Breaking of the ion temperature saturation in electron heated plasmas with turbulence stabilization

[1]P. Manas, [2]J. Ruiz Ruiz, [1]J. Garcia, [1]J.F. Artaud, [1]C. Bourdelle, [1]T. Fonghetti, [3]Y. Kazakov, [1]J. Morales, [1]V. Ostuni, [4]J. Citrin and the WEST Team*

[1] CEA, IRFM, Saint-Paul-les-Durance, France
[2] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, OX1 3NP, UK
[3] Laboratory for Plasma Physics, ERM/KMS, TEC Partner, 1000 Brussels, Belgium
[4] Google Deepmind, London, UK
* see http://west.cea.fr/WESTteam

Contact pierre.manas@cea.fr

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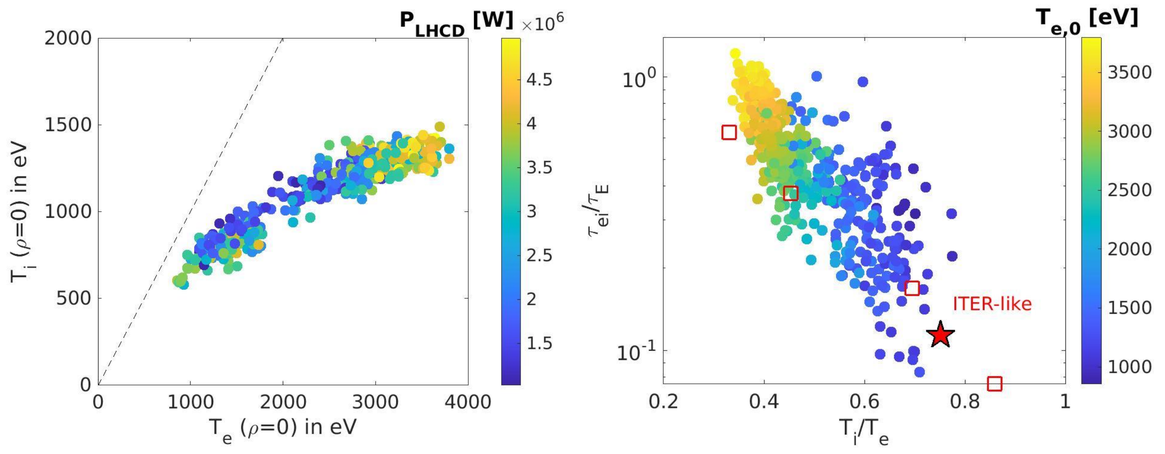
Introduction

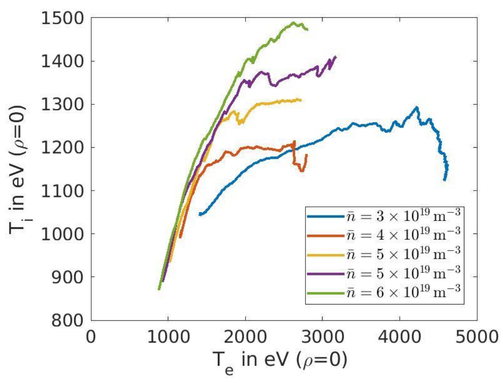
- Central ion temperature saturation (~1.5 keV) has been observed in several machines with electron heated plasmas e.g. [1,2,3]
- This has raised concerns for future reactors as the fusion yield depends strongly on the achievable core ion temperature
  - Fusion power scales with T_i
  - Alpha heating dominantly heats electrons
- It has been shown that the central T_i/T_e is strongly correlated to the ratio of the collisional heat exchange time and the energy confinement time [2]
- Integrated modelling with METIS [7] and QLKNN-10D [6] are able to reproduce this experimental trend and allows extrapolation to reactor relevant conditions
- **This results in reduced predicted saturation for bigger machines with increased confinement time and larger densities**
- While the saturation at low T_i in medium sized machine limits the achievable performances in electron heated plasmas, **scenarios featuring reduced saturation have been observed** [4,8,9]
- **These present core turbulence stabilization, in particular for the ion heat transport**

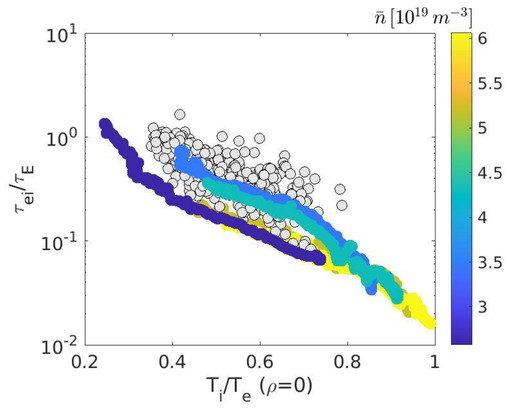
WEST LHCD heated plasmas



Dynamical simulations: density/power scan in WEST LHCD heated plasmas

- Several important parameters explored to minimize τ_{ei} and maximize τ_E -> increase in T_i/T_e [2]
- Previous integrated modelling work identified the density as a key parameter but were obtained with simplifying assumptions:
  - QLKNN-10D transport model with inputs outside of training domain (strong gradients outside $\rho = 0.6$ due to large aspect ratio)
  - Fixed LHCD power deposition
  - Simulations for steady states only



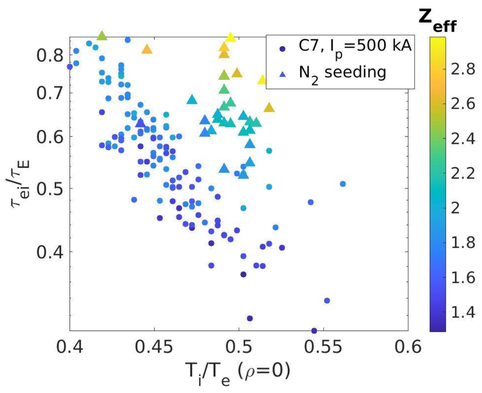


- The impact of these assumptions are explored with the HFPS [17]
  - TGLF-sat2 [16] for turbulent transport up to the separatrix
  - Reduced model for LHCD power deposition [15]
  - **Dynamical simulations with increasing P_{LHCD}**
- **Similar results are obtained:**
  - Increased central ion temperature saturation with increased line averaged densities
  - Lower τ_{ei}/τ_E at high densities following increased collisional heat exchange
  - Consistent with range of variation of WEST experimental data

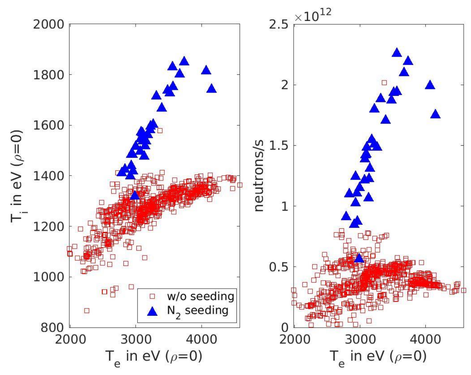
Central ion temperature saturation breaking

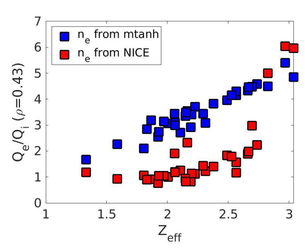
- Breaking of the ion temperature saturation characterized by increased τ_{ei}/τ_E at constant central T_i/T_e and increased T_e

WEST nitrogen seeded



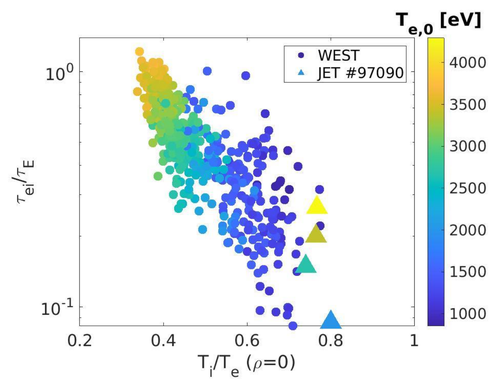
- Ion temperature saturation breaking observed in WEST L-mode seeded discharges, e.g. [14] (LHCD heating)
- **Progressive increase in T_i with increased Z_{eff}**
- Same A/Z as main ions -> same collisional heat exchange
- **Impact on ion heat transport investigated in [18]**



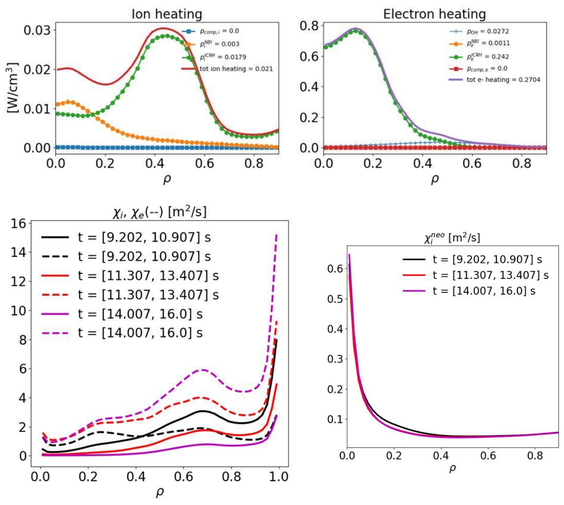


- Gradient driven simulations in the core suggest increasing reduction of ion to electron heat fluxes
- Consistent with ITG stabilization observed in [19, 20]

JET ICRH heated

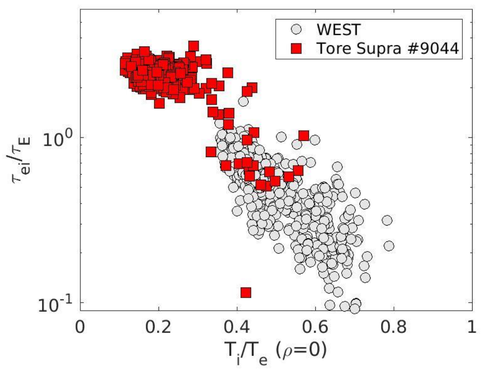


- ICRH heated L-mode JET plasmas with 3 ion scheme [5] resulting in dominant electron heating
- Breaking of central ion temperature observed [4]
- **Presence of Alfvénic activity together with reduced ion heat transport**



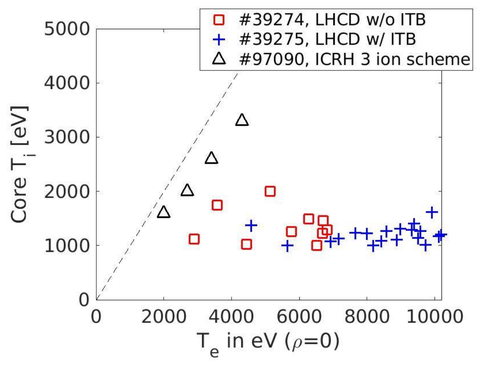
- Core densities $n_e \sim 3.5 - 4 \times 10^{19} m^{-3}$ and ICRH up to 7 MW
- Ion heat transport down to neoclassical levels (below $0.1\ m^2/s$ outside $\rho = 0.1$)
- Electron heat transport increased (electron heat deposition most likely overestimated)

Saturation maintained even in presence of ITBs



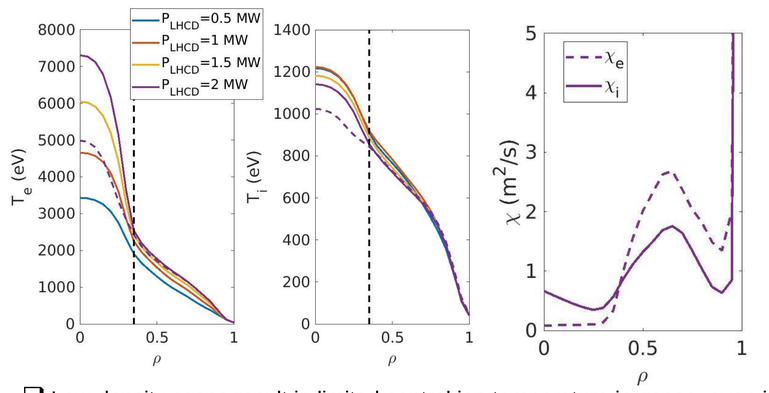
- Shot #9044 of Tore Supra features a strong increase in central electron temperature **but central T_i remains of the order of $1.6\ keV$** despite significant reduction in heat diffusivities [12]
- In parallel, **JET shots #39274 and #39275 with and without a central ITB also feature a central T_i saturation**

- Impact of reduction of core turbulent transport on ion temperature saturation investigated in central ITB formation following safety factor reversals
- These have been routinely obtained in Tore Supra, e.g. [12] and JET, e.g. [10,11,13] LHCD plasmas (electron heating only) and at low densities $\bar{n} \sim 1.5 \times 10^{19}\ m^{-3}$



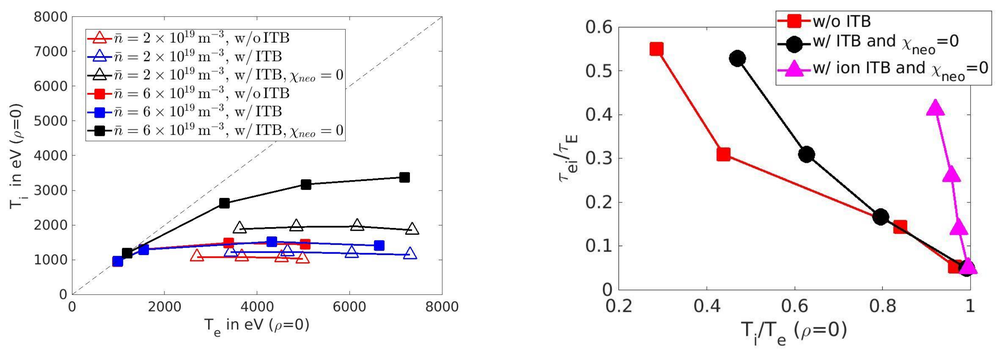
Qualitative impact of collisional heat exchange and ion to electron heat transport

- Impact of collisional heat exchange and turbulence stabilisation, integrated modelling using METIS and QLKNN-10D on a WEST reference case [2] is used.



- Different assumptions tested:
  - **Ad-hoc transport barrier inside $\rho = 0.35$**
  - Reduction of ion neoclassical heat diffusivity
  - Low $\bar{n} = 2 \times 10^{19}\ m^{-3}$ and high density cases $\bar{n} = 6 \times 10^{19}\ m^{-3}$
- From $\rho = 0.35$ to the separatrix, transport provided by QLKNN-10D
- Heat transport only, density profiles and impurity contamination held fixed ($f_{rad} \sim 50\%$)

- Low density cases result in limited central ion temperature increase, even in most favourable cases with no turbulent and neoclassical ion heat diffusivities (a minimum of $0.1\ m^2/s$ is provided for numerical stability)
- High densities cases can result in large increase in central ion temperature (up to 3.5 keV) in pure electron heated simulations
- Nevertheless, the main feature obsverved from JET ICRH heated plasmas and WEST N_2 seeded scenarios is not recovered, that is, increase in τ_{ei}/τ_E at constant central T_i/T_e
- The latter is obtained only in particular conditions where the ion to electron heat transport is reduced
- This suggest that the most efficient way of breaking the core ion temperature saturation, for a given input electron heating power, results from a combination of high densities and reduction of ion heat transport compared to electron heat transport, to optimize the collisional heat exchange.



Conclusions

- Central ion temperature saturation observed in medium sized machines but can be broken in certain conditions, including core turbulent stabilization [4,8,9]
- This is observed for WEST nitrogen seeded and JET ICRH heated (3 ion scheme) plasmas
- In contrast LHCD Tore Supra and JET plasmas with reversed safety factor profiles feature large increase in central electron temperature but limited in central T_i despite core turbulence stabilization
- Integrated modelling suggest that the main mechanisms to optimize the collisional heat exchange are:
  - Increased densities
  - Reduced ion to electron heat transport
- These, result in modest increase in central T_e with heating power, thus favorizing equipartition with main ions for which heat transport is reduced

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