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Report on a Chalmers Symposium on the Role of Alpha Particles in Magnetically Confined Fusion Plasmas at Aspenäsgarden, Lerum in the area of Göteborg, Sweden, 24 - 27 June 1986

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Recent progress in the confinement of hot plasmas in magnetic fusion experiments throughout the world has intensified interest and research in the physics of D-T burning plasmas especially in the wide range of unresolved theoretical as well as experimental questions associated with the role of alpha particles in such devices.

In order to review the state-of-the-art in this field, and to identify new issues and problems for further research, the Symposium on the Role of Alpha Particles in Magnetically Confined Fusion Plasmas was held from 24 to 26 June 1986 at Aspenäsgarden near Göteborg, Sweden. The meeting was organized by the Institute for Electromagnetic Field Theory and Plasma Physics at Chalmers University of Technology in Göteborg and sponsored by EURATOM-FUSION, the Nobel Institute for Physics, the Board of Energy Research in Sweden, and Chalmers University of Technology. The scientific committee of the symposium consisted of the following members:
F. Engelmann (NET), T. Kammash (University of Michigan, USA), Ya. I. Kolesnichenko (Institute for Nuclear Research, USSR), M. Lisak (Chalmers) and H. Wilhelmsson , chairman (Chalmers).

About 25 leading experts from nine countries attended the Symposium and gave invited talks. The major part of the programme was devoted to alpha-particle effects in tokamaks but some aspects of open systems were also discussed. The possibilities of obtaining ignition in JET and TFTR as well as physics issues for the compact ignition experiments were considered in particular. A special session was devoted to the diagnostics of alpha particles and other fusion products.

In the following are summarised some of the highlights of the symposium.

The presentations started with an invited talk by *D. J.Sigmar (MIT) which* by using the total power balance of an ignited tokamak plasma surveyed a range of alpha driven effects and considered their impact on achieving and maintaining a fusion burn. Specific examples of MHD and kinetic modes and multi-species transport dynamics were discussed. It was pointed out that the power balance approach rather than a straight-forward enumeration of possible effects serves to reveal their non-linear dependence and the ensuing fragility of our understanding of the approach to and maintenance of ignition. Specific examples were given of the interaction between alpha-power driven sawtoothing and ideal MHD stability, and direct alpha-effects on MHD modes including kinetic corrections. Anomalous ion heat transport and central impurity peaking mechanisms as well as anomalous and collisional alpha-transport including the ambipolar electric field were discussed.

The consequences of the interaction of alpha particle populations with MHD modes depend strongly on the parameter range and type of mode under consideration.

An invited paper by D.A.Spong (ORNL) discussed the influence of alpha populations on tokamak stability due to coupling between the trapped alpha precessional drift and the kinetic ballooning mode frequency. Both Maxwellian and slowing-down energy models were used for the alpha energy dependence while deeply trapped and isotropic pitch angle dependences were examined. The results indicated that alpha populations can reduce significantly the first stability window for ballooning modes as the alpha pressure gradient is increased and as the background electron temperature is raised (for the slowing-down model) or, equivalently, the ratio of alpha to background temperature is lowered (for the Maxwellian model).

A related investigation was presented by J.Weiland (Chalmers) who considered the excitation of global Alfvén modes due to their coupling to the trapped alpha precessional drift. It was shown that both the real part of the wave frequency and the growth rate are of the order of the precessional frequency. Since the convection damping is absent for the global Alfvén modes, the instability threshold is much lower than that for the fishbone instability of the pressure-driven internal kink. Consequently, the considered instability might have a strong influence on tokamak stability.

Since the time for plasma heating to thermonuclear temperatures should be relatively small compared with the discharge duration in a tokamak reactor, the full-scale fusion reaction will take place in tokamaks during almost the total time of plasma existence and the reaction products will affect the plasma and the first wall. This means that the study of the fast alpha particle transport processes and the alpha particle confinement are of great importance.

A review of modern transport concepts for the high energy alpha particles in tokamaks was given by Ya I Kolesnichenko (Kiev). The main problems discussed in this paper were :

i) the collisionless mechanisms of alpha particle transport,
ii) a theory of collisional alpha particle transport in the corrugated toroidal field,
iii) the transport processes in the plasma central region (including the magnetic axis).

Several aspects of alpha particle transport in toroidal systems that are relevant to next step burning plasmas as well as Alfvén-wave related kinetic instabilities in both toroidal and mirror systems were considered in an invited paper by G.H. Miley (Univ. Illinois). It was emphasized that a potentially important effect of alpha particle transport and losses in a Tokamak is the development of a radial electric field. This could effect plasma transport, impurity transport and plasma rotation. Potential kinetic instabilities were considered from the point of view of threshold requirements. Calculations indicated that the tokamak is susceptible to an alpha-driven fast magnetosonic wave instability if conditions occur to trigger it. In a new analysis of the alpha-driven Alfvén instability in a mirror confined plasma with an anisotropic distribution caused by the loss cone, it was shown that threshold values and growth rates are quite sensitive to the details of the distribution function in the region of velocity space affected. This finding represents an important consideration for future analyses of such problems where high accuracy is desired.

An invited paper given by M.Haegi (Frascati) considered the single alpha particle effects in tokamaks with a special application to the Frascati Tokamak (FT). The computational investigation was based on a single particle trajectory numerical analysis by using a 2D code for an asymmetric configuration and a 3D-code for a non-symmetric model including the magnetic field ripple. The orbits of fast ^{3}He-particles produced by the D-D reaction were followed during their slowing down on plasma electrons. For the FT operating conditions : $B_T = 100$ kG, $I_p = 1$ MA, $n_{eo} \approx n_{io} = 2.10^{14}$ cm^{-3}, $T_{eo} = T_{io} = 1$keV; it was found that about 2% of the trajectories were directly lost during the first orbit. It was also shown that all banana orbits, which represented 28% of the fast ^{3}He-production, were lost within the first few hundred orbits. The dominant loss mechanism was the diffusion of the turning points out of the confinement region and into the ripple loss cone. The distribution of the impact on the wall was strongly peaked for Θ_{max} = 105° and Θ_{max} = 0° and the wall bombardment at these points was enhanced by a factor 77 respective to a uniform distribution.

A novel topic was presented by H.E.Mynick (Princeton) who described a new type of computational tool under development, employing techniques of symbolic computation and artificial intelligence to automate the research activities of the human plasma theorist. Its present and potential uses were illustrated by applying it to the area of the theory of alpha particle effects in fusion plasmas as a sample domain.

Recent developments in the US have to led to interest in constructing and operating a small experiment which can investigate the physics of ignition size. The original idea for such an experiment was due to B. Coppi.

The physics of compact ignition experiments was extensively discussed in an invited talk by B Coppi (MIT). It was pointed out that the analysis, carried out by transport codes, of the sequence of regimes that are encountered as a magnetically confined plasma approaches ignition conditions has revealed the importance of several issues such as :

i) the density limits that result from the onset of collective modes (e.g. ion mixing modes) producing an enhanced transport of the thermal energy of the fusing nuclei,
ii) the excitation of modes producing magnetic reconnection in the central region of the plasma column when the peak electron temperature and current density associated with it tend to rise, locally, as a result of alpha particle heating.

A discussion elucidated the relationship between the adopted design criteria and the indications and uncertainties of both theory and experiments.

An invited paper given by D.Post (Princeton) presented the proposal of the Compact Ignition Tokamak (CIT) experiment. The role of this experiment would be to explore the physics of alpha particle heating. The basic concept is to achieve ignition in a modest-size, minimum cost experiment by using a high plasma density to achieve $n\tau_E \sim 2 \times 10^{20}$ s/m³ required for ignition. The high density requires a high toroidal field (10T). The high toroidal field allows a large plasma current (10 MA) which provides a high level of ohmic heating, improves the energy confinement, and allows a relatively high beta (~6%). The present CIT design also has a high degree of elongation (~1.8) to aid in producing the large plasma current. A double null poloidal divertor and pellet injector are part of the design to provide impurity and particle control, improve the confinement, and provide flexibility for improving the plasma profiles. Auxiliary heating is expected to allow ignition, and 10-20MW of ICRF is to be provided.

K.Borrass (NET) in his invited talk reviewed the different schemes for burn temperature control in tokamaks with respect to stability, compatibility with other system components, impact on cost, viability of the underlying physics and validity of the modules used for the theoretical description. Open problems of burn temperature control were also discussed.

TFTR is expected to produce approximately 5MW of alpha heating during the Q=1 D/T phase of operation in 1989-90. At that point the collective

confinement properties and the heating effects of alpha particles become accessible to study for the first time. An invited paper by S.J. Zweben (Princeton) outlined the potential performance of TFTR with respect to alpha particle production and the physics issues which can be studied both before and during D/T operation. Specific physics issues to be addressed include the effects of plasma current, toroidal field ripple, sawteeth, and turbulence on alpha confinement. At its Q=1 performance level TFTR can also be used for preliminary studies on the collective behaviour of alpha particles and the effects of alpha heating on plasma confinement.

The prospects for alpha particle heating in JET was discussed in an invited paper by M.L.Watkins (JET). A computational model was developed to represent adequately the neutron yield from JET plasmas heated by neutral beam injection. This neutral beam model, augmented by a simple plasma model, was then used to determine the neutron yields and fusion Q-values anticipated for different heating schemes in future operation of JET with tritium. The relative importance of beam-thermal and thermal-thermal reactions was pointed out and the dependence of the results on, for example, plasma density, temperature, energy confinement and impurities was shown. Full 1½-D transport code calculations, based on models developed for ohmic, ICRF and NBI heated JET discharges, were also used to extrapolate to high power JET operation in tritium in the low density, high temperature regime. The results were shown to be in good agreement with the estimates made using the simple plasma model and indicated that, based on present knowledge, a fusion Q-value close to unity should be achieved in JET.

A brief summary of studies carried out in the Novosibirsk Institute of Nuclear Physics during the last few years was presented by P.Z. Chebotaev (Novosibirsk). Their research program covers alpha-particle effects in three types of possible open-ended reactors: multi-mirror, gas-dynamic and tandem mirror.

In an invited survey talk by U.Schumacher (Max Planck Institut, Garching), consideration was given to alpha particle diagnostics. It was pointed out that the understanding and experimental proof of alpha particle heating and loss mechanisms as well as the He ash removal as important conditions for burning thermonuclear plasmas requires the development of diagnostics for the alpha particle spatial and energy distributions in three different respects:

for the alpha particles escaping from the plasma, for the thermalized ("He ash") and for the fast confined particles in the fusion plasma. Besides the results obtained from neutron diagnostics and secondary fusion products in present-day experiments a variety of diagnostic methods offer indirect or specific information on the alpha particle distributions, closely related to

the necessary future developments, which are greatly influenced by the high neutron and X-ray background.

The escaping alpha particles can be detected near to the vacuum vessel wall, e.g. by scintillator screens combined with fibre optics (TFTR), by nuclear emulsion foils (ASDEX) or by shielded surface-barrier detectors at the end of a "magnetic periscope".

A scintillation detector for escaping alphas and tritons in TFTR, was presented in a talk by SJ. Zweben (Princeton). The detector is presently being tested on TFTR. It consists of a ZnS scintillator screen located inside a moveable probe at the bottom of the TFTR vacuum vessel. The alphas or tritons hit the scintillator screen where they create visible light pulses which are fibreoptically coupled to photo-multiplier tubes and/or an intensified video camera for recording and analysis.

The measurement of the pitch angle distribution of energetic alphas escaping from a burning plasma represents a key next step diagnostics problem. A unique wall detector design was proposed in a talk by G.H. Miley. This detector concept uses a combination of curved collimation, thin scintillator and a past multi-channel signal processing unit to allow detection of 10^{-5} alphas per fusion neutron despite the intensive background radiation field involved.

The thermalised alpha particles can be diagnosed by charge exchange recombination spectroscopy applying a diagnostic neutral beam or doped pellet injection. For the distribution of the high-energy alpha particles confined in the plasma bulk different methods are proposed, e.g. by applying neutral beams for single charge exchange recombination spectroscopy and double charge exchange neutral He analysis, using laser scattering (CO_2 forward scattering) or wave phenomena (LH wave damping or ion cyclotron wave emission) or using nuclear reactions (Be).

The utilisation of (α,n) and (α,γ) reactions to determine confinement and velocity distribution of fast alpha particles was discussed in a talk by T. Elevant (Stockholm). It was concluded that one needs to utilize several reactions and also different kinds of diagnostics to fully explore confinement and velocity distributions of the alpha particles.
Measurement of neutron and proton energy spectra of the d + ^{3}He and d + t fusion reactions were considered in a talk by J. Källne (JET).

It was reported that proton spectra have recently been measured at JET from the reaction $d + {}^3He \rightarrow p + \alpha$ at energies around $E_p = 14.6$ MeV. In some of these discharges ^3He was introduced into the deuterium plasma by gas puffing (to allow ICRF minority heating) but is otherwise always present as a product of the reactions $d+d \rightarrow {}^3He+n$.

It was also noted that neutrons of about 14.1 MeV from the reaction $d + t' \rightarrow \alpha + n$ (where the 1.0 MeV tritons t'come from $d+d \rightarrow p+t'$) can be detected given a spectrometer of high efficiency: at the same time the sensitivity to 2.5 MeV neutrons needs to be low since this flux from a deuterium plasma is 100 times higher. A proposed neutron spectrometer design and its envisaged

diagnostics capabilities was discussed, the neutron spectrum being of particular interest for comparison with α-particles as these have similar larmor radii to the 1.0 Mev tritons.

Related questions were discussed in a talk by G. Martin (Cadarache) who considered the 15-MeV proton emission from the JET plasma during sawtooth collapse : results and interpretation. The phenomena observed for the 15 MeV $d - {}^3He$ protons measured at JET during ^3He minority RF heating were the following:

a. The proton spectra show a strong peak above the thermonuclear energy,

b. During the sawtooth collapse, protons reach the detector in bursts with their energy shifted downwards.

By using a simple model which had been developed to explain the spectra it was found that certain important features of the experimental data could be reproduced with a classical simulation of the RF heating process and an accurate calculation of the detector efficiency.
The sawtooth collapse is found to have a strong effect on the very fast ^3He particles, i.e. those in the energy range of 100-300KeV. This is of particular interest since it can yield information on alpha particle behaviour in future Tokamak operation.

The final summing up and discussion of the symposium was conducted by F. Engelmann, who also during the meeting gave an invited talk entitled: Importance of alpha-particle physics for Tokamak reactor design. It was concluded that issues related to the presence of fusion alpha-particles which are of importance for the design of a tokamak reactor, although to a large extent directly connected to the general problems of tokamak physics, require more attention to provide the information needed for designing a tokamak reactor.