Fast-Ion Physics: What, Where, and Why

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What What do we understand? Not understand?

Where What scale experiment is most likely to deliver understanding?

Why Will the tokamak burning plasma experiment work? Will we learn anything applicable to other concepts?

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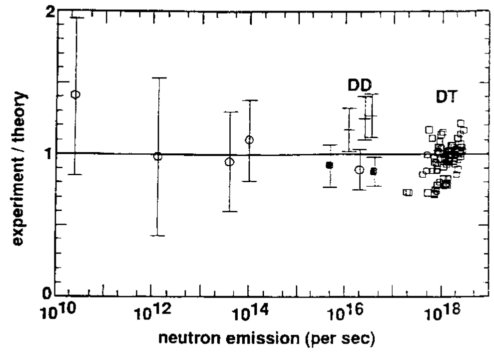
1) Experimental review by Heidbrink and Sadler, Nucl. Fusion **34** (1994) 535.
2) ITER review by Putvinskii et al., Nucl. Fusion **39** (1999) 2471.
3) TFTR DT review by Strachan, Plasma Phys. Cont. Fusion **39** (1997) B103.
4) TFTR alpha review by Zweben et al., Nucl. Fusion **40** (2000) 91.
5) TAE review by Wong, Plasma Phys. Cont. Fusion **41** (1999) R1.

Sources of Fusion Products and Beam Ions

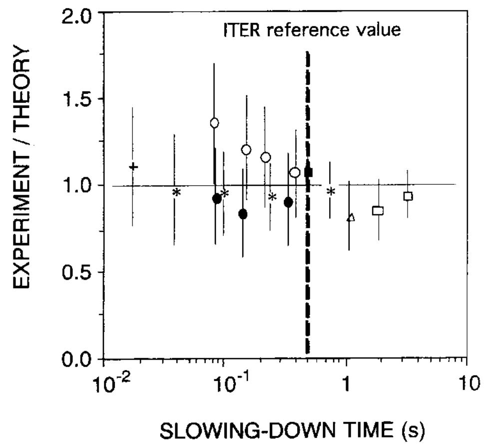


Fusion product rate, profile, and energy distribution known accurately.

Beam deposition known to within 20%.

High confidence for burning tokamak and other concepts.

Velocity Distribution Function



Coulomb deceleration accurate to within ~10%.

Pitch-angle scattering and energy diffusion less certain but probably OK.

Alpha deceleration understood for burning tokamak--applicable to other concepts.

ICRF Source and Acceleration

Minority Heating

Modified Stix formula for ICRF acceleration agrees to within ~10% with measurements.

Spatial position of the tail is approximately correct if non-standard orbits and Doppler shifts are included.

Higher harmonic minority heating

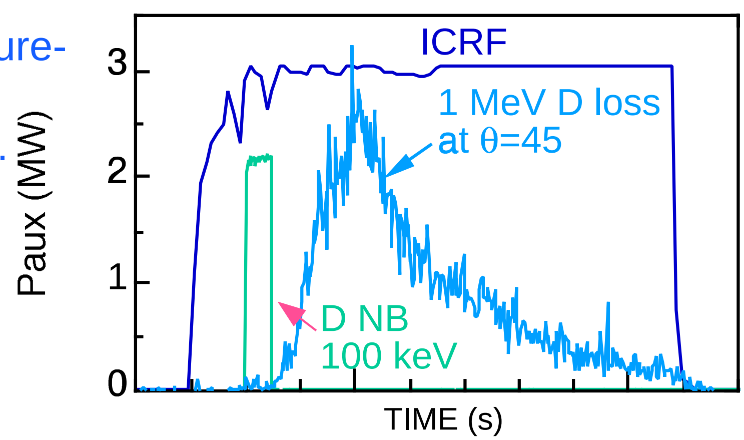
Acceleration OK but less rigorously tested.

Mode conversion

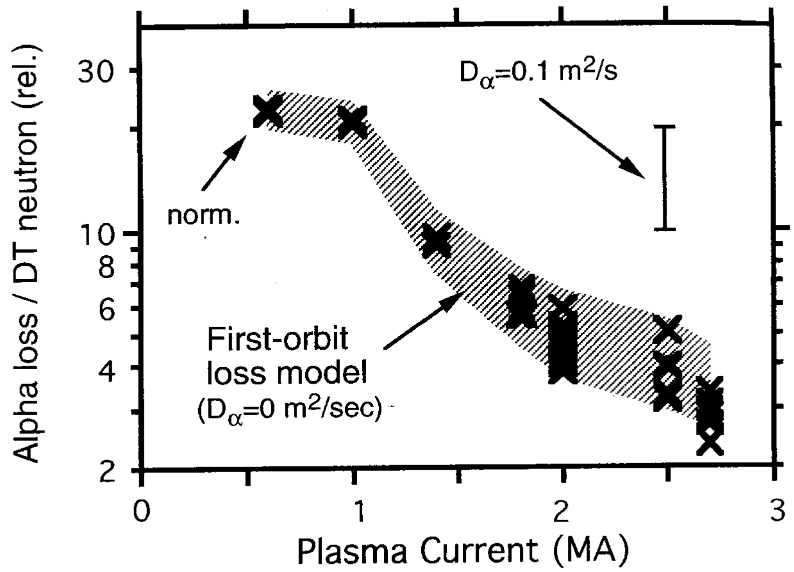
Energy diffusion much greater than expected.

Detailed RF field and fast-ion measurements in small-to-JET scale devices.

Minority heating is reliable for a burning tokamak.



Orbits in Static Fields



Loss boundaries are accurately known.

Ripple losses accurately calculated. Stochastic ripple boundary roughly verified.

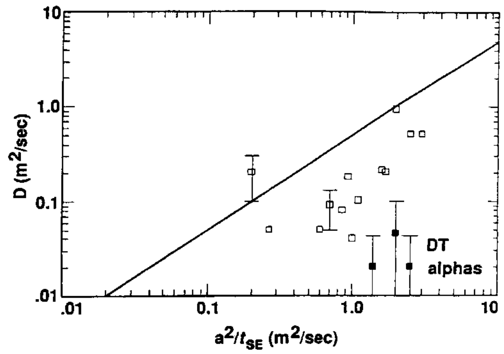
Error fields unimportant.

Small machine could study ripple boundary.

Burning tokamak projections reliable.

Burning tokamak does not address key issues for other concepts.

Turbulent Transport of Fast Ions



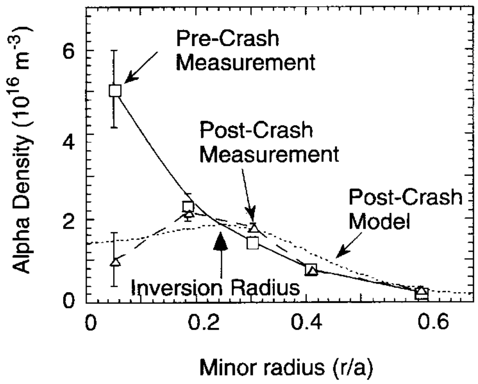
Observed transport in MHD-quiescent plasmas is barely detectable. Plausible explanation is gyro-averaging over background fluctuations.
Test explanation on a small machine.

RF-induced transport hardly measured. More experiments at both small and JET scale.

Alpha diffusion will be small in a burning tokamak.

Little contribution to other concepts.

Transport by plasma MHD



Sawteeth cause transport if the crash time is short compared to characteristic orbit times.

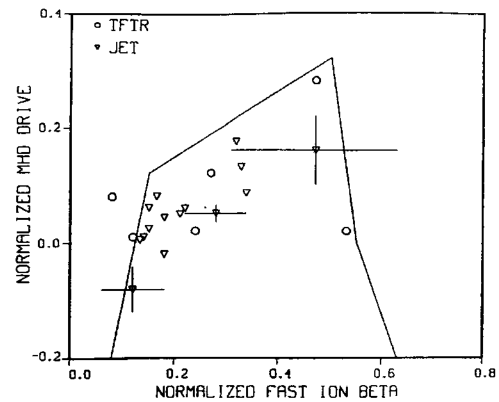
Tearing modes cause transport when island overlap occurs in orbit phase space.

Test selective transport of fast ions by propagating long wavelength modes in a small-to-moderate scale device. (Alpha ash removal & channeling)

Given the MHD characteristics, can predict alpha transport.

Little contribution to other concepts.

Sawtooth and Fishbone Stability



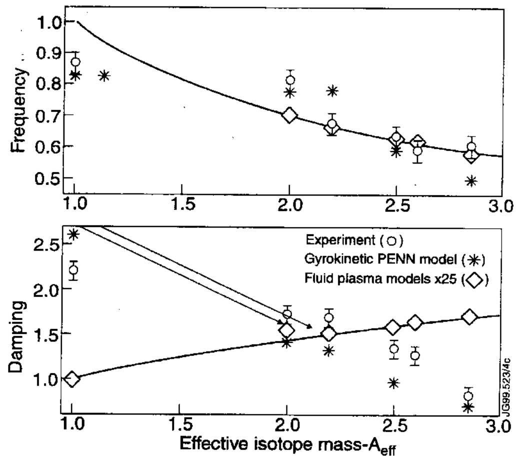
A plausible but complicated theory exists. Rough comparisons exist but detailed confirmation is lacking.

Comparisons in existing tokamaks with accurately measured plasma parameters and well known fast-ion populations are needed. A well-diagnosed burning tokamak experiment is useful.

Estimates for ITER indicate that alpha particles should lengthen the sawtooth period but may drive fishbones unstable.

Little contribution to other concepts.

TAE Physics



The gyrokinetic PENN code matches measured damping rates better than theories based on perturbative MHD.

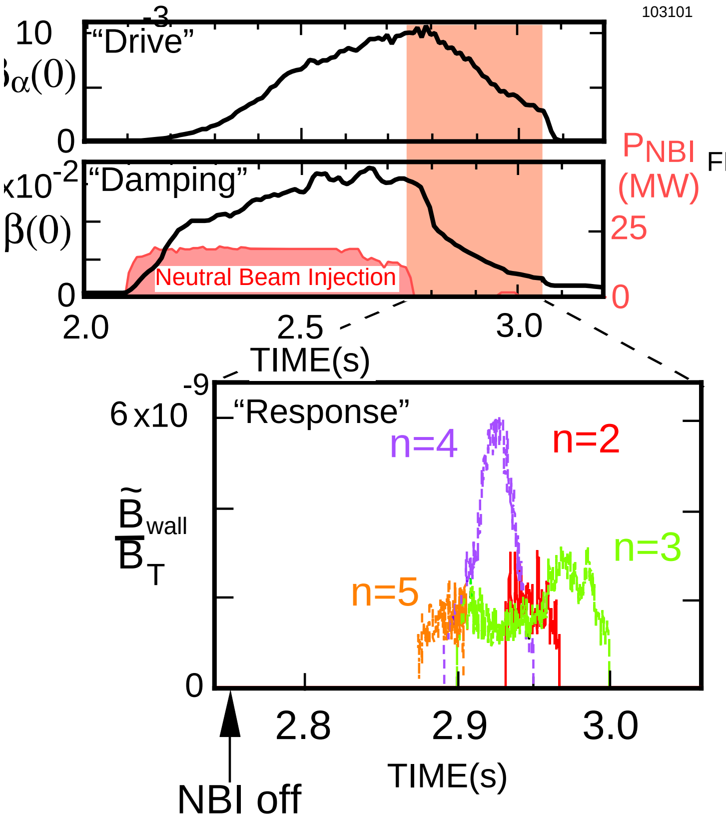
Perturbative MHD does give rough agreement with alpha-driven TAEs in TFTR.

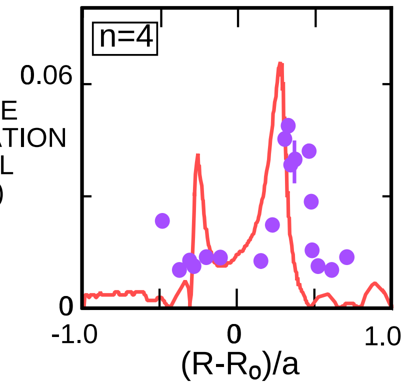
The most unstable toroidal mode scales approximately with RB_T.

Calculated eigenfunctions vary enormously but measurements are inaccurate.

Simplified models explain qualitative features of saturation phenomena but no quantitative comparisons.

Alpha-Driven TAEs Appear After NBI: Beam Damping Dominates in Plasma Core





- Core localization of most unstable alpha driven mode confirmed on TFTR
- Expect core localized modes in a burning plasma

TAE Physics (continued)

Better eigenfunction measurements on existing tokamaks.

Further JET stability studies with accurate q profile.

Since higher n numbers and more unstable modes are anticipated, stability and saturation behavior for a burning tokamak are valuable.

A burning tokamak could be unstable.

The results are relevant to other toroidal concepts.

Transport by Fast-Ion Driven MHD

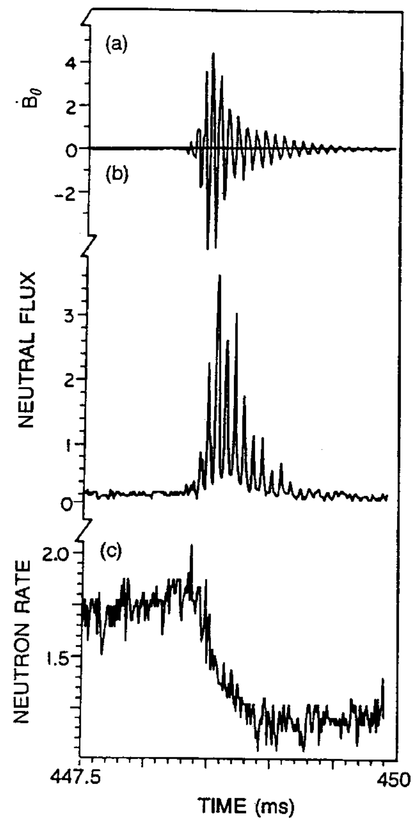
Fishbone transport in PDX well understood.

No detailed comparisons in larger devices.

Transport by Alfven instabilities poorly understood.

Need measurements of the Alfven eigenfunction and fast-ion transport in existing tokamaks. Must also study in a large RB_T device.

Can calculate fishbone transport in a burning tokamak. We do not know what Alfven modes will do.



The results are relevant to the viability of all toroidal reactors.

	Understand?	Small/Existing/Burning			Extrapolate	Other
Source						
Fusion Products	yes				yes	
Beam	yes				yes	
RF	mostly		E		yes	
Velocity						
Coulomb	yes				yes	
RF acceleration	mostly	S	E		yes	
Transport						
Drift orbit	yes				yes	
Ripple	yes	S			yes	
Fluctuations	probably	S			yes	
RF-induced	possibly				yes	
MHD	yes				yes	
Fishbone	yes		E	B	yes	
TAE	not yet		E	B	no	toroidal
Stability						
Sawtooth/Fishbone	probably		E	B	probably	
TAE	somewhat		E	B	maybe	toroidal
EPM	no		E	B	no	toroidal

Notes added on this slide after presentation:

1. The logic of this slide (and indeed the whole talk) is that, if we already understood something after three generations of tokamak experiments and it was subsequently corroborated by the TFTR alpha experiments, then it is already part of the general knowledge base. For these items, the performance of a burning tokamak can be confidently predicted. However, a "fifth-generation" tokamak experiment will contribute little to other confinement concepts in these categories, since the physics is already well understood.

2. Note that it is in areas where we can't confidently predict the outcome that a burning plasma experiment can contribute the most to our knowledge base. A frontier entails risk.