Review of D-T Experiments Relevant to Burning Plasma Issues

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Frontiers in Plasma Confinement and Related Engineering/Plasma Science

Toki, Japan

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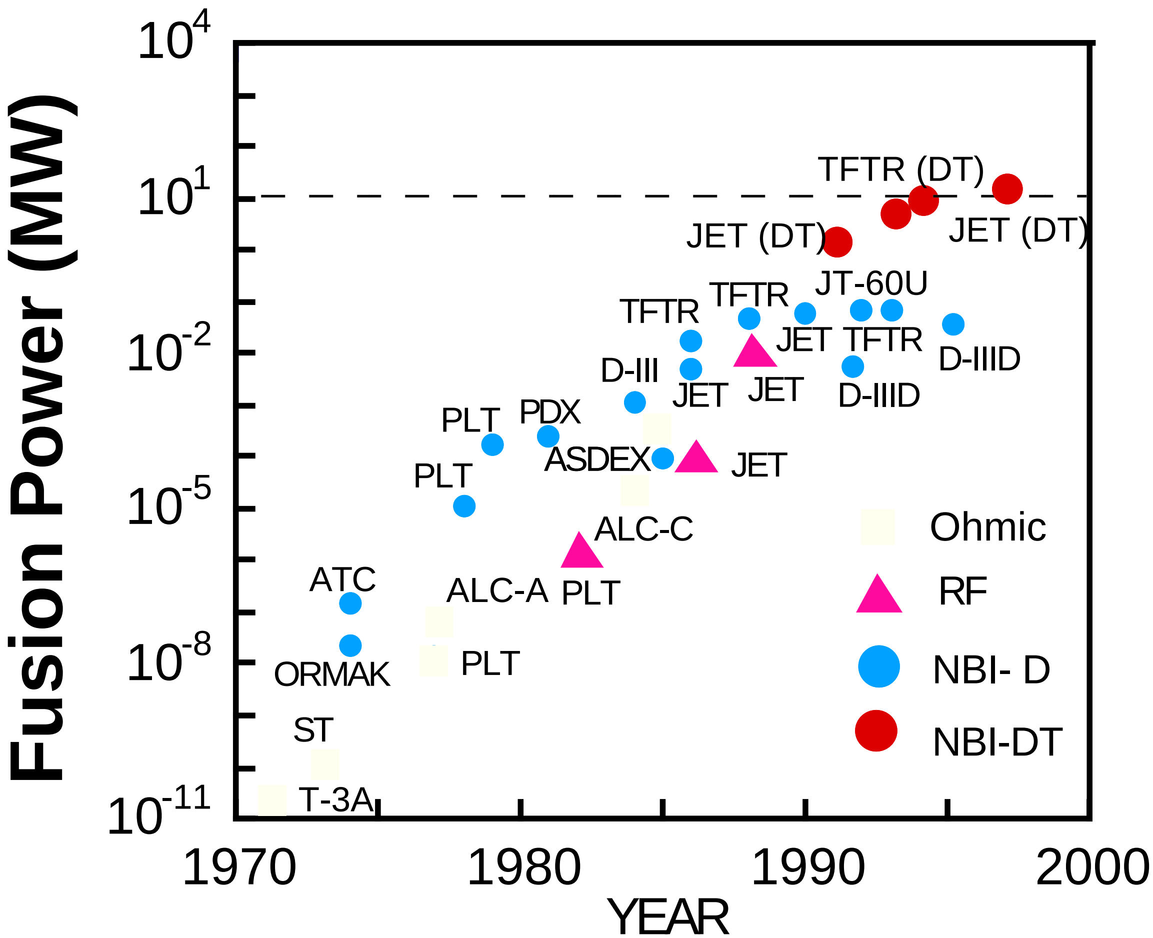
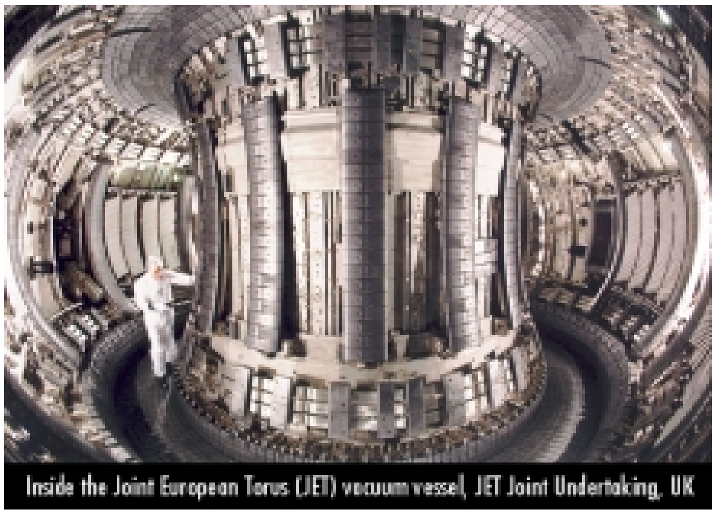
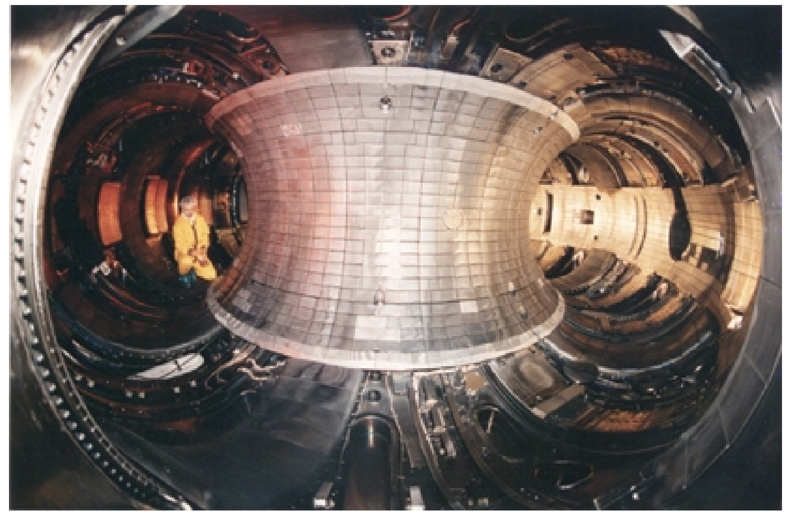
Excellent Technical Progress Has Enabled TFTR and JET to Begin Studying Burning Plasmas



JET and TFTR were Designed to Perform Deuterium-Tritium Experiments

Joint European Torus (JET)	Tokamak Fusion Test Reactor (TFTR)
	

	JET	TFTR
I_p(MA)	4.0	2.7
B_T(T)	3.6	5.6
P_{DT}(MW)	16.1	10.6
$P_{DT}/P_{in}=Q_{DT}$	0.64	0.27
Fusion Energy (GJ)	0.68	1.70
Tritium Proc. (g)	99.3	99.

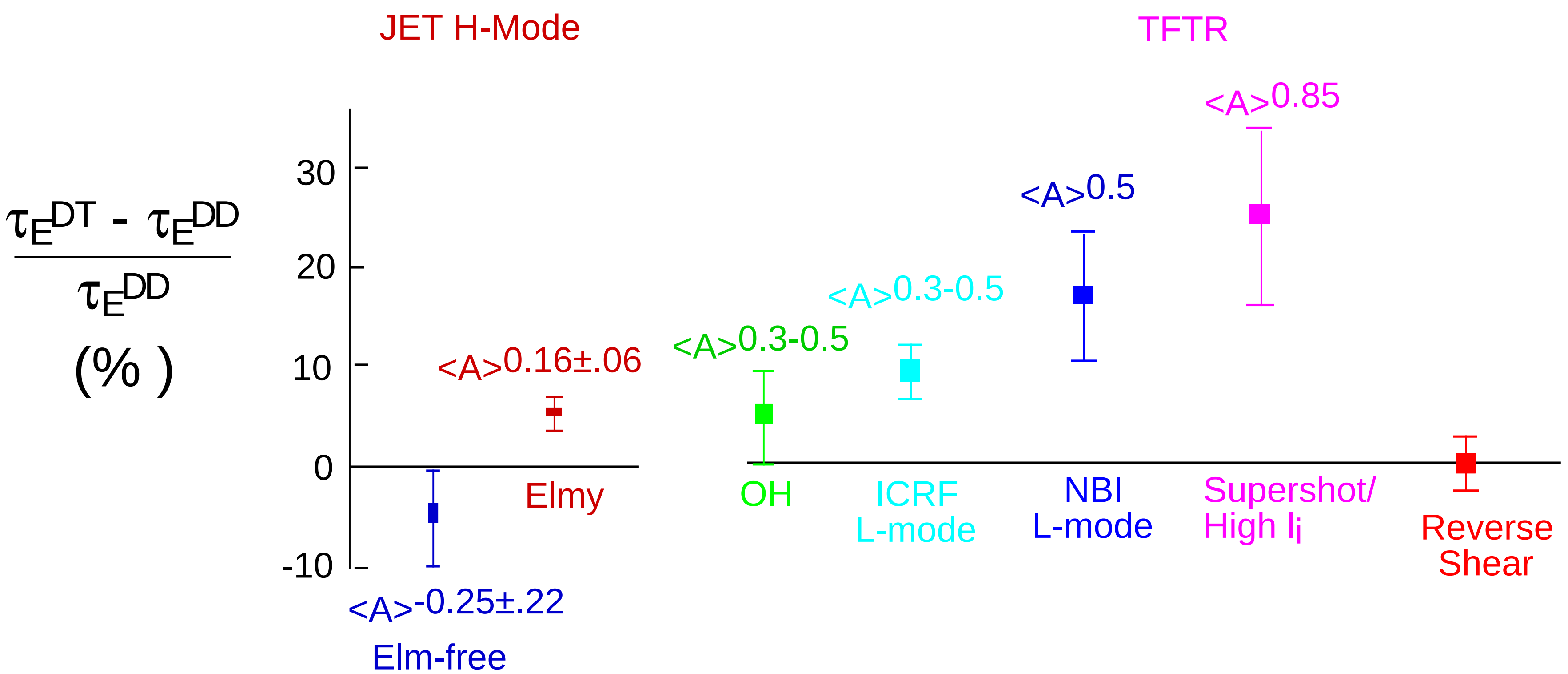
How are D-T Experiments Different from D?

- **Isotope Effects**
  - **Transport**
  - **Wave-particle Interactions**

- **Alpha-particle Physics**

- **Technology**

Isotope Effect Studied in a Wide Variety of Operating Regimes



- **Challenge to theoretical interpretation and to gyro-Bohm scaling, $\langle A \rangle^{-0.2}$**
- **Recent ITER scaling $\langle A \rangle^{0.19}$**

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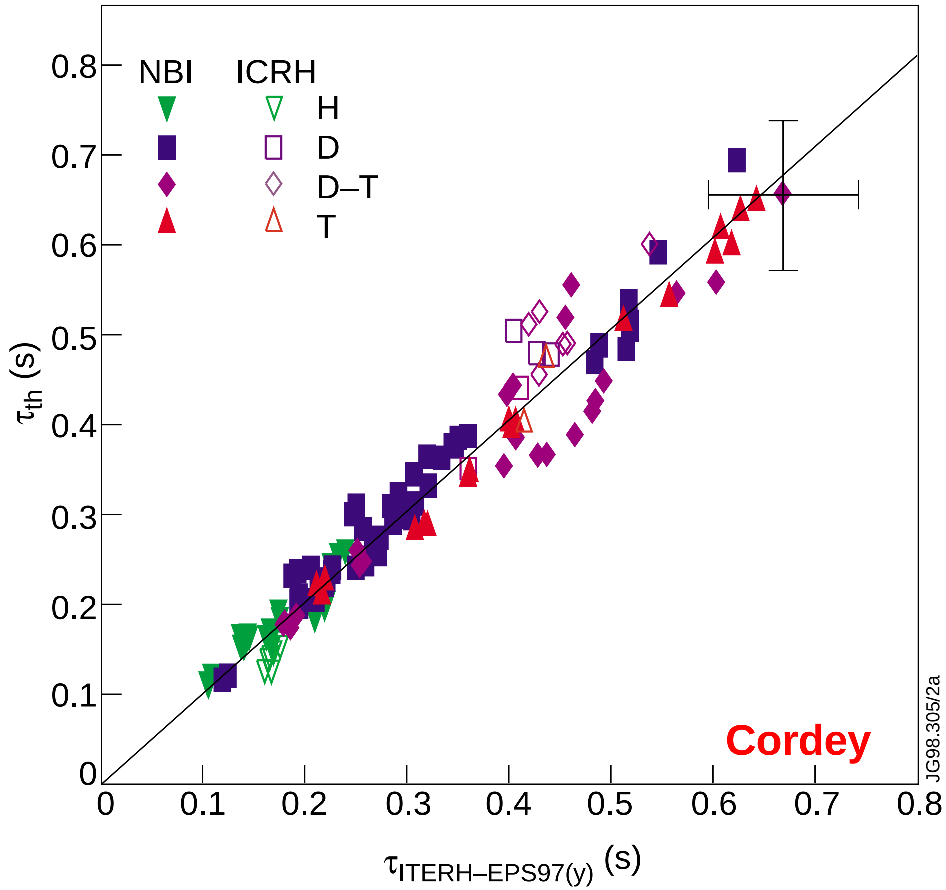
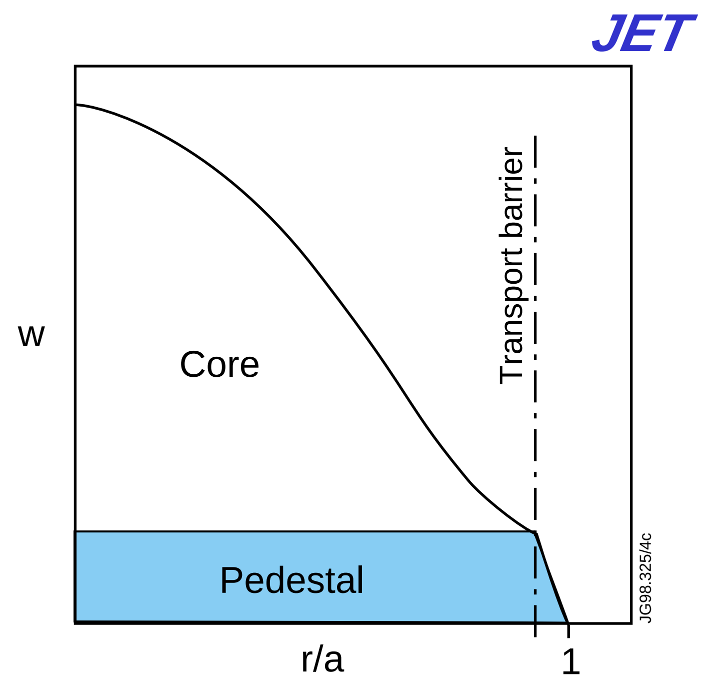
JET D-T Elmy H-mode Experiments Consistent with ITER Scaling

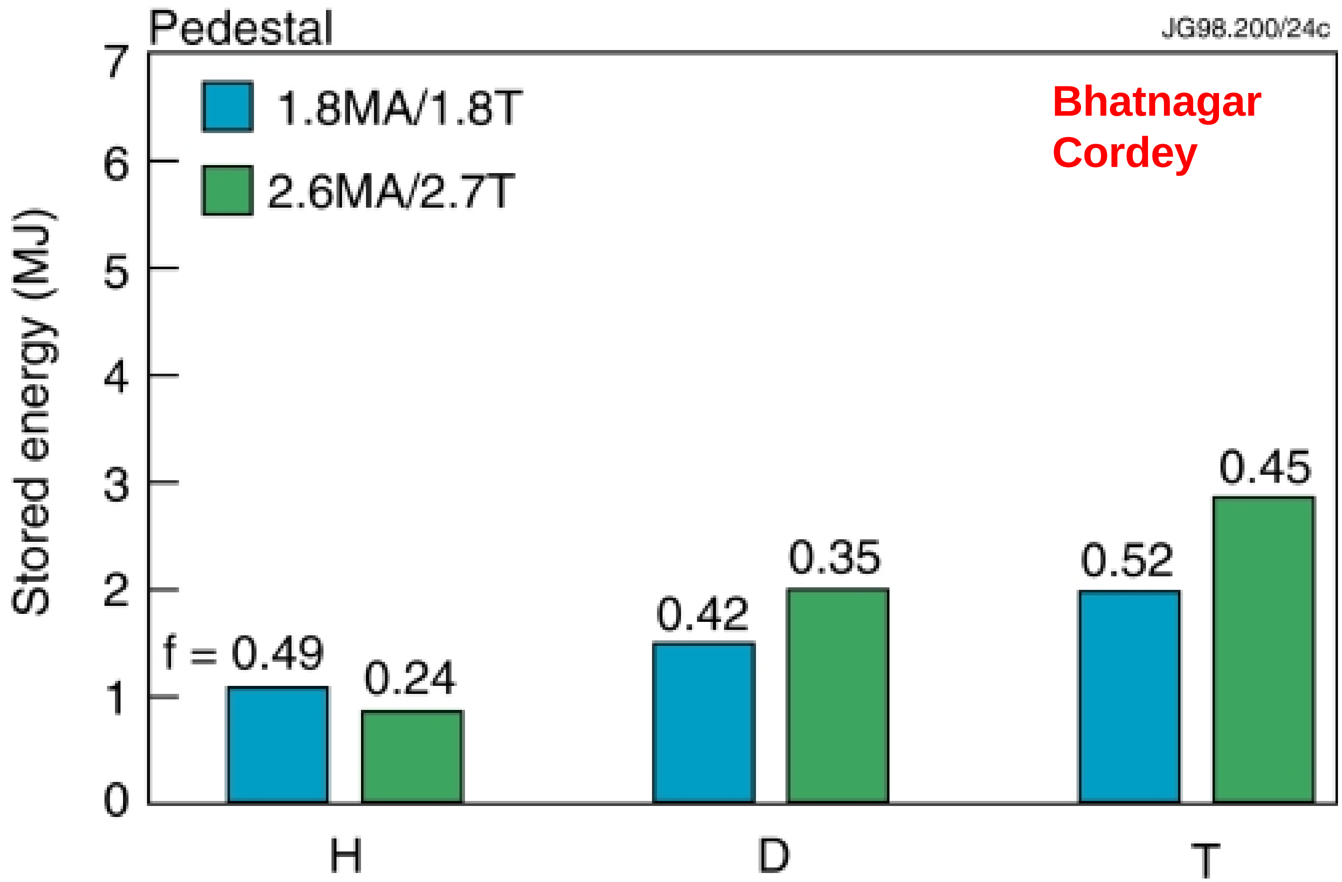


- $\tau_{th} \propto \langle A\rangle^{0.16\pm0.06}$



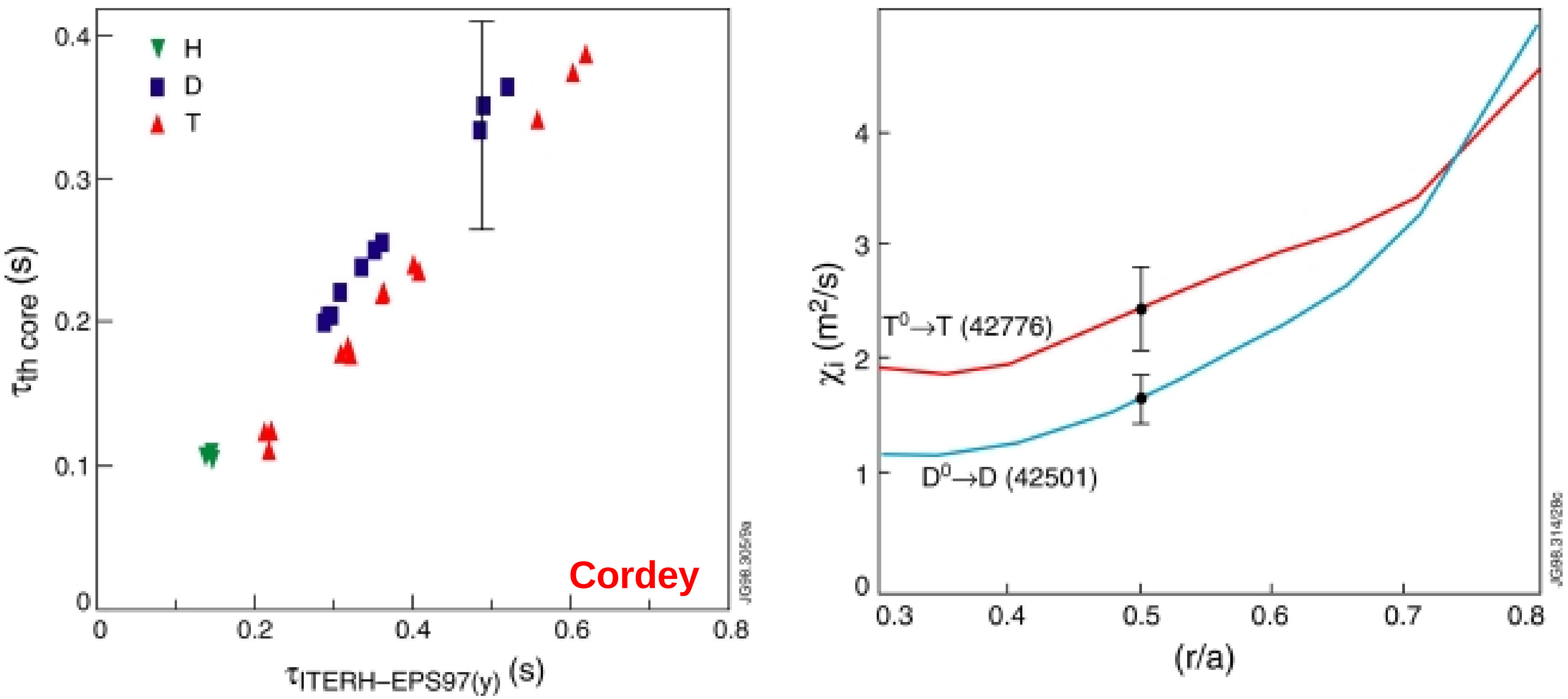
- **What is the role of the pedestal and the core?**

Stored Energy Associated with Pedestal Increases with <A>



- $W_{ped} \propto \langle A\rangle^{0.96}$
- **Power loss by ELMs decreases**

In JET H-mode Discharges Thermal Conductivity Degrades in the Core



- **Confinement scaling in the core consistent with gyro-Bohm.**
  - $\tau_{thcore} \propto \langle A \rangle^{-0.16\pm0.1}$

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

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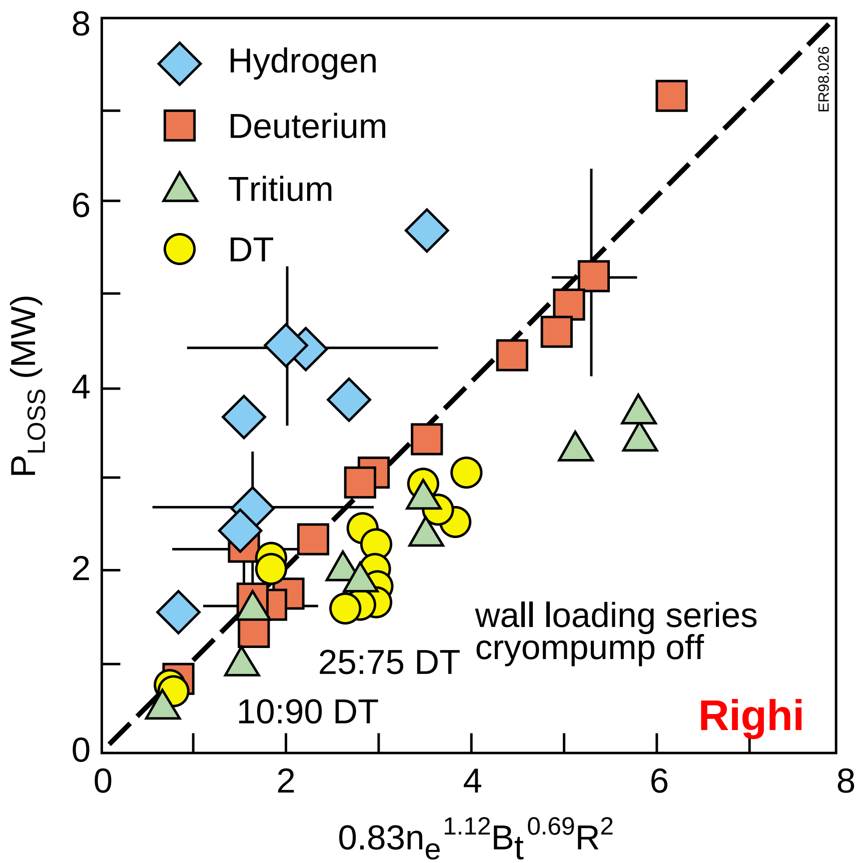
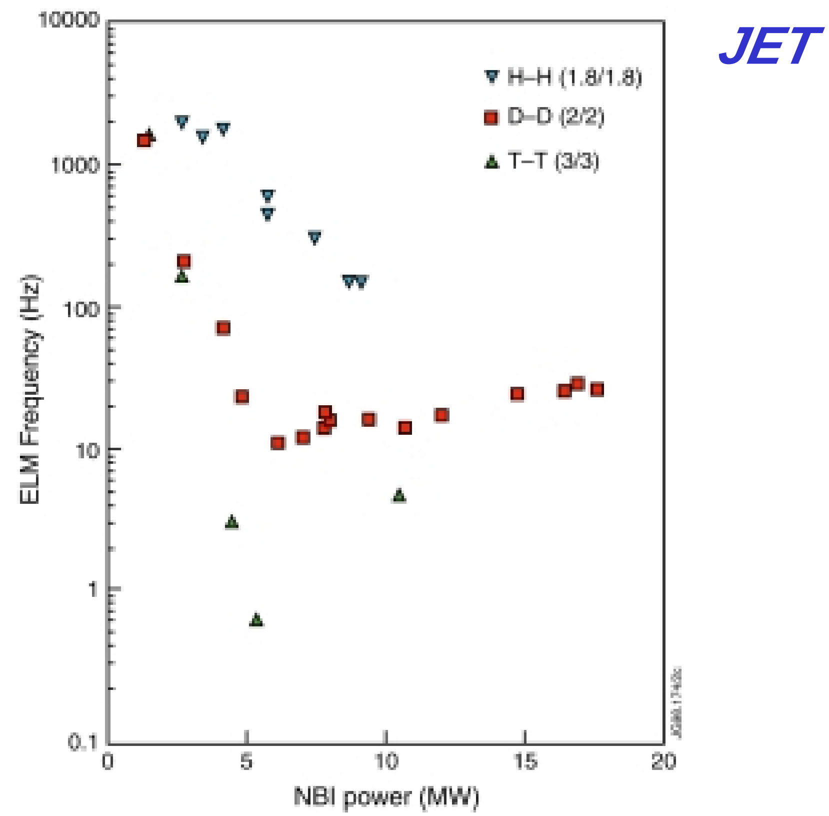
Power Threshold Going from L to H-mode Shows Favorable Isotope Scaling





- $P_{loss} \propto \langle A \rangle^{-1}$
- **ELM frequency decreases with <A>**

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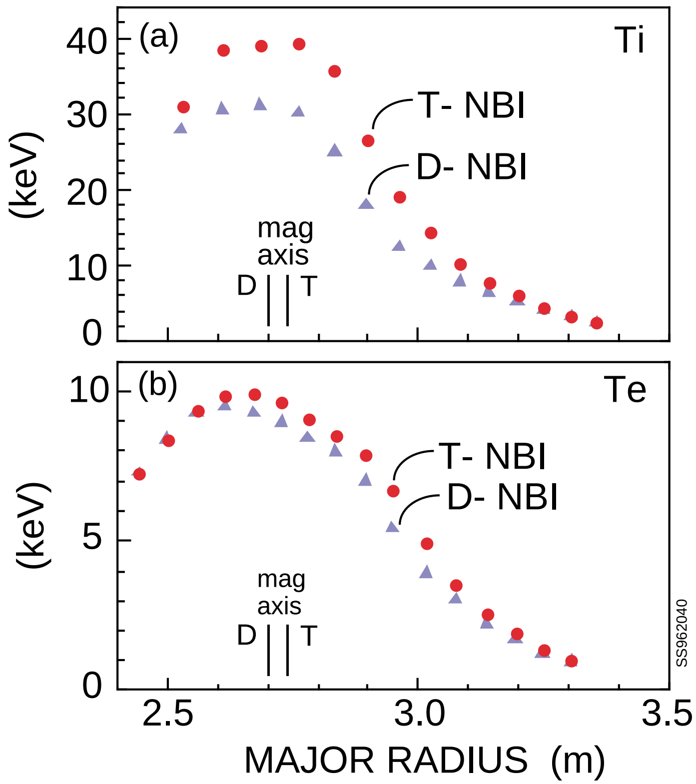
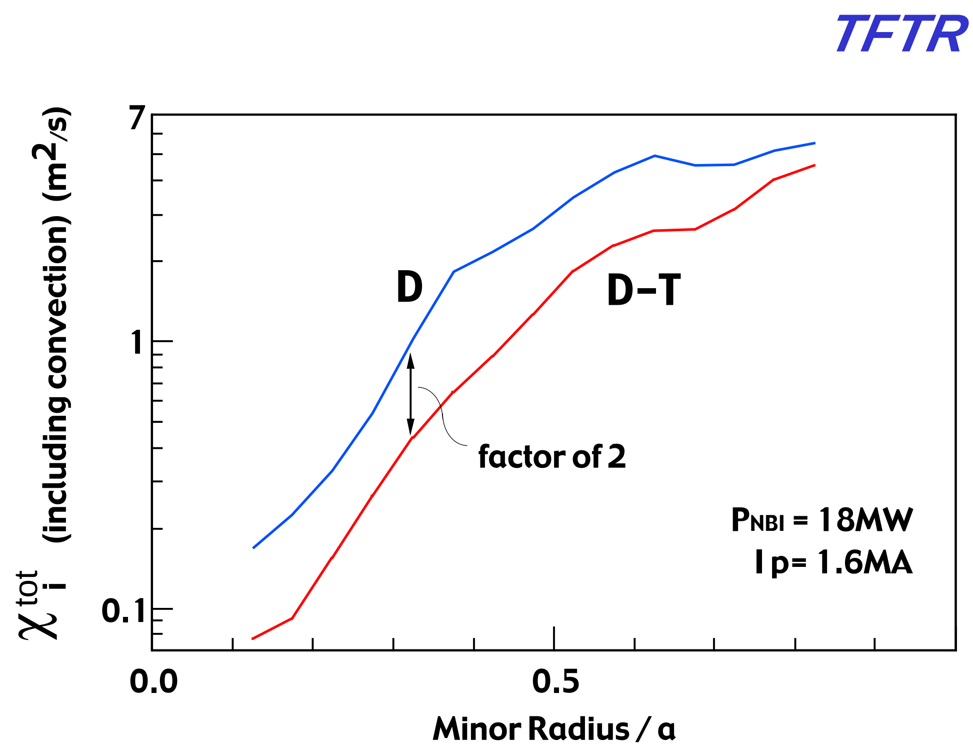
Improvement of χ_I in Core of TFTR Supershots in DT





- $n_i(0)\tau_E T_i(0)$ increased by ~55% from D to DT
  - Some cases up to 80% increase

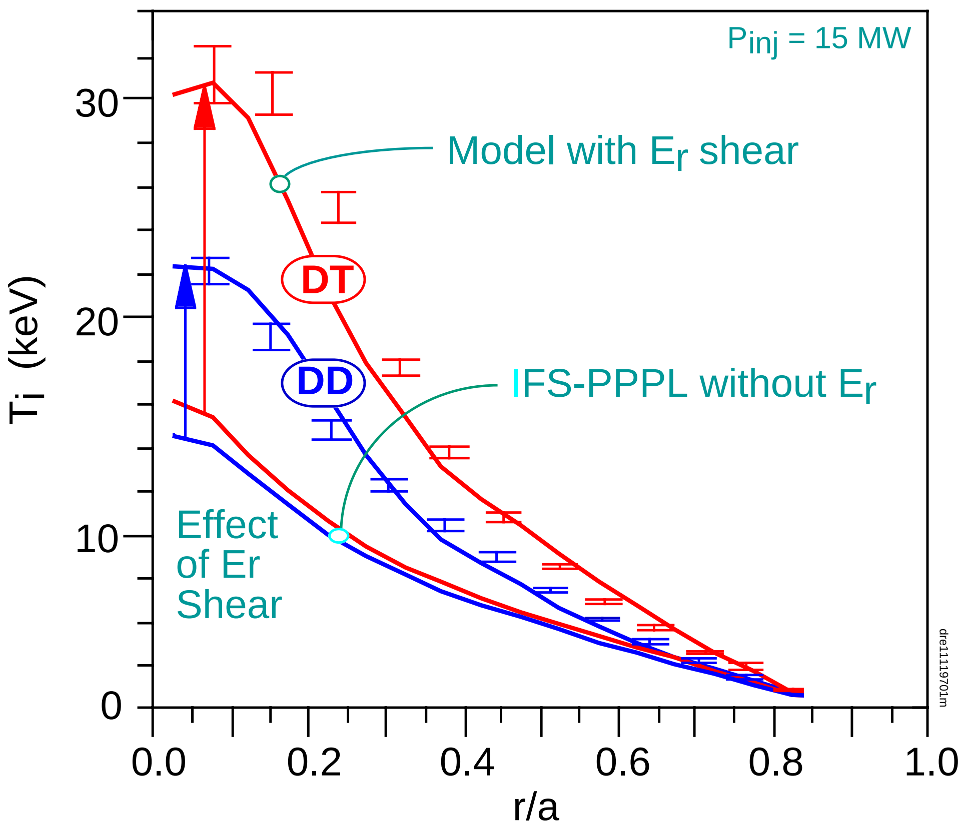
$\tau_E^{thermal} \propto \langle A \rangle^{0.89\pm0.1}$

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

Scott

ITG Model with Radial Electric Field Reproduces the Ion Temperature

TFTR



- Maximum linear growth rate decreases with ion mass.
- Er shearing rate increases with Ti.
- Radial Electric Field Shear Reproduces Strong Isotope Effect.
- ==> Isotope Effect depends on Operating Regime

Ernst

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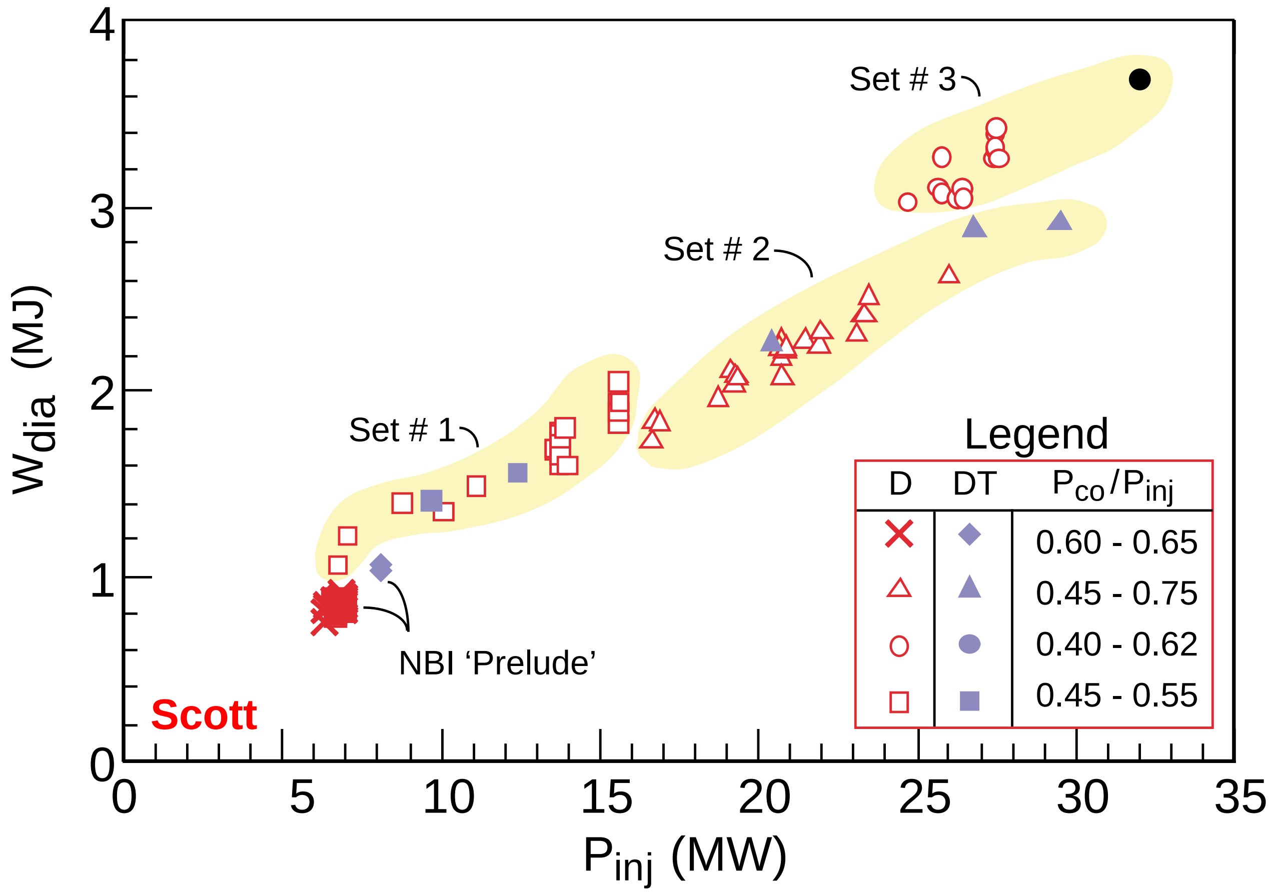
Favorable Isotope Scaling Not Observed in Reverse Shear Experiments

TFTR



- **Power threshold for internal barrier formation increased with <A>.**

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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.
  - Variation in different operating regimes.
  - What is the role of radial electric field shear?
  - What are the implications for advanced operating modes?

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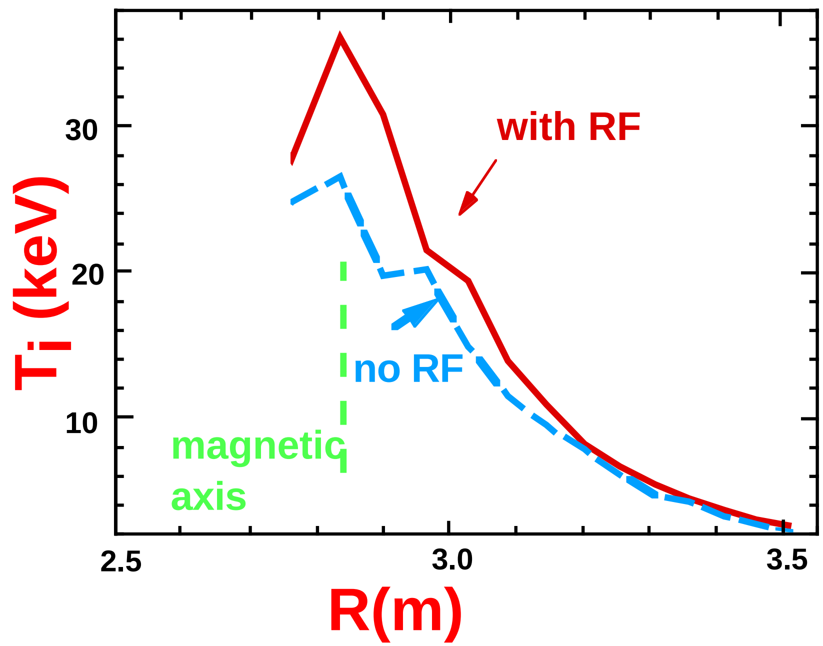
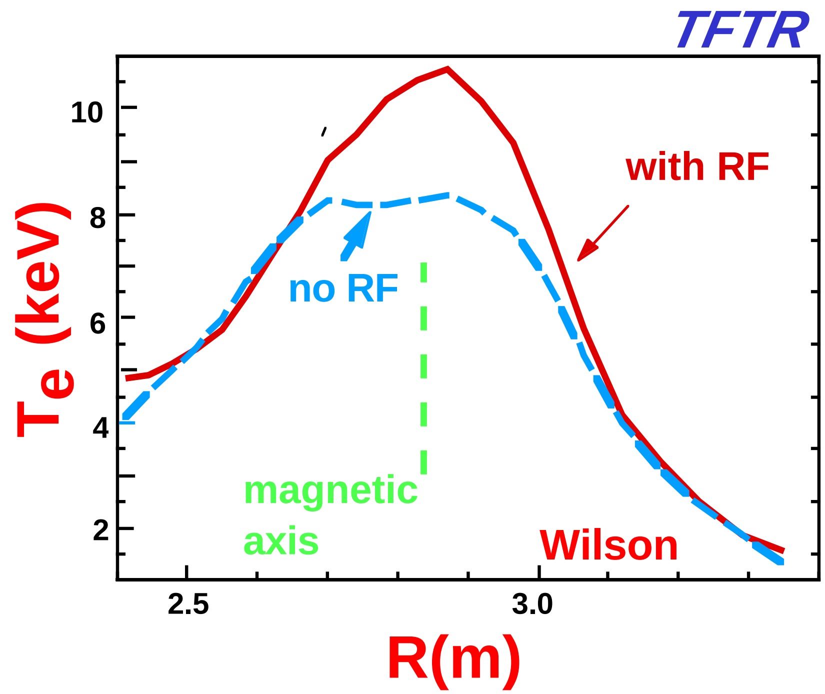
ICRF Successfully Heated DT Supershot Plasmas in TFTR



ΔT_i due to 2nd harmonic tritium heating



ΔT_e due to direct electron and ^3He minority ion heating

- Power deposition calculations in good agreement with experiment.

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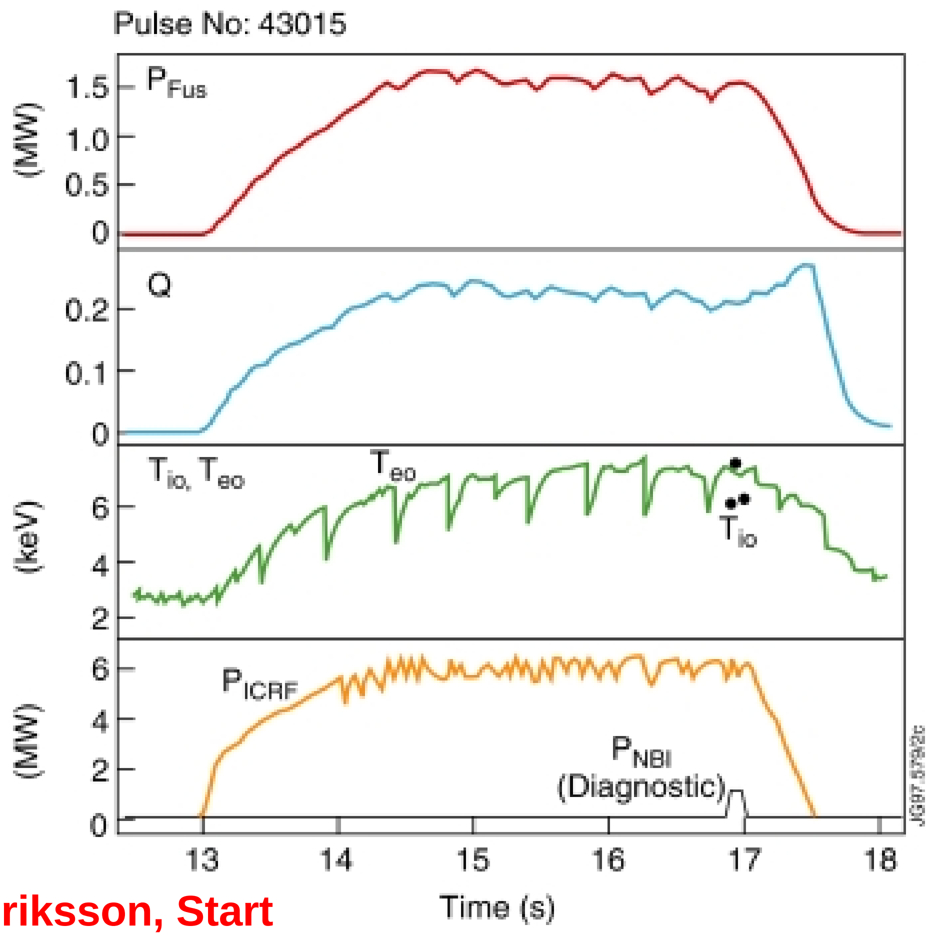
JET Demonstrated Successful Deuterium Minority Heating of Tritium Plasmas



Eriksson, Start

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

- **Physics of ICRF heating well established.**
  - Technology challenges remain.

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Alpha-particle Physics Studies

- **MHD Quiescent**
  - **Alpha-particle heating**
- **MHD Affects Alpha Confinement**
- **Alpha Particle Induced MHD Activity**
- ***Diagnostic Development Critical for these Studies***

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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	0.08	0.43
$\beta_\alpha(0)$%	0.30	0.4	0.8
–R•grad(β_α)%	2.0	2.3	4.0
$V_\alpha(0)/V_{Alfvén}(0)$	1.72	2.52	1.76
P_α/P_{heat}	0.03	0.09	0.66

Budny

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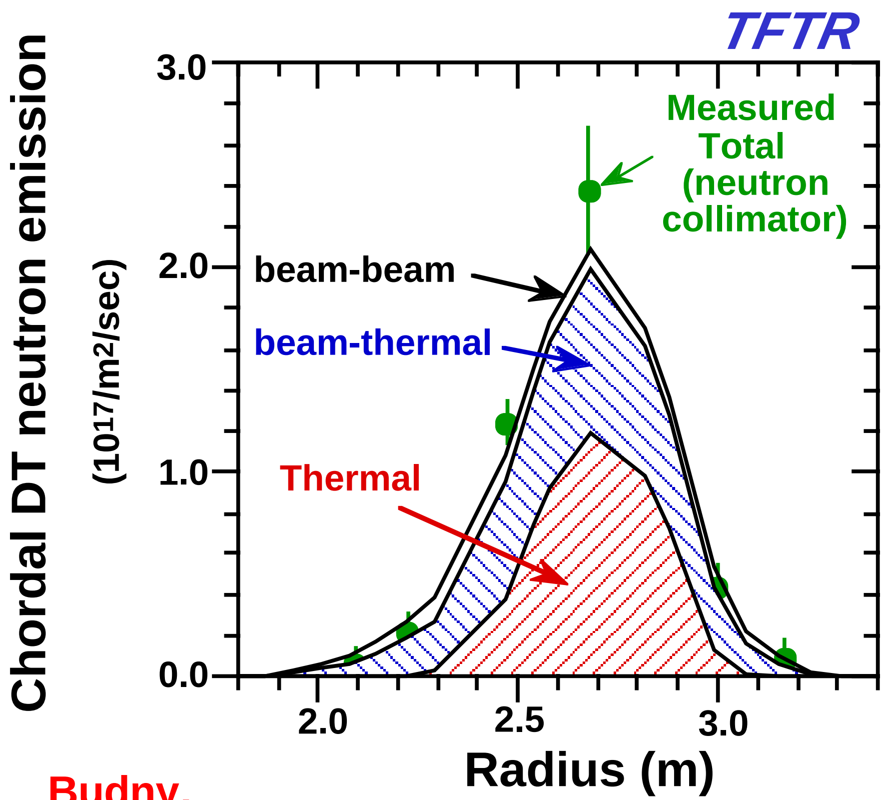
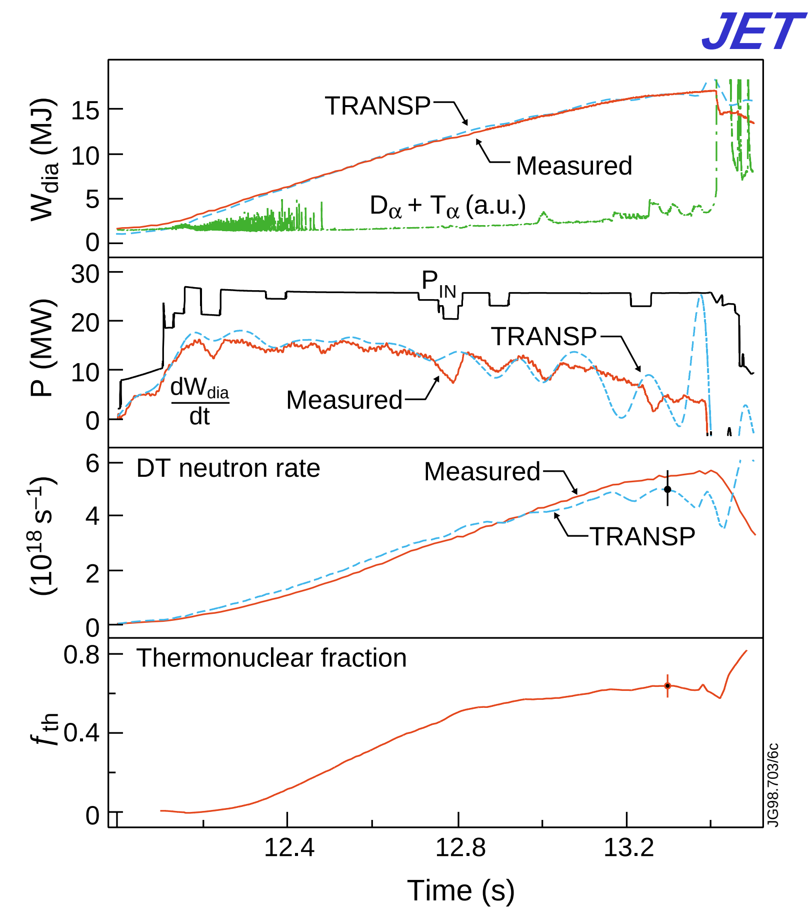
D-T Neutron Emission is Consistent with Calculations Based on Plasma Parameters

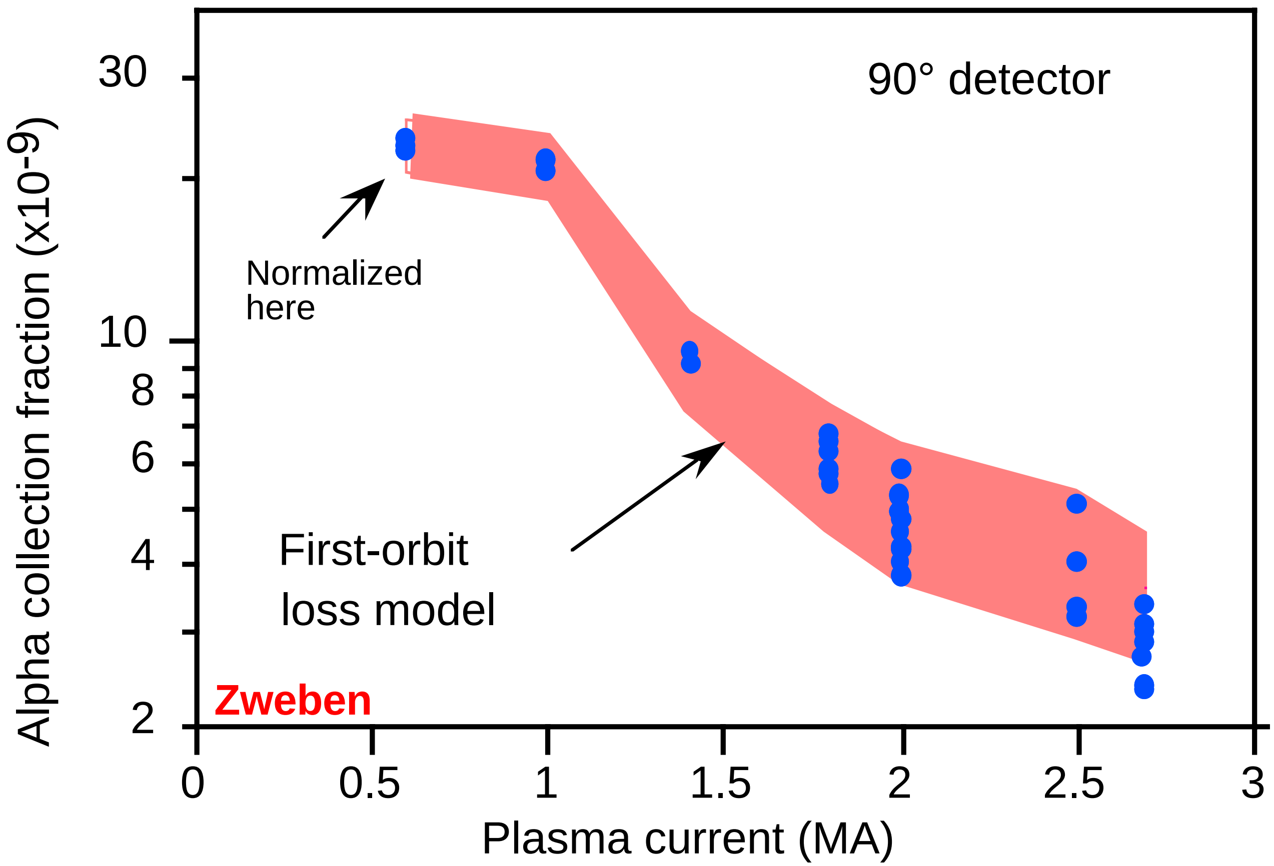


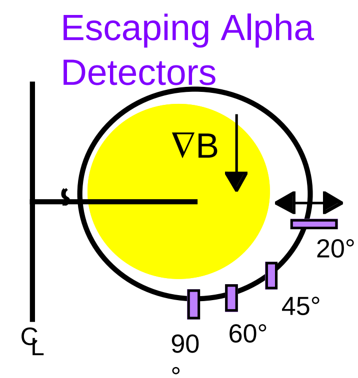


Budny, Keilhacker

- Alpha birth rate and profile are adequately modeled.

Escaping Alpha Flux at 90º Detector is Consistent with Classical First Orbit Losses





- **At 2.5 MA in TFTR , first orbit loss ≈ 3% globally**

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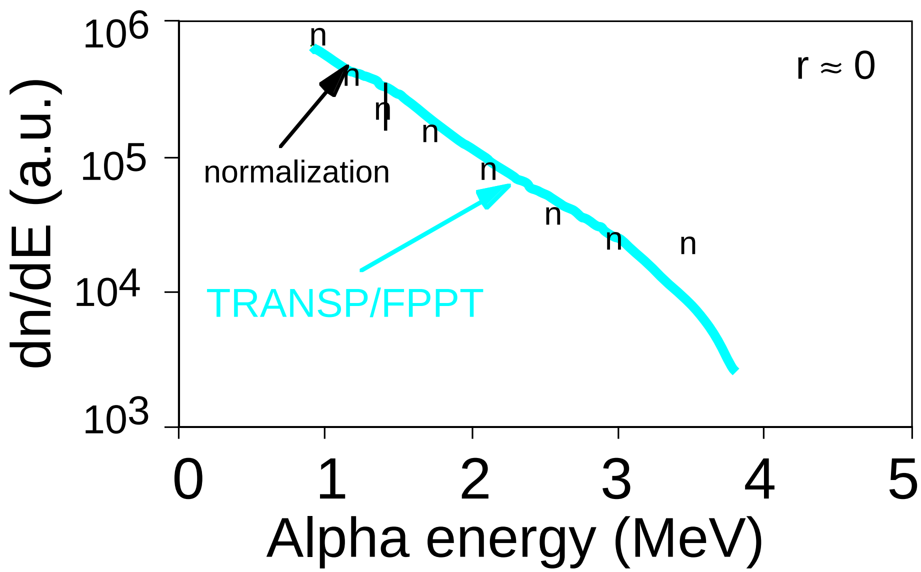
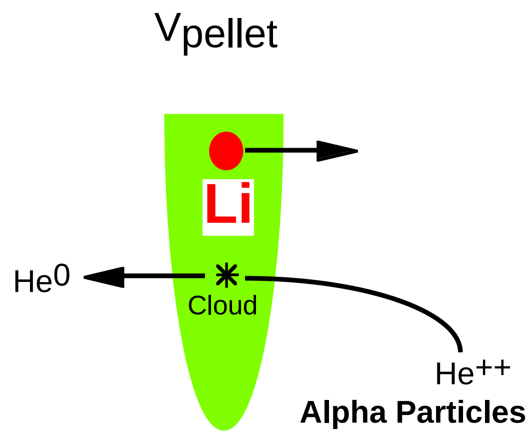
Confined Alphas in the Plasma Core Show Classical Slowing Down Spectrum

TFTR



Double Charge Exchange Technique

$He^{++} + Li^{+} \Rightarrow He^{0} + Li^{3+}$



- **TRANSP calculation includes:**
  - **orbit trajectories**
  - **classical slowing down**
  - **time dependence of alpha production**

Fisher, Petrov, Medley

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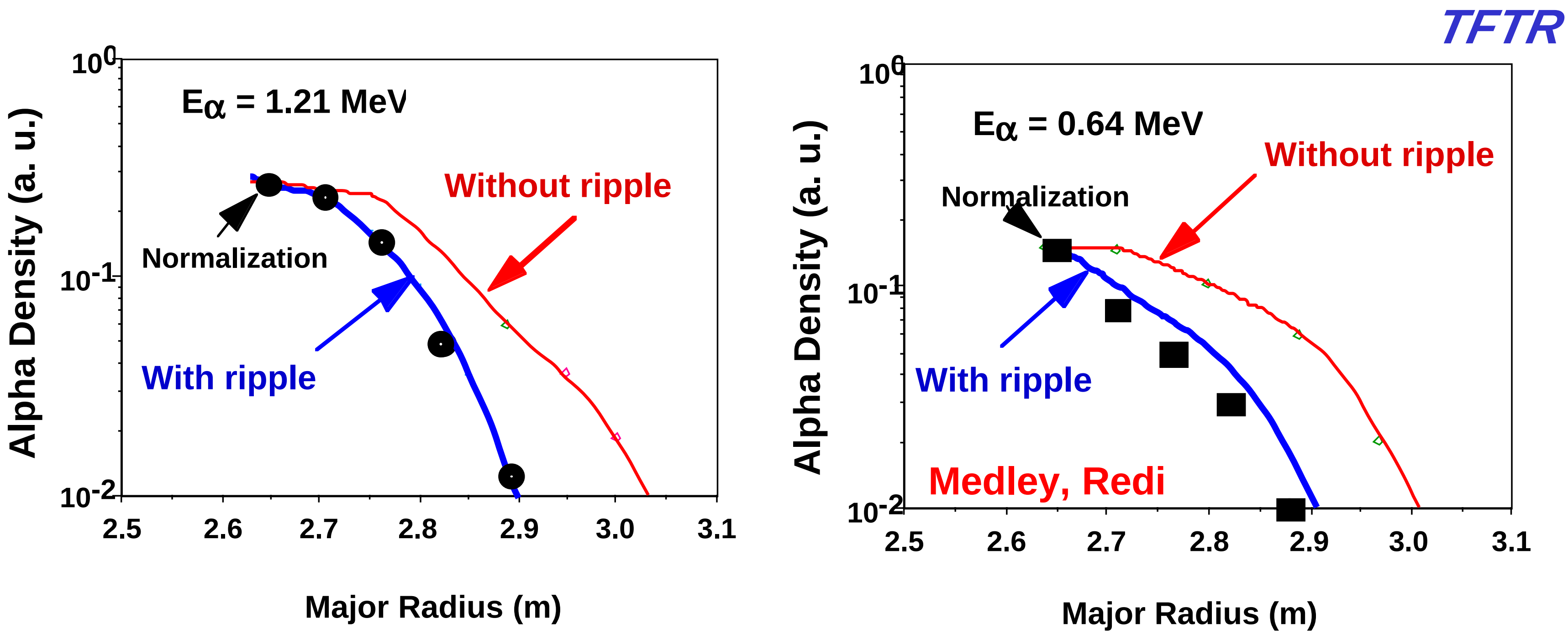
Stochastic Ripple Diffusion Affects Confinement of Deeply Trapped Particles



- **FPPT includes modeling of stochastic ripple diffusion.**
- **Heat deposition due to ripple loss of fast ions imaged on JT60U.**

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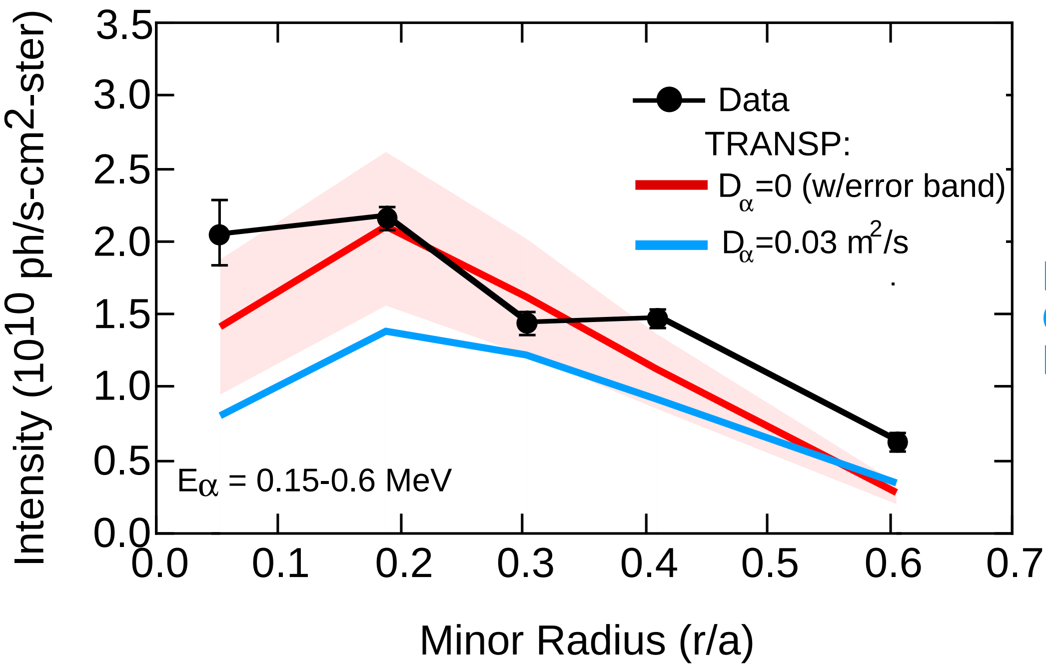
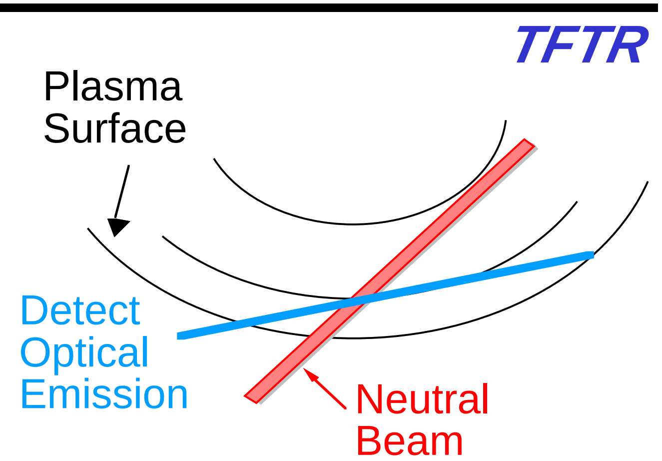
Alpha Particles Are Well Confined



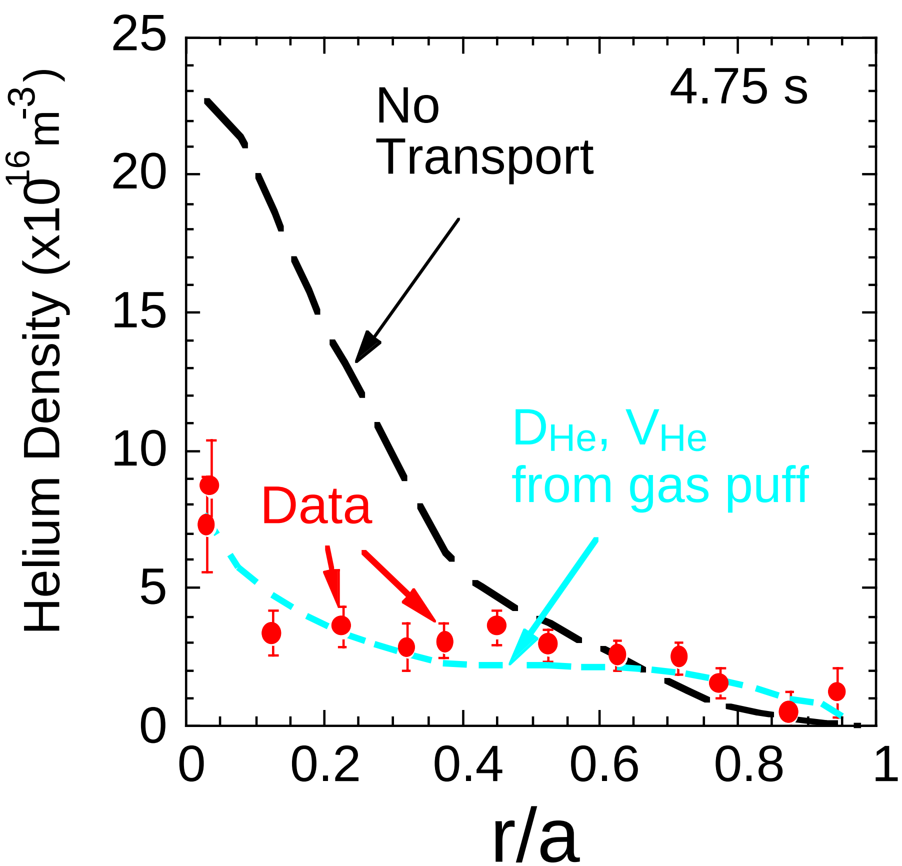


Charge exchange between fast beam neutrals and nonthermal alphas

- $0 \leq D_{\alpha} \leq 0.03\ m^2/s$

McKee

Rapid Ash Transport from the Core to the Edge in Supershots



- Consistent with $\tau_p^{*He}/\tau_E = 8$, acceptable for a reactor

$D_{He} / \chi_D \sim 1$

Synakowski

- **Confinement of ash consistent with impurity transport and edge conditions.**

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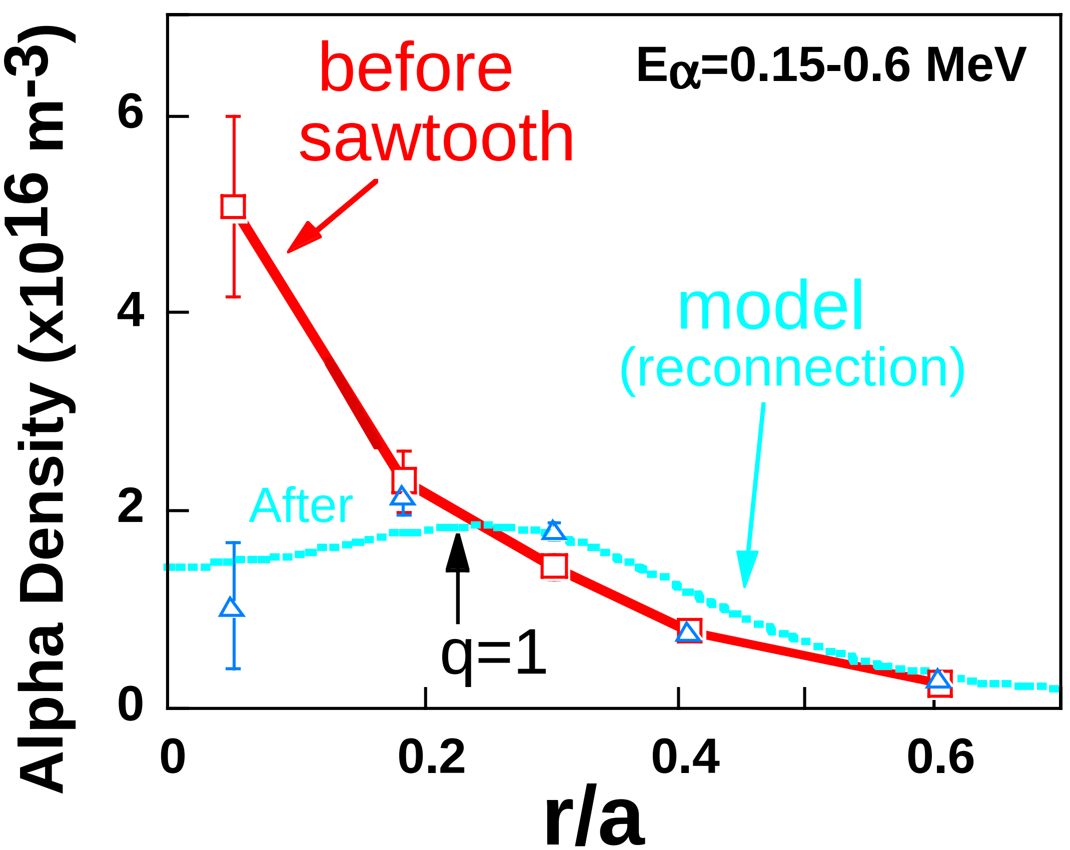
Sawteeth Cause a Large Radial Redistribution of Alpha Particles

TFTR

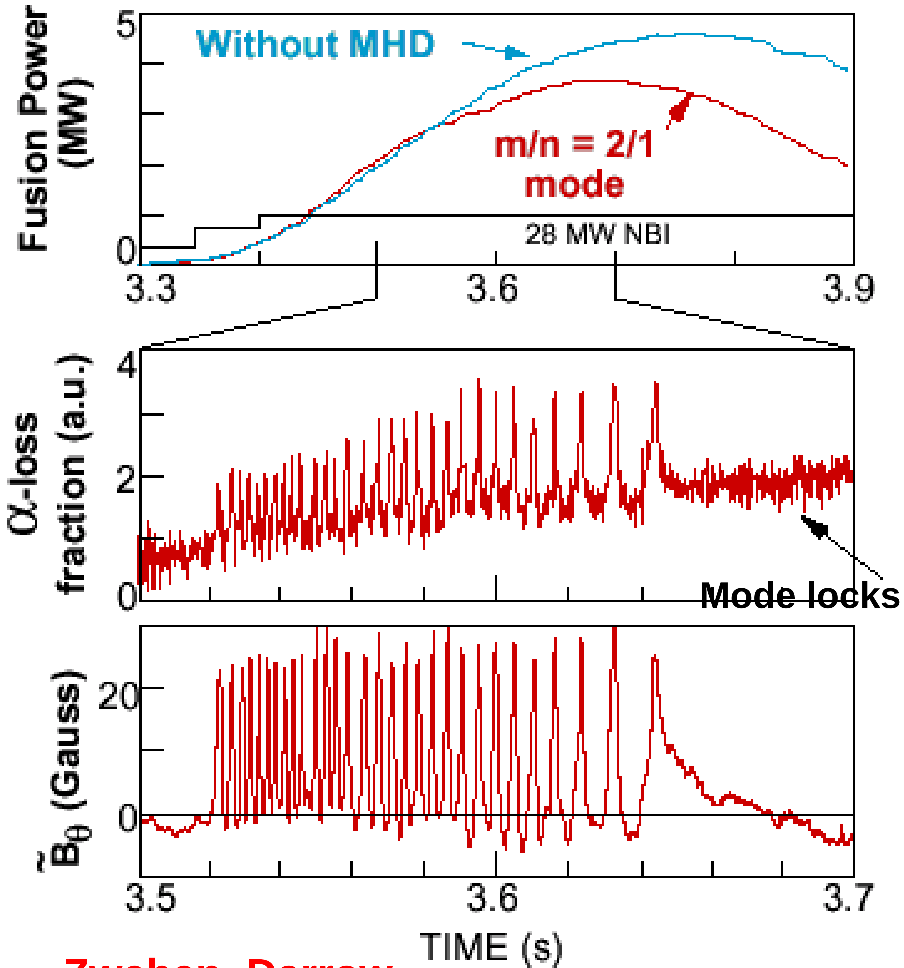


Stratton

- **Alpha heating profile in a burning plasma will depend upon sawtooth activity, although only transiently**

MHD Activity can Cause Enhanced Loss of Alpha Particles

TFTR

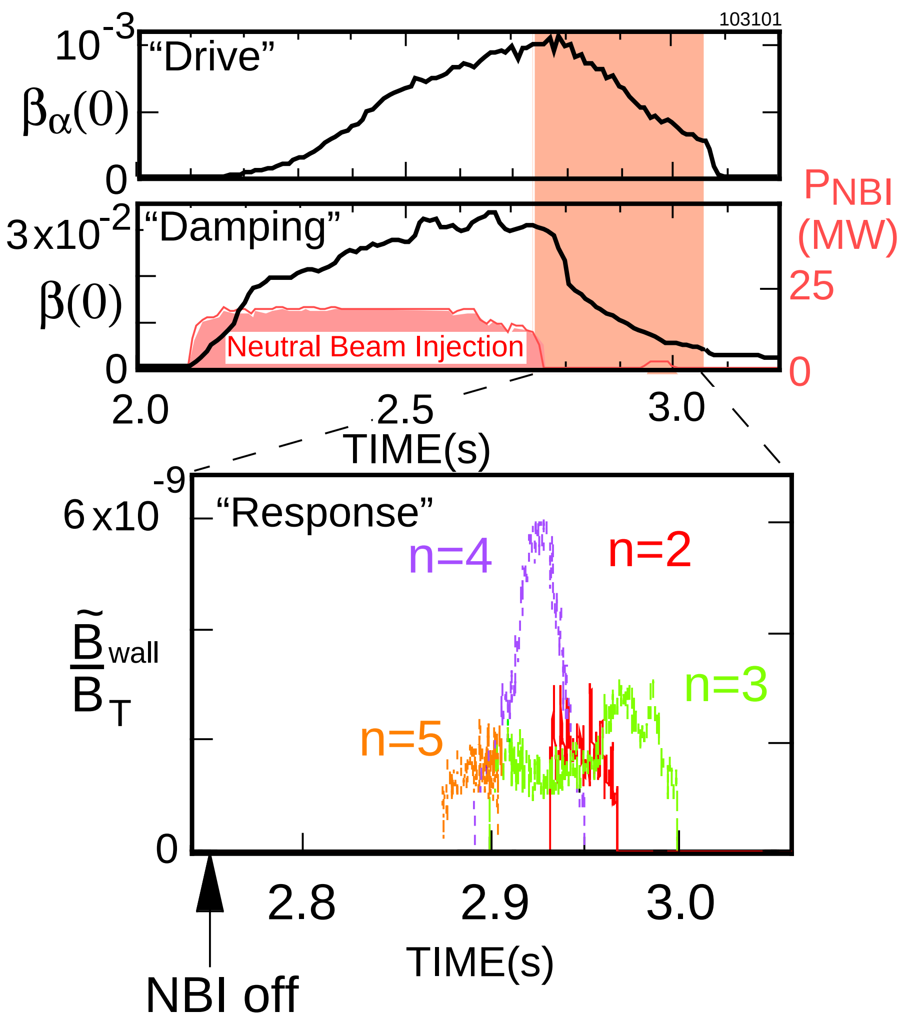


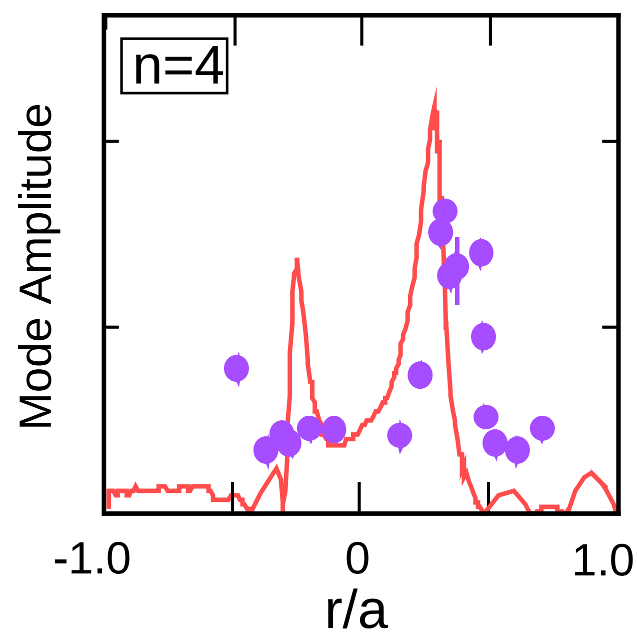
Zweben, Darrow

- Strong toroidal anisotropy in loss apparent as NTM mode is rotating
- Enhanced loss observed due to:
  - disruptions
  - kinetic ballooning modes
- Concern for plasma-facing components.

Observation of TAE Instability Driven by Fusion Alphas

TFTR

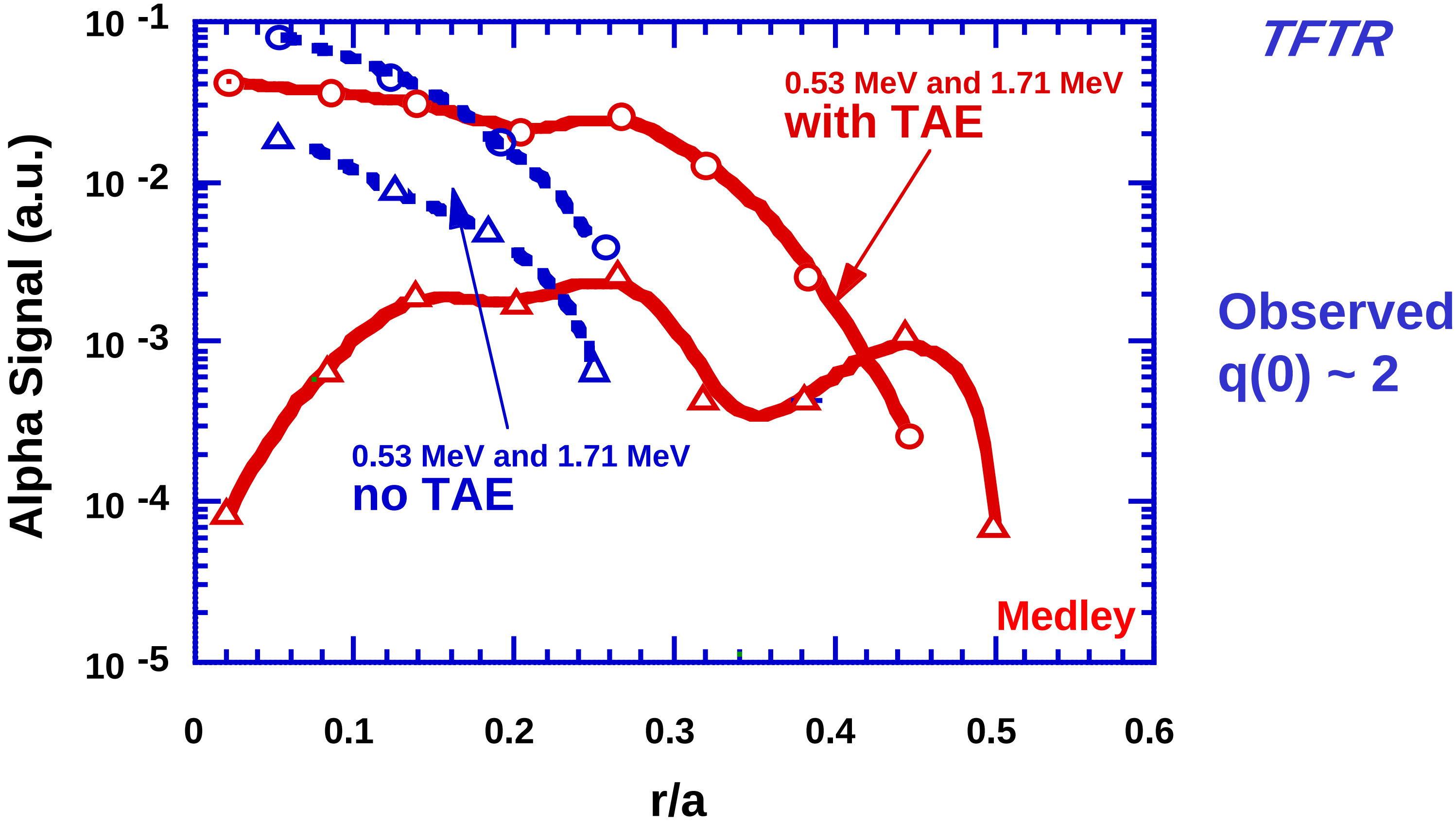




Radial mode structure via microwave reflectometry.

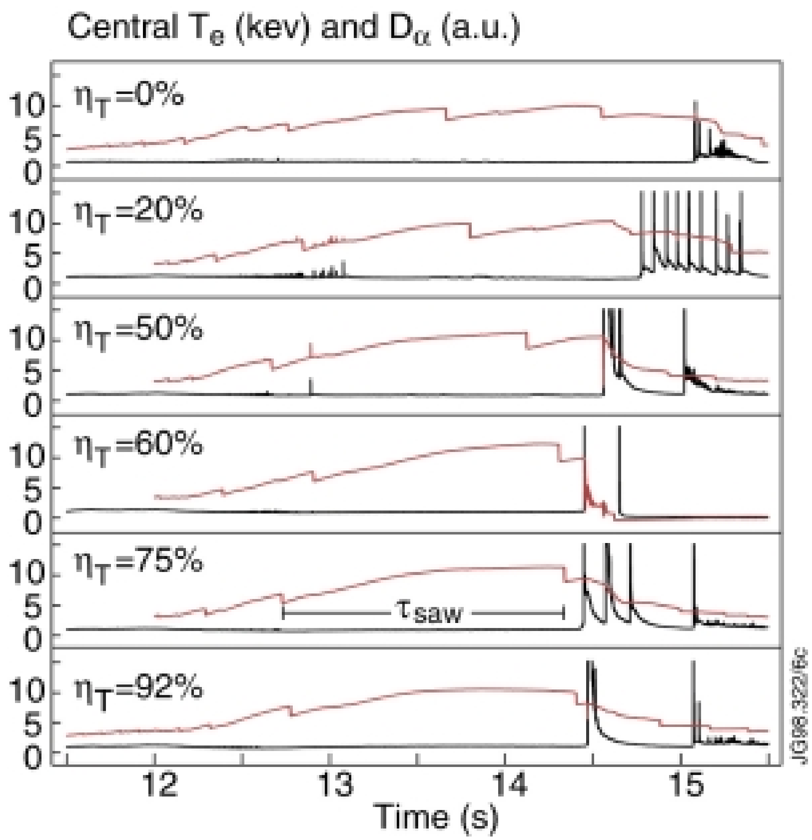
Nazikian

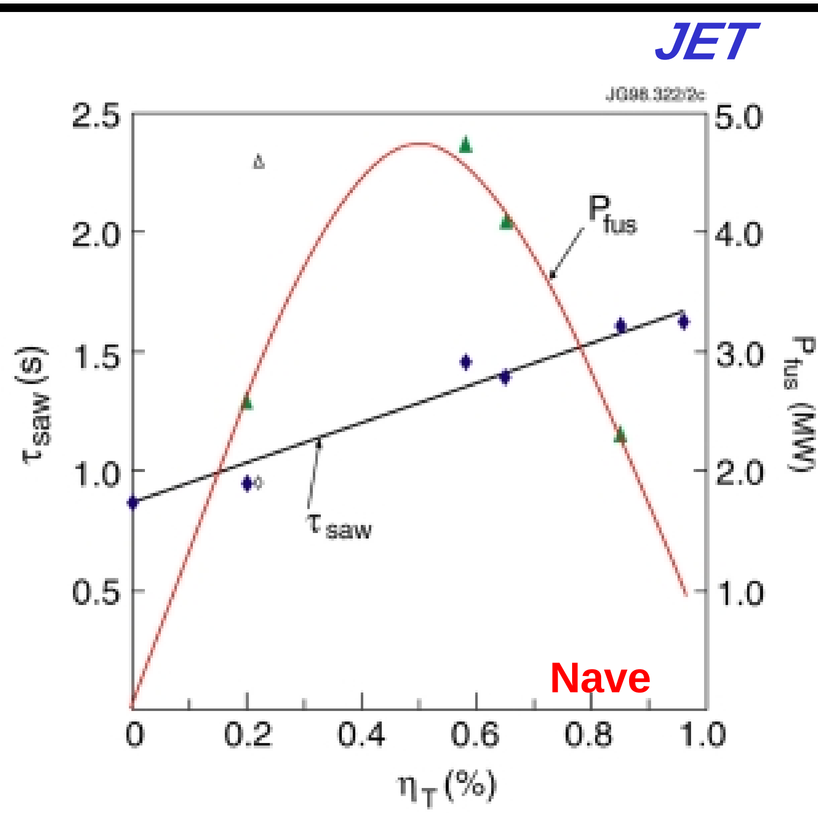
TAE Modes Redistribute Deeply Trapped Alpha-Particles



- Further work required to benchmark models.
- NNBI experiments on JT60U have observed strong radial redistribution.

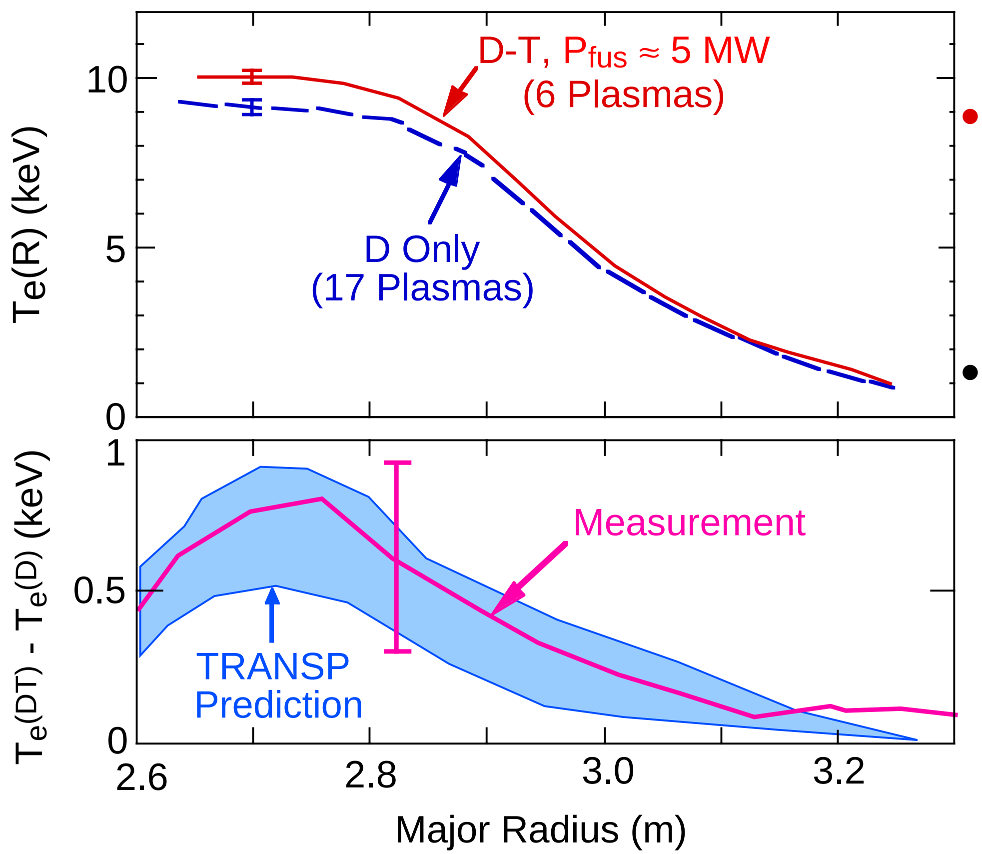
Sawtooth Frequency Decreases with Isotopic Mass





- **Change in sawtooth period attributed to increase in slowing down time and beam ion perpendicular energy density.**
- **Calculations imply that alpha particles had a stabilizing effect in highest performance D-T discharges.**

Initial Evidence of Alpha-Particle Heating



TFTR

- **Alpha heating ~15% of power through electron channel**
- **Plasmas matched for dominant Te scaling in D only plasmas.**
  - **$T_e(0) \propto \tau_E^{0.5}$**
  - **account for the isotope effect on confinement**
- **No sawteeth or adverse MHD.**

Taylor, Strachan

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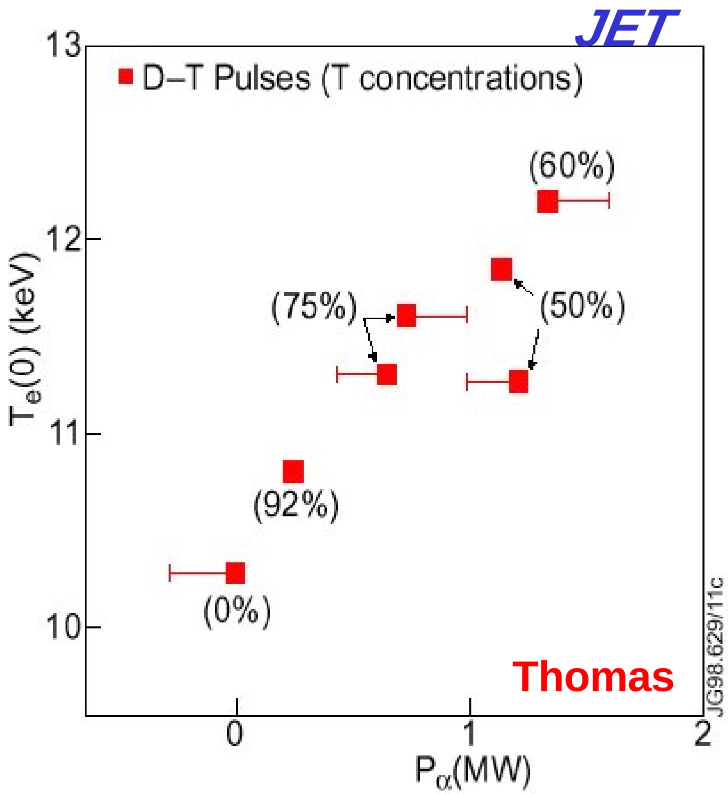
Alpha Heating Observed in JET



- P_{alpha}/P_{heat} ~12%
  - 30-40% through the electron channel
- Larger range in T concentration
  - analyze the effects associated with isotopes
- Sawteeth variability
  - limited number of pulses

- Alpha heating observed on both TFTR and JET.
- Comprehensive study of alpha heating requires higher values of P_{alpha}/P_{heat} .

Can Alpha Particles Be Harnessed to Further Improve Reactor Potential?

- Theoretical work on alpha channeling, frequency sweeping of waves, and stochastic ion heating raise the prospects of:
  - Increased ion heating
  - Alpha ash control
  - Modify alpha heating profile
  - Reduce alpha pressure to decrease instability drive
  - Current drive

- Need for experimental study
  - Fundamental wave-particle physics studies begun on TFTR.
  - D. Gates et al. predicted the role of stochastic ion heating in NSTX discharges when $V_{NBI} >> V_{Alfven}$
  - P. Thomas at EPS suggested possibility of increased ion heating due to alpha particles.
    - *Limited data*

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Summary Alpha-Particle Physics

- Alpha-particle confinement, transport, and slowing down well understood in MHD quiescent discharges.
  - Not as extensively studied in reversed shear experiments.
- Alpha-particle confinement affected by MHD.
- Alpha particle driven instabilities studied
  - Nonlinear consequences remain to be studied.
- Alpha-particle heating observed.
  - Higher power alpha particle heating experiments are required.

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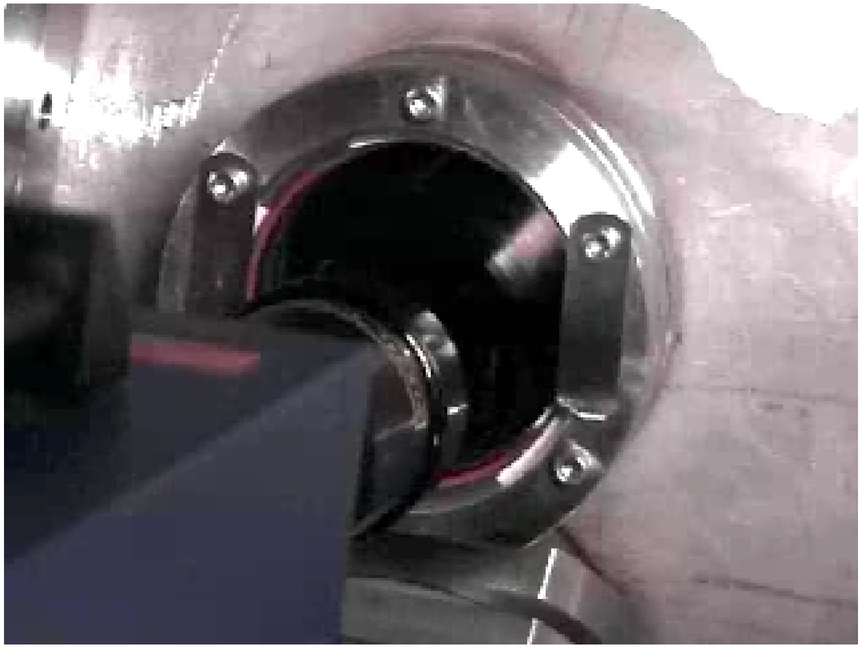
Tritium Processing Safely Performed

- **On-site tritium processing successful.**
- **Tritium retention in graphite is a serious concern.**
  - **TFTR tiles 16% retention**
  - **JET 12% retention**
  - **One year after extensive removal efforts**
- **Need for in-situ removal**
  - **Alternative materials**



PPPL-JAERI Collaboration
Gentile,Skinner (PPPL)
Shu (JAERI)

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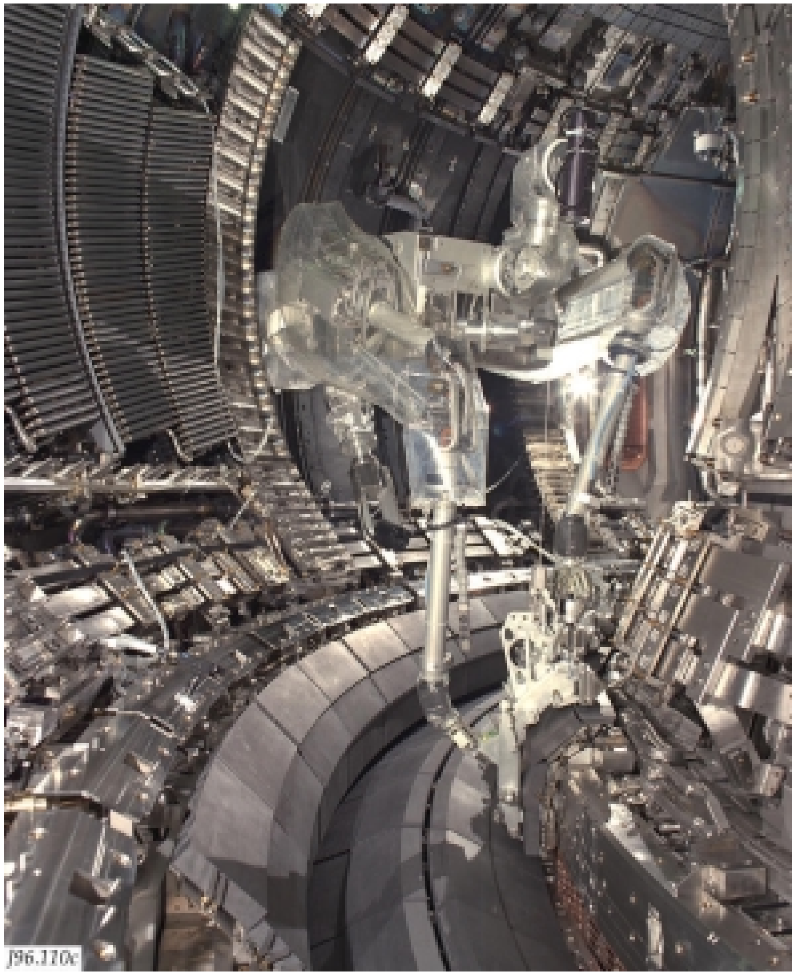
In-vessel Remote Handling Demonstrated on JET



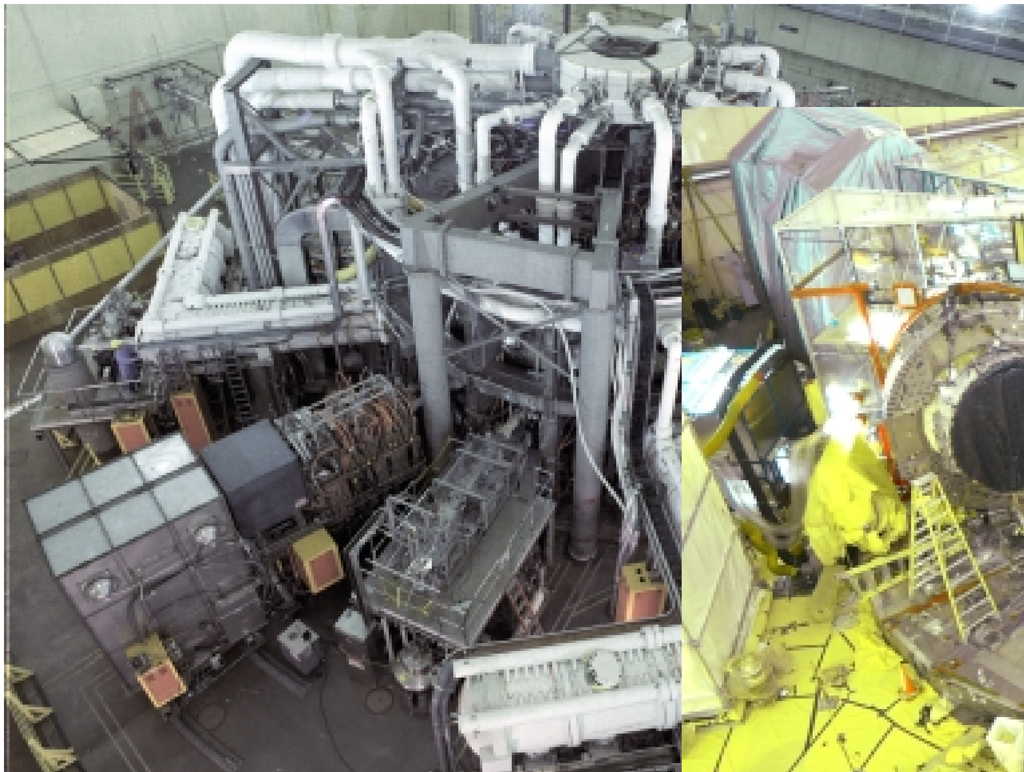
Telescopic Articulated Manipulator

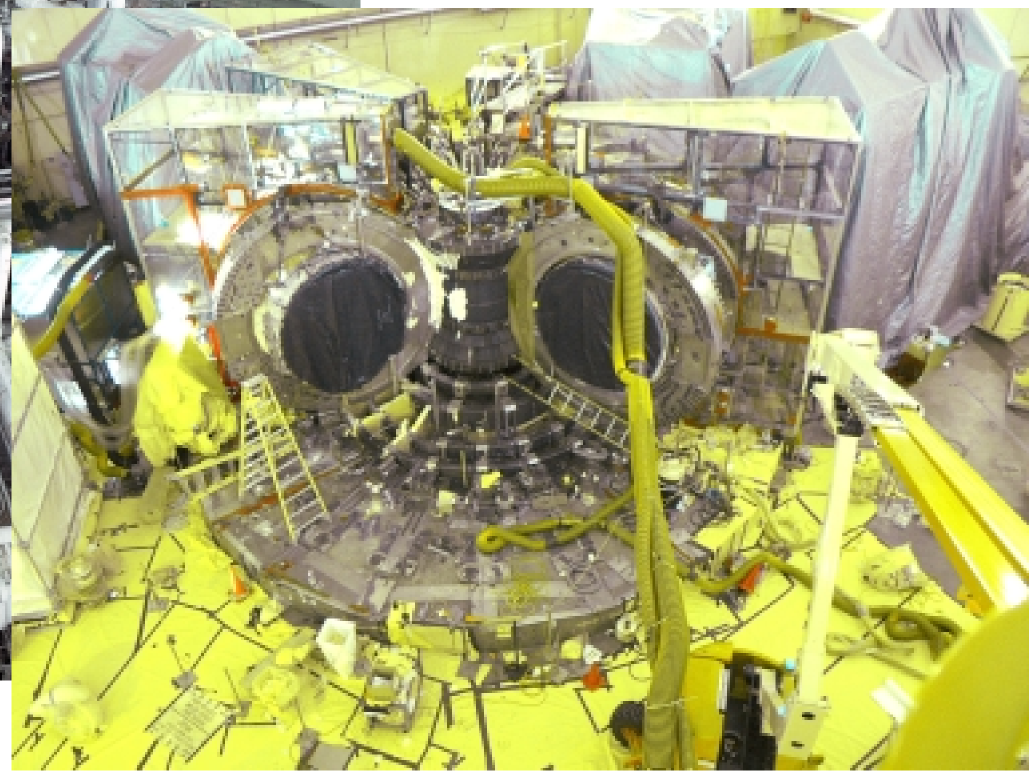
JET

- **Critical technology for future burning plasma experiments**
  - Fluence ~ 10^4 greater

Successful Demonstration of Decommissioning of a Fusion Facility

TFTR





- **Machine activation in future burning plasma experiments will require remote disassembly.**

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Summary

- **Results from TFTR and JET:**
  - **Provided solid design basis for a burning plasma experiment.**
  - **Identified opportunities to learn new science and technology.**
- **Critical aspects of the technology for a burning plasma experiment were utilized**
  - **Burning plasma experiment will be far more demanding due to the higher fluence, tritium retention and processing requirements.**
- ***Full potential and consequences of alpha heating have not been explored!***

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