Confinement in TFTR and Alternative Approaches to Ignition

M.G. Bell, R.V. Budny, D.R. Ernst, D.M. Meade, D.R. Mikkelsen

Princeton Plasma Physics Laboratory
P.O. Box 451, Princeton, N.J. 08543-0451

Abstract

One of the main conclusions drawn from the experiments in TFTR, and other tokamaks with neutral beam heating, is that energetic ions are very well confined in the core of conventional tokamaks. In TFTR, this was first apparent in the Supershot regime, where the ion temperature approached the convective limit, and, more recently, in the Enhanced Reversed Shear regime where the ion transport approached neoclassical levels. Experiments with ICRF heating and the fusion alpha particles in D-T plasmas support the conclusion. This suggests that it may be possible to approach D-T ignition with substantially lower electron confinement and somewhat lower total plasma pressure than normally considered necessary. Such an alternative was first discussed by Clarke [J.F. Clarke, Nuclear Fusion, **20** (1980) 563]. Indeed, as predicted then, the plasma conditions (density and temperatures) necessary for hot-ion ignition were approached in TFTR, although the confinement was still too low to permit alpha particle heating to dominate. Aspects of the confinement scaling and future possibilities will be presented.

Conventional Approaches to Ignition Are Too Expensive

- ITER design based on sawtoothing, ELMy H-mode scaling:

$$\tau_E \propto H \cdot I_p \cdot R^2 \cdot P^{-0.5}$$

  - Fusion power requirement (~1GW) set by nuclear mission
  - Negative power dependence must be offset by large plasma current
- Confinement characteristics of H-mode ($\chi_I \approx \chi_e$) mean $T_I < T_e$
  - alpha particles heat electrons preferentially
  - More β in non-reacting electrons
- High density in edge region (H-mode barrier) where T_I below optimum
- Sawtooth relaxations prevent peaking of pressure profile

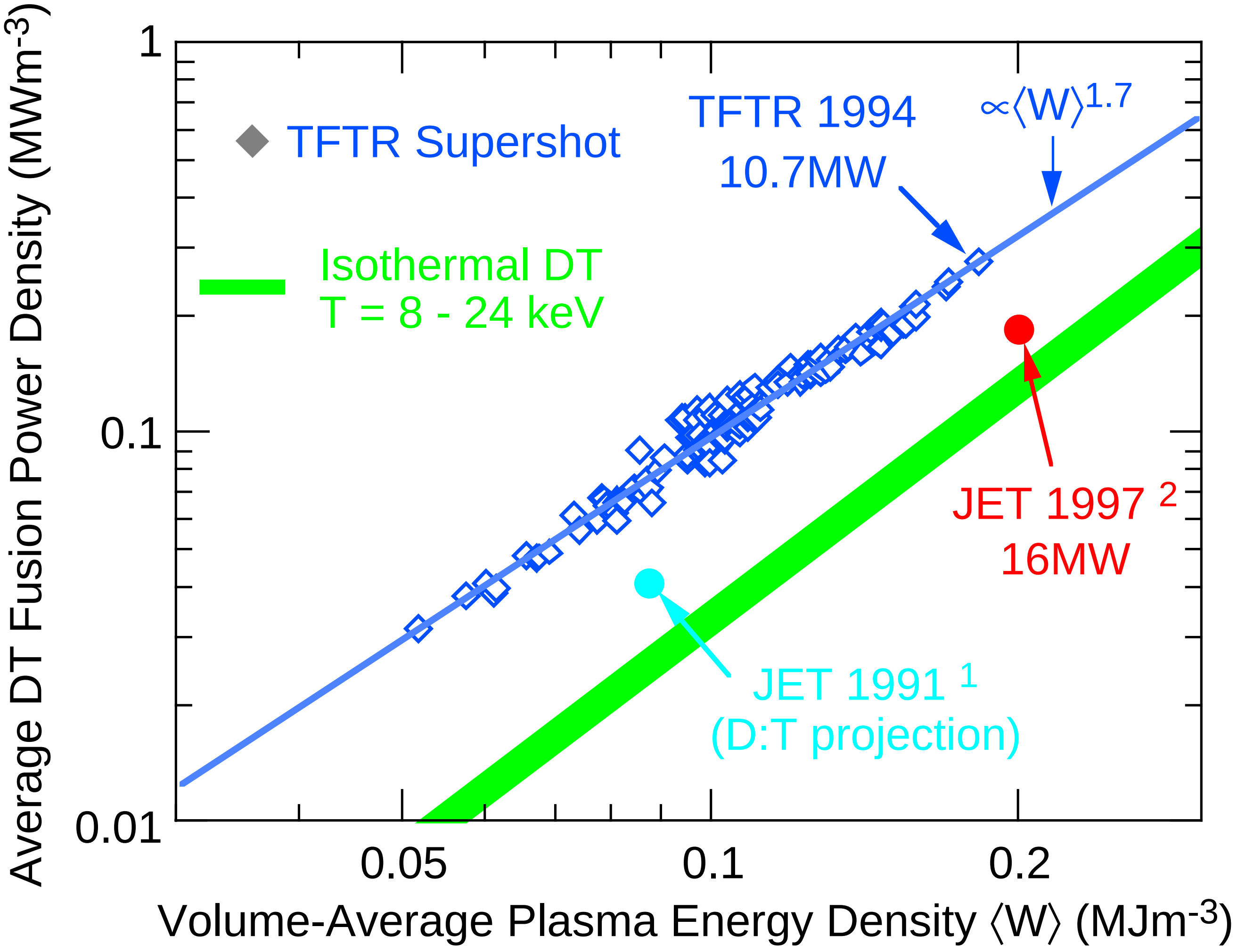
$\Rightarrow$ *Poor ratio of fusion power to square of volume-average plasma pressure*

Ignited Plasmas with $T_i > T_e$ are Possible and Interesting

- Success of hot-ion operation with neutral beam heating in PLT (H. Eubank *et al.*, Proc. 7th IAEA Conf., Innsbruck,1978)
- J.F. Clarke investigated the possibility of ignition with $T_I > T_e$ (Nucl. Fusion **20** (1980) 563
  - neoclassical ions: $\tau_{Ei}[s] = 0.73\ I_p[MA]^2\ T_I[keV]^{1/2}\ n_i[10^{20}m^{-3}]^{-1}$
  - Alcator scaling for electrons: $\tau_{Ee}[s] = 0.76\ \ a[m]^2\ n_e[10^{20}m^{-3}]$
  - ⇒ $n\tau$ for ignition reduced by factor ~2 with $T_i \approx 30keV$; $T_e \approx 25keV$
  - ⇒ Improved thermal stability at ignition *but* penalties on β_α
  - ⇒ Further improvement by “channeling” alpha energy directly to ions
- Discovery of L-mode scaling in early 1980’s quelled enthusiasm
  - both electrons and ions worse than originally hoped *but*
  - hot-ion modes continued to produce the best fusion performance

Hot-Ion Plasmas Have High Reactivity

TFTR



*[1]Nuclear Fusion **32** (1992) 187; [2]Phys. Plasmas **5** (1998) 1839*

Comparison of Achieved Plasma Parameters with ITER

Central values	**ITER[1]**	**TFTR**	**JET[2]**	**JT-60U[3]**
Plasma composition	DT	DT	DT	D
Mode	ELMy H-mode	Supershot	Hot-ion ELM-free H-mode	Reversed-shear High-β_P
n_e $[10^{20}m^{-3}]$	1.3	1.02	0.42	0.85
n_{DT} $[10^{20}m^{-3}]$	0.8	0.60	0.35	0.48 (n_i)
n_{He} $[10^{20}m^{-3}]$	0.2	0.002		
T_I [keV]	19	40	28	16
T_e [keV]	21	13	14	7
Z_{eff}	1.8	1.8	2.1	3.2
p_{tot} [MPa]	0.8	0.75	0.37	0.22
P_α $[MWm^{-3}]$ (source)	0.5	0.45	0.14	
P_{aux} $[MWm^{-3}]$	0	3.4	0.8	0.3

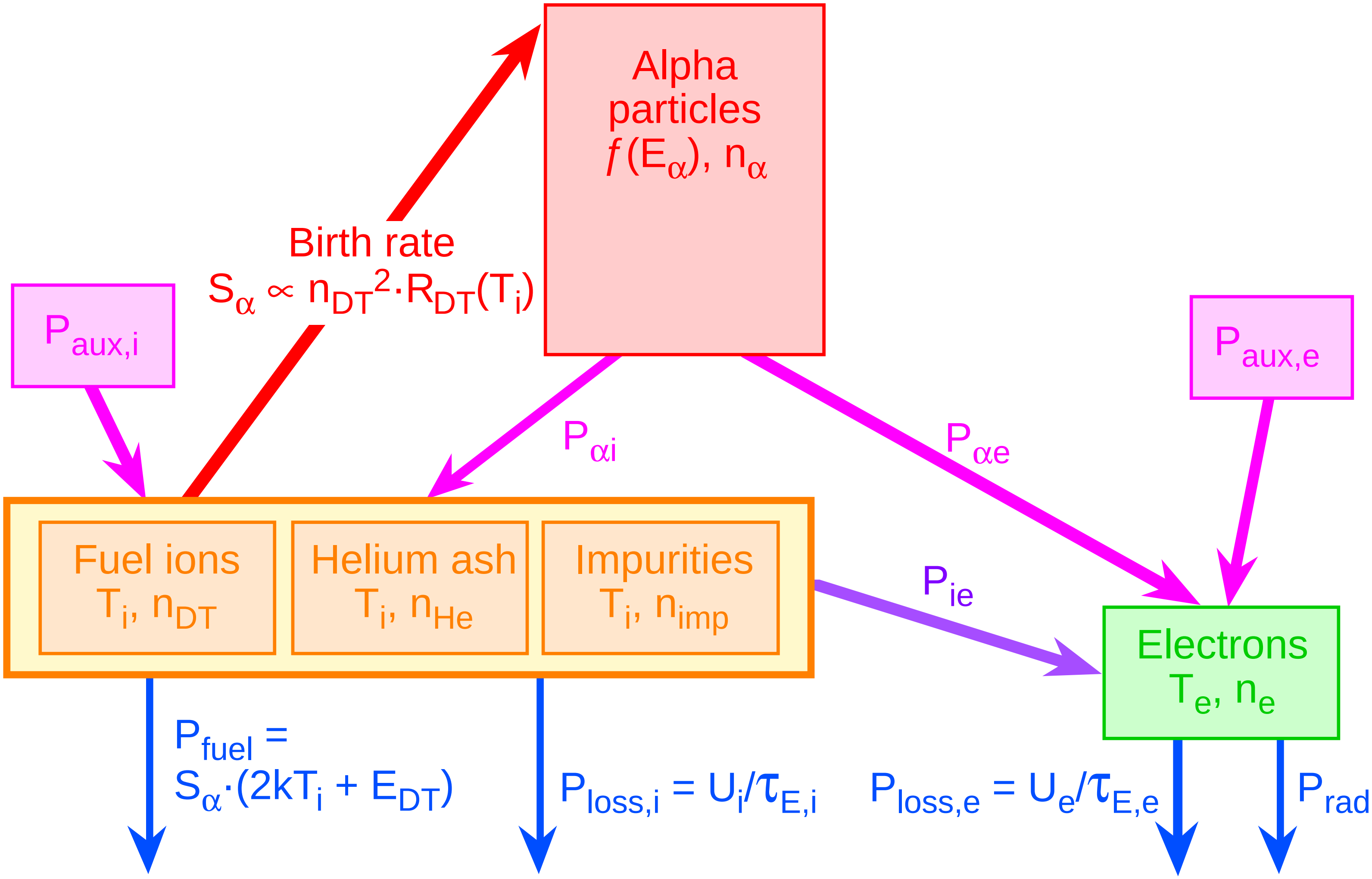
[1] ITER Final Design Review Document

[2] A. Gibson *et al.* Phys. Plasmas **5** (1998) 1839

[3] S. Ishida *et al.*, paper IAEA-CN-69/OV1/1, IAEA Fusion Energy Conference, Yokohama, Oct. 1998

- *Confinement and pulse length are the remaining issues!*

Power Flow in an Ignited Plasma



Alpha particles
$f(E_\alpha)$, n_α

Birth rate
$S_\alpha \propto n_{DT}^2 \cdot R_{DT}(T_i)$

$P_{aux,i}$

$P_{aux,e}$

$P_{\alpha i}$

$P_{\alpha e}$

Fuel ions
T_i, n_{DT}

Helium ash
T_i, n_{He}

Impurities
T_i, n_{imp}

P_{ie}

Electrons
T_e, n_e

$P_{fuel} =$
$S_\alpha \cdot (2kT_i + E_{DT})$

$P_{loss,i} = U_i/\tau_{E,i}$

$P_{loss,e} = U_e/\tau_{E,e}$

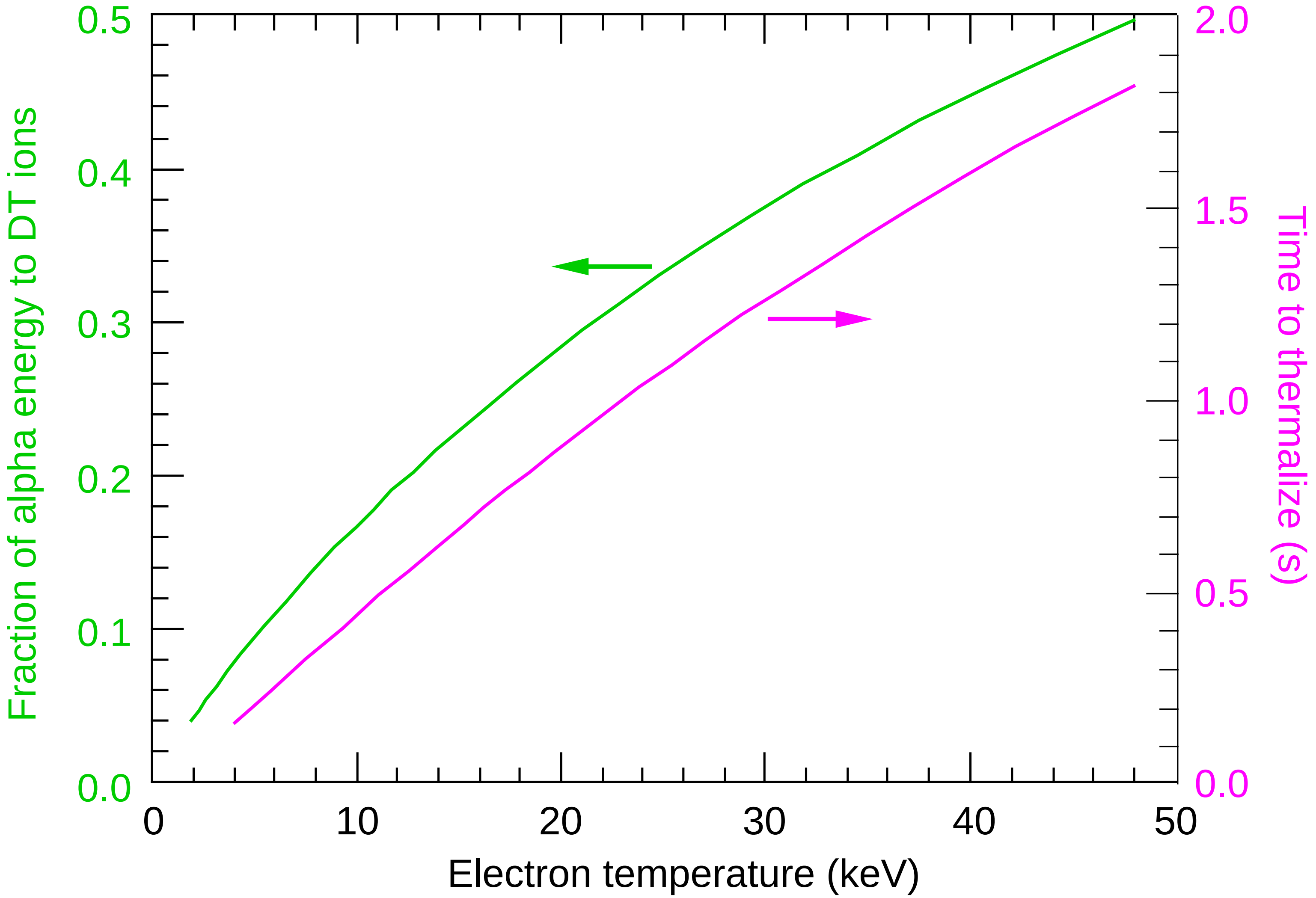
P_{rad}

Steady-State Power Balance in Self-Heated Plasma

- $0 = P_{\alpha i} + P_{aux,i} - P_{ie} - P_{fuel} - \dfrac{U_i}{\tau_{Ei}}$
- $0 = P_{\alpha e} + P_{aux,e} + P_{ie} - P_{rad} - \dfrac{U_e}{\tau_{Ee}}$
- $P_\alpha = P_{\alpha i} + P_{\alpha e} = E_{\alpha 0} \cdot n_D \cdot n_T \cdot \langle \sigma_{DT} \cdot v \rangle_{T_i}$
- $\dfrac{dE_\alpha}{dt} = -(\nu_E^{(\alpha e)} + \sum_i \nu_E^{(\alpha i)})\, E_\alpha$ Integrate from birth to thermal energy assuming perfect confinement
- $\nu_E^{(\alpha e)} = 10.1 \cdot \lambda_{\alpha e} \cdot n_e \cdot T_e^{-3/2} \cdot (1 - {}^{3}\!/_{2}\, T_e / E_\alpha)$ [s^{-1}; $10^{20}m^{-3}$; keV]
- $\nu_E^{(\alpha i)} = 4.6 \times 10^3 \cdot \lambda_{\alpha i} \cdot \dfrac{Z_i^2}{A_i} n_i \cdot E_\alpha^{-3/2} \cdot \mathbf{F}_i(E_\alpha / T_i)$; $\mathbf{F}_i \sim 1$ [s^{-1}; $10^{20}m^{-3}$; keV]
- $P_{ie} = 0.24 \cdot \lambda_{ie} \cdot \dfrac{(T_i - T_e)}{T_e^{3/2}} \cdot n_e \cdot \sum_i \dfrac{Z_i^2}{A_i} n_i$ [MWm^{-3}; keV; $10^{20}m^{-3}$]
- *P_α and $P_{ie} \propto n^2 \Rightarrow$* ***$T_i/T_e$ independent of density***

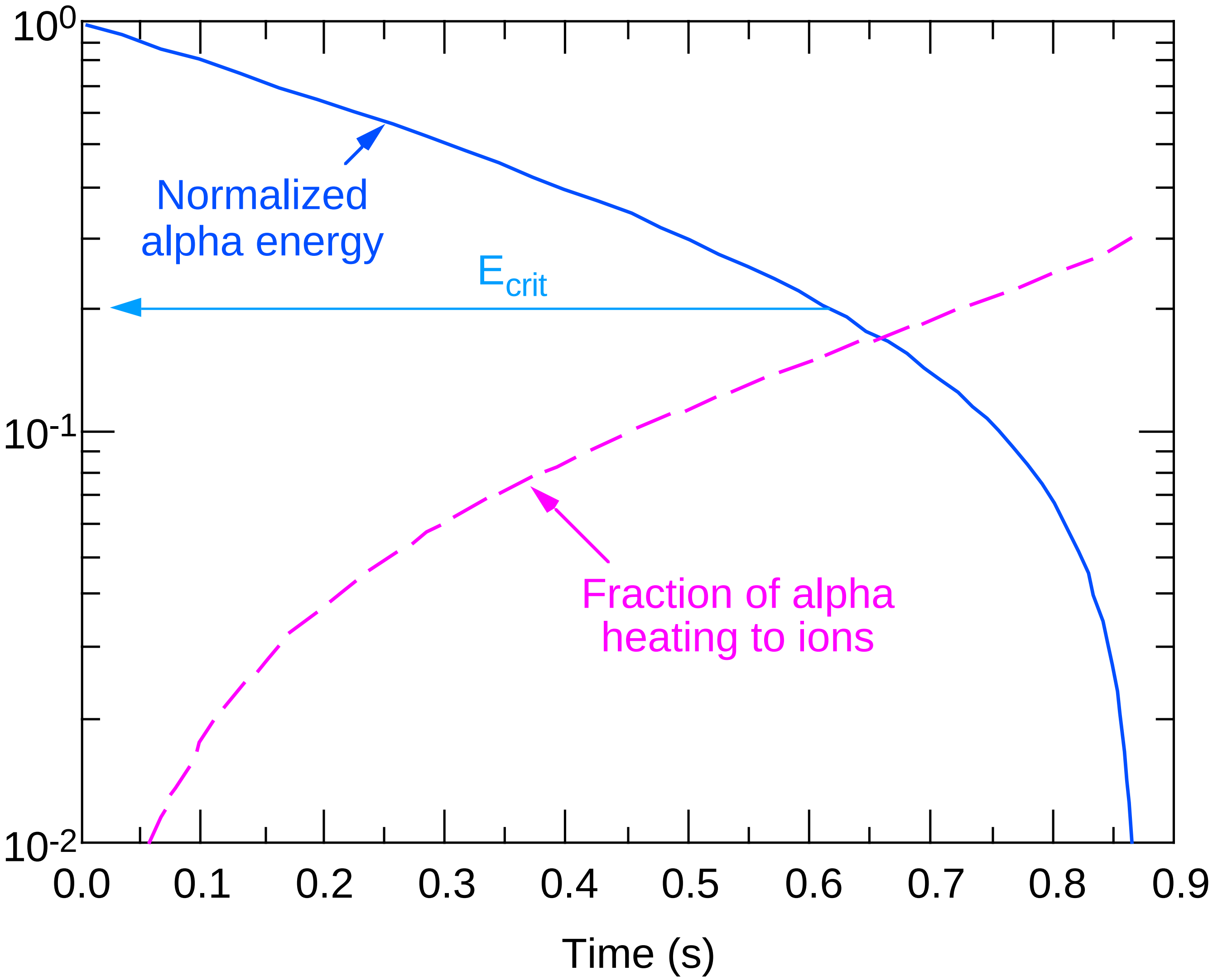
Substantial Direct Alpha Heating of Ions for T_e > 15 keV

$n_e = 1.0 \times 10^{20} m^{-3}$, $n_{DT} = 0.9 \times 10^{20} m^{-3}$, $Z_{eff} = 1.50$, $Z_{imp} = 6.0$

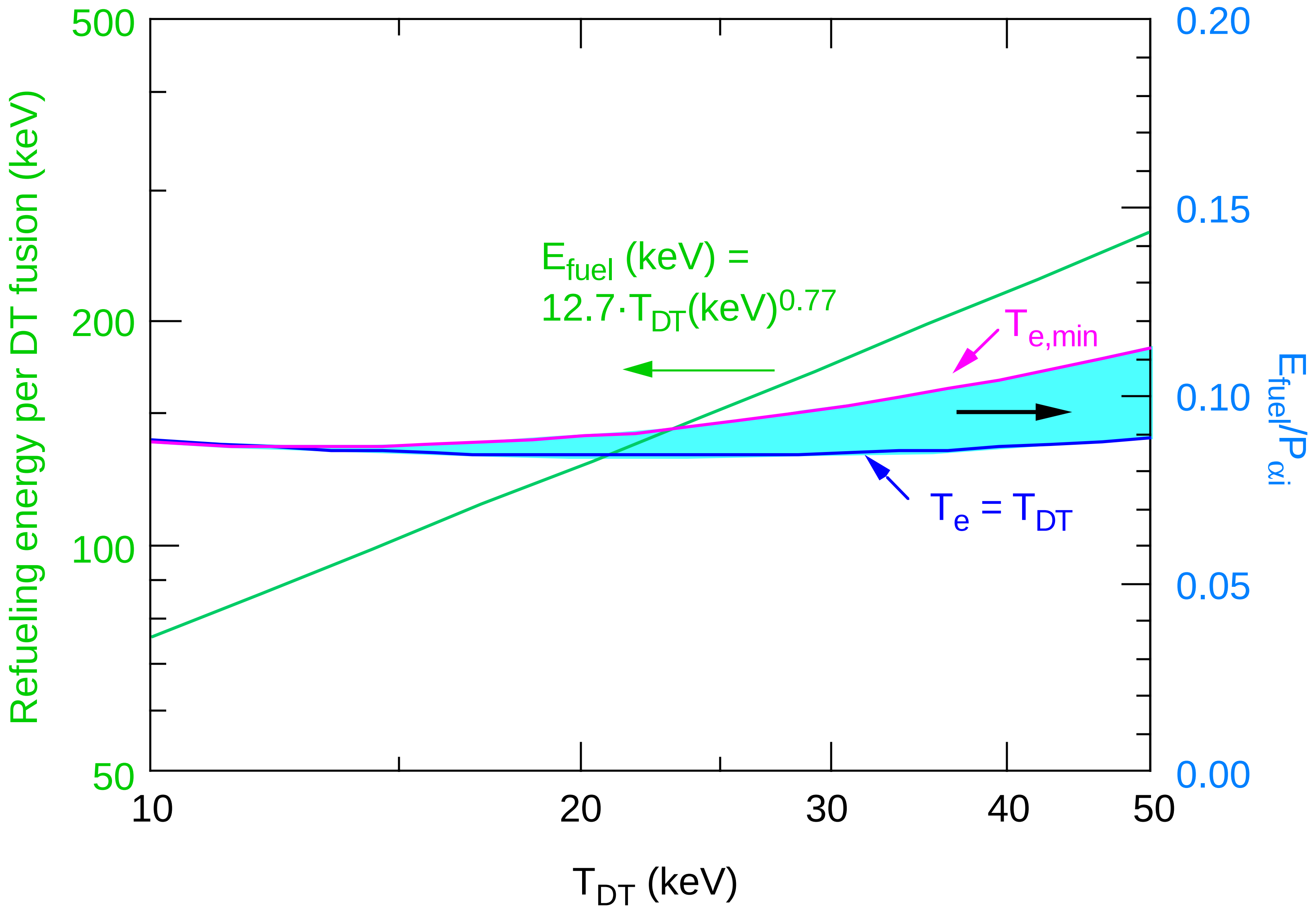


Good Alpha Confinement Essential for Ion Heating

$T_e = T_i = 20\text{keV}; n_e = 1.0 \times 10^{20}\text{m}^{-3}$, H:D:T=0.06,0.47,0.47; Z_{eff}=1.50



Refueling Power is Significant in Self-Heated Plasmas

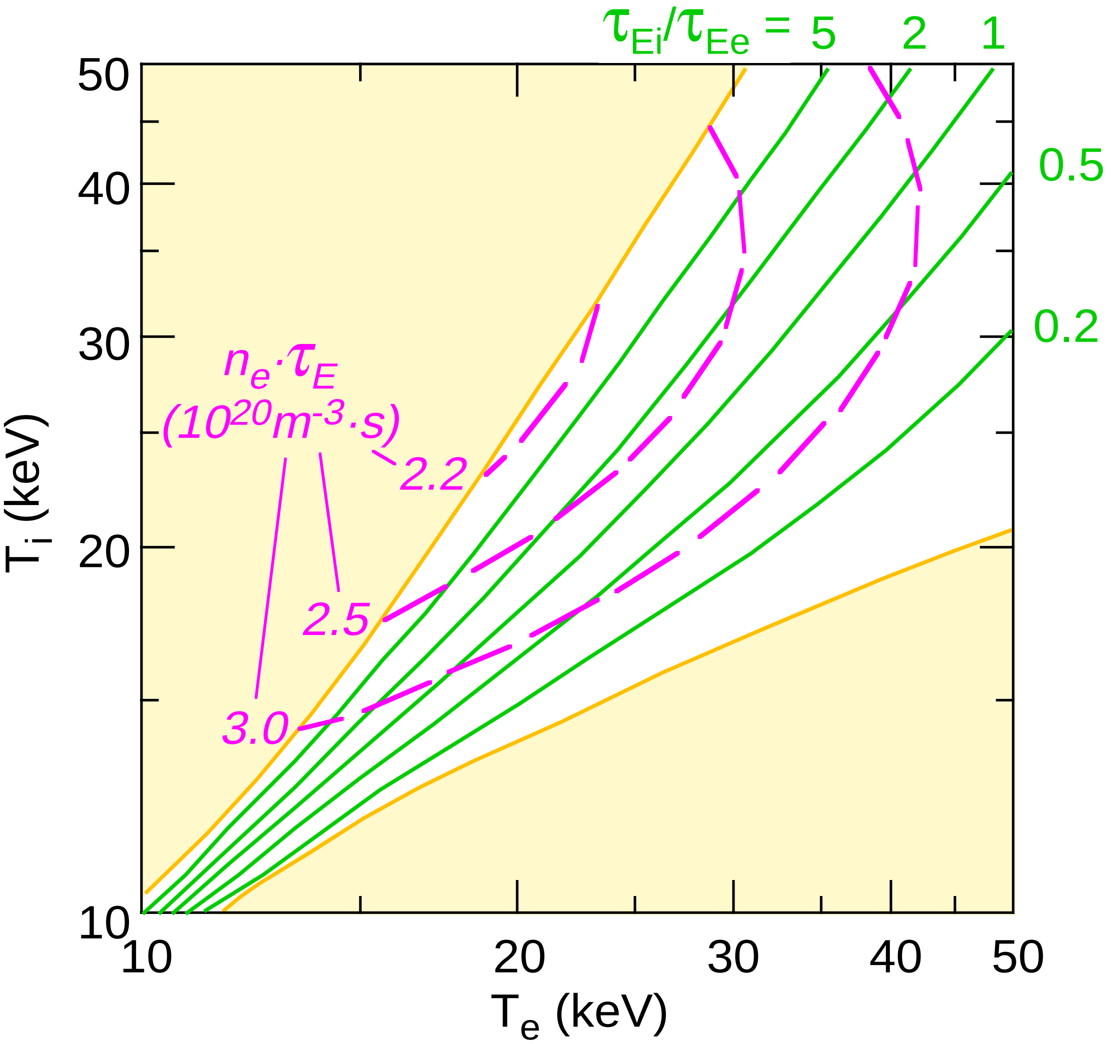


0-D Solutions of Power Balance Equations

TFTR

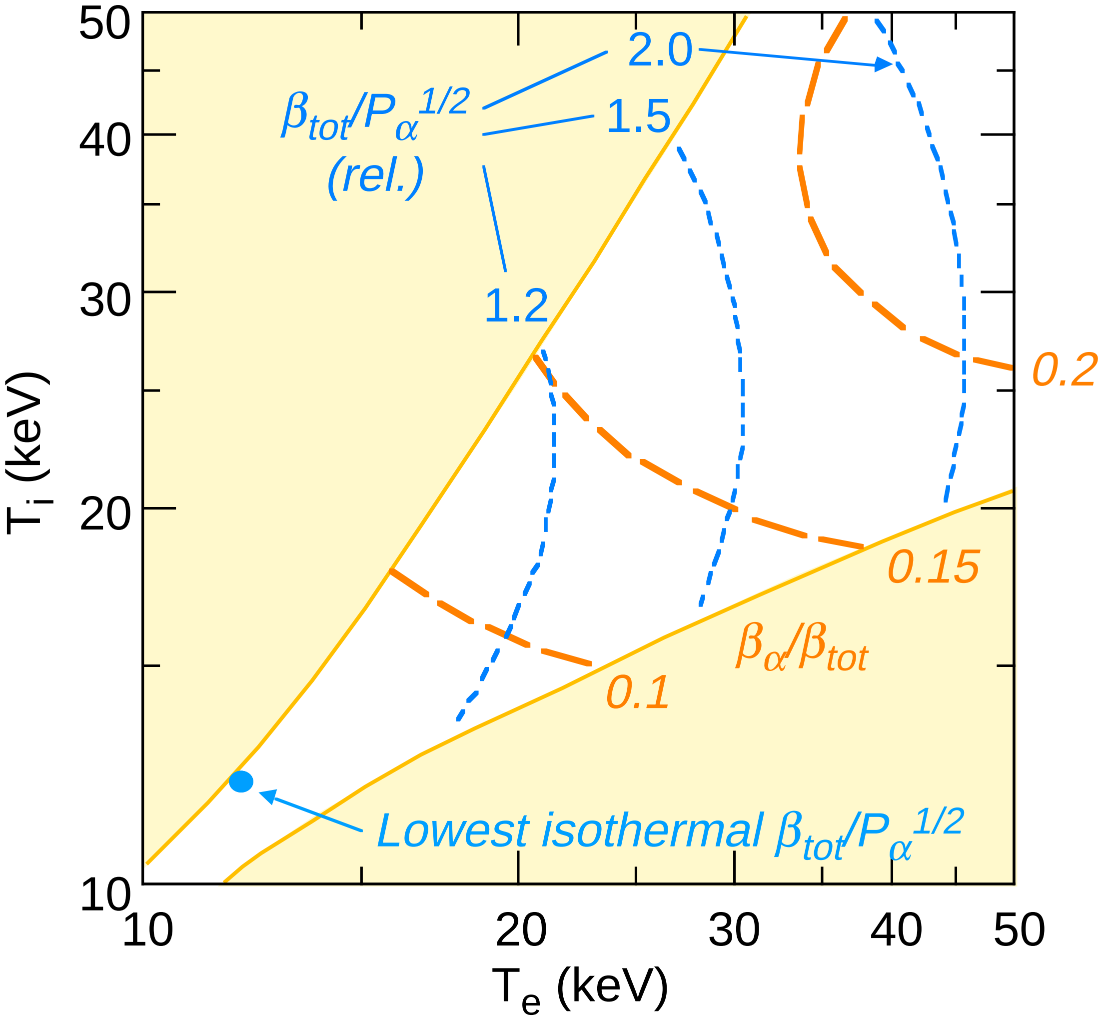
- Fix composition of isothermal, isobaric plasma:
  - $n_{DT} : n_H : n_{He} : n_C = 0.80 : 0.05 : 0.05 : 0.01$
  - based on TFTR experience with addition of helium ash
- Choose global Q and partition of auxiliary heating, $P_{aux,i}$, $P_{aux,e}$
- Scan through T_i, T_e space, calculating self-consistently
  - DT reaction rate
  - Alpha heating terms $P_{\alpha i}$, $P_{\alpha e}$, unthermalized alpha density n_α, β_α, n_e
  - Ion-electron coupling P_{ie}, refueling power P_{fuel}
  - Conducted power and implied confinement time
- Calculate limits of accessible region and contours of $n\tau$, β_α/β_{tot} *etc.*

Good Ion Confinement Produces Hot-Ions at Ignition



- Total nτ requirement reduced by improving ion confinement

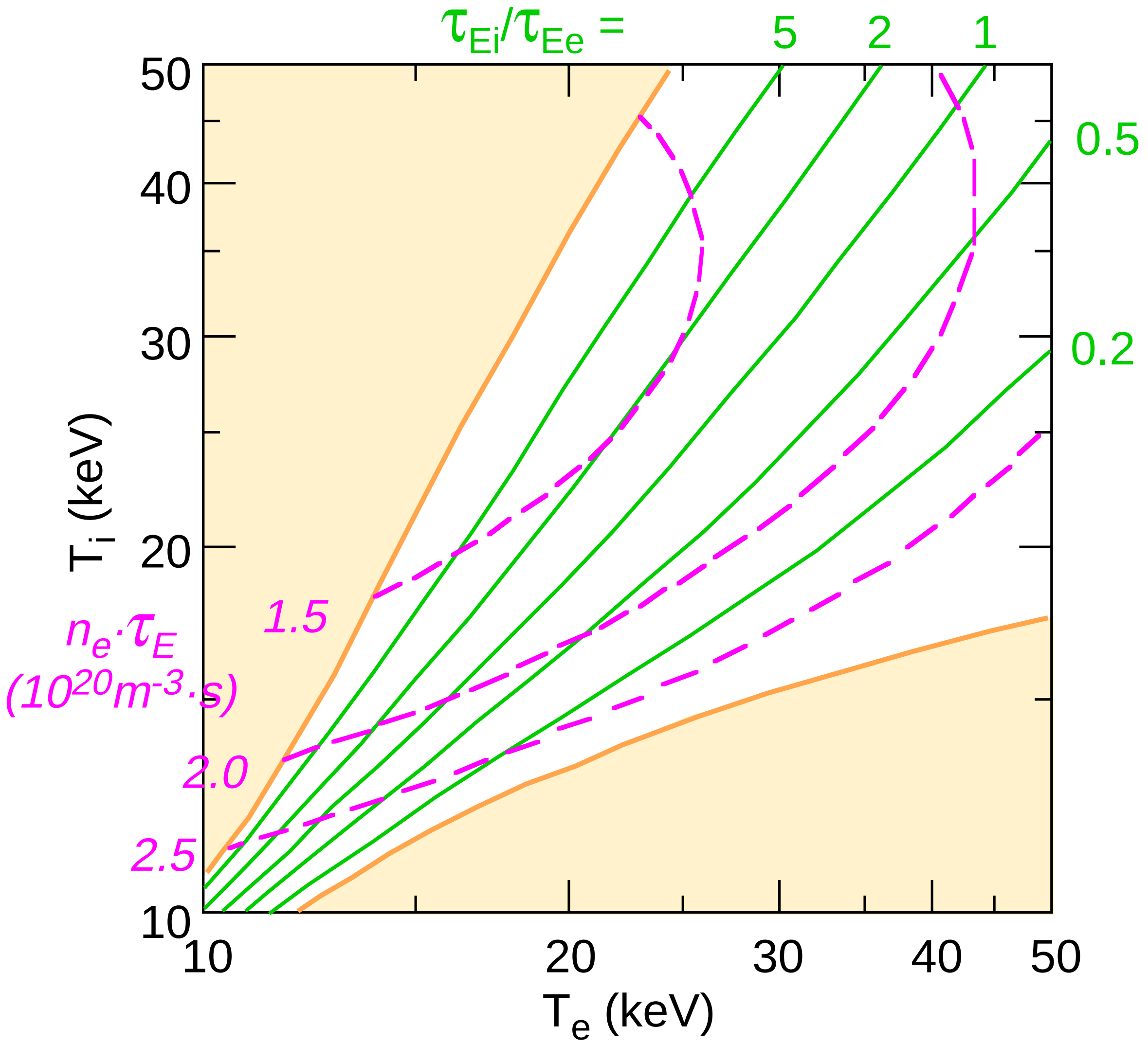
Penalty is Higher β_{tot} and β_α/β_{tot}



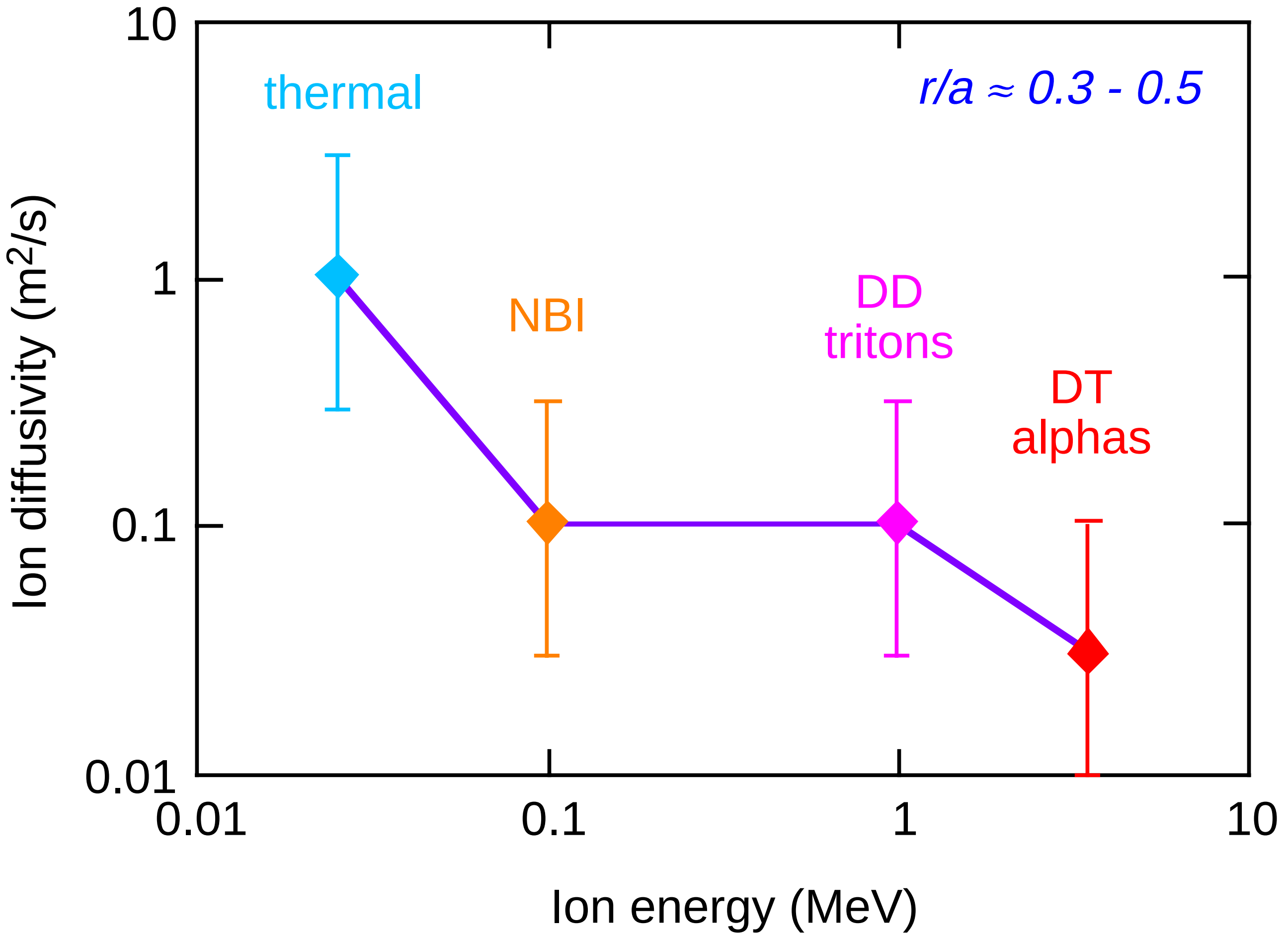
- Cannot simultaneously minimize $n\tau$ and β_{tot} at ignition

Regime Expands for High-Q with Preferential Ion Heating

- **Q = 10; $P_{i,ext}$ / $P_{e,ext}$ = 2**



Apparent Ion Diffusivity Decreases with Ion Energy in TFTR

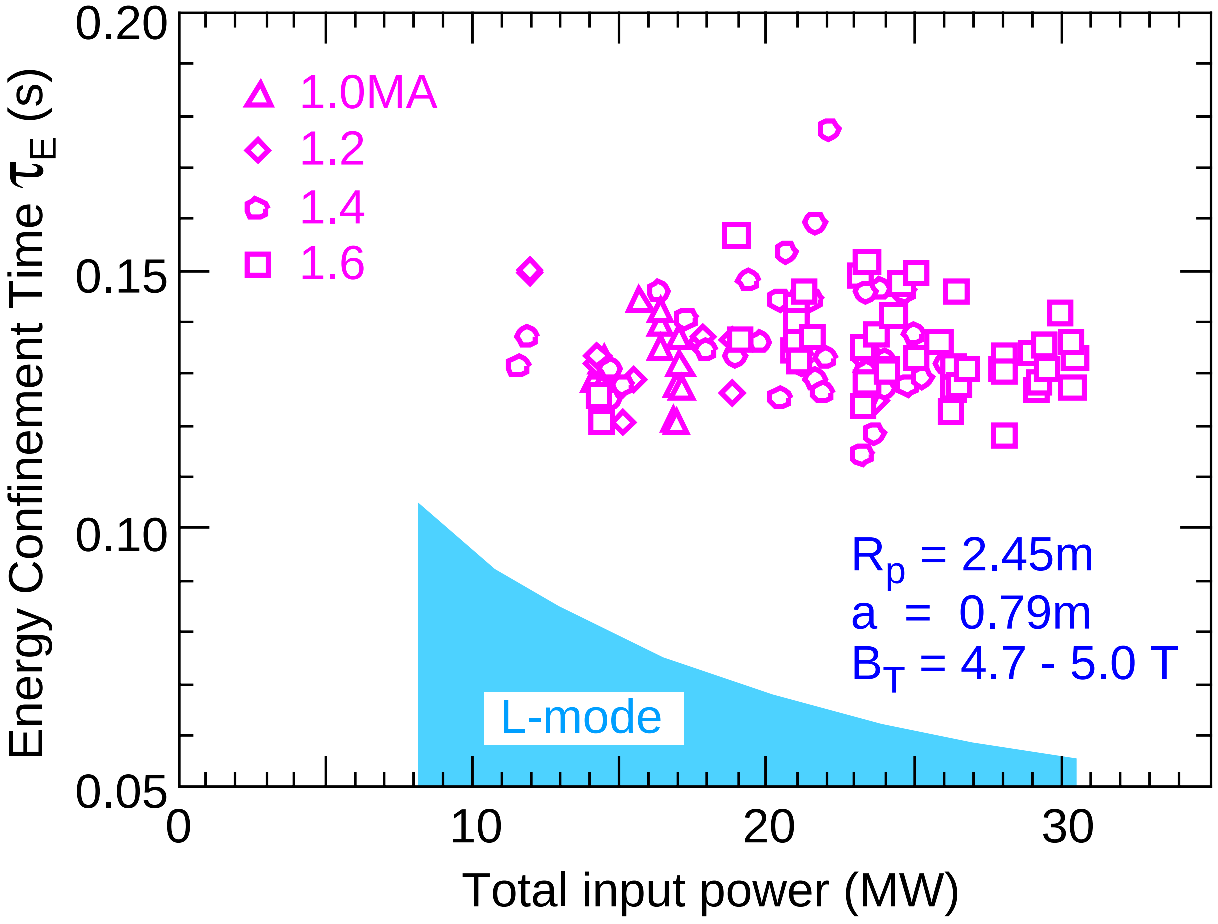


S. Zweben,
J. Strachan,
E. Ruskov,
P. Efthimion

- Diffusivity for alphas is probably adequate for achievement of hot-ion ignited regime.

Supershot Confinement does not Degrade with Power

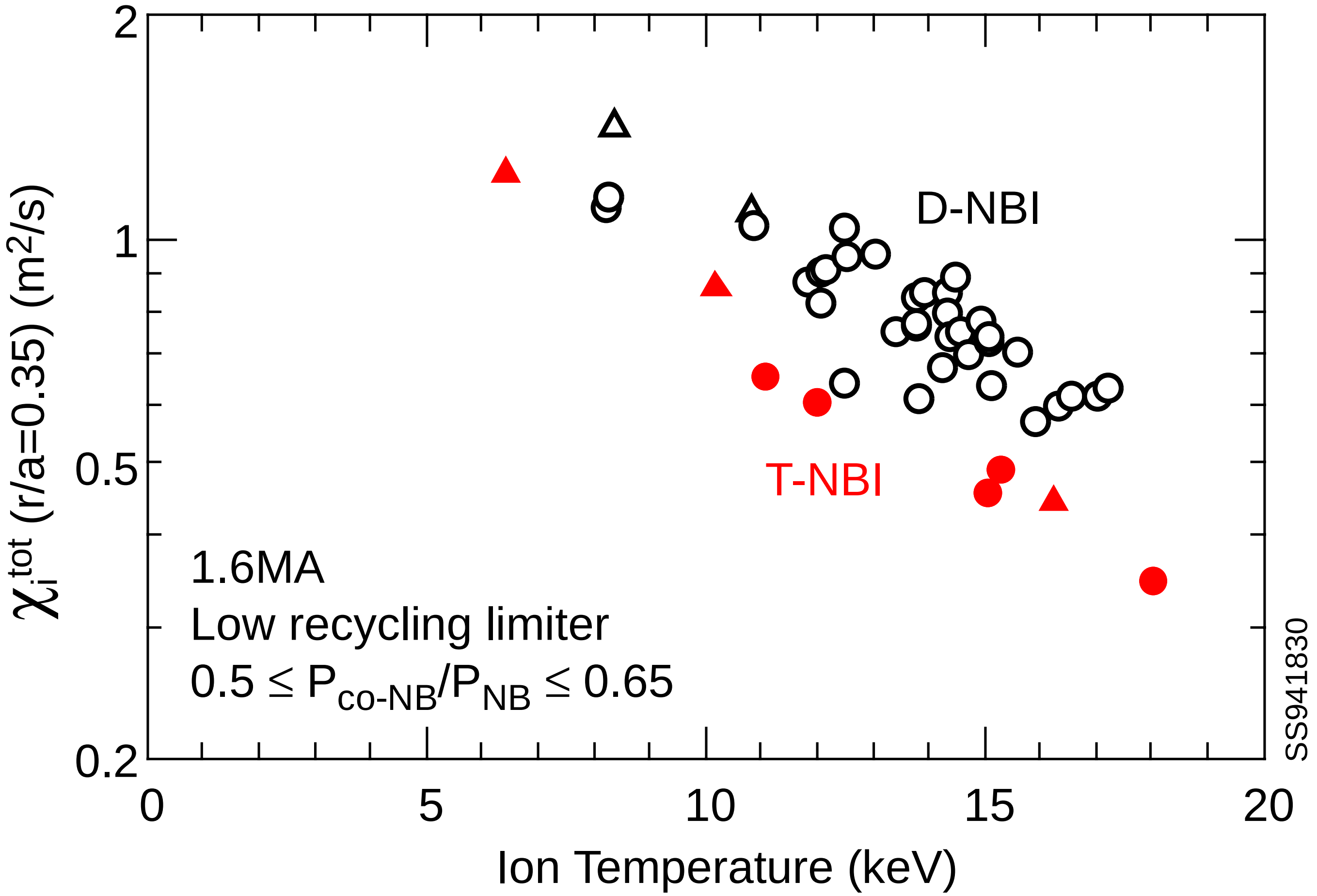
TFTR



- Confinement dependent on “non-traditional” scaling parameters
  - created difficulties for comparing tokamaks to develop scaling

Ion Thermal Diffusivity Appears to Decreases with T_I

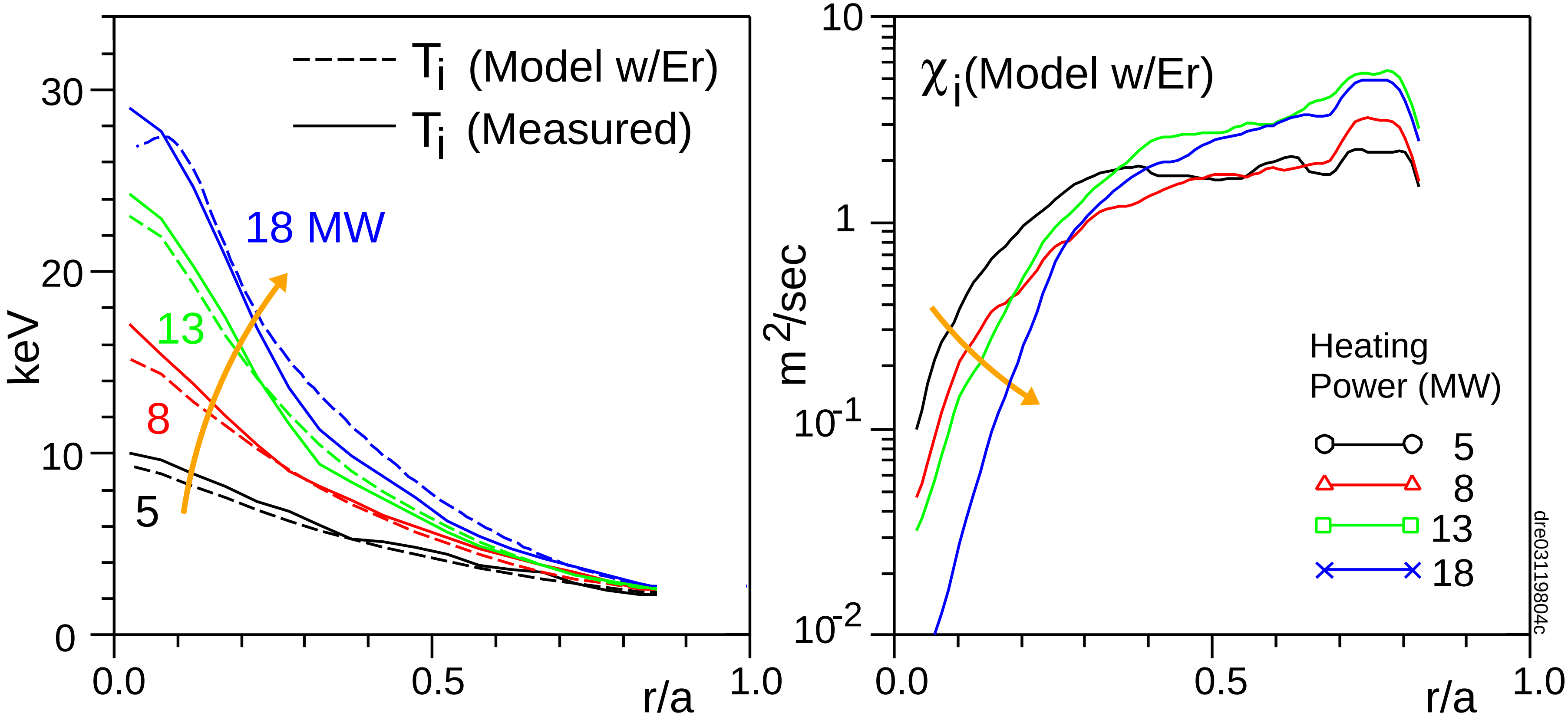
TFTR



- Both temperature and mass dependence are favorable and not consistent with naïve expectations of Bohm or gyro-Bohm scaling

Model for Suppression of ITG Turbulent Transport by Self-Consistent Plasma Flow Reproduces Behavior of χ_I

TFTR

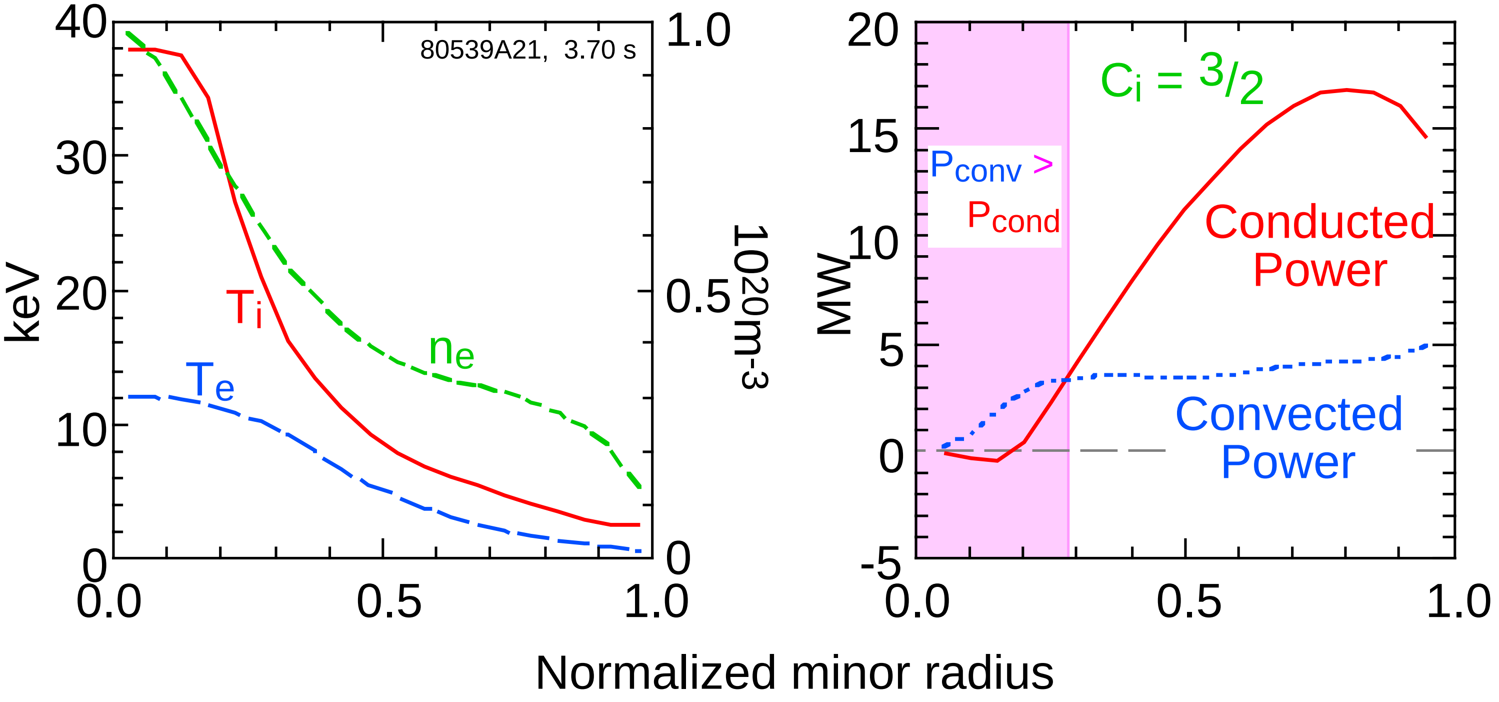


- Favorable apparent dependence of χ_I on T_I and broadening of region of reduced transport as heating power increased *(D.R. Ernst, this conference)*

Convective Losses Dominate in Core of Supershots

TFTR

- Ion thermal flux: $q_i = -n_i \chi_i k \nabla T_i + C k T_i \Gamma_i$; Γ_i = particle flux
  - C = $^5/_2$ for uniform losses (= average particle energy + p.dV work)
  - C = $^3/_2$ for supershots consistent with energy dependence of D_i

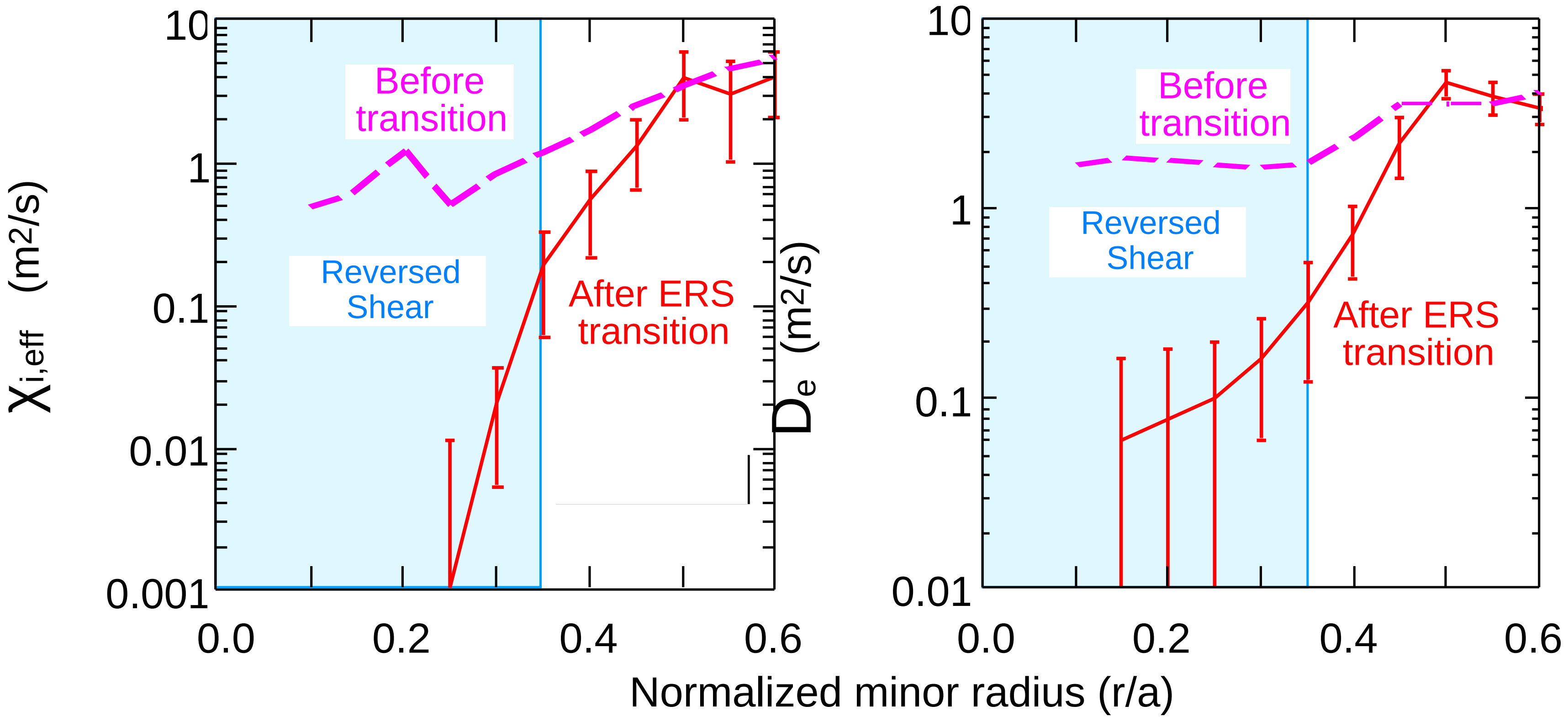


- Convective losses probably too high in standard supershots to ignite, *but*
  - Balance of conduction and convection in core not well determined

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

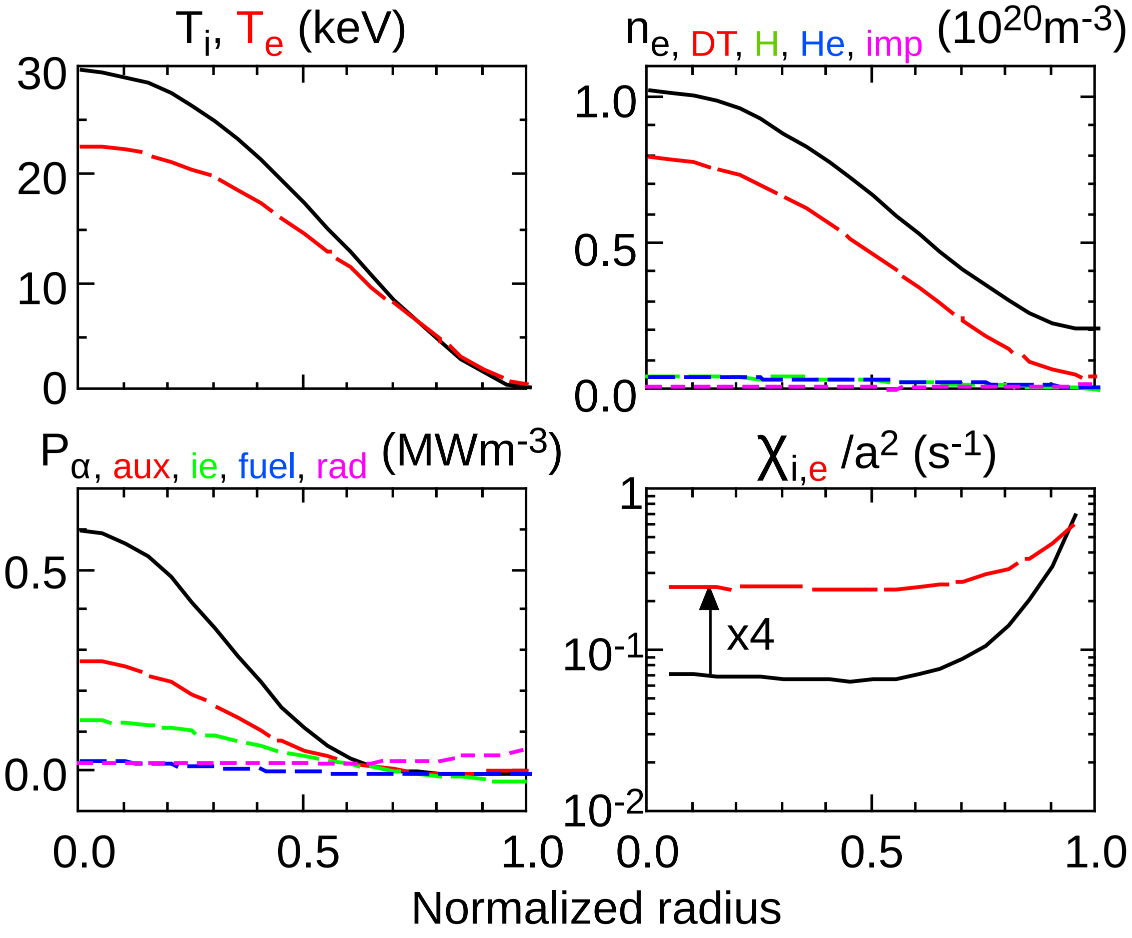
ERS Plasmas Combine Low χ_I with Greatly Reduced D_e

TFTR



- Flux balance effective χ: $q = - n \cdot \chi_{eff} \cdot$ T (includes convected heat flow)
- χ_e reduced near q_{min} but *increased* inside *(M. Zarnstorff, this conference)*

Construct Simple 1-D Solution for a Hot-Ion Q = 10 Plasma



- $\langle P_{fus} \rangle \approx 0.45\ MWm^{-3}$ (ITER: 0.75); $\tau_E = 2.7$ s (ITER: 5.8 s for ignition)

Embodiment of a Hot-Ion Q = 10 Plasma

- From 1-D calculation: $\langle p \rangle = {}^{2}/_{3} \left(\langle P_\alpha \rangle + \langle P_{aux} \rangle\right) \tau_E = 0.25$ MPa
- Choose moderately conservative assumptions
  - Inverse aspect ratio: $\varepsilon = 1/3$
  - Elongation: $b/a = \kappa = 1.6$
  - Engineering safety factor: $q_e = (\pi/\mu_0)\,(1 + \kappa^2)\,\varepsilon\, a\, B / I = 3$
  - Troyon-normalized-β: $\beta_N = 10^8 \langle \beta \rangle\, a\, B / I = 80\, \pi \langle p \rangle\, a / B\, I = 2$
- Calculate
  - Toroidal field: **$B = 5.6$ T**
  - Ratio of plasma current to minor radius: **$I / a = 5.5$ MAm^{-1}**
  - For **$a = 1.5$m, $R = 4.5$m, $I = 8.2$MA** **$P_{fus} = 150$MW, $P_{aux} = 15$MW**
  - **$H_{ITER\text{-}89P} = 3.4$**
  - Would need $\chi_i \sim 0.2\ \mathrm{m^2 s^{-1}}$ and $\chi_e \sim 0.8\ \mathrm{m^2 s^{-1}}$ for $r/a < 0.6$
- *This is within the bounds of what might be achievable*

Conclusions and Future Directions

- We should re-examine approaches to ignition in regimes than the “traditional” (*i.e.* since *ca.* 1985) ELMy H-mode route

- Hot-ion regimes have produced the best performance in all large tokamaks and are not incompatible with high-Q and, possibly, ignition in DT

- Hot-ion regimes are thermally stable at ignition
  - probable natural operating point for uncontrolled burn

- Study hot-ion regimes *per se* in other large tokamaks
  - mechanism: sheared flow, $T_i/T_e > 1$, L_n ⇐ theory progress
  - is strong central fueling necessary? ⇐ reduced D regimes
  - MHD stability margins ⇐ optimize r.m.s. pressure
  - size scaling in comparable regimes ⇐ controlled experiments
  - put effort into controlling what matters ⇐ edge control
  - investigate alpha channeling ⇐ improves prospects