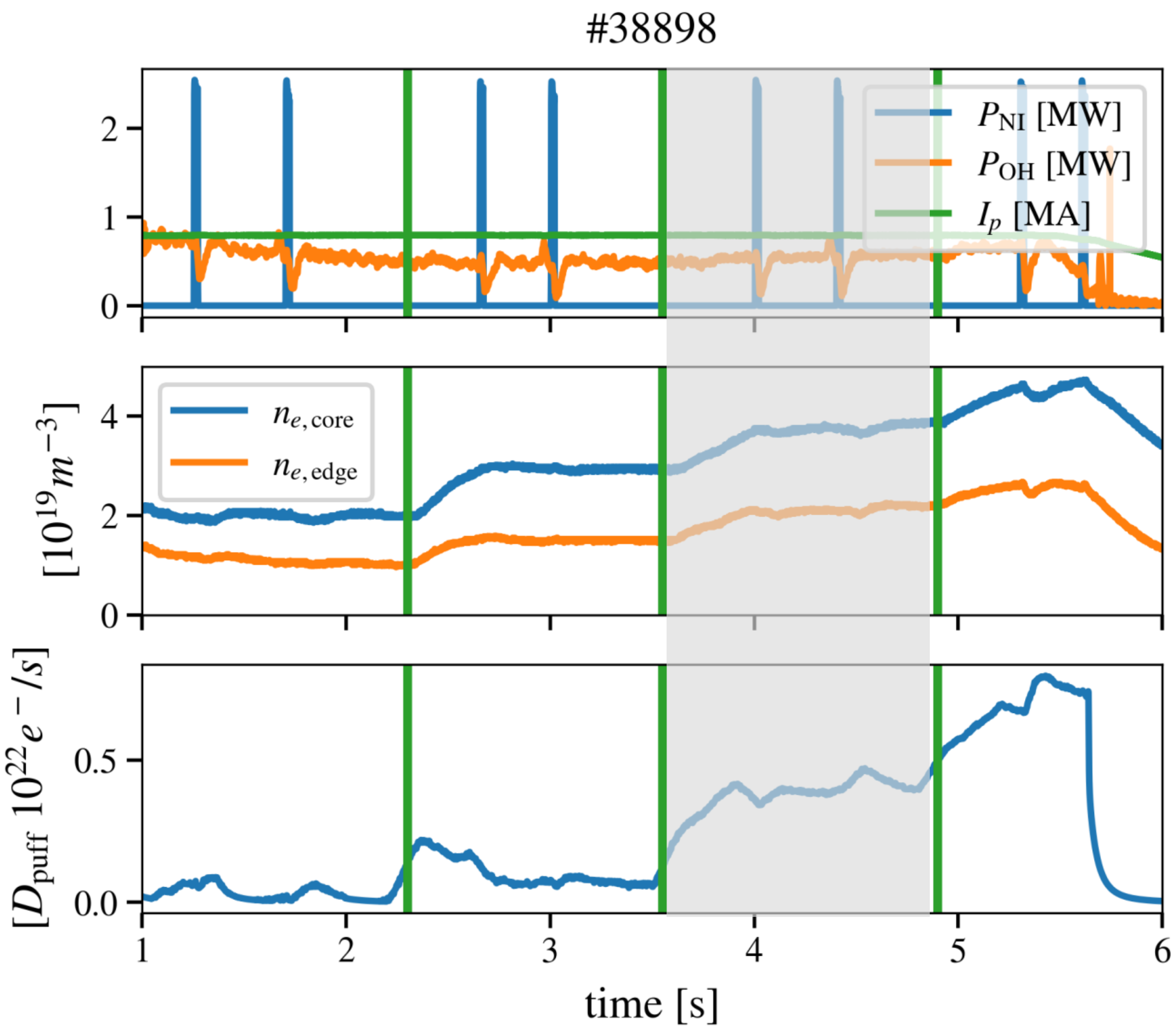
Problem 2: Cross-correlation of parameters (in our case only n_H and n_{H2})



Simultaneous measurements from n=3 to 7 and 2D (n_e, T_e)

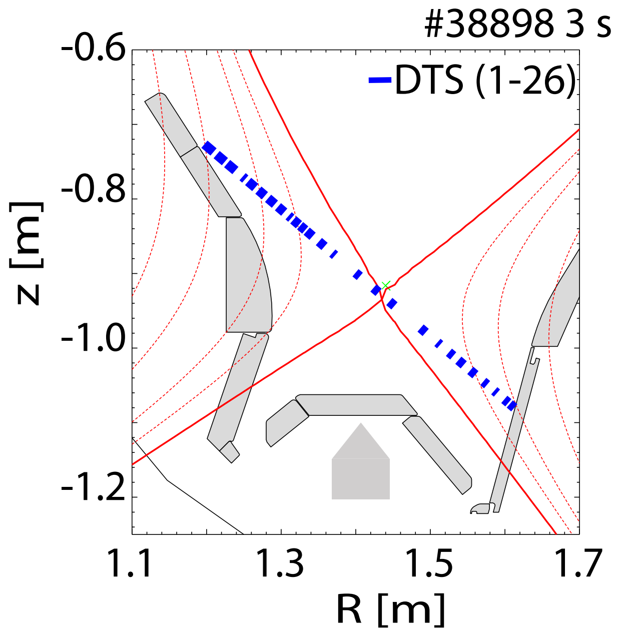
A. Perek *et al*, this session
K Verhaegh *et al* 2021 *Plasma Phys. Control. Fusion* 63 035018
B Lomanowski *et al* 2020 *Plasma Phys. Control. Fusion* **62** 065006
C Bowman *et al* 2020 *Plasma Phys. Control. Fusion* **62** 045014
Fantz, U. *et al.* (2001) *Jour. of Nucl. Materials*, 290–293, pp. 367–373

Detachment in experiments – Step 3

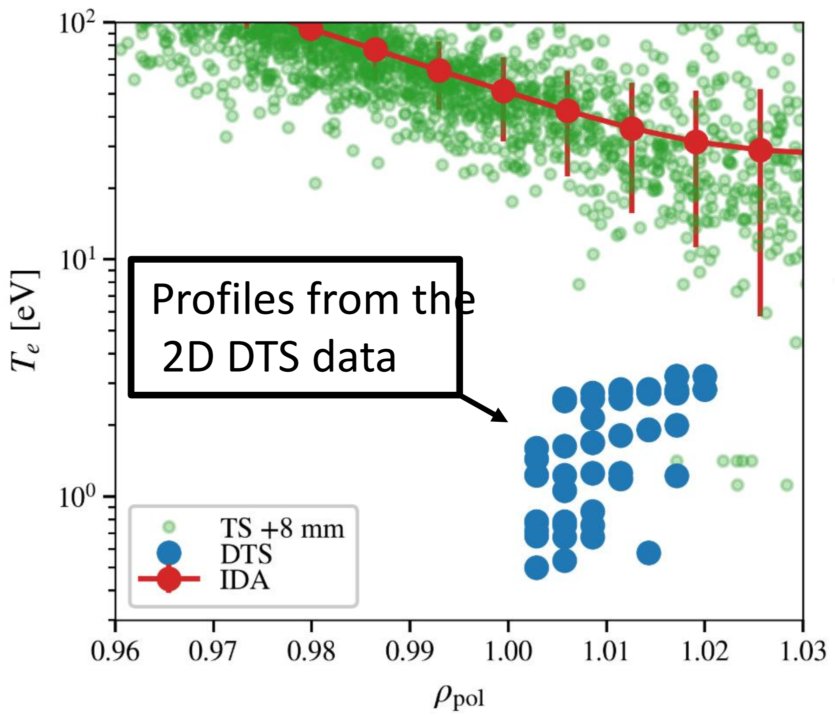


Discharge parameters:

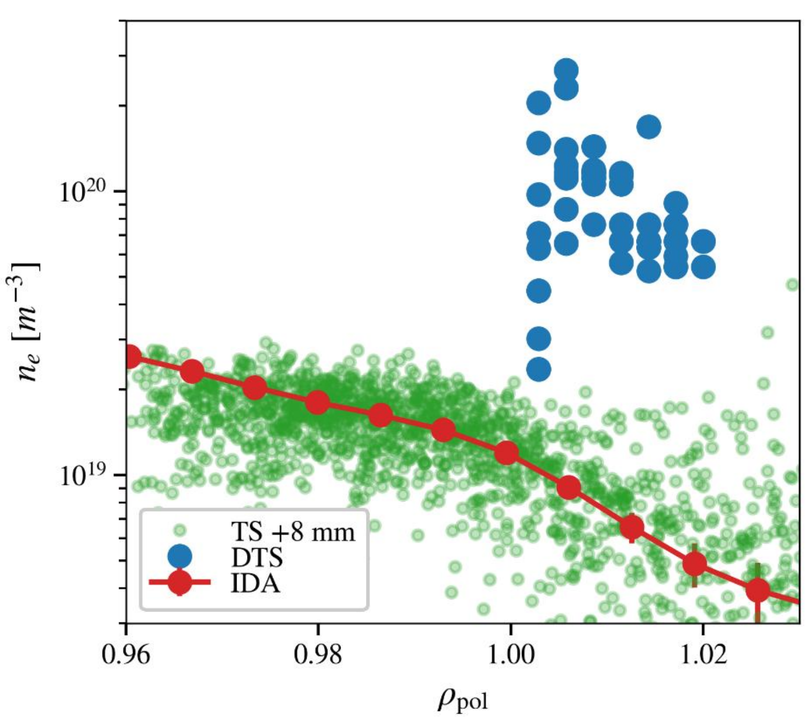
- 0.8 MA, 3 T, 0.4 MW ECRH
- Beam Blips for CX
- Density ramp in 4 steps
- Measurements at the target (LP), mid-plane (TS and IDA), and in the divertor volume (TS)



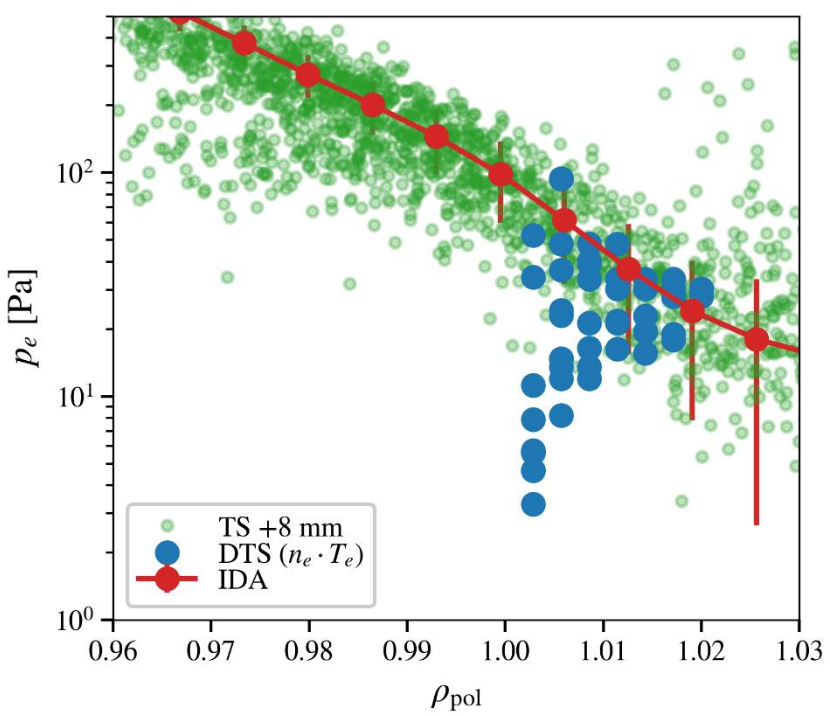
Detachment – Phase 3



- Very strong ∇T_e
- LP not trustworthy at such low T_e

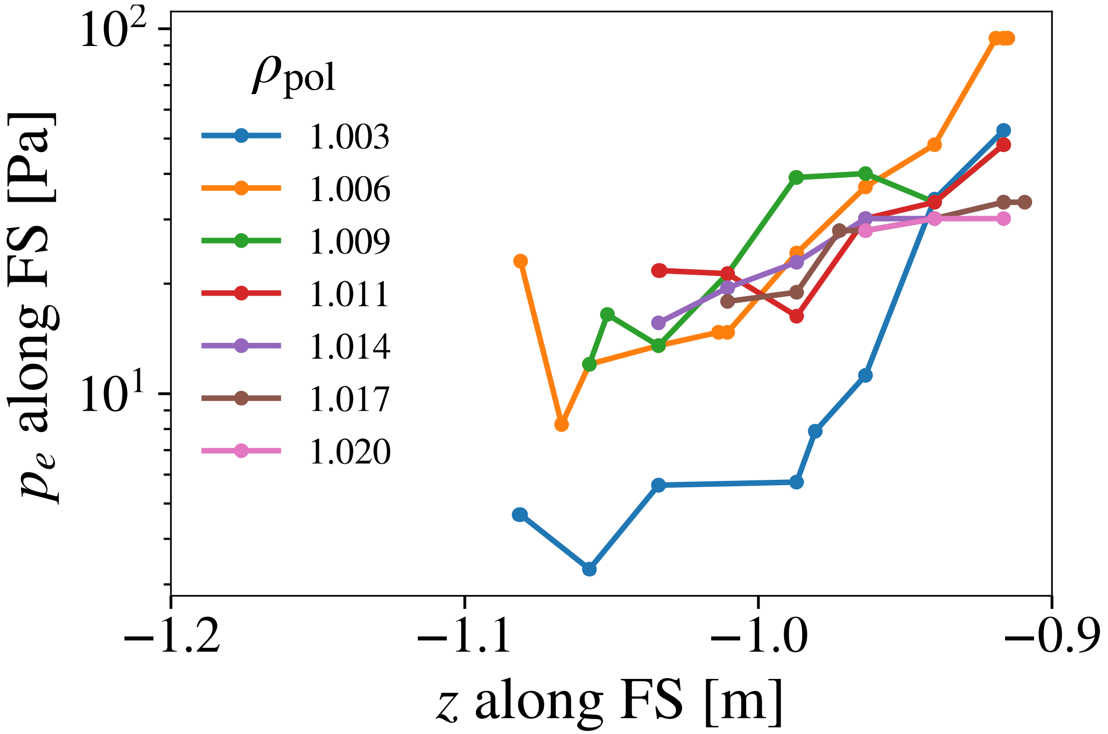


- Very high n_{DTS}
  → Ionization at the DTS

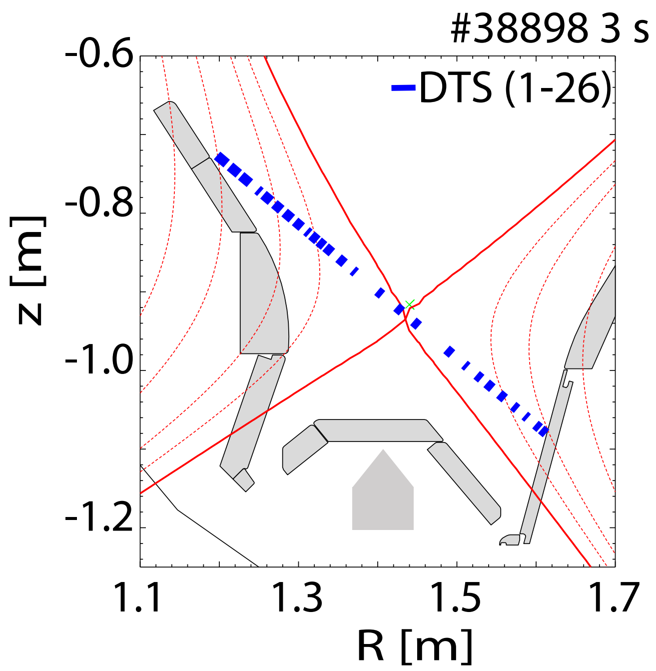


- Pressure not conserved

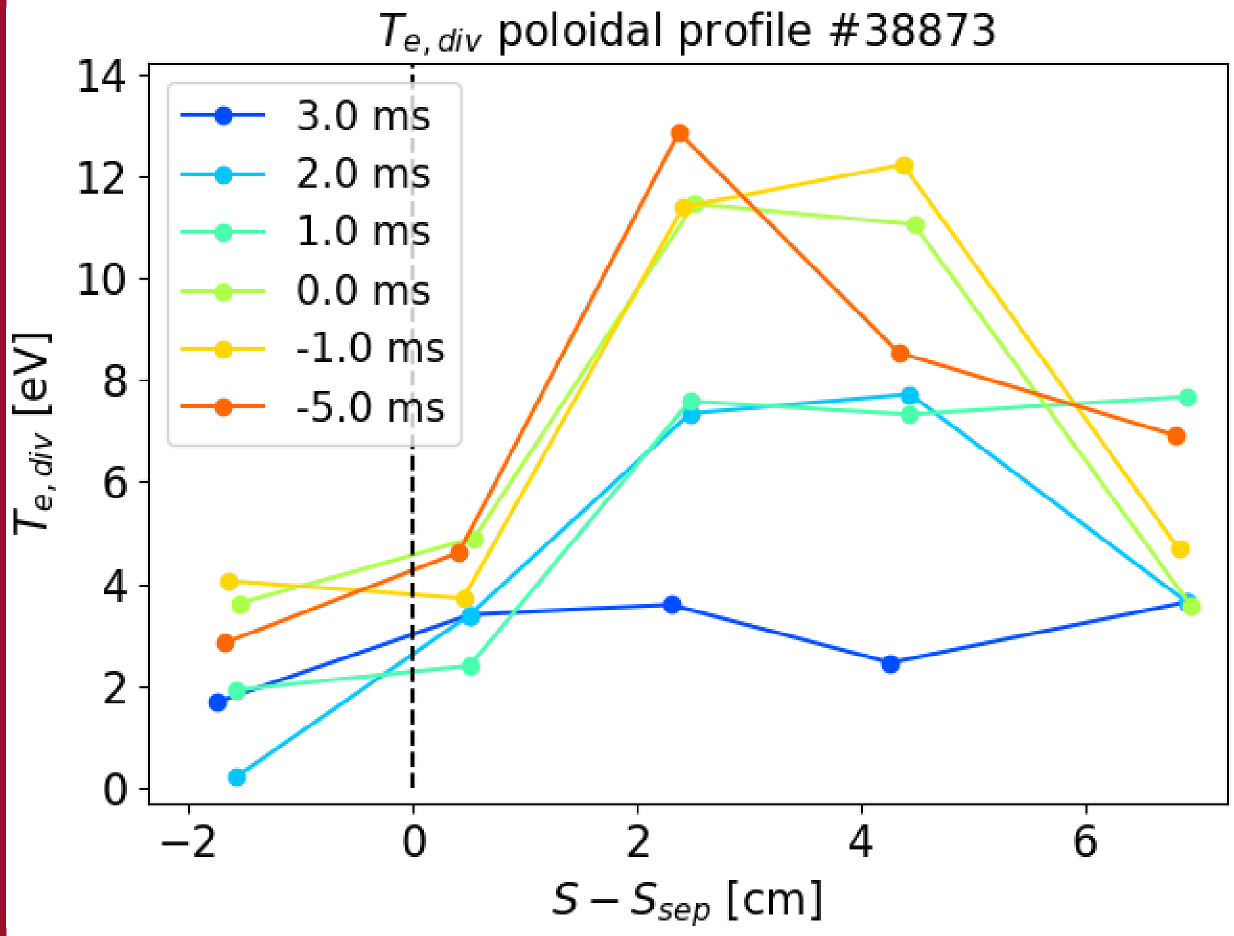
Pressure Profile

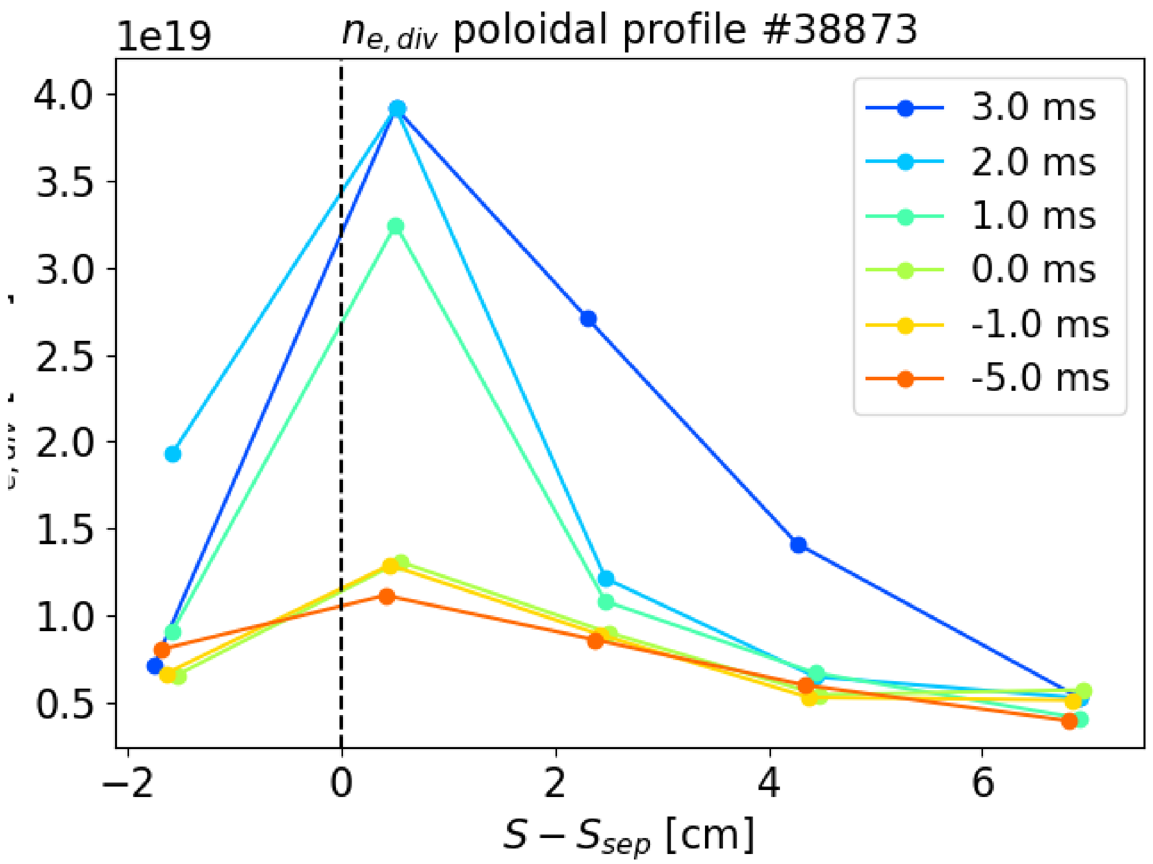


- $\nabla_{\parallel} p_e \neq 0$
- Dynamic pressure: $\max(p_{dyna}) = m\, n\, c_s^2 = n\, k\, T$



LP profiles during the "cliff"





Slide from L. Scotti

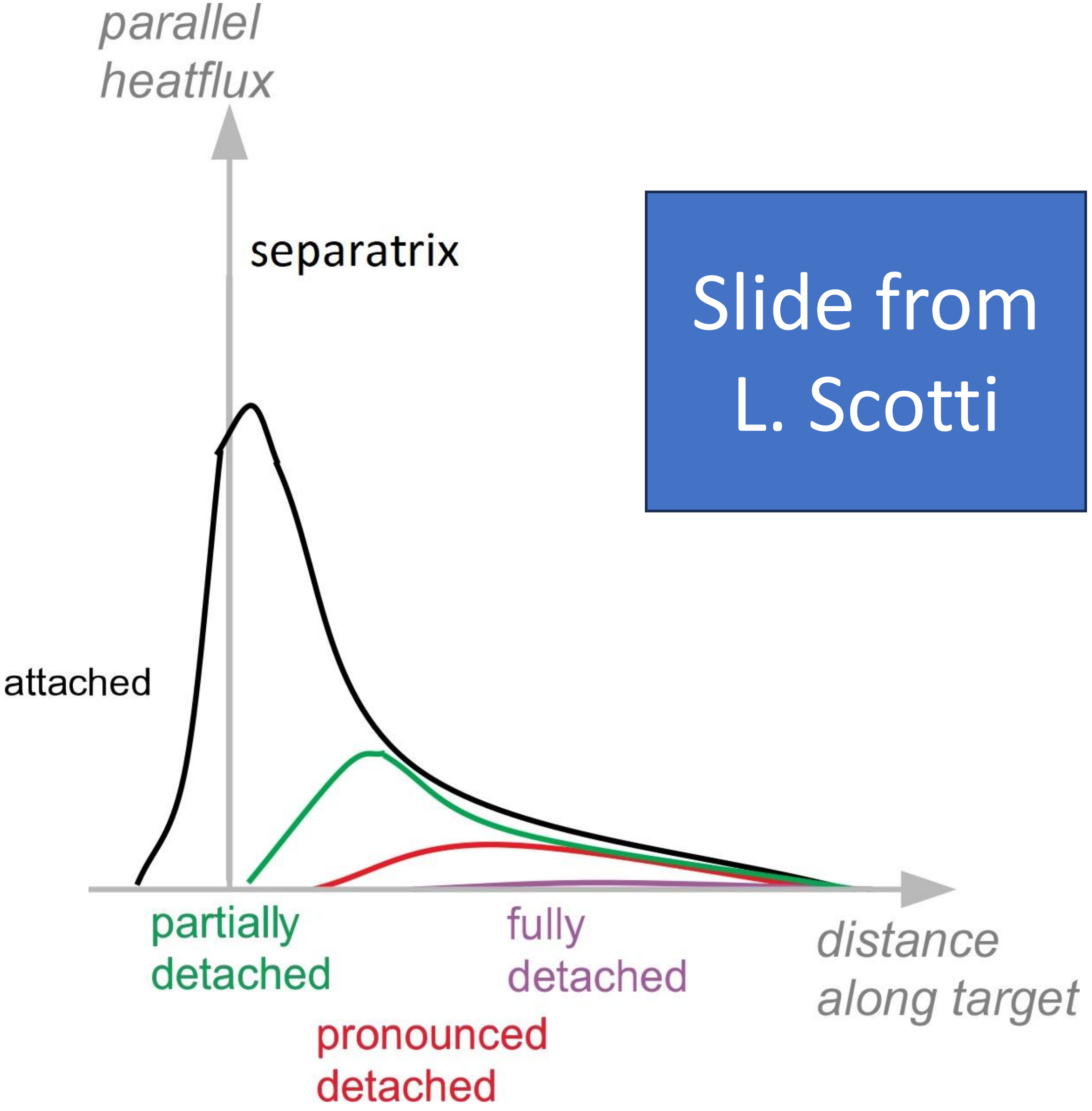
2. What is the detachment cliff? McLean JNM 2015

- The partial detachment occurs only near the separatrix

→ Also the detachment cliff occurs only at $\rho_{pol}\approx 1$

To summarize:

- Bifurcative transition towards partial detachment
- Occurs close to the separatrix
- Transition time less than ≈10ms
- Occurs with $\Delta n_e<10\%$

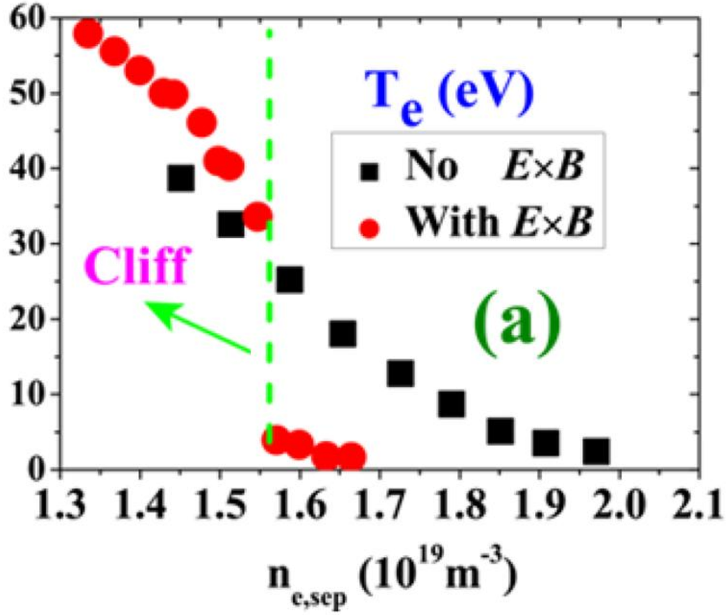


[Kallenbach et al. NF 2015]

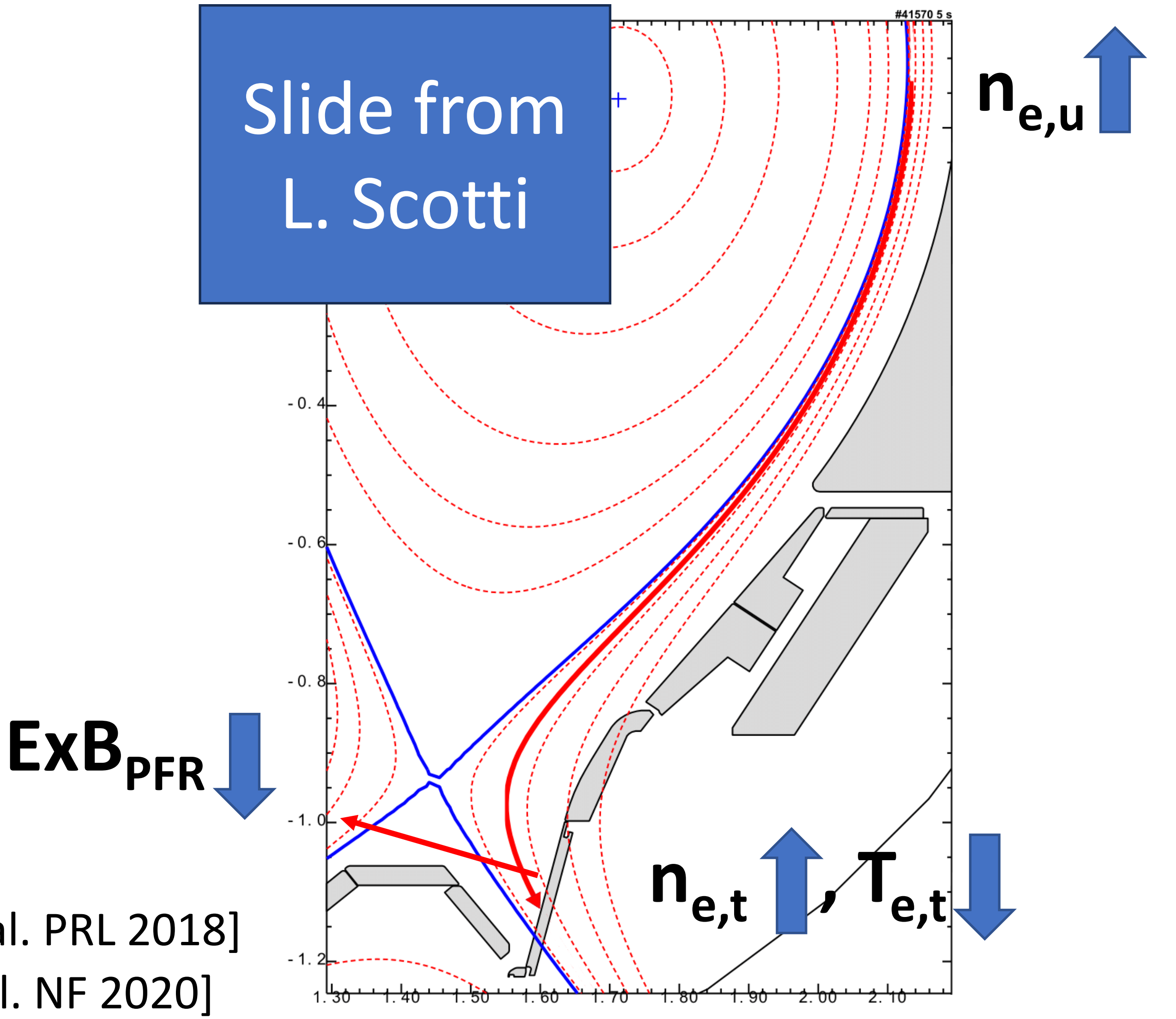
Slide from L. Scotti

Approach to detachment:

- Positive feedback between $n_{e,u}$ ↑ and ExB_{PFR} ↓
- Impurities enhance the positive feedback process



[Jaervinen et al. PRL 2018]
[Hailong et al. NF 2020]



16. H-mode: influences on the stable high temperature values

The effect of the input power, of the upstream density and of the injected impurity species on the stable high temperature value has been investigated

McLean: $T_{e,start} \propto \sqrt{P}$