Development of Advanced Inductive Scenarios for ITER

by

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for the ITPA Integrated Operation Scenarios Topical Group Members and Experts

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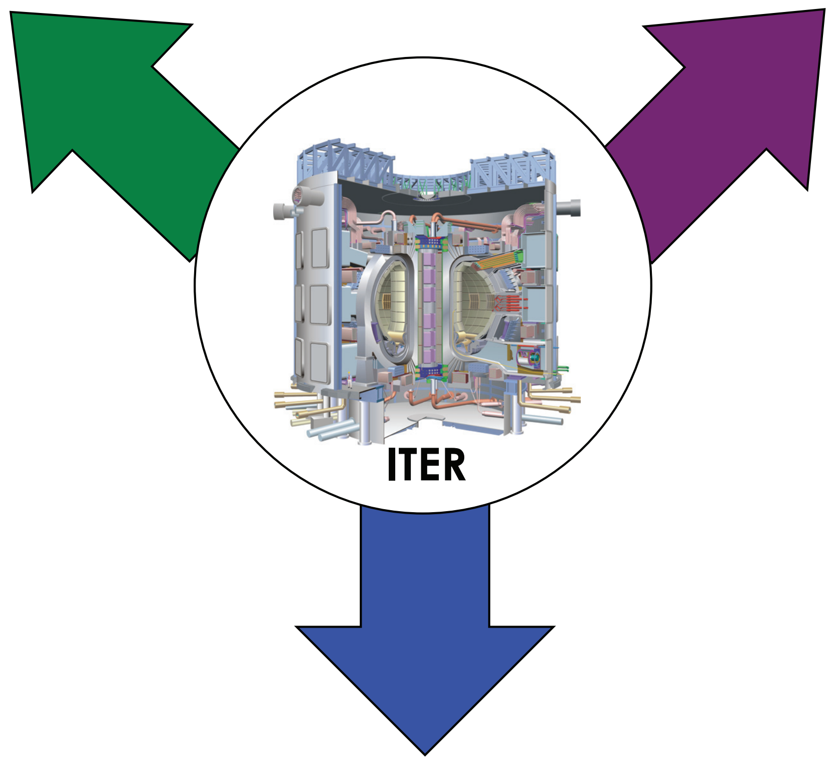
Operational Scenarios Investigated by the ITPA IOS Group Are Focused on ITER Project Goals

Sustained operation at high fusion gain (P_{fus} = 500 MW, Q = 10)

Sufficient fluence for nuclear testing



In-principle steady-state operation (Q = 5)

"Advanced Inductive" Scenarios Should Contribute Significantly to 2 of the 3 ITER Project Goals

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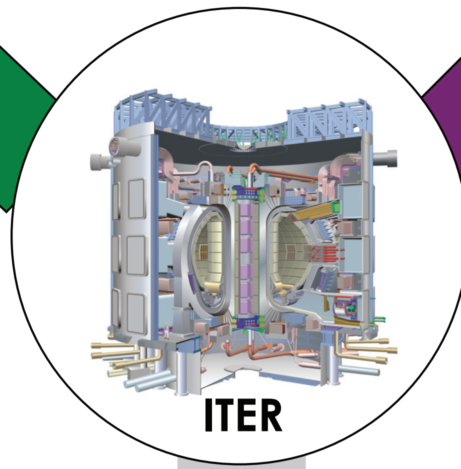


Possibility of Q = 10 at reduced current (11 MA)

Possibility of higher fusion power and gain at 15 MA

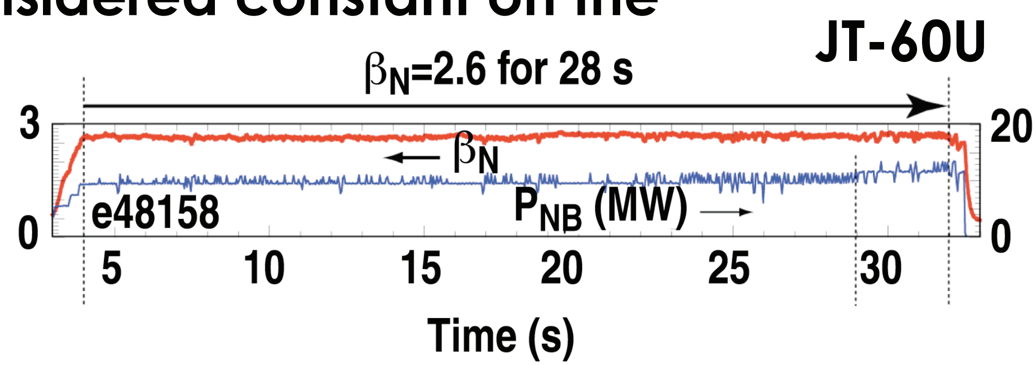
Maximum fluence/pulse combining inductive and non-inductive current drive ("hybrid")

In-principle steady-state operation (Q = 5)

Metrics for Assessing Advanced Scenarios

- **Normalized quantities are used to compare performance on existing tokamaks and project to ITER**
  - Pressure: $\beta_N \equiv \beta / (I/aB)$
  - Energy confinement: H-mode scaling (H_{98y2}), L-mode scaling (H_{89P})
    - $H_{98y2} = 1$, $H_{89P} = 2$ are "good" confinement
  - Fusion gain: $G \equiv \beta_N H_{89P} / q_{95}^2$
    - G = 0.4 corresponds approximately to Q = 10 in ITER

- **"Stationary" plasmas are considered constant on the current relaxation timescale**
  - 4 tokamaks have achieved durations ≥ 3 τ_R
  - Longest duration is >15 τ_R on JT-60U



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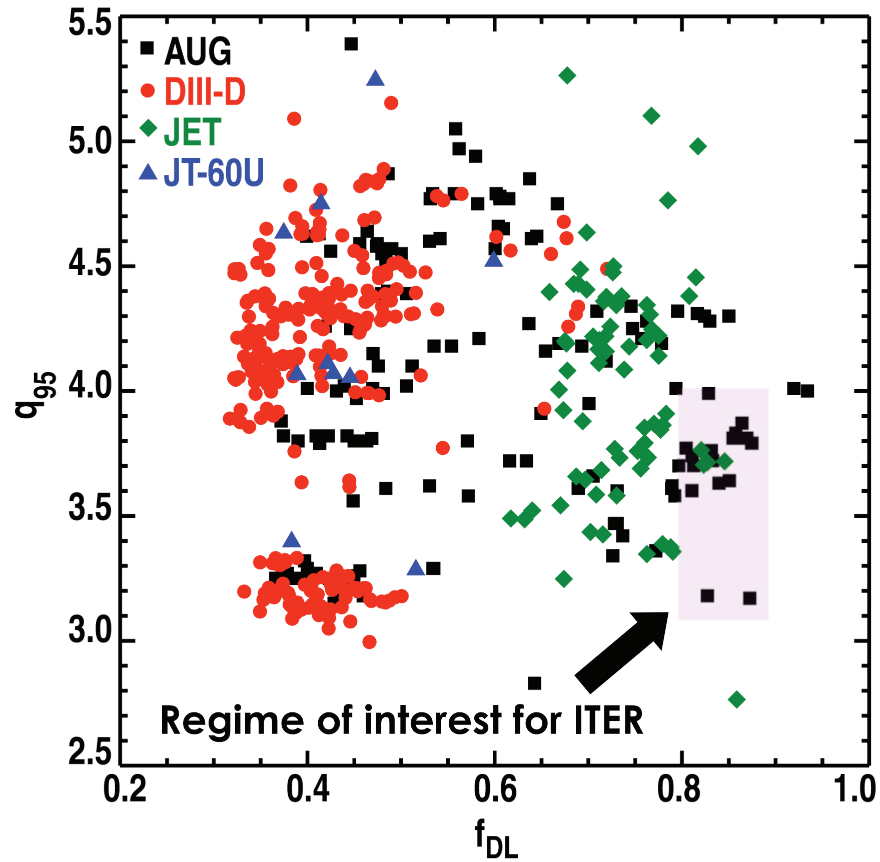
Outline of ITPA Role in Establishing the Physics Basis for Advanced Inductive Scenarios

- **Establishing Performance Domain and Boundaries**
- **Projecting present performance to ITER**
- **Open questions and conclusions**

For this presentation, "advanced inductive" scenarios will be defined as those that achieve $\beta_N \geq 2.4$ and $H_{98y2} \geq 1$ for durations $\geq 5\ \tau_E$

Advanced Inductive Plasmas Are a Robust Operating Scenario

- **Advanced inductive plasmas are found throughout the operational current and density domains of interest for burning plasmas**
  - Current limits are given by the safety factor (q_{95})
  - Density limit is the fraction of the Greenwald empirical limit (f_{DL})
- **ITER dimensionless plasma parameters and operational space parameters not possible simultaneously in present-day experiments**
  - e.g., collisionality and proximity to the density limit



Database of >500 plasmas from AUG, DIII-D, JET, JT-60U meet the definition of advanced inductive

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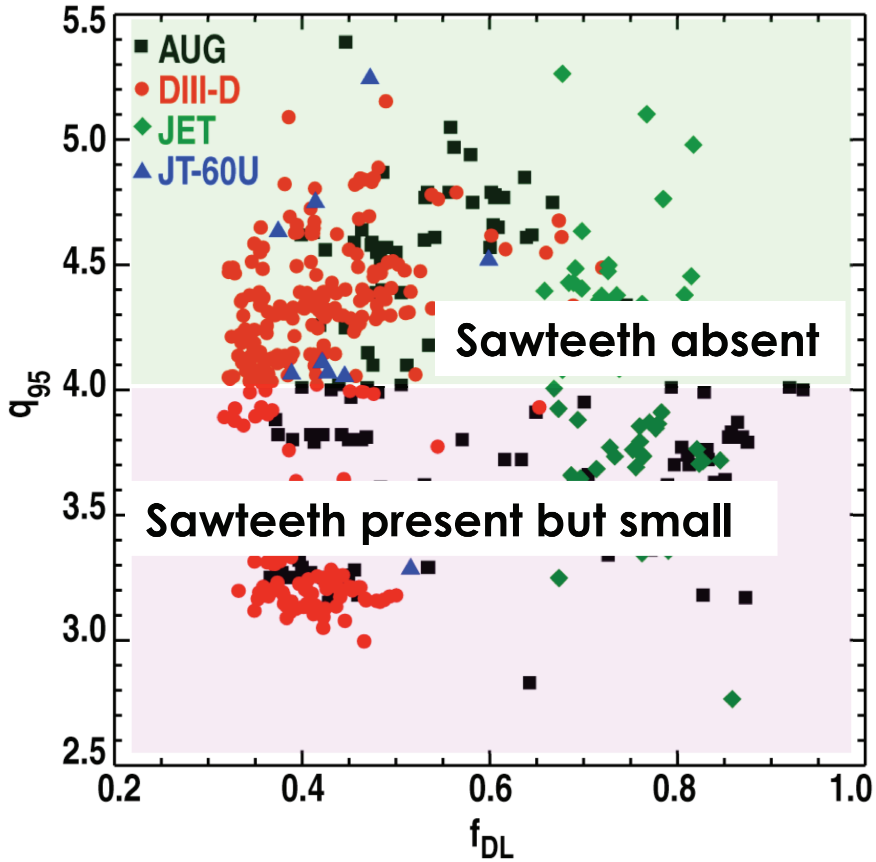
MHD Phenomena Exhibit Qualitative Similarities

- **Trends in MHD appear similar**
  - Sawteeth usually absent for q_{95}>4 and small or infrequent for q_{95}<4
  - Fishbones tend to be the dominant instability at high density, while n>1 tearing modes tend to dominate at low density (not correlated with the density limit)
- **Limit to pressure is almost always an n=1 tearing mode**
  - Limit is rarely disruptive because the relatively slow growth rate allows the possibility of mitigation or shutdown



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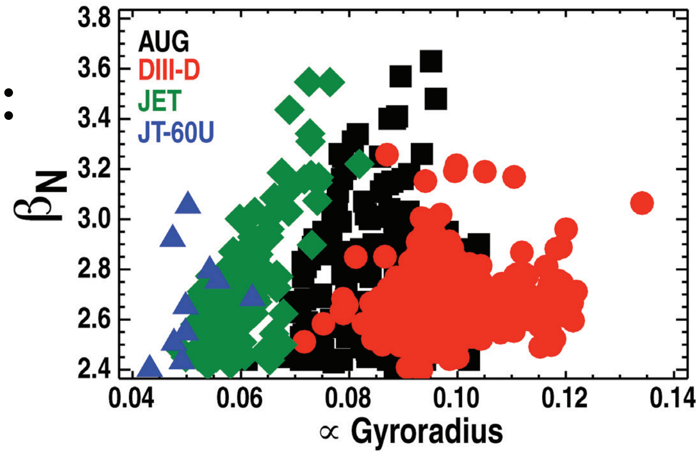
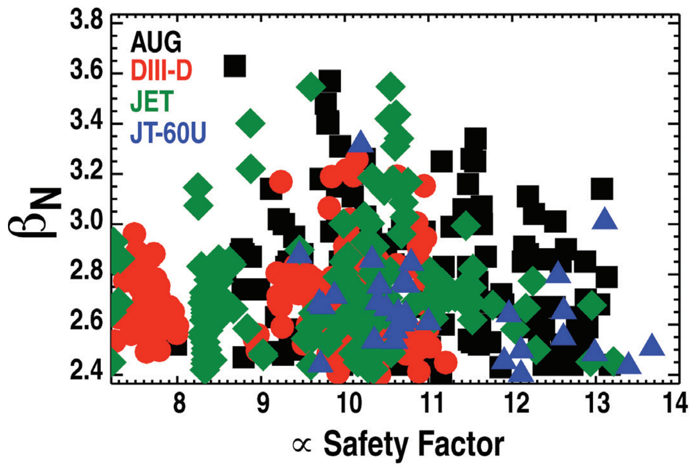
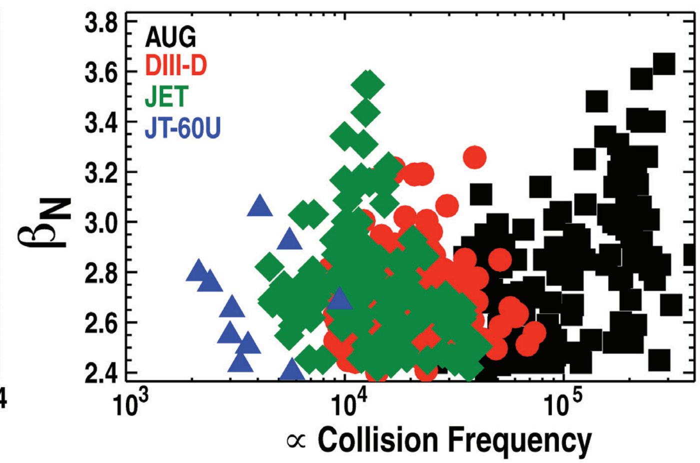
Achieved Pressure Appears Insensitive to Dimensionless Plasma Parameters

- **Pressures giving significant fusion performance (β_N up to 3) found across a broad range of normalized gyroradius, normalized collision frequency, and safety factor**
- **Scalar proxies derived from the database are used for the dimensionless parameters:**
  - Gyroradius $\propto (W_{th}/nV)^{1/2}/Ba$
  - Pressure $\propto W_{th}/VB^2$ (used later)
  - Collision frequency $\propto (n^3V/W_{th}^2)(R^5/a^3)^{1/2}$
  - Safety factor $\propto BV/IR^2$







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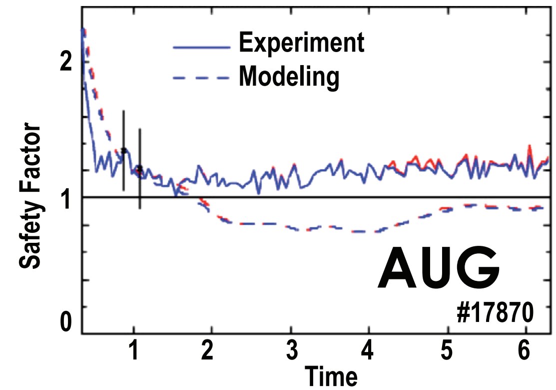
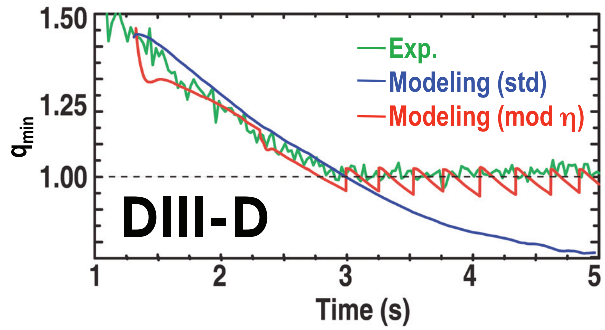
Current Profile Evolution is Not Described by Standard Model In Many Cases

- **Modeling of the evolution of the current profile in AUG and DIII-D shows min(q) < 1, contrary to experimental measurements**
  - Standard conductivity and current drive models used

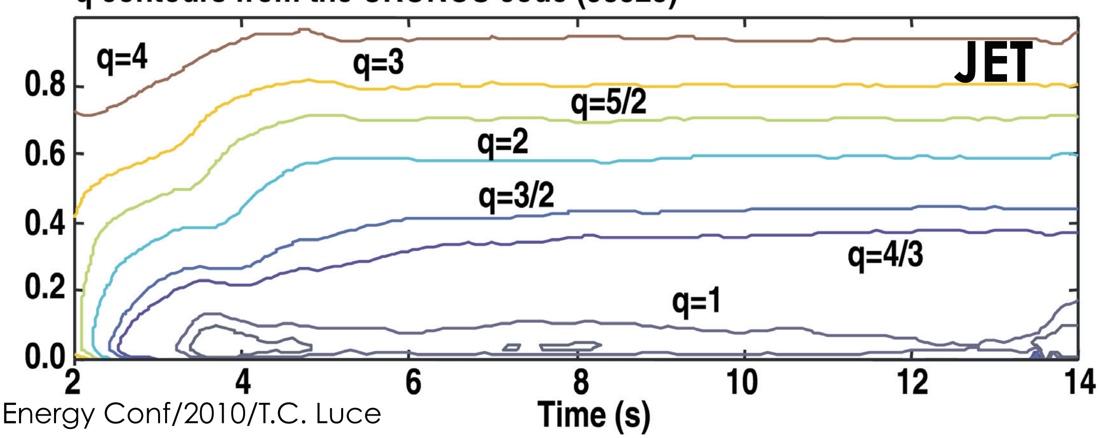


- **DIII-D experiments show m=3/n=2 tearing mode is essential to maintaining min(q) > 1**
  - Not by broadening of the conductivity profile



- **Modeling of the current profile evolution in JET shows min(q) ≈ 1, consistent with lack of sawteeth**

q contours from the CRONOS code (58323)



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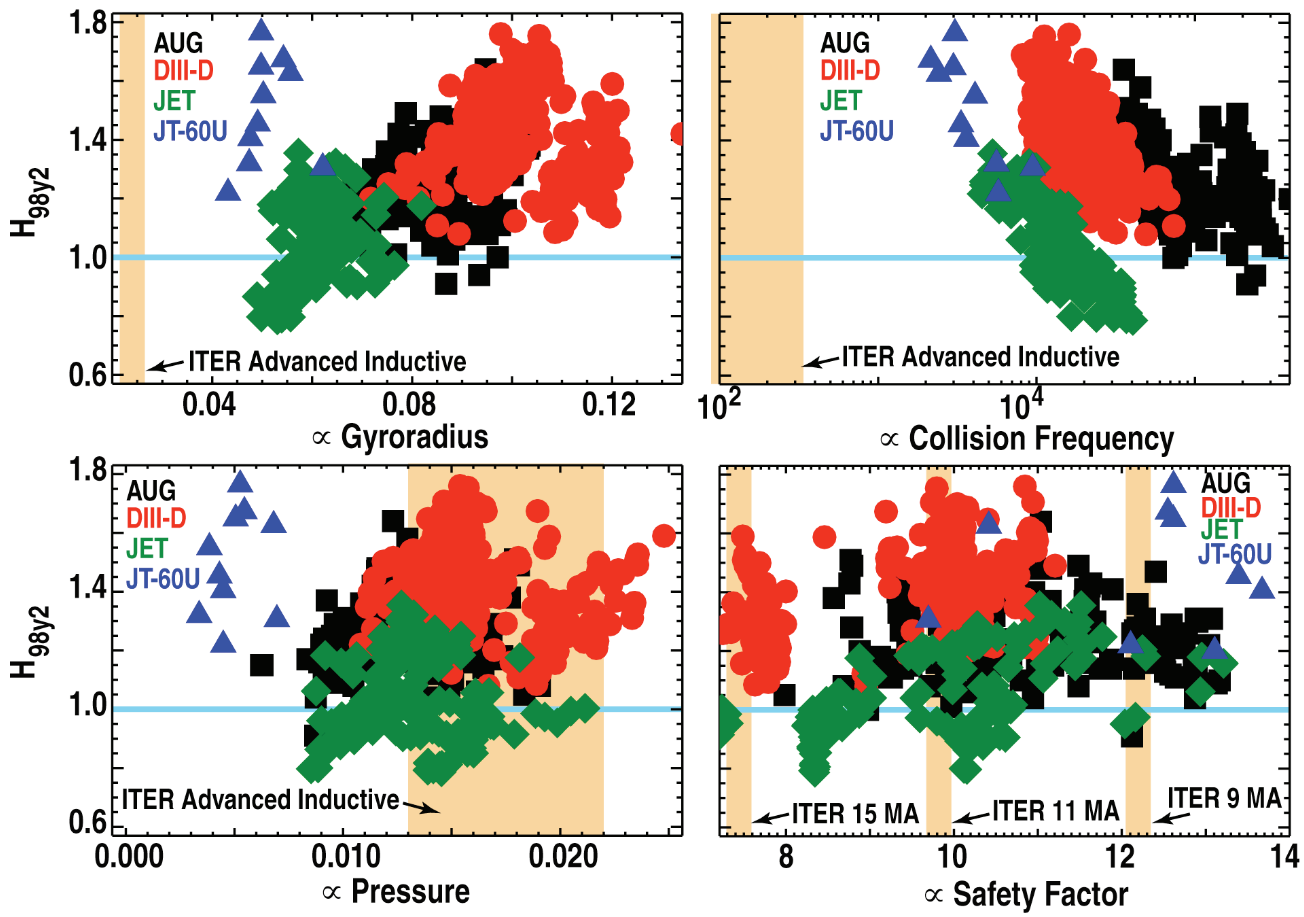
H-Mode Scaling Does Not Describe Energy Confinement of Advanced Inductive Plasmas Well

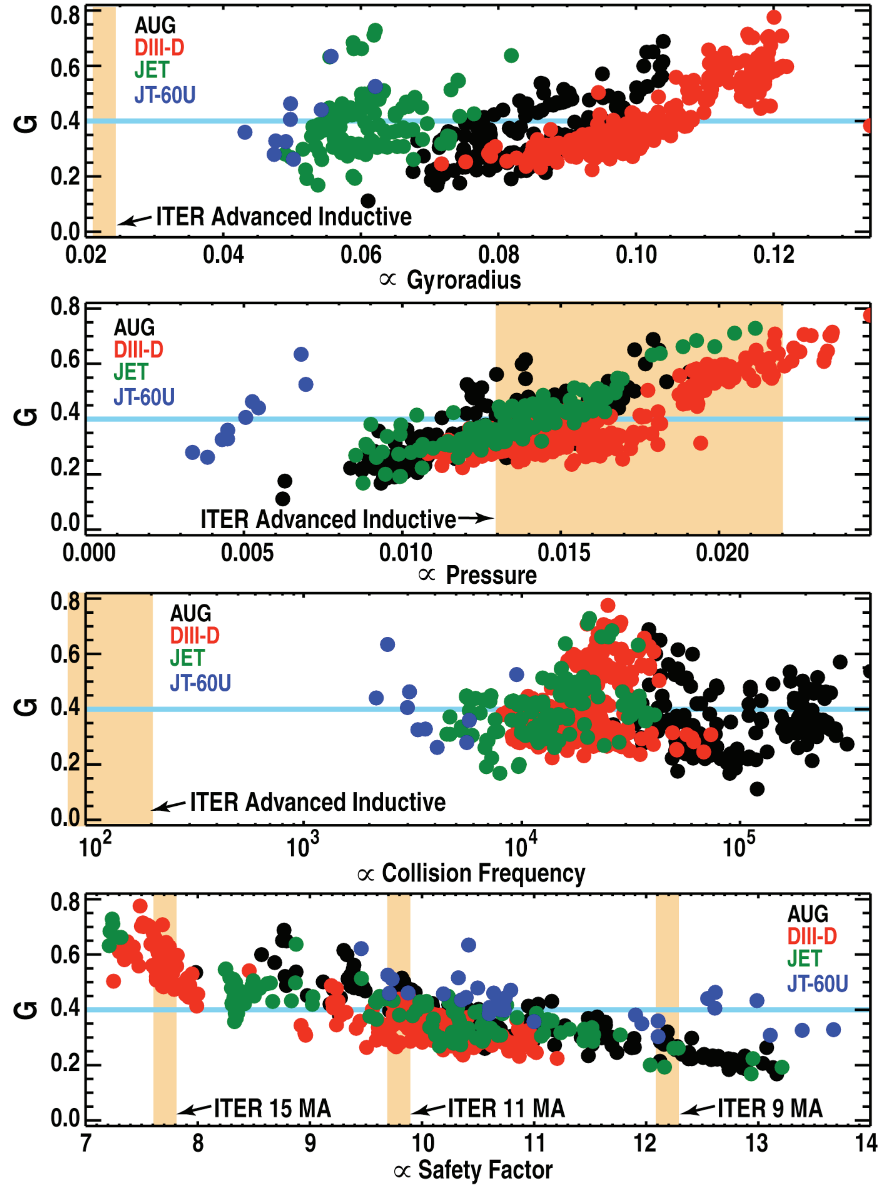
- Large variations in H_{98y2} indicate either a missing parameter in the scaling or a different regime
- Strongest trends in variables farthest from ITER values
- Magnetic shear, rotation, T_e/T_i not in H_{98y2}



- Specialized experiments are needed to clarify these issues

Fusion Gain Metric Shows Q=10 Equivalent Operation Is Observed Over a Broad Range of Parameters

- G improves with increasing pressure and decreasing safety factor as expected
- Strong trend in H_{98y2} with collisionality is not reflected in G
- Strong trend in H_{98y2} with gyroradius remains in G



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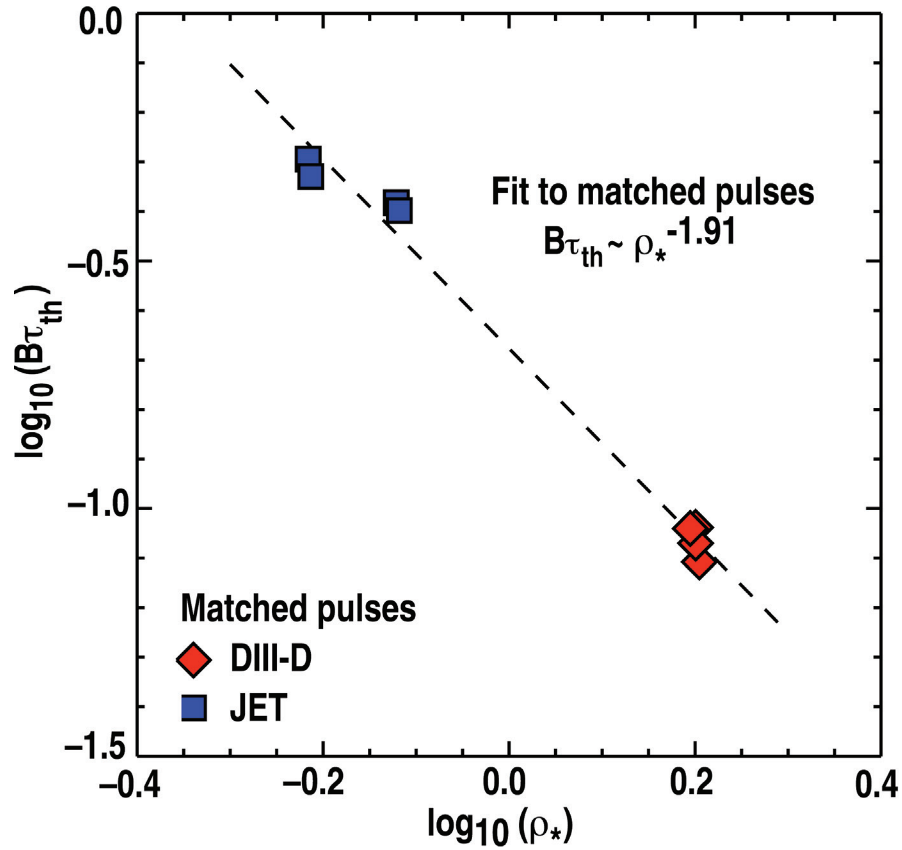
Accurate Projection to ITER Will Require Both Empirical Scaling and Validated Models

- **Scalings from multi-tokamak databases will not be feasible for advanced inductive scenarios**
  - Too little variation in engineering parameters obtained in the tokamaks where the scenario is demonstrated
- **Dimensionless parameter scaling isolates the physics variables for which the extrapolation is the largest**
  - Normalized pressure and safety factor can chosen at the ITER values
  - Gyroradius, collision frequency, rotation (Mach number), and T_e/T_i can be varied sufficiently to gain an empirical scaling
- **Data along critical directions are obtained for model validation, even if the resulting empirical scalings are not sufficiently accurate**

Dimensionless Parameter Scaling Experiments Show Gyroradius Scaling Consistent With Database Trends

- **Matched "identity" plasmas on DIII-D and JET indicate scenario is the same in both tokamaks**
- **Correlated gyroradius (ρ_*) scan shows weaker ρ_* scaling than H_{98y2}**
  - Measured scaling ($B\tau_{th} \propto \rho_*^{-1.9}$) is close to Bohm scaling ($B\tau_{th} \propto \rho_*^{-2}$)
  - Less favorable than ρ_* scaling implicit in H_{98y2} ($B\tau_{th} \propto \rho_*^{-2.7}$)
- **Simple extrapolation in ρ_* would give plasmas above the density limit in ITER**
  - Must account for collisionality scaling seen in database



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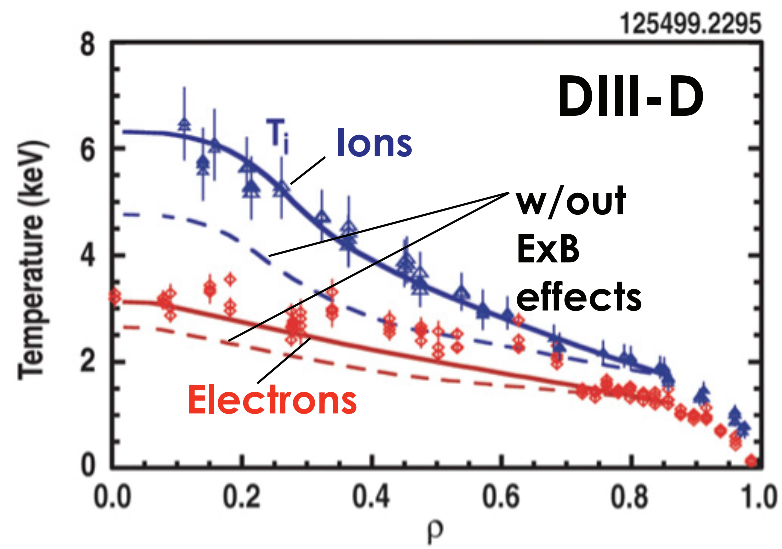
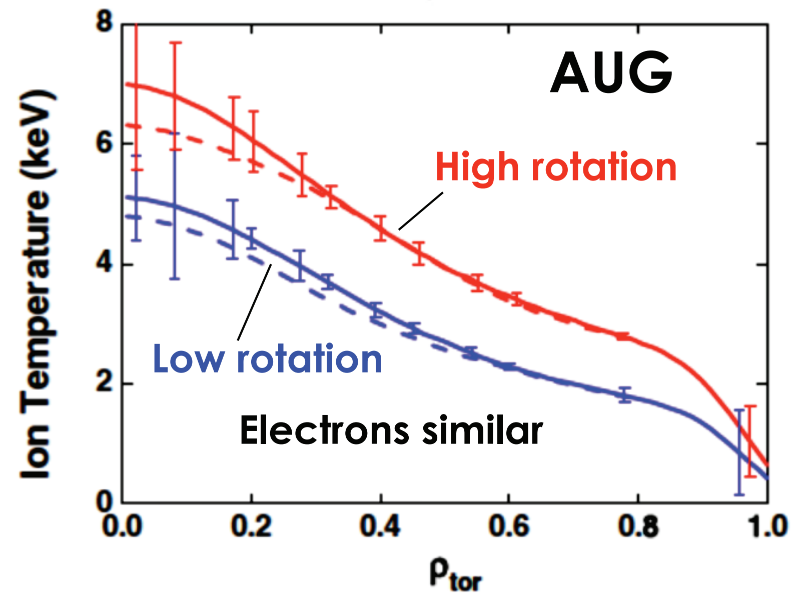
Comparison of Theory-Based Models With Experiments Shows No Clear Favorite

- **GLF23 model reproduces DIII-D rotation scan data**
  - Improved performance at high rotation is consistent with ExB shear stabilization of turbulence
- **Weiland model reproduces AUG data**
  - Effect of rotation is weak in this model
- **Modeling of data from all 4 tokamaks could not validate definitively any model**





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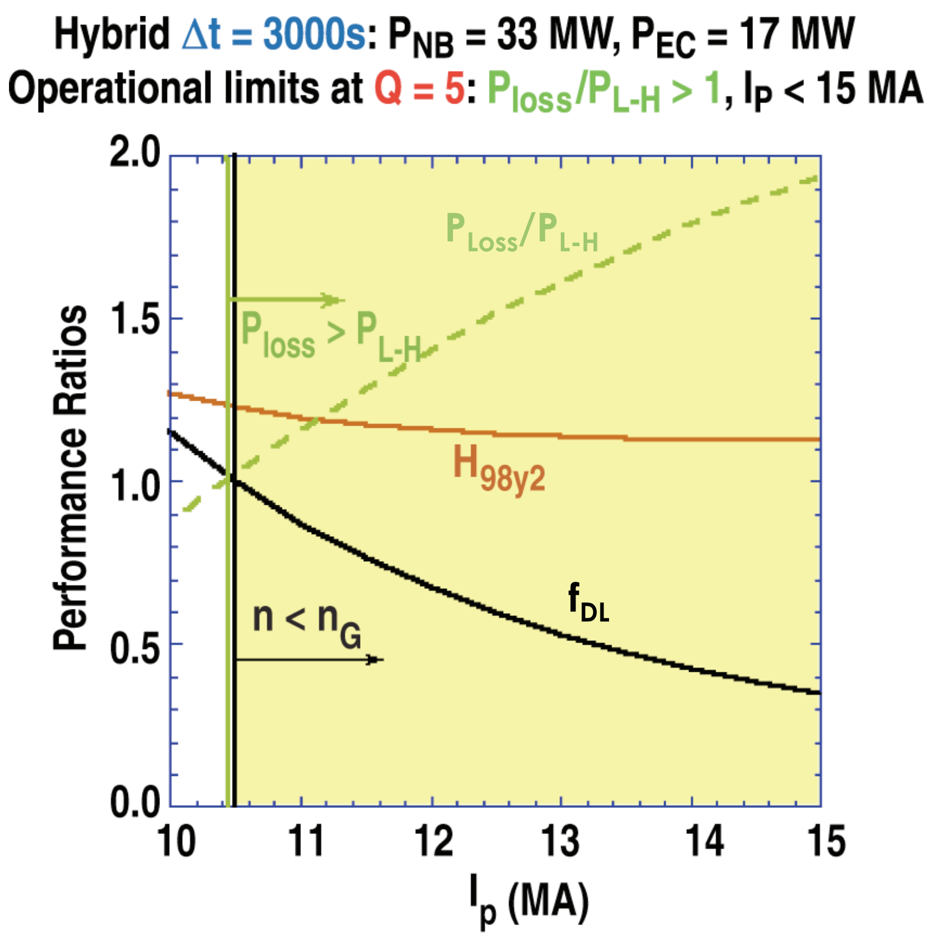
Extrapolation Backward From ITER Shows Required Conditions Exist in Present Experiments

- **Desired pulse length, auxiliary power, and gain are specified**
- **Operational limits define the parameters consistent with the specifications**
  - Density limit and necessity for H-mode require operation with I > 10.5 MA
  - Required H_{98y2} lies between 1.1 and 1.3
  - Divertor power load and required β_N are reasonable
- **Conditions needed for ITER operation at Q=5 for almost 1 hour are consistent with present experience**



Several Other Critical Issues Have Been Addressed

- **Pedestal behavior is similar to conventional H mode**
  - Joint experiments showed pedestal height continues to increase as power flow through the edge increases
- **Confinement change with electron heating is dominantly due to the change in rotation due to reduced applied torque**
  - Change due to variation in T_e/T_i is smaller than the correction for rotation
- **ELM suppression with resonant magnetic perturbations has been observed in advanced inductive scenarios**
- **Reduction in average heat flux by radiative divertor operation has been successfully extended to advanced inductive scenarios**

Open Questions

- **Is advanced inductive operation a "new regime"?**
  - Necessary and sufficient conditions for access in ITER remain to be defined
  - No threshold behavior is observed; however, the initial conditions can be important for stable access
- **Is the current profile evolution anomalous?**
  - New experiments run to resistive equilibration with accurate measurements of the current profile are essential to answer this
- **Are the transport scalings different from standard H mode?**
  - Preliminary experiments indicate that the ρ_* scaling is different
  - Theory-based models used for standard H mode plasmas work equally well on advanced inductive plasmas
  - Perhaps the current profile that allows stable operation at higher pressure also allows good confinement

Conclusions

- **Advanced inductive operation is routine in present experiments across a broad range of operational parameters relevant to fusion energy**

- **Coordinated experimental and modeling efforts facilitates more rapid progress toward characterizing these scenarios**

- **Advanced inductive plasmas should play a key role in ITER reaching its physics and technology goals**
  - Parameters consistent with 1 hour operation with present experience
  - Q=10 at lower current and higher gain operation at 15 MA possible with favorable confinement scaling

Acknowledgements

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