IAEA-CN-64/A2-2

Sawtooth Mixing of Alpha Particles in TFTR D-T Plasmas*

M. P. PETROV[+], N. N. GORELENKOV[1], R. V. BUDNY[2], Z. CHANG[2],
D. S. DARROW[2], H. H. DUONG[3], R. K. FISHER[3], R. J. FONCK[4],
H. W. HERRMANN[2], G. R. MCKEE[4], S. S. MEDLEY[2], A. ODBLOM[5],
A. L. ROQUEMORE[2], B. C. STRATTON[2], F. WISING[6], R. B. WHITE[2],
Y. ZHAO[2], AND S. J. ZWEBEN[2]

A. F. Ioffe Physical-Technical Institute, St. Petersburg, 194021, Russia

[+] A. F. Ioffe Physical-Technical Institute, St. Petersburg, 194021, Russia.
Present affiliation: Princeton Plasma Physics Laboratory.

[1] TRINITI, Troitsk, 142092, Russia.
Present affiliation: Princeton Plasma Physics Laboratory.

[2] Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA.

[3] General Atomics, San Diego, California, USA.

[4] University of Wisconsin-Madison, Madison, Wisconsin, USA.

[5] Chalmers University of Technology, Gothenburg, Sweden.

[6] Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

---

[*] Work supported by U. S. Department of Energy Contract DE-AC02-76CH0-3073
and U. S. Department of Energy Grant DE-FG03-92ER54150

IAEA-CN-64/A2-2

Sawtooth Mixing of Alpha Particles

in TFTR D-T Plasmas

Abstract

Radially resolved confined alpha particle energy and density distributions are routinely measured on TFTR using two diagnostics: PCX and α-CHERS. The Pellet Charge-eXchange (PCX) diagnostic uses the ablation cloud formed by an impurity pellet (Li or B) for neutralization of the alphas followed by analysis of the escaping helium neutrals. PCX detects deeply trapped alpha particles in the energy range 0.5 - 3.8 MeV. The α-CHERS technique, where the alpha signal is excited by charge-exchange between alphas and the deuterium atoms of one of the heating beams and appears as a wing on the He^+ 468.6 nm line, detects mainly passing alphas in the range of 0.15 - 0.7 MeV. Studies of alpha losses during DT experiments on TFTR have also been conducted using lost alpha detectors located on the walls of the plasma chamber. All of these diagnostics were used for investigating the influence of sawtooth crashes on alphas in high power D-T discharges in TFTR. Both PCX and α-CHERS measurements show a strong depletion of the alpha core density and transport of trapped alphas radially outwards well beyond q = 1 surface after a sawtooth crash. Lost alpha detectors measure bursts of alpha loss coincident with sawtooth crashes which represent a very small fractional loss of the previously confined alphas (<1%). Thus, a sawtooth crash leads mainly to radial redistribution of the alphas rather than losses. For modeling of alpha sawtooth mixing, a code is used which is based on the conventional model of magnetic reconnection and the conservation of particles, energy and magnetic flux. The effect of the particle orbit averaged toroidal drift in a perturbed helical electric field generated by the crash has also been included in the code. It is shown that mixing of the passing alphas is dominated by the magnetic reconnection whereas trapped alphas are affected mainly by ExB drift.

1. Introduction

Effective operation of a D-T fusion reactor requires that the alpha particles deposit most of their energy in the plasma before they are lost. MHD activity (e.g. sawtooth oscillations) can transport alphas from the plasma core which might affect ignition and/or damage of the first-wall components of the vessel by feeding the alphas into the stochastic ripple loss region. The purpose of this paper is to report both the experimental observations of alpha mixing and the efforts to model the effect of sawteeth on fusion alpha transport.

In D-T experiments on TFTR, the behavior of fast confined alphas was investigated in both quiescent plasma regimes and also in the presence of MHD activity. The radially resolved confined alpha particle energy and density distributions are measured using two diagnostics: PCX [1] and α−CHERS [2]. In MHD-quiescent plasmas, both diagnostics observed classical slowing down and neoclassical confinement [2, 3]. Both diagnostics have observed evidence for sawtooth mixing of confined alphas by sawtooth crashes [4, 5]. The influence of sawtooth effects on injected neutral beam ions, RF driven minority ions and fusion products in DD plasmas has been discussed elsewhere [6 - 8]. Below we present experimental data on alpha sawtooth mixing taken by PCX and α-CHERS diagnostics in TFTR D-T discharges and describe the approaches for modeling of these phenomena. Also, we present the results of measurements of lost alphas [9] during sawtooth crashes in TFTR D-T discharges.

2. PCX Experimental Data

The Pellet Charge-eXchange (PCX) diagnostic on TFTR uses the ablation cloud formed by an impurity pellet (Li or B) injected along a midplane major radius with velocities in the range of 500-700 m/s to neutralize alphas by double or sequential single electron capture. The escaping helium neutrals are mass and energy analyzed using a high energy Neutral Particle Analyzer (NPA) having eight energy channels. The NPA views the pellet from behind with a sight line at a toroidal angle of 2.75^o to the pellet trajectory. Consequently, only near perpendicular alphas with velocities close to $v_{||}/v = - 0.048$ are detected in these experiments.

The radial position of the pellet as a function of time is measured using a linear photodiode array located on the top of the vacuum vessel. By combining this measurement with the time dependence of the observed NPA signals, radially resolved alpha energy spectra and radial density profiles can be derived in the energy range of 0.5 - 2.0 MeV for Li pellets and 0.5 - 3.8 MeV for B pellets with a radial resolution of ~ 5 cm. The PCX diagnostic is not absolutely calibrated because of the difficulties in determining the densities of the ion charge states in the cloud [1].

Pellets are injected 0.2 - 0.5 s after termination of neutral beam heating. This timing delay leads to deeper penetration of the pellet as a result of decay of the electron temperature as well as to enhanced signal-to-noise ratio because the neutron background decays significantly faster than the confined alpha population.

The experiments were performed in standard TFTR D-T supershots [10] with a plasma current of 2.0 MA, a toroidal magnetic field of 5T, major and minor radii of R = 2.52 m and a = 0.87 m and 20 MW of DT neutral beam power injection. Sawteeth do not normally occur during beam injection in these supershots. Large sawtooth crashes begin to develop 0.2 - 0.3 s after the termination of beam injection when the plasma β drops below the level required to suppress sawteeth. To get PCX data , a Li pellet was injected before and after the sawtooth crashes in sequential similar discharges. Measured alpha radial density profiles for alpha energies of 0.64 MeV and 1.21 MeV for precrash (open circles) and postcrash moments (solid symbols) are shown in Fig. 1 (a and b). Postcrash experimental data for three discharges are shown. There is some variation in the postcrash data due to minor differences in the timing and amplitude of the sawteeth. Solid lines are the results of modeling which will be described below. The PCX data indicate that a significant broadening of the trapped alpha density profile occurs for postcrash conditions. It is also seen that this broadening decreases with increasing alpha energy.

3. α-CHERS Experimental Data

In the α−CHERS technique [2], the alpha signal is excited by charge exchange between alphas and heating beam deuterium atoms and appears as a wing on the long-wavelength side of the He^+ 468.6 nm line. Five spatial channels are available, with sightlines intersecting three of the heating neutral beams in the toroidal midplane at radii spanning the region r/a = 0.05 - 0.6. Three spatial channels may be observed in a single discharge, making it necessary to combine data from two similar discharges to get a complete five-point radial profile. The data were averaged over 0.2 s intervals to improve the signal-to-noise ratio. The α-CHERS system is absolutely calibrated, allowing absolute measurements of the alpha density to be made.

The experiment was performed in standard TFTR supershots similar to those which were used for the PCX measurements. The time evolution of the injected neutral beam power and core electron temperature are shown in Fig. 2 (a and b). The sawtooth crash was induced in this experiment by dropping the beam power 0.2 s after termination of the D-T beam phase, as shown in Fig. 2a. By inducing the sawtooth in this way, the alpha density profile could be measured before and after the sawtooth crash. The alpha density profiles were obtained by combining data from two similar discharges. The results of these measurements are presented in Fig. 3. Alpha energies here are averaged over the range 0.15 - 0.6 MeV. The α−CHERS measurements show a sharp drop in the core alpha density (by a factor of ~5) after the crash and broadening of the passing alpha radial density profile. However, the relative broadening of the passing alphas is significantly smaller than that observed by the PCX diagnostic for the trapped alphas. The total number of alphas in the observed energy and radial profile ranges is consistent with particle conservation. The lost alpha detectors measure no alpha loss in these shots.

4. Lost Alpha Detector Data

Extensive studies of alpha losses during DT experiments on TFTR are routinely conducted using lost alpha detectors located on the walls of the vacuum vessel [11]. Here we present the data for the detector located 20 degrees below the outer midplane . The detector integrates the data over a pitch angle range of 45 - 85 degrees with respect to the co-toroidal direction and over an alpha energy range of 0.5 - 4 MeV.

Figure 4 shows the neutral beam time evolution, core electron temperature and lost alpha signal in a TFTR discharge with a plasma current of 1.4 MA, a toroidal magnetic field of 3.2 T, 7.5 MW of neutral beam power and major and minor radii R = 2.52 m and a = 0.87 m, respectively. There were three strong sawtooth crashes during the neutral beam heating period due to low NBI power and low q(a) and the lost alpha detector measured 0.1 - 1 ms bursts of alpha loss coincident with the crashes. The integrated loss in the bursts represent a very small fractional loss of the previously confined alphas (<1%). The lost alpha measurements on plasmas similar to those where the PCX and α−CHERS data were taken indicate that the alphas are not ejected.

5. Modeling of Alpha-Particle Distributions in TFTR

The slowing down alpha particle energy spectra in a quiescent plasma (without any MHD activity), was modeled with the TRANSP [12] Monte-Carlo code which follows the orbits of alphas as they slow down and pitch-angle scatter by Coulomb collisions with the background plasma. TRANSP assumes that alphas are well confined during slowing down and takes into account the spatial and temporal distributions of plasma parameters in each discharge. TRANSP was recently modified to include stochastic ripple diffusion of alphas [13]. Since the Monte-Carlo methods used in TRANSP are computationally intensive, we developed a Fokker-Planck post-TRANSP (FPPT) processor code [14]. The FPPT code solves the drift-averaged Fokker-Planck equation using the pitch angle integrated alpha source distribution provided by TRANSP as input and includes modeling of the ripple effect. The FPPT code is very effective for rapid modeling of the PCX data which is acquired in a narrow pitch angle window during a very short time interval (~1 ms),

The curves 1 in Fig. 1(a and b) present FPPT modeling results for the alpha radial density profiles normalized to the precrash PCX experimental data. These modeling examples for the PCX data show that for sawtooth free conditions, the alpha distribution functions have the classical character.

Models of the effect of the sawtooth on confined fast ions [15] were developed for neutral beam injected passing particles having small radial deviations from the magnetic surface. Conservation of particle energy during mixing was assumed. In such an approach, the fast particles follow the magnetic surface during the crash and the models tended to describe the sawtooth effect on the measured neutron fluxes due to beam-plasma fusion reactions [6]. This model was used for the α-CHERS data for fast particle mixing (postcrash model curve in Fig. 3). A small radial diffusion coefficient $D_\alpha = 0.03\ m^2/s$ (consistent with neoclassical diffusion and α-CHERS measurements of alpha radial profiles in MHD-quiescent discharges [16]) was implemented into the model to allow comparison with the experimental data averaged over 0.2 s. The agreement of the model with the experiment data indicates that energetic passing alphas redistribute with the magnetic flux [5].

Application of a similar model to the PCX data (curves 2 in Fig. 1 a and b), however, does not yield satisfactory agreement: the measured local density of trapped alpha particles on the outside of the torus is significantly higher after the sawtooth crash than indicated by the model, as might be caused by radial expulsion of trapped alphas from the center accompanied by a change in their energy. Recent theoretical research [14, 17] treats this phenomenon by inclusion of an electric field produced by the crash. The toroidal drift in the perturbed helical electric field determines the energy change of alpha particles during the sawtooth crash. In [14], a simple approach to alpha particle energy redistribution was proposed which is shown to obey a diffusion type of equation. An analytical transformation formula for alpha particle redistribution was obtained and included in the FPPT code. A helical electric field is assumed to be generated during the so-called "collapse" period of the sawtooth oscillation on a very short time scale $\tau_{cr} \sim 10^{-5} - 10^{-4}$ s where τ_{cr} is the crash time. In this approach, particles can undergo significant displacement within the alpha mixing radius during the crash. The interaction of the fast particles with the perturbed electric field can be considered as resonant, even though the mode itself has very low frequency and was assumed not to be rotating during the short crash. Therefore, particles with energy higher than some critical value E_{cr} perform toroidal precession during the crash and do not interact with perturbed electric field (see also [17]). We define $E_{cr} = 2\omega_c m_\alpha rR/\tau_{cr}$ from comparison of the particle toroidal rotation time and the sawtooth crash time τ_{cr}, where ω_c is the cyclotron frequency, m_α is the alpha particle mass, and r, R are the minor and major radii, respectively. E_{cr} plays the role of an adjustable parameter in simulations of the experimental data as discussed below. Introducing E_{cr} as an adjustable parameter avoids the need for precise knowledge of the crash time τ_{cr} $\{E_{cr}(\mathrm{MeV}) = 35/\tau_{cr}(10^{-5}\ \mathrm{s})\}$. A more consistent model of fast particle redistribution has been presented in [18], where the fast particle drift kinetic equation, including sawtooth-generated electric and magnetic fields, was solved numerically. The analysis is based on results of [17] and shows qualitatively the same dependence of the trapped fast particles on energy as in [14].

A different approach for fast particle-sawtooth interaction was used by Y. Zhao and R. White, where direct Monte-Carlo simulation of fast particle orbits in the presence of two or more nonlinearly interacting modes was performed. Results show rather flat fast particle profiles versus minor radius after the crash and agree with the α-CHERS measurements which relate to mainly passing particles. The results of this analysis for trapped particles give more peaked profiles than measured by PCX. This probably indicates that the time scale length of the perturbations was chosen to be too long and all trapped fast particles have performed more than one toroidal precession around the torus or $E > E_{cr}$ in the terminology of Refs. [14, 17].

Figure 5 illustrates the procedure used to determine the adjustable parameter, E_{cr}, used in application of the Gorelenkov model including ExB drift of the alphas [14] to the experimental PCX data for sawtooth mixing of trapped alphas. The PCX experimental points are shown as solid circles. The precrash curve is normalized to the PCX data for a similar shot without sawteeth. One can see from profile comparisons that $E_{cr}/E_{\alpha o} = 1$ gives the best fit to the data. In all the calculations, a mixing radius of $r_m = 1.5r_s$ ($q(r_s) = 1$) was used. This mixing radius is a second adjustable parameter used in the model. The value of $r_m = 1.5r_s$ is about the sawtooth mixing radius for the bulk plasma and yields the best fit to the PCX data. Figure 6 (a and b) shows the comparison of the PCX data with the ExB sawtooth mixing model for two alpha energies. The model describes well both the broadening of alpha radial profiles and the dependence of this broadening on the alpha energy (higher energy corresponds to smaller broadening) that is observed experimentally.

An additional limitation on the parameter r_m is the stochastic ripple diffusion boundary. Models which incorporate stochastic ripple diffusion indicate that beyond the stochastic ripple boundary, the energetic trapped alphas diffuse out of the plasma in a few milliseconds. Figure 7 shows ExB modeling of the postcrash PCX data with and without toroidal field ripple. The stochastic ripple diffusion boundary according to the Goldston-White-Boozer theory [19] is also indicated. The alphas are redistributed by the sawtooth crash very close to, but not beyond, the stochastic ripple boundary. This is consistent with the fact that lost alpha detectors do not detect significant losses of the alphas, as it was shown in Sec. 3. If we use $r_m > 1.5r_s$ in the modeling of the post crash alpha profile, large ripple and prompt alpha losses are predicted.

Within the accuracy of the PCX measurements and the model, good agreement is seen in comparisons of the experimental alpha density profiles and spectra with the ExB model. The application of this model to the passing particles does not produce alpha redistribution because of the very fast toroidal rotation of those particles. A unified version of the FPPT sawtooth mixing code is being developed which includes both the freezing of the particles to the magnetic surfaces and the ExB drift model, which is expected to describe sawtooth mixing for both passing and trapped alpha particles.

6. Conclusion

PCX and α-CHERS diagnostic measurements show significant radial redistribution of trapped and passing alphas after sawtooth crashes in TFTR DT plasmas. Modeling of the experimental data has shown that two different mechanisms dominate the sawtooth mixing of the passing and trapped alphas: 1) the freezing of the passing alphas in the magnetic field and, 2) the drift of the trapped alphas in the electric field produced by the sawtooth crash. Comparison of the PCX and α-CHERS data with lost alpha measurements shows that in the sawtooth crashes, radial redistribution of the alphas occurs without significant ripple losses of particles. The sawtooth oscillations effectively transport the alphas outward along the major radius close to the stochastic ripple domain. Under conditions of larger mixing radius than occurs in TFTR, this transport might lead to enhanced ripple loss of fusion alpha particles in tokamaks. Theoretical understanding of the effect of sawteeth on nonthermal alphas has progressed sufficiently so that the effects of sawteeth on alpha behavior in ITER can be predicted.

Acknowledgments

The authors wish to acknowledge the dedicated efforts of the entire TFTR Group who provided excellent support for these experiments. H. H. Duong is a General Atomics ORAU Fellow at PPPL.

References

[1] FISHER, R.K., *et al*., Phys. Rev. Lett. **75** (1995) 846
[2] McKEE, G. R., *et al*., Phys. Rev. Lett. **75** (1995) 649

[3] MEDLEY, S.S., *et al.*, Plasma Phys. Control. Fusion **38** (1996) 1
[4] PETROV, M.P., *et al*., Nuclear Fusion **35** (1995) 1437
[5] STRATTON, B., *et al.*, Nucl. Fusion (1996) Accepted for publication.
[6] ANDERSON, D., *et al.*, Nucl. Fusion **34** (1994) 217
[7] MARCUS, F.B., *et al.*, Nucl. Fusion **34** (1994) 687
[8] DUONG H.H., HEIDBRINK, W.W., Nucl. Fusion **33** (1993) 211
[9] ZWEBEN, S.J., *et al.*, Nucl. Fusion **35** (1995) 1445
[10] STRACHAN, J.D., *et al*., Phys. Rev. Lett. **72** (1994) 3526
[11] DARROW, D.S., *et al*., Rev. Sci. Instrum. **66** (1995) 476
[12] BUDNY, R.V., *et al*., Nucl. Fusion **35** (1995) 1497
[13] REDI, M.H. *et al*., Nucl. Fusion **35** (1995) 1509
[14] GORELENKOV, N.N., *et al.*, PPPL Report 3184 (1996) Submitted to Nuclear Fusion
[15] KOLESNICHENKO, Ya. I., *et al*., Nucl. Fusion **32** (1992) 449
[16] McKEE, G. R., *et al.*, Submitted to Nucl. Fusion (Dec. 1995),
[17] KOLESNICHENKO, Ya. I., *et al*., Nucl. Fusion **36** (1996) 159
[18] KOLESNICHENKO, Ya. I., *et al.*, 23rd EPS Conference on Controlled Fusion and Plasma Physics, Kiev 1996
[19] GOLDSTON, R.J., *et al*., Phys. Rev. Lett., **47** (1981) 647

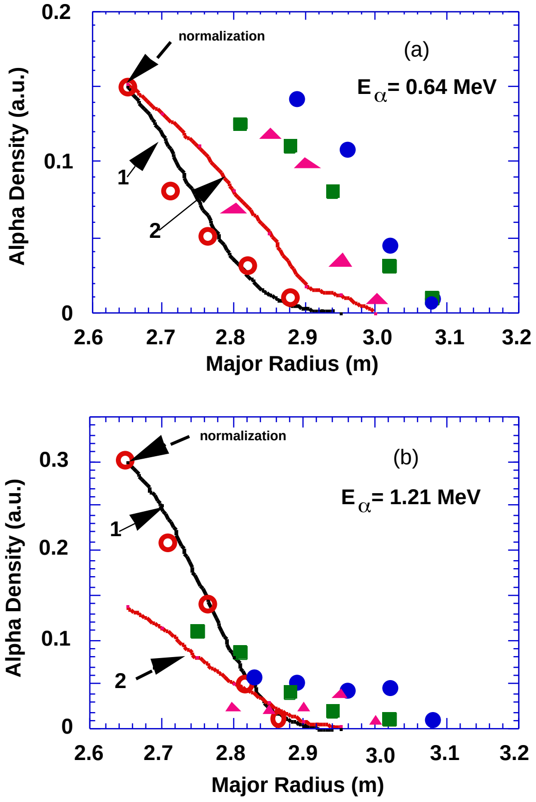

Fig. 1 Precrash (open circles) and postcrash (solid symbols) PCX alpha particle density radial profiles for (a) E_α *= 0.64 MeV and (b)* E_α *= 1.21 MeV. Curves 1 are for precrash conditions using the FPPT model normalized to PCX data. Curves 2 are for postcrash conditions using the model based on the freezing of trapped alphas into the magnetic field and conservation of energy.*

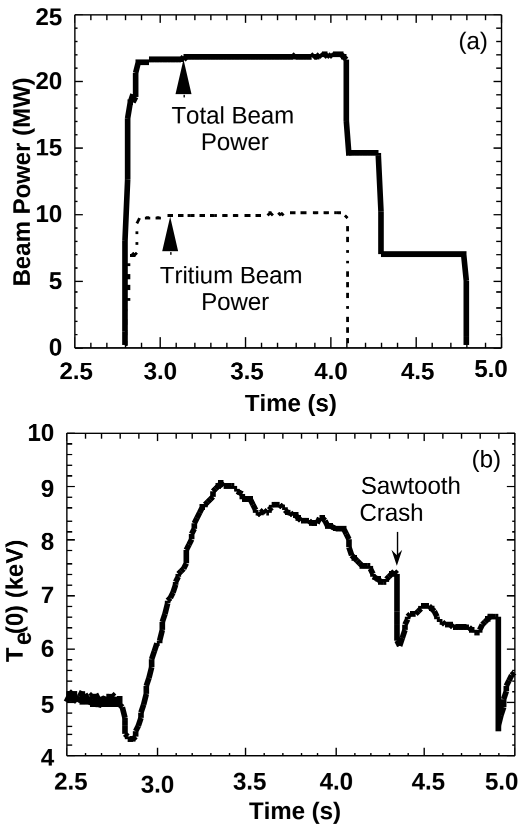

Fig. 2 Time evolution of the injected neutral beam power (a) and core electron temperature (b) in the α-CHERS experiment.

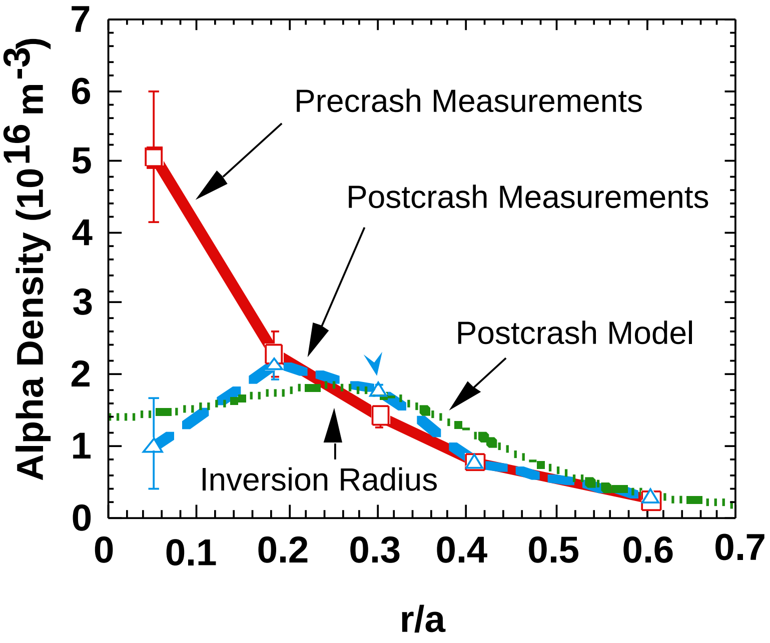

Fig. 3 Experimental data and modeling results for α-CHERS measurements during precrash and postcrash sawtooth conditions.

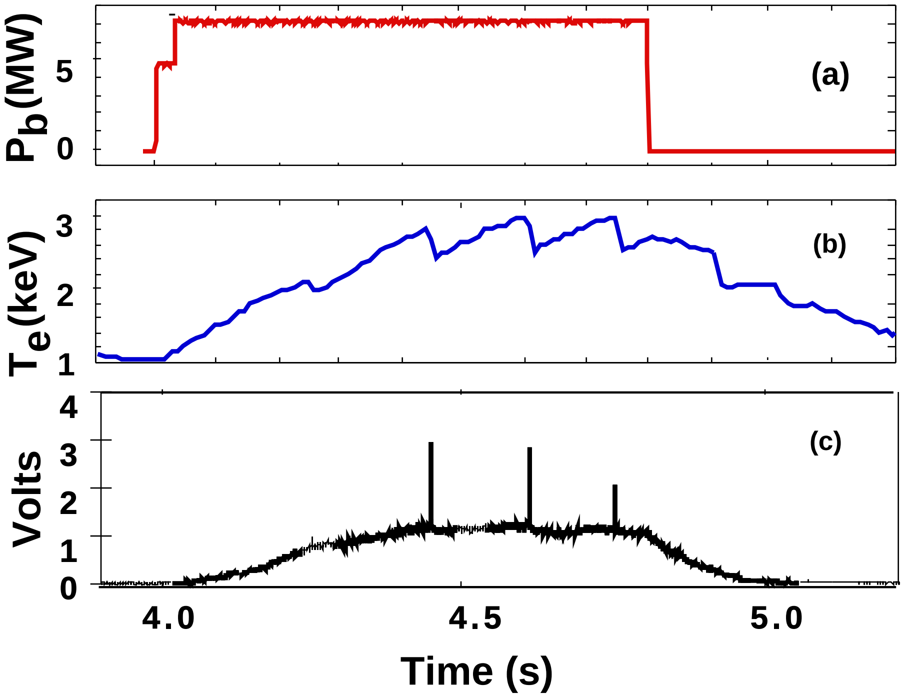

Fig. 4 Time evolution of (a) neutral beam power, (b) core electron temperature, and (c) the lost alpha detector signal.

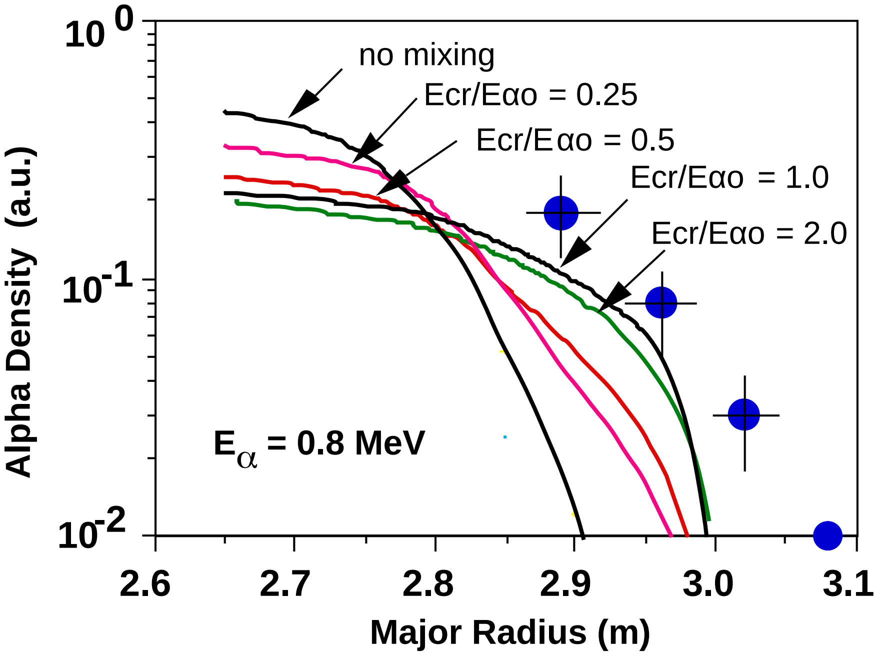

Fig. 5 Application of the ExB model in the FPPT code to the experimental PCX data.

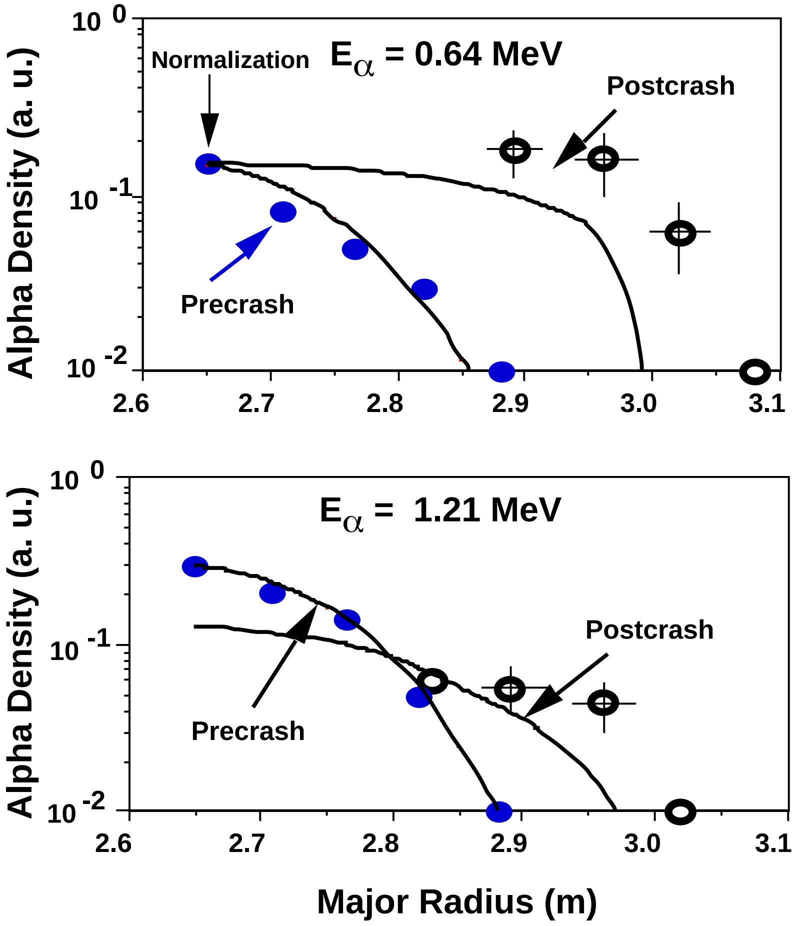

Fig. 6 Comparison of PCX experimental data with the FPPT model for alpha energies E_α *= 0.64 MeV and* E_α *= 1.21 MeV with* $E_{cr}/E_{\alpha o} = 1$ *and* $r_{mix} = 1.5\ r_s$.

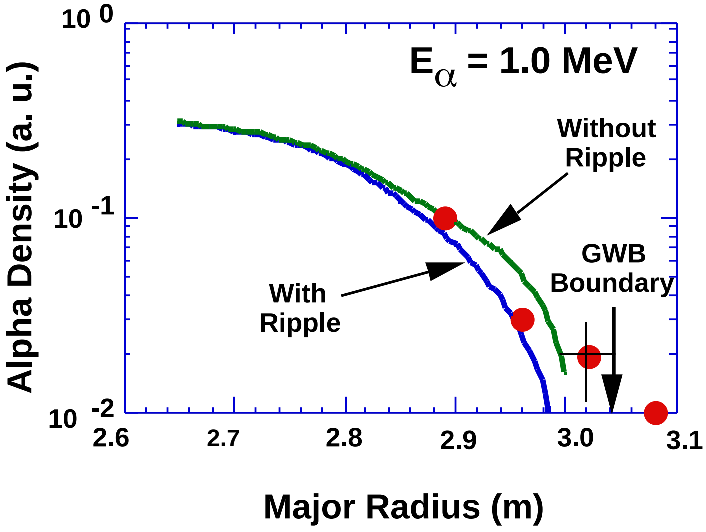

Fig. 7 PCX experimental postcrash sawtooth data and FPPT modeling with and without toroidal field ripple.