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

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Key findings of this work

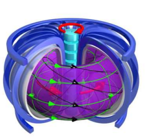
- In electron heated plasmas in both AUG and W7-X, clamping of the ion temperature occurs at Ti ~ 1.5 keV independent of magnetic configuration.
- The ions in such plasmas are heated through the energy exchange power as $n_e^2\,(T_e - T_i)/T_e^{3/2}$, which offers a broad ion heating profile.
- At the same time this heating mechanism puts a strong constraint on the ion heat transport, as the ratio $T_e/T_i > 1$ exacerbates ITG/TEM core turbulence.
- Therefore, in practical terms the strongly "stiff" core transport translates into Ti-clamping 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:
    1. fast ions stabilisation (tokamaks and stellarators)
    2. enhanced density gradients (stellarators and negative-magnetic-shear-tokamak)
    3. designing turbulence resilient magnetic configurations such as e.g. negative triangularity configurations in tokamaks or configurations with low elongation in stellarators

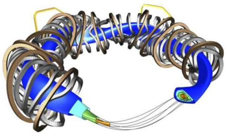
Magnetic confinement concepts

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

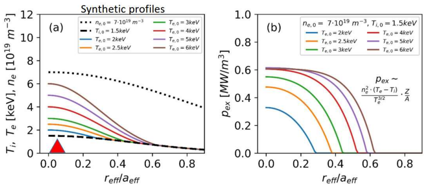
Wendelstein 7-X: Stellarator (3D)



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

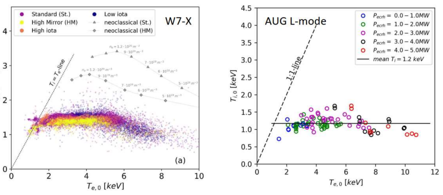
Electron heated plasma

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

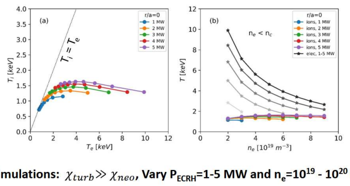


Electron heated plasmas using ECRH

- **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?



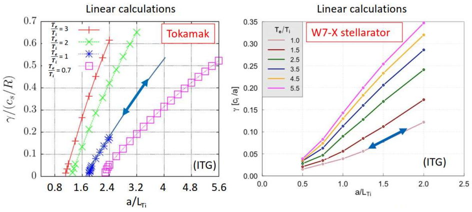
configuration independent gyroBohm transport



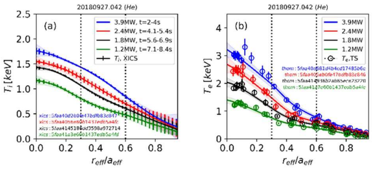
- **NTSS simulations: $\chi_{turb} \gg \chi_{neo}$, Vary P_{ECRH}=1-5 MW and $n_e=10^{19}$ - 10^{20} m^{-3}**
- **GyroBohm ion diffusivity: $\chi_{i,gB} = \sqrt{\frac{m_i}{e}}\frac{T_i^{3/2}}{aB^2}$, (electrons: $\chi_{e,turb}$ = constant)**
- **Tried in AUG and W7-X configurations → clamping is configuration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

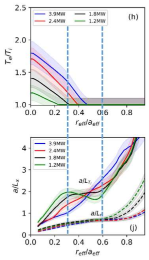


Wendelstein 7-X power scan experiment



- **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}**

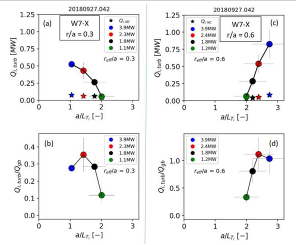
Wendelstein 7-X power scan experiment



With increasing PECRH	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	$a/L_n << a/L_{Ti}$	$a/L_n << a/L_{Ti}$

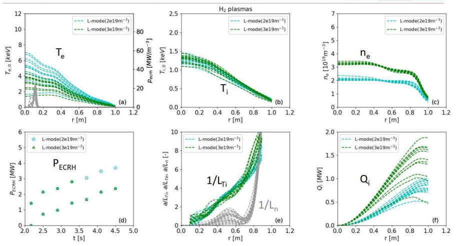
- Profiles of a/L_{Ti} cross over at r/a~ 0.5
- This intersects with radius from where T_e/T_i = 1

Wendelstein 7-X power scan experiment



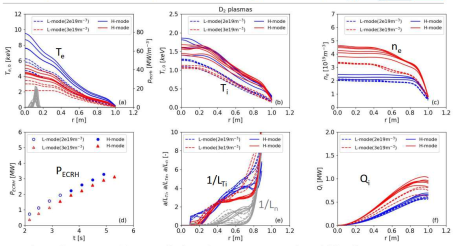
- **At r/a = 0.3 we find a reduction of a/L_{Ti} with increasing $Q_{i,turb}$**
- **At r/a = 0.6, a/L_{Ti} increases with increasing $Q_{i,turb}$**

AUG power scan experiment in H_2 (L-mode)



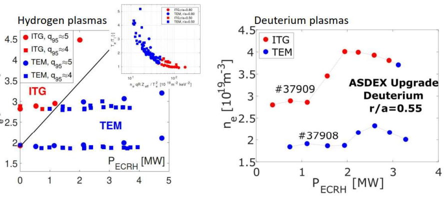
- Large variation of T_e, clamping of T_i < 1.5 keV in L-mode H2 plasmas
- Q_i varied by factor 3

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)

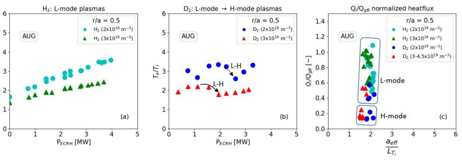
ASTRA-TGLF simulations: TEM or ITG dominant



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

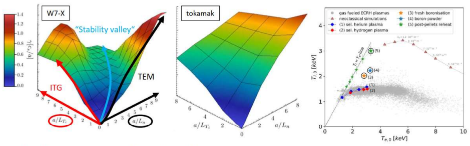
Clamping due to turbulent tranport



- 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 alsmost fully depends on the achievable pedestal

Example of turbulence suppressed scenario

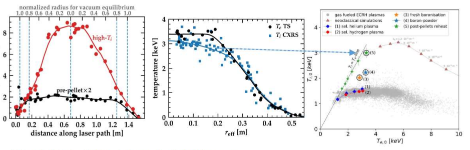


Wendelstein 7-X vs tokamak stability map

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

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

Example of turbulence suppression scenario



Wendelstein 7-X vs tokamak stability map

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

Post pellet experiments confirm reduced turbulence scenario:

- Enhanced density gradients a/L_n ~ a/L_{Ti} help suppress ITG turbulence
- T_i clamping is (transiently) broken to get T_i = 3 keV
- Explore enhanced performance with cryo pumps and continuous pellet injector

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