This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Max-Planck-Institut für Plasmaphysik

ID: IAEA-CN-EX/6-3

Electron heated plasmas in Wendelstein 7-X and ASDEX Upgrade; necessity to control turbulent transport

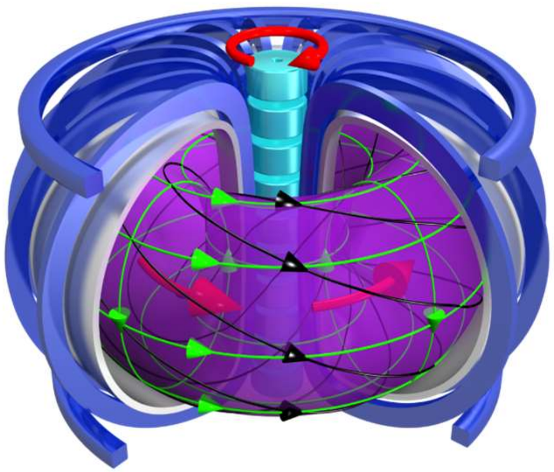
M.N.A. Beurskens, C. Angioni[1], S. Bozhenkov, O. Ford, G. Fuchert, C Kiefer[1], J. Stober[1], P. Xanthopoulos, Y. Turkin, J.A. Alcusón, J. Baldzuhn, C. Beidler, G. Birkenmeier[1], R. Burhenn, A. Dinklage, E. Fable[1], B Geiger[1], O. Grulke, M. Hirsch, M. Jakubowski, H. Laqua, S. Lazerson, M. Reisner[1], P. Schneider[1], E. R. Scott, T. Stange, A. von Stechow, U. Stroth[1], F. Warmer, Th. Wegner, G. Weir, D. Zhang, R.C. Wolf, H. Zohm[1] , the Wendelstein 7-X, the ASDEX-upgrade, and the MST1 teams.

Max-Planck Institut für Plasmaphysik, EURATOM Association, Greifswald, Germany

[1]Max-Planck Institut für Plasmaphysik, EURATOM Association, Garching, Germany

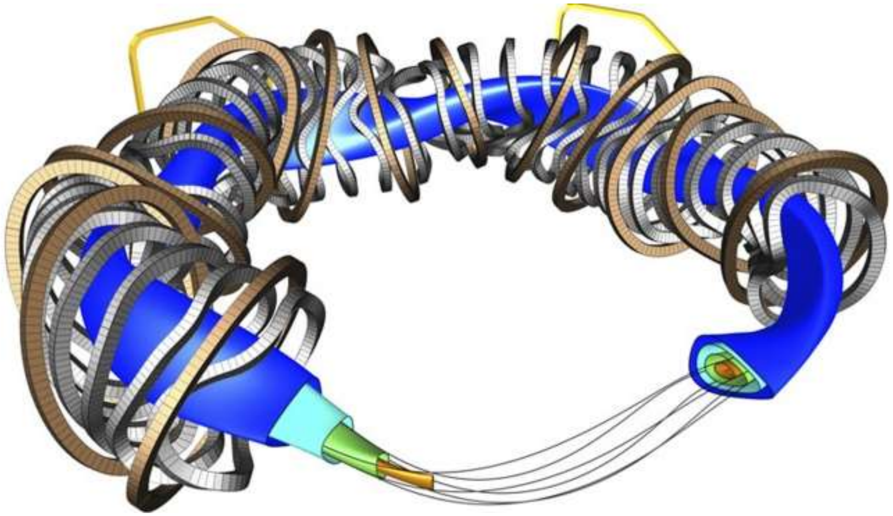
Magnetic confinement concepts

ASDEX Upgrade : Tokamak (2D)



- current I_p ~ 1 MA
- a = 0.5 m, R= 1.6 m, B = 2.5T
- P_{ECRH} = 5 MW
- low neoclassical transport

Wendelstein 7-X: Stellarator (3D)

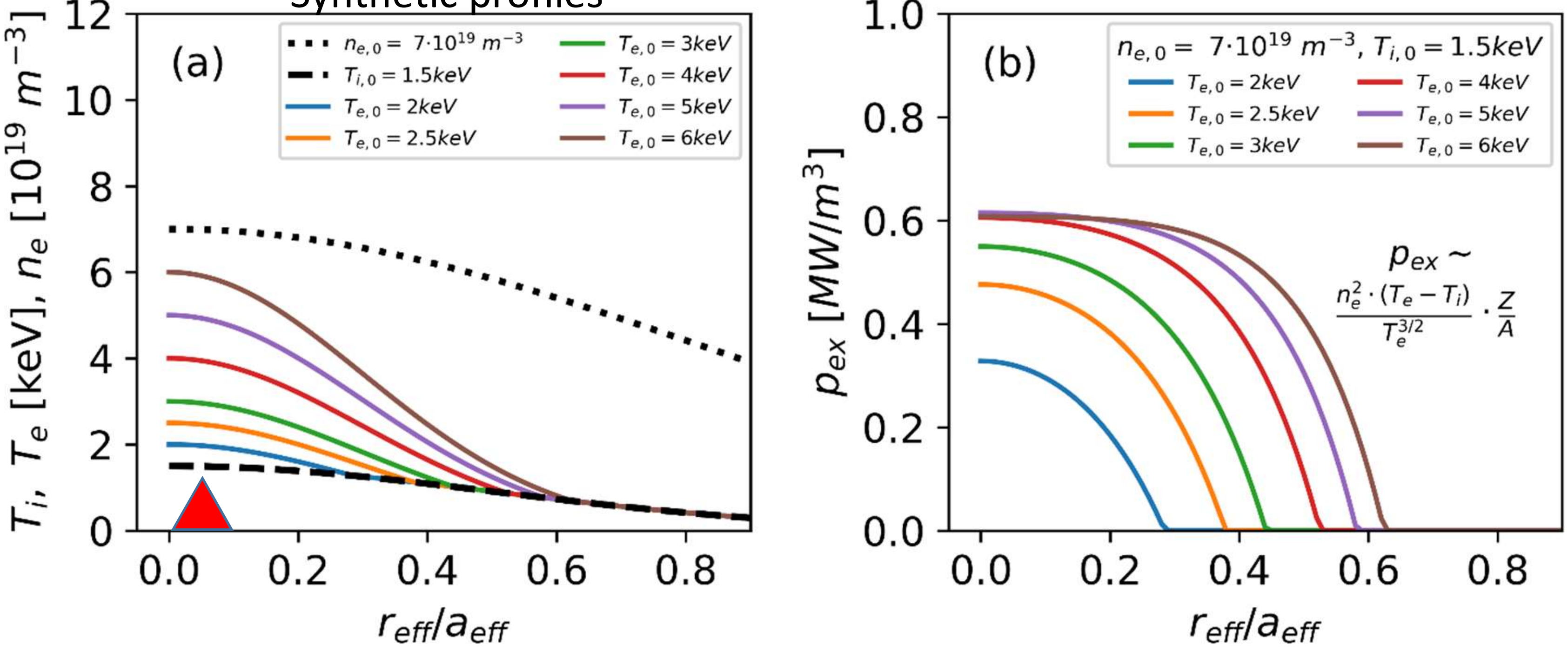


- No induced plasmas current
- a = 0.5 m, R= 5 m, B = 2.5T
- P_{ECRH} = 7 MW (15 MW envisaged)
- Optimised neocl. transport ε_{eff} < 1%

Electron heated plasma

- **ECRH electron heating is very localised**
- **Ion heating (exchange power) is broad,** $\mathbf{p_{ei} \sim \frac{n_e^2\,(T_e - T_i)}{T_e^{3/2}} \cdot \frac{Z}{A}}$

Synthetic profiles

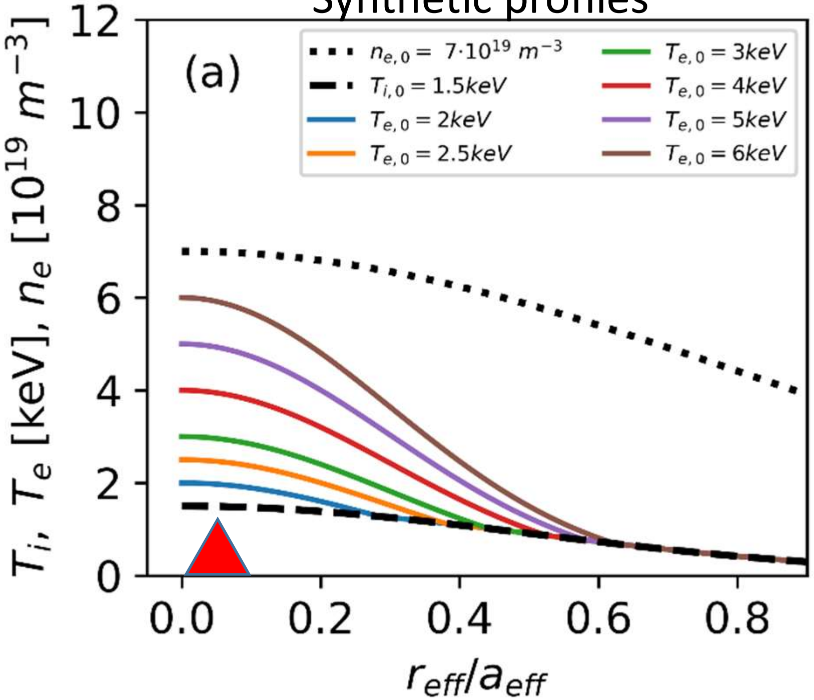


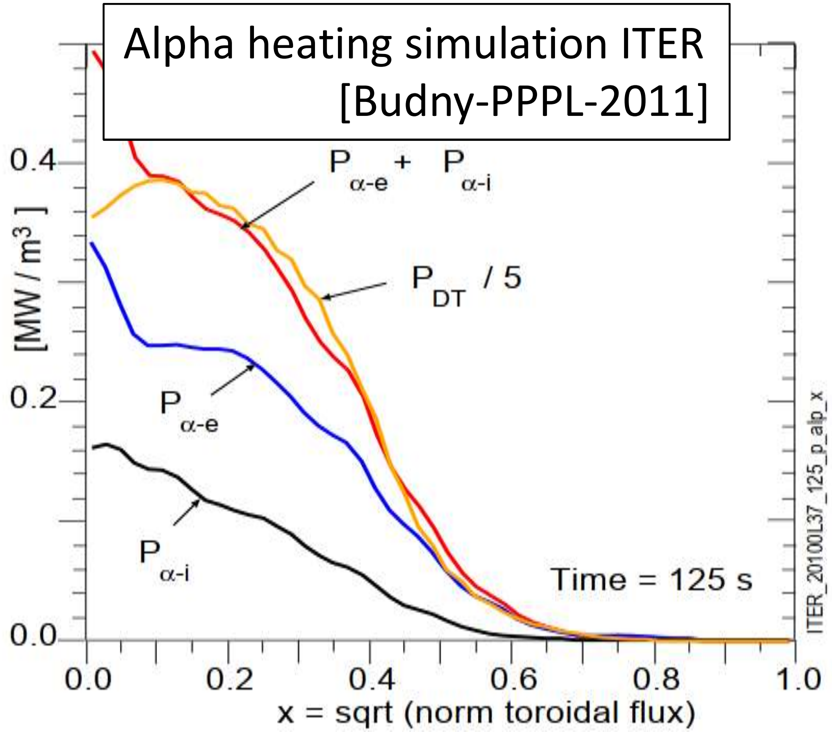
Electron heated plasma

- **ECRH electron heating is very localised**
- **Ion heating (exchange power) is broad**
- **In a reactor alpha heating will predominantly heat electrons…**

→ e-heated plasma performance important to study!

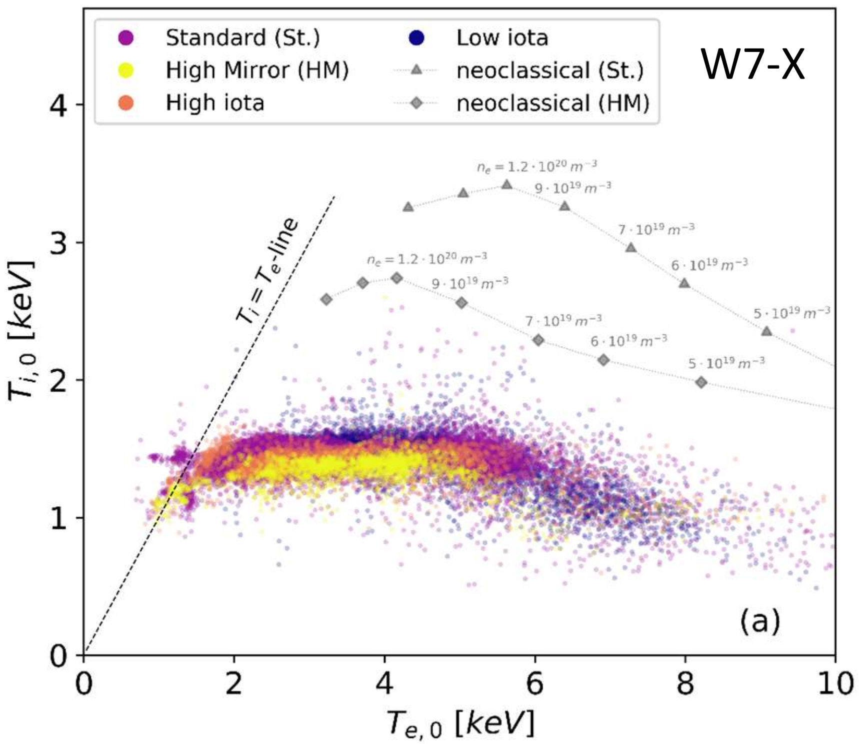
Synthetic profiles

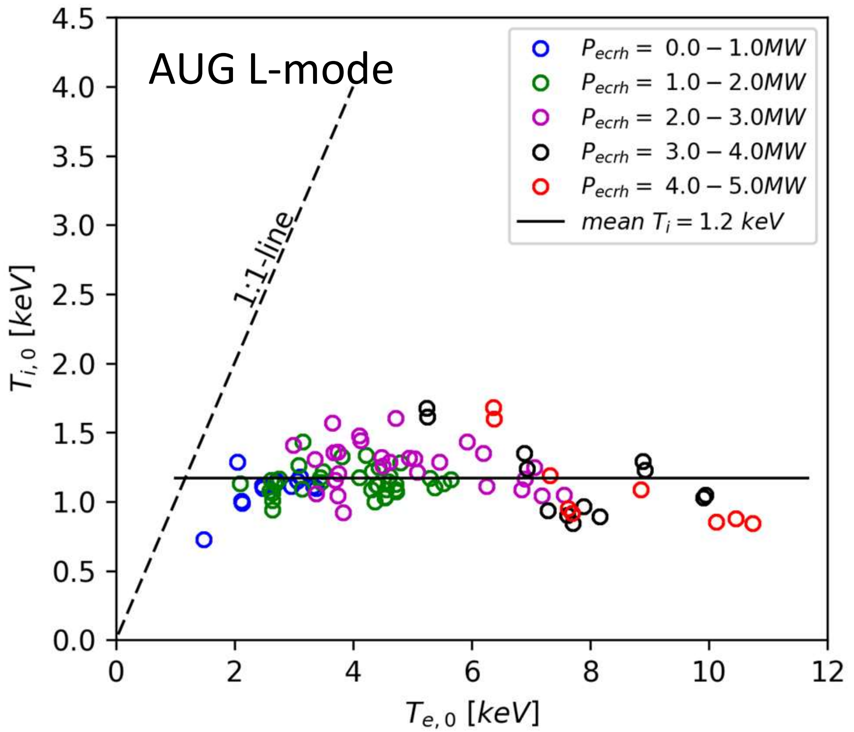




Electron heated plasmas using ECRH

- **Ion temperature T_i-clamping in both devices: $T_i \leq 1.5$ keV**
  - Low exchange power with broad ion heating profile?
- **Under these conditions, turbulent tranport is dominant**
  - Which type of turbulence is at play? Profile stiffness?





Ion temperature clamping in electron heated plasmas

In electron heated L-mode plasmas of ASDEX Upgrade and Wendelstein7-X, the ion temperature clamps at T_i ~ 1.5 keV, independent of magnetic configuration:

- The ions are heated by energy exchange $p_{ei} \sim \mathrm{n_e^2}\,(\mathrm{T_e} - \mathrm{T_i})/\mathrm{T_e^{3/2}}$, which offers a broad ion heating profile only where $T_e/T_i > 1$.
- Heat transport due to ITG/TEM turbulence is strongly exacerbated as $T_e/T_i > 1$ even at small positive ε with $T_e/T_i = 1 + \varepsilon$
- The resulting "stiff" core transport leads to T_i-clamping.

To remedy the impact of clamping, tokamaks and stellarators either feature:

1. an **H-mode** with a strong **edge pedestal** to lift the "stiff" core T_i profiles
2. **suppressed or reduced core turbulence** by means of:
    i. Fast ions stabilisation (tokamaks and stellarators)
    ii. Enhanced density gradients (stellarators and negative-magn.-shear-tokamak)
    iii. Designing turbulence-resilient-configurations with e.g. negative triangularity tokamaks or e.g. low elongation in stellarators.

Key findings of this work

In electron heated plasmas :

- T_i-clamping at ~ 1.5 keV occurs independent of magnetic configuration.
- Ion are heated through exchange power as $T_e/T_i > 1$.
- At the same time clamping puts a stronger contraint on T_i than profile stiffness as $T_e/T_i > 1$ exacerbates ITG/TEM turbulence.
- Therefore, in practical terms T_i-clamping leads to an apparent strongly "stiff" core transport in both AUG and W7-X

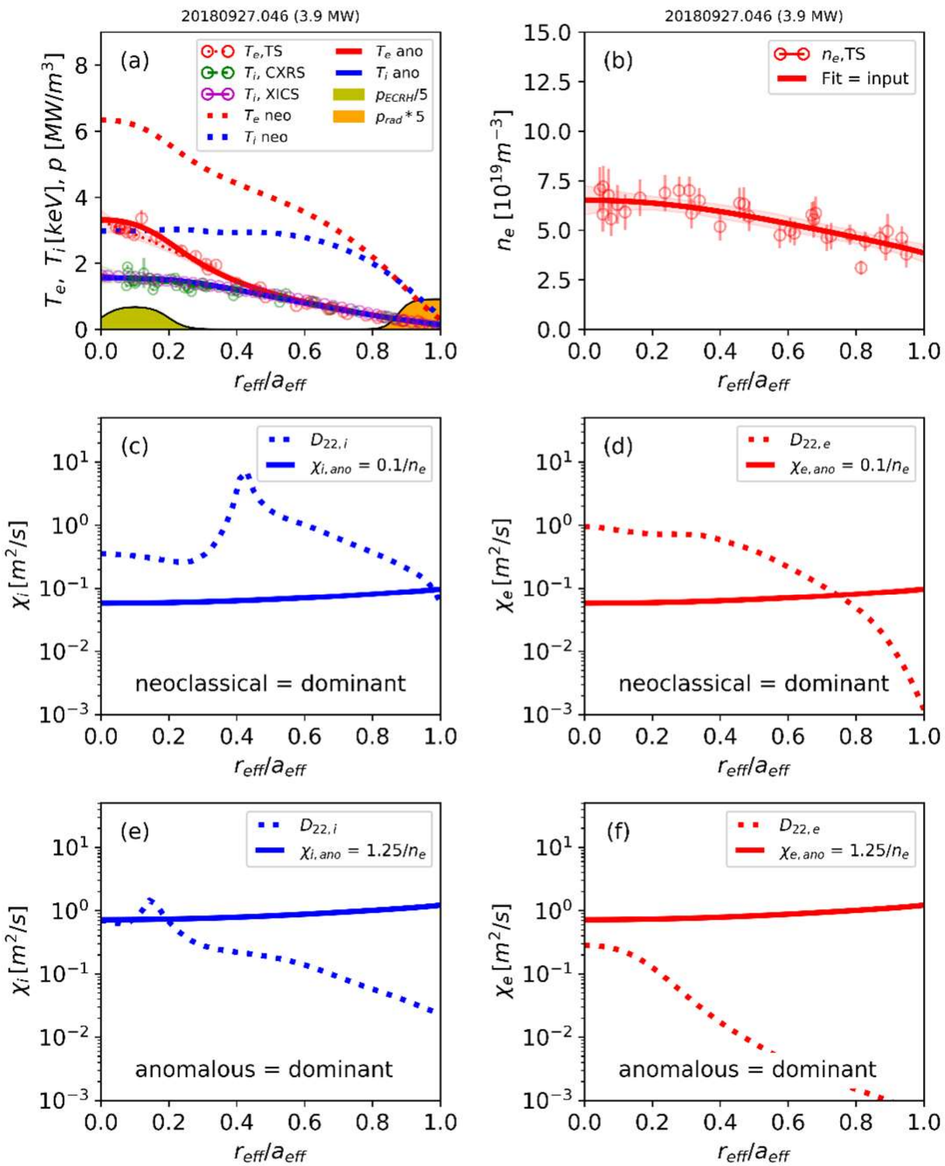
$T_e/T_i \leq 1$ reduces tranport, but is not possible.

→therefore T_i clamping is unavoidable in electron heated plasmas

To remedy the impact of clamping, tokamaks and stellarators either feature:

1. an H-mode with strong **edge pedestal** to lift the "stiff" core T_i profiles
2. **suppressed or reduced** core turbulent transport by means of:
   i. Fast ions stabilisation (tokamaks and stellarators)
   ii. Enhanced density gradients (stellarators and negative-magnetic-shear-tokamak)
   iii. Negative triangularity (tokamaks only – exploratory)

W7-X: neoclassical transport overestimates performance



Wendelstein 7-X:

Comparing NC to experiment:

- P_{ECRH} = 4MW, $n_{e,0}$ = 7e19 m^{-3},
- Central ECRH deposition
- Edge radiation assumed

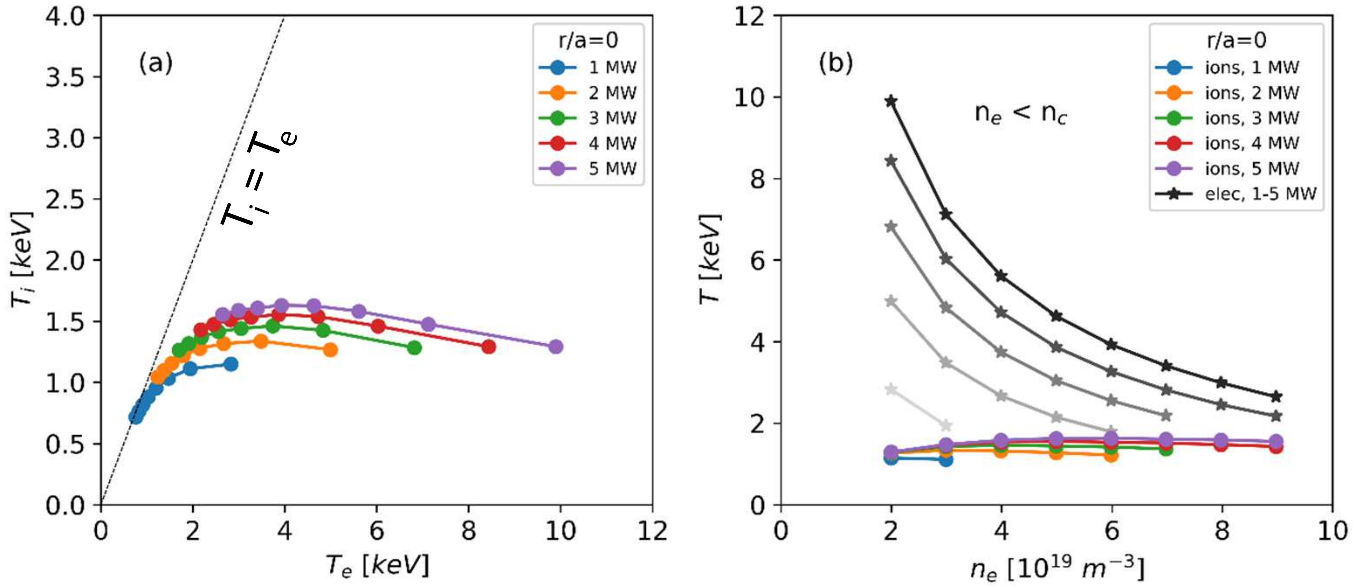
Experiments result:

$T_{i,0}$ ~ 1.6 keV

Neoclassical transport simulation:

$T_{i,0}$ ~ 3.0 keV

configuration independent gyroBohm transport

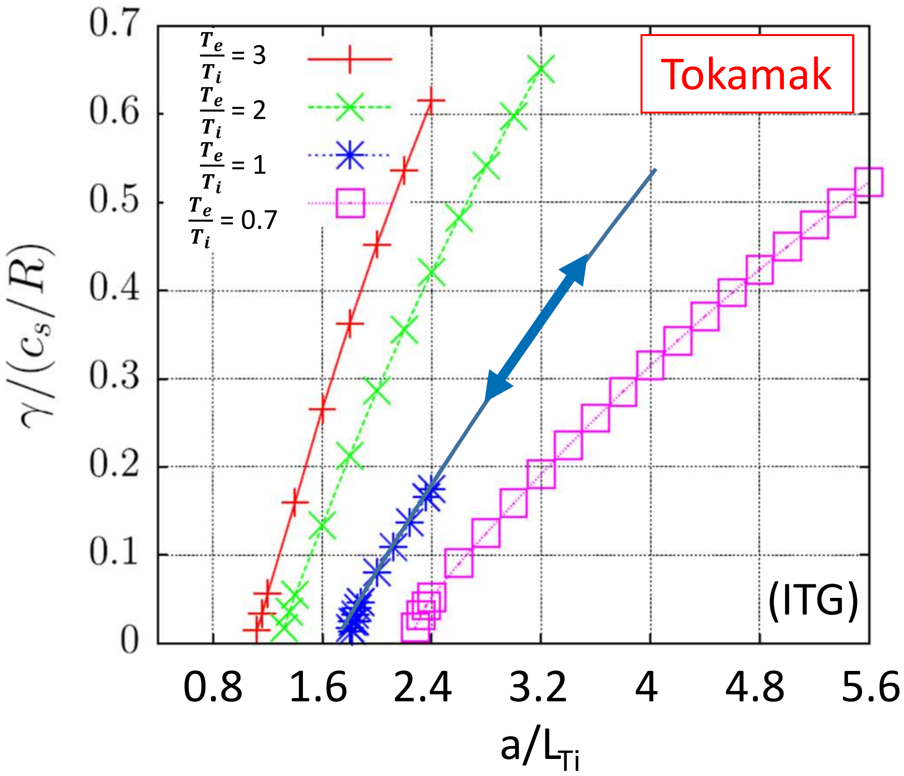


- **NTSS simulations:** $\chi_{turb} \gg \chi_{neo}$**, Vary P_{ECRH}=1-5 MW and n_e=10^{19} - 10^{20} m^{-3}**
- **GyroBohm ion diffusivity:** $\chi_{i,gB} = \sqrt{\frac{m_i}{e}}\frac{T_i^{3/2}}{aB^2}$**, (electrons: $\chi_{e,turb}$ = constant)**
- **Tried in AUG and W7-X configurations → clamping is configuration independent:**
  - Due to broad ion heating profile (exchange power)
  - Large anomalous transport

Expectations for ion turbulent heat transport

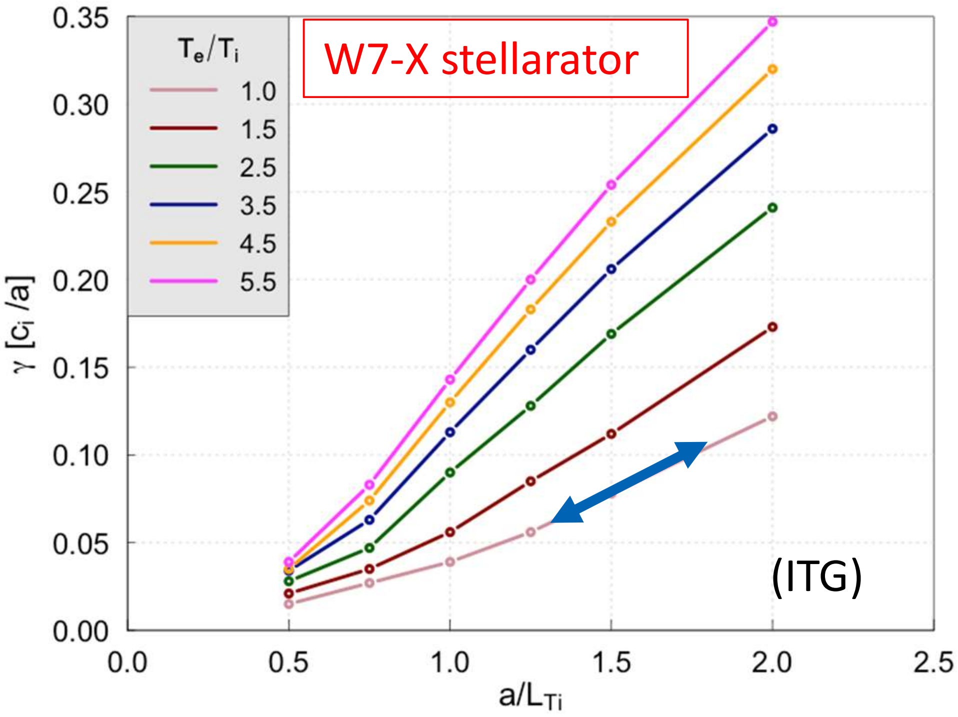
- **Ion heat transport can be driven by Ion Temperature Gradient (ITG) or trapped electron modes (TEM)**
- **Both devices may also feature a strong T_e/T_i drive for ion transport**

Linear calculations



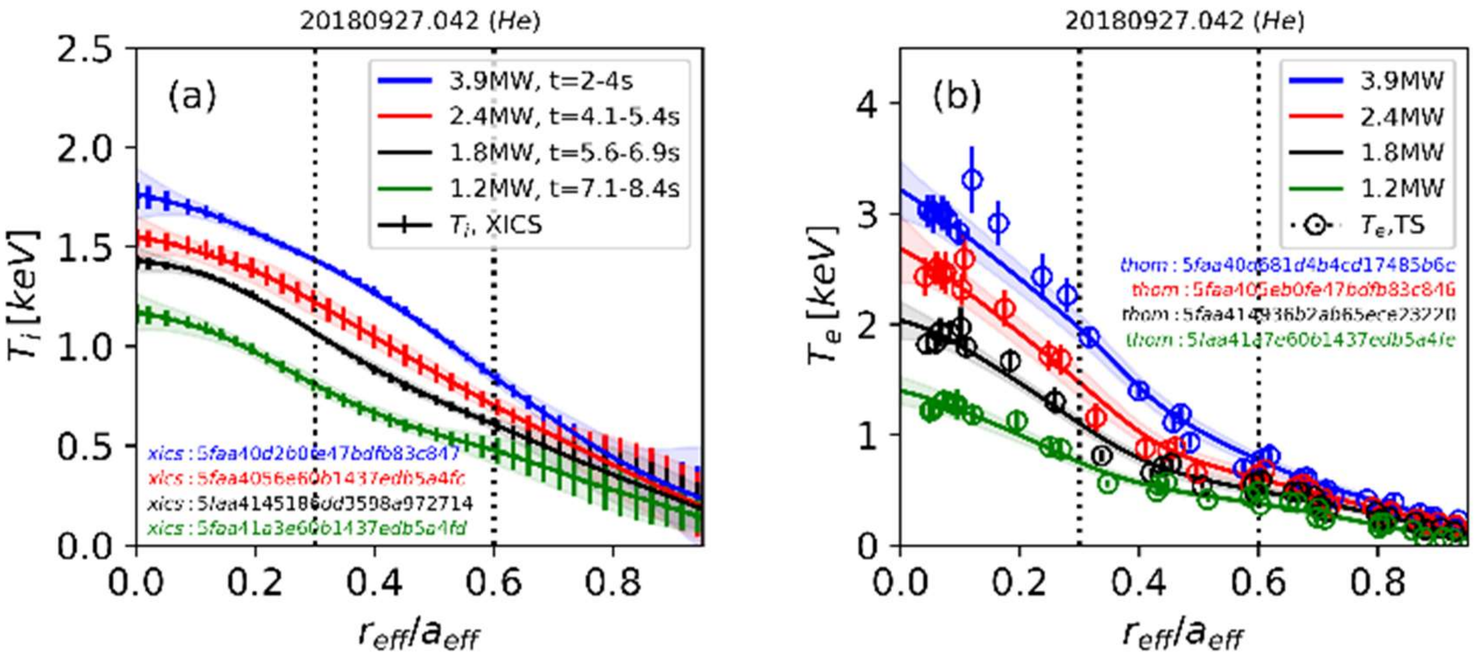
[Zocco, Xanthopoulos et al. JPP 84 (1), 2018]

Linear calculations



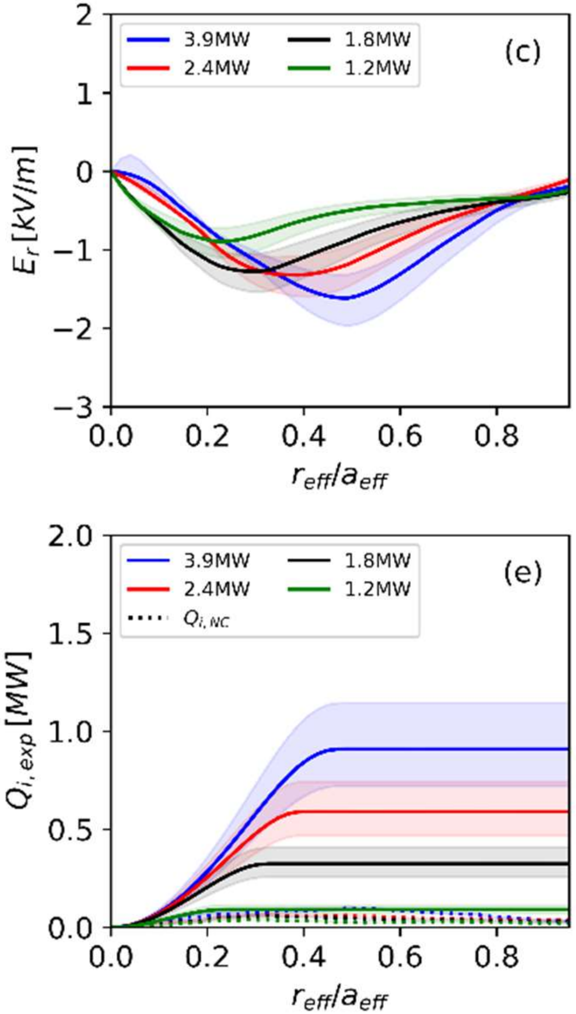
γ is growth rate of most unstable mode

Wendelstein 7-X power scan experiment



- **Steps down P_{ECRH}= 3.9 - 1.2 MW**
- **T_e varies 3 → 1.3 keV**
- **T_i varies 1.7 → 1.2 keV**
- **n_e is virtually constant at 7 10^{19} m^{-3}**

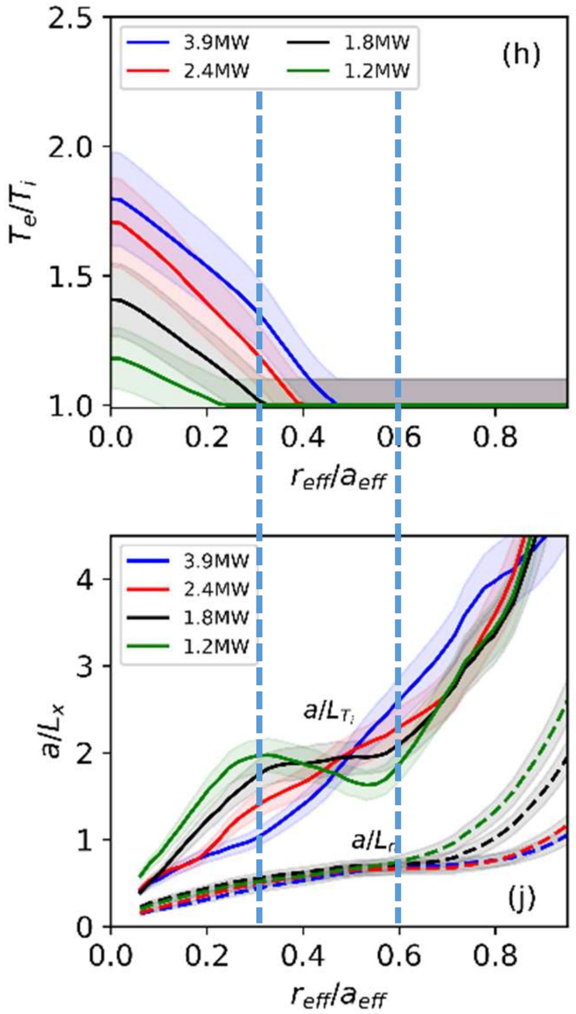
Wendelstein 7-X power scan experiment



With increasing P_{ECRH}	r/a = 0.3	r/a = 0.6
Er	ion root	ion root
$Q_{i,turb} = Q_{i,exp} - Q_{i,NC}$	0.1 - 0.5 MW	0.1 - 1 MW
T_e/T_i		
a/L_{Ti}		
a/L_n		

- Avoid root transitions for accuracy of $Q_{i,turb}$
- Turbulent tranport dominates: $Q_{i,turb} >> Q_{i,NC}$

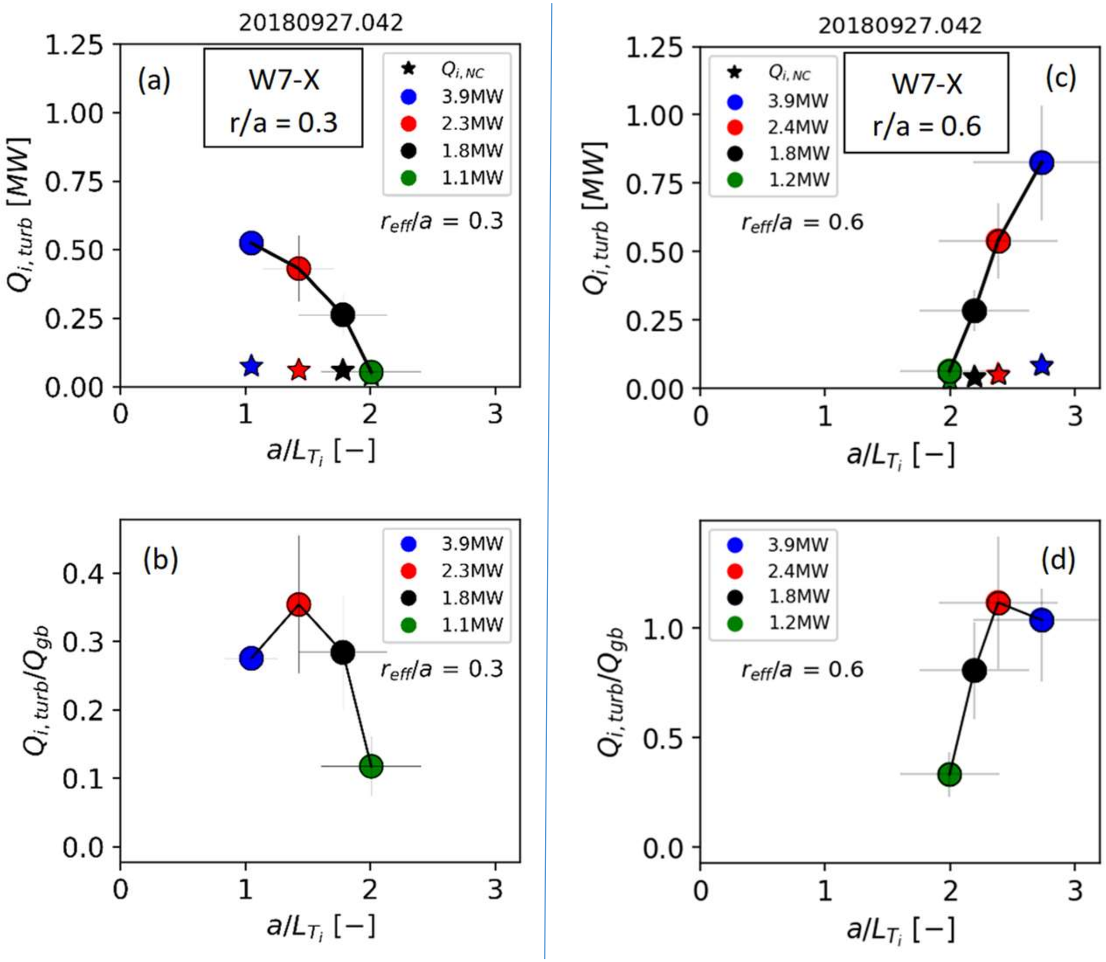
Wendelstein 7-X power scan experiment



With increasing P_{ECRH}	r/a = 0.3	r/a = 0.6
Er	ion root	ion root
$Q_{i,turb} = Q_{i,exp} - Q_{i,NC}$	0.1 - 0.5 MW	0.1 - 1 MW
T_e/T_i	increases 1 - 1.3	constant 1
a/L_{Ti}	decreases 2 - 1	increases 1.5 → 2.5
a/L_n	$a/L_n << a/L_{Ti}$	$a/L_n << a/L_{Ti}$

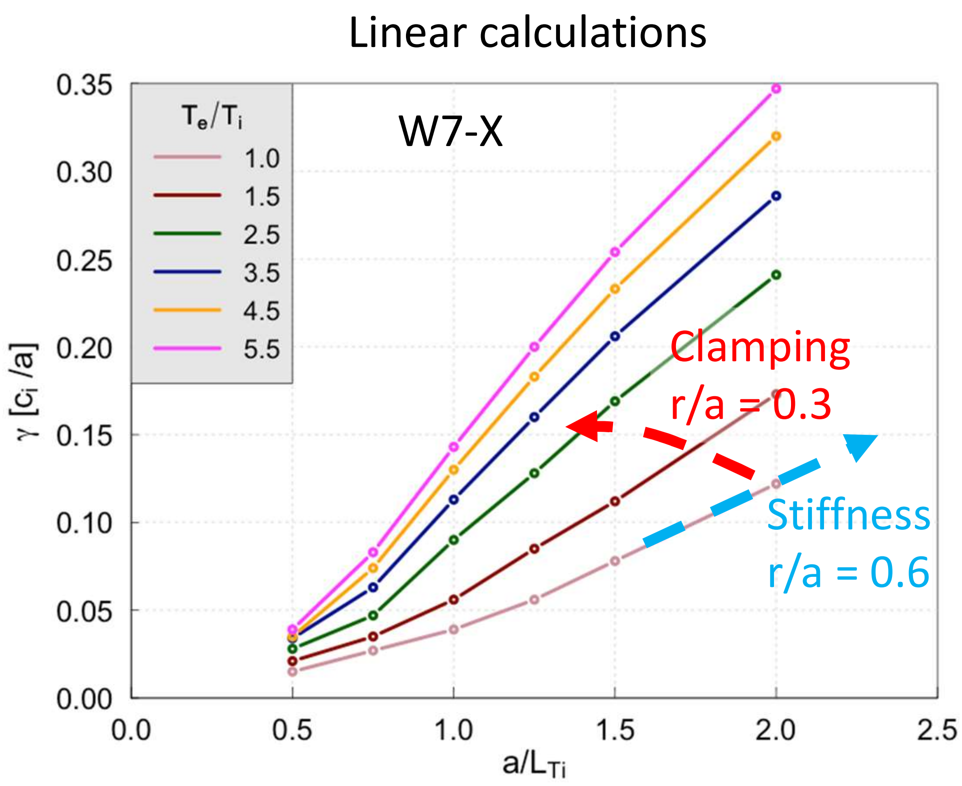
- Profiles of a/L_{Ti} cross over at r/a~ 0.5
- This intersects with radius from where T_e/T_i = 1

Wendelstein 7-X power scan experiment



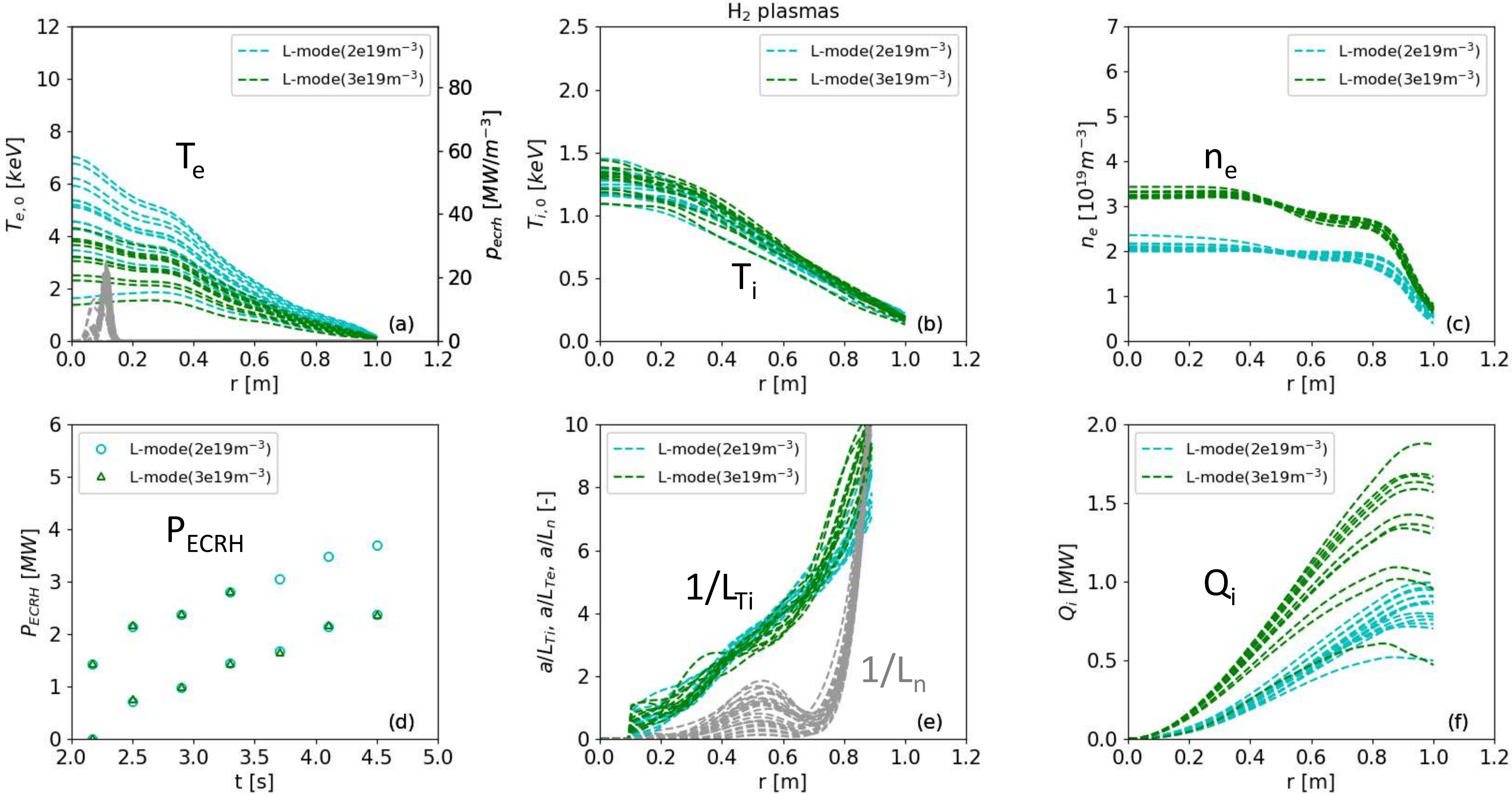
- **At r/a = 0.3 we find a reduction of a/L_{Ti} with increasing $Q_{i,turb}$**
- **At r/a = 0.6, a/L_{Ti} increases with increasing $Q_{i,turb}$**

Wendelstein 7-X power scan experiment



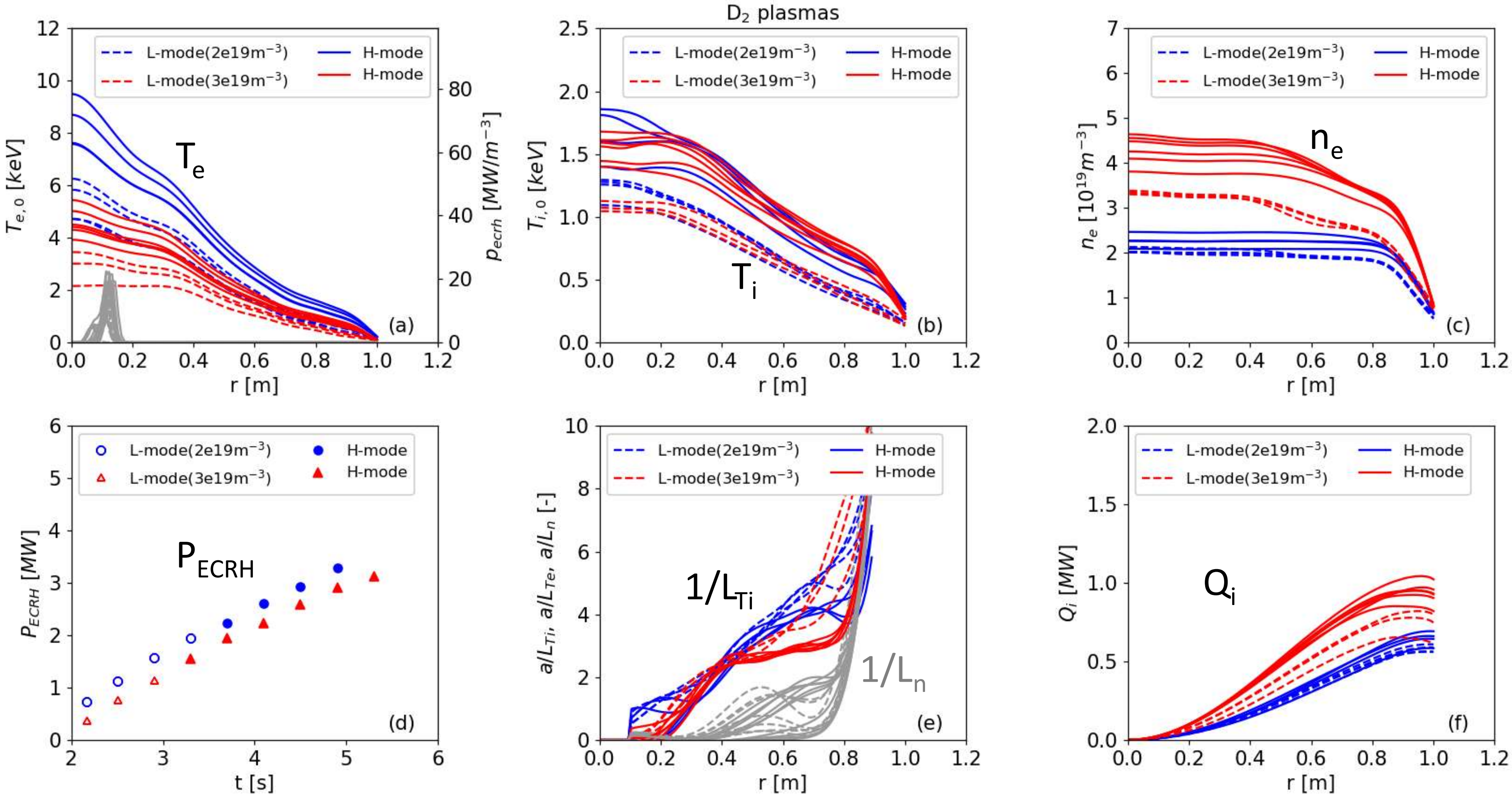
- At r/a = 0.3, both T_e/T_i and clamping increases (jump curves)
- At r/a = 0.6, as T_e/T_i = 1, the stiffness = constant (stay on curve)

AUG power scan experiment in H_2 (L-mode)



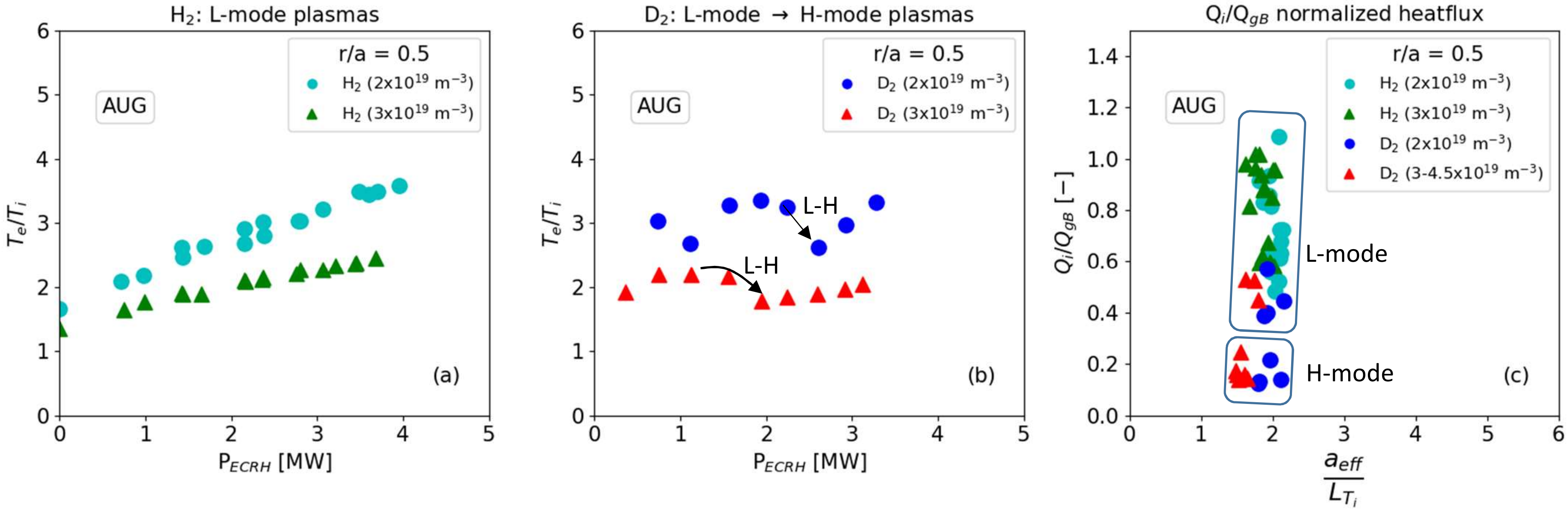
- Large variation of T_e, clamping of T_i < 1.5 keV in L-mode H2 plasmas
- Q_i varied by factor 3

AUG power scan experiment in D_2 (H-mode)



- Tokamak L-H transition can help enhance $T_{i,0}$ as pedestal lifts the core
- Although local gradients remain the same (or reduce somewhat)

Clamping due to turbulent tranport

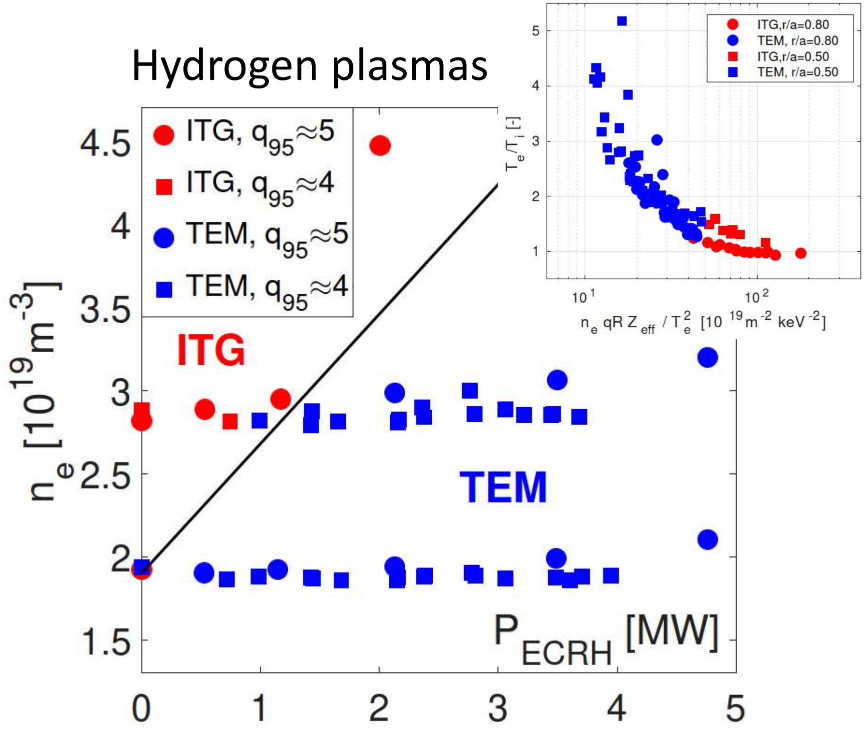


- Ion temperature gradient clamped at a/L_{Ti} ~ 2
- Variation of T_e/T_i from 1.5-3.5 enhances clamping (this is not infinite stiffness!)

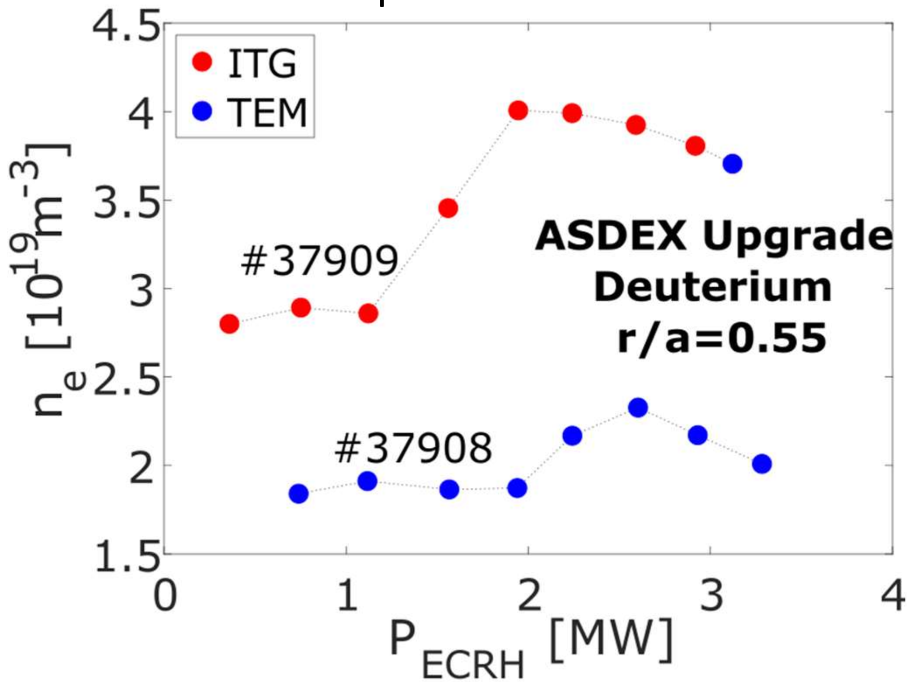
- Issue for L-mode tokamak fusion reactor → impact on size requirement
- H-mode performance almost fully depends on the achievable pedestal

ASTRA-TGLF simulations: TEM or ITG dominant

Hydrogen plasmas



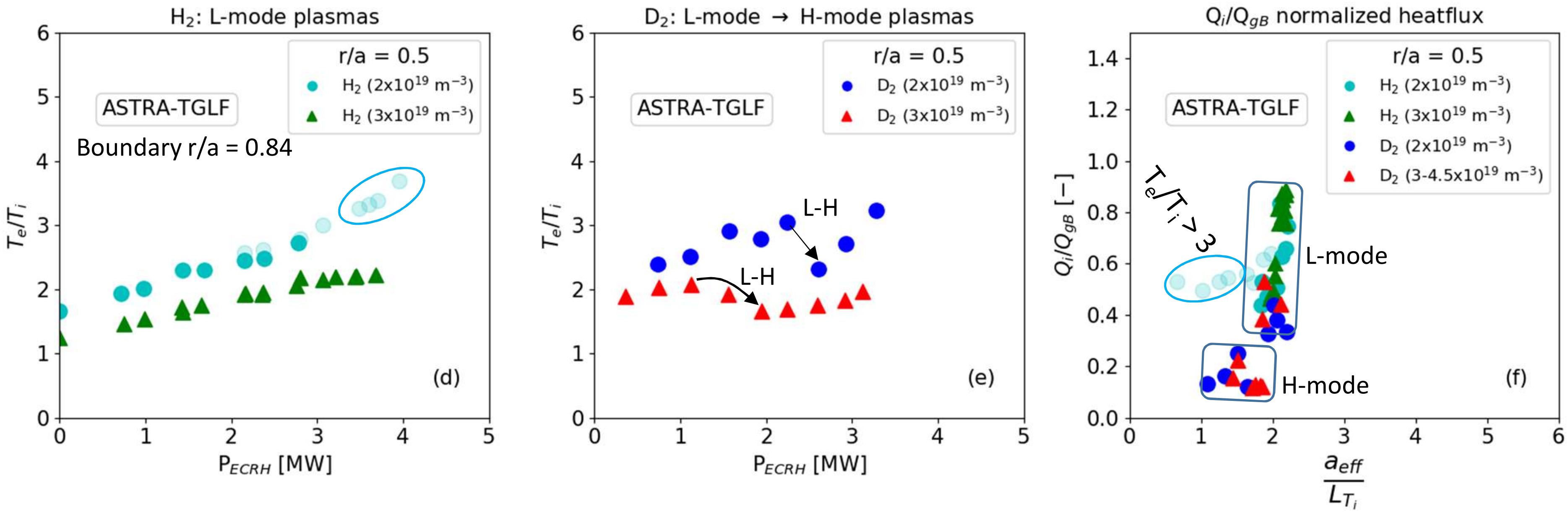
Deuterium plasmas



Using ASTRA-TGLF simulations with quasi-linear gyrokinetic calculations

- Depending on collissionality either TEM or ITG is the dominant micro-instability
- Both instabilities feature enhanced stiffness with increasing T_e/T_i

ASTRA-TGLF simulations reproduce clamping

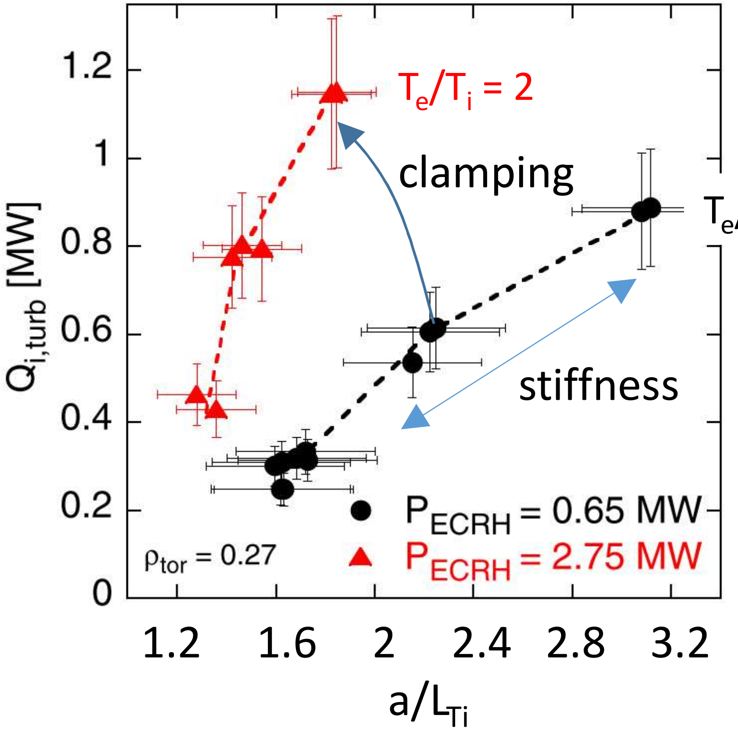


- ASTRA-TGLF simulations show good quantitative agreement of core transport (pedestal from experiment):
  - With some systematic deviations

- L-mode plasmas: clamping effect is reproduced for $T_e/T_i < 3$
- H-mode plasmas: TGLF penalises T_e/T_i stronger than experiment

Clamping is not Stiffness

[F. Ryter et al 2019 Nucl. Fusion 59 096052]



Clamping >> Stiffness

In controlled profile experiment (NBI and ECRH deposition scan)

- with T_e/T_i = constant: much wider variation of a_{eff}/L_{Ti} = 1.5 – 3
- Here also, jumping curves when T_e/T_i changes enhances clamping.

T_i clamping is independent of configuration!

Strong T_i-clamping is equally found in AUG and W7-X electron heated plasmas.

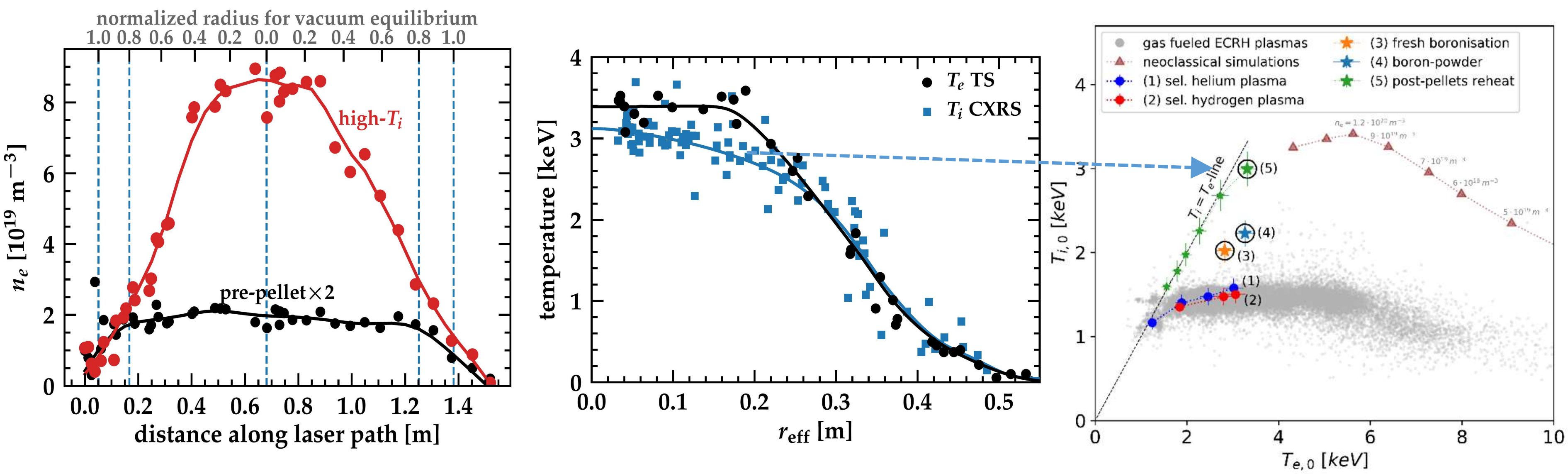
For tokamaks:

- Strong limitation on L-mode reactor (constraint on size!)
- H-mode operation may be a necessity (pedestal lifts core)
- Also beneficial effect of fast particle stabilisation and/or neg. triangularity concepts to be explored

For Stellarators (HELIAS):

- H-modes with good confinement still to be found. (J. Geiger this conference)
- Core turbulence suppression is possible through density gradient: “Stability valey“ thanks to maximum-J configuration (T.S. Pedersen this conference)

Example of turbulence suppression scenario

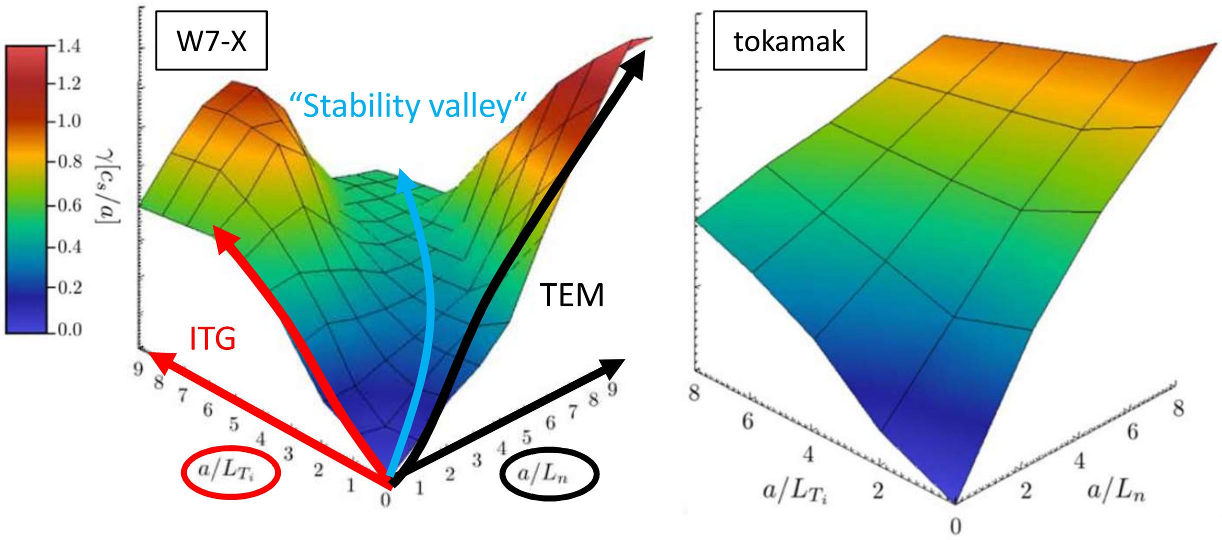


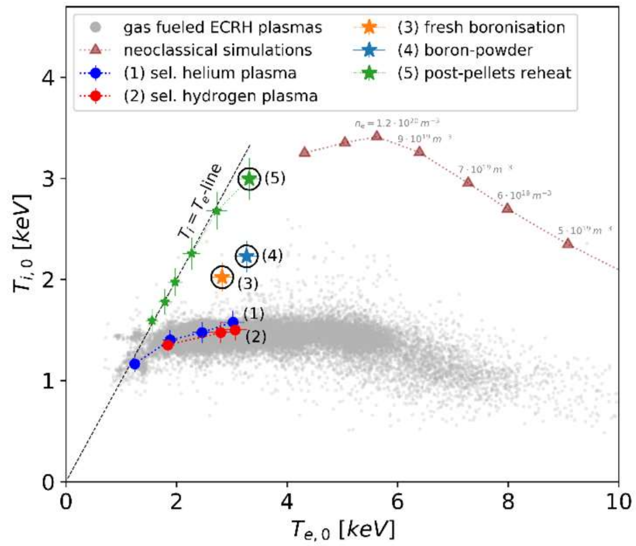
Post pellet experiments confirm reduced turbulence scenario:

- Enhanced density gradients $a/L_n \sim a/L_{Ti}$ help suppress ITG turbulence
- T_i clamping is (transiently) broken to get T_i = 3 keV

In W7-X we will attempt to make this a steady scenario and explore enhanced performance with new cryo pumps and a new continuous pellet injector

Example of turbulence suppressed scenario





Wendelstein 7-X vs tokamak stability map

- Linear gyrokinetic simulations show **"Stability valley"**

Post pellet experiments confirms reduced turbulence scenario: T_i = 3keV

Key findings of this work

In electron heated L-mode plasmas of ASDEX Upgrade and Wendelstein7-X, the ion temperature clamps at T_i ~ 1.5 keV, independent of magnetic configuration:

- The ions are heated by energy exchange $p_{ei} \sim \mathrm{n_e^2}\,(\mathrm{T_e} - \mathrm{T_i})/\mathrm{T_e^{3/2}}$, which offers a broad ion heating profile only where $T_e/T_i > 1$.
- Heat transport due to ITG/TEM turbulence is strongly exacerbated as $T_e/T_i > 1$ even at small positive ε with $T_e/T_i = 1 + \varepsilon$
- The resulting "stiff" core transport leads to T_i-clamping.

To remedy the impact of clamping, tokamaks and stellarators either feature:

1. an **H-mode** with a strong **edge pedestal** to lift the "stiff" core T_i profiles
2. **suppressed or reduced core turbulence** by means of:
   1. Fast ions stabilisation (tokamaks and stellarators)
   2. Enhanced density gradients (stellarators and negative-magn.-shear-tokamak)
   3. Designing turbulence-resilient-configurations with e.g. negative triangularity tokamaks or e.g. low elongation in stellarators.

IAEA-CN-EX/6-3