MEETING REPORT

SUMMARY OF THE WORKSHOP ON ALPHA-PARTICLE DIAGNOSTICS, ABINGDON, UNITED KINGDOM, DECEMBER 9–10, 1986

INTRODUCTION

An informal workshop was held under the auspices of the Joint European Torus (JET) Joint Undertaking, Abingdon, United Kingdom, December 9-10, 1986, to discuss the options available for making experimental measurements on alpha particles in deuterium-tritium (D-T) plasmas. There were 57 participants—26 from European laboratories, 10 from the United States, 2 from Japan, and the remainder from JET. All the presentations were by invitation.

In his introductory talk, M. Keilhacker (JET) indicated that the study of alpha-particle production, confinement, and consequent plasma heating is one of the main objectives of the JET project. The motivation for holding the workshop was to present and assess the experimental techniques that could be applied to the investigation of alpha-particle phenomena in D-T plasmas for such machines as JET, Tokamak Fusion Test Reactor (TFTR), and Compact Ignition Tokamak (CIT). The role to be played by conventional diagnostic techniques was not overlooked, but attention was naturally focused on methods specific to the presence of alpha particles and for which the feasibility has yet to be established.

Two distinct classes of alpha-particle phenomena can be distinguished: The simpler class contains phenomena exhibited by individual alpha particles under the influence of bulk plasma properties, while the more complex class includes the effects (possibly collective) due to the alpha-particle density becoming significant. The first class is already being studied intensively in JET and TFTR with deuterium plasmas, using the deuterium-deuterium (D-D) reaction products (tritons and ^{3}He ions) as analogs of the D-T reaction alpha particle. These zero-order effects (alpha transport and confinement) can be studied in D-T plasmas, but only at levels of negligible alpha-particle power.

The source term for the alpha-particle heating of D-T plasmas can be established quite reliably by a combination of measurement and calculation. O. N. Jarvis (JET) and J. D. Strachan [Princeton Plasma Physics Laboratory (PPPL)] reported that measurement of neutron production gives the total number of alpha particles produced and their spatial profile. Neutron spectrometry should quantify their effectiveness in heating the plasma. Calculation provides their birth energy distribution; for example, 140-keV D° beams injected into a tritium plasma give rise to an alpha- particle energy distribution with full-width at half-maximum of 1.5 MeV centered at 3.5 MeV (the energy associated with low-velocity reactants). In the absence of anomalous transport, instabilities, and alpha-particle-related collective effects, it is a straightforward matter to derive the steady-state alpha-particle velocity distribution $f_\alpha(v,r,t)$. Our problem is that, while the aforementioned phenomena are all present, their importance in relation to the achievement of ignition and steady-state burn conditions is entirely a matter of theoretical conjecture. Their study in plasmas for which $Q \sim 1$ is clearly mandatory.

From the vantage point of theory, D. J. Sigmar [Massachusetts Institute of Technology (MIT)] listed the quantities to be measured in alpha-heated plasmas as follows:

1. alpha heating power, $P_\alpha(r,t)$
2. particle and energy confinement times for fast alpha particles $\tau_{\alpha p}$ and $\tau_{\alpha E}$
3. alpha-particle pressure gradient dp_α/dr
4. fast alpha-particle velocity distribution $f_\alpha(v)$
5. alpha-particle fluctuation frequencies near certain critical values
6. correlation between $df_\alpha/dv < 0$ and anomalous slowing down
7. the helium ash problem; $n_\alpha(r,t)$ for thermalized alpha particles
8. correlation between ejected fast alpha particles [due to magnetohydrodynamic (MHD) events] and changes in E_r (e.g., abrupt changes in plasma rotation)
9. correlation between D_α^{anom} and noise at frequencies for shear and global Alfvén waves.

The diagnostic techniques specifically devoted to the investigation of alpha-particle-related phenomena can be separated into two general classes:

1. study of escaping alpha particles (prompt or delayed losses)
2. study of the distribution function for confined fast alpha particles, and of the containment of thermalized alpha particles.

A wide range of diagnostic techniques was covered in the workshop, as reported below, but K. M. Young (PPPL), in the context of CIT, noted that to be successful all diagnostics will have to be tolerant of the very high radiation background accompanying operation of D-T plasmas in the region of $Q = 1$ and will need to operate reliably with essentially no maintenance on or close to the tokamak.

ESCAPING ALPHA PARTICLES

The observation of charged fusion reaction products from deuterium plasma using solid-state detectors inside the tokamak vacuum vessel has become almost routine [e.g., G. Sadler (JET)], but these detectors will not be usable with D-T plasmas. S. Zweben (PPPL) reported that work at TFTR is well advanced toward the development and testing of an alpha-particle detector using thin ZnS(Ag) crystals that should operate in the D-T environment. A conceptual design for a sophisticated diagnostic has also been proposed by G. H. Miley (University of Illinois). It would appear that fast lost alpha particles can be studied by such means, with rather poor energy resolution but excellent time resolution.

G. McCracken [Culham Laboratory (CL)] reported that surface collector probes can also be used to study the losses of fast alpha particles, although these measurements offer poor time resolution at best and become postmortem examinations at worst. Nevertheless, such measurements can be regarded as being easy to secure.

The problems addressed by lost alpha measurements include particle and energy confinement times for fast alpha particles, implications for fast alpha-particle velocity distributions $f_\alpha(v,r,t)$, and correlations with MHD events.

CONFINED FAST ALPHA PARTICLES

Thomson Scattering Methods

The study of fast ($E_\alpha > 140$ keV) confined alpha particles was the most important, and most challenging, task considered by the workshop. A diagnostic technique that has received a lot of attention in recent years involves the Thomson scattering of electromagnetic radiation from the electrons closely accompanying fast alpha particles. The scattering parameter $\alpha = 1/k\lambda_D$, where $|k| = 2|k_i|\sin\theta/2$, should be greater than unity if ion features are to be distinguished from the electron background. The ideal radiation source for this application would have a wavelength of ~ 100 μm. Unfortunately, no sufficiently intense source exists, and one must choose from the CO_2 laser at 10.6 μm and gyrotron radiation at ~ 2 mm. The former necessitates working with small scattering angles of ~ 1 deg, whereas the latter can select any angle.

An account of the CO_2 radiation scattering technique was presented by R. K. Richards [Oak Ridge National Laboratory (ORNL)], who stressed the advantages of a system that can determine $f_\alpha(v,r,t)$ at a number of discrete values of v (due to selection of narrow frequency bands of scattered radiation). M. Forrest (CL) described a sweep-heterodyne technique for obtaining measurements continuous in v. The CO_2 technique is to be tested for proof-of-principle at the Advanced Toroidal Facility (ORNL), but will examine only the electron feature. The main problem seems to be the need to work at very small scattering angles with correspondingly small solid angles for light collection.

The gyrotron technique proposed by P. Woskoboinikov (MIT) has rather different problems. The scattering angle can be large, but the refractive effects will be serious. There is also a requirement to choose an operating frequency that does not coincide with the electron cyclotron emission from the plasma electrons.

The two Thomson scattering techniques were also considered by T. Hughes (University of Essex) with particular reference to JET. The high-temperature, low-density operating regime for JET apparently identifies the gyrotron technique as being preferred, although, for CIT, the much higher densities are favorable for the CO_2 system. Both approaches require further study before a definitive preference for JET can be determined. A key question is whether or not use can be made of the enhancement in the scattered power that occurs at specific geometries due to the lower hybrid resonance.

A related proposal, involving the scattering of far infrared radiation from electron density fluctuations associated with mode conversion of radiant energy from strong radiofrequency sources, was not discussed. (It appears rather improbable that useful information on alpha-particle velocity distributions can be obtained from the measurement of changes in wave damping due to the presence of an alpha-particle population.)

Atomic and Nuclear Methods

Strachan (PPPL) discussed threshold nuclear reactor techniques but considered them unlikely to be very helpful in determining the fast alpha-particle velocity distribution function, although the $\alpha(t,\gamma)^7$Be, $\alpha(^9$Be$,n)^{12}$C, and $\alpha(^9$Be$,\gamma)^{13}$C reactions are under investigation. The ^{9}Be reactions are of interest if beryllium is used for limiters and hence becomes a significant impurity element.

Injection of pellets to serve as a target for fast confined alpha interactions was considered by D. Crandall (U.S. Department of Energy) and M. Sasao (Nagoya University). Effects to be observed include nuclear reactions, charge-exchange (CX) resulting in emission of Doppler shifted radiation, and double CX to provide a source of escaping neutral helium atoms. The time window for the measurements is only ~ 100 μs as pellet ablation is rapid. Only light elements are considered for the pellet (lithium, beryllium, boron, and carbon). Problems include the provision of a fast injection velocity for metallic pellets (10^4 to 10^5 m/s) or reduced velocity for doped fueling pellets ($\leqq 5 \times 10^3$ m/s) and the requirement that the diagnostic instrumentation directly views the pellet trajectory (which effectively removes nuclear measurements from consideration for JET).

The employment of a diagnostic neutral beam instead of a pellet injector was also considered by Sasao; the beam technique is preferable in that it can provide a continuous measurement and the ion velocity can be matched to the problem ($v_i \sim v_\alpha = 1.3 \times 10^7$ m/s). A ^{6}Li beam is favored by some proponents, but the source (6-MeV ions) requires development. A ^{3}He beam (1.7 MeV) appears to be a more practical proposition. The usefulness of such beams was not questioned, but the problems of implementing one for the D-T phase of JET operation are comparable with those of operating the heating beams (costly and manpower intensive). Furthermore, access for diagnostic beam and associated measuring systems would be in competition with other already installed equipment. An 800-keV H^0 beam is under serious consideration for CIT.

M. Von Hellerman (JET) reported that the heating beams (of D^0 or T^0 ions) can themselves be used for diagnostic purposes, using CX recombination spectroscopy on helium lines. The absolute thermalized alpha-particle concentration should be measurable by this technique (the ash problem), and information is obtainable for alphas in the 20- to 200-keV range, provided the CX cross section can be determined reliably as a function of energy.

Another application for a diagnostic beam (200-keV H^0) was described by Y. Kusama (JT-60). This involves a small-angle (Rutherford) scattering of the neutral ions into an energy analyzer. The energy transferred during the collision with a plasma ion depends on both the ion's motion and its mass, permitting determination of energy distributions for different constituents. Unfortunately, this Rutherford scattering technique is unsuitable as an alpha-particle diagnostic because the particle mass is intermediate between the far more abundant major plasma species (D-T) and the primary impurities (beryllium, carbon); it is the presence of the latter that obscures the alpha-particle signature.

Finally, the ion cyclotron radiation from fusion products has already been studied by G. Cottrell (JET). By measuring at sufficiently high harmonics of the fusion alpha-particle emission spectrum, it should be possible to determine the alpha-particle power $P_\alpha(r,t)$ for low-power situations ($P_\alpha < 10$ MW). It may also be possible to model $f_\alpha(\nu_\perp, r, t)$ by measuring the strengths of the different harmonics; however, this is an area in which the theoretical understanding has not yet been developed to the extent required.

ALPHA TRANSPORT AND THERMALIZATION EFFECTS (D-D PLASMAS)

As discussed by Strachan (PPPL) and exemplified by Sadler (JET), G. Martin (Cadarache), and M. Pillon and P. Battistoni (Frascati), the existing tokamaks (especially JET and TFTR) can already address alpha-particle transport issues and are, indeed, particularly well suited to the purpose. Collective alpha-particle effects are not expected, but nevertheless the measurements have already shown the unexpected ejection of fast reaction products by sawtooth and fishbone phenomena, and triton burnup studies have yielded results that vary considerably from one discharge to another, although the controlled plasma parameters are essentially unaltered; this, presumably, is a direct manifestation of MHD effects. These results clearly demonstrate that there is no reason to be complacent about the benign nature of alpha-particle heating.

CONCLUSIONS

It is clear that it will be very important to obtain a good understanding of the behavior of alpha particles released in D-T plasmas at or near ignition conditions. Unfortunately, it is also clear that the task of measuring the complete velocity distribution functions will be one of the most challenging yet encountered in fusion research.

The studies with charged-particle fusion reaction products, which are already being pursued in deuterium plasmas, will be of great assistance in predicting the behavior of alpha particles in D-T plasma under conditions of very weak alpha-particle heating. However, once the potential alpha-particle heating contribution approaches the megawatt level, one must expect collective alpha-particle phenomena that will be of an entirely novel character.

The various techniques that were discussed in the workshop can be summarized in the context of JET as follows.

1. *Neutron diagnostics*. These should provide the birth profile of the alpha particles.

2. *Active escaping alpha particles*. The use of scintillator/CX measurement techniques may be feasible and is well worth exploring.

3. *Passive escaping alpha particles*. Foil deposition techniques using the established probes should certainly be developed.

4. *Forward scattering of CO_2*. This may be unsuitable for JET because of low electron densities and high temperatures.

5. *Large-angle scattering of gyrotron radiation*. The outlook is promising, but account needs to be taken of the effects of electron cyclotron emission. It may well provide the only direct measurements of $f_\alpha(v,r,t)$.

6. *Nuclear reaction techniques*. It is unlikely that these techniques will prove useful, but ideas have not yet been fully explored.

7. *CX spectroscopy using pellets*. This requires very high speed injectors and appropriate viewing locations, and it is unlikely that it will be compatible with JET space requirements.

8. *CX with diagnostic beams*. This is a potentially valuable technique, but it is unlikely to be pursued at JET for access and resource considerations.

9. *CX spectroscopy with heating beams*. This is a simple diagnostic that should be attempted. It attacks the ash problem and may give partial distribution functions.

10. *Ion cyclotron emission*. This is a simple technique, but interpretation may be difficult.

It is unfortunate that the most direct technique for measuring $f_\alpha(v,r,t)$, involving the use of double CX with a diagnostic beam and analysis of the resulting neutral helium atoms, makes such demands on resources and access that it is unlikely to be pursued. This places much emphasis on proving the large-angle Thomson scattering technique as a more practical alternative. The ability to diagnose the full alpha-particle distribution in the plasma therefore remains problematic. The measurement of the thermalized alpha-particle density and of the escaping alpha particles (the latter possibly via post-mortem studies) is, however, reasonably secure.

There will be no official workshop proceedings.

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