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(Report on the IAEA Technical Committee Meeting on Alpha Particle Physics in Thermonuclear Reactors, Trieste, Italy, 10-14 May 1993)

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1. INTRODUCTION

The meeting in Trieste on physics and diagnostics of fusion-produced alpha particles was the third in a series of IAEA meetings on this topic (the first meeting was held in Kiev [1] and the second one in Aspenäs [2]). ENEA in Frascati was the general organizer of the present meeting. Local arrangements were made by the International Centre for Theoretical Physics ICTP in Trieste under the auspices of the UNESCO. The programme committee consisted of the following members: F.Engelmann (NET, CEC), M.Haegi (ENEA-EURATOM, Frascati, Italy), Ya.I.Kolesnichenko (INR, Kiev, Ukraine), S.Mahajan (ICTP, Italy), D.J.Sigmar (MIT, Cambridge, USA), K.Tani (JAERI, Naka-gun, Japan), H.Wilhelmsson (CTH-IEFT, Göteborg, Sweden). The IAEA was represented by V.V.Demchenko, and M.Haegi (ENEA) and S.Mahajan (ICTP) were responsible for the local arrangements. The meeting was attended by about 40 participants from 10 countries; 40 papers were presented.

The purpose of the meeting was to discuss the current issues of physics of α-particles and other fast ions produced as a result of fusion reactions, neutral beam injection and RF-heating. The following major topics were discussed:

- Behaviour of fast ions in experimental devices.
- Alfvén instabilities driven by fast ions.
- Ion-cyclotron emission from tokamak plasmas.
- Influence of sawtooth oscillations on fast ions.
- Ignition and thermonuclear burn.
- Diagnostics for α–particles.

The material presented at the meeting will be published by the IAEA as a Technical Document. In addition, the journal 'Fusion Technology' (editor G.Miley) has kindly offered to produce a special issue of all, journal quality, reviewed manuscripts.

2. THEORY OF FUSION PLASMA

2.1 Neo-classical Transport of Alpha Particles [3, 5, 6]

A powerful, semi-analytic, semi-numerical approach for studying neo-classical transport of fast ions in axisymetric tokamak plasmas has been recently developed and was presented by V.O.Yavorskii (INR, Kiev) [3]. He formulated the bounce-averaged 3-D second-order Fokker-Planck equation and the boundary conditions for fast ions having an arbitrary banana width. This equation is written in terms of the constants of the particle motion (energy, ratio of the magnetic moment to the energy, maximum radial excursion) and is solved numerically. V.O.Yavorskii showed that three qualitatively different regimes of fast particle collisional transport were possible in tokamaks. Two of them correspond to tokamaks containing fast ions with large banana widths, $\Delta r_b \sim a$, i.e. for tokamaks with small plasma currents. One of these regimes is called "cone-less" because none of the particles with orbits in the vicinity of the separatrix between trapped and circulating particles is confined and thus the possibility for other particles to be lost due to pitch-angle scattering into the loss-cone region is negligibly small. This regime takes place in plasmas with low or negative shear. The second regime is called "separatrix-less" because trapped particles close to the trapped-passing particle boundary are not confined whereas counter-circulating particles are confined and can be lost due to collisional scattering into the loss-cone region. This regime has been achieved for D-D fusion reaction products in TFTR operating with a plasma current $I \leq 2$ MA. The third regime takes place when the banana width is small, $\Delta r_b \ll a$, and the collisional exchange through the separatrix between the counter-circulating particles (which are best confined) and the rest of the particles can occur. O.Yavorskii reported results of calculations relevant to the two first regimes, which are the easiest to study. The results are rather surprising: collisional losses of D-D reaction products increase with increasing plasma current, $0.8 < I$ (MA) $<$ 1.6 and they exceed the prompt losses at $I > 1.5$ MA. This seems to explain the recent results obtained on TFTR as reported by Zweben [4]. However, to make quantitative comparisons of theoretical and experimental results, more detailed analyses as well as an extension of the calculations for larger currents, up to $I \sim 2.5$ MA, are required.

An important problem, for the feasibility of a steady-state reactor-tokamak with it's current sustained by neo-classical processes, is the production of a seed-current in the near-axis region. In 1983 the generation of the neo-classical current at $r \to 0$ by α–particles was predicted (V.Ya.Goloborod'ko et al., Nucl. Fusion, 23 (1983), 399). However, the predicted current is rather small and the calculations neglected pitch-angle scattering of the α-particles. Now Ya.I.Kolesnichenko (INR, Kiev) [5] presented results where pitch-angle scattering was taken into account. Here a neo-classical kinetic equation for the bounce-averaged distribution function of α-particles with orbits intersecting the tokamak magnetic axis is formulated. The exact solution of the derived equation can only be found numerically and the authors are planning to do this in the near future. In the work presented, the solution is found analytically after simplification of the pitch-angle scattering term. Based on the solution so obtained, the α–particle bootstrap current at the magnetic axis is found and a simple approximate expression for this current deduced. The ratio of the a current induced by pitch-angle scattering (j^x) to the current due to slowing down (j^0) may be estimated as:

$$\frac{j^x}{j^o} \cong \frac{T_e(keV) \cdot Z_{eff}}{130 \cdot s^{2/3}} \qquad (1.1)$$

where $s = 2\ q\ \rho_\alpha / R$, ρ_α is the gyro radius of the 3.5 MeV α–particles, R is the major radius of the torus and q the safety factor. Eq. (1) shows that pitch-angle scattering strongly enhances the α–particle induced bootstrap current in the axial region. This circumstance is favourable for the use of α–particles for generating the seed current. However, α's themselves can hardly produce a sufficiently large current density to provide a central safety factor, q_o of about unity. In particular, in the example considered $q_o \sim 3$.

On moving away from the magnetic axis, the contribution of pitch-angle scattering to the α–particle induced bootstrap current decreases. Nevertheless, it is of interest to find the α–particle bootstrap current beyond the axial region taking into account both slowing down and pitch-angle scattering. Earlier this was done by Hsu et al. (Phys. Fluids, B2 (1992) 4023) using an expansion technique of the alpha drift kinetic equation in the small banana width limit. At the present meeting C.S.Chang (Courant Inst. Math. Sci., New York) [6] showed a new variational approach and found a bootstrap current similar to Hsu's results. As an example, for ITER steady-state operation mode with T(0) = 30 keV, n(0) = 1.8 x 10 m^{-3} , B = 4.85 T, $Z_{eff} = 2$ and $I_{tot} = 21.7$ MA, C.S.Chang obtained an α–particle bootstrap current of 1.7 MA and a thermal bootstrap current of 10 MA. In addition, he reported the results on an α current driven by ICRH. Assuming that the term in the kinetic equation describing the α–wave interaction is small and of the same order as the term responsible for the bootstrap current ($\overline{v}_d \cdot \nabla f$) he obtained $I_{ICRH} = 0.9 - 1.2$ MA for RF power levels in the range P = 50 - 70 MW. This current is located in the central region of the plasma, but it goes to zero when $r \rightarrow 0$.

2.2 Alfvén Instabilities

2.2.1 Excitation of Alfvén Waves [7, 8, 9, 10, 11]

The excitation of Alfvén waves by α–particles was first considered 23 years ago by V.S.Belikov, Ya.I.Kolesnichenko, V.N.Oraevskij (Zh. Eksp. Teor. Fiz., 55(1968) 2210; Sov. Phys. - JETP, 28 (1969) 1172) who assumed that the velocity distribution of the α–particles is non-monotonic, $f_\alpha = \delta(v-v_\alpha)$, $v_\alpha = 1.3 \times 10^9$ cm s^{-1}. Later, in 1975, A.B.Mikhailovskij investigated Alfvén instabilities associated with the spatial in-homogeneity of α–particles (Zh. Eksp. Teor. Fiz., 68 (1975) 1772; Sov. Phys.-JETP 41 (1975) 890). In both of these papers, the analysis was based on a local approach. Since 1986 Alfvén instabilities have been the subject of intensive studies using a non-local approach, which enabled the discovery of instabilities with a large region of localization, e.g. instabilities of TAE (C.Z.Cheng, M.S.Chance, Phys. Fluids, 29 (1986) 3695), GAE (Y.M.Li., S.M.Mahajan, D.W.Ross, Phys. Fluids, 16 (1987) 1466; J.Weiland, M.Lisak, H.Wilhelmsson, Phys. Src., T16 (1987) 50, EAE (J.R.Betti, J.P.Freidberg, in Proc. IAEA Tech. Comm. Meeting, 1991, vol.2, 667) and to obtain more information on the KAE-instability which has a small width of localization. Note, that a number of essential features of these instabilities could be obtained in the framework of a local analysis as well. The interest in Alfvén instabilities increased after the first experimental observation of the TAE-instability on TFTR (K.L.Wong et al., Phys. Rev. Lett. 66 (1991) 1874). This explains the large attention paid to XAE-instabilities (X = T, E...) at the 1st (Kiev) and, especially, at the 2nd (Aspenäs) and the present IAEA TC meeting on α–particles.

Usually the theoretical study of XAE-instabilities is carried out assuming that the driving force for them is generated by a spatial inhomogeneity of fast ions. A distinct excitation mechanism of the TAE-instability was reported by V.S.Belikov (INR, Kiev) [7]. Developing the results of a recent publication by V.S.Belikov et al. (Nucl. Fusion, 32 (1992) 1399) where the existence of a pure "beam mechanism" for driving the TAE instability was found (due to the velocity anisotropy of the fast ions), V.S.Belikov obtained results which are of importance for the interpretation of experiments with neutral beam injection. He showed that for the case: $v < v_A$ (where v_A is the Alfvén velocity) the anisotropy drive is much stronger than the pressure gradient drive by as much as a factor of 10. The instability is possible even when:

$$\partial f_\alpha / \partial v|_{\chi=\text{const}} < 0$$

where $\chi = v_{\parallel} / v$ is the cosine of the pitch-angle. The conditions for instability depend on the injection pitch-angle. The theory so developed was successfully applied to TAE observations on DIII-D involving the $v_{||} = v_A/3$ resonance of the fast ion-wave interaction.

F.Zonca (ENEA, Frascati) [8] presented a paper on continuum damping of TAE's using a full 2-D model of the mode structure. The coupling between discrete TAE modes and continuous shear Alfvén spectra is investigated for high n modes in the ballooning formalism including finite β. A general expression for the damping of high-n TAE modes in an equilibrium tokamak plasma with shifted circular magnetic flux surfaces is obtained. It is shown that, when β approaches the Troyon-Sykes limit, the TAE modes coalesce with the continuum resulting in strong mode coupling. The excitation of TAE's in a reactor operating close to the Troyon limit is therefore not very likely.

Analytic theory on the KTAE (Kinetic Toroidal Alfvén Eigenmodes) was reported by C.Z.Cheng (PPPL, Princeton) [9, 10] and S.Mahajan (IFS, Texas) [11]. KTAE is a branch which owes it's existence to electron dissipation. KTAE was mentioned in the 1989 work by C.Z.Cheng, L.Chen and M.S.Chance who called it the Periodic Shear Alfvén wave (PSA). Present KTAE theory involves electron Landau dissipation, ion finite larmor radius (FLR) effects and the α-particle drive.

2.2.2 Non-Linear Evolution of Alfvén Instabilities [12, 13, 14, 15, 16]

Significant progress has been made in developing the non-linear theory of the fast ion pressure driven Alfvén instabilities since the previous α-particle meeting [2]. Most of the results were obtained by numerical simulations.

The non-linear TAE simulations by D.A. Spong (ORNL, Oak Ridge) [12] treat the MHD in the fluid limit and the α-particle response in the so-called gyro-fluid model that is capable of including α-particle and bulk plasma MHD wave-particle interactions. This so-called Landau fluid closure permits a compact description of the α response in a time-dependent (initial value) code describing the evolution from the linear to the non-linear stage until saturation. Saturation is produced by n = 0, m = 0 beat waves which modify the q-profile (and thus the gap structure) and other essential fluid quantities such as the α-particle fluid velocity. Foremost, a poloidal flow velocity with n = 0, m = 0 is observed to arise, exhibiting strong radial shear which leads to saturation by breaking up the mode structure. This gyro-fluid code has been applied to very detailed equilibria and profiles of the NBI experiments in TFTR using R. Budny's 'TRANSP' simulation of expected supershots. The simulation produces fluctuation spectra essentially similar to those observed in the experiments and saturation amplitudes of 10^{-4} for the perturbed magnetic field. When applied to anticipated D-T runs in TFTR, it seems that the TAE mode may be quenched in the high ion temperature regime but may be observable in pellet injection and other special scenarios.

G.Vlad (ENEA, Frascati) [13] showed preliminary results from a new initial value code where the α–particles will be modelled as single particles, requiring as many as 500,000 for good statistics. So far, the fluid-MHD part of the code is running and - using a mock up α–particle drive term - unstable TAE spectra are seen to modify the gap structure non-linearly when saturation is approached. Only continuum damping is included. The code reproduces the analytic expressions of F.Zonca and L.Chen.

Alfvén wave turbulence driven by α-particles has been considered in two presentations by F.Y.Gang (MIT) [14, 15]. A hybrid code (MHD Alfvén wave, drift kinetic α-particles) capable of studying, fully self-consistently, the α–particle Alfvén spectrum interaction, albeit in slab geometry with finite shear, has been developed. Simultaneously, with strong analytic developments, the turbulence is investigated showing that the long and short wavelength parts of the spectrum display distinctly different α-particle transport mechanisms while being simultaneously coupled through Ion Compton Scattering. In the long radial wavelength limit ($k_\perp \cdot \rho_i << 1$) the coupling between the two waves with opposite wave number generates a zero frequency mode (similar to that seen in Spong's gyro-fluid code) which saturates due to strong E x B convection and redistributes the α-particle density in a global way without producing many losses. This behaviour is particularly well established in the zero shear case characteristic for the inside of the q = 1 surface. In the sheared region outside q = 1, the shear produces short wavelength turbulence and enhanced diffusive losses.

In order to treat this case separately, F.Y.Gang showed the analytical and numerical solution in the $k_\perp \cdot \rho_i \leq 1$ limit. This leads to coupled equations for the fluctuation potential and the alpha particle density. Ion Compton scattering provides energy transfer from long to short wavelengths producing saturation without strong flattening of the α-particle density profile. The concomitant alpha particle diffusion coefficient is of the order 1 m^2 /sec.

This analytic form of the diffusion coefficient is used in a work reported by G.Kamelander (ARC, Seibersdorf, Austria) [16] to calculate the deleterious effect of fast α–particle diffusion on the α coupling efficiency to the bulk plasma. With the above-mentioned magnitude of D_α, the coupling efficiency in an ITER-like machine can drop to 0.95. Including transport modelling (Rebut-Lallia) of the bulk plasma, a time dependent impact on ignition is observed at high ion temperatures (above 20 keV, due to a shortening of τ_E) but can be avoided at lower temperatures.

2.3 Ion Cyclotron Emission [17, 18, 19]

Ion cyclotron emission from the plasma edge near the outer mid-plane of the torus has been observed on JET and TFTR. Results from JET were reported at the previous α-particle meeting in Aspenäs [2]. Now R.O.Dendy (JET) [17] presented an overview on this problem with emphasis on recent results from the JET preliminary tritium experiment. He paid attention to the importance of ICE as a potential diagnostic for confined α-particles in the forthcoming tritium experiment on JET. A general conclusion, which follows from experimental observations, is that ICE is directly associated with the fusion reactivity in tokamak plasmas. It is based on the following: the proportionality of ICE intensity to the measured fusion reactivity in a discharge database covering a range of six decades in signal intensity; correlation in the time-evolution of the ICE signal and neutron flux during discharges; correlation between ICE and observed impact of MHD activity, such as sawteeth and ELMs, on energetic ions. It appears that the ICE results from the excitation of the magneto acoustic-cyclotron instability, a first extensive account of which was given in 1976 (V.S.Belikov and Ya.I.Kolesnichenko, Sov. Phys. -Tech. Phys. 20 (1976) 1146). Recently R.O.Dendy, C.N.Lashmore-Davies and K.F.Kam (Phys. Fluids B4 (12) (1992) 3396) extended their results from the previously mentioned work to the low frequency regime. Now Dendy reported results which also cover the case of oblique wave propagation ($k_{//} \neq 0$).

In all previous studies of the magneto acoustic-cyclotron instability, the distribution function of fast ions was assumed to have a form: $f_\alpha \sim \delta(v-v_\alpha)$ or close to it. This seems justified for experiments with deuterium plasma (where there is a correlation between ICE and the sawtooth crashes). However, this is inappropriate for the JET D-T experiment, where the population of α-particles near the plasma edge mainly consists of the trapped particles produced in the plasma core. The α-particles distribution function relevant to the JET tritium experiment is calculated in a work presented by Ya.I.Kolesnichenko (INR, Kiev) [18]. The distribution function obtained strongly depends on the radial profile shape of the a source in the plasma periphery and is characterized by a positive derivative $\partial f_\alpha(v_\perp, v_{//})/\partial v_\perp$ in the velocity region of marginally trapped particles. It is shown that the presence of a small number of α-particles, $n_\alpha/n < 10^{-4}$, is sufficient for the excitation of fast magneto acoustic waves with $\omega \approx l\omega_{B\alpha}, l >> 1$. This as well as the other conditions for instability seem satisfied in the JET tritium experiment.

B.Coppi (MIT) [19] considered the same waves ($\omega \approx k_\perp v_\alpha \approx l\omega_{B\alpha}$) and found a mode structure showing its localization around the $r \cong a/\sqrt{\sigma+1}$ surface, where σ is obtained from the plasma density profile: $n(r) = n_0 (1-r^2/a^2)^\sigma$. He assumed that the instability arises due to a resonant wave-α interaction (rather than being coherent as assumed in Refs. [17, 18]). However, Coppi has not specified the distribution function of the α-particles and obtained no instability threshold.

Thus, ICE seems to be a manifestation of a thermonuclear instability of fast magneto acoustic waves, but further theoretical studies are required for a reliable description.

2.4 Sawtooth Oscillations and Fishbones [20, 21, 22]

Experimental observations show that sawtooth oscillations can strongly affect the confinement of fast ions in the plasma core. Experimental evidence and theoretical studies of this phenomena were presented at the preceding meeting on α-particles [2]. Further progress in this field, namely, the use of a new model for sawtooth crashes and a quantitative description of the experimental data, was reflected at the present meeting.

M.Lisak (CTH, Göteborg, Sweden) [20] reported on work where a theory for the change of the neutron emission observations from sawtoothing plasmas is developed and applied to the interpretation of neutron emission observations in JET experiments with neutral beam injection. The theory uses two models of sawtooth crashes, namely, the well-known Kadomtsev model (predicting the central safety factor in a tokamak to be equal to unity after a crash $q_0^+ = 1$) and a recently published model (Ya.I.Kolesnichenko et al., Phys. Rev. Lett. 68 (1992)

3881) using a q_o^+ value well below unity, in agreement with measurements of q from e.g. JET.

It has been found that crashes with $q_o^+ < 1$ always lead to a strong drop of the neutron emission at r = 0, which significantly exceeds the corresponding increase near the sawtooth mixing radius, r_{mix}. A similar behaviour of the local neutron emission is obtained for crashes with $q_o^+ = 1$ but only if the beam density is peaked in the region $r < r_s$ and if it is flat or hollow in the region $r_s < r < r_{mix}$ (r_s is the radius of the q = 1 surface).

The global neutron emission has been found to be more affected by crashes with $q_o^+ = 1$ as compared to those with $q_o^+ < 1$. It has also been shown that the change of the global neutron emission during a crash can vary from negligibly small values up to 50-70% depending on the radial distribution of the fast ions at $r < r_{mix}$. For parabolic radial distributions of plasma and beam particle densities, the change of the global emission depends on the values of r_s/a.

In order to make direct comparisons with NBI heated JET discharges, an extensive numerical investigation has been carried out. The radial distribution of the neutron emission integrated along the line-of-sights of the JET neutron profile monitor have been obtained numerically for short time intervals immediately before and after a sawtooth crash. The corresponding change of the global neutron emission has been calculated as well. The calculations have been carried out for JET pulses: No. 18768, 20981, 20222, 20991. A sensitivity analysis of the neutron emission calculations has shown that the results obtained are most sensitive to the position of the mixing radius r_{mix} and the radial distribution of beam particles.

A general conclusion, following from the comparison between the numerical and experimental neutron results, is that the developed theory is consistent with experimental observations. Both the Kadomtsev model and the recent model can be used for calculations of the neutron emission to yield results in satisfactory agreement with experimental observations. To finally conclude on which model is the most appropriate one to describe sawtooth crashes in neutral beam heated JET discharges, additional experimental information is required, particularly concerning the q-profiles. However, from the point of view of existing experimental data, only the recent model is consistent with the experimentally inferred constraints on the q-profile, e.g. the observed small changes of q_o during crashes and the persistence of the q = 1 surface as evidenced by snake observations.

D.Anderson (CTH, Göteborg, Sweden) [21] has extended the approach presented above, Ref.[20], to describe the fast ion distribution n(r), and concomitant neutron emission during 100 ms after a sawtooth crash, i.e. after smoothing of n (r) in the vicinity of the q=1 radius. This is of importance in connection with the coarse time resolution of measurements of 14 MeV neutron emission produced by tritons from D-D reactions in JET. He applied this approach for finding the redistribution of the neutron emission during sawtooth oscillations with a period exceeding the triton slowing down time.

G.Miley (University of Illinois, Urbana, USA) [22] presented an improved analysis of the linear stage of the 'fishbone' mode including plasma rotation, hot ion kinetics and finite aspect ratio effects. The Frieman-Rotenberg equation is solved numerically for realistic geometries. It is found that, in general, the Kink Mode ω_r is attributable to plasma rotation. With $q_0<1$, internal Kinks become increasingly unstable at higher rotation velocities. At these high rotation velocities they can even be destabilized when $q_0>1$. Results for ITER-like and TFTR-like equilibria were presented. Hot ion contributions are introduced perturbatively and the drift-kinetic equation is inverted along the flux surfaces. It is found that the ω_r of the 'fishbone' oscillation can be partly attributed to rotation and that this basic rotational mode is increasingly up-shifted by the hot ion resonance. Predictions for ITER show that 'fishbones' are to be expected, but they will not be too detrimental to the α-particle confinement.

2.5 Ignition and Thermonuclear Burn [23, 24, 25, 26, 28, 27]

The problem of burn control was addressed in a paper by Hui et al. [23], which was presented by G.Miley (University of Illinois, Urbana, USA). Using a 0-D plasma model and feedback control theory, a robust control system model is constructed; the 'full information almost optimal' algorithm of Doyle et al. (IEEE transactions on Automatic control, 34:8 (1989),831) is used. The results from simulations based on ITER/CDA parameters show that the robust controller leads to a much larger domain of stability than a previously used 'pole-placement' controller. By modulating the refuelling rate alone, the stability domain covers a wide range of possible operating points. A comparison with burn control using auxiliary heating (Bromberg & Cohn, Nucl. Fusion, 20:2

(1980), 203) shows that a system based on refuelling alone has very attractive properties, but further work is required.

V.V.Lutsenko (INR, Kiev) [24] presented results of extensive analytical and numerical studies of the influence of sawtooth oscillations on the thermonuclear reactor power. He showed that sawteeth lead to the following:

First, sawtooth crashes are accompanied by sharp changes in the generated fusion power (δI_G). These changes are typically small, less than a few percent. The sign of δI_G can be either negative (as observed in present-day experiments) or positive. With T(0) > 16 keV, a peaked T(r) profile and a flat n(r) profile inside $r<r_{mix}$, a growth in fusion power may occur. The reactor power change depends on the kind of the crash and/or on the model of the crash. The largest changes take place in the case of full mixing (e.g. due to turbulence) and in the case of the Kadomtsev model applied to a plasma with a parabolic $[q(r)]^{-1}$ profile.

Second, a short post crash period ($\Delta t<<\tau_r$) is characterized by an increase in the change of the reactor power which occurred during the crash. This effect is strongest when the period of the sawtooth oscillations is large, $\tau_r > \tau_E$, τ_E being the plasma energy confinement time. In the example considered, the sharp growth of the reactor power by 3% during the crash is followed by a further increase leading to a power increment of about 18% with respect to the pre-crash level within $\Delta t \sim 0.5$ s and then by a decrease to the pre-crash level within $\Delta t \sim 2$ s. This evolution during the post-crash period is explained by the formation of sharp gradients of the plasma parameters due to the crash and the concomitant enhanced diffusion. At the beginning, the post-crash diffusion leads to an increase of the effective mixing radius, playing the role of an amplifier of δI_G. Later, diffusion dominates and restores the pre-crash power level.

Third, the pre-crash power as well as the time-averaged power differ from the power of a reactor without sawtooth oscillations. This fact constitutes the main practical consequence of frequent sawteeth ($\tau_r << \tau_E$) leading to a possibly controlled reduction of the power in a reactor. The reason for the power reduction is the flattening and decrease of the plasma density and temperature at $r < r_{mix}$ caused by small values of τ_r which does not allow the restoration of the n(r) and T(r) profile shapes during the ramp up phase of the sawteeth. However, if the operating temperature without sawteeth is very high (~ 100 keV) then the presence of sawteeth would have a positive influence on the reactor characteristics: it would decrease the plasma temperature (and pressure) and increase the fusion power. However this example seems to be of little practical interest as the required plasma temperature is too high.

F.Wising (CTH, Göteborg, Sweden) [25] showed a simple ignition criterion, indicating whether a given temperature profile in a fusion plasma, established by auxiliary heating, will evolve towards ignition. This criterion is derived from an integral criterion by Ya.I.Kolesnichenko, V.V.Lutsenko, S.N.Reznik (see Ref.[2]) assuming the plasma density to be homogeneous and taking the initial temperature profile in a form: $T(r,t=0)=T_0\ (1-r^2/a^2)^\gamma$ with $T_0 > 10$ keV.

A.Airoldi (Inst. Plasma Phys., Milano, Italy) [26] presented results from numerical simulations of plasma dynamics in Ignitor. The 'JETTO' code, which includes both equilibrium and transport equations, was used. It follows from these calculations that the onset of the $q < 1$ region can be delayed and, ignition or at least $Q>5$ is achievable.

G.Miley (University of Illinois, Urbana, USA) discussed He transport scaling law studies [27]. Using $D_\alpha(r)$ and $V_\alpha(r)$ profiles derived from measured $He^{2+}(r)$ profiles during helium puffing experiments into L-mode plasmas at TFTR (Synakowski et al., Phys.Rev. Lett.,Vol. 65, 2265), best fit power-law expressions in $\{n_e, T_i, dn_e/dr, q\}$ space were obtained for the α-particle diffusion coefficent:

$D_\alpha = 1.09\ n_e^{-0.16}\ T_i^{0.21}\ \ |\ dn_e/dr\ |^{-0.01}\ q^{1.54}$ and for the pinch velocity:
$V_\alpha = 1.29\ n_e^{-0.30}\ T_i^{0.44}\ \ |\ dn_e/dr\ |^{-0.01}\ q^{1.16}$, where n_e is in $[10^{13}\ cm^{-3}]$, T_i is in [keV], dn_e/dr is in $[10^{13} cm^{-4}]$, D_α is in $[m^2/s]$ and V_α is in [m/s].

M.Lontano (Inst. Fisica del Plasma, Milano, Italy) [28] considered a problem of α-particle slowing down in a high density plasma, which is of interest for inertial confinement fusion. The analysis is based on a classical dielectric theory which describes the collective interaction between the α-particles and the bulk plasma. An effect of enhanced slowing down had been demonstrated in the framework of a simple system constituted by two close α-particles.

3. EXPERIMENTS

3.1 D-D Fusion Products and Single Particle behaviour of Fast Ions [4, 29, 30, 31 ,32, 33, 34]

Charged D-D fusion products provide good test particles for simulating the "single particle" behaviour of α-particles. S.Zweben (PPPL, Princeton, USA) summarised the observations on anomalous losses of D-D fusion products in TFTR [4]. These were classified into three groups: *MHD induced* losses, anomalous *delayed* losses and *ICRH induced* losses.

An increased loss of D-D fusion products is often observed at high heating powers in TFTR. This loss is attributed to the effect of MHD activity and is seen during coherent low n oscillations, beam driven fishbones, sawtooth crashes and pre-disruptive MHD activity. At 1.8 MA the observed losses can exceed the expected first orbit losses by a factor 3 to 4 leading to a total loss of 20-30%. The losses can be continuous; they can also appear in bursts during fishbones or spikes (0.1-1 ms) at sawtooth crashes.

Observations of anomalous delayed losses were discussed. Fusion products with energies about half their birth energy are detected by a detector located 90° below the outer mid-plane with a time delay 0.2 s with respect to first orbit losses. The delayed losses increase relative to the first orbit losses with increasing plasma current and NBI power and most of the lost particles have a high pitch angle, χ = 70°, corresponding to deeply trapped ions. Possible explanations were discussed but failed to explain all experimental observations.

Experimental observation of ICRH-induced losses of fast particles were also reported. The observations are not yet fully understood and it is difficult to distinguish between fusion product losses (first orbit and ICRH induced) and ion losses from the tail of the RF-driven minority population. During electron heating experiments, when no minority tail is supposed to be created, the observed losses have to be attributed to the interaction of the ICRH waves with fusion products (second harmonic resonance with 1 MeV tritons).

Finally, scaling from TFTR measurements and using known theory, a prediction for losses from single-particle effects in ITER was made: α-particle heating will only be marginally affected but losses to the first wall could cause some problems.

G Sadler (JET, CEC) [29] gave an overview of observations on fast particles made at JET. Emphasis was on the fact, that in the absence of strong MHD activity, all measurements concerning the single particle behaviour of fusion products as well as NB-injected and RF-accelerated particles seem to be compatible with classical behaviour (confinement and slowing down), with the exception of a few, very well known, examples of triton burnup measurements with exceptionally long slowing down times $\tau_s > 2$ s [1,2]. A re-analysis of previously published data from ICRH ^{3}He-D experiments (J. Jacquinot, G.Sadler and the JET Team, Fusion Technology, Vol. 21, (1992), 2254) including orbit effects shows good agreement between theory and experiment as far as fast ion stored energy and fusion yield is concerned. However, some concern was expressed about the lack of evidence for a clear redistribution of tritons during sawtooth crashes using the burnup technique (measurement of 14 MeV neutrons created during the interaction of D-D produced tritons with deuterium background plasma ions)[1].

The α-particle statistics for the preliminary tritium experiment (JET Team, Nucl. Fus. 32 (1992) 187 and B.Balet et al. Nucl. Fus. (1993) in press) were summarized. During discharge 26148 a total fusion power of 1.7 MW corresponding to a Q of 0.15 was achieved. The central (r<15 cm) α-particle density was $n_\alpha/n_e = 4.8\ 10^{-4}$ and the central (r<15 cm) $\beta_\alpha = 8.0\ 10^{-4}$. The total power transferred from α-particles to electrons was 210 kW (25 kW to ions), the effect of which cannot be isolated from the power transferred by the beam ions to the electrons: 1.6 MW (8.9 MW to ions). However, recent simulations based on the highest D-D yield JET discharge, pulse 26087, assuming a 50:50 D-T mix show that the total power transferred from α-particles to electrons of 1.35 MW compares well with the power of 1.74 MW transferred from beam ions. Central values (r < 15 cm) are 67 kW/m^3 and 48.3 kW/m^3, respectively, and should lead to an observable electron heating after beam switch off.

Correlation of the strength of the observed ion cyclotron emission, ICE with the fusion yield (D-D and D-T) of over six orders of magnitude shows that ICE is driven by fusion products as opposed to NBI-particles (see also section 2.3).

Operating JET with only 16 toroidal field coils out of a total of 32 leads to an increase of the TF ripple at the position of the outer limiter from ~1% to ~ 12 %

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[1] Discussions at the meeting and further investigations at JET have led to the conclusion that, for the discharges analyzed, the triton profiles were already flat before the sawtooth crashes (to be published : F.B.Marcus et al).

(G.Sadler, P.Barabaschi, E.Bertolini et al. Plasma Physics and Controlled Fusion vol. 34, no.13 (1992) 1971); apart from a complete absence of plasma rotation and the difficulty to obtain an ELM-free H-mode, the following effects on the behaviour of fast particles were observed: loss of ripple-well trapped NBI ions and RF accelerated minority particles and a reduction in the triton burnup in the range from 30 to 60% , in rough agreement with predictions for stochastic triton losses (see also [31]) .

A.Gondhalekar (JET, CEC) [30] reported on measurements using a high energy neutral particle analyzer (see 4.2.2). An unexpected observation is that protons in the MeV range can be measured without the need to inject charge donor atoms. This is made possible due to strong single electron capture reactions by MeV H^+ ions with C^{+5} and Be^{+3} ions present in the plasma. From measurements of H^+ minority ions during an ICRH resonance scan, the power deposition profile could be obtained. Comparisons with profiles obtained with a Fokker-Planck simulation were discussed. Slowing down spectra of D-D generated protons have also been measured and are in agreement with expectations from classical behaviour. Finally, results from RF heated ^3He minority ions double charge-exchanging with injected ^4He ions show the potential of this instrument for measuring α-particle spectra during future tritium experiments.

A new, fast, computer code for studying ripple losses, based on the bounce-averaged Fokker-Planck kinetic equation, was described by S.Putvinskii (JET, CEC) [31]. The ripple effect is treated as a diffusion of banana particles and the kinetic equation is replaced by Langevin equations for random particle motion which are solved using the Monte-Carlo technique. A gain in CPU time of several orders of magnitude is obtained when benchmarked against full Orbit Following Monte-Carlo OFMC codes. The OFMC code 'DRIFT' from the Kurchatov Institute was used for validation purposes. The main conclusions from using this code together with the 'TRANSP' code to model the JET ripple experiment (16 coils vs. 32 coils) are: a) the ripple loss of beam ions (15 %, predominantly from the edge) is too low to explain the observed 30 % reduction in stored plasma energy and reaction rate. The power balance obtained from 'TRANSP' simulations including additional ripple-induced transport shows that ripple-induced ion heat conduction is about ten times larger than predicted by theory (0.02 m^2/s), b) the main loss channel for NBI ions is collisional scattering into the ripple-well loss-cone, c) ripple stochastic diffusion determines the loss of ICRH minority ions and D-D fusion tritons, d) ripple losses predicted by theory are in reasonable agreement (within a factor of two) with those observed in the experiment. Finally, the stochastic diffusion boundary in the JET (and ITER) configuration is defined not by overlapping of the primary islands but by an increase in the number of toroidal harmonics in the perturbation near the ripple well boundary.

K.Tani (JAERI, Naka-gun, Japan) [32] reported on measurements of ripple losses of NB-injected fast ions in JT-60U and the numerical analysis thereof. JT-60U has 18 TF coils leading to a ripple of ~ 2% in the outer mid-plane. Using a fast infrared TV camera, IRTV and toroidal-poloidal arrays of thermocouples, local measurements of the temperature rise of the first wall were performed during NB-injection (E_{NBI} = 80 - 90 keV, P_{NBI} = 10 - 18 MW). Extra heat loads due to ripple trapped and banana-drift loss particles could be observed in the locations predicted by an OFMC code. A quantitative assessment shows the necessity for introducing an $\vec{E}\times\vec{B}$ drift term (where the electric field is obtained from $\Phi(\psi) = CT_e(\psi) + \Phi_s$ with Φ_s being the electric potential on the plasma surface) into the OFMC code in order to reproduce the details of the 2-D distribution of the heat load. The integrated power loss fractions, however, proved to be insensitive to internal as well as external electric fields.

First experimental observations of interactions between lower hybrid, LH waves and fusion products were presented by G Martin (CEN Cadarache, France) [33]. Three peaks appear in the D-D fusion proton spectra measured during LH current drive experiments in Tore Supra: one at the nominal birth energy (3 MeV) and two satellites, the energies of which change with B_T and I but not with LH power and n_e. A preliminary model taking into account the proton orbits and wave induced diffusion explains qualitatively the appearance of the satellite peaks; only certain classes of particles can reach the detector. A quantitative interpretation will have to await further development of the model.

V.Basiuk (CEN Cadarache, France) [34] reported measurements of anomalous fast particle losses in Tore Supra, which were not correlated with any measured MHD activity. Graphite probes, usually used to detect TF ripple-induced fast ion losses during additional heating (ICRH or NBI), show the ejection of fast ions during periods of sawtooth stabilization with hydrogen minority (10%) heating. The lost particles seem to originate from the central region of the plasma and almost certainly have higher energies than the particles from 'steady state' background losses. The results are not yet understood; the possibility that magnetic islands could be involved was mentioned. A new diagnostic to measure the energy distribution of these ions is under construction.

3.2 Fast Particle Induced Collective Phenomena [35, 36, 29]

At present, the only practical way of simulating possible collective effects of α-particles is by using neutral beam injected or RF accelerated particles. Beam ion losses in TFTR during TAE modes and other MHD activity were discussed by D.S.Darrow (PPPL, Princeton, USA) [35]. During TAE simulation experiments, bursts of ions with the full injection energy (100 keV) are detected by a scintillator positioned at the outer mid plane of the vacuum vessel. These bursts occur during TAE activity and the total ion loss is estimated from drops in the neutron emission rate (~ 0.5 ms delay corresponding to ~ 100 bounce times). Up to 10% of the injected ions can be lost during a single burst leading to an accumulated reduction of 50% in the beam ion population. The frequency of the mode is in rough agreement with theory, $\omega = v_A / 2qR$. The lost ions have a pitch angle spectrum comparable to that observed in the absence of the mode. Ion losses are also observed at very low toroidal field (B_T = 1.5 T) and low power P_{NB} =2 MW. In this case, the losses are correlated with modes which fit the description of ABMs (Axisymetric Beam-driven Modes as described by E.D.Fredrickson, et al. in Europhysics Conf. Abstracts, Venice, 1989, Part 2, 481). MHD activity in the 25-50 kHz range with characteristics similar to those of the TAE modes has been observed to expel passing particles as well. These are not TAE modes, as the observed frequency scaling does not agree with theoretical predictions.

In TFTR, TAE modes can also be excited by ICRH accelerated ions (P_{RF} > 3 MW and W_{Tail} > 70 kJ). The power lost by escaping tail ions increases strongly with P_{RF} (factor of 5 between P_{RF} = 5 MW and P_{RF} =11 MW) and linearly with the TAE amplitude. Tail ion losses account for 10% of the total ICRH power at P_{RF} =11 MW). Attempts to excite possible KBM modes failed, but other, unidentified instabilities have been seen to cause particle losses.

Observations on Alfvén instabilities in the DIII-D tokamak were reviewed by W.W.Heidbrink (University of California, Irvine, USA) [36]. In DIII-D eigenmodes can exist theoretically in 3 gaps: TAE (coupling of m and m+1), EAE (coupling of m and m+2) and BAE (β-induced). Large beam ion losses (up to 70 % of the beam power) are observed by many diagnostics and are concentrated near the outer mid-plane. The dominant loss mechanism is probably resonant convective transport (mode-particle pumping). In order to calculate the mode frequency in the plasma frame, the Doppler shift is inferred from the spectrum and from rotation measurements. The observed modes seem to clamp the beam β near the point of marginal stability and they appear in bursts. This is explained by the large beam-ion losses, which results in a reduction of the fast-ion drive and the consequent stabilization of the mode. A non-linear 'predator-prey' cycle results. The observed threshold is in agreement with theory to within a factor of three. At high β, the frequency drops into the BAE gap. These instabilities also affect the confinement of non-resonant fusion products, as proven by the observation of losses of 0.8 MeV ^3He ions and 1 MeV tritons.

The possibility that TAE modes (excitation by $v_{//} \sim v_A/3$) have been observed in certain JET discharges was mentioned by G.Sadler [29]; the frequency scaling with B_T and n_e seems to be in agreement with theory. However, marginal stability curves based on α-particle pressure profiles from 'TRANSP' simulations show, that neither for the JET preliminary tritium experiment, nor for a future tritium experiment (simulation based on best D-D pulse and 50/50 D:T mix) are TAE's expected to be excited.

3.3 Future Outlook [37, 29, 38]

The plans for D-T α-particle experiments in TFTR [37] were presented by S.J.Zweben (PPPL, Princeton, USA). The physics plan consists of 3 main items: a) fusion power demonstration, b) confinement and heating in D-T plasmas (α-heating, species dependence, tritium particle transport, ICRH heating issues), c) confinement and transport of α-particles (loss of α-particles, collective effects and ash accumulation). The experiment is planned in 2 phases; phase I, which will take place in the period from September to December 1993, has as its main objective the production of 5 MW of fusion power and phase II, which will follow in 1994, is intended to study the physics of D-T plasmas. Recent supershot performance using extensive lithium pellet conditioning is characterised by: $n_e T_i \tau \approx 5.8 \times 10^{20}$ keV s m^{-3}, $n_i T_i \approx 4.6 \times 10^{20}$ keV s m^{-3}, $n_e = 1.0 \quad 10^{20}$ m^{-3}, $T_i = 29$ keV and $\tau_E = 0.2$ s. The peak neutron emission rate exceeds $5.5\ 10^{16}$/s with Q_{DD} 2.1×10^{-3} (equivalent to a $Q_{DT} \approx 0.38$).

Specific experiments planned for the tritium phase are: α–particle heating, TAE mode destabilization at low T_i and with added ICRH, β-induced Alfvén eigenmodes (KBM), α-driven sawteeth and fishbones, effects of α-distribution functions, high β_{pol} collective effects, ICRH-α interactions, α ash transport, α heating during sawtooth reheat and α-particle - lower hybrid wave interaction. Although predicted to be relatively small (20%), it is hoped that the α-particle electron heating effect can be isolated.

The possibility of a second tritium experiment in JET before the main D-T programme commences [29] was mentioned by G.Sadler (JET, CEC). It would consist of a single full power discharge with a 50:50 D-T mix. Based on the best D-D discharge, predictions show that such a discharge should achieve $Q \sim 1$.

It is also planned to continue the ripple experiment. The installation of an imbalance cable (bus bar) between the two interleaved sets of 16 coils, which will be connected in series, will provide the possibility to change the ripple continuously.

The excitation of TAE modes with the newly installed stabilization coils is another possible experiment. Part of the system would be used as a receiver. Predicted mode amplitudes are in the 15-100 mG region, i.e. too weak to affect fast particles, but the coupling of the fast particles (NBI, RF) with the mode is predicted to be detectable in the received spectrum.

B.Coppi (MIT, Cambridge) [38] gave a status report on the Ignitor project (B.Coppi, M.Nassi ans L.Sugiyama., Physica Scripta 45 (1992) 112). Good progress is being made and, although no official decision has yet been taken to proceed with the construction of the machine, some critical components (vacuum vessel and C clamp) are actually under construction. He showed a series of photos of finished components being tested at the factory. The present reference design parameters of Ignitor are: R_o = 1.32 m, plasma cross section = 0.47 x 0.87 m^2, triangularity = 0.4, I_p = 12 MA, B_T = 13 T, q_a = 3.3, plasma volume = 10 m^3, plasma surface area = 36 m^2 and additional heating power (ICRH; 100-210 MHz) = 18 MW.

The optimization of D-^{3}He fusion power output was also discussed by Coppi; a lower density regime ($n_o \sim 3\ 10^{14}$ cm^{-3}) than that found optimal to achieve D-T ignition ($n_o \sim 1\ 10^{15}$ cm^{-3}) is required to allow the ICRH system to generate a relatively large population of fast ^{3}He ions with energies $E \geq 0.25$ MeV. The effect of the 14.6 MeV fusion protons, which will be confined in plasmas with a current above 6 MA, in relation to that of the 3.7 MeV α-particles was also discussed.

The second stability region can be investigated in relatively low magnetic field and plasma current regimes. An added benefit here is that the discharge duration can be easily extended as the Ignitor magnet can be cooled to an initial temperature of 30 K by the adopted gas-helium cooling system.

4. DIAGNOSTICS

4.1 Diagnostics for D-T Experiments on TFTR and JET [37, 29]

The α-particle diagnostics to be used on TFTR for the forthcoming D-T experiments were reviewed by S.J.Zweben (PPPL, Princeton, USA). The α-particle source will be characterized from measurements of the global neutron emission-rate and the neutron source profile. Escaping α-particles will be diagnosed using scintillation detectors, a foil deposition detector and by measuring ion cyclotron emission. Confined α-particles will be studied with charge exchange recombination spectroscopy (α-CHERS), α-particle charge-exchange (ACX) and collective Thomson scattering. Finally, for investigating α-particle induced fluctuations, the following systems will be available: Mirnov loops, a microwave reflectometer, electron cyclotron emission (ECE) diagnostics, beam emission spectroscopy (BES) and a microwave scattering system.

JET will have a comparable set of fast particle diagnostics available for its next operations period. The systems were summarized by G.Sadler (JET, CEC) [29]. The main differences are: the more comprehensive set of neutron diagnostics, notably the use of neutron spectrometers and the absence (at present) of any lost particle diagnostic. The development of passive systems based on α-particle depth profiling has come to a halt as the main potential tool to accommodate such a diagnostic, i.e. the fast boundary train, had to be abandoned due to its incompatibility with the new divertor configuration. The high first wall temperature of JET (T> 300°C) during operations prevents the use of a conventional scintillator-based fast particle detection system as used on TFTR [37]. Diamond detectors as developed by R. Wagner (Los Alamos USA) are thought to be an alternative and are under investigation. The advantage would be the inherent potential of insensitivity to radiation (14 MeV neutron induced) damage as well as the proven use at high temperature. The JET neutron profile monitor is in the process of being upgraded to accommodate two detectors per channel and remotely controllable collimators in order to accommodate the very large range of predicted neutron fluxes (thermal D-D to full power D-T).

4.2 Specific Diagnostics

4.2.1 High Energy Neutral Particle Analyzer [30]

A.Gondhalekar (JET, CEC) [30] described the new high energy neutral particle analyzer (NPA) deployed on JET during the last operating campaign. The NPA is of the conventional E // B type with eight energy channels with common mass selection and spanning $0.5\ \text{MeV} \leq E \leq 3.5\ \text{MeV}$. Absolute fluxes and energy spectra ($\Delta E/E \sim 8\%$) of H, D, T, ^3He and ^4He ions can be measured. The detectors consist of 3 cm^3, 8 mm thick Cs(Tl) scintillators coupled to photomultipliers.

4.2.2 Neutron Diagnostics [39, 40]

J.Källne (University of Uppsala, Sweden) [39] discussed the information on α-particles obtainable from neutron observations in a next step device. Apart from the α-particle birth profile and energy spectrum, information on the slowing down of the α-particles should also be obtainable as well as indirect information concerning the effect of α-particles on the fusion reactivity (with the last two points being considered controversial). Neutron diagnostics for such a next step device should comprise flux monitors for determining the total neutron yield, neutron spectrometers for deducing energy spectra and neutron cameras for measuring emissivity profiles. Fundamental limitations concerning efficiency and resolution of neutron detection methods based on elastic scattering in hydrogenous foils were discussed. A magnetic proton recoil spectrometer, MPR, with an intrinsic efficiency of $\varepsilon = 0.7\ 10^{-4}\ cm^2$ and an energy resolution of $\Delta E/E = 2.5\%$ was described. Its main qualities were described as: being fast, having high efficiency, allowing for absolute calibration, having good reliability and high radiation insensitivity. Using the achievable count rate, C_n , as a figure of merit, possible count rates of C_n = 1 MHz for JET (P_{fus} = 30 MW) and C_n = 20 MHz for ITER (P_{fus} = 1 GW), leading to a time resolution $\Delta t \sim 200$ ms for determining central T_i values and profile information at a 3% level were claimed.

A proposal for neutron diagnostics for Ignitor was presented by G.Gorini (University, Milano, Italy) [40]. Only multiple instruments can cover the wide range of expected fluxes in Ignitor when operated in D-T, D-D, D-^3He and D-T(10%) as well as meeting the stringent requirements on time resolution (short pulse length with 4 s flat top and transient plasma conditions during the approach to ignition). Although an approach very similar to the one taken by

Källne [39] was adopted, the system is complemented by one or more Time-of-Flight spectrometers to cover the lower end of the expected yields. The expected fluxes at the location of the instruments range from 4 10^{10} n/cm^2 s downwards to less than 10^{-3} this value. For D-T operation a Multi-gap MPR neutron camera yielding a count-rate of 20 MHz in its inner channel (40 kHz in outer channel) was also considered. For profile measurements from D-D plasmas, a suitable counter remains to be found.

4.2.3 γ-ray Diagnostics [41, 42]

V.G.Kiptilyj (Ioffe Phys.-Tech. Institute, St Petersburg, Russia) [41] gave a status report on ongoing work at the Ioffe Institute on identifying and charaterizing suitable fast particle reactions for γ–ray spectroscopy. Information on fast particles can be obtained by measuring the intensity and the Doppler shifts of γ-rays emitted in nuclear reactions of fast particles with low Z impurity ions. γ-ray line intensities from reactions with ^{12}C and ^{9}Be ions have been used extensively at JET [1, 2]. The anisotropy of the distribution function together with the relatively modest Doppler shifts shows the need for using high energy resolution detectors such as HPGe diodes. Model calculations of the Doppler broadening as well as measurements of γ-ray yields and γ-ray energy spectra for the ^{19}F (p,α+γ) ^{16}O reaction show the potential of F impurity ions as a fast proton diagnostic. Reactions of fast deuterons with ^{14}N and ^{3}He ions with ^{7}Li , ^{9}Be, ^{11}B and ^{13}C were discussed. The ^{10}B (α,p) ^{13}C reaction was proposed to complement the ^{9}Be (α,n) ^{12}C reaction as an α–particle diagnostic; the useful range would be extended from $E_\alpha > 1.9$ MeV to $E_\alpha > 1.4$ MeV.

B. Robouch (EURATOM-ENEA, Frascati, Italy) [42] presented results from shielding calculations for a γ-ray diagnostic intended to measure the D (D,γ) +^{4}He γ-rays ($E_\gamma = 23.8$ MeV). He draw the attention to some recent measurements of the cross-section at low energies, which indicate values about three orders of magnitude higher than those obtained from extrapolations of previous experimental data. Nevertheless, the low γ/n branching ratio of ~ 10^{-7} for thermonuclear plasmas puts stringent requirements on the shield design: neutrons have to be strongly attenuated while only marginally affecting the γ-ray transmission. First results, assuming the use of a HPGe-detector, indicate that with a multilayered shield, signal ratios of 23.8 MeV γ-rays to 2.45 MeV neutrons in the range 10^2 to 10^5 can be achieved.

5. CONCLUDING REMARKS

F.Engelmann and D.Sigmar summarized the results presented at the meeting in the final section. They noted that, compared to the previous meetings, one could observe an increasing focus on experimental-theoretical connection with the objective of optimizing the experimental plans for tritium experiments on TFTR and JET.

The participants thanked the local hosts and organizers for the outstanding quality of the arrangements in Trieste.

This series of alpha physics meetings will be continued, with the next meeting tentatively scheduled for 1995 in Princeton, USA.

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