Status of RFP confinement for 2 different development paths.

Standard RFP Path:

- **Steady-induction and magnetic relaxation from tearing instability**
  - Stochastic magnetic transport dominant
  - Existing $a \sim 0.5$ m devices:

    $\tau_E \sim 1$ ms , $\beta \sim 10\%$, $T_e < 1$ keV

J(r)-Control Path:

- **Current drive for tearing stability and minimized magnetic relaxation**
  - Magnetic fluctuations reduced
  - Improved confinement & beta:

    $\tau_E \sim 10$ ms — *ten-fold increase!*

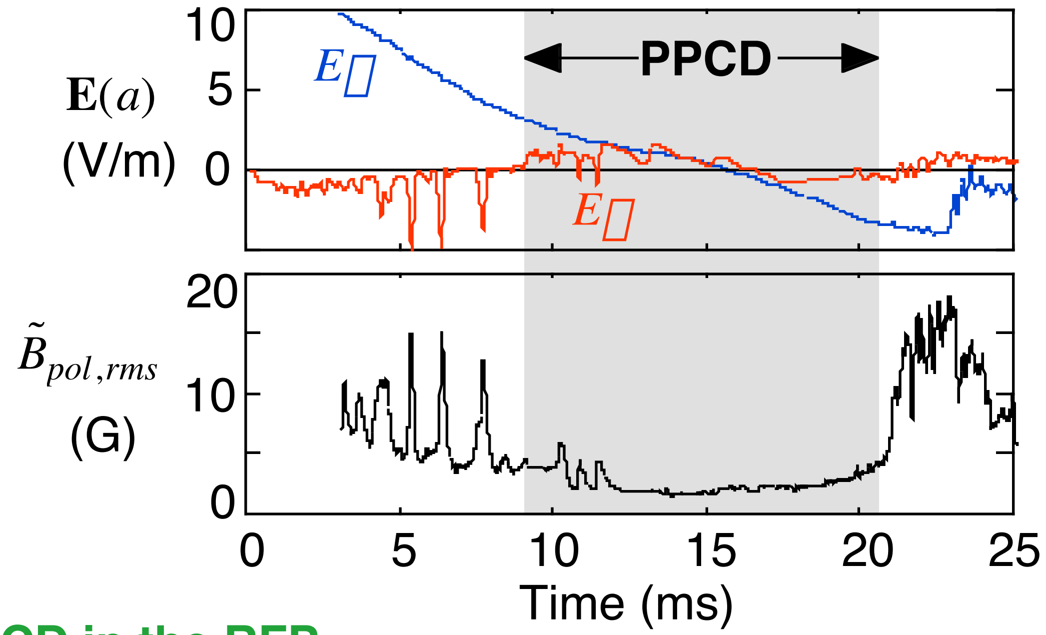
    $\beta \sim 15\%$ — *roughly doubled!*

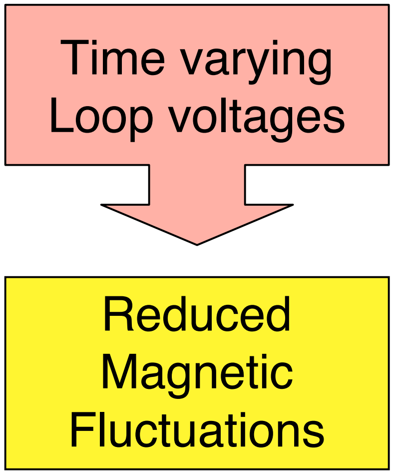
    $T_e = 1.3$ keV max. — *roughly tripled!*
  - Fast electrons confined $\Rightarrow$ closed magnetic surfaces
  - $\chi_e \sim 5$ m^2/s

Tokamak-like confinement at high beta and low $\boldsymbol{B}(a)$ achieved in MST

Programmed inductive loop voltages provide current drive targeted to edge region.

“PPCD” – Pulsed Poloidal (or Parallel) Current Drive





Time varying Loop voltages

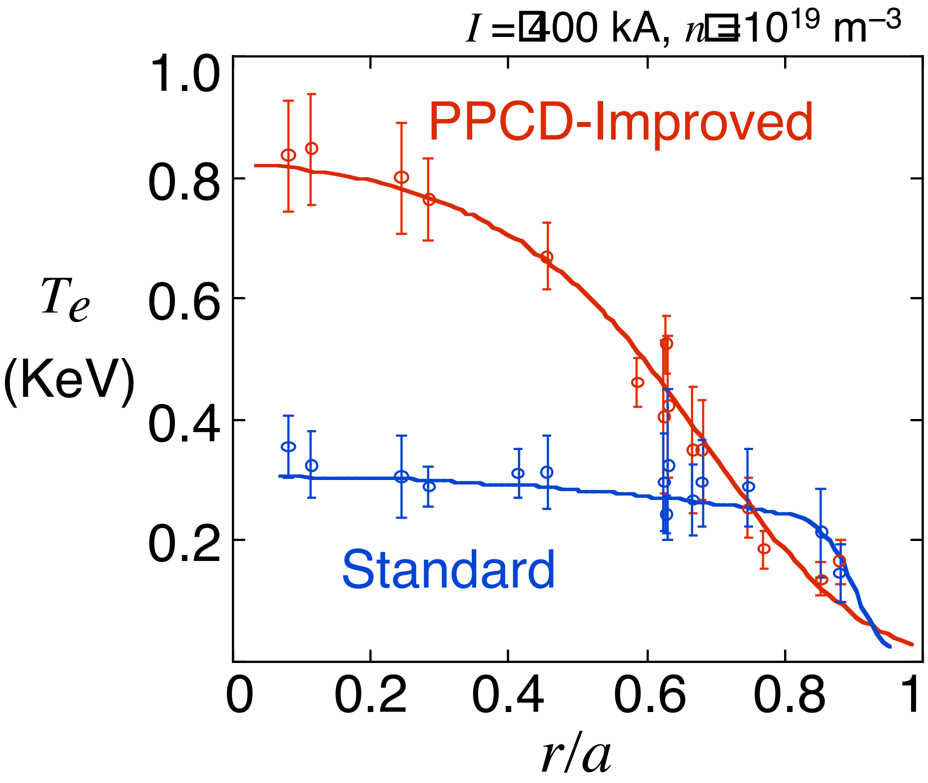
Reduced Magnetic Fluctuations

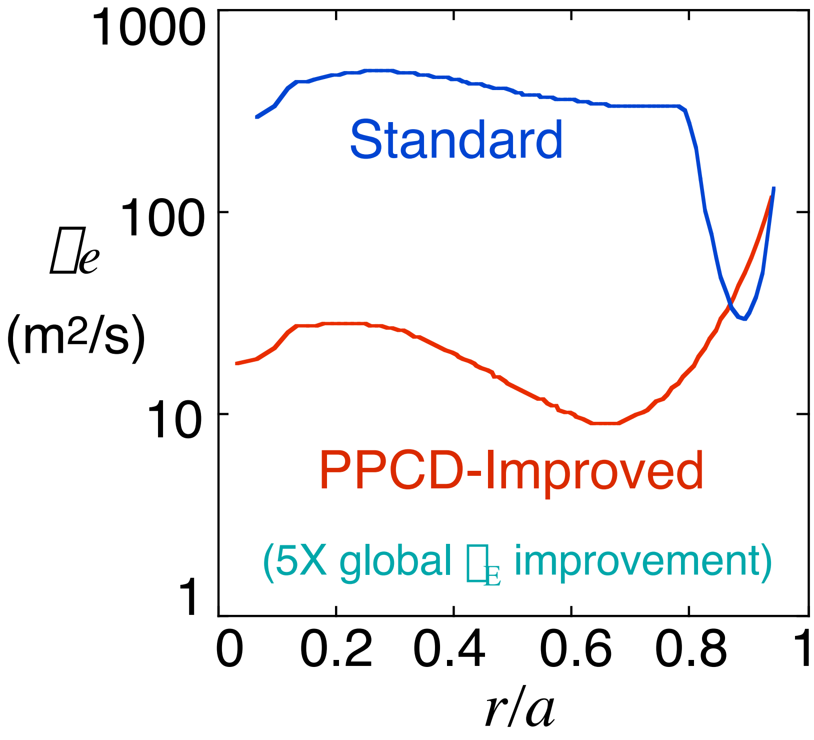
PPCD in the RFP:

J. Drake (Extrap T2R)—EX/P2-02
M. Puiatti (RFX)—EX/P5-05
H. Sakakita (TPE-RX)—EX/P2-07
D. Brower (MST)—EX/C4-6

Temperature profile peaks, χ_e greatly reduced.

- Electrons are hotter with **reduced** Ohmic heating.
- Gradient extends into the core.





MST maximum $T_e(0)$ = 1.3 keV
for I = 500 kA PPCD

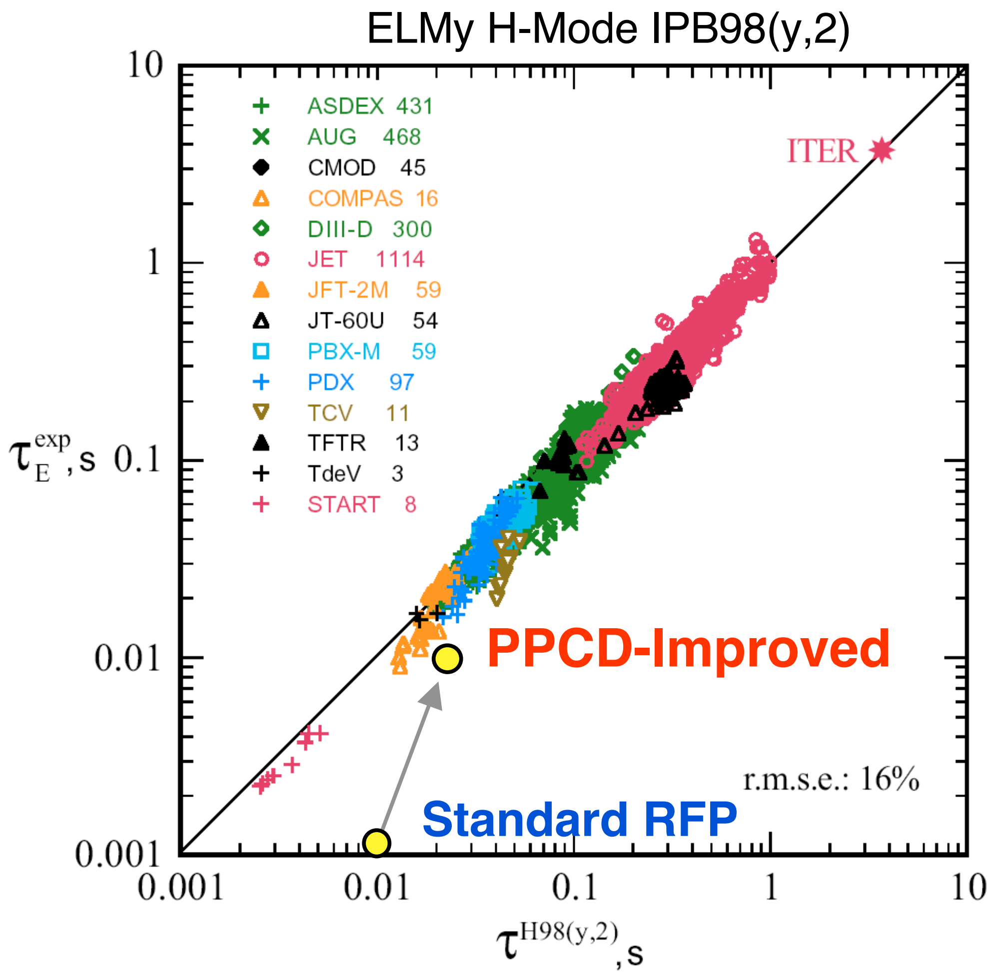
PPCD confinement comparable to same-current tokamak, but with 10X smaller $B(a)$ in the RFP.

- Compare $\tau_E \approx$ 10 ms for 200 kA PPCD with tokamak τ_E empirical scaling:
  - use "engineering" formulas with MST's I, n, P, size & shape,
    but tokamak $B_T(a)$ = 1.0 T (corresponding to $q_a = 4$).

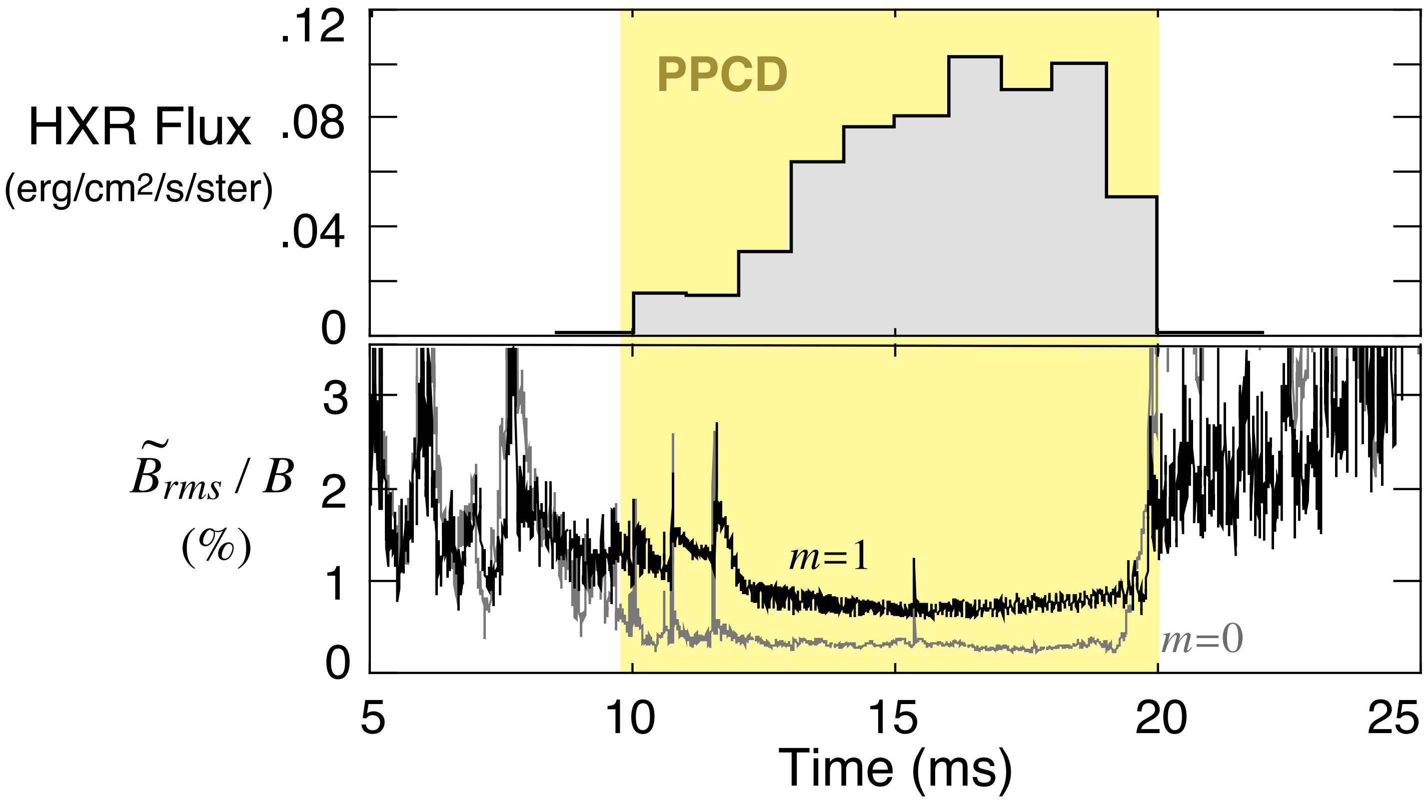
τ_E = 23 ms (ELMy H-mode)
= 18 ms (L-mode)
= 31 ms (Neo-Alcator Ohmic)

Same-current RFP:
- **$B_T(a)$ = 0.04 T → 20X smaller**
- **$B(a)$ = 0.09 T → 10X smaller**

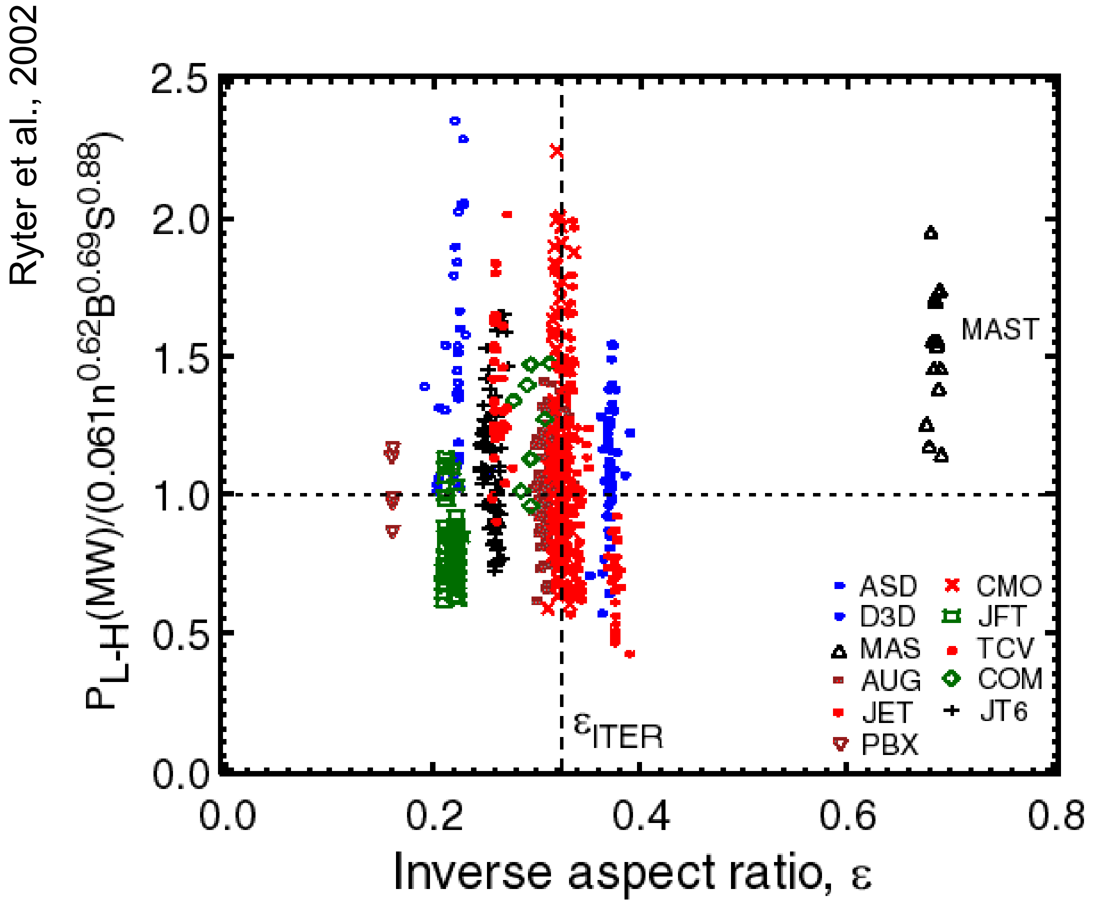
Comparable τ_E does not imply tokamak empirical scaling applies to the RFP.


ELMy H-Mode IPB98(y,2)

100-fold increase in hard x-ray bremmstrahlung evidences confined fast electrons during PPCD.



H-mode Threshold Scaling



MAST data significantly extends range of ε in ITPA database

MAST data clearly favours scaling of the form $P_{L-H} \sim S$, rather than $P_{L-H} \sim R^2$

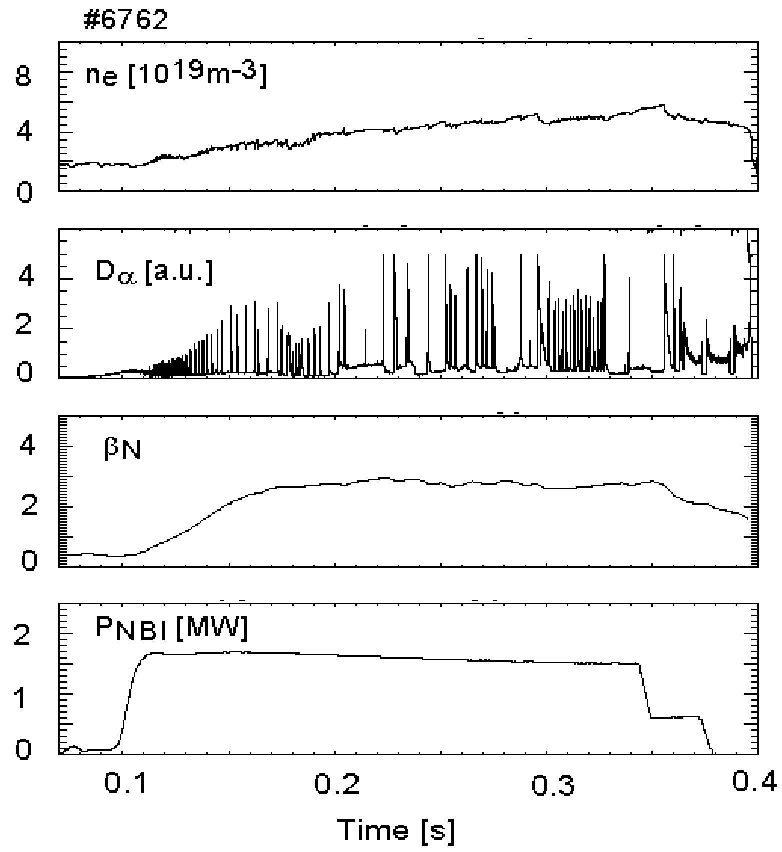
Enhanced threshold power in MAST would imply $P_{L-H} \sim \varepsilon^{0.5}$ if not due to other factors (e.g. differences in divertor geometry)

Detailed analysis requires a regression on the whole database [Snipes et al. Fri a.m. CT/P-04]

UKAEA Fusion Working with Europe

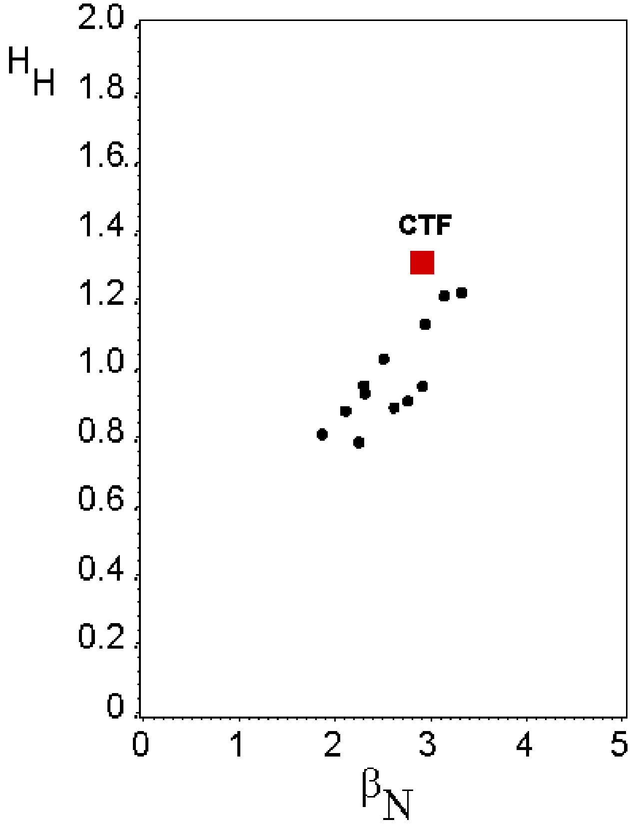
Quasi-stationary H-modes with $\tau_E \sim \tau_E^{IPB98(y,2)}$

β_N ~3, H_H ~ 1, n_e/n_{Gr} ~ 0.5 sustained for ~200ms (~ $4\tau_E$)



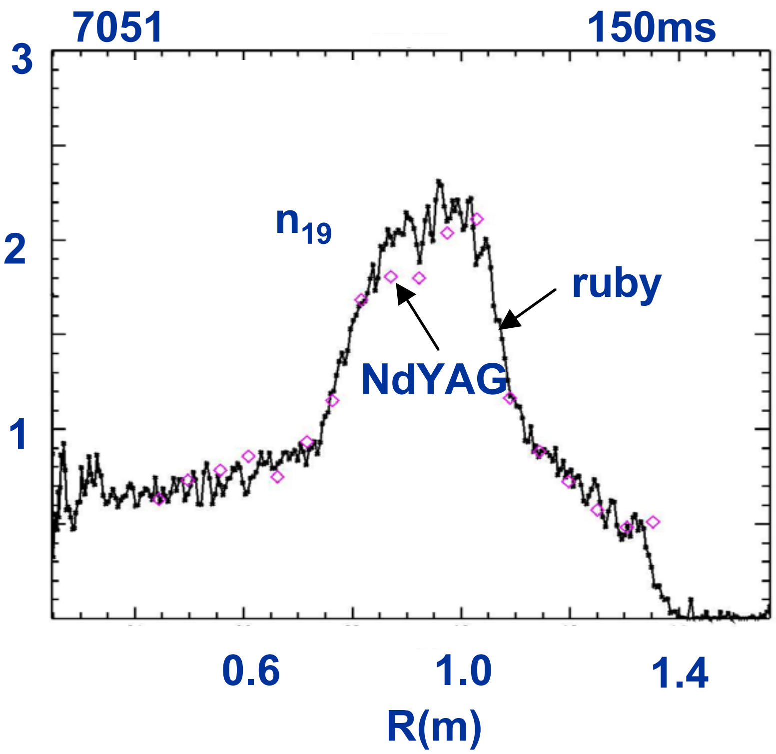
$W_{kin} \sim W_{mag}$; $W_{fast} \sim 10\%$

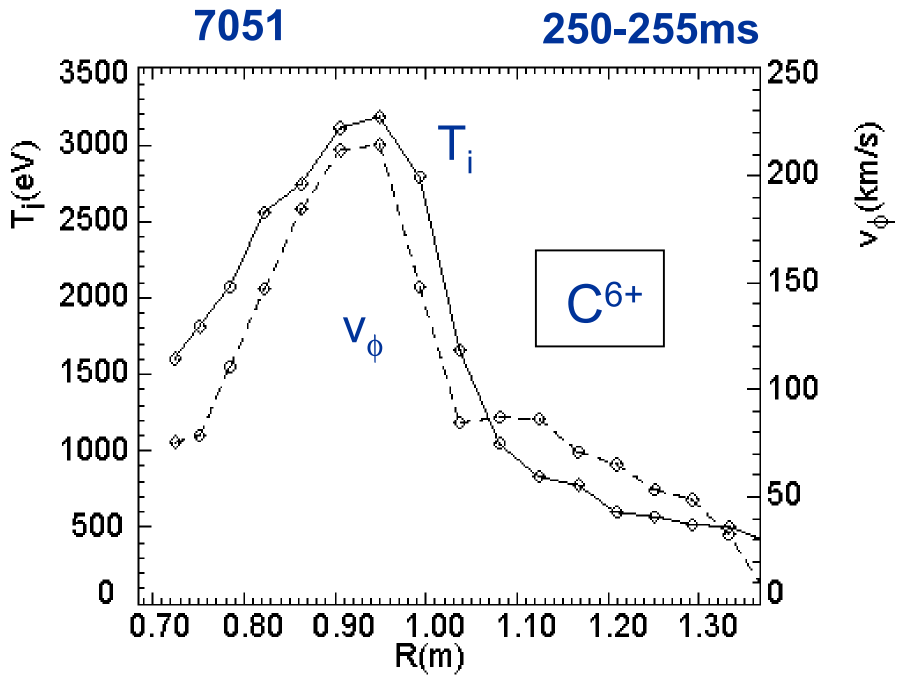
Normalised parameters achieved comparable with requirements of a Component Test Facility (CTF) based on ST volume neutron source



Internal Transport Barriers

Strong indications of ITBs in MAST





Early NBI (~2MW) to inhibit current penetration ⇒ weak central shear (EFIT)

Modest density ($\bar{n}_e \sim 1 - 3 \times 10^{19} m^{-3}$) for good beam penetration and high momentum input per particle to maximise flow shear

SIMULATIONS AND FLUCTUATION DIAGNOSTICS ALLOW FOR QUANTITATIVE COMPARISONS OF TURBULENCE CHARACTERISTICS

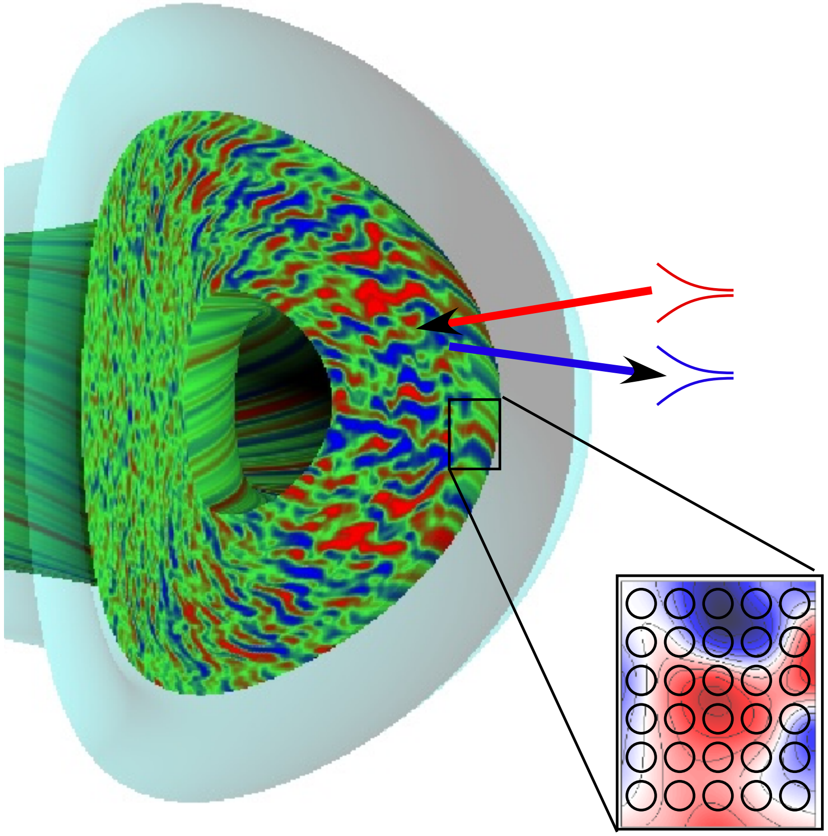
Simulation Codes

GRYFFIN-Flux-tube
gyrofluid

UCAN-3D Global
Gyrokinetic,
Particle-In-Cell,
electrostatic

GYRO-3D Global,
Gyrokinetic
Eulerian,
electromagnetic,
shaped plasmas,
rotation

BOUT-3D Braginskii
simulation
(edge/SOL)



[picture from GYRO,
courtesy J. Candy]

Diagnostics

Correlation Reflectometer

- $L_{c,r}$, $S(k_\theta)$
- High sensitivity

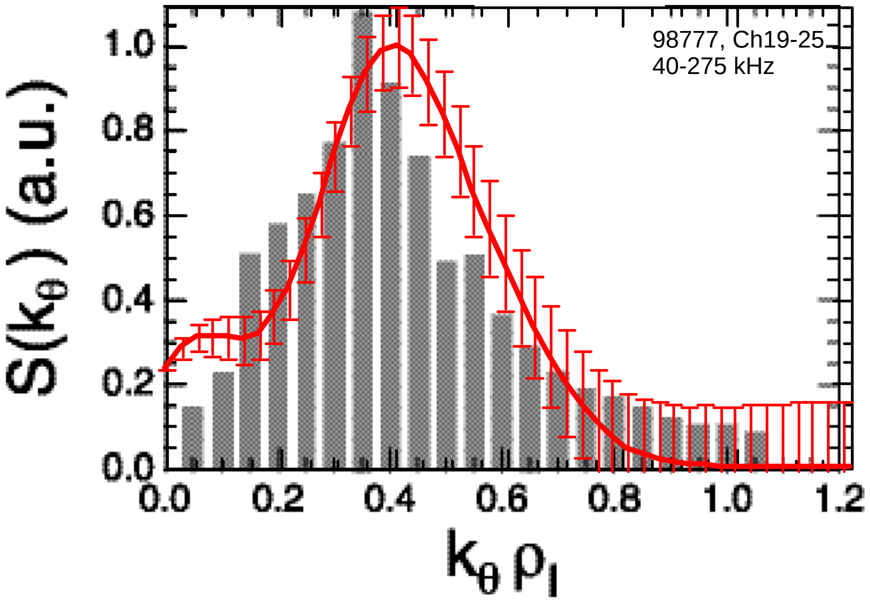
Beam Emission Spectroscopy

- $\tilde{n}/n$
- $L_{c,r}$, $L_{c,\theta}$, τ_c
- 2D, flows

SIMULATION AND MEASURED WAVENUMBER SPECTRA COMPARE WELL

Local density fluctuation poloidal wavenumber spectrum (from BES) from a DIII-D discharge is compared to GRYFFIN calculation (r/a = 0.7)

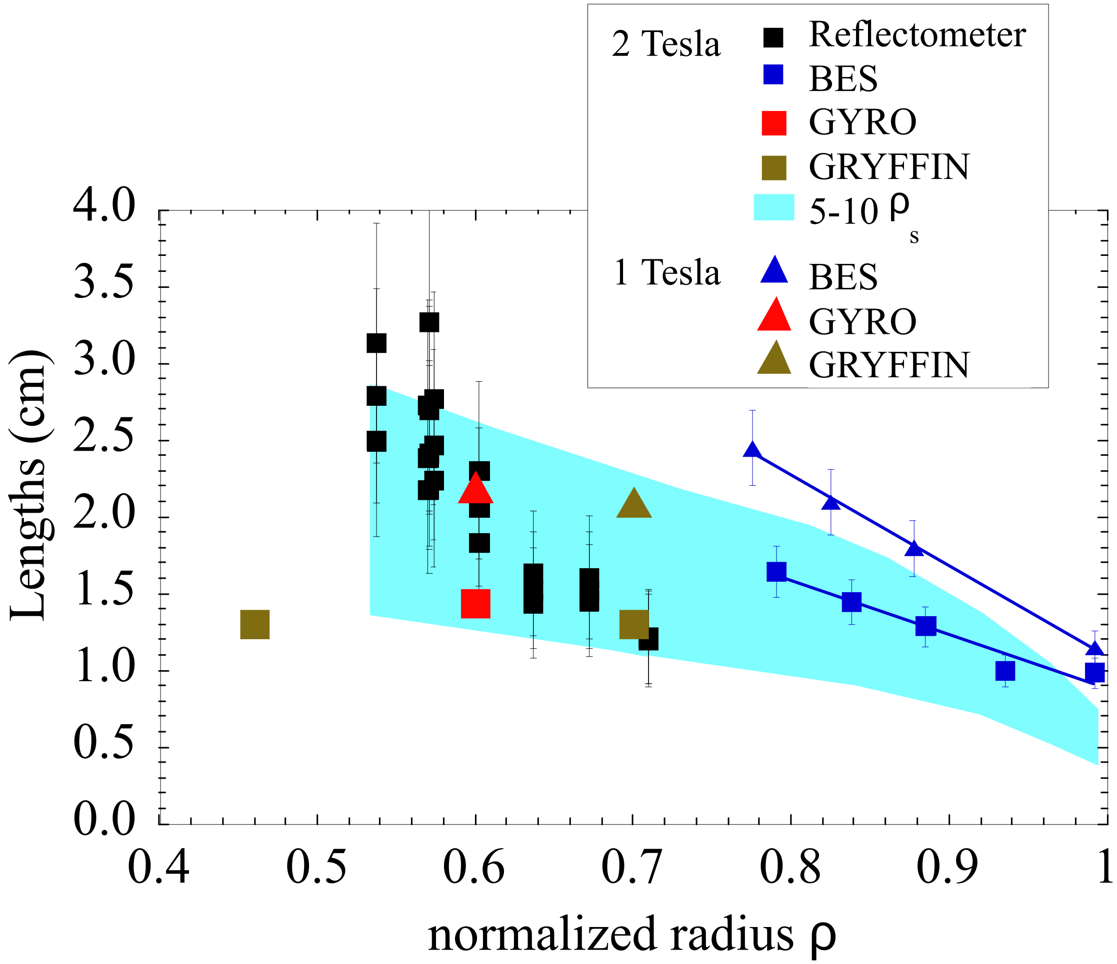
Overlayed BES & GRYFFIN $S(k_\theta)$ Spectra



(Amplitude is normalized)

- Spectral shape, peak wavenumber and width agree
  - Calculated flux and amplitude ($\tilde{n}/n$) agree within a factor of 2
  - GRYFFIN does not include profile effects

RADIAL CORRELATION LENGTHS FROM BES AND CORRELATION REFLECTOMETER COMPARE WELL WITH SIMULATIONS



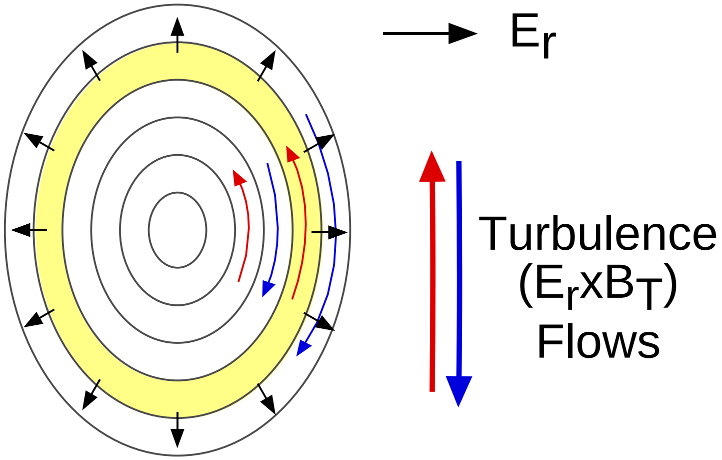
- Reflectometer and BES data close given different radial positions
    - follow 5-10 ρ_s scaling
- GYRO & GRYFFIN

  predictions for 1 and 2 T are consistent with ρ* scaling of Δr
- Magnitude of GYRO within uncertainty of measurements

- Quantitative agreement within uncertainties crucial to validation

SELF-REGULATING ZONAL FLOWS THOUGHT CRUCIAL TO MEDIATING FULLY SATURATED STATE

- Predicted theoretically to regulate turbulence through time-varying $E_r x B_T$ flows
  - observed in simulations
- Axisymmetric (n=0, m=0), radially-localized electrostatic potential structures. Zonal flows have two dominant branches:
  - Low-frequency residual (Rosenbluth-Hinton) mode (f < 10 kHz)
  - Higher-frequency Geodesic Acoustic Mode (10-200 kHz)



(poloidal cross-section)

Suggests looking directly at the time-dependent turbulence flow field to discern experimental evidence for zonal flows.

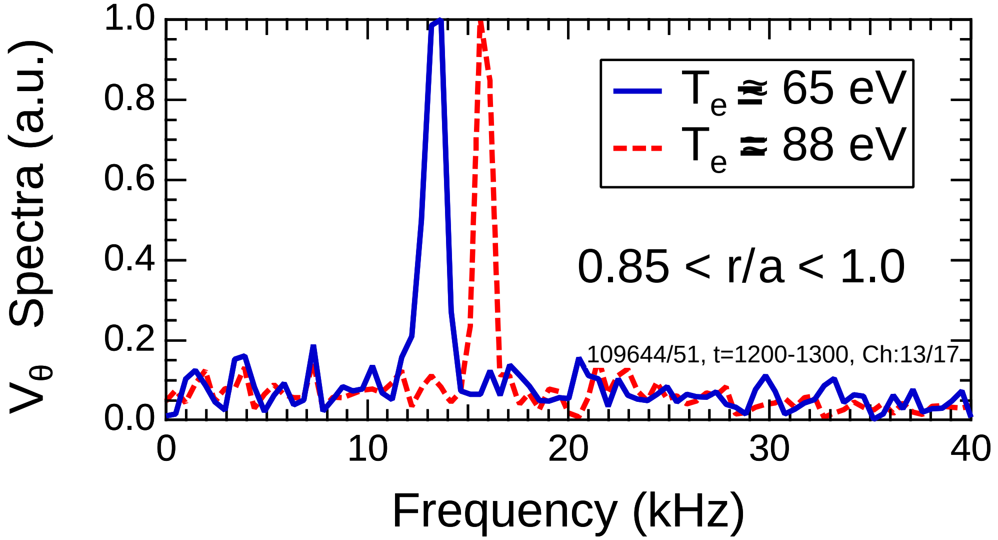
- Time-delay estimation (TDE) analysis applied to turbulence imaging with BES

Direct measurement of of Turbulence Flow Field: $v_\theta(r ,Z ,t)$

COHERENT V_θ FEATURE OBSERVED:

EXHIBITS POLOIDALLY EXTENDED, RADIALLY LOCALIZED STRUCTURE

- Semi-coherent feature near 15 kHz on broadband weak velocity turbulence

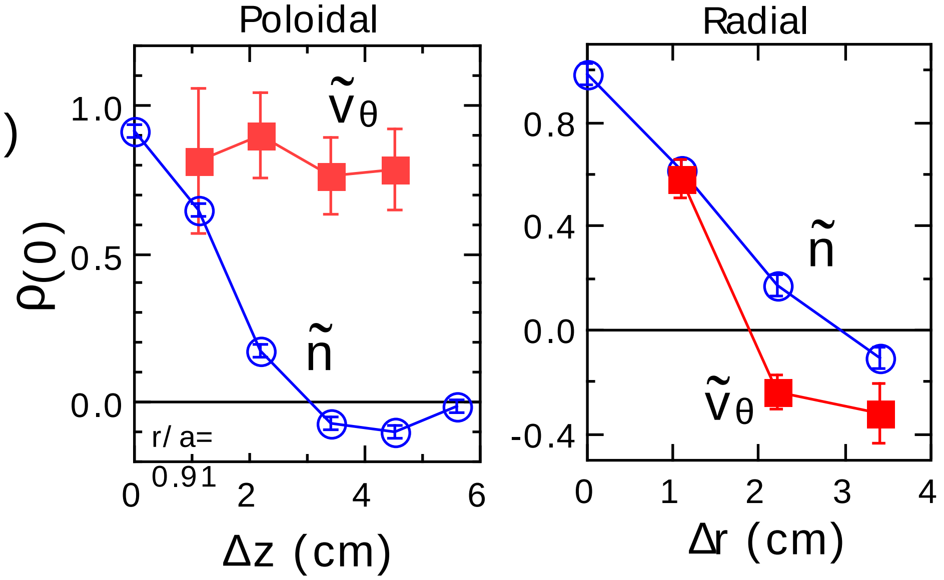


- Mode frequency increases with edge T_e:

  - suggests oscillation is a Geodesic Acoustic Mode: $f = c_s/2\pi R = 12$ kHz

- Poloidally extended structure (low-m)
- Radially narrow ($\sim\Delta r_n$)
- Amplitude sufficient to affect turbulence: $\omega_s < 1/\tau_c$

  (Not associated with MHD)

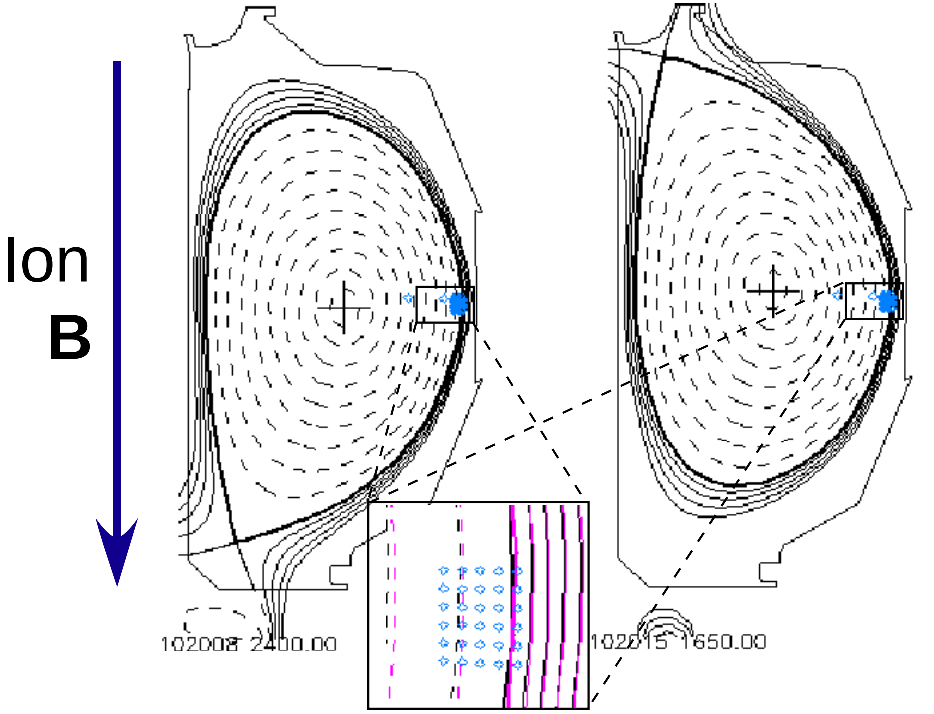


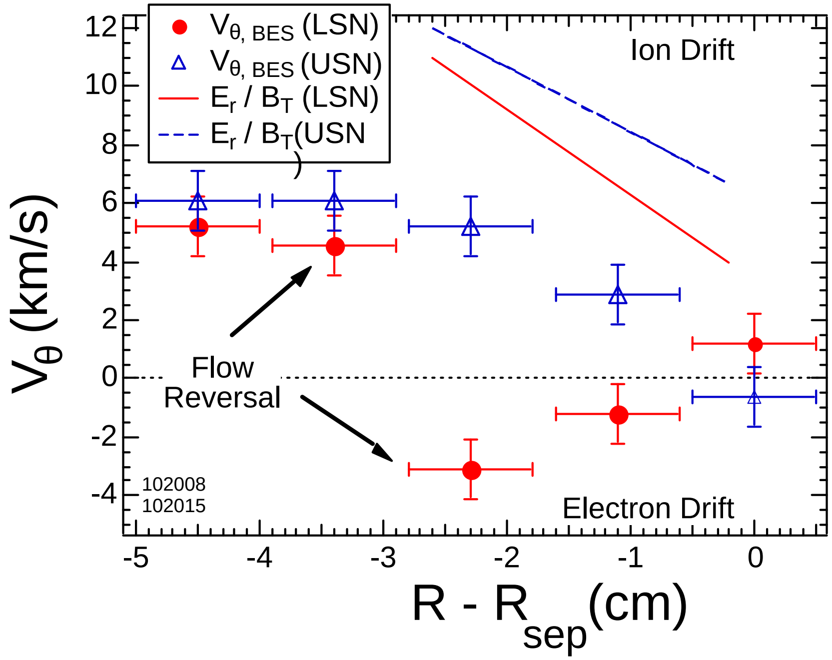
ION B DRIFT DIRECTION STRONGLY AFFECTS L-MODE TO H-MODE POWER THRESHOLD: TURBULENCE SHEAR VARIES DRAMATICALLY

Ion B towards
dominant X-point:
(lower single null):

Ion B away from
dominant X-point:
(upper single null)

v_θ Profile compared
with $E_r x B_T$





*P_{LH}(LSN) ~ 1/3 * P_{LH}(USN)*

- Most edge profiles are similar (n_e, T_e, T_I)

- Measured turbulence poloidal flow exhibits sharp flow reversal in LSN
- $\omega_s > 1/\tau_c$: Natural shear *may* facilitate LH transition