Understanding Confinement In Advanced Inductive (AI) Scenario Plasmas – Dependence On Gyroradius And Rotation

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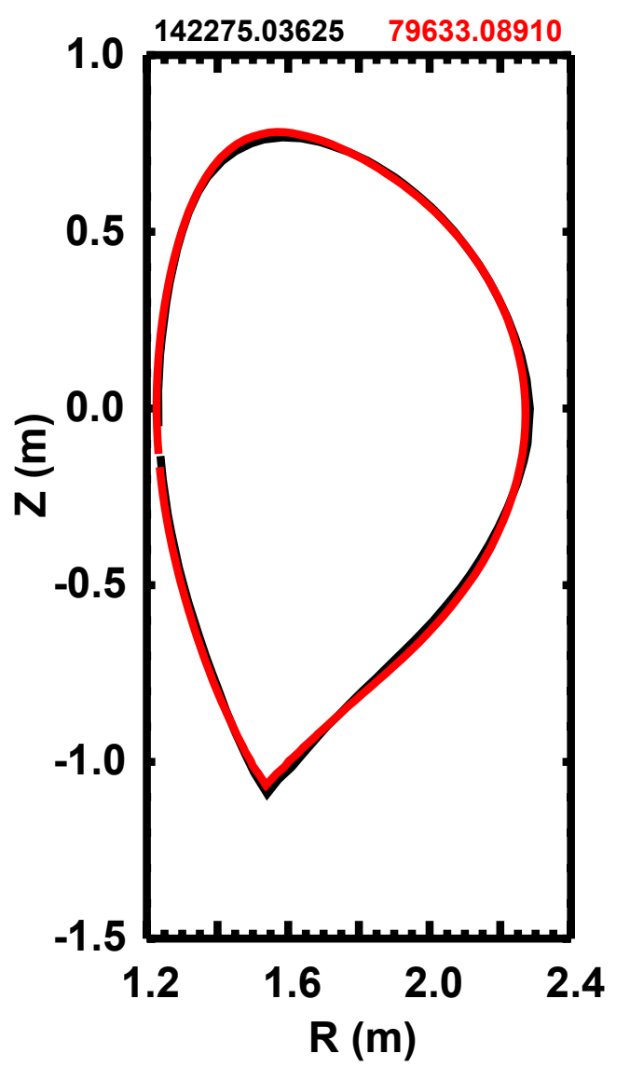
SUMMARY OF OBSERVATIONS AND RESULTS

- Determined the scaling of global energy confinement and local heat transport with normalized plasma size ($\rho_* \equiv \rho_i/a$) for AI (hybrid) scenario plasmas.
  - Obtained good matches between JET and DIII-D plasmas for
    - › global energy confinement scaling
    - › identity plasmas (all dimensionless parameters the same)
    - › at the extremes of the ρ_* range (all except ρ_* matched)
      - a range of ~2.7; about the same as from JET to ITER.
  - Key results:
    generally Bohm-like transport,
    global scaling: $B\tau_E \propto \rho_*^{-1.9}$,
    local transport:
    matched profiles for $0.45 \leq \rho \leq 0.85$,
    for $\chi_{i,e}/\chi_B \propto \rho_*^{\alpha_{i,e}}$, obtain α_i = -0.57 and α_e ~ -0.42, at ρ = 0.65,
    ($\chi_B = T/eB$)
  - Projection to ITER performance will require scaling with ν_*, and better understanding of rotation and T_e/T_i dependences.
- Determined the dependence on rotation of global confinement for AI plasmas in DIII-D.
  - over the accessible rotation range (a factor of ~4.5) τ_E increases by ~60% and the scaling multipliers H_{89} and H_{98y2} increase by ~30%.
  - determined the behavior of the m/n=3/2 NTM island as rotation changes and the effect of the NTM on confinement:
    - › at low rotation, there is a 10-15% penalty in τ_E due to the NTM; at high rotation, this decreases to 5-10%.

JET and DIII-D shapes are very well matched



- Discharges from identity comparison data set.
- JET plasma dimensions reduced by 1.675.
- rms gap between shapes is 19 mm
  - largest deviation is lower-outer squareness.
- Shapes are similar to ITER:
  ε = 0.31 (ITER = 0.32)
  κ_X = 1.75 (ITER = 1.85)
  δ = 0.36 (ITER = 0.480

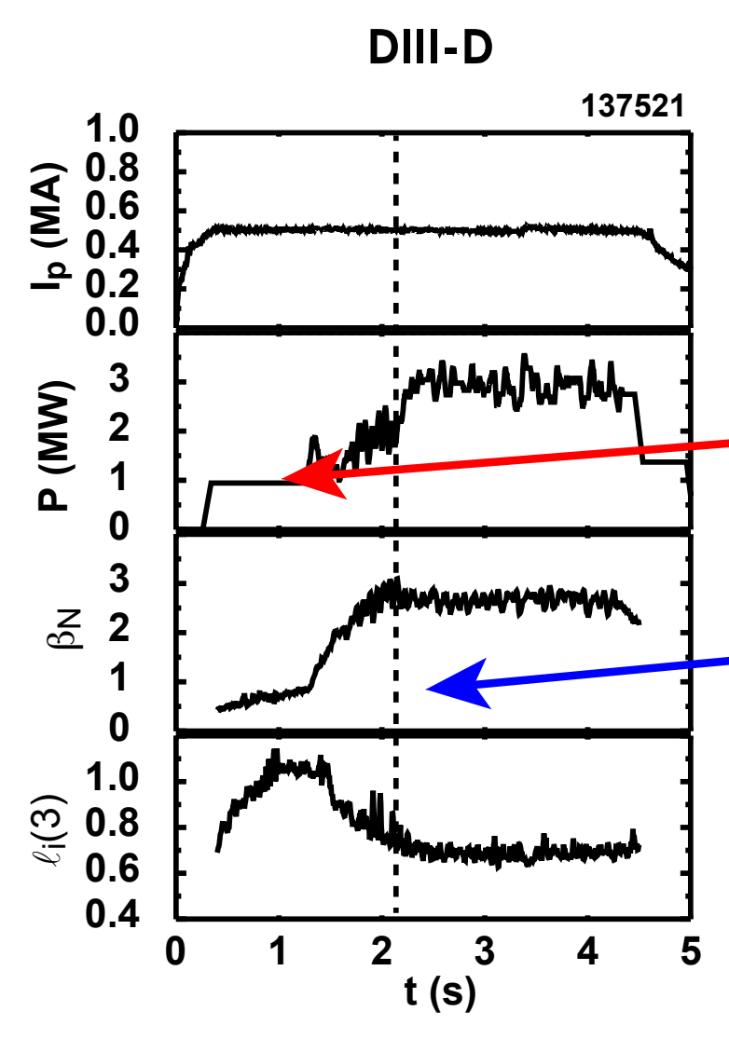
Physics-based extrapolation by nondimensional scaling

- Advanced inductive plasmas are a realization of the ITER hybrid scenario, providing high neutron fluence in a long duration inductive discharge,
- Extrapolation of the performance of AI plasmas depends on the scaling of transport with plasma size.
- Determining the scaling of performance with dimensionless parameters is a robust and rigorous method for development of scaling laws.
- A key parameter for extrapolation to ITER and reactors is ρ_* = (ion gyroradius)/(minor radius).

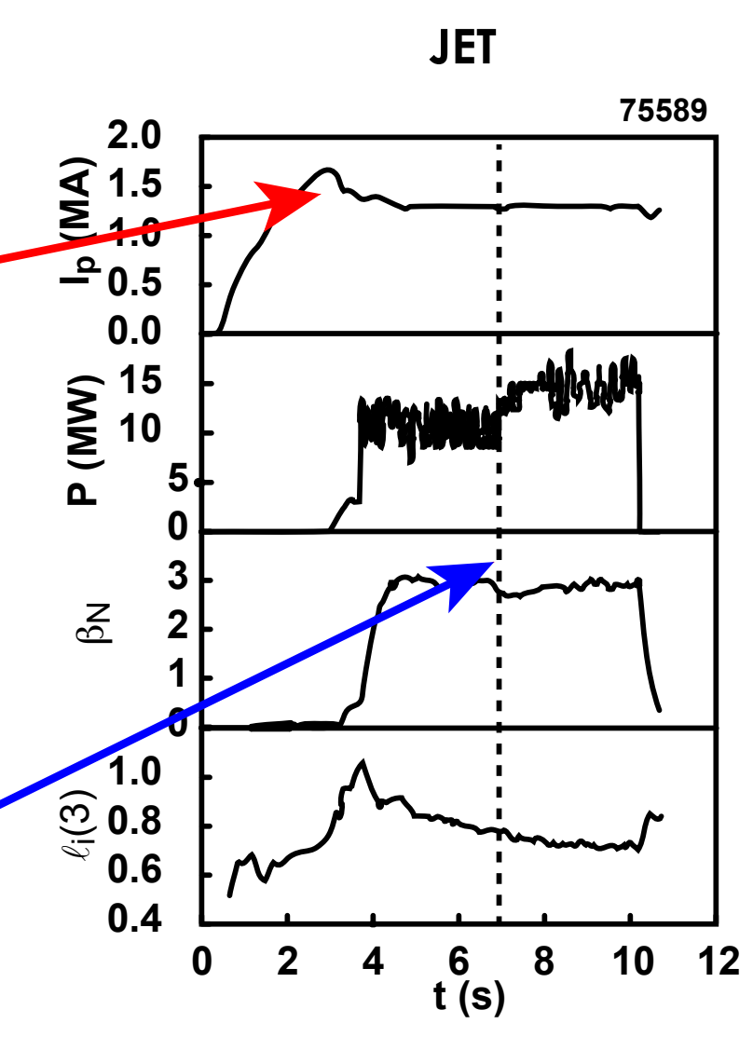
Using both JET and DIII-D extends ρ_* scaling range

- The accessible range in ρ_* is large:
  ~2.7 from high ρ_* in DIII-D to low ρ_* in JET,
  - about the same as the range from JET to ITER.
- There are three key elements to this study:
  - determining the scaling with ρ_* of the global energy confinement time normalized to the ion gyro-period, $(eB/m_i)\tau_E$ (or $B\tau_E$ for convenience),
  - demonstration of identity discharges in the two tokamaks, and
  - assessment of the scaling with ρ_* of the local heat diffusivity (normalized to the Bohm diffusivity), $\chi/\chi_B = \chi/(T/eB)$.

DIII-D (high ρ_*) and JET (low ρ_*) use different methods to prepare AI plasmas



- A broad current profile is thought to be a key element of AI operation.
- In JET, broad current profile is established by current overshoot; in DIII-D, early heating is used.
- In DIII-D, NTM appears at beginning of high β phase
  - plasma is stationary afterward;
  in JET, NTM occurs after evolution of current profile,
  - JET has several seconds of NTM-free high β operation.



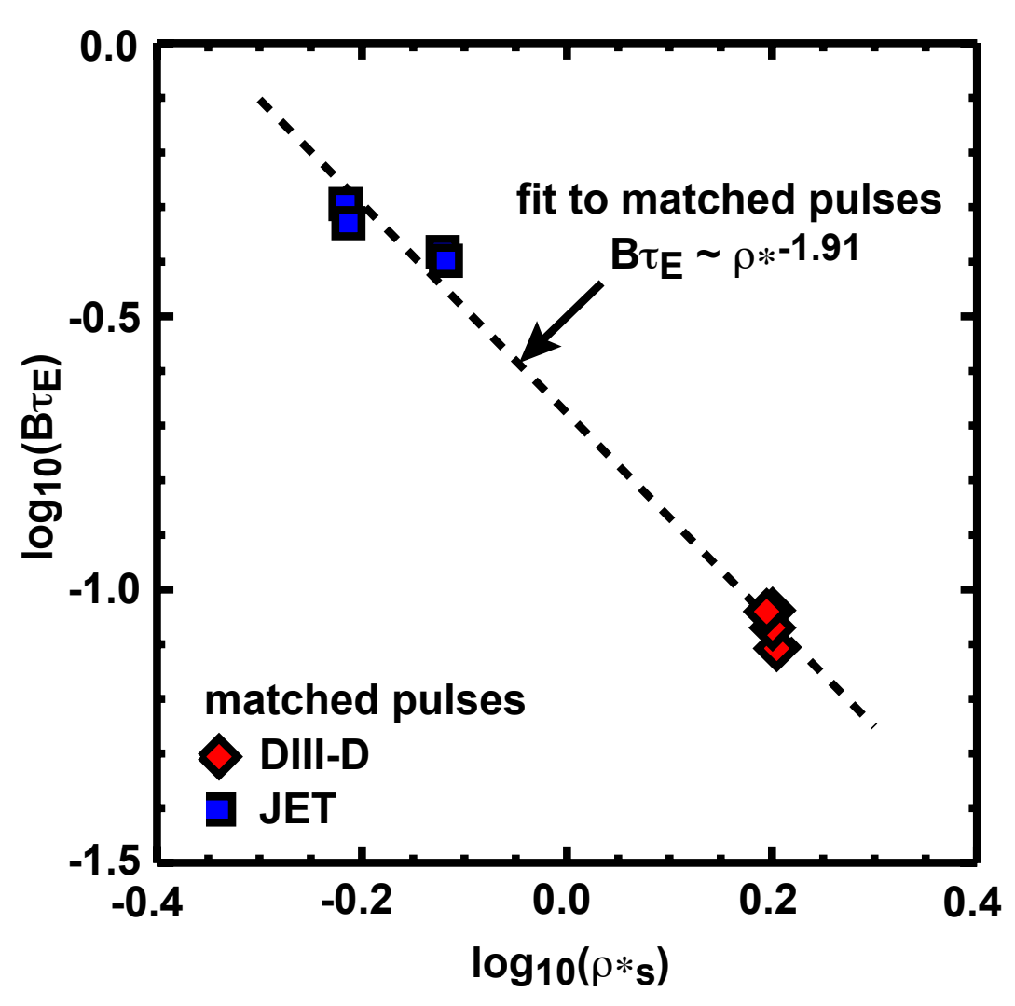
Global scaling of energy confinement time is Bohm-like

- Assume that the thermal diffusivity has a power law dependence on ρ_*:
  $$\chi/\chi_B \propto \rho_*^{\alpha}$$
  where
  $$\chi_B = T/eB$$
  then the global energy confinement time will scale like
  $$(eB/m)\tau_E \propto \rho_*^{-(2+\alpha)}F(\nu_*, \beta, q, T_i/T_e, \varepsilon, \ldots)$$
  › If all other parameters are fixed, the dependence of $B\tau_E$ on ρ_* can be determined.
- Eight matched time slices (4 JET & 4 DIII-D) were selected for this global comparison.
  - good matches of n_e, T_e, and T_i profiles,
  - also good matches of β, ν_*, and M.

parameter	JET mean	DIII-D mean	Δ/Σ %
a/R	0.315	0.298	2.7
κ_a	1.51	1.54	0.7
$q_{cyl}^{\dagger}$	2.92	2.68	4.4
$\ell_i(3)$	0.854	0.715	8.9
$\nu_{*e}^{\dagger}$	0.594	0.563	2.7
$\beta_T^{\dagger}$	5.58	5.45	1.2
T_i/T_e	1.097	1.222	5.4
H_{98y2}	1.29	1.32	1.2

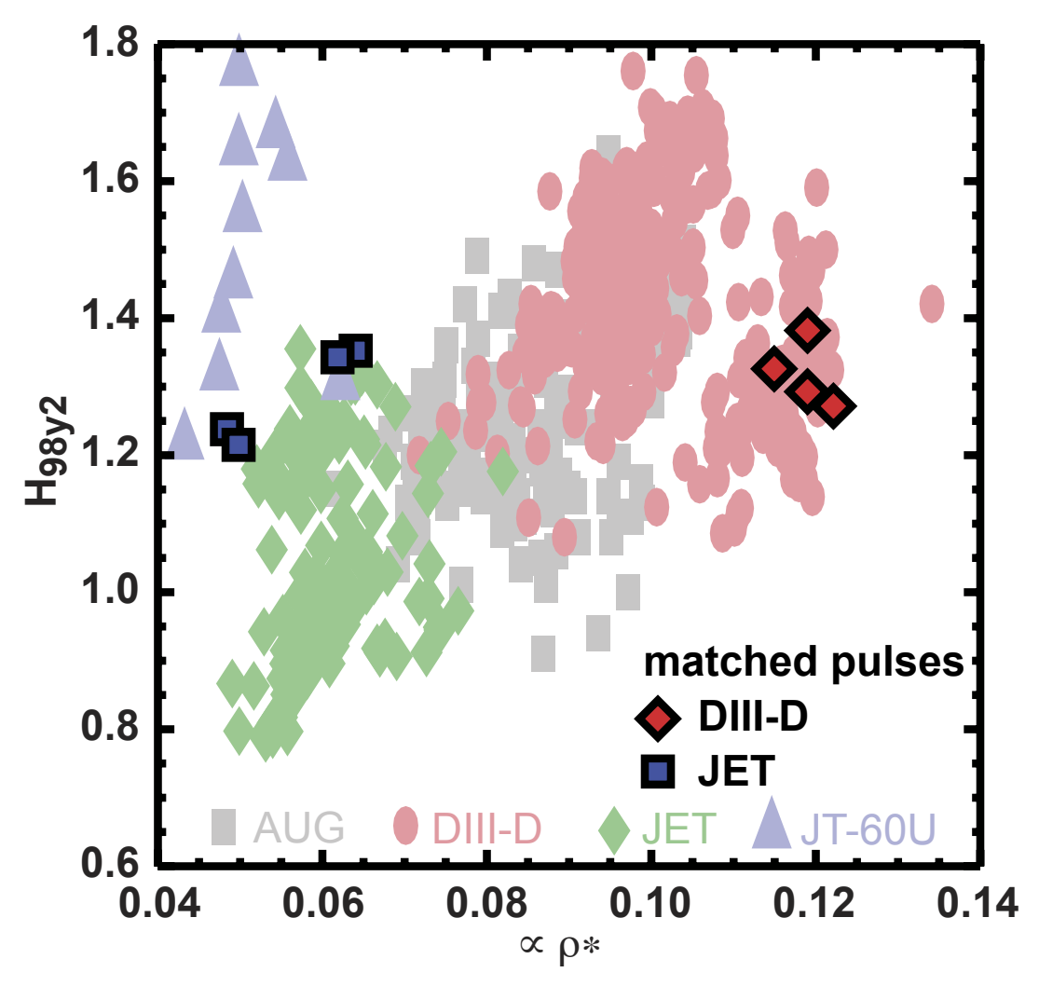
$\kappa_a = V/2\pi^2Ra^2$
$q_{cyl}^{\dagger} = 5Ba^2\kappa/IR$ (@ρ=0.5)
$\nu_{*e}^{\dagger} = n_e a/T_e^2$ (@ρ=0.5)
$\beta_T^{\dagger} = n_e(T_e+T_i)/B^2$ (@ρ=0.5)
Δ = difference
Σ = sum

- The best fit for the eight selected plasmas is $B\tau_E \propto \rho_*^{-1.91}$.



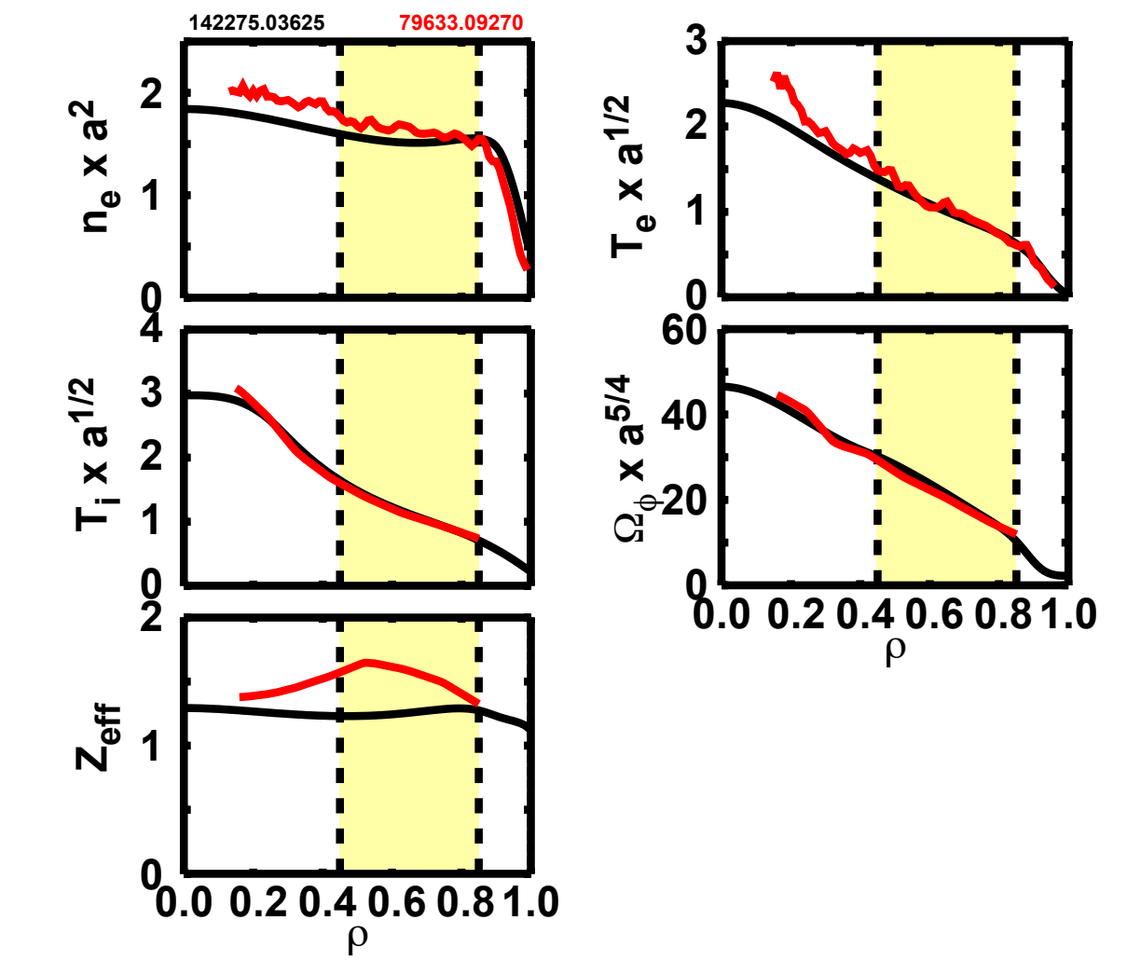
- Here ρ_{*s} is obtained using the target temperature for each point ($T = a^{1/3}B^{2/3}$). Using the volume-averaged T yields $\rho_*^{-2.12}$; using W_{th}/n_e gives $\rho_*^{-2.51}$.
- Can account for small variations in q and β using ITER98(y,2) scaling: $B\tau_{98y2} \propto q^{-3}\beta^{-0.9}$, giving $\rho_*^{-2.30}$.

- The ITPA database of hybrid discharges (AUG, DIII-D, JET, and JT-60U) shows a strong dependence of H_{98y2} on ρ_*.
  When only the matched plasmas are compared, little or no dependence is seen.

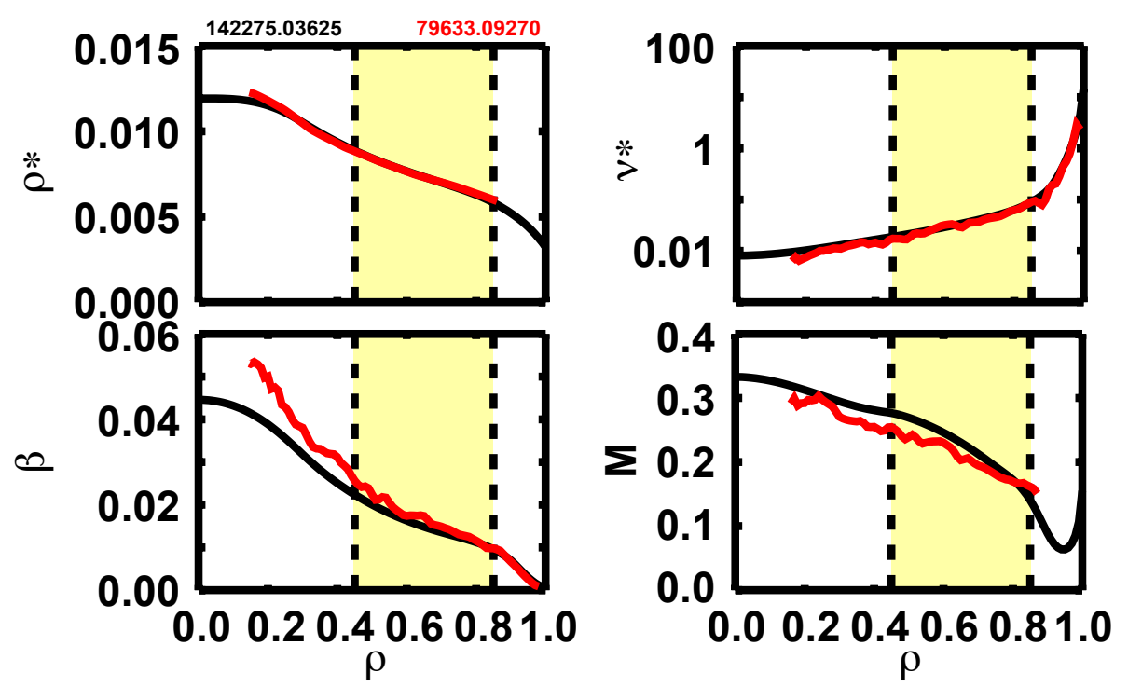


Identity matches confirm physics basis

DIII-D & JET measured profiles scaled by plasma size

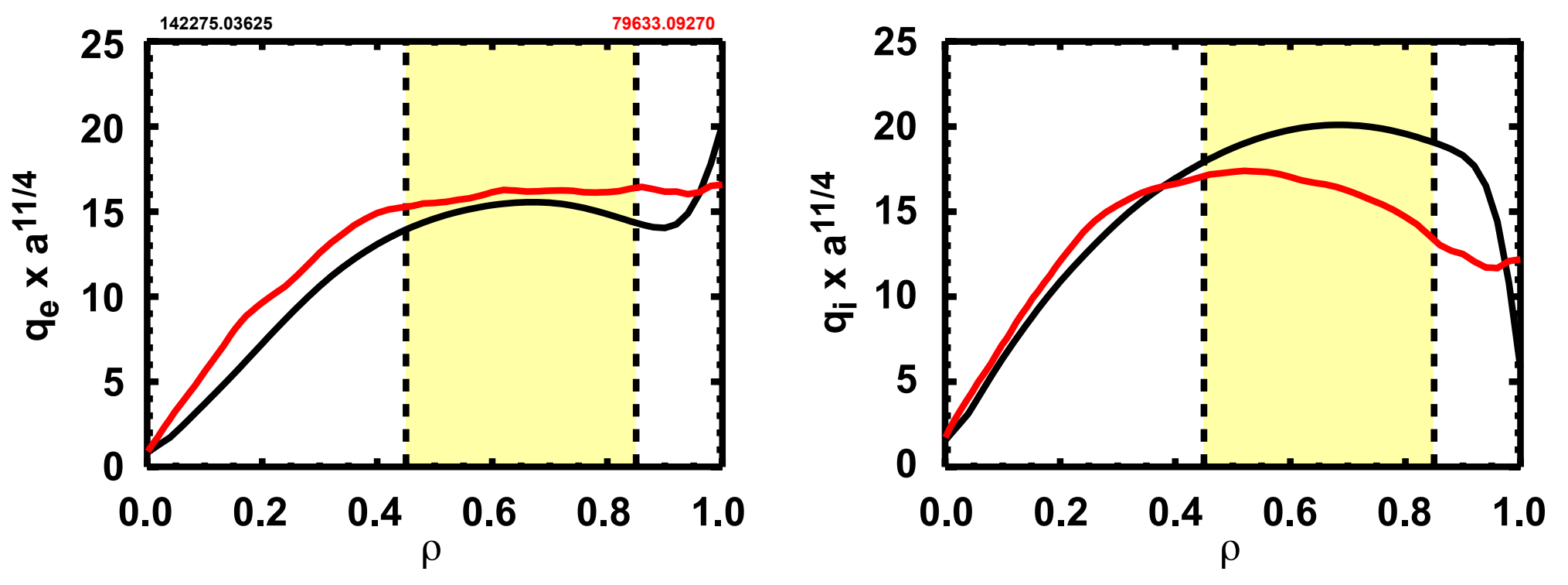


dimensionless parameters – not scaled



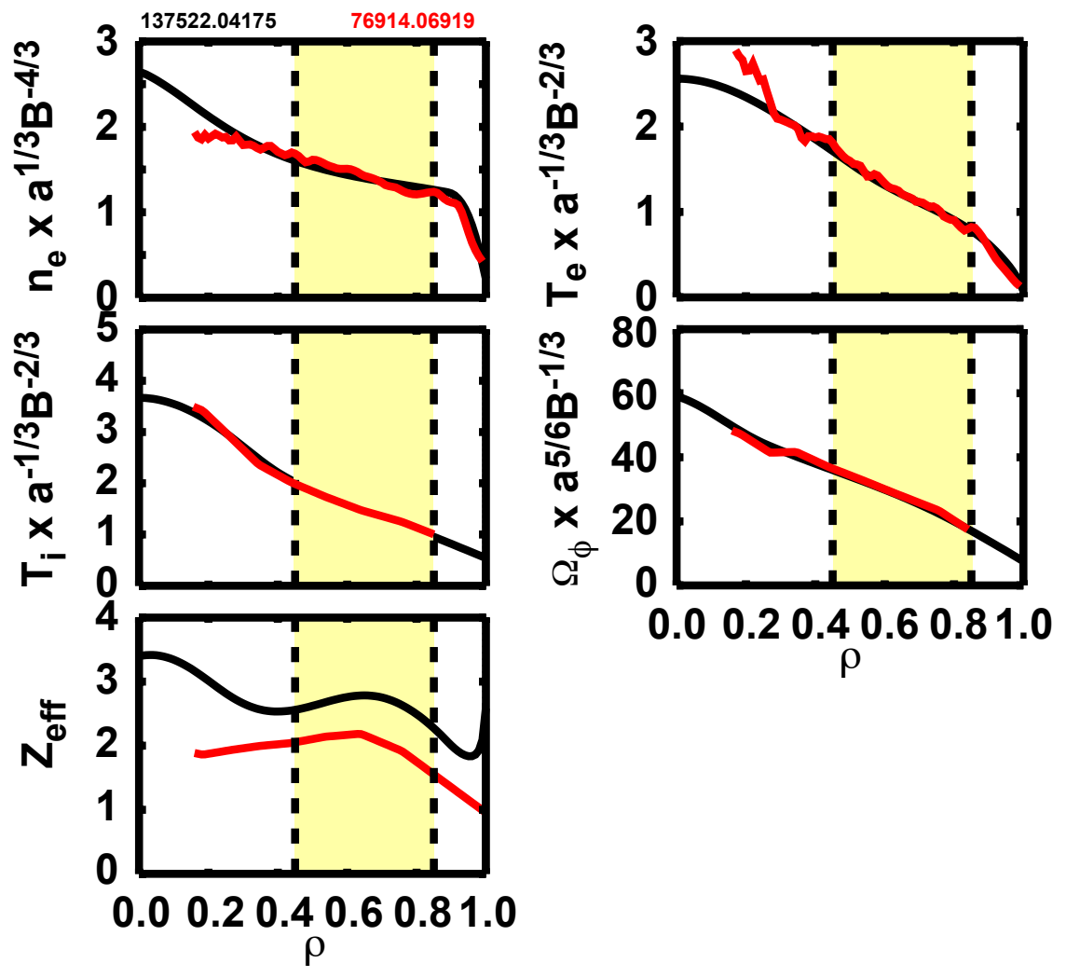
- Identity match:
  - only the plasma dimensions are varied
  - all dimensionless parameters are fixed.
- Good match indicates
  - same physics governs both tokamaks
  - the set of dimensionless parameters represents these processes.
- Profiles compared for $0.45 \leq \rho \leq 0.85$ (52% of plasma volume)
- Good matches found for pairs of time slices in three JET and eight DIII-D discharges.
- Dimensionless parameters (ρ_*, β, ν_*, M) match without scaling.
- Test whether same physics is occurring:
  ⇒ compare scaled heat flux:
  $$q = -n\chi\nabla T \propto a^{-11/4}, \quad (a_{JET}/a_{DIII\text{-}D})^{11/4} = 4.1$$

DIII-D & JET scaled electron and ion heat fluxes

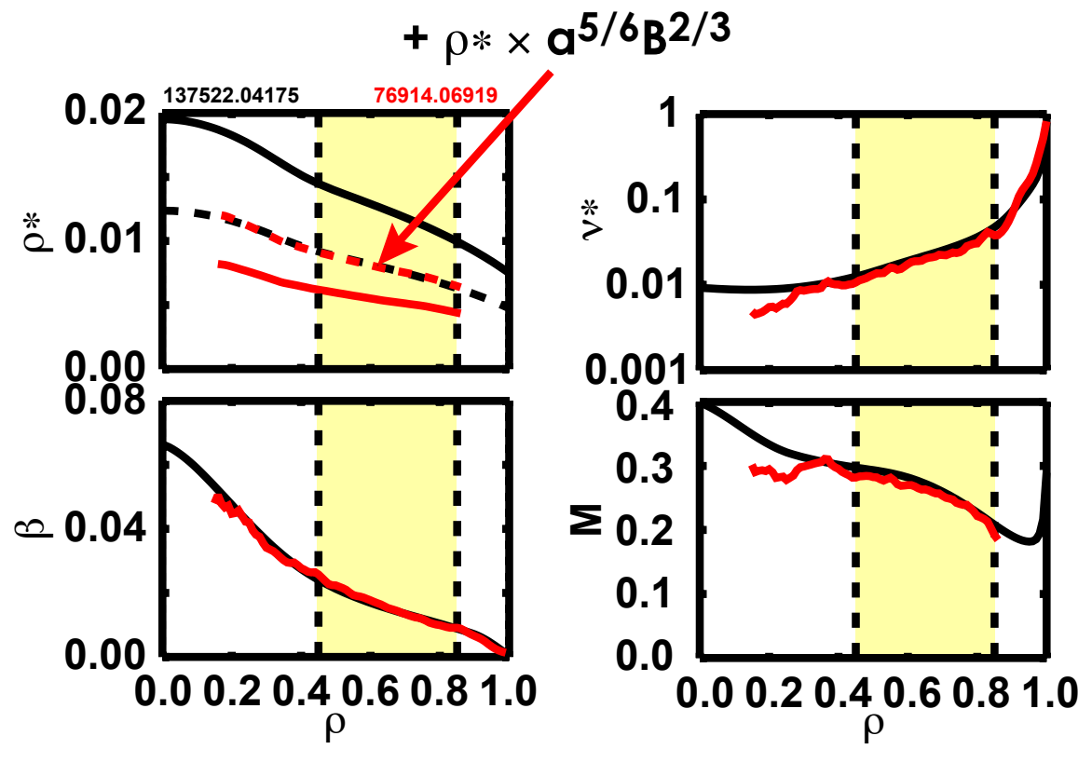


Matching at extremes of ρ_* range gives local transport scaling – also Bohm-like

DIII-D & JET measured profiles scaled by size and magnetic field

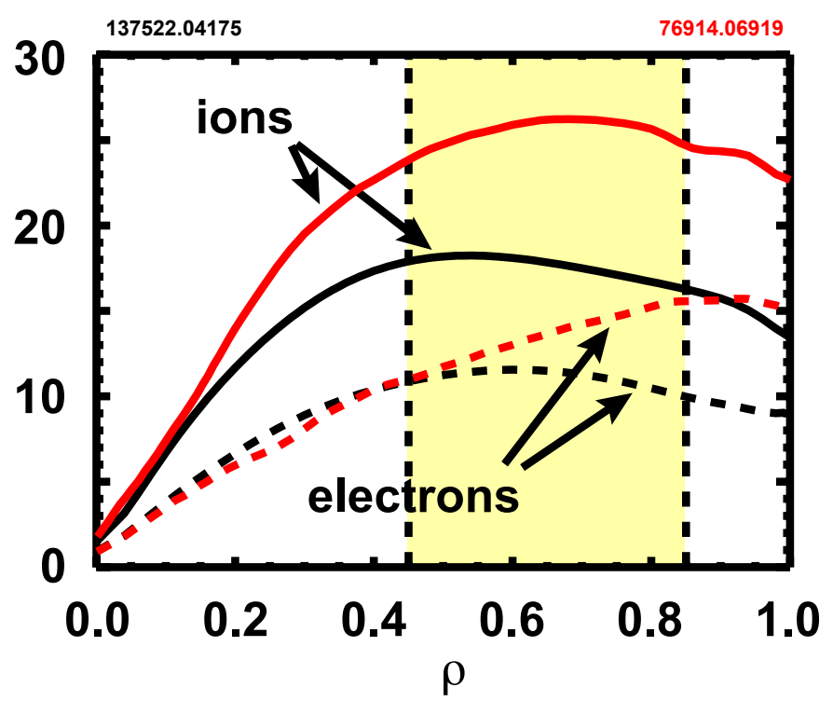


dimensionless parameters – not scaled

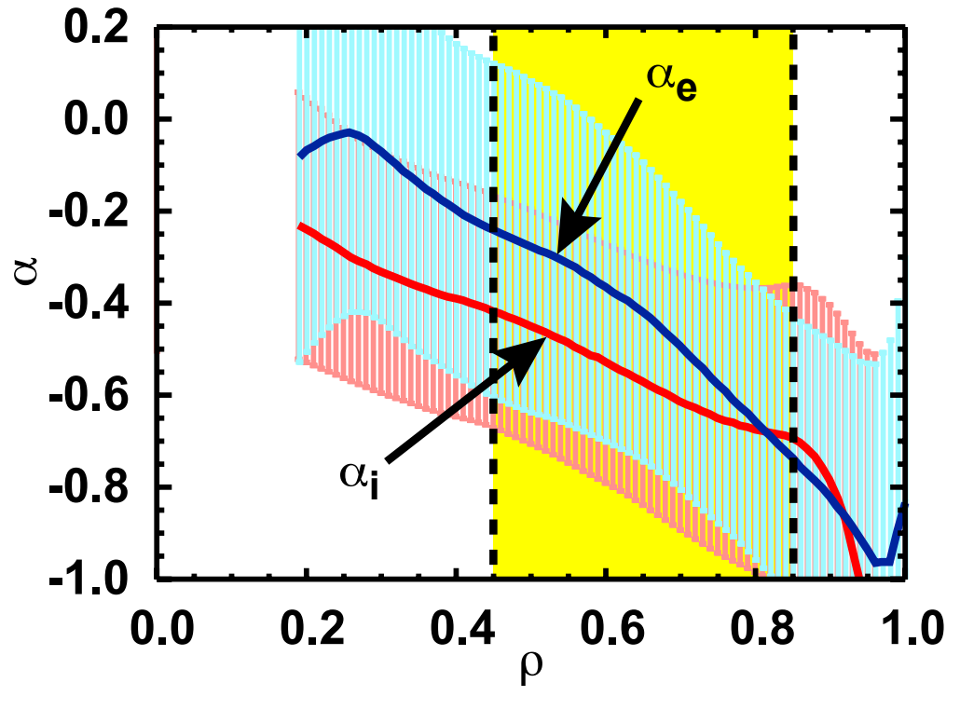


- compare lowest ρ_* in JET with highest in DIII-D
  - select pairs with
    $\rho_{*DIII\text{-}D}/\rho_{*JET} \geq 2.3$ @ ρ = 0.65
- Measured profiles match well when scaled by a and B
- Dimensionless parameters (except ρ_*) match without scaling,
  - ρ_* profiles match when scaled.
- For $q = -n\chi\nabla T$ and $\chi = \chi_B\rho_*^{\alpha}$,
  $$q \sim a^{-2/3}B^{5/3}\rho_*^{\alpha}$$
  - α can be determined from the ratio $q_{JET}/q_{DIII\text{-}D}$ (scaled).

DIII-D & JET scaled heat fluxes



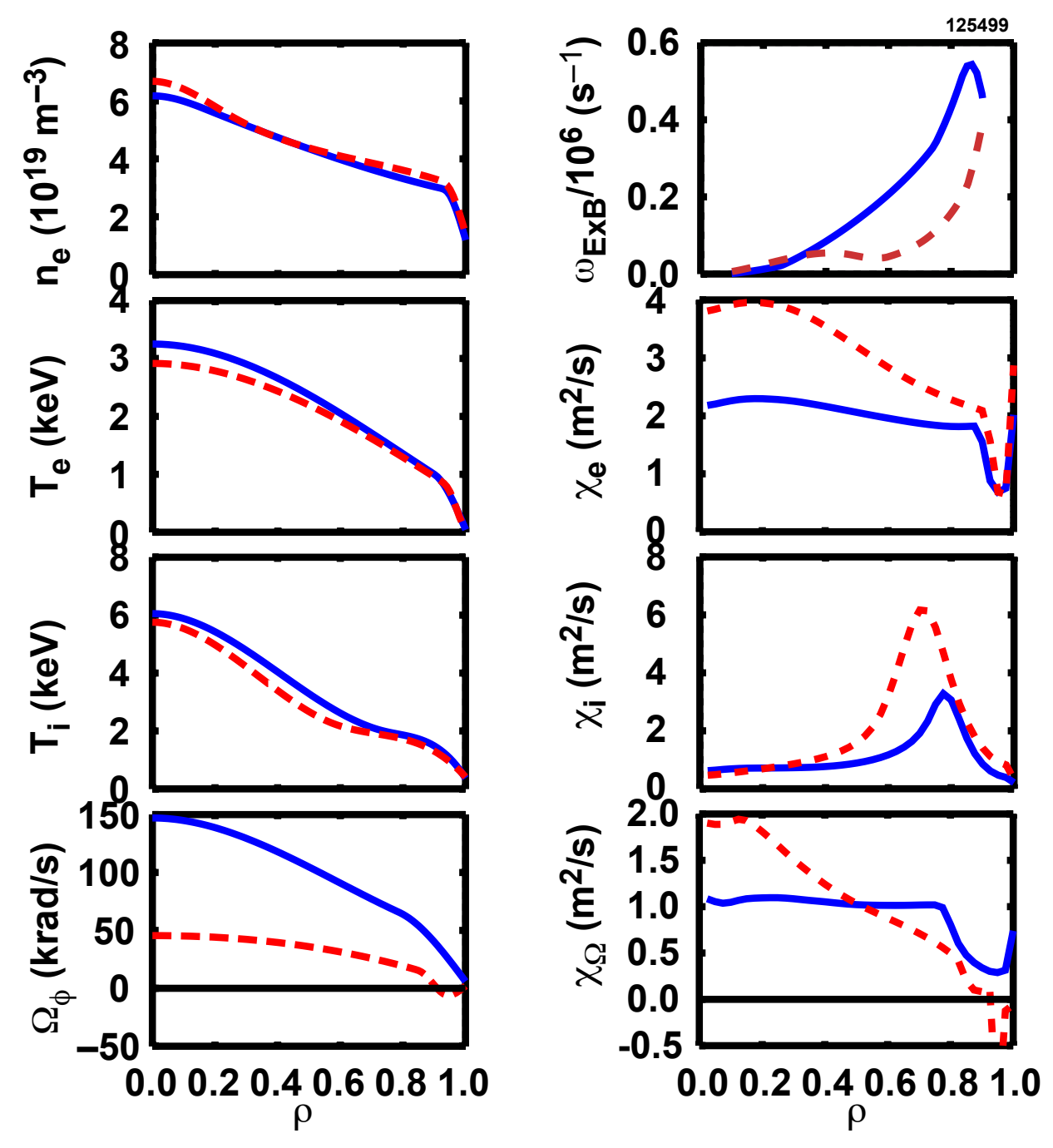
ρ_* exponents for χ_e and χ_i



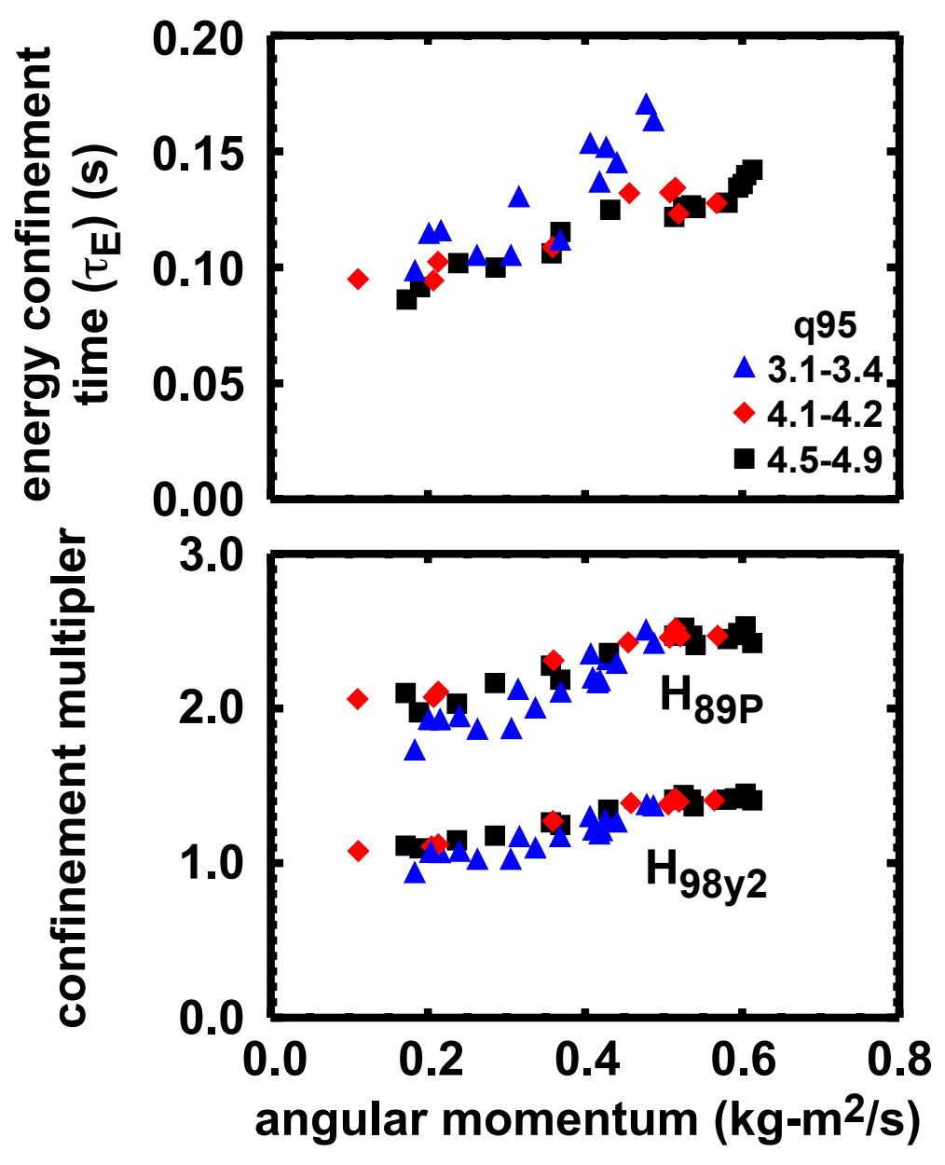
- Mean and std. dev. for best 25 pairs.
- Result is consistent with global confinement scaling.
- $\alpha_e \approx \alpha_i$.
- Strong dependence on radius
  - α more negative as radius increases.
- Indicates that scaling to ITER will be Bohm-like.

In DIII-D AI plasmas, global confinement improves as rotation increases; effect of NTM island is also reduced

- Compare high and low input torque at constant β,
  - vary the mix of co- and counter-NBI.
- In spite of large difference (factor of 3) in rotation, density and temperature profiles are little changed.
- Large decrease in ExB flow shear.
- Large (factor of 2) increases in all transport coefficients.

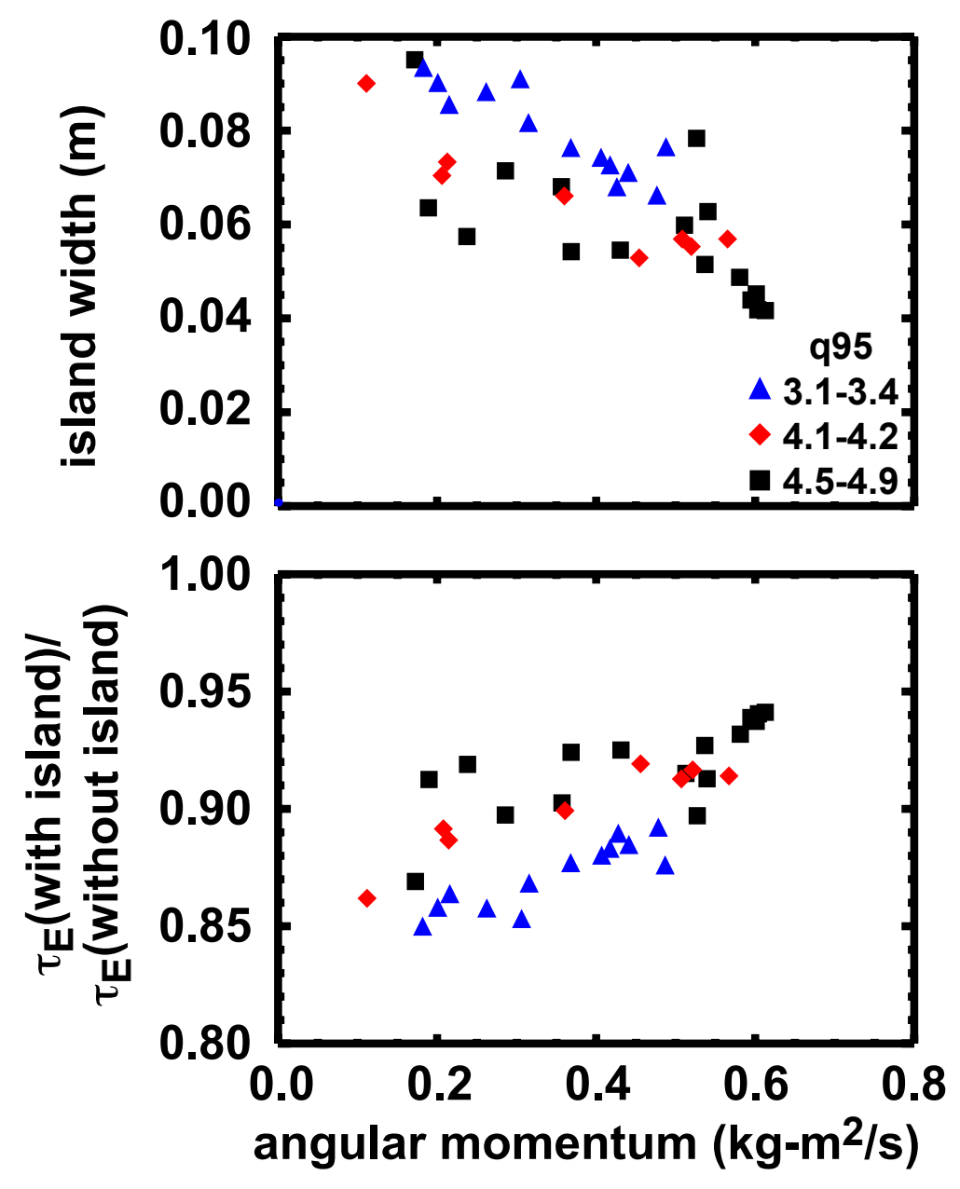


- From lowest to highest accessible rotation (factor of ~4.5), both H_{89P} and H_{98y2} increase by ~25%.
- Dominant effect is increase in ExB flow shear
  - supported by transport modeling.
- Energy confinement time is more sensitive to change in rotation at lower q_{95}.



– Central Mach number is proportional to angular momentum: M(0) ≈ 0.83 L

- Island width of m/n = 3/2 NTM decreases as rotation increases.
  - probably due to increased flow shear.
- Effect on confinement is stronger at low q_{95}
  - island width is larger and q = 3/2 surface is at larger radius.
- Difference in confinement effect of NTM at low vs high rotation is 4-6%
  - effect of NTM is smaller than that of ExB flow shear.



Density decrease with ECH appears to be coupled to rotation change

- DIII-D experiments have addressed the dependence of confinement on T_e/T_i.
- For a matched pair of discharges, with the same values of β and rotation
  - one with 3.5 MW of ECH
    and the other using counter-NBI to match the rotation,
  ⇒ the same density decrease occurs in both.
- This appears to indicate that the density 'pump-out' often seen with ECH is an indirect consequence of electron heating
  - coupled to the reduction in rotation
- Indicates an avenue for further research.