Transitionless Enhanced Confinement and the Role of Radial Electric Field Shear

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In collaboration with:

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E_r shear is shown to play a significant role in development of transitionless enhanced confinement regimes

- regimes without sharp bifurcations ("transitionless")
- regimes without reversed magnetic shear

⇨ **New understanding of strong role of Er shear in supershots**

- Absence of clear transition makes problem difficult:

  Must self-consistently simulate radial electric field and temperature

- Model and interpretation: Turbulence suppression of toroidal Ion Temperature Gradient Turbulence by intrinsic, equilibrium E_r shear

- Enhanced confinement scalings are simulated using a new code TRV
  - improves numerical convergence

- Criterion for near-complete turbulence suppression describes supershot core Ti profiles (self-regulating scenario):

(ExB shearing rate) ~ (toroidal ITG growth rate)

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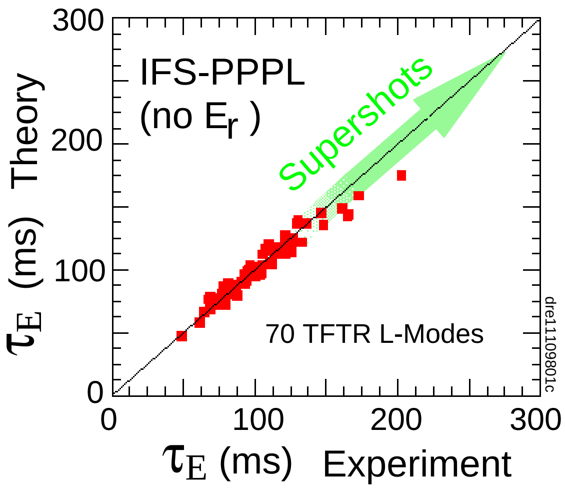
E_r shear becomes more important as T_i increases

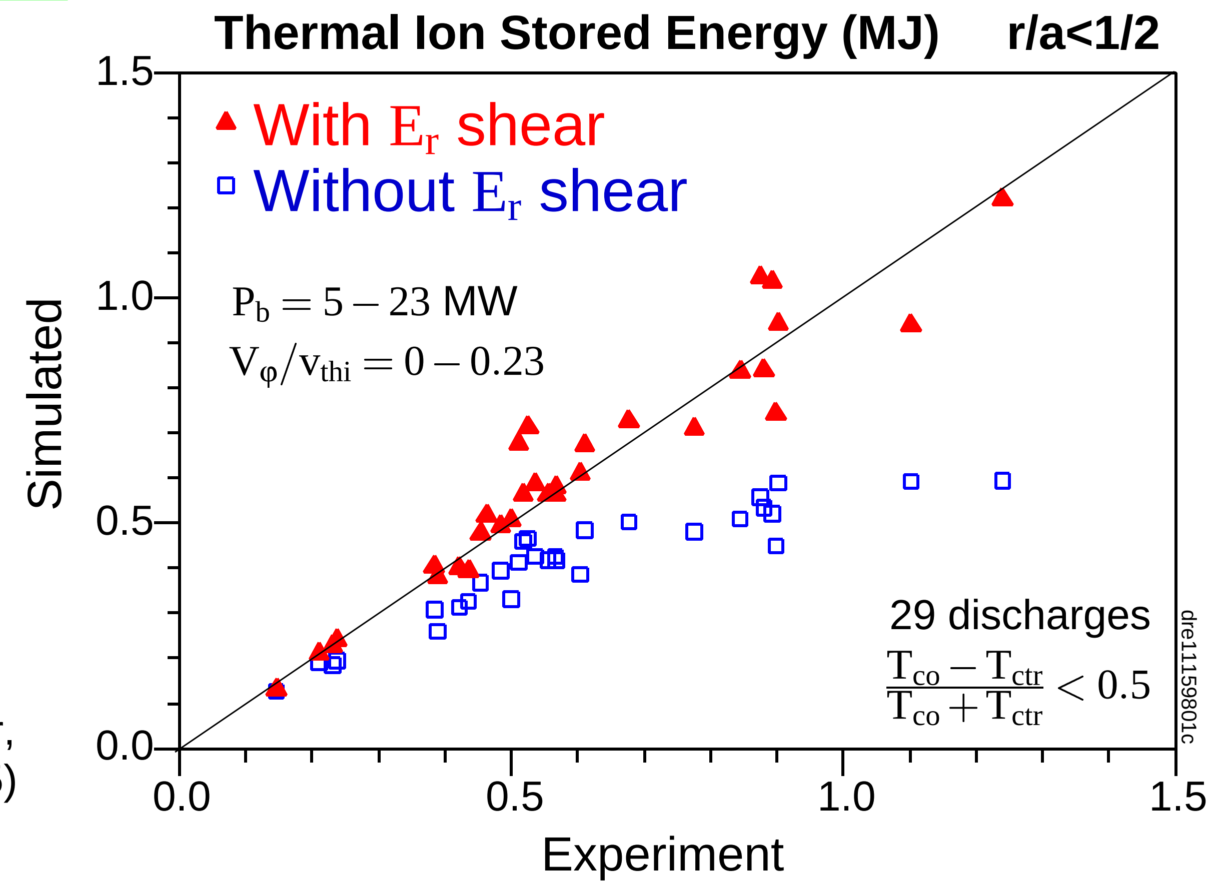
- 1994 IFS-PPPL model reproduces balanced deuterium NBI L-Modes
- At higher temperatures in supershots, the 1994 IFS-PPPl model falls short of reaching measured temperatures by up to 50%

~ Balanced D0 L-Mode



Kotschenreuther, Dorland, Beer, Hammett, Phys. Plasmas (1995)

~ Balanced D0 & T0 Supershots



- *Including Er, using new scaling for V_θ, reproduces supershots*

Ernst, et al., Phys. Rev. Lett., Sept. (1998) & IAEA (1998)

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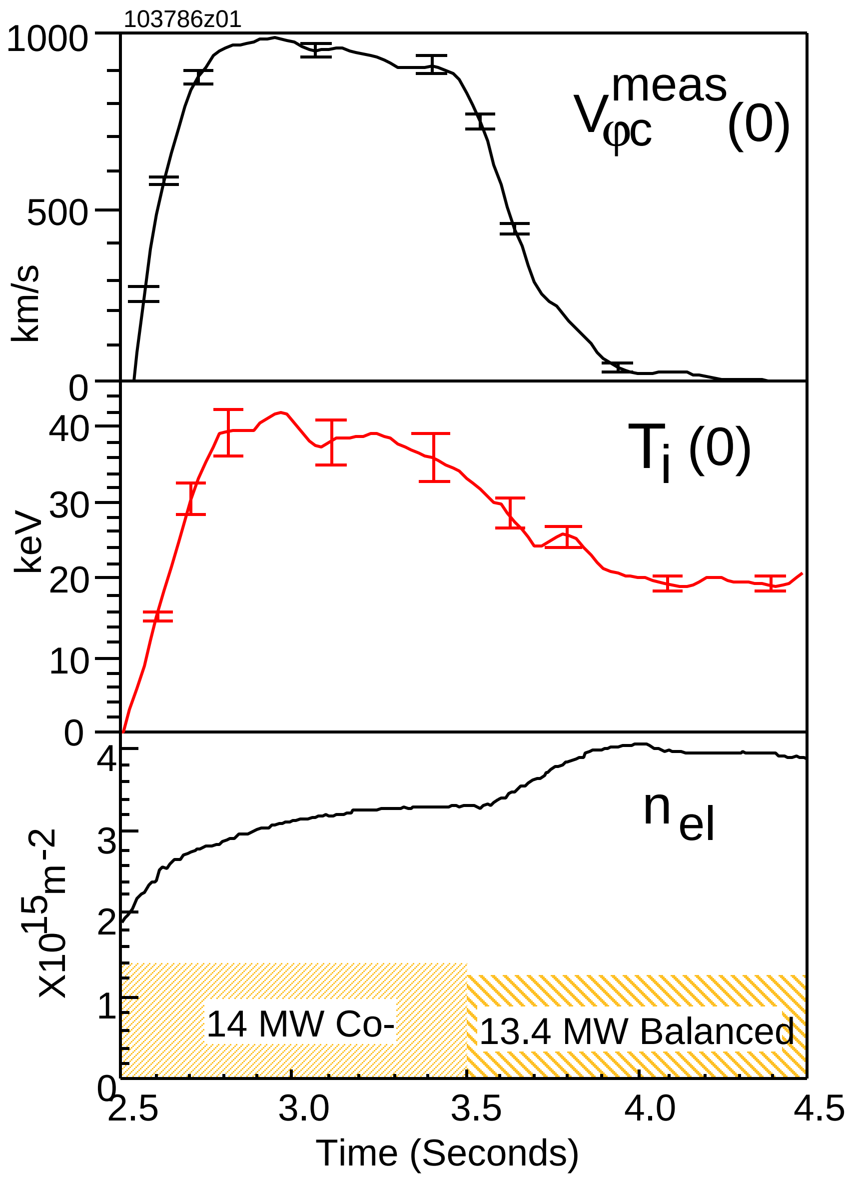
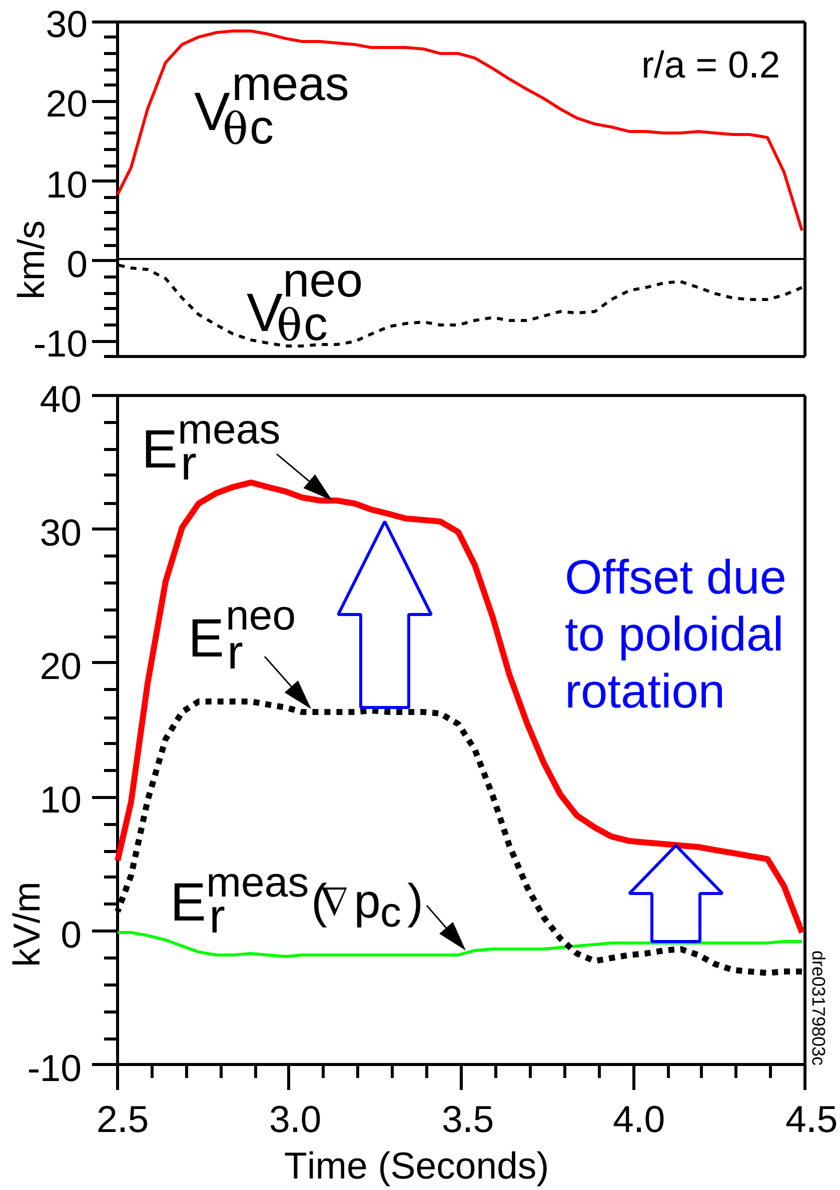
Co- to Balanced torque change reveals importance of $v_{\theta C}$





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Numerical neoclassical solution uses 4x4 viscosity matrix with integration over velocity space [Phys. Plasmas, March (1998)].

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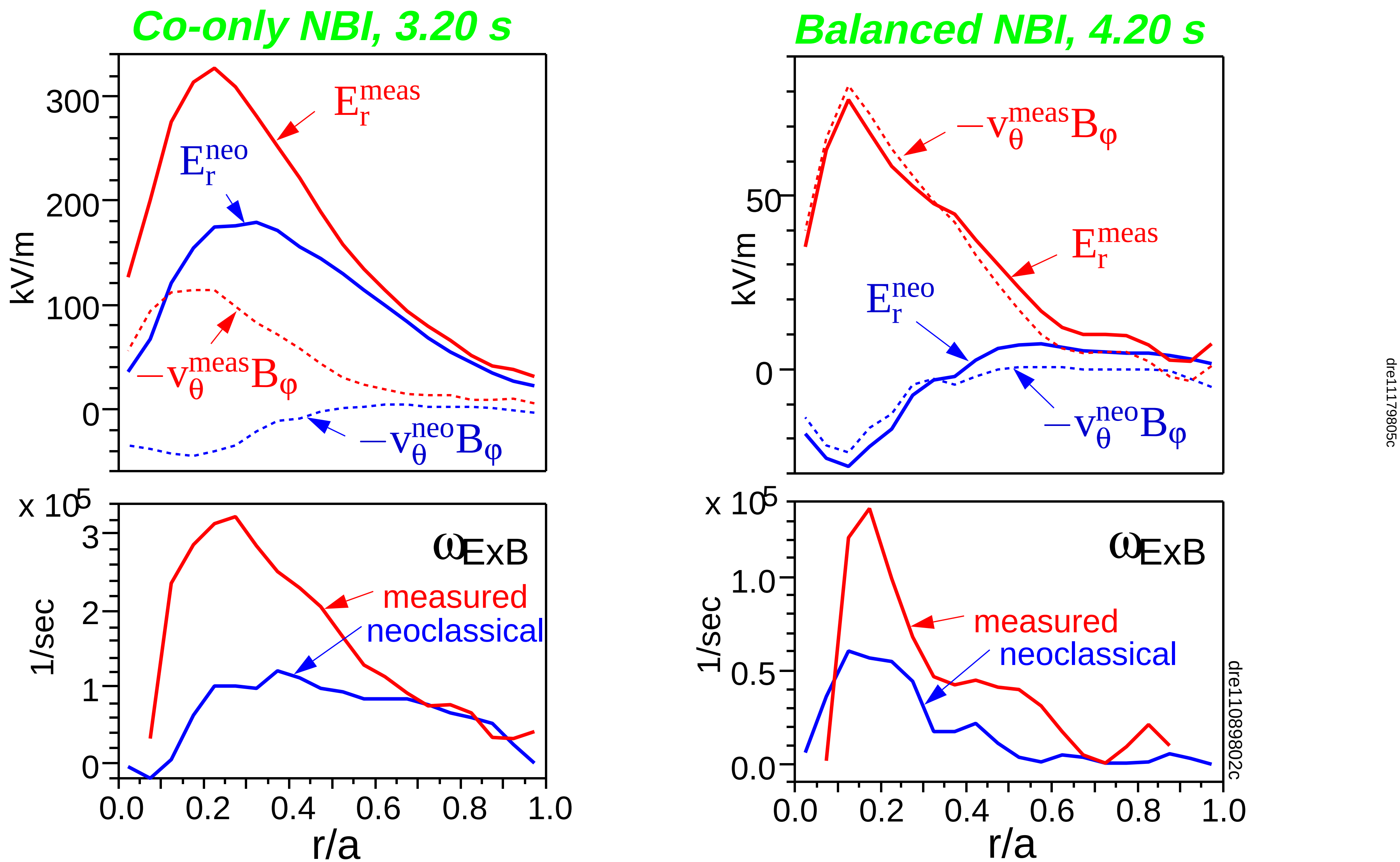
Co- to balanced torque change isolates discrepancy: measured vs. neoclassical carbon poloidal rotation



- Shearing rate qualitatively similar for both cases

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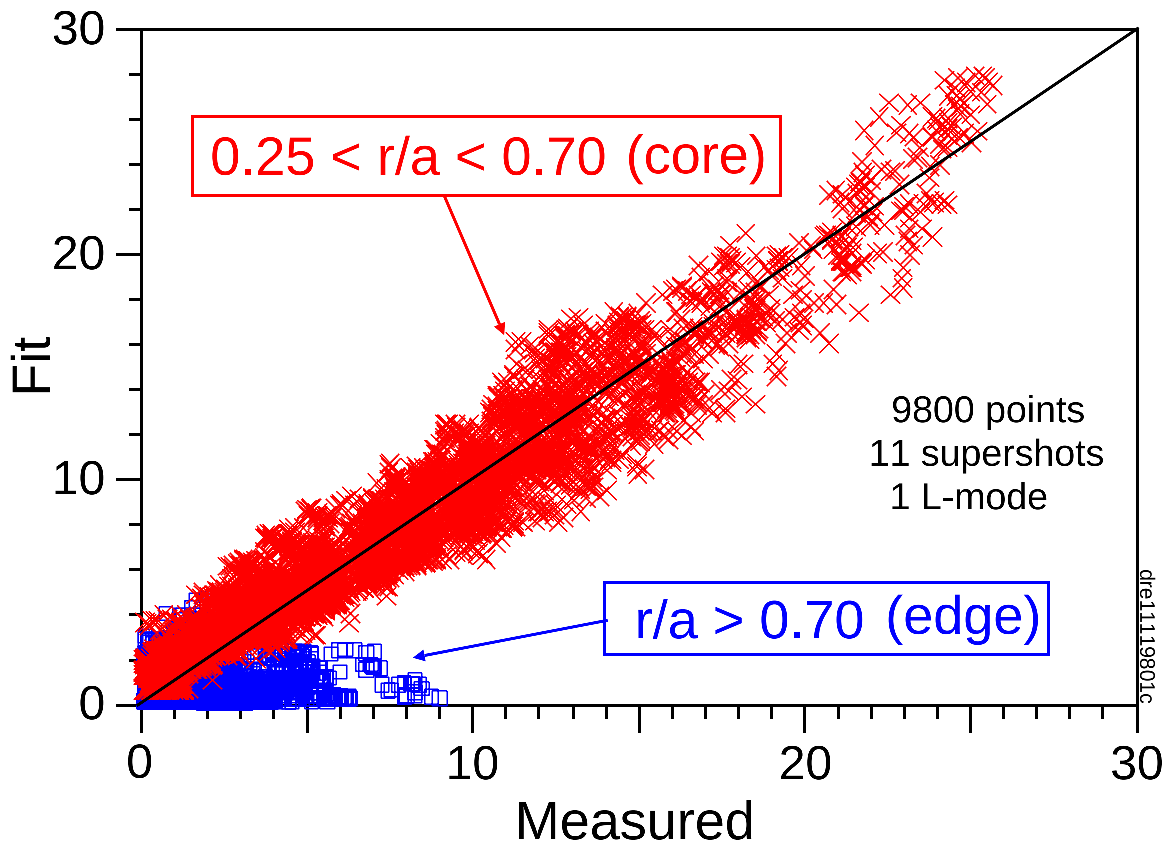
TFTR Supershot data indicates carbon poloidal rotation is proportional to ion temperature except near edge

$$V_\theta^{carbon}\,(\mathrm{km/s}) = 0.182 + 1.43\{T_i - T_i(\mathrm{edge})\}(\mathrm{keV})$$



- *Better fit than* $\Phi \propto T_i$ which would imply $v_\theta \propto \nabla T_i / B$

See also R. Bell, K6Q1, this afternoon.

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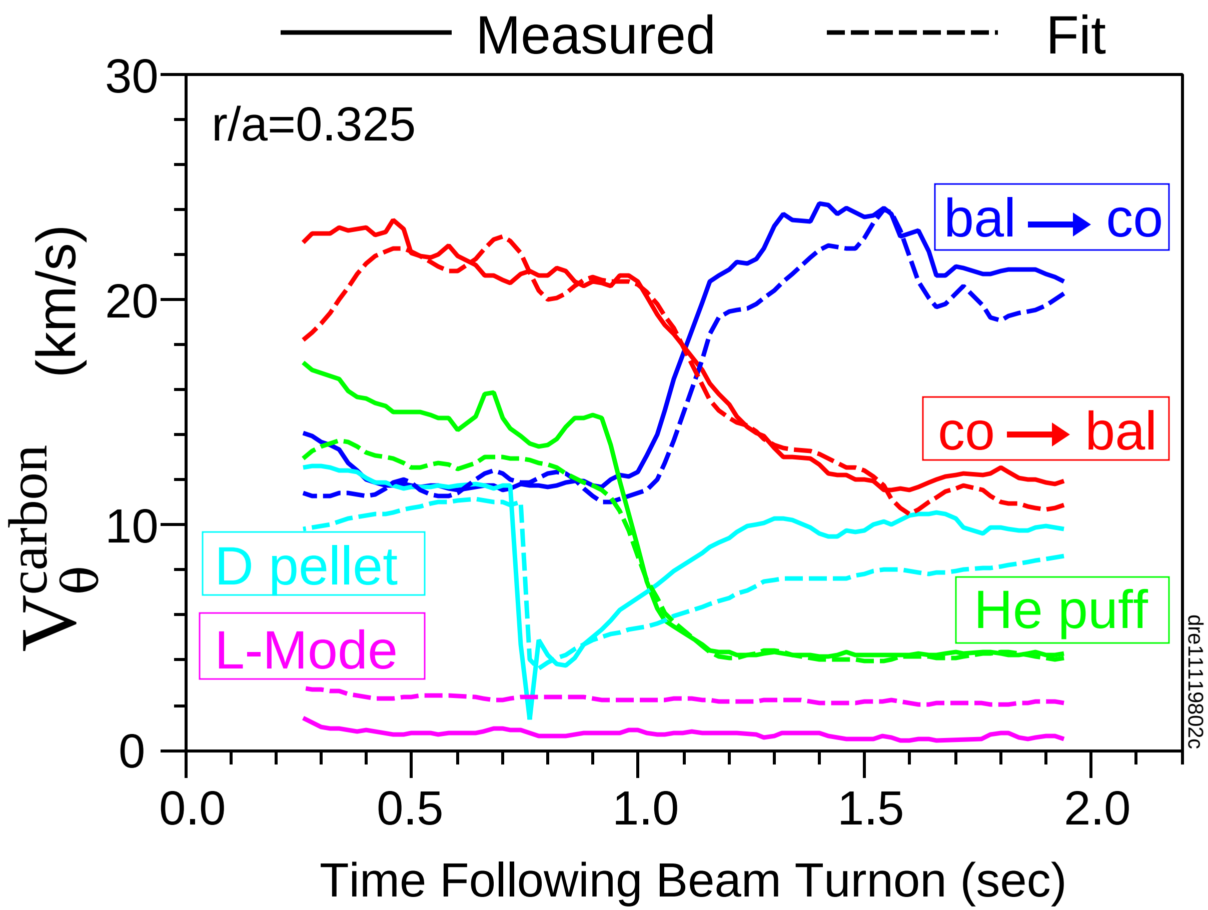
Evolution of measured carbon poloidal rotation closely follows T_i in supershot perturbation experiments



Limited dataset:

4.8 T

1.6 MA

12.1-13.5 MW

251 cm / 86 cm

b/a=1

positive shear

$$V_\theta^{carbon}\,(km/s) = 0.182 + 1.43\{T_i - T_i(edge)\}(keV)$$

- Demonstrates insensitivity of scaling to beam torque, density & recycling

See R. Bell, K6Q1, this afternoon.

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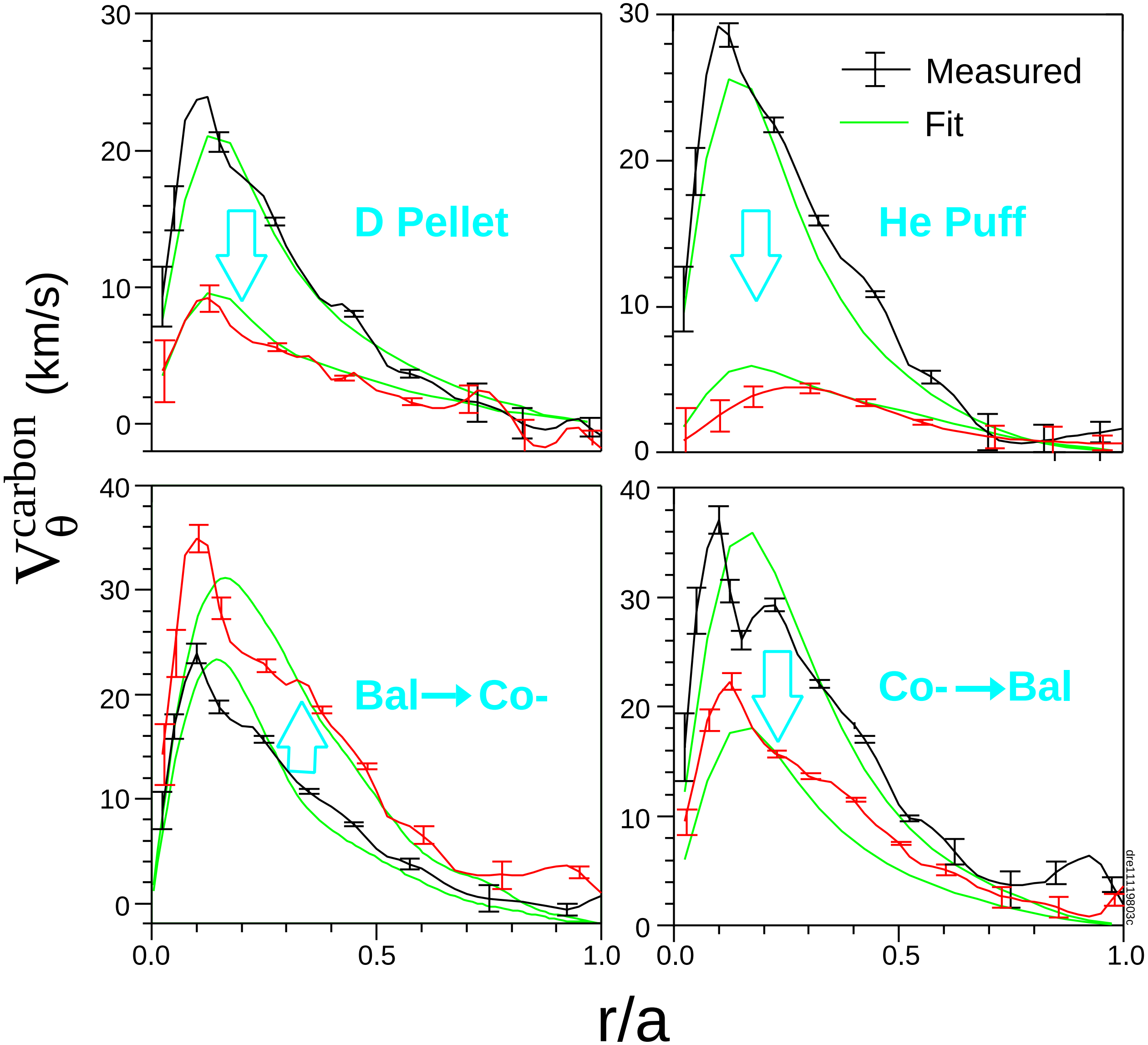
Shape of measured carbon poloidal rotation profile closely resembles supershot T_i as well

$$V_\theta^{carbon}\,(\mathrm{km/s}) = [0.182 + 1.43\{T_i - T_i(\mathrm{edge})\}(\mathrm{keV})] \times \begin{cases} \sin\left(\frac{\pi}{2}\frac{r}{a_1}\right), & r < a_1 \\ 1, & r > a_1 \end{cases}$$

$a_1 \sim 0.15a$



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Model describes Toroidal Ion Temperature Gradient Turbulence suppressed by E_r Shear

- Toroidal ITG modes described using 1994 IFS-PPPL model
- E_r shear suppression included via parameterization of Waltz 1994 gyrofluid results

$$\chi_i = \max \begin{cases} \chi_i^{\mathrm{IFS-PPPL}} \times \left(1 - \alpha_E \dfrac{|\omega_{E\times B}|}{\gamma_{\mathrm{lin}}^{\max}}\right) \\ \chi_i^{\mathrm{neo(CH86)}} \end{cases}$$

$\gamma_{\mathrm{lin}}^{\max} =$ Max. linear growth rate

$\omega_{E\times B} = \dfrac{RB_\theta}{B_\varphi} \dfrac{d}{dR} \dfrac{E_r}{RB_\vartheta}$ = Hahm-Burrell shearing rate

- $\alpha_E = 0.5$ for all simulations in this talk
- General result of simulations using measured E_r :
  $\alpha_E \omega_{E\times B} \simeq \gamma_{\mathrm{lin}}^{\max}$ in inner half-radius (near-complete suppression)
  Describes self-regulation by intrinsic equilibrium flows
- Using $v_\theta(\mathrm{km/s}) \simeq \alpha_{T\theta} T_i(\mathrm{keV})$ $\alpha_{T\theta} \simeq 1.0$ $\omega_{E\times B} \simeq \gamma_{\mathrm{lin}}^{\max}$
  an equation for core T_i has been derived:
  - predicts stronger isotope effect at high temperatures

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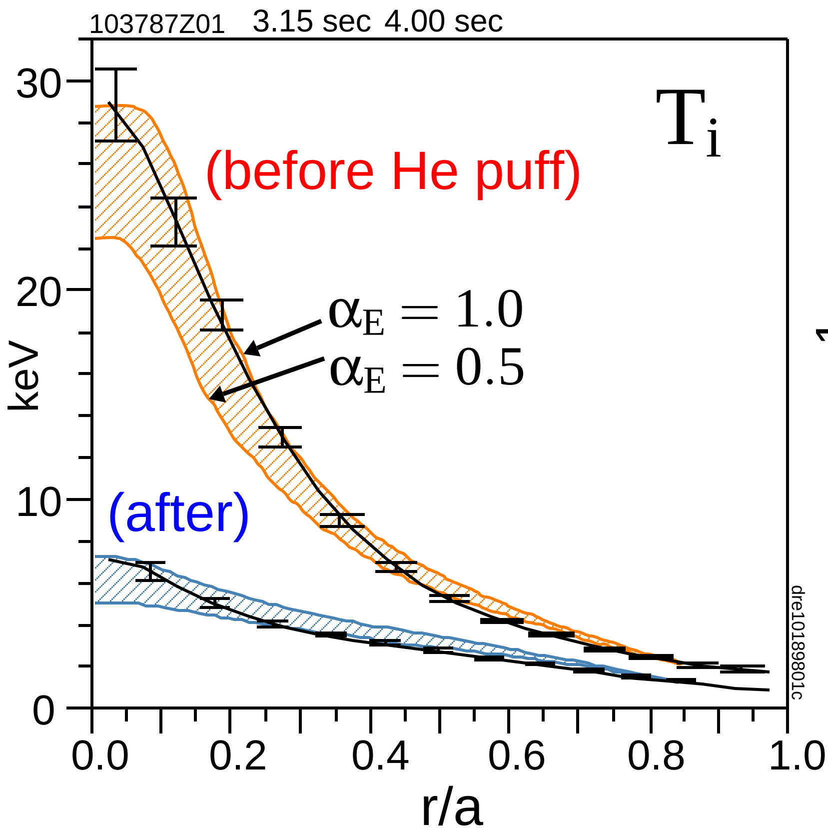
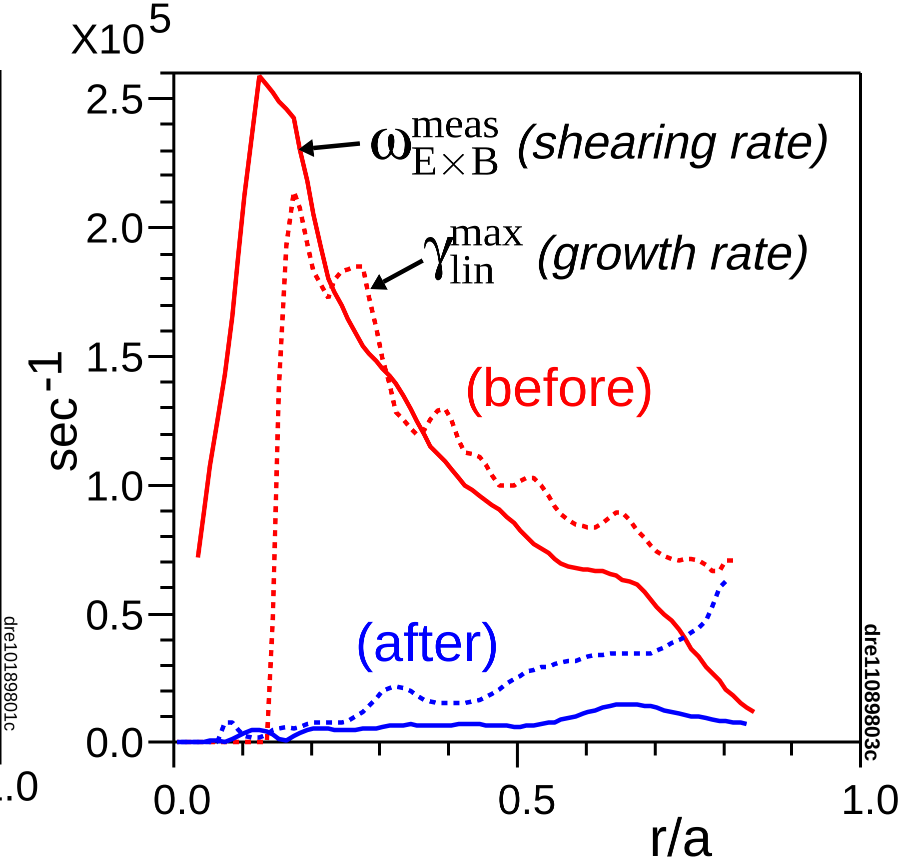
"Spoiling" of supershot by transient helium puff reproduced

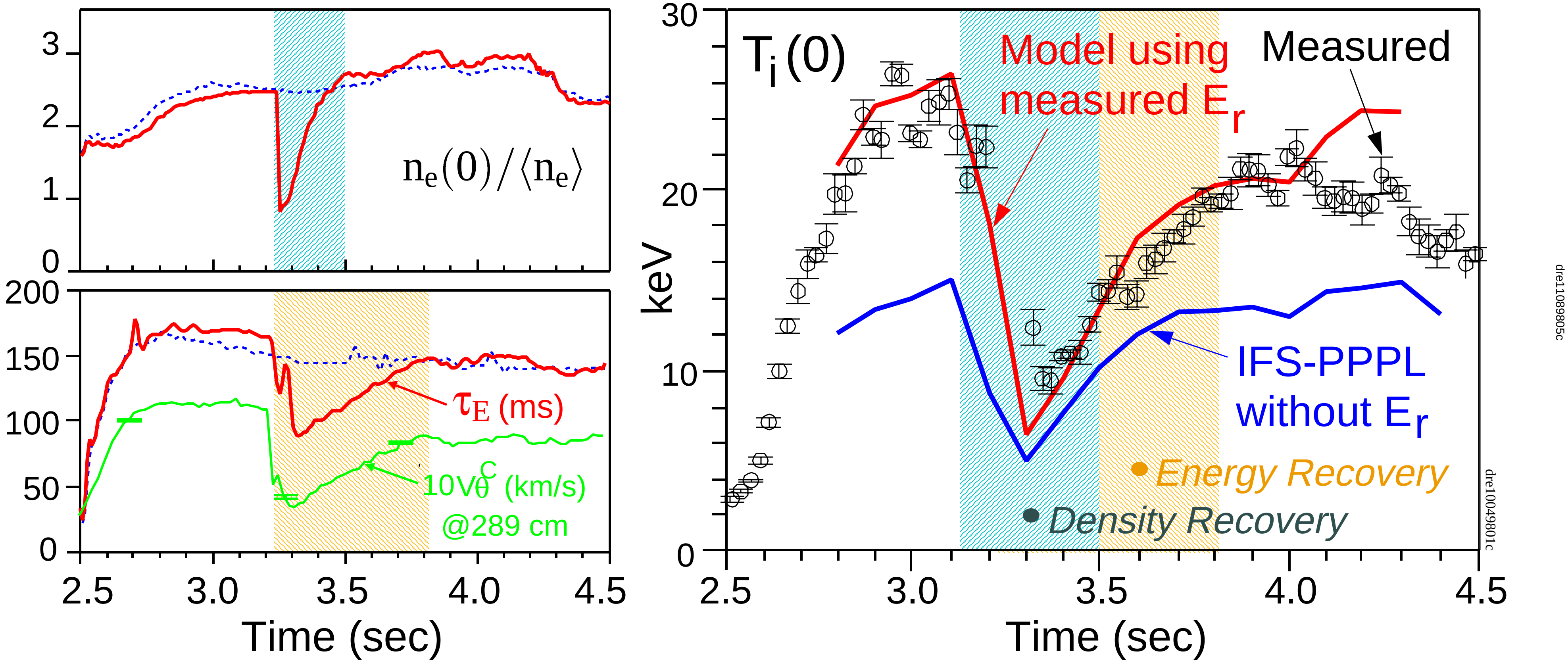
- Core: E_r shearing rate ~ max. linear growth rate: $\alpha_E \omega_{E\times B} \simeq \gamma_{lin}^{max}$





- He puff increases recycling without significant dilution
- Drastic drop in ion temperature reproduced (τ_E : 175 → 86 ms)
- Varying coefficient of shearing rate does not affect conclusions

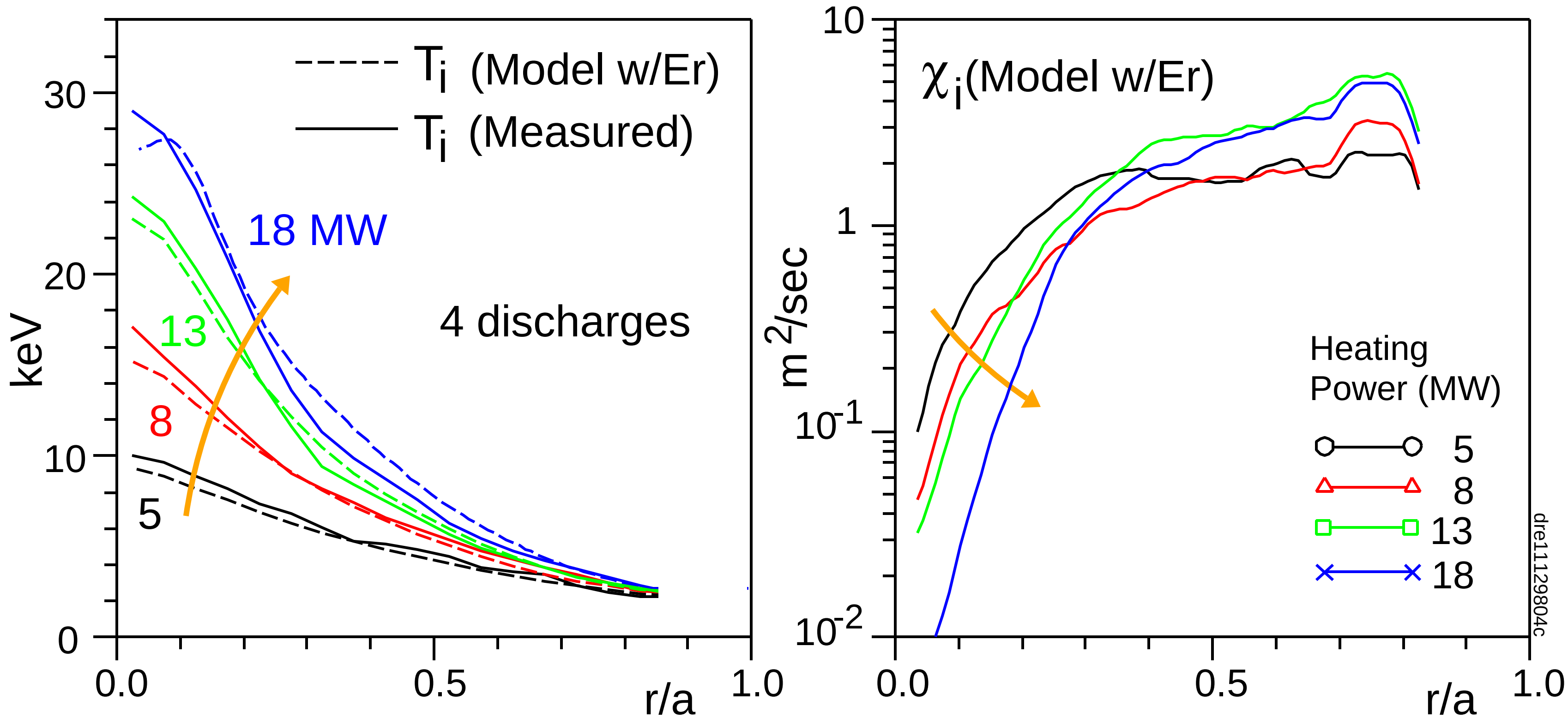
D Pellet decouples T_i & E_r from n_e, creating temperature scan



- Rapid recovery of density profile largely removes influence of toroidal ITG mode stability for later times
- T_i/T_e dependence not sufficient to account for observed recovery
- E_r shear necessary to reproduce extended recovery of T_i

Transport-suppressed core expands with heating power

- E_r shear plays essential role



- Model provides explanation for apparent $\chi_i \propto 1/T_i$ scaling at fixed radius previously observed (Meade, IAEA '90)
- Supershot behavior resembles weak and reverse shear internal barrier behavior on DIII-D, JET, JT60-U, etc. (Burrell, Rettig, Greenfield, Gormezano, Koide, Ishida, ...)

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Er shear plays unique role in D-T supershot isotope effect

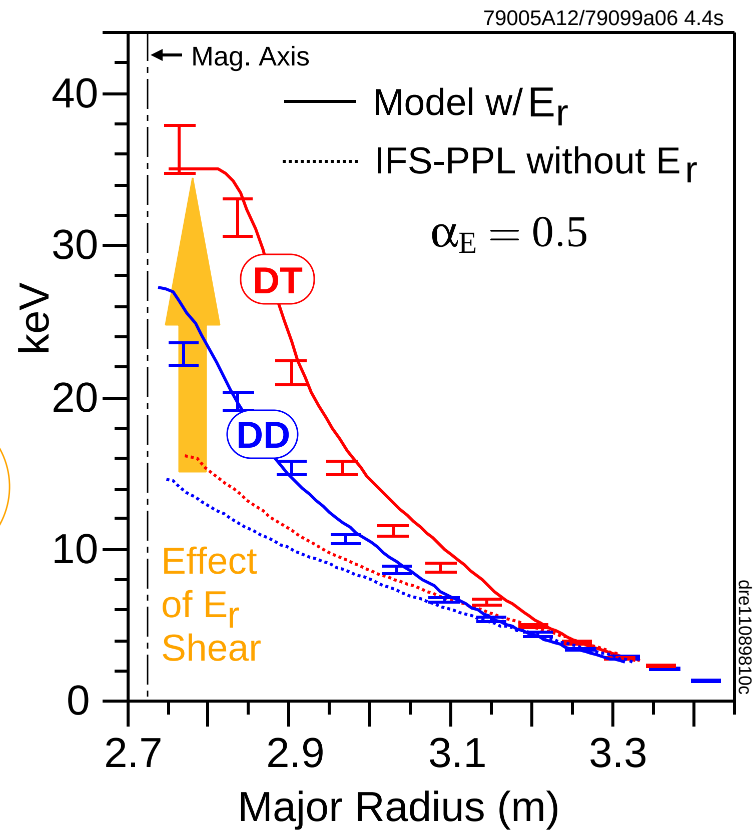
- Growth rate inversely proportional to $\sqrt{A_i}$

- Consistent with $\gamma_{lin}^{max} \simeq \alpha_E \omega_{E\times B}$, using $E_r \simeq \alpha_{T\theta} T_i B$:

$$(k_\theta \rho_i)_{max} \frac{T_e}{T_i} \left(\frac{R}{L_T} - \frac{R}{L_T^{crit}}\right) \frac{v_{thi}}{R} \simeq \alpha_{T\theta} \frac{1}{1 + d\Delta/dr} \frac{T_i}{L_T}$$

giving

$$\frac{1}{L_T} = \frac{1}{L_T^{crit}} \times \frac{1}{1 - \frac{\alpha_E}{(k_\theta \rho_i)_{max}} \frac{T_i}{T_e} \frac{\alpha_{T\theta} T_i}{v_{thH}} \frac{1}{1 + d\Delta/dr} \sqrt{A_i}}$$



- Implies stronger effect at high T_i:

  Supershot: $\tau_E \propto A^{0.89}$

  L-Mode: $\tau_E \propto A^{0.2-0.5}$

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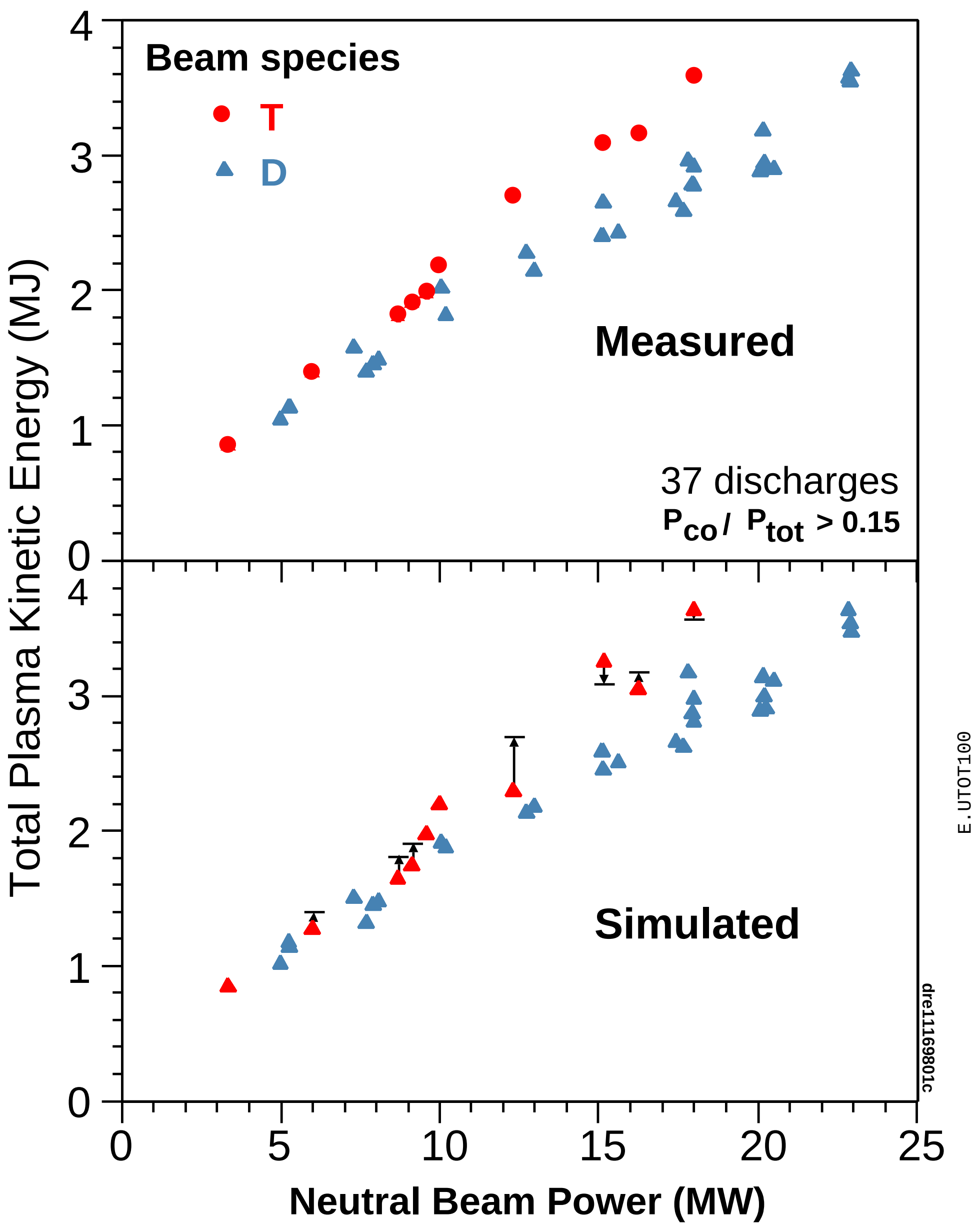
Stronger isotope effect at higher beam powers



Original experiments designed to isolate isotope effect from

$\chi_i \propto 1/T_i$

[Scott, APS inv. 94 & Zarnstorff, IAEA 94]

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Model distinguishes isotope effect except for strong toroidal rotation

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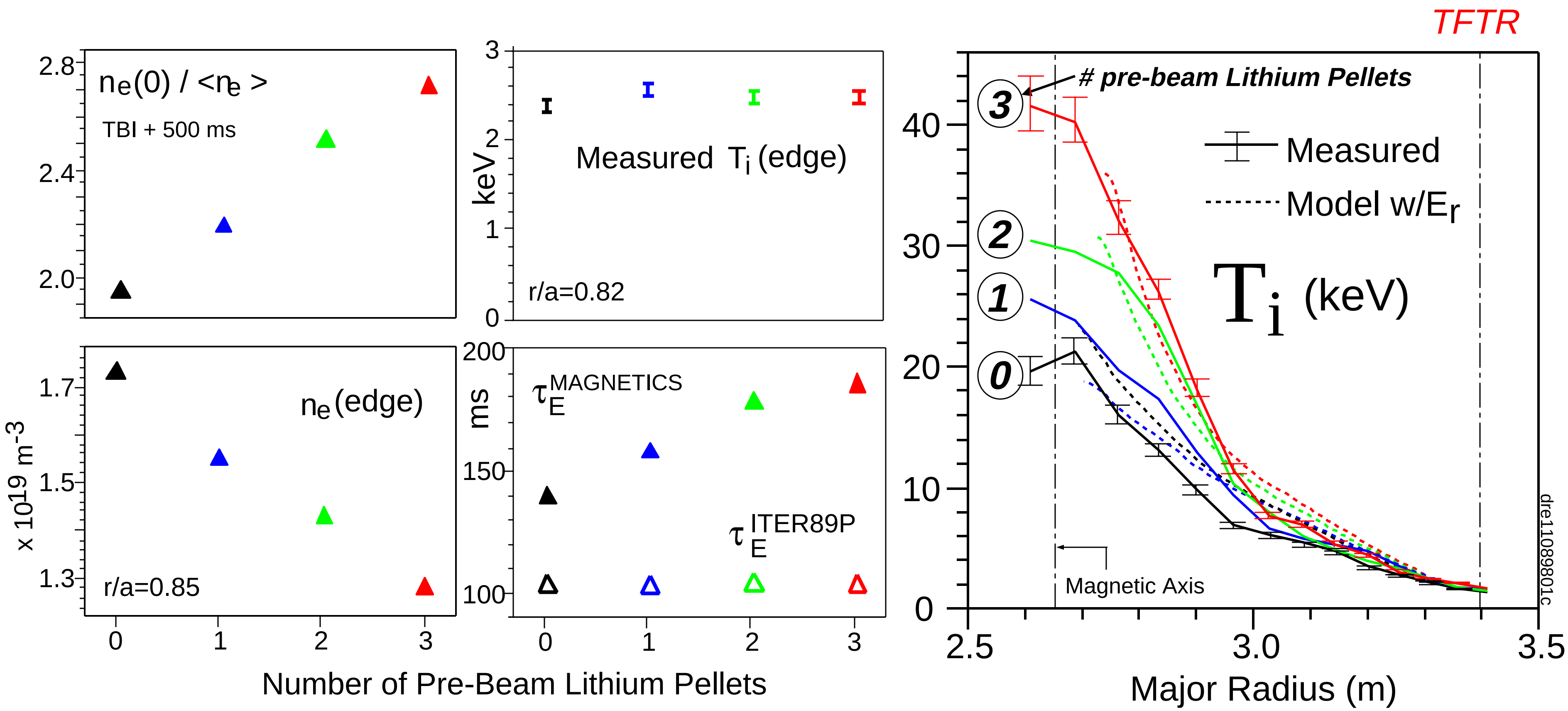
Dramatic improvements with Lithium injection



- Pre-beam Li pellets reduce edge recycling during beam heating
- With three pellets: density 50% more peaked; T_i doubles
- Model with Er shear reproduces large change in T_i
- Improvement due to coupled improvements in particle and ion thermal transport - edge Ti is constant

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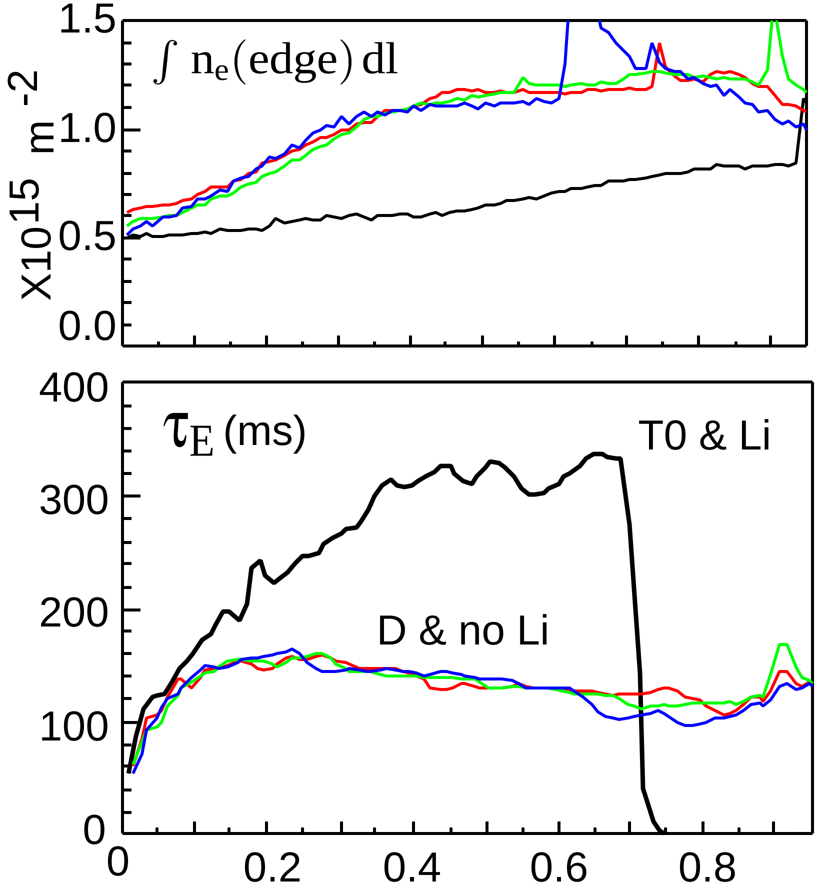
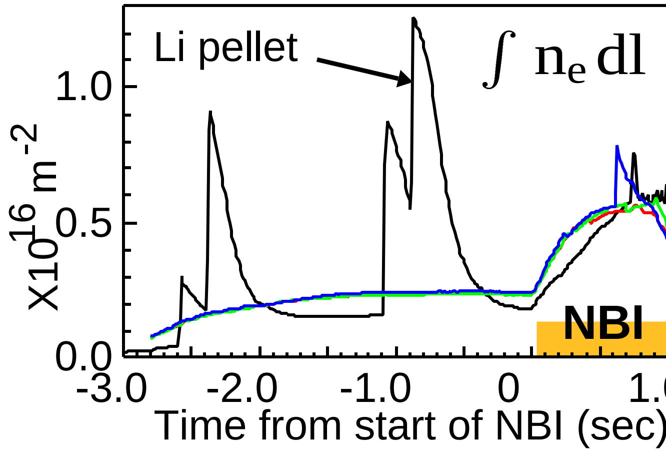
Pre-beam Lithium pellet injection produced 330 ms confinement time in TFTR supershots

Lower edge density allows better beam penetration and very peaked density profiles





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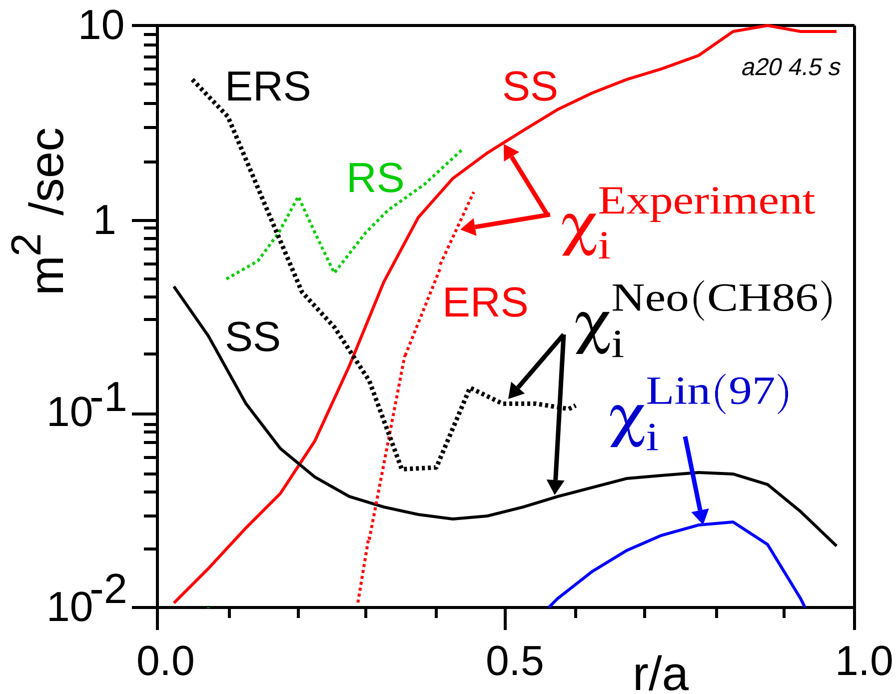

TFTR record $n_i\tau_E T_i$ discharge with 4 Li pellets (83546)

D. K. Mansfield et al., APS Inv. 1996

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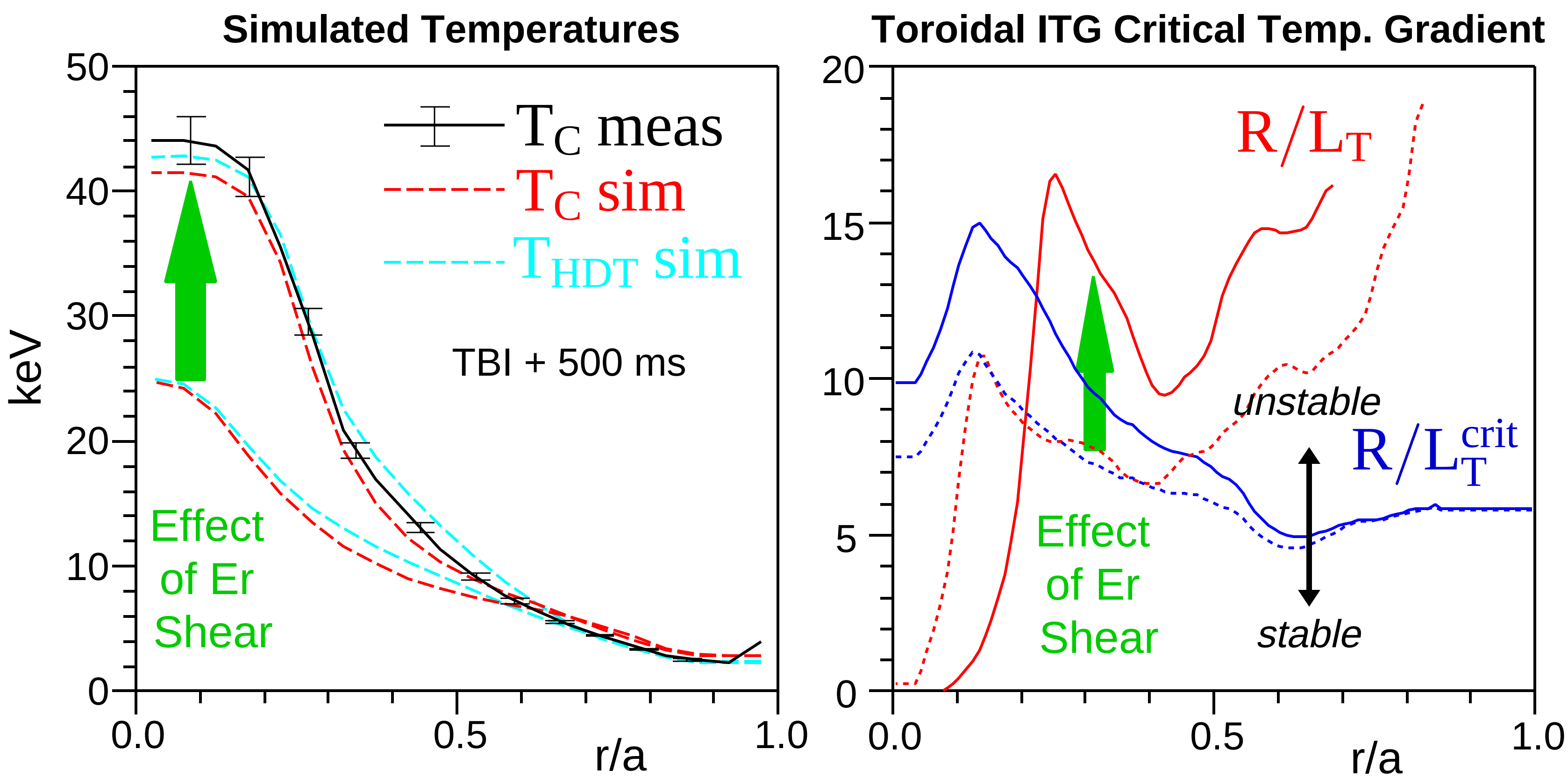
Radial electric field shear is necessary to reproduce high-confinement Lithium-enhanced supershots

TFTR record $n_i \tau_E T_i$ discharge with 4 Li pellets (83546) *D. K. Mansfield et al., APS Inv. 1996*



- E_r shear required to reach measured temperature gradient
- Using $\alpha_E \omega_{E\times B} \simeq \gamma_{lin}^{max}$ & $E_r \simeq -v_\theta B_\varphi$:

$$\frac{R}{L_T} = \frac{R}{L_T^{crit}} \times \left\{1 - \alpha_E \frac{4T_i}{T_e} \frac{\alpha_{T\theta}}{310} \sqrt{T_i(\mathrm{keV})A_i}\right\}^{-1}$$

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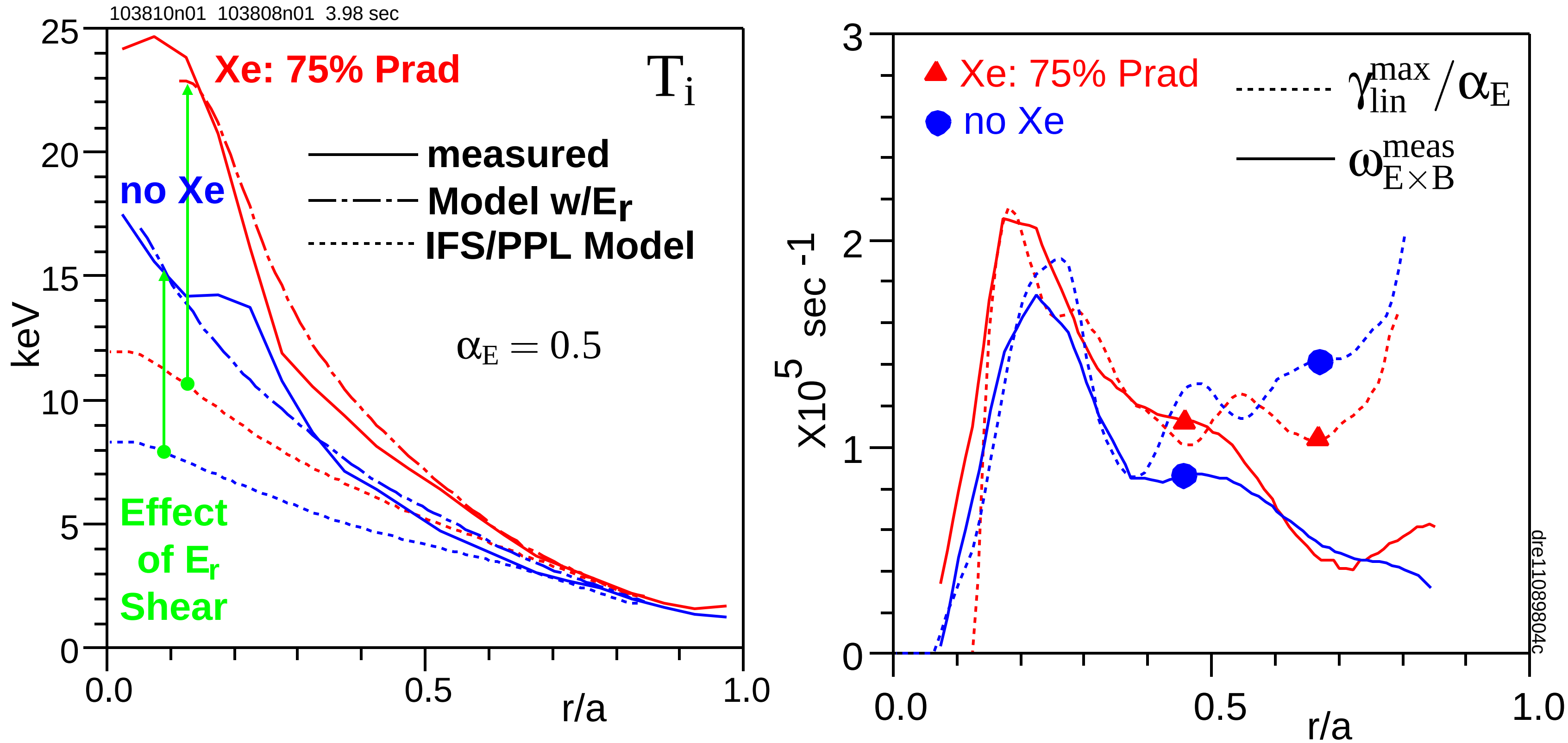
Role of Er shear in paradoxical improvements with xenon



- Edge recycling lower, density more peaked with Xe puffing, reducing ITG growth rate (dilution negligible)
- Core E_r shear larger, amplifies improvement in T_i, couples back to particle confinementd

See also Ernst, IAEA '98

Original experiments: K. W. Hill, APS '97, IAEA '98

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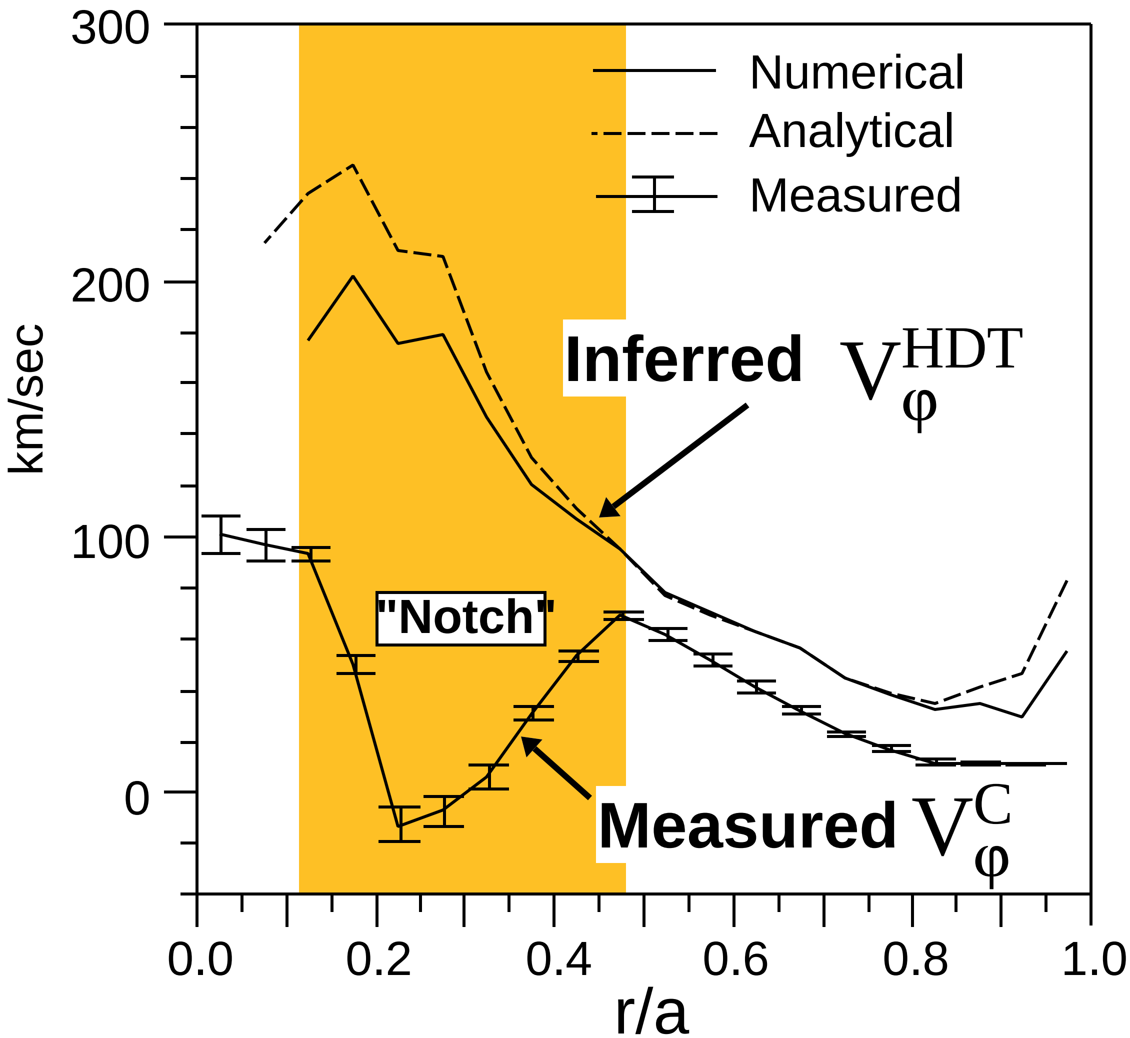
Neoclassical part of previous model reproduces "notch" in measured toroidal velocity profiles



Phys. Plasmas, March (1998)

- Compute $V_\varphi^{HDT} - V_\varphi^{C}$ from neoclassical theory (4x4 matrix) add to measured V_φ^{C} to obtain V_φ^{HDT}
- "Notch" due to temperature gradient

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Model with E_r shear draws together disparate features of enhanced ion thermal confinement in TFTR

- Turbulence suppression of toroidal Ion Temperature Gradient Turbulence by intrinsic, equilibrium E_r shear

- Criterion for near-complete turbulence suppression describes supershot core Ti profiles (self-regulating scenario):

  (ExB shearing rate) ~ (toroidal ITG growth rate)

- Now using parameterization of measured poloidal rotation
  - Originally used multi-species TRV neoclassical calculation
  - New measurements show $v_\theta \propto T_i$

- Evolving toward predictive capability consistent with new poloidal rotation measurements

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[1] D. R. Ernst, R. E. Bell, M. G. Bell, R. V. Budny, M. Beer, B. Coppi, G. W. Hammett, R. J. Hawryluk, K. W. Hill, D. K. Mansfield, D. R. Mikkelsen, M. Porkolab, G. Rewoldt, S. D. Scott, E. J. Synakowski, M. C. Zarnstorff and the TFTR Group, Invited Paper J5I1.04, presented at the Annual Meeting of the American Physical Society Division of Plasma Physics, New Orleans, 16-20 November, 1998. Submitted to *Physics of Plasmas*.

[2] D. R. Ernst, S. Batha, M. Beer, M. G. Bell, R. E. Bell, R. V. Budny, B. Coppi, W. M. Dorland, P. C. Efthimion, T. S. Hahm, G. W. Hammett, R. J. Hawryluk, K. W. Hill, M. Kotschenreuther, F. M. Levinton, Z. Lin, D. K. Mansfield, D. R. Mikkelsen, R. Nazikian, M. Porkolab, G. Rewoldt, S. D. Scott, E. J. Synakowski, M. C. Zarnstorff and the TFTR Group, *17th IAEA Fusion Energy Conference*, Yokohama, Japan, 19-24 October 1998, paper IAEA-F1-CN-69/EXP1/14(R). Also to appear in *Nuclear Fusion.*

[3] D. R. Ernst, B. Coppi, S. D. Scott, M. Porkolab, TFTR Group, *Phys. Rev. Lett.* **81** (1998) 2454.

[4] D. R. Ernst, “Radial Electric Field and Model for TFTR Supershot Confinement,” Invited Talk, 1998 DOE National Transport Task Force Meeting, Atlanta, GA, March 18-20, 1998.

[5] D. R. Ernst, M. G. Bell, R. E. Bell, C. E. Bush, Z. Chang, E. Fredrickson, L. R. Grisham, K. W. Hill, D. L. Jassby, D. K. Mansfield, D. C. McCune, H. K. Park, A. T. Ramsey, S. D. Scott, J. D. Strachan, E. J. Synakowski, G. Taylor, M. Thompson, R. M. Wieland, “Notched Velocity Profiles and the Radial Electric Field in High Ion Temperature Plasmas on the Tokamak Fusion Test Reactor,” *Physics of Plasmas* **5** (1998) 665-681.

[6] D. R. Ernst, Ph.D. Thesis, Physics Dept., Massachusetts Institute of Technology, Cambridge, MA, 1997.

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