Experimental observations of MHD-induced EP transport and loss
(*e.g.*, AE, 3D-fields, ripple, NTMs...)

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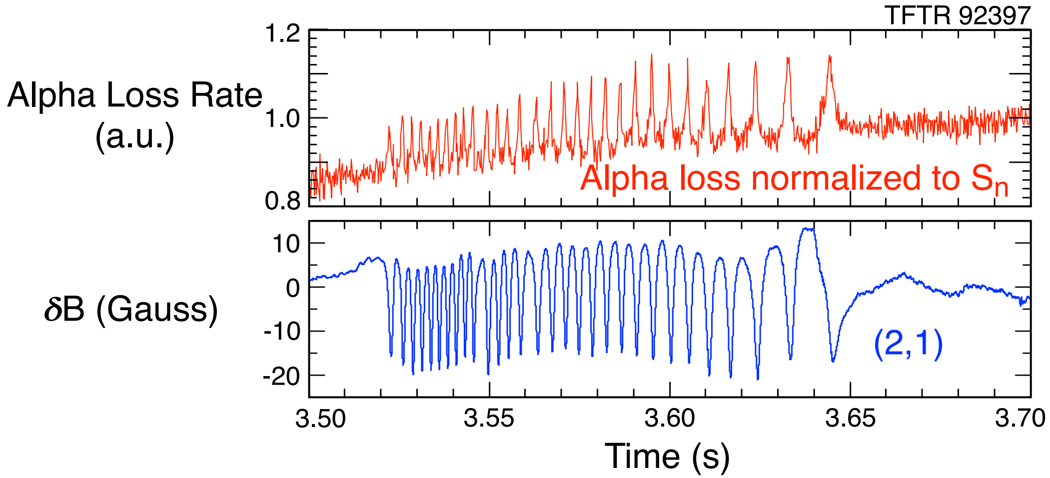
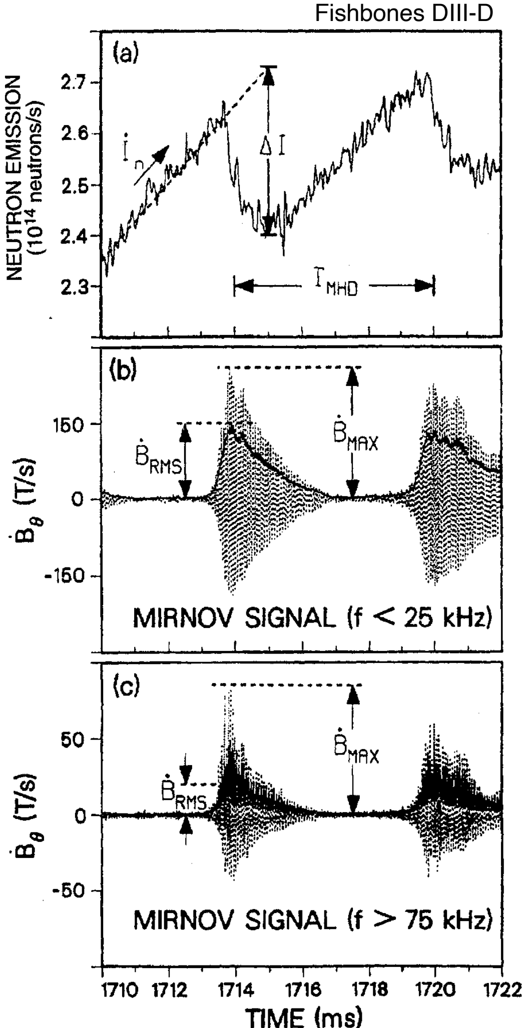




Good confinement of α's needed for ITER success

- Confinement in the idealized machine is good, but there are many sources of symmetry breaking perturbations.
- Non-resonant sources:
  - Ripple, error fields,
  - Kink modes, tearing modes, locked modes,
- Fast reconnection events:
  - sawteeth, ELMs, disruptions.
- Resonant sources (energetic particle and Alfvénic modes):
  - Fishbones, kinetic ballooning modes
  - BAAE, BAE (beta-induced)
  - TAE, rsAE (Toroidal and reverse shear Alfvén Eigenmodes - shear)
  - GAE (Global Alfvén Eigenmodes – shear)
  - CAE (Compressional Alfvén Eigenmodes – compressional)
  - ICE (Ion-cyclotron emission – no experimental evidence for losses, possible diagnostic)
  - Wave-induced (ICRF resonances) losses

Difficult for smaller tokamaks to match all of ITER's relevant dimensionless numbers

- JET and TFTR came close to some of the α parameters,
  - JT-60U never ran D-T plasmas.
- In many tokamaks the beam-ions have similar parameters to the fusion-α's in ITER
  - but different distribution
- Predictions for ITER fast-ion losses depend on accurate modeling (and extrapolation).

Parameter	TFTR	JET	ITER
P_{fus} (MW)	10.6	16.1	1500
$P_\alpha(0)$ (MW/m^3)	0.3	0.1	0.3
τ_α (s)	0.4	0.7	1.0
a/ρ_α	20	14	70
$n_\alpha(0)/n_e(0)$ (%)	0.3	0.4	0.3
$\beta_\alpha(0)$ (%)	0.3	0.62	0.7
$\langle\beta_\alpha\rangle$	0.04	0.11	0.2
$R\nabla\beta_\alpha$	0.02	0.03	0.06
$V_\alpha/V_A(0)$	1.7	1.6	1.9

Zweben, Nucl. Fusion 2000 – TFTR tokamak

Experimental studies of fast-ion transport typically need modeling to fill in the "gaps"

- Diagnostics only measure limited moments of fast-ion distribution:
  - Full spatial distribution, pitch angles and energies of lost fast-ions not measured.
  - Likewise it's not possible to fully characterize the confined fast-ion population.
- Experimental studies typically don't provide a full description of modes:
  - Mode laboratory frequencies well known, but interpretation with sheared rotation needs modeling.
  - For some modes the radial structure can be measured, but typically not the poloidal structure (or toroidal structure).
- Understanding the damping and resonant drive also requires precise data on the equilibrium plasma, which is often incomplete.
- By collecting as many pieces of information as possible, it is possible to test various theoretical models of mode stability and fast-ion transport.

So far, so good – no major issues identified

- Numbers on right are enhancement over first-orbit losses – negligible at full field.
- TAE/fishbones typically more of an issue in smaller tokamaks with low toroidal field, low current.
- However, TAE not a problem in high-field TFTR plasmas as beam-ion velocity << V_{Alfven}.
- If ITER has tearing modes, ELMs or disruptions, it has more serious problems than fast-ion losses.

Table 7. Types of MHD– and RF–alpha interactions in TFTR

Interaction	Frequency range (kHz)	Relative alpha loss[a]
Locked modes	$\ll 0.1$	2
Tearing modes	0.1	3
ELMs [69]	1	2
Fishbones [67]	10	0.5
Disruptions [8, 68]	10	100–1000
Sawtooth [67, 72, 91, 102]	100	10
BAE [131]	100	n.o.[b]
KBM [71, 176]	100	2
TAE [138]	100	n.o.[b]
AFM [71]	100	0
IBW [173]	10^5	n.o.[b]
ICRF [148]	10^5	2
ICE [151]	$>10^5$	n.o.[b]

[a] Maximum alpha loss in the scintillator detectors during these phenomena, normalized to alpha loss without these phenomena.
[b] n.o. means not observed on TFTR DT discharges.

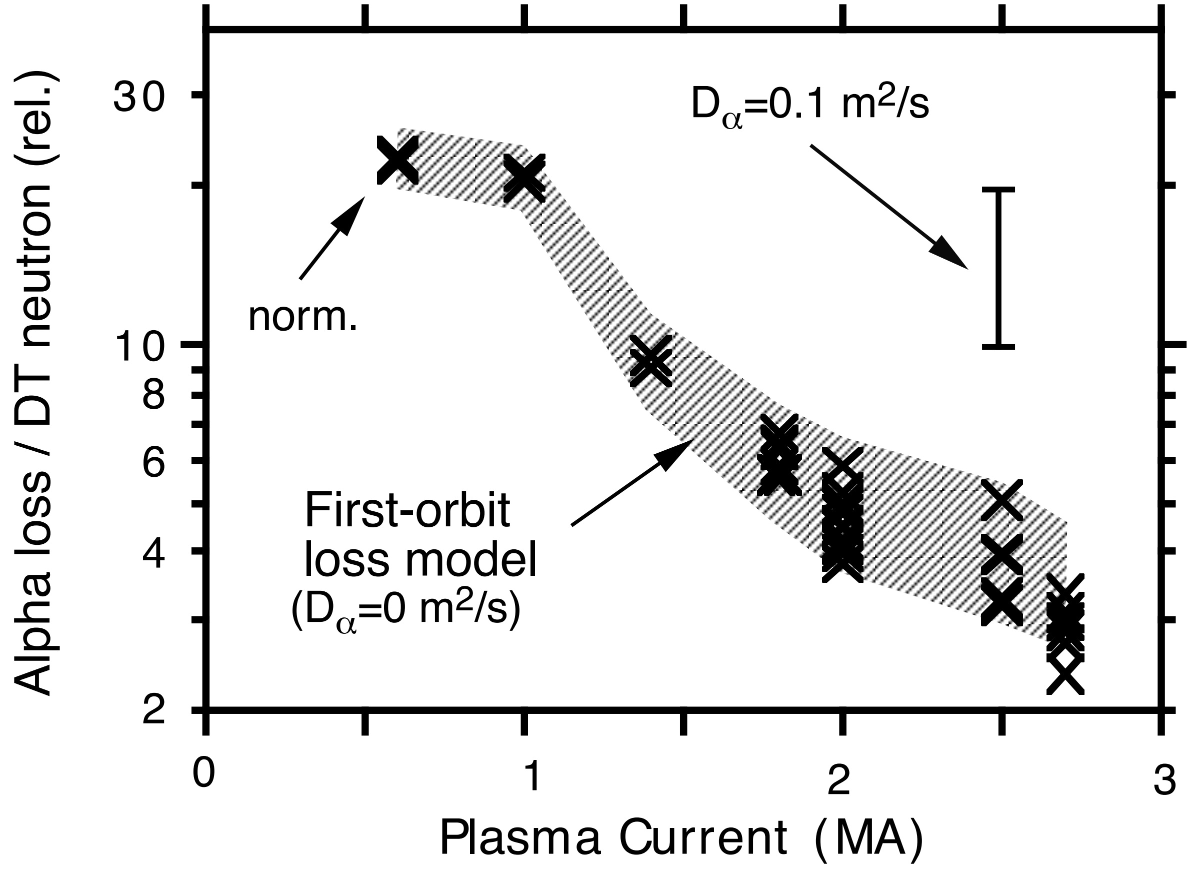
Note: BAE, β-induced Alfvén eigenmode; KBM, kinetic ballooning mode; TAE, toroidal Alfvèn eigenmode; AFM, Alfvén frequency mode; IBW, ion Bernstein wave; ICE, ion cyclotron emission.

Zweben, Nucl. Fusion 2000 – TFTR tokamak

Ripple/1st Orbit loss

Losses decrease at higher current

- Alpha loss measured at the scintillator detector located 90º below the outer midplanel
- Model is of first-orbit losses of fusion-generated alphas (without diffusion).
- Measurement at -90º will miss most of the stochastic ripple diffusion losses.
- Losses are normalized to the data at I = 0.6 MA where-orbit losses are assumed to dominate.
- The vertical bar at I = 2.5 MA represents the calculated alpha loss for $D_\alpha = 0.1\ m^2/s$;
  - implies the radial diffusion for alphas near the plasma centre was considerably less than this.
- The vertical axis also represents the approximate percentage global alpha loss calculated for each plasma current.



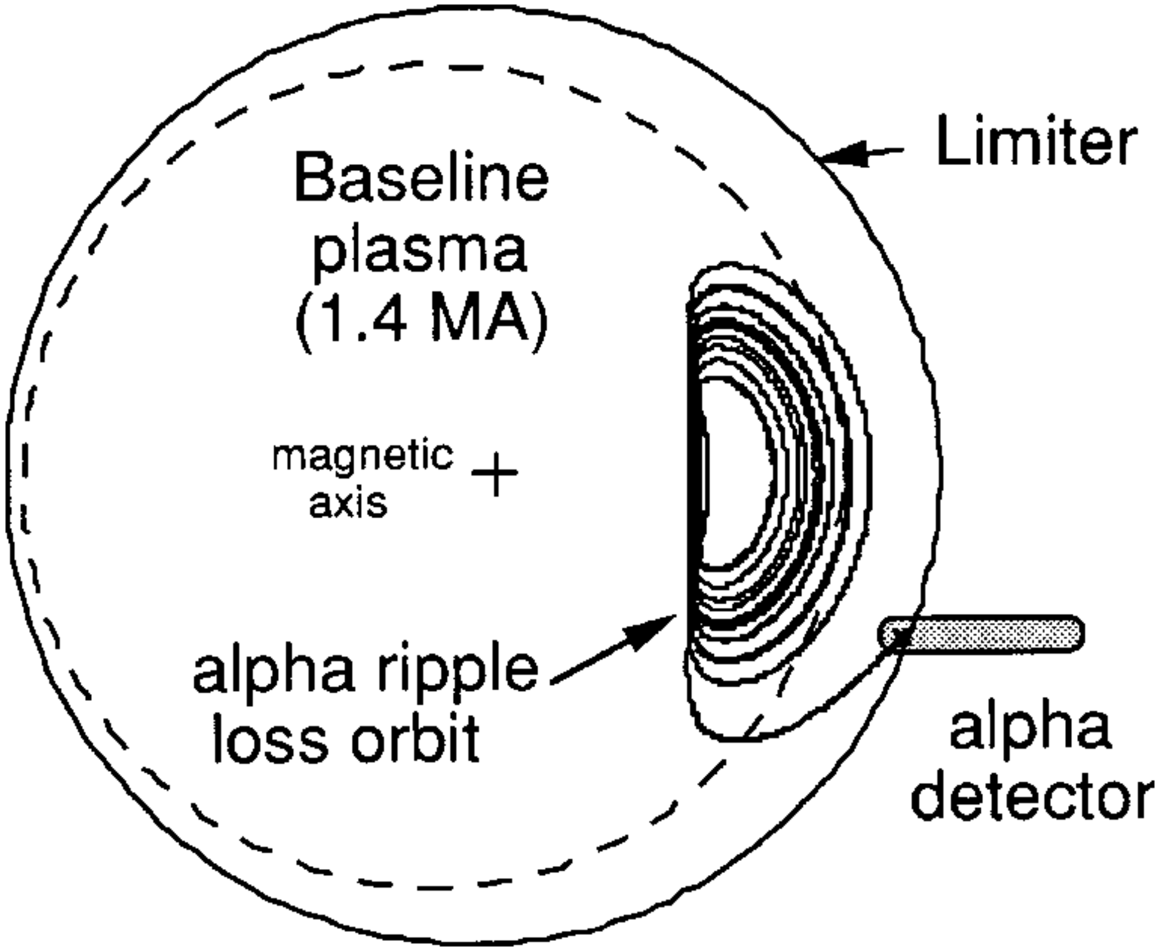
Zweben, NF 2000 Fig. 8, TFTR

Stochastic ripple diffusion causes loss to outer midplane region

- Causes loss of trapped ions whose banana tips are in a region where the ripple exceeds*:

$$\delta_{GWB} \approx (\varepsilon/N\pi q)^{3/2}(1/\rho q')$$

- Banana tip locations decorrelate between bounces, causing radial diffusion.
- Different from "ripple trapping" in the ripple magnetic well,
  - ripple trapping can be important for ICRF minority heating schemes which create deeply trapped fast ions

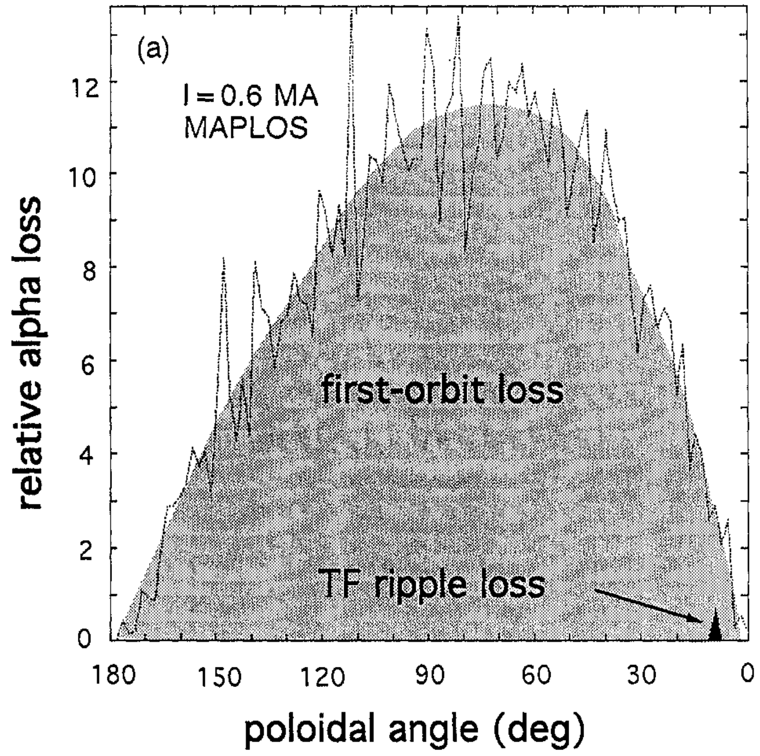


*Goldston-White-Boozer Phys. Rev. Lett. **47** (1981) 647

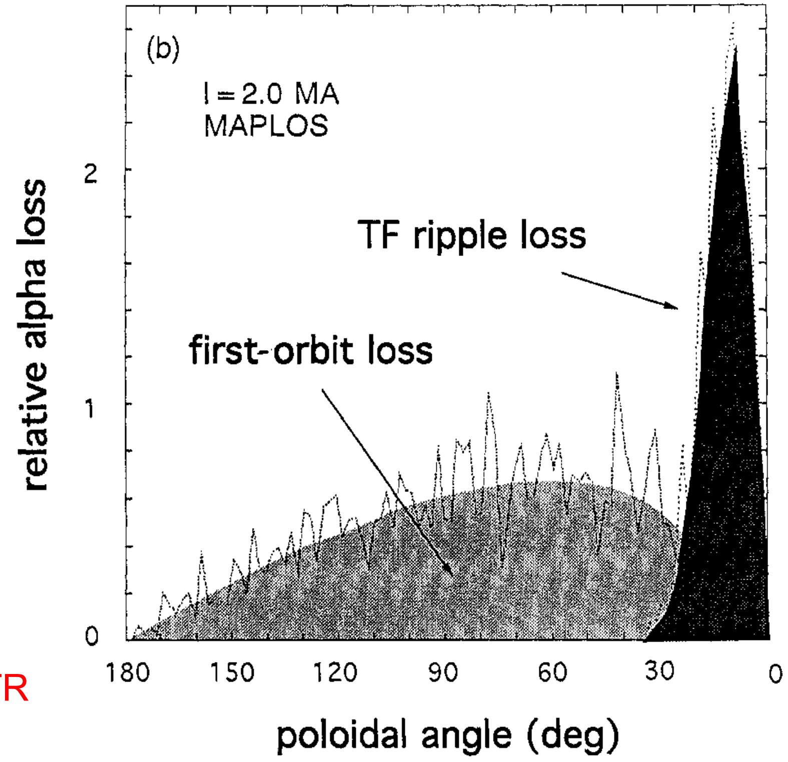
Zweben, NF 1998 Fig. 14, TFTR

Only at "high current" does ripple loss dominate first-orbit losses

- Poloidal distributions of 3.5 MeV alpha loss at the wall in TFTR.
- Prompt loss has broad peak between 60º and 90º below the midplane.
- At 2.0 MA TF ripple induced alpha loss dominates near midplane

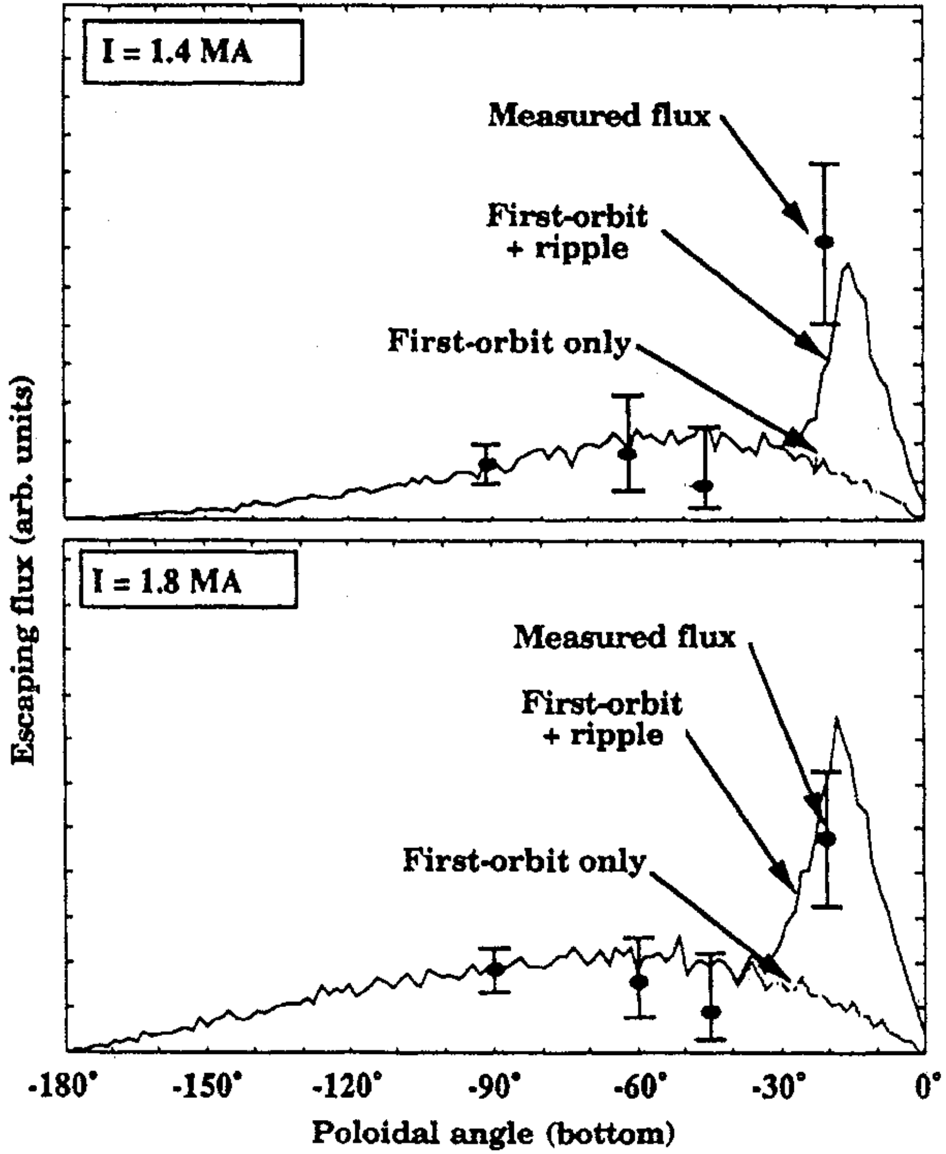


Zweben, NF Fig. 22, TFTR



Comparison of measured ripple loss and first-orbit losses to modeling

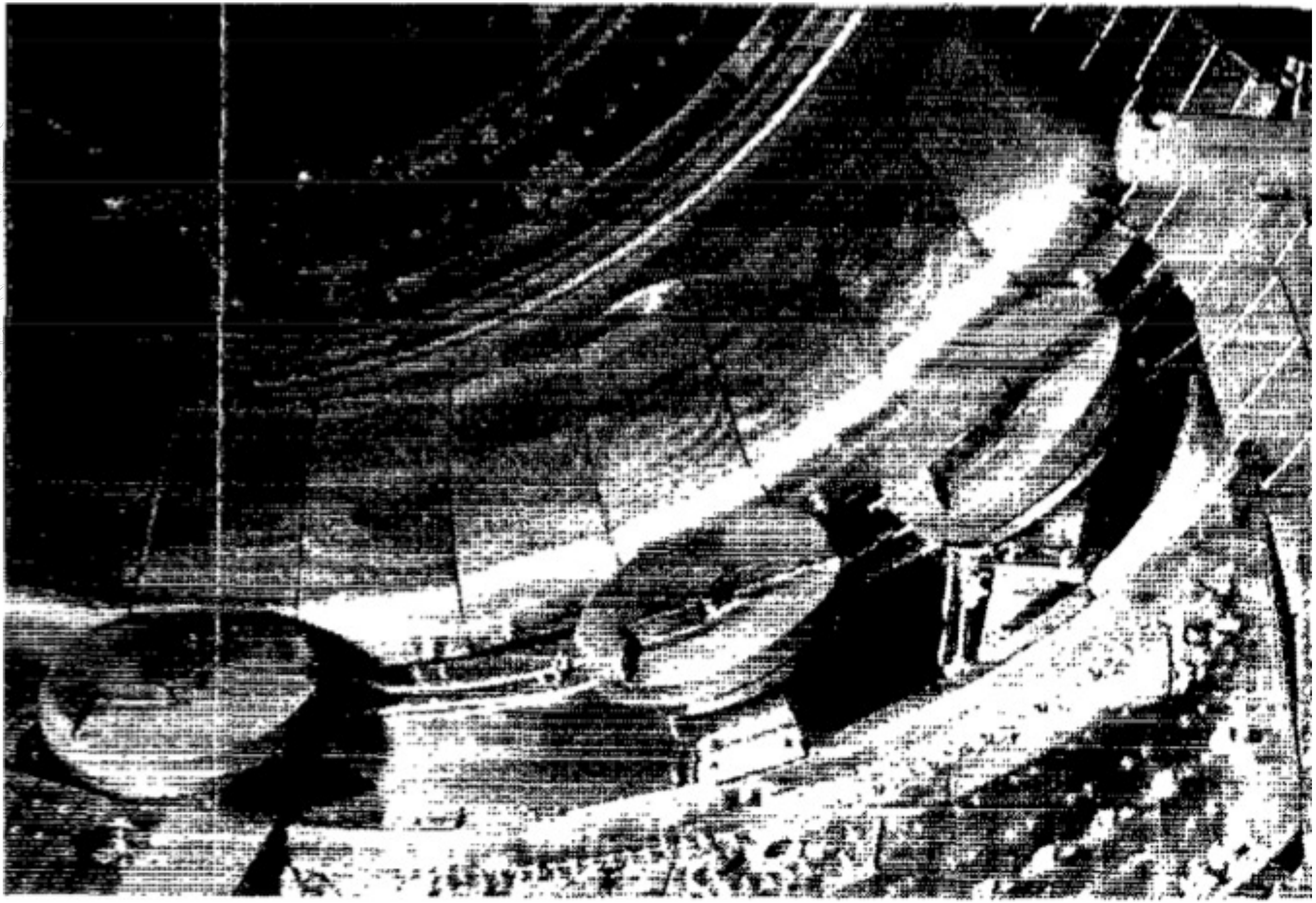
- Poloidal distribution D-D fusion product losses;
  - lines show calculated prompt and prompt + ripple losses,
  - B_T = 4T, R_0 = 2.60m, larger major radius maximizes edge ripple.
- The ripple at the outboard limiter edge (2.6m) is ≈2% and at the outboard plasma edge (2.39m) is ≈ 0.6%.
- The experimental points are normalized at θ = -90º where the loss is dominantly first-orbit.
- D-D fusion products:
  - 1 MeV Triton, 3 MeV proton,
  - 0.8MeV ^{3}He (not sensitive)



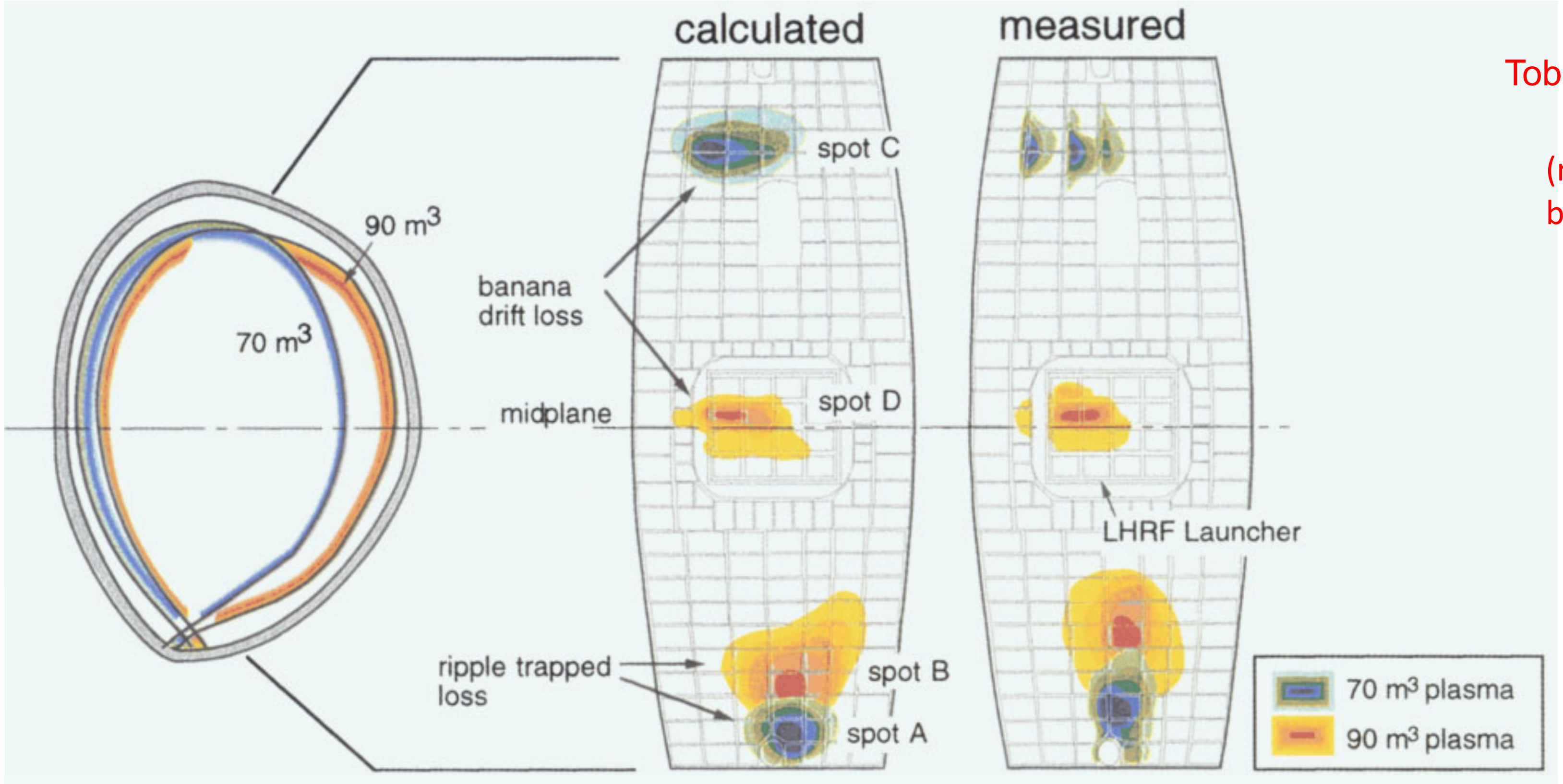
Boivin, NF 1993 Fig. 14, TFTR

TFTR Lost Alpha scintillator detectors

FIG. 7. Measured
plasmas. This ratio in
(1.0–4.5 MW) and IC
NBI), compared with
cannot easily be expl
induced loss mechanis
digitized within pixel



Ripple losses on JT-60U created measurable heating of outboard limiters

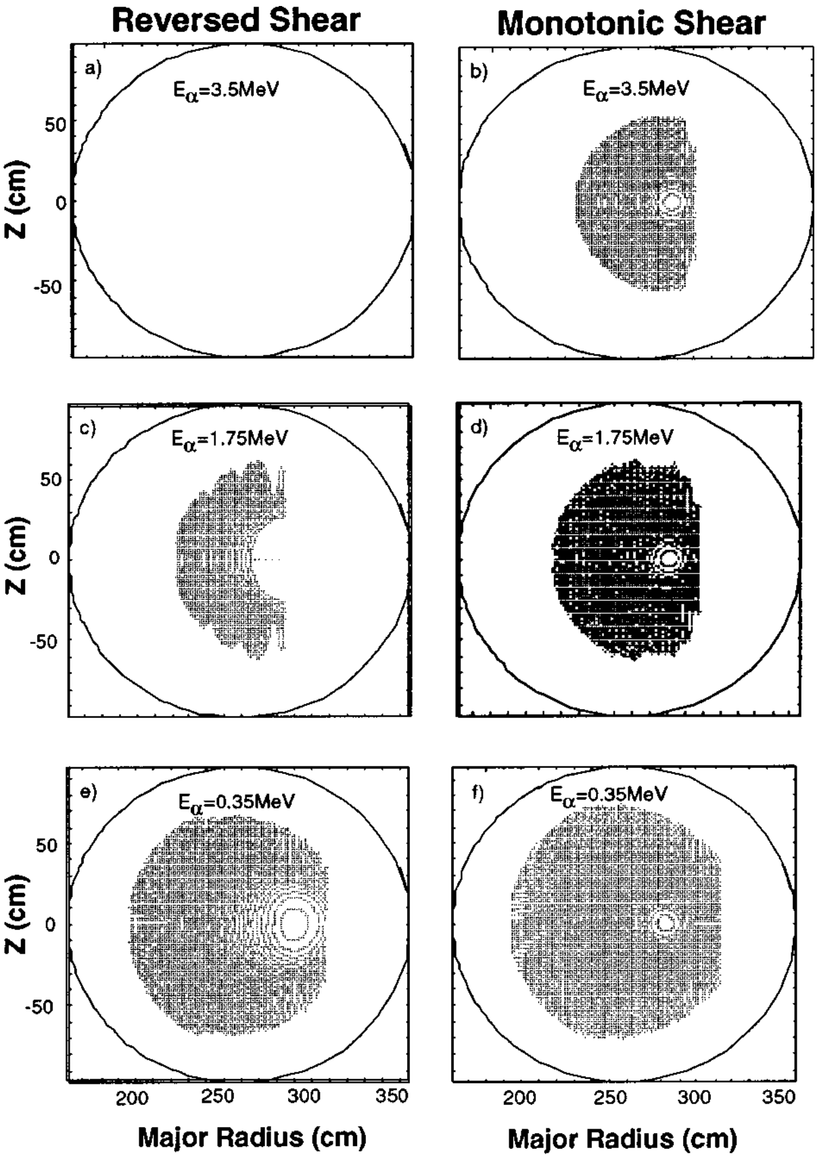


Tobita, NF 1995 Fig. 4, JT-60U

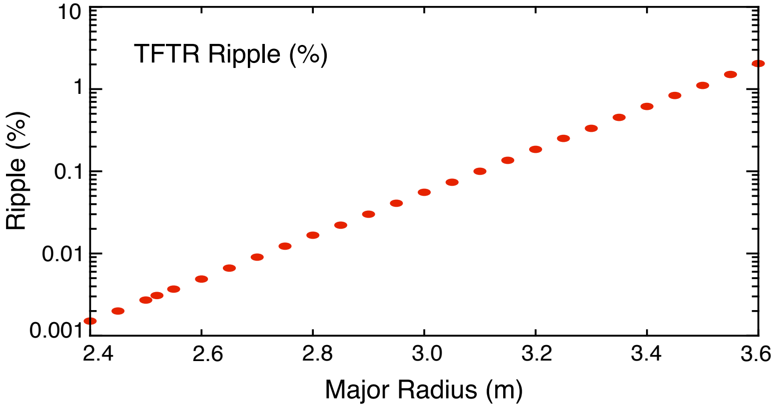
(near-perpendicular beam injection)

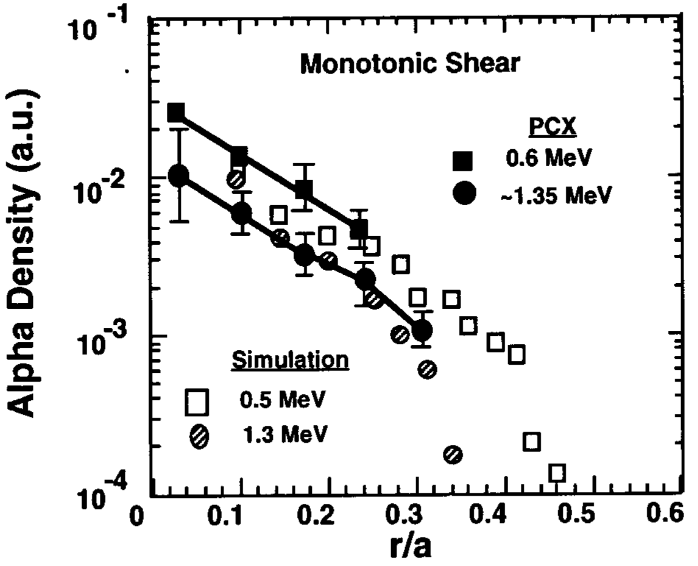
- Calculated and observed hot spots due to ripple losses on the wall for 70 m^3 and 90 m^3 plasmas.
- In the calculation E_r, is not included, which causes small differences in the hot spot position and profile for ripple trapped loss.

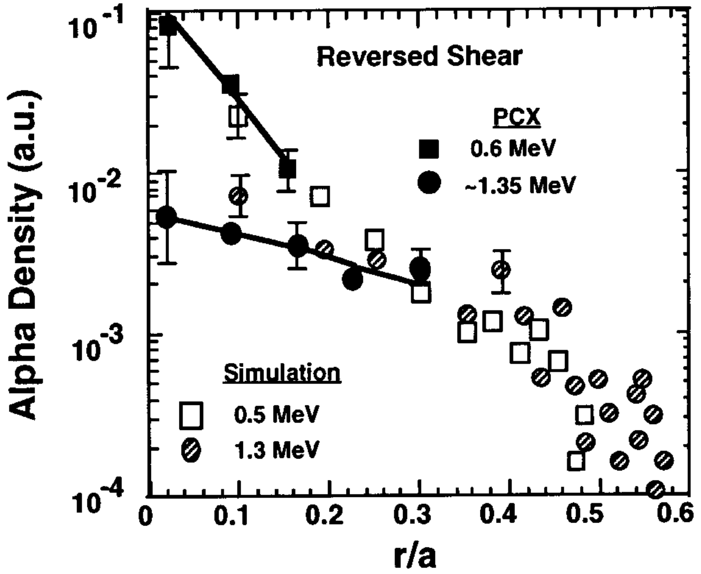
Reverse shear plasmas (high q_0) show reduced core fusion-α confinement



- On left, trapped-α confinement region in monotonic and reversed shear plasmas.
- On right, PCX measurements of fusion-α profiles.
- Bottom, ripple profile for TFTR - $\delta B/B \approx 0.055\%$ @3 m







Fishbones

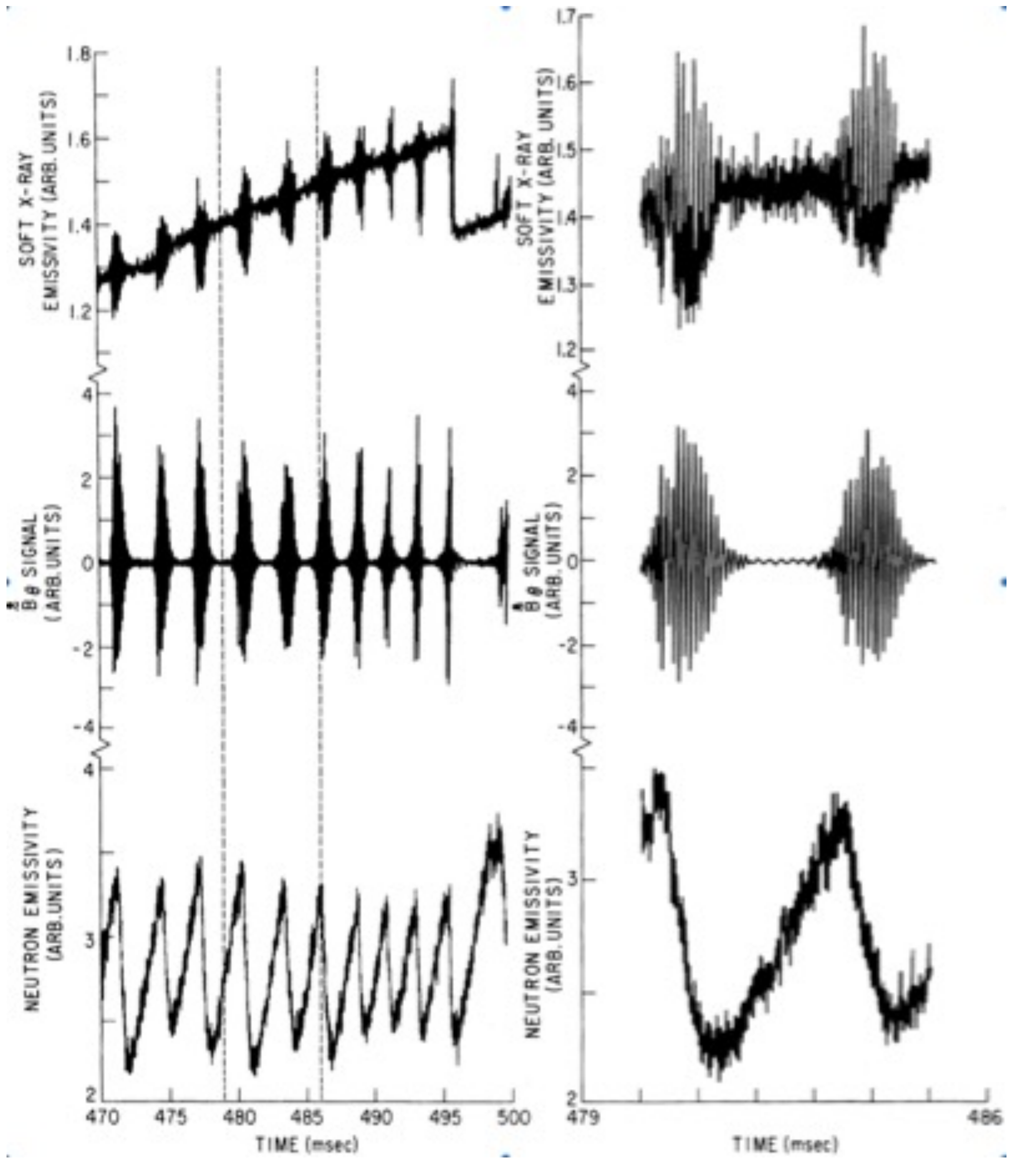
PDX Fishbones were an iconic study of MHD-induced fast ion losses on tokamaks

- PDX, Poloidal Divertor Experiment, was a medium sized, shaped tokamak with toroidal field up to 2.4T, plasma current up to 500 kA and major/minor radii of 1.43/0.44m.
- Fishbones were first reported *ca.* 1982-1983 on PDX with 40-50 kV perpendicular neutral beam injection.
- Fishbone-induced large neutron rate drops, enhanced losses of energetic neutrals (charge-exchange losses) were seen.
- Experimental measurements of the mode structure were made.
- Theory of the drive mechanism was developed.
- Modeling of the expected losses with orbit following code were made.
- In retrospect, TAE were also probably seen, but TAE theory came much later.

PDX "fishbone" fast ion losses (PRL 1983)

- Early observations of fast ion losses.
- Primary diagnostics for fast ion losses were neutron emision rate drops and charge-exchange losses, supported by modeling.
- Losses were significant, > 30% drops in neutron rate.
- Neutron rate drops can result from redistribution, loss of ion energy as well as actual losses.

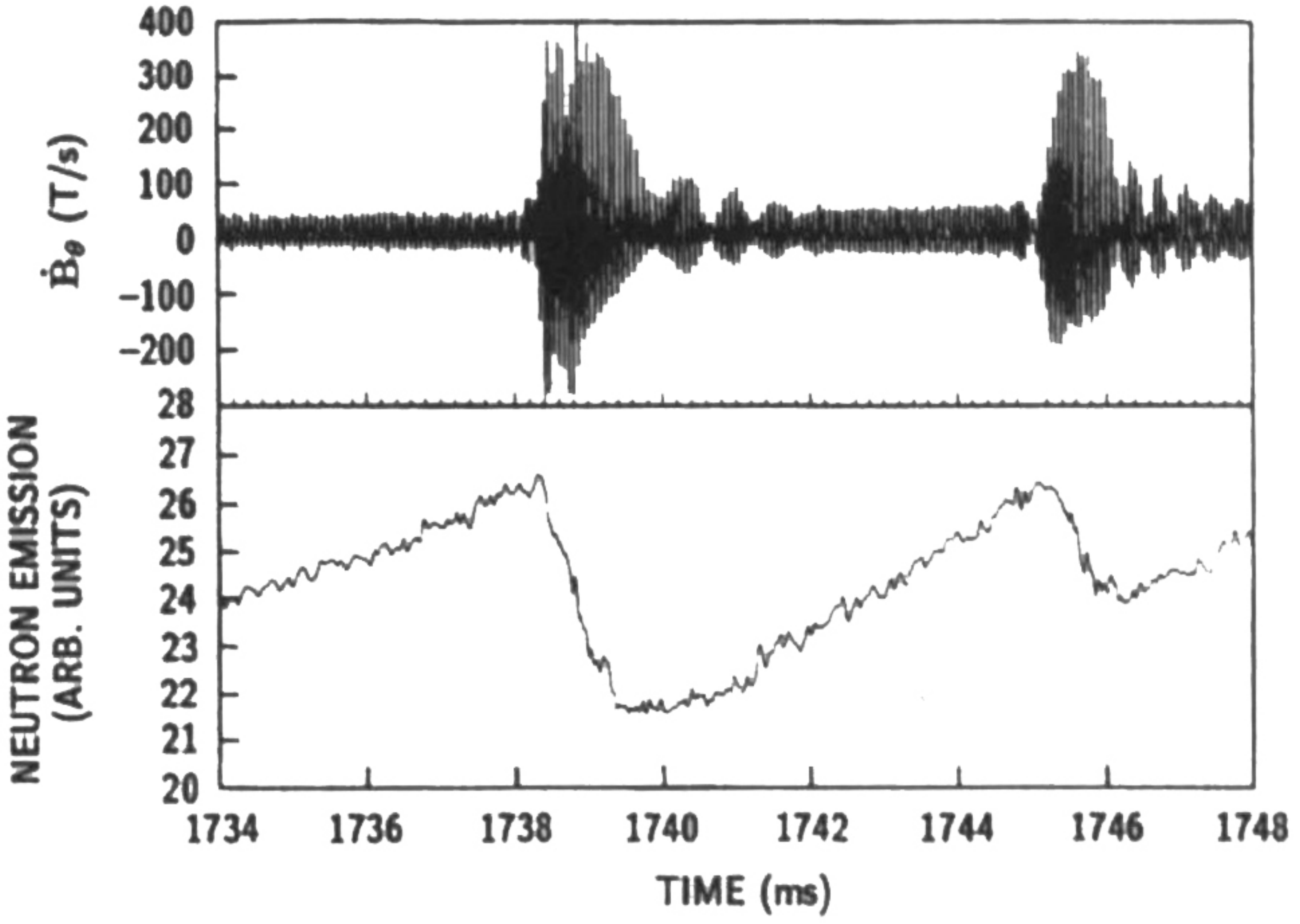
a/R_0 = 0.42m/1.43m
B_{tor} ≈ 0.7 – 1.7 T
E_{beam} ≤ 50 keV
ρ^*/ρ^*_{ITER} ≈ 2.43 – 5.90
loss ≈ 20% - 40%



McGuire, Phys. Rev. Lett. 1983 – PDX tokamak

Subsequently, fishbones have been observed in most beam-heated plasmas, e.g., DIII-D

- Observed when $\beta_P \geq 1.5$ and $n_e \leq 5.5 \times 10^{13}$ cm
  - These bursts are usually of minor significance operationally
- However, in one case over 50% of the beam power was lost.
- Operation at large values of normalized beta on DIII-D without fishbone activity is possible.

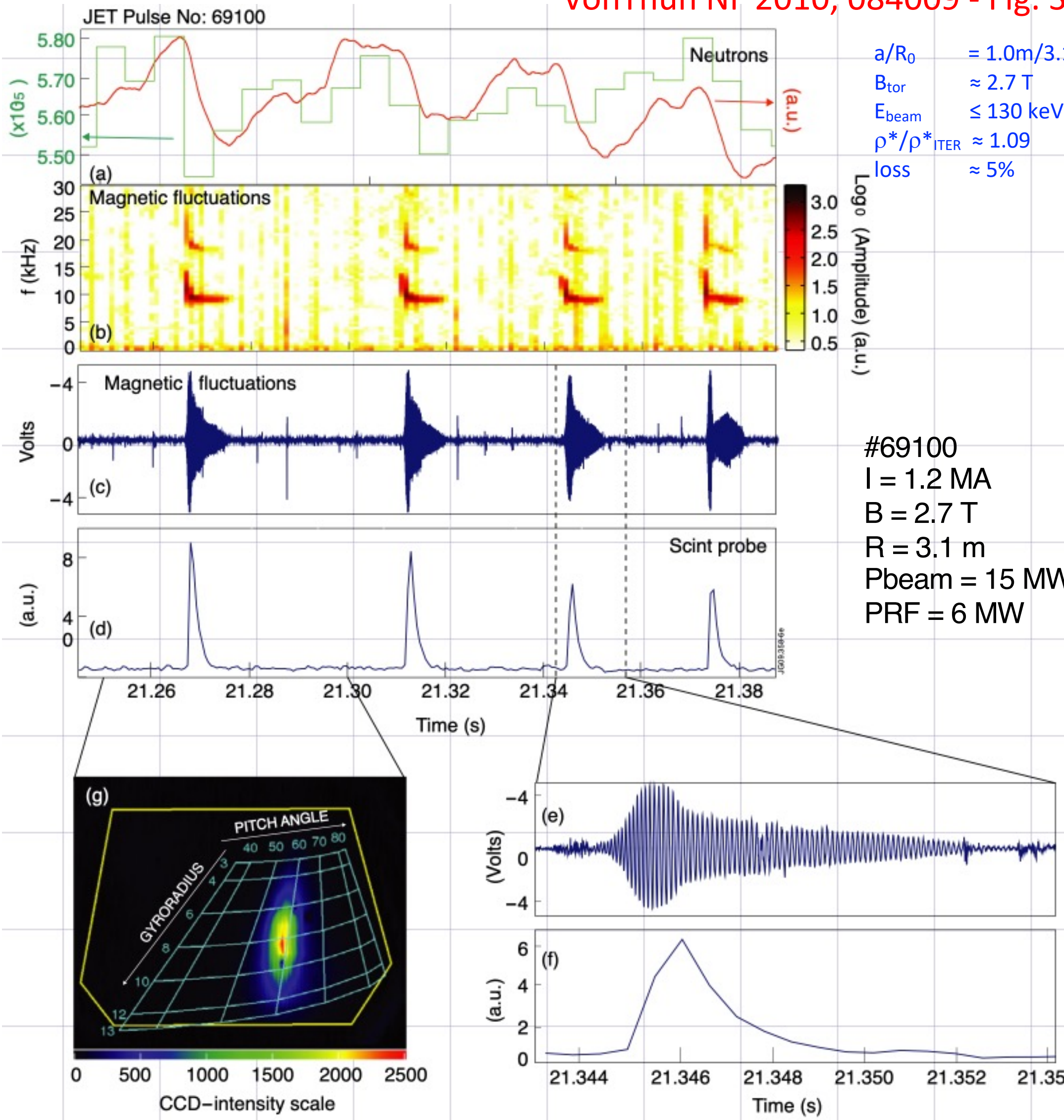


Heidbrink, Nucl. Fusion **30** (1990) 1015 – DIII-D tokamak

Fishbone losses of H-minority tail ions (JET)

- The fishbones are again beam driven, H-minority tail-ion losses are non-resonant.
- Neutron rate drops of up to 5% are seen.
- Modeling of the non-resonant losses were partially successful in reproducing the observed losses.
- In simulations, for these parameters, up to 0.1% of fast ions lost for each fishbone.

VonThun NF 2010, 084009 - Fig. 3

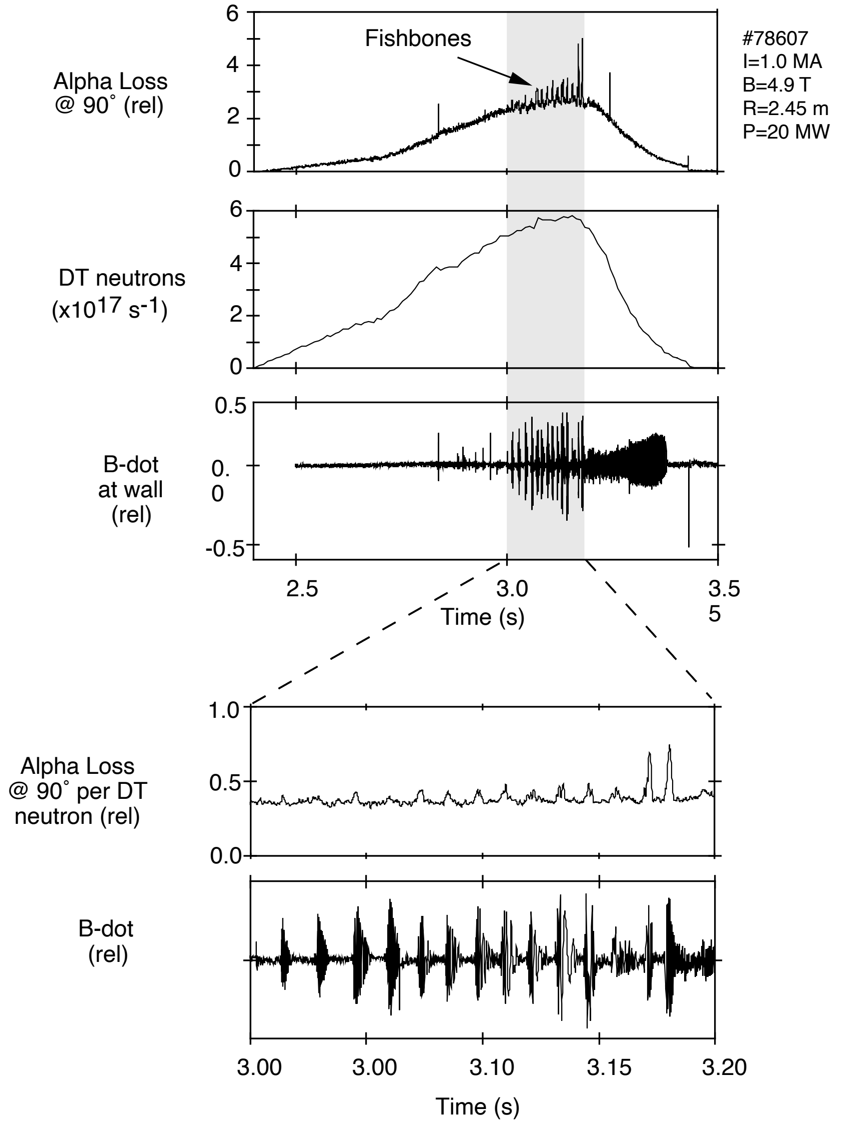


a/R_0 = 1.0m/3.1m
B_{tor} ≈ 2.7 T
E_{beam} ≤ 130 keV
ρ^*/ρ^*_{ITER} ≈ 1.09
loss ≈ 5%

#69100
I = 1.2 MA
B = 2.7 T
R = 3.1 m
Pbeam = 15 MW
PRF = 6 MW

Fishbone-induced α losses (TFTR)

- Fishbones were generally weaker on TFTR.
- This experiment shows stochastic losses of fusion α's in a low current shot with neutron rate drops of up to ≈2%.
- While the increase in fusion-α losses was small, the alphas were not likely resonant with the fishbones.
- The lost-alpha detectors do not see lower energy fast-ions such as the neutral beam.
- "...does not appear to affect significantly the alpha-particle heating power." Coppi FST 1988



Zweben, Nucl. Fusion 1999 Fig. 2 – TFTR

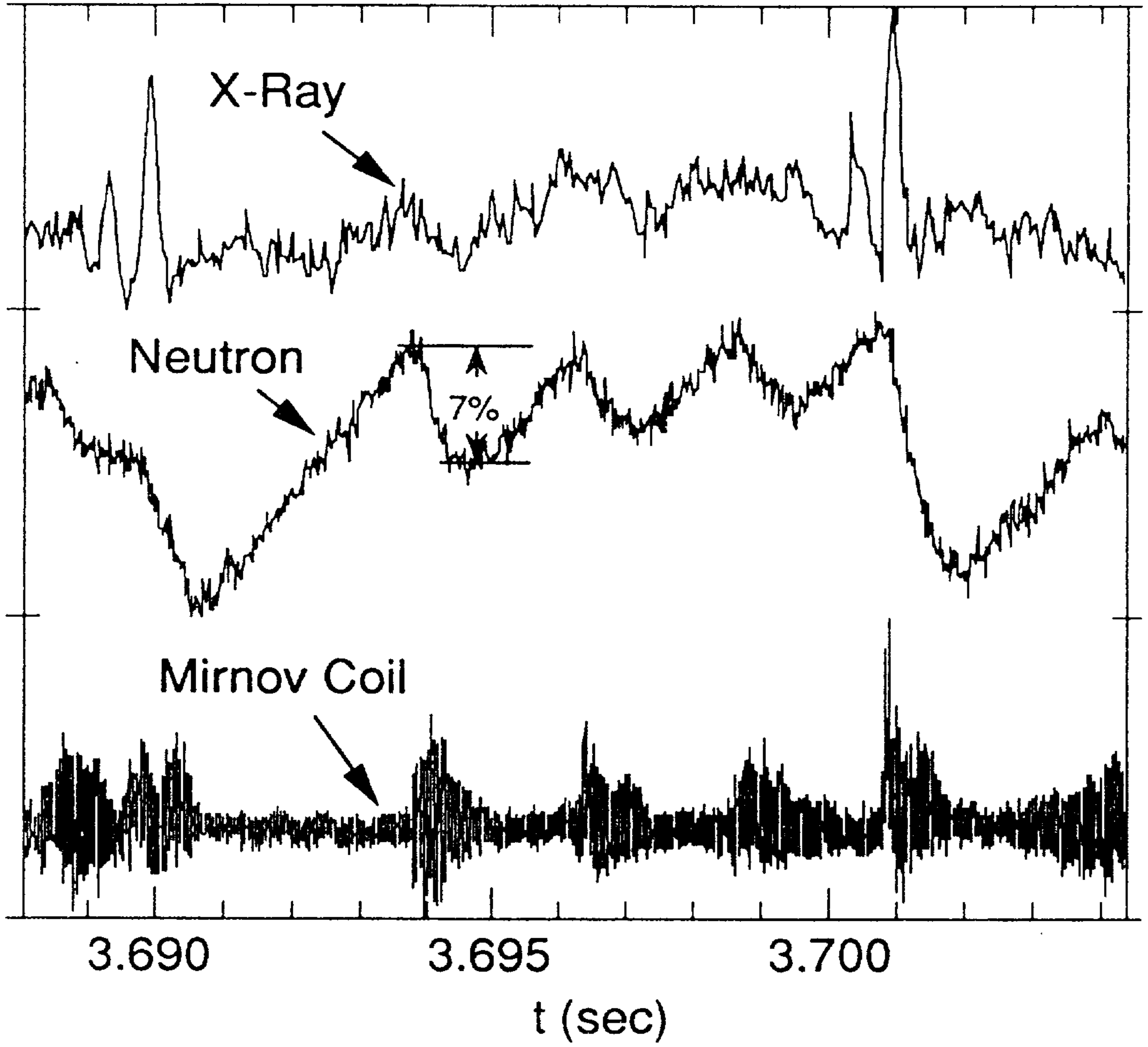
Alfvénic modes

Fast-ion transport from Alfvénic modes

- Complicated subject, most relevant modes are probably toroidal and reverse-shear Alfvén eigenmodes (TAE and rsAE).
- Alfvénic modes are typically weakly damped and can be de-stabilized by small amount of resonant fast-ions.
  - Requires $V_{fi} \geq (1/3)\, V_{Alfvén}$ to match resonance conditions,
  - and $\beta_{fast} > \beta_{crit}$ to overcome damping
- Multiple modes needed for losses if ρ/a is small, as in ITER.
- Current experimental studies provide guidance and validation of theoretical modes for ITER simulations.
- No current tokamak can match all relevant dimensionless terms with ITER with ITER-like fast-ion distribution.

First observations of TAE were from dedicated experiments on TFTR and DIII-D

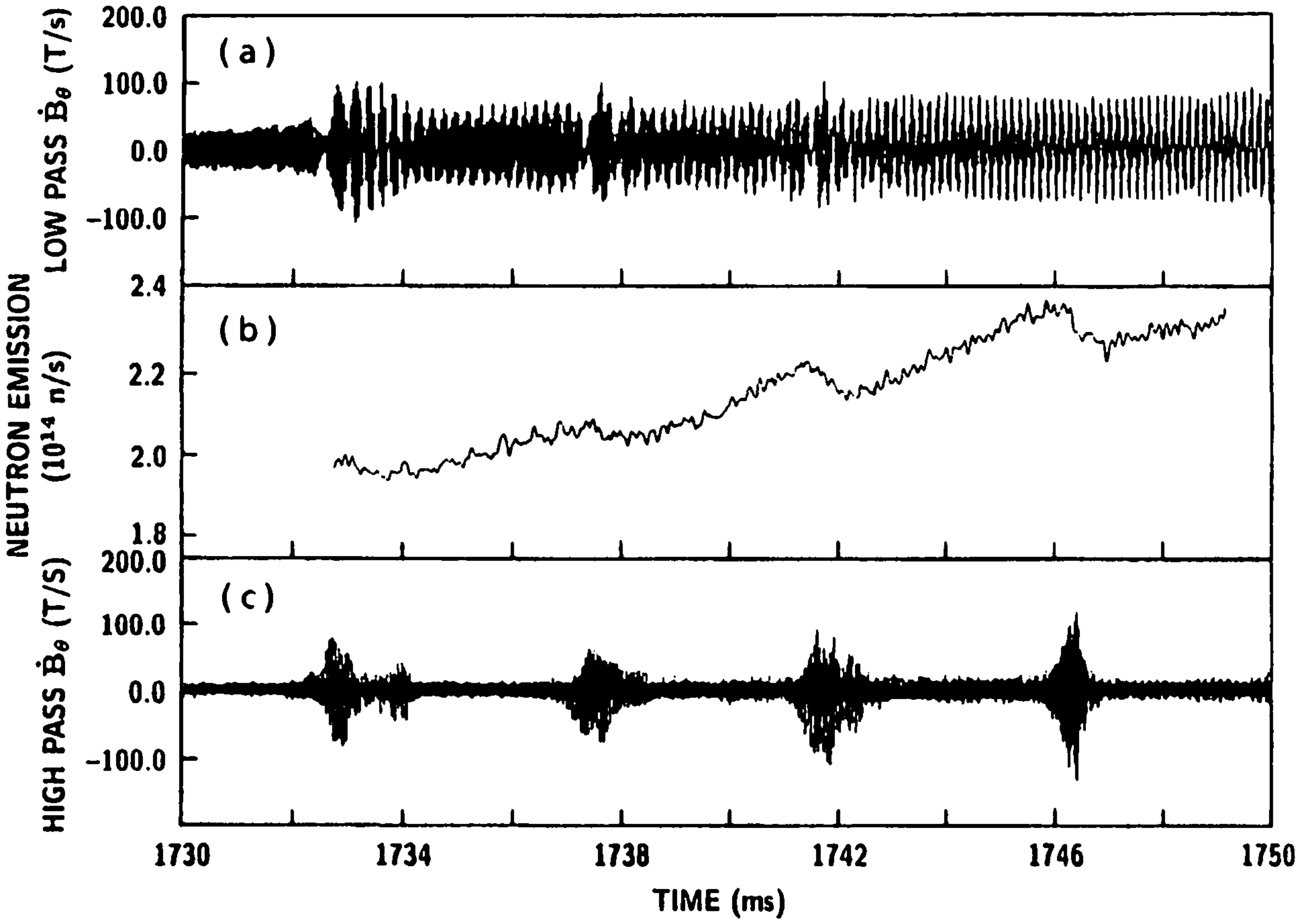
- Meeting $V_{beam}/V_{Alfvén} \approx 1$ required TFTR to operate at very low field,
  - B_{tor} = 1 T, $n_e \approx 3 \times 10^{13}/cm^3$
- Drops in the neutron rate of up to 7% are seen at the TAE bursts (the larger drops also include sawteeth).
- In retrospect, the 1/3 resonance meant that beam-driven TAE were seen at fields up to 2 T,
  - losses much smaller at higher field.



Wong, PRL 1991, Fig. 4 – TFTR

TAE were seen under similar "low field" conditions on DIII-D

- In the search for TAE, DIII-D was also operated at reduced field to lower the Alfvén velocity
  - B_{tor} = 0.8 T, n_e = 3.8 x 10^{13} cm^3
  - $V_{beam}/V_{Alfvén} \approx 1.4$
- The lower field also meant that ρ_{beam}/a is larger; predicted to enhance fast-ion losses.
- TAE theory suggests that $k_{\perp}\rho_{fast} \approx 1$ for instability.
- Means for ITER will need a "sea-of-TAE" for significant transport.

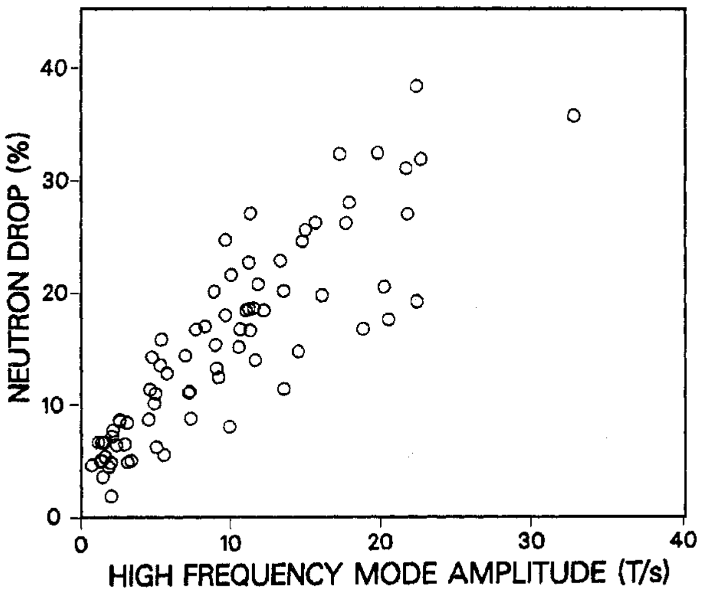


Heidbrink, Nucl. Fusion 1991, Fig. 2 – DIII-D tokamak

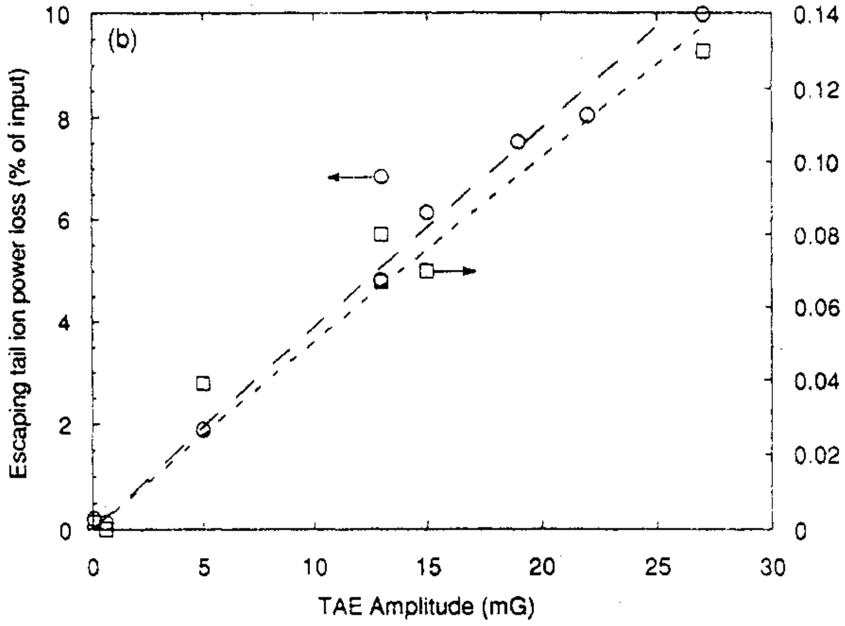
Total losses scale (mostly) linearly with Alfvénic mode amplitudes DIII-D, TFTR, JET

- JET data is better fit with an offset-linear curve, suggesting a possible threshold amplitude for fast-ion losses.
- Linear dependence suggests dominantly convective losses.

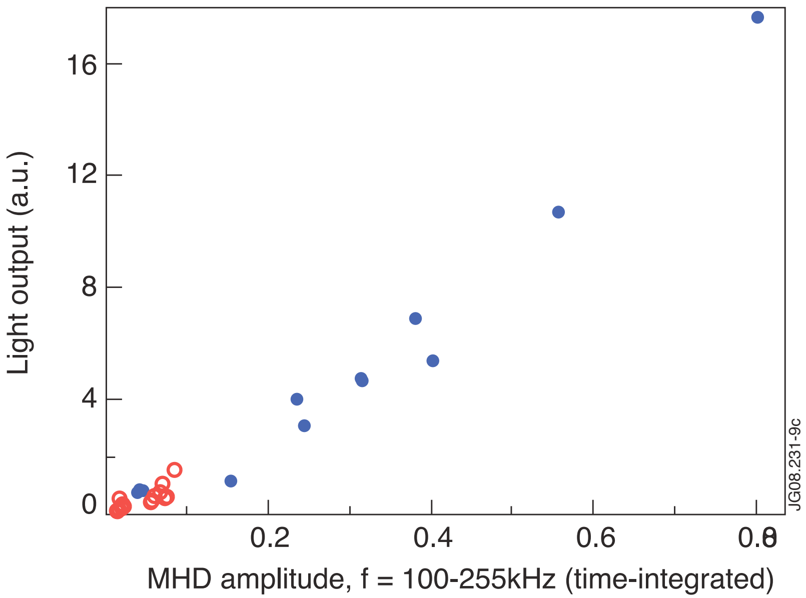
DIII-D (Duong NF 1993 Fig. 8)



TFTR (Darrow NF 1997 Fig. 10)



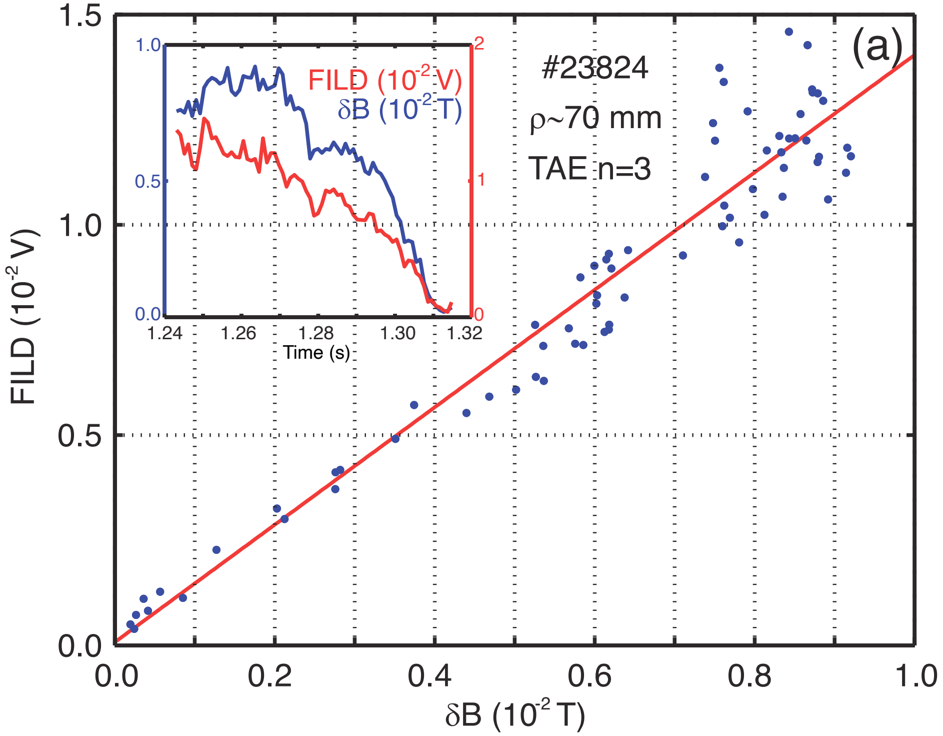
JET (Kiptily NF 2009 Fig. 5)

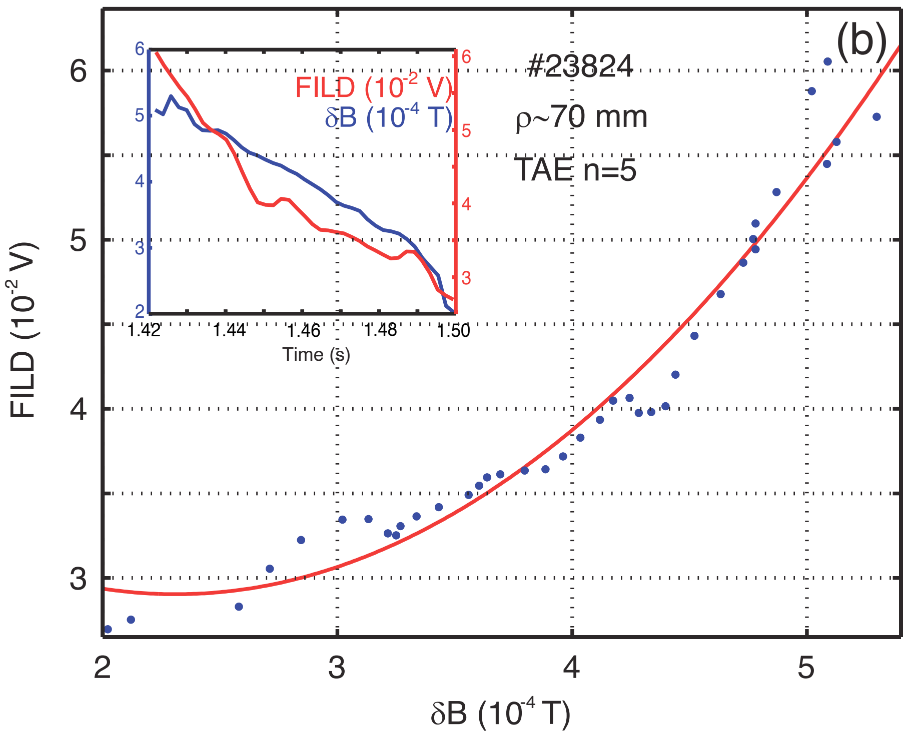


Diffusive losses have also been seen on AUG

- Fast-ion losses in these experiments were a mix of convective and diffusive losses (left figure).
- Overlap of phase-space structures, e.g., from multiple modes, can lead to diffusive losses (right figure).

Garcia-Münoz, PRL 2010, Fig. 2 – DIII-D tokamak

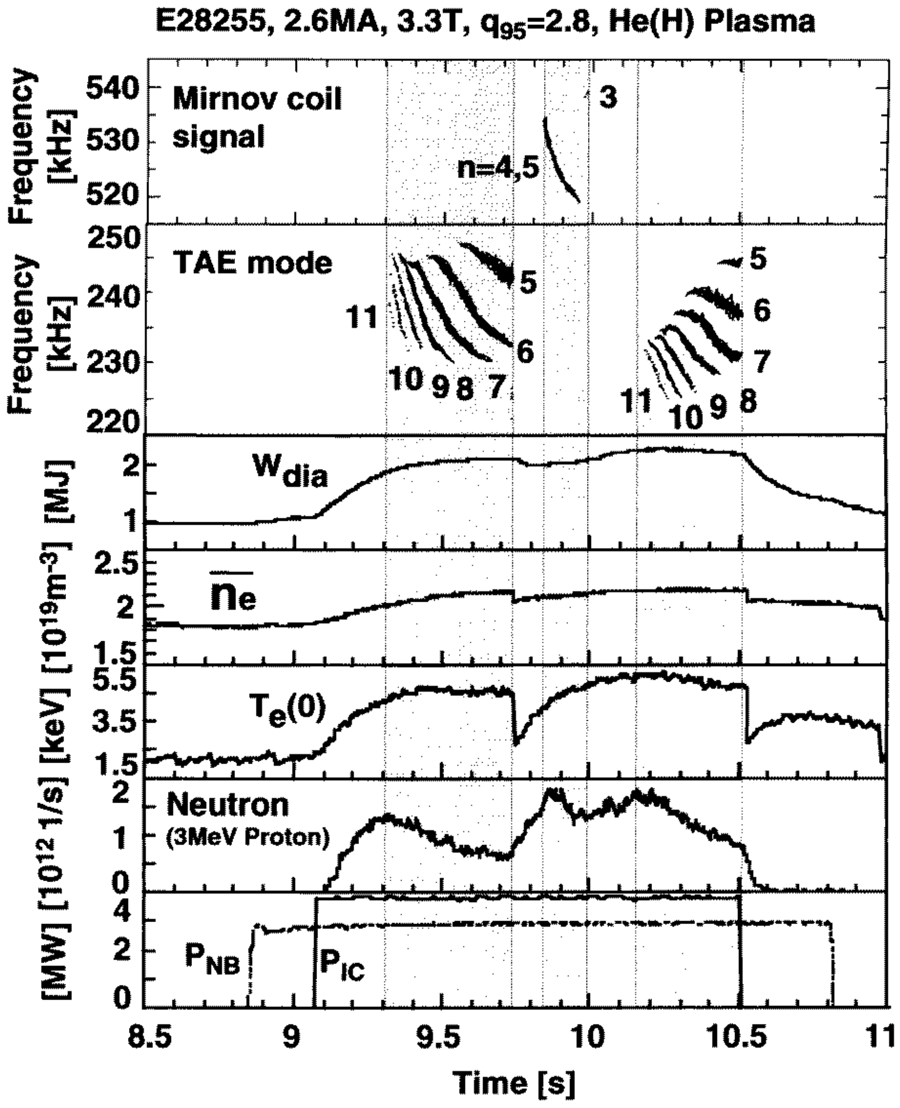




Strong losses of H-minority ICRF tail ions seen in JT60-U

- Neutrons here aren't from the neutral beams but from p-Boron fusion from the high-energy tail protons.

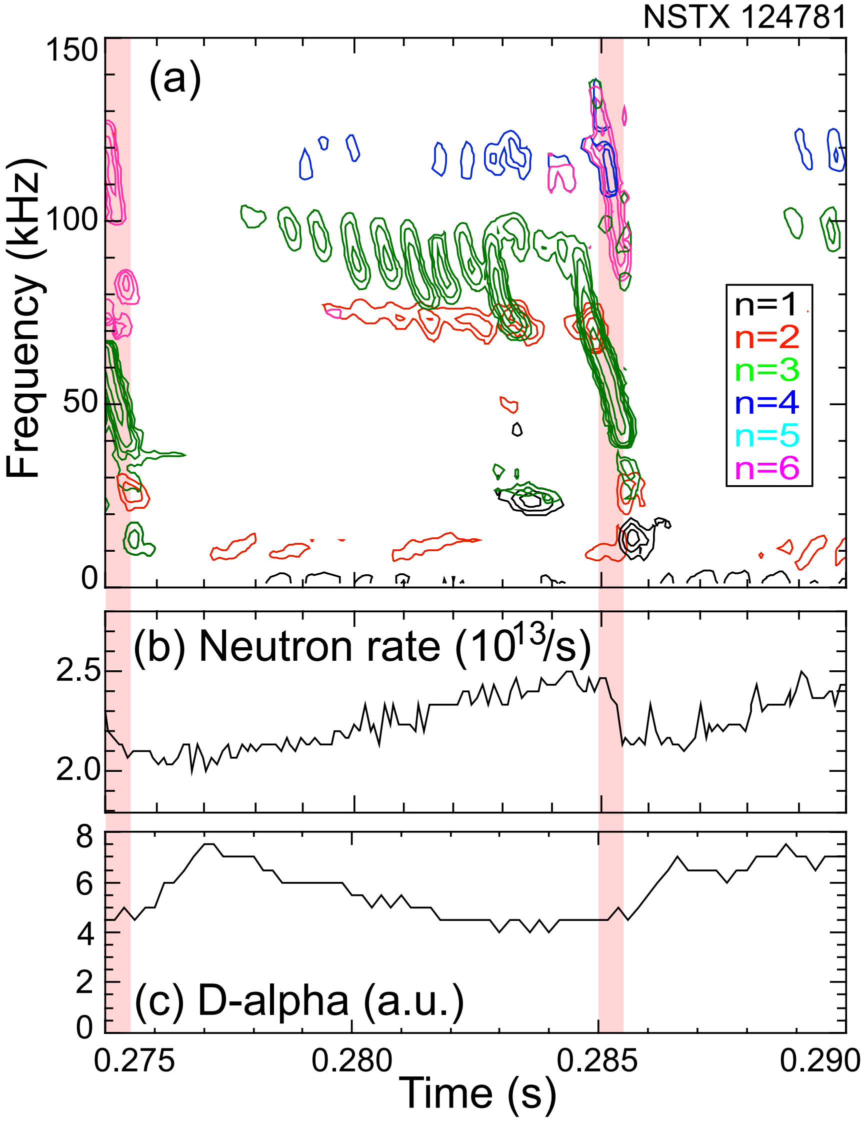
- Significant drops in the p-Boron neutron rate are seen during the core-localized TAE or "tornado" modes.



Saigusa, PP&CF 1998, Fig. 10 – JT-60U

Neutron rate drops don't necessarily reflect fast ion losses or redistributions

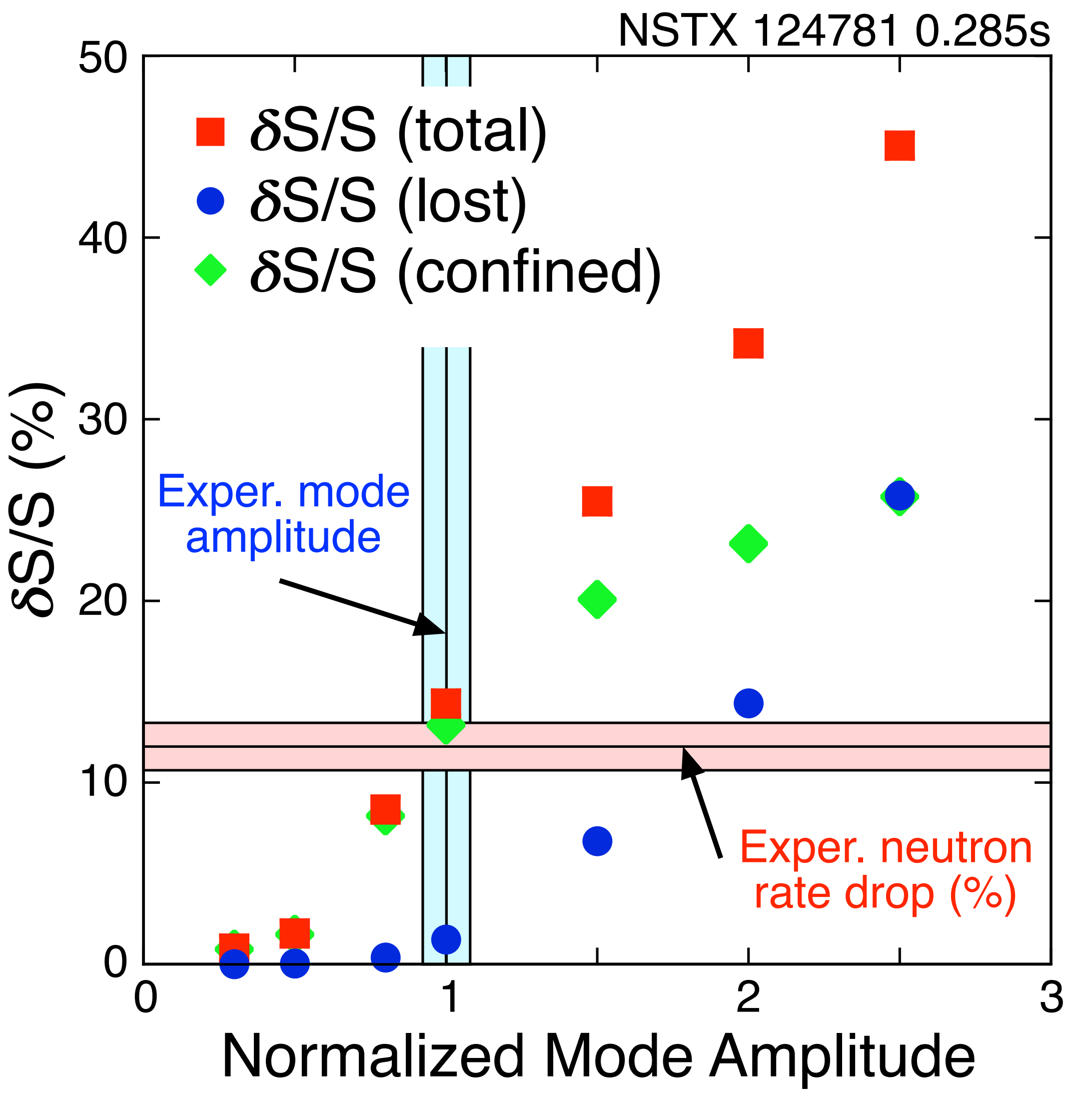
- The toroidal mode numbers, the radial profiles of mode amplitudes and the frequency evolution (chirping) were well documented.
- Plasma equilibrium parameters (density and q profiles) were well measured.
- Eigenmode structures were calculated with NOVA(-k)
- Effect of TAE on fast-ions was simulated with the ORBIT code.
- For this example on the spherical tokamak NSTX it was found that a significant fraction of the "lost" fast-ion energy flowed through the TAE into the thermal plasma.



Fredrickson, Nucl. Fusion 2013, Fig. 2 – NSTX

Neutron rate drop mostly due to energy lost from fast-ions driving TAE

- Simulated neutron rate drop due to TAE avalanche (red),
- Neutron rate drop resulting from lost beam ions (blue)
- Neutron rate drop in confined beam ion population from energy loss (green).
- Simulation used multiple TAE and measured frequency and amplitude evolutions

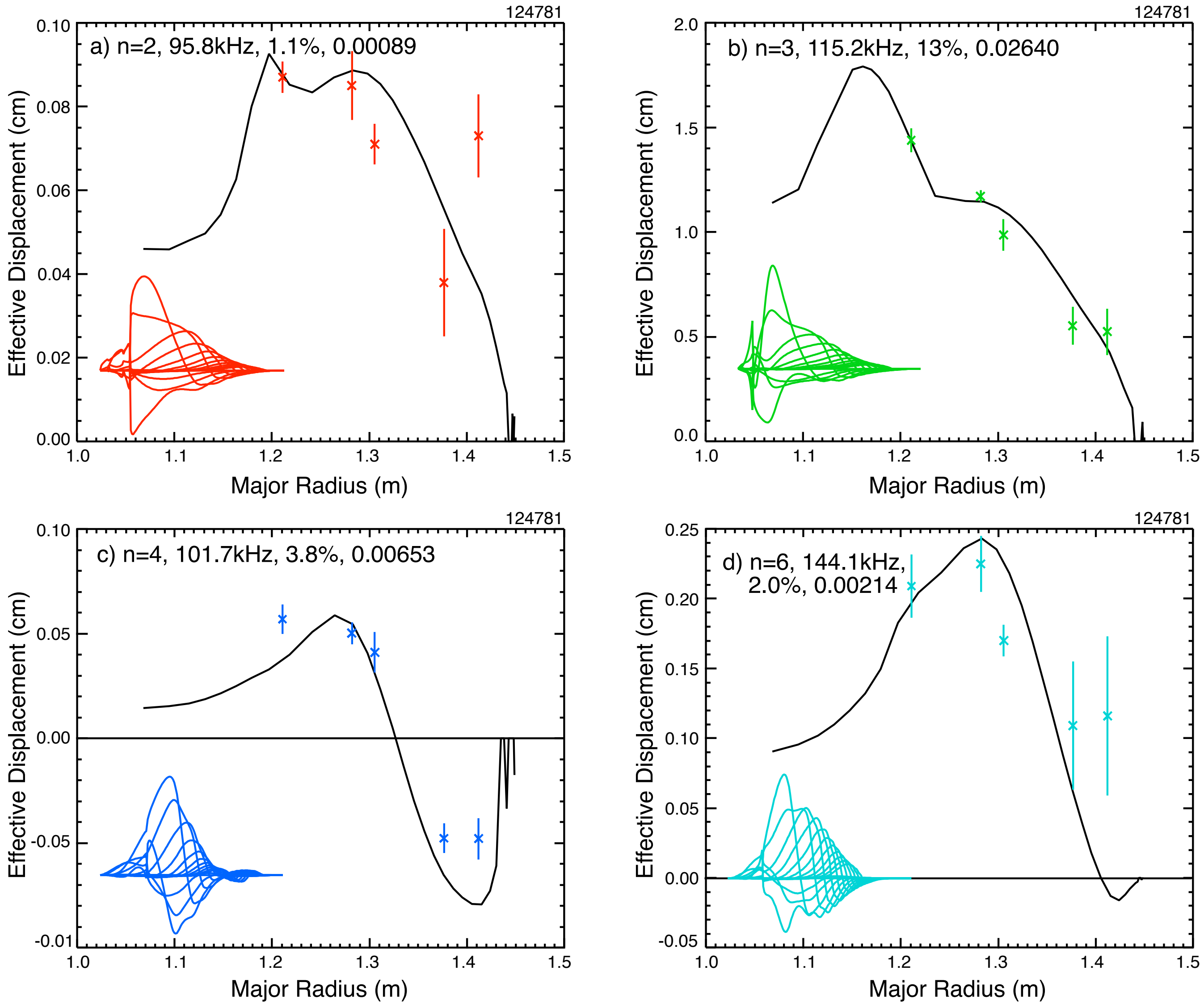


Fredrickson, Nucl. Fusion 2013, Fig. 2 – NSTX

a/R_0 = 0.65m/1.0m
B_{tor} ≈ 0.32 T
E_{beam} ≤ 90 keV
$V_{fi}/V_{Alf.}$ ≈ 2.8
ρ^*/ρ^*_{ITER} ≈ 9.9
loss ≤ 13%

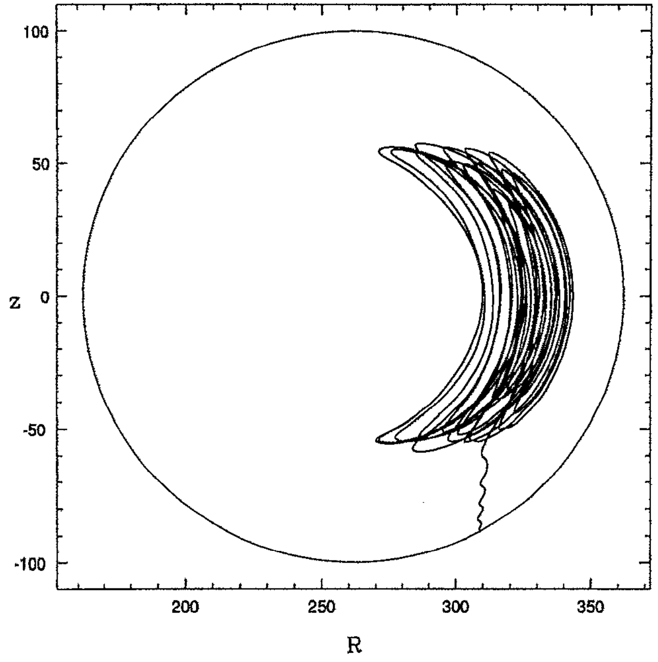
Internal eigenmode amplitudes measured with multi-channel reflectometer

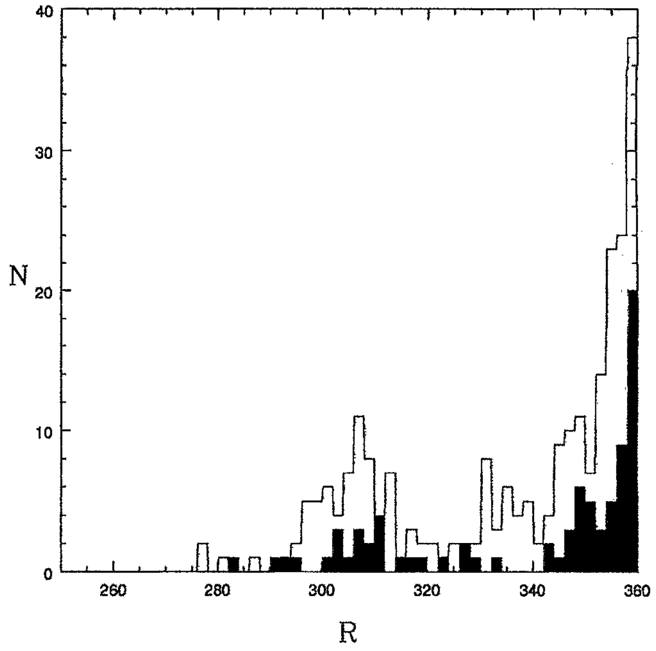
- Solid curves are simulated reflectometer response, points are reflectometer data,
- inset are NOVA poloidal harmonics including sheared rotation profile
- a) n=2 mode, b) n=3 mode, c) n=4 mode and d) n=6 mode.



Synergy between TAE and ripple trapping led to localized heating and failure of port weld on TFTR

- TAE diffused H-minority ICRF tail-ions into higher ripple region.
- Eventually ion became trapped in a ripple well and quickly walked out of plasma.
- Large major radius plasmas to improve antenna coupling – means large ripple.



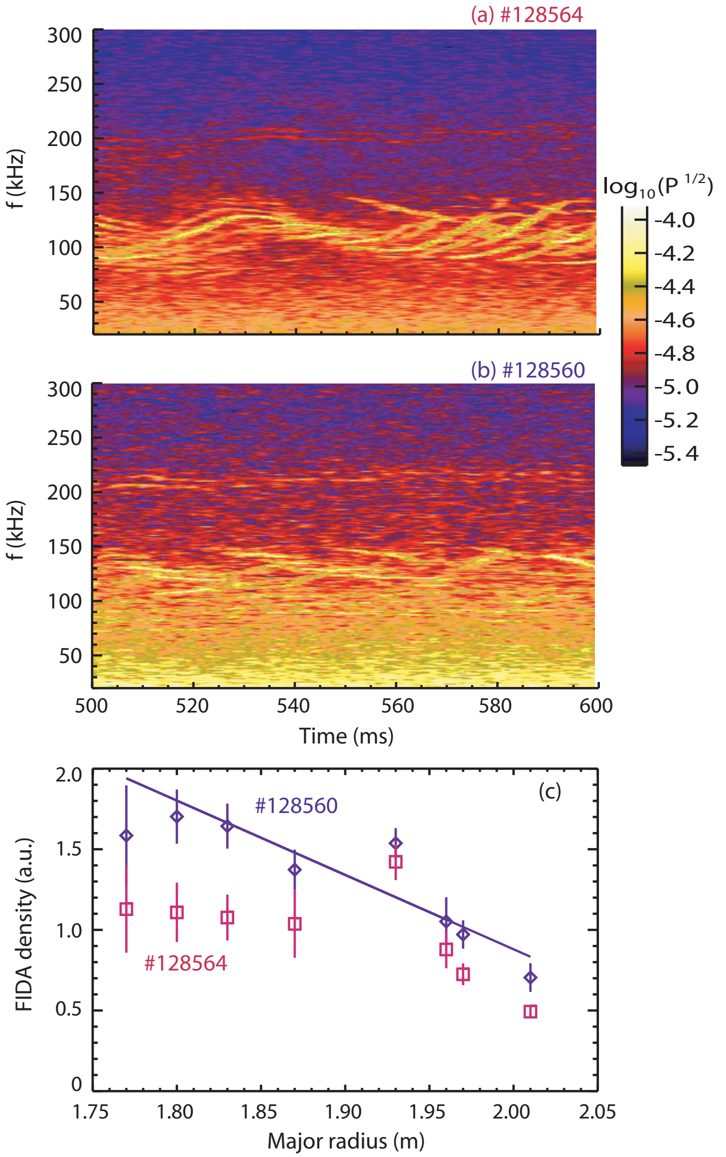


- Simulations showing fast-ion losses vs. major radius with (white) and without (black) TAE included.
- Losses were very localized at vacuum vessel bottom between TF coils on port welds.

White, Phys. Plasmas **2** 1995 (2971), Figs. 2&3 – TFTR

Anomalously large losses also seen in reversed shear DIII-D plasmas with rsAE

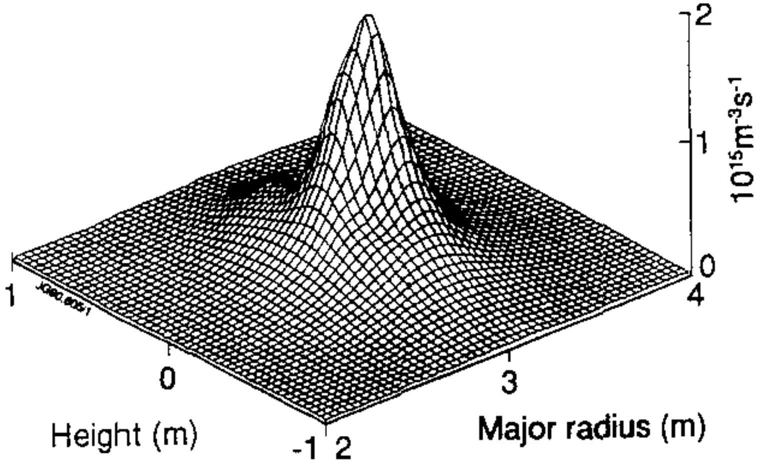
- Experimental evidence of fast-ion losses was found in a number of diagnostics.
- In the experiment at right, ECH was used to suppress the rsAE, resulting in improved fast ion confinement.
- The losses couldn't be well modeled using experimental parameters.
- Ripple is lower in DIII-D with 24 vs 20 TF coils and was not included in simulations.



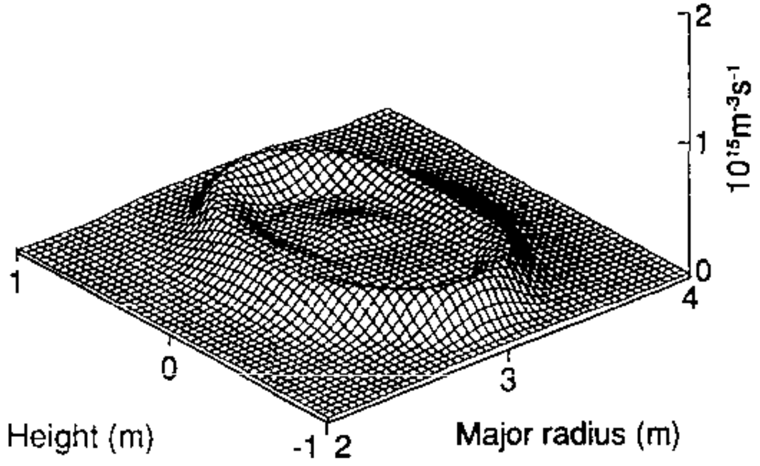
Sawteeth

Neutron emissivity profiles measured with collimated neutron detectors on JET

- Neutron emissivity profile before the sawtooth crash (time integrated from 10.738 to 10.748 s) versus major radius and vertical height for discharge 20981.



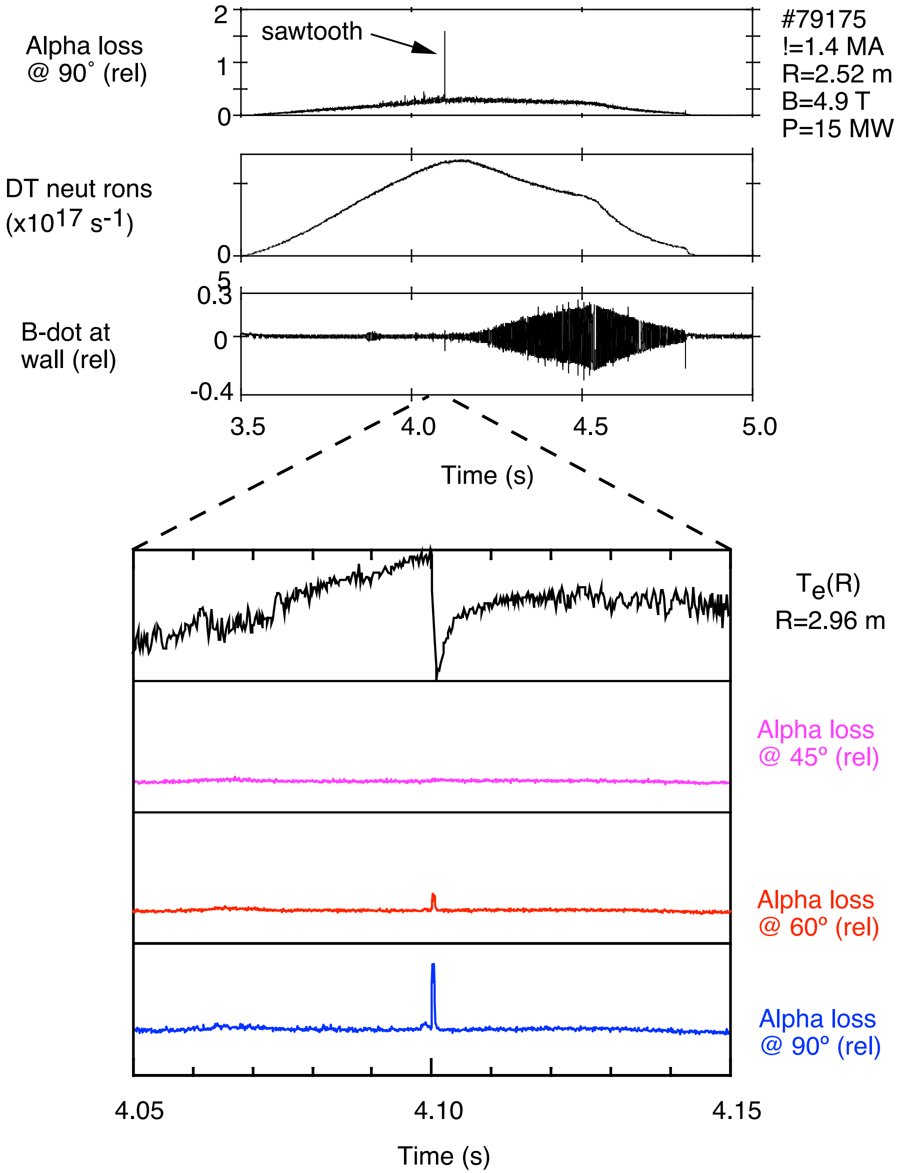
- Neutron emissivity profile after the sawtooth crash (time integration from 10.756 to 10.766 s) versus major radius and vertical height for discharge 20981.



- Sawtooth at ≈ 10.750 s, profiles ≈ 18 ms apart.

Fusion-α loss during sawteeth

- Example of the effect of a sawtooth crash on alpha loss.
- The sawtooth crash caused a factor of 5 increase in the alpha loss at 90º
  - less of an increase in the 60º and 45º detectors.
- While the enhancement is large compared to the prompt losses, it is transitory.
- With the possible exception of a localize heating issue, the other deleterious effects of sawteeth are probably more important to ITER than the fast-ion losses.

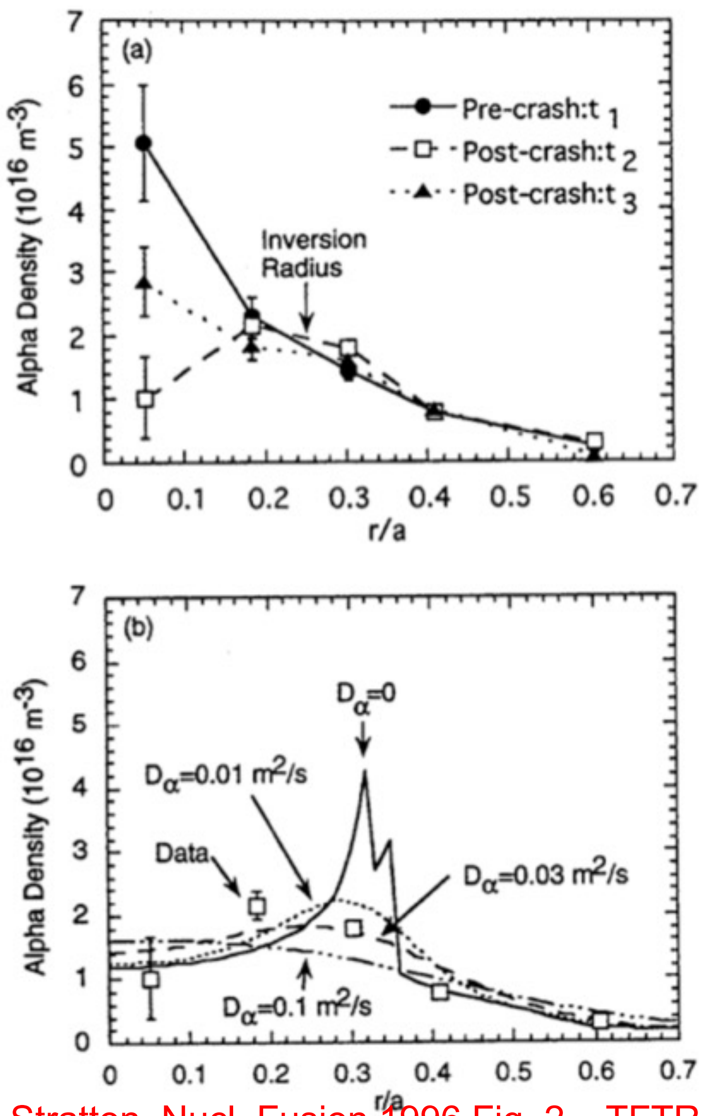


a/R_0 = 0.87m/2.52m
B_{tor} ≈ 4.9 T
E_{beam} ≤ 110 keV
r/a ≈ 0.017
loss ≈ negligible

Zweben, Nucl. Fusion 1999 Fig. 4 – TFTR

Fusion-α redistribution during sawtooth crash

- Measured alpha density profiles from before and at two times after a sawtooth crash. (b)
- Measured post-crash alpha density profile compared with model profiles assuming various values of D_α.
- This measurement provides a rough measure of fusion-a diffusivity.
- (Data from the α-CHERS diagnostic)

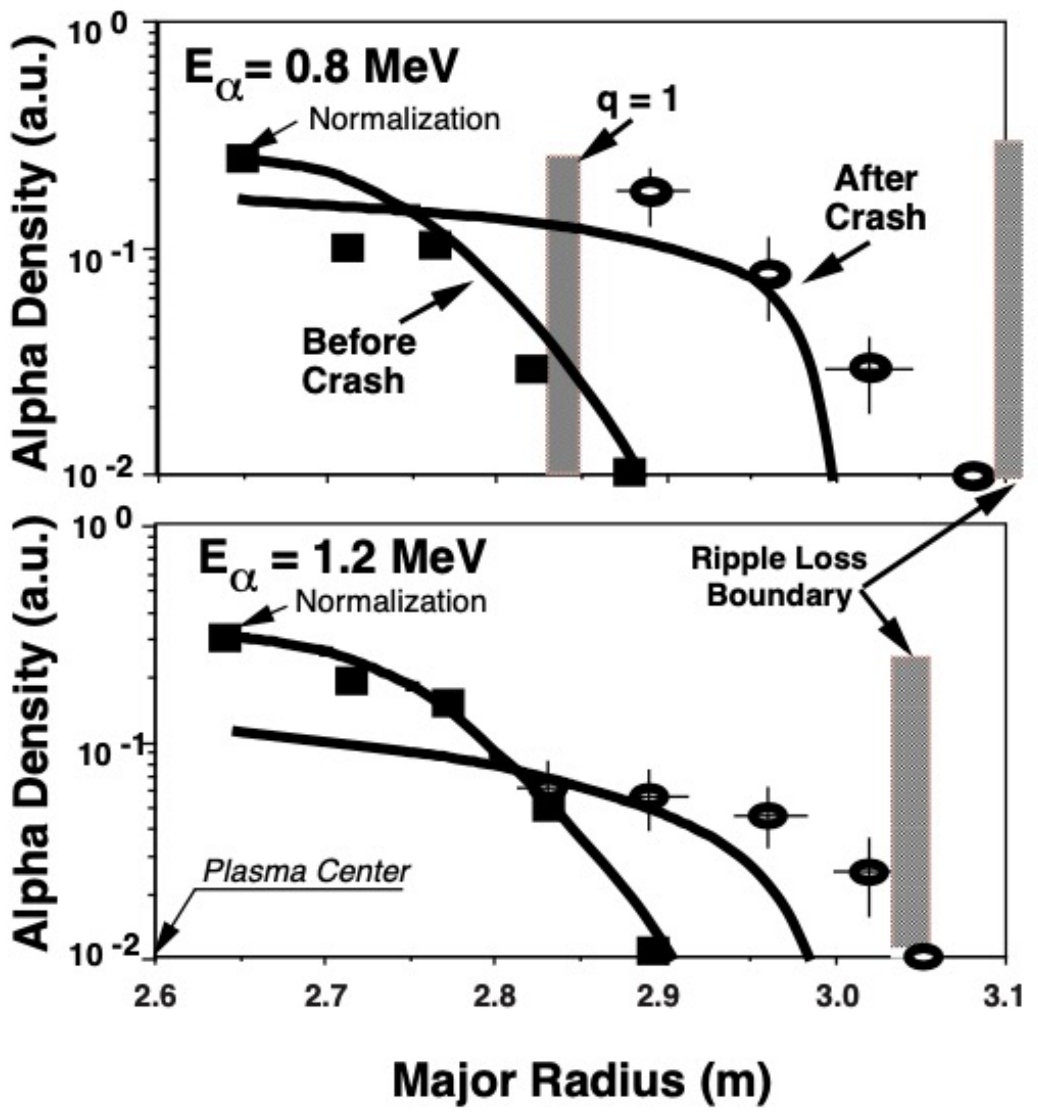


a/R_0 = 0.87m/2.52m
B_{tor} = 5.1 T
IP. = 2.0 MA
$E_{beam} \leq$ 110 keV
r/a ≈ 0.017

Stratton, Nucl. Fusion 1996 Fig. 2 – TFTR

Similar results were measured with the Pellet Charge exchange (PCX*) diagnostic

- α's were depleted in the core and redistributed to well outside the q = 1 radius
- Redistribution not observed beyond the stochastic ripple boundary for the associated energy.
- The observed broadening decreased with increasing alpha energy.
- Reasonable agreement between the PCX sawtooth measurements and the FPPT simulation
- Larger q=1 radius would move ions past ripple loss boundary, causing greater losses?



a/R_0 = 0.87m/2.52m
B_{tor} = 5.1 T
IP. = 2.0 MA
$E_{beam} \leq$ 110 keV
r/a ≈ 0.017

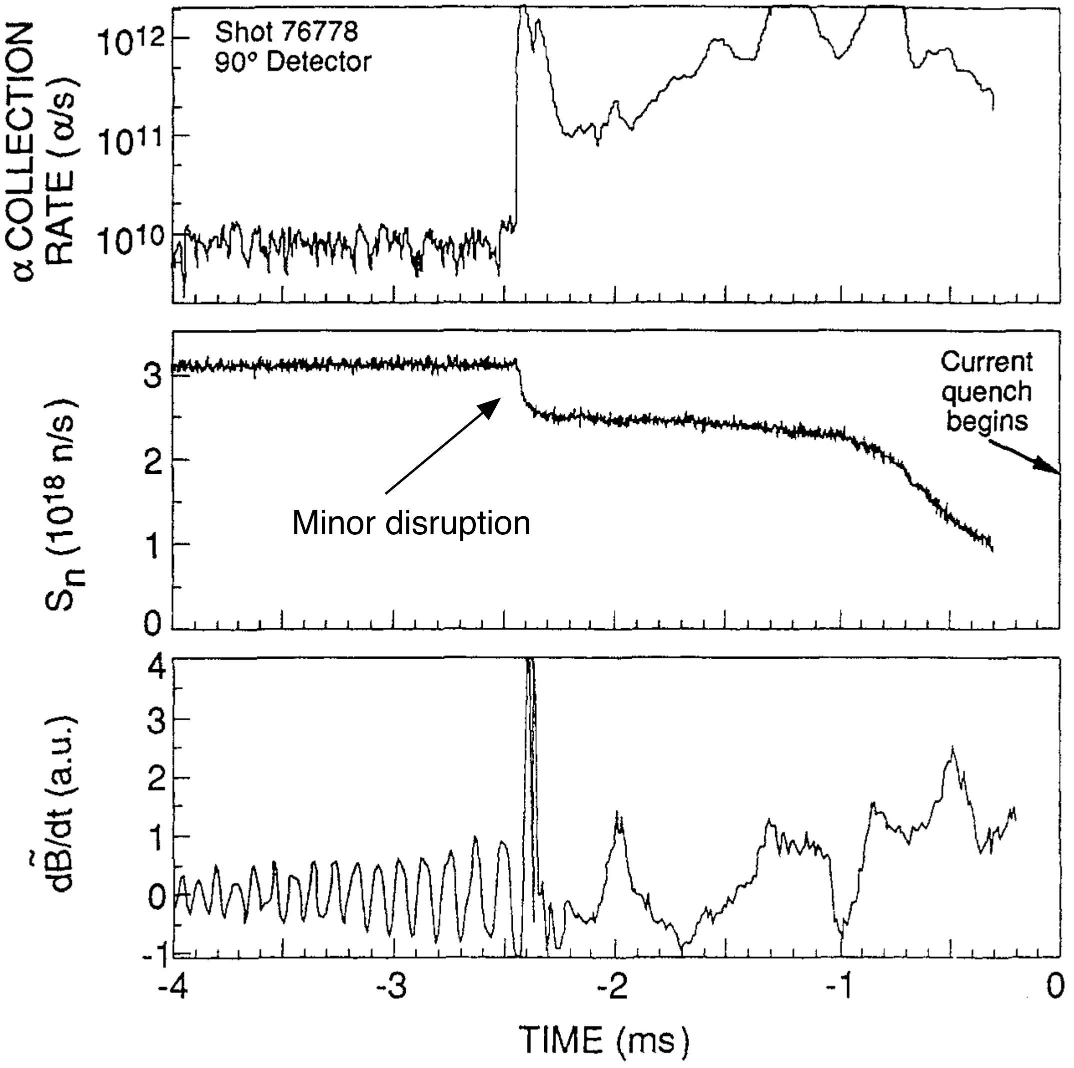
Zweben, Nucl. Fusion 2000, Fig. 18 – TFTR tokamak

*Fisher, R.K., et al., Rev. Sci. Instrum. 63 (1992) 4499.

Disruptions

Fusion-α loss during major disruption

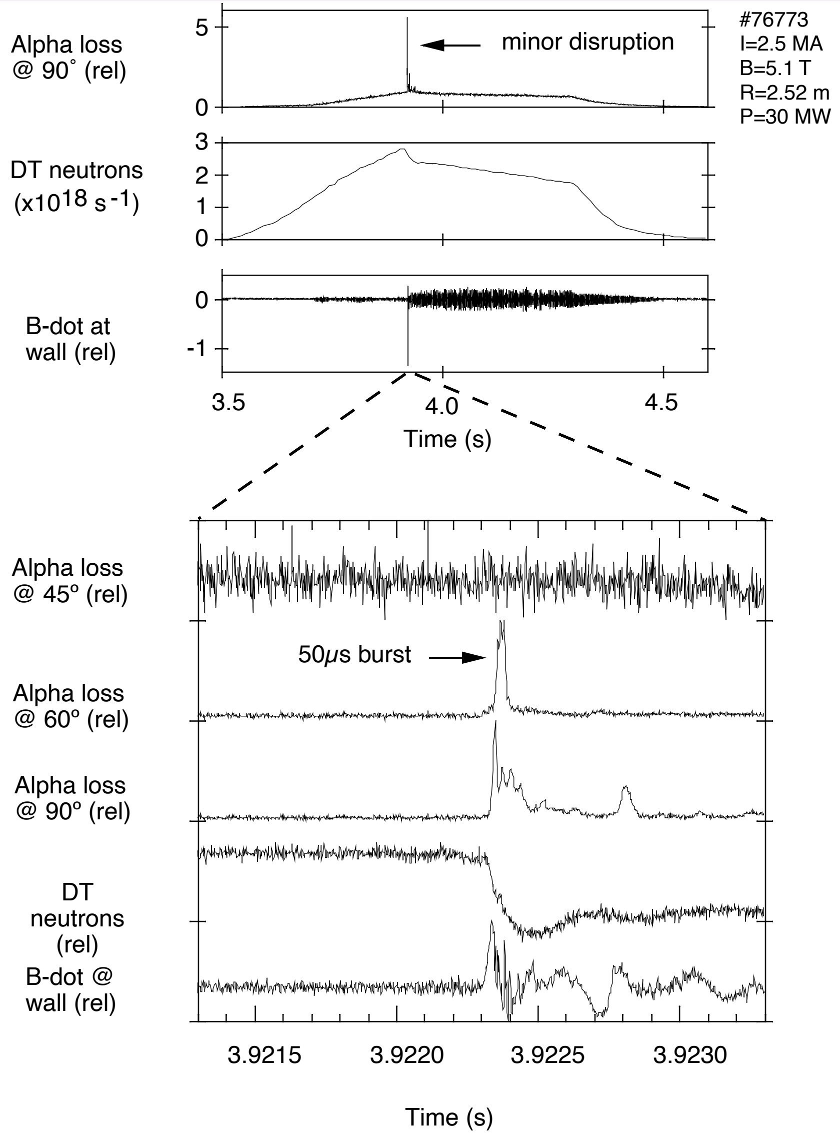
- Fast ions are lost during disruptions, but...
- ...that really isn't the thing to worry about.
- This major disruption was triggered by a minor disruption releasing about 10% of the plasma thermal energy.
- The plasma current hasn't changed in this time window, but a cold wave of carbon and deuterium is coming in from the limiter.



Zweben, Nucl. Fusion 1995 Fig. 20 – TFTR

Fusion-alpha loss during minor disruption

- Very similar α losses for minor disruptions and sawteeth (except for abrupt neutron rate drop).
- ≈ 2 – 3 % of 6 MJ of stored energy lost in ≈50 μs.
- ITER not likely to tolerate "minor" disruptions due to relatively larger stored energy.
- TFTR major disruptions (current quenches) triggered by "minor" disruptions.

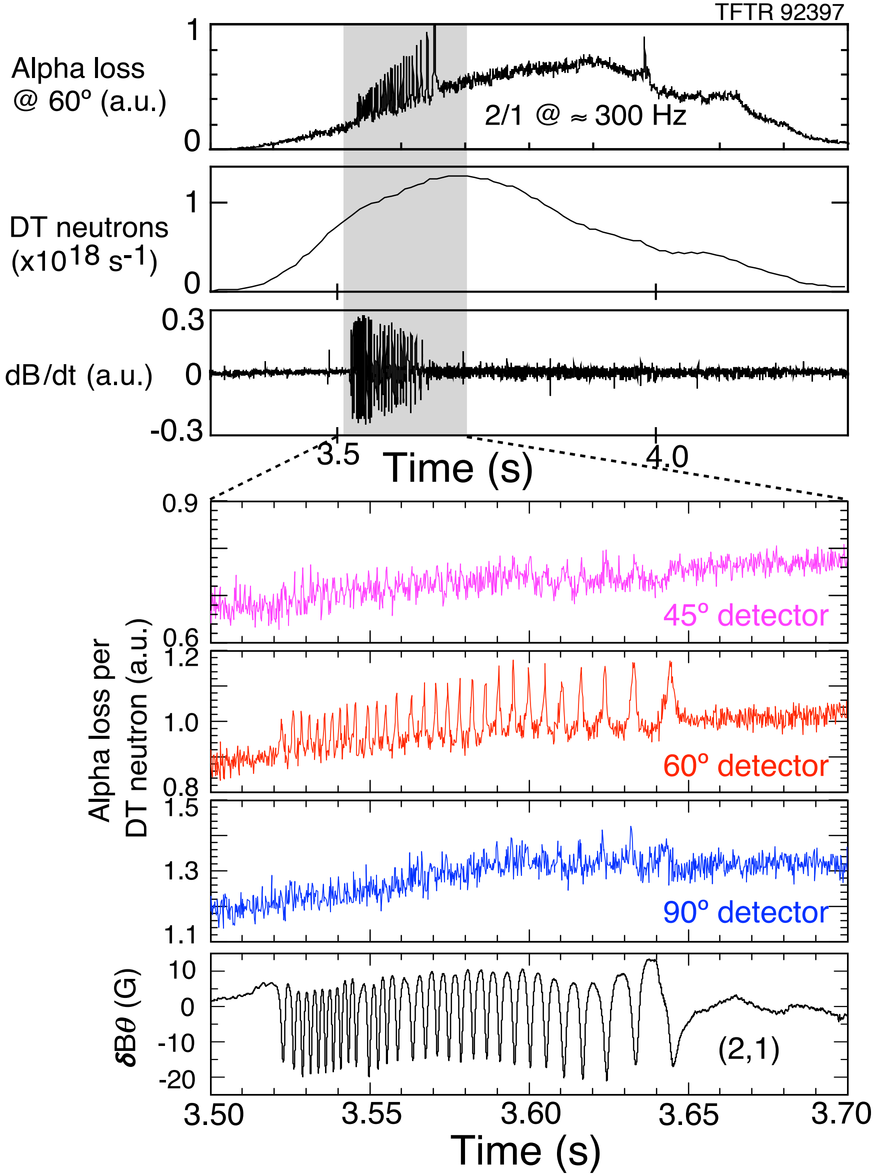


Zweben, Nucl. Fusion 1999 – TFTR tokamak

Tearing modes

Localized Fusion-α loss during 2/1 MHD

- (2,1) tearing mode + (1,1) internal kink induced alpha loss in TFTR.
- The magnetic fluctuations and alpha loss are well correlated.
- Loss is predominantly to detector 60º below the midplane.
- Detectors 90º and 45º show less MHD induced alpha loss. The peak alpha loss at the 60◦ detector is about double the loss without MHD activity.
- Island width ≈ 7%

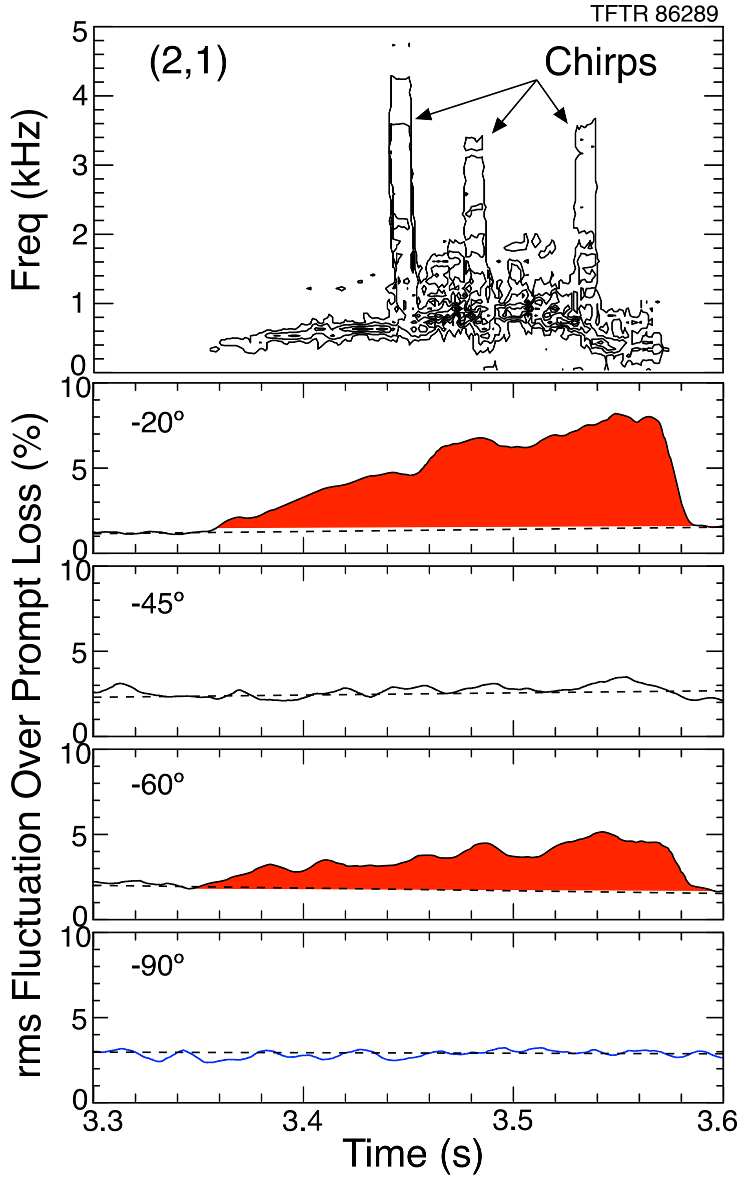


a/R_0 = 0.87m/2.52m
B_{tor} ≈ 5.0 T, Ip ≈ 2.3MA
E_{beam} ≤ 110 keV
r/a ≈ 0.017

Zweben, Nucl. Fusion 2000 – TFTR tokamak

Losses can be very poloidally localized

- These are coherent losses, the fluctuation amplitude as a percent of the prompt losses is shown here.
- Most(?) modeling of fast ion losses shows relatively simple poloidal dependencies.
- Single-point measurements could be misleading if that "point" were where there were no losses, or strong losses.
  - Even multi-point measurements, as here, could miss a lot of structure.

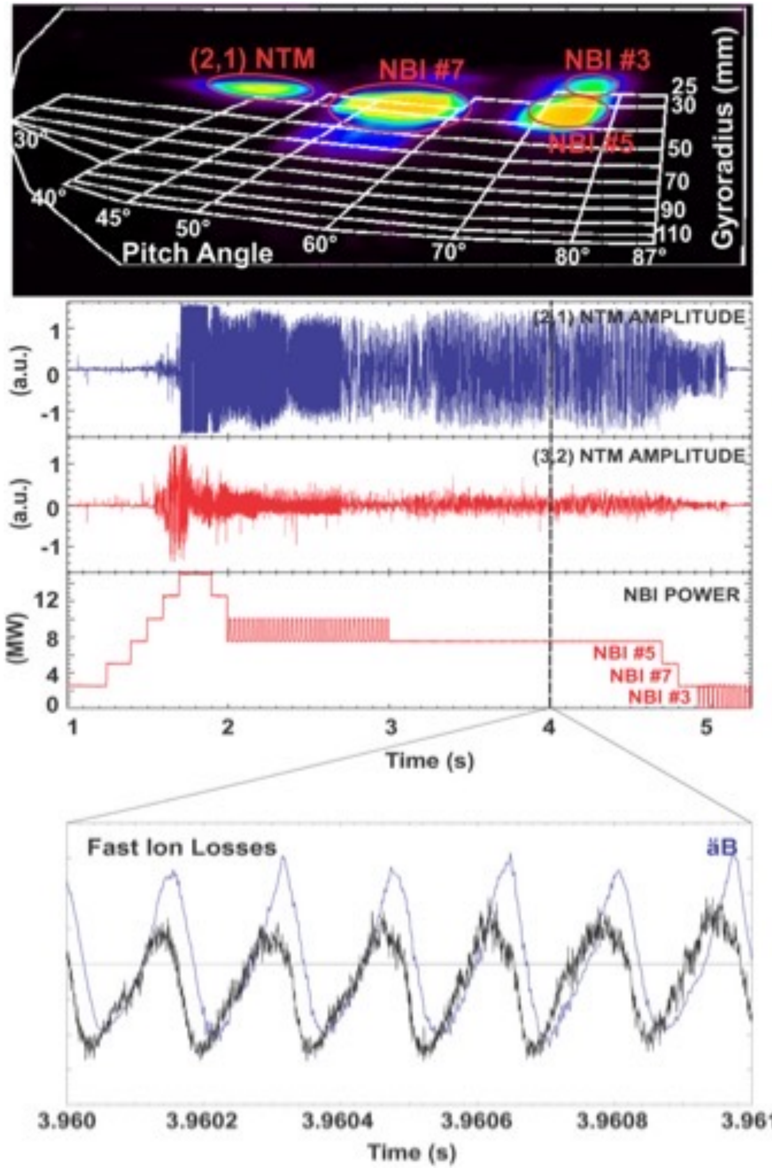


4.9 T, 1.5 MA, 2.45m

Similar coherent losses seen on other machines, notably AUG

- These would be equivalent to the losses seen on the “20º” probe on TFTR.

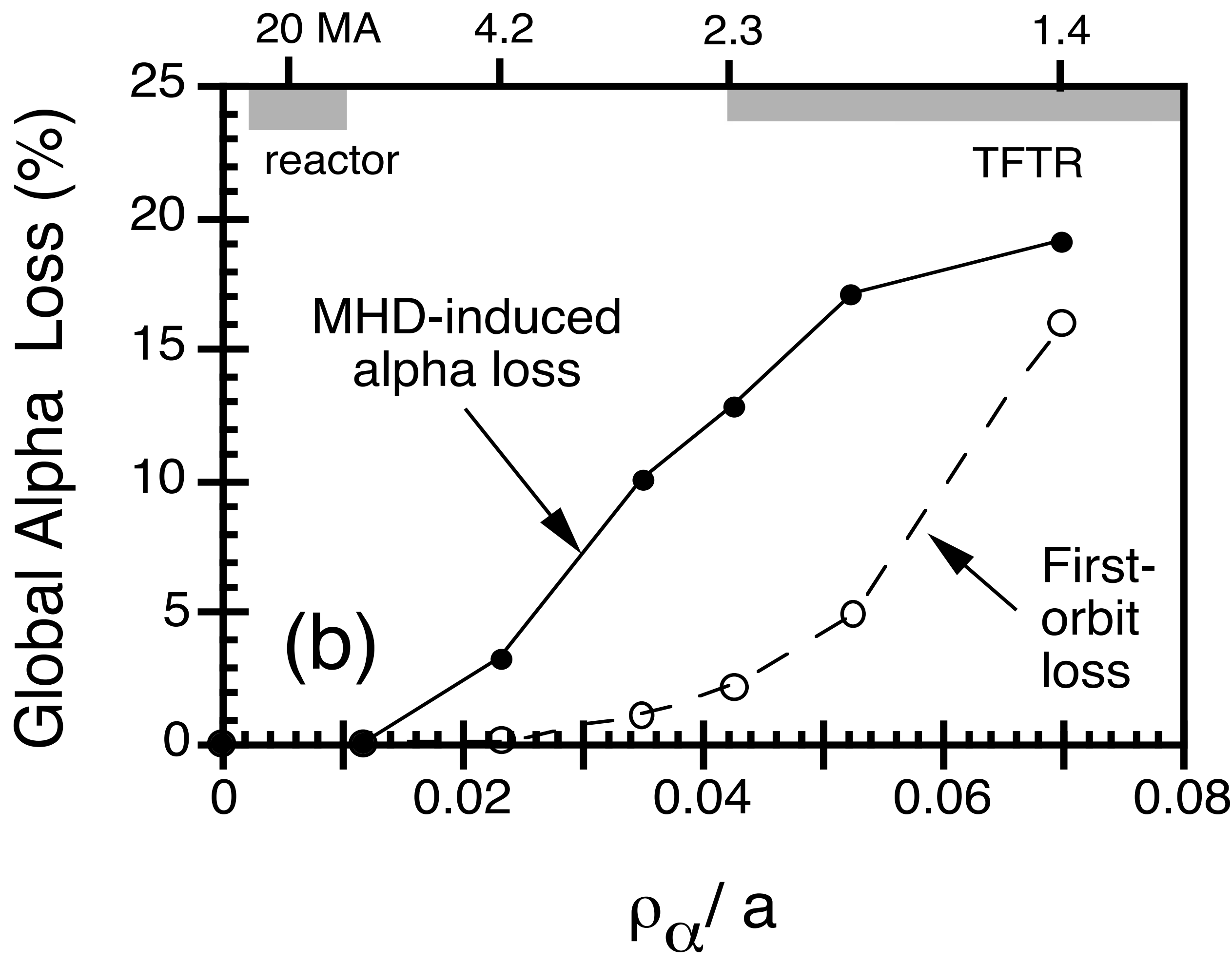
- The tearing mode introduces losses at lower pitch-angle than the prompt losses seen before the mode appeared.



Garcia-Munoz, Nucl. Fusion 2007 – AUG

Higher toroidal field also tends to reduce losses

- Alpha loss fraction versus ρ_α/a for a fixed ratio of island width to minor radius for a large m = 2, n = 1 mode
- ρ_α/a varied by changing the birth energy).
- The coherent MHD induced alpha loss should be negligible for reactor relevant ρ_α/a.

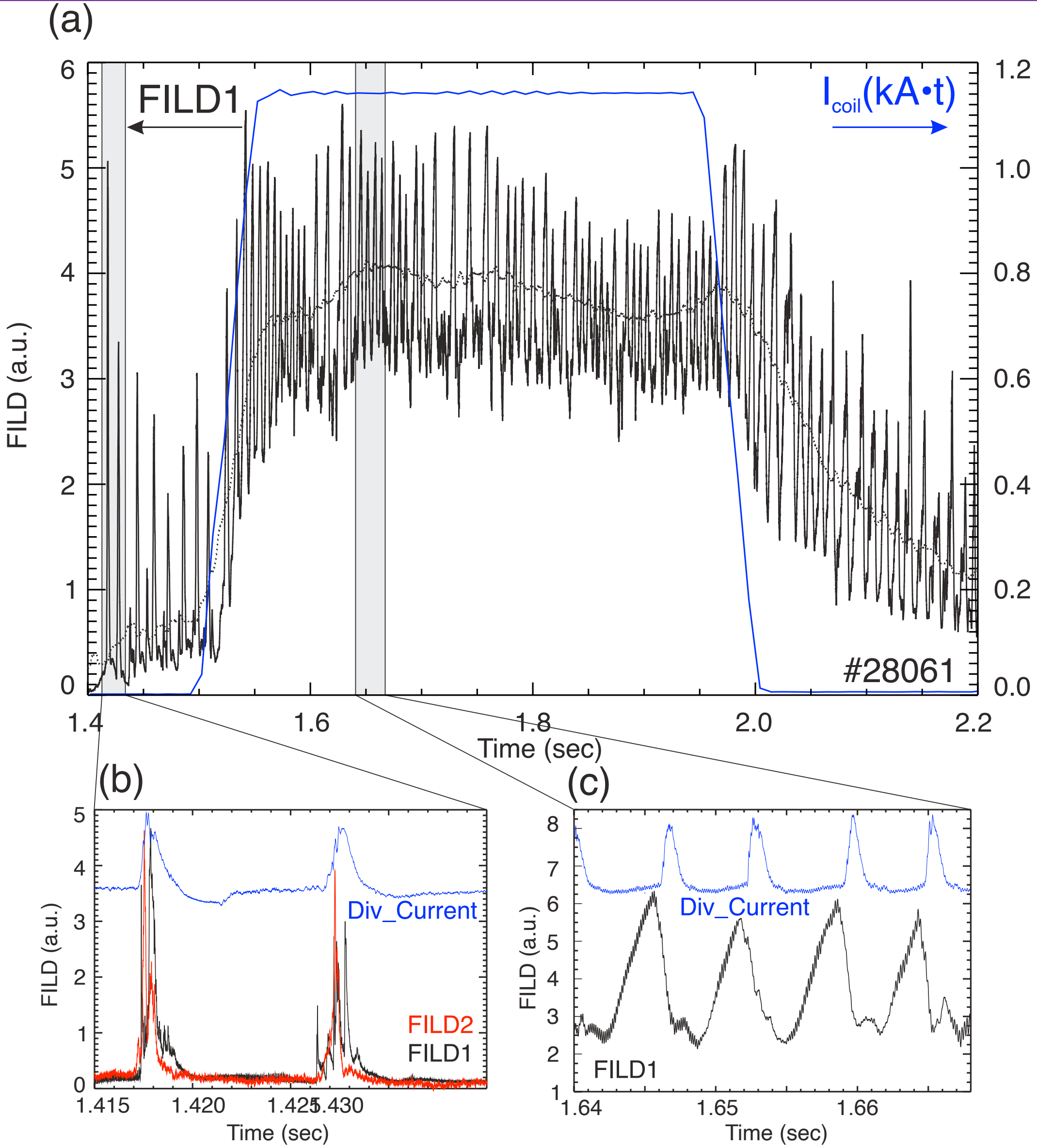


Zweben, NF 1999 Fig. 12, TFTR

ELMs

Fast-ion losses from ELMs with and without external magnetic perturbation

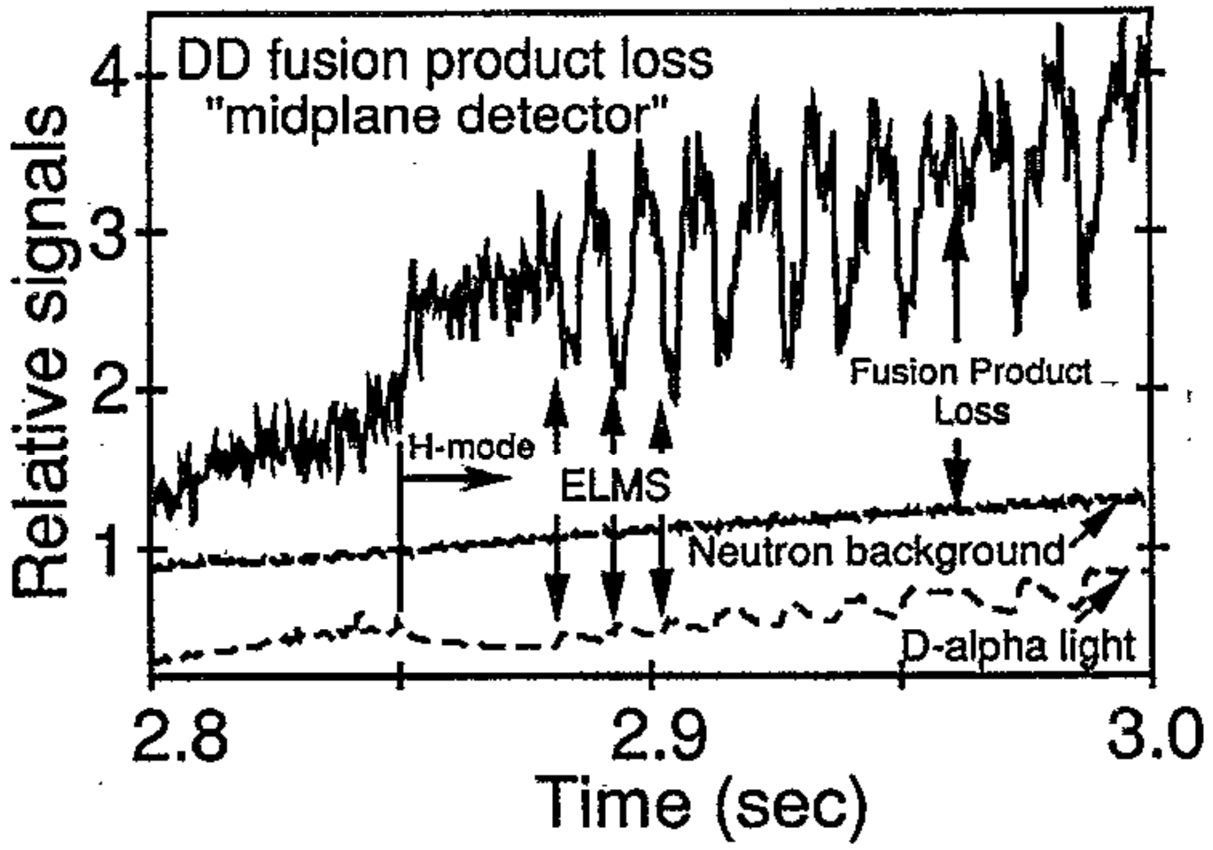
- Fast-ion losses are seen during ELMs.
- But with magnetic perturbation fast-ion losses decrease during ELMs.



Garcia-Munoz, PP&CF 2010 – AUG

TFTR ELMs

- α loss to 20º detector jumps at H-mode transition, drops to pre-H-mode level at ELMs.
- α-loss relatively unaffected at 90º detector by H-mode transition or ELMS



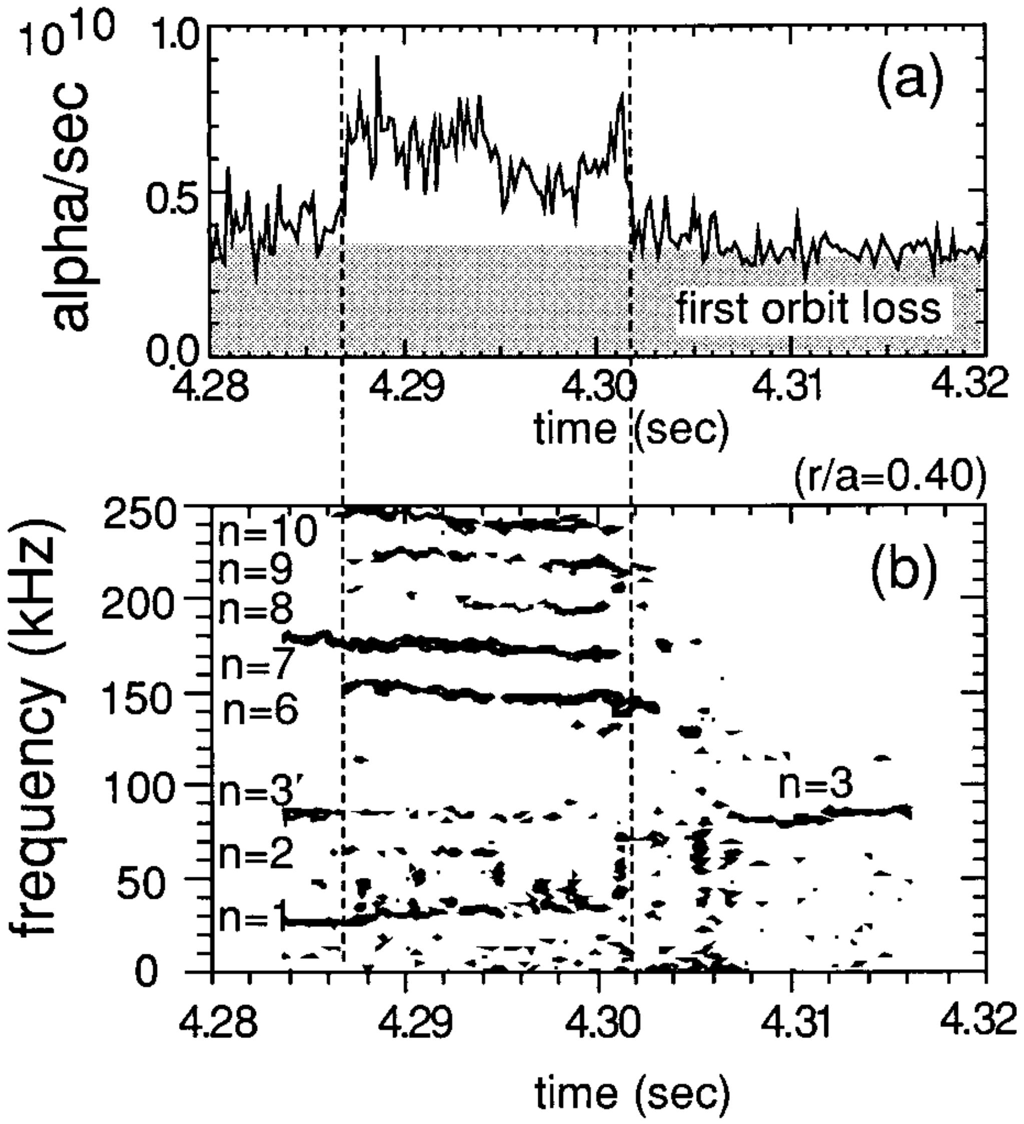
Bush PoP **2** (1995) 2366.

Zweben, Nucl. Fusion 1999 – TFTR tokamak

KBMs

Fusion-α loss due to KBMs on TFTR

- As far as I know, the only experimental observations of Kinetic Ballooning modes (KBMs) were on TFTR.
- Like TAE, they led to a modest enhancement of fusion-α losses.

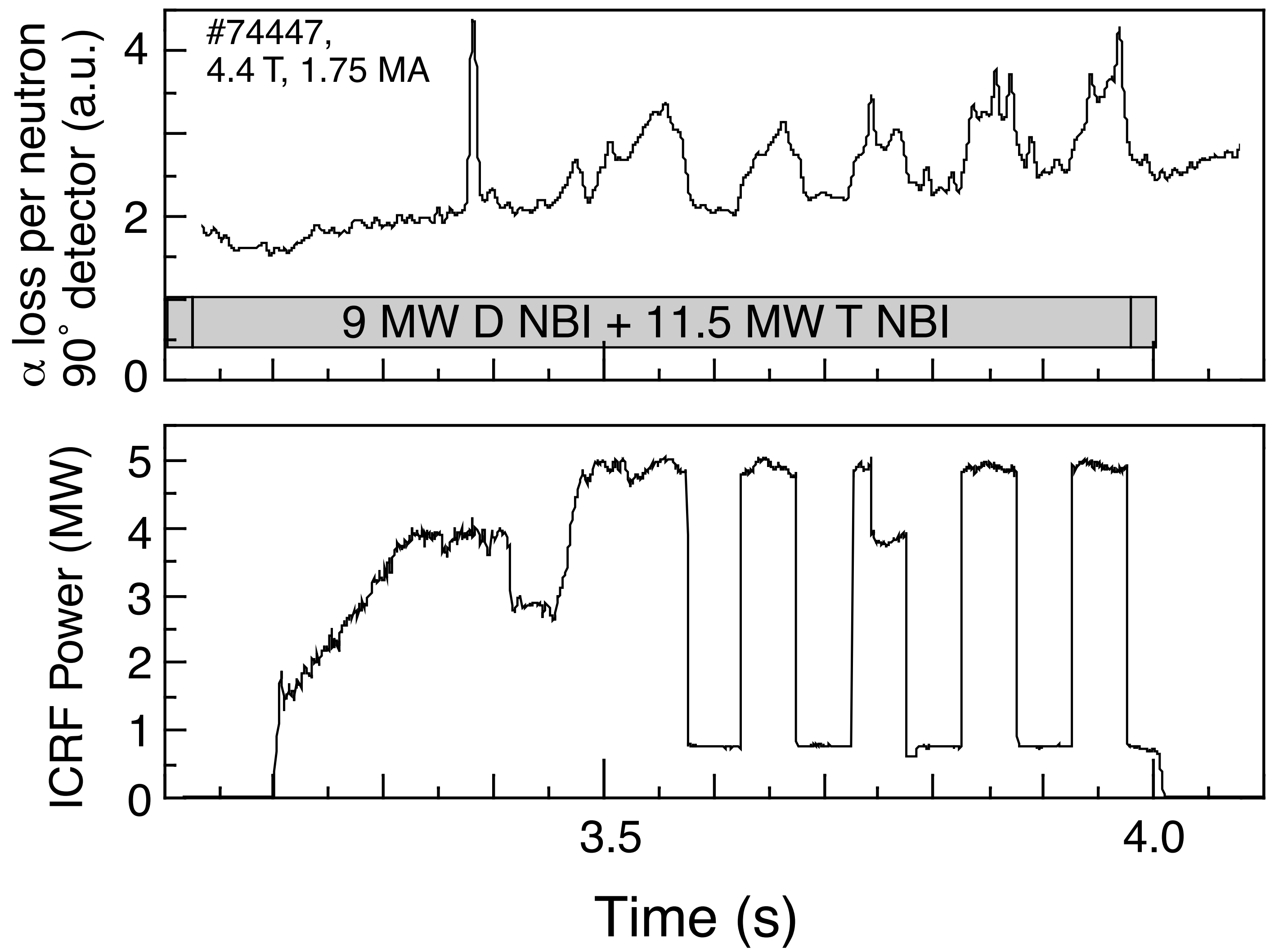


Z. Chang, Phys. Rev. Lett. 1997 – TFTR

ICRF

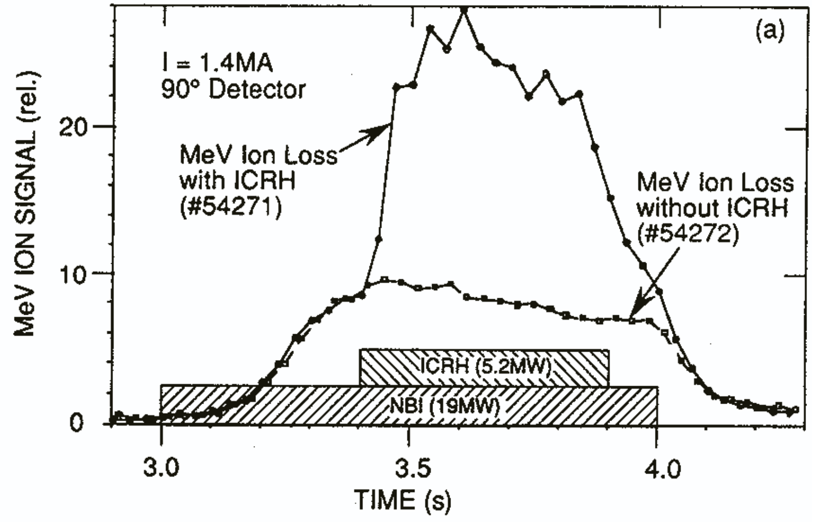
High-harmonic fast wave heating causes α losses

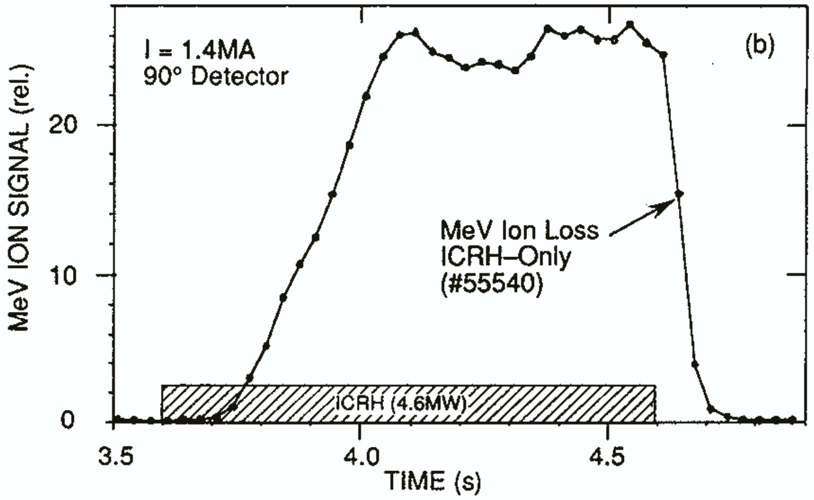
- The “non-resonant” high-harmonic fast wave heating was being used to heat electrons.
- Fusion-α’s were lost when resonant with the HHFW.
- The loss was from marginally passing particles converted to ”fat” banana orbits, which were lost.
- Similar losses seen in mode-conversion Bernstein α-channeling experiments



MeV ion loss during ICRF (w/wo NBI)

- Data from ^{3}He minority heating.
- These ICRH induced signals are interpreted as being due to first-orbit loss of the 3.7 MeV alpha particles from D-^{3}He reactions.
- MeV ion loss signals versus time to the 90º detector.
    a) Increase (x2-3) in the MeV ion loss signal during 5.2 MW ICRH in a 19 MW NBI plasma.
    b) MeV ion loss with 4.6 MW of ICRH alone (without NBI).





Zweben, Nucl. Fusion 1992 – TFTR tokamak

Summary

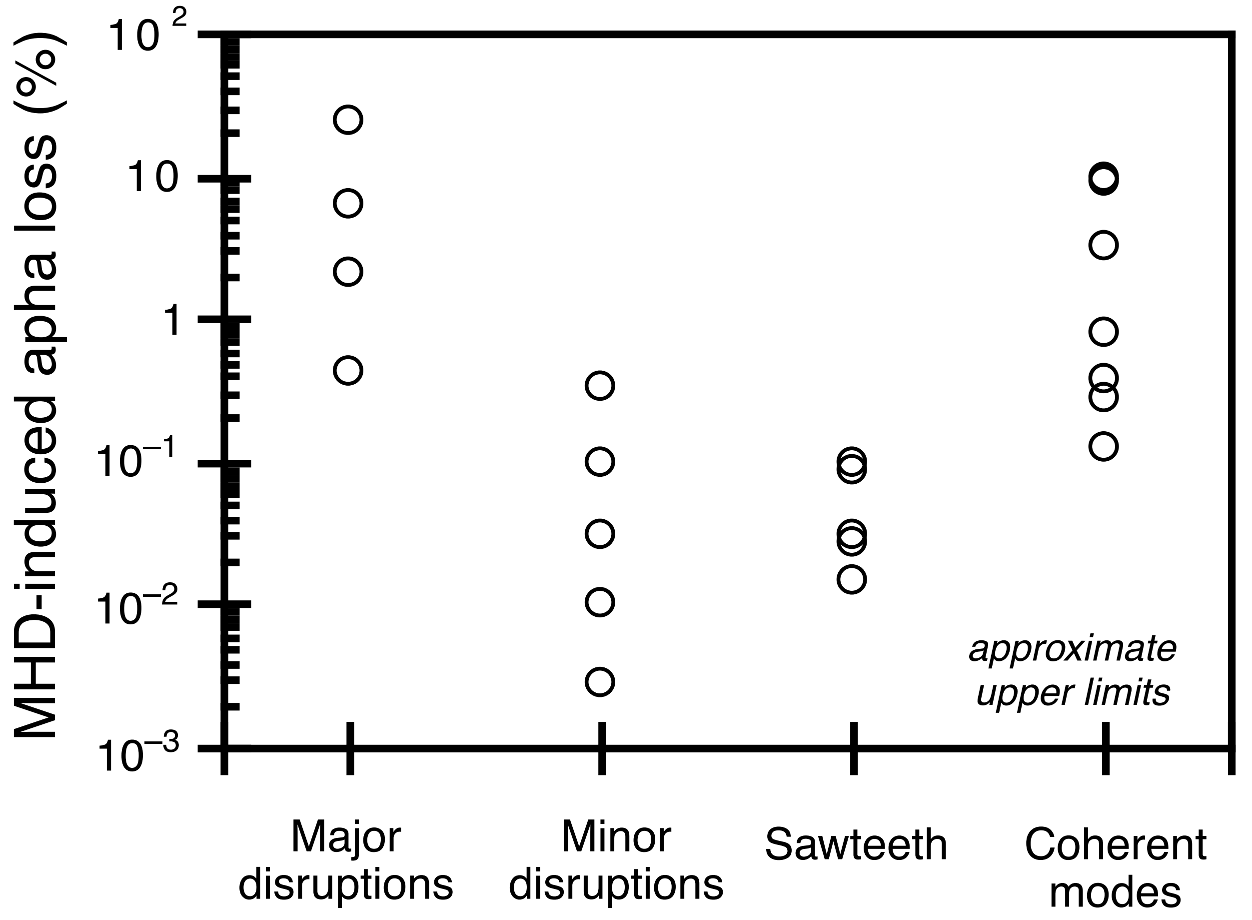
The good news: no serious problems identified

- Most cases of fast-ion redistribution are found to have modest impact on the fast-ion population, or occur in conditions that are relatively easy to avoid.
- The extrapolation from present machines to reactor parameters generally reduces the expected impact of instabilities on the fast-ion population.
- The uncorrected magnetic ripple in ITER may be a problem, but a solution exists.
- ITER is still a big step from present tokamaks and surprising discoveries in tokamak plasma physics are not uncommon.
- Localized PFC heat loads could still potentially create problems.
- This is not necessarily true for the two leading alternatives to tokamaks:
  - Stellarators somewhat intrinsically tend to focus fast-ion losses to small regions.
  - ”Spherical” tokamaks aim to reach reactor conditions in smaller, lower field devices.

Fraction of fusion products lost to wall due to MHD (FMHD) in TFTR was tolerable.

Figure 9. Estimate of the MHD induced alpha loss fraction for various types of MHD activity in TFTR, averaged over the three fixed poloidal detectors and the duration of the MHD activity. The vertical scales are order of magnitude estimates for the alpha loss fractions; for example, the alpha loss during a single sawtooth event is <0.01%, i.e. negligible with respect to that during a major disruption.

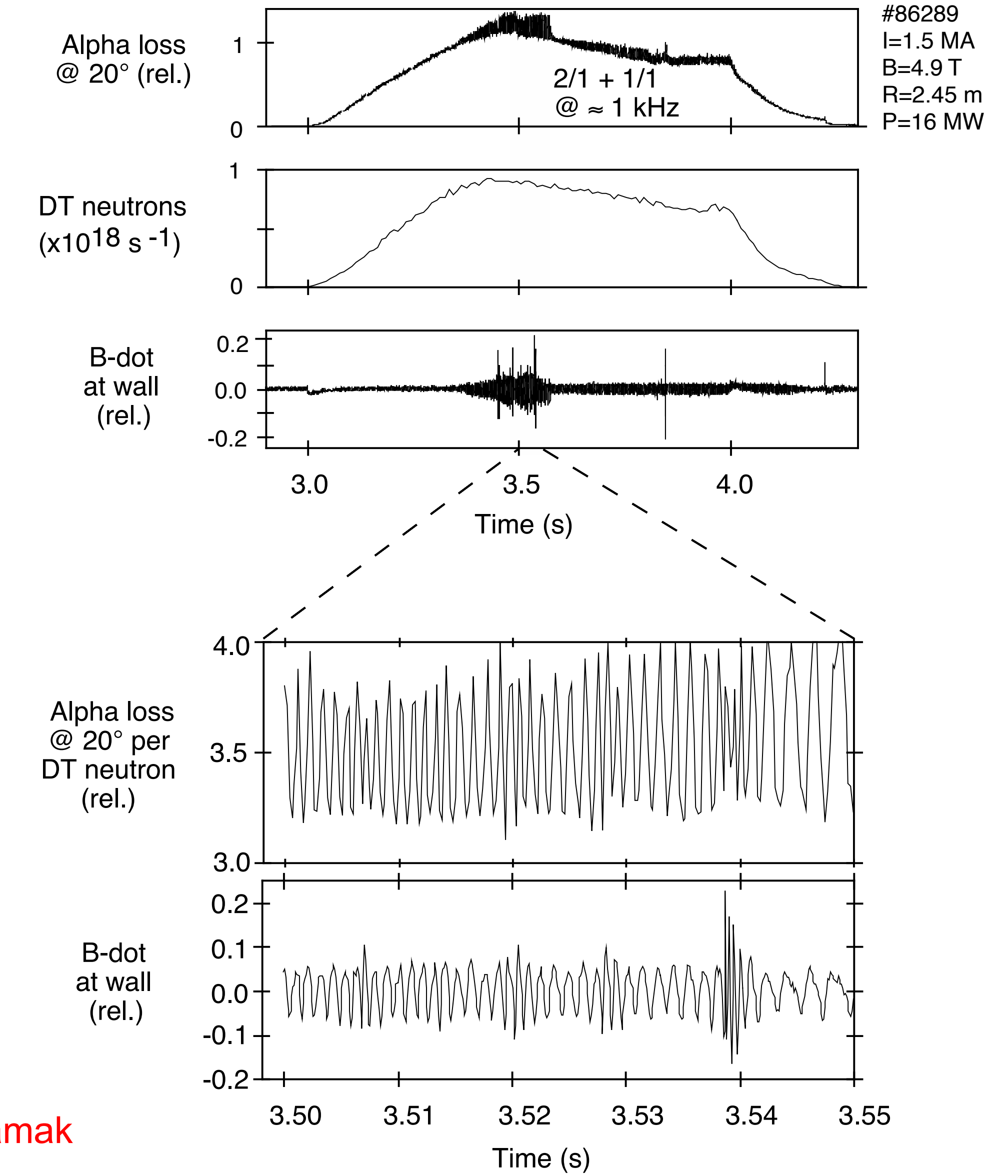
Of course, these FMHD are only order of magnitude estimates given the approximations used in Eq. (1), particularly since only a small fraction of the wall area was used to estimate the factor M. However, one confirming measurement is that described in Ref. [26] where alpha loss due to a sawtooth crash as estimated from α-CHERS was found to be negligible, which is consistent with Fig. 9.



Zweben, NF 1999 – TFTR tokamak

Fusion-α loss during 2/1 MHD

Figure 1. Example of coherent MHD induced alpha loss in a standard TFTR DT supershot with I = 1.5 MA and15MW of NBI. This discharge had m=2,n=1 and m = 1,n = 1 components at about 1 kHz, which caused an increase in alpha loss by up to ≈30% in the midplane detector. The midplane detector aperture in this discharge was at −2 cm with respect to the limiter shadow. The B-dot signal measured the MHD perturbation at the wall.



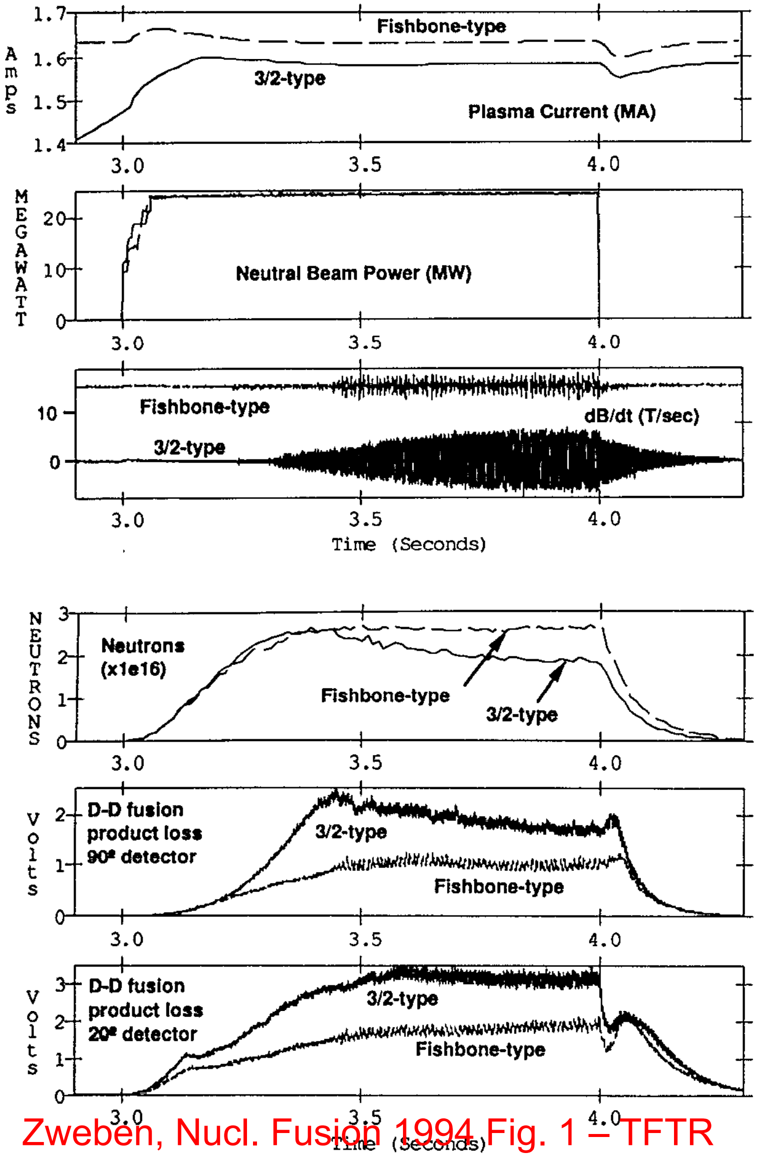
a/R_0	= 0.80m/2.45m
B_{tor}	≈ 4.8 T
E_{beam}	≤ 102 keV
Width/a	≈ 0.06
ρ^*/ρ^*_{ITER}	≈ 0.67
loss	≤ %

Zweben, Nucl. Fusion 1999 – TFTR tokamak

D-D fusion product loss 3/2 NTM

FIG. 1. MHD-induced loss of D-D fusion products during NBI for R =2.45 m, I= 1.6 MA, 24 MW NBI discharges in TFTR. These shots differ in their type. of MHD activity, most likely due to the different plasma current evolution before NBI (and not the slightly different final current). The MHD-induced loss in the fishbone-type shot (#66896) starts at about 3.45 s, while the MHD-induced loss in the 3/2-type shot (#66869) appears to start at ≈ 3.25 s. The D-D fusion product loss at both the 90º and 20º (midplane) detectors increases by ~20% at each fishbone, and by ≈x2-3 above the MHD-quiescent level during 3/2-type MHD. Without the MHD activity, the escaping fusion product signals at 90º follows the time dependence of the first-orbit loss early in time (≤0.2 s), with delayed loss dominating the signals later. The Mirnov signals are taken from a coil at the vessel wall near the outer midplane.

a/R_0	= 0.80m/2.45m
B_{tor}	≈ 4.8 T
E_{beam}	≤ 99 keV
Width/a	≈ 0.06
ρ^*/ρ^*_{ITER}	≈ .67
loss	≤ 13%



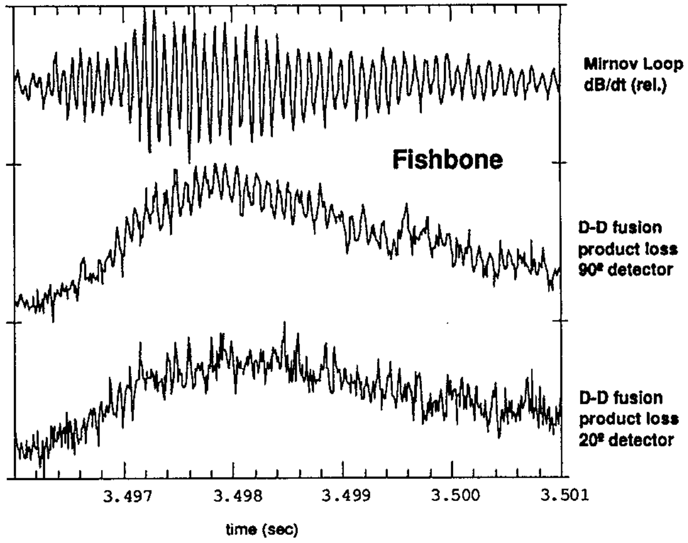
Zweben, Nucl. Fusion 1994 Fig. 1 – TFTR

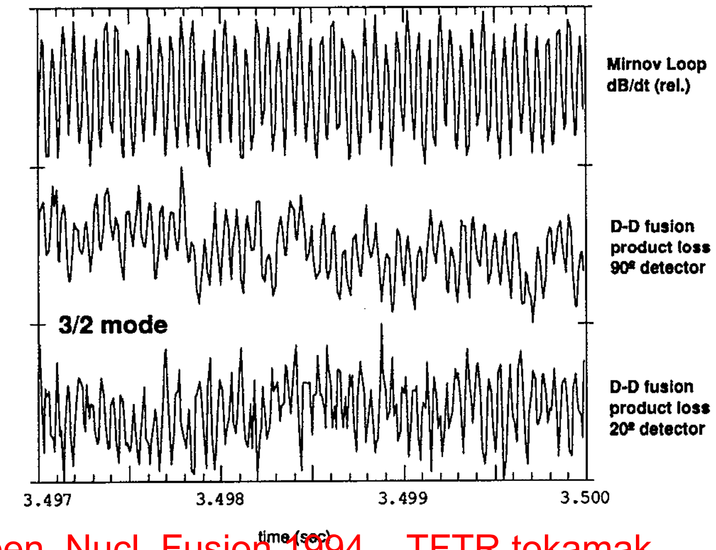
FIG. 1. MHD-induced loss of D–D fusion products during NBI for $R=2.45$ m, $I=1.6$ MA, 24 MW NBI discharges in TFTR. These shots

FIG. 2. Comparison over a time scale of ≈3–5 ms of the MHD activity and fusion product loss for the same two shots shown in Fig. 1. The escaping D–D fusion product signals are only weakly modulated at the

D-D fusion product loss 3/2 NTM

FIG. 2. Comparison over a time scale of -3-5 ms of the MHD activity and fusion product loss for the same two shots shown in Fig. 1. The escaping D-D fusion product signals are only weakly modulated at the fishbone frequency of ≈ 10 kHz, or the 3/2 mode frequency of ≈20 kHz. The inferred amplitude of the magnetic perturbation near the q= 1 surface during the fishbone is roughly $B_r/B_T= 10^{-3}$ and the amplitude of the 3/2 mode is roughly $B/B_T \approx 10^{-4}$ near the q=3/2 surface.





a/R_0 = 0.80m/2.45m
B_{tor} ≈ 4.8 T
E_{beam} ≤ 99 keV
Width/a ≈ 0.06
ρ^*/ρ^*_{ITER} ≈ 0.67
loss ≤ 13%

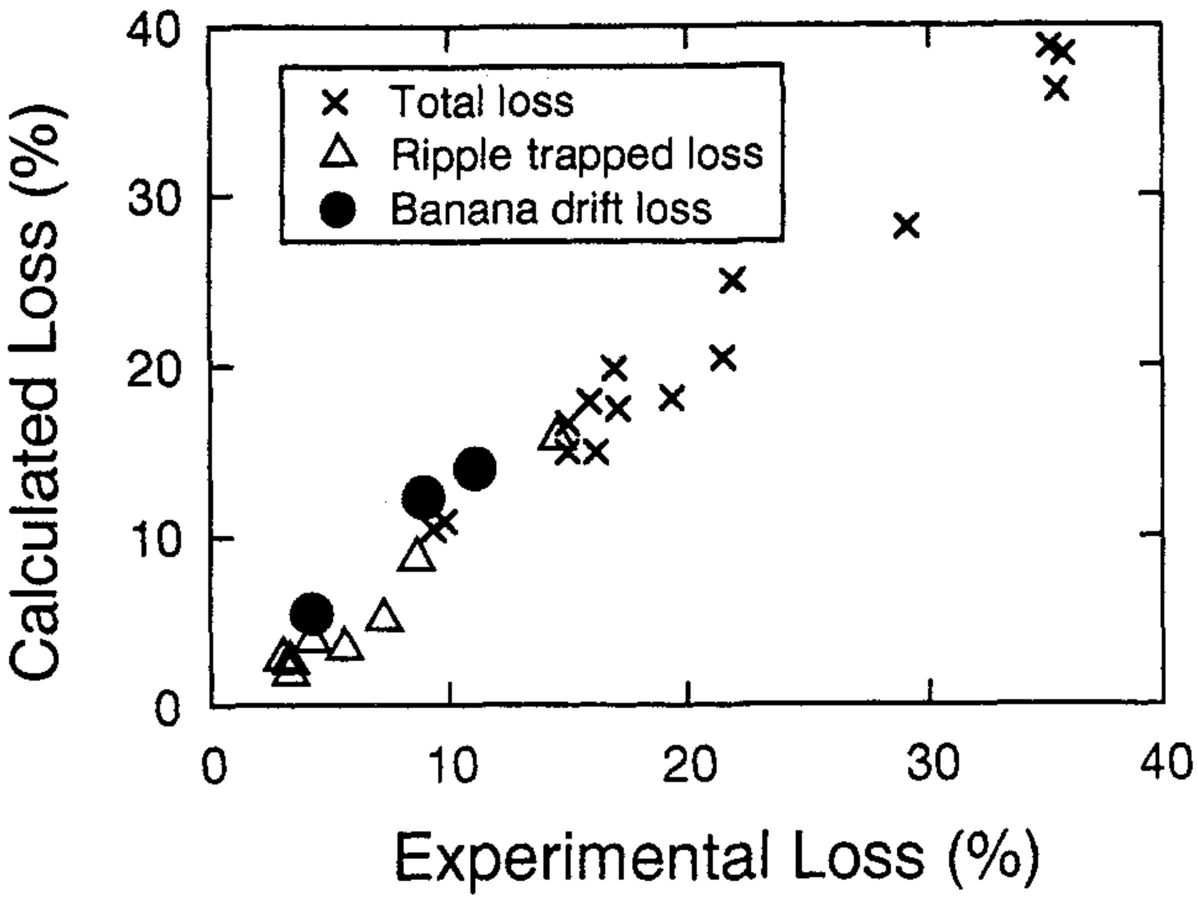
Zweben, Nucl. Fusion 1994 – TFTR tokamak

Fishbones

- Fishbones were first(?) coherent mode studied regarding fast ion losses.
- They were discovered on PDX (Poloidal Divertor Experiment), one of the first diverted tokamaks.
- A theoretical explanation for the mode, an energetic particle mode was quickly developed.
- Fishbones have subsequently been observed on most auxilliary-heated tokamaks.
- Fast-ion losses (neutron drops) reached 20% - 40% per burst , but in larger tokamaks at higher field losses are typically much lower.
- Multiple drive resonances for the fishbone (precession drift, w*, bounce frequency, ...) have been observed.
- “Classical” fishbone requires q=1 surface, although fishbone-like instabilities have been observed in reverse-shear plasmas with q > 1.

Summary of JT-60U ripple loss experiments

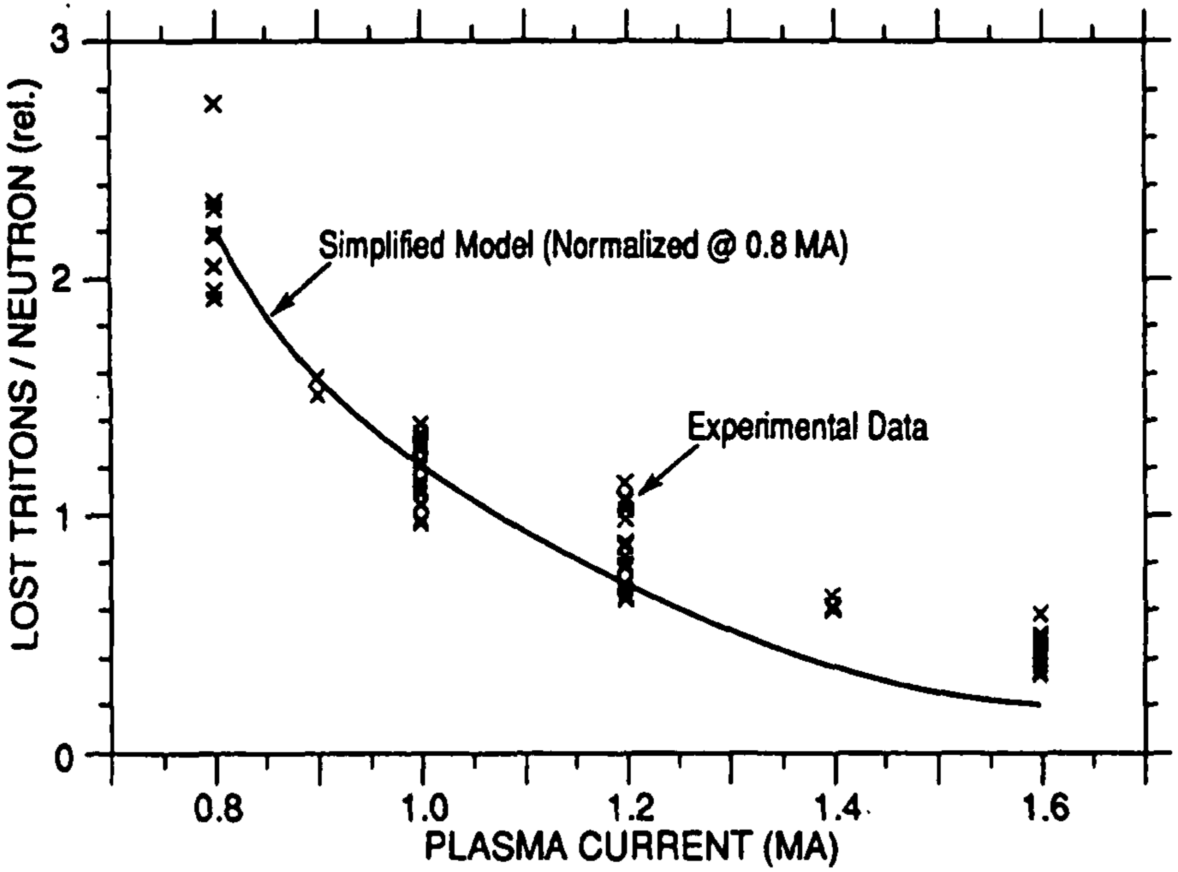
- Comparison between experimental and calculated ripple loss power fractions.
- Total loss is deduced from neutron decay for NBI blips,
- Partial ripple losses (ripple trapped and banana drift loss) are estimated from the heat load on the first wall.
- The error of experimental loss is typically ±15% of the values.



Tobita, NF 1995 Fig. 5, JT-60U

Losses drop quickly with increasing plasma current

- Triton loss fraction to 45°, 60° and 90° detectors versus plasma current.
- Measurements at fixed toroidal field of 4.8 T, R = 2.45m, a = 0.8m.
- Roughly consistent with a simplified first-orbit loss model.
- Deviation at highest currents possibly due to ripple-loss.



Zweben, NF 1990 Fig. 14, TFTR

Fast ion losses in ideal devices are typically easily predicted and negligible. However, the perfect magnetic geometries envisioned in conceptual machines are seldom achieved in practice. Necessary compromises in the design of coils, unavoidable errors in construction, and imperfect materials result in perturbations (error fields, ripple) to the idealized magnetic geometry. Further, instabilities driven by the inherent non-equilibrium nature of the thermal plasma (tearing modes, sawteeth, turbulence, disruptions, ELMs) and instabilities driven by the non-equilibrium fast ion populations themselves can all interact synergistically with each other and with field errors to result in significant losses of fast ions. Of particular concern for ITER, heating of the plasma with waves in the ion-cyclotron range of frequencies has also been seen to enhance losses. We describe here experiments which have documented the reduction of fast ion populations either by directly measuring the lost fast-ion flux, or by measuring the change in the confined fast ion population. The major concern is developing the ability to predict losses of fusion alphas in future ignited plasma devices such as ITER. Current and past experiments have studied the losses of D-D fusion products, beam ions, RF-generated ion “tails”, and some limited data on D- T fusion alphas (JET and TFTR). While alpha-driven TAE were seen on TFTR, their amplitude was low and the losses expected from those modes are presumed to be small. Measured losses have largely been found to be consistent with theoretical predictions (based, for example, on experimental estimates of mode amplitudes).

- Controlled thermo-nuclear fusion means fusion-α's must transfer their energy to the thermal ions and gracefully leave the plasma.
- Not all fast ion redistribution or losses are necessarily bad; the "Holy Grail" would be to discover "α-channeling", waves that take energy from α's while transporting them outwards and then damping on the thermal plasma.
- Resonant vs. stochastic losses
  - neutron rate drops can result from resonant energy transfer from fast ions to thermal plasma (good?) as well as loss of energetic ions.
  - stochastic losses often(?) result from synergies between coherent modes and other loss mechanisms, e.g., magnetic ripple.
  - generally, stochastic losses are bad in that energy is lost from the plasma.
- Parameters that affect losses:
  - mode amplitude
  - resonances (spatial or temporal)
  - normalized larmor radius, $\rho* = \rho_{fi}/a$ (I will show $\rho*$ normalized to the typical ITER value of $\rho* = 0.025$).
- Pretty much every machine with neutral beam or RF heating has studied fast-ion confinement; this talk can only lightly touch the depth of the experimental database.

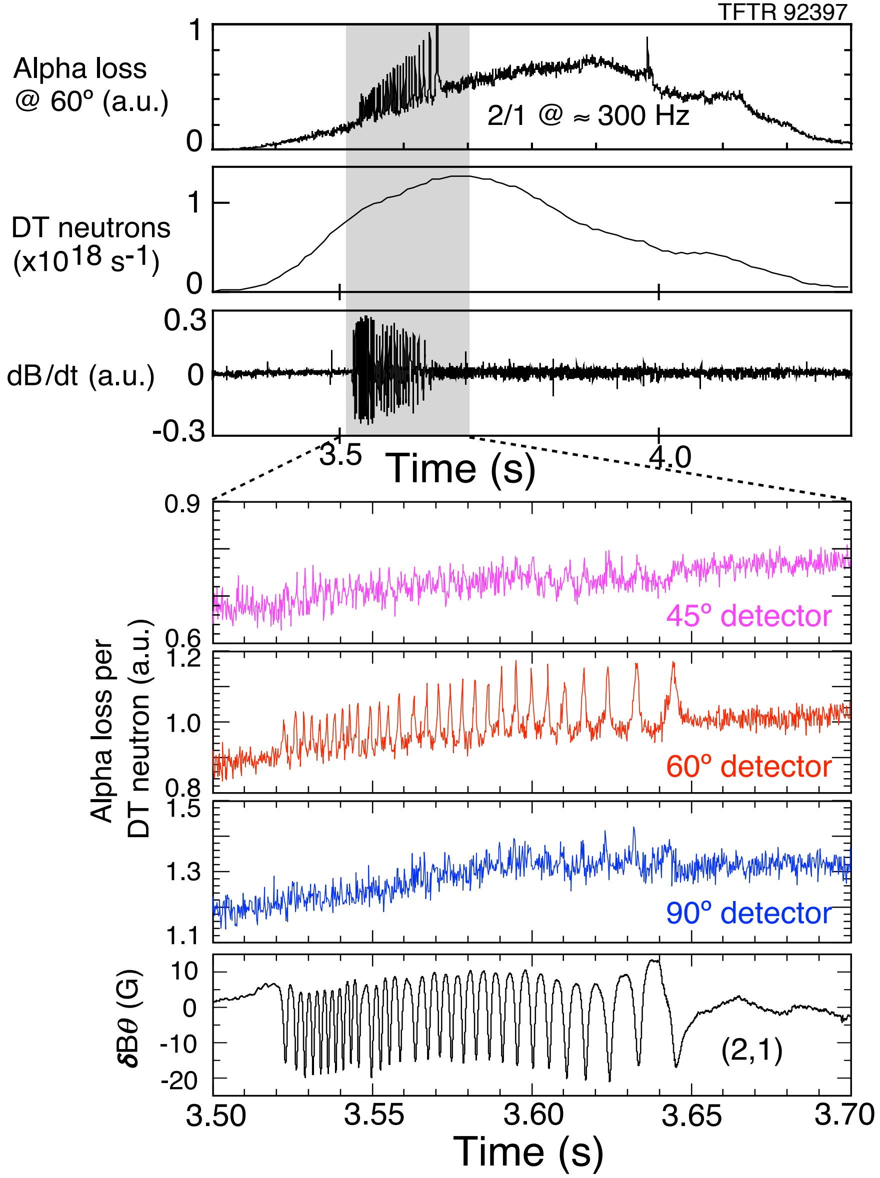
Need theory, modeling to project to ITER

- Experimental measurements of fast ion losses are necessary to:
  - validate codes used to accurately predict ignition margins in future reactors; because losses and profile flattening both reduce fusion reactivity
  - design plasma facing components to handle possible localized heat loads
  - (Best to avoid regimes with large fast-ion losses.)
- Conversely, too good confinement of fusion products reduces the plasma reactivity as fusion α's will displace the deuterium and tritium fuel.
- An ideal situation would be where waves extracted the energy from the fusion products while moving them out of the plasma, and depositing the energy in the thermal ion population, "**α-channeling**".
- Here we will discuss experiments to find regimes with large fast ion losses

non-uniform
ion losses

Losses may be very spatially localized

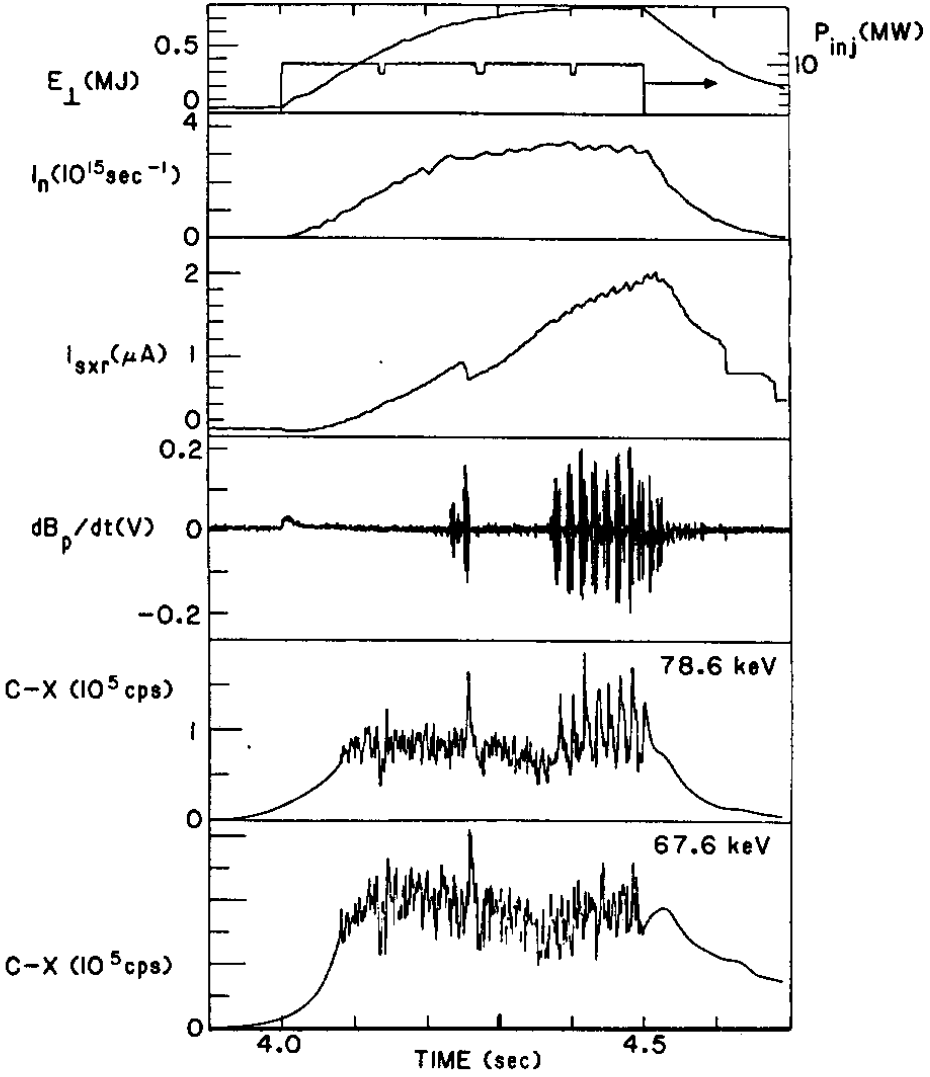
- In this example, virtually no losses seen on probes 45º and 90º below the midplane, but “large” enhancement in losses seen on 60º probe.
- Modeling is necessary to convert limited experimental data to total loss estimates.
- Experiments are needed to validate modeling codes.



D-D fusion product loss with f.b.

- At moderate toroidal fields (B_{tor} = 2.88 T), the impact of fishbones becomes largely ignorable.
- They do redistribute fast-ions in the core region.
- In TFTR they were beneficial for limiting the pressure profile peaking which otherwise would have led to disruptions.

a/R_0	= 0.80m/2.45m
B_{tor}	≈ 2.88 T
E_{beam}	≤ 95 keV
ρ^*/ρ^*_{ITER}	≈ 1.09
loss	≈ 1%



Kaita, Phys. Plasmas 1990 Fig. 1 – TFTR