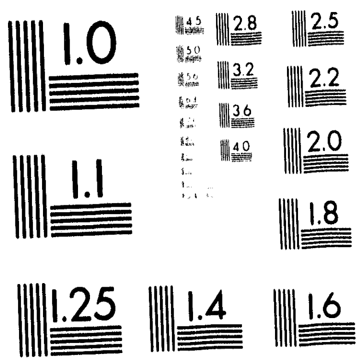
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Summary of the IEA Workshop on Alpha Physics and Tritium Issues in Large Tokamaks

Held During Feb. 17-19, 1993 at the Princeton Plasma Physics Laboratory

C.Z. Cheng, C.S. Pitcher*, B. Stratton, and S.J. Zweben

Princeton Plasma Physics Laboratory
P.O. Box 451, Princeton, New Jersey 08543 USA

* University of Toronto, Downsview, Ontario, Canada

Abstract

A brief summary is presented of the talks given during this meeting, which was held at PPPL and sponsored by the IEA (International Energy Agency) as part of the Large Tokamak Collaboration. These talks are summarized into four sessions: tritium issues in large tokamaks, alpha particle simulation experiments, alpha particle theory, and alpha particle diagnostics.

A) Overall Summary

An IEA Workshop on Alpha Physics and Tritium Issues in Large Tokamaks was held at the Princeton Plasma Physics Laboratory on Feb. 17-19, 1993. The Workshop was attended by about 50 people from outside PPPL, and a total of 40 talks were given over three days.

A major motivation for this workshop was the upcoming D-T experiment on TFTR, presently scheduled for the Fall of 1993. The new features of this D-T experiment involve tritium handling and alpha particle issues (experiments, theory, and diagnostics). This workshop provided a timely forum for discussion of these topics by members of the IEA Large Tokamak Collaboration (TFTR, JT-60U, and JET) and other interested scientists and engineers from the US fusion program.

The talks were organized and into four sequential sessions: tritium issues in large tokamaks, alpha particle simulation experiments, alpha particle theory, and alpha particle diagnostics. The summaries below were extracted from a collection of the viewgraphs presented at the meeting.

B) Tritium Issues in Large Tokamaks

This session was begun by a short talk by **McGuire** (PPPL) on the goals and objectives of TFTR during the DT experiments in FY94. The DT plan is split into a phase I and a phase II. Phase I consists of preliminary experiments, first with trace tritium ($\approx$2%) and then with a limited number of high concentration tritium shots. The technical goals include testing some of the tritium systems, evaluating tritium retention and the effect of 14 MeV neutrons on diagnostics. Physics goals include achieving 5 MW of fusion power, measuring escaping alphas and tritium transport. Phase II consists of more detailed high concentration tritium studies. Technical goals include commissioning of the Tritium Purification System and running 20 high-concentration tritium plasma shots per week. Physics goals include, maximizing fusion power production, evaluating alpha collective effects, alpha transport, and RF heating and pellet fueling of DT plasmas.

Ulrickson (PPPL) gave a summary of deuterium (tritium) retention data obtained from post-exposure tile analysis taken over the last 5 years. He identified three means by which tritium is retained in the vessel: (1) saturation of the near-surface of the graphite (20 nm depth, present on both regions of net erosion and deposition), (2) retention of tritium at radiation damage sites deep in the material, and (3) trapping of tritium in redeposited layers (i.e. co-deposition). It appears that co-deposition is the dominant mechanism for long-term retention of tritium, with 50% being retained on the front surface of the bumper limiter, 20% on the sides of the gaps between the limiter tiles and 30% on the walls of the vacuum vessel. Over a period of 5 years the deuterium retention of the TFTR vessel was approximately 50%. This amount of retention should allow 500 full power beam shots before the in-vessel limit of 2 g is reached (this assumes no attempt at recovering in-vessel tritium).

Andrew (JET) presented a summary of the tritium retention study at JET following the two high concentration tritium shots in November 1991. JET had a large number of means of deducing the rate of tritium exhaust from the vessel, including, sample bottles, ionization chambers, residual gas analyzer, DT neutron rate, and post-exposure analysis of tiles. A number of means were employed to extract tritium from the vessel: (1) deuterium discharges, (2) helium discharges, (3) planned disruptions, (4) deuterium gas soaks, and (5) glow discharge cleaning. All techniques showed rather similar removal efficiencies, although the planned disruptions and the deuterium gas soaks appeared to be particularly effective. Three months of deuterium operation following the tritium experiment reduced the tritium content to 3% of that originally injected into the torus. However, extrapolating the same behavior for TFTR would be risky because (1) the vessel temperature in JET is 300 ºC compared with TFTR's 30 ºC, and (2) the large quantities of beryllium in JET. It is difficult to say whether the situation will be better or worse in TFTR.

Taylor (DIII-D) gave a summary of post-exposure tritium measurements in DIII-D following their recent shut-down ,which started in August 1992. Most of the tiles in the vessel where removed and subjected to a grit-blasting to remove the top 50 μm from the surface, cleaned in an ultra-sonic alcohol bath and baked in vacuum to 1000 ºC. They found that most of the tritium in the tile sits close to the surface (i.e. < 50 μm) and could be thermally released at 1000 C. The highest concentration appears to be in regions of heavy net deposition (as in TFTR), for example, the inner strike point region of the divertor plate (i.e. the outer strike point is a net erosion region).

Caorlin (TFTR) gave results of the most recent He/O_2 glow discharge cleaning on TFTR (100 hours during Nov. 1992). The purpose of the He/O_2 glow discharge cleaning is to remove hydrogen isotopes form the carbon tiles by "etching" the surface with oxygen atoms/ions. Oxygen atoms/ions react with a carbon surface to form CO and CO_2 with a probability of unity. The liberation of carbon from the surface will presumably release the tritium which is trapped in the graphite. The removal rate is initially found to be high (for the first 20 hours) and then levels out to a steady state removal rate. The estimated steady-state carbon removal rate is 0.2 A/s, or 7 µm in 100 hours.

Causey (Sandia-Livermore) presented results from deuterium retention and outgassing experiments with copper samples taken from the NBI ion beam dumps in TFTR. There appear to be two distinct means of trapping deuterium in the beam dumps: (1) a near surface trap which can be released by baking to 400 ºC and probably corresponds to trapping at grain boundaries or within surface impurities (carbon), and (2) deeper traps which can only be released by baking to 800 ºC and beyond and may correspond to the formation of gas bubbles.

Wampler (SANDIA-Albuquerque) presented preliminary results with a new diagnostic proposed for TFTR to detect tritium within the internal surfaces of the vessel (in situ). The detector is essentially a beta particle detector, consisting of a PIN diode, which enters the vessel using the Bay D basement probe drive system. The detector is very sensitive, for example, it has already been used to measure the tritium content on the surface of a TFTR tile removed in January 1989. It may be possible using the horizontal, vertical and toroidal field coils on TFTR to "focus" emitted betas from well defined points within the vessel onto the detector. There are, however, a number of concerns regarding this technique (1) it can only detect the very near surface buried tritium, i.e. < 1 µm deep (this is the range of energetic beta particles in carbon) (2) there may be an interfering background level from the decay of neutron activation.

Skinner (PPPL) described the first results and analysis from the H, D, T alpha emission Fabry-Perot Interferometer on TFTR. The purpose of this diagnostic is to give real-time information on the hydrogenic composition of the boundary plasma and graphite limiter during the DT experiments. The diagnostic will be able to follow the H, D and T content with a time resolution of 100's of ms. Unfortunately, the three spectral lines overlap and a multi-parameter curve-fitting routine must be run to interpret the data. This limits the sensitivity for the minor components, for example, the lower limit on the detection of T amongst a large D background is probably 5%.

Funsten (LANL) presented two relatively new techniques for distinguishing H, D, T, He-3, He-4 known as SENTRI and PEMS. SENTRI stands for Sensitive Environmental Tritium Detector and basically combines ultra-thin foil technology and negative ion mass spectrometry.

PEMS provides simultaneous mass and energy analysis. Such detectors could be used to analyze the torus gas exhaust, the gas holding tank or for post-exposure analysis of TFTR tiles.

Longhurst (Idaho National Engineering Laboratory) presented an overview of tritium-related safety and environmental concerns for TFTR and beyond (i.e. ITER), including issues facing the plasma-facing components, the choice of first-wall and blanket coolant and technologies for processing tritiated gas streams. The role of TPX in simulating the interaction of the plasma with the first-wall components was discussed.

C) Alpha Particle Simulation Experiments

This session was begun by a short talk from **Hawryluk** (Head of TFTR) welcoming the group and introducing them to the TFTR program. This was followed by a comprehensive talk by **McGuire** (PPPL) about the TFTR D-T plan. McGuire discussed the capabilities of TFTR, the TFTR Task Force structure, and the mechanisms of external collaborations. He outlined the details of the planning of the various task forces for the D-T experiments in FY93-94.

The JT-60U group presented four talks at this session. The first was an overview of the present status and future plans of JT-60U by **Nishitani** (JAERI). In addition to their current work summarized below, JT-60U is planning many future activities in the area alpha particle physics, e.g. on the interaction of energetic alphas with LH waves, high-harmonic ICRH heating of energetic ^{3}He beams, TAE mode studies, and confined alpha diagnostics using a He beam. A major effort is the negative ion beam program, which aims to have a 10 MW, 500 keV, 10 sec long beam injected into JT-60U by about 1994. Designs for their proposed machine JT-60SU were described briefly, including a DT option.

Nishitani (JT-60U) described their recent work on triton burnup experiments. The diagnostic was a silicon surface barrier detector measuring 14 MeV neutrons through the Si(n,α) and Si(n,p) reactions. The results were that the slowing-down time of 1 MeV tritons was found to be classical, and the triton burnup rate was found to be in the range 0.2-1%, similar to other triton burnup measurements. This was ≈20-30% smaller than the burnup calculated by the orbit following Monte Carlo (OFMC) code including orbit loss and ripple loss.

Tani (JT-60U) described calculations of the effects of TF ripple on triton burnup in JT-60U. The experiments described by Nishitani (above) were modeled by the OFMC code including NBI distributions. The OFMC predicts burnup ratios which agree well with the experimental data. The degradation of triton burnup is mainly due to ripple losses during triton slowing down. There was no significant difference between the degradation effects of ripple-trapped and banana-drift losses of tritons.

Tobita (JT-60U) described experimental support for OFMC calculations of ripple-induced lost of fast NBI ions in JT-60U. The diagnostics were a fast IRTV camera and thermocouples, which measured the heat flux due to fast ions onto the outer wall of JT-60U. The heat load was localized poloidally and toroidally, and its parametric dependence on q(a) and δ (midplane edge ripple) was described. The calculated heat loss of ripple trapped NBI ions agrees well with these results, including the possibility that the internal and external radial electric field affect the detailed heat loss distribution.

The TFTR talks covered various experimental results concerning alpha particle simulation from the 1992 D-D run. **McCauley** (PPPL) described his thesis work on fast ion diffusion measurements from radial triton burnup studies on TFTR. The diagnostic was a set of 4 vertically viewing ^{4}He neutron spectrometers, which could measure the radial profile of 14 MeV neutron emission and triton burnup. The measured burnup yields were ≈60%-85% of TRANSP predictions, which implies a fast triton diffusion coefficient of D≈0.1 m^2/sec, which would be adequate for alpha confinement in an ITER-sized machine.

Darrow (PPPL) described measurements of fast ion losses in TFTR during ICRF-driven Alfven instabilities. The diagnostic was a set of escaping ion scintillation detectors which can measure loss of ICRH hydrogen minority tail ions. Above ≈3 MW ICRH power an Alfven mode develops which causes tail ion loss in the energy range ≈0.5-1.0 MeV. The loss at 45° below the outer midplane is well correlated with the amplitude of ≈200 kHz magnetic fluctuations, possibly due to TAE modes, and the tail ion loss fraction is estimated to be ≈10% at 11 MW ICRH input power.

Zweben (PPPL) described a search for ICRH tail-ion driven kinetic ballooning modes in TFTR. Theory by Biglari, et al had suggested that trapped minority tail ions could cause KBM modes near the beta limit in TFTR. The experiment showed no signs of such modes, and also showed that the TAE-type activity usually observed at ICRH powers of ≈3-4 MW with hydrogen minority heating appears to be absent when ≥10 MW of NBI is added. Finite banana width stabilization effects could have been the cause of the absence of KBM modes in this experiment.

Zweben (PPPL) discussed anomalous losses of D-D fusion products in TFTR. The diagnostic was a set of escaping alpha scintillator detectors. Normal plasma-driven MHD activity sometimes causes an estimated ≈20-30% loss of confined D-D fusion products during high NBI power Ip=1.4-2.0 MA discharges. A separate anomalous delayed loss process also occurs (without MHD), which increases the total loss to the vessel bottom by ≈2 above the prompt loss. These loss mechanisms are not yet understood quantitatively. Collective alpha instability experiments in D-T should be designed avoid these MHD-induced loss regimes.

Budny (PPPL) discussed experiments and TRANSP calculations of alpha parameters for reproducible long-duration high-performance supershots for the TFTR D-T run. Stable supershots with a predicted $\beta_\alpha(0) \approx 0.3\%$ and ≈1 MW of alpha heating can be created in TFTR without large background plasma MHD. The central electron temperature of such discharges is expected to rise from ≈11 keV to ≈12 keV due to alpha heating. This scenario is being optimized to observe alpha heating in the D-T experiment.

Wilson (PPPL) talked about MHD modes driven by energetic ICRH tails in TFTR. The ICRH system has been operated up to ≈11 MW with hydrogen minority heating, and a fast ion tail is created which can be used to simulate alpha particles. ICRH driven TAE modes have been observed on TFTR above ≈3 MW, which are in general agreement with theoretical predictions. These modes seen in the Mirnov loops and microwave reflectometer at ≈200 kHz, and are accompanied by a significant enhanced fast ion loss, which may contribute to a confinement degradation observed at higher powers (≥5 MW).

Strait (GA) presented an experimental and theoretical description of Alfven eigenmodes in DIII-D high beta discharges. A new type of global Alfven eigenmode, the beta-induced Alfven eigenmode or BAE, has been predicted numerically due to the coupling to sound waves. This mode is consistent with observations of large amplitude Alfven waves appearing as β increases in DIII-D. The observed mode frequencies at high beta agree well with predictions for central BAE modes. The BAE could be an important alpha loss mechanism for TFTR and other D-T experiments.

Heidbrink (Irvine/GA) discussed the saturation of beam-driven instabilities, with application to TAE modes in DIII-D in which up to 70% of beam ions can be lost. A simple model for was used to explain the time dependencies of the neutron rate and magnetic fluctuations, and to infer the damping rate and loss mechanism (resonant loss). The particle loss clamps the fast-ion beta near the marginal stability point, and so linear stability theory is the most important practical issue. Initial analysis indicates that the threshold for BAE activity is 2±1 time lower than for TAE activity in DIII-D.

Cottrell (JET) discussed measurements and theory of ion cyclotron emission during the JET DT experiments. The measured superthermal ICE power was proportional to the neutron flux over 6 orders of magnitude, including pure D and D-T mixes. Multiple IC harmonics of deuterons or alphas are detected from a region ≈20 cm thick at the outer edge of the plasma. Theory and modeling suggests that this is due to a class of fusion products near the trapped-passing boundary which make an unstable ring distribution near the outer edge, creating the ICE.

Arunasalam (PPPL) described theory of ion cyclotron and spin-flip emissions from fusion products in tokamaks. Single particle emissions can account quantitatively for all the observed features of ICE in TFTR. The splitting of the ICE line into doublets is due to the small contribution of the 0-mode riding on the main contribution due to the X-mode. The localized nature of the ICE can be understood from the wave propagation and orbit physics. Thermally excited spin-flip laser emission is fully accessible to the outside receiving antenna.

D) Alpha Particle Theory

The IEA workshop on alpha physics and tritium issues in large tokamaks covered almost all aspects of alpha particle physics theory for burning plasmas: (1) energetic ion/alpha particle effects on global MHD modes (internal kinks, TAE, EAE, BAE modes) and their impact on fast ion/alpha transport, (2) finite beta, continuum damping, and kinetic effects on TAE and KTAE modes, (3) alpha loss due to toroidal magnetic field ripple and global MHD perturbations, (4) ion cyclotron emission (ICE) due to high energy ions and alpha particles. Many practical issues for burning plasmas were discussed. The fast ion/alpha loss to the wall must be small for a fusion reactor, since a few percent of fast alpha loss in ITER would produce large (possibly poloidally localized) alpha power loss to the wall. Therefore, the alpha loss issue is more stringent than the power balance issue.

It was generally agreed that interaction between theory and experiment on alpha physics research has been very close. In particular, steady progress in TAE theory and experiments has been achieved. Fast ion effects on TAE physics were established in TFTR and DIII-D experiments. The outlook is very positive on the future progress of alpha physics due to the scheduled systematic DT experiments on TFTR and the second DT experiments to be scheduled in JET.

A major part of the theory presentations was on TAE and KTAE modes. Comparison between the theoretical calculations from the NOVA-K code and the observed TAE thresholds in TFTR NBI and ICRF experiments were presented [**Fu**]. Theoretical studies of TAE instabilities in JET indicated that TAE modes with n up to 5 can be unstable[**Kerner**]. Experimental effort is now planned to look for TAE instability in JET. A new Alfvén eigenmode was found by DIII-D in high beta operations and is identified as the BAE mode[**Strait**]. Kinetic effects on TAE and KTAE modes were discussed. The thermal ion FLR effect is reported to enhance the damping of the TAE mode and reduce the damping of the KTAE mode[**Sharapov, Rosenbluth**]. But, the TAE mode can easily couple to the fast ion drive, and remains the most viable candidate to be destabilized by fast ions[**Rosenbluth**]. The KTAE mode couples weakly to the fast ion drive and seems unlikely to be driven unstable by fast ions. The consensus is that thermal ion FLR and fast ion drive must be both included in studying the stability of TAE mode even when continuum damping is present. The continuum damping of TAE poloidal harmonic side bands (if occurs) decreases with the toroidal mode number[**Chen, Rosenbluth**]. As the plasma beta increases above the Troyon beta limit, the main poloidal harmonics of the TAE mode will move into the continuum and the TAE mode suffers heavy continuum damping[**Chen, Cheng, Cowley**].

The TAE stability studies for the coming TFTR DT experiments from the numerical solutions of the NOVA-K code were reported[**Cheng**]. The dominant damping mechanism is the thermal ion Landau damping, a result which is also obtained by the gyro-fluid code[**Spong**]. Several TFTR DT operational scenarios were proposed to excite alpha driven TAE instability. A key consideration is to minimize the ion Landau damping by operating in lower ion temperature and beta regime. Another consideration is to operate in the lower electron density regime so that the ratio of alpha speed to Alfvén speed is in the most unstable regime.

In the area of neoclassical theory, effect of TF ripple on the confinement of fast ions was discussed. The numerical studies from the test particle codes can explain the experimental observations of NBI ion loss in JT-60 well[**Tani, Tobita**]. The fusion product loss due to low-n zero frequency MHD mode was studied by an analytically based method of determining stochastic diffusion based on the overlapping condition of particle drift islands[**Mynick**]. The alpha transport due to multiple TAE modes was studied by the ORBIT code and is found to be enhanced significantly over the single TAE mode case[**Hsu**]. The stochastic alpha diffusion threshold of multiple-n TAE mode amplitudes was found to be about one order of magnitude smaller than the single-n TAE mode case. The nonlinear saturation mechanism of TAE instabilities may be related to the strength of the alpha instability source. On the other hand, the gyro-fluid simulation indicated that the TAE saturation is due to the quasi-linear flattening of the alpha profile[**Spong**]. A convective loss mechanism was proposed and seems to be able to explain the fast ion loss during TAE activity in DIII-D well[**Heidbrink**]. The convective nature of the fast ion loss implies that fast particle loss can clamp the fast ion beta even near the marginal stability of the TAE mode and the linear stability of the TAE mode is the most practical issue.

Theoretical explanations on the ion cyclotron emission (ICE) due to fusion fast ions in TFTR and JET are being developed. One explanation is based on the ion cyclotron instability due to non-monotonic velocity distribution which excites waves on fast Alfvén/ion Bernstein branches propagating across the magnetic field with frequencies close to the cyclotron harmonics[**Cottrell**]. Another theory is based on the dressed test particle Trubnikov (X and O mode) spontaneous emissions from the fusion product ions[**Arunasalam**]. The Trubnikov emission calculations seem to be able to account quantitatively all the observed features of ICE. Other theories attempting to explain the ICE observation were not presented in the meeting.

E) Alpha Particle Diagnostics

Stratton (PPPL) described the Alpha-CHERS diagnostic being developed to observe lower energy confined alphas (thermal to 0.5 MeV) during D-T operation of TFTR. Charge exchange excited emission from alpha-neutral beam interaction is observed as a broad wing on the thermal He^+ 4686 Å line. Energetic ^3He ions produced by ICRF heating were observed with energies up to 400 keV with an initial single channel system. The temporal and spatial behavior of the signals were as expected for this RF heating case. An upgraded 6 spatial channel system is being installed for D-T operation of TFTR.

Herrmann (PPPL) talked about two new escaping alpha detectors for use during the TFTR D-T run. The first is a moveable probe with a head containing a stack of 10 1 μm thick nickel foils which would be exposed to escaping alphas during a D-T shot and later removed for analysis. This detector offers the possibilty of improved energy and pitch angle resolution compared to existing lost alpha detectors. Also discussed was the use of a radiation-hardened photodiode detector in the existing probe assembly to perform pulse-height-analysis of the lost alphas.

McChesney (General Atomics) showed initial results from the Alpha Charge Exchange diagnostic on TFTR. Confined alphas are neutralized by charge exchange in the ablation cloud of an injected impurity pellet (lithium or carbon), escape the plasma, and are detected by a neutral particle analyzer. Energetic ^{3}He ions produced by ICRF heating were successfully observed and their energy distribution was found to be in good agreement with the predicted distribution for this case. The observed spectrum of slowing down 1 MeV tritons produced in beam-heated discharges was found to be consistent with a classical slowing down spectrum.

Machuzak (MIT) discussed a possible collective Thomson scattering diagnostic ("gyrotron scattering") for confined alphas in TFTR. The gyrotron scattering diagnostic originally planned for TFTR would have operated at 200 kW RF power; however, this project was canceled. A lower power version (0.2-1.0 kW) in which an enhanced scattered signal is observed at the lower hybrid resonance has been proposed for TFTR.

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