MEETING REPORT

SUMMARY OF THE IAEA TECHNICAL COMMITTEE MEETING ON TOKAMAK PLASMA BIASING, MONTREAL, CANADA, SEPTEMBER 8-10, 1992

CONFERENCE SITE AND PARTICIPATION

The first International Atomic Energy Agency (IAEA) Technical Committee Meeting on Tokamak Plasma Biasing was held at the Radisson Gouverneurs Hotel in Montreal, Canada, from September 8-10, 1992. This conference was sponsored jointly by the IAEA and the Centre Canadien de Fusion Magnetique (CCFM). The latter operates the Tokamak de Varennes (TdeV), a research program that strongly emphasizes electrostatic biasing of its plasma.

This meeting attracted a total of 43 registrants: 12 from Canada, 17 from the United States, and 17 from outside North America; a few of these had multiple affiliations. These registrants represented 11 countries and 28 different research laboratories. The three-day meeting included a total of 34 oral papers, consisting of 30-min contributed papers and 45-min invited papers, including time for discussion. These 34 papers were presented by authors from nine countries; 8 papers were from Canadian laboratories, 15 from U.S. laboratories, and 11 from research groups outside North America. Of these 34 papers, 8 were theoretical or computational,and 26 reported experimental results on the biasing of tokamak or other plasmas.

The conference arrangements allowed plenty of opportunity for socializing and conversations during lunch and the morning and afternoon coffee breaks. The city of Montreal was celebrating the 350th anniversary of its founding, and thus, it was appropriate that a very enjoyable banquet for the conference participants was held in a 300-yr-old inn in the historic district of Montreal on Wednesday evening.

On Tuesday evening, September 8, the conference participants toured the TdeV, located in Varennes, a suburb of Montreal, which is operated by the CCFM on the very impressive site of the Hydro Quebec research facilities. The parameters of TdeV are as follows: $B_T = 1.5$ T, $R = 0.866$ m, $a = 0.27$ m, $I_p \leq 240$ kA, $T'_{e0} = 1000$ eV, $T'_{i0} = 600$ eV, and $\bar{n}_e = 3 \times 10^{19}/\text{m}^3$. The CCFM is a joint venture of Hydro Quebec, Atomic Energy of Canada Limited, and the Institut National de la Recherche Scientifique (INRS). Hydro Quebec is the provincewide electric utility of Quebec and provides ~40% of the financial support for the TdeV experiment, making the TdeV probably the only tokamak experiment in the world that is receiving substantial support from an electric utility, its ultimate user. By the standard of tokamaks of moderate size, the TdeV is very well supported with utilities, staff, office and laboratory space, and plasma diagnostic equipment. This tokamak has found an important niche in the world fusion effort in its pioneering electrostatic plasma biasing experiments, which were reported at this meeting.

TERMINOLOGY AND JARGON

Not surprisingly, this new field of research has produced some terminology and jargon with which other plasma physicists may not be familiar. Terms used at this conference include the following:

1. *Magnetoelectric confinement* is the use of a combination of magnetic and electric fields to improve confinement, and possibly to heat a plasma. Gross confinement of the plasma is provided by a background magnetic field—usually a tokamak configuration at this conference. The plasma confinement is improved by applying radial electric fields normal to the plasma, which can do work on the plasma to push it inward against the density gradient while at the same time producing a heating effect from E/B azimuthal drift. In the papers presented at this conference, magnetoelectric improvements as large as a factor of 10 in number density and confinement time were reported for some toroidal devices; the heating effect of radial electric fields produced deuterium ions with kinetic temperatures as high as 2500 eV as a result of thermalized E/B drifts; and bulk plasma heating at a level of 3 MW was reported in DIII-D.

2. The *separatrix* is the surface that separates open from closed magnetic flux surfaces and, when particles follow magnetic field lines, is just beyond the last closed flux surface.

3. The *last closed flux surface* (LCFS) is the last toroidal surface on which long-term confinement can be expected. Outside the separatrix, magnetic flux surfaces are open and come in contact with other structures on the wall including the divertor plates.

4. The *scrape-off layer* (SOL) is a region of high density gradients at the edge of the plasma, which results either from the presence of the separatrix or the presence of a limiter at the plasma edge. Most papers at this conference were concerned with phenomena in and around the SOL of tokamak plasmas.

5. The *limiter* is a solid surface in contact with the edge of the plasma, which defines the plasma edge, thus producing

an SOL. Several papers discussed the effects of biasing the entire plasma by connecting direct current (dc) power supplies to a limiter. Limiters have the disadvantage of introducing impurities at the plasma edge.

6. A *divertor* is an arrangement of magnetic flux surfaces at or just beyond the separatrix, which is created by special coils to divert the radially diffusing edge plasma toward cooled collector plates at some distance from the main plasma. At such a remote location, the effect of the divertor in introducing impurities is greatly reduced. Several tokamaks described at this meeting were biased by putting dc potentials on the collector plates in the divertors of the tokamak plasmas described.

7. *Edge-localized modes* (ELMs) are time-varying, usually propagating, disturbances at the edge of the plasma that are not the result of instabilities in the plasma core. As their name suggests, they are localized at the plasma edge. These ELMs are characteristically fluctuations in density or electrostatic potential that propagate at the edge with the local E/B drift velocity.

8. *Orbit squeezing* describes the effect of electric fields on banana orbits in formulating a neoclassical theory of radial diffusion in plasmas with strong radial electric fields. The effect is to distort the banana-shaped orbits, usually by squeezing them closer together, thus affecting the neoclassical transport coefficients. There was much evidence at this conference, however, that radial transport processes at the edge of electric-field-dominated plasma are not describable by any classical binary diffusion theory.

9. The *E/B Mach number* describes the ratio of the E/B drift velocity at the plasma edge to either the ion or electron thermal velocity at the same location. Some authors at this meeting even referred to "subsonic" or "supersonic" flow with respect to this "Mach number."

10. The *L mode* (low-confinement mode) is the usual or first-observed confinement state of tokamaks, usually associated with limiter operation.

11. The H *mode*, (high-confinement mode) is a state of improved confinement in which containment times are approximately twice that of the L mode, usually associated with divertor operation.

NEW PHYSICS

Because this is the first conference devoted to the subject and also because the physics of magnetoelectrically contained plasmas is not widely taught in universities and is thus unfamiliar to most workers in magnetic fusion research, some of the physical processes that may be responsible for some of results reported in the papers at this conference are briefly summarized here.

Until recently, the dominant approach to magnetic fusion research has been the use of pure magnetic containment to confine a plasma long enough to be of fusion interest. This approach has a fundamental drawback in that a static magnetic field cannot do work on a charged particle, and thus, an attempt to confine a plasma in a static magnetic field is ultimately doomed to failure since an investigator can only stand by and watch as the confined plasma is transported toward the walls by the operation of the second law of thermodynamics. The addition of radial electric fields to a magnetically confined plasma introduces the possibility of doing work on a plasma, as was shown by several papers at this conference. This work, which can be provided by relatively inexpensive dc power supplies, can manifest itself in charged-particle transport inward against the density gradient with concurrent improvements in density or containment time; the work done on the plasma can also manifest itself in heating the ions and electrons by E/B drift.

Experimental evidence emerged at this meeting, from multiple sites, that magnetoelectric confinement of a toroidal plasma was possible by biasing the entire plasma to a high dc potential. In the various biasing schemes, one electrode was usually a limiter or the collector plates of a divertor, and the other electrode was the grounded walls of the vacuum vessel in which the plasma was confined. These biasing schemes characteristically produced a toroidal plasma with an electric field along the minor radius of the plasma that varied from tens of volts to several kilovolts per centimetre. Although this was the first conference on magnetoelectrically contained toroidal plasmas, the use of magnetoelectrically contained plasmas has a long history in open-ended devices such as the Penning discharge and tandem mirrors.

As mentioned earlier, one major beneficial effect expected from magnetoelectric containment of a toroidal plasma is strong plasma heating due to E/B drift around the minor circumference of the toroidal plasma. The drift velocity acquired in crossed electric and magnetic fields is given by

$$v_d = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} = \frac{E}{B} \ , \tag{1}$$

and the kinetic energy of particles due to this E/B drift is, therefore,

$$E = \frac{1}{2} m v_d^2 = \frac{1}{2} m \frac{E^2}{B^2} \ . \tag{2}$$

Equation (1) states that ions and electrons both drift in the same direction with equal drift velocities, thus greatly reducing the opportunities for polarization, charge separation, and polarization-induced instabilities. This drift velocity is independent of the sign of the charge, the mass of the particle, and the particle energy. Equation (2) contains the interesting result, for fusion applications, that the energy from the dc power supplies, which maintain the radial electric field, is fed preferentially into the ion population to an extent given by the mass ratio between the ions and electrons. Some evidence for this preferential ion heating was presented in which the data showed a factor of $\sim$100 difference between the ion and electron kinetic temperatures in a magnetoelectrically contained toroidal plasma. Evidence for such E/B heating also appeared in many other papers at this meeting, which reported particle thermal velocities approximately equal to the E/B drift velocity. To produce deuterium ion energies on the order of kilovolts, radial electric fields of >3 kV/cm are required, values that were beyond the reach of most of the biasing experiments reported here.

A second potential advantage of magnetoelectric confinement is the ability to do work on the plasma and thus to slow down the outward radial diffusion of ions and electrons from the plasma interior. With sufficiently strong radial electric fields, it may be possible to reverse the radial transport and achieve inward transport of ions or electrons against the density gradient. Several papers produced clear-cut evidence of slowing down or reversal of the radial transport in the form of containment times and number densities as much as a factor of 10 higher than that of the unbiased plasmas or plasmas biased to the opposite polarities.

Magnetoelectrically contained plasmas are usually extremely turbulent at their edge. Evidence was presented that when radial electric fields were sufficiently strong, binary particle collisions were no longer the dominant method of radial transport. Other mechanisms, such as fluctuation-induced transport, became the dominant mechanism. Several authors reported electron number density profiles in the SOLs in which the density declined linearly with radius or in which the radial profiles had a positive second derivative. In such profiles, the divergence term of the continuity equation must be zero (in the case of a linearly decreasing profile) or making a positive contribution of particles to the plasma edge (in the case of a positive second derivative). When the diffusion term of the continuity equation, which contains the second derivative, is zero or contributing particles to the plasma volume rather than removing them, this is a definitive indication that other, nondiffusive processes are dominant and must be maintaining the steady-state particle balance.

PRESENTATIONS

The conference program began on Tuesday morning, September 8, with an invited paper by M. Tendler of the Alfvén Laboratory of the Royal Institute of Technology, Sweden. The author discussed the effects of unbiased, naturally occurring electric fields and currents induced by biasing and turbulence in tokamaks. This theoretical paper was concerned with the effects of biasing on closed field lines in toroidal devices with transport in the vicinity of the separatrix and with the convective transport in the SOL. Tendler discussed a theory for the transition between the L and the H mode that derived a relation between the radial current and the poloidal rotational velocity that was said to be in reasonable agreement with the currents induced by biasing in tokamak plasmas. Equations governing the radial profiles of poloidal and toroidal rotation indicated that in the L mode, conductive and convective contributions to transport are both important. Tendler concluded that steep radial density gradients are associated with strong radial electric fields, that large radial electric fields are usually highly sheared, and that shear is beneficial for confinement.

The second paper was by R. R. Weynants et al. from the Royal Military Academy, Belgium, who presented an overview of recent experiments in the Tokamak Experiment for Technology-Oriented Research (TEXTOR) by means of a biasing electrode protruding inside the limiter. Weynants reported that biasing improved the electron number density and confinement time in this experiment. The plasma was biased to levels of ± 1 kV, and the radial electric field at the SOL increased with biasing voltage. The maximum value of the radial electric field was 1000 V/cm just inside the limiter radius. Plasma floating potentials of up to ± 600 V were reported, indicating bias to at least these values. Weynants et al. looked at the confinement of various impurity species in the TEXTOR plasma, and they found that the sign of the radial electric field has an important influence on confinement, that large amplitude fluctuations of number density and potential occur at the plasma boundary, and that the radial transport is a function of the phase angle between the density and potential fluctuations. These are characteristic features of fluctuation-induced transport.

In the third paper, J. J. Zielinski reported for the Advanced Toroidal Facility (ATF) group at Oak Ridge National Laboratory (ORNL). Most of their experiments biased the ATF plasma to positive potentials of 120 V. They found that this improved the particle containment time, but no significant improvement of the energy containment time resulted. Biasing to these levels had little effect on the impurities in the ATF plasma. The positive bias increased the average electron number density by a factor of 2 in the plasma core, however, and changed the sign of the naturally occurring radial electric field at the plasma edge.

In the fourth paper, M. A. Pedrosa and her colleagues at EURATOM/CIEMAT, Spain, reported on the effects of electric fields on the edge turbulence in the TJ-1 tokamak. The focus of this research was to study changes induced by fluctuations on the edge radial electric fields. They observed that the nature of the turbulence changes near the natural velocity shear layer. They used a biased electrode inserted from the top of the containment vessel with up to ± 500 V potential, and they found that the electrode current increases to ~ 50 A at 100 V, with both positive and negative polarity, and then decreases after 100 V of positive or negative bias. This behavior of current with bias voltage was consistent with observations on several other machines that were capable of biasing their plasmas to potentials above a few hundred volts and therefore above the natural plasma potential. Pedrosa et al. observed a peak in edge fluctuations at 350 kHz at a bias voltage of ~ 150 V for both polarities. This peak frequency became more prominent with higher bias voltages. They were able to observe changes in both edge and global plasma parameters as a result of biasing.

The fifth paper was presented by M. Ono of Princeton Plasma Physics Laboratory (PPPL), who reported on an emissive limiter bias experiment for improved confinement of tokamaks performed on the Continuous Current Tokamak (CCT) at the University of California–Los Angeles (UCLA). The object of these experiments was to see whether a radial electric field can be created inside the plasma by charging up the surface layers with electrons emitted from an emissive probe. With a heated cathode, a transition to the H mode was observed for bias voltages less than -150 V and injection currents >30 A. With a cold or less emissive cathode, a more negative bias voltage is required for the transition from the L to the H mode. Only negative biases were applied to the probe in this experiment to ensure electron emission. It was found that the magnitude of the radial electric field had a linear dependence on the bias voltage for a fully emissive cathode.

The sixth paper was presented by K. K. Jain from the Institute for Plasma Research, India, who reported observations of improved behavior by electrode biasing of a toroidal plasma. This was one of several papers reporting biasing of plasmas other than tokamaks. The Basic Experiment in Toroidal Assembly (BETA) experiment was a simple axisymmetric torus biased by a fine wire across the minor diameter of the plasma. This plasma contained no poloidal magnetic field, no axial currents, and no rotational transform. This discharge was quasi-steady, lasting ~ 1 s, and the toroidal magnetic field had values up to 0.1 T. Positive bias up to 63 V was applied, and the average electron number density in the plasma increased, while the fluctuations in electron number density decreased. An asymmetric, double-sided probe was used to measure flow velocities, and these indicated a poloidal flow. Positive biasing of the electrode raised the potential from negative to positive values. The radial electric field in this experiment ranged from ~ 5 to 20 V/cm.

The seventh paper of this conference was given by J. Reece Roth, University of Tennessee, who described the electrostatic biasing and radially inward fluctuation-induced transport in a magnetoelectrically confined bumpy toroidal plasma. These experiments were done on the U.S. Aeronautics and Space Administration (NASA) Electric Field Bumpy Torus (EFBT) between 1972 and 1978, and this paper contained some previously unpublished results. Positive and negative potentials as high as 50 kV were applied to electrodes that drew currents as high as 20 A. Radial electric fields >1 kV/cm were observed in as far as half the plasma minor radius. The very strong E/B drift velocities, which formed rotating spokes as a result of the diocotron instability, raised deuterium ions to kinetic energies of >1 kV. This experiment was operated in the steady state, and up to 150 kW of dc power was fed into the plasma during these experiments. Unlike many other experiments, the plasma was confined, heated, and sustained entirely by magnetoelectric effects, with no electron cyclotron resonance, ohmic heating currents, or other plasma-generating mechanisms in play. This experiment demonstrated the ability of a magnetoelectrically confined plasma to heat ions to kinetic temperatures >1 keV and also demonstrated the dominance of fluctuation-induced transport at the plasma edge. It was found that when the radial electric field pointed into the plasma (negative bias) *and* when the phase angle between density and potential fluctuations had the proper value, radially inward transport of ions against the density gradient was possible. Like many other biasing experiments, it was also found that negative bias greatly improved the number density and containment time, by factors as large as 5, when compared with positive plasma bias, for which the fluctuation-induced transport was always radially outward.

The eighth paper was by A. Mase and his colleagues at the Plasma Research Center of the University of Tsukuba, Japan, who described potential control and fluctuation studies in the GAMMA-10 tandem mirror. In this experiment, the effect of a radial electric field on low-frequency waves and instabilities in the GAMMA-10 mirror was studied by biasing annular electrodes in the end plates of this mirror machine, which were in contact with the plasma. The fluctuation level was observed to have a maximum value when the radial electric field was essentially zero but decreased with increasing radial electric field regardless of the sign of the electric field. As the radial electric field increased, the root-mean-square amplitude of electron number density fluctuations decreased, and the particle containment time in the experiment increased.

The ninth paper was from the Maryland Theory Group at the Laboratory for Plasma Research and was presented by P. N. Guzdar. Guided by the experimental observations on tokamak edge plasmas that the anomalous flux of particles and energy have a strong poloidal asymmetry, the authors identified the drift resistive ballooning mode as the likely candidate for causing transport in the edge region. Three-dimensional simulations of the nonlinear Braginskii equations showed that these modes can give rise to anomalous particle transport that has a strong poloidal asymmetry, with three to four times higher transport on the outside. Furthermore, these fluctuations and the asymmetric transport can drive poloidal shear flows.

The tenth paper was presented by Y. Uesugi and colleagues from Nagoya University, Japan, who discussed the response of the edge plasma potential during radio-frequency limiter biasing in the HYBTOK-2 tokamak plasma. An attempt was made to modify the radial electric field by limiter biasing at the edge of the plasma in this small research tokamak. An unusual feature of this experiment was that the biasing potential on the limiter was alternating current (ac) and operated at a variable frequency, from 1 to 100 kHz, limiter currents of up to 60 A, and maximum voltage up to 100 V. The plasma potential of the entire tokamak plasma follows the biasing potential up to tens of kilohertz. The amplitude of the driven fluctuations decreases as the frequency increases. The change in potential due to ac bias appears throughout the plasma volume, and the change in radial electric field approaches 90 V/cm as the frequency goes to the low end of the range. At the high end of the range, the radial electric field decreases to values of ~30 V/cm in the vicinity of 70 kHz. The oscillating radial electric field in this experiment (as opposed to the potential) does not penetrate very deeply into the plasma, no more than ~1 cm.

The 11th paper of the conference was by S. Sasaki and colleagues, also from Nagoya University, Japan, who described edge density profile measurements during limiter biasing by laser blowoff lithium beam probing, also on the HYBTOK-II tokamak. Data were taken on the electron number density profiles, using this diagnostic, under conditions for which the bias voltage was ~60 V and the bias current was ~40 A. Radial profiles of the electron number density at the plasma edge, with a spatial resolution of millimetres, revealed electron number density profiles with no second derivative during biased operation. These profiles showed a linear decrease in electron number density with radius, implying that the diffusive term, which contains the second derivative of the electron number density in the continuity equation, must be zero. This was one of several indications that diffusive processes resulting from binary collisions were not the dominant form of radial transport in the plasma regions investigated.

The 12th paper of the conference was presented by Z. Wang and a colleague from CCFM, who presented a theoretical paper on neoclassical transport in tokamaks with large electric fields. This was an attempt to modify conventional classical diffusion theory beyond the assumptions of neoclassical transport, to account for the effects of radial electric fields. A radial diffusion coefficient was derived in the plateau and banana regimes that considered, among other factors, rotation speeds at the edge of the tokamak plasma. The theory included a squeezing factor intended to account for the changes (compression) in banana width that result from radial electric fields. Radial electric fields of <50 V/cm were predicted in the ohmic heating regime of tokamaks, and it was further predicted that in the H mode, radial electric fields up to 150 V/cm should be observed. This theory was compared with results from the TdeV with agreement that was said to be good.

The 13th paper was presented by J.-L. Lachambre and colleagues from CCFM, who presented extensive results on current injection and plasma biasing in the TdeV. Measurements were made on the plasma edge with actuated Langmuir probes in the outboard equatorial plane and from the top of the plasma, and spectroscopic measurements were made in both the major tangential direction and in a cross-sectional plane of the plasma. The current injection experiments on TdeV consisted of electrical current flowing along a drift surface, usually the separatrix, from one electrode to another; for example, from the bottom divertor to the top divertor. The *I-V* curves for current injection resemble those of a double Langmuir probe. It was found that there was no significant change in the plasma parameters, no change in the SOL, and the current distribution was typically no more than ~1 cm thick. The plasma biasing experiments on TdeV were more interesting. The divertor plates at the top and bottom of the chamber were biased with respect to the wall, producing a radial electric field at the plasma edge proportional to the biasing voltage. The TdeV was limited in these experiments to biasing voltages no larger than approximately ±130 V by arcing, but within this range, the radial electric field barely reverses with negative bias on the electrodes. The bias current is proportional to the global average electron number density, and the *I-V* curve for positive and negative biasing goes through zero: i.e., the current flowing to the biasing electrode is zero when the bias voltage was zero. For both polarities, there was a significant reduction in microturbulence. The electron number density profile at the plasma edge has a negative second derivative, suggesting that binary diffusional processes may still be dominant at the edge of this plasma. Biasing has an effect on the poloidal rotation velocity, reported by many other investigators, and also has an effect on the *toroidal* rotation velocity, a measurement that seems to have been made by very few other groups. It was concluded that biasing allows control over the radial electric field outside the separatrix, and this in turn allows some control over impurities, the global plasma density, and the levels of plasma turbulence at the plasma edge.

The 14th paper was by L. Schmitz from the Institute of Plasma and Fusion Research, UCLA, who reported an $M = 1$ divertor bias experiment carried out in collaboration with PPPL on the PBX-M tokamak. In these experiments, the outboard divertor plates in a double-null configuration were biased with respect to the inboard plates. Bias voltages of ±70 V have been applied so far. A radial electric field of −25 V/cm was seen inside the LCFS without biasing, increasing to values as high as −60 V/cm when the outboard plates were biased positively. For a positive bias voltage as low as 25 V, the neutral beam power required to access the H mode was substantially reduced (by 35%). No changes in the line-averaged plasma density were observed. Depending on the bias polarity, the plasma was exhausted preferentially through the upper or lower divertors as a result of $E_r \times B_t$ drifts in the SOL. The electron number density profiles at the plasma edge had a positive second derivative, suggesting that some form of classical binary collisional diffusion was not dominant in this plasma.

The 15th paper at this conference was presented by W. Choe and colleagues from the PPPL, who described a proposed experiment on electron ripple injection in the CDX-U plasma. This electron ripple injection concept is intended to create a radial electric field in a nonperturbing way by injecting energetic electrons radially into the plasma, where they are trapped on a drift surface and build up a radial electric field. This concept utilizes an externally provided magnetic field ripple and electron cyclotron heated electrons. Ripple coils and the resonant cavity have been installed. Preliminary results confirm the inward electron drift due to the field ripple.

The 16th paper of the conference was presented by Y. B. Kim and a colleague from the University of California-San Diego, who described the effects of neutral beam injection on poloidal rotation and heat conduction in tokamaks. This paper was concerned with the theory of the edge region of tokamaks and addressed the question of whether the drift velocities observed near the edge of tokamaks can be described by a simple neoclassical theory. An example was presented in which the poloidal rotation expected theoretically was −2 km/s, but the experimental measurements indicated velocities of 10 to 20 km/s in the opposite direction. Kim et al. concluded that the rotation cannot be described by neoclassical theories at the edge of tokamaks. They examined five theories of the poloidal rotation in tokamaks, most of which predict increases in the poloidal rotation velocity at the transition from the L to the H mode. These velocities have been measured in many experiments by the Doppler shift, and experimental data are available from the JFT-2M experiment, the DIII-D experiment, and the Axially Symmetric Divertor Experiment (ASDEX). The ion drift velocity at the edge of these experiments is equal to the *E/B* drift velocity, a result consistent with many other experiments reported at this meeting.

The 17th paper of the conference was presented by B. L. Stansfield and colleagues from CCFM, who presented data on toroidal velocities measured in the edge plasma during biasing of the TdeV. In this experiment, velocities around the major circumference of the torus were measured with a so-called "gundestrup" probe, which has collecting surfaces pointing in various directions radially outward from a circular array at the end of a probe. The collecting surfaces only are exposed to the plasma, thus making it possible to plot the flux of incident particles impinging on the probe from various directions in a plane normal to the probe axis. These measurements of the particle fluxes were supplemented with spectroscopic data taken tangential to the equatorial plane of the TdeV plasma. With positive bias, the direction of toroidal rotation is along the main toroidal magnetic field, opposite to that of the ohmic heating current. The direction of toroidal rotation changes to the opposite value with negative bias of the plasma. Typical values are that with a positive bias of 150 V, the toroidal velocity is 40 km/s. With −150 V applied, the toroidal velocity is 15 km/s in the opposite direction. This was observed when the radial electric field varied from −20 to +50 V/cm, and good agreement was seen in all cases between the *E/B* drift velocity and the observed poloidal drift velocities in the plasma. It was found that the toroidal velocity decreases as one goes radially inward to the center of the plasma.

The 18th paper of the conference was presented by N. Hawkes and a colleague from the JET Joint Undertaking, United Kingdom, who described edge poloidal rotation measurements on the Joint European Torus (JET). This experiment did not report the results of biasing experiments but simply the "natural" characteristics of the edge region in the JET tokamak during H-mode operation. These results, therefore, provide a point of comparison for other experiments on biased plasmas. They found no evidence of changes in the shape of the ion temperature profile on transition from the H to the L modes, but they did see clear-cut evidence of the formation of a particle transport barrier in the H mode. They saw no sign of poloidal rotation with a diagnostic that allowed them to see rotation as high as ±5 km/s, but their diagnostic would not allow them to detect the presence of a rotating layer with 1-cm thickness and speed of 15 km/s. They saw no evidence of poloidal rotation in either the L or the H mode under these limits.

The 19th paper was presented by M. J. Schaffer and colleagues from the General Atomics DIII-D group, who reported on edge effects during DIII-D biasing. In this large tokamak experiment, an electrically insulated axisymmetric ring electrode was installed on the bottom of the vacuum vessel at the divertor flux interception point, which allows flux surfaces in the vicinity of the separatrix to be biased by up to ±1 kV with respect to the grounded vacuum wall. The biasing currents used in these experiments as the potential was changed varied from −12 to +8 kA, and no significant radial leakage of this current was reported. The biasing of this plasma led to an "$\boldsymbol{E} \times \boldsymbol{B}$ plasma pump" that produces a major vacuum pumping effect comparable in magnitude with the deuterium gas flow into the system. A negative bias on this divertor during the H mode reduces the global electron number density and increases the plasma temperature. The bias of this electrode increases the electron number density at the plasma edge and shields against impurities.

The 20th paper was a theoretical study by M. E. Rensink and colleagues from Lawrence Livermore National Laboratory, who reported on simulation of the DIII-D divertor biasing with the LEDGE code. This code uses a fluid model in which the convection velocity includes E/B drifts and toroidal flow along $\boldsymbol{B}$. Many computer generated plots of convective flow patterns were shown to illustrate E/B drifts in the edge region of the DIII-D plasma. A conclusion of the study was that cross-field fluxes have a strong effect on the plasma profiles at the divertor plates.

The 21st paper was presented by R. Marchand and colleagues from INRS Energie et Materiaux, Canada. This paper was a theoretical study using a computer program that included a contribution from anomalous mobility. It attempted to model the plasma edge during biasing experiments on the TdeV experiment. Although this was only a one-dimensional model, it apparently reproduced well the toroidal rotation velocities and the *I-V* curves resulting from biasing. Further work on this model is planned, which will include the effects of momentum conservation and recycling of plasma.

The 22nd paper was presented by B. Terreault and colleagues from the CCFM TdeV team, who discussed hydrogen, carbon monoxide, helium, and neon pressures in a biased tokamak. The motivation of this paper was the prospect of active control of divertor particle and power loads by neon injection. In experiments on the TdeV, they found that negative bias steepens the radial electron number density profile at the plasma edge and that the fluxes to the limiter increase with any biasing. They found that, contrary to *limiter* biasing, negative divertor plate biasing improves density control. Strong particle retention in the divertor chamber resulted, e.g., up to 80% retention of injected neon.

The 23rd paper was presented by G. M. Staebler and colleagues from General Atomics, who reported on a bias-sustained shield plasma in the DIII-D tokamak. Using the axisymmetric ring electrode at the bottom of the DIII-D vacuum vessel described in paper 19, Staebler and his colleagues were able to modify the impurity content of the DIII-D plasma and inject up to 3 MW of heating power into the edge plasma in this major tokamak experiment. This was the highest power level achieved in any of the plasma biasing experiments reported at this conference. This power input created a layer of hot electrons at the outer surface of the plasma, a bias-sustained "shield plasma." With negative bias up to 600 V, the width of the edge plasma increased by a factor of 2 to 3, and the electron number density in this layer also increased by a factor of 2 or 3.

Paper 24 was presented by E. Haddad and colleagues from CCFM, who described the effect of divertor plate biasing on impurity levels and transport in TdeV's central plasma. For C III, O V, O VII, and Ne IX, biasing to either positive or negative potentials (±130 V) reduced the intensity of these species over the natural or zero biased state of the plasma. However, soft X rays, total radiation from bolometers, and Z_{eff} increase (decrease) with positive (negative) biasing. This apparent contradiction is explained by the increase (decrease) in the inward velocity with positive (negative) biasing. This inward velocity is related to the electric field in the outer region of the plasma. In summarizing their results, this group felt that the impurity levels were reduced in the central plasma as a result of a reduction in the impurity source term at the plasma edge.

In the 25th paper, R. J. Taylor from UCLA discussed deep bias experiments and material probing on the CCT and the Texas Experimental Reactor (TEXT) tokamaks. The CCT is located at UCLA, and TEXT is at the University of Texas. This paper summarized comparative results made by probing the edge plasma in both of these devices. In the CCT, asymmetries exist in the direction along and opposite the magnetic induction. There was evidence in this tokamak that the information flow about ions, electrons, and waves is asymmetric along a field line. A directional probe with one surface conducting and the other insulated was biased to ion saturation and used to probe for asymmetries of plasma flow along the field lines. The Mach number, the ratio of the E/B drift velocity to the thermal velocity, was >1 in the direction along a magnetic field line in these experiments. Data from the TEXT experiment were obtained by biasing the plasma to ±500 V, which drew ion currents of ±100 A. "Mini H modes" with negative bias were observed, and the H mode appeared to be nonrotating. It was concluded that the azimuthal rotation on TEXT can be braked. The effect of a radial electric field on the TEXT plasma can vary from indetectable to dominant. The probes used, which went in to 0.65 of the plasma radius, did not disrupt the plasma. As a practical note, it was remarked that boron nitride is the best insulating material for tokamak biasing experiments.

The 26th paper was presented by K. C. Shaing of ORNL, who discussed a unified theory of L to H-mode transition in tokamaks. This theory was not based on some form of classical transport or binary collisions. Shaing pointed out that in the H-mode boundary, the ratio of E/B drift to ion thermal velocity is usually on the order of unity, but many theoretical approaches assume that it is small. He considered a poloidal rotation velocity with two contributions, one from E/B drift and one from a pressure-driven diamagnetic term. He pointed out that the most important equation is the poloidal momentum equation that includes a Lorentzian term. At the edge of tokamak plasmas, the transport is dominated by fluctuations and charge exchange.

The 27th paper was presented by A. F. Almagri and colleagues from the University of Wisconsin–Madison, who reported initial results of prototype biased electrode experiments in the Madison Symmetric Torus (MST). The principal interest in this experiment is dc helicity injection into this magnetic configuration, but many of the results were relevant to the question of plasma biasing. They used a biased graphite electrode in contact with the plasma that was capable of injecting 1000 A into the plasma at bias voltages of −300 V. Because of the emphasis on helicity injection, the electrode face is located normal to the field lines. Graphite electrodes inject impurities into the plasma, especially at the highest voltages. The authors looked at other electrode materials but finally decided to use a biased plasma gun that was capable of injecting 700 A at a potential of −200 V. The *I-V* curve of this injector saturates at −250 V at a current of 800 A. They detected a localized structure rotating with a velocity of 10 km/s in the ion diamagnetic direction. The preliminary results indicate that a radial electric field, generated by biasing a graphite electrode at the edge of the plasma, can be used to reduce locked modes in the MST.

The 28th paper was presented by H. Sanuki and colleagues from the National Institute for Fusion Science, Japan, who discussed the self-consistent analysis of radial electric fields and fast ion losses in the Compact Helical System (CHS) torsatron/heliotron. The CHS device has a major radius R = 1 m, and a minor plasma radius a = 20 cm. It is an L = 2 torsatron with a magnetic induction of 1 T in which radial electric fields near the edge, ranging from −120 to +40 V/cm, have been observed at a location 80% of the way from the center to the plasma edge. The observed radial electric fields in this device are two to three times the neoclassical prediction, and it appears that orbit losses and charge-exchange losses are responsible for this.

Paper 29 was presented by C. Xiao from the Plasma Physics Laboratory at the University of Saskatchewan, Canada, who presented a discussion of current pulse and biasing-induced improved confinement in the STOR-M tokamak. The STOR-M tokamak is a small tokamak with a major radius R = 46 cm, a minor radius a = 12 cm, a maximum axial magnetic induction of 1 T, and a maximum ohmic heating current of 50 kA. In this device, the current-pulse-induced H mode is accompanied by autobiasing. The STOR-M is outfitted with a semicircular biasing electrode located 80% of the way from the plasma minor axis to the edge. The natural plasma bias is −60 V. With an imposed bias of +100 V, the bulk average electron number density increases by a factor of 2, and the energy containment time also increases by a factor of 2. For an electrode bias of −400 V, there is also a factor of 2 improvement in the average electron number density and an improvement of a factor of ~1.5 in the energy containment time. No significant change in the average electron number density is observed over the range of bias from 0 to −150 V. There appears to be a linear increase in $\bar{n}_e$ with the bias voltage outside that range, within the limits imposed by the experiment, which are between −450 and +150 V. During the discussion after this paper, it developed that when the researchers attempt to apply a bias greater than +150 V, the electron density increases excessively and causes a disruption. Similar phenomena have also been observed with bias voltages below −450 V.

Paper 30 was presented by K. Ida and colleagues from the National Institute of Fusion Science, Japan, who described edge poloidal rotation profiles of H-mode plasmas. Data have been taken in the JFT-2M tokamak. The poloidal rotation is localized near the plasma edge, and the ion and electron kinetic temperatures increase inside the plasma edge as the plasma enters the H mode. The E/B drift velocity changes sign at the plasma edge, as does the radial electric field. In their experiments, the radial electric field is of the order of 50 to 150 V/cm in these plasmas, in which no biasing is attempted.

Paper 31 was presented by S. I. Krasheninnikov from the Kurchatov Institute of Atomic Energy, Russia, who discussed the plasma flow and electric current at tokamak reactor divertor plates. This paper contained a computational simulation of the recycling and particle flows in the vicinity of divertor plates, and was primarily concerned with the unbiased state of tokamak operation.

Paper 32 was presented by X. Q. Xu and a collaborator from the Electronics Research Laboratory of University of California–Berkeley, who presented an analytical and a computational study of electron temperature-gradient-driven turbulence in boundary plasmas. Their linear analysis shows that potential fluctuations due to modes in the SOL decay exponentially in the radial direction inside the separatrix. When the two plates of the divertors are biased, instabilities at the edge of tokamak plasmas are suppressed at long wavelengths. For a critical normalized voltage, $V_c = V_{bias}\omega_{ci}/\phi_{sh}\omega_{pi} > 1.95$, where ϕ_{sh} is the sheath potential at the plates. The instabilities, however, are enhanced at long wavelengths for $V_c < 1.95$.

Paper 33 was presented by M. Ali Mahdavi of General Atomics, who spoke on reactor applications of divertor biasing. This paper related some of the critical issues in the International Thermonuclear Experimental Reactor (ITER) design study. This paper pointed out that E/B flows due to biasing can be used effectively for density and impurity control, a conclusion strongly reinforced by many papers at this conference. It also was pointed out that the observed effects reported at this conference, if applied to ITER, could include decoupling the divertor exhaust from the core plasma density and maintaining the particle exhaust during divertor strike-point sweeping designed to reduce the average heat load on the divertor target plates.

The last paper of the conference was presented by P. Couture from the CCFM, who presented an overview of the current activities and coming experiments. With that, the conference proceeded on to some discussion and adjourned late Thursday afternoon, September 10. There was general satisfaction among the conference participants with our sponsors at the IAEA for having the foresight to organize such an interesting and timely meeting and with our hosts from the CCFM for their kind hospitality and skilled planning and organization of the meeting.

I believe that most participants at this conference were favorably impressed by the timeliness of the meeting and the large ground swell of interest and activity in this rapidly developing field. The papers presented at this meeting collectively make a strong case for the beneficial effects of electrostatic biasing of toroidal plasmas, including tokamaks, since radial electric fields have been shown to improve particle containment time in toroidal devices, increase the electron number density in the core plasma, reduce impurity levels, heat a surface layer of shield electrons in the outer regions of the plasma, and even raise ions to kilovolt kinetic energies. A good case can be made that electrostatic biasing may be the single most important development in tokamak research for more than a decade and indeed may constitute a paradigm shift from pure magnetic containment of plasmas to magnetoelectric containment.

The proceedings of the IAEA Technical Committee Meeting on Tokamak Plasma Biasing are expected to be available after November 1992. These proceedings will contain full-length papers based on the presentations at the meeting, where the authors have supplied them. These proceedings can be obtained from the IAEA at the following address: Dr. Vladimir Demchenko, International Atomic Energy Agency, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria.

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