RFP Performance Enhancement Through MHD Mode Control

John Sarff & MST Team

THE UNIVERSITY of WISCONSIN MADISON

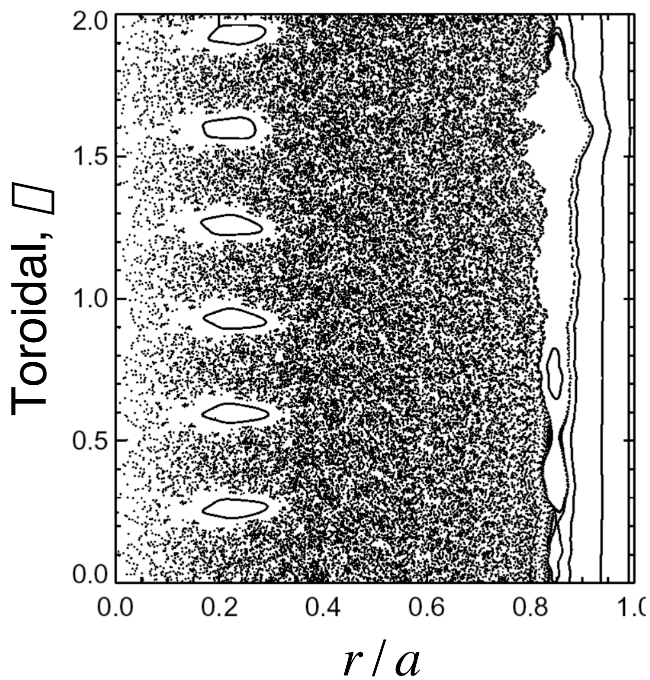
MHD Mode Control Workshop — Columbia University

November 18-20, 2002

Standard RFP confinement is limited by MHD tearing.

- Steady toroidal induction in low BT geometry drives current profile peaking:
  - m = 1,0 resistive MHD tearing unstable
  - Instability saturates by $J(r)$ self-flattening through dynamo relaxation

- Performance characteristically high beta □ < 20%, but relatively poor confinement □ > 50 m^2/s.



multiple tearing modes

□

global stochasticity

Two paths to improved RFP confinement.

- **Optimized magnetic relaxation:**
  a) Induce and control “single-helicity” dynamo (*P. Martin’s talk*)
  b) Possible favorable Lundquist number scaling for “multiple-helicity” relaxation (all tearing modes decrease together at higher temperature)

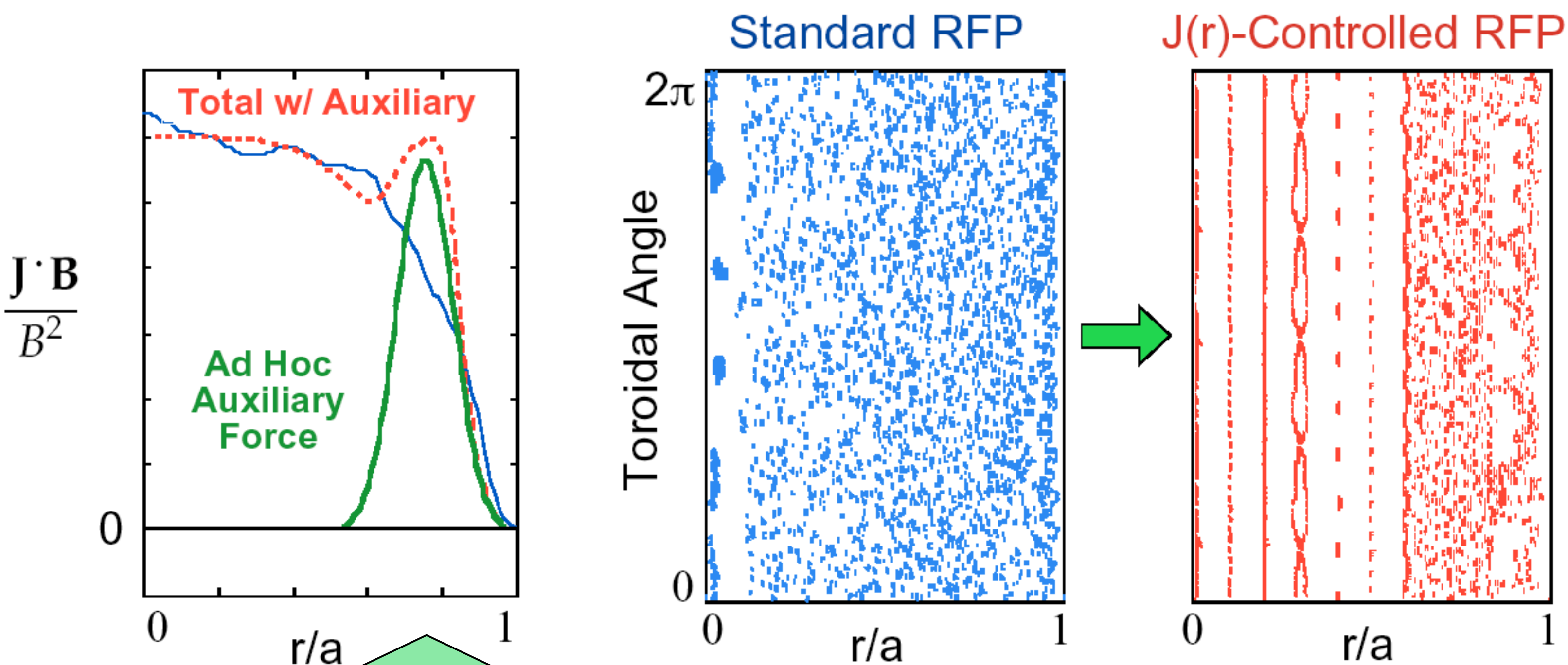
- **Current profile control for tearing stability:** (***this talk***)
  – Minimize magnetic relaxation
  – All tearing modes vanish (in principle)

Goal for both paths is reduced magnetic stochasticity.

Outline.

- MHD foundation for an RFP without dynamo
- Improved confinement in MST:
  - $J(r)$ modification via inductive current drive
  - Tokamak-like confinement at high beta, low BT in MST
- Broadband mode reduction key to reduced transport in the RFP
- Control tools in development:
  - RF current drive (& heating)
  - Neutral beam heating

MHD computation predicts current drive in outer region reduces tearing and magnetic stochasticity.



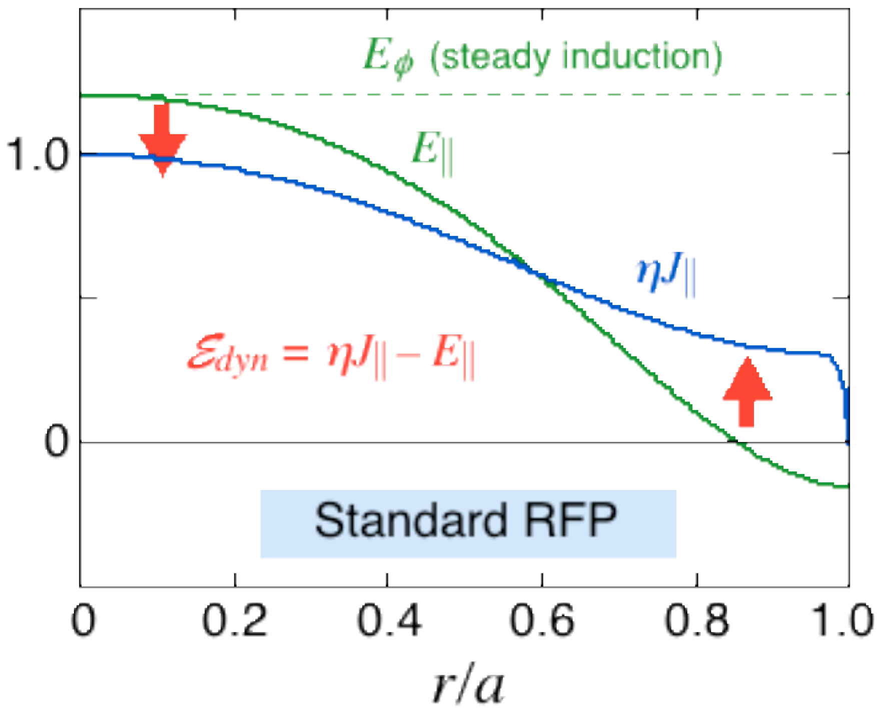
Add current drive in outer region (mostly poloidal)

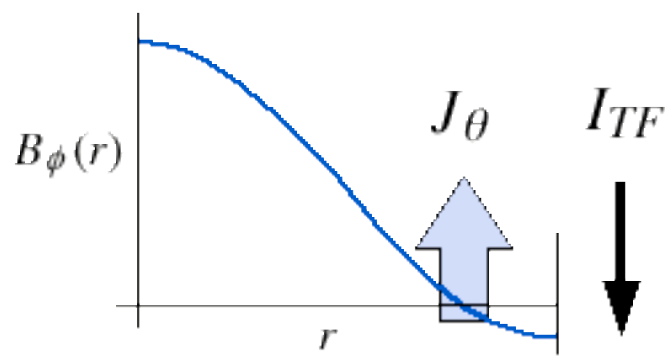
leads to …

Reduced MHD tearing

Steady toroidal induction E_ϕ cannot support outer-region $J_\parallel$.

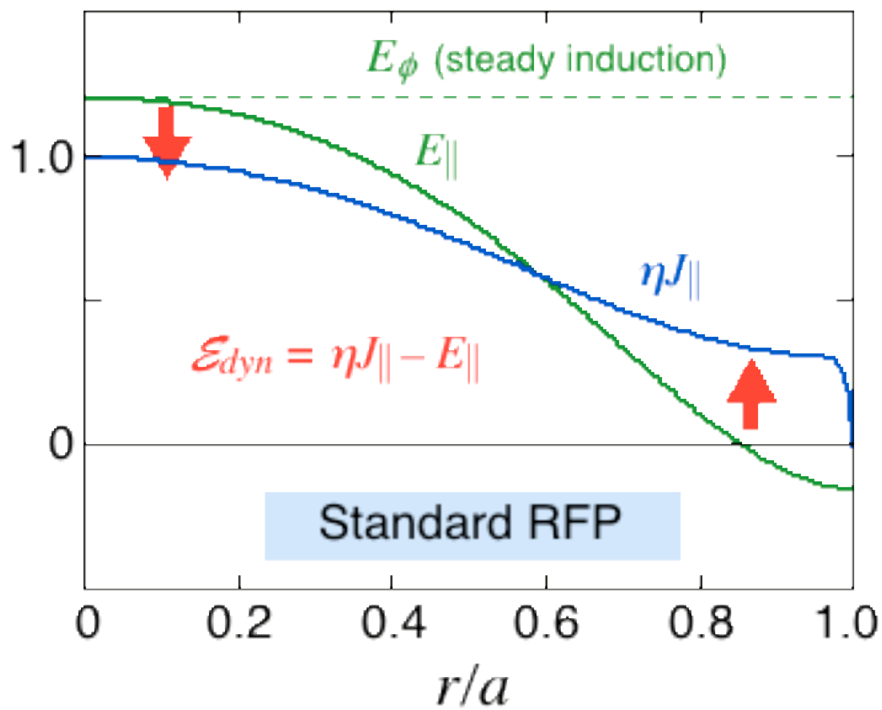
- Standard RFP requires dynamo current drive .

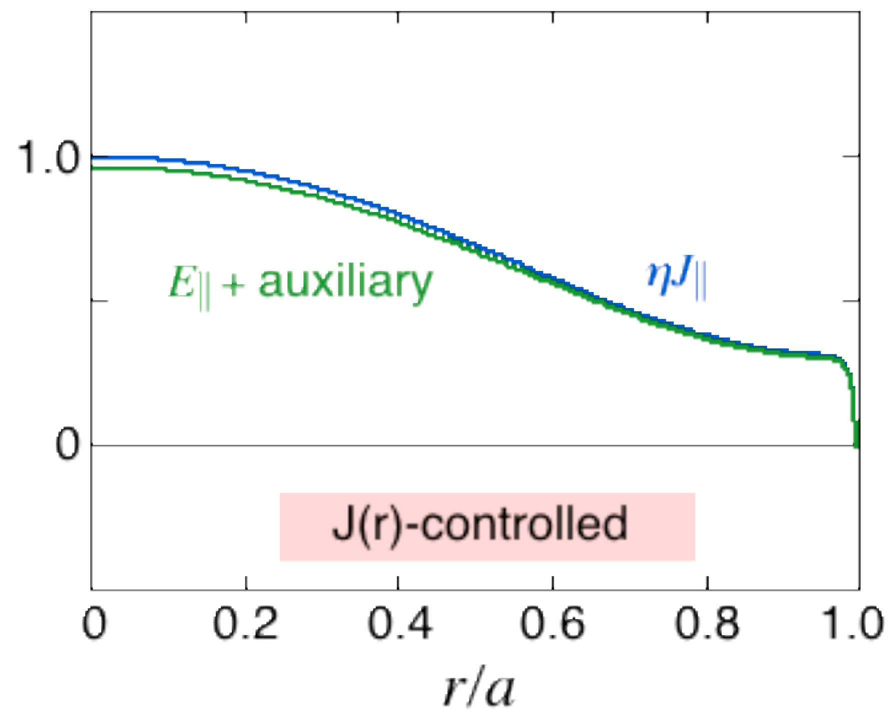




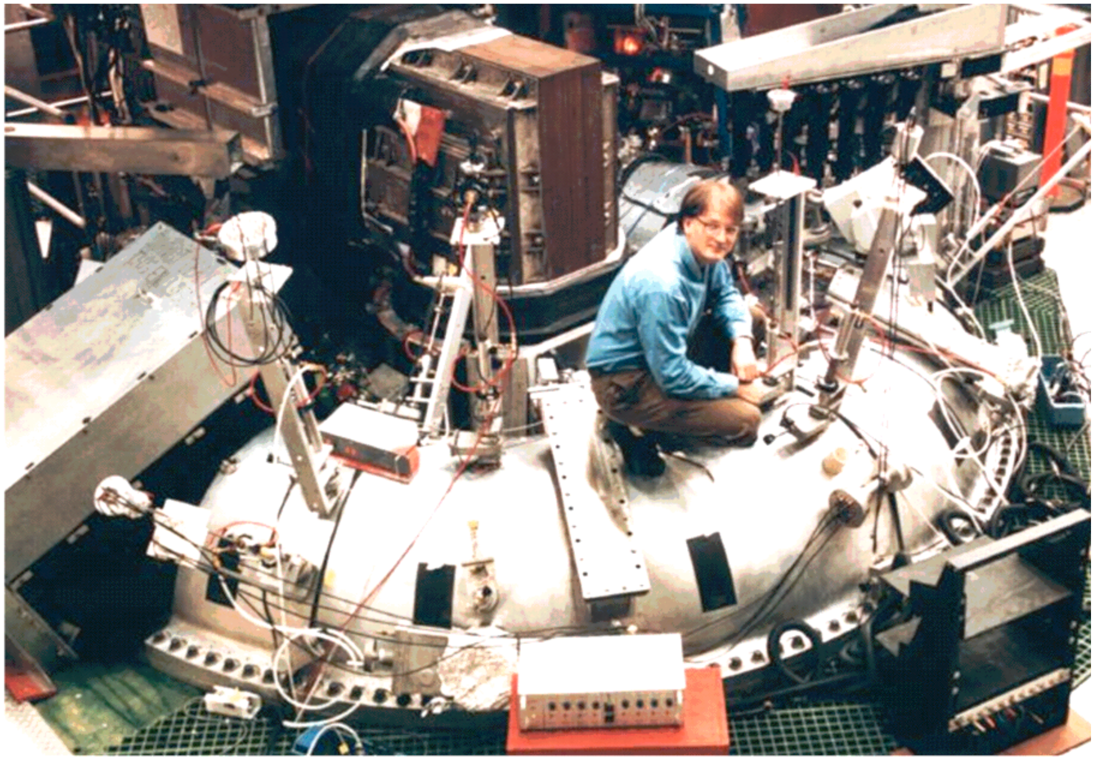
Auxiliary current drive replaces dynamo sustainment of the required poloidal current.

- Current drive "aligned" to current profile.

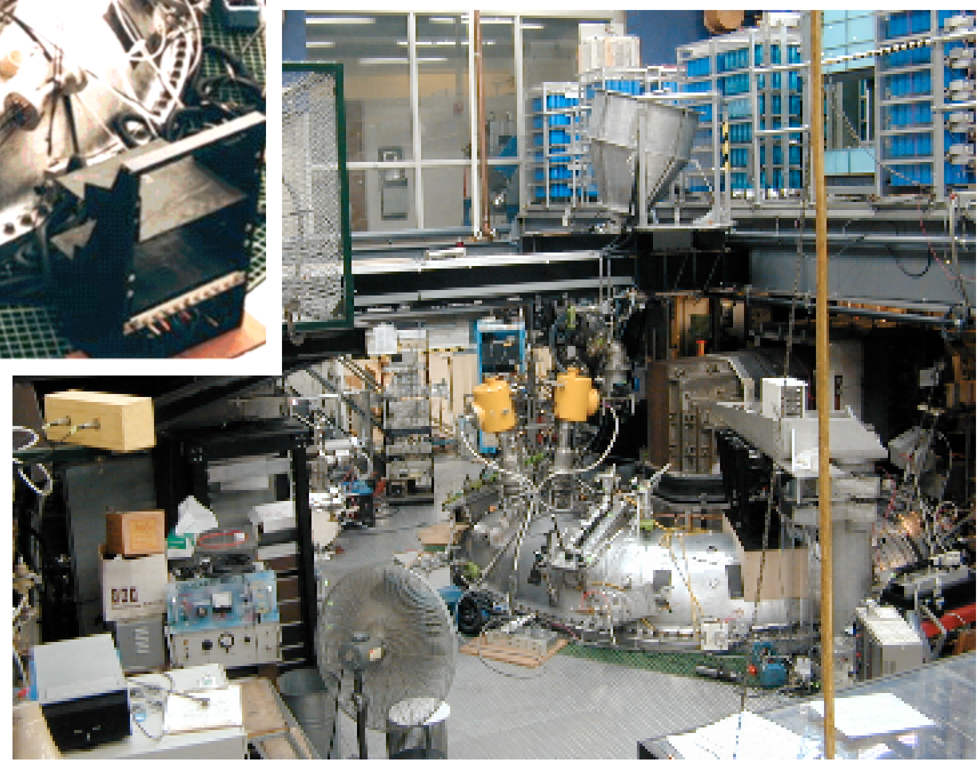




Madison Symmetric Torus (MST)



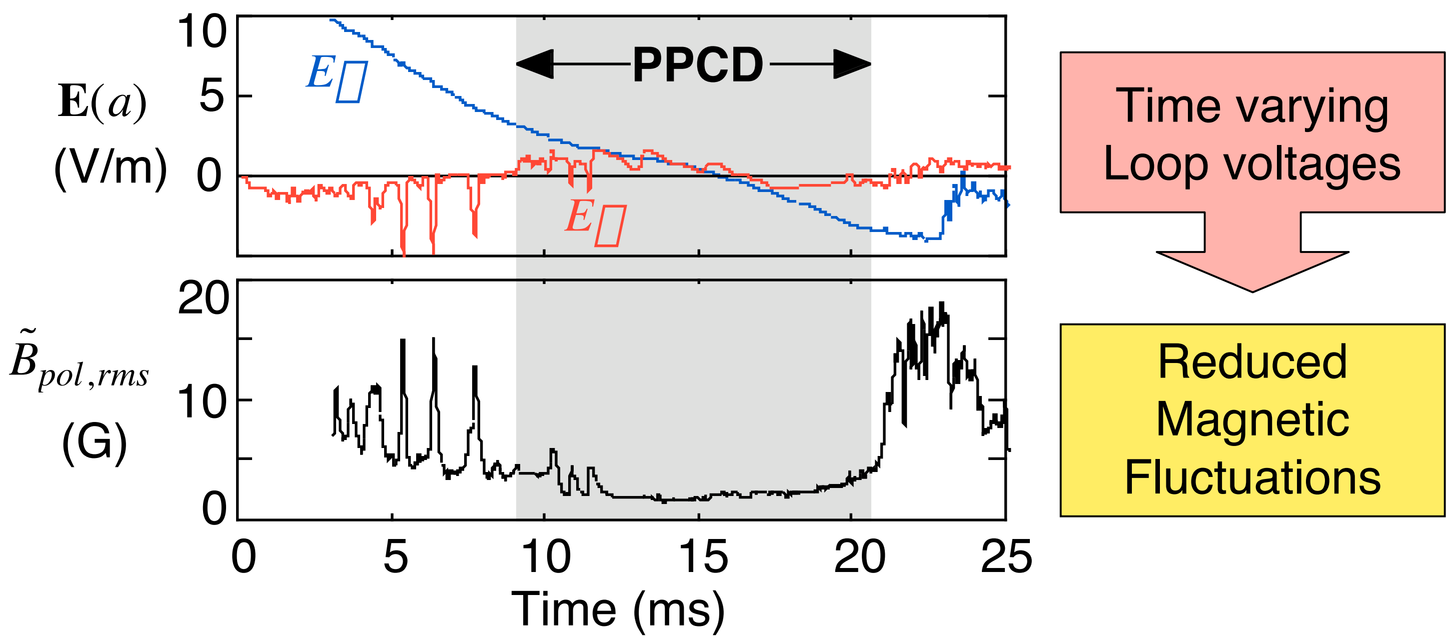
$a = 0.5$ m
$R = 1.5$ m
$I \leq 0.5$ MA

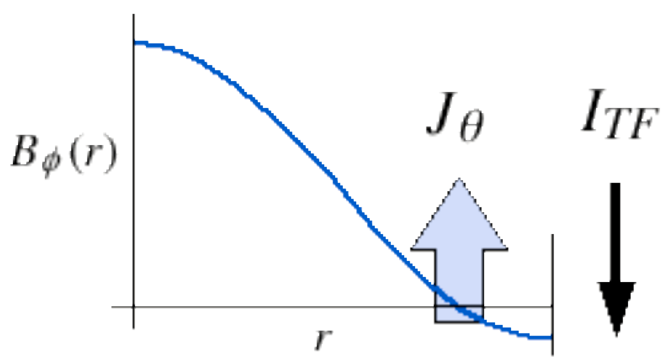


THE UNIVERSITY of WISCONSIN MADISON

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

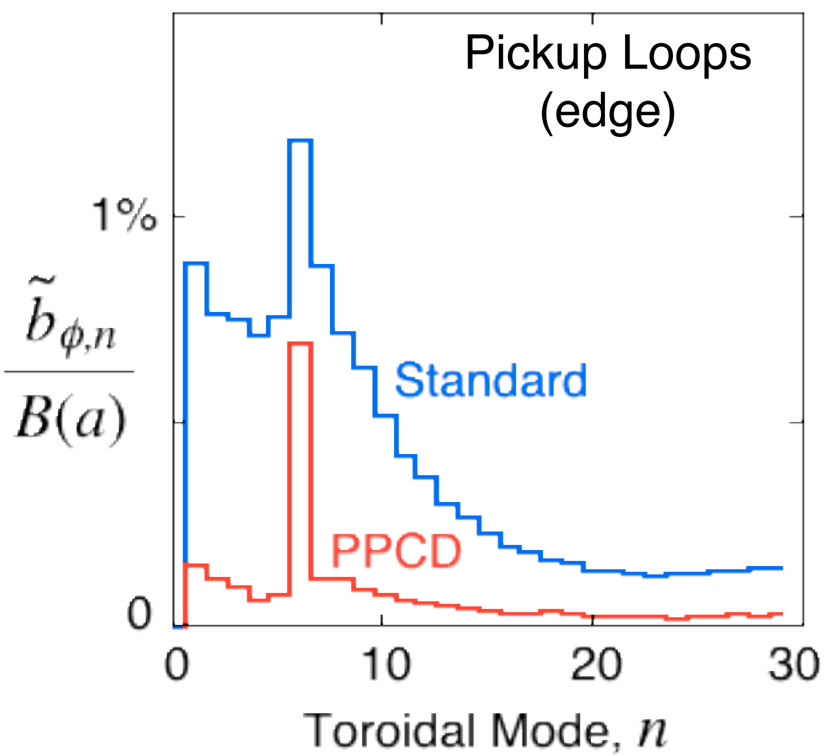
"PPCD" – Pulsed Poloidal (or Parallel) Current Drive

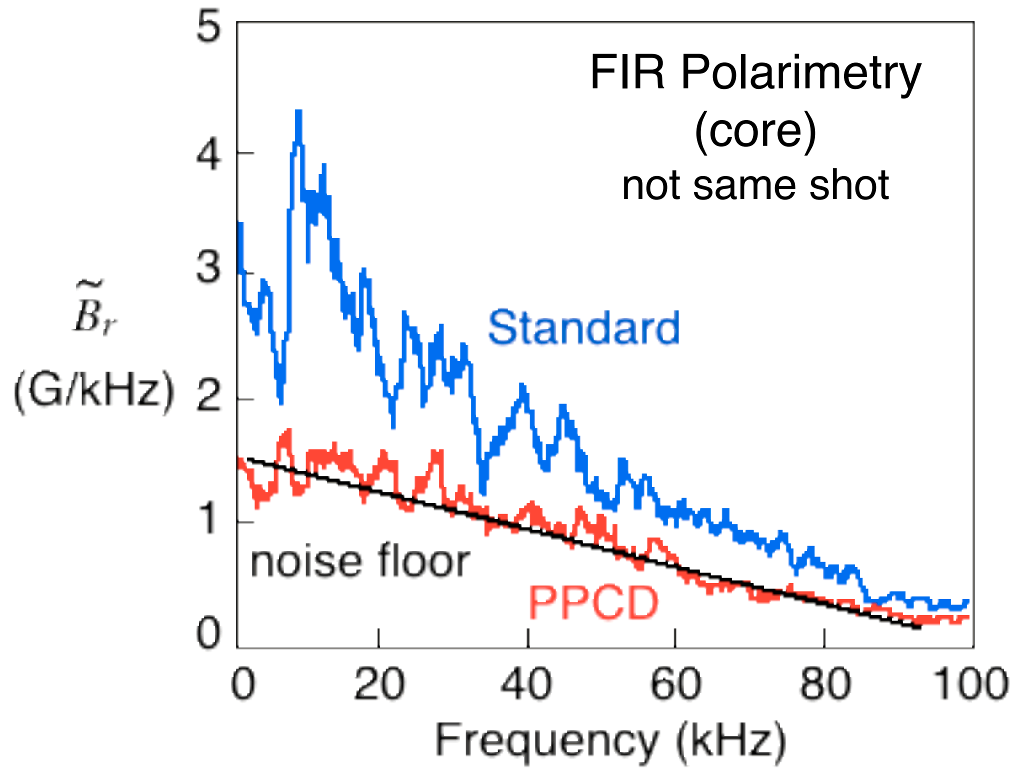


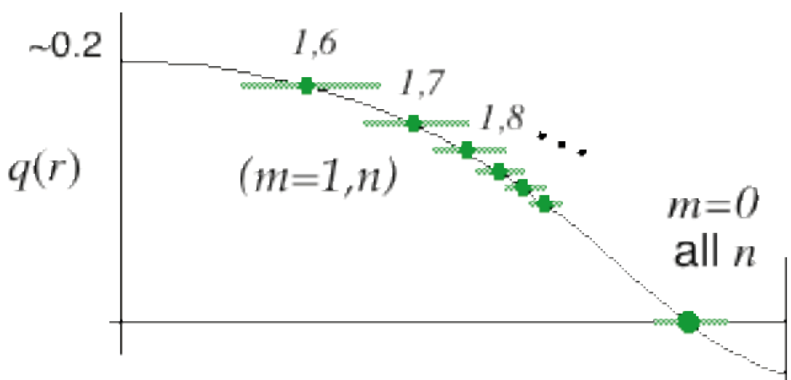


Edge current drive simultaneously controls many modes.

- Broadband mode suppression during PPCD.



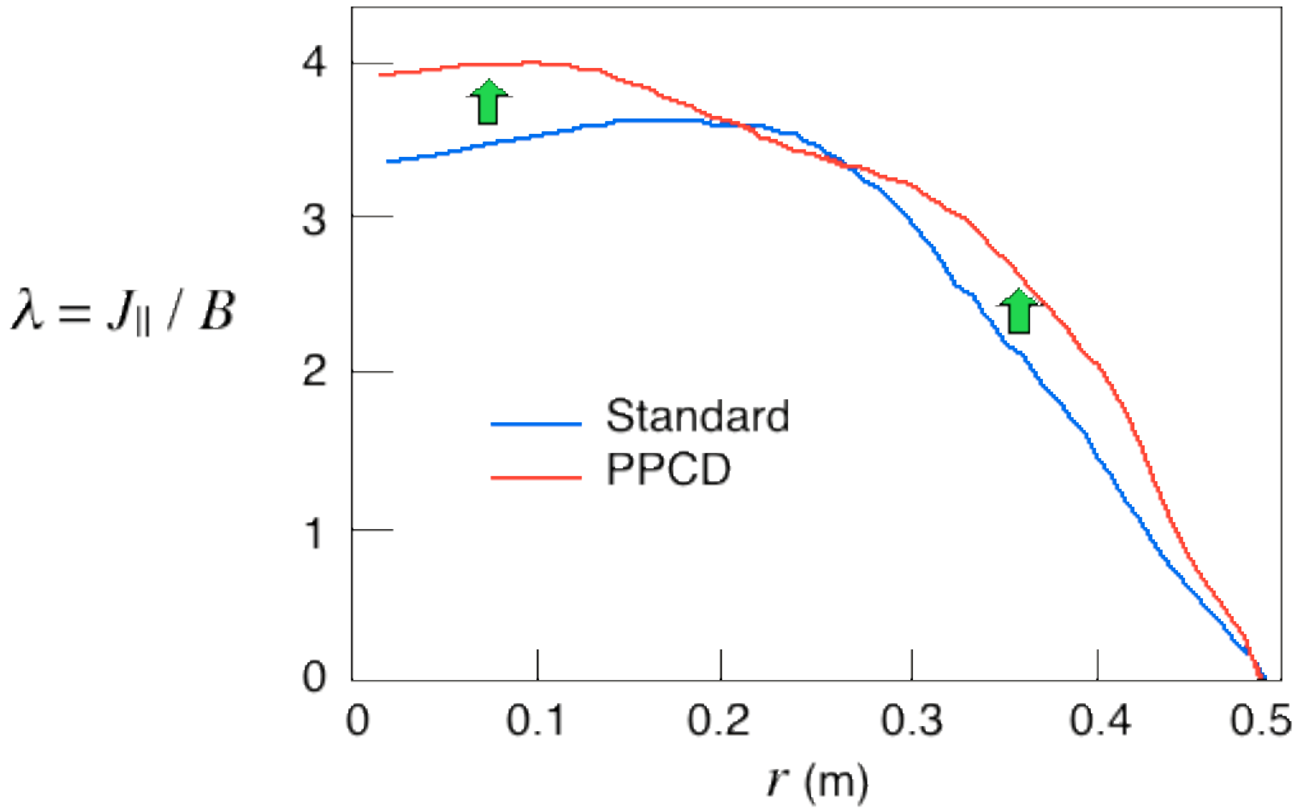




UCLA

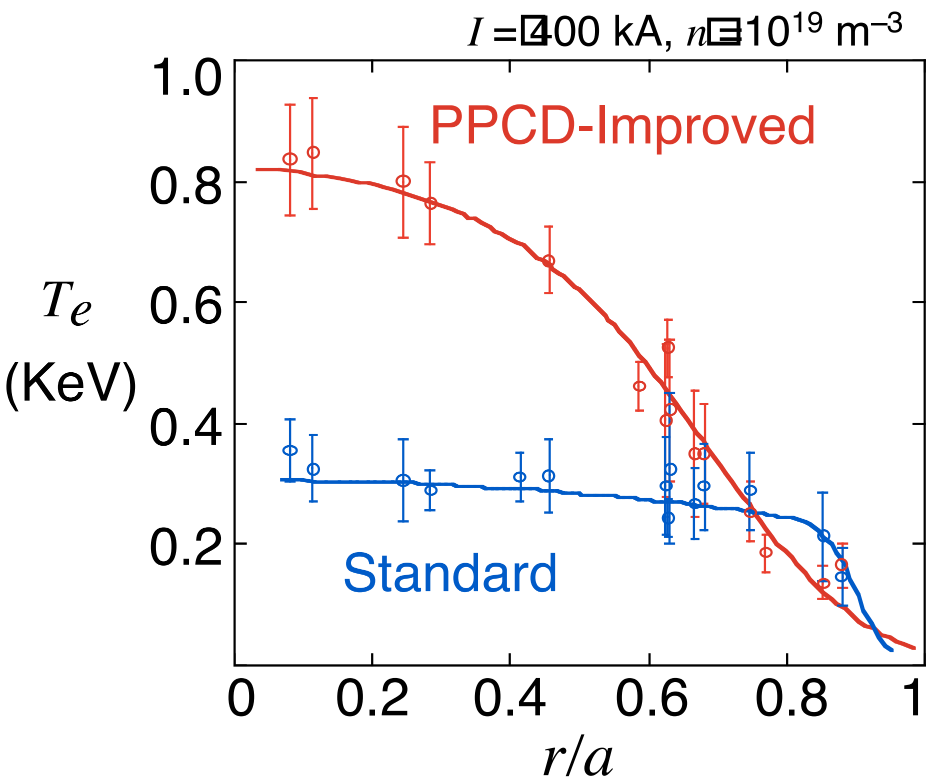
J/B larger in outer region, as intended.

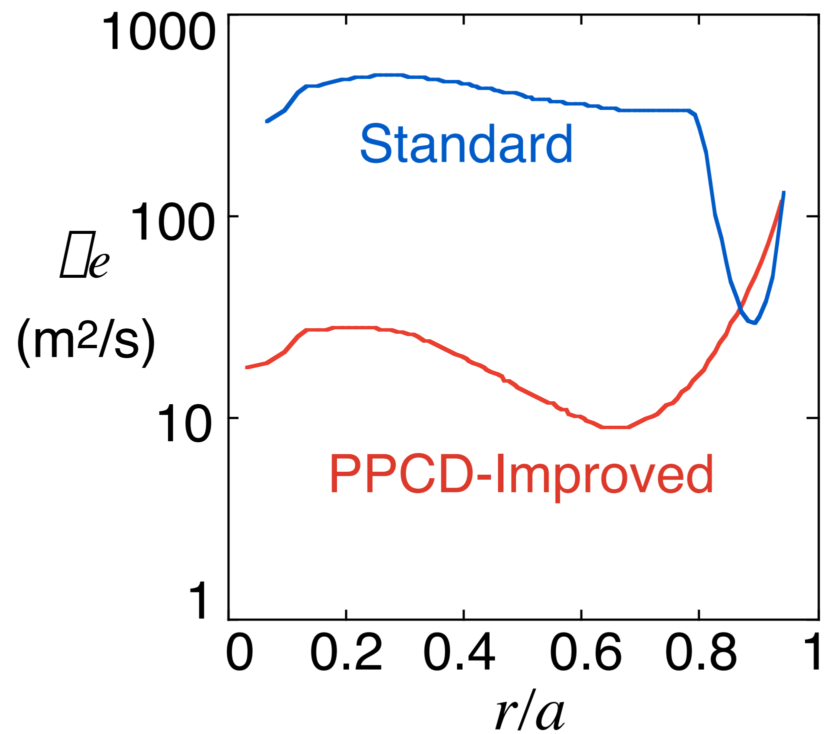
- Toroidal equilibrium reconstruction using:
  - 11-chords FIR polarimetry (UCLA collab.)
  - $B(0)$ from MSE with DNB (BINP collab.)
  - Conventional edge magnetics



Temperature profile peaks, χ_e greatly reduced.

- Electrons are hotter with **reduced** Ohmic heating, gradient extends into core.
- 100-fold increase in hard x-ray bremsstrahlung implies confined fast electrons.





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

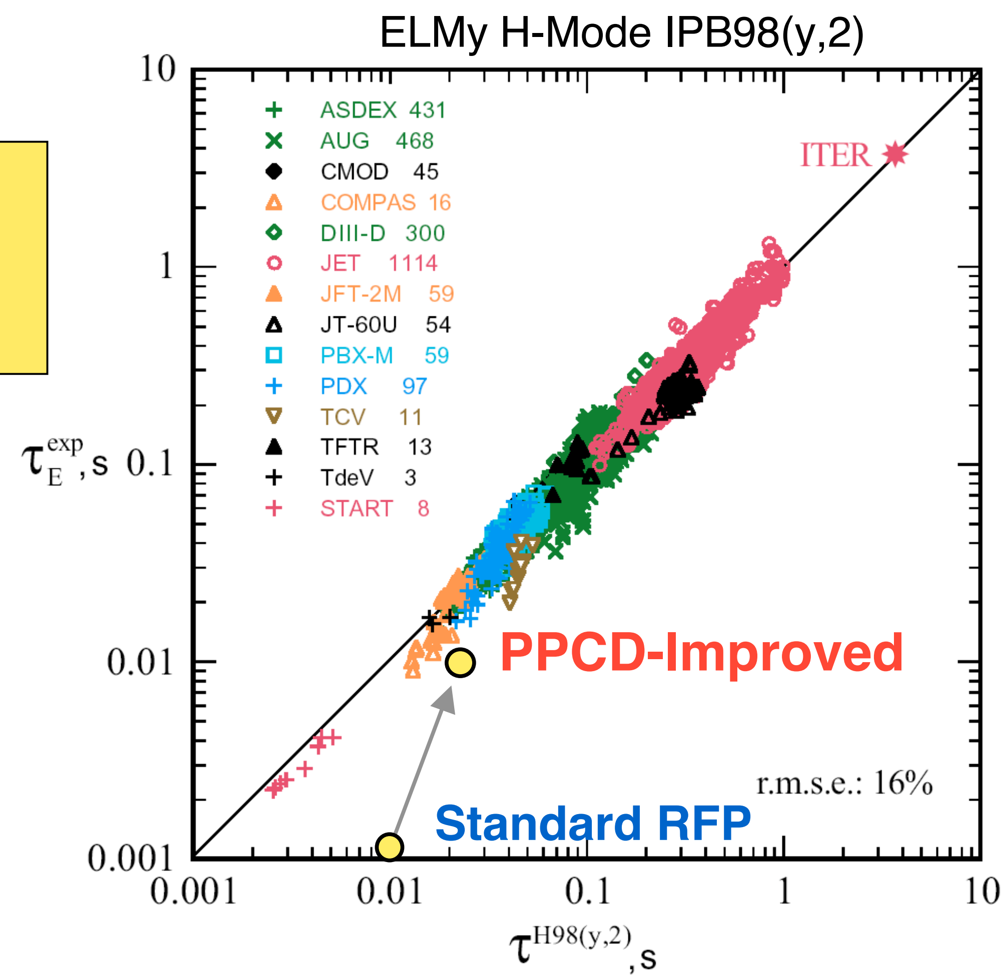
PPCD confinement comparable to same-current tokamak, but with 10X smaller $B(a)$ in the RFP.

- 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).

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.



PPCD doubles the already high beta value in RFP.

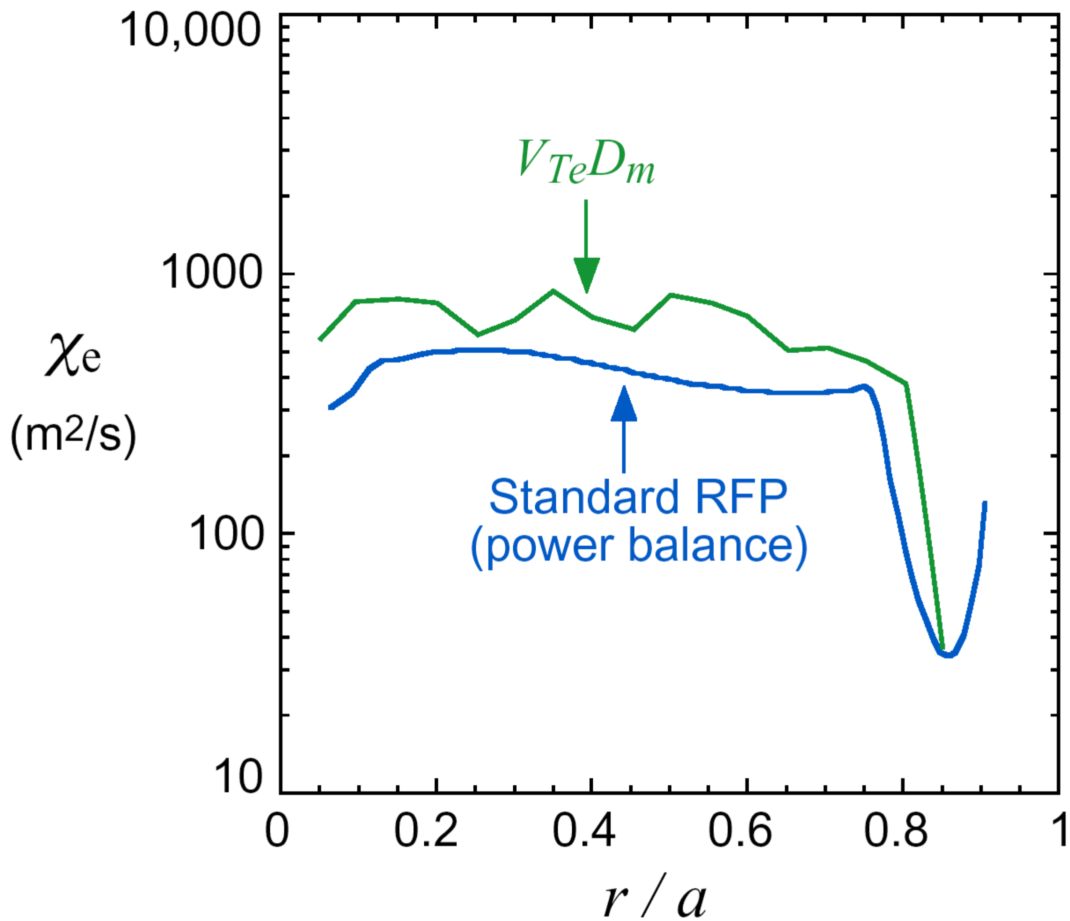
- Experimental β-limit unknown in the RFP (possibly pressure-tearing or g-mode??)

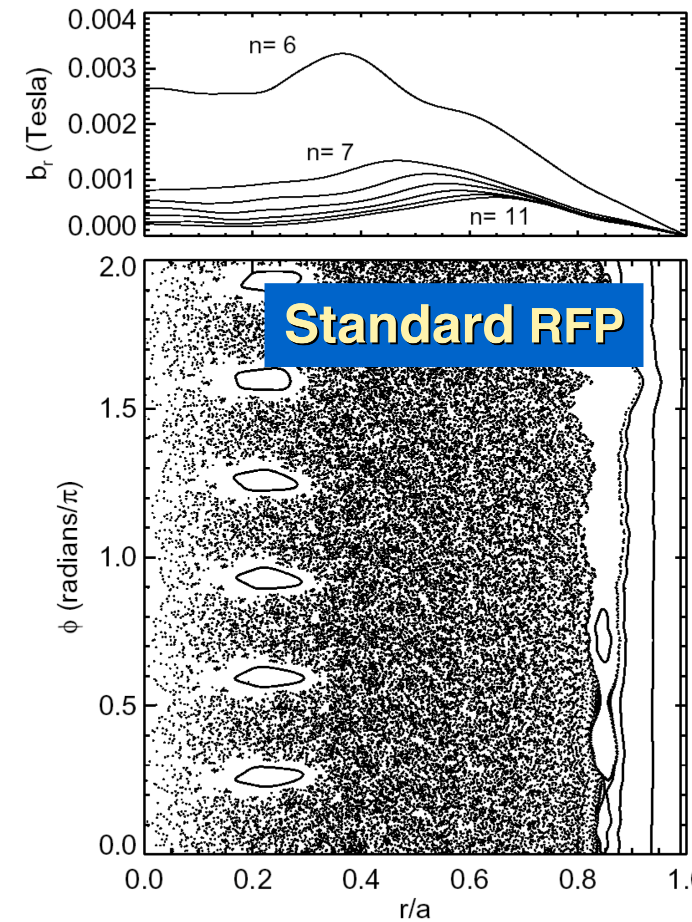
	Total Beta $\beta_{total} = 2\mu_0\langle p\rangle / B^2(a)$ Standard		Total Beta $\beta_{total} = 2\mu_0\langle p\rangle / B^2(a)$ PPCD-Improved
200 kA	9%	× 1.7	15%
400 kA	5%	× 2.2	11%

Toroidal beta *decreases* during PPCD to β_T ~ 80% (from >>100%)

Bulk electron heat transport in standard plasmas agrees with stochastic diffusion expectations.

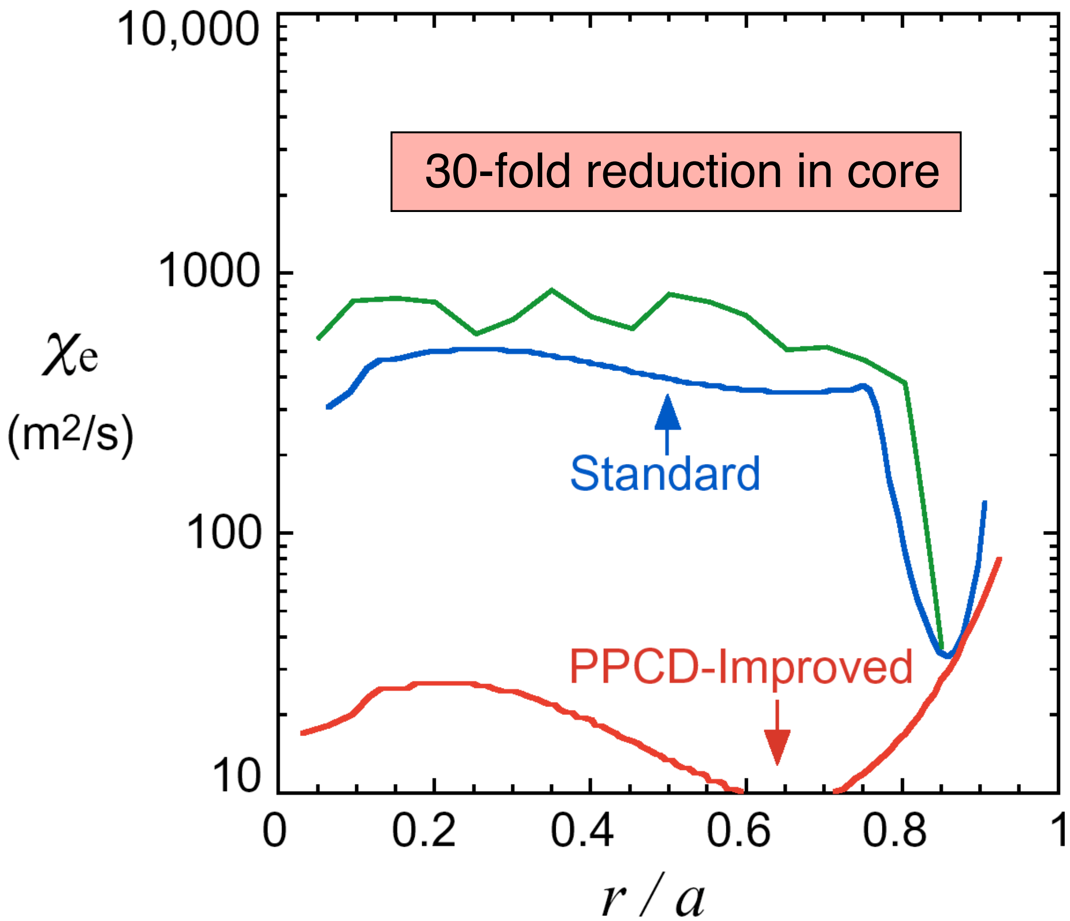
- Field line tracing used to directly evaluate $D_m = \langle(\Delta r)^2/\Delta L\rangle$.

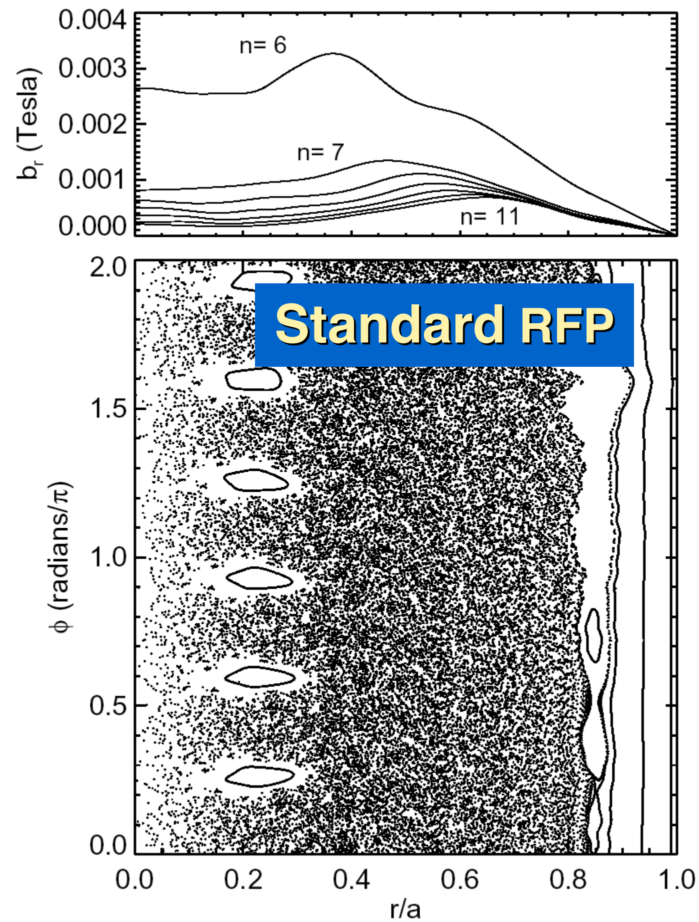




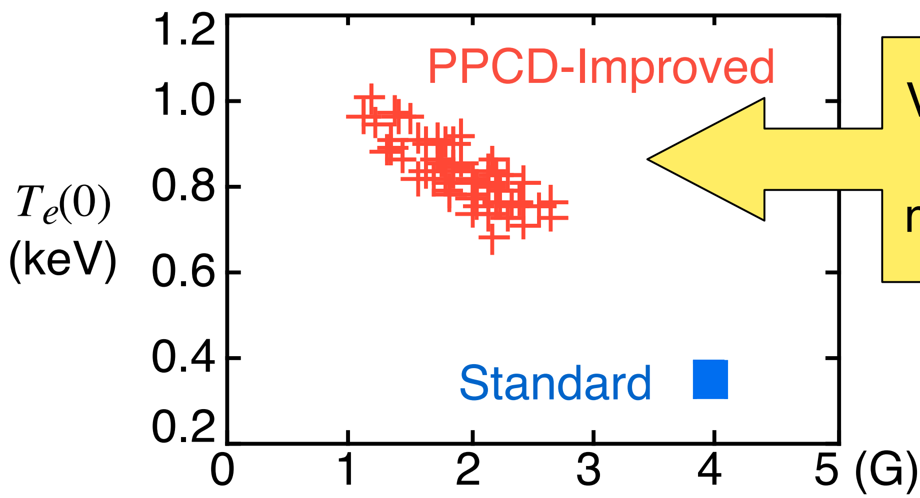
3D resistive MHD computation
$S = 10^6$, $R/a = 3$
expt. measured □(r) profile

Heat conductivity reduction greatest where stochasticity is usually most intense.



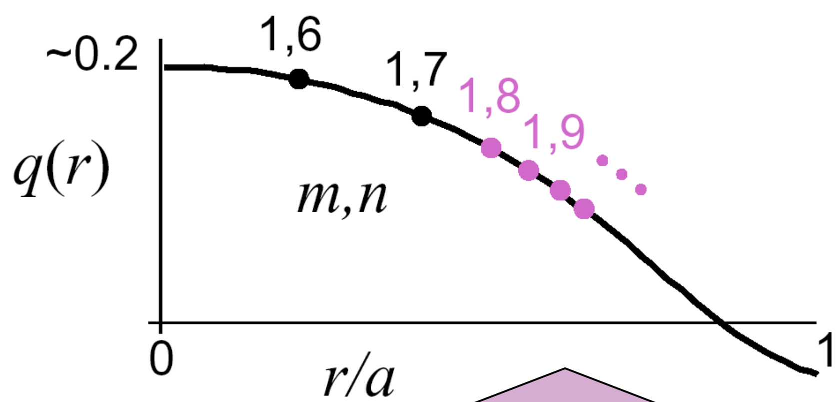


Sustained reduction of mid-radius resonant modes leads to highest $T_e(0)$, therefore largest τ_E .



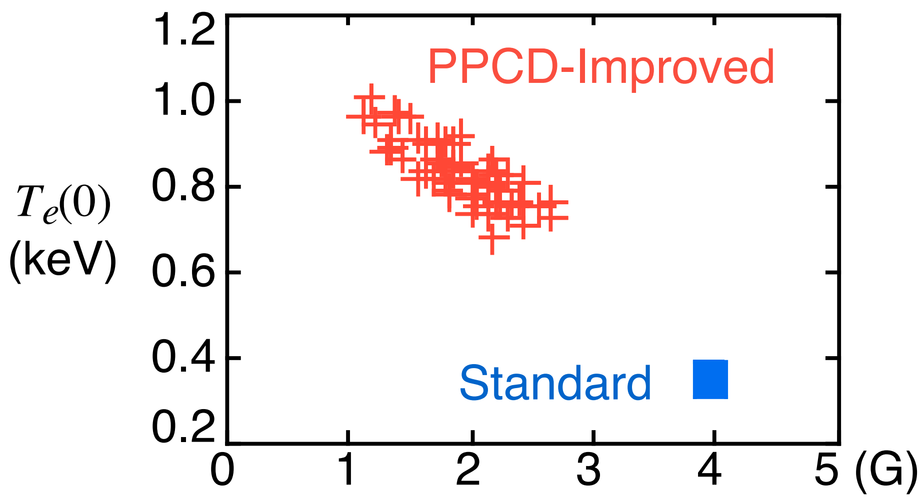
Variable fluctuation reduction reveals mode dependence.

Time Average $b_{\theta rms} = \sqrt{\sum_{n=8}^{15} b_{\theta n}^2(a)}$

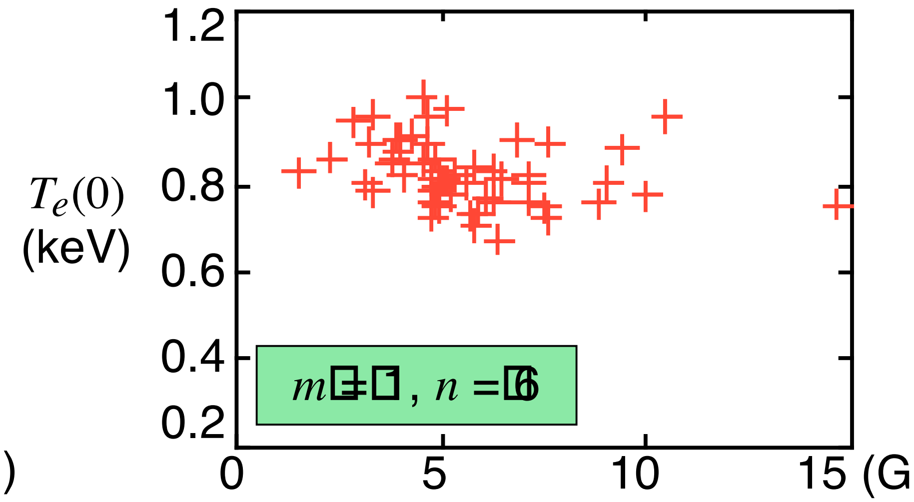


mid-radius modes
$m = 1$, $n \geq 8$

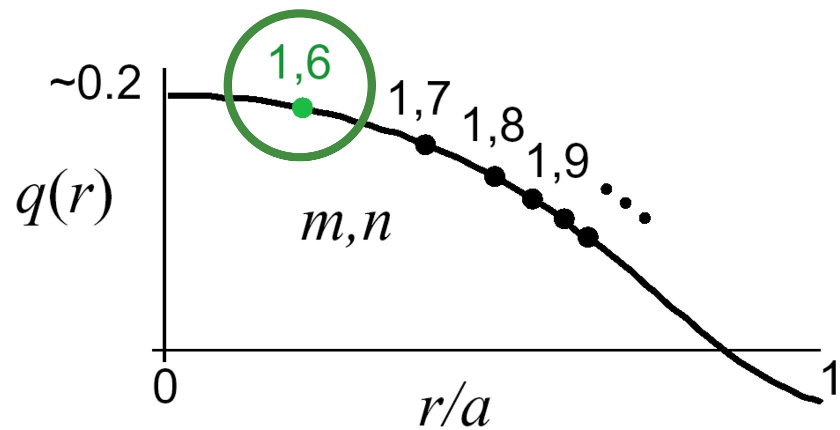
$T_e(0)$ weakly correlated with dominant core mode.



Time Average $b_{\theta rms} = \sqrt{\sum_{n=8}^{15} b^2_{\theta n}(a)}$



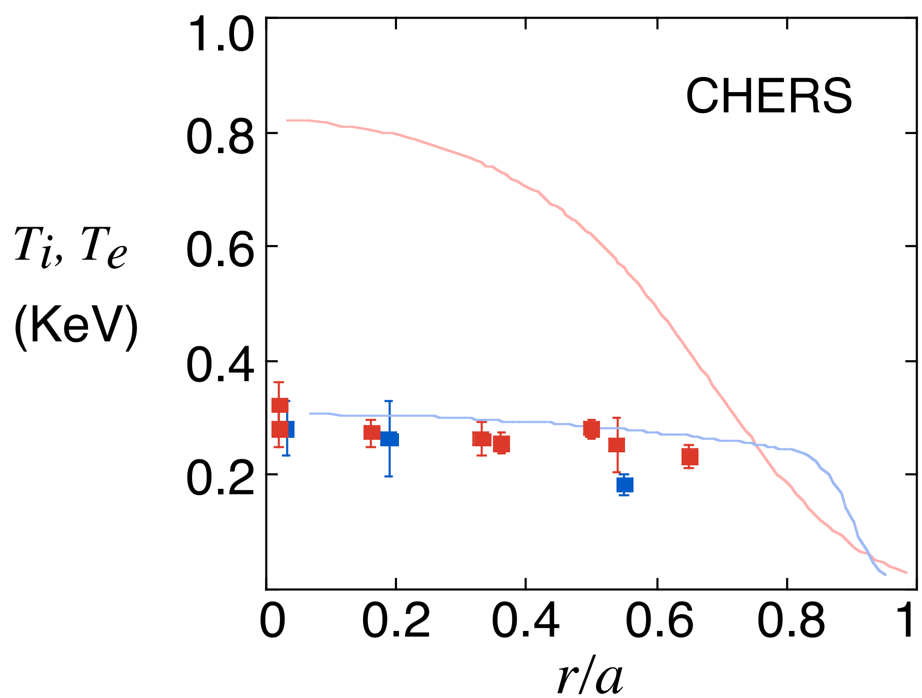
Time Average $b_{\theta 1,6}$



Broadband mode suppression key to improved RFP confinement.

The ion temperature doesn't change during PPCD.

- **Standard:** $P_{e\text{-}i} \leq P_{CX}$; $T_i / T_e > 0.5$ (>1 at sawtooth crash) □ anomalous ion heating
- **PPCD:** $P_{e\text{-}i} \geq P_{CX}$; $T_i / T_e < 0.5$



Stochastic Transport

$$\Box_i^{R\Box R} = \sqrt{\frac{T_i}{T_e}\frac{m_e}{m_i}}\;\Box_e^{R\Box R}$$

Standard
~ 10 m²/s core
~ 1 m²/s $q = 0$

PPCD
~ 0.3 m²/s

Classical

$$\Box_i^{classical} \sim \Box_i^2 / \Box_i \sim 0.1\ \mathrm{m}^2/\mathrm{s}$$

Tools to extend plasma control in development.

- RF current drive for precise, localized $J(r)$-control and auxiliary heating:
  - Lower-hybrid (800 MHz, $n_{||}$ = 8, stripline antenna)
  - Electron Bernstein wave (~ 3.5 GHz, waveguide antenna)
  - Required power ~ 1-2 MW both waves (LH theoretically more efficient)

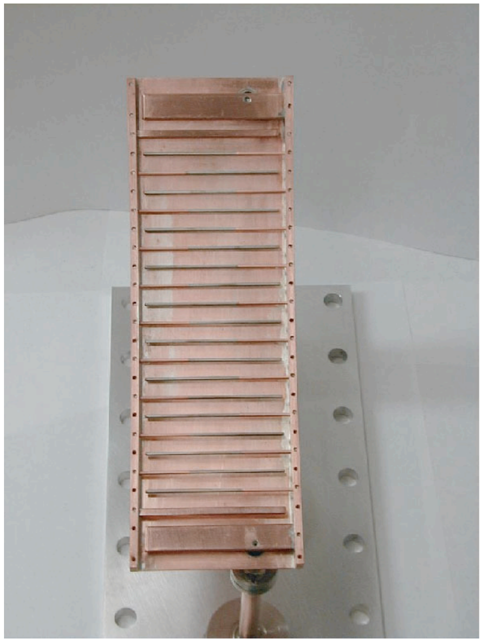
- Oscillating Field Current Drive for DC current sustainment (and possibly profile control) from purely AC inductive loop voltages (AC helicity injection).

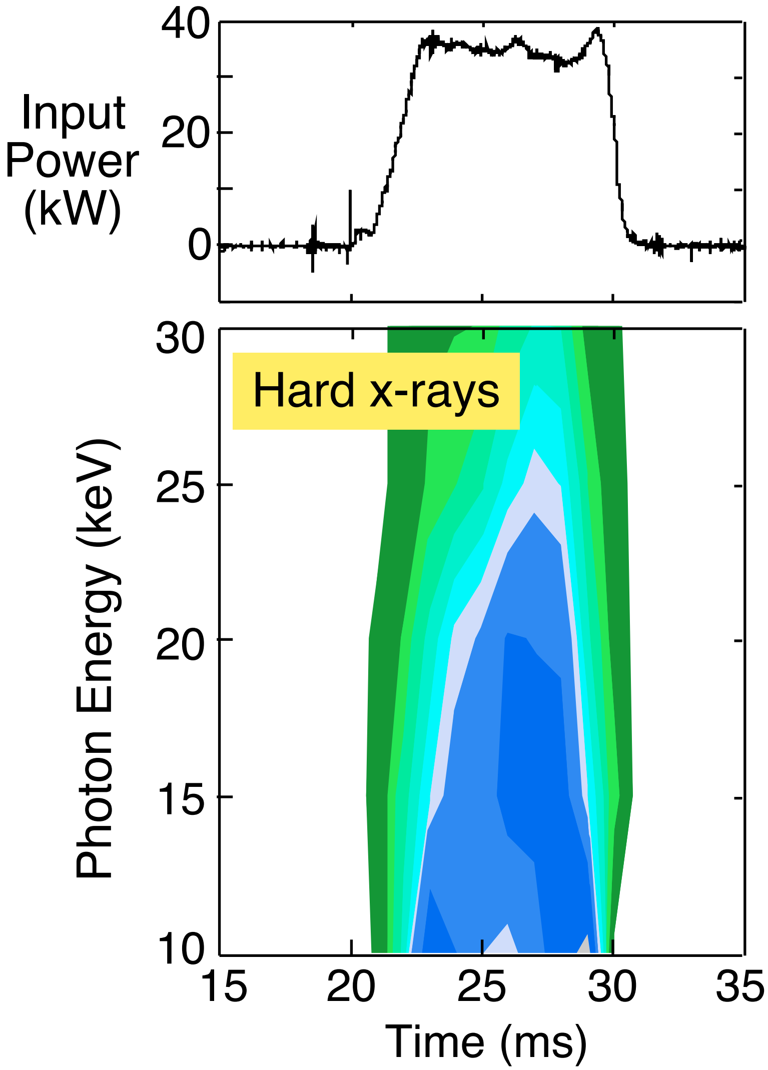
- Neutral beam heating, e.g., investigate beta limit ($P_{\square}$ < 1 MW during PPCD).

Second generation lower-hybrid antenna installed.

MST

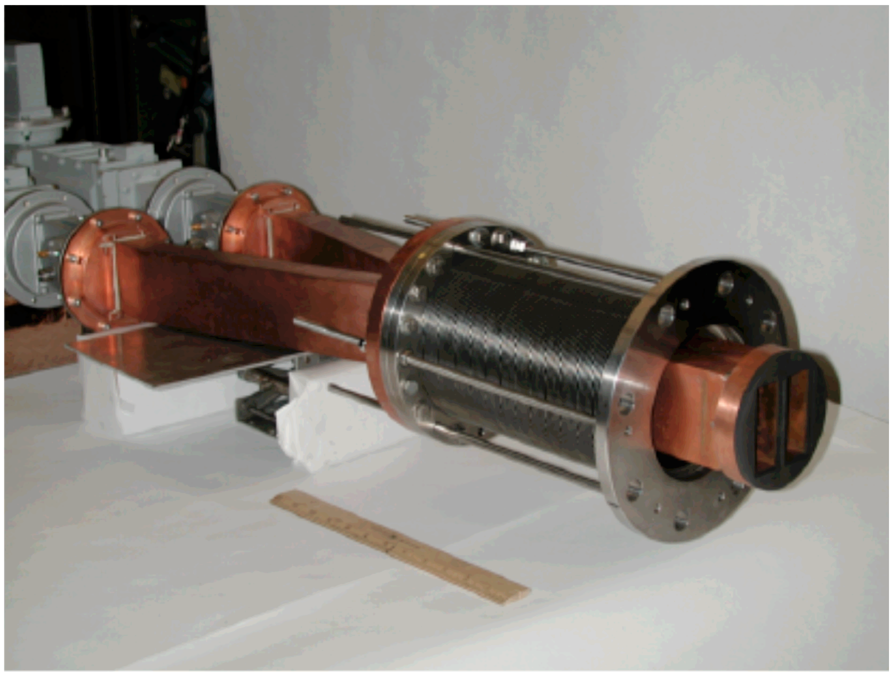
- Interdigital line antenna, 800 MHz, $n_{||} = 8$

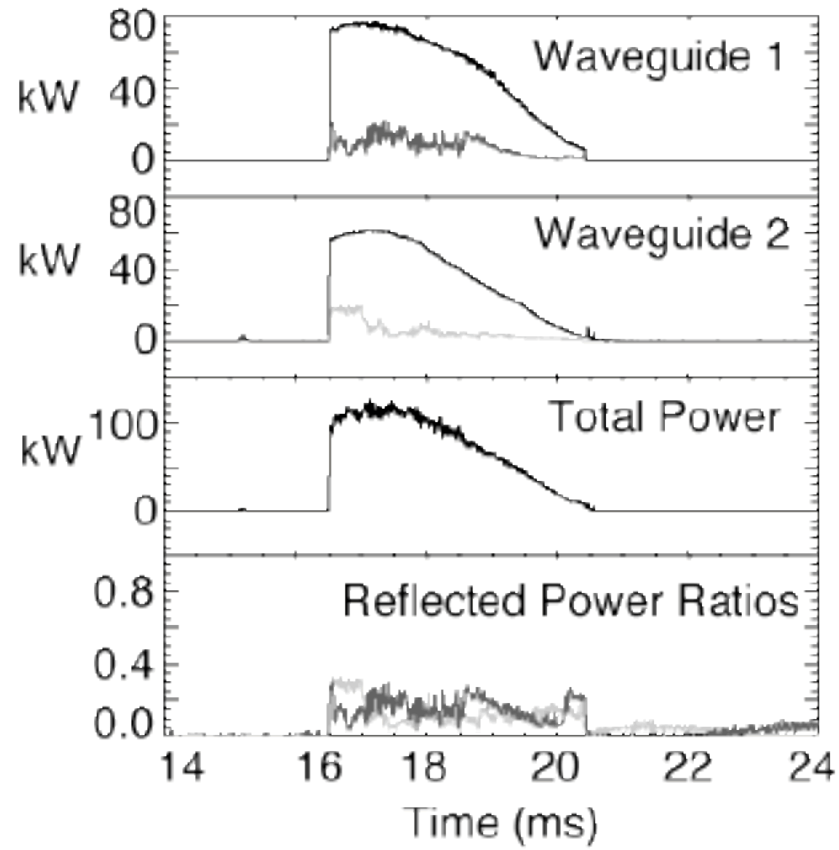




Twin-waveguide installed to drive EBW in overdense RFP

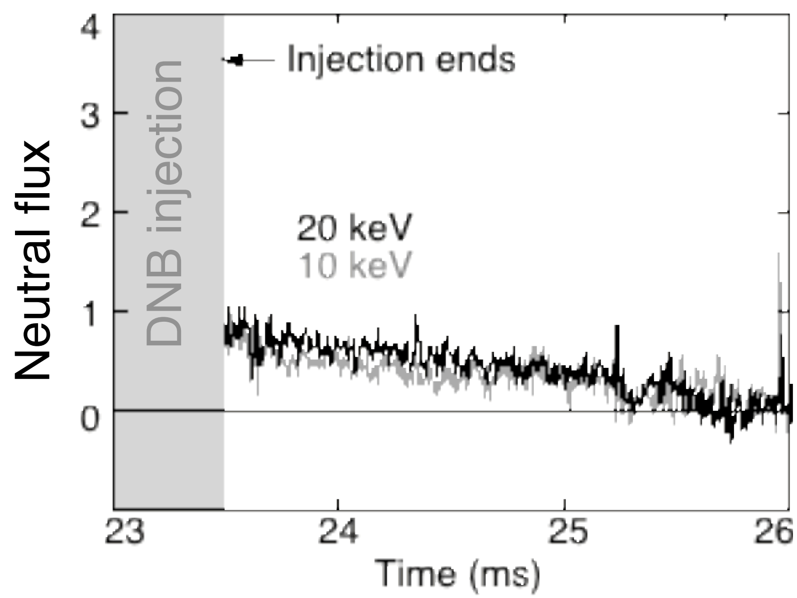
- 3.2-3.7 GHz (variable) from two 60 kW traveling wave tube sources.



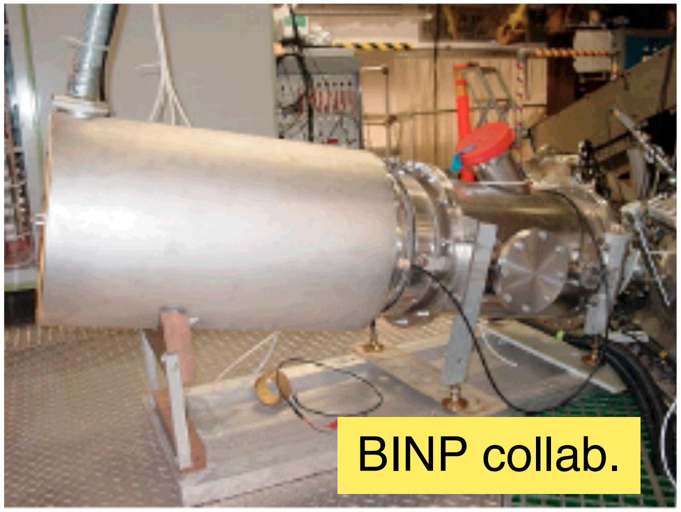


Good fast ion confinement encouraging for NB heating.

Fast neutral-decay following DNB



1 MW short pulse next step



Summary.

- Two paths for enhanced RFP energy confinement, with one common goal — reduced transport from magnetic stochasticity

- Tokamak-like energy confinement demonstrated at high beta and 10X smaller $B(a)$ in MST with (transient) edge inductive current drive:
  - χ_e ~ 5 m^2/s and $\beta_{total} \leq 15\%$
  - Fast electrons confined, with velocity-independent diffusivity

- Broadband mode reduction key to improved confinement, but one remaining large mode is tolerable (analogous to tokamak sawtoothing)
  - Bodes well for “single-helicity” dynamo ... maybe even for multiple-helicity dynamo if high-n scaling is strong

- Extending plasma control
  - RF, neutral beam, and OFCD tools in development (low power)
  - PPCD: find the optimum $\mathbf{E}(a,t)$, evaluate pulsed-reactor scenario