Physics of Superthermal Ions in Tokamak Fusion Test Reactor Plasmas

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Abstract

In magnetically-confined fusion plasmas, superthermal ions with typical energies of tens to hundreds of keV are often used to heat the plasma to temperatures where the fusion reaction rate is significant, ie T_i>5 keV. These ions can originate from the injection of energetic neutral atoms, the application of radiofrequency waves at the ion cyclotron frequencies, or as products of various fusion reactions. For a tokamak plasma, in which the confinement of single particle trajectories is determined by fundamental symmetries of the configuration and conserved dynamical quantities, several distinct categories of trajectories can be identified, which have different confinement properties. Superthermal ions undergo collisions with the bulk plasma particles that can both affect their confinement and eventually cool the energetic ions while heating the plasma. Collectively, a population of superthermal ions can act as a source of free energy to drive electromagnetic instabilities in the plasma. Such instabilities can break the underlying symmetries and increase the rate of deconfinement of superthermal ions and bulk plasma. Typical instabilities are the fishbone and toroidal Alfvén eigenmode. Results from a variety of superthermal ion studies in the Tokamak Fusion Test Reactor (TFTR) will be presented.

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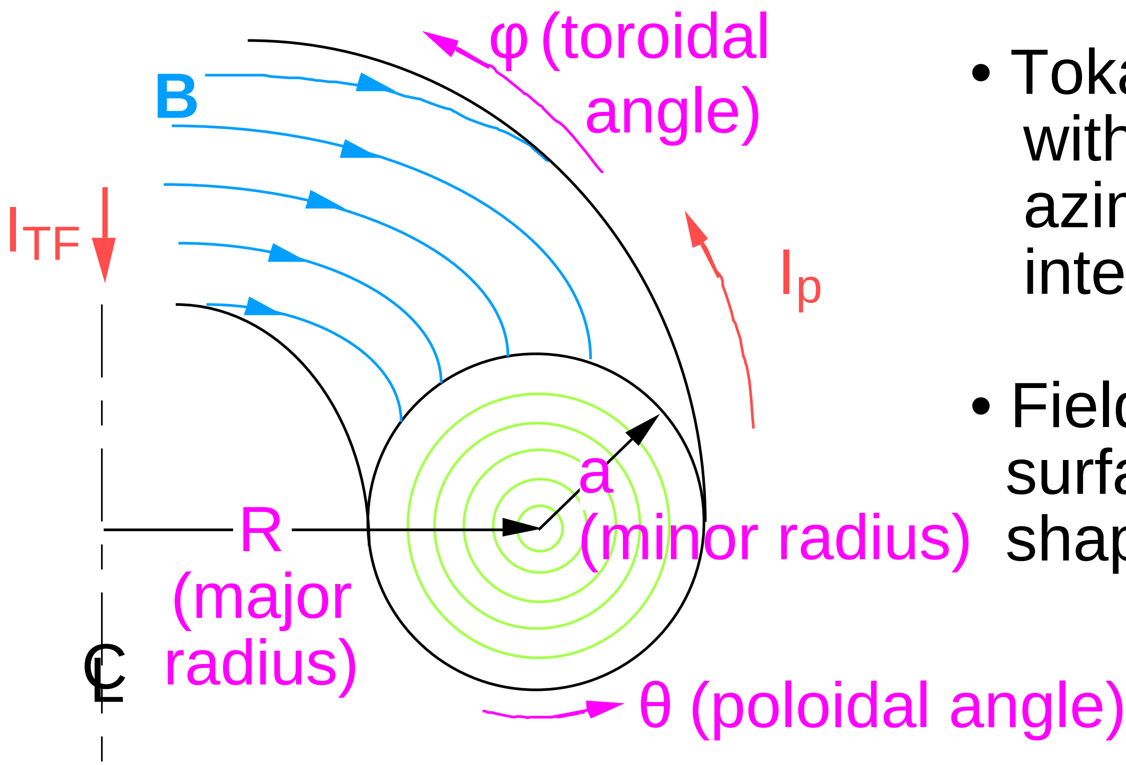
Fusion and the Tokamak

TFTR

- Goal is reactor which can harness the energy of nuclear fusion reactions, e.g. D + T --> ^{4}He (3.5 MeV) + n (14.1 MeV)

- Need high temperature (~2×10^8 °K) to overcome Coulomb repulsion of nuclei==>plasma state

- Magnetic fields can confine reacting plasma



- Tokamak is a toroidal plasma with externally-supplied azimuthal (toroidal) field and internally-supplied poloidal field

- Field lines lie on nested surfaces and are helical in shape

Tokamak Fusion Test Reactor Parameters

TFTR

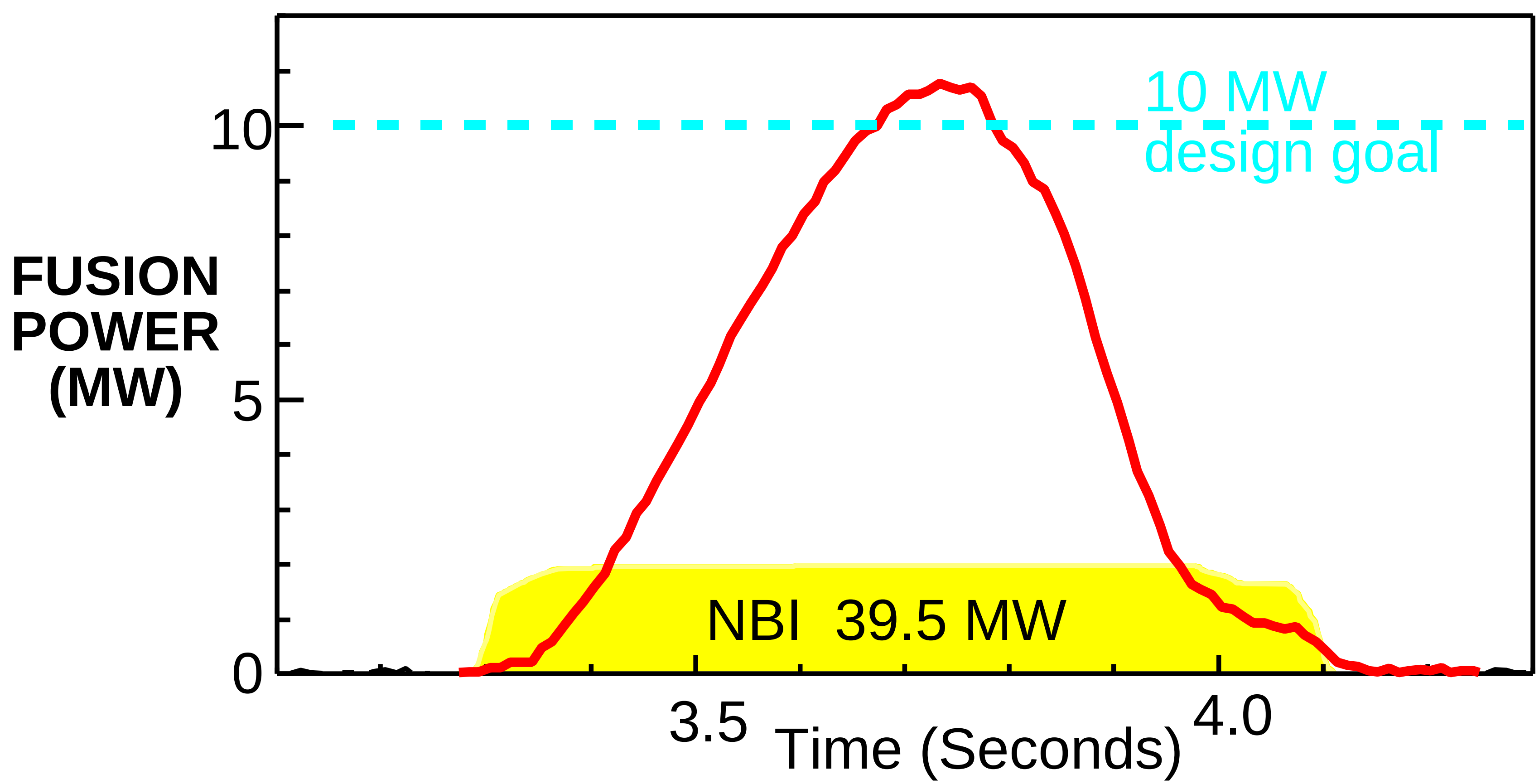
Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory was the largest magnetic confinement fusion experiment in the US. Characteristic plasma parameters are below

Major radius (R)	2.6 m
Minor radius (a)	1.0 m
Magnetic field (B)	≤5.6 T
Plasma current (I_p)	≤3 MA
Electron temperature (T_e)	1–12 keV
Ion temperature (T_i)	1–45 keV
Electron density (n_e)	$0.1–5\times10^{20}$ m^{-3}
Neutral beam power (P_{NB})	≤40 MW
Ion cyclotron heating (P_{RF})	≤10 MW
Fusion power (P_{fus})	≤10 MW

TFTR began operation in December 1982 and ceased in April 1997

TFTR achieved a maximum of 10.7 MW of fusion power from DT fusion reactions

TFTR



I_p =	2.7 MA	W_{TOT} =	6.9 MJ	$n_e(0)$ =	$1.0 \times 10^{20} m^{-3}$
B_T =	5.6 T	τ_E =	0.21 sec	$T_e(0)$ =	13.5 keV
		Q =	0.27	$T_i(0)$ =	32 keV

- The Joint European Torus in England achieved 16 MW in 1997

Heating fusion plasmas produces or involves fast ions

TFTR

- Optimal temperature for fusion reactions is ~20 keV

- Ohmic heating from plasma current insufficient to reach 20 keV

- Auxiliary heating methods often involve or create superthermal ions:

  - Neutral beam injection (NBI): acceleration of ions which are then neutralized and cross **B** to enter plasma (100 keV D in TFTR)

  - Ion Cyclotron Range of Frequencies (ICRF) Heating: launching of waves near the ion cyclotron frequency into plasma to heat ions; often produces a “tail” of superthermal ions (up to ~1 MeV in TFTR)

  - Fusion products: DT fusion reactions produce 3.5 MeV alpha particles which can collisionally heat the plasma

Principal physics issue: how well are fast ions confined?

TFTR

- The main physics issues for fast ions in tokamaks are:

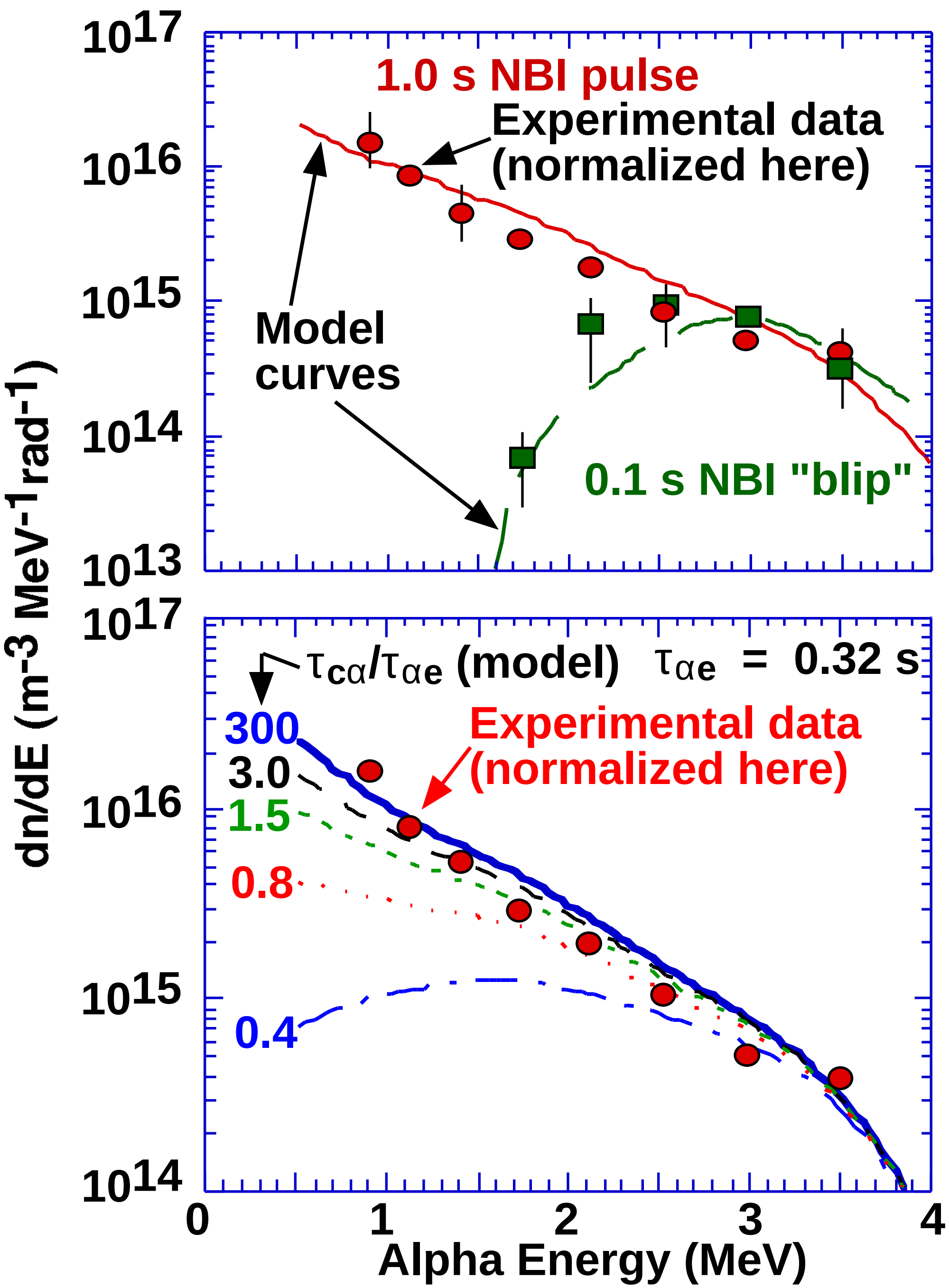
  - How well are they confined?
  - How well to fast ions transfer their energy to the plasma?

- Associated questions include:

  - Is the classical (Coulomb) collisional model correct?
  - What do fast ion orbits look like?
  - What is the irreducible level of fast ion loss?
  - What processes cause fast ions to be lost?
  - What level of wall heating is produced by lost fast ions?
  - How strong is radial diffusion of fast ions?
  - How do magnetic fluctuations and turbulence affect fast ion confinement?
  - Can fast ions drive instabilities that will affect fast ion confinement?

Alpha particle slowing down appears classical

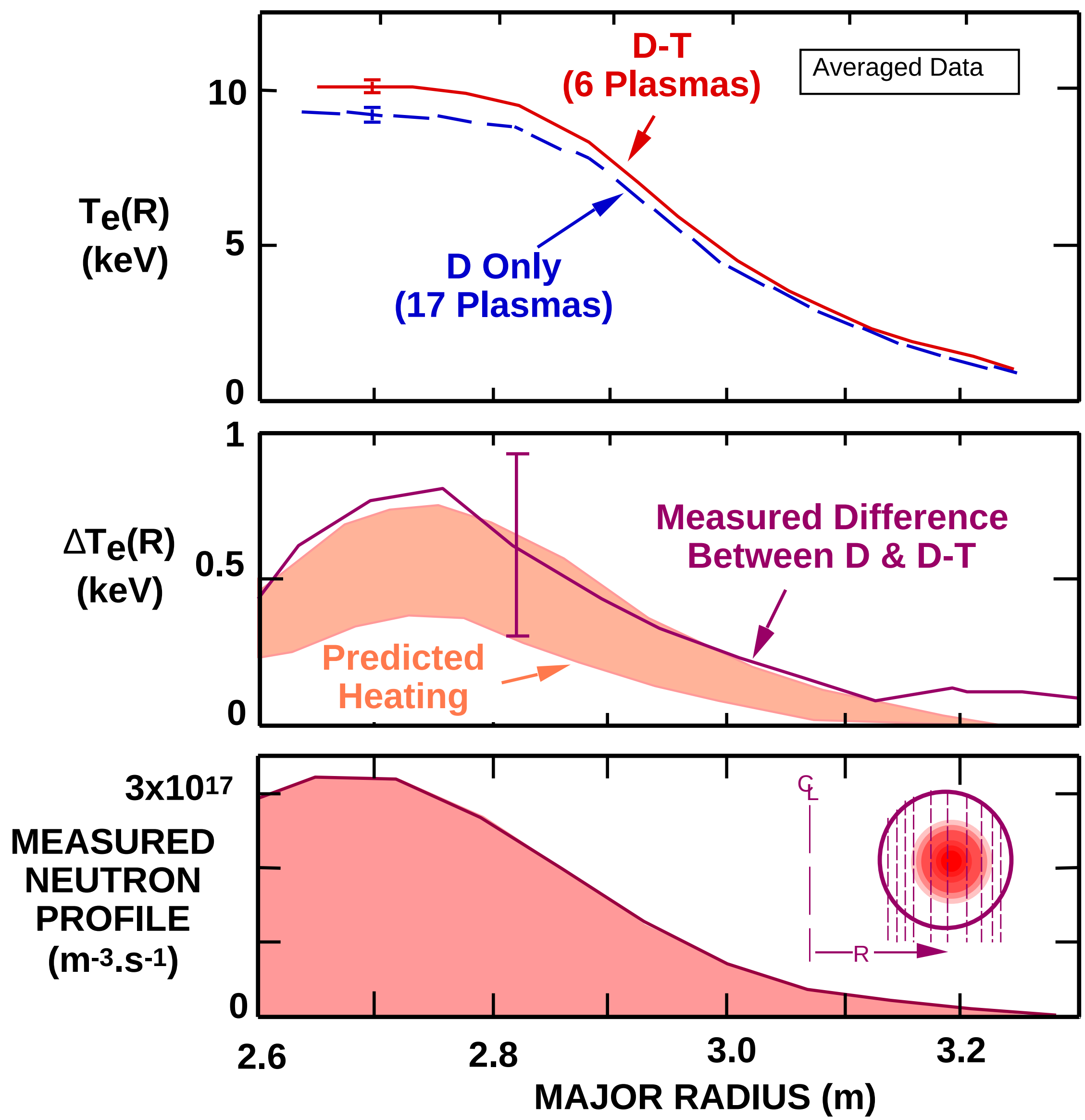
TFTR



- Measured alpha energy distributions match results from model which includes only collisional slowing down on electrons
- Match is good for both $t<\tau_{\alpha e}$ and $t>\tau_{\alpha e}$
- If additional radial diffusive loss of alphas is included in model, diffusion time scale must be several to many times alpha slowing down time to match experimental data

Change in temperature profile with T consistent with classical alpha particle heating of electrons

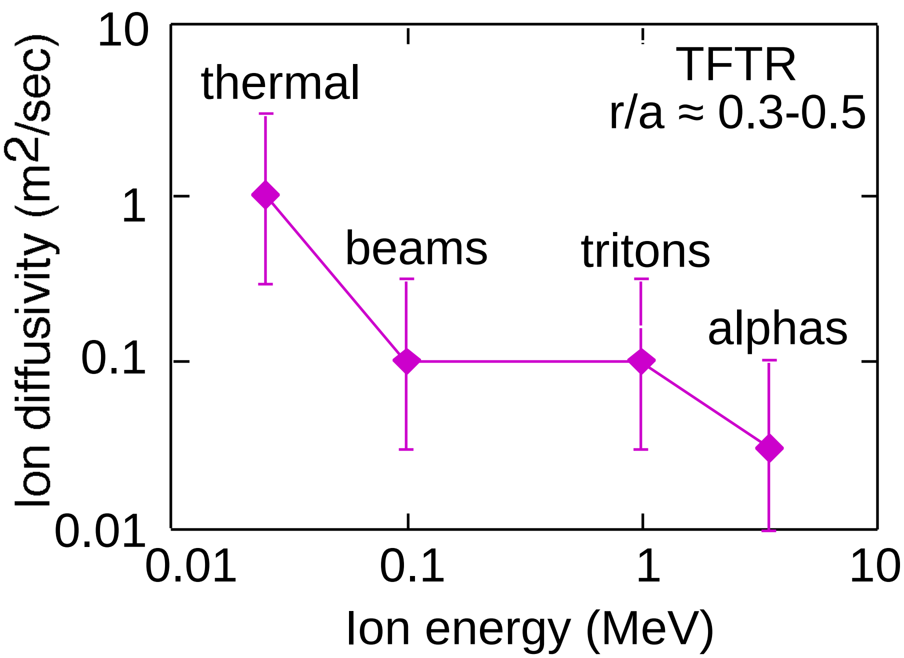
TFTR



- Compare identical plasmas with and without tritium (T)
- Alpha particles from fusion reactions will give most of energy to electrons as they slow down
- Higher T_e consistently seen in DT plasmas; magnitude and profile match classical model
- Neutron profile = alpha birth profile

Under quiescent conditions, rates of fast ion radial diffusion are low compared to bulk plasma

TFTR

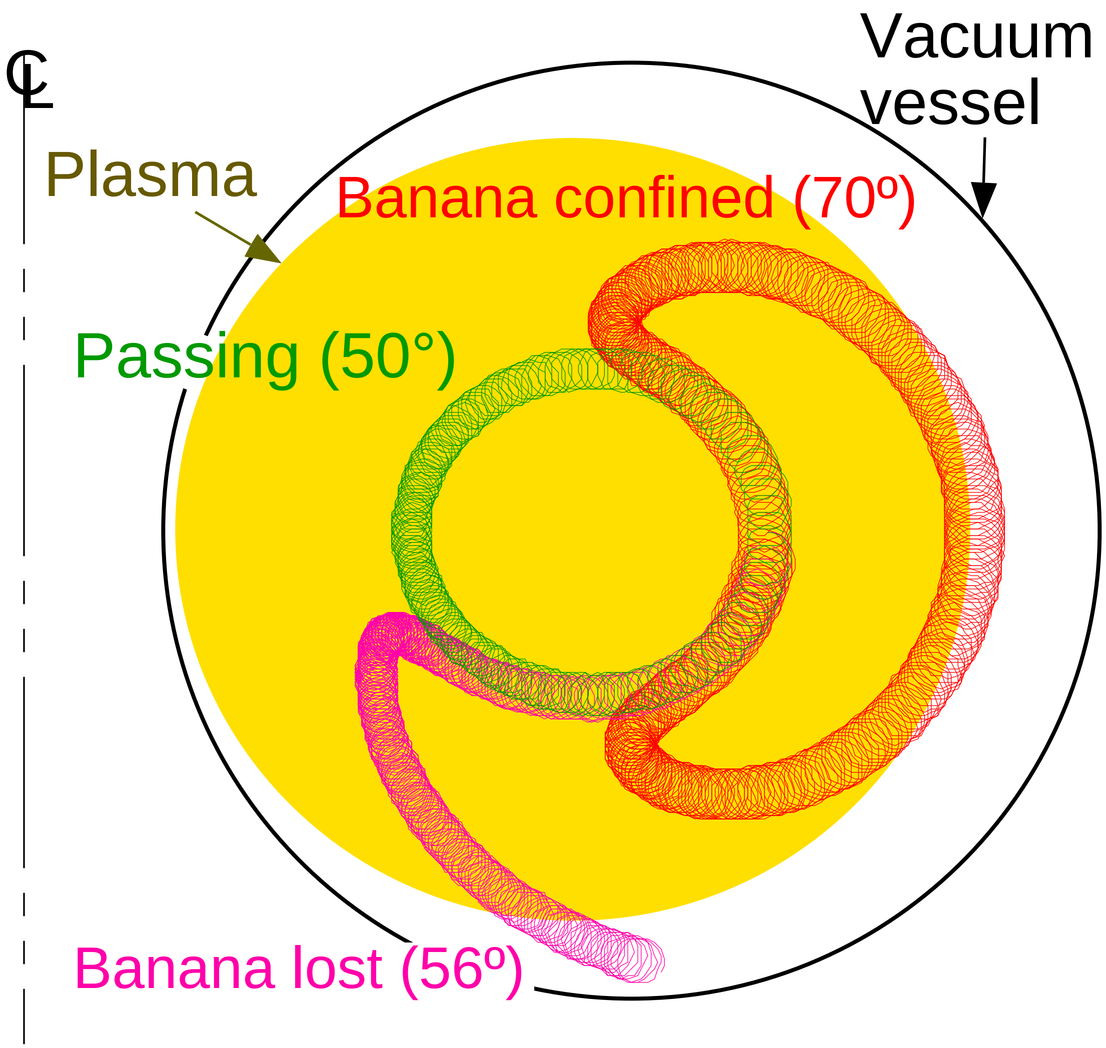


- Ion radial diffusivity can affect heating efficiency
- Radial diffusivity also affects heat load on wall
- Fast ion diffusivities have been measured with several methods:
  - loss measurements at wall (α)
  - neutron radial profile (NBI)
  - 14 MeV neutron production (T)

- Radial diffusion rates are found to be 10 to 100 times slower than for thermal ions, and small enough that plasma heating will be effective and wall heat loads manageable

Alpha orbit geometry determines loss rate and defines “first orbit loss”

TFTR



Alpha Orbits at Various Pitch Angles
(I_p=2.5 MA)

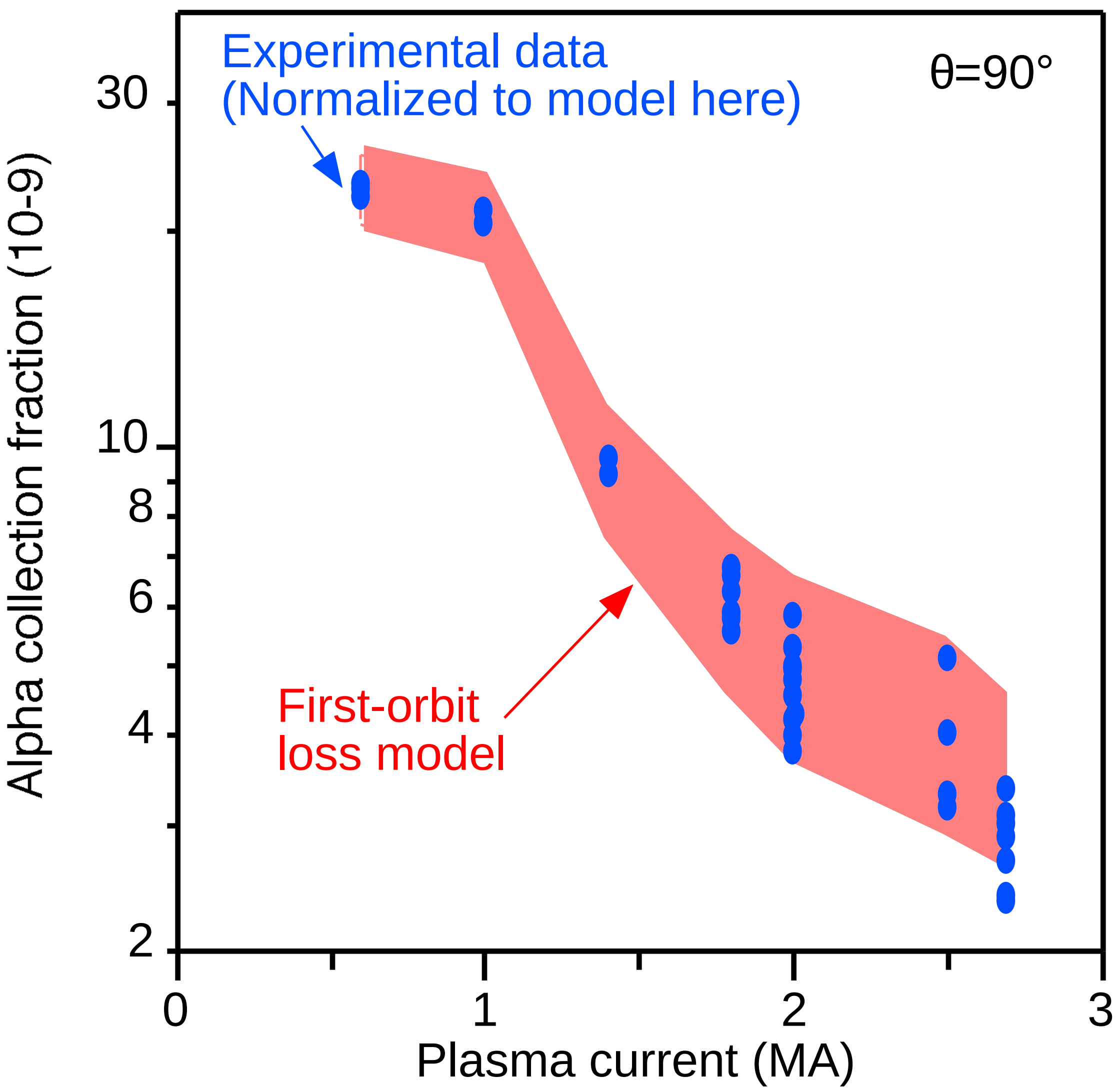
- Alpha orbit shape in tokamak B-field depends upon pitch angle, χ:

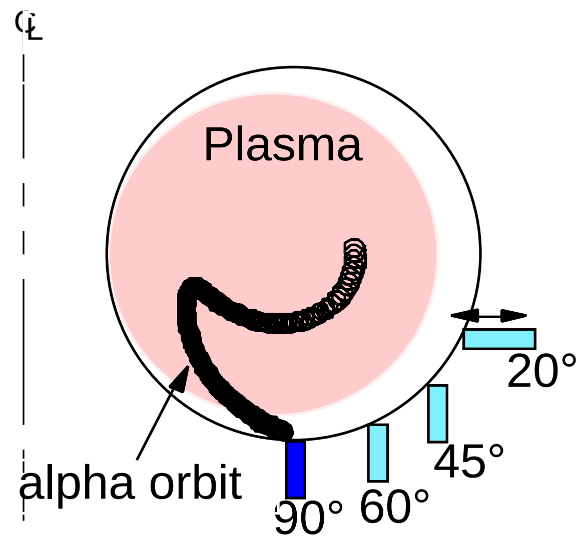
  χ = arccos(**v•B**/|**v**||**B**|)

- 2 classes of orbits: passing & banana
- Some banana orbits strike wall: “first orbit loss”
- Alphas born isotropically in χ

Alpha flux at detector on wall is consistent with classical first orbit loss

TFTR



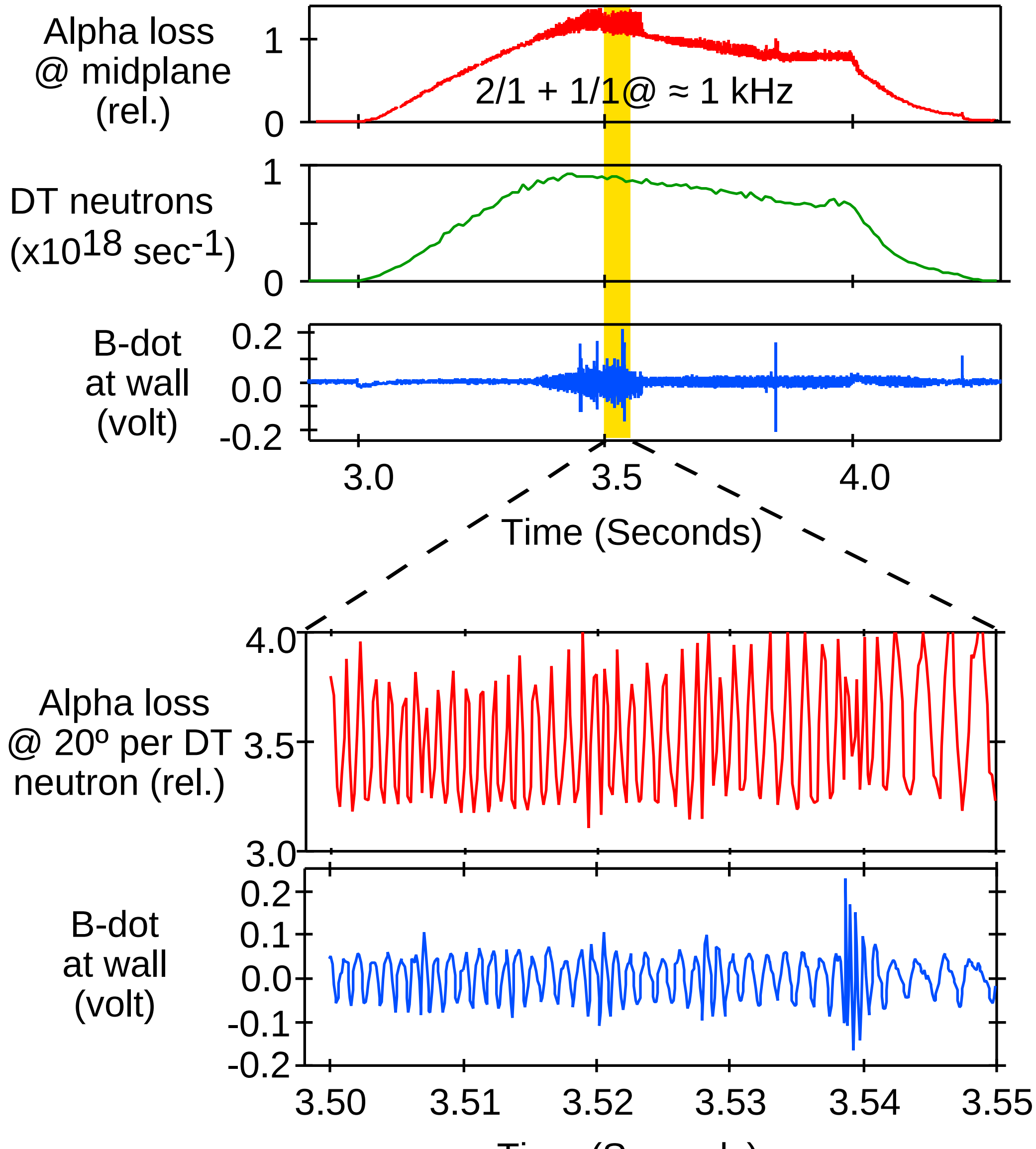


- Loss results from fat banana orbits which strike wall
- Calculated global first orbit loss: ~3% at 2.5 MA in TFTR

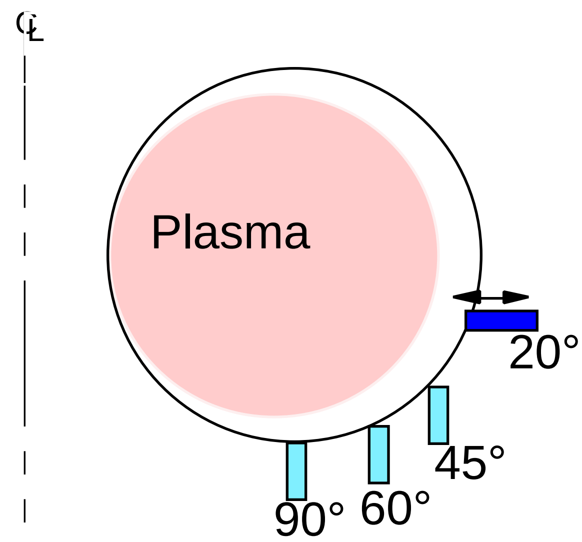
S. J. Zweben, *et al.*, *Nucl. Fusion* **35**, 893 (1995)

Magnetohydrodynamic (MHD) instabilities can augment alpha loss rate

TFTR



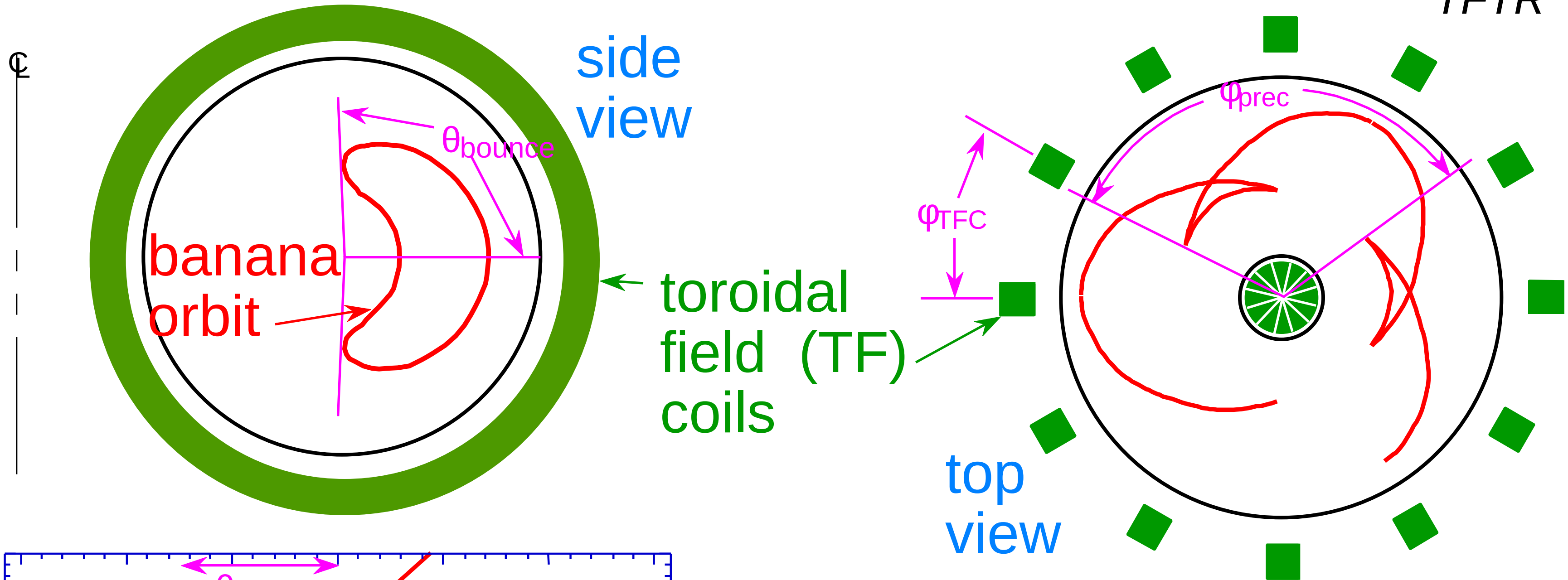
#86289, I=1.5 MA, B=4.9 T, R=2.45 m, P=16 MW

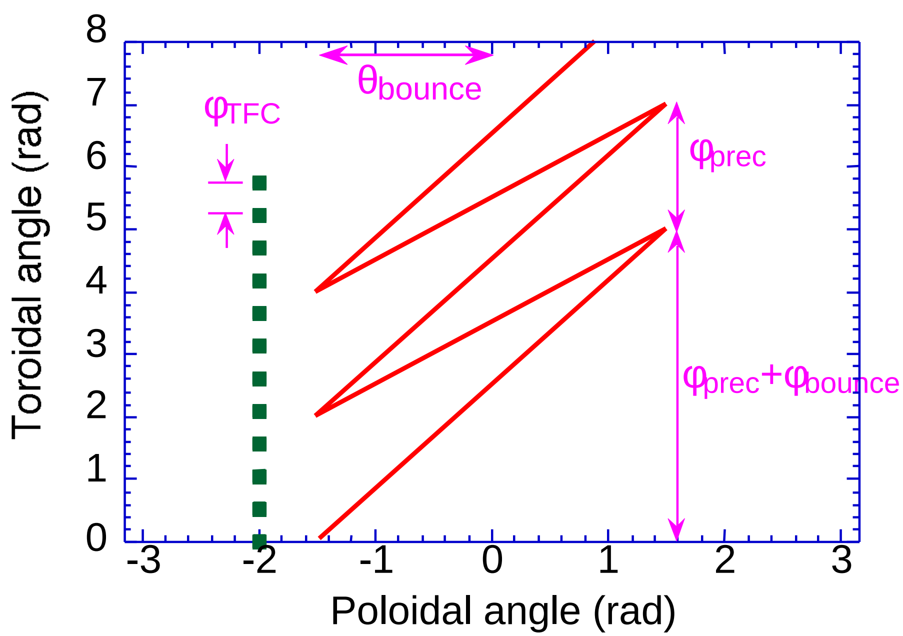


- MHD instabilities, driven by pressure or current, cause magnetic perturbations that can expel alpha particles
- Scaled to a reactor-sized plasma, such losses will be small

Stochastic toroidal field ripple diffusion (SRD) arises from discreteness of toroidal field coils

TFTR





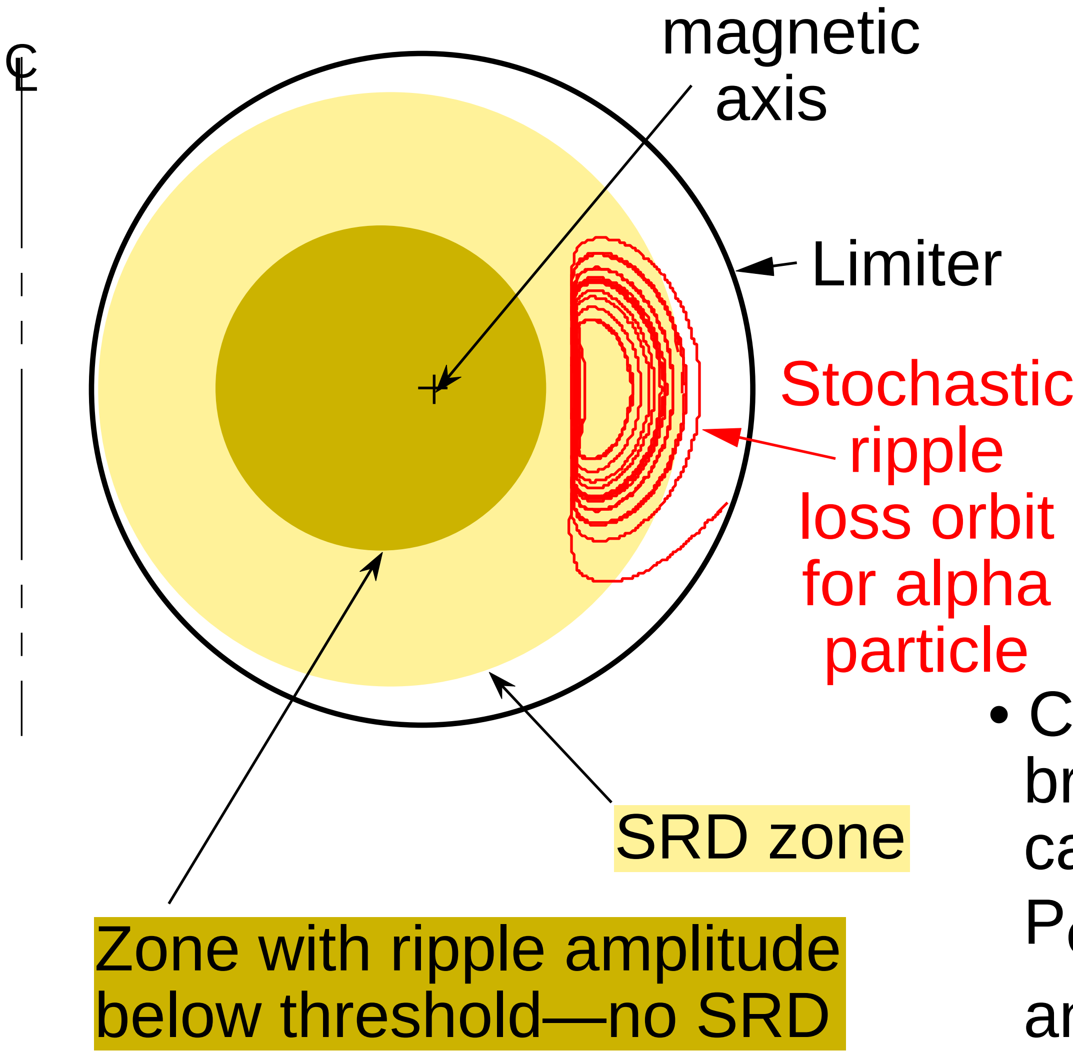
- SRD affects only banana orbits; is due to discreteness of TF coils
- Stochasticity arises when resonance occurs:

$$n\,\varphi_{TFC} = m\,\varphi_{prec}$$

n & m integers; φ_{prec} depends on pitch angle and energy of ion, and on plasma magnetic structure

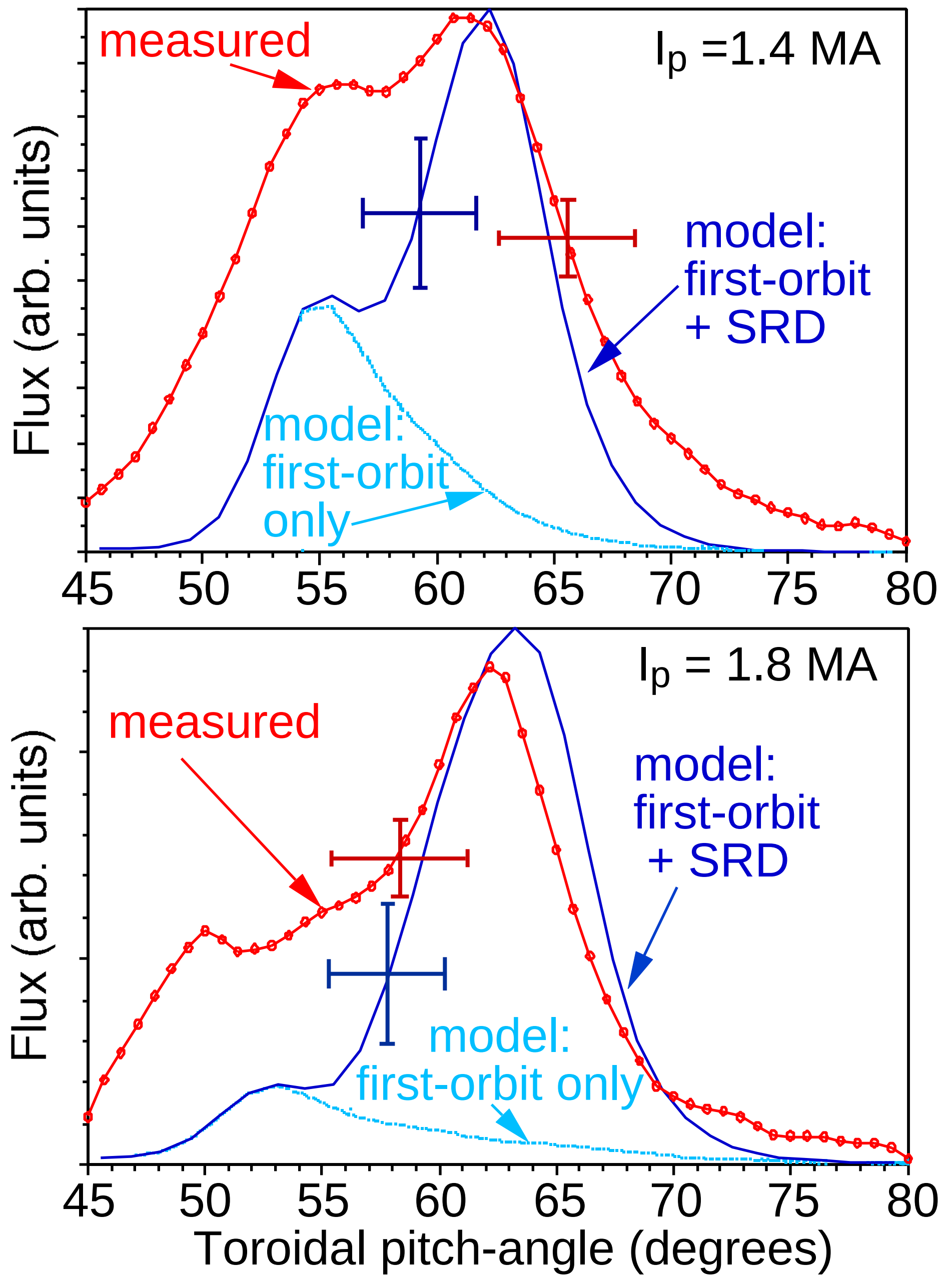
SRD can cause fast ion radial diffusion and loss

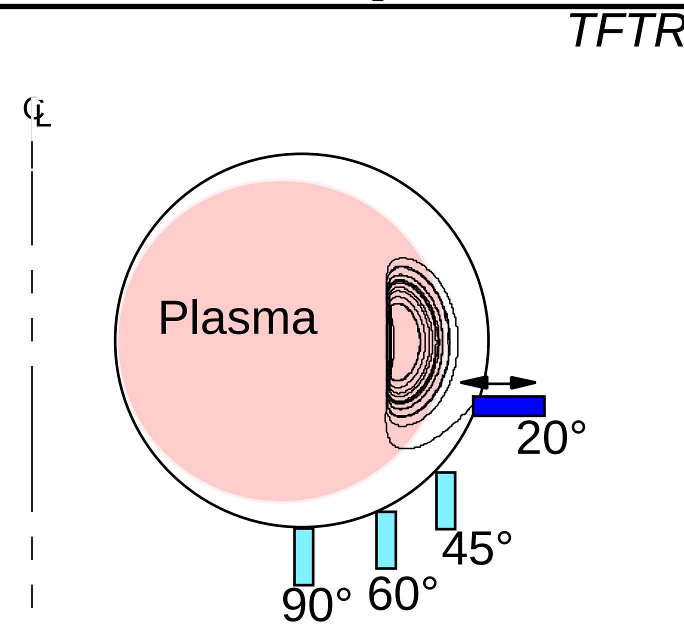
TFTR



- Ripple amplitude must exceed a threshold before SRD occurs
- Threshold for alphas in TFTR typically exceeded in outer half of plasma
- Presence of ripple breaks azimuthal symmetry
- Consequence of symmetry breaking is that toroidal canonical angular momentum, $P_\varphi = m_i \varphi R + q_i A_\varphi$, is no longer an invariant of the motion, so radial diffusion of the orbit can occur

SRD model matches observed lost fast ion characteristics near TFTR midplane

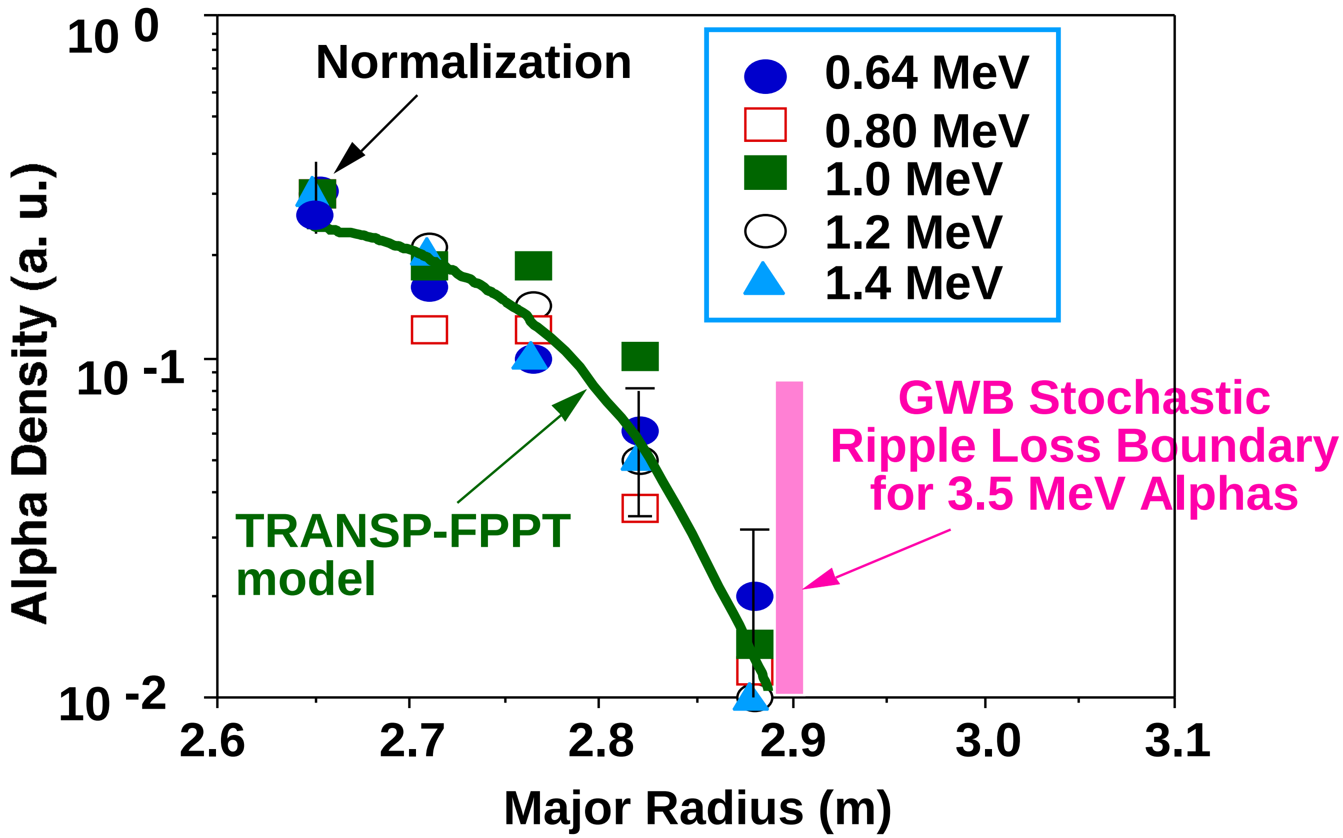




- Computational orbit-following model including SRD demonstrates same peak pitch angle, scaling with Ip, and loss rate relative to first orbit loss as seen in measured flux

Confined alpha density profiles show SRD effect

TFTR

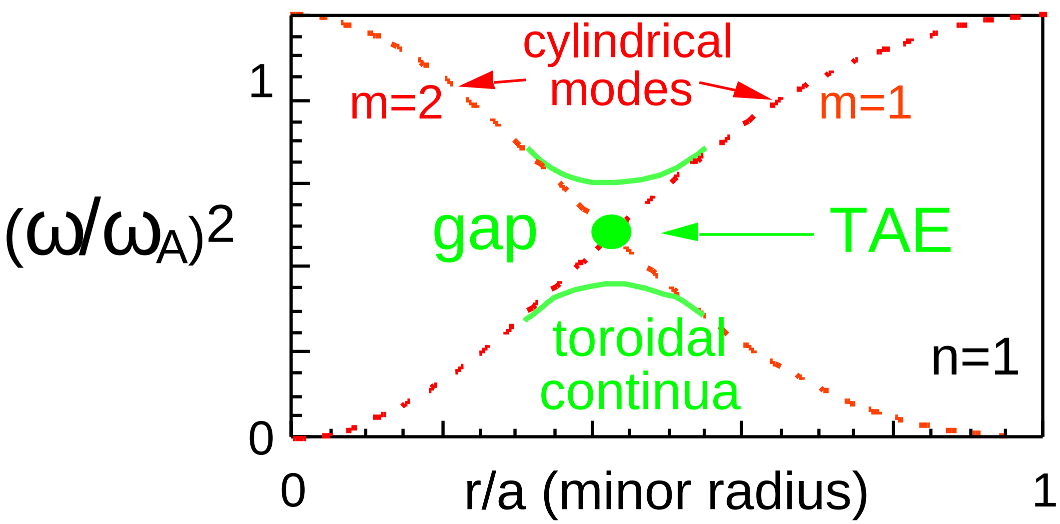


- Measured trapped alpha density profile does not extend to edge of plasma, but vanishes at stochastic ripple diffusion boundary for 3.5 MeV alphas
- Profile of subsequent slowed-down alphas matches model with SRD only and no additional radial diffusion
- Measurements from Pellet Charge Exchange diagnostic

Toroidicity-induced Alfvén eigenmodes (TAEs): What are they?

TFTR

- TAEs are shear Alfvén waves in a torus, where toroidicity couples modes (standing waves) with poloidal mode numbers *m* and *m+1* to form "gaps" in the spectrum



<u>Shear Alfvén waves:</u>

$\omega_A^2 = k_{||}^2 V_A^2$

$V_A = B/\sqrt{4\pi\rho} \approx V_\alpha$

$k_{||} = (m-nq)/Rq$

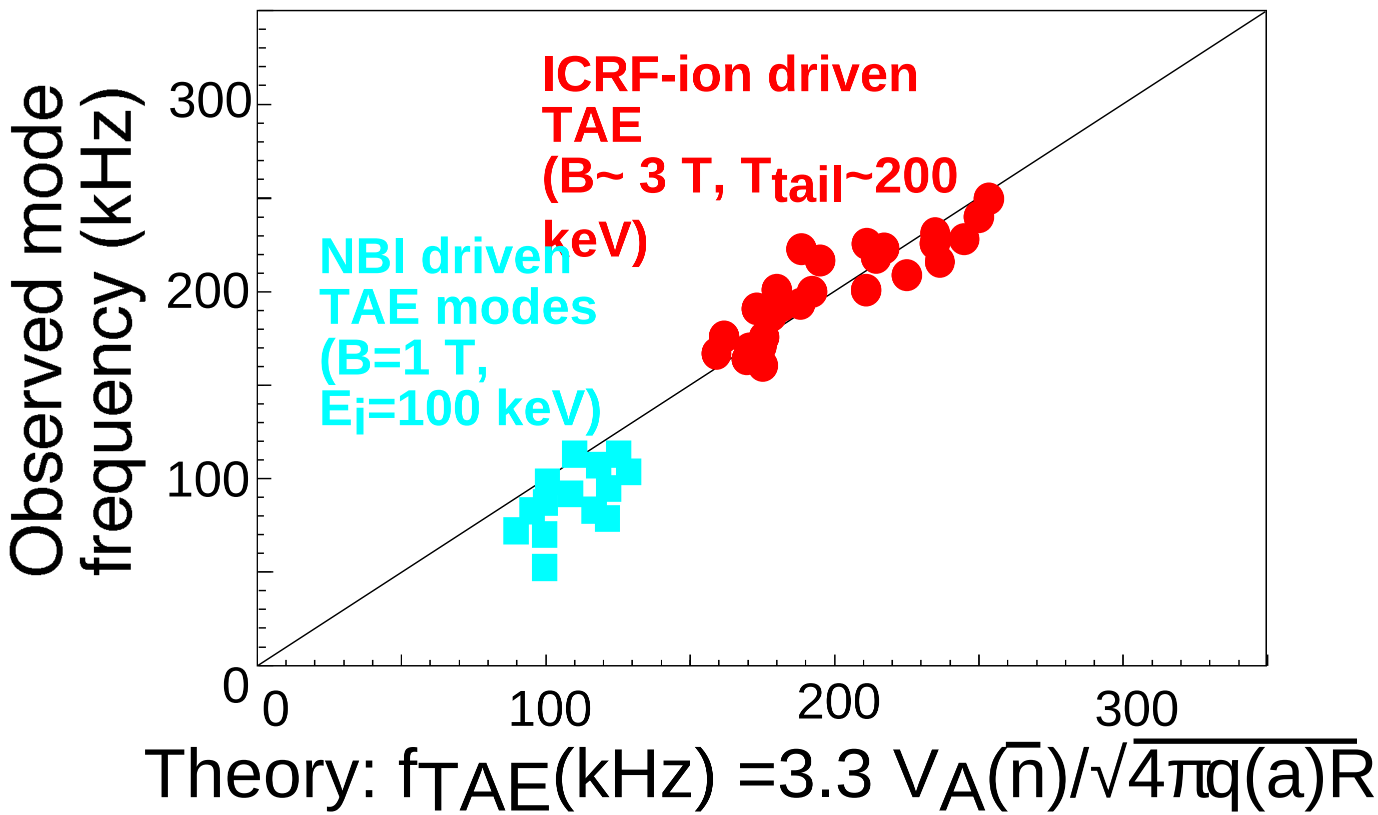
n = toroidal mode number

- Energetic ions, including alpha particles, can resonate with the TAEs inside the gap in the toroidal shear Alfvén spectrum, driving them unstable
- Gap modes are weakly damped - main damping processes are <u>radiative</u>, plus beam and thermal ion Landau damping

Frequencies of observed magnetic fluctuations match those expected for TAEs

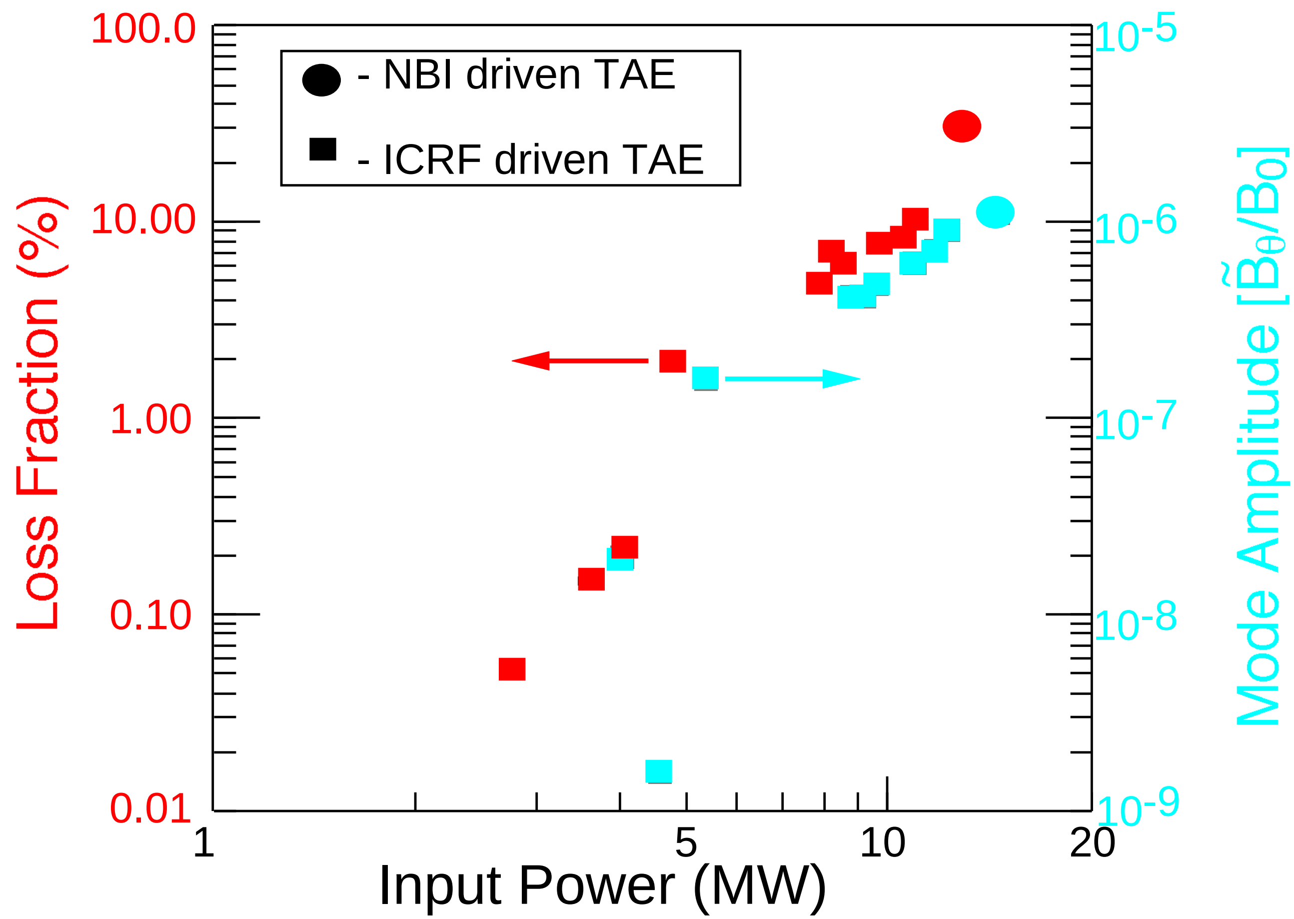
TFTR

- Certain fluctuations observed by magnetic pickup coils near plasma only when NB or ICRF ions are present above a threshold power level
- Observed mode frequencies are good matches to theoretical TAE frequency scaling, implying these are TAEs



TAE modes driven by neutral beam or ICRF tail fast ions cause substantial fast ion losses

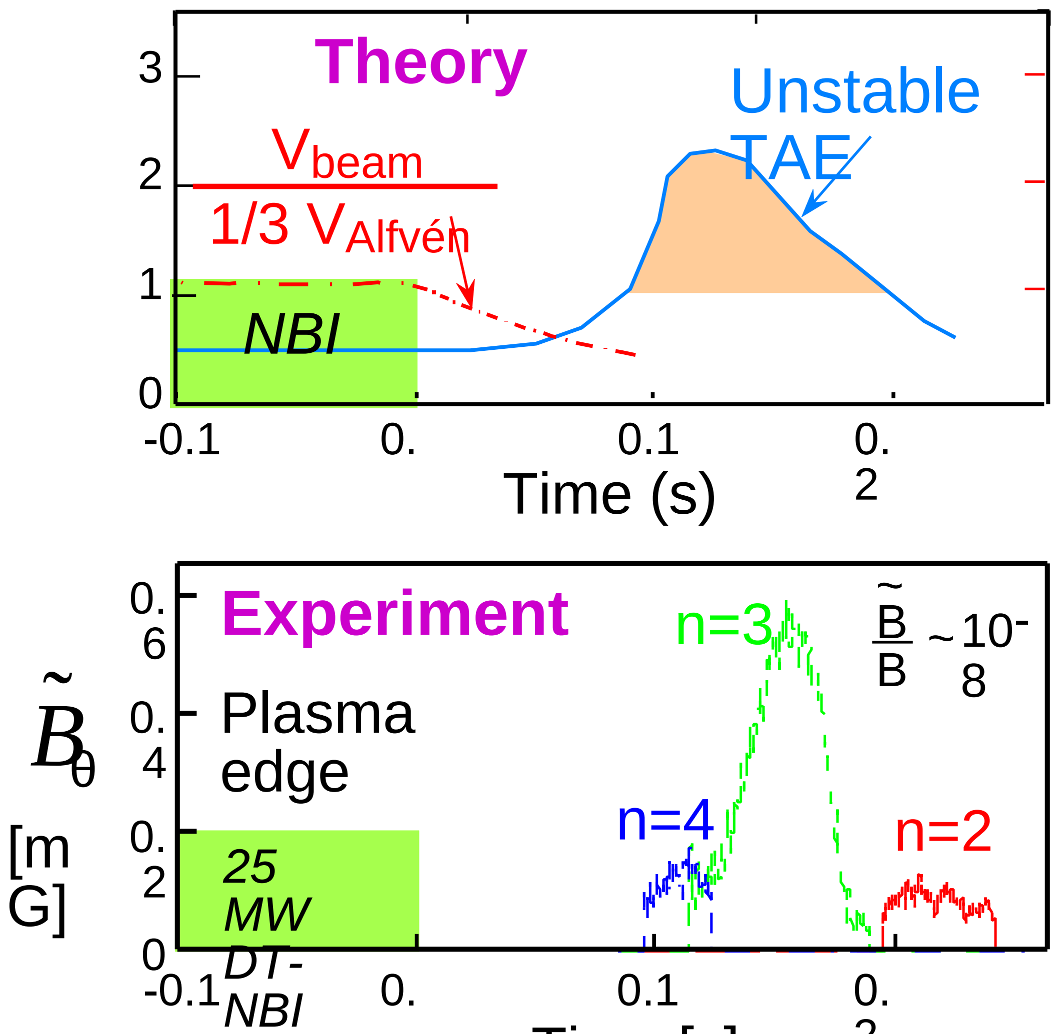
TFTR



- Minimum input power ~2.8 MW required to excite TAE in TFTR
- Alpha loss fractions >5% in a reactor are unacceptable

TAE driven by alpha particles matches theoretical prediction

TFTR

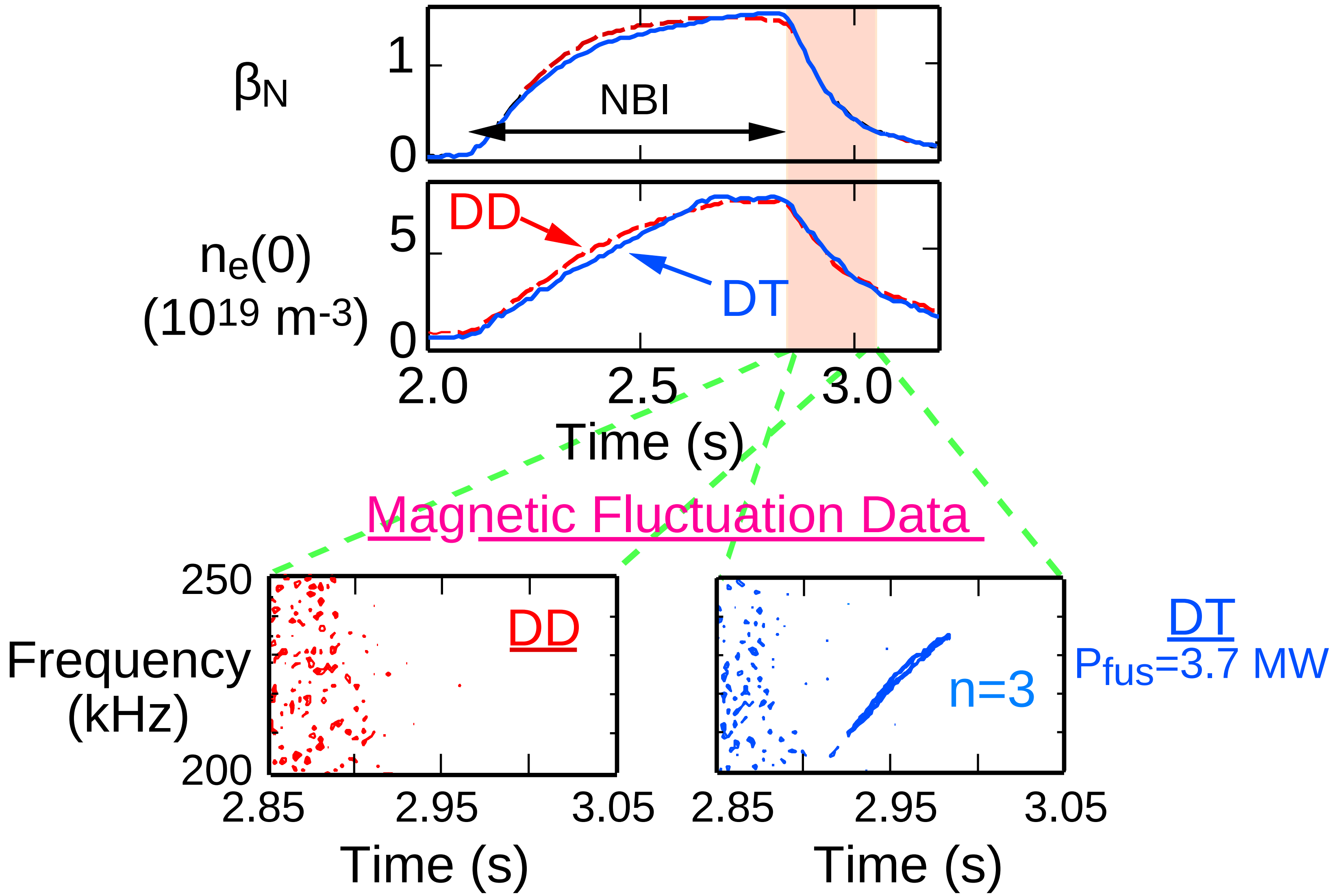


- Alpha-driven TAE occurs under select conditions in TFTR
- Conditions for mode occurence and time history closely match numerical model results

- Alpha particle pressure too small to drive TAEs in TFTR except under specially-tailored conditions with low magnetic shear

TAEs in DT plasma are clearly driven by alphas, not other fast ions

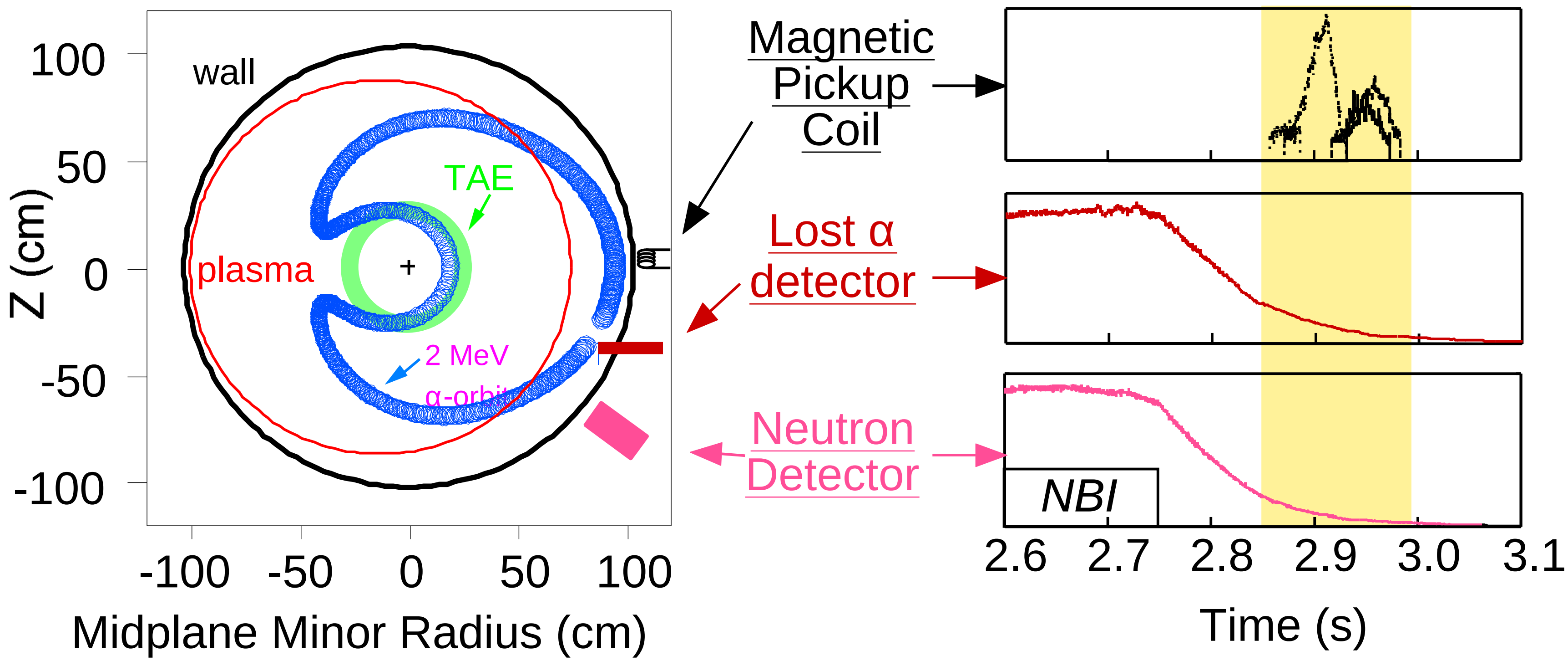
TFTR



• Modes do not appear in identical DD plasmas (no alpha particles)

No Observed Increase in Alpha Loss During TAE

TFTR



- 2 MeV trapped alphas intersect mode location and alpha probe
- Loss expected near banana-passing boundary

- TAE studies on TFTR have allowed benchmarking of theoretical models of TAE and resultant fast ion losses. Recent modeling results indicate reactor losses will be small

Summary

TFTR

- A program of experiments on TFTR has tested the quality of alpha particle confinement in a tokamak reactor using both surrogate fast ions and actual DT alpha particles
- In general, the confinement of alpha particles was found to be classical:
  - alphas slow down classically on electrons
  - alpha radial diffusion is small
  - first orbit and SRD models match observed loss patterns reasonably
- TAEs were studied extensively in TFTR and evidence from the experiments has substantially aided reactor modeling
- TAE-induced alpha particle losses in a reactor-scale tokamak will be small
- Consequently, tokamak fusion reactor designs can confidently be based upon readily calculable alpha heating densities and loss distributions