Conf-910857--6

ALPHA-PARTICLE DIAGNOSTICS

PPPL-CFP--2476

DE92 001831

Kenneth M. Young

Plasma Physics Laboratory, Princeton University
P.O. Box 451, Princeton, NJ 08543 USA

1. Introduction

The continuing development of plasma diagnostics has made an enormous contribution to the successful evolution of the tokamak program. The most recent examples of new non-intrusive techniques are those for measuring density fluctuations and the current density distribution, which are now being used in developing understanding of the confinement of the hot plasmas. The newest area of development is that of measurement of the alpha-particles (α-particles) created in the deuterium-tritium nuclear fusion reaction which will be the heating source for the first phase of fusion power reactors.

$$D + T \rightarrow He^4 \text{ (3.52 MeV)} + n \text{ (14.06 MeV)}$$

These α-particles will heat the core of the plasma as they slow down by Coulomb collisions with the background plasma particles. Classical slowing down has been assumed in calculations of the heating effectiveness. If they are well-confined, they will tend to build up a residue of thermalized particles which will detract from the density of fuelling particles. This "ash" build-up and techniques for its removal, cause concern for the next phase of tokamak development. There is another concern that the very fast α-particles, close to their birth energy, will generate instabilities in the plasma, leading to enhanced transport across the magnetic field of the plasma or of the α-particles themselves. It has also to be determined whether these very fast particles will respond sensitively to other instabilities present in the plasma, such as MHD activity. The core alpha heating will modify the temperature and density profiles of the plasma and could significantly modify the plasma confinement.

Hence, with TFTR and JET both approaching the first tokamak experiments making use of mixed DT fuelling, it is essential to prepare diagnostics which can enable the physics study of the behavior of α-particles in tokamaks to begin. Some initial guidance has already been obtained, particularly in studying the loss of the charged fusion-product particles from the deuterium-deuterium reactions,

$$D + D \rightarrow T\ (1.01\ MeV) + p\ (3.03\ MeV)$$

and

$$D + D \rightarrow He^3\ (0.82\ MeV) + n\ (2.45\ MeV)$$

and deuterium-Helium-3 reactions

$$D + He^3 \rightarrow He^4\ (3.67\ MeV) + p\ (14.67\ MeV) \quad .$$

For DD reactions, the escaping proton is especially suitable for comparison to the α-particle. It has also been possible to look at the confinement of the high energy tritons created in the DD reaction, through their fusion reactions with the background deuterons and measurement of the 14 MeV neutrons. By using ion cyclotron minority heating of He^3 ions, studies of α-particles have already been started.

This paper will focus on the state of development of diagnostics which are expected to provide the information needed for α-physics studies in the future. Conventional measurement of detailed temporal and spatial profiles of background plasma properties in DT will be essential for such aspects as determining heating effectiveness, shaping of the plasma profiles and effects of MHD, but will not be addressed here. This paper will address i) the measurement of the neutron source, and hence α-particle birth profile, ii) measurement of the escaping α-particles and iii) measurement of the confined α-particles over their full energy range. There will also be a brief discussion of iv) the concerns about instabilities being generated by α-particles and the methods necessary for measuring these effects.

Two reviews of α-particle diagnostics have been published previously /1,2/. The fusion product studies in JET /3/ and TFTR /4/ have also been described recently. This paper can, to some extent, be viewed as a progress report since these earlier reports. It will focus principally on those techniques which are continuing to be developed for the upcoming experiments. Reference 1 provides a good summary of the α-particle physics issues with which we are concerned

2. The α-Particle Source

The birth rate and the spatial distribution of the α-particles at birth will be determined by measurement of the neutrons. This technique is already used in the studies of the behavior of the charged fusion products in the DD reactions, since a 2.5 MeV is produced in the DD reaction. Measurements of neutrons with good spatial resolution have also recently become possible because of the high source strengths in TFTR (up to 5×10^{16} fusion neutrons per second) and JET. A direct measurement of the source is valuable because the neutrons are not being created primarily in reactions of thermal deuterons; they arise from combinations of beam-plasma reactions, beam-beam reactions and thermonuclear reactions in TFTR. While modelling is possible using electron temperature and density profiles, ion temperature profiles and a beam-deposition profile, it is indirect and potentially inaccurate.

The neutron source intensity over the very high dynamic range of source strength is measured with a number of fission proportional counters located near the tokamak /5,6/. These counters provide a reliable time-dependent measurement. However, their initial calibration is complex and of paramount importance and it must be maintained over a very long period of time /7/. These systems are very dependent on the geometry of scattering material in the space surrounding them and between them and the plasma. The total counts during a pulse can be compared to integrated fluences obtained by measurements using the activation of foils placed close to the plasma, which however, are also sensitive to the local surroundings /6,8/.

The spatial localization of the neutron measurement is achieved using detectors behind long collimated shielded tubes reaching toward the plasma. These arrangements have been called multichannel neutron collimators, usually when there is a parallel array of tubes as in TFTR /9/, or neutron cameras where the tubes converge towards the plasma as in JET /6/, or proposed for ITER /10/. The most difficult issue for these systems is the need to shield the whole arrangement, particularly the detectors, so that the large sea of background neutrons from the large toroidal neutron source do not overwhelm the neutrons passing down the collimated tube. The external dimensions of the shielding of the TFTR multichannel collimator are about 3 m x 5 m /9/. Approximately 80 tons of lead, polyethylene and concrete is used. It is conveniently mounted off the basement floor and its sight lines look through the tokamak substructure and the plasma into a region without any reflecting structure. The disadvantage of a major radial view is that it faces the solid metallic core of toroidal and poloidal field coils which provide a source of back-scattered flux. An example of a neutron profile measured in TFTR is shown in Fig. 1. The data is compared to the predicted value using the TRANSP modelling code using data from the other plasma diagnostics /11/.

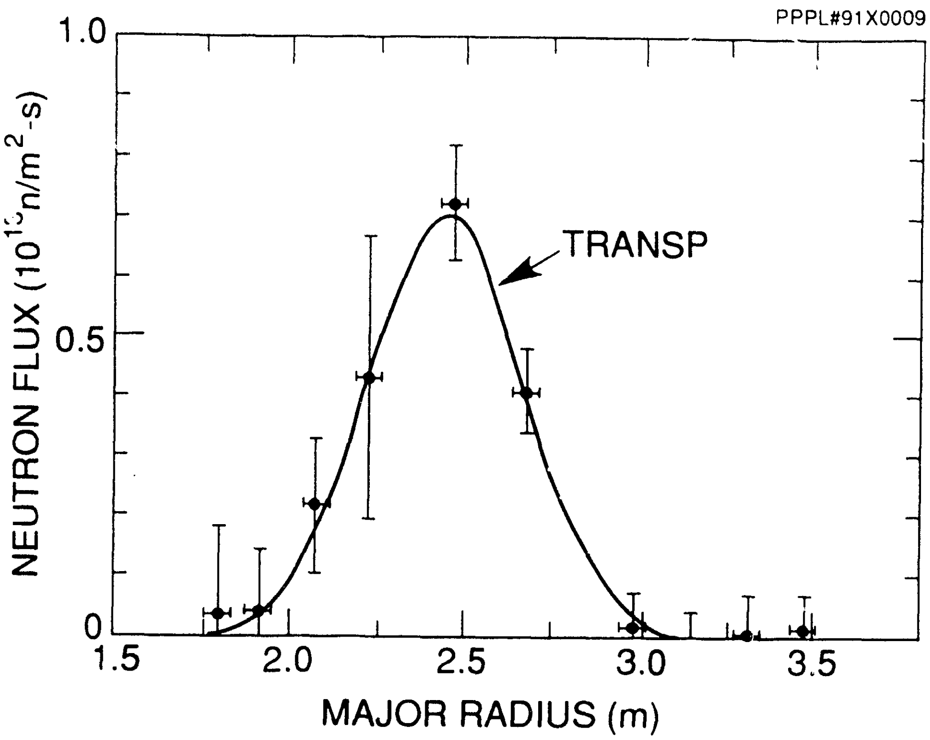

Fig. 1. An example of the measured neutron profile (points) and the neutron source region calculated using the TRANSP code using measured profiles of the electron density and temperature and the ion temperature.

A 2-D spatial distribution of the neutron emissivity can be obtained at JET with a horizontal radial-viewing camera and a vertical-viewing camera on the top /12/. For sampling times of about 10 ms and for a plasma of total source strength $\sim 1 \times 10^{16}$ ns^{-1} it has been possible to evaluate the source profiles before and after a sawtooth crash due to MHD activity in the plasma. These results suggest an excellent sensitivity, and demonstrate that good spatial resolution is possible with a neutron camera. When one considers that the DT neutron flux will be about two orders of magnitude larger than the DD flux, some of the proposed measurements on ITER, with very thick shielding and relatively small penetrations appear to be feasible.

3. Escaping α-Particle Diagnostics

Methods of measuring the loss of charged fusion products have been extensively developed and used on tokamaks. We will only consider here the direct measurement of particles leaving the plasma and detected near the wall of the vacuum vessel, and will not consider the triton burnup type of experiment where the confinement of the particles is determined from the time behavior of measured 14 MeV neutrons /13, 14/. Escaping fusion product detectors have been used on PLT,

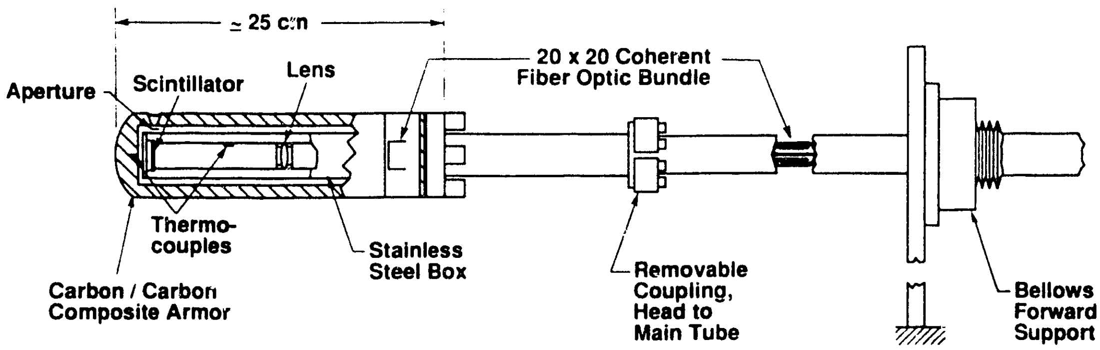

Fig. 2. A diagram of the escaping α-particle detector mounted on a moveable arm for study of ripple-induced losses in TFTR.

ASDEX, JET and TFTR (see reference /15/ and references given there). Most earlier detectors have used silicon surface barrier detectors with good energy resolution. The TFTR detectors make use of small scintillators which can give information about the incoming particle's pitch angle and gyroradius.

Figure 2 is a sketch of one of these detectors, which was mounted slightly below the midplane of TFTR on a moveable probe arm with the explicit purpose of being able to move the detector with respect to the plasma /16/. The probe was located here to do specific studies of the diffusive loss of the trapped fusion product particles, which is induced by ripple in the toroidal field, in order to provide guidance to the designers of future tokamaks. Otherwise the detector head is very similar to the detectors mounted at the bottom of the vacuum vessel in the direction of the gradient-B drift of these ions for TFTR. The detector is a ZnS(Ag) scintillator, mounted behind a slit covered by a thin foil to prevent plasma light from entering the detector, and a pinhole. This thin scintillator is chosen because of its relative insensitivity to neutrons and γ-photons. Light from the scintillator is collected by a lens onto a coherent fiber bundle, transmitted out through a vacuum window to another fiber bundle and on to a gated intensified video camera. The detector head must be protected from the plasma by a cover of carbon-carbon composite with an access aperture through it. This cover was thermally monitored to prevent the operator from moving the probe too close in. The geometric arrangement of the scintillator, slit and pinhole leads to a two-dimensional imaging according to the particle's pitch-angles and gyroradii.

In one type of measurement, obtained with one of the detectors at the bottom of the vacuum vessel, it is found that the total particle loss (integrated over pitch angle) falls by a factor of about five when the plasma current is increased from 0.5 to 2 MA for moderately beam-heated plasmas /17/. Model curves, taking account of different levels of diffusive loss have been developed and compared to the experimental points. It is found that the model which only contains first-orbit losses is a better fit than those including slow diffusive losses. There is thus a very low level of diffusive loss for these fast particles.

Figure 3 shows an example where the loss of the charged fusion products could be correlated with MHD activity in the plasma. The figure shows that the tritons and protons lost to a detector, (again at the bottom of the vacuum vessel with its light being collected onto a photomultiplier), are correlated tightly with the observed MHD, while the overall neutron flux is barely affected at all. It is crucial that the relationship

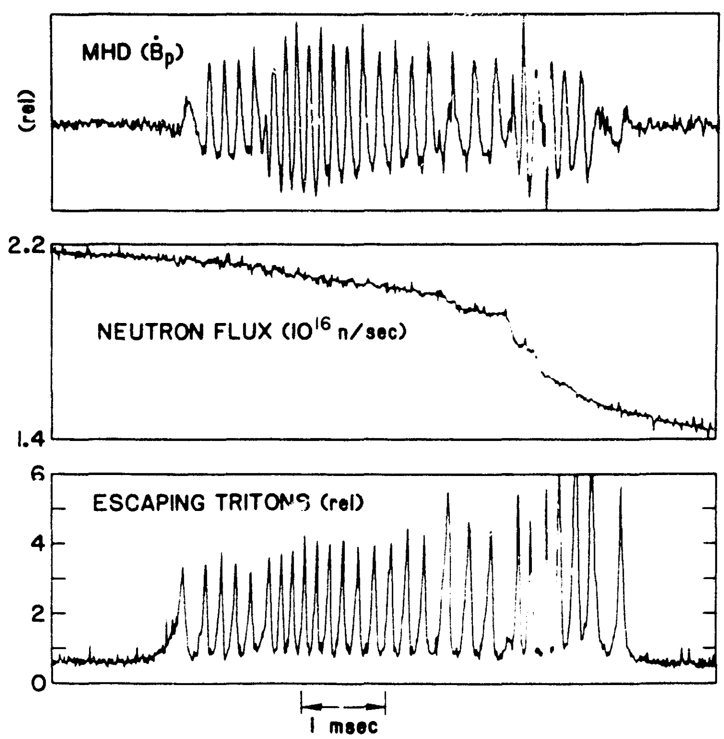

Fig. 3. An example of time dependent measurements of MHD activity, neutron flux and escaping tritons from TFTR.

between instabilities and the loss of the fusion products be understood form the point of view of optimizing α-heating.

Mounting such detectors will not be easy on devices like BPX or ITER where the wall loading and nuclear radiation backgrounds will be much more intense /18/. Already in TFTR the bottom detectors have to be covered by thick carbon-carbon composite "mushrooms" to protect them from the heat load. The covering was necessitated by limiters being added toroidally, which required that the detector be moved closer to the plasma to be on alpha-particle trajectories not interrupted by a limiter. In ITER the peak α-heat load, due to trapping of α-particles in the magnetic wells between coils, is estimated to be as high as 0.1 MW m^{-2}. Furthermore the high neutron fluxes will cause damage to the scintillators and optical components. Hence the materials constituting the detector system will have to be different or the capability of changing them out periodically will be necessary. A recent proposal for the DT phase of the JET operation will use a Faraday cup as the detector in a probe configuration similar to that described above /19/. Time-integrating methods using removeable samples incorporated into the first-wall tiles are a clearly possible solution to this problem /20/.

4. Confined α-Particle Diagnostics

4.1 Neutral Beam Based Techniques

The use of penetrating neutral beams to provide a high density of particles with which the α-particles can exchange one or two electrons was amongst the earliest proposals /21/. Double charge exchange leads to fast neutral helium atoms leaving the plasma, which can be detected by relatively conventional particle energy analyzers. The single charge exchange leads to production of an excited, single charged He^+ ion which radiates its characteristic spectrum and is measured spectroscopically. However, the atomic cross sections are only significant if the velocity of the neutral atom is close to that of the α-particle ($<1.3 \times 10^7$ ms^{-1}) so that the beam energy has to be high. For measurement of the energy spectrum up to the full energy α-particles, beams with energy of 2.6 MeV He^3 or 5.5 MeV Li would be required. The extensive and costly development needed for such beams and their limited applicability for the high density BPX or very large ITER tokamaks has prevented their further development but the use of hydrogen beams for spectroscopic measurement is being continued. In general, only the lower part of the slowing-down spectrum is made available using current beamline technology ($E_b \sim 100$ keV) but high energy beams ($E_b > 1$ MeV) using negative ion beam technology are being developed for heating beams at JT-60 U and for ITER. Since the signal strength depends on the beam particle density, currents of order 10A, in short bursts, would be necessary for a device like ITER /10/ so that an adequate density is available close to the plasma axis.

A double-charge exchange, neutral particle analysis, experiment was proposed for CIT (now named BPX) /22/ and is independently being developed for use in the DT Program at JET /23/. The key to the applicability of this method in JET is the use of a 160 keV He^4 heating beam. The escaping neutralized He atoms particles have an electron stripped by passage through an aluminum foil and their energy is determined in a magnetic analyzer. During DD and DHe^3 studies in JET, the beam will contain He^3 and the analyzer capability can be checked out without the thick radiation shielding which will have to surround the thin scintillator photomultiplier detectors against the high-flux DT neutrons. The JT-60U group in Japan plan to use their 200 keV helium diagnostic beam to study the α-particles from DHe^3 ICRF experiments with a particle analyzer capable of resolving up to an energy of 400 keV /24/.

Spectroscopic measurements of the α-particles can make use of hydrogen beams and are being developed for both TFTR /25/ and JET /26/. They are also a

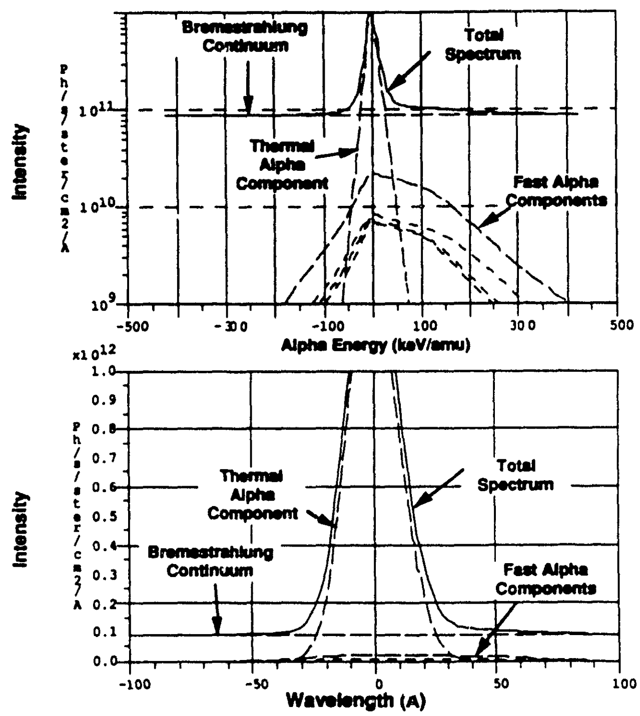

Fig. 4. The spectral line at 2686Å of He emission from charge exchange spectroscopy of α-particles. The spectral components due to the three different energy components of the TFTR heating beams and the bremsstrahlung background are shown.

preferred method for BPX /27/ and ITER /10/. The high current densities required for good neutral densities in the interior of the plasmas of the latter two devices suggest that special short-pulse beam techniques will be necessary so that the diagnostic beam is not a major perturbation for the plasma. Extensive modelling of the charge exchange recombination spectroscopic signals has been necessary because the line spectrum from the α particles has to be discriminated from the bremsstrahlung continuum. The density of α-particles is calculated to be between 0.1% and 1% of the electron density. Furthermore, the spectral contribution from the fast alpha components will appear in the tail of the spectral line. Figure 4 shows the calculated shape of the spectral line at 4686 Å for TFTR for an α-particle density of 1×10^{18} m^{-3} for a realistic 120 keV D° heating beam in the line-of-sight of the spectrometer. The lower figure shows the spectrum relative to the central wavelength and is an enlargement of the total spectrum shown in terms of the alpha energy in the upper figure. The latter shows the component parts of the spectrum, including the contributions from each of the three different energy components present in a TFTR heating beam. Discrimination of the high energy part of the spectral line will require a very high throughput spectrometer and, in the testing phase of the experiment with DHe^3 plasmas, modulation of the beamline intensity. A view looking down on the tangential beam is being implemented. The instrument will have five spatial channels. Measurement of particles at energies up to 800 keV is the experimental goal.

Initial transport studies mocking up the behavior of the helium ash have been done already using recombination spectroscopy but with a small seeding of the plasma with helium gas /28, 29/.

4.2 <u>Pellet Ablation Techniques</u>

It was indicated earlier that the atomic cross section becomes very small if the velocities of the charge exchanging particles differ significantly. But the signal intensity might still be sufficient from such charge exchange reactions if the target particle density for the α-particles were sufficiently high. Such densities (of order 10^{24} m^{-3}) are achieved in the ablation clouds of impurity pellets as they penetrate the plasma /30, 31/. A prototype experiment is under development for particle analysis of neutralized He-atoms created by charge exchange of α-particles in a carbon or lithium pellet cloud in TFTR /31/. Initially, He^3 ions, heated in He^3 minority heating, will be used in demonstrating feasibility.

The pellet must both be able to reach the core of the plasma where the alpha particles are born and also be non-perturbing of the plasma. Carbon pellets of diameter

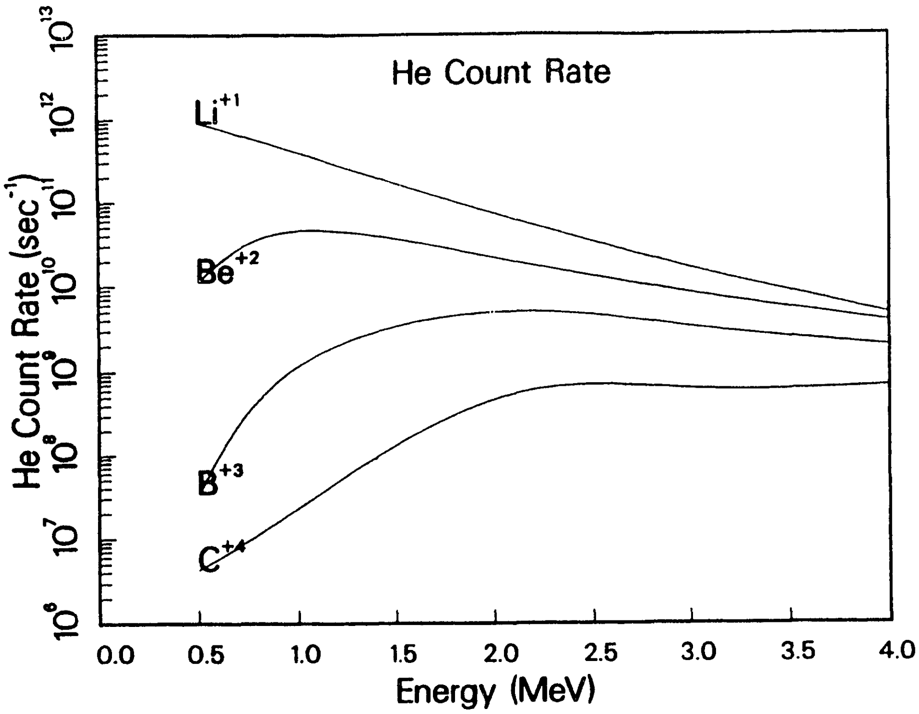

Fig. 5. Predicted signal levels in TFTR for neutral particle analysis after α-paticle neutralization in the ablation cloud from four different pellet materials.

0.6 mm injected with a velocity of 4 km s^{-1} will penetrate along a minor radius to about 0.2 a, where a is the plasma radius. In the initial TFTR experiment, a 2 mm diameter carbon pellet with velocity 0.8 km s^{-1}, will reach to almost the same distance. Because of a large step in the ionization potential, there will be a large spatial region in the impurity cloud which is dominated by ions in the Helium-like ionization state. These ions will dominate the neutralization of α-particles. Figure 5 shows the result of calculations made for TFTR for four different pellet materials. The assumptions made were, $n_\alpha = 4 \times 10^{16}$ m^{-3} at r/a ~ .5, α-particle energy 1 MeV, the target area within the cloud is 10^{-3} m^2 and the equilibrium fraction of neutrals produced is 3.5×10^{-5} for C^{4+}. The instrument and viewing assumptions were that the energy channel width of the detector is 150 keV, the detector efficiency is unity and the solid angle of the detector is 2×10^{-7}.

Pellet injection can also provide target nuclei for nuclear reactions as a potential α-particle detection technique. The nuclear cross-sections are small but at pellet particle densities, the emitted γ-photons are expected to be sufficiently intense, relative to the background produced by neutron reactions in the structural materials of the tokamak

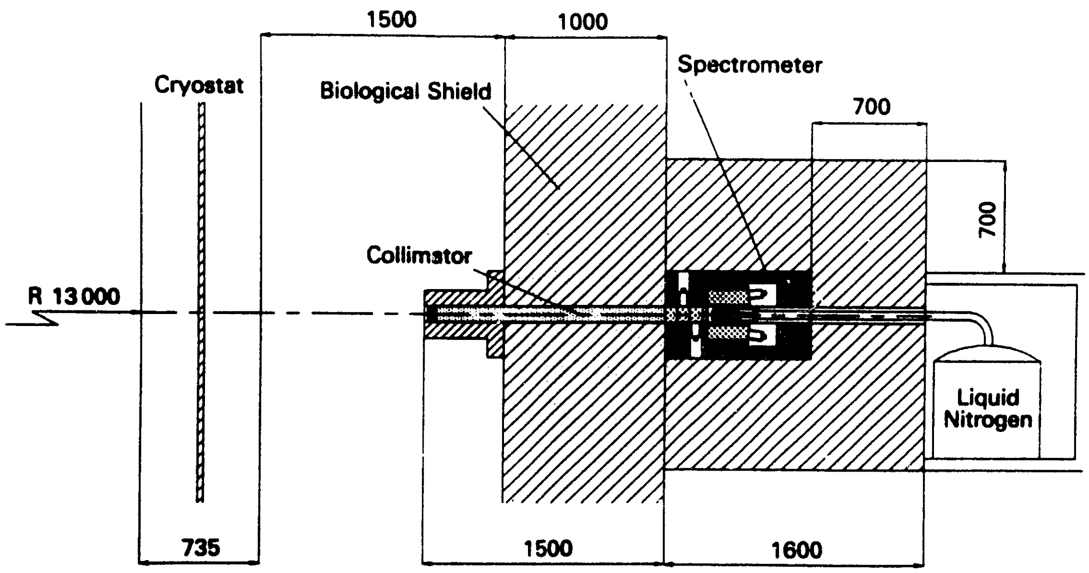

Fig. 6. Sketch of a multicrystal gamma spectrometer and its associated shielding proposed for the BPX tokamak.

and surrounding facilities, to be measurable. The original concepts of Medley et al. /32/ have been extended to studies for T-14, BPX and ITER by Kiptilij /33/. Measurements of gammas from DHe^3 reactions with minority ICRF heating of the He^3 tails have been described for JET /34/ and TFTR /35/. For DT plasmas, the resonance capture nuclear reaction $^7Li(\alpha,\gamma)^{11}B$ was originally proposed. But for DT operation, the γ-yields are too small relative to the background. The largest cross-section is that for the $^9Be\ (\alpha, \eta, \gamma)^{12}C$ reaction, with the γ-transition to the ground state being at 4.44 MeV. The cross-section is only significant for α-particle energies greater than 1.7 MeV, so the technique will only be useful for particles close to their birth energy. Kiptilij /33/ has estimated a signal-to-noise ratio of five for the BPX tokamak for a multicrystal gamma spectrometer surrounded by a thick lead and hydrogenous neutron shield. A diagram of this spectrometer is shown in Fig. 6. The narrow colliminating tube between the vacuum vessel and the detector has to be plugged with a ^6LiH compound to absorb neutrons while transmitting high energy gammas; otherwise the neutrons would create excessive background gammas in the shielding material.

4.3 Collective Thomson Scattering

Collective Thomson scattering has been demonstrated to be a viable technique for measuring the ion temperature in tokamak plasmas. Extending the method for measurement of confined α-particles is very attractive because it does not affect the plasma and has a strong theoretical basis. Both JET /36/ and TFTR /37/ are preparing scattering systems, based on gyrotron sources in the millimeter wavelength range /38/, and a concept using a 200 μ source is included in the plan for ITER diagnostics /10/. The scattering is from the collective motion of the electrons with the necessary scattering condition that $\alpha = 1/k\lambda_D = 1/2k_i \lambda_D \sin(\theta/2) > 1$ where λ_D is the Debye length and $\underline{k} \equiv \underline{k}_s - \underline{k}_i$, where $\underline{k}_s$ and $\underline{k}_i$ are the wave vectors of the scattered and probing waves respectively and θ is the angle through which the waves are scattered. There are two significant issues for this technique; i) will the signal-to-noise ratio be high enough to enable the high energy α-particles to be observed? and ii) will the propagation of the waves in the plasma be sufficiently far from cut-off to minimize refraction, or at least make interpretation of the interaction region straightforward?

Figure 7 shows the predicted scattering spectrum for the system proposed in the Conceptual Design Phase for the ITER device /10/. The proposal is based on a far

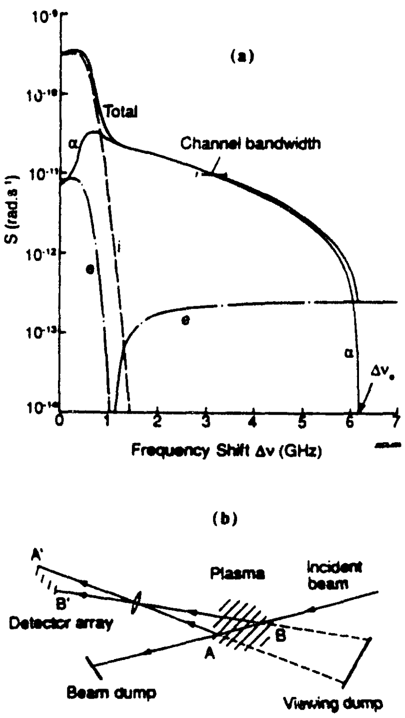

Fig. 7. Predicted spectrum for a collective Thomson scattering measurement of α-particles on ITER.

infrared laser system with frequency ~1.5 THz with the incoming beam tangential to the toroidal plasma. The plasma conditions assumed were $n_e = 0.5 \times 10^{20}$ m^{-3}, $n_\alpha = 2 \times 10^{18}$ m^{-3}, $T_e = T_i = 10$ keV and $B_o = 4.85$ T. The scattering angle is 5.5° and the angle between $\underline{k}$ and $\underline{B}$ is 52.25°. The figure shows the contribution to the spectrum of the scattered signal from the plasma particles, with the thermal ions contributing a high unshifted peak and the electrons providing a broad background. The α-particle velocities map onto the frequency shift of the scattered radiation; a slowing down spectrum was assumed in deriving the spectrum shown. Note that a significant program will be required to develop a short-pulse laser source at power levels over 200 MW for this application.

The penetration of the waves into the plasma and the background noise levels are critically dependent on the electron density and magnetic field properties. At short wavelengths, such as 10 μ CO_2 laser wavelengths, initially proposed by Hutchinson et al., /39/ the background is low but the scattering condition above requires that the scattering angle be very small (≤1°). Geometrically this is very difficult to accommodate in the tokamak geometry, a detector arrangement sufficiently insensitive to the direct beam is difficult to arrange and the spatial resolution is relatively poor. The JET Group have chosen a 2 mm (140 GHz) wavelength system using a gyrotron /36/. This frequency falls between the first and second harmonics of the electron cyclotron frequency in a region where relatively low background noise had been observed. Their wave propagation will be O-mode since the frequency being used is high compared to the plasma frequency and cutoff of the propagation. For TFTR a frequency below the cyclotron harmonic was chosen because of its higher central operating magnetic field of 5 T. Cut off of the O-mode at the plasma frequency would occur at a density of ~4 × 10^{19} m^{-3}, an unacceptably low level, so that the experiment will make use of X-mode propagation, similar to that used at low power in the microwave scattering experiment for measurement of density fluctuations on TFTR /40/. Extensive ray-tracing has been done to evaluate refraction effects with plasmas with peak density up to 1 × 10^{20} m^{-3}.

A detailed discussion of all the components of such a diagnostic, costing many millions of dollars, is not feasible here. A schematic of the main components of the proposed JET System /36/, is shown in Fig. 8. The TFTR concept is very similar. An important aspect of the JET System is the ability to obtain spatial resolution by having a mirror with several possible fixed orientations.

An alternative collective Thomson scattering scheme, making use of the large enhancement of the spectral function due to lower-hybrid fluctuations has been suggested by Wong /41/. It had previously been shown that lower-hybrid waves can

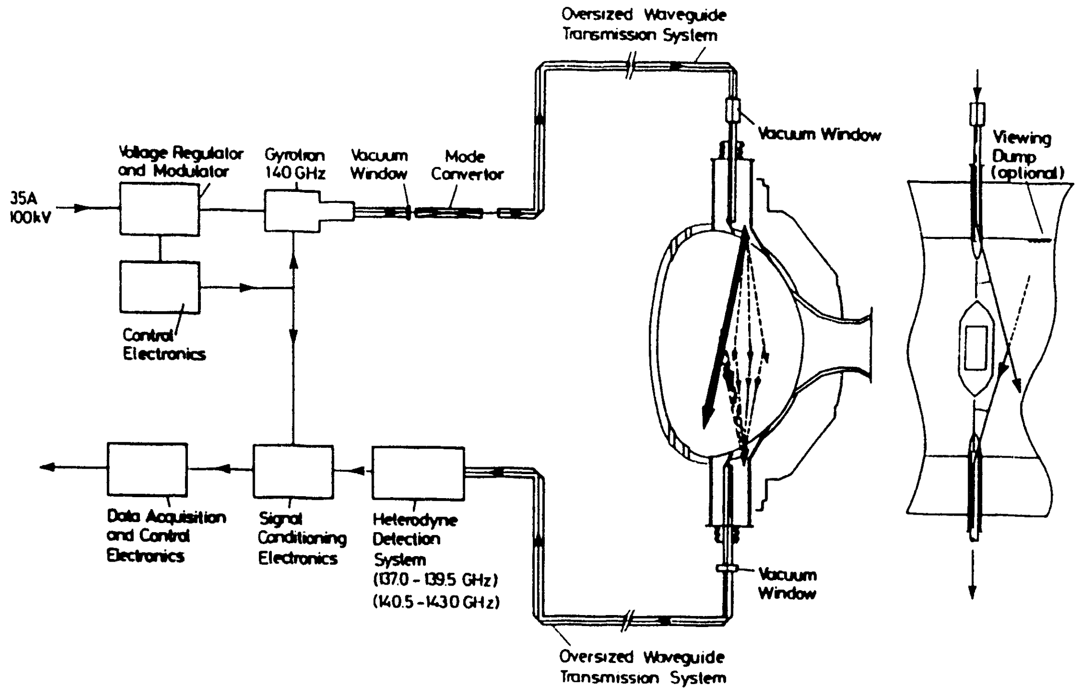

Fig. 8. A schematic diagram of the main components of the collective Thomson scattering system being developed for the JET tokamak.

be strongly damped by energetic alpha particles /42/ so that this new proposal should be carefully assessed.

4.4. Ion Cyclotron Emission

Some measurements have been made of the harmonics of the ion cyclotron emission from the plasmas in JET and TFTR, since it had been predicted that the high energy α-particles should emit preferentially at these higher harmonics relative to the fuel deuterons. The first detection of such harmonics was on the TFR tokamak /43/. Measurements by the JET group /44/ make use of one of the large RF heating antenna on the low field side of the torus while Greene at TFTR /45/ has used small magnetic detector loops on the top and bottom of the vacuum vessel. Spectra up to 500 MHz are obtained on TFTR.

The results from TFTR and JET do not give a unique and clear result relating the observed sequences of harmonics to confined fusion charged fusion products. It is clear that the separation of the harmonics, in both cases, is the ion cyclotron frequency at the outer plasma edge, at large major radius. For deuterium ohmic discharges the JET peaks are at $n\omega_{CD}$, the deuteron cyclotron frequency, while the TFTR peaks are at

$(n+1/2)\omega_{CH}$, the hydrogen frequency. For hydrogen neutral beam injection into deuterium plasmas, the JET peaks are at $n\omega_{CD}$, the frequency of the background plasma, while TFTR finds, on injection of hydrogen into a helium-4 plasma, $n\omega_{CH}$, the frequency of the injected ions, simiiar to the result obtained on PDX /46/.

These differences are difficult to resolve. They may be due to the sensitive nature of the instability that generates the harmonics, or to some involvement of the antenna configuration or of the vessel as a resonant cavity. The differences in the case of the beam-heated plasma could be related to differences in the beam configurations. Some of the fast confined ions do have orbits which pass through the outer scrape-off region so that the specific harmonic frequency observed could relate to confined fusion products, or beam ions. Recent observations from JET, correlating perturbations in the ICE spectrum with sawteeth internal to the plasma have been tentatively interpreted as due to the thermal pulse leading to enhanced fusion reactions in this outside region /47/. In TFTR, a peak corresponding to He^3 has been observed, though not unequivocally from the fusion product. Also the background intensity of the spectrum at frequencies above 140 MHz underlying these peaks has been shown to be proportional to the neutron intensity.

Further work, both experimental and theoretical, is clearly necessary to allow any firm conclusions to be drawn about the value of these measurements for fusion product studies. The diagnostic hardware, small magnetic loops close to the vacuum vessel wall, is potentially very simple so that the technique has to be considered attractive.

5. Instability Effects

The presence of a high population of α-particles providing central heating of the plasma could modify the plasma confinement and possibly its stability. These collective instabilities, driven by the free energy of the α-particles, have been the subject of an increasing theoretical study, and it will certainly be necessary to determine if new fluctuation levels appear in the changeover from DD plasmas to DT plasmas. It is clearly very important for the "ignition" tokamak devices, but it is possible to do some study of the phenomena in TFTR and JET. Since a large fraction of the α-particles derive from non-thermal reactions in TFTR, the central values of β_α, n_α/n_e and v_α/v_{Alfven} for TFTR can be nearly comparable to those of BPX and ITER.

Table 1 gives a summary of the possible collective α-particle driven instabilities. It is derived from reference /48/ with an additional column showing the diagnostics on TFTR which will detect the fluctuations. The instabilities range from

Table 1: Collective Alpha Instabilities

Instability	Frequency (kHz)	Physical Mechanism(s)	Important Parameters	Possible Effects	TFTR Diagnostic(s)
Alpha Driven Sawteeth	<0.1	Central Electron heating by alphas → sawtooth crash	$\frac{P_\alpha(0)}{P_{heat}(0)}$	Modification of q(r) profile; expulsion of α's from the center	Gyrotron α Scattering; soft X-ray emission
Alpha-Driven Fishbones	~10^1 - 10^2	Resonance of α precession and internal m = 1 mode	$\beta_\alpha(0)$ β_{th} $\omega_{d\alpha}/\omega_A$	Expulsion of trapped alphas from the center	Escaping alpha detectors
Alpha-Driven Drift Wave or Ballooning Modes	~10^1 - 10^3	Resonance of alphas with m >> 1 modes	Gradients of β_α and n_α/n_e	Reduction of beta limit; change of plasma transport	μ wave scattering escaping alpha detectors
α-Driven Alfven Waves (e.g., TAE mode)	~10^2 - 10^3	Passing alphas with $v_\alpha > v_A$ excite Alfven modes	v_α/v_A $\omega_{*\alpha}/\omega_A$ $\nabla\beta_\alpha$	Anomalous loss of passing alphas; electron heating	μ wave scattering; Mirnov loops
Alpha-Loss Cone-Driven Alfven Waves	~10^4 - 10^5	Velocity space instability near trapped/ passing boundary	TF Ripple n_α/n_e $\omega_{c\alpha}$	Anomalous loss of trapped alphas; ion heating	Ion cyclotron emission escaping alpha detectors
Alpha-Population Inversion Driven Alfven Wave	>10^5 - 10^6	Bump-on-tail instability due to fast alpha turn-on	$\frac{1}{S_\alpha}\frac{\partial}{\partial t}(S_\alpha \tau_\alpha)$	Anomalous alpha slowing-down; ion heating	Ion cyclotron emission escaping alpha detectors

Symbols: $\omega_{d\alpha}$ = alpha precession frequency; ω_A = Alfven frequency, $\omega_{c\alpha}$ alpha cyclotron frequency, $\omega_{*\alpha}$ = alpha diamagnetic frequency, S_α = alpha source rate.

low frequency sawteeth at frequencies of 10 - 100 Hz to very fast Alfven waves at up to 10^8 Hz. Among the most damaging modes are the α-particle driven fishbones and the sawteeth with their potential for ejecting large fractions of the heating particles. The relationship of MHD observations and the escaping fusion products was indicated above.

A simulation experiment for one of the modes has been done already. By lowering the toroidal field in TFTR to enhance the Alfven velocity so it was comparable

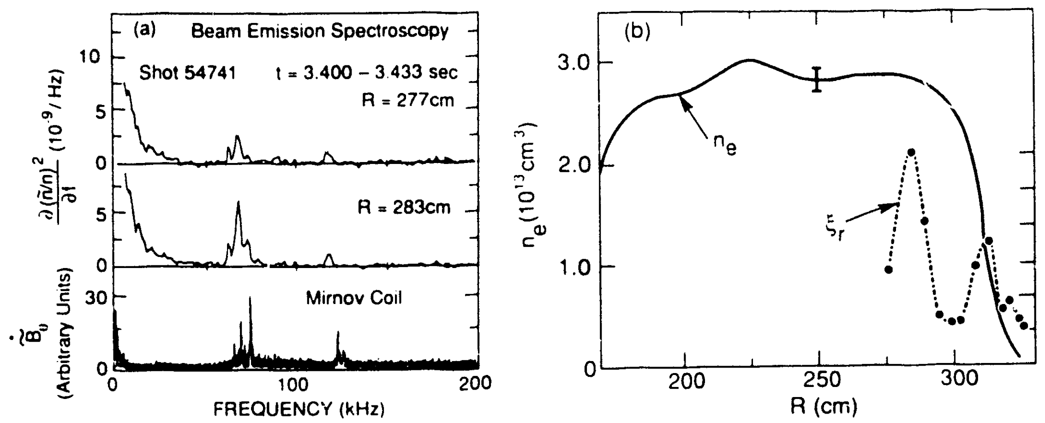

Fig. 9. Observation of the TAE mode in TFTR. a) Fluctuation spectra measured by two channels of beam emission spectroscopy internal to the plasma and Mirnov loops external to the plasma. b) Spatial dependence of the electron density and the inferred plasma radial displacement.

with the injection velocity of the heating neutral beam ions, a simulation of the conditions predicted for instability of the α-particle driven Alfven wave, or toroidal Alfven eigenmode (TAE mode) was carried out /49/. Figure 9a shows the fluctuations observed by two diagnostics; beam emission spectroscopy measures fluctuations in electron density inside the plasma (shown for two radii) and the Mirnov coils detect magnetic field fluctuations from outside. The observed frequency of about 80 kHz is characteristic of this TAE mode. Figure 9b shows the spatial electron density profile and the inferrred plasma radial displacement which should be large where the fluctuations are largest. The presence of Mirnov loop fluctuations correlates with loss of neutron signal, consistent with the heating ions being ejected from the plasma. The JT-60 group should make an important contribution to these instability studies using their new 500 keV heating beam /50/.

A theoretical modelling of this instability of TFTR has been carried out for conditions expected in DT plasmas /51/. Figure 10 shows stability boundaries for the TAE mode driven by α-particles . Two different density gradients of the α-particles

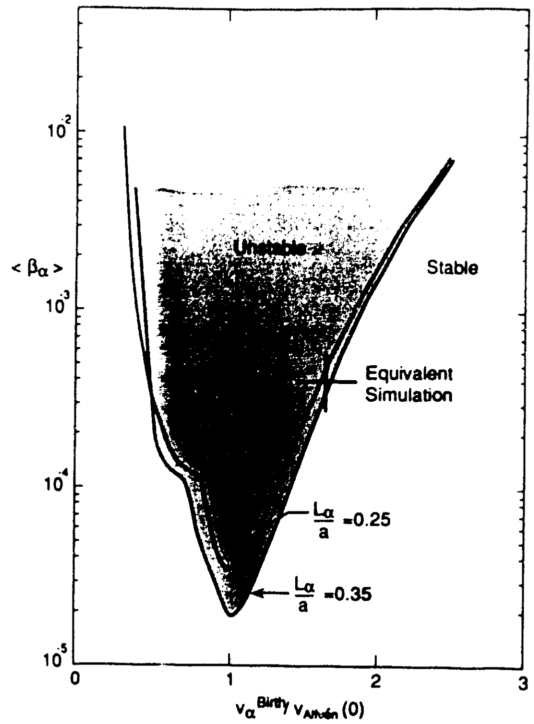

Fig. 10. Stability boundaries calculated for the TAE mode driven by α-particles in TFTR. Two different gradients of the α-particle density profile have been assumed.

are shown. The figure shows that this instability may be present in the TFTR plasmas where v_α/v_{Alfven} of 1.7 and $\beta_\alpha(0)$ of 0.3 - 1% are anticipated in DT plasmas.

This short description indicates the importance of these instabilities and also suggests that a capability for measurement of a very high range of frequencies of instabilities must be available on BPX and ITER. Internal measurements of density fluctuations will require reflectometer techniques which must be developed considerably from their present state.

6. Summary

Very substantial progress has been made in the last few years in developing the theory of α-particle physics and in the development of diagnostics to study the particle behavior. But the next few years will see the first experiments and will provide the first crucial tests of the new diagnostic methods. First intimations of plasma behavior with reactor-relevant α-particle populations will be observed and the first use of a new family of diagnostics will be tested and used. There will also be the first demonstrations that high quality plasma measurements can be achieved in the presence of significant neutron fluxes. JET and TFTR will provide complementary demonstrations, which are absolutely crucial for future devices, such as BPX and ITER. The operation of these last two devices is now clearly seen to depend on understanding of the physics of the plasma, and they are no longer thought to be straightforward engineering activities for investigation of reactor problems.

It is apparent that few new concepts have been put forward for α-particle diagnostics in the last five years, despite the fact that all the methods being developed are difficult and have significant limitations. This is true even though theorists are strongly advocating good energy and spatial resolution for the measurement. In part, the reason may be that it is only shortly that relevant plasmas for the measurements will become available, but it is also true that the proposed methods are expensive to build and will take a long time to bring to demonstration. One method, the use of a very high energy neutral impurity beam (e.g. 6 MeV Li°) to provide double charge-exchanged neutral particles, which would require development of such a beam, is no longer being considered. A lower energy ($\leq$ 200 keV) helium beam might be considered for optimizing the atomic cross-section and penetration of the plasma for recombination spectroscopy or neutral particle exchange with low energy α-particles, but significant signal-to-noise will require a modulated high current beam. Studies of the penetration of this beam must be completed soon to see whether it will be valuable beyond the possibility of studying the thermalized α-particles in the scrape-off layer and divertor region. The impurity-pellet-based methods will be of interest if they can use fuelling pellets seeded with the necessary impurity atom; presently both ITER and BPX are dependent on high-velocity (≥ 5 km s^{-1}) pellets for fuelling.

The experimental programs of DT plasmas for TFTR and JET will provide valuable test beds for these methods. They will also achieve interesting alpha-physics parameters, very relevant to future devices.

I am very grateful to my many colleagues at TFTR and elsewhere who have been actively pushing forward developments in diagnostics of the fusion product particles. In particular, I want to thank J. Strachan and S. J. Zweben, who have provided a great deal of the motivation toward improving fusion product diagnostics and the development of their use in understanding tokamak plasma behavior.

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO3073.

References

/1/ D. Post, S. J. Zweben, and L. Grisham, Proceedings of the Course, "Basic and Advanced Diagnostic Techniques for Fusion Plasmas," Varenna, Italy, Vol. III, (1986) 721.

/2/ S. J. Zweben, Rev. Sci. Instrum. 57 (1986) 1723.

/3/ G. J. Sadler et al., Fus. Technology 18 (1990) 556.

/4/ S. J. Zweben, J. D. Strachan, and K. M. Young, Fus. Technology 18 (1990) 573.

/5/ H. W. Hendel, IEEE Trans. Nucl. Sci. 33 (1986) 670.

/6/ O. N. Jarvis et al., Nucl. Fusion 30 (1990) 307.

/7/ J. D. Strachan et al., Rev. Sci. Instrum. 61 (1990) 3501.

/8/ E. B. Nieschmidt et al., Rev. Sci. Instrum. 57 (1986) 1757.

/9/ A. L. Roquemore et al., Rev. Sci. Instrum. 61 (1990) 3163.

/10/ V. Mukhovatov et al., "ITER Diagnostics," ITER Documentation Series #33 (IAEA, Vienna, 1991).

/11/ W. W. Heidbrink et al., Princeton Plasma Physics Laboratory Report PPPL-2777 (1991); to be published.

/12/ F. B. Marcus et al., Plasma Phys. and Contr. Fusion 33 (1991) 277.

/13/ J. D. Strachan et al., in Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna) I (1989) 257.

/14/ S. Conroy et al., Nucl. Fusion 28 (1990) 2127.

/15/ S. J. Zweben et al., Nucl. Fusion 30 (1990) 1551.

/16/ R. L. Boivin, Ph. D. Thesis, Princeton University (1991).

/17/ S. J. Zweben et al., Princeton Plasma Physics Laboratory Report, PPPL-2771 (1991); to be published in Nucl. Fusion (1991).

/18/ S. J. Zweben et al., Rev. Sci. Instrum. 61 (1990) 3505.

/19/ S. W. Conroy et al., Proc. 18th European Conference on Controlled Fusion and Plasma Physics, IV (1991) 265.

/20/ R. Bastasz, D. Buchenaur and S. J. Zweben, Rev. Sci. Instrum. 61, (1990) 3234.

/21/ D. Post et al., Journal of Fusion Energy 1 (1981) 129.

/22/ A. S. Schlachter, J. W. Stearns and W. S. Cooper, Rev. Sci. Instrum. 59 (1988) 1729.

/23/ M. P. Petrov et al., Private Communication.

/24/ Y. Kusama et al., Rev. Sci. Instrum. 61 (1990) 3220.

/25/ R. J. Fonck, B. Stratton and E. J. Synakowski, "Fast-Alpha CHERS Measurements in TFTR," presented at the First Workshop on Alpha Physics in TFTR (1991), Proceedings summarized briefly by R. Petrasso in Nature 350 (1991) 661 and more fully by S. J. Zweben and H. Biglari, PPPL Report #2779 (1991).

/26/ M. von Hellerman et al., Rev. Sci. Instrum. 61 (1990) 3479.

/27/ S. S. Medley et al., Rev. Sci. Instrum. 59 (1988(1745).

/28/ R. J. Fonck and R. A. Hulse, Phys. Rev. Lett. 52 (1984) 530.

/29/ E. J. Synakowski et al., Phys. Rev. Lett. 65 (1990) 2255.

/30/ M. Sasao et al., Proceedings of the Course "Basic and Advanced Technologies for Fusion Plasmas," Varenna Italy, Vol. II (1986) 775.

/31/ R. K. Fisher et al., Rev. Sci. Instrum. 61 (1990) 3196; also R. K. Fisher et al., "Measurement of Fast Alphas using Impurity Pellet Injection" in the Workshop report of Ref. /25/.

/32/ S. S. Medley et al., Rev. Sci. Instrum. 56 (1985) 975; F. E. Cecil et al., Nucl. Instrum. Methods in Phys. Res. 245 (1986) 547.

/33/ V. G. Kiptilij, Fus. Technology 18 (1990) 583.

/34/ G. Sadler et al., Proc. 15th European Conference on Controlled Fusion and Plasma Heating, I (1988) 131.

/35/ F. E. Cecil and S. S. Medley, Nuc. Instrum. Methods in Phys. Res. 271 (1988) 628.

/36/ A. E. Costley et al., JET Report R(88) 08 (1988).

/37/ P. P. Woskov et al., Rev. Sci. Instrum. 59 (1988) 1565.

/38/ P. Woskoboinikow, Rev. Sci. Instrum. 57 (1986) 2113.

/39/ D. P. Hutchinson et al., Rev. Sci. Instrum. 56 (1985) 1075.

/40/ N. Bretz et al., Rev. Sci. Instrum. 61 (1990) 3031.

/41/ K. L. Wong, Phys. of Fluids B3 (1991) 1501.

/42/ K. L. Wong and M. Ono, Nucl. Fusion 24 (1984) 615.

/43/ TFR Group, Nucl. Fusion 23 (1983) 425.

/44/ G. A. Cottrell and R. O. Dendy, Phys. Rev. Lett. 60 (1988) 33.

/45/ G. Greene and the TFTR Group, Proc. 17th European Conference on Controlled Fusion and Plasma Heating IV (1990) 1540.

/46/ D. Buchenaur et al., Proceedings of 4th International Symposium on Heating in Toroidal Plasmas, 2 (1986) 111.

/47/ P. Schild, G.A. Cottrell and R.O. Dendy, Nucl. Fusion 29 (1989) 834.

/48/ S. J. Zweben et al., Nucl. Fusion 28 (1988) 2230.

/49/ K. L. Wong et al., Phys. Rev. Lett, 66 (1991) 1874.

/50/ A. Funahashi et al., Proc. 18th European Conference on Controlled Fusion and Plasma Physics, I (1991) 169.

/51/ R. Budny et al., to be published, and C. Z. Cheng and M. S. Chance, Phys. Fluids, 29 (1986) 3695.

END

DATE FILMED

11 / 20 / 91

I