Approaches to the diagnostics of alpha particles in tokamaks (invited)

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Alpha particles from D/T reactions are expected to be produced at a power level of about 5 MW in $Q \cong 1$ beam heated experiments in the tokamak fusion test reactor (TFTR) and will become the dominant heating mechanism in future tokamak ignition devices. Although alphas should be well confined according to neoclassical orbit theory, the effects of plasma instabilities on alpha confinement and the effect of alphas on plasma confinement and heating remain to be seen. This paper describes the physical context for alpha particle measurements in tokamaks and reviews the status of recent approaches to their diagnosis.

INTRODUCTION

Alpha heating will begin to affect the energy balance of near-term tokamak devices at $Q \cong 1$ (where Q is the ratio of total fusion power production to total energy input), and future ignition devices will be totally dominated by the effects of alpha heating. Yet there are presently few proven diagnostic techniques available for measuring the behavior of high-energy alphas in the tokamak environment. This is partly because present tokamaks are operated without tritium (and so have produced few alphas), but it is also due to the intrinsic novelty and technical difficulty of the proposed alpha diagnostics, as discussed below.

Given this situation, it is timely to reconsider the possible approaches to the measurement of alpha particles in tokamaks. In this paper I will first summarize the physical context for alpha behavior in tokamaks, and then list the proposed techniques, citing their apparent advantages and disadvantages.

I. ALPHA PHYSICS ISSUES FOR IGNITION EXPERIMENTS

The main alpha physics questions for tokamak ignition devices are

(1) How well are alphas confined in the tokamak plasma?

(2) Is the alpha distribution itself stable?

(3) How efficient is alpha heating?

(4) Does the thermalized alpha "ash" accumulate in the plasma?

(5) How can alpha heating be controlled for a steady "burn"?

The first three of these questions can be addressed on experiments at $Q \cong 1$ such as tokamak fusion test reactor (TFTR) and joint European tokamak (JET), although their final answers will only come from fully ignited plasma experiments such as the proposed compact ignition device (CIT). The last two of these questions might be addressed on a machine like the CIT, but probably require a long-pulse device such as the international tokamak reactor (INTOR) or the next European tokamak (NET) for their resolution. Before discussing the diagnostics necessary for answering these questions, I will review some basic physics of alpha particles in tokamaks.

II. SOME PHYSICS OF ALPHAS IN TOKAMAKS

Alpha particles are created in the fusion reactions

$$\mathrm{D} + \mathrm{T} = n(14.1\ \mathrm{MeV}) + \alpha(3.5\ \mathrm{MeV}),$$

$$\mathrm{D} + {}^3\mathrm{He} = p(14.7\ \mathrm{MeV}) + \alpha(3.6\ \mathrm{MeV}),$$

and in several other less likely ways. Although the principal interest for tokamak ignition experiments will be in the 3.5-MeV alpha from D-T, the 3.6-MeV d-^{3}He alpha can be readily produced, albeit at low rates, in presently operating tokamaks. Note also that the "burnup" of deuterium into tritium creates a small number of D-T alphas in present experiments, even without the explicit addition of tritium.

The single-particle confinement of alphas in tokamaks has been treated by many authors.[1–4] The fundamental loss mechanism depends on the finite gyroradius of the alpha, which is typically 5 cm in a 50-kG toroidal field. For axisymmetric tokamaks, a rough criterion for good first-orbit alpha confinement is $I \geqslant 2$–3 MA, where I is the plasma current; thus present tokamaks like TFTR and JET should be capable of good alpha confinement. Nonaxisymmetric effects such as toroidal field ripple may cause additional losses.[5,6]

If the alpha is confined on its first orbit, it begins to lose energy by Coulomb scattering from electrons; however, during this process, it remains well confined, since the angular scattering is small. The slowing down or thermalization time for 3.5-MeV alphas decreases linearly with increasing plasma density and increases approximately linearly with increasing temperature[7,8]; for typical ignition conditions, the alpha slowing down time is roughly 100–300 ms. If the alpha is not confined on its first orbit, it hits the wall in typically 1–10 μs with very nearly its initial energy.

The expected alpha distribution function and alpha density can be calculated from the neoclassical particle confinement model plus a classical (i.e., Coulomb) slowing down model.[1–9] Typical steady-state alpha densities for a tokamak ignition experiment are in the range $n_\alpha \sim 10^{12}$–10^{13} cm^{-3}, i.e., $n_\alpha/n_e \cong 0.1\%$–2% for plasma temperatures in the range 10–30 keV. The alpha heating rate and ash accumulation

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rate can also be calculated from this "classical" model, thus providing tentative theoretical answers to questions (1)–(4) above; however, the possible (or probable) existence of "anomalous" alpha transport process requires that these questions be addressed experimentally.

III. SOME PREVIOUS EXPERIMENTS ON ALPHALIKE PARTICLES

The confinement of alphalike 1-MeV tritons and 0.8-MeV ^{3}He particles has been measured by the "burnup" technique on PLT,[10] PDX,[11,12] and FT.[13] As reviewed recently by Strachan,[14] these fusion products generally show classical confinement (within an uncertainty level of about a factor of 2), except during strong magnetohydrodynamic (MHD) activity when large anomalous losses are observed.[11,12] Although improved confinement with increasing plasma current has been observed on PDX up to $I = 0.5$ MA, the classical confinement was, at best, only marginal ($\sim 50\%$), so that the near-perfect confinement expected at higher plasma currents remains to be seen.

The radial density profile of thermal He^{++} has been measured by charge exchange recombination spectroscopy on PDX.[15,16] Although the He^{++} energy was only in the 1-keV range, the same technique can probably be used for higher-energy alphas, as described below. As it stands this technique can measure thermalized alpha ash at densities of below 10^{12} cm^{-3}.

So far the only actual measurement of fusion product alphas in a tokamak has that on PLT using a plastic track detector.[17] The radial profile of the D-^{3}He emission rate was inferred from the pitch angle distribution of unconfined alphas, as described below.

IV. CLASSIFICATION OF ALPHA DIAGNOSTICS

For discussion purposes we will divide alpha diagnostics into three categories:

Escaping alphas, which are to be detected at the wall outside the plasma at energies typically in the range 0.5–3.5 MeV. Note that these measurements are relatively simple, in part because these alphas can deposit their whole energy in the detector.

Slow confined alphas, which are to be detected inside the plasma at energies typically in the range 10 keV–0.5 MeV. Note that this alpha population consists of substantially thermalized alphas, thermal alpha ash, possibly recycled helium from the walls.

Fast confined alphas, which are to be detected inside the plasma at energies typically in the range 0.5–3.5 MeV. This alpha population is the hardest of these three categories to measure, in part simply because plasma diagnostic techniques have not yet been developed for this rather unfamiliar species of particle.

V. ESCAPING ALPHA DIAGNOSTICS

The first goal of escaping alpha diagnostics is to determine the flux of high energy alphas at the wall in order to find the net alpha heating rate inside the plasma, from which an assessment of the effects of alpha heating can be made. The escaping alpha flux can be compared with the simple classical confinement and thermalization models discussed in Sec. I, given information about the alpha creation rate from the neutron emission profile and information about the plasma current distribution from the electron temperature profile. Anomalous losses can also be detected by looking for time variations in the escaping alpha flux (e.g., correlated with MHD activity), or by looking at the energy spectrum of the escaping alphas (which should contain relatively few low energy alphas), or by looking at the spatial distribution of alphas on the wall (which should be strongly up/down asymmetric if classical).

A secondary goal of escaping alpha diagnostics is to use the information gained to determine other plasma properties such as the plasma temperature, density, or current distribution. As discussed recently by Karulin and Putvinskij,[4] this goal will be somewhat restricted in high current plasmas by the fact that there is a "dead zone" at the center of the plasma from which no alphas are expected to escape, according to classical theory. Of course, if the alpha confinement is strongly anomalous, then the escaping alphas themselves should provide important clues as to the internal instability responsible for their deconfinement.

In the long term, escaping alpha diagnostics will be useful in order to monitor wall damage due to alpha impact and possibly to verify intentional alpha losses imposed for burn control, e.g., ripple-induced losses. Diagnostics for thermalized escaping alphas might also be useful for monitoring ash removal schemes such as helium enrichment in pumped limiters.[8]

Escaping alpha fluxes have been calculated in detail by Hively and Miley,[1] Kolesnichenko,[2] and others[3–9] according to the neoclassical model. Typical results are $\sim 10^{11}$–10^{12} $\alpha/$(cm^2 s) at the bottom of TFTR for $Q \cong 1$ scenarios with 2.5-MA plasma current.[4] Besides the total alpha flux, the most important measurement for escaping alphas is the pitch-angle distribution of the escaping flux; that is, the flux versus angle with respect to the toroidal field at the wall. The pitch angle determines the alpha's magnetic moment, which in turn determines the alpha's orbit in the plasma (assuming the energy is known). Thus the measured escaping alpha flux versus pitch angle can be directly compared to the neoclassical predictions through computer code calculations of the escaping particle orbit, given the radial profiles of the alpha source rate and the plasma current profile. Similar calculations have already been used to interpret the results of measurements of escaping 3-MeV[18] and 15-MeV protons.[19]

The following types of escaping alpha diagnostics have been proposed:

A. Scintillation detectors

High-energy alphas are easily detected through the visible scintillations they produce in phosphor screens (such as are used in oscilloscopes). For a thin phosphor coating of ~ 10-μ ZnS the alpha detection efficiency is $\sim 100\%$, while the neutron and gamma detection efficiency is $\sim 10^{-4}$–10^{-5}, thus allowing a good signal-to-noise ratio for an escaping alpha fraction as low as $\sim 10^{-5}$ alphas/neutron incident on the detector.

Such escaping alpha detectors have been proposed by Seiler and Hendel,[20] Elevant,[21] and Kislev and Miley,[22] and a prototype detector is presently being tested on TFTR.[23] With a ZnS(Ag) phosphor the time resolution is $\lesssim 50\ \mu$s, and pitch angle and energy resolution can be obtained by choosing appropriate collimators and filters. Multichannel capability is readily available by imaging the scintillator screen directly onto a sensitive camera.[23] The main disadvantages of this method are its lack of intrinsic energy resolution (due to the microcrystalline structure of most phosphors) and eventual radiation damage (e.g., decreased luminosity in ZnS at $\sim 10^{13}$ alphas/cm^2).

In practice, this and all other escaping alpha diagnostics also share another difficulty, which is that at least part of the detection system must be placed inside the vacuum vessel as close as possible to the plasma edge in order to collect the maximum information about the orbits of the escaping alphas. This exposes the detector to severe mechanical and thermal stresses and makes maintenance difficult.

B. Charge neutralization by foils

In order to minimize this latter difficulty, Gerdin, Mueller, and Wehring[24] have proposed a method in which the escaping alphas are neutralized in thin foils at the plasma edge, such that the neutralized alphas can stream outside the tokamak radiation shield to be measured by more accessible detectors. The reduced radiation background at that point also improves the potential signal-to-noise ratio.

For an alpha to be neutralized in a foil via charge exchange its energy must be reduced to about 400 keV; thus a foil must be chosen which is thick enough to slow alphas down to this energy range, but thin enough to allow the neutralized alpha to escape. Carbon foils of about $10\,\mu$ thickness are most appropriate for this purpose; the conversion efficiency to neutrals is $\sim 20\%$ at 400-keV post-foil energy.

The main difficulty with this method is the fragility of the foil, which must be exposed to the severe in-vessel environment. Also, the total system efficiency for alpha detection is relatively low mainly because of the small solid angle available for collection of the neutrals; thus near-term tests of this system are relatively difficult, compared to the scintillation detector.

C. Foil deposition

Langley[25] has proposed that escaping alphas can be measured very simply by exposing a set of layered foils to collimated alphas, such that the alphas are deposited in various foils according to their energy. The required foil thicknesses are in the range 0.25–10 μm, and an energy resolution of ~ 200 keV is possible.

After an integrated exposure the foils are removed for anlaysis by vaporization in a mass spectrometer, where a sensitivity of $\sim 10^8$ alphas/cm^2 sample is possible. Foils of aluminum, nickel, and copper are appropriate since their helium diffusion rate is very low.

The principal advantage of this approach is its simplicity and relative immunity to backgrounds; however, time resolution must be obtained by some mechanical means, such as through use of a rotating probe head. Of course, a method must also be devised for removing the foils from the vacuum system.

D. Nuclear activation

If foils can be removed from the vacuum vessel, then nuclear activation of these foils can be used as an escaping alpha diagnostic, as proposed by Cecil.[26] An earlier approach using liquid or gaseous materials for activation was also discussed by England.[27]

Typical activation reactions include $^{10}\mathrm{B}(\alpha,n)\ ^{13}\mathrm{N}$ and $^{14}\mathrm{N}(\alpha,\gamma)\ ^{18}\mathrm{F}$, which have half-lives of 9.9 and 110 min, respectively. Cross sections for these processes are in the range of 10 mb, which should give a sensitivity of $\sim 10^9$ alphas/cm^2. As for the foil deposition technique, the principal difficulties are in obtaining time resolution by some mechanical means and in removing the sample from the vacuum vessel.

E. Track detection

As mentioned in Sec. II, the only method so far used to measure alphas in tokamaks was track detection in the plastic CR-39 in PLT.[17] It is possible that this method can also be applied to future tokamak ignition devices, although some more rugged high-temperature track medium must be used. The principal difficulty in this approach is that of measuring the tracks through microscopic examination, although of course the detector also shares the lack of time resolution and mechanical difficulty of the previous two approaches.

VI. CONFINED ALPHAS

For confined alphas, the main diagnostic goal is to measure as much as possible about the alpha distribution function inside the plasma, $n_\alpha(\mathbf{x},\mathbf{v},t)$. From this the alpha confinement, alpha stability, and alpha heating can be inferred, given information about the alpha source rate from the neutron emission profile and some theoretical interpretation.

For example, if the alpha confinement and thermalization is classical (see Sec. II), the expected steady-state alpha distribution function will be of the form[8]:

$$f_\alpha(v) \sim S\tau_s/[4\pi(v^3+v_c^3)],$$

where S is the alpha creation rate (in cm^{-3}/s), τ_s is the slowing down time, and v_c is the critical velocity at which the slowing down is equally shared between ions and electrons. Typically, v_c is about $\frac{1}{3}$ of the initial alpha velocity of 1.3×10^9 cm/s, such that the alpha density at the critical energy $E_c \cong 300$ keV is about 15 times the alpha density near its birth energy.

This quest for the internal alpha distribution function should be put in perspective: Even after years of diagnostic experience with fast ion populations created in tokamaks by neutral beam or rf heating, relatively little is known of the local fast ion distribution functions and local heating rates through direct measurement. In all likelihood the confined alpha measurements will be limited to some subset or average over the internal distribution, so that the results will have to be interpreted through some assumptions or modeling.

Some specific issues which might be resolved by confined alpha diagnostics are: Is there a radial diffusion of fast alphas such that the low energy part of the central alpha distribution function is depleted relative to the classical expectation? Is there a nonisotropic alpha distribution due to ripple losses of trapped particles? Are there plasma instabilities related to the local alpha density or beta? Do thermalized alphas accumulate in the center of the discharge? Tentative answers to these questions are already incorporated into computer codes wihich simulate the approach to ignition in next-generation tokamaks.

The following confined alpha diagnostics have been proposed:

A. Charge exchange recombination spectroscopy for slow confined alphas

The basic idea here is to inject a neutral atom beam into the plasma which allows a single charge exchange interaction to occur with a slow confined alpha, i.e., $He^{++} + e = He^{+}$. Once the alpha has an electron, it begins to emit spectral lines characteristic of an excited state of He^{+}, and so can be detected by standard spectroscopic techniques. This method is described in detail by Post *et al.*[28] and Fonck[16] and has already been used successfully to measure the thermal He^{++} density profile in PDX.[15]

Good spatial resolution is obtained since the neutral source density is well defined by the injected beam and the spectrometer is also collimated. Velocity resolution can be obtained from the Doppler broadening or shift of the spectral lines. The signal-to-noise ratio depends on the strength of the injected neutral source, on the alpha population, and on the background light emission from the plasma; preliminary calculations suggest that this measurement should be feasible for slow alpha densities characteristic of ignited plasmas, given only modest refinements of current technology.

The principal limitations of this approach are set by the requirement that the neutral beam penetrate into the center of the plasma, and that the neutral atom have the appropriate speed for resonant charge exchange with the alpha. The first requirement is fulfilled by standard neutral hydrogen beams at energies of about 80 keV for plasmas like TFTR, but might require several times higher beam energies for high density ignition plasmas like those planned for the CIT. The second requirement sets a limit to the detectable alpha energy of $\lesssim 500$ keV for 80-keV injected hydrogen beams. Thus, for presently available neutral hydrogen beams, this diagnostic is limited to sampling the slow confined alphas of energy well below 1 MeV.

Another difficulty of this approach is the need for access to the vacuum vessel for neutral beam injection and for spectroscopy. The latter is particularly difficult if the spectrometer must be operated in the harsh radiation environment nearby the tokamak, as might be required if UV emission lines are monitored.

B. Charge exchange recombination spectroscopy for fast confined alphas

The same basic technique as in Sec. VI A can be used for fast confined alphas if the neutral atom beam has higher energy; typically, 1 MeV/amu of beam energy is required for charge exchange for 3.5-MeV alphas.[28] Unfortunately, beams of the required power at these energies do not yet exist. Two approaches have been suggested: Negative ion beam hydrogen sources can potentially be made with good efficiency at energies up to 1 MeV, although present limits are about 80 keV at 1-A beam current,[29] and lithium beams at 5–6 MeV, which would require considerable source and accelerator development, as described below.

C. Lithium beam double charge exchange for fast alphas

Post *et al.*[28] and Grisham, Post, and Mikkelson[30] have proposed that a high-energy neutral lithium beam could be used to doubly charge exchange fast alphas, such that the neutral alphas can leave the tokamak and be detected outside the radiation shield, similarly to the foil neutralized escaping alphas discussed in Sec. IV. (b) This has the advantage that the potential background problems associated with spectroscopy of He^{+} are eliminated, although some backgrounds due to neutron and gamma radiation remain.

Good spatial resolution can be obtained since the injected beam and detector system can both be narrowly collimated. Velocity resolution can be obtained by varying the energy of the neutral beam, since the charge exchange cross section is a strongly resonant process. The escaping neutralized alpha can also be energy analyzed to help unfold the internal alpha velocity distribution.

The principal difficulty with this approach is that the required 5–6-MeV 100-mA neutral lithium beams do not yet exist. The required Li^{-} source, rf accelerator, and neutralizer all have to be developed. This development appears to be feasible but would require considerable time and support. For slower confined alphas a presently available $\sim$80-keV He beam might also be used for double charge exchange.[31]

D. Small-angle Thomson scattering

An entirely different approach to confined alpha diagnostics has been proposed by Hutchinson *et al.*,[32] which consists of measuring the small-angle scattering of a CO_2 laser beam passing through the tokamak. This scattering can be visualized as being from the localized "cloud" of electrons which shields the charge of the alpha; thus the characteristic wavelength of this scattering is the Debye length, and the characteristic frequency shift is that of the Doppler shift due to the fast alpha velocity. Typically, this implies angular scattering at $\sim 1°$ for a CO_2 laser beam and a frequency shift of $\sim$10 GHz.

This detection system should have fairly good spatial resolution, depending on the scattering geometry, and good time resolution of the scattered, frequency shifted electromagnetic radiation. Velocity resolution can be obtained from a detailed analysis of the angular and frequency dependence of the scattered power. A significant advantage is that this diagnostic would not require direct access to the vacuum system; however, it does require optical access, probably through a vertical chord.

The principle difficulty with this approach is to detect the scattered radiation, and to discriminate against scattering from thermal ions at lower frequencies and scattering from electrons over a wide range of frequency. Checks of the scattering backgrounds from ions and electrons can be performed to some extent on present tokamaks.

E. Lower hybrid wave damping

Wong[33] has proposed another approach in which the confined alphas are detected by the effect they have on the damping of lower hybrid waves, which can be launched from the plasma edge with conventional techniques. Calculations have shown that considerable damping is expected for alpha populations typical of ignited plasmas, since the phase velocity of the wave can be approximately the same as the alpha velocity. The damping rate would be detected by the amplitude of the lower hybrid was as measured for example by FIR laser scattering.

This technique should have some spatial resolution, given by the localization of the LH wave trajectory and of the detection scattering system, and would have good time resolution. An advantage is that the technology for both wave launching and detection are well developed, and might, in fact, already be incorporated to some extent in the tokamak design.

The principle disadvantage lies in the subtlety of the LH wave physics, which depends for example on the scattering effects due to tokamak edge turbulence. Another disadvantage lies in the required access to the vacuum system.

F. Gamma spectroscopy

Slaughter[34] and Cecil, Zweben, and Medley[35] have proposed that characteristic gamma rays from nuclear reactions involving high-energy alphas can be used to diagnose the alpha energy distribution inside the plasma. For example, the $^7Li(\alpha,\gamma)\ ^{11}B$ reaction has a resonance at about 1 MeV, so that the flux of its characteristic 4.8-MeV gamma ray is a measure of the population of alphas at 1 MeV. The detection system would consist of standard gamma spectroscopy detectors such as NaI, appropriately shielded from competing background effects of neutrons.

The advantage of this method is that it requires no access to the vacuum vessel and uses standard technology. The disadvantages are that it probably requires some "seeding" of the plasma with appropriate reactant atoms, and that the expected gamma count rate is rather low, probably requiring averaging over space and time.

G. ICRF emission

A novel approach to the confined alpha diagnostic problem has been proposed by Rosenberg, Krall, and Moses,[36] who have pointed out that superthermal alphas should spontaneously emit electromagnetic radiation that can be detected with a simple loop antenna inside the vessel wall. Although alphas and deuterium have the same gyrofrequency, the alphas should preferentially emit radiation in the (4–12)th harmonic of its gyrofrequency, analogously to high harmonic emission regularly observed from superthermal electrons. Calculations have indicated that this radiation can be detected with a conventional rf spectrum analyzer at frequencies in the range 100–300 MHz. Recently, such radiation has been detected from D/D fusion products in JET.[37]

The advantge of this technique is its extreme technical simplicity, which requires essentially no development. The disadvantage lies in the subtley of the wave physics, which requires considerable theoretical analysis for interpretation of the received signals in terms of, for example, the alpha beta. However, even if the unfolding of the confined alpha properties is not possible, such an ICRF receiving antenna would be useful for monitoring radiation from alpha instabilities which might occur at these frequencies.

VII. CONCLUSION

Alpha diagnostics will be necessary in order to understand the physics of tokamak ignition. Some of the required information can come from escaping alpha diagnostics, which can be implemented relatively easily. Information about the slow confined alphas can be obtained using conventional charge exchange recombination spectroscopy, assuming the diagnostic neutral beam can penetrate to the plasma center. However, diagnostics for fast confined alphas have not yet been demonstrated, in part because there has been no suitable test source, but also because in most instances they require either new technology or detailed understanding of tokamak wave physics.

All of these alpha diagnostic approaches share the practical problems associated with the harsh radiation environment and restricted access of a tokamak ignition experiment. It will be difficult to test a new alpha diagnostic without access to a burning plasma source, and it will be difficult to "debug" that diagnostic once it has been installed next to such a source. However, development of these diagnostics on TFTR and JET will no doubt resolve most of these difficulties.

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