Alternative Approaches to Ignition in Tokamaks

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Topics

- What have we learned about ion confinement from tokamak experiments?
  - 25 years of non-DT experiments across a wide range of machines
  - 4 machine-years of DT experiments in TFTR and JET
- Are there ways to exploit this experience in a next step?

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Conventional Tokamaks Confine Energetic Ions Well

- Neutral beam and minority ICRF heating depends on this
  - PLT first demonstrated hot-ion (T_i ~ 7keV) operation with NBI (1978)
  - very successful in many tokamaks
- J.F. Clarke investigated 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: $\tau_{Ee}[s] = 0.76\ \ a[m]^2\ n_e[10^{20}m^{-3}]$
  - $\Rightarrow$ $n\tau$ for ignition reduced by factor ~2 with $T_i \approx$ 30keV; $T_e \approx$ 25keV
- Discovery of L-mode scaling in 1980's quelled enthusiasm
  - both electrons and ions worse than originally hoped *but*
- Hot-ion modes continued to produce the best fusion performance
  - L-mode, H-mode, ERS/ERS/OS; limiter/divertor
- DT experiments showed good confinement of fusion alpha-particles

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!*

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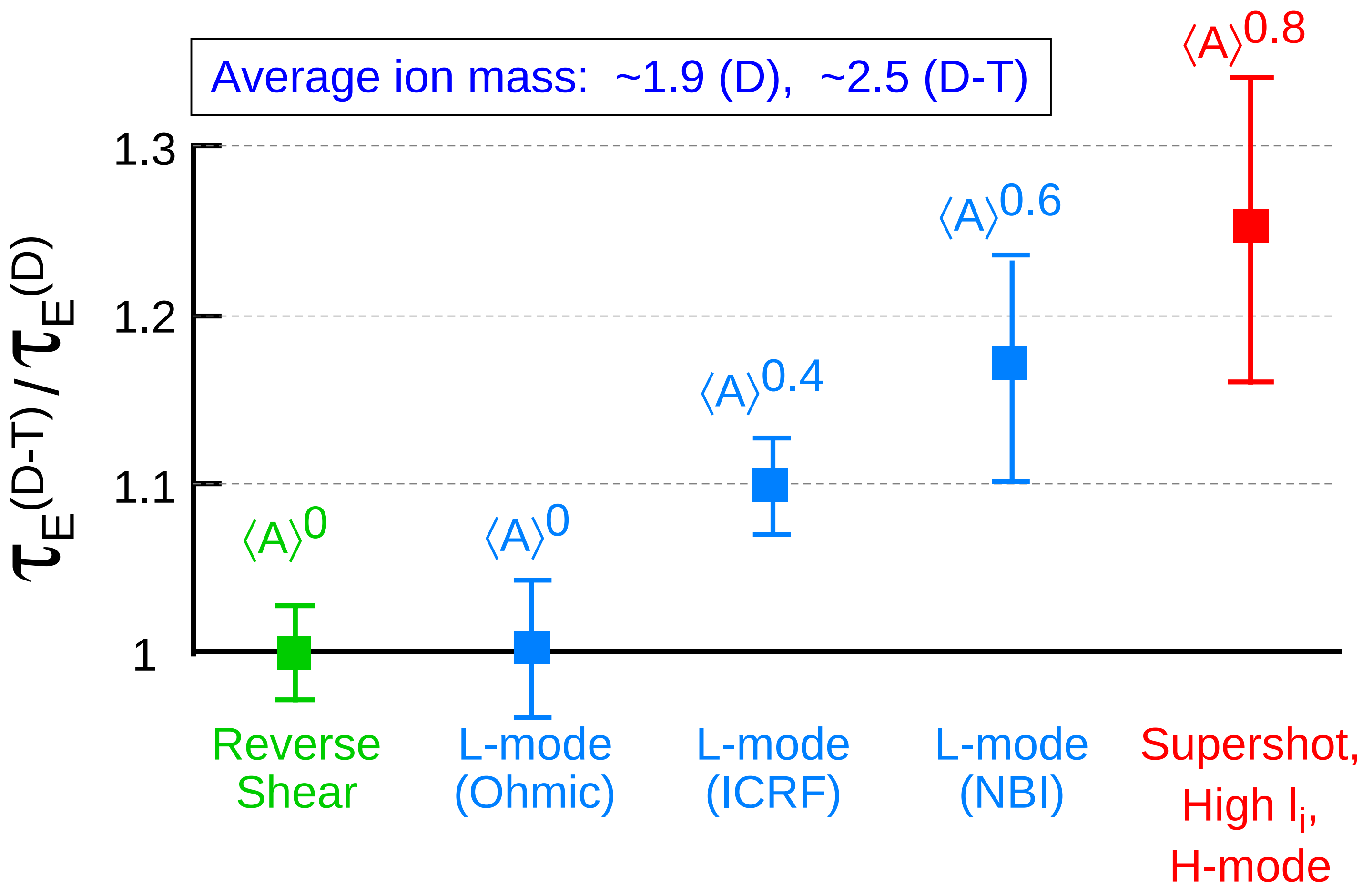
DT Plasmas are NOT the Same as Their D Progenitors

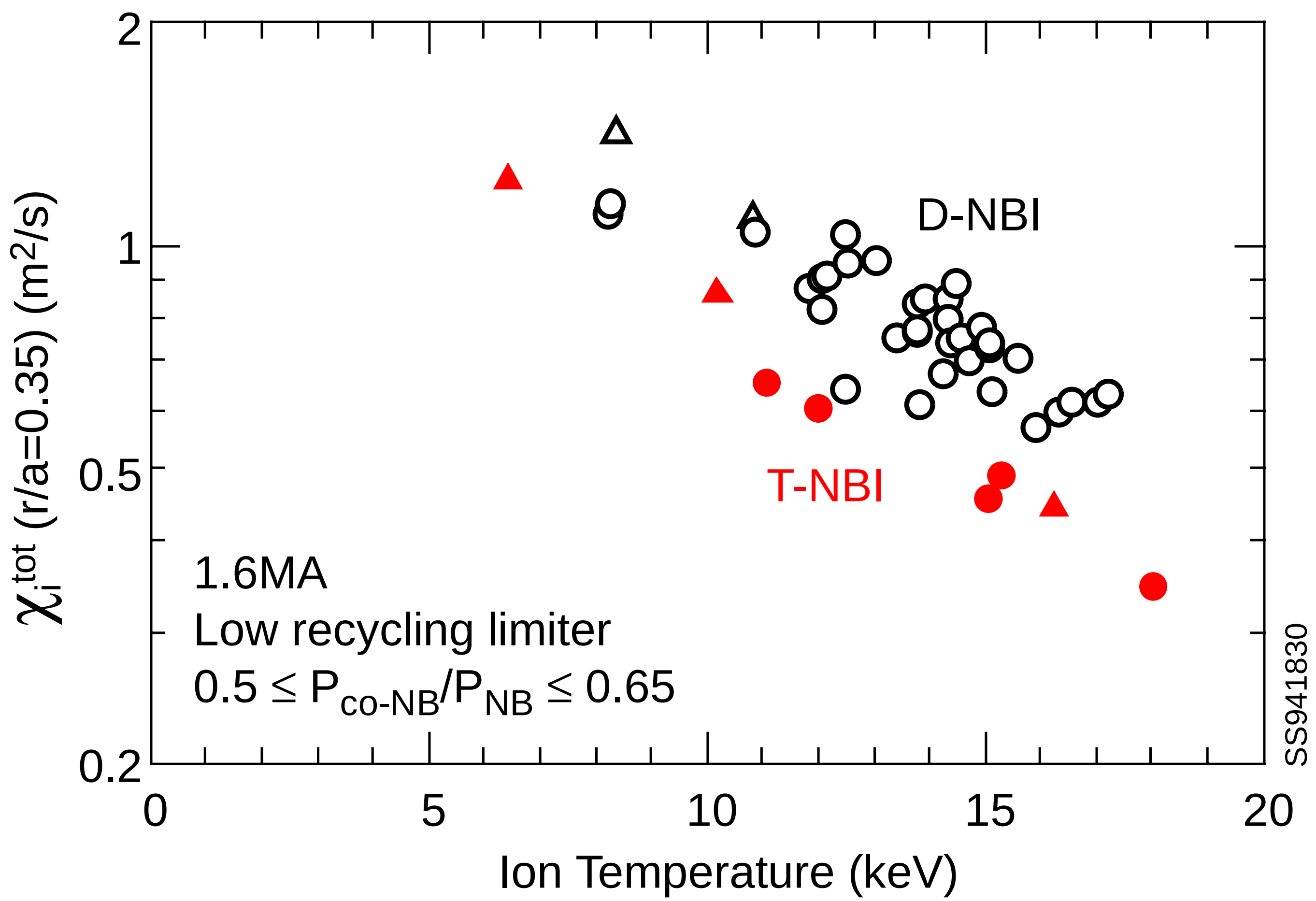
- There was a pronounced isotope scaling of confinement in TFTR



- JET H-modes showed positive mass scaling of pedestal, *negative in core*

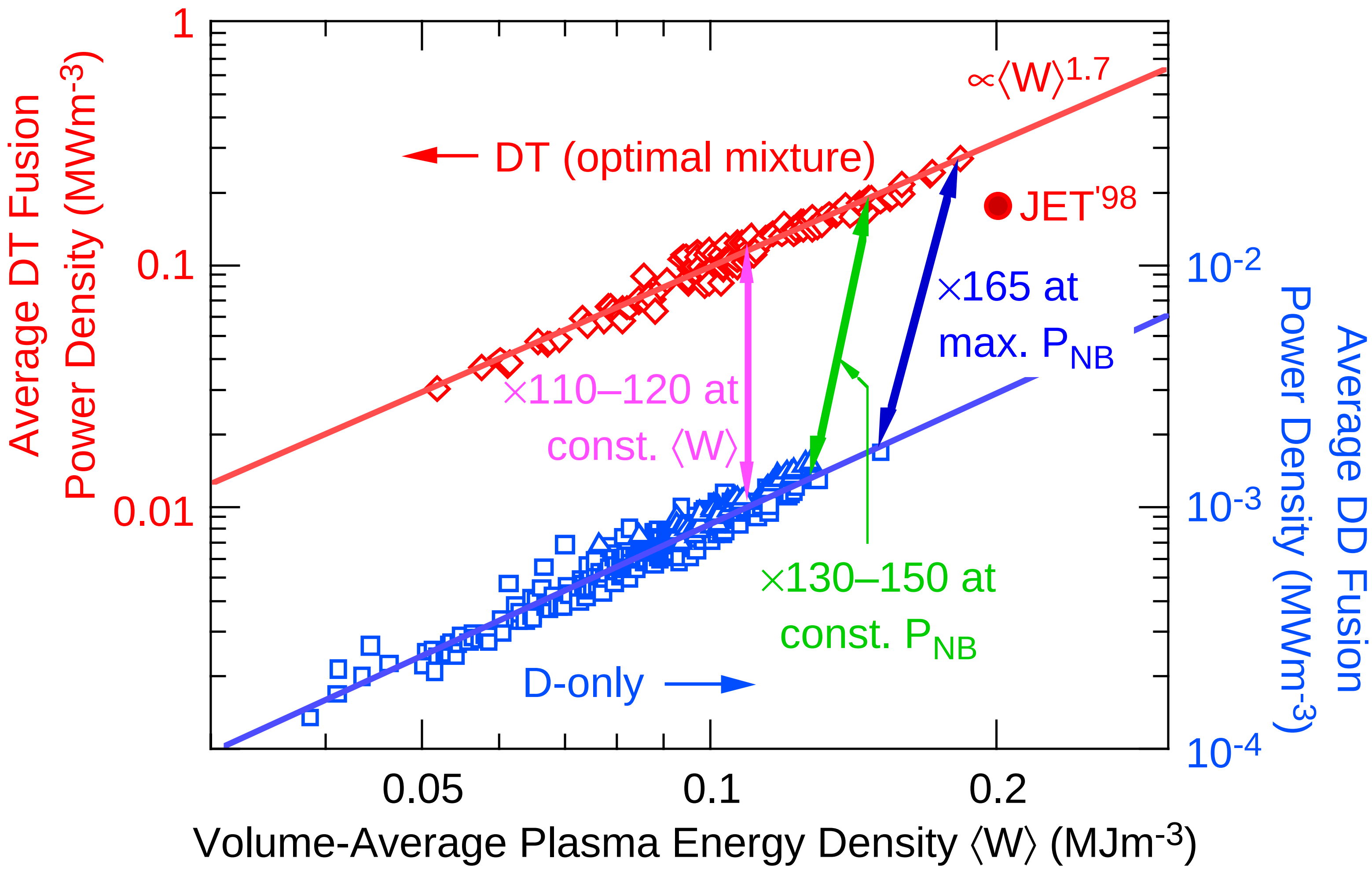
Hot Ion Plasmas in TFTR Showed a Favorable T_i Scaling

TFTR



- Trends are not consistent with naïve Bohm or gyro-Bohm scaling *but*
- Can be modeled by invoking turbulence suppression by E×B shear

Isotope Scaling Changed Constraints on DT Operation



- TRANSP had predicted a DT:DD power ratio of ~180 at constant T_i (1990)
- Needed to operate at higher I_p, B_T to accommodate higher P_{NB}, T_i

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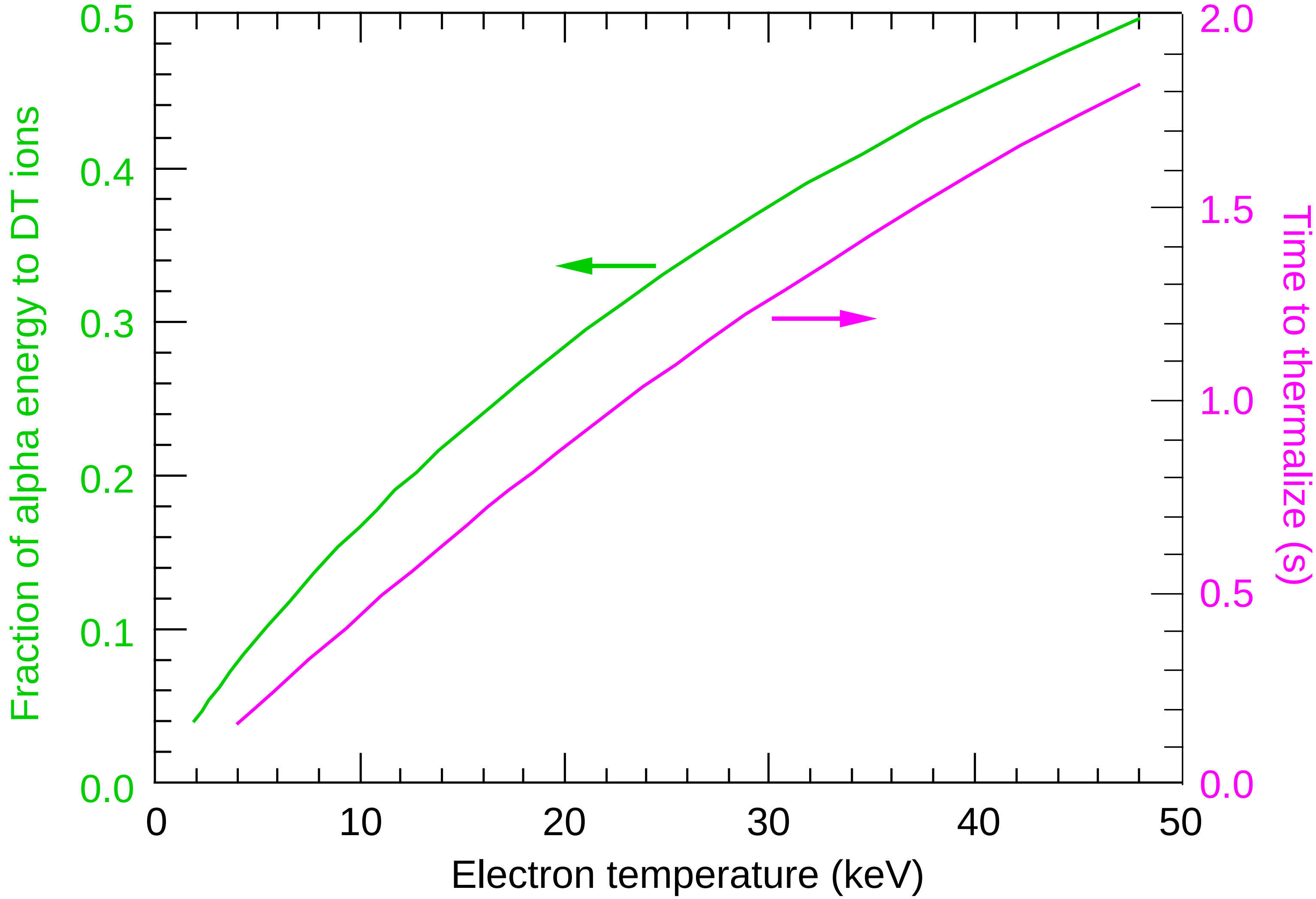
Substantial Direct Alpha Heating of Ions for T_e > 15 keV

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



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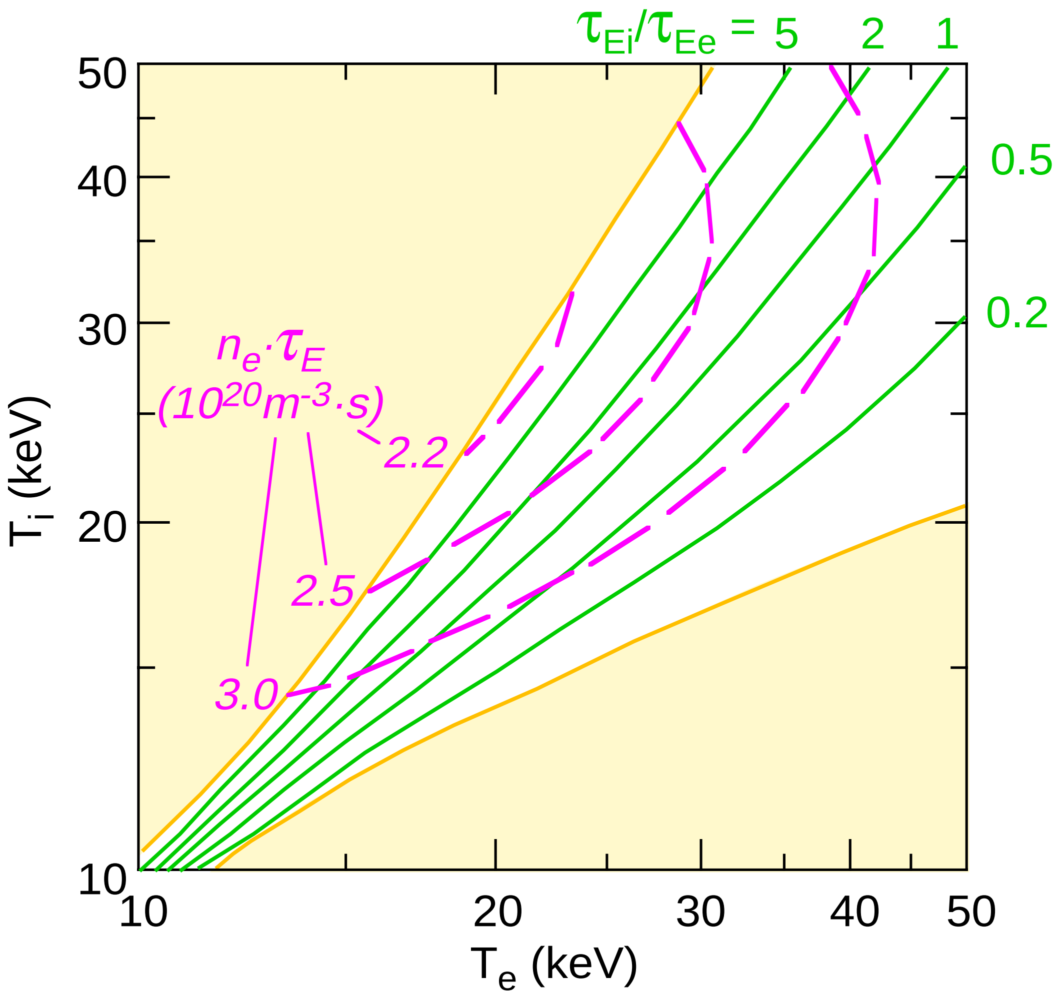
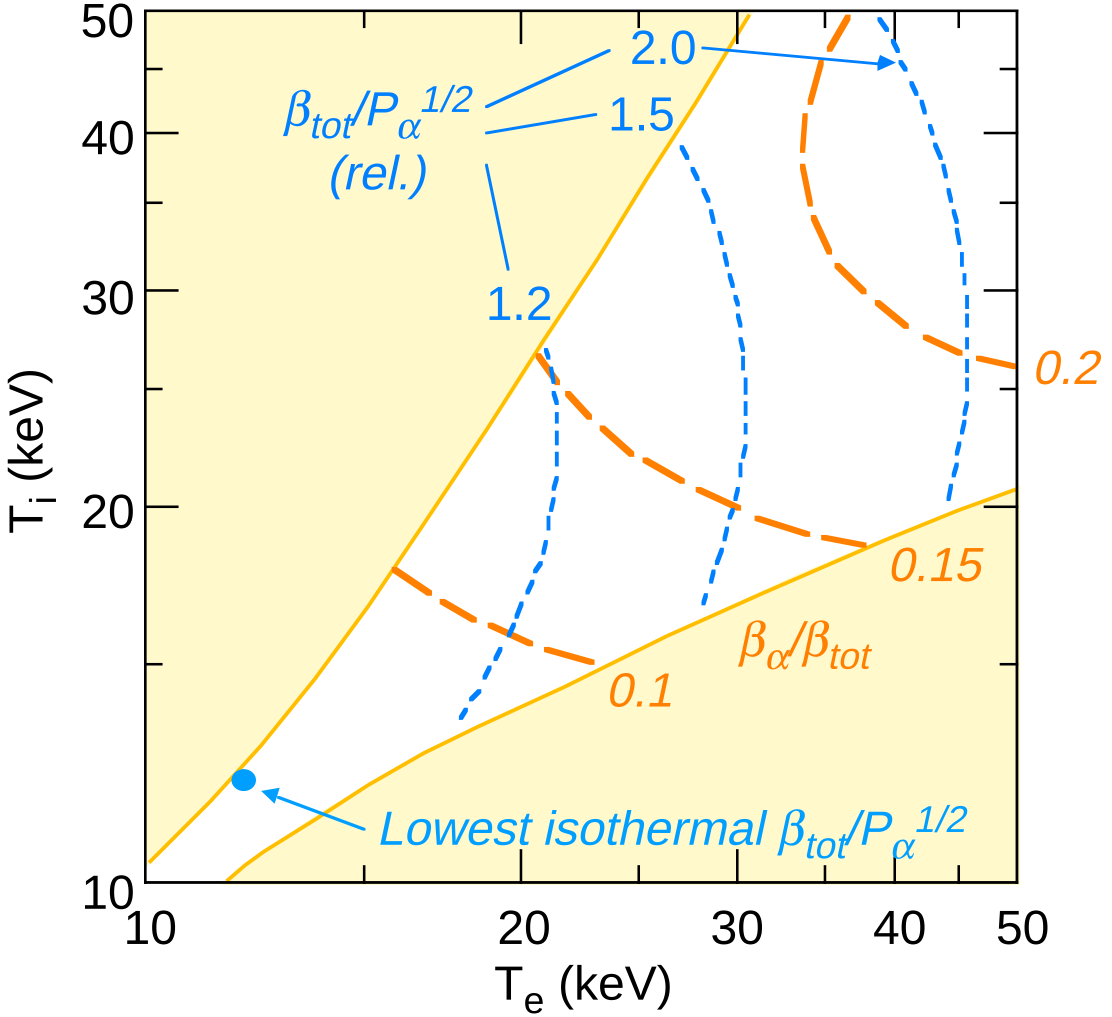
Good Ion Confinement Produces Hot-Ions at Ignition



- $n_{DT} : n_H : n_{He} : n_C$ = 0.80 : 0.05 : 0.05 : 0.01 (based on TFTR experience)
  - *P_α and $P_{ie} \propto n^2 \Rightarrow T_I/T_e$ independent of density at ignition*

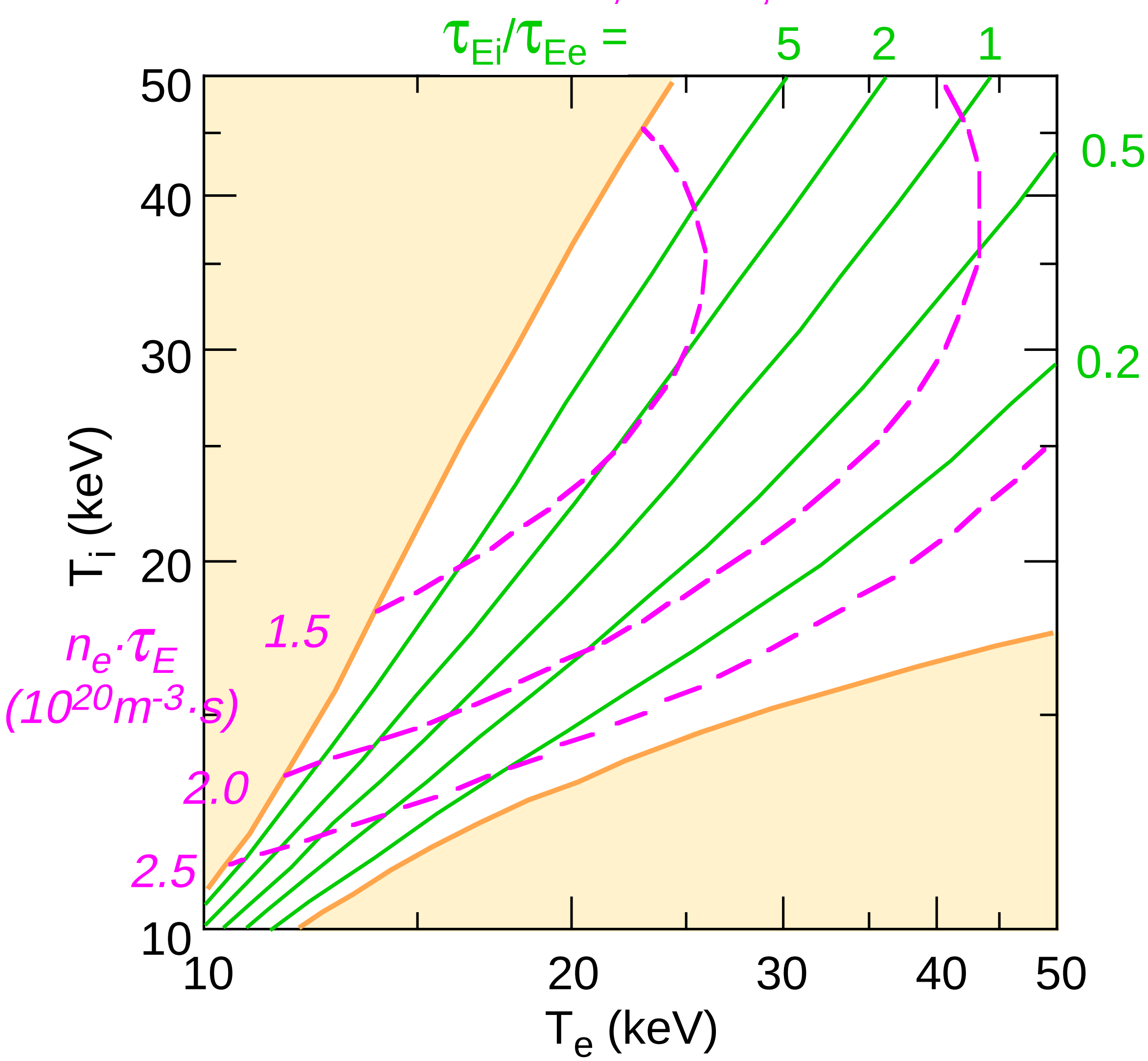
Penalty is Higher β_{tot} and β_α/β_{tot}



- 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**



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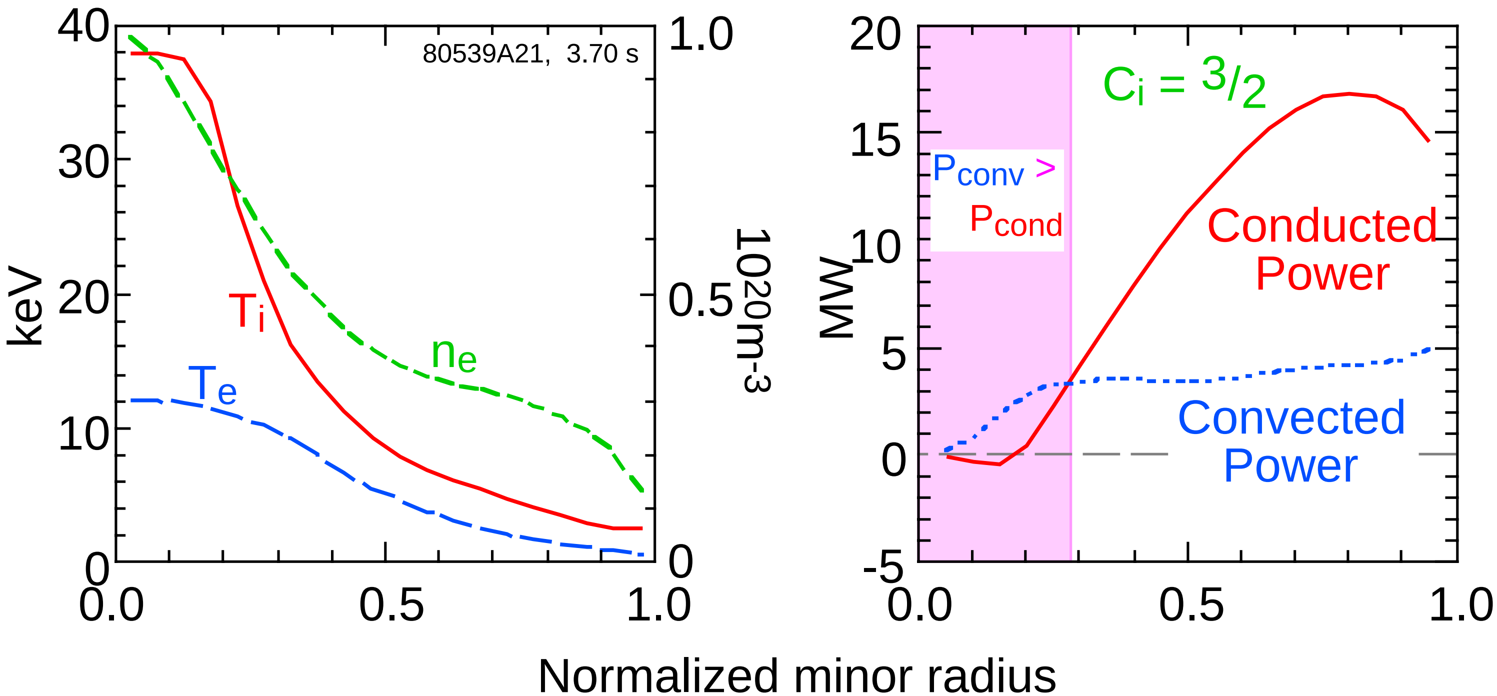
Convective Losses Dominate in Core of Supershots

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

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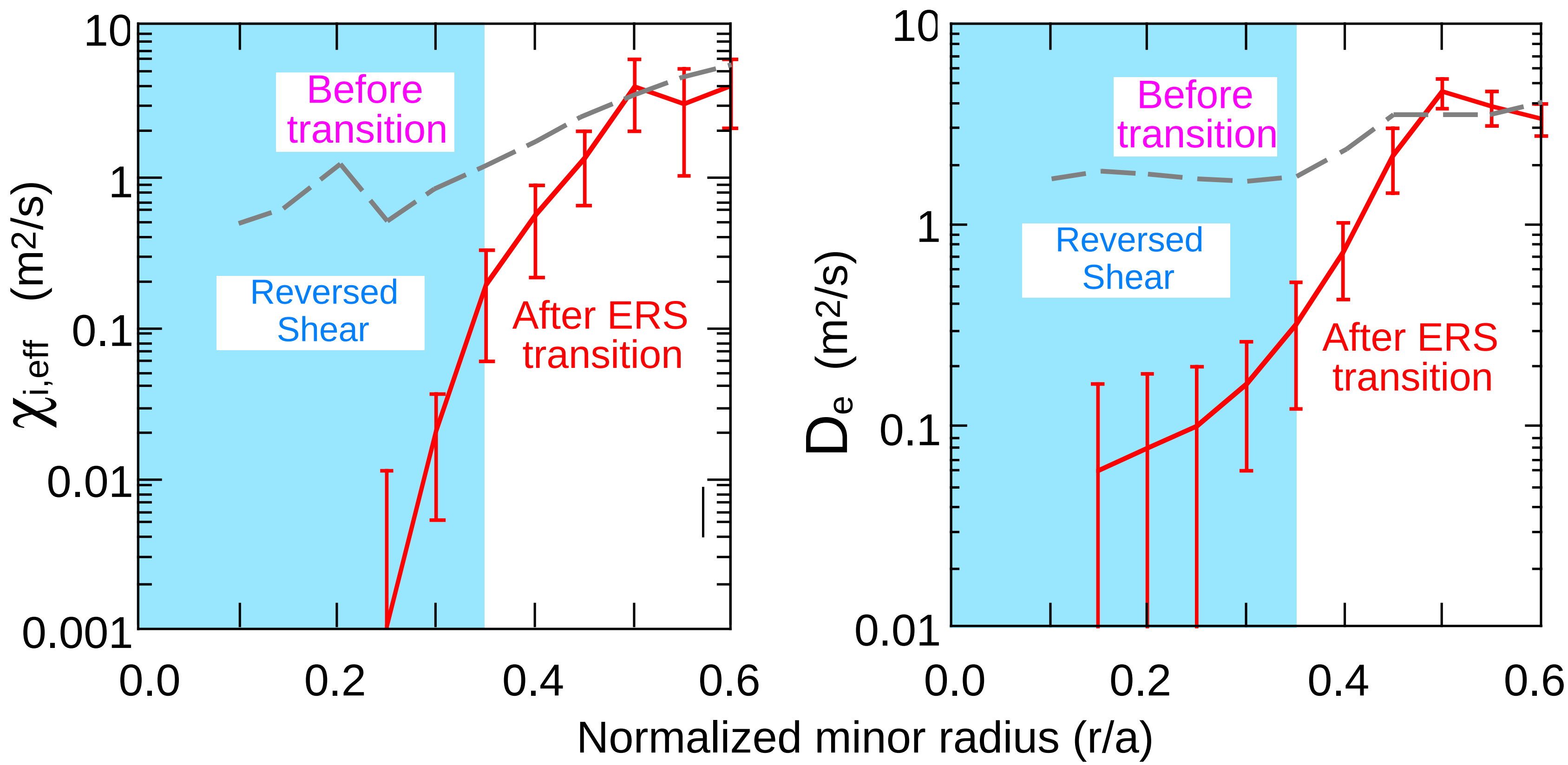
ERS Plasmas Combine Low χ_I with Greatly Reduced D_e

TFTR



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

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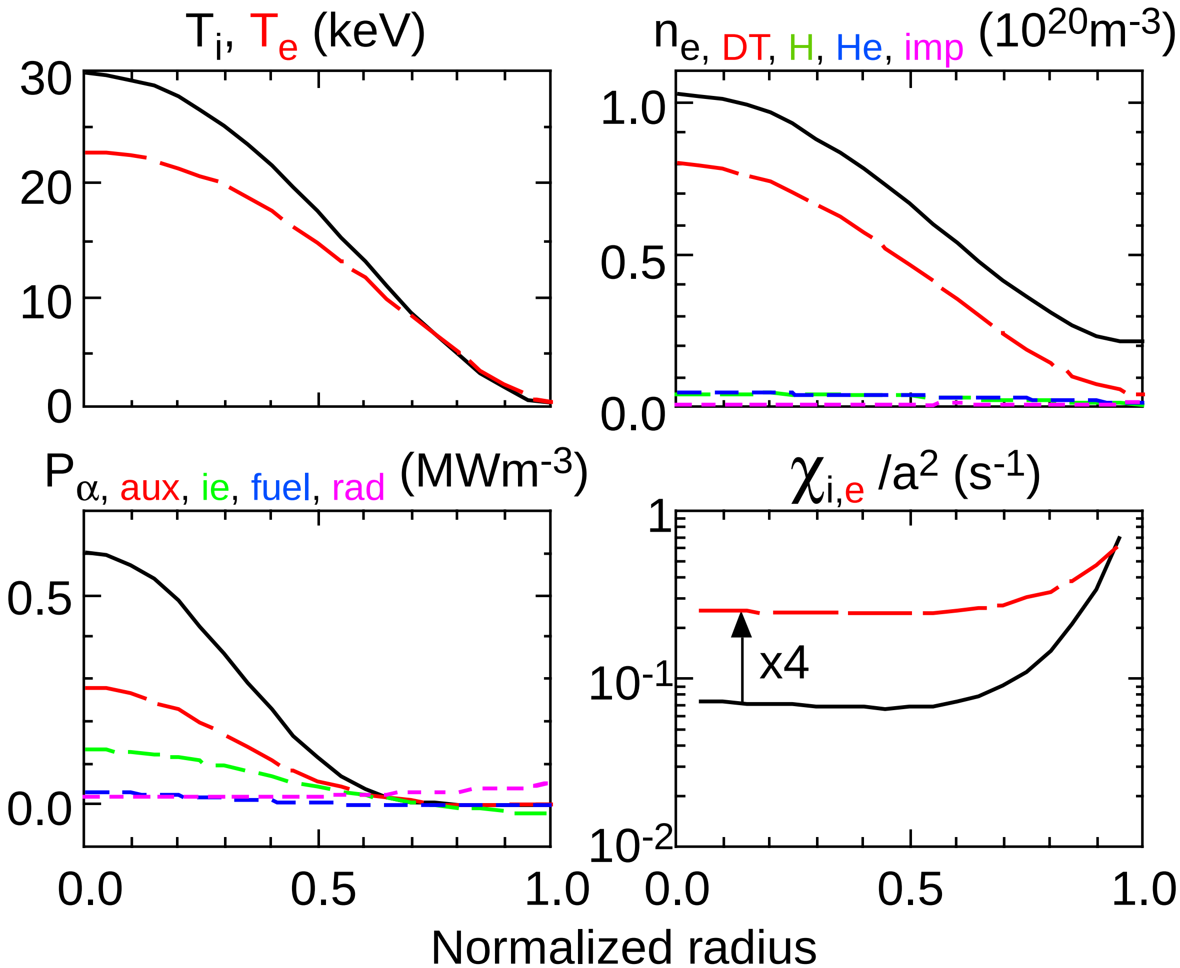
Construct Simple 1-D Solution for a Hot-Ion Q = 10 Plasma



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

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Embodiment of a Hot-Ion Q = 10 Plasma

- From 1-D calculation: **<p>** = $^{2}/_{3}$ (<P_α> + <P_{aux}>) τ_E = 0.25 MPa
- Choose moderately conservative assumptions
  - Inverse aspect ratio: ε **= 1/3**
  - Elongation: b/a = κ **= 1.6**
  - Engineering safety factor: $\mathbf{q_e} = (\pi/\mu_0)\,(1+\kappa^2)\,\varepsilon\, a\, B / I$ **= 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 = 1.5m, R = 4.5m, I = 8.2MA $\Rightarrow$ P_{fus} = 150MW, P_{aux} = 15MW**
  - **$H_{ITER-89P}$ = 3.4**
  - Would need χ_i **~ 0.2 m^{2}s^{-1}** and χ_e **~ 0.8 m^{2}s^{-1}** for r/a < 0.6
- *This is within the bounds of what might be achievable*

Conclusions and Future Directions

- We have to use DT plasmas ("the real thing") if we are interested in fusion
- We should re-examine approaches to ignition in regimes than the “traditional” 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
- *It is quite conceivable that a hot-ion mode is a stable self-organized state of a predominantly self-heated tokamak plasma*
- In the meantime, study hot-ion regimes in large tokamaks
  - mechanism: sheared flow, $T_i/T_e > 1$, L_n ⇐ theory progress
  - is strong central fueling necessary? ⇐ reduced D regimes
  - MHD and TAE 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

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