H vs. D density-peaking in GYRO simulations of C-Mod plasmas

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Alcator C-Mod

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Overview of density peaking simulations

Angioni, et al., Phys. Plasmas **10** (2003) 3225.
GLF23 simulations apparently explain observations.
Higher collisionality reduces the anomalous pinch due to trapped electrons.

Angioni, et al., Phys. Plasmas **12** (2005) 112310.
GS2 *quasilinear* gyrokinetic estimates of particle flux.
raising collisionality turns off the pinch, but the transition is much too early.
poor mode choice: low $k_\theta \rho_i \sim 0.2$ (motivated by TEM heat transport study)

Mikkelsen, et al., APS-DPP 2007; *nonlinear* GYRO, C-Mod H-mode
pinch is driven by modes with $k_\theta \rho_i > 0.5$ - missing from quasilinear work!

Maslov, et al., Nucl. Fusion **49** (2009) 075037, QL peaking in JET H-modes.
different mode choice: modes at max. growth rate do generate a pinch.
raising T_e/T_i increases the pinch (if ITG is still the dominant instability).

Angioni, et al., Phys. Plasmas **16** (2009) 060702.
nonlinear GYRO for AUG: k-spectrum of particle flux similar to C-Mod.
collisionality and energy dependence in analytic quasilinear expression.

Is Peaking Factor the Same for D & H?

Different peaking factors for D & T in ITER could be important:
stronger tritium peaking would make tritium fueling easier (and *vice versa*).

Phase-contrast-imaging system on C-Mod enables core n_H/n_e measurement.
Measured core n_H/n_e is lower than edge $n_H/(n_D+n_H)$ (from D_α light);
and plausible Z_{eff} may not explain the diffference.
A dedicated experiment with controlled H puffing is planned with n_H~n_D.

GYRO simulations can be used to derive the density profile shape that is 'predicted' to produce null particle flux, when the pinch balances diffusion; this applies to steady-state C-Mod plasmas with no core fuelling.

Quasilinear estimates of particle flux are unreliable, particularly with ‘hybrid’ ITG/TEM turbulence, so nonlinear 'global' simulations are used here.

C-Mod peaked-density regime

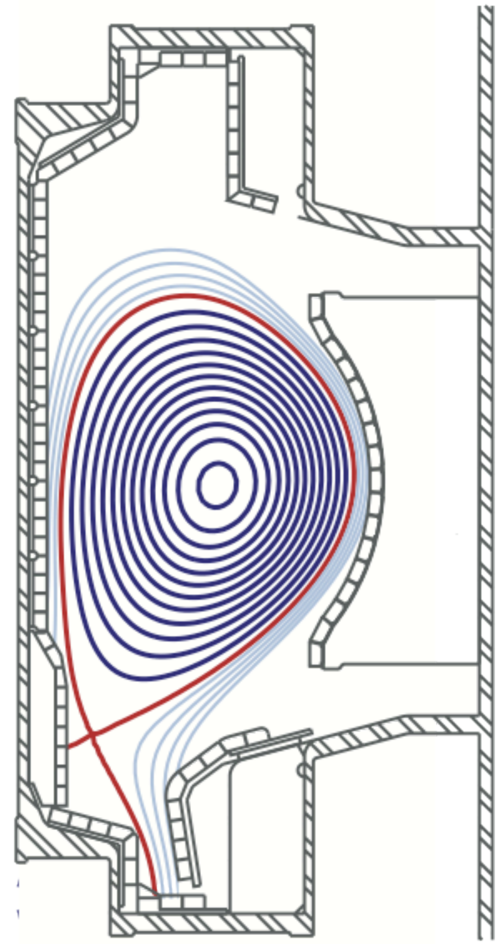
Discovered with JFT-2M shape: produced low-density H-mode plasmas. low κ, high δ_{lower}>0.75, lower target density.

Pedestal density is especially low, and T_{ped} is high, 0.8-0.9 keV

Pedestal is wider, infer larger D causes lower n_e, higher T_e $\rightarrow$ELMs.

Higher density ohmic EDA H-modes with same profile shape are not unusual.

Density peaking also seen in standard shape, with lower I_p.



Surprise result:

Density profile is peaked; in RF-heated H-mode plasmas peaking is never seen at higher densities.

ITBs have central density peaking, but flat periphery;

this regime has flat central region and a density gradient for r/a > 0.5

Lower Density H-Modes Have Peaked Profiles

Greenwald, et al.,

Nuclear Fusion **47** (2007) L26

Lower L-H threshold density

ELMs seem to reduce rate of density rise in H-mode

Whatever the cause:

Standard H-mode

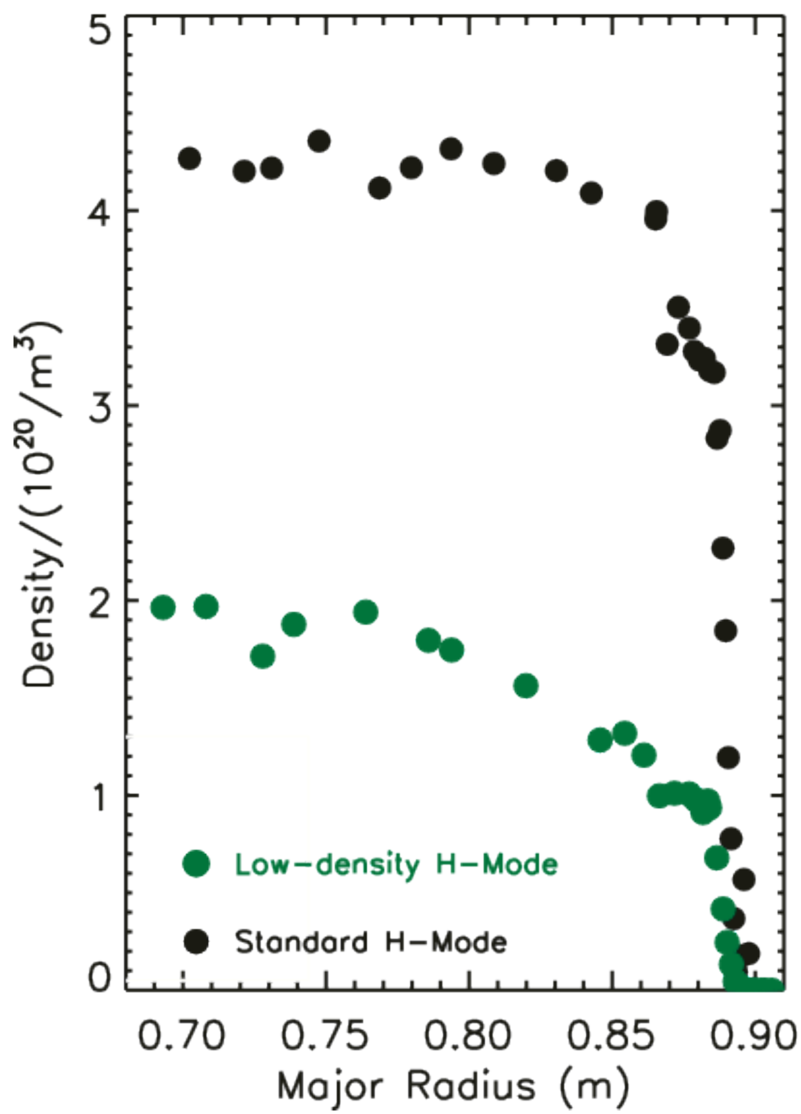
$n_{e0}/\langle n_e\rangle$ = 1.1-1.2

$L_n \gg a$, $R/L_n \sim 0$, $R/L_{Te} \sim 6\text{-}7$

Low-Density H-mode

$n_{e0}/\langle n_e\rangle$ = 1.5

$R/L_n \sim 3\text{-}4$, $R/L_{Te} \sim 6\text{-}7$



Difference In Profile Shape Is Notable

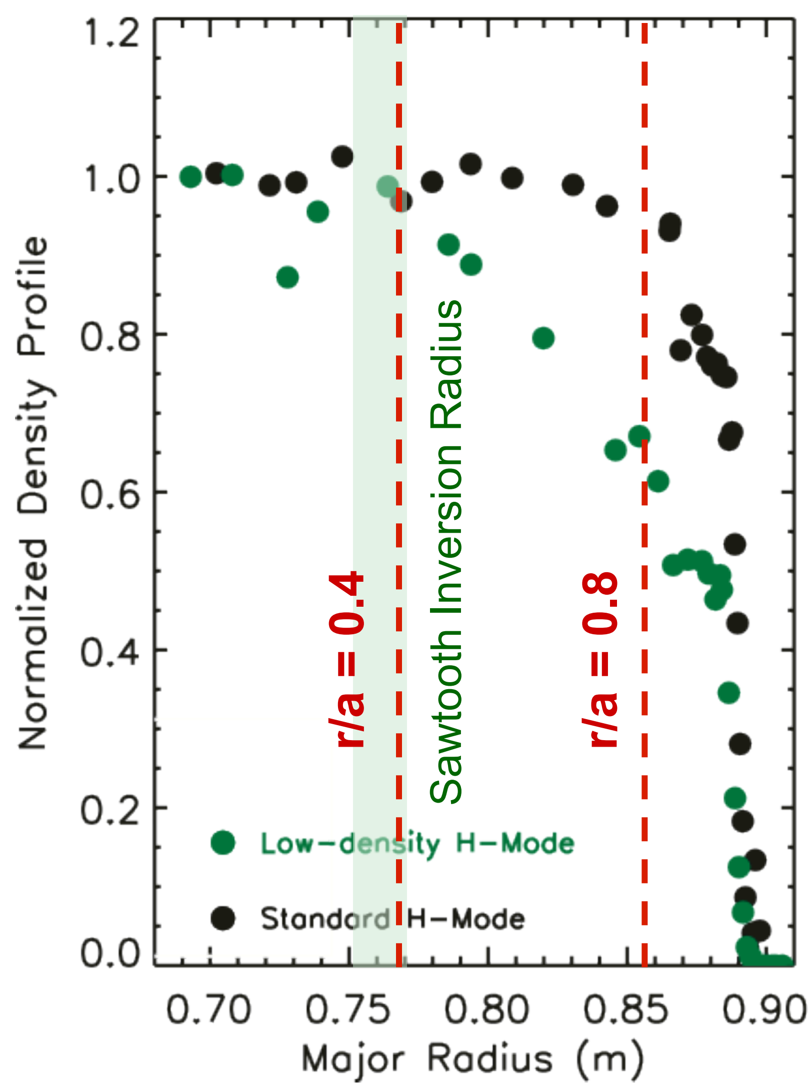
Peaking is seen over outer 60% of plasma radius

H-mode profiles evolve quickly; $\tau << a/V_{WARE}$

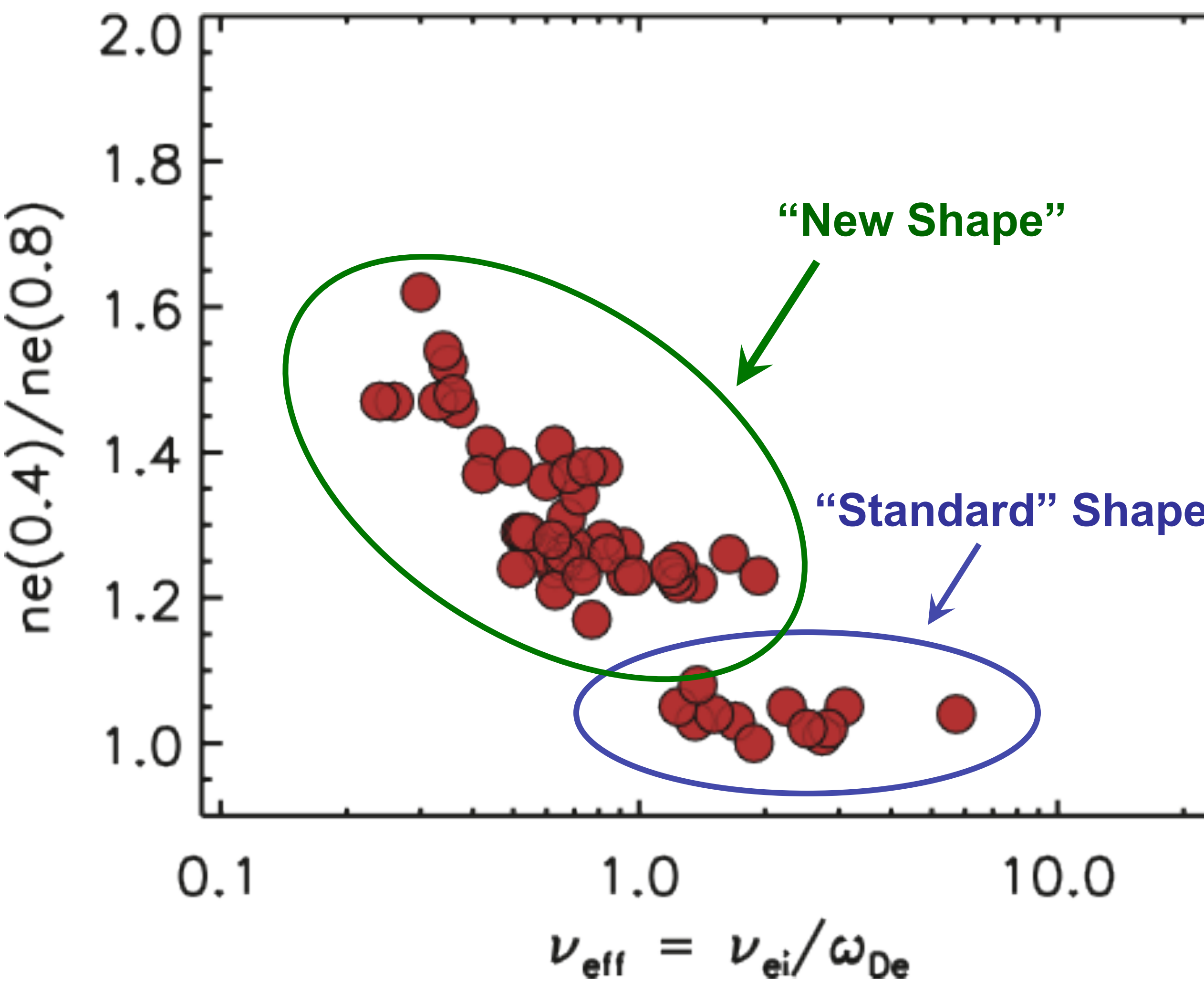
Transport in center of plasma may be affected by sawteeth

> These are of large amplitude; $\delta T_e/T_e \sim 25\%$

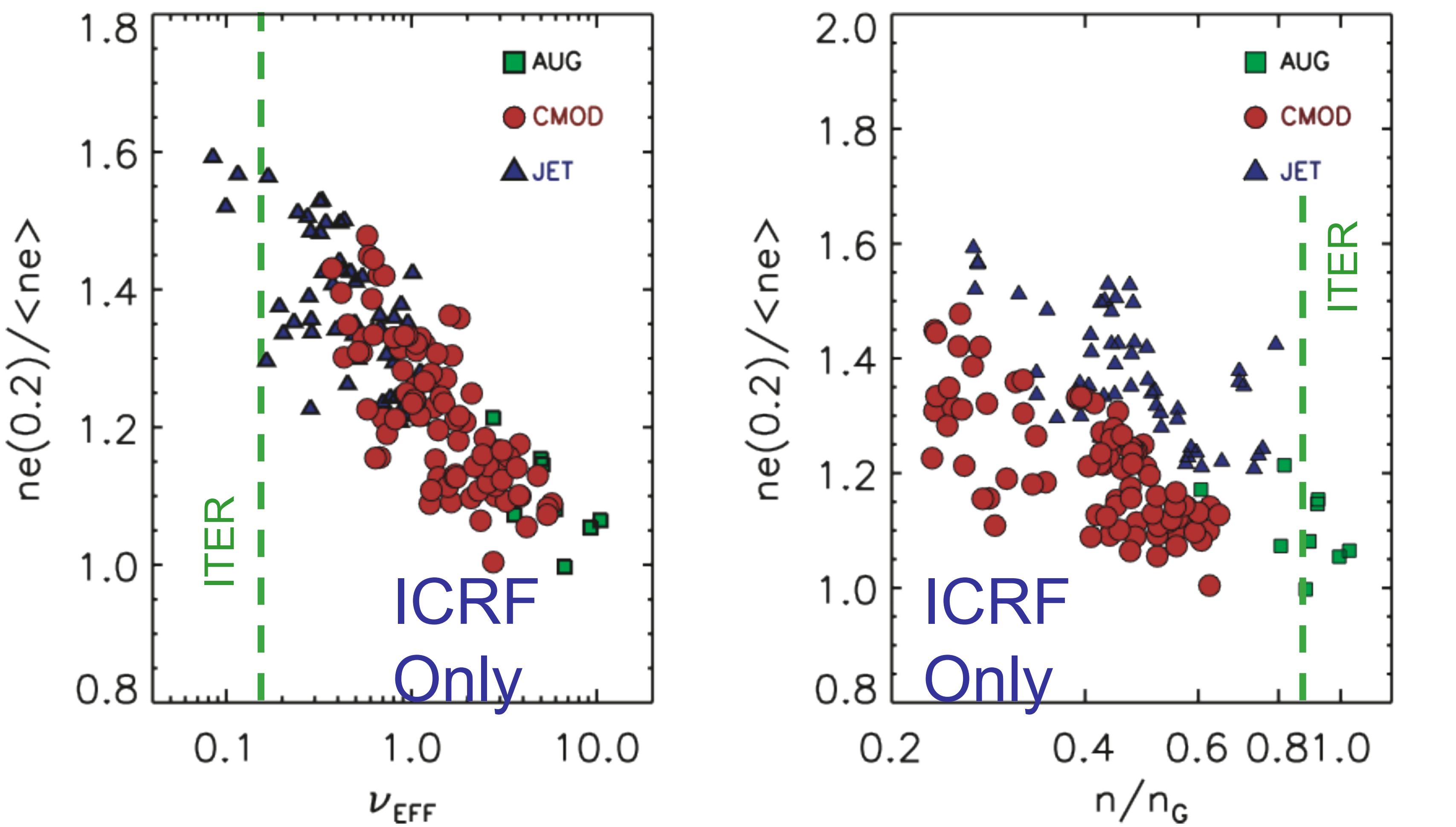
Radii chosen to characterize peaking in ASDEX-U are appropriate for C-Mod profiles



Increased Density Peaking At Low Collisionality Observed For ICRF Heated H-Modes In C-Mod



C-Mod Data Helps Break Covariance Between ν_{eff} and n/n_G



$\nu_{EFF} = \nu_{ei}/\omega_D \equiv 0.1RZ_{EFF}\langle n_e\rangle/\langle T_e\rangle^2$

T_i Differs from T_e at Low Density

Low collisionality is linked to other important changes in C-Mod plasmas.

T_i profile is less peaked than T_e in low-density H-mode plasmas.

T_e-T_i can be large, but Q_{ie} is < 1 MW.

central T_i is apparently not consistent with the neutron rate, but

is the deuterium distribution Maxwellian at 2nd harmonic of ICRH?

Measured L_{Ti} is longer than L_{Te} for r/a~0.6

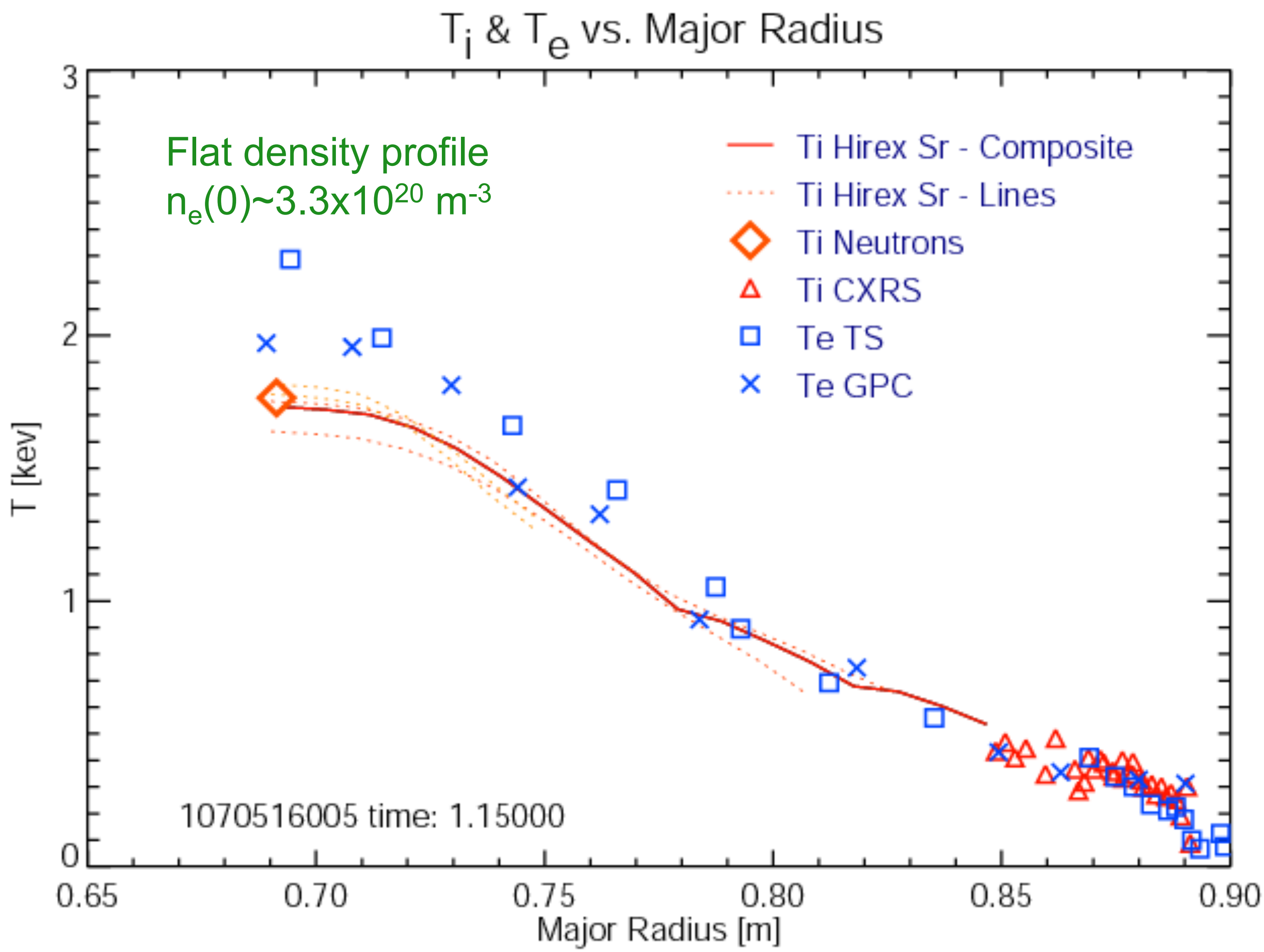
relaxed T_i profile at low density reduces the ITG drive, but

Higher T_e/T_i increases ITG drive.

Kinetic electron drive depends strongly on collisionality at these densities.

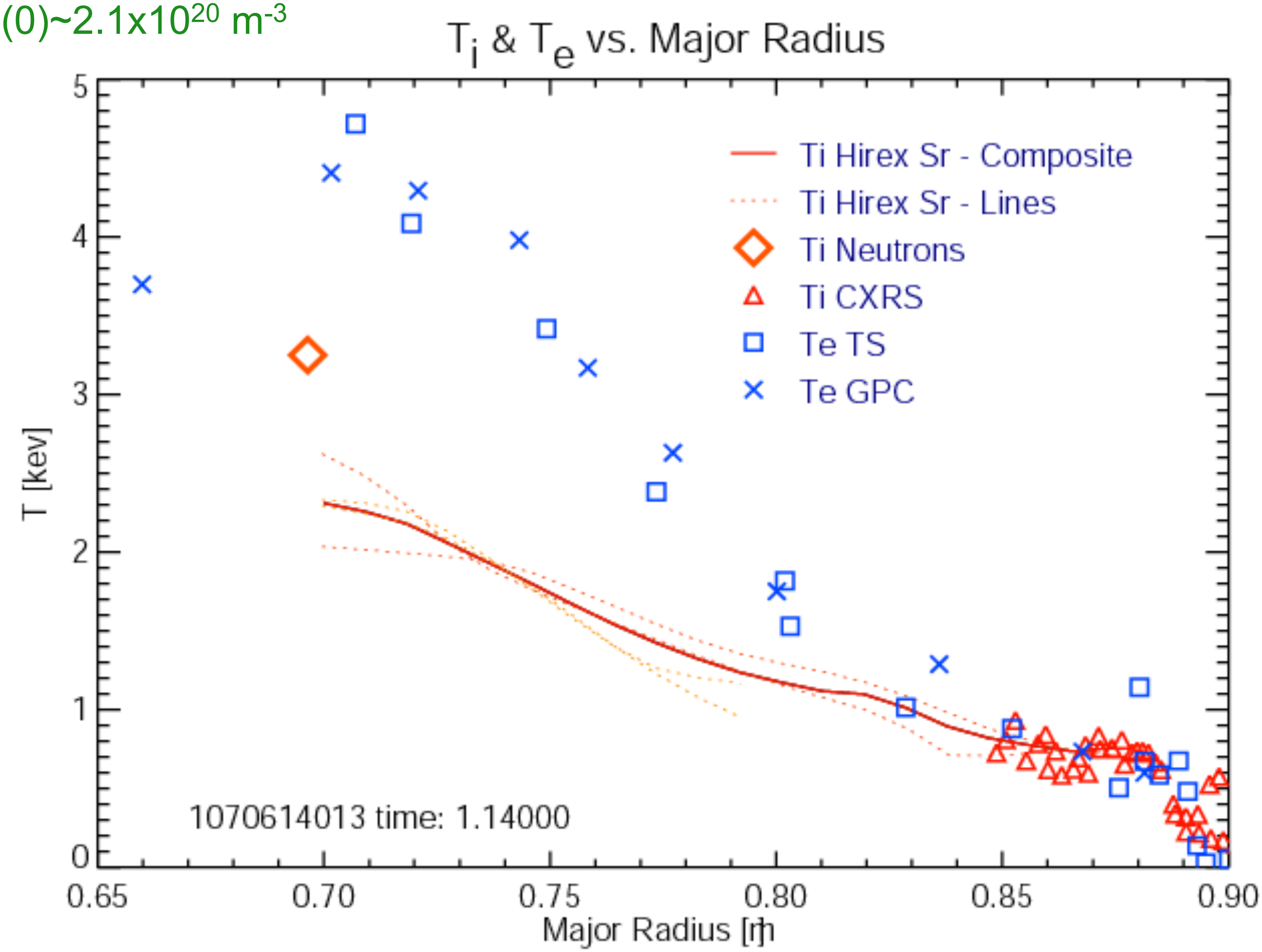
The relative importance of different microinstability drives changes as collisionality is reduced, so the details may differ from JET and AUG.

Standard H-mode

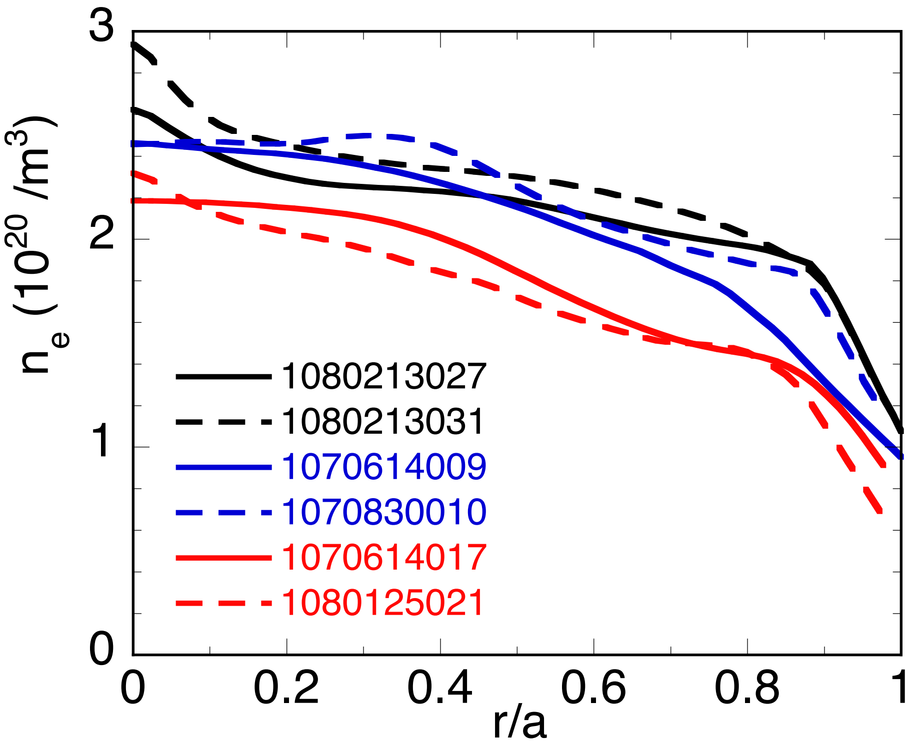


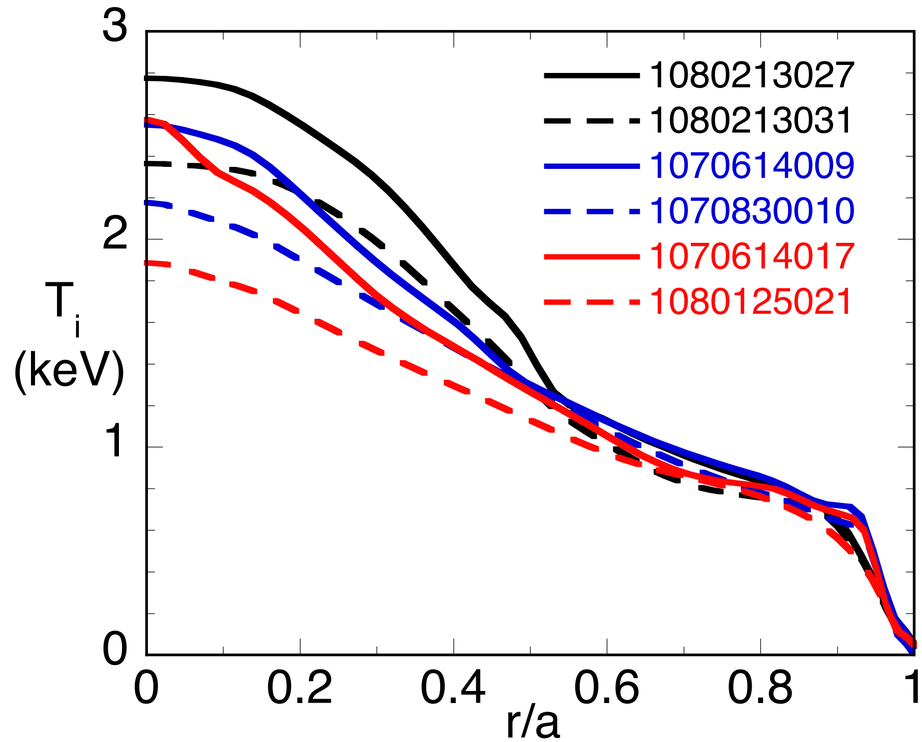
Peaked density H-mode

$n_e(0)$~$2.1\text{x}10^{20}$ m^{-3}



T_i profile relaxes as density drops





As density is lowered the density peakedness rises, and $T_i(0)$ drops (T_i is less tightly coupled to T_e at all radii). Consequently, the L_{Ti} is longer than L_{Te} for r/a~0.6

The relaxed T_i profile at low density reduces the ITG drive, very close to the ITG threshold for the lowest density cases.

Initial Simulation Procedure

Electrostatic turbulence, with kinetic ions and electrons.

Measured $T_e(r)$ and $n_e(r)$ are used in GYRO simulations presented here.

The measured $T_i(r)$ has been used but these have stable regions, so oscillations in R/L_{Ti} are removed to smooth the profiles.

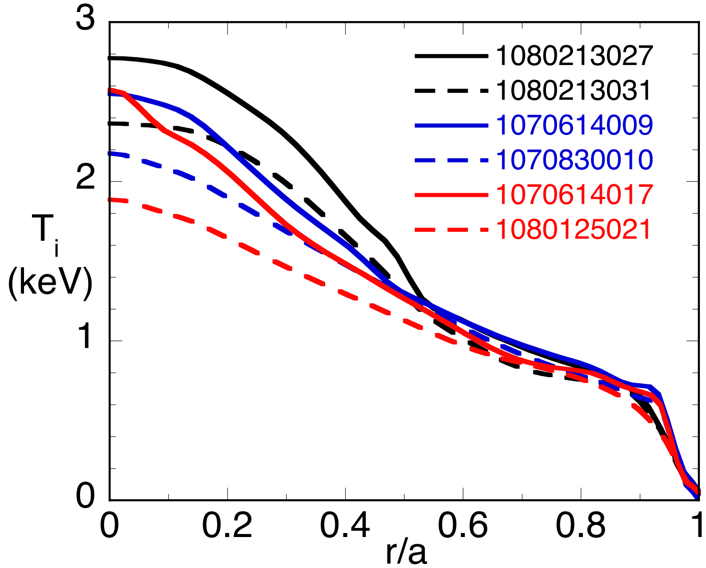
Simulations have only deuterium and electrons, but the 'resistive' Z_{eff} value is used in the collisionality.

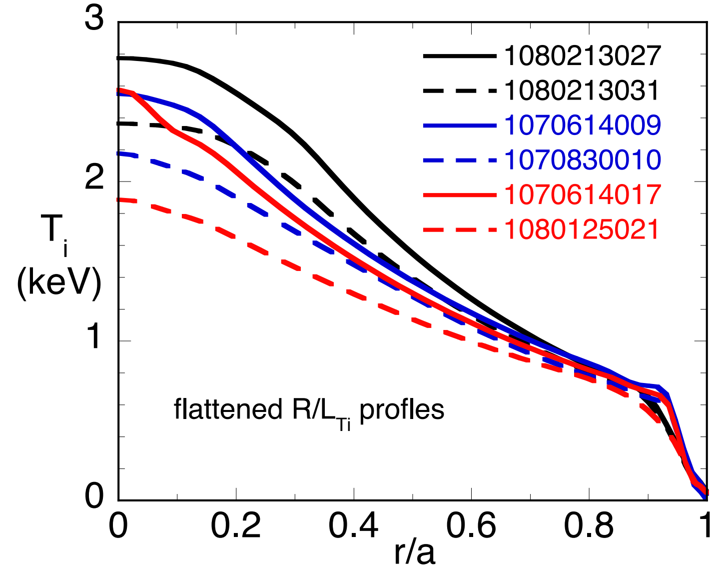
Shaped geometry is used.

ExB shear is ignored (but expected to have a small effect).

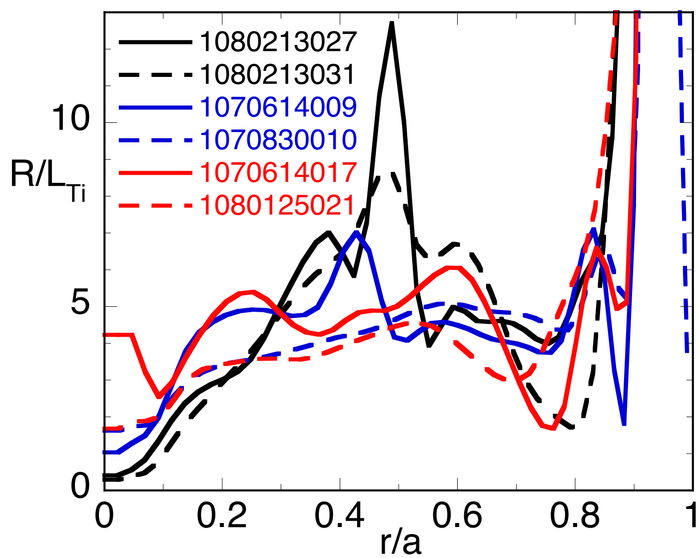
As the density gradient is varied, the particle flux changes; this is used to estimate the a/L_n that would produce null particle flux at each radius.
The extrapolated a/L_n is integrated to find the 'predicted' density profile.
Caveat: changing a/L_n changes the turbulence level – and character?

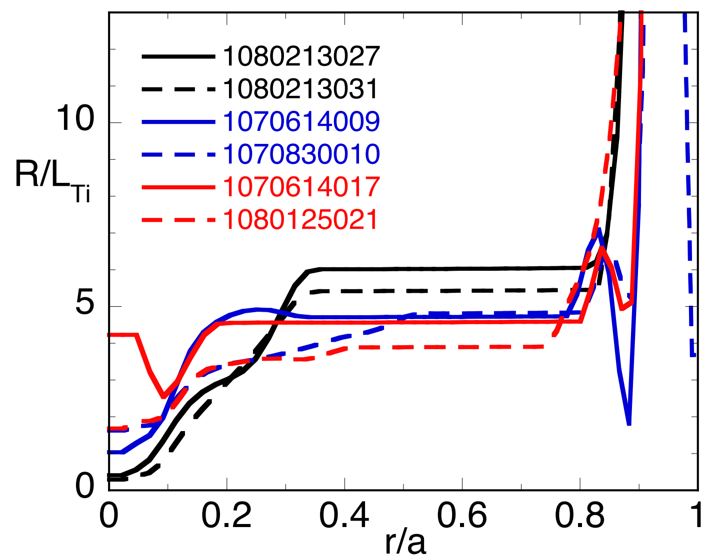
T_i modifications are modest



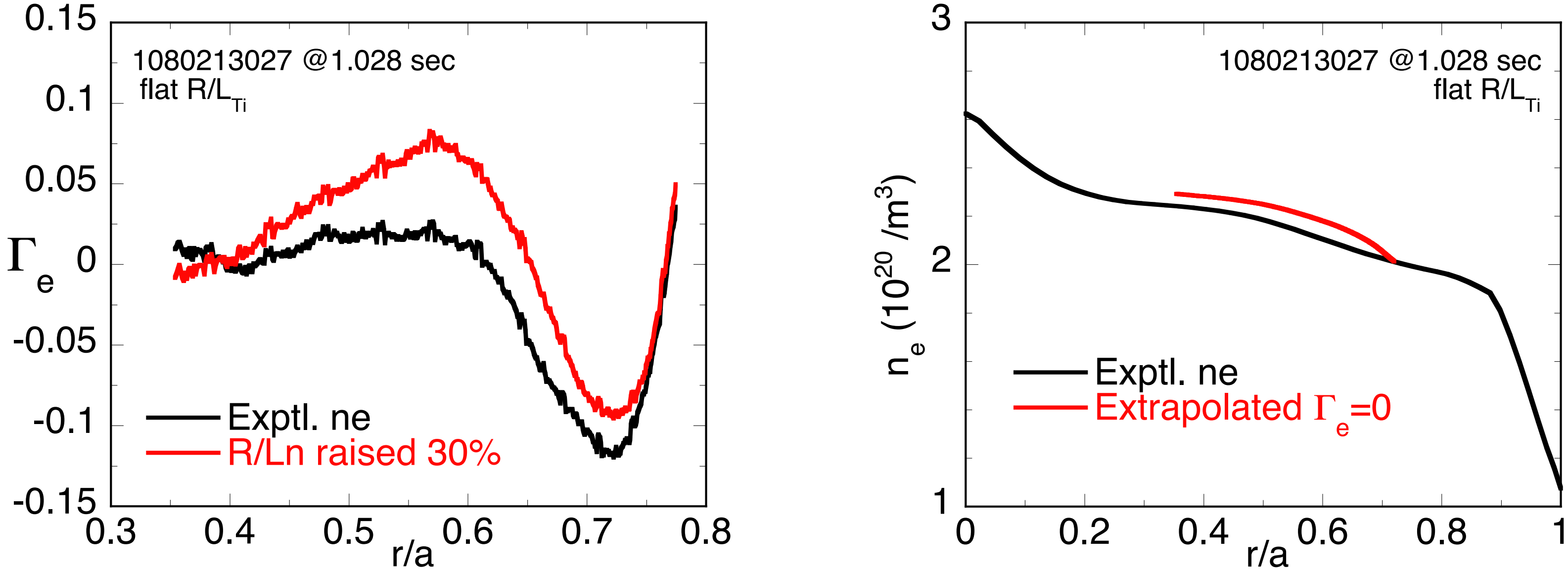


Measured $T_i(r)$ is matched near center and edge, R/L_{Ti} is smoother in between.

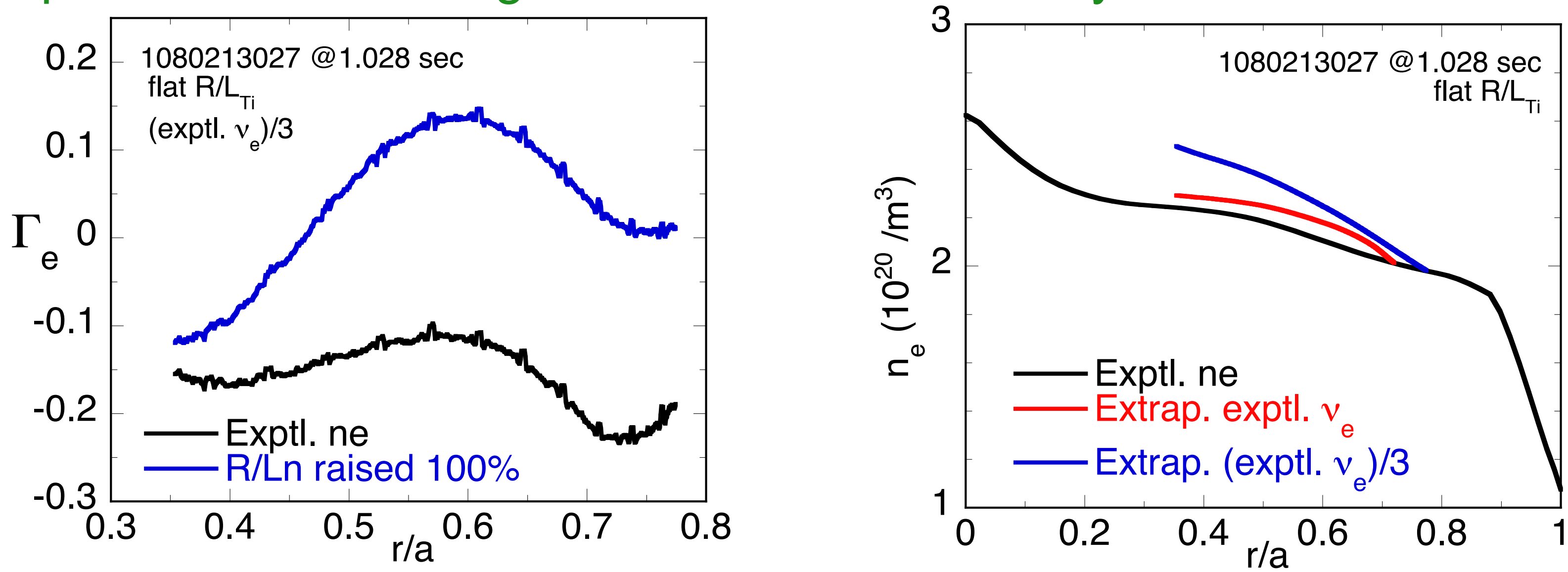




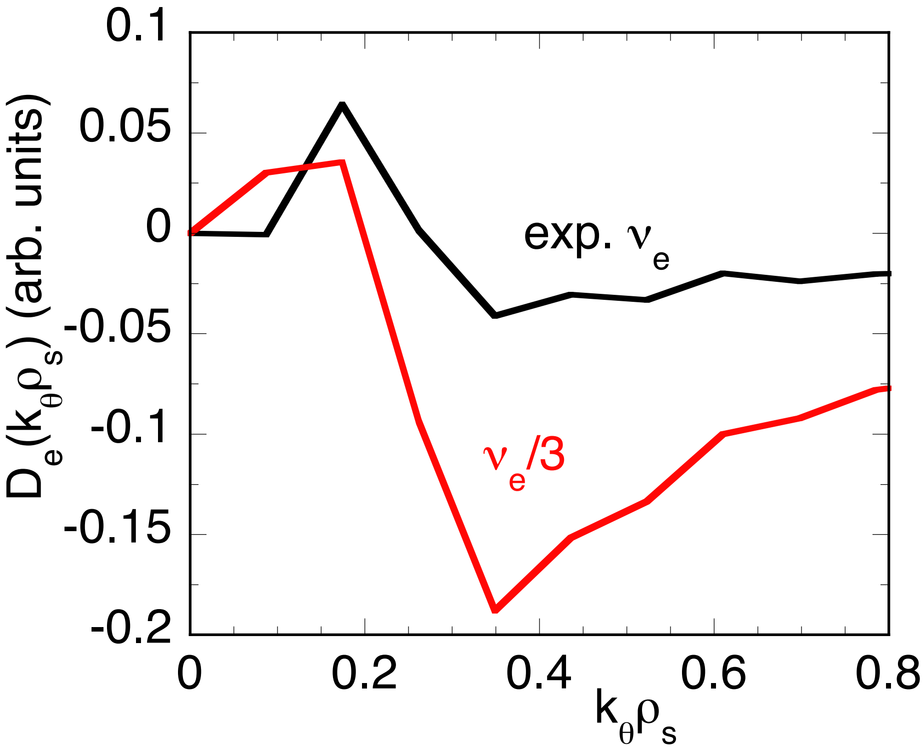
Stronger density peaking at low ν_e

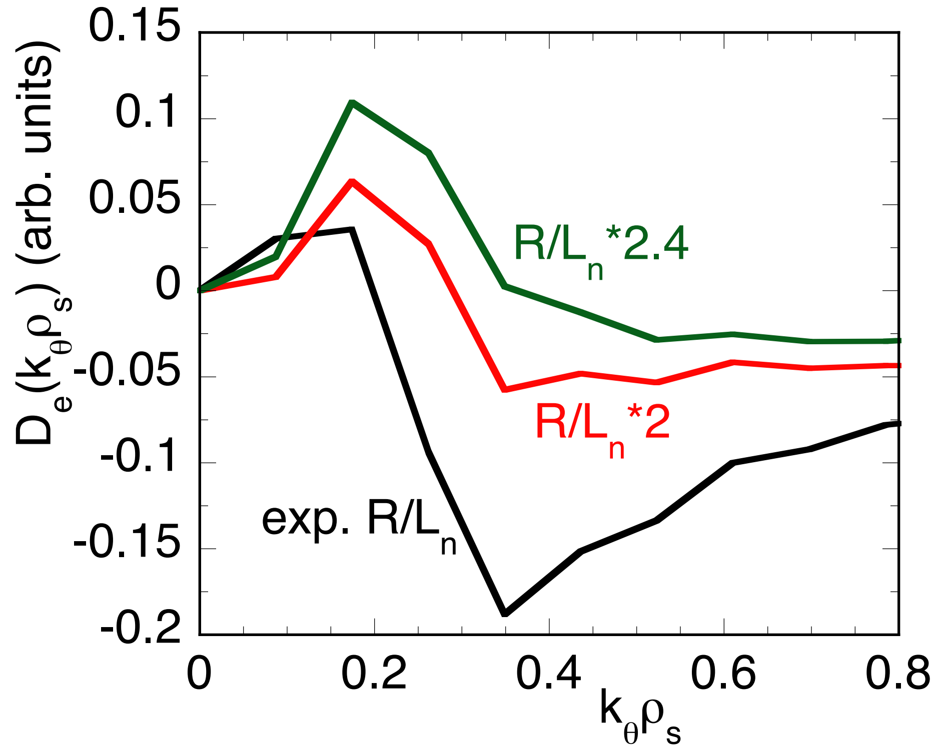


Inward pinch is much stronger with lower collisionality below.



Higher k modes are responsible for the pinch





More modes contribute to the pinch at lower collisionality.

Raising the density gradient reduces the pinch at all $k_\theta\rho_s$.

Need to do some simulations with higher maximum $k_\theta\rho_s$.

Missing inward flux at low collisionality is probably larger than missing outward flux at high collisionality, so the present simulations probably underestimate the density peaking at the null flux condition.

a/L_n, a/L_{Ti} and Mix of Ions is Varied

Results from six pairs of simulations are shown next.
Use particle fluxes, Γ_x, for the standard a/L_n & lower a/L_n of each pair to estimate the a/L_n that would give Γ_x=0.

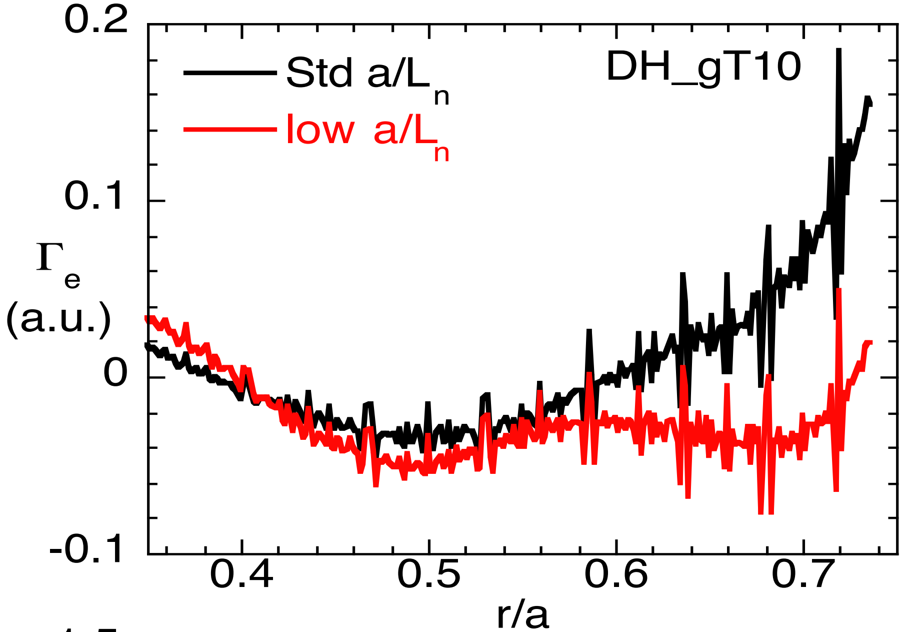
Two sets of a/L_{Ti} are used for each combination of ions.
Need assessment of power dependence of peaking factor, simulations with more ITG drive may show less peaking.

Only D, with standard a/L_{Ti} and 10% boost.

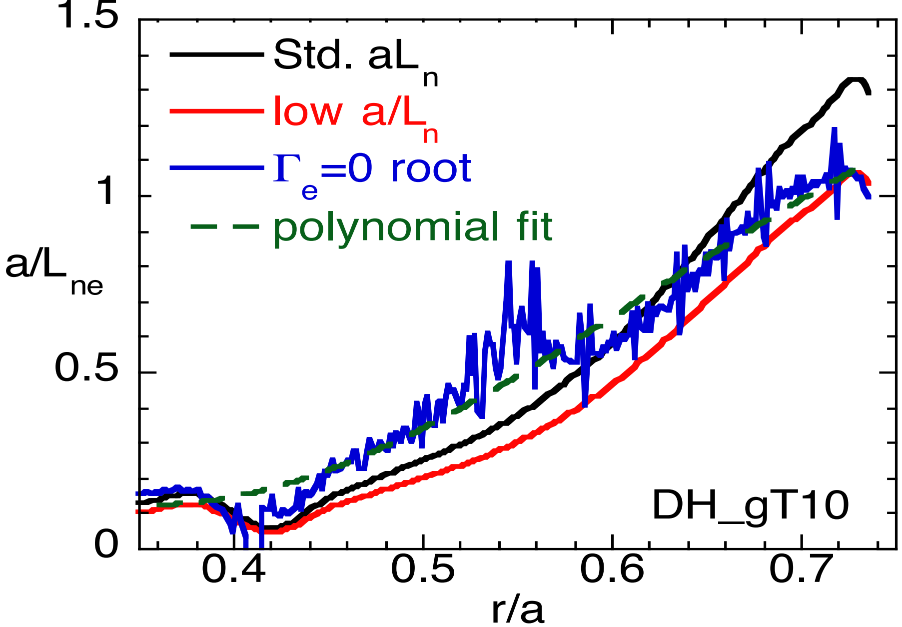
50:50 D:H at all radii, with standard a/L_{Ti} and 10% boost.

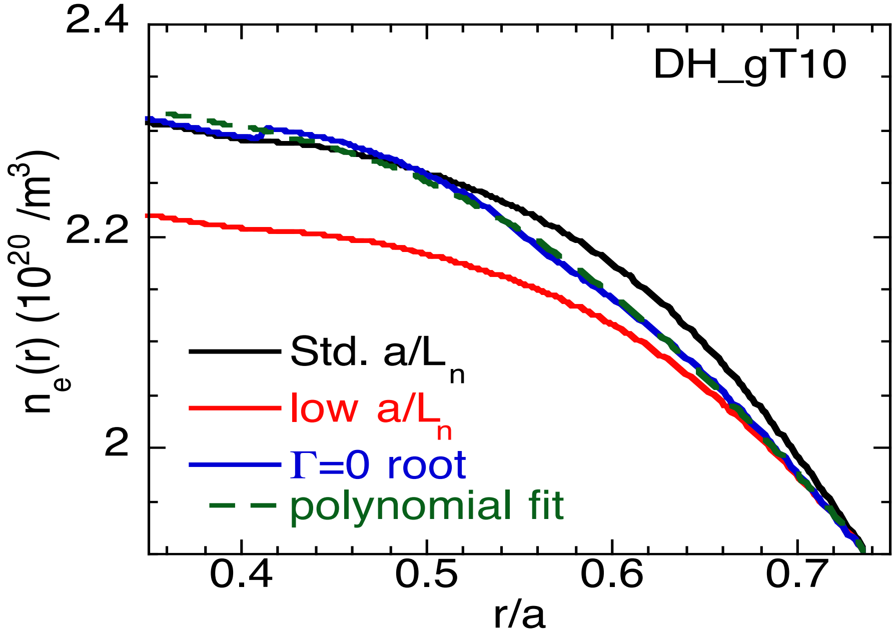
42:42:3 D:H:B at all radii, with 20% & 30% boost of a/L_{Ti}.
(dilution of hydrogenic isotopes reduces turbulence)

Extrapolation Exhibits Density Peaking



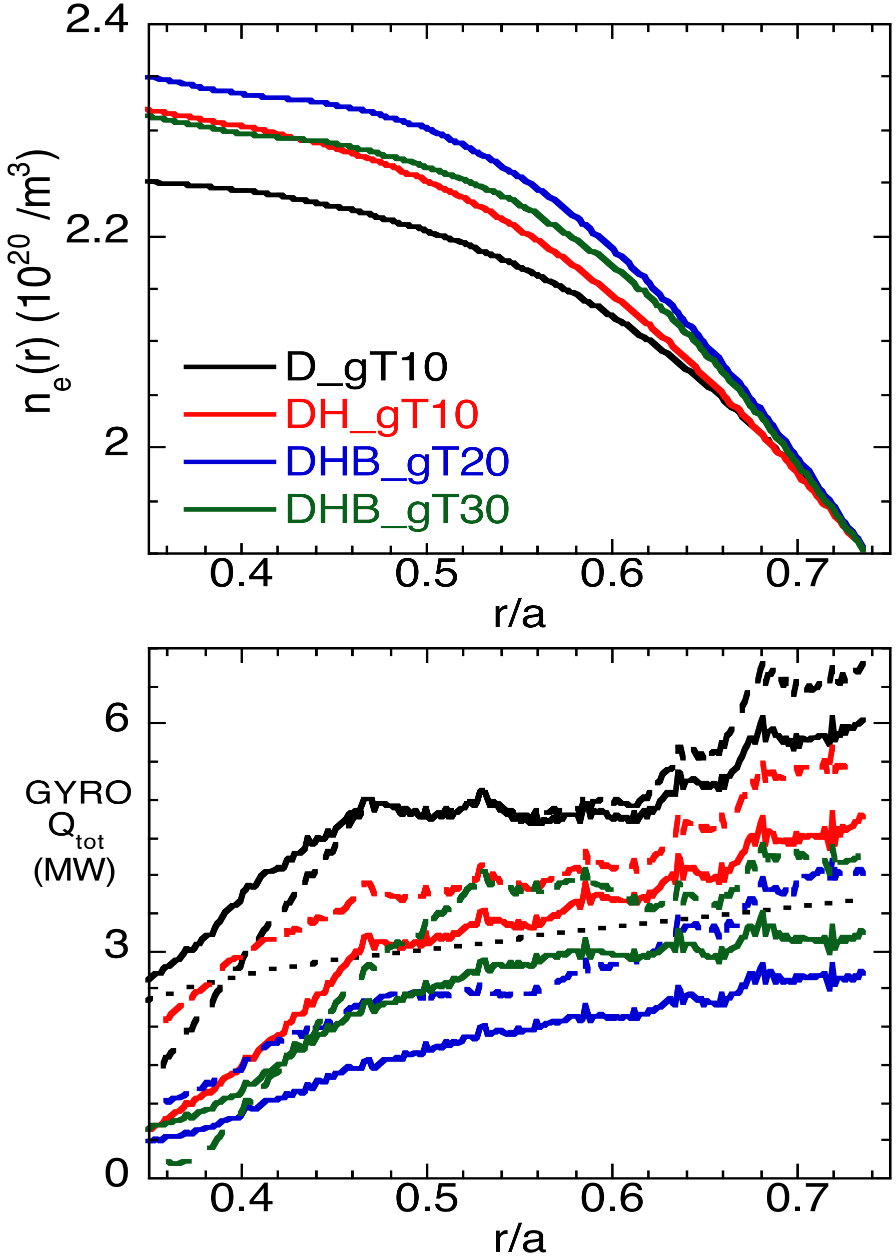
a/L_{ne} for Γ_e=0 diverges where simulated fluxes cross: r/a~0.41, but the extrapolation integrates to make only a small $n_e(r)$ jump. The smoother polynomial fit to the Γ_e=0 root is not needed here.



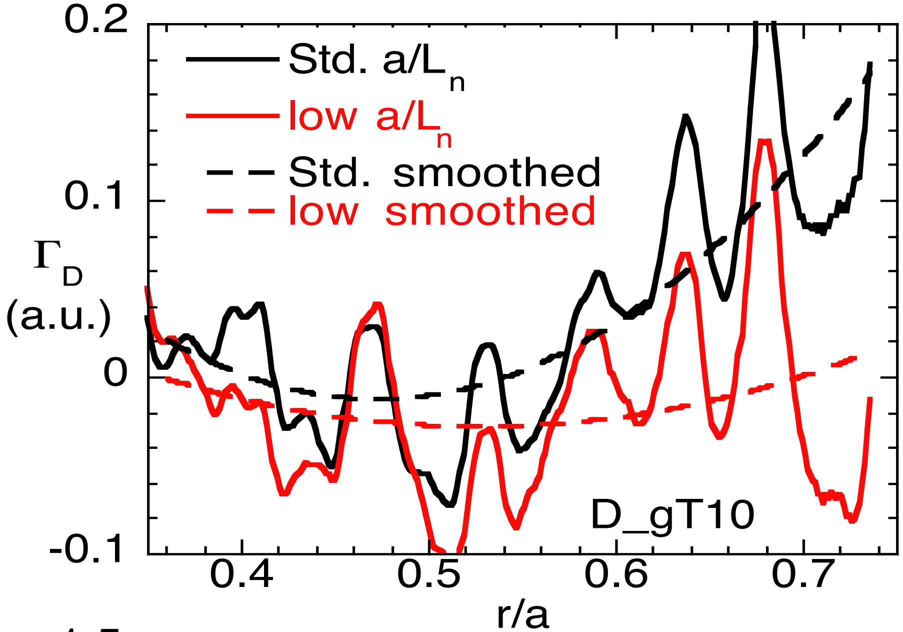


Electron Density Peaking is Robust

Electron density peaking is insensitive to variations in the ion species mix and to a wide range of transport powers.



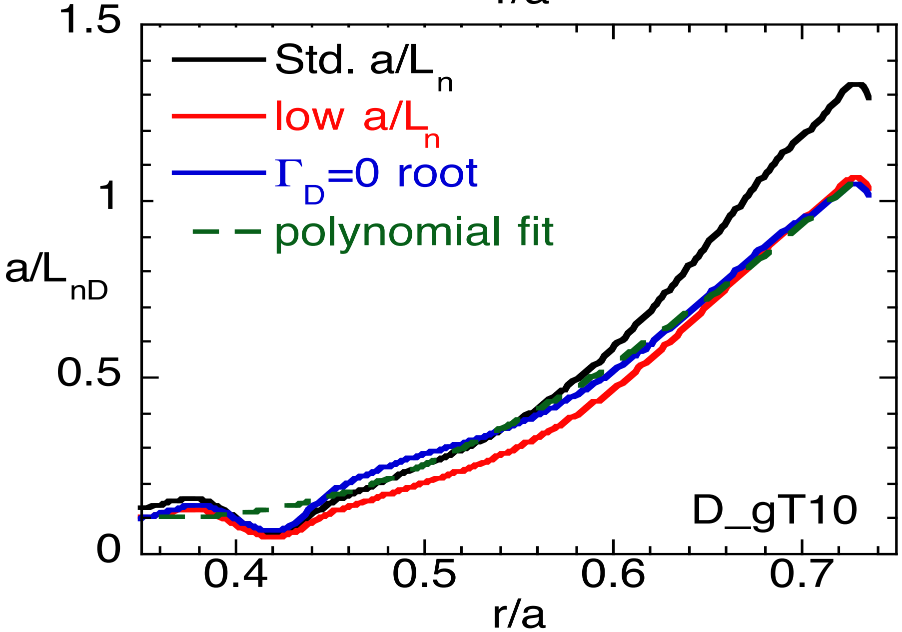
Ion Fluxes Require Smoothing

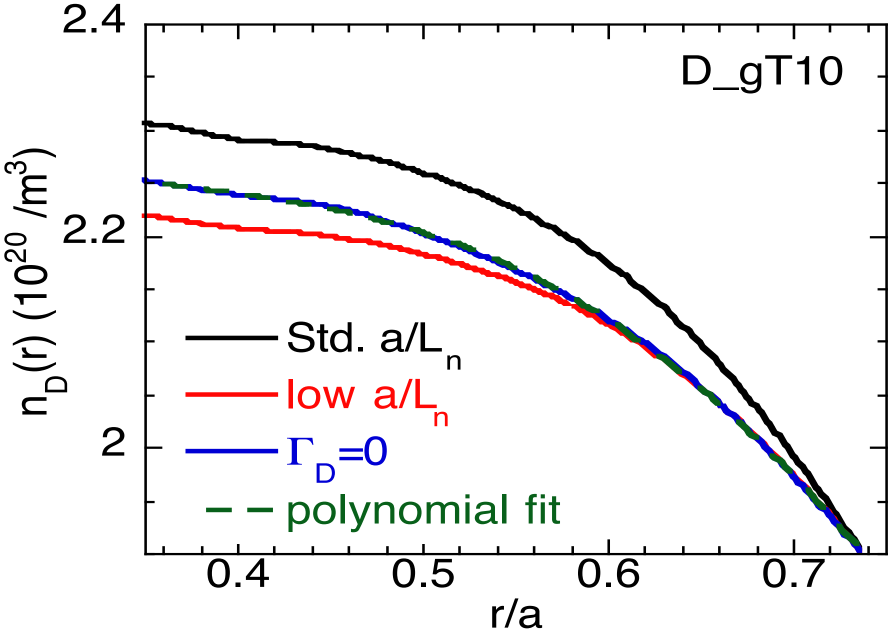


Low-order (n=2,3) polynomial smooths the ion fluxes.

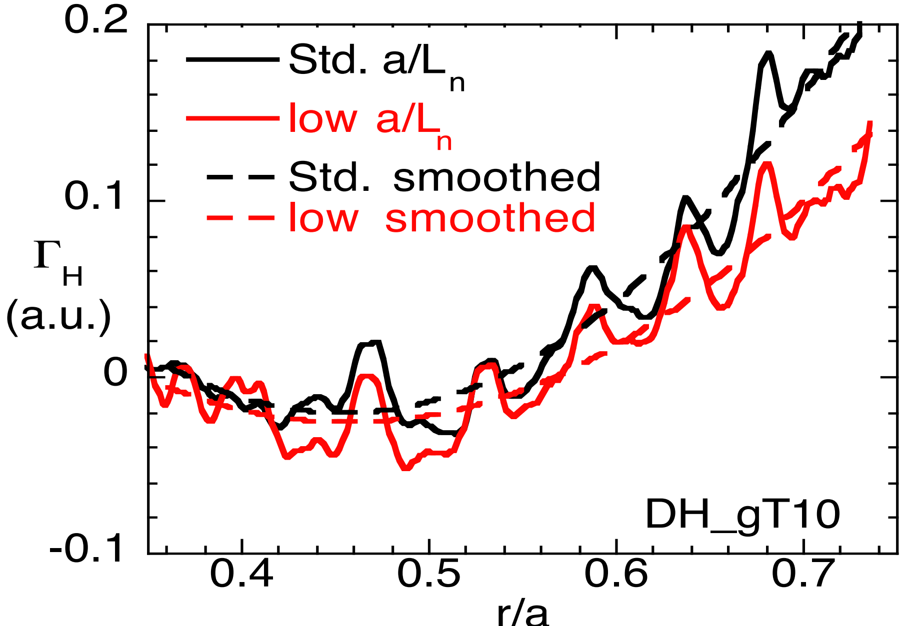
Extrapolated root and $n_D(r)$ are similar to companion run's $n_e(r)$.

Expect this for ambipolar ExB transport with one ion species.

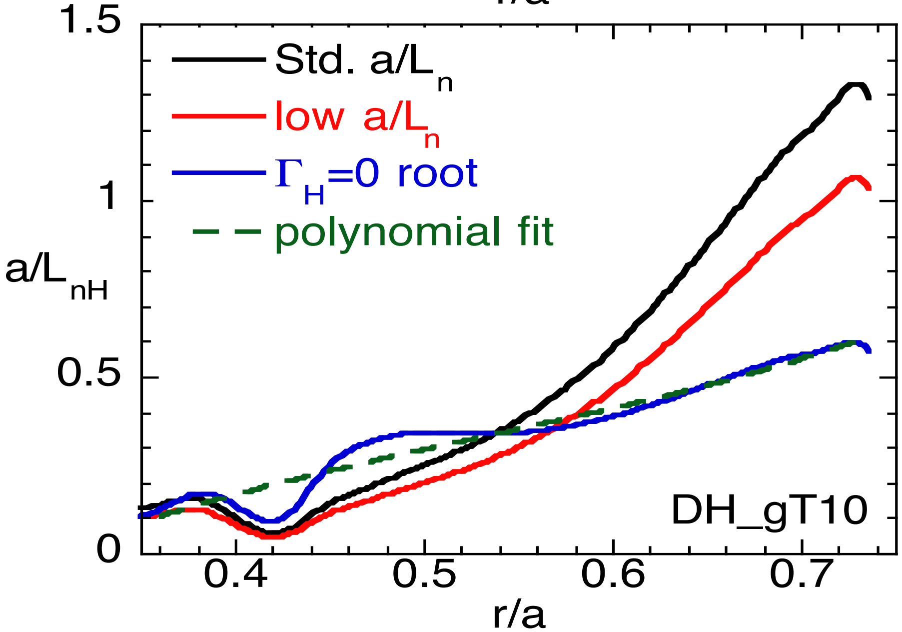


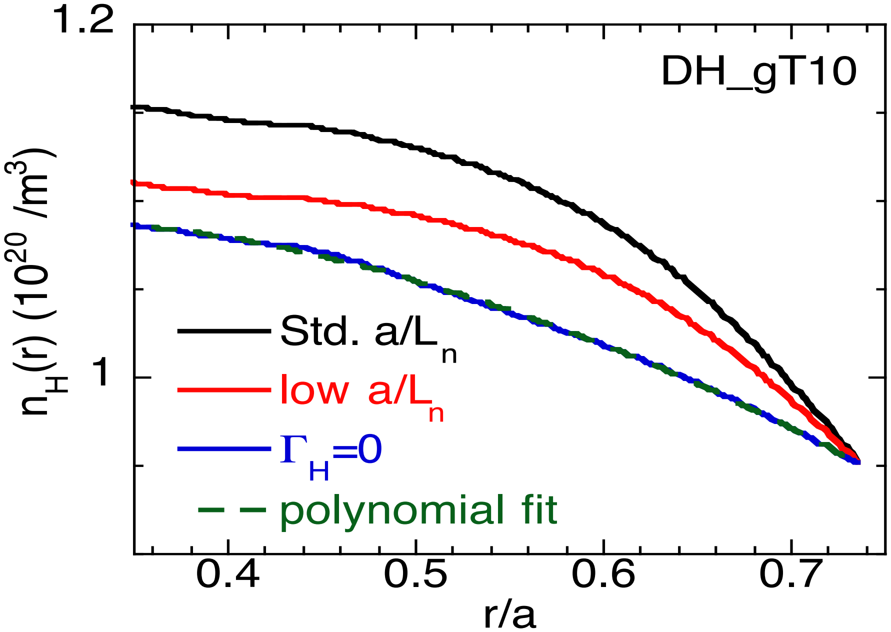


Hydrogen Density is Less Peaked



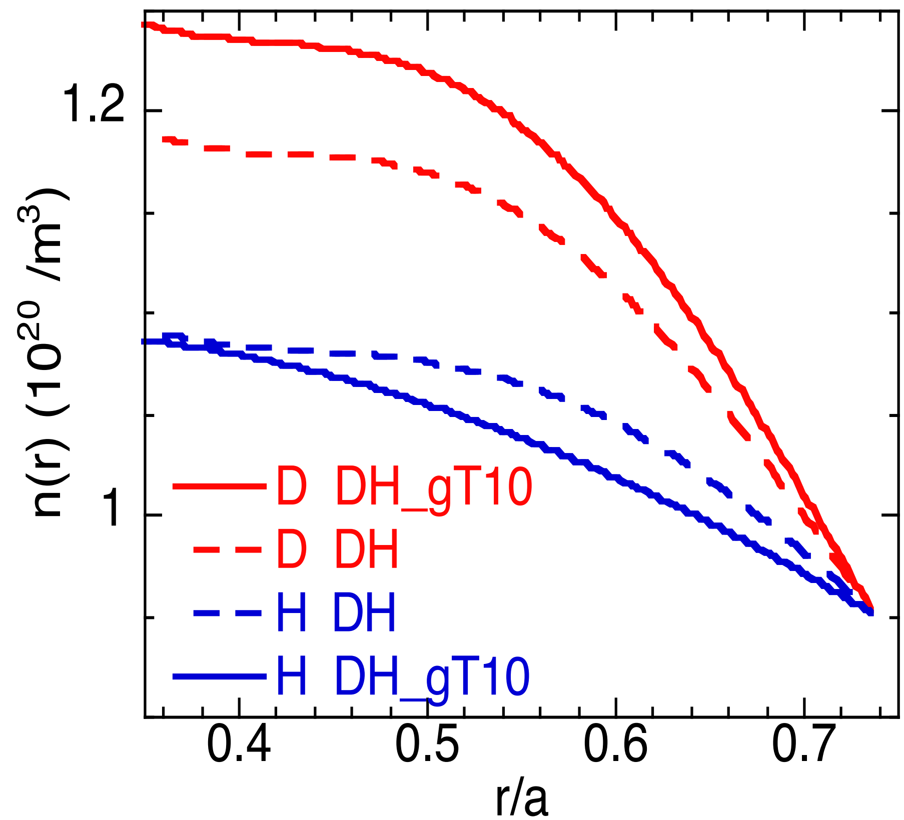
Extrapolated Γ_H=0 root has much lower values of a/L_{nH}, so $n_H(r)$ peaking is lower than for the electron density, and $n_D(r)$ peaking is higher …





Deuterium is More Peaked than Hydrogen

D & H density peaking is insensitive to the variation in the transport power.



Better Simulation Procedure

Narrow range of a/L_n in initial simulations: null-flux root is an extrapolation

Should use two 'species' for D (and two for H), *with different density profiles that sum to the same shape used for electron density*.

These offsetting changes to a/L_n leave total density unchanged.

Consequently,no change in turbulence level, even with wide separation in a/L_n.

The different ion density gradients produce different particle fluxes; *interpolate* to find a/L_n that gives null particle flux at each radius.

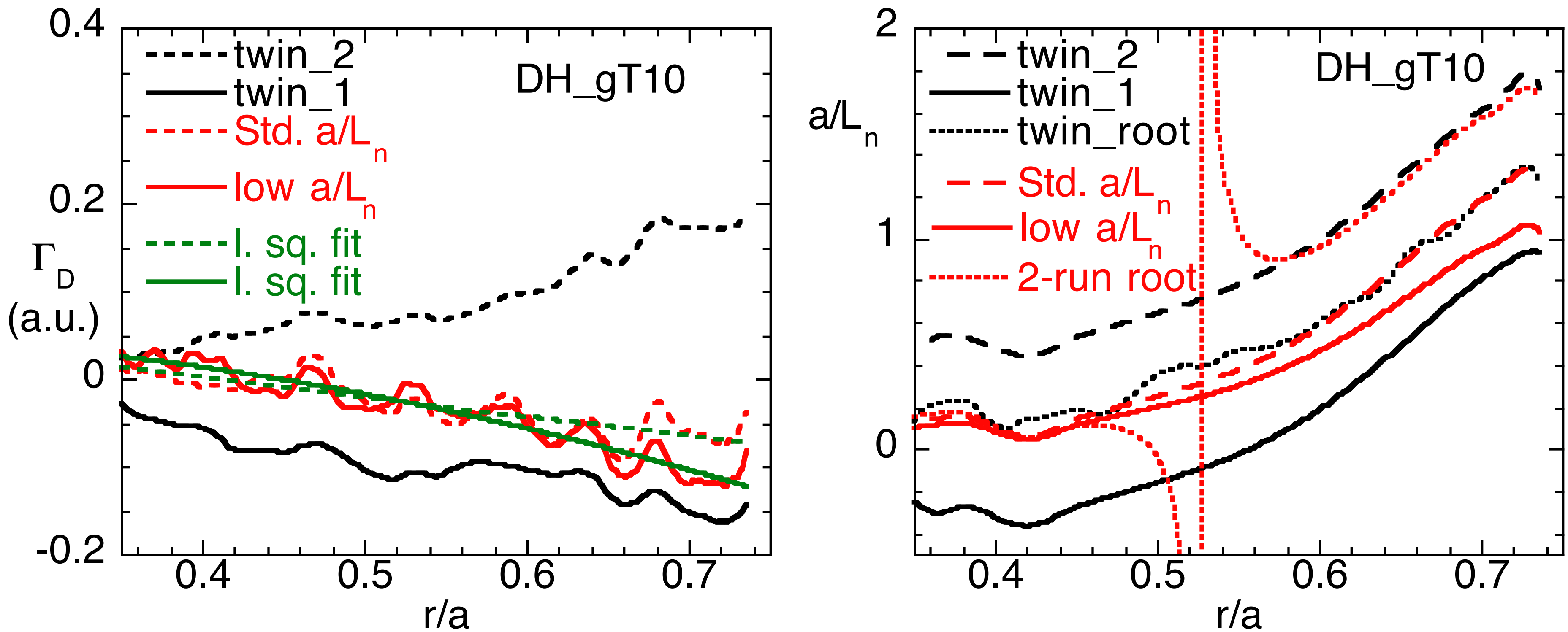
The interpolated a/L_n is integrated to find the 'predicted' density profile.

The same turbulent eddies affect both high- and low-a/L_n 'species', so the dependence on a/L_n is accurately captured in one run.

Two 'species' are sufficient to define D and V_{pinch}.

(three confirm a/L_n linearity in N. Howard's impurity transport simulations)

Null-flux Root is More Robust with Twins

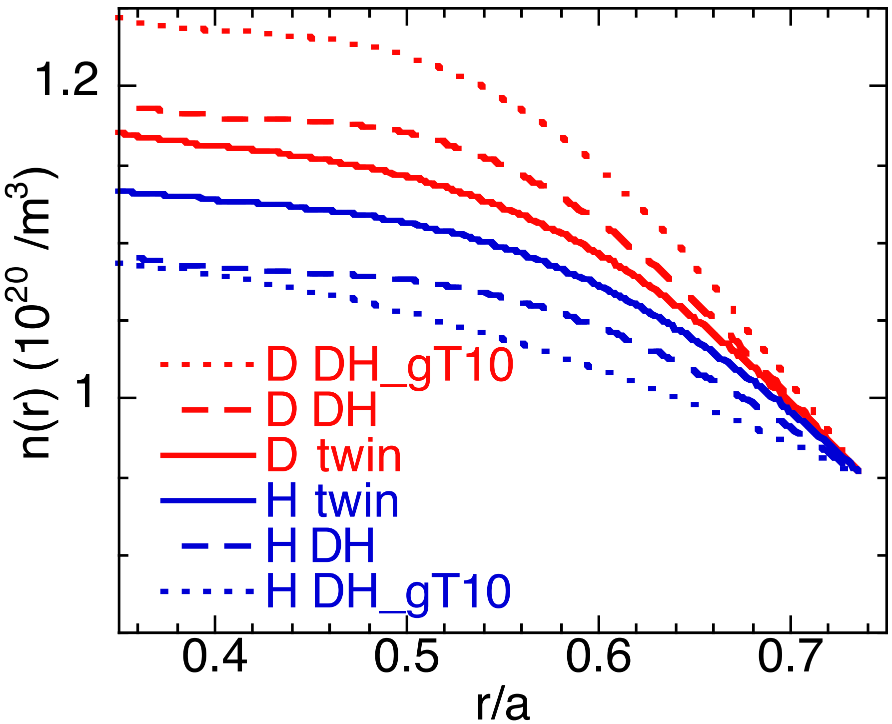


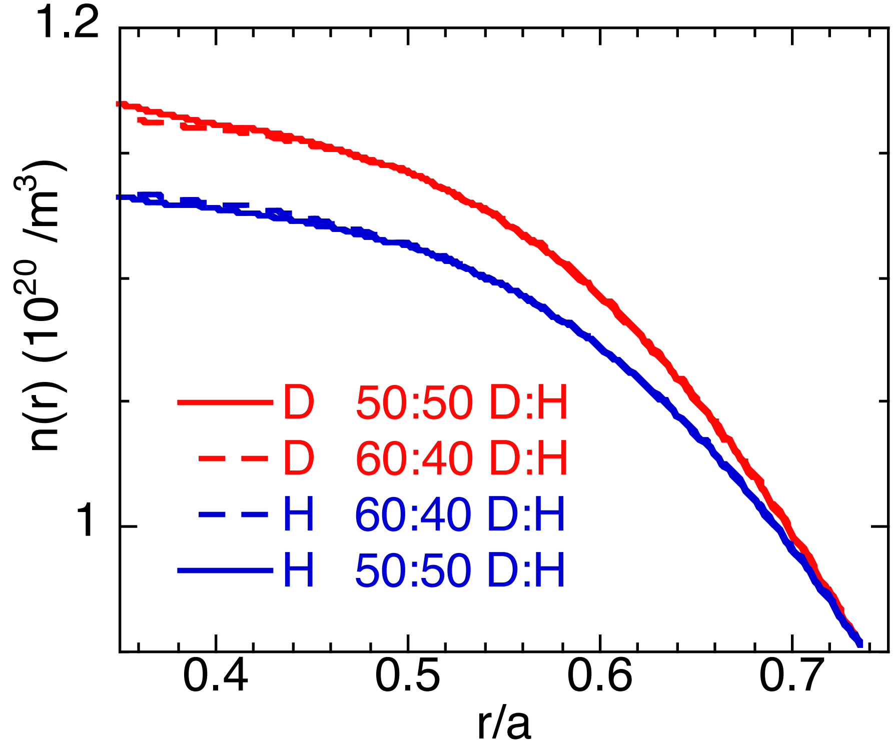
Larger a/L_n change with ‘twin’ D species enables interpolation.

Extrapolated null-flux root was required with first methodology.

Need to do ‘triplet’ D species to confirm flux is linear in a/L_n.

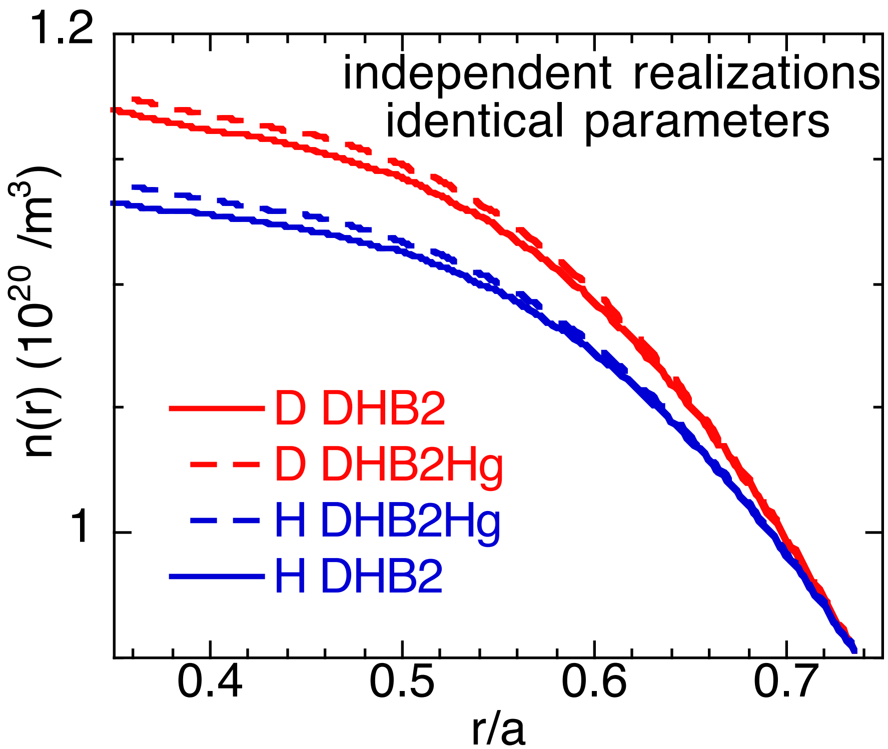
‘Twin’ Method Predicts Small Isotope Effect

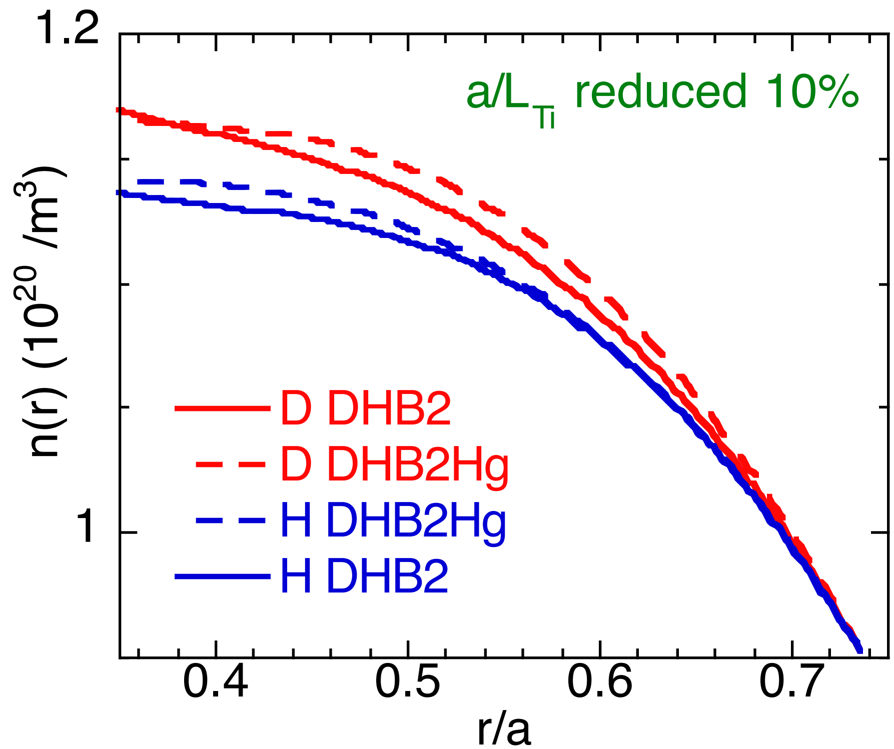




Twin method’s smaller spread is probably more reliable;
need to confirm with ‘triplet’ simulation.
Isotope effect similar for 50:50 and 60:40 D:H mixes.

Small Variation in Predictions





Completely independent turbulence simulations agree well.

30% reduction of turbulent heat flux has weak effect on peaking.

Improved Methodology Works

Large changes in a/L_n at constant Q_{tot} are possible when using 2 'ion species' with identical A,Z for each hydrogenic isotope.

The new null-flux roots are interpolations.
(the input density peaking is close to the 'predicted' null-flux peaking because it was 'tuned' using earlier simulations)

New runs with density profiles far from extrapolation will indicate how robust the extrapolation is; iteration may be needed.

Method works very well for trace impurities (N. Howard talk Sat. AM)

Summary of D vs. H Peaking

D & H have *slightly* different peaking in GYRO simulations.
C-Mod experiment to measure D&H peaking is planned.

D:H mix of 60:40 has the same D&H peaking as 50:50 mix.

The electron density peaking is weakly affected by the ion mix, pure D, 50:50 DH, and DHB all have very similar peaking.

Peaking of D and H is weakly affected by adding Boron.

All peaking is *weakly* affected by the turbulence level.
alternative modifications may differ, in particular:
Changes that affect Q_e/Q_i (a proxy for TEM/ITG dominance) will be explored; *a priori*, we expect this to change peaking.

Will focus on collisionality dependence in future work.