MEETING REPORTS

SUMMARY OF THE COURSE AND WORKSHOP ON BASIC PHYSICAL PROCESSES OF TOROIDAL FUSION PLASMAS, VARENNA, ITALY, AUGUST 26–SEPTEMBER 3, 1985

The Course and Workshop on Basic Physical Processes of Toroidal Fusion Plasmas, organized by the International School of Plasma Physics, Milan, Italy, was directed by R. Bickerton [Joint European Torus (JET), United Kingdom], B. Coppi (Massachusetts Institute of Technology, United States), L. Kovrizhnykh (Academy of Sciences, USSR), P. Rutherford (co-chairman, Princeton Plasma Physics Laboratory, United States), and M. Yoshikawa (Japan Atomic Energy Research Institute). The course and the workshop were attended by about 80 scientists coming from Canada (1), Denmark (1), Federal Republic of Germany (11), France (3), Italy (13), Japan (5), Libya (3), Mexico (1), Poland (2), Sweden (1), Switzerland (3), United Kingdom (1), United States (18), USSR (2), JET (13), and Commission of European Communities, Brussels (2).

During the course sessions 24 lectures were presented by 17 speakers. Their main aims were the following:

1. to review and discuss the experimental results of the present toroidal devices for plasma confinement, making explicit reference to operating tokamaks [JET, Axially Symmetric Divertor Experiment (ASDEX), Tokamak Fusion Test Reactor (TFTR), T-10, FT-1, FT, Doublet III] and stellarators (Wendelstein VII A, Heliotron-E, L-2)
2. to give an exhaustive theoretical basis of the physical models that are used to tackle and discuss the experimental evidence, starting from basic concepts to the last attempts or failures in understanding plasma behaviors.

Within the course, two days were devoted to tutorial sessions. Almost 20 invited papers and 10 short contributions concerning peculiar aspects of the latest experimental results and the efforts toward their theoretical interpretation were presented during the workshop and were the basis for discussions. In particular, three topical discussions were devoted to (a) anomalous ion thermal conductivity (B. Coppi, chairman), (b) numerical simulations of transport (D. Duechs), and (c) β limits (P. Couture). Finally, an exhaustive summary of the conclusions of the course and the workshop sessions was presented and discussed by P. Rutherford, with emphasis on the encouraging and discouraging aspects of the actual status of toroidal fusion plasma physics.

CONFINEMENT AND TRANSPORT IN TOKAMAK EXPERIMENTS
(Bickerton, Goldston, Wagner, Yoshikawa, Wolfe)

Some general remarks concerning the confinement properties of tokamak plasmas were made.

1. Large tokamaks (JET, TFTR, JT-60 first operations) have been operating in high parameter-ohmic regimes: plasma currents up to 5 MA (JET), energy confinement times up to 1 s (JET), peak electron temperatures up to 5 keV (JET), and peak ion temperatures up to 3 keV (JET, TFTR).

2. "Neo-Alcator" scaling for ohmic confinement has been reproduced in high-density, pellet-fueled discharges (Alcator C, TFTR); on the other hand, a systematic confinement study, performed on JET, has shown a weak dependence of τ_E on the line average electron density ($\tau_E \propto \bar{n}^{0.4}$).

3. High-power auxiliary heating methods [$P_{aux} \leq 8$ MW of neutral injection (NI) in Doublet III, $P_{aux} \leq 6.3$ MW of NI in TFTR, $P_{aux} \leq 5$ MW of ion cyclotron resonance (ICR) heating in JET] clearly deteriorate the plasma energy confinement; Goldston's scaling for the L-mode approximately reproduces this negative feature of additional heating regimes.

4. High-performance tokamaks (TFTR, ASDEX, JET, Alcator C) show that ion thermal transport is sometimes stronger than that foreseen by the neoclassical theory; moreover, by peaking the density profile during pellet fueling on Alactor C, χ_i has decreased to the neoclassical value.

5. Edge plasma conditions play a major role in the determination of global transport and confinement.

CONFINEMENT IN AUXILIARY HEATED TOKAMAKS
(Cordey, Furth, Golant, Goldston)

A common feature of neutral beam injection (NBI), ICR, electron cyclotron resonance (ECR), and lower hybrid (LH) heating methods seems to be the deterioration of confinement with increasing auxiliary power. On the other hand, to date LHH and ECRH experiments have been performed only with powers $\lesssim$1 MW, not sufficient to formulate any definite conclusion. During neutral beam (NB) heating, good confinement regimes (H-mode on ASDEX) have been repetitively obtained in divertor configurations.

During NBI Operations

In TFTR, a maximum auxiliary power of 6.3 MW has been injected in the plasma; in high-density ($n \sim 2 \times 10^{14}$ cm^{-3}), pellet-fueled discharges, the plasma-stored energy has increased linearly with P_{tot}, while a real degradation of confinement, with respect to the ohmic case, has been observed. The empirical τ_E scaling seems to be related to $\chi_E(r)$ at the plasma edge while $J(r)$ and $T_e(r)$ profiles are determined by resistive magnetohydrodynamic (MHD) modes in the bulk plasma. Different power deposition profiles [narrow for ohmic heating (OH), flat for NBI, hollow for pellet + NBI] lead to the same $T_e(r)$ shape (profile consistency).

In ASDEX, up to 3 MW of NB power have been injected in the plasma; in general, NBI leads to the degradation of confinement properties ($\tau_E^{NB} \approx 25$ ms) with respect to ohmic operations ($\tau_E^{OH} \approx 70$ ms), following L-regime scaling. In H-regime, no confinement degradation has been found [$\tau_E^{NI}(H^+) \approx 120$ ms]. Experimentally, H-regimes are possible in diverted configurations only [ASDEX, Poloidal Divertor Experiment, Doublet III], under conditions of carbonized walls. A lower plasma-wall interaction than in L-phase, the inaccessibility of H-mode in the presence of dirty wall conditions, and the need of a quite high edge temperature characterize the onset of H-regimes: an edge "thermal barrier" develops, leading to steep T_e, n_e gradients at the plasma boundary and reducing the power outflow.

During ICR Heating

In JET, preliminary data show an L-mode behavior if the coupled power is entirely absorbed by the plasma: $\tau_E \propto \bar{n}^{0.4}(IB/P_{aux})^{0.6}$; during the heating Z_{eff} remains constant and no special impurity problem arises.

In ASDEX, only the L-mode is obtained, possibly because impurities cool the edge too much.

During LH Heating

In Alcator C, where a maximum LH power of ≈ 1 MW has been injected, a reduced global energy confinement and an enhanced metallic impurity content have been observed.

In Petula B ($P_{LH} \leq 700$ kW), a high heating efficiency ($\bar{n}\Delta T_i/P_{LH} \approx 4$ eV $\times 10^{13}$ cm$^{-3} \cdot$kW^{-1}) has been obtained, while a deterioration of confinement with P_{LH} was observed together with an enhanced impurity content.

During ECR Heating

In T-10 ($P_{EC} \approx 1$ MW, $f_{EC} = 83$ GHz), for on-axis resonance, the energy content increases with increasing auxiliary power, independently of plasma current ($I_p \approx 180 \div 500$ kA). For off-axis resonance, at high plasma current ($q_L \approx 3$) the energy content increase ΔW does not change, moving the resonance up to 20 cm from the center, while at lower I_p a degradation of ΔW occurs for small shifts. The stabilization of $m = 2$ modes was achieved when the ECR was located just outside the surface $q = 2$; electron cyclotron (EC) power of 200 kW was sufficient for the stabilization.

In FT-1, the heating was observed to be efficient up to three times the theoretical cutoff density for the inside launch; reflections could play an important role.

BOUNDARY PHENOMENA IN TOROIDAL CONFINEMENT
(Duechs, Lackner)

Two comprehensive lectures on the interaction between edge plasma and limiters or target plates were presented, showing the theoretical and numerical procedures presently used to study the relevant problems. It seems that impurity levels in large tokamaks can be controlled and limited; although no theory of H-modes is available, diverted configurations exhibit relative superior performances.

NONAXISYMMETRIC TOROIDAL CONFINEMENT EXPERIMENTS
(Iiyoshi, Ikegami, Renner)

Promising experimental results on energy confinement during auxiliary heating have been obtained on Heliotron-E and Wendelstein VII A stellarators. In Heliotron-E, characterized by a high rotational transform and a high shear, up to 500 kW of EC power, 3 MW of NB power, and 500 kW of ion cyclotron (IC) power were injected; EC waves form the plasma and increase the electron temperature up to 2.5 keV; then, to increase the ion temperature, NBs or IC waves are injected. A high-density plasma is obtained with pellet injection during the NB pulse: in such conditions a global energy confinement time of ≈ 40 ms has been obtained. Transport analysis of ECRH plasmas and OH plasmas show that the local electron thermal conductivity is a linearly increasing function of the drift parameter. Furthermore, it is seen that, in the ECRH plasmas, only at the periphery does the radial profile of χ_e sensitively depart from the neoclassical one. Finally, in high-β experiments, two different regimes of operations have been identified: a quiescent (Q) regime ($\bar{\beta} \approx 2\%$), characterized by a flat n_e profile and no sawtooth activity, and a sawtoothing (S) regime ($\bar{\beta} \approx 1.5\%$) where fluctuations are detected and profiles are more rounded.

In Wendelstein VII A, perpendicular NBs (up to 400 kW) and EC waves (at 28 and 70 GHz up to 200 kW) have been injected to form and heat a currentless plasma. In NI operations, a maximum central $\beta \approx 1\%$ has been obtained at $n_0 \gtrsim 10^{14}$ cm^{-3} and with $\tau_E \approx 10$ ms; the highest β values were observed for $\iota \simeq 0.45$. In ECRH operations, a better confinement has been obtained at larger magnetic fields ($\tau_E \approx 10$ ms). In both cases, the presence of a small current ($I_p \approx 2 \div 4$ kA) turns out to avoid strong deterioration of confinement at the rational values of $\iota(a)$. Best confinement is approximately described by the neoclassical theory except for the boundary region, where it deteriorates. During auxiliary heating, a radial electric field (300 to 1000 V/cm) produces a poloidal rotation that can strongly reduce the transport coefficients.

Finally, it has been observed that off-axis EC wave injection leads to flat density and temperature profiles, showing no tendency toward definite shapes.

MHD STABILITY OF TOKAMAKS
(Okabayashi, Overskei, Sato, Schlueter, Troyon)

The theory and the numerical investigation of the existence of a maximum pressure that can be confined in a tokamak were presented. The extrapolation of Troyon β-limit scaling to reactor-size tokamaks seems quite pessimistic; on the other hand, Troyon limit well describes the operational maximum β values for auxiliary heated tokamaks

[Princeton Beta Experiment (PBX) (3%), Doublet III (≤4.5%), ASDEX (≤1%)]. Pinches have reached higher β values (up to 10% in TPE – 2 and Torus II). Distorted sawteeth and large amplitude $m = 1$, $n = 1$ oscillations have been observed in all auxiliary heated devices at high β values; furthermore, $n > 1$ activity arises close to the predicted β limit. In Doublet III, β limits turn out to be always disruptive and possibly to coincide with either ballooning mode or kink mode limits. In PBX, during fast current ramp operations ($\dot{I}_p \gtrsim 1.5$ MA/s), $\beta \gtrsim 5.3\%$ has been obtained in sawtooth-free discharges; this value was reached with 4 MW of NB power and with an indentation of 20%. A strong beneficial effect of bean-shaped configuration on fishbone activity has also been observed.

MHD STABILITY OF STELLARATORS

(Boozer, Holmes, Kovrizhnikh)

The theory of equilibrium, stability, and transport in nonaxisymmetric toroidal devices was reviewed and discussed with connections to relevant experiments [L-2, Advanced Toroidal Facility, JIPP-II, Wendelstein VII A, Heliotron-E]. Stellarators are more stable against current-driven modes than tokamaks (no disruptions), but pressure-driven modes can determine the maximum β values. A compromise solution between equilibrium and stability requirements suggest that A (aspect ratio) = 6 ÷ 10, M (periodicity) = 10 ÷ 14, $\iota(a_p) \approx 1$ should give a stable plasma with $\beta(0) \approx 10 \div 15\%$. In these conditions the plasma can reach the "second stability" region.

RESISTIVE PROCESSES IN TOROIDAL CONFINEMENT

(Alladio, Robinson, Rutherford, Wesson)

Standard models of sawtooth instabilities cannot explain the sawtooth behavior observed in large tokamaks. During current rise in JET, an $m = 1$ oscillation usually precedes the sawtooth. Furthermore, flattop phases in JET are characterized by "giant" sawteeth accompanied by "postcursor" but no "precursor" oscillations; the typical excursion of the electron temperature due to the sawtooth ranges from 15% (in ohmic discharges) up to 30 to 50% (during ion cyclotron heating) of the central temperatures. The observed collapse time (≈ 100 μs) is much shorter than the Kadomtsev time ($\approx 5 \div 10$ ms): A rapid thermal quench occurs with no reconnection.

In TFTR discharges, three types of sawtooth activity have been observed: simple sawteeth, small sawteeth, and "compound" sawteeth; compound sawteeth consist of (a) a small normal sawtooth with precursor activity, (b) a subordinate sawtooth with successor oscillation, and (c) a large main sawtooth, sometimes accompanied by successor oscillations. The occurrence of compound sawteeth seems to be associated with relatively flat or hollow current density profiles.

A systematic investigation of the operational limits of FT tokamak was presented; typical observations are:

1. large amplitude $m = 2$ tearing modes without sawteeth, at low density ($q_L \gtrsim 3$)
2. the presence of $m = 2$ tearing modes with sawteeth, at low q_L
3. disruption preceded by the disappearance of sawteeth, at intermediate density ($q_L \approx 3$)
4. high-density disruption accompanied by D_α radiation enhancement.

Finally, it has been pointed out that appropriate schemes of injection of radio-frequency (rf) in tokamak plasmas can be useful to suppress resistive modes; in particular, the deposition of rf power on the resonant surface (both to heat locally and to generate a noninductive current), by modulating the rf pulse in phase with the island poloidal rotation, seems to be a valuable method.

MICROINSTABILITIES AND ANOMALOUS TRANSPORT IN TOROIDAL CONFINEMENT SYSTEMS

(Coppi, Perkins, Stringer)

There is an almost general agreement that the strong turbulence ($\Delta\omega_k \approx \omega_k$) existing in tokamaks is responsible for the observed anomalous χ_e; strong turbulence techniques have recently been developed but have not led to a coherent description. Experimentally, the measured values of $\tilde{n}$ are in agreement with the drift wave turbulence theory, but no clear relationship to anomalous transport has been found; in most tokamaks estimated losses, due to $\boldsymbol{E} \times \boldsymbol{B}$ drifts, exceed those predicted from $\tilde{B}_r$.

The solution of a simplified system of equations, describing the heat transport in the presence of drift wave turbulence, gives χ_e scalings in agreement with empirical laws. Ignition experiments have to be performed at high toroidal magnetic fields (10 to 12 T) and high densities (2×10^{15} cm^{-3}).

In conclusion, fluctuation measurements are required on large tokamaks.

PHYSICS OF FUSION BURNING PLASMAS

(Coppi, Sigmar, Strachan)

In present-day tokamaks, energetic fusion products behave classically; an analysis performed on TFTR and Princeton Large Torus (PLT) has shown that deuterium-deuterium (D-D) products are well confined, while 15-MeV protons, coming from D-$^3_2$He reactions, are not contained. Anomalous confinement of D-D products is found when low q sawteeth (PLT), $m = 2$ activity, or fishbones (TFTR) are present.

The β limits for ballooning modes can be degraded in the presence of a significant pressure of α particles. A kinetic analysis of ballooning modes for $\omega \lesssim \bar{\omega}_{D_\alpha}$ (bounce-averaged precession drift frequency) shows that a slowing down distribution function is strongly unstable; furthermore, a high plasma temperature ($T_e > 20$ keV) is unfavorable to stability; both predictions come from the enhanced fraction of α particles that fall in the energy range of the drift resonance.

Finally, it was pointed out that ignition conditions, in a compact toroidal machine, are achievable by means of ohmic heating alone.

The proceedings of the course and workshop will be available in early 1986; for relevant information write to: Prof. E. Sindoni, International School of Plasma Physics, Via Celoria 16, 20133 Milano, Italy.

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