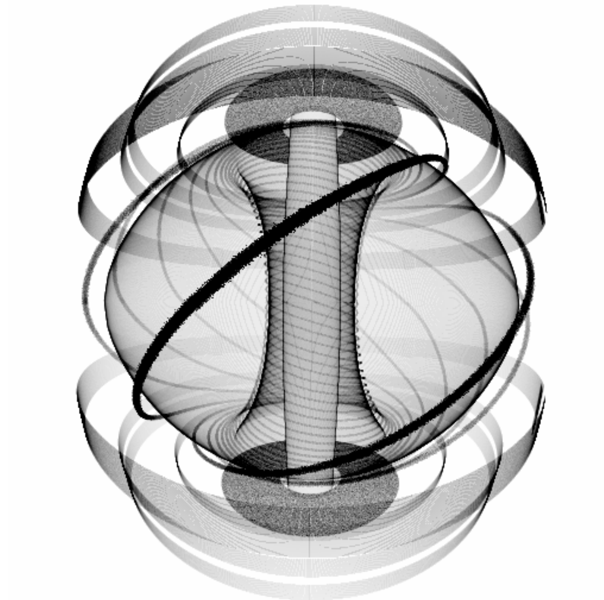
Comparison of plasma performance and transport between tangential co and counter-NBI heated MAST discharges.



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P.Helander, A.R.Field, C.Brickley, D.Muir, N.J.Conway, M.Wisse, A.Kirk, A.Patel, A.Thyagaraja, C.M.Roach and the MAST and NBI teams.

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Contents

1. Introduction.
2. The MAST device and NBI systems.
3. Energy confinement.
4. Particle confinement.
5. Momentum confinement.
6. Micro-stability.
7. Summary.

Introduction

Why study counter-NBI?

1. The discovery of high performance, ELM free regimes (QH/QDB mode).
2. NBCD experiments.
3. The ability to change the applied torque and radial electric field.

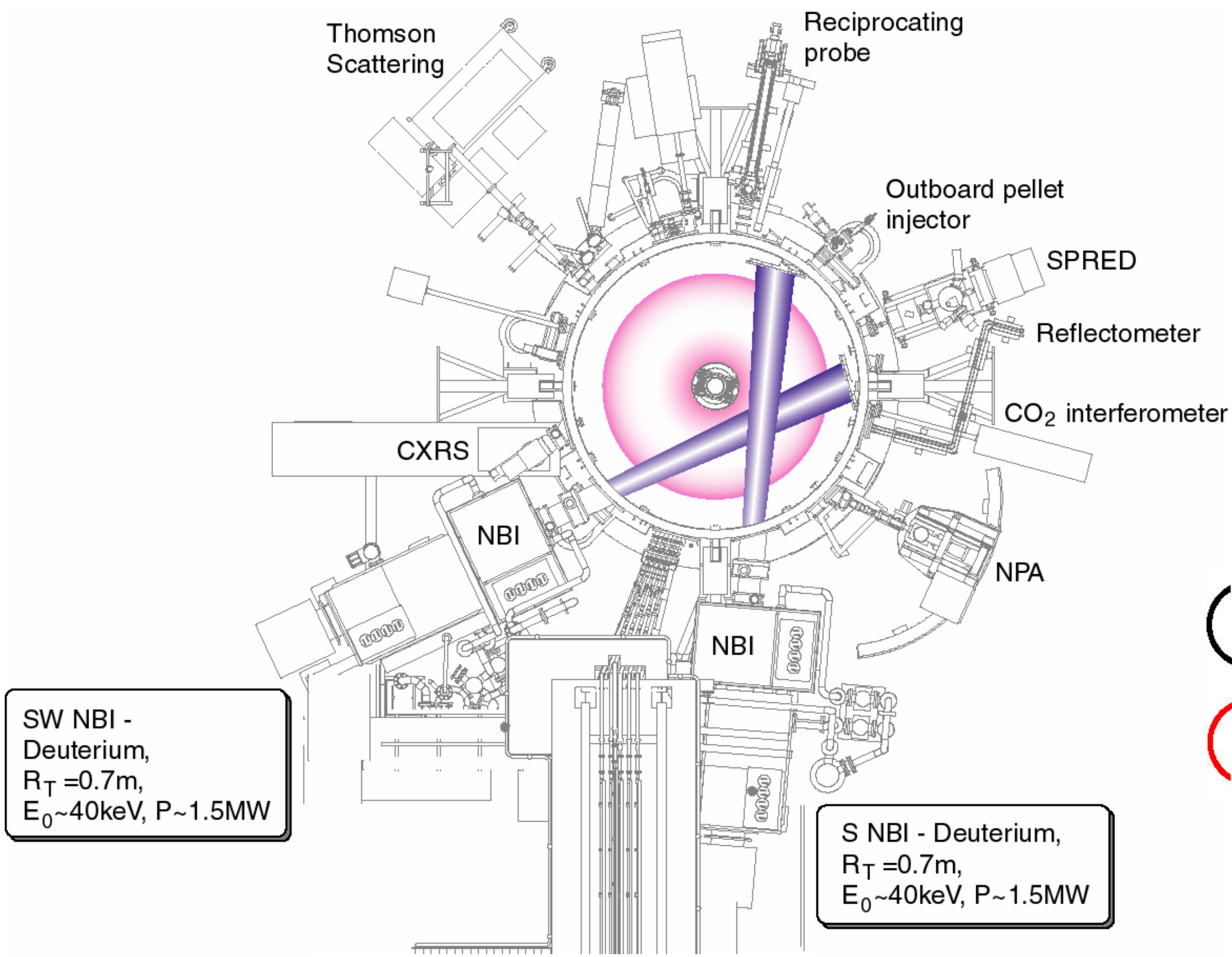
Concerns:

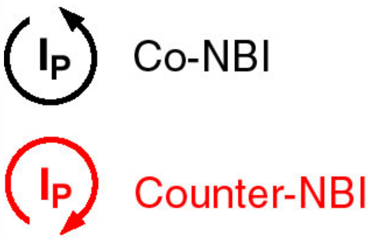
1. Fast ion confinement (power loading to plasma facing components).
2. Impurity accumulation.

Modelling & Analysis:

1. TRANSP + NUBEAM (PPPL) (guiding centre NBI/transport code + FLR correction)
2. LOCUST (Culham) (full gyro parallel NBI Monte Carlo code)
3. **12 counter-NBI** heated and **11 co-NBI** heated comparison discharges.

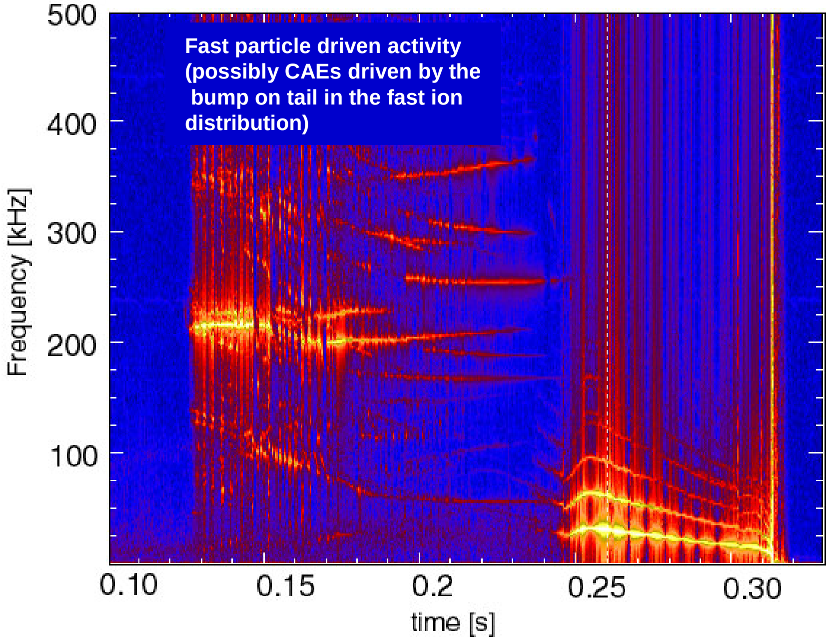
MAST - NBI and diagnostics

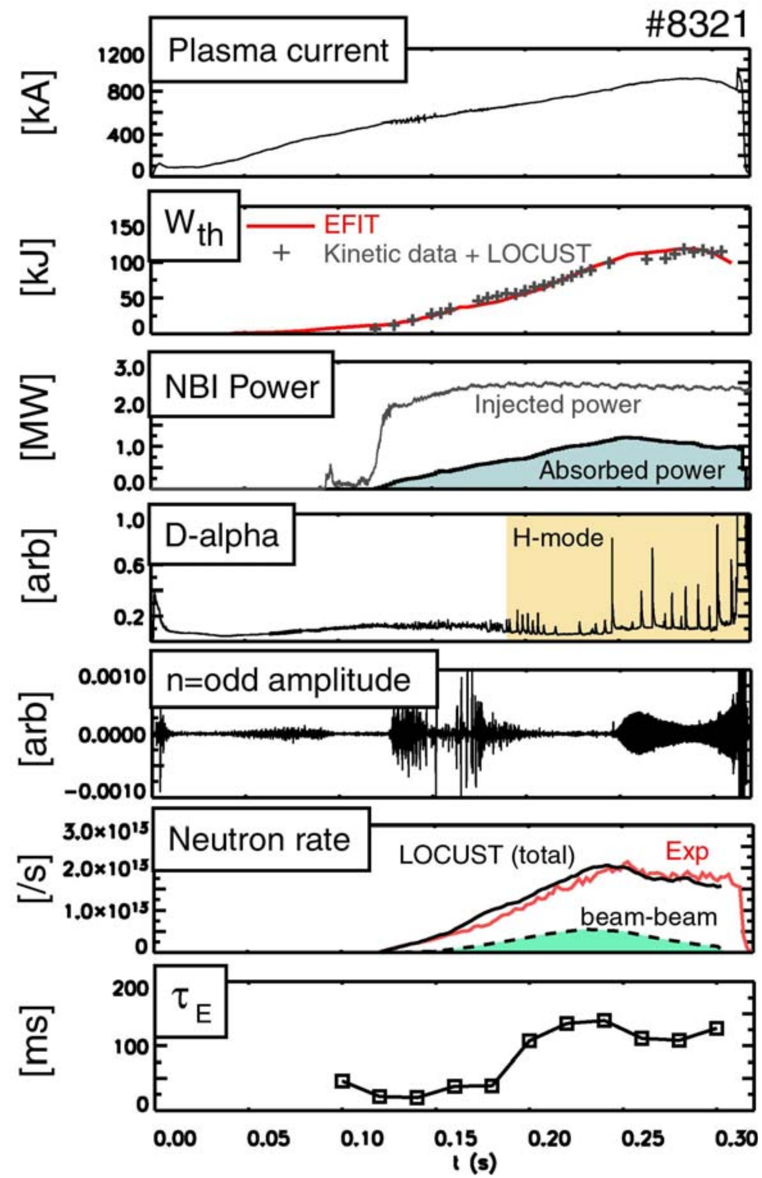




Simulations indicate that ~30-50% of the counter-NBI fast ion power should be absorbed (in contrast to ~100% for co-NBI) - see later.

Counter-NBI heated discharges are a high confinement regime.





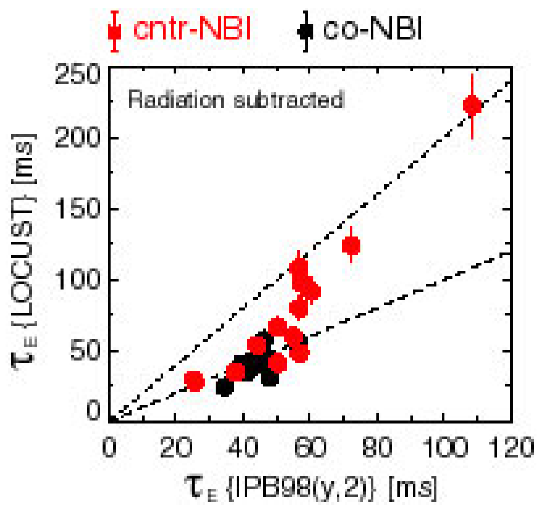
- Fast ions seen on fast magnetics
- Fast ion losses (>50%) well modelled

  - Stored energy from EFIT vs. kinetic profiles
  - neutron rate from LOCUST/TRANSP
  - Power deposited at targets

- H-mode readily accessed (due to large E_r? [1]).
- H_H[IPB98(y,2)] >1.5, τ_E~150ms, W~120kJ.

[1] J.Kim et al., PPCF **38**, 1479 (1996).

Counter-NBI heated discharges are a high confinement regime.

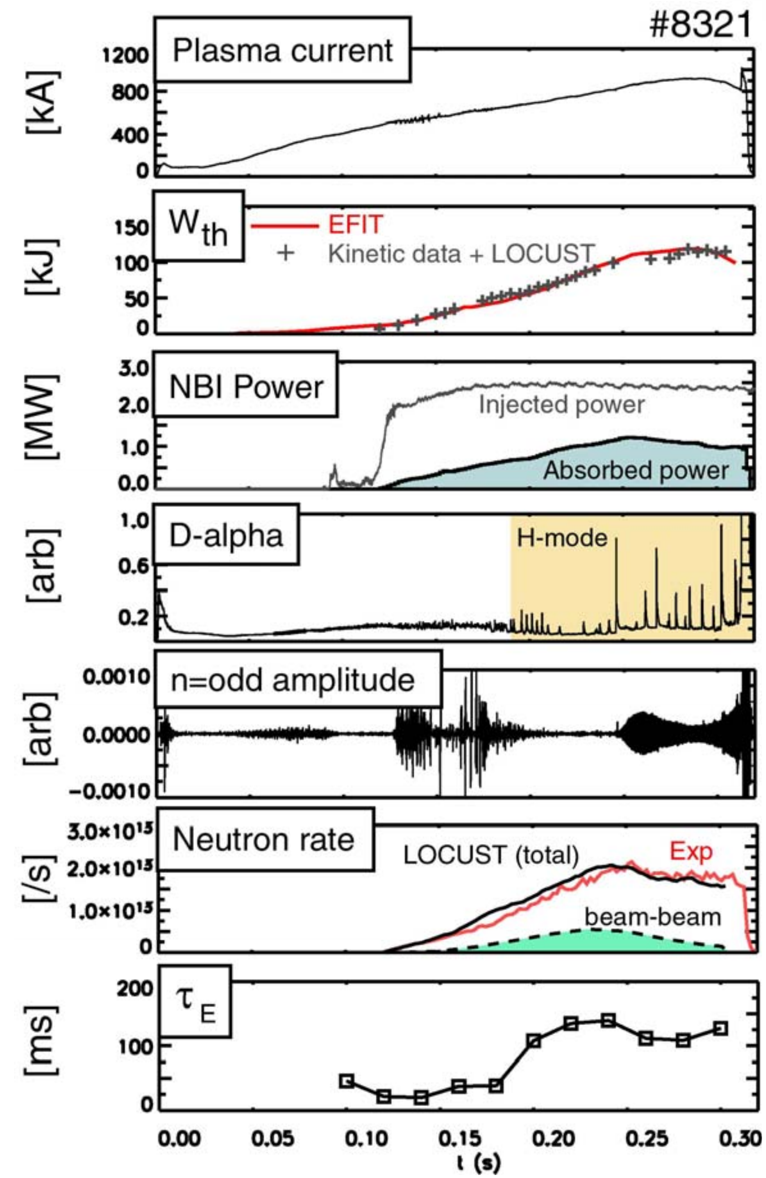


Due to radiation being a large fraction of P_{abs} for counter-NBI, here τ_E is "radiation subtracted".

Confinement time ~2-3 times higher than for co-NBI. c.f.

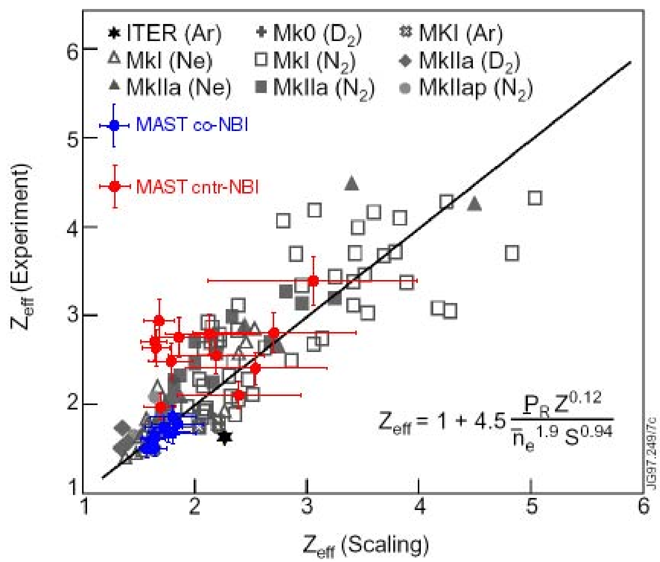
- ISX-B	[2]
- ASDEX: τ_E~43ms (co), τ_E~80ms (counter)	[3]
- JFT-2M: τ_E~18ms (co), τ_E~24ms (counter)	[4]

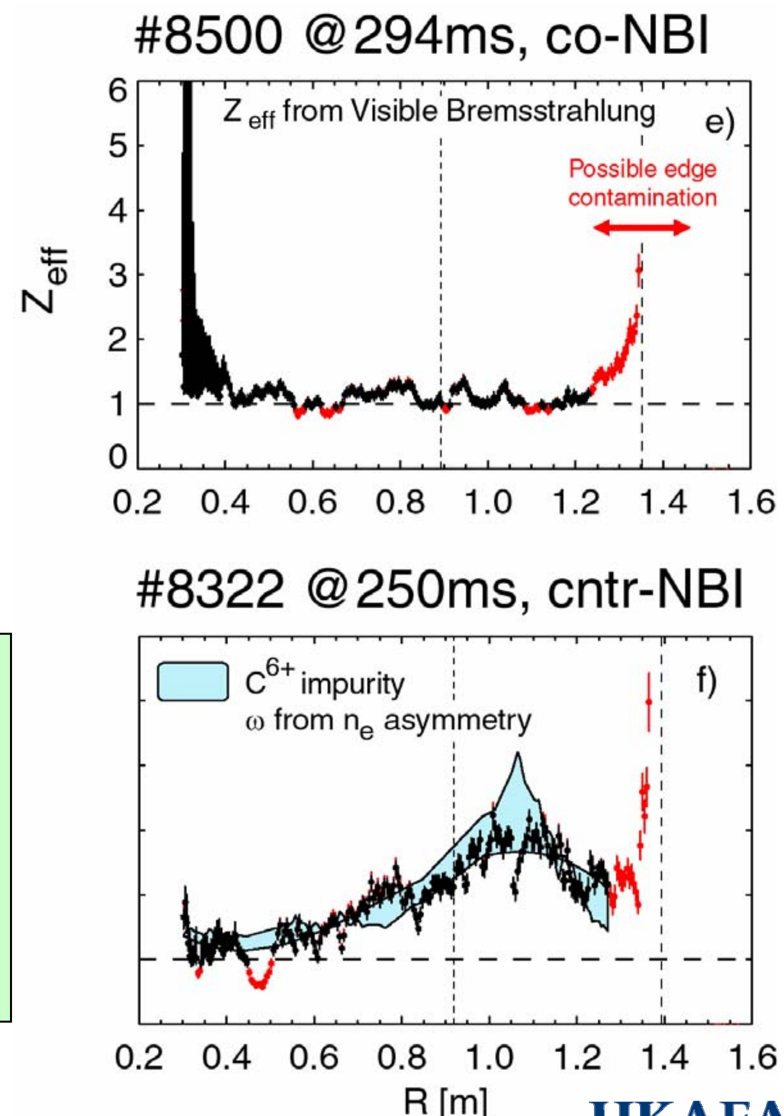
[2] M.Murakami, 10th ICPP, London, Vol. I, 87 (IAEA, Vienna) (1985)
[3] O.Gehre et al., Phys. Rev. Lett. **60**, 1502 (1988).
[4] K.Ida et al., Phys. Rev. Lett. **68**, 2 182 (1992).



Plasma purity is good without the need for dedicated boronisation

JET divertor Z_{eff} scaling, G.Matthews et al.

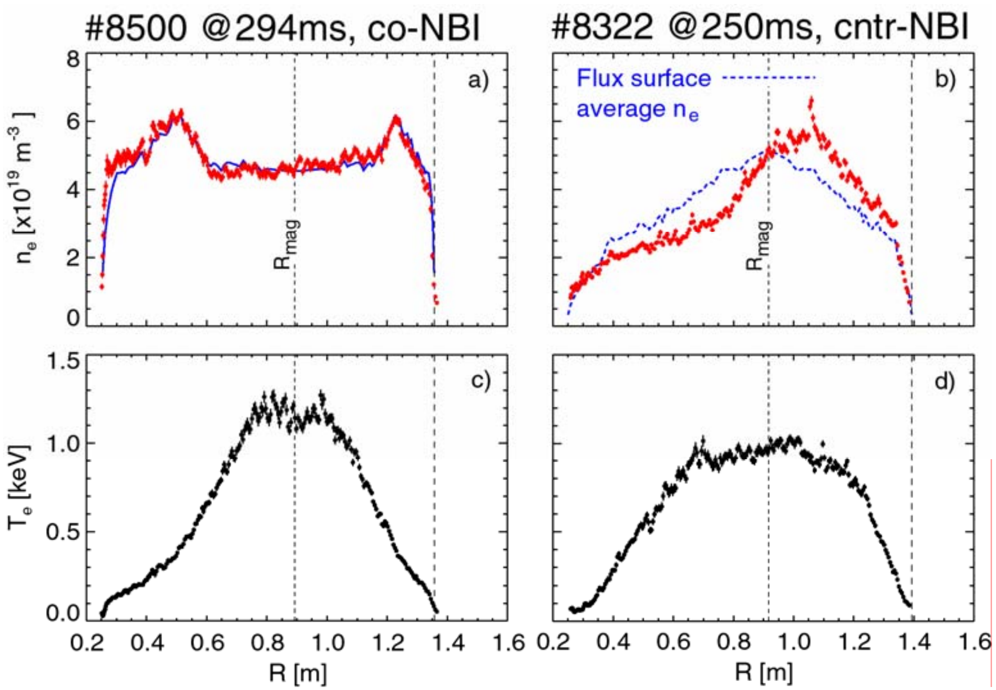


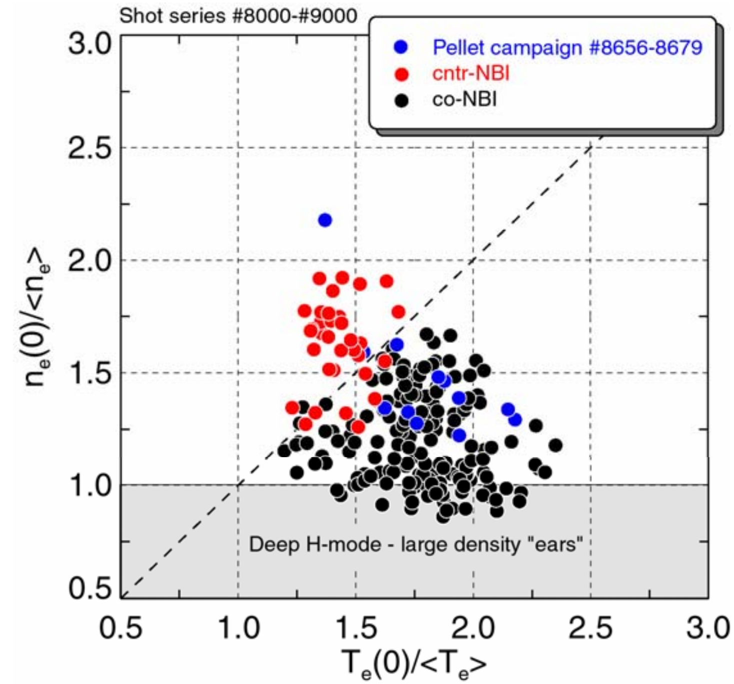


- Quasi-steady state co-NBI H-mode discharges have Z_{eff}~1 (flat) and very low radiated power.
- For counter-NBI, Z_{eff} is typically ~2-3 (peaked).
- Z_{eff} comparable to that achieved in AUG QH-mode (C and O) but without need for pre-shot boronisation [5].

[5] W.Suttrop et al., PPCF **46**, A151 (2004).

Electron density and temperature profiles are strikingly different to co-NBI





Density peaking also observed on:

ASDEX	[3],
JFT-2M	[4],
DIIID QDB mode	[6],

JFT-2M explain the density peaking by invoking a “turbulence driven pinch”.

The model fits the observed level and rate of density peaking.

[3] O.Gehre et al., Phys. Rev. Lett. **60**, 1502 (1988).
[4] K.Ida et al., Phys. Rev. Lett. **68**, 2 182 (1992).
[6] C.M.Greenfield, Phys. Rev. Lett. **86**, 20 4544 (2001)

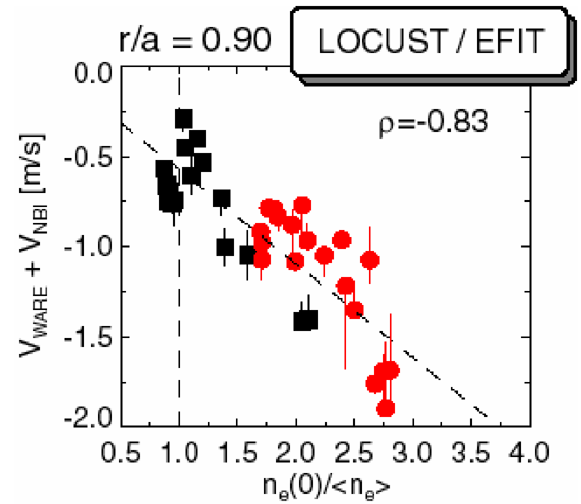
Electron density is peaked due to the enhanced Ware pinch

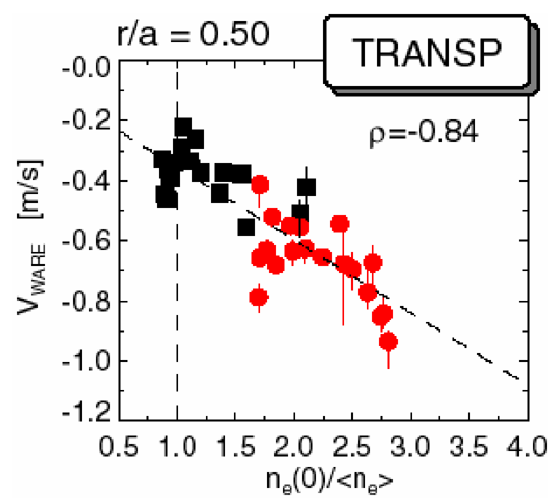
$$\left\langle \vec{\Gamma}_e \cdot \nabla\psi \right\rangle^{\text{pinch}} = \frac{I}{m_e \tilde{\Omega}_0^2 \tau_e}\Bigg[\overbrace{\frac{\ell_\parallel^e Z_f}{Z_{eff}}\langle j_f B\rangle + \frac{1}{1+\nu_*}\frac{Z_f/Z_{eff}}{\langle B^{-2}\rangle}\left(\left\langle\frac{j_f}{B}\right\rangle - \left\langle\frac{1}{B^2}\right\rangle\langle j_f B\rangle\right)}^{\text{NBCD DRIVEN PINCH}} \underbrace{- \frac{\ell_{13}^2}{\langle B^2\rangle\langle B^{-2}\rangle}\frac{n_e e^2\tau_e}{m_e}\langle E_\parallel B\rangle}_{\text{WARE PINCH}}\Bigg]$$

- Ware pinch is dominant (low NBCD).
- Due to higher Z_{eff} and neoclassical resistivity (T_e~1keV), Ware pinch is strong on MAST.

  V_{WARE}~1m/s.

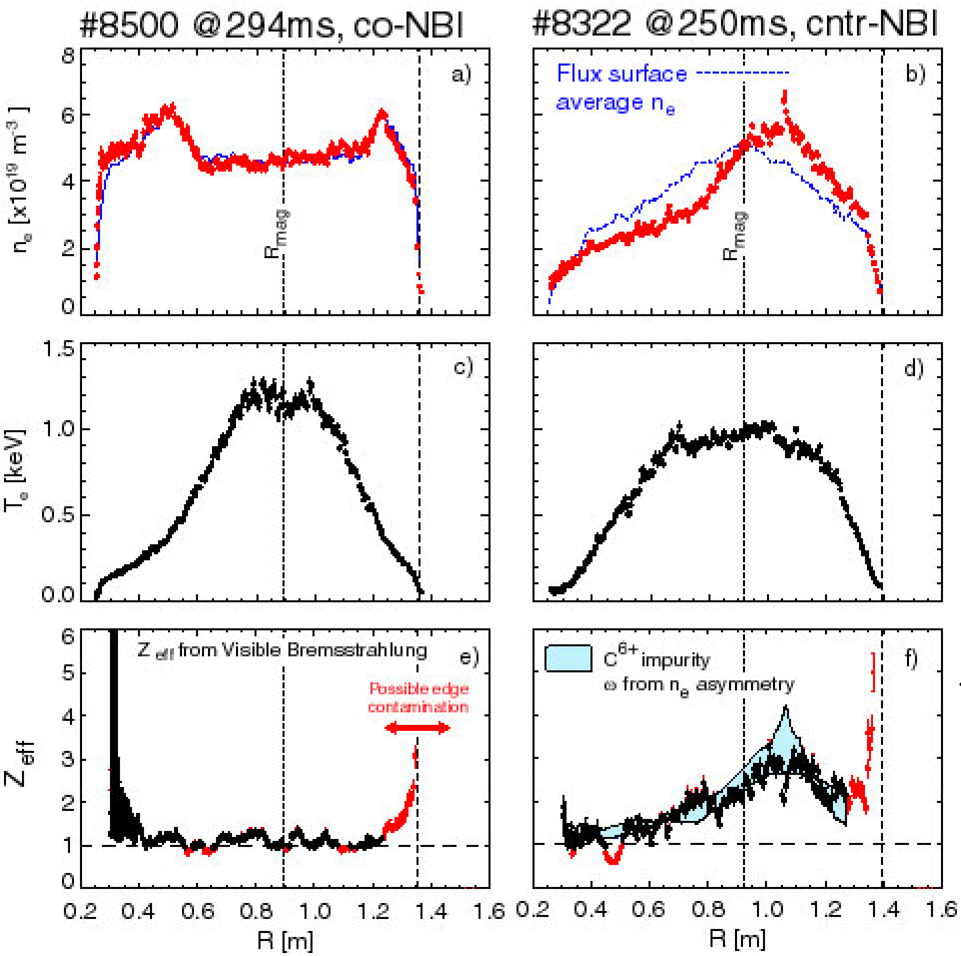
- Estimates suggest D<0.25m²/s (V<1m/s) - Ware pinch clearly strong enough to influence density profile.
- For quasi-steady state H-mode, core density dominated by NBI fuelling and Ware pinch [7].





[7] M.Valovič et al., **EX/P6-30**, *this conference*.

Highest performance is accompanied by supersonic toroidal flow



Electron density in-out asymmetry

$$n = n_0 \exp\left(\frac{m_i \omega^2 (R^2 - R_0^2)}{2(T_i + T_e)}\right)$$

(assuming T_i a flux surface quantity, $V_\theta << V_\varphi$, low fast ion content)

Z_{eff} in-out asymmetry

$$\frac{n_Z}{n_Z(0)} = \exp\left[\left(1 - \frac{T_e}{T_i + T_e} Z \frac{m_i}{m_Z}\right) \frac{m_Z \omega^2 (R^2 - R_0^2)}{2T_Z}\right]$$

Consistent with dominant C^{6+} impurity

Electron density asymmetry used for rotation in absence of CXRS data.

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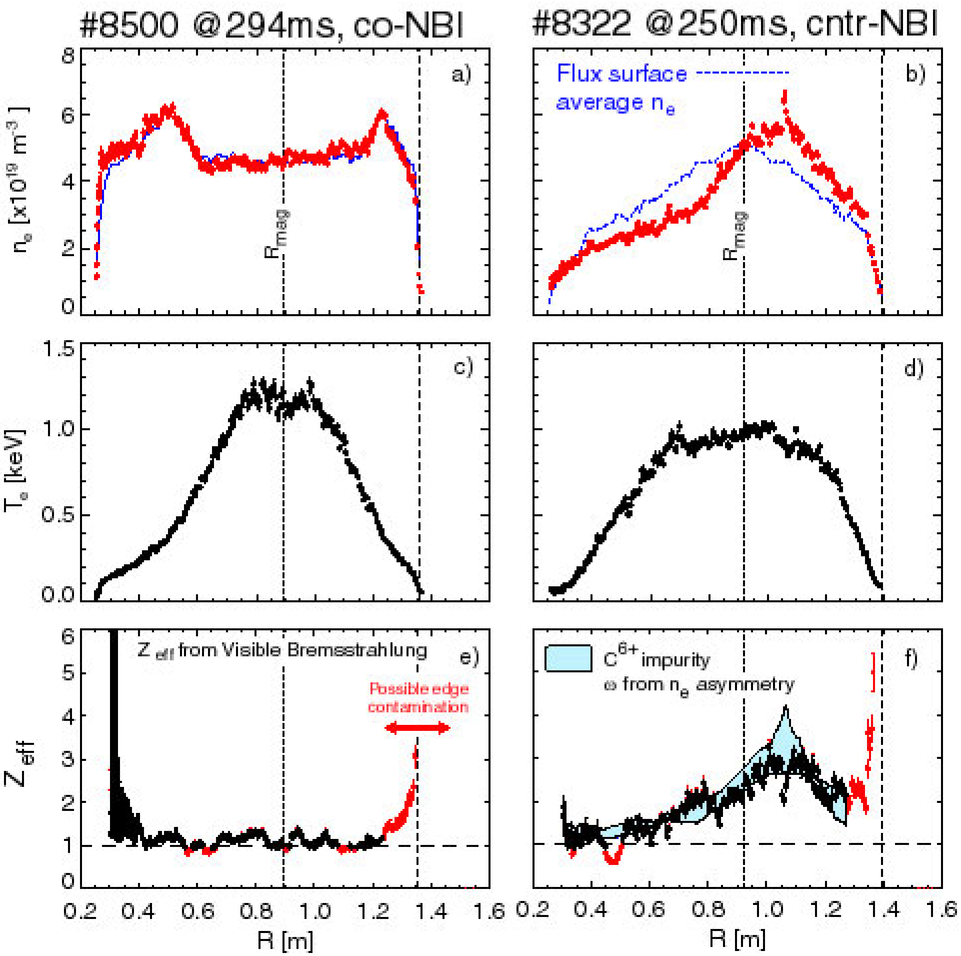
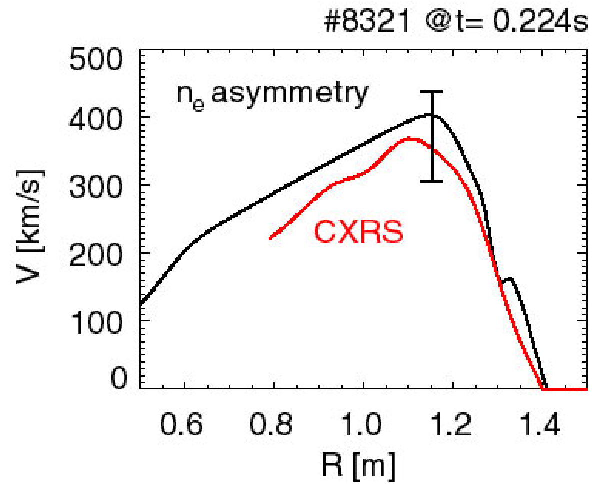
Highest performance is accompanied by supersonic toroidal flow





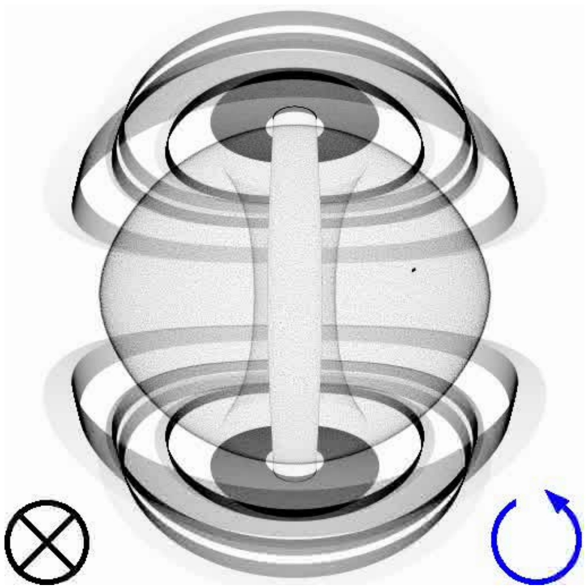
V_{max} ~ 400km/s

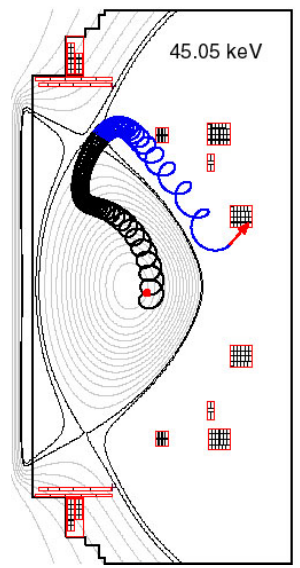
$M_\phi = V_\phi / \sqrt{2T_e/M_D}$ ~1.2

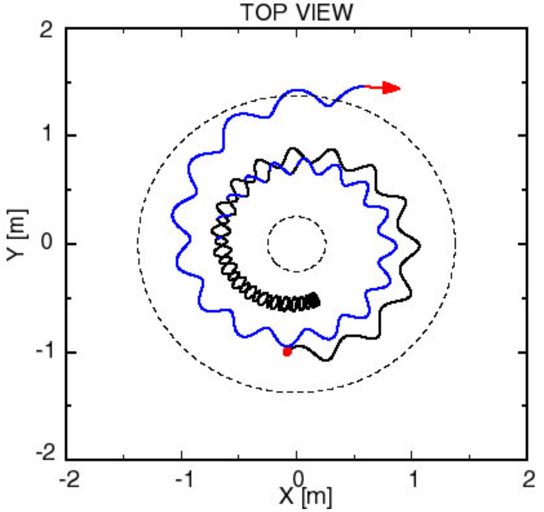
$V_r(0)$~ -12kV

Analysis indicates a ~20-25% uncertainty between the two techniques - treatment of fast ions and inclusion of rotation in EFIT in progress.

P_{abs} is lower, but applied torque is higher with counter- compared with co-NBI.







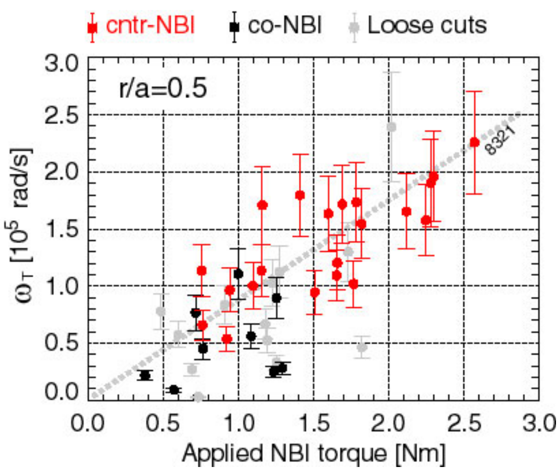
- Some orbits impact the upper div-coil armour (load ~2x10^{19}/s).
- Many fast ions are however free to orbit outside plasma (large outer gap) - reason for low Z_{eff}?
- Losses mainly due to CX on co-leg. (A large JxB torque acts upon the plasma, ~50% higher than without losses).
- Some evidence that momentum transport reduced (as on ASDEX) - χ_ϕ, averaged between r/a= 0.3 and 0.6, drops from around ~0.6-2.0m^2/s to 0.3-1.0m^2/s.

High τ_E is most likely due to flow shear suppression of μ-instabilities.

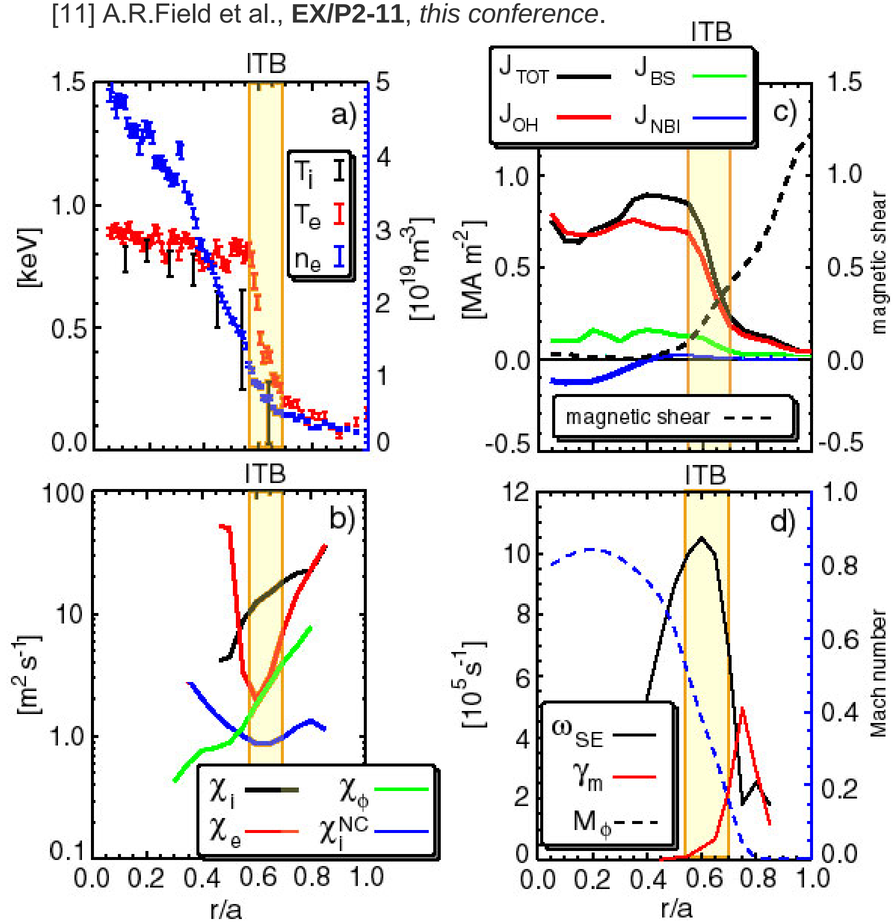
ASDEX [1] → data consistent with η_i mode theory.

JFT-2M → no clear connection with η_i mode theory.

MAST → $\eta_{e/i}$ <1 in the core of counter-NBI heated discharges, however, $\chi_{e/I}(0)\rightarrow\infty$. Also seen in DIIID QDB mode, and on other machines [8,9]. Tearing parity modes?



[11] A.R.Field et al., **EX/P2-11**, *this conference*.



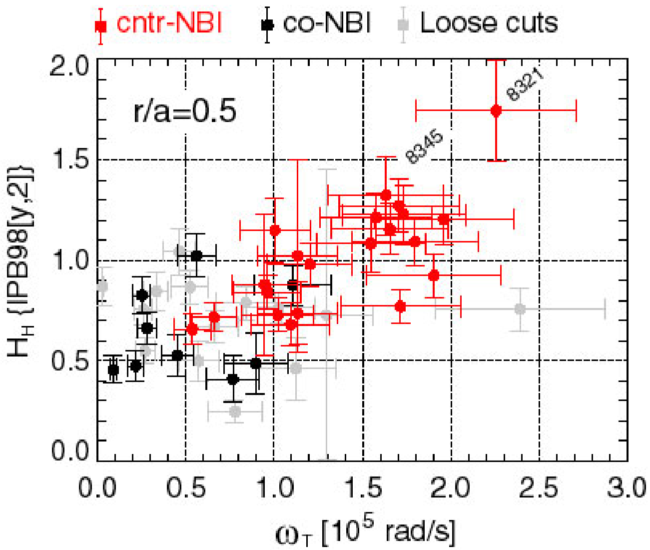
ω_{ExB} is "of order" the ETG growth rate
~10^6s^{-1} (GS2 simulation of #6502).

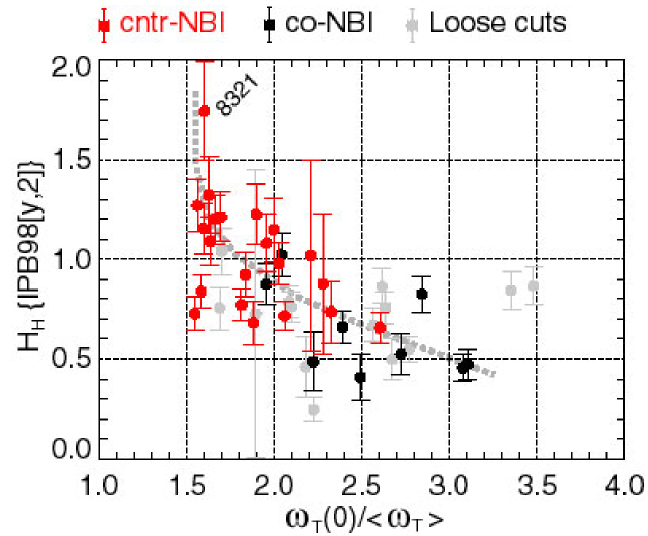
FLOW SHEAR SUPPRESSION OF μ-INSTABILITIES:

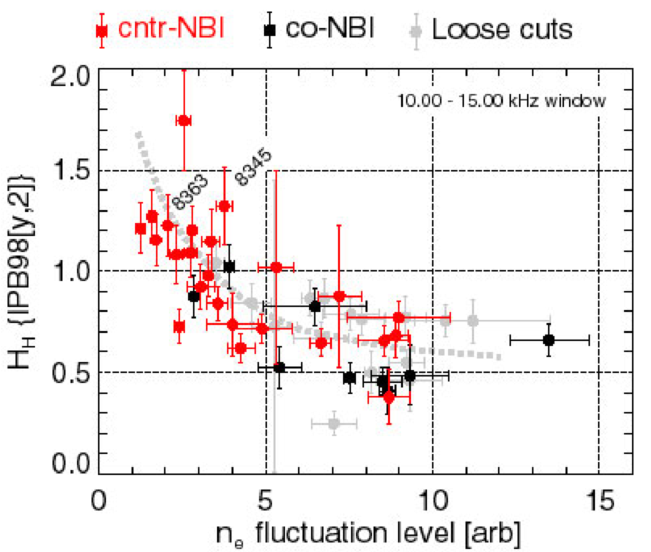
Mechanism proposed by DIIID to explain turbulence suppression in DIIID counter-NBI L-mode [10].

[8] B.W.Stallard et al., Phys. Plasmas **6** 1978 (1998),
[9] M.Zarnstorff, Bull. Am. Phys. Soc. 43, 1635 (1998),
[10] C.L.Rettig et al., Phys. Plasmas **3** 6, 2374 (1996).

Rotation ↑ and profile broadens, n_e fluctuations ↓ and τ_E ↑

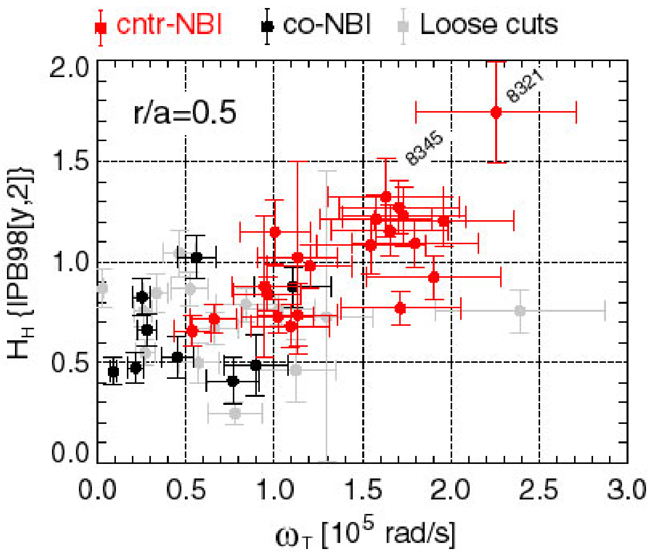


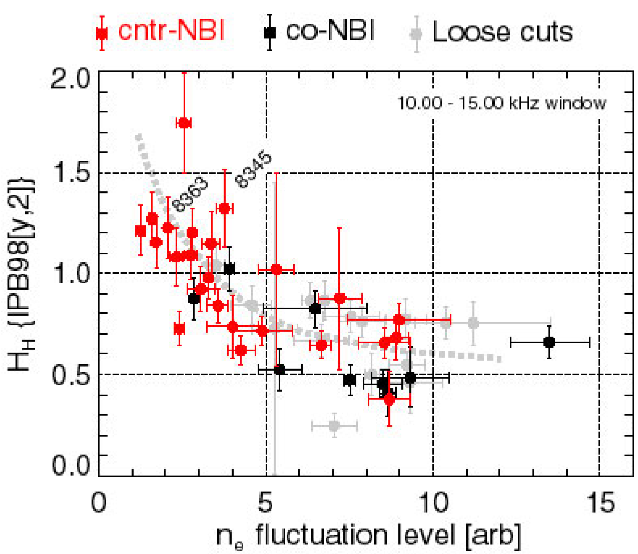


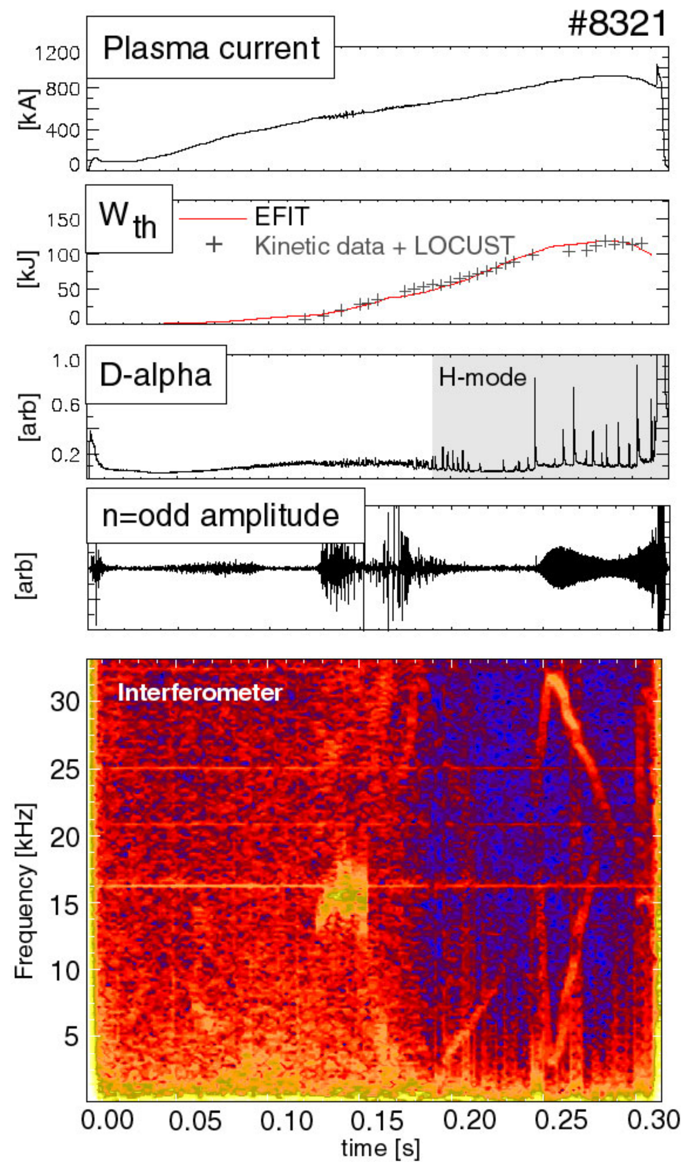


- Confinement increases with ω_T.
- Rotation profile broadens.
- A clear reduction in density fluctuations is seen.

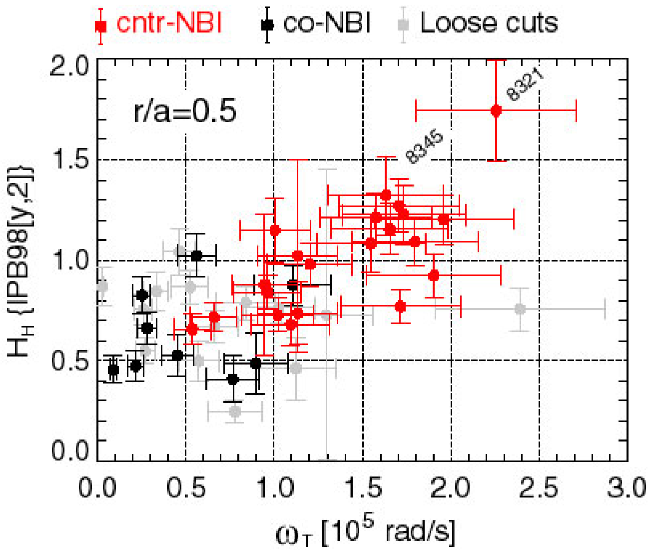
Rotation ↑ and profile broadens, n_e fluctuations ↓ and τ_E ↑

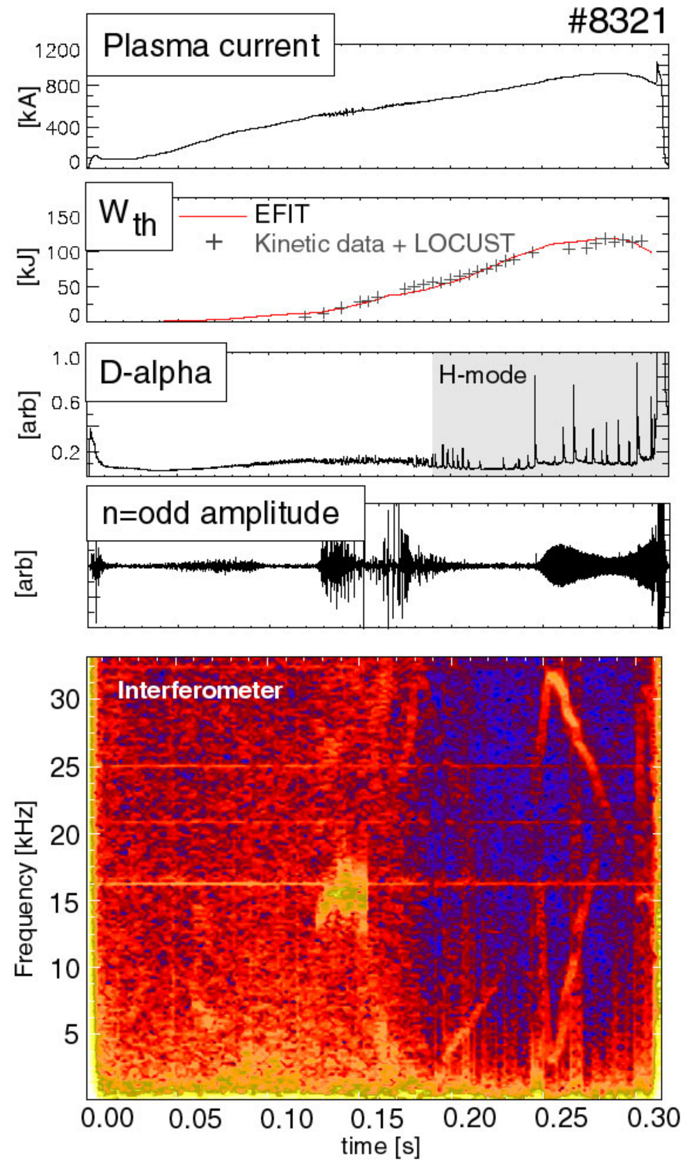






Rotation ↑ and profile broadens, n_e fluctuations ↓ and τ_E ↑





Similar line integrated density fluctuation magnitude to that predicted by the CUTIE 2-fluid electromagnetic turbulence model.

Similar to interferometer results on JET [12].

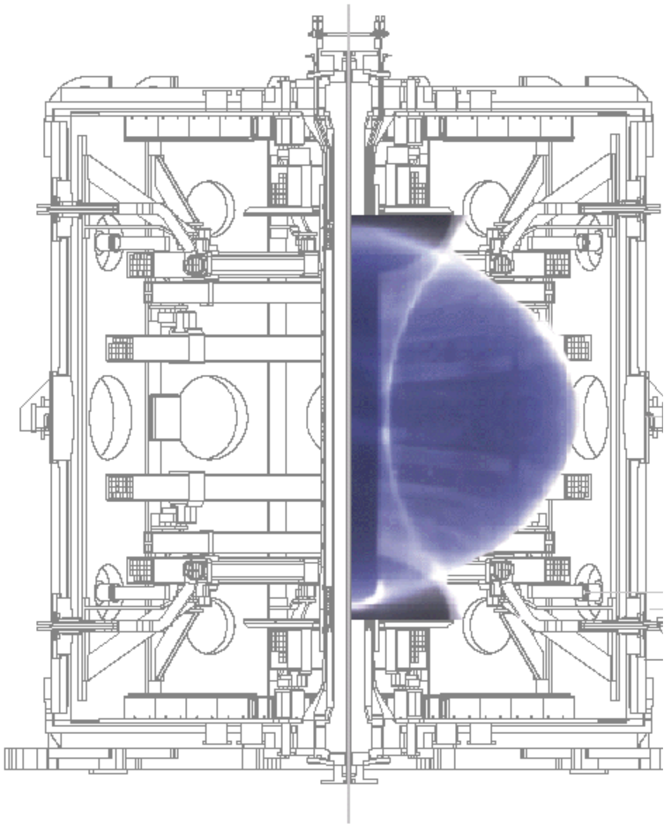
[12] S.Sharapov et al., Phys. Rev. Lett. **93** 16, 165001 (2004).

Summary

1. Counter-NBI heated discharges have been studied for the first time in an ST.
2. τ_E is 2-3 times higher than for co-NBI, τ_E ~150ms, W~120kJ.
4. H-mode is readily accessed (perhaps due to modification of edge E_r).
5. Plasma purity is good, Z_{eff} is peaked (due to peaked n_e) with core Z_{eff} ~2-3.
6. Density profiles are peaked due to neoclassical pinch and T_e profiles are broad.
8. n_e profiles and Z_{eff} profiles are skewed towards low field side consistent with theory.
9. Rotation is high with broad profiles (in some cases exceeding the sound-speed).
10. High performance scales with rotation speed and is accompanied by reduced n_e fluctuations and a broadening of the rotation profile.
11. Although $\eta_{e/i}$ <1 in the core, $\chi_{e/I}(0)\rightarrow\infty$. All the confinement is at r/a>0.5.
12. Transport analysis of an “extreme” counter-NBI discharge (#8302): ExB shearing rate exceeds ITG growth rate, of order ETG growth rate from linear GS2 calculations.
13. Further experiments, transport and μ-stability work planned to assess whether flow shear stabilisation is responsible for high confinement, broad T_e profiles etc.
14. Outcome of this work (including all code, theory and diagnostic modifications needed to deal with supersonic rotation) will have important impact upon CTF design (~50-60MW NBI into a MAST sized plasma [13]).

[13] H.R.Wilson, **FT/3-1RA**, *this conference*, 14:30 Friday.

MAST - the Mega Amp Spherical Tokamak



			Design	Achieved
Minor and Major radii	a, R	[m]	0.65, 0.85	0.65, 0.85
Elongation	κ		≥ 2	2.45
Aspect ratio	A		≥ 1.3	1.3
Plasma current	I_P	[MA]	2	1.35
Toroidal field	$B_\phi @R$	[T]	0.52	0.52
Aux. Heating				
NBI power	P_{NBI}	[MW]	5	3.3
ECRH power	P_{ECH}	[MW]	1.4	0.9
Pulse length	t_P	[S]	5	0.7