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MAY 1996

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GENERAL ATOMICS

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This is a preprint of a paper presented at the Eleventh
Topical Conference on High Temperature Plasma Di-
agnostics, May 12-16, 1996, Monterey, California
and to be printed in the *Proceedings*.

Work supported by
U.S. Department of Energy
Grant DE-FG03-92ER54150
and Contract DE-AC02-CH03073

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GENERAL ATOMICS PROJECT 3937
MAY 1996

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Alpha Diagnostics Using Pellet Charge Exchange: Results on TFTR and Prospects for ITER

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Confinement of alpha particles is essential for fusion ignition and alpha physics studies are a major goal of the TFTR, JET, and ITER DT experiments, but alpha measurements remain one of the most challenging plasma diagnostic tasks. The Pellet Charge Exchange (PCX) diagnostic has successfully measured the radial density profile and energy distribution of fast (0.5 to 3.5 MeV) confined alpha particles in TFTR. This paper describes the diagnostic capabilities of PCX demonstrated on TFTR and discusses the prospects for applying this technique to ITER. Major issues on ITER include the pellet's perturbation to the plasma and obtaining satisfactory pellet penetration into the plasma.

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INTRODUCTION

Achieving fusion ignition requires that DT alpha particles deposit a substantial fraction of their energy in the reacting plasma via collisions before they are lost to the tokamak walls. Because of the importance of alpha particles in fusion research, a number of diagnostic techniques are under development.¹⁻⁶ The ongoing DT experiments on TFTR represent the first opportunity to test these diagnostics, and there has been considerable success.¹⁻³ All of the proposed alpha diagnostics face significant technical challenges on ITER. This paper summarizes the results of the Pellet Charge Exchange (PCX) diagnostic on TFTR, and shows how PCX can be applied to achieve a similar high level of success on ITER.

PCX measures the energy spectrum of energetic helium neutrals resulting from charge exchange interactions of fast confined alpha particles incident on the ablation cloud surrounding a pellet injected into a tokamak.⁶ By correcting the measured neutral spectrum dn_0/dE for the fraction $F_0(E)$ of incident alphas neutralized in the cloud, the incident alpha energy spectrum can be obtained $dn_\alpha/dE \propto dn_0/dE \div F_0(E)$. The energy dependence of the alpha neutralization fraction should be nearly independent of the cloud density and charge state mix for the pellet cloud conditions expected in tokamaks.^{7,8} Figure 1 shows the calculated neutralization fractions for impurity (Li, B) and fueling (D, T) cloud targets at cloud densities high enough to produce an equilibrium fraction of helium neutrals. The results are shown for the helium-like ionization states of Li and B because a large portion of their pellet ablation clouds are expected to be predominately in these states due to their large jump in ionization potential.

Radial profiles of the alpha density and energy distributions can be measured using the time history of the PCX signals and the measured radial position of the pellet cloud.⁹ Details of the diagnostic technique and its design and operation on TFTR are described elsewhere.⁸

TFTR RESULTS

The energy distribution of alpha particles in the plasma core of quiescent TFTR discharges has been measured using both lithium and boron pellets. Figure 2 compares the PCX results for four similar high power beam heated TFTR discharges. In all cases the pellets are injected 0.2 sec after the beam heating is turned off to allow deeper pellet penetration. Boron pellets provide a

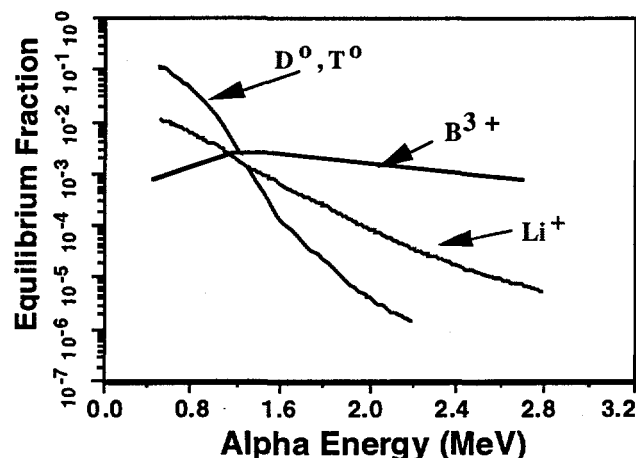


Fig. 1. Calculated equilibrium fractions for alphas incident on helium-like Li and B and neutral D and T pellet ablation clouds.

more effective neutralization target above ~ 2 MeV and allow measurements up to the alpha birth energy of 3.5 MeV. The shapes of the measured energy spectra for boron and lithium pellets are in good agreement, despite the very different energy dependence of their neutralization fractions (Fig. 1) used in calculating the alpha spectra. The fact that the corrected lithium measurements fall somewhat below the boron results is most likely an indication that the lithium cloud contains a larger fraction of ions that are more highly ionized than the helium-like states assumed in the analysis. This would not be surprising given the lower ionization potential for lithium. The uncertainty in the cloud ionization state mix does not significantly affect the energy dependence of $F_0(E)$ and hence the shape of the measured alpha energy spectral.^{7,8} This conclusion is strongly supported by the agreement in the shape of the alpha energy spectra measured by the boron and lithium pellets shown in Fig. 2

Figure 3 compares the measured alpha energy spectra with the results of a Fokker-Planck Post TRANSP (FPPT) code¹⁰ under slowing-down and birth-phase conditions. The slowing-down data (open squares) are PCX data taken 0.2 sec after 1.0 sec of high power neutral beam heating. The agreement with the FPPT classical prediction confirms that fusion alphas in the plasma core of quiescent TFTR plasmas are well-confined and slowing down classically.¹¹ The birth phase data (solid circles) are PCX data taken 0.02 sec after a short 0.1 sec beam heating pulse. Reasonable agreement between the data and FPPT is again observed, with FPPT assuming a preliminary model for the alpha birth distribution based on the measured TFTR neutron broadening.

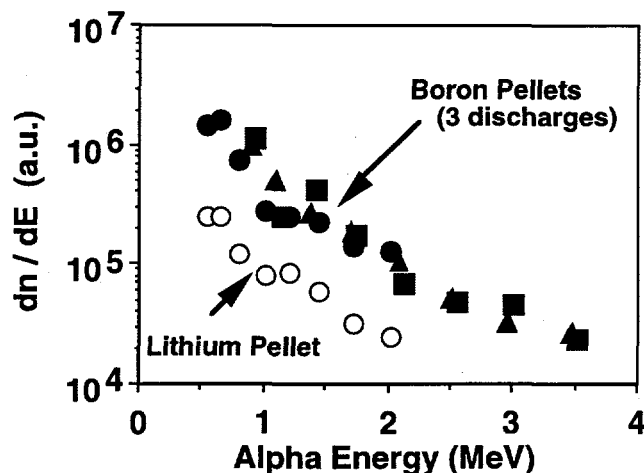


Fig. 2. Comparison of PCX measured alpha energy distribution using B and Li pellets.

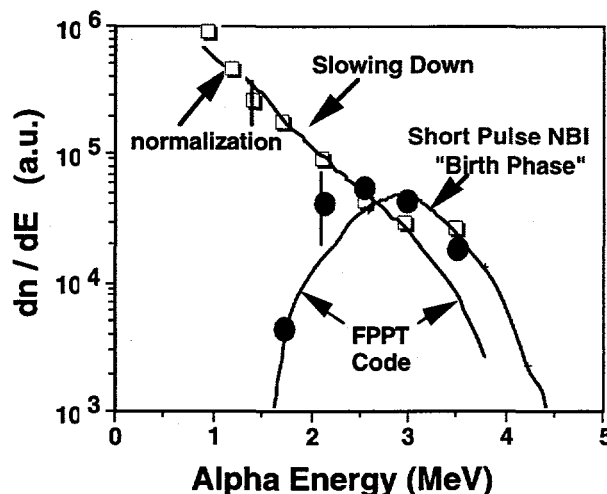


Fig. 3. PCX measurement of trapped alpha energy distribution on TFTR during steady state and short beam pulse experiments. Agreement with the FPPT classical code predictions shows that alphas in the plasma core of TFTR are well confined and slowing down classically.

The radial alpha density profile capability of PCX is illustrated in Fig. 4. Before the first large post-beam sawtooth crash on this high power beam-heated TFTR supershot, the alpha density profile (closed circles) agrees with classical predictions (FPPT). After the first sawtooth crash, the measured alpha profile (squares) is broadened to well outside the $q = 1$ radius. This figure also illustrates the ability of PCX to investigate the effects of toroidal field ripple on trapped alphas. Trapped alphas are studied in the present TFTR geometry since the neutral particle energy analyzer views alphas emitted at an observation angle only 2.75° from radial. Before the first crash, the alpha distribution at all

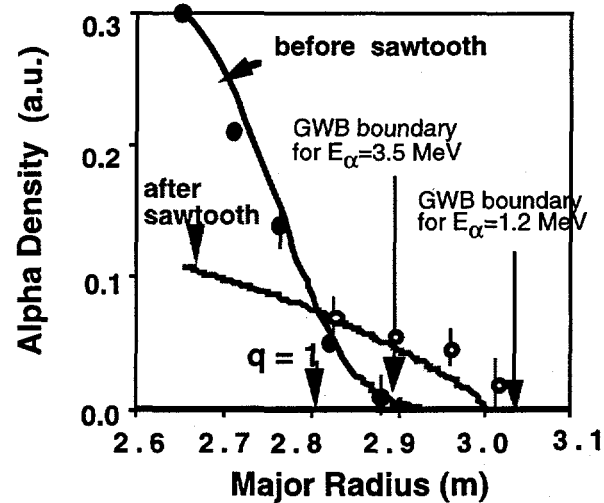


Fig. 4. Density profiles of 1.2 MeV alphas measured by PCX before (solid circles) and after (open circles) sawtooth instabilities on TFTR. Also shown are results of FPPT code calculated profiles (solid lines) and the Goldston-White-Boozer stochastic ripple loss boundaries.

energies extends to $R \sim 2.95$ m, the stochastic ripple diffusion loss boundary for 3.5 MeV alphas. Outside of $R = 2.95$ m, alphas born at 3.5 MeV are lost before they can slow down. The sawtooth crash redistributes alphas so that the radial profile now extends outward to the stochastic ripple boundary appropriate to the energy of the observed alpha, *e.g.*, 1.2 MeV in the data shown in Fig. 4. The measured post-sawtooth radial profiles at other alpha energies show an energy scaling for the observed ripple boundary which is consistent⁹ with that predicted by the Goldston-White-Boozer model¹² of stochastic diffusion.

Still another area where PCX has been proven to be very useful on TFTR is in studies of energetic hydrogen,¹³ tritium,¹⁴ and helium¹⁵ ion tails during ICRF heating experiments.

PROSPECTS FOR ITER

A major issue for ITER is pellet penetration. To obtain better pellet penetration, one can increase the pellet size and/or velocity. The maximum velocity of existing pellet injectors is the ~ 4 km/sec used in the Toré Supra experiments. Impurity pellets penetrate further than similar size fueling pellets but also produce a larger perturbation on the plasma in terms of electron density and increased plasma radiation losses, and the resultant drop in the plasma temperature. While small lithium pellets may go essentially unnoticed by

TFTR operators, larger lithium pellets and boron pellets create large enough density and temperature changes that pellet injection for PCX is usually done at the end of the "useful" portion of that plasma discharge.

Figure 5 shows the results of a TRANSP calculation of the predicted alpha density profile on ITER¹⁴ without sawtooth instabilities (open squares) and with sawtooth instabilities (closed diamonds). As shown, a 2 mm radius beryllium pellet injected at 4 km/sec should penetrate approximately one-third of the way into ITER. Beryllium is of interest for ITER because it is the leading candidate for the first wall coating. The pellet ablation model used in these calculations is the low Z pellet ablation model of Parks *et al.*,¹⁵ modified to include the experimentally observed reduced ablation rate for impurity pellets in the high temperature portion of TFTR plasmas.¹⁶ This enhanced penetration is thought to be due to the effects of pellet charging.¹⁷⁻¹⁹ A 2 mm radius beryllium pellet would only increase the volume-averaged electron density by approximately 8% on ITER, but would penetrate sufficiently to study approximately one-third of the trapped alpha population, and would allow studies of the effects of sawteeth and toroidal field ripple on alpha particles in ITER.

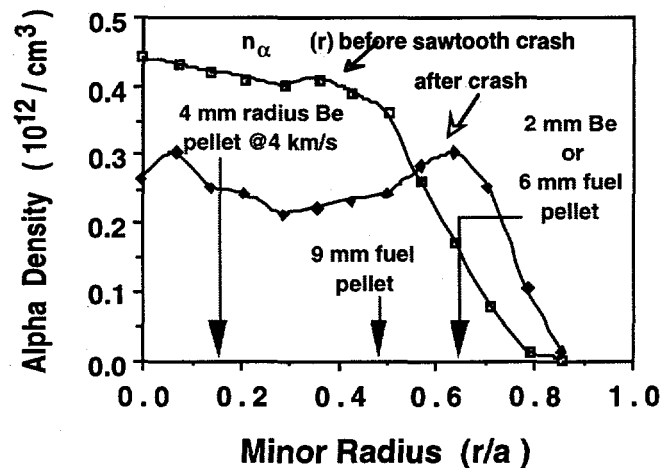


Fig. 5. Expected pellet penetration for Be and T pellets injected radially into ITER in comparison with TRANSP production of ITER alpha density profiles with and without large sawtooth instabilities.

This size pellet should not raise concerns of possibly causing disruptions on ITER. While we do not have experience with beryllium pellets on TFTR, 2 mm diameter lithium and boron pellets are routinely injected. Although they produce a large (~50%) drop in the electron temperature on TFTR and a significant (~30% for Li and ~150% for B) rise in the line average electron density, they do not cause plasma disruptions.

A 4 mm radius Be pellet injected at 4 km/sec should penetrate more than 80% of the way to the plasma center for a full power ITER discharge. This should provide a very significant and powerful PCX alpha diagnostic capability. Because of the larger size of ITER, a 4 mm radius Be pellet would only raise the volume averaged density by ~60%, somewhat smaller than the density rise produced on TFTR by the presently used B and Li pellets, and hence would not be expected to cause plasma disruptions on ITER.

The plasma perturbation issue on ITER is complicated by other factors. The present divertor design employs a radiative divertor that may not tolerate large edge density perturbations due to pellets. Radiative divertors have not been experimentally demonstrated, but there is concern that the divertor density may have to be carefully controlled. This may even require pellet fueling to be done with a large number of small pellets. If radiative divertor operation limits PCX pellet injection to times near the end of the "useful" portion of ITER discharges, very useful alpha data can still be obtained as illustrated by our successes on TFTR under this constraint. ITER is studying the injection of "killer" pellets of frozen krypton or xenon to mitigate the effects of plasma disruptions.²⁰ Experiments on DIII-D and analysis show that "killer" pellet injection may be the most benign way to terminate all ITER discharges, even ones that are not disrupting.²¹ This would allow injection of a deeply penetrating large low Z pellet such as beryllium for alpha diagnostic measurements near the end of an ITER discharge. Any concerns about initiating a disruption would be avoided by the subsequent injection of a "killer" pellet to benignly terminate the discharge a few milliseconds later.

A discussion of the plasma perturbation issue would not be complete without pointing out that impurity pellets also have beneficial effects in tokamaks. Lithium pellet injection is routinely used on TFTR for wall conditioning. In fact, up to four such lithium pellets have been injected into each TFTR discharge, reducing the hydrogen recycling from the walls and the carbon density in TFTR. Lithium pellet wall conditioning is used to obtain the TFTR discharges with the maximum fusion power output and neutron production rate. Boron pellets may also be useful for wall conditioning given the results of boronization experiments on tokamaks using gas injection. It is not clear how useful impurity pellet wall conditioning will be for ITER given the very long time scales for ITER discharges.

PCX alpha measurements could also be done on ITER using fueling pellets. The neutral equilibrium fraction for alphas incident on a neutral deuterium or tritium cloud is comparable to that of helium-like B or Li clouds, as shown in

Fig. 1. The neutralization fraction for a fueling pellet ablation cloud containing a mixture of neutral and ionized atoms would be smaller, but have a similar energy dependence. Fueling pellets will yield the largest PCX signals at $E_\alpha \leq 1$ MeV, although measurements at higher energies may also be possible given the larger alpha density in ITER. Figure 5 shows that a 4 mm radius tritium pellet ($\Delta n/n \sim 20\%$) will penetrate about a third of the way into ITER while a 6 mm radius tritium pellet ($\Delta n/n \sim 70\%$) will penetrate half way. Tests of PCX using fueling pellets will not likely be possible on TFTR because the present location of the neutral particle analyzer does not view the fueling pellet ablation cloud. Tests are under consideration at other tokamaks. PCX measurements using fueling pellets will be a potentially attractive option on ITER if deep pellet fueling is used to reduce the tritium inventory²² and the divertor perturbation issue is resolved, or if very large deuterium pellets are used as killer pellets to benignly terminate ITER discharges.

Pellet penetration is also an issue in our present TFTR experiments and we have explored techniques to improve the pellet penetration. We typically inject the diagnostic pellet 200 msec after the end of neutral beam heating on TFTR. This improves the pellet penetration because of the drop in the electron temperature and density during the post beam-heating plasma decay. The alpha population is also falling but with a decay time equal to the alpha slowing down time (~ 400 msec) which is longer than the energy confinement time (~ 200 msec) in TFTR. This technique should be less useful on ITER because the ratio of the plasma energy confinement time (~ 4 sec) to alpha slowing-down time (~ 1 sec) will significantly increase.

A second technique involves injecting two "stacked" pellets separated by a short time delay (5 to 20 msec). The first pellet produces a significant drop in the plasma electron temperature via radiation losses, etc., allowing the second pellet to penetrate further.⁸ This technique has been successfully used on TFTR to obtain 10% to 25% more radial penetration. The time delay must be short compared to the alpha slowing down time (200 to 500 msec) to measure the alphas before the perturbation effects of the first pellet are significant. Comparisons of the alpha radial and energy distributions measured using the first and second pellets usually show similar results, indicating the alpha perturbation issue is not a problem.⁸ This "stacked" pellet technique may also be useful on ITER.

The large size of ITER will require that the measured energy spectrum of the helium neutrals from PCX be corrected for the energy-dependent fraction of neutrals which are reionized by the tokamak plasma between the electron

cloud and the neutral particle analyzer. At $n_e = 2n_D = 2n_T = 1.2 \cdot 10^{14} \text{ cm}^{-3}$ ($Z_{\text{eff}} = 1$), the mean free path for a 3.5 MeV helium neutral would be $\sim 600 \text{ cm}$ and even at 1 MeV would still be $\sim 120 \text{ cm}$. The presence of significant helium ash in ITER will reduce these mean free paths. For an ash density $n_{\text{He}} = 2 \cdot 10^{13} \text{ cm}^{-3}$, the net mean free path of a 3.5 MeV alpha would be reduced to 280 cm and that for a 1 MeV alpha would be only $\sim 80 \text{ cm}$. Assuming ITER operates at $Z_{\text{eff}} \leq 1.5$, the effect of other impurities would not be that significant. For these high density DT plasmas, 43% of the 3.5 MeV and 5% of the 1 MeV alphas will escape from $r/a \sim 0.15$, while 61% of the 3.5 MeV and 17% of the 1 MeV alphas will escape from $r/a \sim 0.5$. At high Z_{eff} , the uncertainties in the plasma impurity concentrations and radial profiles would affect the accuracy of the correction for the core alphas. But to ignite, ITER will have to operate with Z_{eff} close to 1.5, and hence the correction to the alpha spectrum for this energy dependent neutral escape probability should be fairly accurate.

CONCLUSIONS

Pellet Charge Exchange (PCX) has proven to be a powerful alpha diagnostic tool on TFTR, providing the first direct measurements of the confinement and slowing-down of energetic confined DT alpha particles in a fusion plasma, as well as important information on the effect of large sawtooth instabilities and stochastic toroidal field ripple losses on alphas. Prospects for ITER are excellent if the usual concerns on pellet penetration and perturbation can be satisfactorily addressed. Alpha particle energy distributions and radial profiles into $r/a \sim 0.65$ should be possible by injecting 2 mm radius beryllium pellets ($\Delta n_e/n_e \sim 8\%$) or 6 mm tritium pellets ($\Delta n_e/n_e \sim 20\%$) at 4 km/sec, allowing important information on the effects of sawtooth oscillations and toroidal magnetic field ripple on alpha particles in ITER. Plans for "killer" pellet injection for ITER disruption control and/or benign plasma termination should allow injection of the larger impurity and/or fueling pellets needed in order to obtain data on alphas in the ITER plasma core using PCX.

ACKNOWLEDGMENT

This is a report of work supported by the U.S. Department of Energy under Grant No. DE-FG03-92ER54150 and Contract No. DE-AC02-76CH03073.

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