The Role of the Neutral Beam Fueling Profile in the Performance of TFTR and other Tokamak Plasmas*

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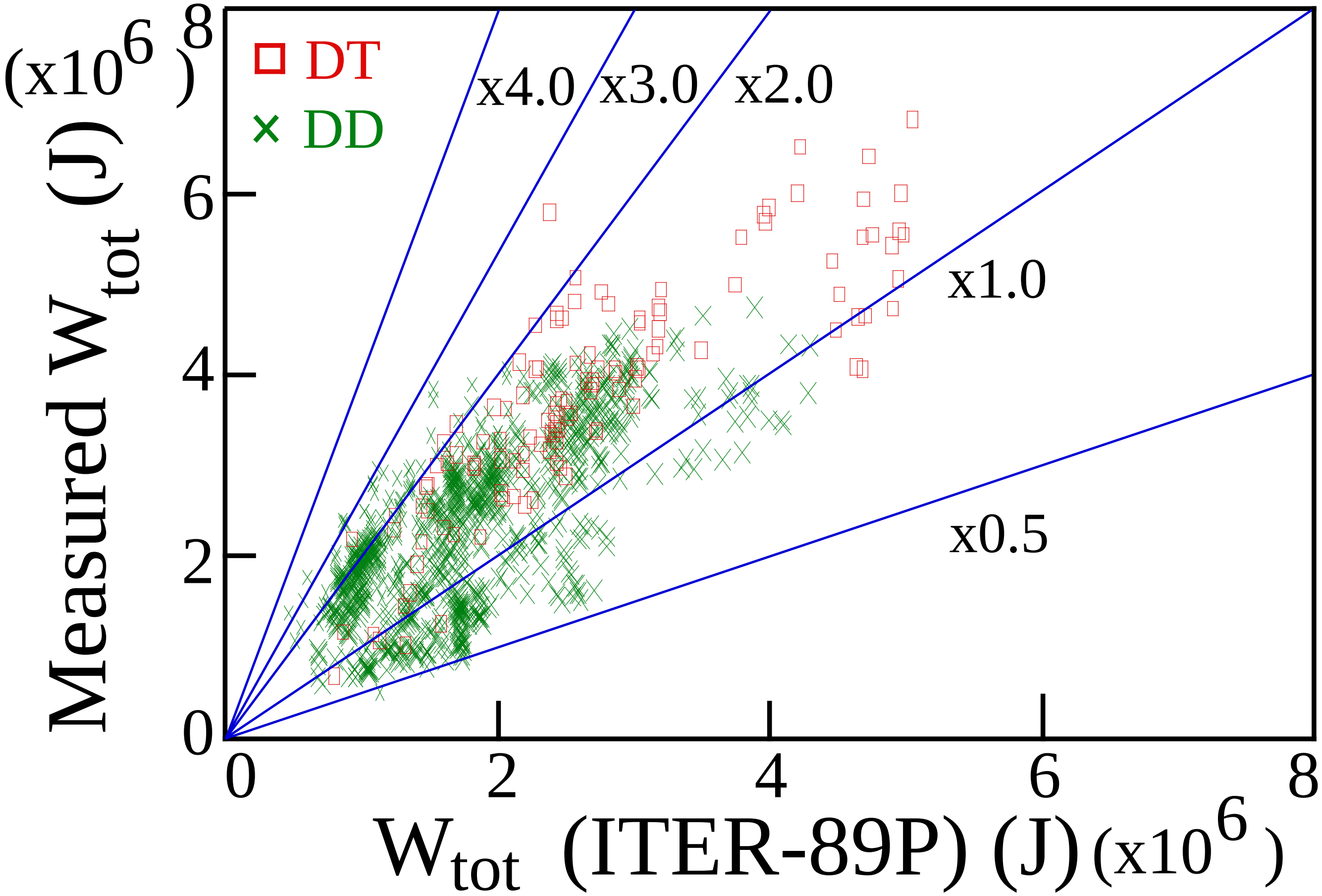
Motivation Significant Deviation from L-mode Scaling

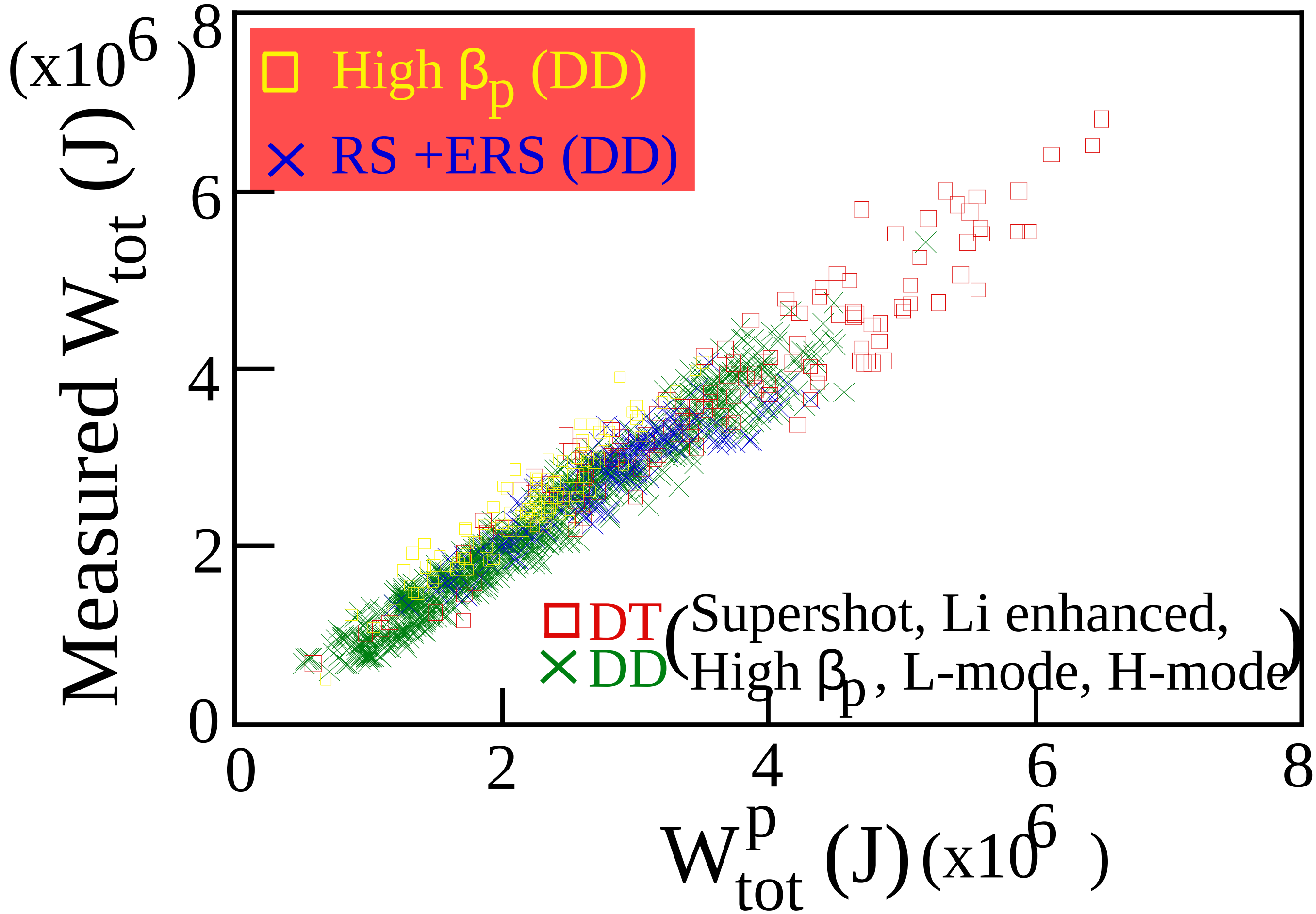
- Factor of ~ 7 variation in stored energy in TFTR
- Similar diversity observed in other tokamaks



$$(I_P^{0.85} P_B^{0.5} R^{1.2} a^{0.3} n_e^{0.1} B_T^{0.2} M^{0.5} \kappa^{0.5})$$

Improved correlation achieved with new W_{tot} scaling

- Key independent parameter: beam fueling profile peakedness (H_{ne})



$$\left(2.04 \times 10^4 \, P_B^{1.3} H_{ne}^{0.8} + 310 \, P_B^{0.7} I_P^{0.4} \right)$$

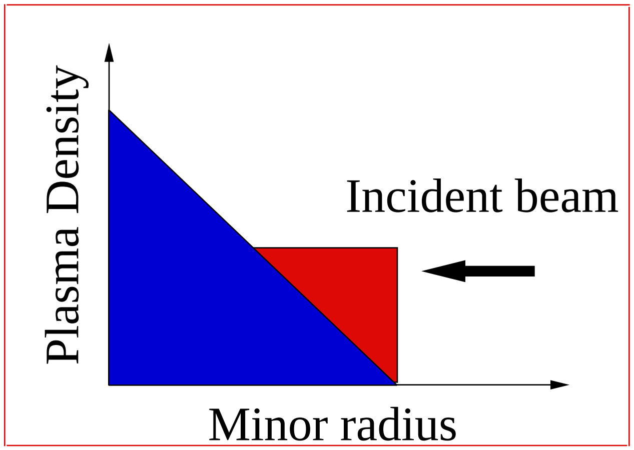
(Ions) (Electrons)

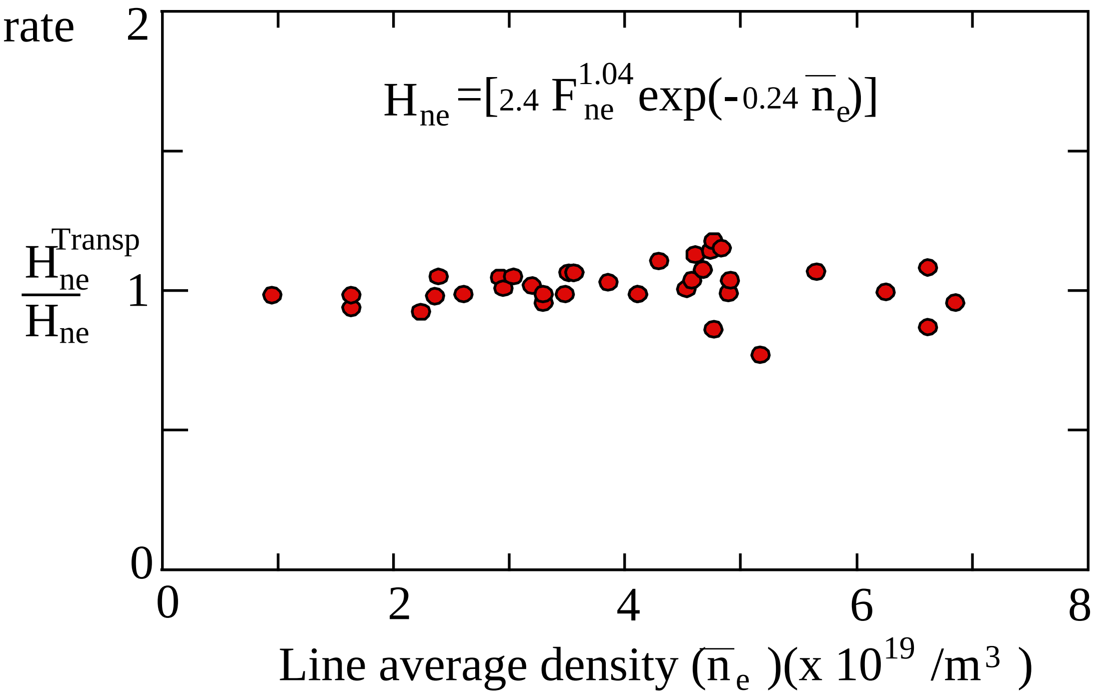
Outline

- **Modelling of the beam fueling profile peakedness, H_{ne}**
  - H_{ne} is a key independent parameter in the scaling study
- **Scalings for stored energy and fusion reactivity**
  - Importance of considering separate ion and electron species
  - Insensitivity to major radius and toroidal field variation
- **Application to all TFTR beam-heated plasmas**
  - L-mode, H-mode, Li enhanced Supershots, High β_p, and High l_i, Reversed-shear and DT discharges
  - Results from other tokamaks
- **Relationship to recent transport theories**

Beam Fueling peakedness is modelled as a plasma density and density profile shape

$$H_{ne} = \frac{\text{Central beam fueling rate}}{\text{Volume average beam fueling rate}}$$

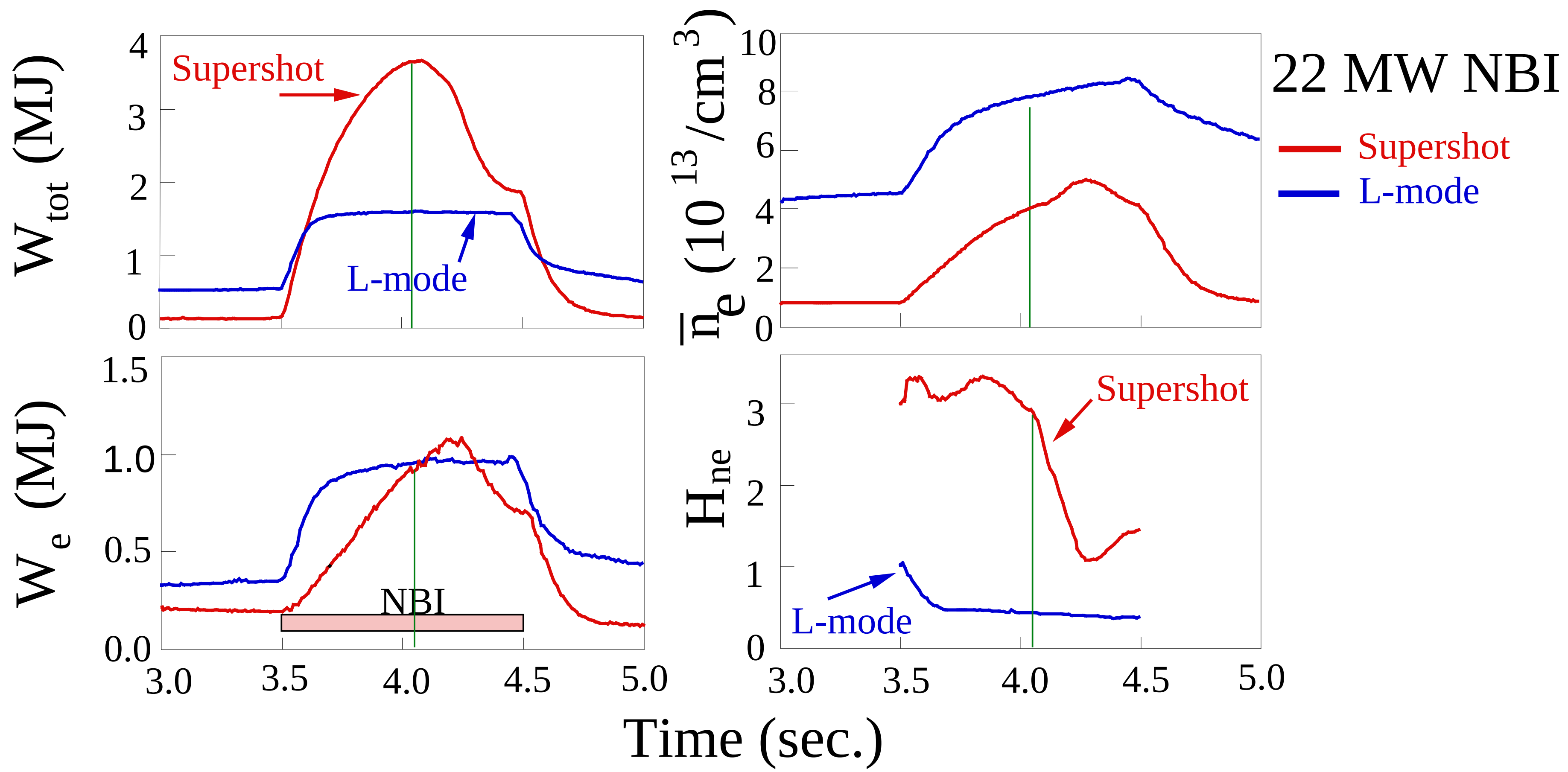




- H_{ne}^{Transp}: TRANSP calculated beam fueling peakedness
- H_{ne} : Modelled as $H_{ne} \;\; \alpha\, F_{ne}^{\beta} \exp(-\gamma \bar{n}_e)$

$\bar{n}_e$ = line average density, $F_{ne} = n_e(0)/\langle n_e \rangle$.

Ion stored energy is strongly correlated with H_{ne}



- Electron stored energy is not strongly correlated with H_{ne}
- Suggests separate scaling for ions and electrons

Confinement Scaling is Deduced from Data at Fixed Major and Minor Radii

- Range of plasma parameters (at the time of maximum stored energy):

  I_P = 0.9 ~ 2.0 MA
  H_{ne} = 0.3 ~ 4
  R_0 = 2.45 m

  P_B = 5 ~ 33 MW
  B_T = 4.0 and 4.8 T
  a_0 = 0.8 m

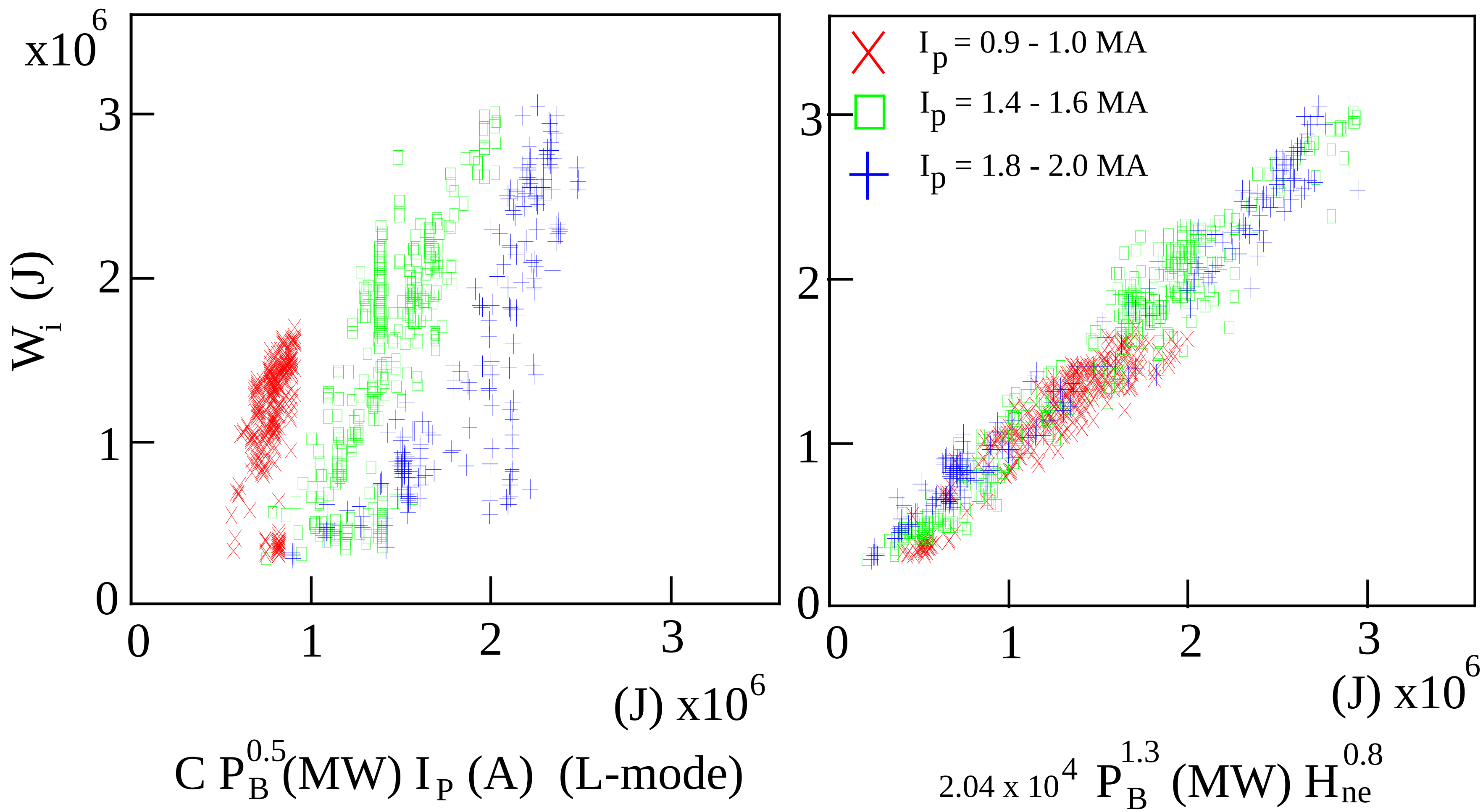
  - W_{tot} is total stored plasma energy

  - W_e is electron stored energy
    (calculated using the measured n_e and T_e profiles)

  - W_i is ion stored energy (thermal + non thermal)

- Practical difficulty in separating thermal and non-thermal components at high T_i

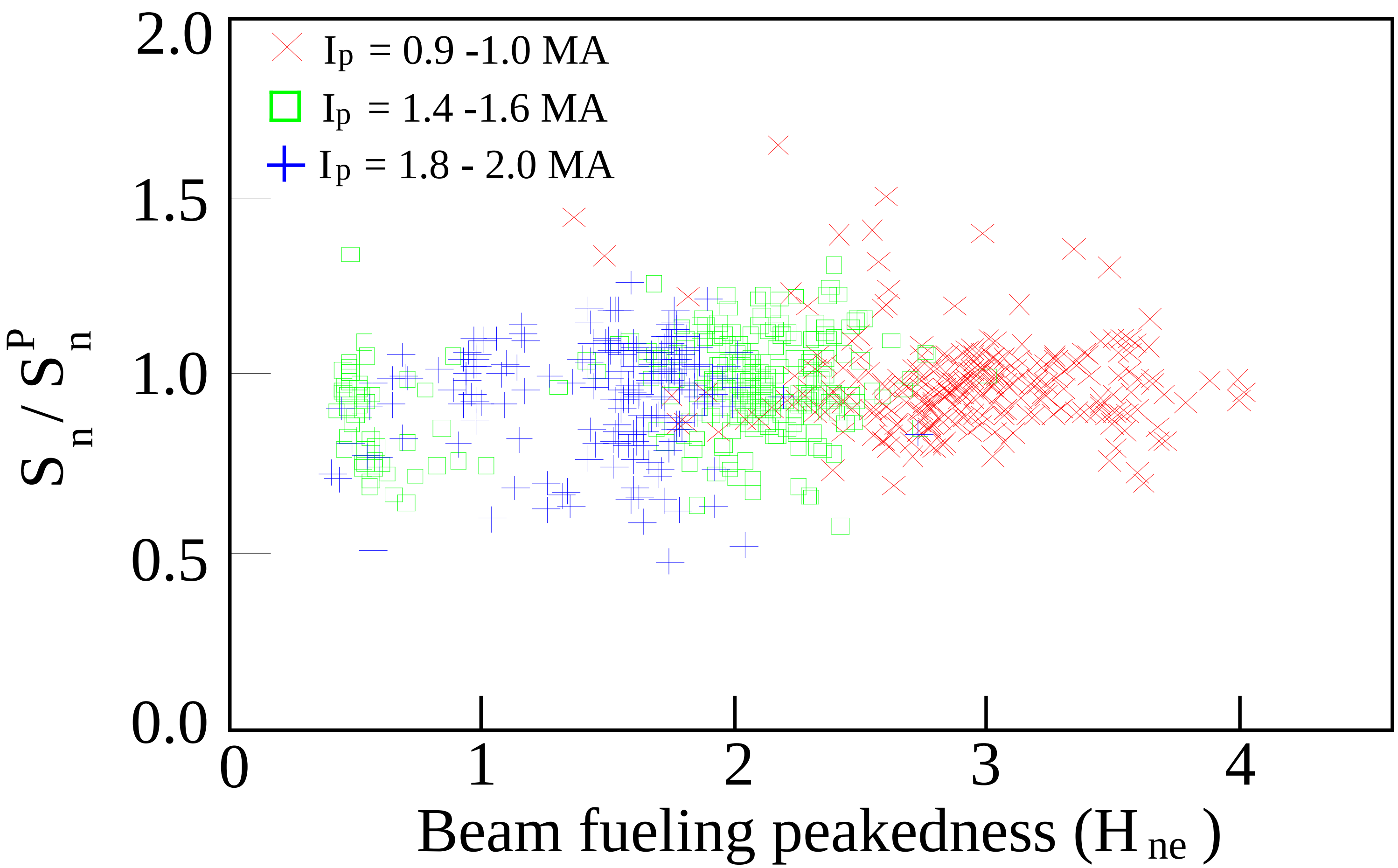
Ion Stored Energy Scaling is Approximately Linear in H_{ne}



- Scaling for electron stored energy is independent of H_{ne}

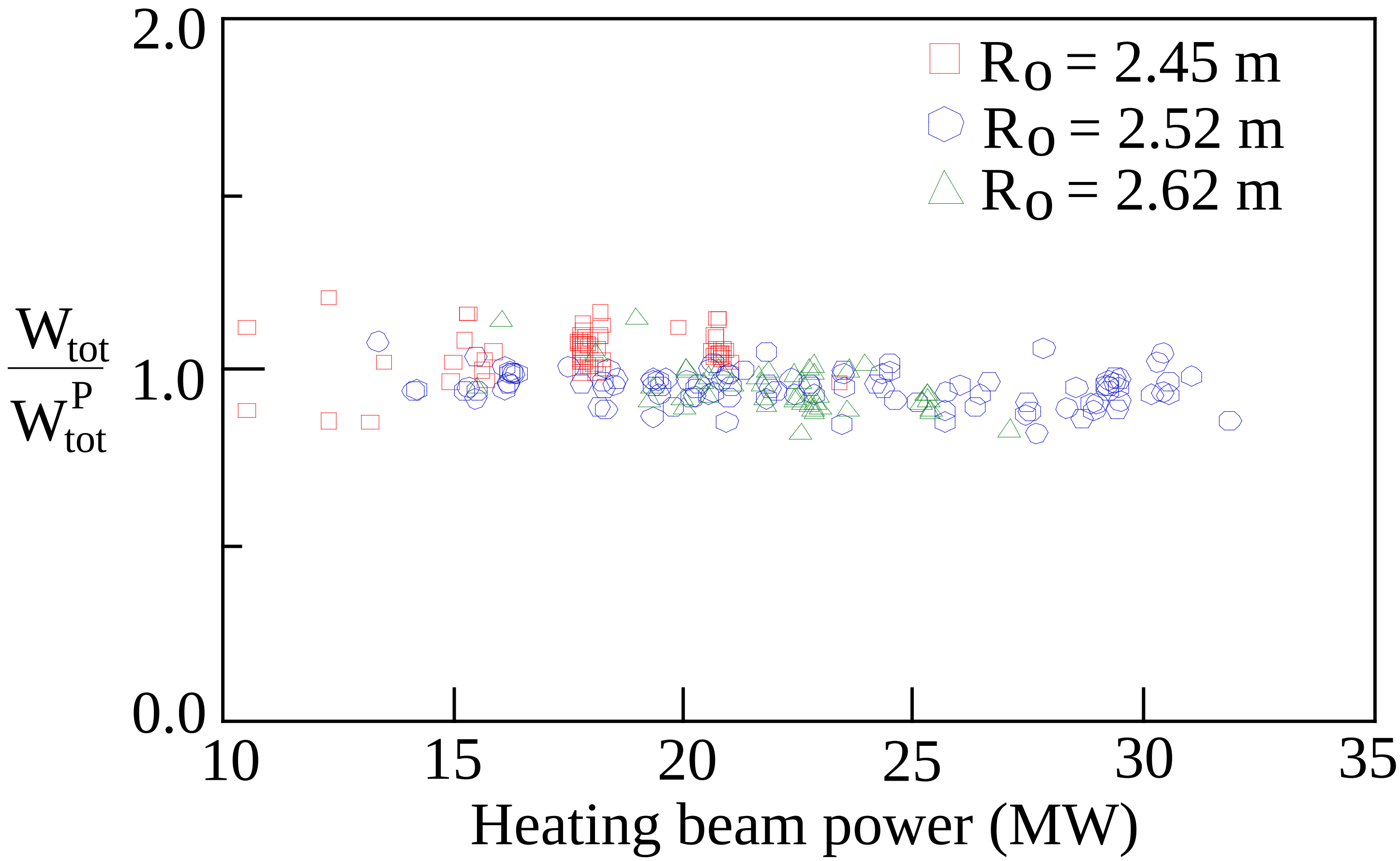
$$W_e\,(J) = 310\, P_B^{0.7}(MW)\, I_P^{0.4}(A)$$

Neutron Yields are Strongly Correlated with Ion Stored Energy



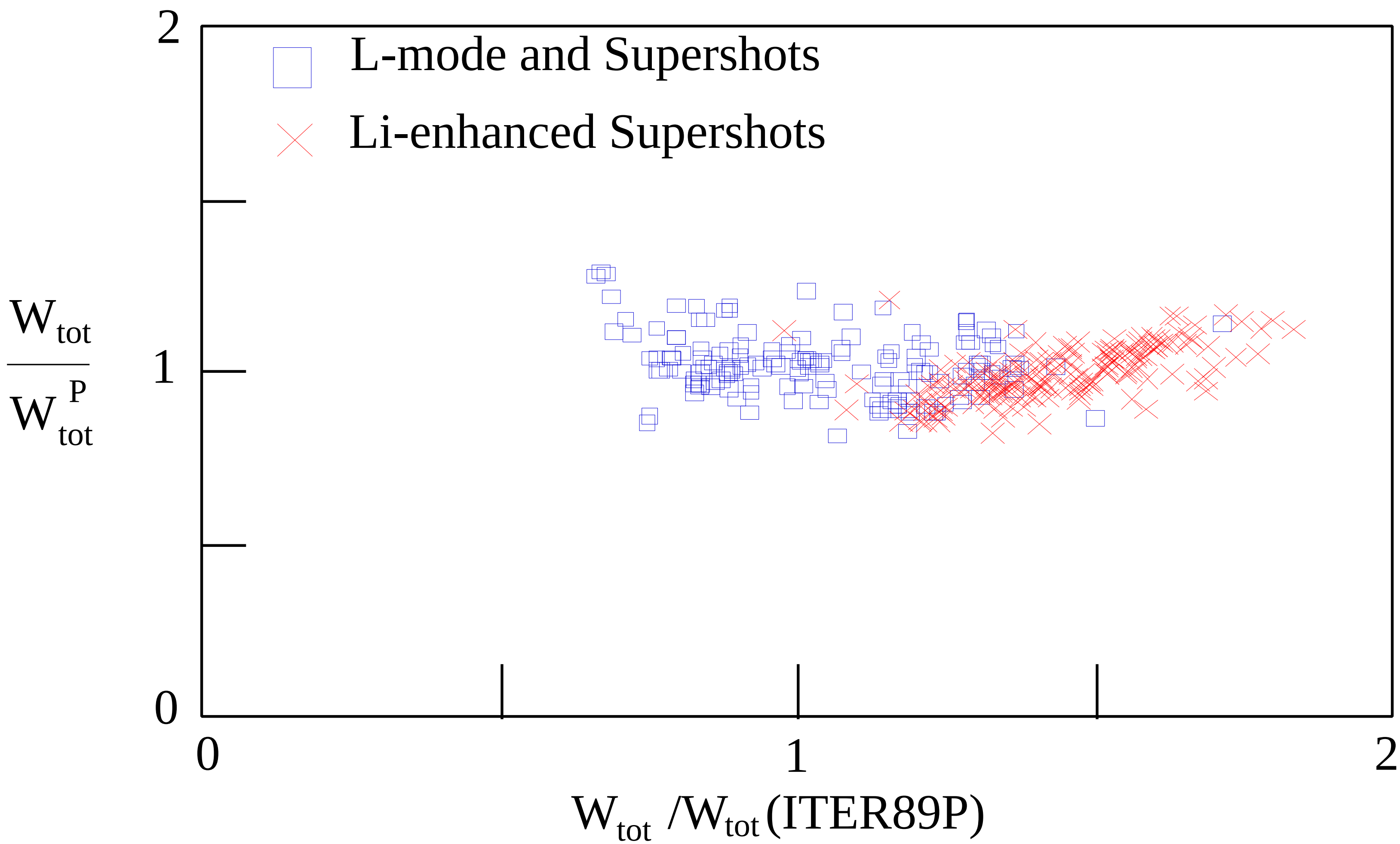
- $S_n^P(/\text{sec}) = 2.71 \times 10^{14}\ P_B^{1.2} H_{ne}^{1.3} / V_p$ (V_p is plasma volume)
- Fusion power gain for TFTR : Q $S_n / P_B = P_B^{1.2} H_{ne}^{1.3}$

Stored Energy is Independent of Major Radius



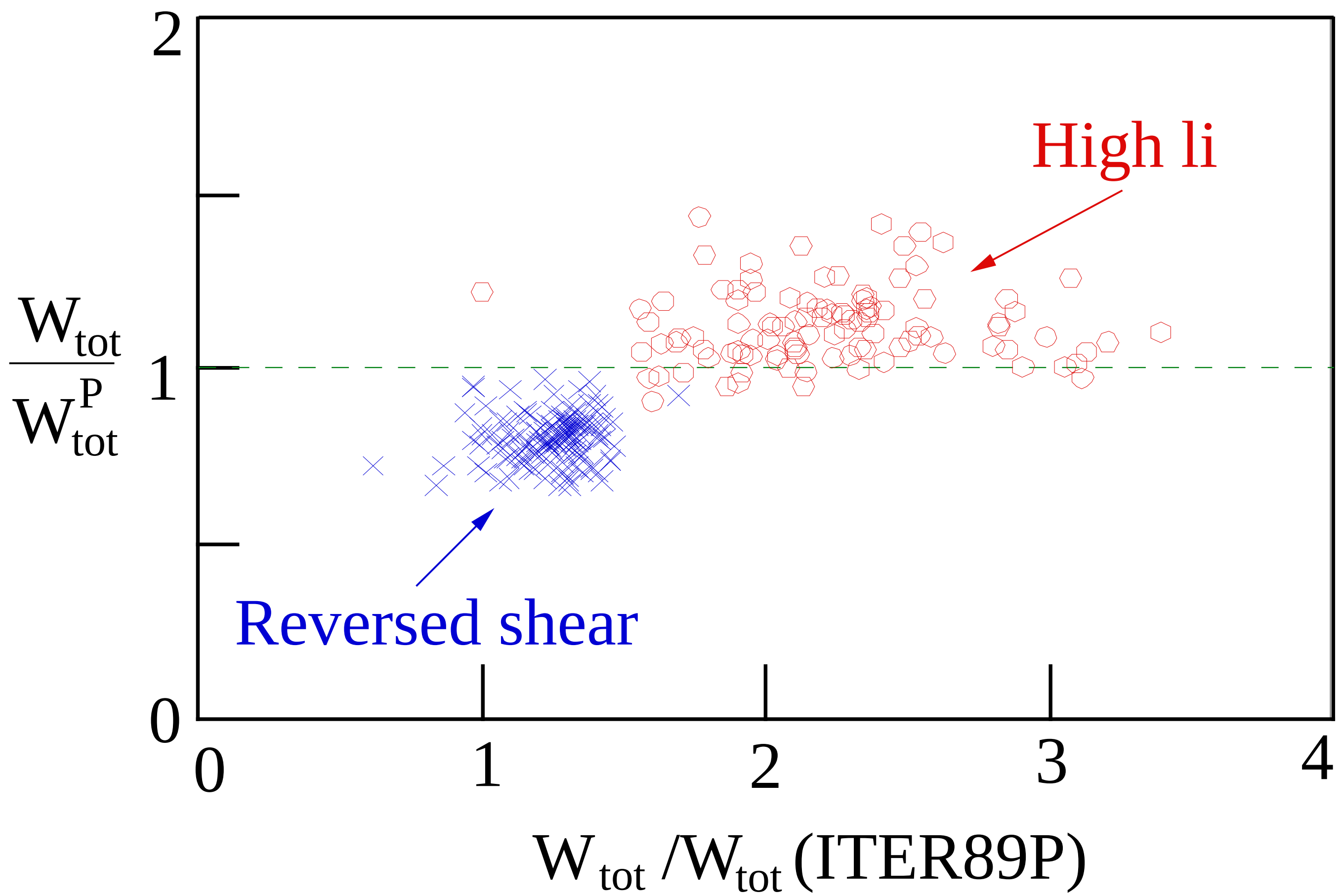
- Significant departure from L-mode scaling
- Scaling with R might be included in H_{ne}

Present Scalings Apply to all TFTR Beam Heated Plasmas



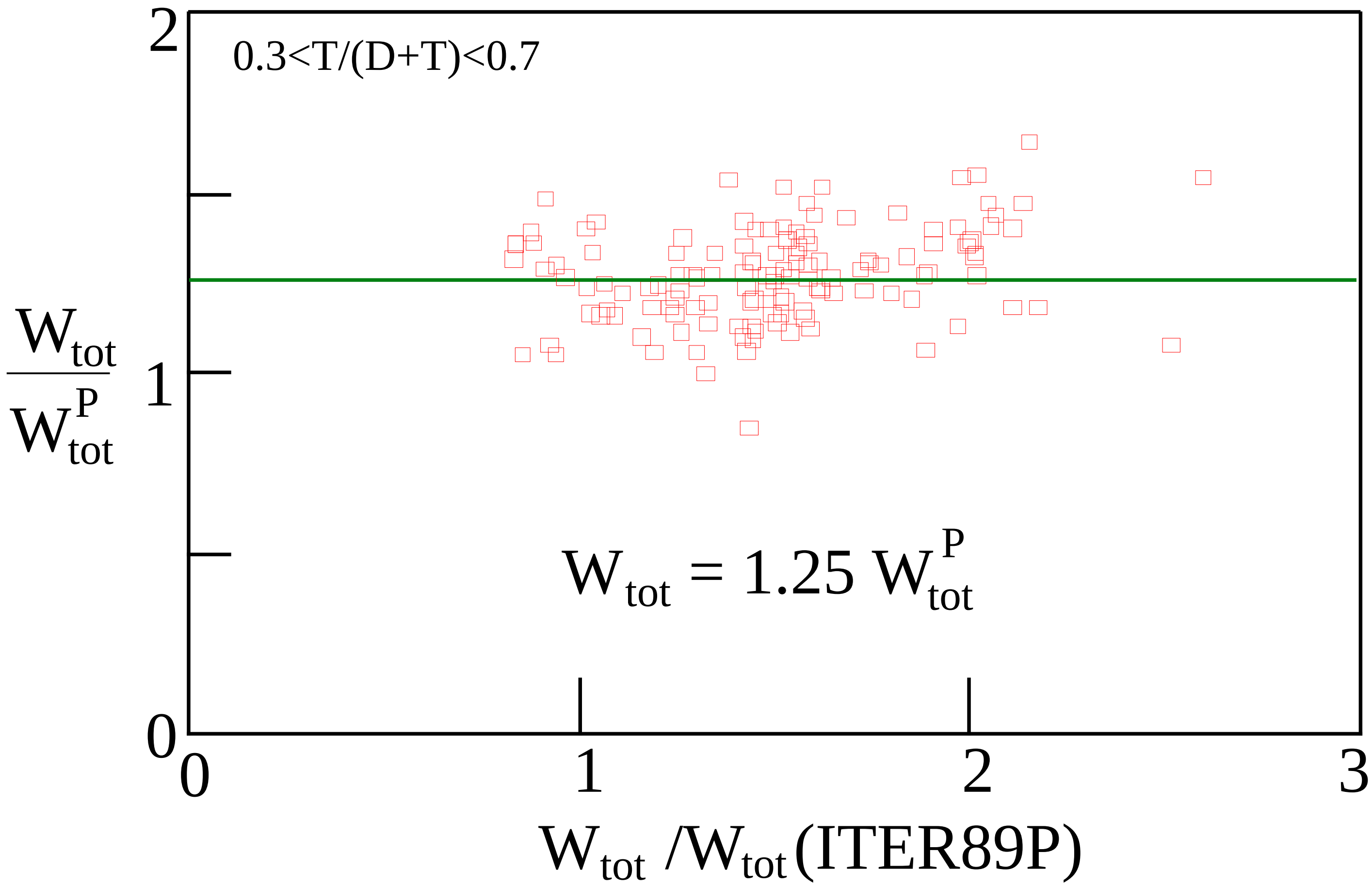
- Includes Li-enhanced Supershots, Supershots, and L-mode discharges at different major radii
- Incorporates both low and high performance plasmas

Variations Observed in Plasma with Current Profile Modification



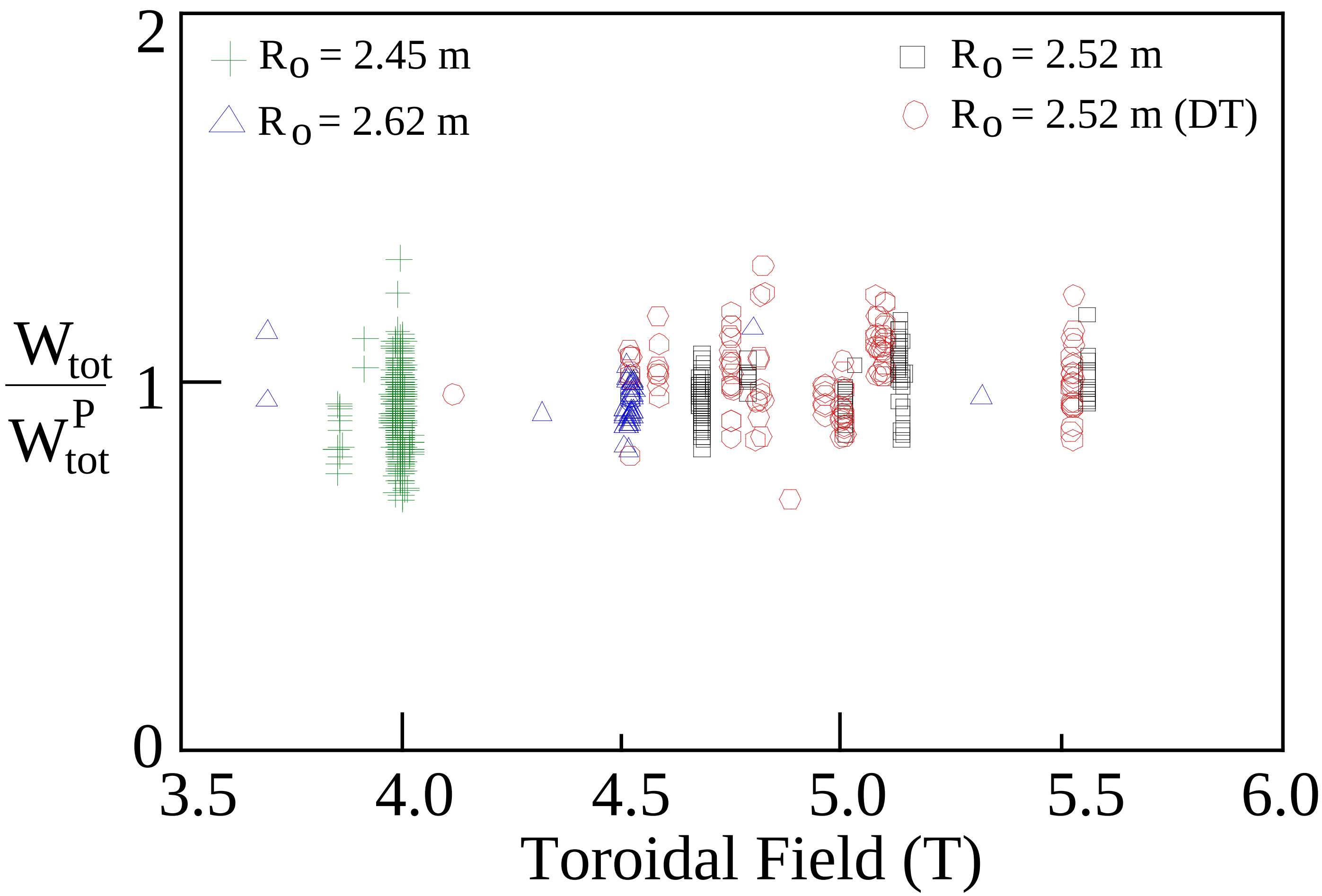
- May provide guidance to examine current profile effect on transport

DT discharges have 25 % greater stored energy compared with the scaling



- Increase attributed to T isotopic effect
  (Scott, et al., IAEA, 96)

Toroidal Magnetic Field is not Important in Determination of the Stored Energy



- Magnetic field and plasma current are extremely important in the determination of plasma stability

Importance of H_{ne} is Evident in Other Tokamaks

JET

Fusion power gain expression is similar to that of TFTR

$Q = P_B$ (central) [JET]

Thompson et al., Phys. Fluids B, V5 1993, 2474

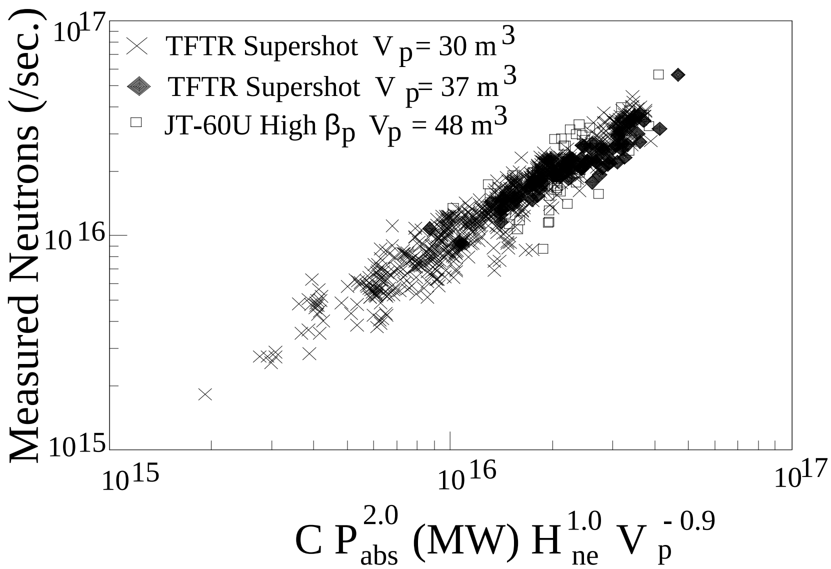
$Q = P_B^{1.2}\ H_{ne}^{1.3}$ [TFTR]

Figure 10 of the reference that is quoted.

JT-60U

Fusion power yield from high bp regime is similar to TFTR Supershot

Park, et al, Proceedings of 15th IAEA V.1, 1995, 211



DIII-D

"L-mode edge" operation has 90 % central beam fueling

Strait, et al, Bull of APS, Vol 40
No. 11, 1645, 1995

Two shots from DIII-D shows how the Hne is evolving in time. As beam starts, Hne is about 4 and rising up to 4.5 and reduced as H-mode is introduced. Otherwise, it will disrupt due to low field.

Shaped Plasmas have Advantages in Obtaining High H_{ne}

	Central beam fueling (H_{ne})	Density profile peakedness (F_{ne})	Elongation (kappa)	Wall recycling
TFTR (Supershot)	(2.5 ~ 6)	(2.5 ~ 4.0)	~1.0	Low
JET (hot ion mode)	(2.5 ~ 4)	(1.2 ~ 2.0)	> 1.6	High
JT-60U (highβ_P)*	(2.5 ~ 4)†	(2.0 ~ 3.0)†	> 1.6	High
DIII-D (L-mode edge)	(2.5 ~ 4)	(1.5 ~ 2.0)	> 1.6	High

† estimated values

* Only operational regime where central beam fueling is feasible

- Geometric factors allow high H_{ne} at reduced F_{ne}

Several Transport Theories Include Central Beam Fueling as an Essential Factor

- Central pressure models:core confinement enhancement due to the physics associated P_i

$$E_r = \frac{1}{n_i e_i}\frac{\partial}{\partial r}P_i + u_\phi B_\theta - u_\theta B_\phi$$

  - Enhancement of **E x B** shear
    => Enhancement of confinement

    - Burrel, et al, 3RV.01, - Diamond, et al, 4Q.16, - Hahm, et al, 5R.07

  - Enhancement of **Shafranov shift and/or Drift reversal**
    => Enhancement of confinement

    - Beer, et al., 2IB.02, - Drake, et al., 2Q.19 , - X. Li, 2Q.17

Non-local Nature of Core Transport May Implicitly Incorporate H_{ne}

- Core transport affected by edge conditions _
  - ITG marginality
    (Kotschenreuther et. al., Biglari, Diamond, Rosenbluth, Hahm, Tang, ...)

$$\eta_i \equiv \frac{L_i}{L_{T_i}}, \eta_i(r) \quad \eta_i^{crit}(r) \text{ at core}$$

    - H_{ne} is not an essential part in this model
    - Peaked n_e enhances confinement further

  - Self-organized criticality
    (Diamond and Hahm, Carreras, Newman et al., ..)

    - H_{ne} is an essential part in this model
- In TFTR, low edge recycling leads to increased H_{ne}

Summary

- **Energy confinement scaling based on H_{ne} is superior to L-mode scaling in TFTR**
  - Ion stored energy is strongly correlated with H_{ne}
  - Electron stored energy is independent of H_{ne} (similar to L-mode scaling)
  - Stored energy does not scale with major radius and toroidal field
- **The importance of H_{ne} appears in other tokamaks**
  - Important in high performance regimes in JET, JT-60U,and DIII-D
  - Shape factors can provide improved H_{ne} at reduced density peaking
- **Physics basis of H_{ne} supported by transport theories**