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Comments about Proposed D-He³ Experiments in the TFTR

by

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Comments about Proposed D-He³ Experiments in the TFTR

Abstract

D-He³ experiments to simulate DT burns in TFTR have been proposed by members of the Fusion Studies Center at the University of Illinois. In this report some basic considerations, involved in planning these experiments, are discussed along with important results to be obtained from such measurements. It is argued that fusion-product orbits, instabilities, and other phenomena can be investigated by D-He³ simulation of DT burns, before the TFTR is contaminated by tritium. This approach will allow changes in experimental design before subsequent DT burn studies.

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1. Introduction

If D-T fuel is used in the initial stages of the TFTR experiment^[1], radiation problems will be encountered which may impede the fusion physics experiments. Due to the D-T reaction, $D + T \rightarrow n(14.1 \text{ MeV}) + \alpha(3.5 \text{ MeV})$, these difficulties will include:

- a. shielding from 14-MeV neutrons,
- b. neutron induced radioactivity,
- c. tritium handling and vessel contamination.

To avoid these problems in the initial stages of the work, Furth and Jassby^[2] have proposed the simulation of D-T burns by neutral-beam injection experiments, including:

- a. alpha particle confinement,
- b. alpha particle pressure,
- c. plasma heating by alphas.

This technique cannot simulate synergistic effects, nor can the isotropic velocity space distribution and spatial distribution of the alphas be modeled. These and other considerations have led to varied opinions about the adequacy of this method^[2-3].

Petrie and Miley^[4] have alternatively proposed to use the reaction: $D + \text{He}^3 \rightarrow p(14.6 \text{ MeV}) + \alpha(3.7 \text{ MeV})$, to simulate D-T burns (D injected into He³), including:

- a. alpha particle confinement,
- b. alpha particle pressure,
- c. energy deposition in the fusion plasma by alphas,
- d. plasma instabilities due to the alphas.

The purpose of this report is to summarize the various experimental problems which can be investigated by this simulation method and to discuss the theoretical work involved in designing these experiments.

2. Definition of the experimental problems

The alpha fusion products affect the fusion plasma in the following ways:

- 2.1. The large size of the neoclassical orbits causes a significant percentage of alphas to be lost to the wall during the first orbit (preliminary calculations give a loss fraction of 10-30% during the first bounce^[19-20]). Alphas having a component of velocity antiparallel to the toroidal current are preferentially lost. The resulting net momentum loss produces a toroidal rotation parallel to the toroidal current^[5];
- 2.2. Since the neoclassical motion of the alphas is anisotropic in coordinate space (i.e. particles circulate in only one direction for a given orbit), the preferential loss in 2.1 also results in a net vertical loss rate of momentum, producing a vertical force, $\vec{F}$. The effect of $\vec{F} \times \vec{B}_p$ gives rise to an additional component of toroidal current. There is also an $\vec{F} \times \vec{B}_t$ effect which induces radial drift;

- 2.3. The large size of the neoclassical orbits also produces a charge separation, which, in turn, creates an electric field, $\vec{E}$, directed into the plasma column. The consequent $\vec{E} \times \vec{B}_t$ force causes poloidal rotation;
- 2.4. The centrifugal acceleration due to the poloidal rotation in 2.3 will tend to force ions of large mass out of the plasma column^[6];
- 2.5. The poloidal velocity, $\vec{V}_p$, resulting from 2.3 gives rise to radial transport due to the $\vec{V}_p \times \vec{B}_t$ force;
- 2.6. The spatial anisotropy of the neoclassical alpha orbits plus the change in the perpendicular velocity component along the orbital path produces a net poloidal current, $\vec{J}_p$. The resulting $\vec{J}_p \times \vec{B}_t$ force produces a radial particle transport.

The toroidal rotation, described in 2.1, causes centrifugal acceleration and two-stream instabilities which can disrupt the plasma. Loss cone instabilities, analogous to those for mirrors^[17-18], may also be important. The additional toroidal current resulting from 2.2 will change the poloidal magnetic field, which will modify the neoclassical alpha orbits. Poloidal rotation, discussed in 2.3, produces instabilities and anomalous transport as reviewed by Kadomtsev and Pogutse^[7]; more recent articles by Aldridge and Keen^[8], Rozhkov *et al.*^[9], Hooper^[10] and Dobrowolny^[11] further investigate instabilities in a rotating plasma. It is also necessary to account for damping in the poloidal rotation due to finite plasma viscosity^[21].

The various instabilities mentioned above can also modify alpha-particle slowing down in the plasma. For example, there may be significant particle-Alfven wave coupling^[12].

There may also be other significant plasma instabilities, in addition to those mentioned above. Tang^[22] has recently reviewed the MHD and micro-instabilities associated with Tokamak plasma. Mai and Horton^[23] discuss microinstabilities due to alpha fusion products for a general alpha distribution function (in the two extreme limits, this distribution function becomes a Dirac delta or a Maxwellian) for cyclotron waves, the lower hybrid mode, modes of large $K_{||}$, and low frequency modes; stability conditions for each mode are given. Coppi and Taroni^[13] analyze electrostatic modes due to microinstabilities and find that trapped modes with $\omega(\text{bounce}) = \omega(\text{electrostatic})$ can absorb energy and can even become untrapped; weakly trapped and untrapped particle orbits evolve into a new class of orbits with a non-zero bounce frequency, being alternately trapped and untrapped. Kadomtsev and Pogutse^[7] review other collisionless trapped-particle instabilities. Houlberg^[14] has more recently reviewed transport processes associated with trapped particle instabilities. A further possibility is that the alpha velocities, being much larger than the ion-acoustic wave velocity may introduce significant shock waves in the plasma^[15].

A final effect to be considered is the effect of non-classical slowing down, beyond the effects of particle-wave coupling. Bathke^[16] has calculated slowing-down times which range between 1.05-1.10 times smaller than those given by Fokker-Planck theory.

3. Completed Calculations for D-He³ Simulation of D-T Burns

The goal of D-T burn simulation is the optimal design of experiments to provide preliminary data on D-T burn physics by use of D-He³ prior to the introduction of D-T in TFTR. The advantages of using D-He³ include:

- a. The 3.7 MeV alphas from the D-He³ reaction can closely model the 3.5 MeV alphas from D-T for confinement and heating;

- b. The problems associated with neutron- and tritium-related radiation are eliminated.

The disadvantages of using D-He³ include:

- a. The reaction rate for D-He³ is much less than that for D-T at TFTR temperatures and densities;
- b. The effect of proton fusion products from D-He³ must be taken into account in interpreting the simulation experiments. (Preliminary calculations give a loss fraction on the order of 1/2 for protons during the first bounce^[20].)

Disadvantage a. is not so severe if alpha particle detection is used as a part of the plasma diagnostics. For example, an estimate of the average alpha flux (due to the fusion product loss fraction) hitting the first wall (major radius = 280 cm, minor radius = 120 cm) gives the following values:

- a. For D-T: $8.5 \times 10^7 \text{ cm}^{-2}$
- b. For D-He³: $2.7 \times 10^4 \text{ cm}^{-2}$,

assuming an average reaction temperature of 4 keV and average densities for each reactant of $2.8 \times 10^{13} \text{ cm}^{-3}$ in the TFTR 'B' plasma^[1], having a loss fraction of 10%. This alpha flux is detectable by schemes such as those developed for laser-fusion alpha detection^[24]. Such alpha detectors could be placed in a poloidal array and appropriately collimated to measure the alpha flux at each poloidal position as a function of particle pitch angle. Without instability-induced transport, orbit calculations, based on the guiding-center drift model (see 3.3 below), can be indirectly verified. With instabilities present, loss-fraction corrections can be applied to measure the instability-induced transport.

Work to date in modeling D-T by D-He³ includes:

- 3.1. Petrie and Miley^[4] have shown that by reducing the background He^3 density, the ratio of fusion-product pressure to background pressure can be adjusted to simulate D-T burns;
- 3.2. Petrie and Miley^[25] have also calculated that fusion product energy deposition will be about 1/3 that expected for D-T, under conditions similar to 3.1;
- 3.3. Miley, Rao, Petrie, and Hively^[27] have calculated particle orbits analytically as an energy dependent, guiding-center motion. (See Figures 1-4).

The model includes:

- a. Toroidal magnetic field dependence on the major radius,
 - b. Toroidal current density having an arbitrary dependence on minor radius (which produces the poloidal B-field),
 - c. A constant vertical magnetic field;
- 3.4. Bathke^[16] has calculated slowing-down rates and total slowing-down times for alphas in a D-T plasma using the "unified theory;" the results are presented in Figures 5-8. Choi^[29] has used Bathke's code to calculate slowing-down rates and times for alphas in a D- He^3 plasma. (See Figures 9-12). See Table 1 for the symbol key to these figures.

These studies have identified fusion-product partial pressure, energy deposition, synergistic effects, and microinstabilities as key parameters.

4. Proposed Calculations for D- He^3 Simulation of D-T Burns

The next parameters to be analyzed will include the following:

4.1. Poloidal rotation, discussed in 2.3, can be modeled by:

- a. Use of the guiding-center drift model to find the particle orbits,
- b. Using spatial (ring segments)-, energy-, and pitch angle-groups with average orbital properties within each group,
- c. Combining the group-wise average residence time in each spatial group, and the orbital characteristics, to calculate the space charge density,
- d. Integrating Poisson's equation for this space charge density to obtain the resultant electric field, $\vec{E}$ (a poloidal component of electric field will also be present, in addition to the radial part, because the neoclassical orbits are anisotropic),
- e. Calculation of the $\vec{E} \times \vec{B}_t$ force, which gives rise to the poloidal rotation;

4.2. Previous codes have neglected fusion-product slowing down by assuming complete energy deposition at the birth point (see for example Ref. 5). Independent studies by Tenney^[26] and Hively^[20] have demonstrated that the neoclassical orbits are sensitive to birth-point, pitch angle, and energy. M. P. Rao^[29] has proposed to include these dependences in the following energy deposition model:

- a. Use the guiding-center orbit model discussed in 3.3,
- b. Use spatial (ring segments)-, energy-, and pitch angle-groups with average orbital properties within each group,

- c. From the orbital description, include the particle escape fraction and the consequent energy loss,
 - d. Account for energy deposition within each spatial-group, by fusion-product slowing down, according to the group-wise residence time (at high energies, electron drag is dominant, and pitch angle scattering is negligible),
 - e. Also, include pitch angle scattering (at low energies, ion-ion collisions dominate, producing large momentum direction changes), which, in turn, changes μ (orbital magnetic moment) and J (longitudinal adiabatic invariant);
- 4.3. To calculate the slowing down for the 14.1-MeV protons from the $D-He^3$ reaction, nuclear scattering must be taken into account (see, for example, Figure 2 of [30]). These elastic nuclear scattering and magnetic effects will be added to the Bathke code for slowing down.
- 4.4. The importance of microinstabilities due to the high-energy fusion products, especially those investigated by Mai and Horton, and Alfvén wave coupling will be analyzed as follows:
- a. From the slowing-down model described in 3.4 and 4.3, the fusion-product velocity distribution can be found as the particles slow down. An initial estimate of the instability will be obtained assuming a slab geometry with average temperatures and densities;
 - b. An improved estimate of the instability limits will include the Tokamak toroidal geometry and the temperature and density profiles expected for TFTR.

From the poloidal rotation model discussed in 4.1, the importance of the various rotation-induced instabilities can be evaluated. Micro-instabilities due to the peaked, fusion-product velocity distribution will be examined from 4.4.

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TABLE 1: SYMBOL KEY TO FIGURES 5-12

α Particle Injected into D-T and D-He³ Plasmas

For D-T Plasma:

$$N_e = 1.0 \times 10^{14} \text{ cm}^{-3}$$

$$N_D = 0.5 \times 10^{14} \text{ cm}^{-3}$$

$$N_T = N_D$$

$$T_i = 3 \text{ KeV}, T_e = 3 \text{ KeV}$$

$$T_i = 6 \text{ KeV}, T_e = 6 \text{ KeV}$$

For D-He³ Plasma:

$$N_e = 0.56 \times 10^{14} \text{ cm}^{-3}$$

$$N_o = 0.186 \times 10^{14} \text{ cm}^{-3}$$

$$N_{\text{He}3} = N_D$$

$$T_i = 3 \text{ KeV}, T_e = 3 \text{ KeV}$$

$$T_i = 6 \text{ KeV}, T_e = 6 \text{ KeV}$$

Legends

Unified Theory	Fokker-Planck	Energy Loss Rate vs. Energy	Energy vs. Time
$\frac{\partial E}{\partial t} _{\text{Total}}$	Test Particles Energy
$\frac{\partial E}{\partial t} _{\text{Electrons}}$	Energy Gained by Electrons
$\frac{\partial E}{\partial t} _{\text{Deuteron}}$	Energy Gained by Deuterons
$\frac{\partial E}{\partial t} _{\text{Triton (He}^3\text{)}}$	Energy Gained by Tritons (or He ³)

$$\begin{aligned}
 R_0 &= 250 \text{ cm.} \\
 a &= 56 \text{ cm.} \\
 B_T &= 48.8 \text{ kG.} \\
 B_P &= 3.6 \text{ kG.} \\
 E_\alpha &= 3.52 \text{ Mev.} \\
 q &= 3.0 \\
 j &= j_0 \left[1 - \left(\frac{r}{a} \right)^2 \right]
 \end{aligned}$$

FIGURE 1: Neoclassical orbits in TFTR 'B' plasma [1] for 3.52 Mev alphas born at $x = 30$ cm, having initial pitch angles (ϕ) as shown.

NOTE: The origin lies at the center of the plasma column ($R_0 = 250$ cm). The orbits are symmetric in $\pm y$, so only the upper half of the orbit is shown.

$$\left. \begin{array}{l} R_0 = 250 \text{ cm.} \\ a = 56 \text{ cm.} \\ B_T = 48.8 \text{ kG.} \\ B_p = 3.6 \text{ kG.} \\ E_\alpha = 3.52 \text{ Mev.} \end{array} \right\} q = 3.0$$

$$j = j_0 \left[1 - \left(\frac{r}{a} \right)^2 \right]$$

FIGURE 2: Neoclassical orbits for alphas born at $x = 10$ cm. All other parameters are the same as in Figure 1.

$$\left. \begin{aligned}
 R_0 &= 250 \text{ cm.} \\
 a &= 56 \text{ cm.} \\
 B_T &= 48.8 \text{ kG.} \\
 B_P &= 3.6 \text{ kG.} \\
 E_\alpha &= 3.52 \text{ Mev.}
 \end{aligned} \right\} q = 3.0$$

$$j = j_0 \left[1 - \left(\frac{r}{a} \right)^2 \right]$$

FIGURE 3: Neoclassical orbits for alphas born at $x = -10$ cm. All other parameters are the same as in Figure 1.

$$\begin{aligned}
 R_0 &= 250 \text{ cm.} \\
 a &= 56 \text{ cm.} \\
 B_T &= 48.8 \text{ kG.} \\
 B_p &= 3.6 \text{ kG.} \\
 E_\alpha &= 3.52 \text{ Mev.}
 \end{aligned}
 \quad q = 3.0$$

$$j = j_0 \left[1 - \left(\frac{r}{a} \right)^2 \right]$$

FIGURE 4: Neoclassical orbits for alphas born at $x = -30$ cm. All other parameters are the same as in Figure 1.

FIGURE 5
(See Table 1 for symbol key.)

FIGURE 6: Slowing Down Times for an Alpha, Injected into 3 KeV D-T Plasma.
(See Table 1 for symbol key.)

FIGURE 7
(See Table 1 for symbol key.)

FIGURE 8: Slowing Down Times for an Alpha, Injected in 6 KeV D-T Plasma
(See Table 1 for symbol key.)

FIGURE 9
(See Table 1 for symbol key.)

FIGURE 10: Slowing Down Times for an Alpha, Injected in a 3 KeV D-He³ Plasma
(See Table 1 for symbol key.)

ALPHA INJECTED IN
6 KEV D-HE3 PLASMA

FIGURE 11

(See Table 1 for symbol key.)

FIGURE 12: Slowing Down Times for an Alpha, Injected in 6 KeV D-He³ Plasma
(See Table 1 for symbol key.)