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Alpha Particle Losses from Tokamak Fusion Test Reactor Deuterium-Tritium Plasmas

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Abstract

Because alpha particle losses can have a significant influence on tokamak reactor viability, the loss of deuterium-tritium alpha particles from the Tokamak Fusion Test Reactor (TFTR) has been measured under a wide range of conditions. In TFTR, first orbit loss and stochastic toroidal field ripple diffusion are always present. Other losses can arise due to magnetohydrodynamic instabilities or due to waves in the ion cyclotron range of frequencies. No alpha particle losses have yet been seen due to collective instabilities driven by alphas. Ion Bernstein waves can drive large losses of fast ions from TFTR, and details of those losses support one element of the alpha energy channeling scenario.

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I. Introduction

The Tokamak Fusion Test Reactor (TFTR)[1] has been operating with deuterium-tritium (DT) plasmas since December 1993.[2] The higher fusion rates of the DT reaction have provided an abundant source of energetic alpha particles. This population has afforded the chance to make measurements and understand the physics of alpha particles, particularly their losses from the plasma.

Measurements of the loss of alpha particles are of particular interest in planning tokamak fusion reactors for a number of reasons. First, good confinement of alphas is needed so that their energy sustains the plasma temperatures needed for ignition, and heats incoming fuel. Second, since the energy stored in the alpha population will total hundreds of megajoules in a reactor such as the International Thermonuclear Experimental Reactor (ITER)[3,4], knowledge of alpha particle loss processes is vital to designing the plasma facing components so that they will not be damaged by energetic alpha particle losses. Third, loss measurements give information about collective alpha particle instabilities, and heat fluxes on the wall that may be expected from such instabilities. Reference 5 contains a comprehensive review of fast ion and alpha particle physics including loss measurements and modeling, and issues of concern in reactor design.

Alpha particle loss processes fit into three broad categories: "classical," magnetohydrodynamic (MHD) instability induced, and radiofrequency (rf) wave induced. Classical losses are ones determined by the structure of the tokamak's magnetic geometry and such losses may be computed by following orbits of individual particles numerically. The main examples of such losses are first orbit loss, due to particles born on fat banana orbits which intersect the wall, ripple trapping losses, where particles are mirror trapped between toroidal field coils and drift out of the confinement region, and stochastic toroidal field ripple diffusion, where trapped particles with their banana tips in certain regions can diffuse to the wall due to stochasticity brought on by toroidal field ripple. MHD induced losses result from perturbations to the particle orbits which arise from the magnetic fields of the modes. Any sort of MHD mode, whether pressure driven, current driven, or kinetic, can cause losses. A particularly important subclass of these losses are those due to collective instabilities, where the alpha particles themselves drive the MHD mode. RF wave induced losses arise from interactions between plasma waves and the alphas. Such losses result from wave-driven diffusion of alphas into existing loss cones, e.g. first orbit or stochastic ripple diffusion. Fast ion losses in TFTR have been seen from fast waves in the ion cyclotron range of frequencies (ICRF) and ion Bernstein waves (IBWs). Tore Supra[6] has reported losses arising from lower hybrid waves.[7,8] Nearly any sort of plasma wave has the potential to produce losses of this kind.

Alpha particle losses from TFTR plasmas are measured by a poloidal array of detectors[9-11] just behind the limiter radius, as shown in Fig. 1. These detectors are situated 90°, 60°, 45°, and 20° below the outer midplane. Each, by means of a set of apertures, disperses particles by pitch angle and gyroradius onto a planar scintillator. Light from the scintillator is carried by fiber optic cables to remote detectors which record the total light versus time, and the image of the scintillator at intervals. The probes are sensitive to gyroradii between 2 and 11 cm, and pitch angles (defined as $\chi=\arccos(v_{tor}/v)$) between 45° and 83°. This range of pitch angles does not include ripple-trapped particles. A thin aluminum foil over the apertures of the 90°, 60°, and 45° probes excludes hydrogenic ions with energies below ~400 keV, and helium ions with energies below ~900 keV.

This paper summarizes alpha particle loss measurements to date in TFTR, and covers all three of the categories mentioned above. Section II describes classical losses. Section III covers recent measurements of MHD-induced loss, including results from toroidicity-induced Alfvén eigenmodes (TAEs), kinetic ballooning modes (KBMs), and edge localized modes (ELMs). Section IV briefly describes rf-induced losses. Section V summarizes the paper.

II. Classical Losses

The simplest classical loss is first orbit loss, which results from alphas being born on banana orbits which intersect the vessel walls. The fraction of alphas lost due to this mechanism can be computed from the q profile and the alpha source profile. Global losses in TFTR can vary from 3% of the total source rate[12] at I_p=2.7 MA to ~50% at I_p=0.6 MA. The alpha flux measured in the 90° detector from quiescent DT supershots in TFTR is in good agreement with the first orbit loss model over the entire range.[13] Figure 2 shows the peak pitch angle of the alpha particle loss to the 90° detector as a function of current. Also plotted are the expected peak pitch angles from a first orbit loss model. The model and experiment agree within the error bars at all currents checked.

A second variety of classical losses is stochastic toroidal field ripple diffusion, which results from the ripple in the toroidal field produced by the discrete field coils. The ripple causes radial diffusion of banana orbits whose turning points lie within a certain zone. For alphas in TFTR, that zone is roughly $0.5 \leq r/a \leq 1.0$. Losses due to ripple diffusion arise chiefly near the midplane, and thus are measured only by the 20° detector in TFTR. Because particles affected by ripple diffusion are trapped and are confined particles from the first orbit view, the losses occur at a higher pitch angle than first orbit losses in the same detector. Detailed descriptions of observations of these losses have been published elsewhere.[12,14]

Stochastic ripple diffusion losses for TFTR have been modeled for specific cases with the ORBIT guiding center code[15] and with an ORBIT renormalized model in the TRANSP code[16,17]. It is found that 5-15% of alphas are lost for experiments at 1.0-2.0 MA and R=2.52 m. Measurements made by the lithium pellet charge exchange diagnostic[18] of the radial profile and energy spectrum of alphas (E_α>0.5 MeV) in TFTR are generally consistent with the TRANSP calculations of ripple effects.

III. MHD & Collective Losses

A collective instability, the toroidicity induced Alfvén eigenmode (TAE), has been observed to be driven by neutral beam ions and ICRF H-minority tail ions in TFTR.[19-21] Such modes can cause losses due to the magnetic perturbations they create, which allow fast ions to escape.[22,23] Another loss mechanism was discovered in TFTR which involves a synergy between the TAE and toroidal field ripple. In this case, a TAE driven by H-minority tail ions transports those ions outward in major radius and increases their pitch angle. Some of the tail ions then become trapped in the toroidal field ripple, and drift immediately to the bottom of the vessel. This loss in higher ICRF power shots melted some components at the bottom of the TFTR vessel and, accumulated over many shots, eventually caused a vacuum leak by cracking a weld. Simulations[24] including the TAE and ripple revealed this loss mechanism, and were in reasonable agreement with the observed location of the damage.

A search has been made for the alpha driven TAE in TFTR. In some high fusion power discharges, an increase in the amplitude of a peak in the δB spectrum at the TAE frequency was seen.[25] Subsequent investigation, however, has shown that this peak is due to an edge-localized Alfvén mode, not a TAE.[26] The same mode often appears in ohmic shots and, hence, is not a fast ion driven mode. No additional loss of alpha particles was associated with this mode. The only MHD-enhanced loss of alphas that has been seen in high power DT plasmas results from plasma-driven MHD modes which also occur in D plasmas, i.e. modes which are *not* collective instabilities.

Various experiments have also attempted to destabilize the alpha-driven TAE or related modes, without success. These have included: (1) reducing the ion temperature by helium puffs or D pellet injection in order to reduce the ion Landau damping of the mode;[27] (2) increasing the poloidal beta in order to drive the BAE;[28] (3) increasing q(0) in order to align the TAE with the radius of the largest gradient in β_α;[29] and (4) adding ICRF H-minority tail ions to a DT plasma in order to strengthen the drive.[30] This last experiment did have an unstable TAE, but the alpha particle contribution to the drive was estimated to be only 10 to 20%, and the only observable losses were of H-minority tail ions.

MHD modes with a frequency intermediate between Alfvén modes and the usual low-frequency MHD activity has recently been seen in plasmas with large pressure gradients.[31] Typical frequencies are between 50 and 150 kHz, while the Alfvén frequency is around 250 kHz, and the usual MHD modes are at a few kHz to a few tens of kHz. Some of these new modes have the characteristics expected of kinetic ballooning modes (KBMs), namely they are localized near the radius of maximum pressure gradient in the plasma, they have a considerably larger amplitude on the low-field side of the magnetic axis, and they have frequencies close to the ion diamagnetic drift frequencies. Toroidal mode numbers in the range from 5 to 12 are seen simultaneously. The modes cause alpha particle loss in the 90° detector, resulting in an increased loss of up to three times the first orbit level in that detector. The losses are most strongly correlated with the n=6 mode. Although the alpha particle losses due to the KBM are seen in DT plasmas, similar KBMs also occur in DD plasmas and are therefore not driven by the alpha particle pressure gradient, but by the thermal plasma pressure gradient. Numerical simulations confirm that the fast ions in the discharge contribute only a minuscule amount to the growth rate of the mode.

Figure 3 compares the pitch angle dependence of the loss to the 90° detector before and during the KBM activity in a 2.3 MA discharge. The profile before the KBM represents the normal pitch angle distribution of first orbit loss. During the KBM, which lasts ~50 msec, the loss is strongly enhanced between the pitch angles of 50° and 62°, approximately coincident with the pitch angle of the passing/trapped boundary for this plasma. This behavior is consistent with previous observations of MHD-induced losses.[23] Figure 4 shows a computation of the orbit of the lost particles indicating that they do pass through the region where the T_e measurements show the KBM exists (r/a~0.3). The figure also depicts a nearby confined passing orbit where the loss likely originated. A small change in pitch angle of the particle of the confined orbit, or a small outward radial transport would result in the particle moving to the lost orbit. Either effect could result from an interaction between the KBM and the alpha particle.

IV. RF wave induced loss

ICRF waves can interact with fast ions and cause losses. The interaction occurs when the wave-particle resonance condition is satisfied,

$$\omega_{RF} = \Omega_f(R) - k_{||}v_{||f},$$

where ω_{RF} is the applied rf frequency, $\Omega_f(R)$ is the fast ion cyclotron frequency, R is the major radial position, $k_{||}$ is the parallel wavenumber, and $v_{||f}$ is the fast ion parallel velocity. In contrast to thermal ions, which interact with the wave only very close to their cyclotron resonance layer, the large $v_{||}$ of the fast ions allows them to interact over a considerably larger range of positions. The waves can change all three standard invariants of the particle motion, namely E, μ, and P_ϕ. The loss mechanism which has been seen during rf experiments is similar to the one associated with KBMs, as described in Sec. III, with particles on passing orbits being moved to banana orbits. The mechanism in this case is heating of the particles by the wave, which gives them enough $v_\perp$ to move them into the first orbit loss cone.

Figure 5 shows alpha particle losses produced by ICRF fast wave heating of a supershot plasma in a $2\Omega_T$ heating regime. Depicted is the neutron-normalized rate of alpha loss to the 90° probe. The ICRF power is modulated, and corresponding modulations in the alpha loss rate are seen, amounting to ~30% of the baseline first orbit loss rate. The pitch angle distribution in this detector shows that the ICRF induced losses are at the pitch angle of the passing/trapped boundary, consistent with the picture above of passing particles being heated and moved into the first orbit loss cone.[32]

An interesting possible application of wave interactions with alpha particles is the so-called "alpha energy channeling."[33,34] This concept involves using rf waves to extract energy from the alpha particles, and transfer it to some useful function in the plasma such as driving current or heating ions. To achieve this goal, several conditions need to be satisfied, first among them that the alphas interact strongly enough with the wave that the wave can extract energy from them more rapidly than they give it up to electrons through collisions. While the ICRF fast wave induced losses described above do not exhibit a very strong interaction, recent results obtained with ion Bernstein waves[35] (IBWs) do.

IBWs are created in TFTR by mode conversion of ICRF fast waves in the plasma interior in D^3He plasmas.[36,37] The IBWs are damped ~70% on electrons, and exist only within a few cm of the mode conversion layer. The mode conversion layer can be moved by varying B_T or the relative proportions of ^3He and D in the plasma. Note that for this plasma, the fusion products are principally from DD and D^3He reactions, since no tritium was used. Figure 6 shows the time history of fast ion losses to the 90° detector in two similar IBW shots.[38,39] The lower curve represents approximately the level of first orbit losses of fusion products to this detector, while the upper curve displays the additional loss attributable to IBWs seen in another discharge. The additional loss due to IBWs is ~7 times the first orbit loss level, and similar ratios of enhancement are seen on the other detectors.

The additional losses due to the IBW arise at the passing/trapped boundary, and are attributable to heating and radial transport by the wave. The lost particles are, however, substantially heated by the IBW before loss. Because the fast ion loss probes only measure gyroradius and not the lost particles' charge or mass, it is difficult to determine exactly which fast ions are lost due to the IBW. From various arguments too lengthy to include here, it seems most likely that the lost particles are either 1 MeV tritons produced from DD fusions, or 100 keV D beam ions. In either case, the gyroradius distribution of the enhanced loss shows that the lost particles have been significantly heated by the wave. If the lost particles are tritons, they escape with an energy of ~1.5 MeV, i.e. having been heated by 0.5 MeV. If the escaping ions are D beam ions, then they have gained ~2.1 MeV before being lost. From these values, and the time scales of the loss shown in Fig. 6, it is possible to estimate diffusion coefficients in energy. These are, if tritons, D_E~2 $(MeV)^2$/sec, and, if D beam ions, D_E~25 $(MeV)^2$/sec. Both values exceed the threshold of ~1 $(MeV)^2$/sec necessary for outpacing the collisional transfer of energy to the electrons, and hence satisfy one of the necessary criteria for alpha energy channeling.

The IBW loss process depends sensitively upon the location of the mode conversion layer in the plasma. For instance, in Fig. 6, the two discharges shown both have the same parameters, including IBW power. The only difference between them is in the fraction of ^{3}He in the discharge, which moves the mode conversion layer. The difference in the observed location of the mode conversion layer between these two shots is only 6 cm. A scan of the mode conversion layer position by changing the toroidal field reveals that the maximum loss occurs when the mode conversion layer is at the magnetic axis. The full width at half maximum of this loss versus layer position profile is 15 cm.

The IBW induced fast ions loss has been simulated by computing particle orbits and their interaction with the mode converted IBW.[40] The simulation follows single fast ion orbits. The IBW is taken to exist in a slab 15 cm wide extending from the top to the bottom of the plasma, and at a major radius slightly larger than that of the magnetic axis. If the fast ion traverses this slab and is resonant with the IBW, the particle's energy is given a random increment or decrement. Accumulated interactions with the wave produce diffusion. However, there is no collisional diffusion in this model. When this model is run with a 1 MeV triton starting at r/a=0.1, the particle can gain energy, move outward in minor radius, and eventually move onto a fat banana orbit where it is lost. The energy at the point of loss, which is near the 90° detector, is 1.5 MeV, in agreement with the experimental observation. The theoretical calculations that lead to this model also predict cooling of alpha particles when multiple waves are present.[41]

V. Conclusions & Future Work

In general, alpha confinement in MHD quiescent TFTR plasmas is good, i.e. consistent with classical losses. Measurements of alpha loss at 90° below the midplane match the first orbit loss model well. Measurements of stochastic TF ripple loss in TFTR have been made. Modeling of these losses shows some areas of agreement, but also some discrepancies yet to be resolved. The modeled global first orbit losses in ITER are less than 1% of the alpha source rate. Initial calculations of ripple loss in the 20 TF coil version of ITER indicate that loss levels will be significant, 2-5% of the alpha source rate.[42]

Virtually any type of MHD activity has the potential to increase alpha particle losses. For example, significant alpha particle loss (about three times the first orbit loss level) due to the KBM has been observed in some high-β DT discharges. Most losses due to MHD seen in TFTR arise from moving particles into the first orbit loss cone. In ITER, that loss cone will be small, and will exist only at the edge, so these sorts of losses should be small. However, the larger ripple loss cone noted above and the observed ability of MHD to transport alphas may result in significant losses in ITER. In particular, modeling indicates that sawteeth in ITER will transiently double the fraction of the alpha population subject to ripple loss.[42,43]

No alpha-driven TAEs have yet been seen in TFTR, even at the highest fusion powers reached. However, fast ion losses due to TAEs driven by H-minority ICRF tail ions have damaged the TFTR vessel. ITER will have an $R\nabla\beta_{\alpha}$ three times larger than TFTR's, and may be unstable to this mode. The first wall in ITER should be designed to withstand TAE-induced alpha loss.

ICRF waves have been seen to cause fast ion losses in TFTR. These, again, depend upon pre-existing loss cones. IBWs interact strongly with fast ions in TFTR. It may be possible to harness this interaction to perform alpha energy channeling.

Future plans for TFTR include further investigation of the IBW interaction with fast ions by using the confined alpha diagnostics on TFTR to look for cooled fast ions. In addition, by lowering the ICRF source frequency from 43 MHz to 30 MHz, IBW investigations can be done directly in DT plasmas. There are several proposals, including improved lithium conditioning of the limiters, which might improve the fusion power attainable in TFTR. Accompanying increases in the alpha population will allow further testing of the TAE instability threshold. Finally, infrared imaging of the walls in TFTR should give data on the spatial distribution and intensity of alpha ripple losses.

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Figure Captions

Figure 1: The locations of the four escaping fast ion probes in TFTR, at 20°, 45°, 60°, and 90° below the outer midplane. The 20° probe is moveable radially. A typical loss orbit to the 90° detector is also shown. On the right is a schematic of how the two apertures in a probe disperse the fast ions onto a scintillator based upon their pitch angles and gyroradii.

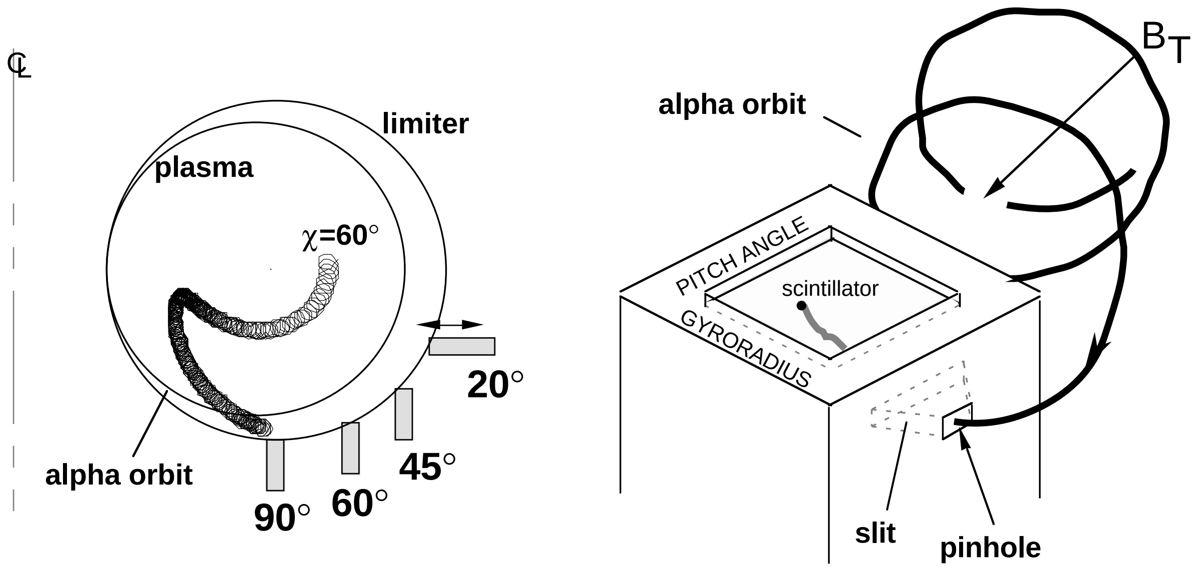
Figure 2: The measured and model peak pitch angle in the 90° detector as a function of plasma current. The model values are obtained from a calculation which includes first orbit loss and the instrumental broadening of the signal in the detector. The experiment and model agree within the errors at all currents tried.

Figure 3: Alpha particle loss versus pitch angle in the 90° detector before and during KBM activity in TFTR. The KBM causes enhanced losses which are greatest in the immediate vicinity of the fattest banana orbit at 57.6°. The instrumental function FWHM is 9°.

Figure 4: Schematic of the lost banana orbit observed during KBM activity, a nearby confined passing orbit, and the proximity of both to the measured mode location in the plasma.

Figure 5: Neutron-normalized alpha particle loss rate to the 90° detector and applied ICRF power versus time, in a fast wave $2\Omega_T$ heating experiment. Note the modulations in loss which are synchronous with the modulations in the ICRF power. The loss modulation is ~30% of the first orbit loss level.

Figure 6: Fast ion loss rate to the 90° detector during mode conversion ion Bernstein wave experiments. The lower curve is approximately at the level of first orbit loss of fusion products while the upper curve shows the additional loss due to the IBW. Both discharges have IBWs, and the only difference between them is in the mode conversion layer position, which has been measured to have moved 6 cm between the two shots.



℄
limiter
plasma
χ=60°
20°
45°
60°
90°
alpha orbit
alpha orbit
B_T
PITCH ANGLE
scintillator
GYRORADIUS
slit
pinhole

Figure 1

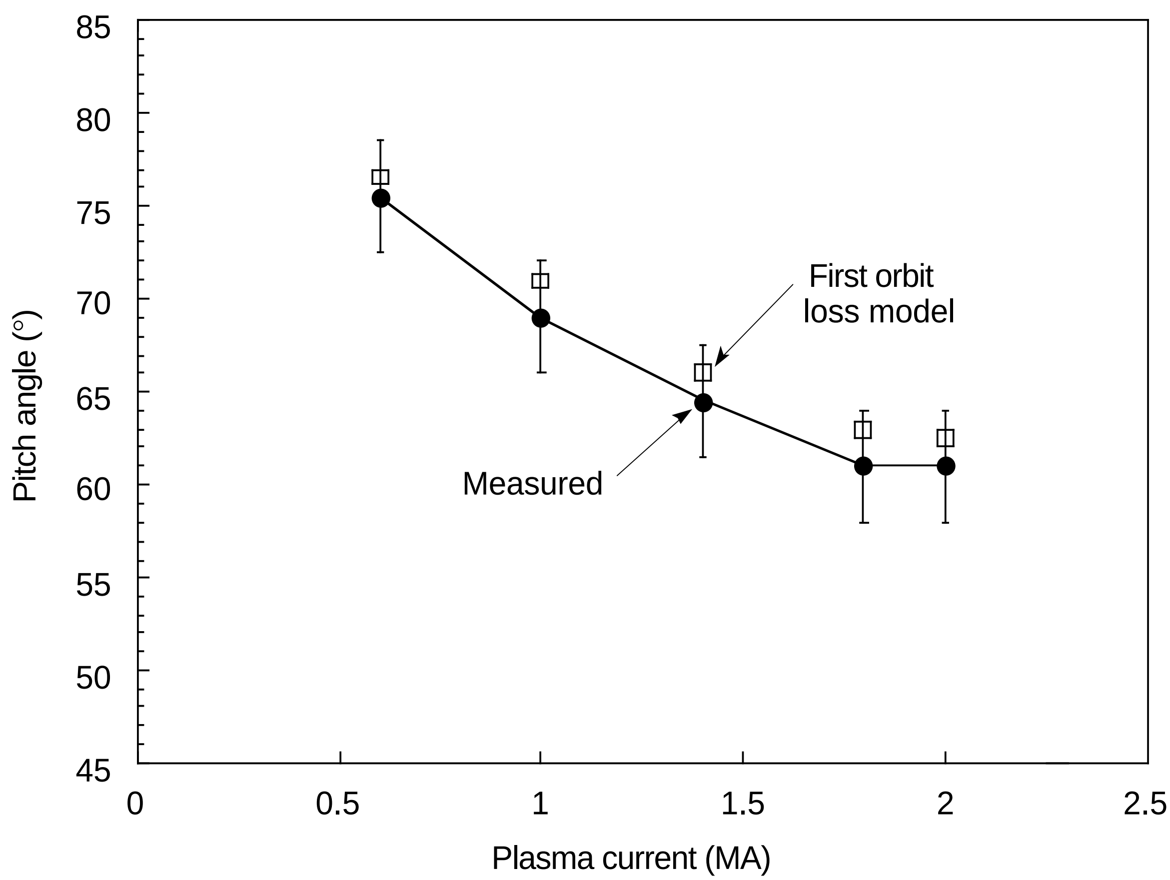

85
80
75
70
65
60
55
50
45
0
0.5
1
1.5
2
2.5
Pitch angle (°)
Plasma current (MA)
First orbit loss model
Measured

Figure 2

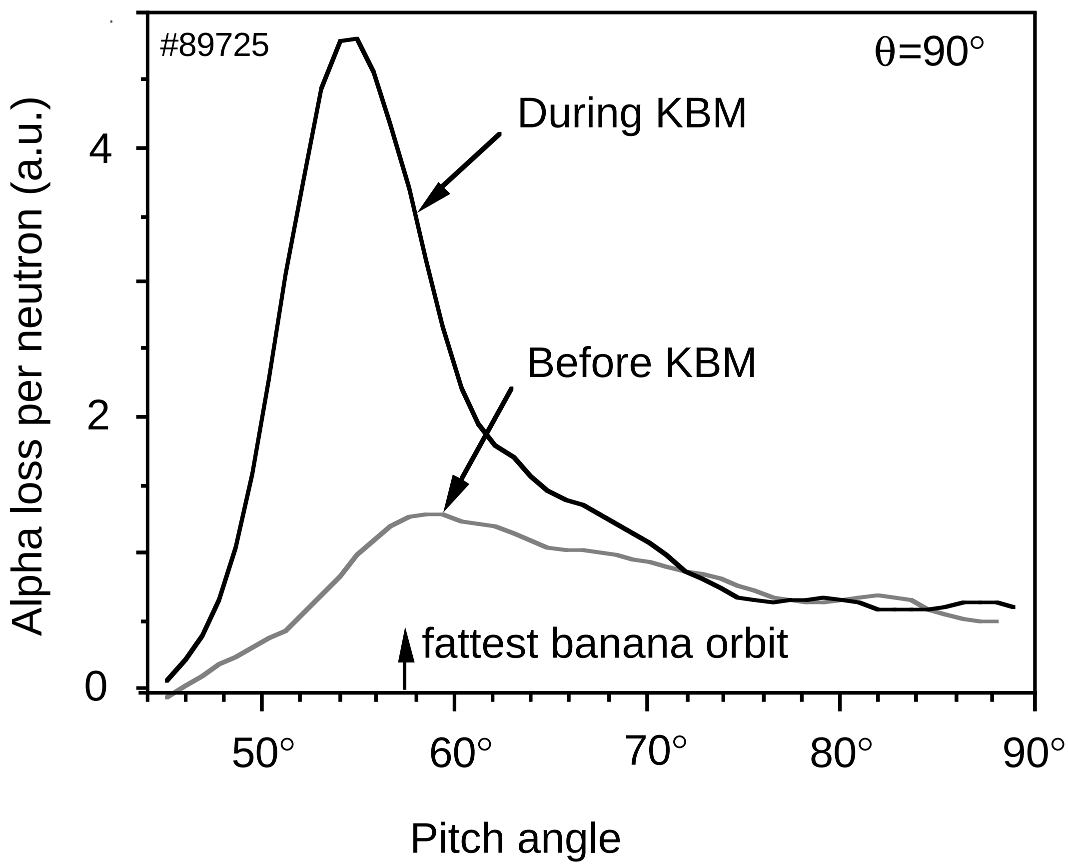
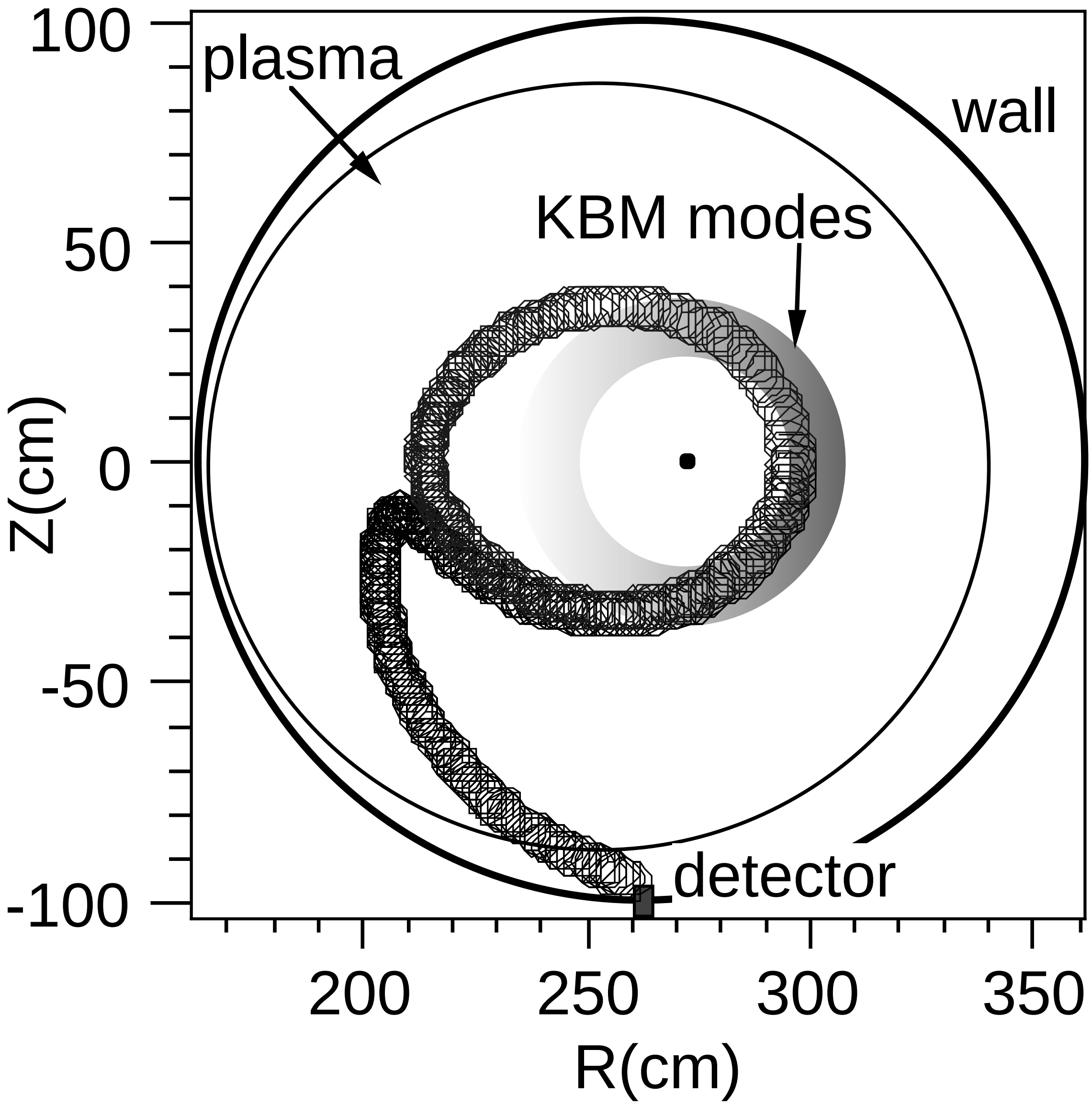
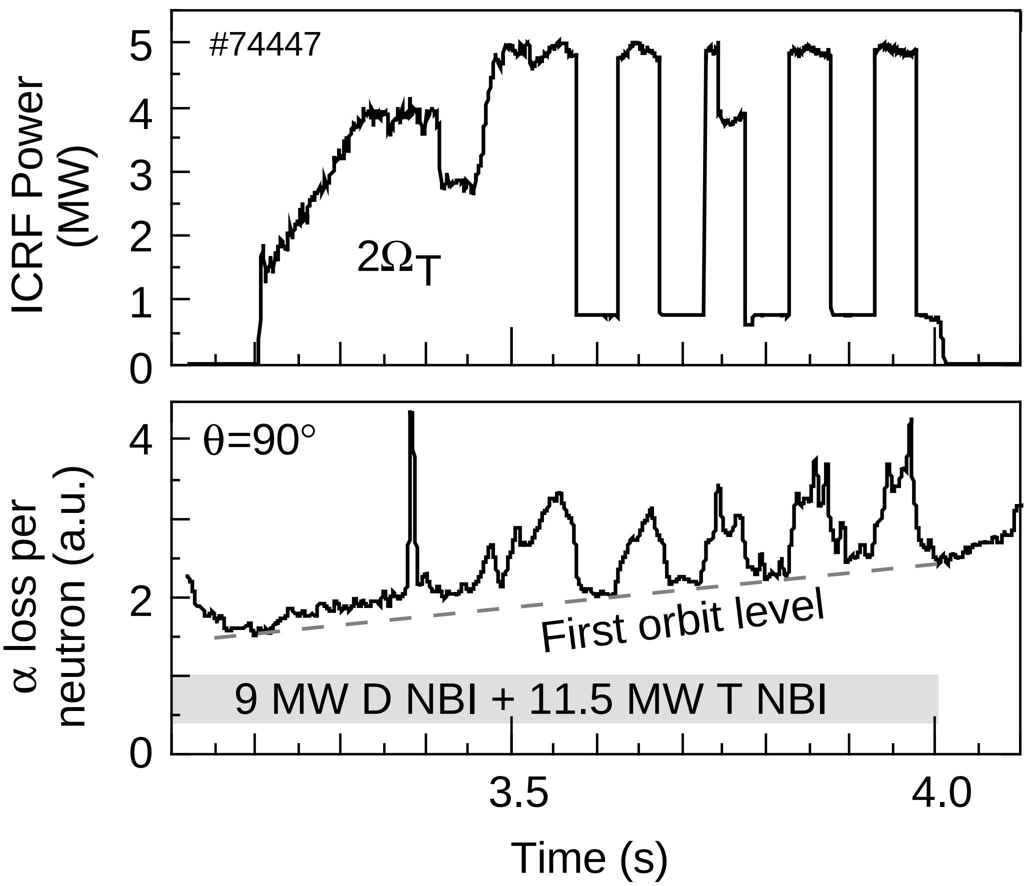

#89725
θ=90°
During KBM
Before KBM
fattest banana orbit
Alpha loss per neutron (a.u.)
4
2
0
50°
60°
70°
80°
90°
Pitch angle

Figure 3



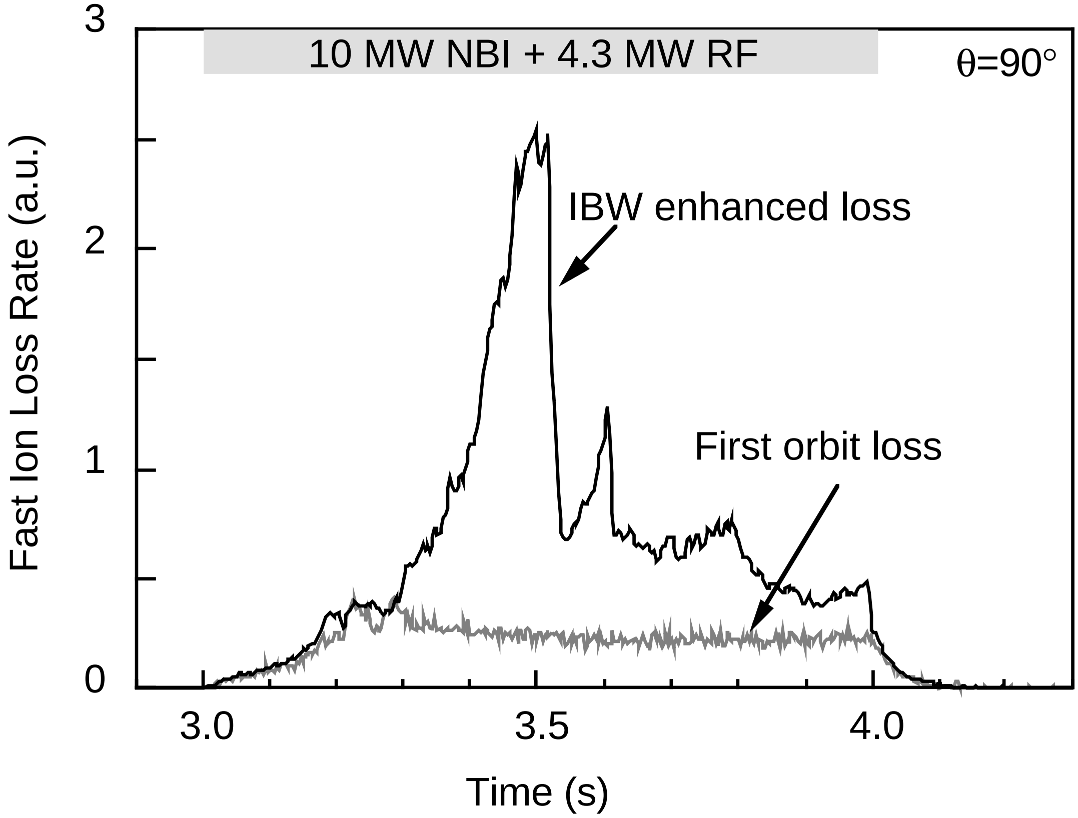
100
50
0
-50
-100
Z(cm)
200
250
300
350
R(cm)
plasma
wall
KBM modes
detector

Figure 4



#74447
ICRF Power (MW)
$2\Omega_T$
θ=90°
α loss per neutron (a.u.)
First orbit level
9 MW D NBI + 11.5 MW T NBI
3.5
4.0
Time (s)

Figure 5



10 MW NBI + 4.3 MW RF
θ=90°
IBW enhanced loss
First orbit loss
Fast Ion Loss Rate (a.u.)
Time (s)
0
1
2
3
3.0
3.5
4.0

Figure 6