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M.L. Sawley and M.Q. Tran

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Centre de Recherches en Physique des Plasmas

Association Euratom - Confédération Suisse

Ecole Polytechnique Fédérale de Lausanne

21, av. des Bains, CH-1007 Lausanne/Switzerland

The 1984 International Conference on Plasma Physics (1984 ICPP) was the third in a series of the biennial joint session of the Kiev International Conference on Plasma Theory and the International Congress on Waves and Instabilities in Plasmas. As for the previous two conferences, Nagoya 1980 and Göteborg 1982, the scope and participation at the Lausanne conference was very broad. Its scientific programme included more than 450 papers, 50 of these being presented as invited talks. More than 400 participants from 35 countries attended the conference.

Many of the papers presented at the 1984 ICPP were of direct interest to the fusion community. However, the main emphasis of this conference series is to provide a forum for the complete spectrum of current plasma physics research. Indeed, the content of the papers

presented - encompassing the whole range of plasma phenomena in environments as different as that of a fusion device to the plasma of interstellar space - illustrated how broad the field of plasma physics has become. The chairman of the 1984 ICPP, F. Troyon, emphasized at the closing session of the 1982 Göteborg conference the need for interchange of ideas between the various branches of plasma physics. In particular, he stressed the important role that "basic" plasma physics must play in current fusion research. It was on this principle that the organization of the 1984 ICPP at Lausanne was based.

It is not the intention of the present report to summarize all recent results and trends in plasma physics, as was observed at the conference. Clearly, such a task would be not possible in the limited space available. We therefore present here a review of only a selection of papers directly related to fusion-oriented research, which emphasize the current status of this branch of plasma physics.

Contributed papers of the conference were compiled into two volumes of proceedings distributed to participants. Invited papers are to be published by Euratom-Fusion.

Tokamaks

The physics of hot plasma in fusion research is now moving into a new era with the operation of JET and TFTR. A. Gibson (Culham) in the first invited talk entitled "Resistively heated plasma in JET: characteristics and implications" traced the evolution of the performances of JET which, at the time of the conference, had reached an energy

confinement time of $\tau_E = 0.35$ s, a temperature larger than 2 keV and a density greater than 2×10^{13} cm⁻³. Work is in progress to improve the relatively high level of impurity ($Z_{\text{eff}} \sim 4$). In the longer term, JET's objectives are to study the confinement and heating of plasmas in a machine, the dimension and parameters of which approach those necessary for a reactor. In his presentation, Gibson discussed the global requirements for the onset of ignition in JET. For a confinement time of $\tau_E \geq 1.3$ s, the required power (≈ 41 MW) and β value ($\approx 6.5\%$) should be within the capability of the JET design. Near-ignition in JET imposes a limit on the tolerable decrease in τ_E in the presence of additional heating: any decrease in the value of τ_E scaled from present ohmic values must be less than a factor of two. A comparison between the required τ_E and various scaling laws indicates that JET with additional heating must come within a factor 1 to 3 of the Asdex H mode scaling or improve by a factor four on Goldston L mode scaling. The uncertainties in major physics issues will be examined in the first three phases of JET operation, with progress to the fourth phase (operation with a deuterium-tritium mixture) dependent on the outcome of the earlier ones.

The Princeton Plasma Physics Laboratory (PPPL) tokamak programme, as reviewed by H. Furth, is directed towards answering some of the major questions raised in the fusion programme. Furth's discussion reported not only on the physics issues but also on their technological implications. The main objectives of the PPPL tokamak program were stated as: (1) exploration of the physics of high temperature toroidal confinement, in TFTR; (2) maximization of the tokamak beta value, in PBX; and (3) development of reactor-relevant rf-techniques, in PLT.

The main test bed for ohmic heating research at PPPL is currently the TFTR device. Energy confinement has been studied at currents up to 1.5 MA and magnetic fields up to 2.7 T - about half the machine design levels. TFTR has confirmed the cubic size dependence of the energy confinement time required for "neo-Alcator" scaling. The maximum value of τ_E attained was ~ 0.3 s. Furth noted that since confinement phenomena in auxiliary-heated tokamaks is complex, the investigation of the ohmic heating regime may be the simplest approach to understanding basic tokamak transport phenomena. The adiabatic compression capability of TFTR is particularly promising in the study of free-expansion transport.

The decrease of τ_E in non-ohmic regimes leads to the question of high beta limits: is it due to "orthodox MHD modes" or some "anomalous high beta mechanism"? This question leads naturally to the discussion of tokamak configurations with good MHD stability properties. The bean experiments (PBX) have just begun operation and show that at low beta the bean shape can be formed. High beta experiments using 7 MW of neutral beam injection will provide within the year a significant test of its stability. Of particular importance is its favourable potential to enter the second stability region and operation at high beta free from MHD modes. In the effort to keep the impurity level low, satisfactory operation with pumped limiters, in PDX, and rotating pumped limiters, in PLT, have been reported.

Recent experiments on PLT have used 200 kW of lower hybrid waves at 800 MHz to ramp up the current to nearly 100 kA. These experiments showed that the problem of induced back currents, especially by the hot electron component, can be successfully avoided. The extension to

a higher density regime is foreseen with the installation of a 2.8 GHz, 1.5 MW lower hybrid system. Both ICRH and ECRH are installed on PLT. For the former method, 6 MW of 30 MHz heating power to the minority ^3He ions and 1.5 MW at 80 MHz for second harmonic heating of hydrogen will be investigated. ECRH will be studied with 400 kW at 60 GHz. The principle objectives of the ECRH system are to assist in the initiation of a purely rf-driven current and to optimize the radial T_e profile.

The understanding of MHD activity and its influence on β limits were addressed in two invited papers. In his review entitled "Observations of finite β MHD phenomena in tokamaks", K.M. McGuire (Princeton) presented a comprehensive review of MHD activity occurring in various tokamaks. Of great importance is the result on the β limit. Available experimental data from ISX-B, PDX, and D-III, operating in various regimes (limiter discharges, expanded boundary, gettered limiter discharges, H mode divertor), show that the Troyon ideal β limit is approached but not exceeded. The experiments indicate that this limit is defined by the onset of a major disruption. MHD fluctuations at high β are dominated by the $n = 1$ mode when the $q = 1$ surface is in the plasma. Toroidal and non-linear coupling drive respectively $m \neq 1$, $n = 1$ and $n > 1$ modes. High frequency broadband fluctuation of the poloidal magnetic field may be responsible for the deterioration of the confinement at high values of β . In the H mode, edge relaxation phenomena were correlated with a decrease in the particle and energy confinement times as observed in ASDEX, PDX and D-III.

On theoretical grounds, the question of the β limits was addressed by Degtyarev (Moscow). Using a code that combines hybrid finite

elements in the flux coordinate and Fourier series in the poloidal angle, and a two-step β optimization, it was shown that the maximum β values obtained were much larger than found using previous techniques. Defining β^C as the limiting value of β for stability of all ideal modes, it was shown that for an INTOR-like plasma, β^C is determined essentially by ballooning modes. In his paper, Degtyarev discussed the effect of the shape of the plasma cross-section on the β limit. For elongated and triangular plasmas, toroidal destabilization of external kink modes is suppressed, allowing a considerable increase in β^C . While indentation of the plasma to form a bean shape results in increased ballooning mode stability, simultaneously there occurs a strong destabilization of kink modes. Increasing the indentation therefore does not result in an increased value of β^C .

The "Nature of disruptions" was discussed at the conference by L. Laurent (Fontenay-aux-Roses). In this paper, experimental data from TFR was compared to the results of other tokamaks and to existing theories in an attempt to give a complete as possible picture of the events occurring during a disruption. During both major and minor disruptions, the destabilization of several modes (e.g. $m = 3, n = 2$; $m = 5, n = 3$) makes the magnetic field lines ergodic and leads to a flattening of the electron temperature at the edge. The plasma centre may also be affected depending on the radius of the ergodic zone or the onset of the $m = 1, n = 1$ instability. Transition from minor disruption to major disruption is accompanied by an enhancement of the growth rates of many modes: modes $m = 4, 5, 6, \dots, n = 2, 3, \dots$ grow to large value (0.5% of the poloidal field) in less than 0.1 ms. In the subsequent quenching of the current, the magnetic energy is dissipated in the plasma core and is transported to the edge by parallel conduction along ergodic lines.

There were many papers presented at the conference which reported on the use of waves for plasma heating and current drive. These showed the continued interest in a wide spectrum of wave types.

Electron cyclotron heating has been applied to both tokamaks and stellarators. As described by V.S. Strelkov (Kurchatov) in his paper "ECRH and plasma transport in the T-10 Tokamak", an electron temperature increase of 3 keV, with a central electron temperature of 4 keV, has been obtained at a deposited power of 0.9 MW. The waves were launched from the low field side with 70% of the power in the ordinary mode. The decrease in τ_{Ee} , the energy confinement time of the electron component, can be explained by a dependence of the type τ_{Ee} proportional to $\langle T_e \rangle^\alpha$ ($\alpha \approx 0.5 - 0.7$), in accordance with the T-11 scaling. Varying the toroidal field and the q at the plasma edge changes only weakly the energy confinement time compared to central heating. This enables the possibility of heating at high density ($n_e(0) > n_{critical}$) where the ion component can be heated through Coulomb heat transfer. Finally, since ECRH allows precise control of the location of the energy deposition, the electron temperature profile $T_e(r)$ can be modified, leading to the stabilization of the $m = 2$ mode, when the power is deposited near the $q = 2$ surface.

Lower hybrid heating and current drive are by now well-proven methods. The results of ion heating studies conducted on the Petula B tokamak were presented by G. Melin (Grenoble). The operating frequency was 1.25 - 1.3 GHz and power levels of up to 830 kW during 50 ms have been applied. The high density range over which good heating was observed is relatively limited: $5 \times 10^{13} \text{ cm}^{-3} < n_e < 6 \times 10^{13} \text{ cm}^{-3}$. At higher densities, a decrease in the figure of merit $n_e \Delta T_{i0} / P_{rf}$

was observed, from its maximum value of 4×10^{13} to about 2.5×10^{13} eV/cm³ kW at $n_e \approx 8 \times 10^{13}$ cm⁻³. This decrease was attributed to a lack of thermalization of the fast ions. At high rf power levels, a dominant increase in heavy ion impurities (iron) was observed. This effect does not depend on the grill material (either titanium or stainless steel), which indicates that the impurities come from the limiter and/or the walls. A large increase in light ion impurities (oxygen) was observed when the grill was moved radially closer to the plasma, which raises the important question of the optimum grill location.

The theory of current drive by lower hybrid waves was addressed in a paper presented by J. Vaclavik (Lausanne). In the model described, the evolution of the electron distribution depends in a self-consistent way on collisions, Cerenkov interaction, the anomalous Doppler effect and a loss term. Both the Cerenkov and Doppler diffusion coefficients depend on the wave spectrum, which is also described self-consistently taking into account the source term. The calculation has elucidated the important question of the influence of the power source spectrum on current generation.

Recent developments in the study of Alfvén wave heating in the TCA tokamak were described by G.A. Collins (Lausanne). A large reduction of the metallic impurities has resulted from a change in the design and material of the antennae and limiters. The electron density increase which is observed during the rf pulse has persisted despite the improvements in plasma purity. This density increase, while making comparison of heating in different regions of the wave spectrum difficult, does allow the observation of the abrupt changes in the macro-

scopic parameters which occur when a new Alfvén resonance surface appears at the centre of the plasma. These recent studies have shown that both ion cyclotron effects and toroidal mode coupling must be considered to model correctly the presence of the resonance surfaces and hence infer the energy dissipation profile.

Stellarators

A comprehensive survey of stellarator research was given by H. Wobig (Garching), with emphasis placed on currentless operation in the two largest existing experiments, Wendelstein VII-A and Heliotron E. While plasmas without ohmic heating currents have been produced in stellarators in the past, recent experiments have enabled net current-free operation in a high density and high temperature regime ($\bar{n} < 10^{14} \text{ cm}^{-3}$, $T_i < 1 \text{ keV}$).

A variety of heating methods have been studied, however the most encouraging results to date have been achieved using neutral beam injection. The target plasma in Wendelstein VII-A was produced by ohmic heating, with attention given to controlling the total rotational transform to avoid tearing modes during the transition to the currentless phase. In Heliotron E, currentless operation could be achieved by using an ECR heated target plasma. In the currentless phase, there are no tearing modes as occur in ohmically heated discharges; the density limit is determined therefore by power balance rather than by disruption.

In his paper, Wobig pointed out the importance of recent β limit studies. High β values ($\bar{\beta} = 2\%$) have been obtained in Heliotron E with neutral beam injection. In this regime, sawtooth oscillations are observed which are explained to be the result of interchange ballooning modes arising around the $q = 1$ surface. A change in the pressure profile by enhanced gas puffing can lead to a quiescent state without these oscillations.

In currentless plasmas, a doubling of the energy confinement time ($\tau_E \sim 10\text{-}20$ ms) and nearly an order of magnitude improvement of the particle confinement time ($\tau_p \sim 50\text{-}100$ ms) compared to ohmically heated plasmas has been observed. Studies on Wendelstein VII-A show a strong dependence of the confinement time on the rotational transform, with deep minima observed around $q = 1/2$ and $1/3$ but regions of optimum confinement close to these values.

Electron cyclotron heating has been applied to the Heliotron E, Wendelstein VII-A and L-2 stellarators at power levels up to 200-400 kW. ECRH predominately heats the electrons ($T_e < 0.5 - 1.4$ keV, $T_i < 0.1 - 0.3$ eV) although an energetic tail of fast ions has been observed indicating some direct wave-ion interaction. A detailed report of the recent ECRH experiment on Wendelstein VII-A was given at the conference by R. Wilhelm (Stuttgart). Waves were launched (linear polarized TE_{11} or HE_{11} mode) with 0-mode polarization from the low field side, with the non-absorbed fraction being reflected back to the plasma from the high field side with X-mode polarization. An increase in central electron temperature, with respect to direct irradiation of the gyrotron modes (mainly TE_{02} mode corresponding to a 50% 0-mode and 50% X-mode mixture), from 0.7 keV to 1.2 keV was observed. However,

there was only a slight increase of the heating efficiency (from 40% to 50%). Wilhelm therefore concluded that the expected conversion of the X-mode into Bernstein waves at the upper-hybrid layer does not contribute to bulk plasma heating, possibly due to local absorption of the Bernstein waves caused by a macroscopically turbulent structure around the upper hybrid layer.

Ion cyclotron heating experiments have been recently conducted on the Uragan III torsatron, at power levels of 2 MW, resulting in an ion temperature $T_i < 500$ eV. Wobig pointed out that the natural divertor of Uragan III offers the opportunity of studying impurity control in an rf-produced plasma. High power ($P < 3$ MW) ICRH experiments are planned for Heliotron E to supplement previous studies at lower power levels.

Two new stellarator experiments are under construction: Wendelstein VII-AS (Garching) and ATF-1 (Oak Ridge). It is anticipated that these devices, which both plan to begin operation in 1986, will extend the present parameter regime to temperatures of several keV. The Wendelstein VII-AS design, an upgrade of Wendelstein VII-A, incorporates two novel features: an improved magnetic field configuration which leads to a reduction in the Shafranov shift and hence to a higher β limit; and the use of modular twisted coils instead of helical windings. The ATF-1 device is of a torsatron design, in which the strong shear plays a major role in plasma stabilization. Investigation of high β equilibrium ($\beta < 8\%$) are planned.

Wobig concluded his presentation by noting that there still remain unsolved problems that may be decisive for stellarators as an

alternative fusion concept. In particular he mentioned:

- The increase in impurity radiation during neutral beam heated discharges is a threat to steady state operation in stellarators. Although, in general, neoclassical theory gives a reasonable fit to experimental data, the theory of impurity diffusion in stellarators is far from complete and must include additional effects before extrapolation to future experiments is possible.
- Localized particle trapping in mirrors along the field lines leads to strong losses which in the reactor regime could exceed neoclassical losses of an axisymmetric system by two orders of magnitude.
- The β limit in stellarators is a crucial point for its viability as a reactor. Only when sufficient agreement between numerical code calculations and existing experiments is obtained can extrapolation to future devices be made.
- Modular coil systems need to be developed which fulfill the necessary requirements for a fusion reactor design.

Tandem mirrors

With the introduction of the tandem mirror concept, a major improvement over conventional mirror systems was made in axial confinement, as both predicted by theory and confirmed by experiment. The new issue in mirror research is that of the competition between radially and axially directed particle losses. In the paper "Physics issues in mirror and tandem mirror systems", R.F. Post (Livermore) reviewed the present status of the theory of these transport processes. Emphasis was placed on two main categories: (1) the generation and control of

ambipolar confining potentials and their effect on axial confinement; and (2) the combined influence of non-axisymmetric magnetic fields (used to ensure MHD stability) and electric and magnetic particle drifts on radial transport.

In the absence of other perturbing influences, ion-ion collisions limit the axial confinement of plasma in a conventional mirror machine. However, enhanced axial loss may result from fluctuations arising from high frequency instabilities, in particular, the drift-cyclotron loss cone mode and the Alfvén ion cyclotron mode. Although the means for stabilizing these two modes are different, results from the tandem mirror TMX-U at Livermore show that both can be stabilized by the creation of a hot plasma in the mirror plugs using a combination of angled beam injection (producing "sloshing ions") and ECRH. Post showed that with the introduction of the "thermal barrier" concept in tandem mirror research, a substantial increase in the confining ambipolar potential can be achieved over that of a simple tandem mirror, even if the central cell density is greater than that of the plugs. He therefore concluded that it is possible in principle to reduce axial losses to a negligible level, so that radial losses become the controlling factor in confinement.

In considering the problem of radial particle transport, Post noted that, in contrast to a closed toroidal system where cross-field particle transport must be ambipolar in nature, in a tandem mirror the dominant radial loss is expected to be non-ambipolar ion transport balanced by axial electron losses. In non-axisymmetric mirror cells, such as those in present-day tandem mirrors, quadrupole magnetic wells closely coupled to the central cell distort the symmetry of that

cell. Since azimuthal particle drift velocities are therefore not constant in azimuth, bounce-drift harmonic resonances can occur leading to enhanced radial transport. Estimates of the radial loss times given by Post based on an approximate analytical theory show that lifetimes resulting from resonant radial diffusion may be comparable to axial lifetimes in present day and fusion tandem mirrors. In addition, Post pointed out the need to minimize azimuthal electric fields (which may arise, for example, from azimuthal variations in the intensity of the ECRH power used in creating a thermal barrier) to avoid enhanced radial transport. Concluding his paper, Post mentioned three means by which radial transport could be reduced: (1) by the use of "choke coils" to decrease the density of particles in the azimuthally varying plug fields, (2) the presence of concentric plates at the outer ends of the tandem mirror to control radial electric fields which can induce electric drifts, and (3) the use of higher-order multipole fields in the plugs.

Many of the points raised in the paper by Post have been investigated experimentally in the TMX-U thermal barrier tandem mirror device. A summary of recent results was given by W.C. Turner (Livermore). These include the demonstration of the formation of microstable sloshing-ion distributions, end plugging with a density larger in the central cell (up to $2 \times 10^{12} \text{ cm}^{-3}$) than the end plug and measurement of the axial potential profile in the thermal barrier. Hot electrons have been created in the thermal barrier region by ECRH using linearly polarized X-mode radiation at a frequency of 28 GHz for both fundamental and second harmonic resonance heating. A 42% heating efficiency has been achieved, increasing the average β of hot electrons to 15%. Ion cyclotron heating was used for bulk heating of the central cell

ions. Using a two-loop, electrostatically shielded antenna, a perpendicular ion temperature of 1.5 keV was achieved, with a heating efficiency of 40%.

Turner reported that the experiments on TMX-U showed the necessity of both sloshing ions and fundamental ECRH in establishing end plugging. The axial ion confinement increased from 5~20 ms to 50~100 ms during strong end plugging. The radial ion confinement time was ~100 ms for moderate central cell potentials, but dropped to 5~15 ms when potentials reached extreme values. The radial transport was found to be independent of end plugging, however a two-fold increase in the radial confinement time was obtained by using electrically floating end plates to reduce the magnitude of the central cell potential above ground. In order to reach the goal of a central cell density of $2 \times 10^{13} \text{ cm}^{-3}$, future experiments on TMX-U will concentrate on additional ICRF heating, improving the efficiency of the neutral beam heating and central cell vacuum and increasing the radial extent of the potential control plates.

Reversed Field Pinches

With the development of reversed field pinches having long toroidal current pulse duration (HBTXIA at Culham and ZT-40(M) at Los Alamos), it has been observed that the reversed field configuration can be maintained for times much longer than calculated decay times due to field diffusion. There must therefore be present a "dynamo" mechanism, associated with plasma fluctuations, which sustains the configuration and controls transport. An important objective of cur-

rent reversed field pinch research is the investigation of models for the dynamo effect that are consistent with the nature and level of observed fluctuations. Papers which addressed this problem were presented at the conference by H.A.B. Bodin (Culham) and R.W. Moses (Los Alamos).

At present, a number of theoretical models exist to explain the sustainment of the reversed field configuration, each providing some way of driving the necessary azimuthal currents at the reversal surface. The theories propose various modifications of the classical Ohm's law, which cannot describe the occurrence of the observed steady state currents, either with additional terms which apply locally or by a global Ohm's law. Only in a few simple cases have the underlying mechanisms been definitely identified experimentally. The investigation of fluctuations in reversed field pinch experiments is a subject of active interest, as witnessed by the presentation of several contributed papers on this topic at the conference. Definite information has been obtained on a variety of unstable modes, including dominant global $m = 1$, $n \sim 8$ modes, global $m = 0$ modes and localized fine scale activity in the core of the discharge. However, attempts to explain the origin of these modes, their contribution to the dynamo effect and to transport are at present somewhat speculative. Both Bodin and Moses concluded that more detailed fluctuation data is needed before a complete understanding of reversed field pinch equilibria, sustainment and transport is obtained.

Rotamak

A novel method of creating and sustaining compact torus equilibria was described by I.R. Jones (Flinders Uni.). In the rotamak device, a rotating magnetic field is used to drive the toroidal plasma current. Equilibrium is provided by the presence of an externally applied "vertical" magnetic field.

In his paper, Jones described in detail the basis of the rotamak scheme: the rotating magnetic field method of driving plasma currents. This technique, which does not depend on coupling to a particular plasma wave, both creates the target plasma and drives the plasma current by providing a directed (toroidal) electron motion (the ions remaining essentially stationary). In recent experiments, currents of greater than 1 kA have been driven reproducibly for ~35 ms forming an oblate compact torus configuration. No obvious gross instabilities have been observed in the rotamak equilibria: the termination of the current pulse coincides with the end of the rotating field pulse. Future experiments will investigate the global energy balance in the rotamak discharges.

Concluding Remarks

Many additional papers directly related to fusion research were presented at the 1984 ICPP. As was made evident by the papers presented at the conference, despite the steady gain of knowledge and experience in fusion research, all areas of current interest contain basic underlying plasma physics phenomena that still need to be

resolved. It is in this effort that the concept of a broad field that is plasma physics becomes not only useful, but essential to future development. Links between different branches need to be retained and strengthened if an effective interchange of ideas is to be utilized. It is hoped that this conference series has and will continue to provide the necessary forum for such an interchange. The next International Conference on Plasma Physics will be held in Kiev, USSR.