Burning Plasma Research on ITER

R.J. Hawryluk

24th IAEA Fusion Energy Conference

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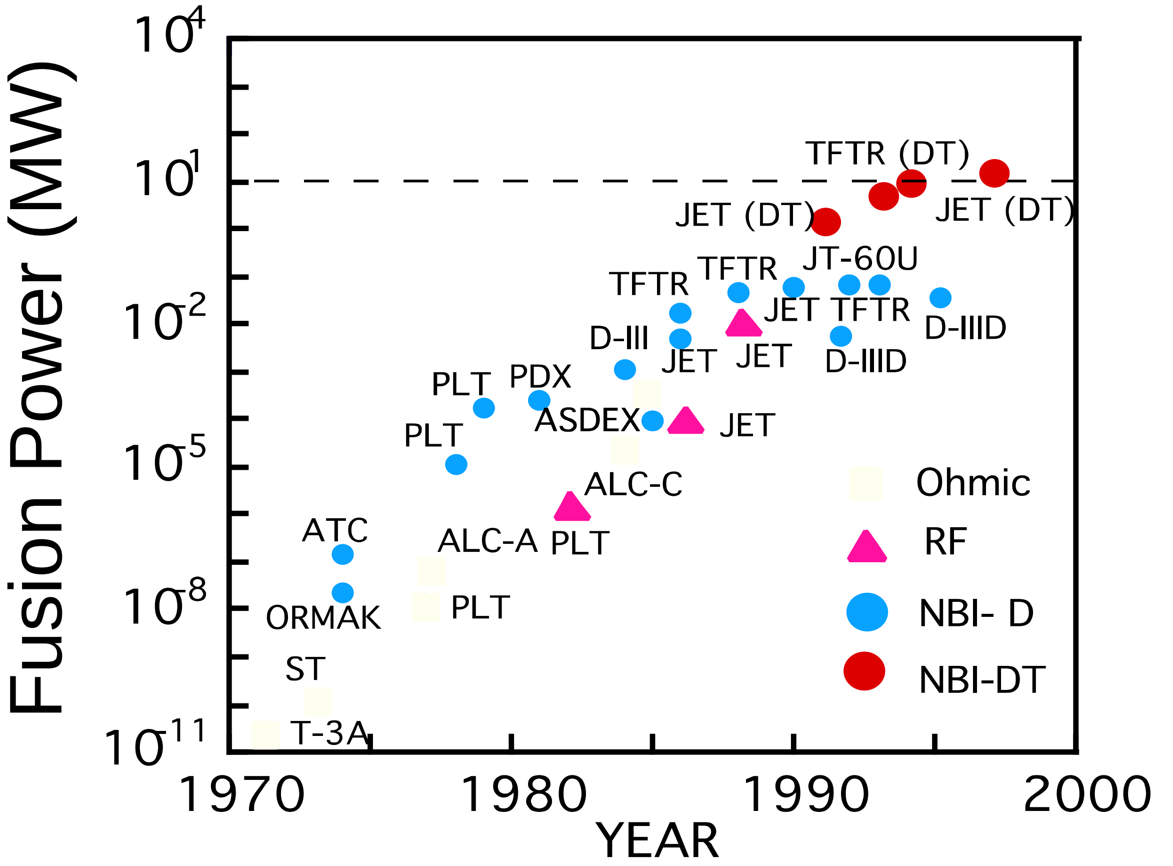
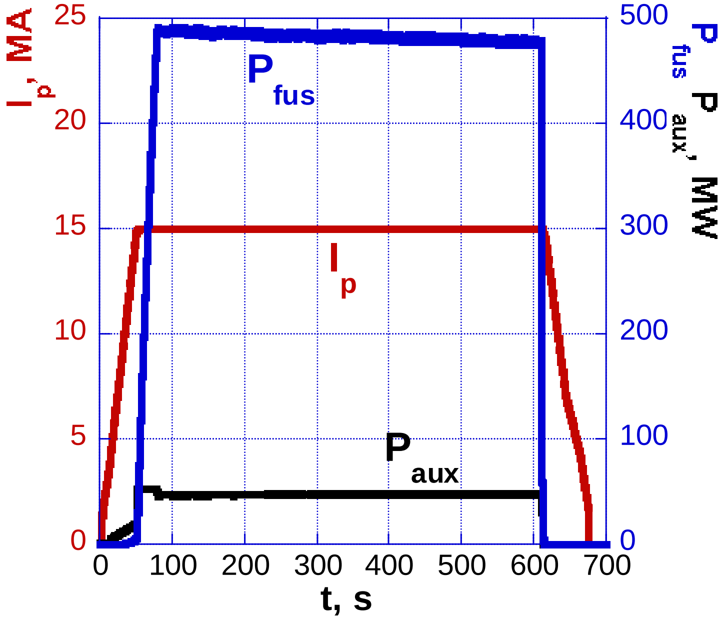
Technical Progress Enabled TFTR and JET to Begin Studying D-T Burning Plasmas



- **Current experiments are setting the stage for the ITER Research Program enabling:**
- **Development of burning plasma conditions and study of burning plasmas**

First High Power D-T Experiments Will Generate More Fusion Energy than All Previous MFE Fusion Experiments

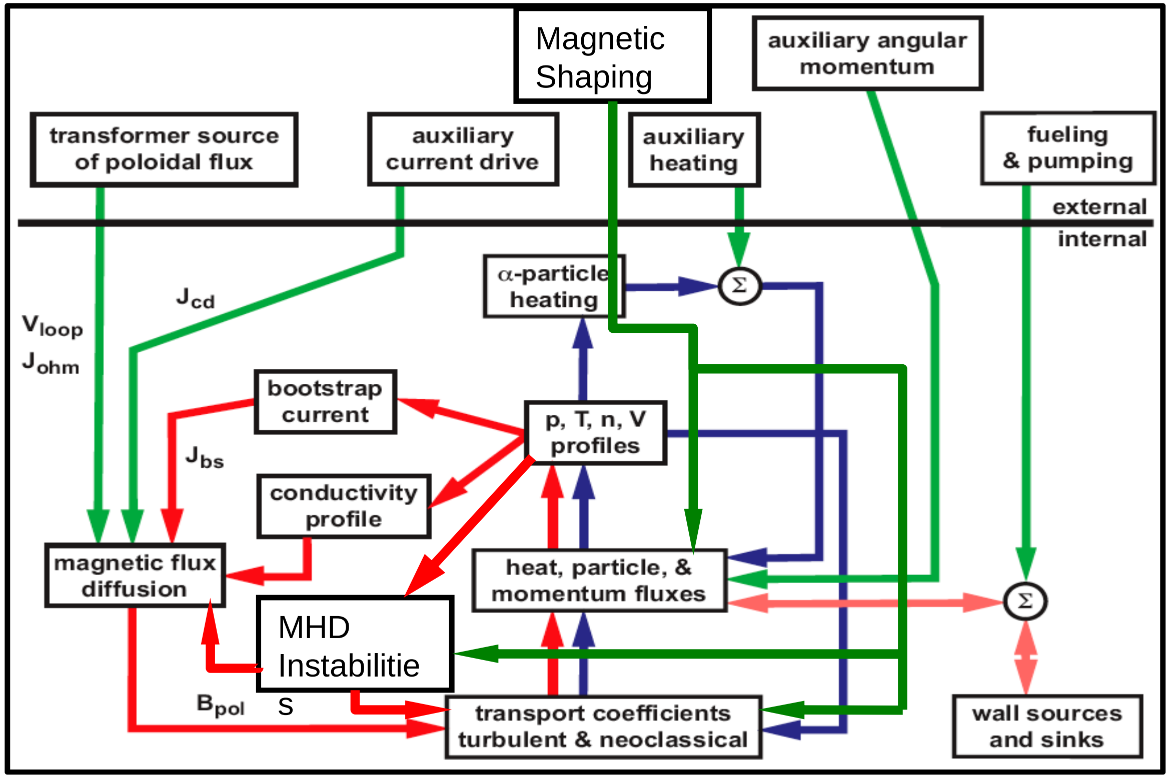


Q=10 scenario
250 GJ

Y. Gribov

- **For comparison, JET produced 0.7 GJ and TFTR 1.7 GJ during their DT campaigns.**
- **ITER will provide a facility to study the physics of burning plasmas**

Burning Plasmas in ITER Will Require an Unprecedented Integration of Scientific Issues



R. Politzer

Nonlinear interaction of turbulence, wall-interaction, external sources, fusion reactivity, macroscopic instabilities.

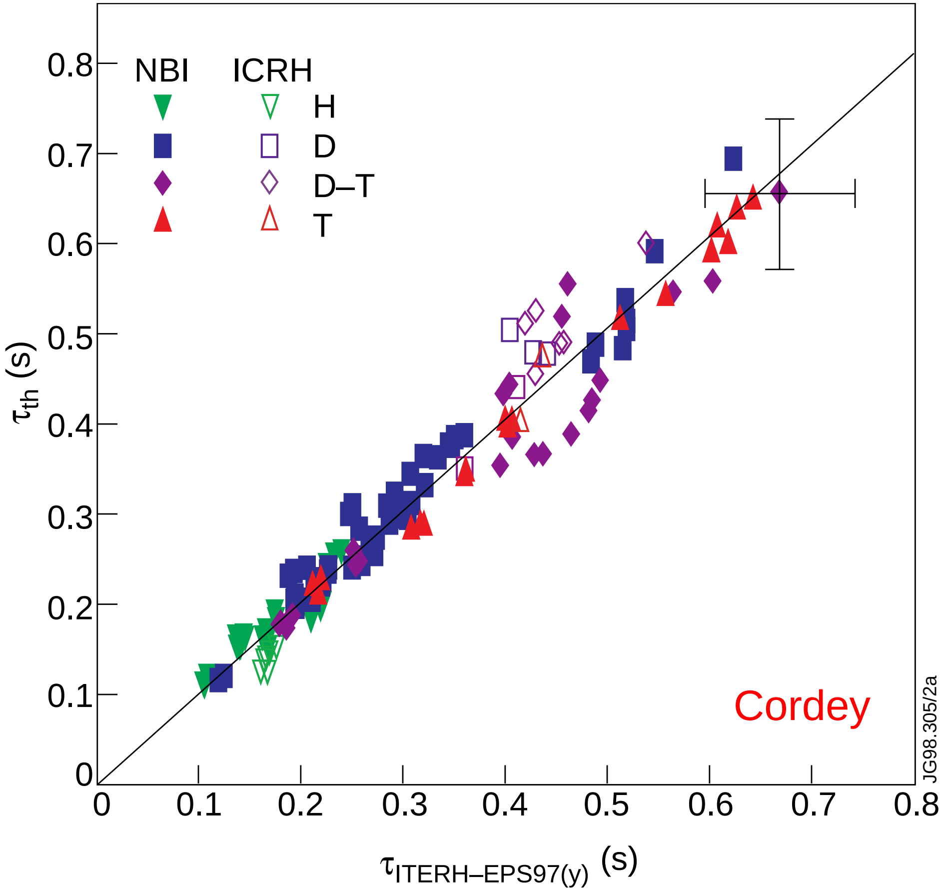
Strong coupling between the plasma and “external” systems especially plasma-wall interactions associated with:

Erosion, tritium retention, high heat loads, transient events

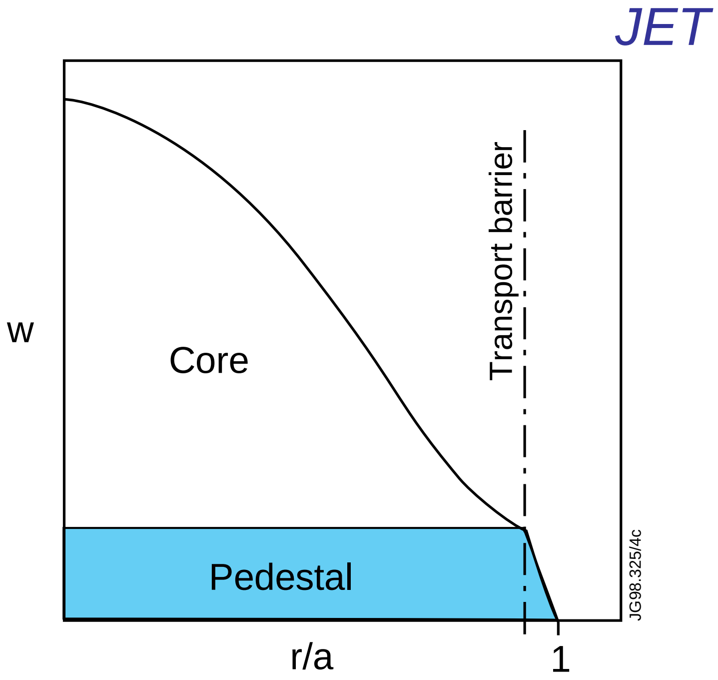
What Questions Will Be Addressed in the Burning Plasma Research Program?

- ✓ **Transport and Turbulence**
  - Isotope Effects
- ICRF Heating
- ✓ **Alpha-particle Physics**
- Stability and Integrated Modeling
- Plasma-boundary Interface
  - See D. Campbell’s talk

JET D-T Elmy H-mode Experiments Consistent with ITER Scaling

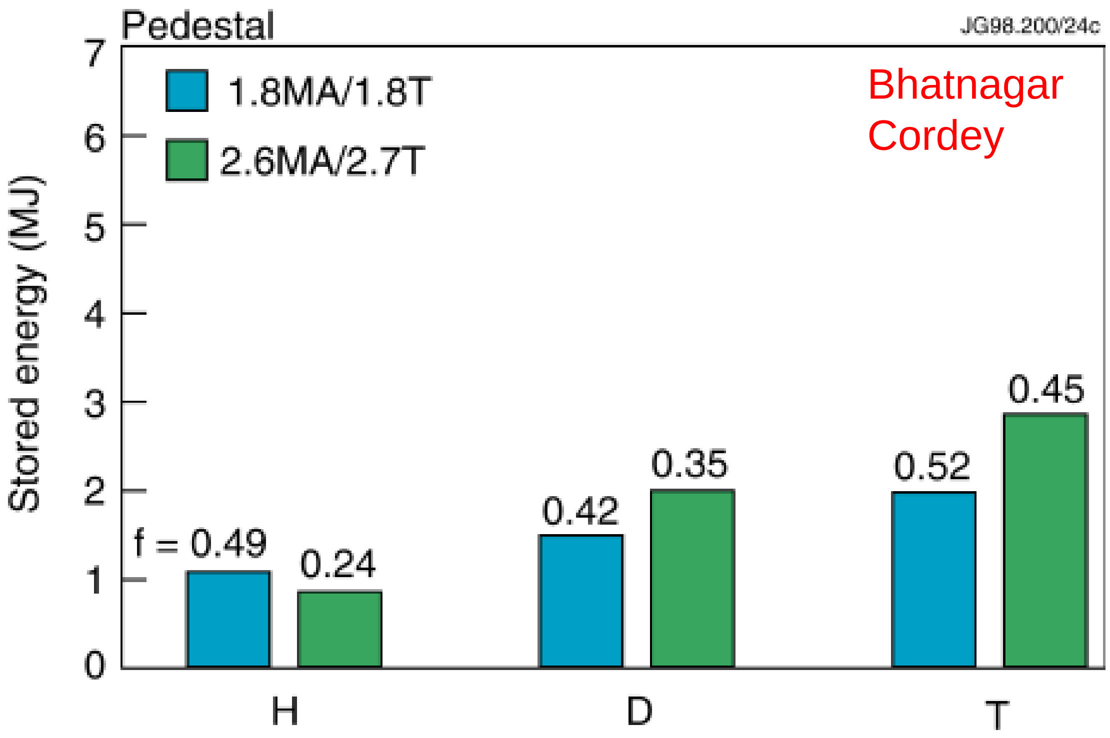


- $\tau_{th} \propto \langle A \rangle^{0.16\pm0.06}$



- **What is the role of the pedestal and the core?**

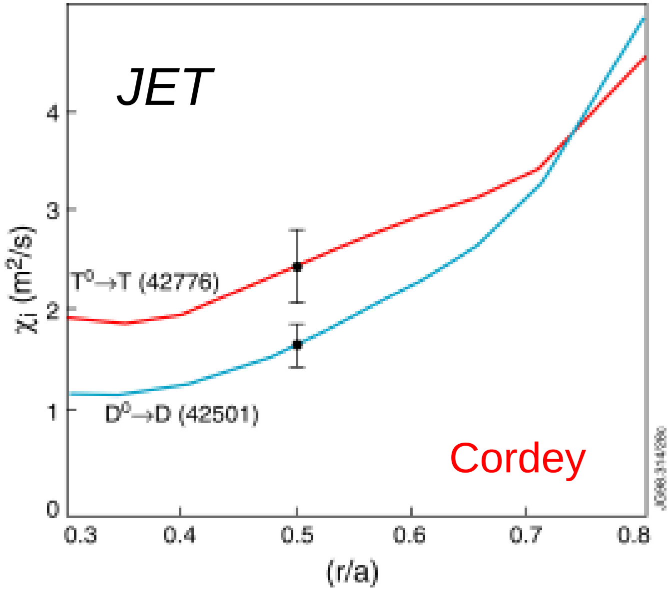
Stored Energy Associated with Pedestal Increased with <A> in JET



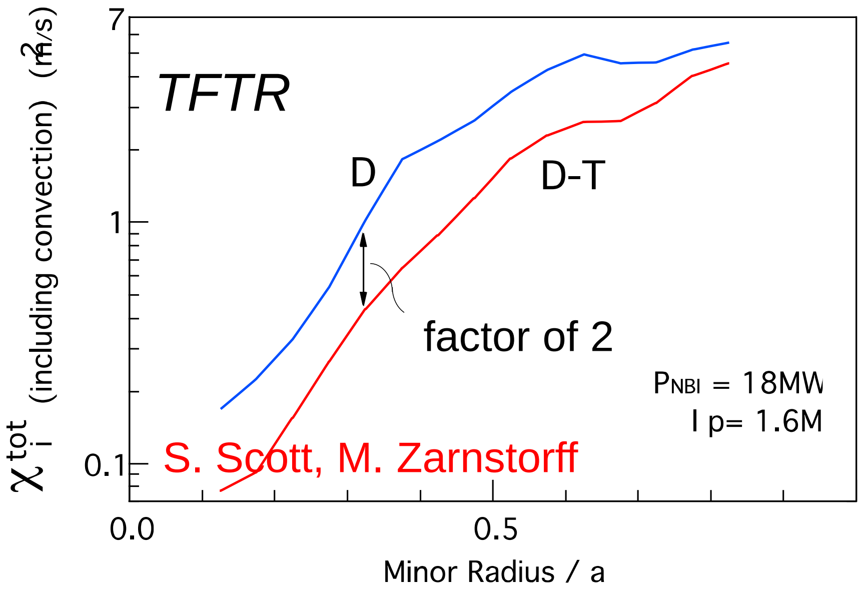
Bhatnagar
Cordey

- $W_{ped} \propto \langle A \rangle^{0.96}$
- **Power loss by ELMs decreases**
- **Stored energy is a complex interplay of access to H-mod and pedestal stability – See Urano's paper**

Ion Thermal Conductivity Changes with <A> Depending on Operating Regimes



Cordey



S. Scott, M. Zarnstorff

- **In JET H-modes, χ_i scaling in the core consistent with gyro-Bohm.**
  - $\tau_{thcore} \propto \langle A \rangle^{-0.16\pm0.1}$

    $\chi_I \propto \langle A \rangle^{0.73\pm0.4}$

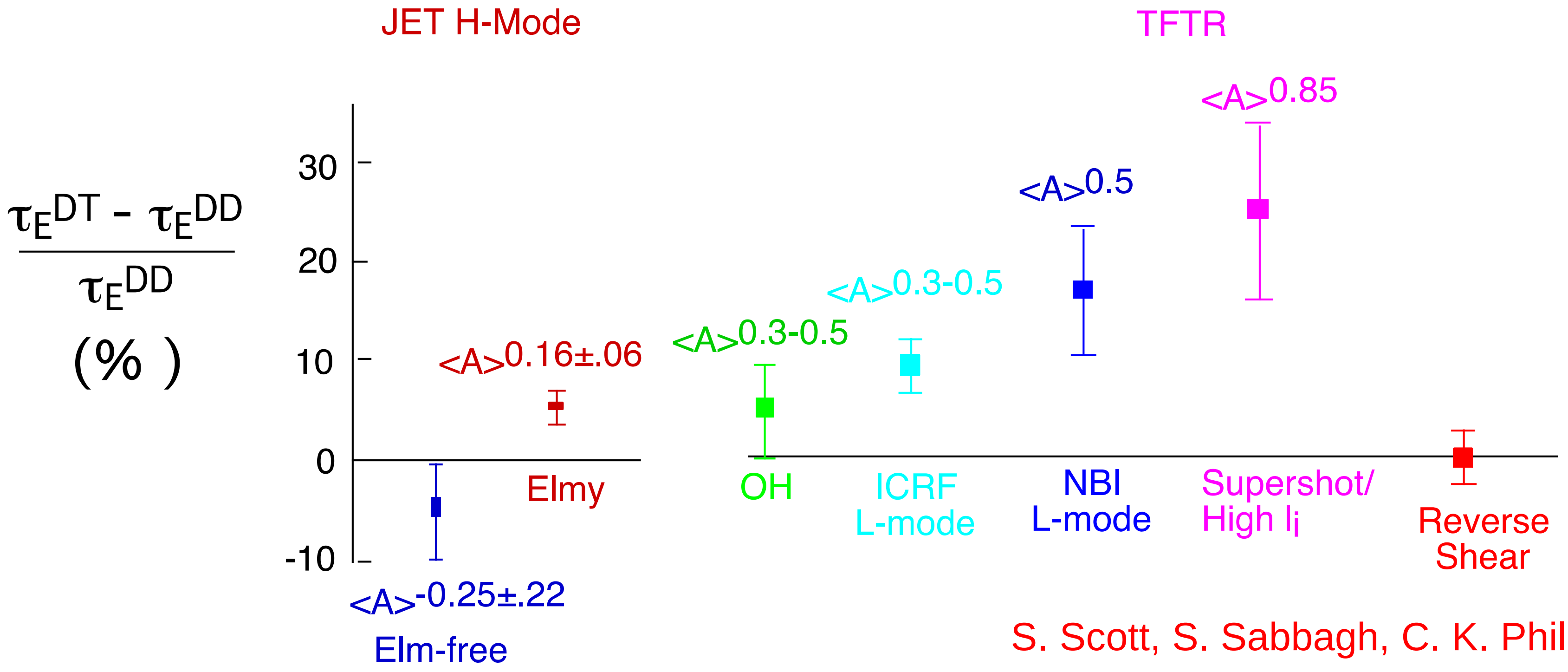
In TFTR Supershots, confinement dramatically improved in the core and χ_i decreased

$\tau_E^{thermal} \propto \langle A \rangle^{0.89\pm0.1}$

$\chi_i^{tot} \propto \langle A \rangle^{-1.8\pm0.2}$

ITG model with radial electric field reproduced the $T_i(r)$ profile, (Ernst)

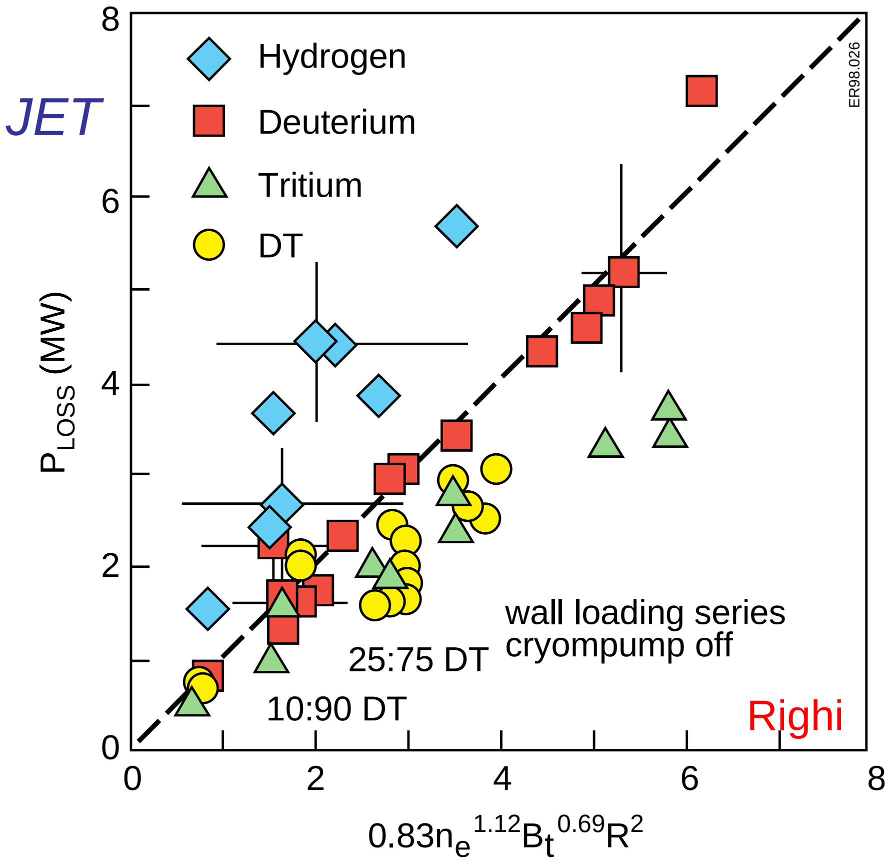
Isotope Effect on Confinement Varied Widely Depending on Operating Regime



S. Scott, S. Sabbagh, C. K. Phillips

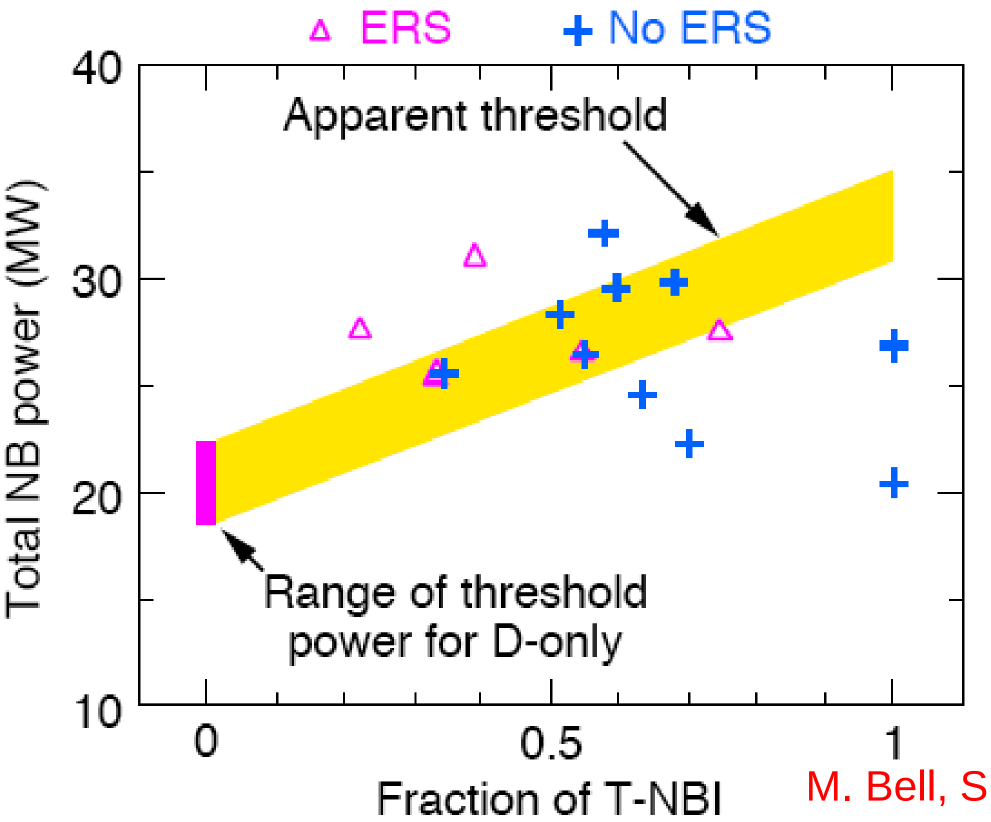
- **Diversity of scalings challenges theory and**
  - gyro-Bohm scaling: $<A>^{-0.2}$
- **ITER scaling for ELMy H-mode: $\tau_E^{thermal} \propto <A>^{+0.19}$**

Power Threshold on JET Going from L to H-mode Shows Favorable Isotope Scaling



- **$P_{loss} \propto \langle A \rangle^{-1}$**

Higher Neutral Beam Power Required for Enhanced Reverse Shear (ERS) Transition in D-T



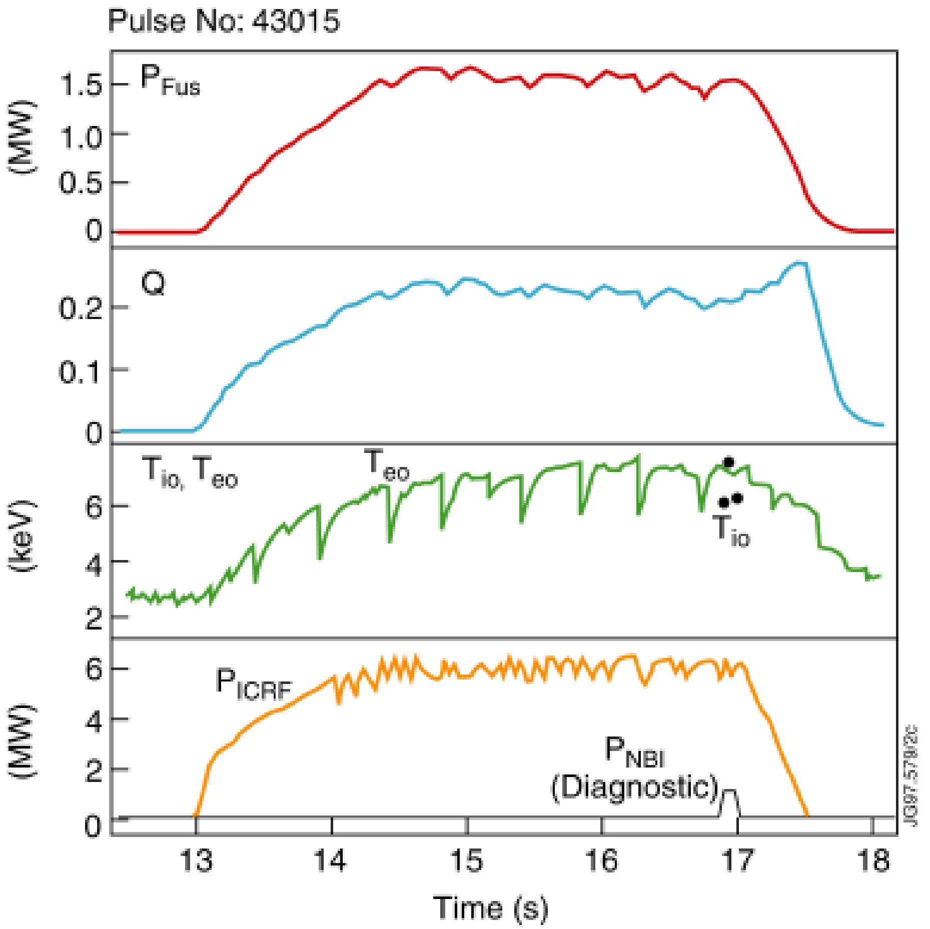
M. Bell, S. Scott, M. Zarnstorff

- **Challenge for theory: same or lower threshold expected**
- **Was this a transport effect or a consequence of the beam deposition profile being different?**

Summary of Isotope Effects on Confinement

- **H-mode isotope scaling studies on JET, together with the worldwide physics database, provide a good technical basis for baseline operation of burning plasma experiments.**
  - Isotope scaling for τ_E and power threshold.
- **Understanding of isotope scaling is incomplete since it depends on operating regime.**
  - Not consistent with naive turbulence theory scaling
  - What is the role of radial electric field shear in the different regimes?
  - What are the implications for advanced operating modes?
- **Power threshold for internal barrier formation increased with <A>.**
  - What are the implications for advanced operating regimes in ITER?

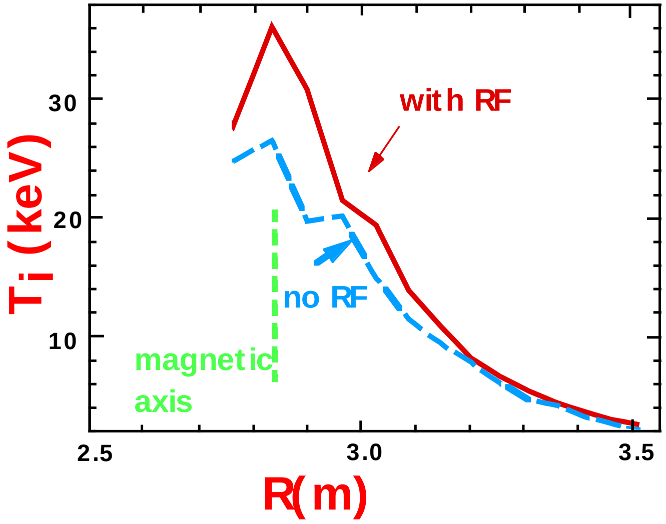
JET Demonstrated Successful Deuterium Minority Heating of Tritium Plasmas

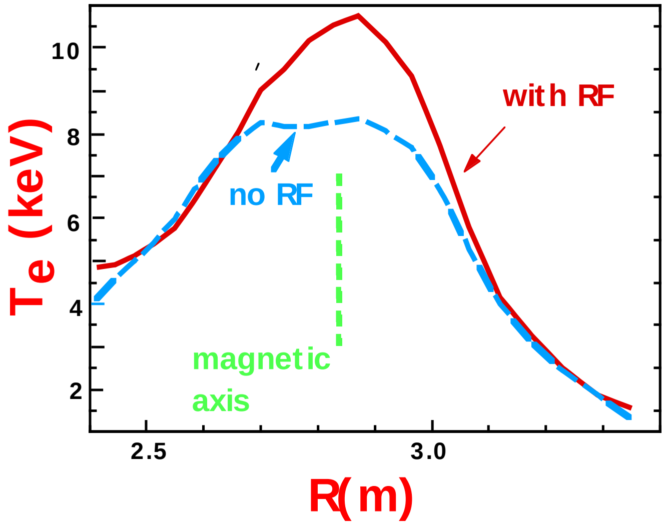


Eriksson, Start

- **Record Q_{DT} for steady-state operation.**
  - – deuterium energy optimized
  - – Not optimal for high Q_{DT}
- **Strong ion heating observed with ^{3}He**
  - – Absorption weaker with $2\Omega_T$
  - – Recommended scenario for ITER
- **Studied tritium minority heating.**

ICRF Successfully Heated D-T Supershot Plasmas in TFTR





Δ T_i due to 2nd harmonic tritium heating

Δ T_e due to direct electron and ^{3}He minority ion heating

- **Power deposition calculations in good agreement with experiment.**
  - Ω_{cHe3} to Ω_{cT} transition heating regime shown to give efficient heating suitable for ITER D-T plasma

G. Taylor, J. R. Wilson, J. Hosea, R. Majeski, C. K. Phillips

Implications of ICRF Heating and Current Drive Studies

Fundamental heating and current drive physics for ICRF has largely been established for D-He^3 minority and second harmonic tritium heating experiments.

Technology and coupling issues need to be further addressed for optimum ICRF application to ITER.

- Antenna power density limited by voltage standoff/coupling resistance.

- Evaluating installing gas feeds near the ICRF antenna.

Alpha-particle Physics Studies

- **MHD Quiescent**
  - Alpha-particle heating

- **MHD Affects on Alpha Confinement**

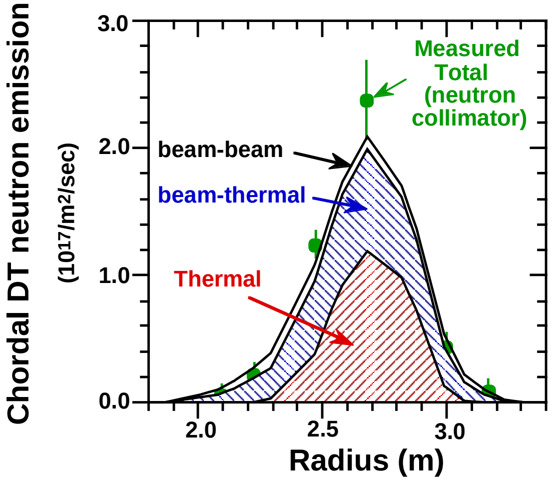
- **Alpha-Particle Induced MHD Activity**

Alpha-Particle Parameters in TFTR/JET Sufficient to Begin Study of Alpha-Particle Physics

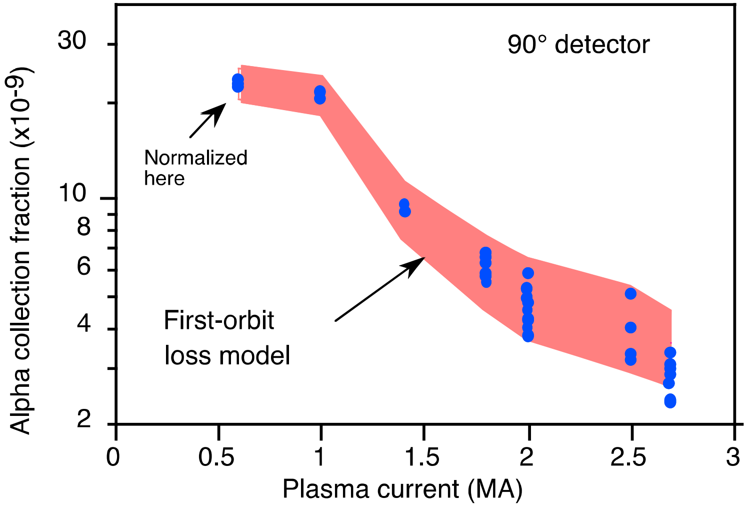
	TFTR	JET	ITER
P_{fusion}(MW)	10.6	16.1	400
$p_\alpha(0)$ (MW/m^3)	0.28	0.12	0.55
$\beta_\alpha(0)$%	0.26	0.7	1.2
–R•grad(β_α)%	2.0	2.3	4.0
$V_\alpha(0)/V_{Alfvén}(0)$	1.6	1.6	1.9

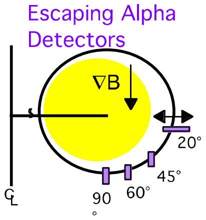
A. Fasoli

Classical Alpha Particle Behavior was Confirmed for Normal Shear (Supershot) Discharges



TFTR





- **Alpha birth rate and profile agreed with modeling.**
  - Neutron flux in good agreement with calculations based on plasma profile in normal shear discharges.

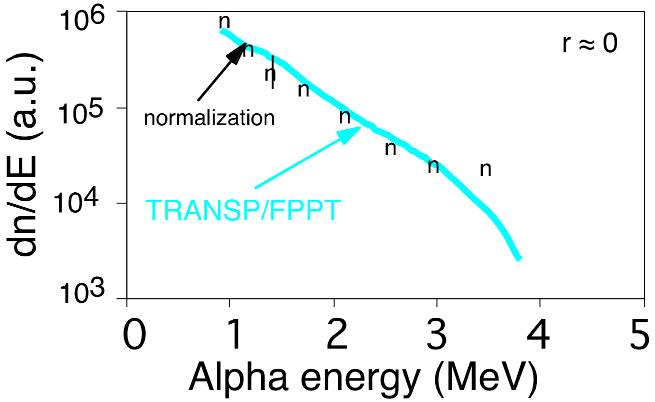
R. Budny, L. Johnson

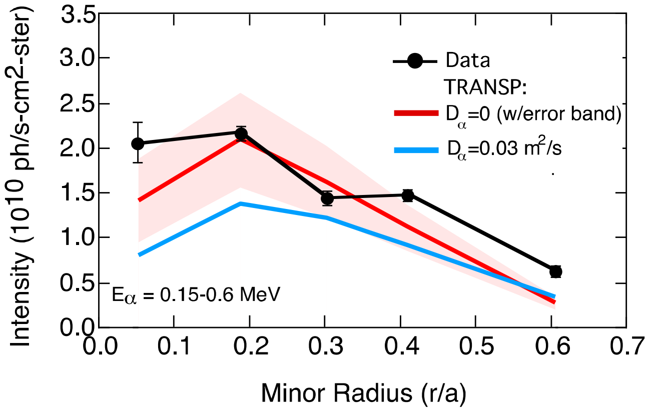
- **Escaping alpha flux at 90º detector was consistent with classical first orbit losses**

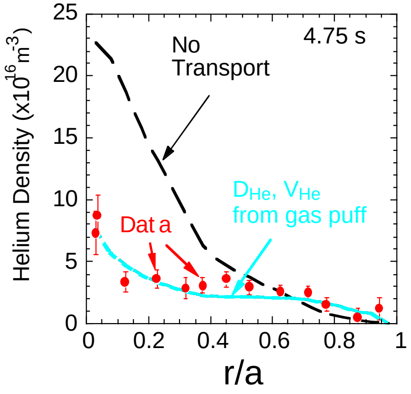
S. Zweben, D. Darrow

Confined Alpha-particles Were Well Confined in Normal Shear (Supershot) Discharges

TFTR







Confined alphas in the plasma core showed classical slowing down spectrum .

Alpha particles were well confined.

0 ≤D_α≤ 0.03 m^2/s

Rapid ash transported from the core to the edge in supershots. (D_{He}/χ_D ~ 1

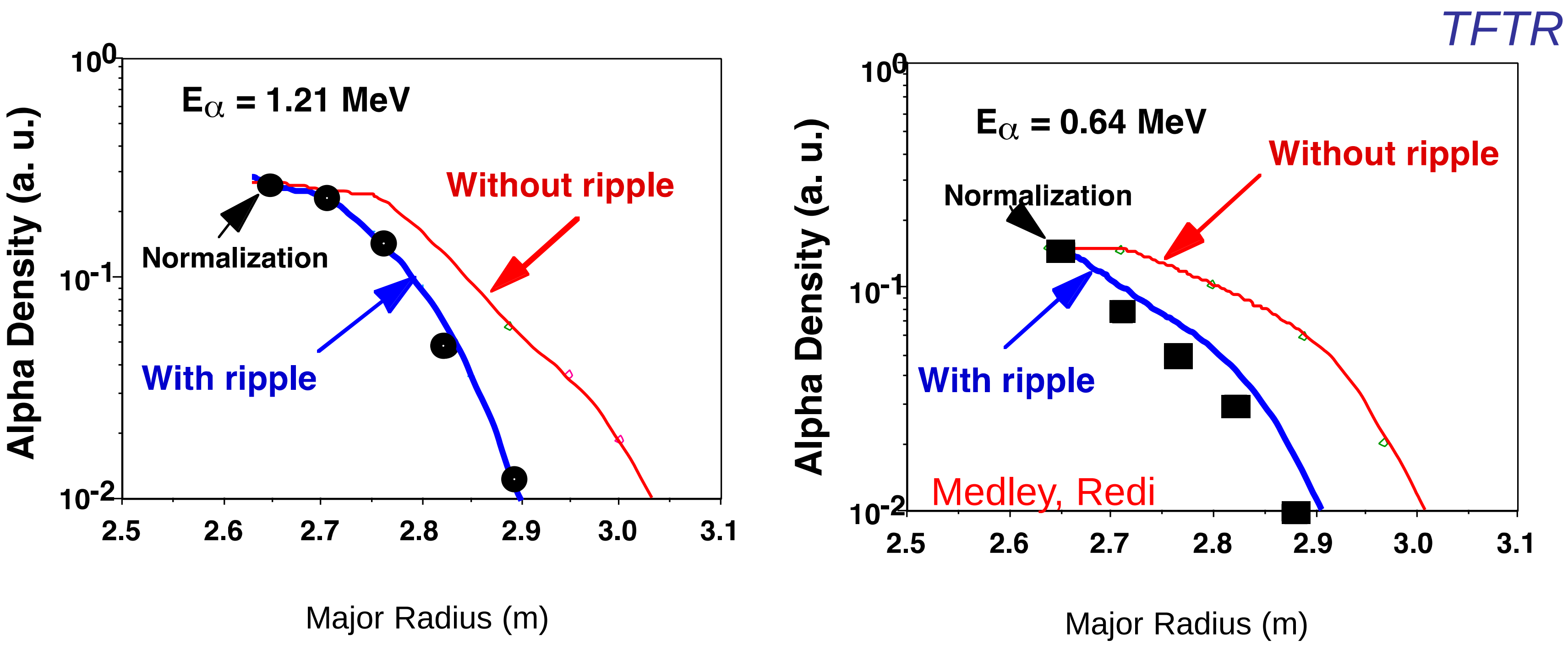
R. Fisher, S. Medley, M. Petrov

R. Fonck, G. McKee, B. Stratton

E. Synakowski

ITER will extend these results especially ash buildup.

Stochastic Ripple Diffusion Affects Confinement of Deeply Trapped Particles

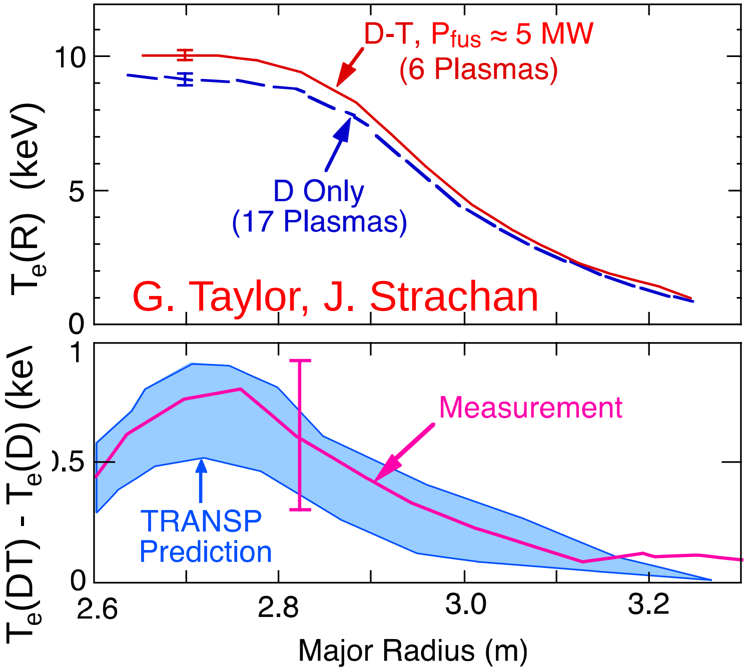

TFTR

Medley, Redi

- **FPPT includes modeling of stochastic ripple diffusion.**
- **Heat deposition due to ripple loss of fast ions imaged on JT60U.**
- **Recent measurements of fast ion loss on DIII-D experiments used to simulate the magnetic field from the ITER Test Blanket are in good agreement with predictions.**

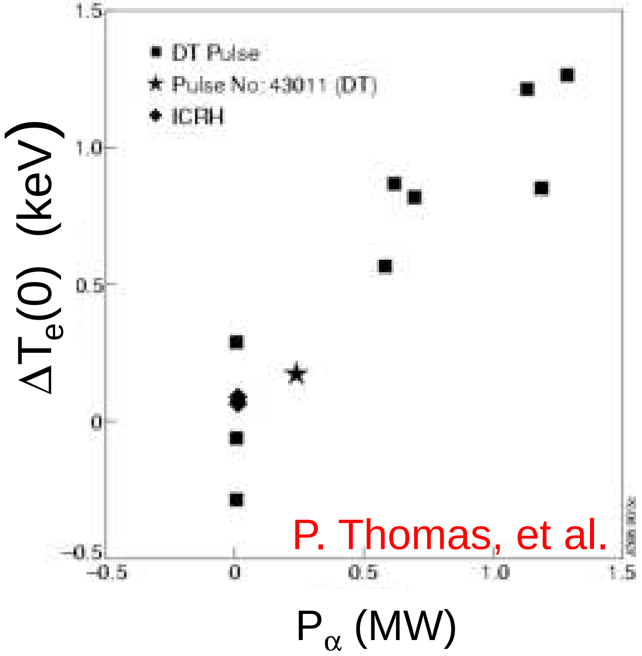
Initial Evidence of Alpha-particle Heating on TFTR and JET

TFTR



G. Taylor, J. Strachan

JET



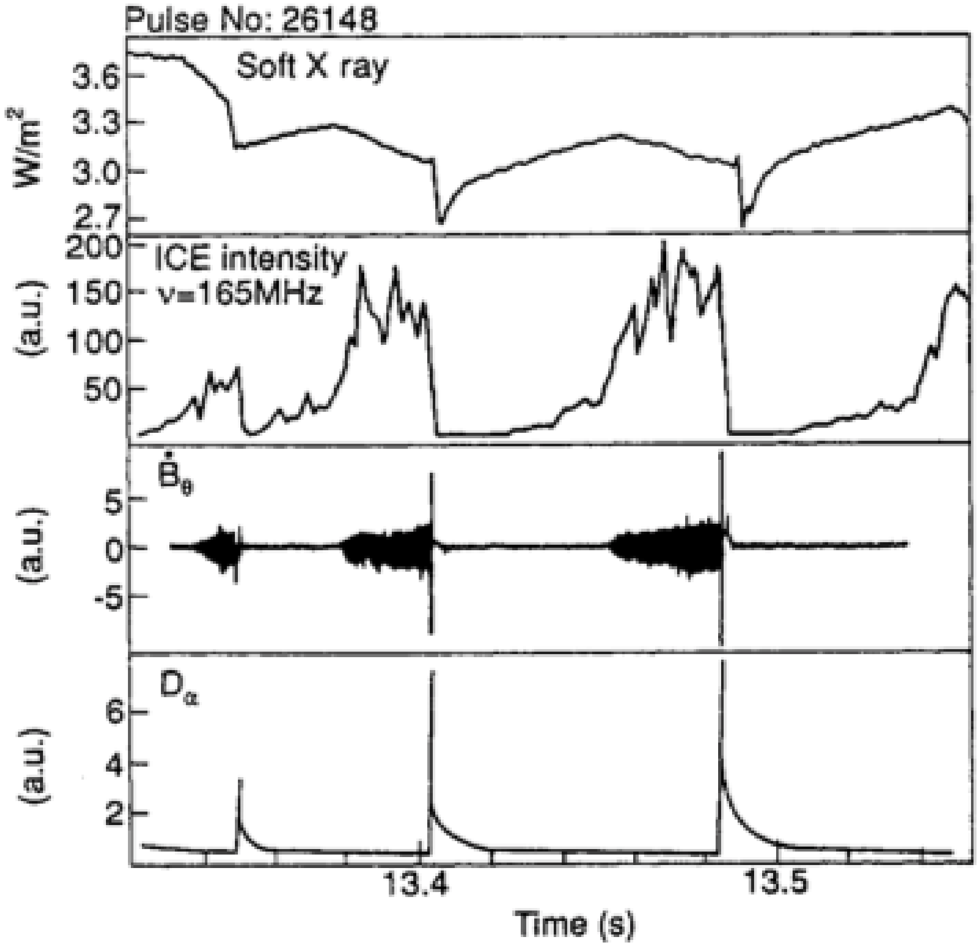
P. Thomas, et al.

- **Alpha heating ~15% of power through electron channel.**

- **P_{alpha}/P_{heat} ~12%**
  - **30-40% through the electron channel**

- **Comprehensive study of alpha heating requires higher values of P_{alpha}/P_{heat} .**

Interaction of External Kink/Peeling Modes with Alpha Particles Observed at JET.



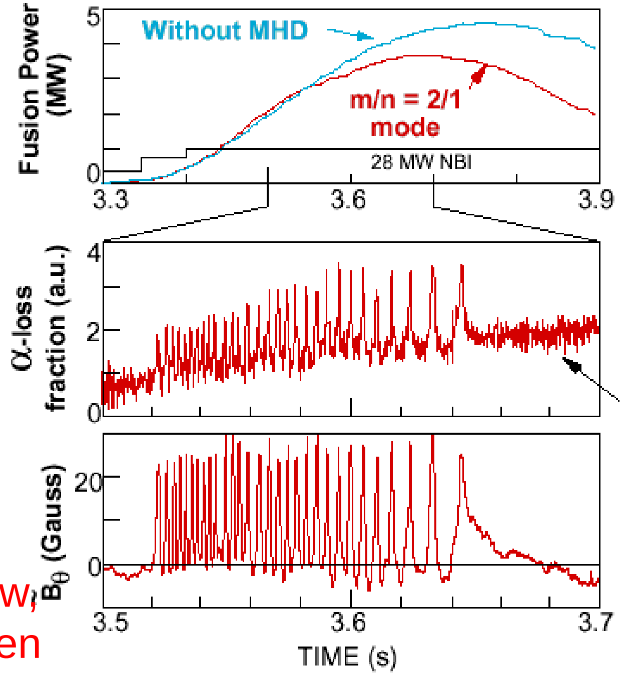
(G. A. Cottrell et al., NF ***33,*** *1365 (1993)) .*

M.F.F. Nave

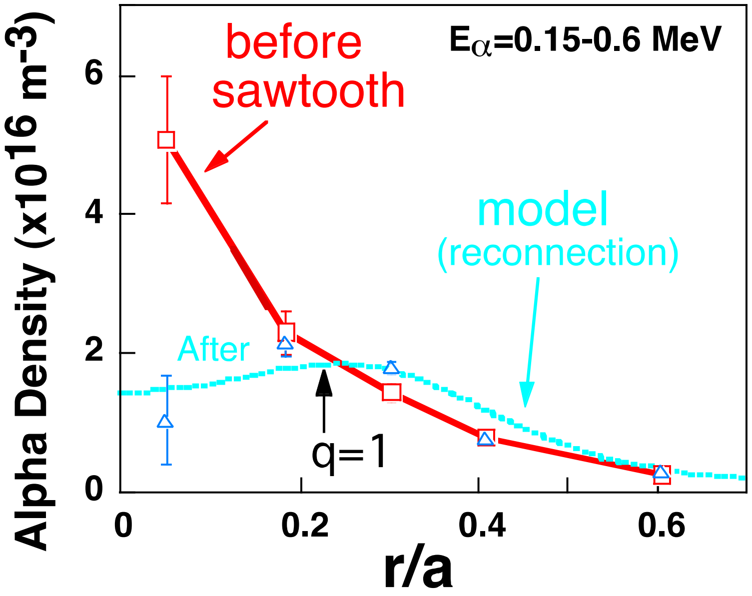
Bursts of the n=1 outer mode, an edge MHD mode interpreted as an external kink/peeling mode, were triggered at a critical alpha particle density as indicated by the ion-cyclotron emission diagnostic.

- Is the outer mode ejecting the edge alphas?
- Are the alphas contributing to triggering the outer mode?

MHD Activity can Cause Enhanced Transport of Alpha Particles



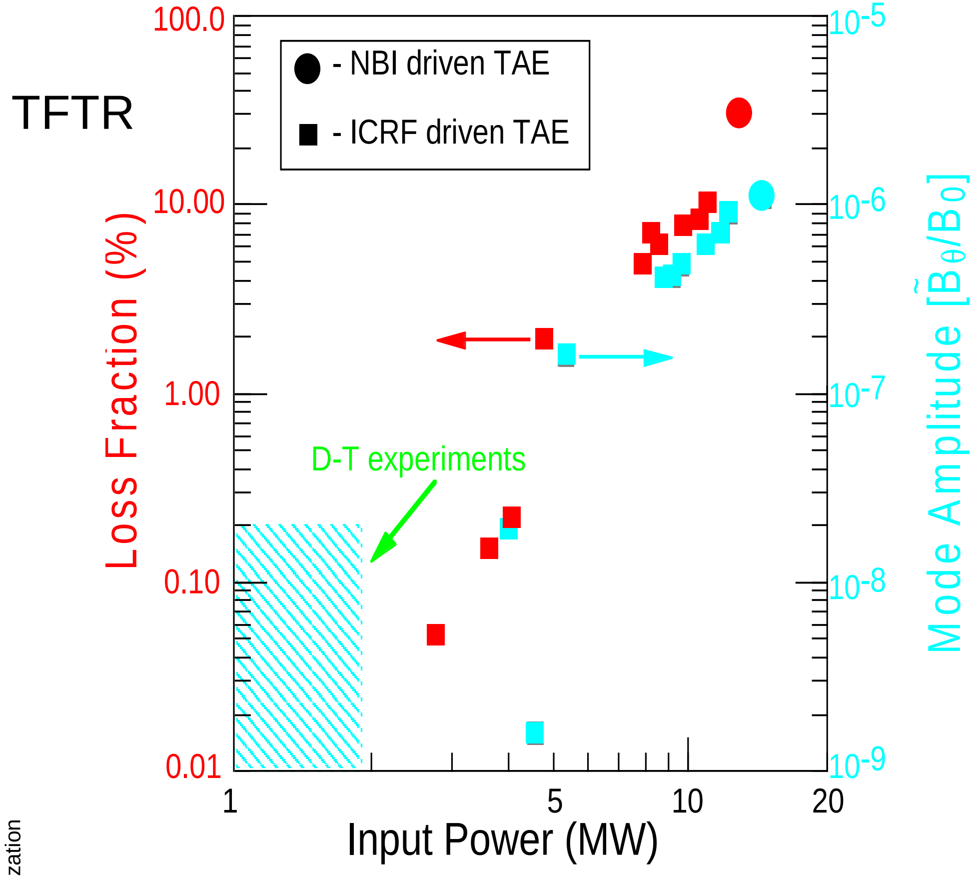
D. Darrow, S. Zweben



R. Fonck, G. McKee, B. Stratton

- **Strong toroidal anisotropic loss apparent as NTM mode was rotating.**
- **Enhanced loss also observed due to:**
  - disruptions
  - kinetic ballooning modes, sawteeth
- **Sawteeth caused a large radial redistribution of alpha particles**

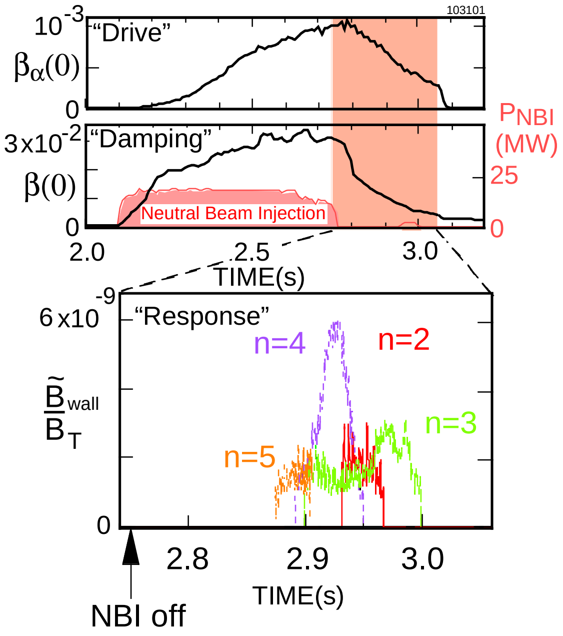
TAEs Driven by Neutral Beam or ICRF Fast Ions Caused Substantial Fast Ion Losses

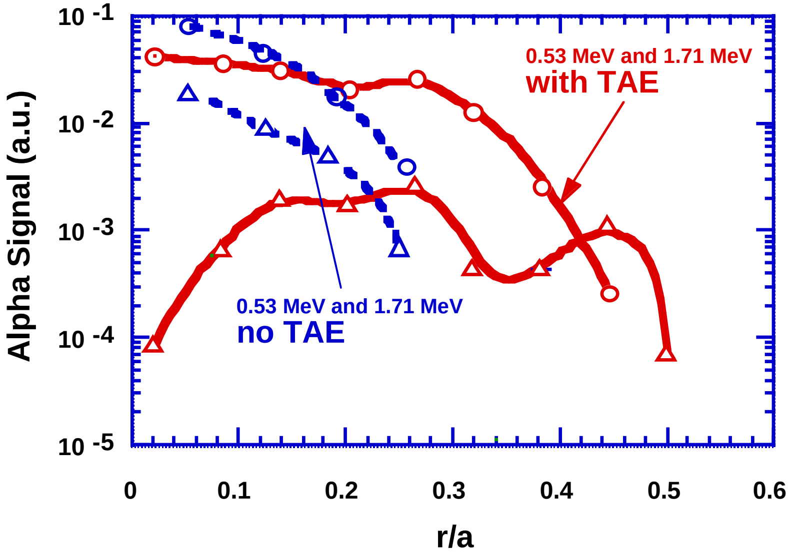


- **In normal shear D-T discharges, TAE was stable on TFTR as well as on JET.**

E. Fredrickson, K. L. Wong, D. Darrow

TFTR Alpha-particle Physics Studies in Reversed Shear Discharges Resulted in New Discoveries.





- **Alpha-driven TAE (subsequently identified as Cascade Modes) were observed.**

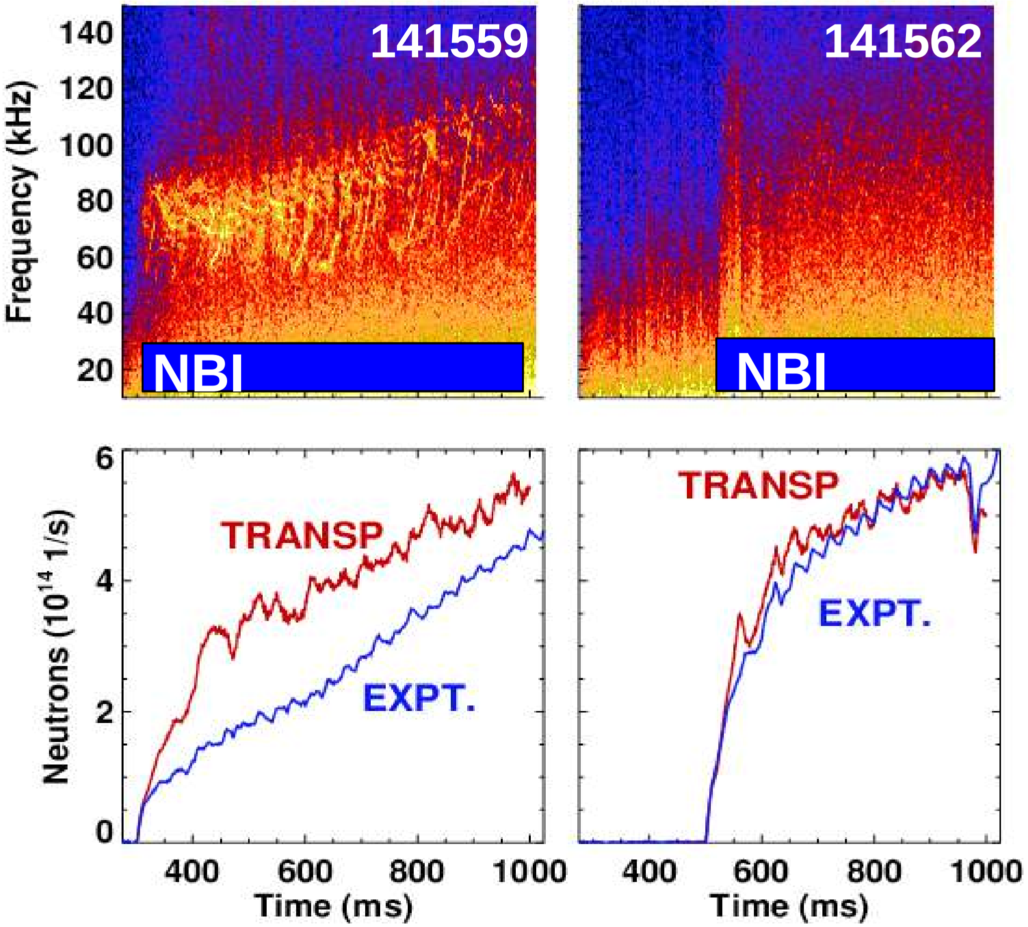
- **TAEs redistributed deeply trapped alpha-particles**

- **Neutron emission in D-T enhanced reverse shear discharges disagreed with TRANSP analysis in some shots by factors of 2-3**
  - **Source of discrepancy was not identified.**

R. Nazikian, Z. Chang, G. Fu

S. Medley, M. Petrov,

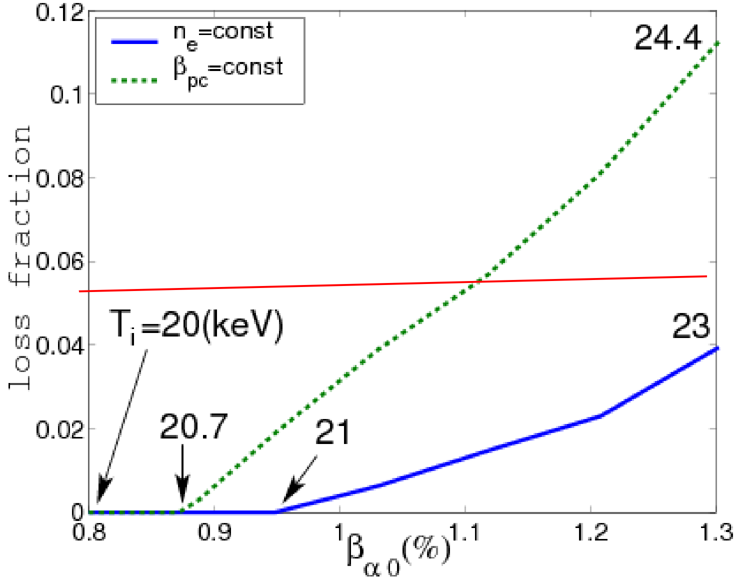
Beam Injection Timing in DIII-D Reversed Shear Also Alters Mode Stability

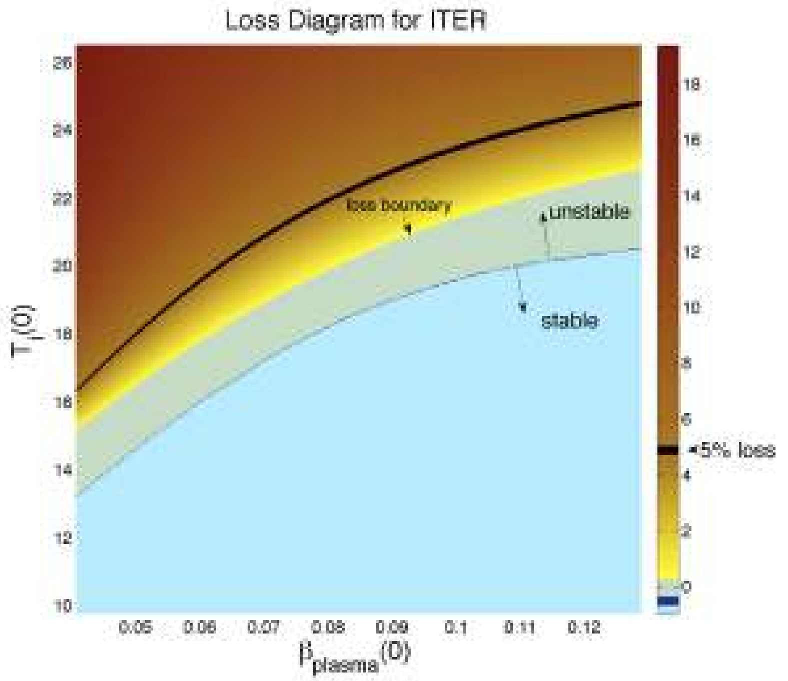


M. A. Zeeland

- **Injection at 300 ms shows clear TAEs and RSAEs**
  - Up to **50% neutron deficit** relative to classical TRANSP predictions due to fast ion transport
- **Delaying beam injection until 500 ms alters current profile (still RS) ➔ NO AEs**
  - With no AEs neutron emission is classical
- **PPPL-IFS Quasilinear Model is in quantitative agreement in similar discharges**
  - H. Berk TH/4-1

Sea of Alfven Waves Calculated to be Marginally Unstable in ITER

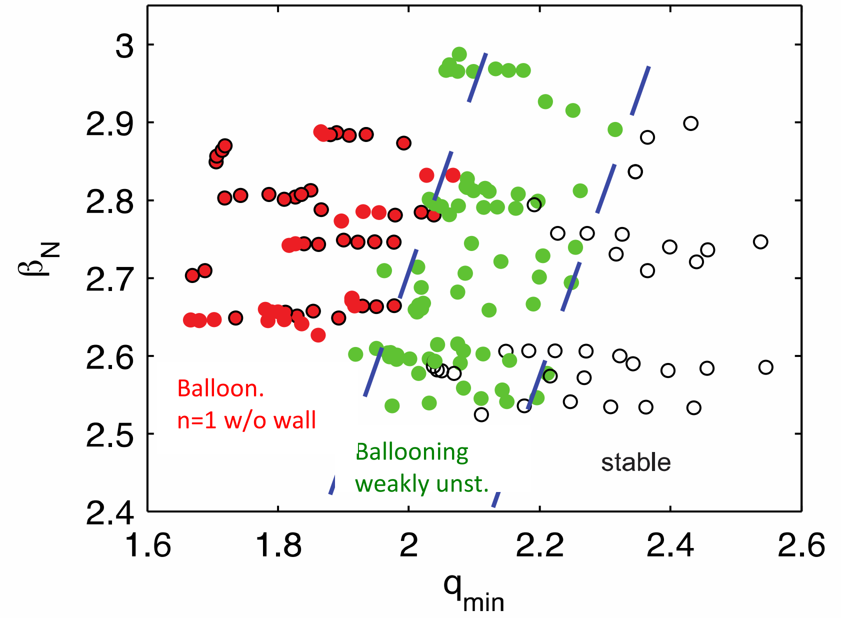




Gorelenkov

- **PPPL/IFS quasilinear model predicts that alpha particle losses are acceptable in normal shear discharges.**
- **Further work required to assess reversed shear or elevated q_{min} operating regimes.**

Steady-state Operating Scenario is a Complex Interplay between Stability, Transport and Alpha Physics



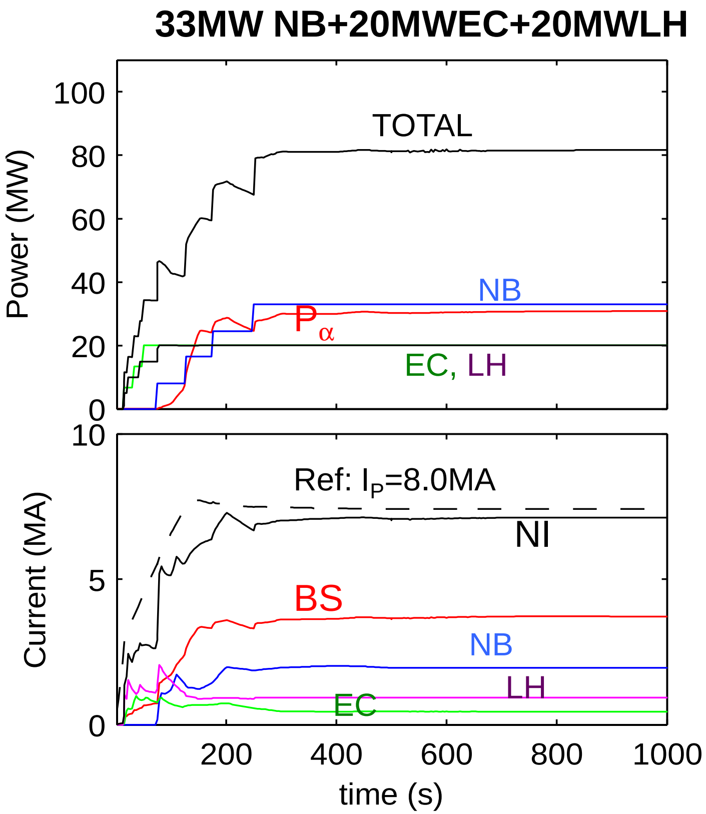
F. Poli

Ideal MHD stability constrains steady-state plasmas to operate with moderate ITBs at mid-radius and with q_{min}>2

MHD stability favors H&CD schemes with off-axis deposition @ r>0.5

- ECRH upper launcher
- LH heating and current drive

Transport Simulations Indicate that EC+LH is Promising towards Steady-state Operation

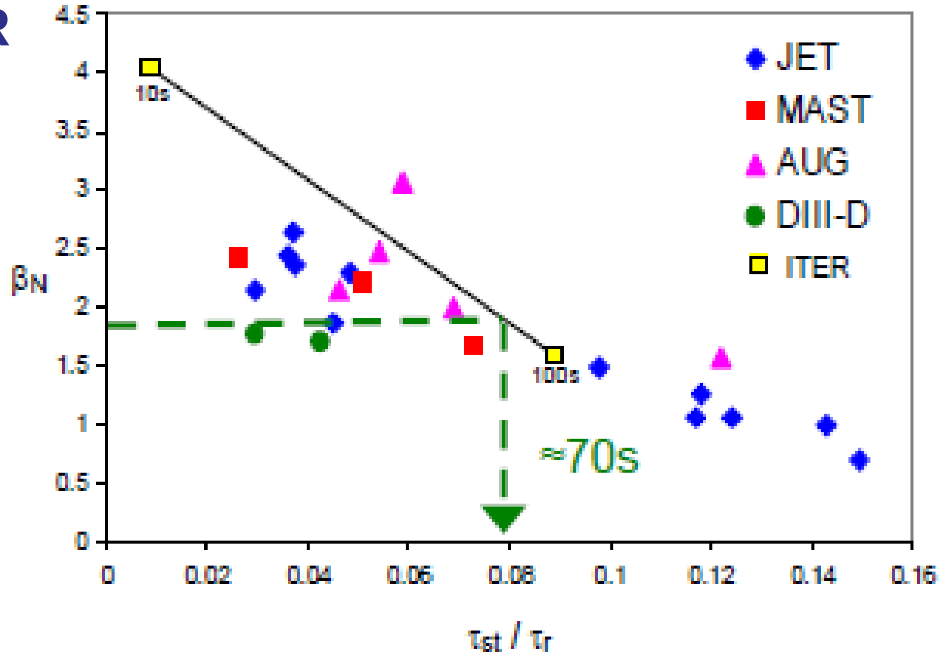


- **Reverse shear in the core is necessary to trigger and sustain ITBs**
  - Obtainable with the day-one heating mix,
  - However I_{NI}~6 and Q<2
  - q_{min}<2, n=1 unstable without wall
- **A broad current distribution, like that obtained with EC+LH**
  - sustains ~8MA (non-inductive)
  - achieves Q~3
  - q_{min}>2, MHD stable
- **Alfven instabilities are likely to be more unstable than in normal shear.**
  - **Will that be a positive or negative effect?**

F. Poli

Sawteeth Control Requirements in ITER

- **Natural sawtooth period in ITER predicted to be approximately same as that required to trigger NTMs**
  - Empirical scaling
- **Stabilizing effects of alpha particles likely to exacerbate by further stabilizing sawteeth**
- **Recent experiments have determined various methods to obtain shorter sawteeth**
  - AUG, DIII-D, JET, MAST, TCV, Tore Supra



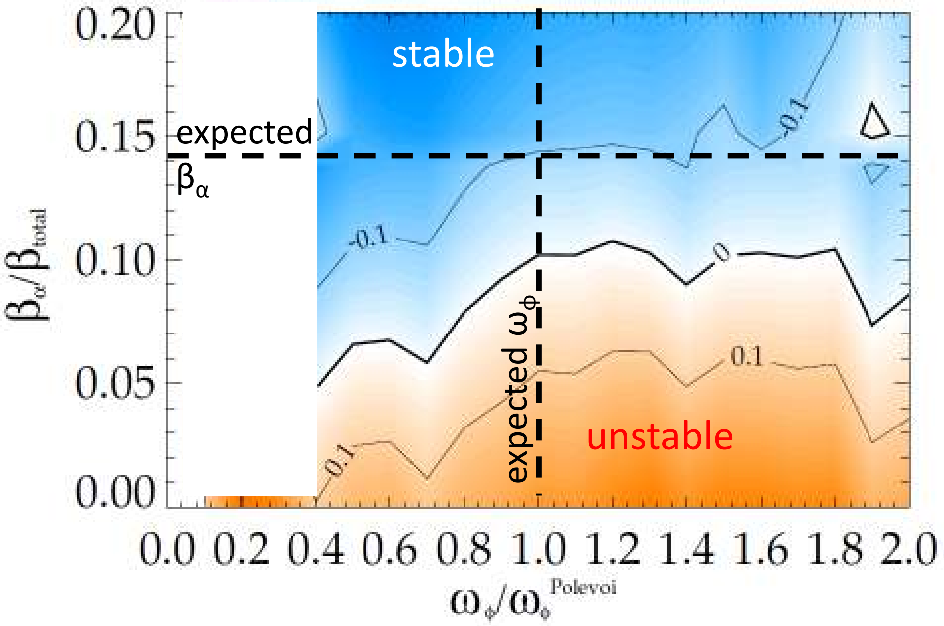
β_N at which an NTM is triggered by a sawtooth v sawtooth period for an ITER-like subset of discharges. Empirical scaling predicting ITER range is overlaid

Chapman et al., ITR/P1-31

IT Chapman et al, Nucl Fusion, **50**, 102001 (2010)

ITER Steady-state Scenario May Benefit from Alpha-Particle Stabilization of RWM instabilities

$\gamma\tau_w$ contours vs. β_α and ω_ϕ



Kinetic resistive wall mode (RWM) stability contours

- Alpha particles can stabliize RWMs
- Significant Re(δW_K), but nearly independent of ω_φ
- Energetic particles are not in mode resonance

J.W. Berkery, S. Sabbagh, R. Betti

Burn Control Can be Assessed in ITER

- **Assess the requirements for burn control on ITER**
  - ITER is expected to be globally stable operating in the high temperature regime
  - In general, depends on the global scaling of confinement with power.
  - Can internal transport barriers be triggered by alpha heating?
    - May require rapid control techniques.
- **Possible actuators:**
  - Heating power
  - Fueling
    - Lower density operation may increase the heat load to the divertor
    - Greenwald limit may limit increasing the density
  - Impurity injection
- **Burn Control is part of a much broader issue –**
  - Discharge control and response to faults including disruptions.

Compatibility with Plasma-Boundary Interface Will Be One of the Most Challenging Aspects of the D-T Campaign

- **Long pulse, high heat flux operation can result in erosion or local damage.**
  - Development of high recycling divertor, ELM and Disruption Mitigation are critical issues.
  - What will be the optimum tradeoff between plasma performance and successful operation of the plasma-wall components?
- **Dust has not been an issue in current experiments but there will be safety restrictions on ITER**
- **Tritium retention in graphite based on JET and TFTR experiments would be a serious concern.**
  - TFTR tiles 16% retention
  - JET 12% retention
- **Results from JET with ILW are very encouraging**
  - ITER will provide a critical assessment

The Burning Plasma Research Program on ITER will Be Exciting

- **Results from TFTR and JET together with the results from the world-wide community has**
  - Provided solid design basis for a burning plasma experiment.
  - Experience on TFTR and JET D-T experiments is that new physics will emerge in ITER

- ***Full potential and consequences of alpha heating have not been explored!***