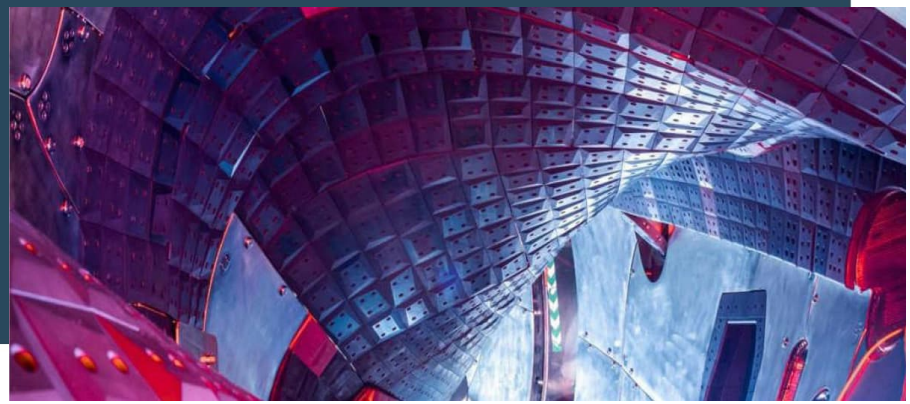
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

High performance scenarios: simulations and projections

Wendelstein 7-X

Marc Beurskens, P. Xanthopoulos, S. Bozhenkov, O. Ford, Y. Turkin, M. Wappl, H.M. Smith, G. Fuchert, A. Langenberg, S. Lazerson, N Pablant. R.C. Wolf



EUROfusion

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Experimental findings (see talk by Golo Fuchert) for 4 scenarios

Generally not (very) impressive T_i values achieved in OP2 → model these results and extrapolate!

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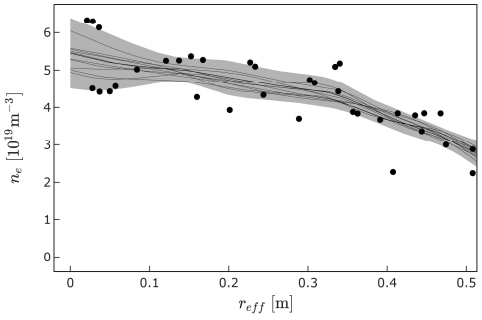

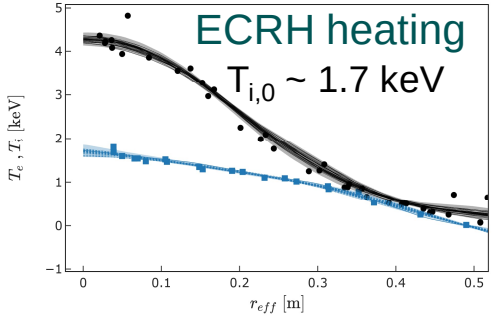

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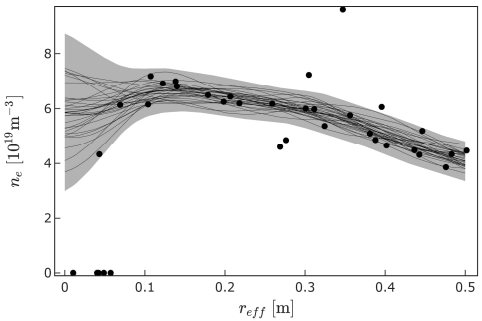

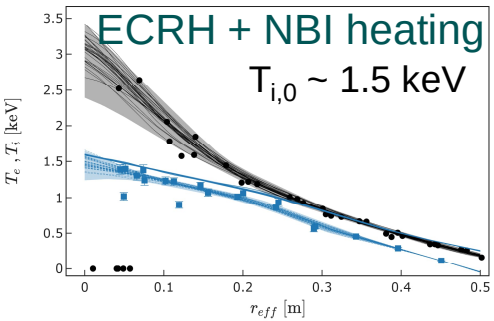

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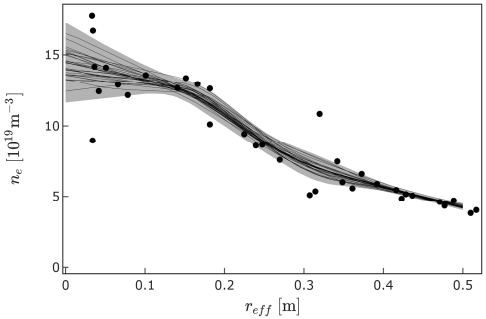

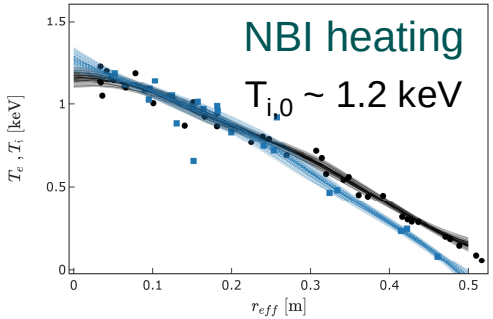

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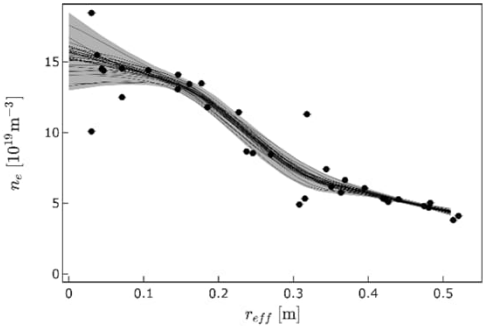
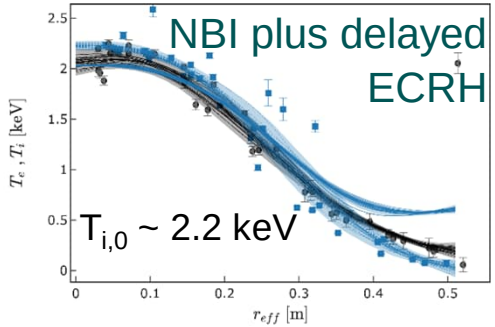
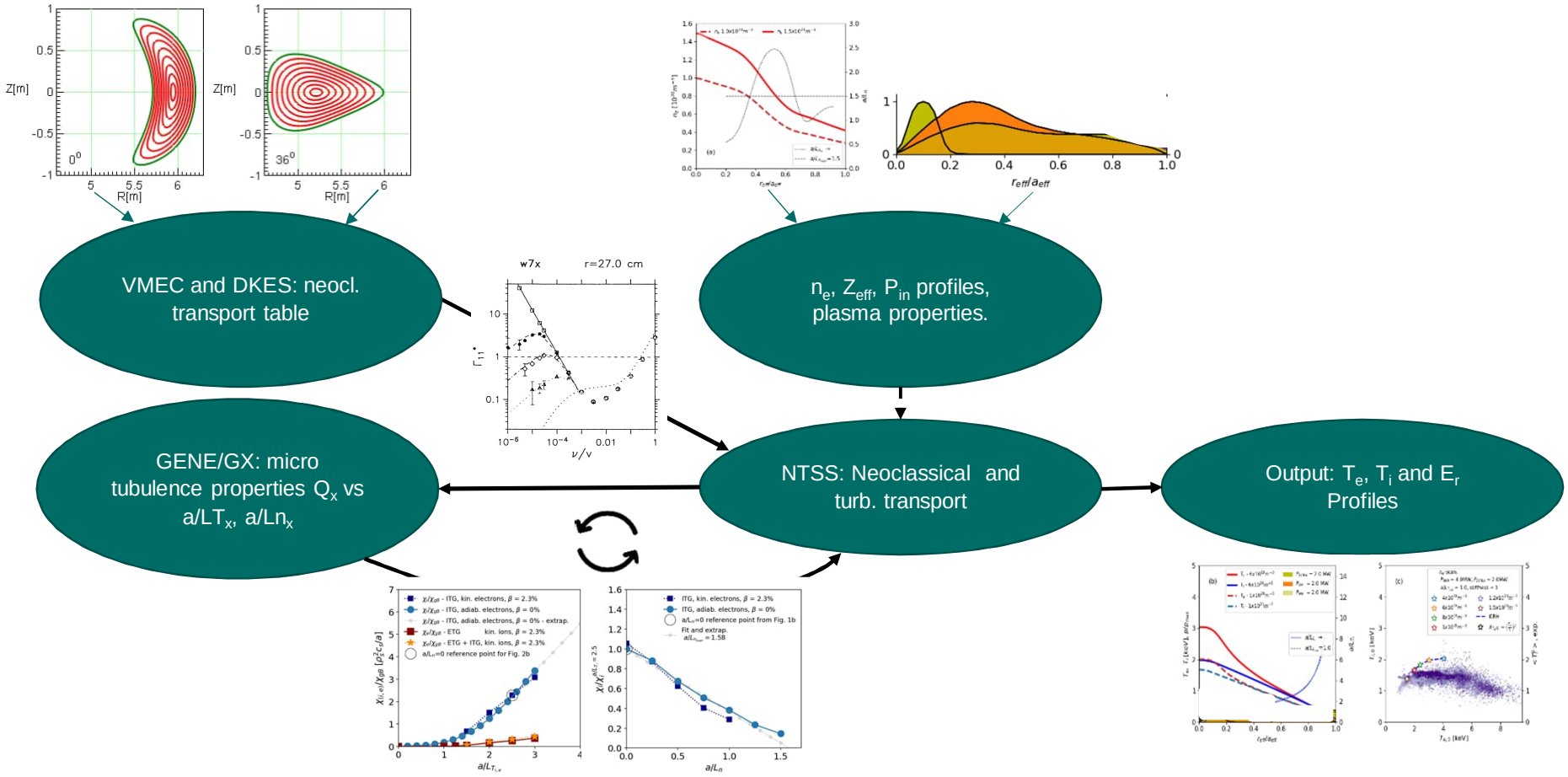




Future performance in various heating scenarios

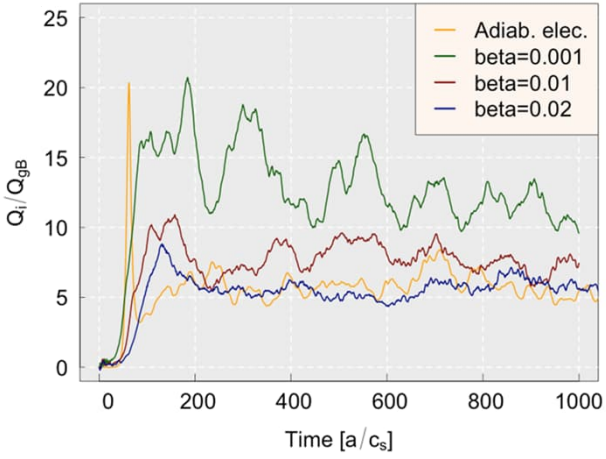
Scenario	OP 2.1/OP1.2 Measured $T_{i,0}$	OP 2.2 Expected $T_{i,0}$	Future upgrades Expected $T_{i,0}$	Density profile
ECRH heated Max (T_i):	P_{ECRH} < 6 MW $T_{i,0}$ ~ 1.5 keV	P_{ECRH} < 10 MW	P_{ECRH} = 20 MW	Flat → no ITG suppression
ECRH + NBI Max (T_i):	P_{ECRH} < 4 MW P_{NBI} < 4 MW $T_{i,0}$ ~ 2 keV	P_{ECRH} < 4 MW P_{NBI} < 8 MW	P_{ECRH} = 10 MW P_{NBI} = 20 MW	Flat → no ITG suppression
NBI + delayed ECRH Max (T_i):	P_{NBI} = 4 MW P_{ECRH} ~ ½ * P_{NBI} $T_{i,0}$ ~ 2.3 keV	P_{ECRH} = 4 MW P_{NBI} = 8 MW	P_{ECRH} = 10 MW P_{NBI} = 20 MW	Peaked → ITG suppression
ECRH + pellet Max (T_i):	P_{ECRH} = 5 MW $T_{i,0}$ < 3 keV			Peaked → ITG suppression

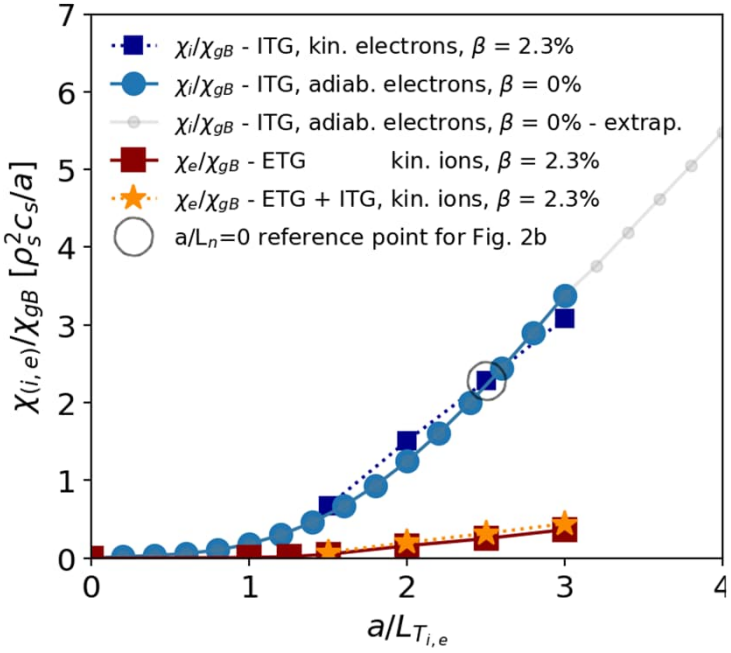
NTGK transport model combining GENE/GX and NTSS

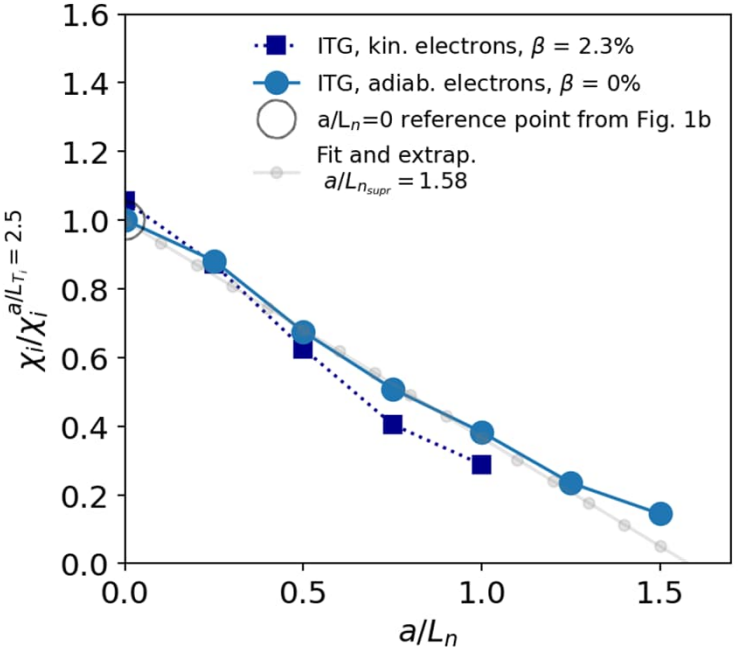


ITG driving ion heat transport,

- ITG: $T_e = T_i$, $a/L_n=0$, $r/a = 0.4$
- Calculations with kinetic electrons (β = 0.001, 1% and 2.3%), as well as with adiabatic electrons.
- Note the foot in the response curve → critical gradient model not adequate.
- Strong beta dependence of Qi/Q_{GB}

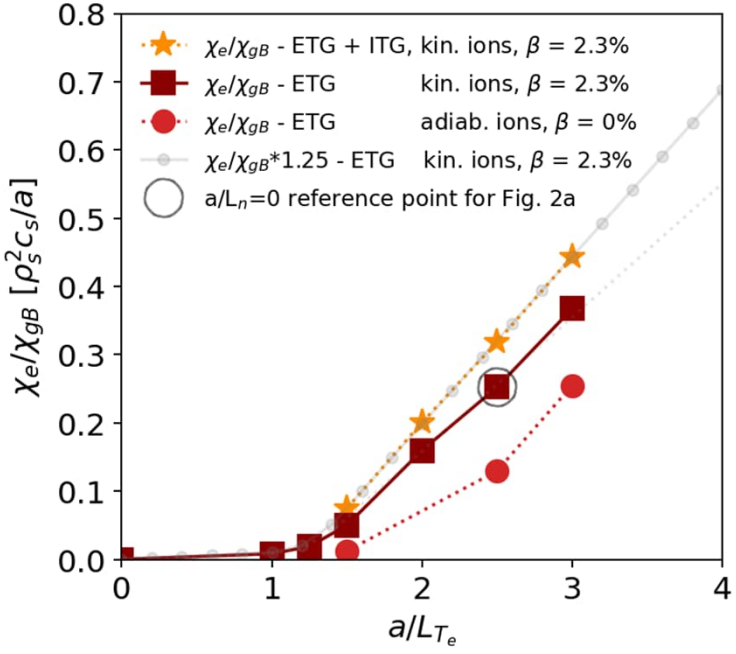


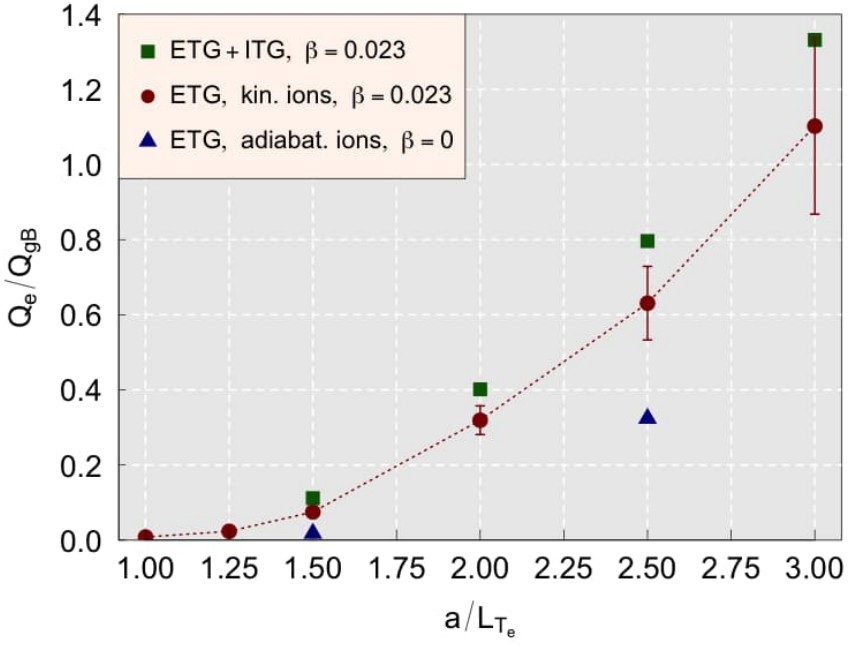




ETG+ITG driven electron heat transport, TEM subdominant.

- ETG: $T_e = T_i$, $a/L_n=0$. ITG: $T_e = T_i$, $a/L_n=0$, $r/a = 0.4$.
- Significant contribution from ETG (with kinetic ions) and ITG with (kinetic electrons)
- Note also here the foot in the response curve → critical gradient model not adequate.
- What is the β dependence of $Q_e^{ITG} + Q_e^{ETG}$?



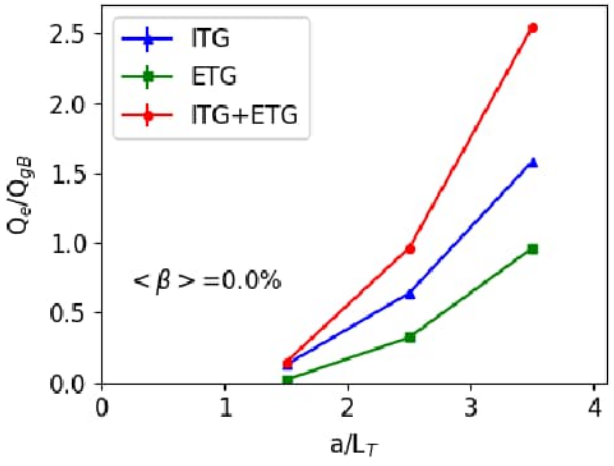


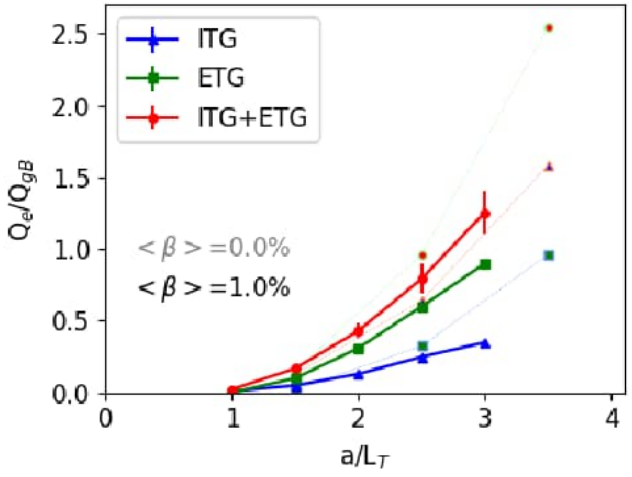
β dependence of ETG/ITG on electron heat transport

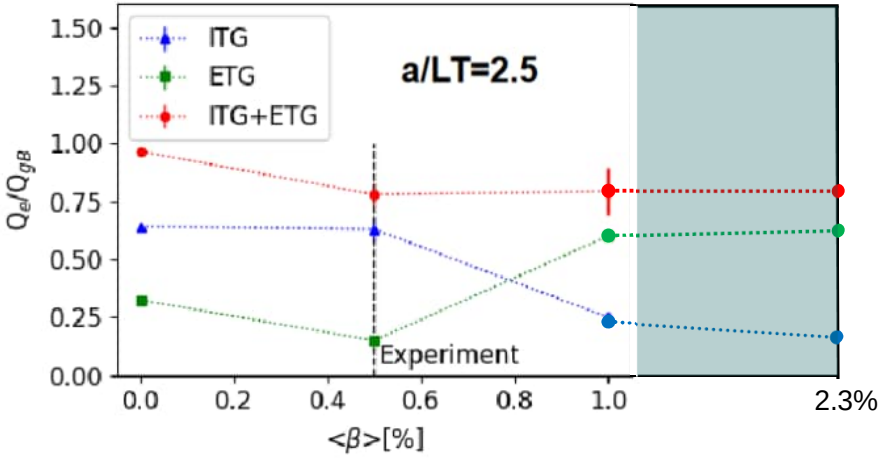
- ETG: $T_e = T_i$, $a/L_n=0$. ITG: $T_e = T_i$, $a/L_n=0$, $r/a = 0.4$.
- Calculations with kinetic ions (β = 0.0, 0.5, 1%) - Weir-APS-2023
- Ratio $Q_{e,ITG}/Q_{e,ETG}$ changes with β !
- But overal $Q_e^{ITG+ETG}/Q_{GB}$ decreases only very weakly with β(!) (20% step between 0 to 0.5%)

Separate study by G. Weir

this study







G. Weir APS 2023

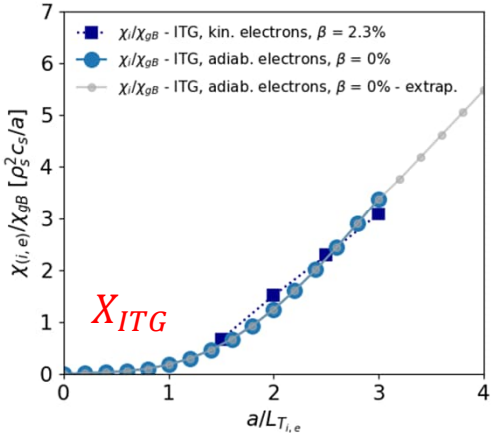
Implementation of ion heat transport in NTSS including T_e/T_i effect

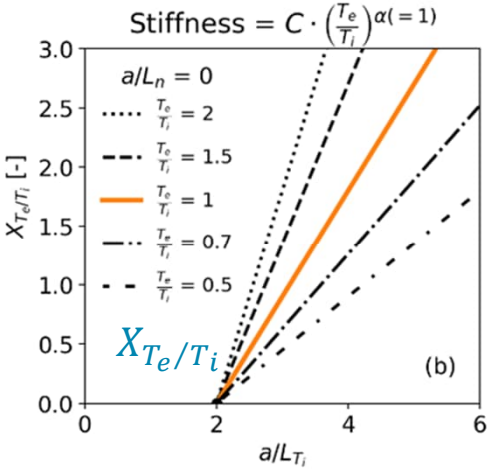
$$\chi_i^{turb} = C \cdot \chi_{gB} \cdot X_{ITG} \cdot X_{T_e/T_i} \cdot X_{\nabla n} = C \cdot X_{ITG} \cdot [(T_e/T_i)^{\alpha}] \cdot [x \cdot H(x)]$$

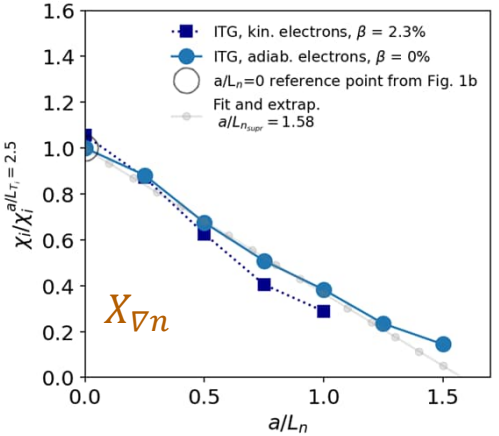
with $\chi_{gB} = \frac{\rho_s^2 c_s}{a}$, $x = (a/L_{n_{supr}} - a/L_n) / (a/L_{n_{supr}})$

$X_{T_e/T_i} \rightarrow \alpha = 2$ $\quad X_{\nabla n} \rightarrow a/L_{n_{supr}} = 1.6$

Future: mutiple radii (~5-7) as well as additional β-dependence will be implemented





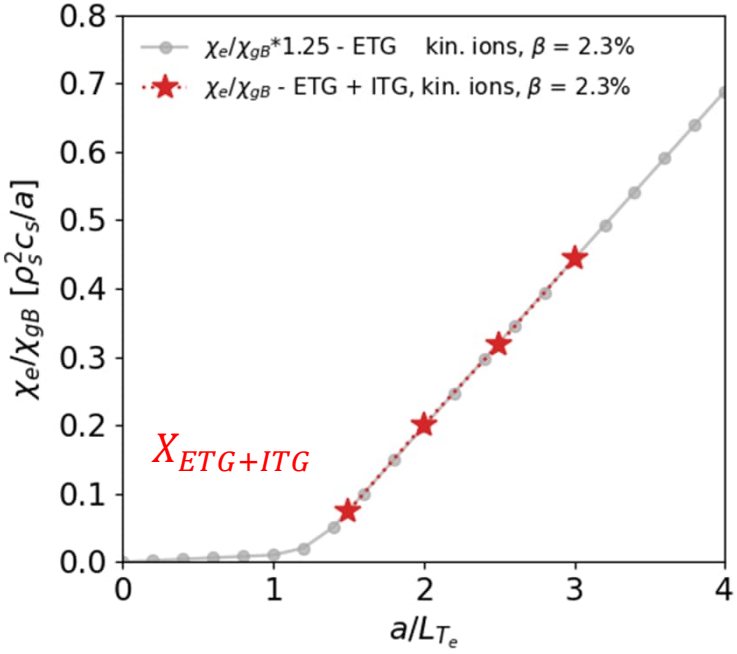


Implementation of electron heat transport in NTSS

$$\chi_e^{turb} = C \cdot \chi_{gB} \cdot X_{ETG+ITG}$$

with $\chi_{gB} = \frac{\rho_s^2 c_s}{a}$

Future: mutiple radii (~5-7), β-dependence, T_e/T_i effect and a/L_n-effect will be implemented

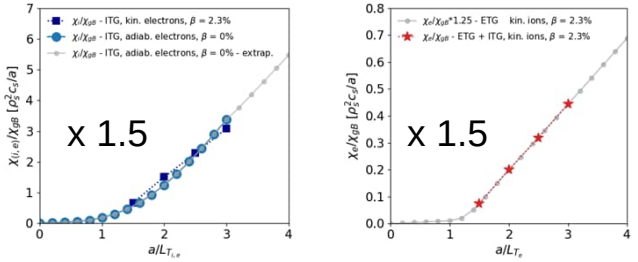


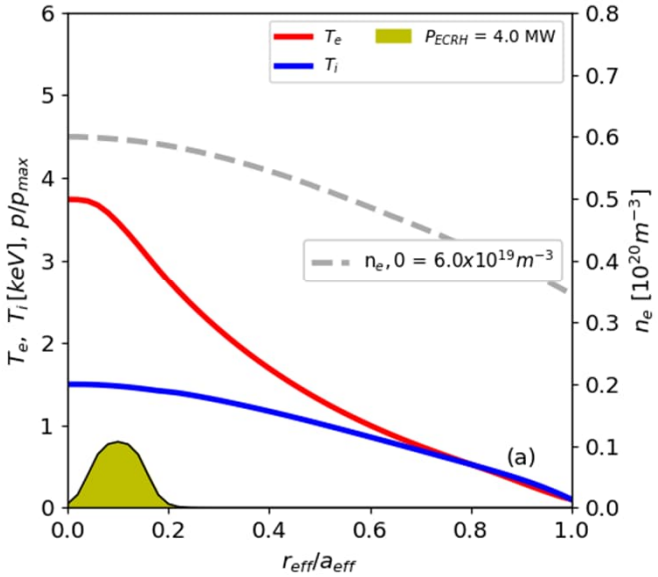
NTGK Simultion of ECRH heated plasma P_{ECRH} = 4MW with density scan

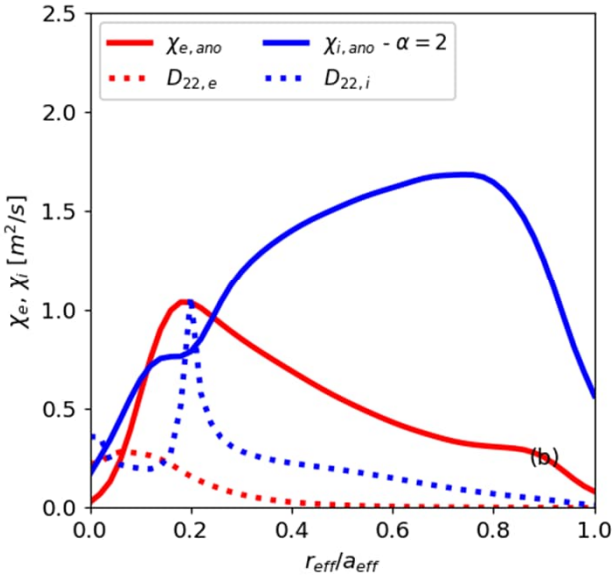
Density scan from 0.4 – 1.6 10^{20} m^{-3} P_{ECRH} = 4 MW

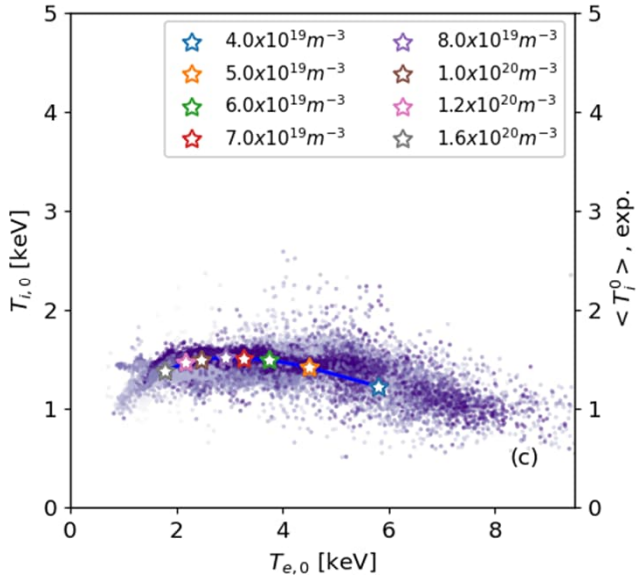
$X_{Te/Ti} = (T_e/T_i)^{\alpha}$ effect with α = 2 implemented

Ti clamped at 1.5 keV, as in the experiments







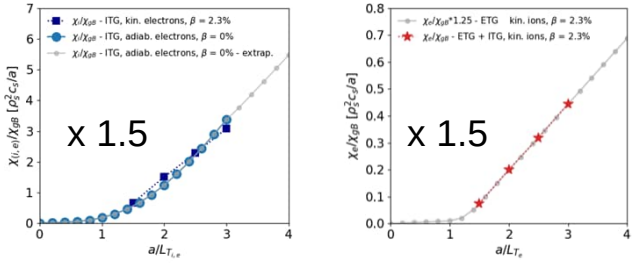


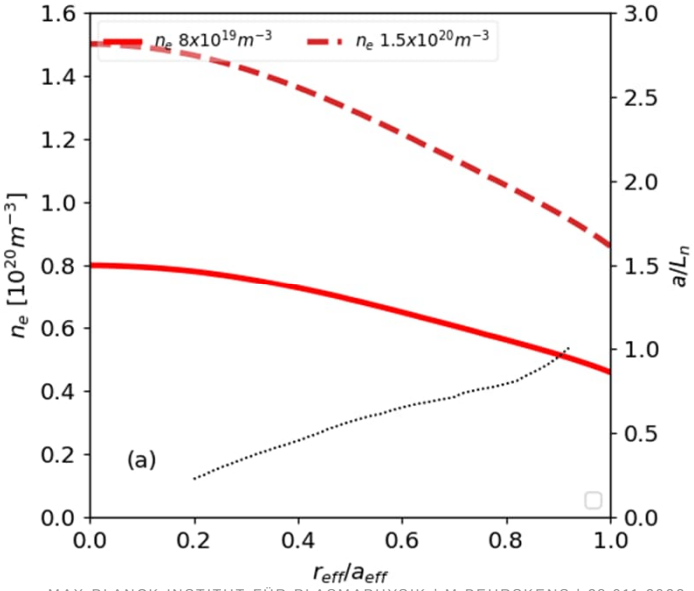
NTGK Simultion of NBI + ECRH heated plasma, P_{NBI} = 4 MW and P_{ECRH} = 2MW with density scan – Flat n_e profile

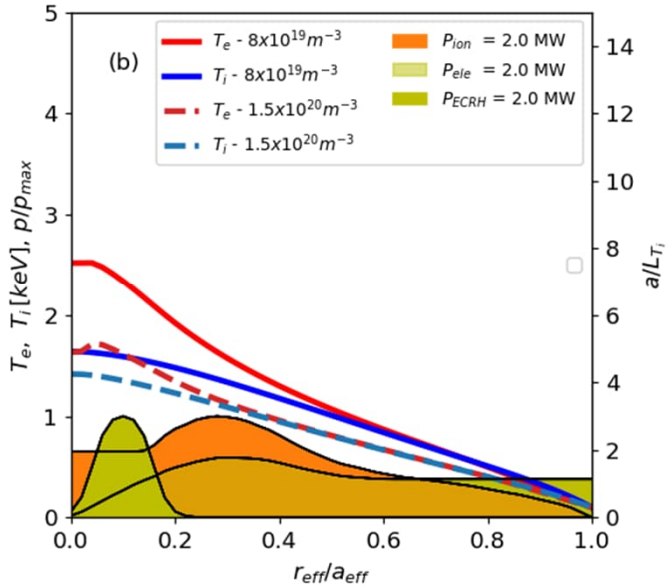
Density scan from 0.4 – 2 10^{20} m^{-3} , P_{NBI} = 4MW P_{ECRH} = 2 MW

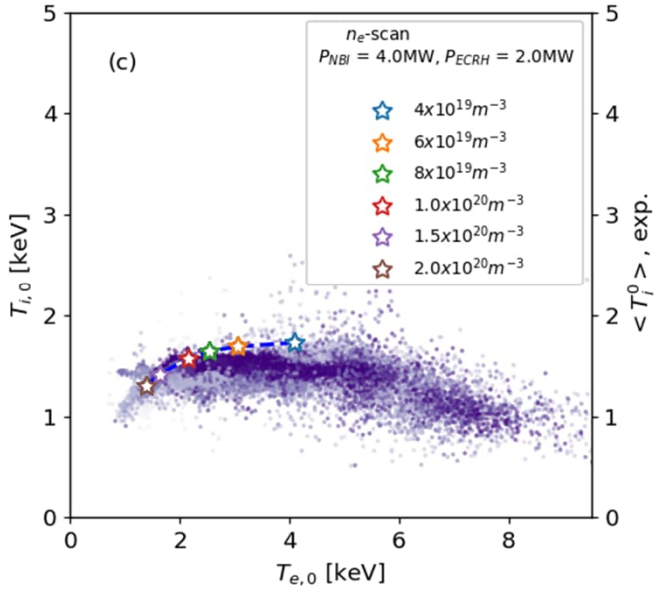
$X_{Te/Ti} = (T_e/T_i)^{\alpha}$ effect with α = 2 implemented

Ti clamped at slightly elevated level







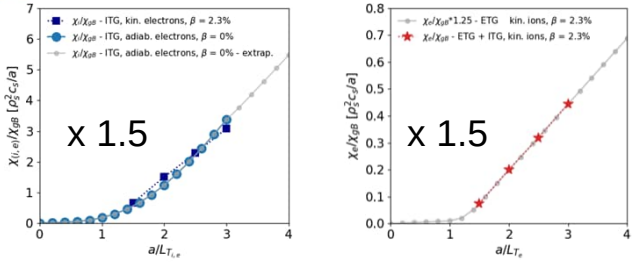


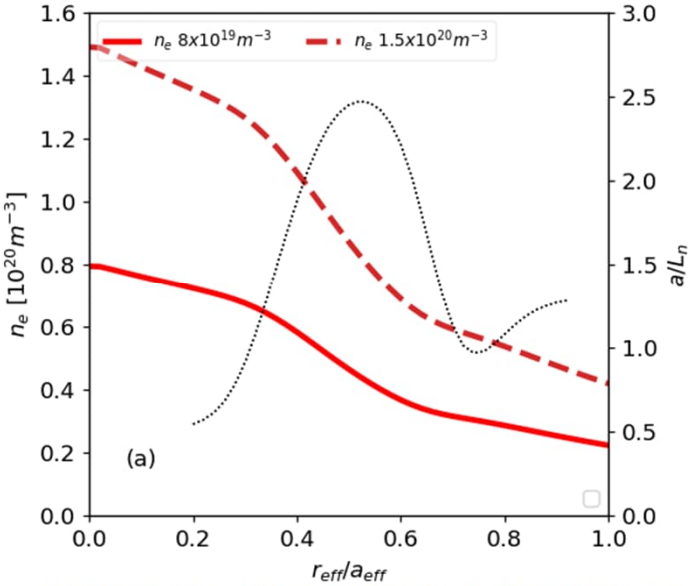
NTGK Simultion of NBI + ECRH heated plasma, , P_{NBI} = 4 MW and P_{ECRH} = 2MW with density scan - peaked density profile

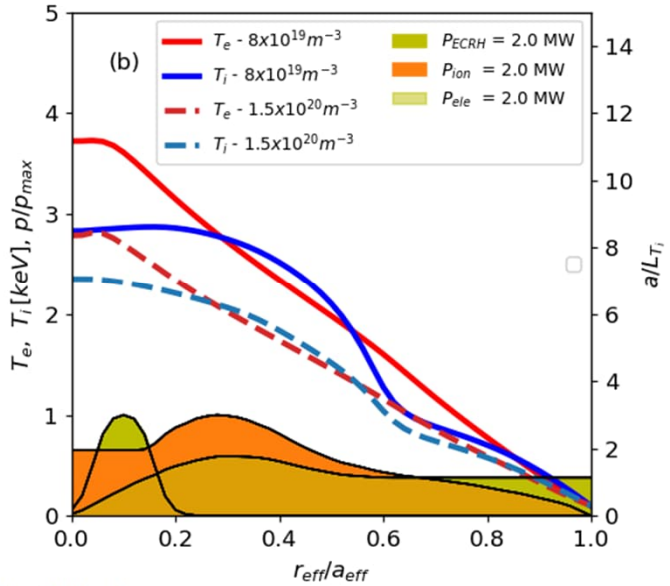
Density scan from 0.4 – 2 10^{20} m^{-3} , P_{NBI} = 4MW P_{ECRH} = 2 MW

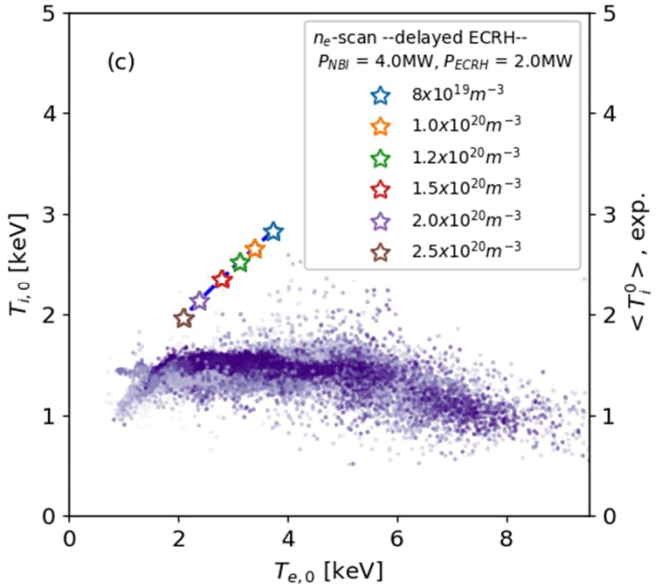
Equivalent to delayed ECRH with peaked density profile

Strong raise of T_i above clamping limit.









Future performance in various heating scenarios

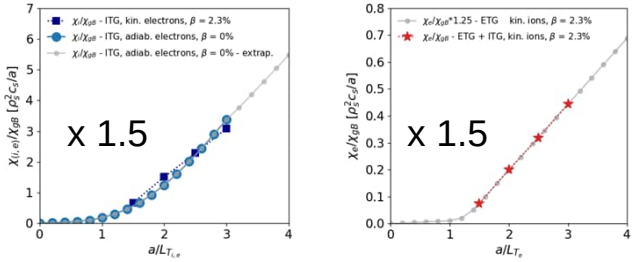
Scenario	OP 2.1/OP1.2 Measured $T_{i,0}$	OP 2.2 Expected $T_{i,0}$	Future upgrades Expected $T_{i,0}$	Density profile
ECRH heated Max (T_i):	P_{ECRH} < 6 MW $T_{i,0}$ ~ 1.5 keV ✓	P_{ECRH} < 10 MW ?	P_{ECRH} = 20 MW ?	Flat → no ITG suppression
ECRH + NBI Max (T_i):	P_{ECRH} < 4 MW P_{NBI} < 4 MW $T_{i,0}$ ~ 2 keV ✓	P_{ECRH} < 4 MW P_{NBI} < 8 MW ?	P_{ECRH} = 10 MW P_{NBI} = 20 MW ?	Flat → no ITG suppression
NBI + delayed ECRH Max (T_i):	P_{NBI} = 4 MW P_{ECRH} ~ ½ * P_{NBI} $T_{i,0}$ ~ 2.3 keV ✓	P_{ECRH} = 4 MW P_{NBI} = 8 MW ?	P_{ECRH} = 10 MW P_{NBI} = 20 MW ?	Peaked → ITG suppression
ECRH + pellet Max (T_i):	P_{ECRH} = 5 MW $T_{i,0}$ < 3 keV ✓			Peaked → ITG suppression

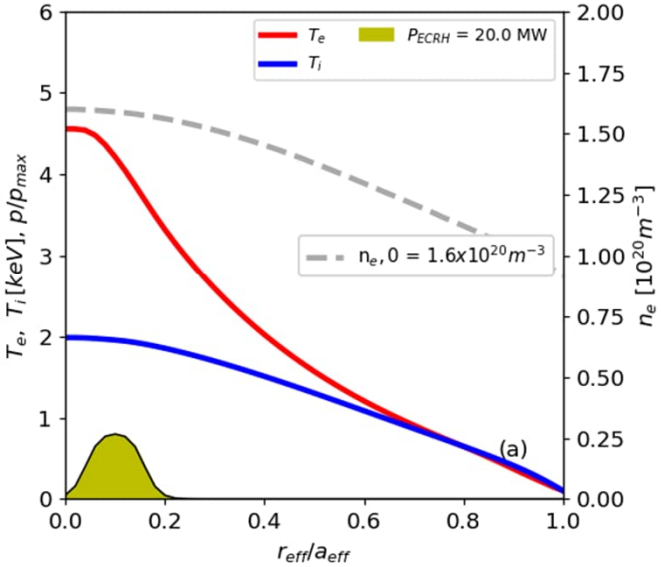
NTGK Simultion of ECRH heated plasma - flat n_e profile Power scan to P_{ECRH} = 20 MW

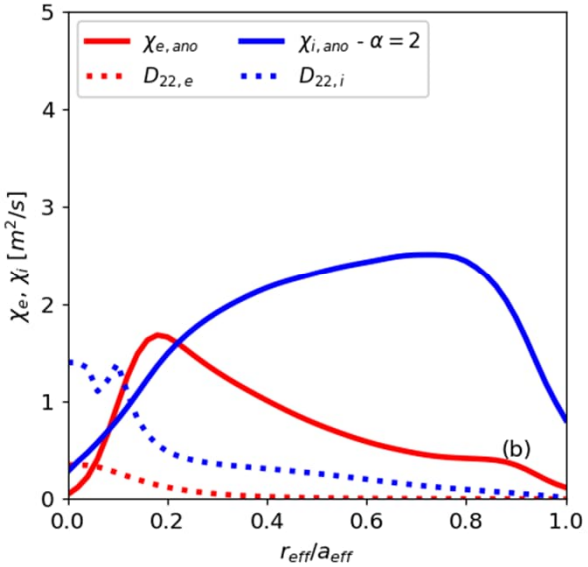
Power scan from 2 – 20MW Density = 1.6 10^{20} m^{-3} P_{ECRH}

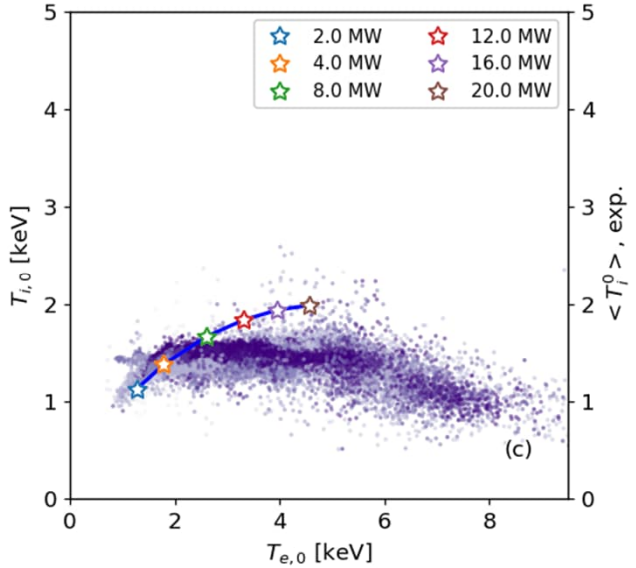
$X_{Te/Ti}$ = $(T_e/T_i)^{\alpha}$ effect with α = 2 implemented

Ti clamped at 1.5 keV, as in the experiments







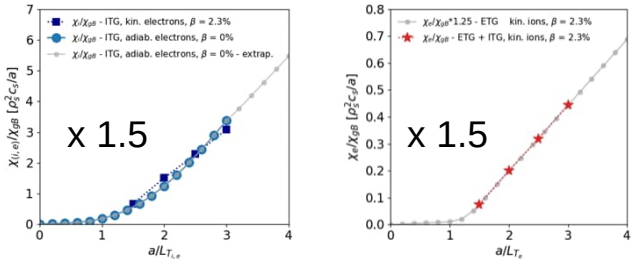


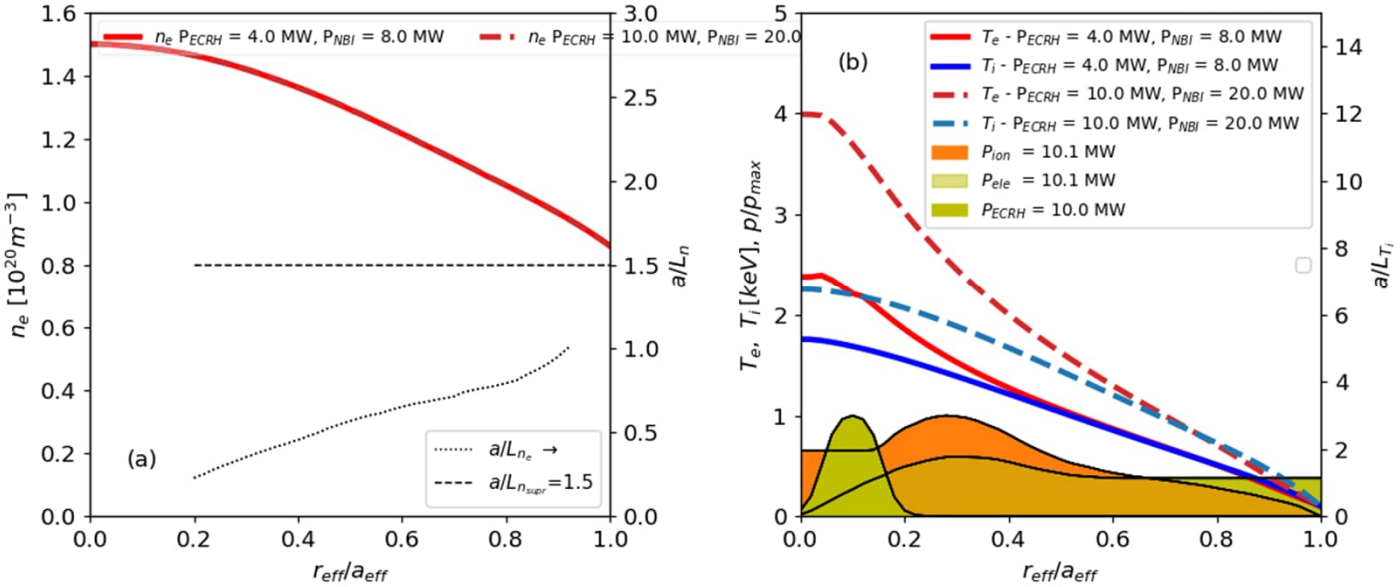
NTGK Simultion of NBI + ECRH heated plasma, flat density power scan P_{ECRH} = 2-10 MW and P_{NBI} = 4- 20 MW

Density $1.5 10^{20}$ m^{-3} , power scan to P_{NBI} = 20MW, P_{ECRH} = 10 MW

$X_{Te/Ti} = (T_e/T_i)^{\alpha}$ effect with $\alpha = 2$ implemented

Ti clamped at slightly elevated , as in the experiments

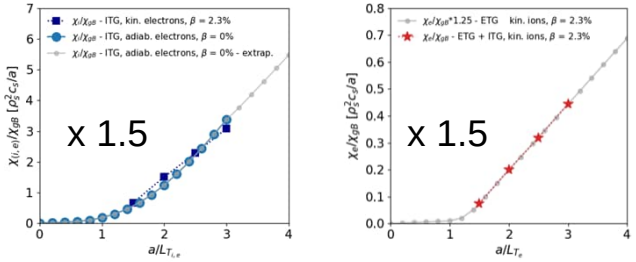


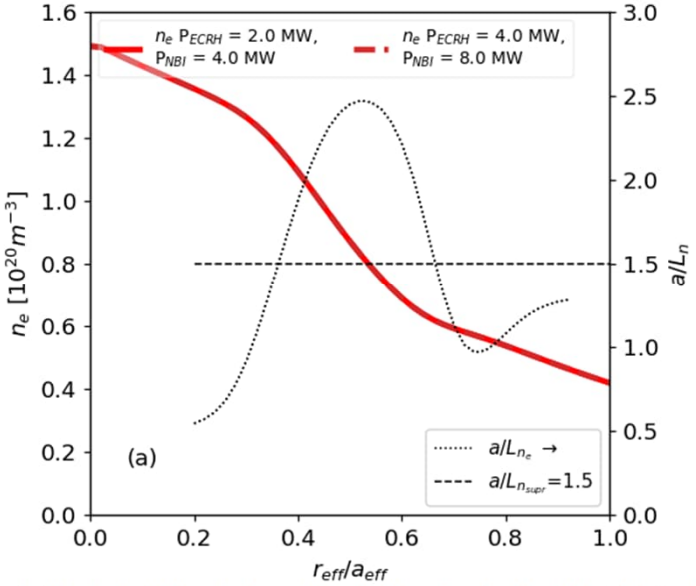


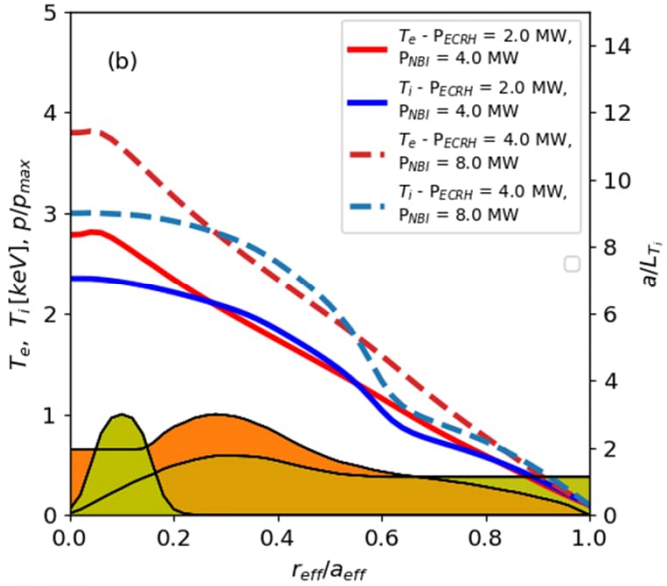
NTGK Simultion of NBI + ECRH heated plasma, peaked density power scan P_{ECRH} 2-10 MW and P_{NBI} = 4- 20 MW

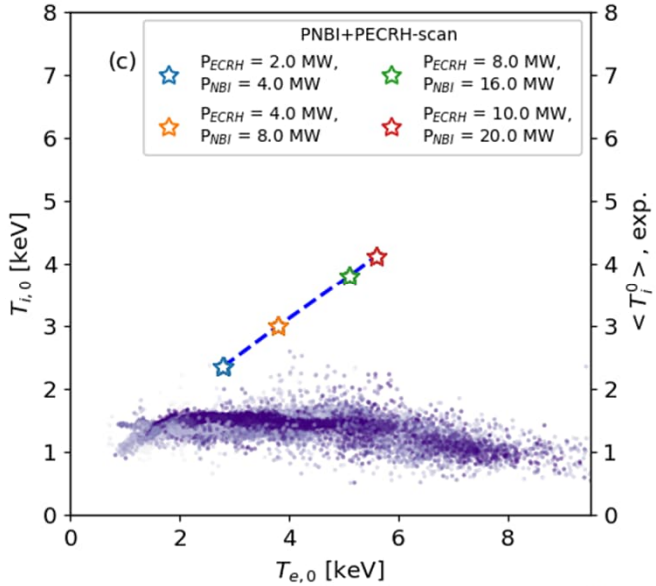
Power scan, P_{NBI} = 4 – 20 MW, P_{ECRH} = 2-10 MW from 1.5 10^{20} m^{-3}

Equivalent to delayed ECRH with peaked density profile









Future performance in various heating scenarios

Scenario	OP 2.1/OP1.2 Measured $T_{i,0}$	OP 2.2 Expected $T_{i,0}$	Future upgrades Expected $T_{i,0}$	Density profile
ECRH heated Max (T_i):	P_{ECRH} < 6 MW $T_{i,0}$ ~ 1.5 keV	P_{ECRH} < 10 MW $T_{i,0}$ ~ 1.5 keV	P_{ECRH} = 20 MW $T_{i,0}$ ~ 2.0 keV	Flat → no ITG suppression
ECRH + NBI Max (T_i):	P_{ECRH} < 4 MW P_{NBI} < 4 MW $T_{i,0}$ ~ 2 keV	P_{ECRH} < 4 MW P_{NBI} < 8 MW $T_{i,0}$ ~ 2 keV	P_{ECRH} = 10 MW P_{NBI} = 20 MW $T_{i,0}$ ~ 2.5 keV	Flat → no ITG suppression
NBI + delayed ECRH Max (T_i):	P_{NBI} = 4MW P_{ECRH} ~ ½ * P_{NBI} $T_{i,0}$ ~ 2.3 keV	P_{ECRH} = 4 MW P_{NBI} = 8 MW $T_{i,0}$ ~ 3 keV	P_{ECRH} = 10 MW P_{NBI} = 20 MW $T_{i,0}$ ~ 4 keV?	Peaked → ITG suppression
ECRH + pellet Max (T_i):	P_{ECRH} = 5 MW $T_{i,0}$ < 3 keV	$T_{i,0}$ ~ 3 keV	$T_{i,0}$ ~ 4 keV?	Peaked → ITG suppression

→ A central density of 1.5 x 10^{20} m^{-3} is assumed for these estimates

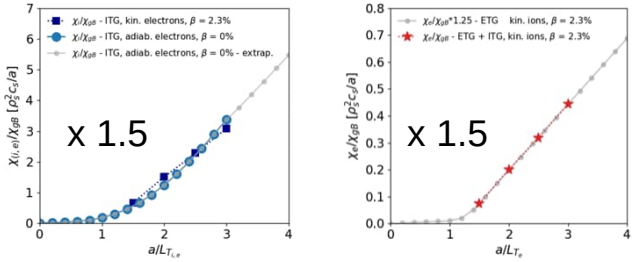
What can we expect from the ICRH experiments?
Very speculative as power deposition and P_i/P_e uncertain

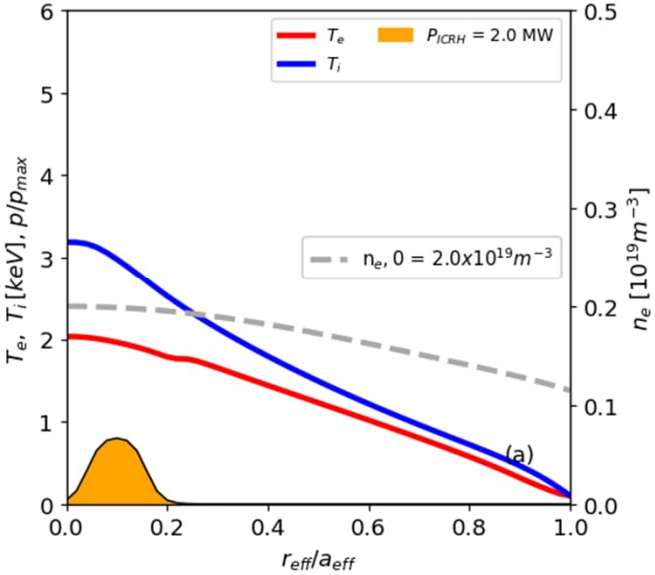
Assume that ICRH deposition profile is same as ECRH

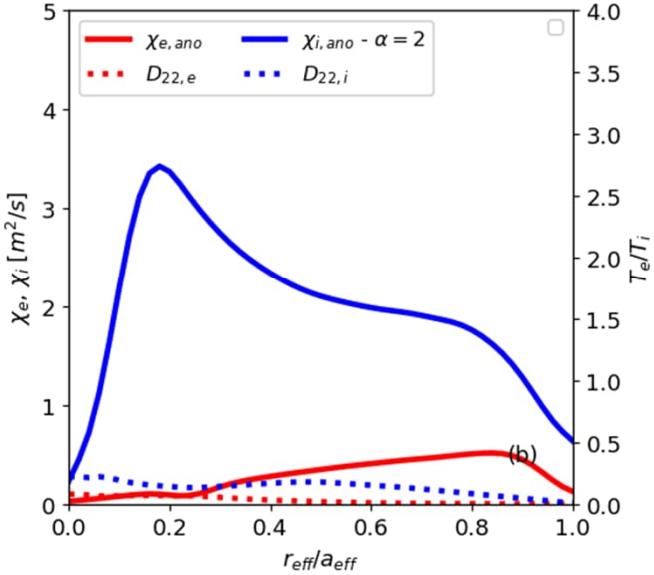
All power is coupled to the ions

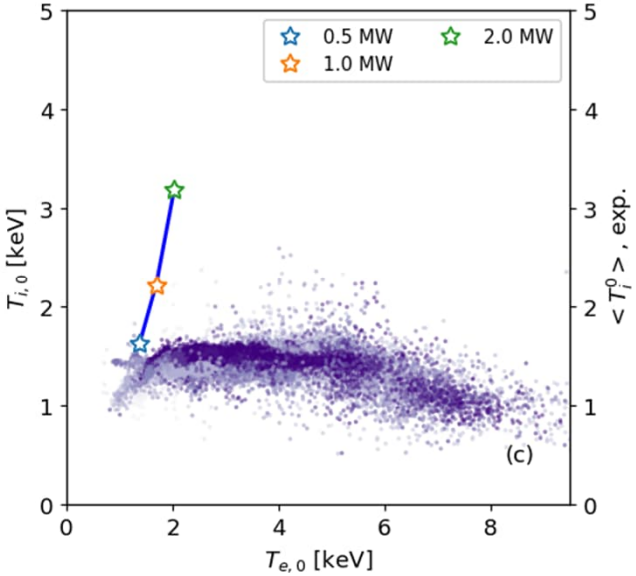
Power scan, P_{ICRH} = 0.5 – 2 MW

$n_{e,0}$ 2 10^{19} m^{-3}









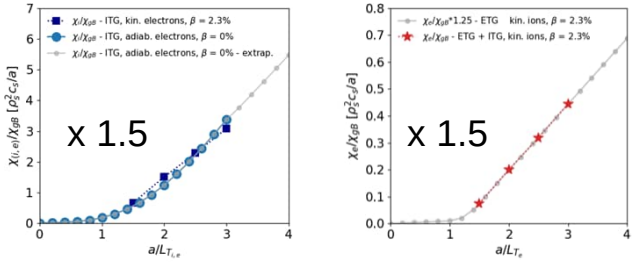
What can we expect from the ICRH experiments?
Very speculative as power deposition and P_i/P_e uncertain

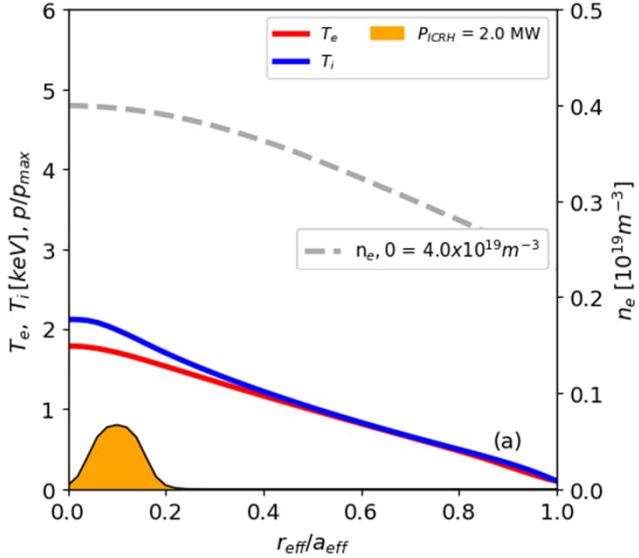
Assume that ICRH deposition profile is same as ECRH

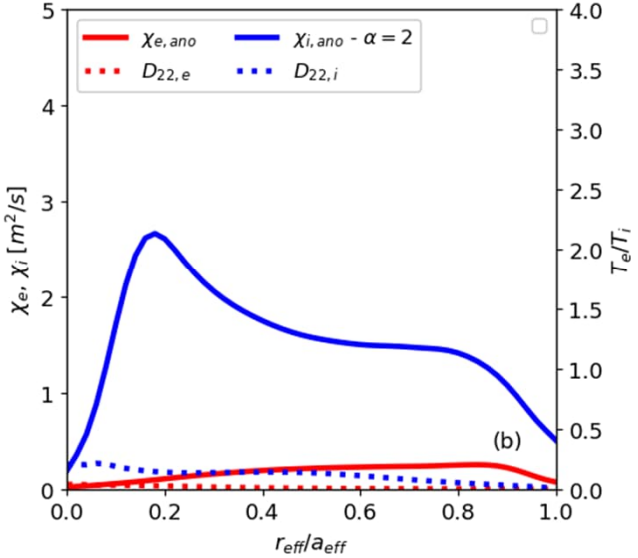
All power is coupled to the ions

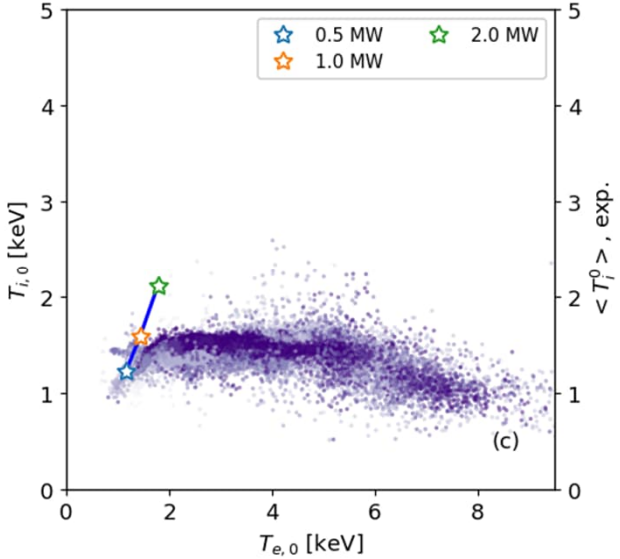
Power scan, $P_{ICRH} = 0.5 – 2$ MW

$n_{e,0}$ 4 10^{19} m^{-3}









Summary and expectations

ECRH heated plasmas with flat n_e profiles suffer from strong (ITG) turbulent transport. In combination with a broad exchange power profile a clamped T_i ~1.5 keV is found. The T_e/T_i effect only weakly contributes to this. In OP2.2 no strong improvements expected. T_i < 2 keV is expected.

Combined NBI and ECRH heated plasmas feature flat n_e profiles and strong ITG turbulence. Therefore the additional NBI heating leads to somewhat elevated $T_{i,0}$. In OP2.2 only moderate improvements are expected. T_i 2-2.5 keV is achievable

NBI and delayed ECRH the density-peaking is controlled. Hence the density level and peaking is tunable and the reduced turbulence leads to elevated $T_{i,0.}$ In OP2.2 strong improvements are expected. T_i 3-4 keV is achievable

"ICRH" simulation are speculative, but potentially high T_i ~ 3 keV can be obtained at low plasma density ($2x10^{19}$ m^{-3}), if all power coupled to ions and central power deposition….

pellet induced density gradient: expect similar performance as NBI + delayed ECRH plasmas. In OP2.2 strong improvements are expected. T_i 3-4 keV is achievable