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General Principles of Magnetic Fusion Confinement

J. T. Hogan

MASTER

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DEPARTMENT OF ENERGY

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FUSION ENERGY DIVISION

GENERAL PRINCIPLES OF MAGNETIC FUSION CONFINEMENT*

J. T. Hogan

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ABSTRACT

In these lectures, we describe a few of the areas in which there is close interaction between atomic/molecular (A&M) and magnetic fusion physics. The comparisons between predictions of neoclassical transport theory and experiment depend on knowledge of ionization and recombination rate coefficients. Modeling of divertor/scrapeoff plasmas requires better low energy charge exchange cross sections for $H + A^{n+}$ collisions. The range of validity of neutral beam trapping cross sections must be broadened, both to encompass the energies typical of present injection experiments and to deal with the problem of prompt trapping of highly excited beam atoms at high energy. Plasma fueling models present certain anomalies that could be resolved by calculation and measurement of low energy (<1 keV) charge exchange cross sections.

1. INTRODUCTION

Recent results with neutral beam heated tokamaks have led to increasing optimism about the prospects for a successful magnetic fusion reactor. The conceptual scheme for providing a fusion driver for a fission-fusion hybrid system has been validated, and a demonstration of "breakeven" ("D-T fusion power out = injector power in") seems quite likely with the Tokamak Fusion Test Reactor (TFTR) device, now scheduled to begin operation in Princeton in 1981. While breakeven, or $Q = 1$, performance should be satisfactory for hybrid systems, in which the fusion driver provides fuel makeup for fission reactors; an economically attractive pure fusion scheme will require $Q \sim 30-40$. To achieve this level, the plasma will have to be maintained in a high- β state for many energy and particle replacement times. This more stringent requirement imposes rigorous demands on our understanding of fusion systems. In particular, it means that we must obtain better understanding of the plasma particle and energy balance, must optimize neutral beam deposition, and must control the plasma energy and particle flux to the exterior through improved limiters or with magnetic divertors. In addition, our diagnostic evaluation of the scaling of particle and energy balance must be improved.

It seems clear that the joint work of fusion and atomic/molecular (A&M) physicists must intensify if these goals are to be attained. Hence, it is the purpose of these lectures to introduce the concepts and trends in present magnetic confinement experiments, especially as they affect the joint work of A&M and fusion physicists. Processes that have a significant effect on the goal of producing a clean, high- β discharge for long pulse lengths are described, with emphasis on the fusion physics. This should serve as a background for the more specialized discussions in the Institute and should be helpful in following the literature in areas where there is a significant interaction of A&M and fusion physicists.

We will first introduce some basic fusion concepts, or rather, we will recommend sources for further study by those interested. Next we will briefly review recent experiments and discuss current trends and

near-term experiments. We will then describe, in more detail, some specific plasma physics processes which enter into many A&M physics-related problems: neoclassical and MHD transport processes, the diver-tor/scrapeoff plasma, neutral beam deposition and thermalization, and plasma fueling processes. Finally, we examine a case study in the interaction between A&M and fusion physics: the way in which calculation and measurement of the impurity/hydrogen charge exchange trapping cross section has affected the understanding of fusion devices.

2. FUSION CONCEPTS

These lectures will dwell entirely on processes and problems arising with tokamak magnetic confinement devices. Of course, there are many other devices and they are quite successful, but they are viewed to be somewhat further removed from the reactor stage at present. In any event, the tokamak is now the subject of the most active collaboration between A&M and fusion scientists.

Useful introductions to tokamak physics have been prepared by Artsimovich, Coppi, and Furth.¹ More extensive discussions of recent neutral beam systems have been given by Murakami and Eubank.² A survey of fission-fusion hybrid ideas has been presented by Bethe.³ For more detailed study, two extensive reviews of tokamak experimental results have been prepared by Artsimovich⁴ and Furth⁵ in Nuclear Fusion.

We will consider here only the essential concepts that are needed for the detailed lectures at the Institute.

2.1 CONFINEMENT PROPERTIES: THEORY

2.1.1 Neoclassical Theory

Neoclassical theory is based on some of the earliest (or classical)⁶ ideas about plasma transport. Essentially, while particles execute closed orbits in the magnetic confinement geometry (Fig. 1), distant collisions that result in small momentum transfer can cause large changes in spatial diffusion by alteration of the particles' orientation with respect to the magnetic field. In this theory, the controlling

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Proton Trajectories in ORMAK.

 $E = 10 \text{ keV} \quad I = 100 \text{ kA} \quad B_T = 15 \text{ kG}$

$$J = J_0 \left[1 - \left(\frac{r}{a} \right)^3 \right]^4$$

Fig. 1. Cross section of the tokamak plasma showing drift orbits for various pitch angles ($\theta = \cos^{-1} v_{\parallel}/v$). Small changes in this angle due to weak collisions can lead to large spatial excursions.

rate for diffusion is the rate at which particles collide: the electron-ion scattering rate (time for a 90° deflection of an electron by scattering from ions) governs electron processes, and the same rate for ion-ion collisions determines the ion loss processes. Because the electron-ion scattering time is shorter and leads to much faster diffusion of electrons than ions, a strong electric field is set up because of the separation of charges, and this electric field pulls the ions after the electrons at a faster rate than the simple collisional processes would allow. The requirement of ambipolarity of fluxes

$$\Gamma_e = \Gamma_p + \sum_k k \Gamma_k \quad (1)$$

thus constrains the transport rates in a plasma with electrons, protons, and more highly charged ions (α particle fusion products or impurities).

Neoclassical theory⁷ predicts that the ratio of electron-ion thermal conductivities should be small ($\chi_e/\chi_i \lesssim \sqrt{m_e/m_i}$). While both χ_e and χ_i are ill-measured in tokamak experiments, the observed upper bound to χ_e actually exceeds the observed upper bound to χ_i , thus making neoclassical theory an unlikely model for electron behavior. Nonetheless, values for χ_i are in tolerable agreement with neoclassical predictions. Further, results from controlled experiments with impurity ion injection confirm some detailed features of the neoclassical model. Equation (1), when applied to the case of protons and a single impurity with charge Z , predicts that $n_z = (n_p)^Z$ in equilibrium. Thus, impurities injected from the outside should settle in the core and have a spatial profile more sharply peaked than that of the protons. It is found that externally introduced impurities do migrate to the core; however, the profile is not necessarily more sharply peaked.

This discrepancy may be resolved by consideration of a class of processes that have only recently been calculated.

2.1.2 MHD Oscillations

The static magnetic field that is used as a model in Fig. 1 and as a basis for neoclassical transport calculations is only an approximation. The strong longitudinal field B_T is required to stabilize

extremely violent motion that would destroy the plasma in an Alfvén time (a/v_a) if this field were absent. However, it is nonlinear stability that is so provided. This means that small stable oscillations in the field are present and can have a significant effect on transport rates. The attainment of high β in future reactors also requires the stabilization of these oscillations, as we shall discuss.

2.1.3 Sawteeth and Saturated Islands

Stability for these fast modes is described entirely by the Kruskal-Shafranov "safety factor," q , which typically varies from a value near unity in the core to 2-4 on the exterior. For values near unity, oscillations with $e^{i(m\theta - n\phi)}$ ($m = n = 1$) can occur. These show a periodic behavior, with intermittent growth followed by expulsion of plasma from the core. This "sawtooth" quality is one of the more striking experimental features of its behavior, and a theory by Kadomtsev has been successful in describing the resulting transport.

When $q = m/n$ ($m = 2, 3, 4 \dots n = 1$), perturbations can also grow in the intermediate plasma region between the core and the edge. These oscillations stabilize nonlinearly and create finite amplitude, helically symmetric field structures superimposed on the axially symmetric tokamak geometry. Thus, particles can move rapidly across this spatial region ($\Delta/a \lesssim 20\%$) much more quickly than by neoclassical processes. There is a strong effect on τ_E scaling when these "islands" are produced.⁸ There is an effect on impurity transport to be expected as well, because there may be a "shorting out" of the radial electric field required for ambipolarity. This screening effect has been invoked to explain the results of experiments in which argon was deliberately injected into a tokamak discharge.

For high values of β ($\lesssim 1.5\%$) a new class of nonsymmetric instabilities with $m \approx n$ is expected to occur. Localized in the outer weak field regions of the torus, these "ballooning" modes are thought to set the upper limit on attainable β . When the energy available for plasma expansion exceeds that available for stabilization by field-line bending,

the plasma could be lost catastrophically at the sound speed. In this case, MHD effects would not simply enhance the transport rate, but would terminate the experiment.

2.2 CONFINEMENT PROPERTIES: EXPERIMENTS

The measured confinement properties in tokamak experiments are described by two empirical formulae. The first, popularly known as "Alcator scaling,"⁹ predicts that

$$\tau_E \equiv 1.9 \cdot 10^{-6} a^2 \left(\frac{\bar{n}_e}{10^{13}} \right) q^{1/2} . \quad (2)$$

The second, proposed by Mirnov,⁸ accounts for the degradation due to MHD oscillations and predicts that

$$\tau_E = 3 \cdot 10^{-9} a \sqrt{\bar{n}_e / 10^{13}} . \quad (3)$$

Each of these must be used in conjunction with an empirical description of the density scaling proposed by Murakami et al.¹⁰

$$\bar{n}_e = 2 \cdot 10^{11} B_T / R . \quad (4)$$

These experimental rules for τ_E must be understood in context. They incorporate all the loss processes: line radiation, ionization losses, and conduction and convection. Moreover, even the effective minor or cross-section radius may vary strongly from discharge to discharge in a device with a given nominal value of a .

Neutral beam heating experiments in Princeton Large Torus (PLT) have indicated an improvement of electron confinement similar to Alcator scaling, but with χ_e decreasing with increasing T_e . The scaling $\chi_e \sim T_e^{-1/2}$ is known as PLT scaling.¹¹

As noted earlier, ion confinement processes appear to be adequately described by the neoclassical model.

Explicit determination of τ_p seems to be most difficult. Neutral beam heating provides a direct power input, which can be estimated;

however, the particle input from the limiter and walls is almost unknown. It is conventionally assumed that $D/\chi_e = 1/5$ because this model leads to reasonable behavior in simulation codes.

2.3 MAGNETIC GEOMETRY

The basic configuration shown in Fig. 1 has been generalized in recent experiments. As seen in Fig. 2, the cross section has been altered to produce D- and Doublet-shaped plasmas. Larger currents can be passed through these configurations, while retaining the same value of the Kruskal-Shafranov safety factor. Also, by maximizing the effect of the high field side of the torus against the $1/R$ toroidal falloff of B_T , this shaping may serve to stabilize the plasma at higher β values than those thought possible with a circular cross section.

Further changes in the geometry are necessary to provide channelling of the plasma efflux to regions which are specially fitted for handling high heat loads and pumping. These magnetic divertor configurations are being tested at present in DIVA and Poloidal Divertor Experiment (PDX).

An even more radical change has been tried successfully in the Divertor Injector Tokamak Experiment (DITE). Toroidally localized coils have been employed to lead a bundle of magnetic field lines out to a plate and thus have shown the effectiveness of this form of divertor. Both bundle and axisymmetric (or poloidal) divertors will be the subject of important trials in the next few years. A double toroidal, or spitzer, divertor has begun operation at the Kurchatov Institute in Moscow. In this variant, the field is disturbed locally at two toroidal locations.

3. RECENT EXPERIMENTS AND NEAR-TERM TRENDS

3.1 NEUTRAL BEAM HEATING EXPERIMENTS

The most dramatic results in recent fusion work have occurred in a series of neutral beam injection experiments with increasing levels of beam power. The early "high power" injection experiments ($P_b \gtrsim P_{OH}$) in Oak Ridge Tokamak (ORMAK), Adiabatic Toroidal Compressor (ATC), and Tokamak Fontenay-aux-Roses (TFR) produced ion temperatures in the

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Fig. 2. By elongating the plasma cross section while maintaining the same value of toroidal magnetic field, the total stable current can be increased.

2-keV range, with $T_i > T_e$ for the first time in tokamaks. Last year's experiments with PLT, in which up to 2.2 MW of 40-keV neutrals were injected, produced ion temperatures in excess of 6 keV, D-D neutron output in excess of 100 W, and an equivalent D-T Q value of 5%. Simple extrapolation of the same parameters to the case of 120-keV D^0 injection in TFTR leads to a $Q_{DT} \approx 1$, because the overwhelming contribution to the neutron output comes from beam-thermal and beam-beam reactions. The PLT experiment has recently been devoted to ion cyclotron wave heating experiments, and good results have been obtained here also. Comparable with those in neutral beam heating, heating efficiencies of ~ 2 eV/kW injected have been obtained.

The PDX experiment has produced 460-kA plasma discharges and in the next year will begin a joint Princeton Plasma Physics Laboratory/Oak Ridge National Laboratory (PPPL/ORNL) 6-MW neutral beam heating project. Equivalent $Q_{DT} \sim 10\%$ is expected.

The Impurity Study Experiment (ISX-B) at ORNL has a circular/D-shaped plasma that allows an elongation up to 1.6. The low toroidal field facilitates studies of limits to β , and values of β in excess of those theoretically predicted to be unstable to ballooning modes have recently been achieved ($\beta \sim 2.2\% > \beta_{CRIT} = 1.5\%$).

Doublet III plasmas with currents in excess of 2 MA have been produced, and injection with up to 7 MW of 80-keV H^0 will be undertaken in the next few years.

DITE tokamak has carried out 1-MW injection experiments, and T-11 in Moscow is equipped with 0.5 MW of power. The Asdex divertor experiment is under construction at Garching. TFR 600, a continuation of the successful TFR device at Fontenay-aux-Roses, is conducting a joint study of neutral beam and wave heating.

The International Atomic Energy Agency's (IAEA) World Survey of Fusion Facilities may be consulted for a more detailed accounting.¹²

3.2 TRENDS IN THE EXPERIMENTS

3.2.1 Confinement Scaling

The central task of the present experiments is to study the parameter dependence of the transport processes. It is desirable, in this respect, to minimize the effects of any process other than plasma transport. However, it is inevitable that there will be some impurity constituents and that the role of recycling of the working gas between the plasma and the limiter or wall will be significant.

The important result of PLT neutral beam heating experiments was to show that the saturation level of possible collisionless instabilities was quite low. It had earlier been feared that transport rates would be greatly enhanced over present values in the high temperature regime needed for reactors.

The Alcator series of experiments is the prototype for a class of "high field" ($B_T \geq 10$ T) reactor designs. In these experiments the highest absolute values of $n_e \tau_E$ have been achieved, in addition to the highest densities ($\geq 10^{15} \text{ cm}^{-3}$). The provision of wave heating (needed because neutral beams require impractically high energy to penetrate these dense plasmas) is expected to increase the temperatures above the presently observed 1-keV level.

3.2.2 Shaping Studies

Scaling with temperature will result as varying amounts of power are applied. Scaling with size (now conventionally accepted as size)² will be tested in detail. By varying the cross-section shape, it is hoped that the higher currents that can be stably produced will reduce neoclassical conduction losses. Elongation should produce a higher β_{CRIT} , and this supposition will be tested in high power beam injection experiments.

3.2.3 Impurity Production

At present, the detailed nature of impurity production and transport is unknown. High power experiments are limited in duration to

~150 msec because of constraints on existing neutral beam technology. The gross measure of impurity content, a weighted average of the ionic charge that enters calculations of momentum transfer, is

$$Z_{\text{eff}} = \sum_{\text{all positive species}} \frac{n_k Z_k^2}{n_e}. \quad (5)$$

An accumulation rate of $Z_{\text{eff}} = 0.05/\text{sec}$ could not be detected in present experiments and yet would be fatal for long pulse reactors.

It has been proposed that impurities can be introduced by

- sputtering of the surface by escaping charge exchange neutrals,
- desorption by charged particles (ions or neutrals leaving the plasma),
- evaporation or melting of the limiter,
- arcing, and
- self-sputtering of the wall or limiter by escaping impurity ions.

The radiation losses produced by these impurities have reached catastrophic levels in some experiments. Tungsten impurities, in particular, have foiled electron heating experiments on the ORMAK device and produced hollow electron temperature profiles in PLT. After tungsten limiters were replaced with water-cooled graphite, neutral beam heating experiments on PLT registered unprecedented temperature rises. A specific study of the effects of heavy metals was made on the ISX-A tokamak, which employed stainless steel limiters from its earliest operation. Energy confinement times exceeding Alcator scaling were produced. In addition, tungsten was deliberately introduced in a laser blowoff experiment, and characteristic degradation of τ_E and concomitant hollow T_e profiles were observed.¹³

There is a trend in present experiments away from heavy metal limiters (such as Mo and W) and toward carbon or stainless steel. This trend may, however, be only temporary. In the PLT device the effective plasma radius was decreased by ~10% when the graphite limiter was used, and the power input levels planned for PDX (with similar size) are three times those injected into PLT. The ISX-A device was relatively

impurity-free with stainless steel limiters, but only ~ 500 kW of ohmic heating power was produced. The ISX-B experiment, with 3 MW of injected power planned, may have different results. The exceedingly difficult atomic physics problems regarding ionization and recombination of heavy metals (such as W and Mo) will, at least temporarily, be accorded a low priority by many fusion researchers.

3.2.4 Plasma Fueling

The Alcator-A tokamak has produced the highest values of $n_e \tau_E$ among fusion devices, attaining high densities ($\sim 10^{15} \text{ cm}^{-3}$) by controlled injection of cold ($\sim \text{few eV}$) gas. A key paradox for confinement theory is the rate at which the spatial distribution of the density relaxes. It seems to be anomalous in comparison with these transport models, which perform reasonably well in predicting steady-state values of parameters. The edge interaction region is complex, however, and it may be that oxygen is admitted with the injected gas. If so, and if the $\text{O}^{n+} + \text{H}_0 \rightarrow \text{O}^{(n-1)} + \text{H}^+$ charge exchange rates significantly exceed those for $\text{H}^0 + \text{H}^+$, then an important anomaly would be removed.

Plasma fueling by injection of frozen hydrogen pellets has recently been given successful trials on the ISX-A and ISX-B experiments. The pellets are injected at a speed $\sim 1 \text{ km/sec}$, and can be deposited at will across the plasma cross section. Interferometric and holographic studies have been used to follow the pellet in flight, and local densities during ablation of $\sim 10^{19} \text{ cm}^{-3}$ have been recorded. The interaction of pellets with stored fast ions from an injected neutral beam ($\sim 40 \text{ keV}$) shows beneficial effects: the stored fast ion energy favorably accelerated the pellet ablation and subsequent heating of the cold plasma that is produced.

3.2.5 High- β Experiments

If the trends we have discussed in confinement scaling continue, then the production of the requisite $\sim 10\text{--}20\text{-keV}$ reactor plasma temperatures seems assured. Reactor studies have shown, however, that high temperature must be accompanied by high density to ensure that the reactor's

fusion power density is sufficient to economically repay the overhead costs in an acceptably small power plan.¹⁴ This implies that the β values must lie in the range of 4-6%. Typical β values in the PLT neutral beam heating experiments were $\leq 1\%$ because of the high (3.2 T) toroidal fields. In ISX-B, however, the combination of low toroidal field (≤ 1.2 T) and high injected power (~ 1.5 MW) leads to a test of the properties of high- β plasmas.

Preliminary tests in a circular plasma configuration have now been completed. They show (Fig. 3) that the β values attained exceed those previously calculated to be unstable to ballooning modes. As the beam power is increased from 0.3 to 1 MW, a steadily increasing rise in MHD activity is observed, which may signal the onset of ballooning instability at a higher β . Nonetheless, the theoretical guidelines for attainable β values have been achieved for the circular configuration, and attention is now turning to the production of the D-shaped plasmas that will yield the high β_{CRIT} needed for reactors.

4. FUSION PHYSICS PROCESSES

4.1 NEOCLASSICAL TRANSPORT OF IMPURITIES

The bulk of the work of atomic physicists in the fusion field concerns the behavior of impurities in the plasma. In a first approximation, the impurities, as an ion species, behave according to neoclassical theory.

There are, however, some important paradoxes with respect to the plasma physics aspects of these models that have cast some doubt on the utility of attempting detailed measurements of impurity behavior. In the impurity light emission seen in tokamak experiments, there are puzzling asymmetries that can reverse polarity even during the course of a discharge. Burrell and Wong¹⁵ have recently analyzed this situation, and we shall describe their resolution of the paradox.

Another contradiction concerns the apparent lack of a continual accumulation of impurities in the core of the discharge. Argon injection experiments on the T-4 tokamak may have resolved this issue, since sawtooth oscillations (in reality, minor disruptions expelling

$\langle \beta \rangle$ INCREASES LINEARLY WITH BEAM POWER, SO FAR.

FOR $P_{beam} \approx 1.5$ MW, $\langle \beta \rangle \geq 2\%$, IF NO INSTABILITIES

Fig. 3. The values of $\beta^* [\equiv 2\mu_0 (\int dV p^2)^{1/2} / B_T^2]$ attained by the ISX-B tokamak for different levels of injected power. Previously, it was thought that $\beta^* \sim 2\%$ was a limiting value.

plasma from the core) were present. In addition, the important effect of possible charge exchange reactions as a recombination mechanism was demonstrated. We pursue the subject in more detail because it is ubiquitous in atomic physics studies, and we shall describe the neo-classical effects here.

4.1.1 General Features of the Theory

The mathematical aspects of the calculations are thoroughly described by Hazeltine and Hinton. Hawryluk, Suckewer, and Hirshman have recently given a review of the status of the transport of low-Z impurities in tokamaks.¹⁶

The evolution of impurity ions in a tokamak discharge is described by

$$\begin{aligned} \frac{\partial n_j}{\partial t} = & -\frac{1}{r} \frac{\partial}{\partial r} (r \Gamma_j) + n_e (n_{j-1} S_{j-1} - n_j S_j \\ & + n_{j+1} R_{j+1} - n_j R_j), \quad j = 1 \rightarrow Z. \end{aligned} \quad (6)$$

These equations, complemented by the requirement of charge neutrality,

$$\sum_j n_j Z_j = n_e, \quad (7)$$

and ambipolarity,

$$\sum_j Z_j \Gamma_j = \Gamma_e, \quad (8)$$

will determine the temporal and spatial evolution, if the relevant rate coefficients are known. The rate coefficients are, in many cases, not known, and this hampers detailed study. The general properties of the neoclassical theory are known, however, and we shall describe these.

The moment of the kinetic equation describing the ion evolution gives, for momentum,

$$n\mathbf{u}_\perp = \frac{1}{m\Omega} \hat{n} \times \left(\nabla \cdot \underline{\underline{P}} - \underline{\underline{F}} - en \underline{\underline{E}} + m \frac{\partial}{\partial t} n\mathbf{u} \right). \quad (9)$$

Considering an expansion of the equations in a small parameter (scale length/gyroradius), the lowest order result is that the distribution functions are Maxwellian. For the component of $\mathbf{u}$ perpendicular to $\underline{\underline{B}}$,

$$\frac{\partial}{\partial t} m n \mathbf{u}_\perp + \nabla \cdot \underline{\underline{P}} - en \left(\underline{\underline{E}} + \frac{1}{c} \mathbf{u} \times \underline{\underline{B}} \right) = \underline{\underline{F}}. \quad (10)$$

To next order, the requirement that the densities depend only on magnetic flux arises, and to second order, deviations in the poloidal direction can be maintained. In second order, the crossfield diffusion flux is

$$n\mathbf{u}_\perp = \frac{1}{m\Omega} \hat{n} \times \left[\nabla \cdot (\underline{\underline{P}} - \overline{\underline{\underline{P}}}) - e(n\underline{\underline{E}} + \hat{n}\nabla\phi) \right]. \quad (11)$$

The latter term introduces the changes resulting from moving flux surfaces and is not a true diffusion effect. The first term expresses the key point: the source of enhanced diffusion in toroidal geometry arises from anisotropy in the plasma stress tensor. For high collision frequencies, the tensor is diagonal, but there are variations within a flux surface. For low collision frequencies, $\underline{\underline{P}}$ is nondiagonal and greatly enhanced anisotropy results.

For most applications, the impurities will have a high collision frequency; thus, the essential ingredient in the theory is the asymmetry of the plasma pressure around a flux surface. To recapitulate, to lowest order (zero gyroradius), there is no deviation from a field line; to next order, there is no deviation from a flux surface; and to second order, where the theory makes its first nontrivial contribution, it is the asymmetry on a flux surface that provides the essential driving term.

Momentum balance in the direction parallel to the field leads to the flux

$$\Gamma_{\parallel}^a = -\frac{1}{Z} \frac{\partial P}{\partial \psi} \frac{1}{B} \left(1 - \frac{B^2}{\langle B^2 \rangle} \right) + \frac{\langle \Gamma_{\parallel}^a B \rangle}{\langle B^2 \rangle} . \quad (12)$$

The variation over a flux surface is present in the first term. The force balance equation

$$\underline{B} \cdot \nabla P_Z = n_Z l_Z (e \underline{B} \cdot \nabla \psi + B R_u) \quad (13)$$

can be integrated to give

$$\frac{n_Z \theta}{\langle n_Z \rangle} = -\alpha \sin \theta \left\{ c_o \left(\frac{Z}{Z} \frac{1}{n_i} \frac{\partial n_i}{\partial r} - \frac{1}{n_z} \frac{\partial n_z}{\partial r} \right) + \left[c_o \left(1 - \frac{5}{2} c_i \right) - \alpha_2 \right] \right\} + \gamma \frac{\partial T_i}{\partial r} . \quad (14)$$

Depending on the relative strengths of ion density and temperature gradients, then, the symmetry (or lack of it) in the impurity spectral emission can vary quite widely. The characteristics can even fluctuate during the course of a single discharge. This effect is inherently present in neoclassical theory, and it should be pronounced even for moderate ionization states. These (or neutral) stages will, of course, reflect the lack of symmetry imposed by the external sources.

4.1.2 Argon Injection Experiments

The deliberate injection of a trace amount of argon into a T-4 discharge showed one neoclassically expected effect very clearly: within 10 msec the argon appeared in the core. Thereafter, however, the rate of accumulation stopped and the argon reached a steady-state level. It has been speculated by the authors of Ref. 17 that charge exchange between the ambient hydrogen neutrals (~ 200 eV in energy) and Ar^{16+} may have been responsible for their observation. Since these rates are unknown in this energy range, however, no conclusions could be drawn. Another mechanism, arising from plasma physics, should be borne in mind.

Kadomtsev¹⁸ has proposed a model for the sawtooth oscillations present in tokamaks. The current density on axis increases, the Kruskal-Shafranov safety factor drops below unity, and an energy surplus is created in the magnetic field that can be released as plasma expansion energy. A reconnection of field lines occurs, and the resulting final state is a uniform image of the initial state. The plasma parameters are carried with the flux as it is redistributed. The reconnection criterion is

$$\psi^*(0) = \psi^*(r_0), \quad (15)$$

and for a parabolic profile this implies flattening out to a radius $r_0 \sim \sqrt{2} r_s$ [$q(r_s) = 1$]. In the T-4 experiments $r_0/a \sim 0.3$. Thus, a substantial part of the plasma was subject to a periodic expulsion (outflux) mechanism, and this can resolve the paradox with neoclassical theory.

A different explanation has been advanced by Mirnov.¹⁹ He points out that large-scale magnetic islands are typically produced in tokamaks. These magnetic structures are the result of nonlinearly saturated tearing instabilities. However, they effectively couple two previously disjointed flux surfaces ψ_1 and ψ_2 , having electron temperature $T_e(\psi_1) \neq T_e(\psi_2)$. Thus, an electrostatic barrier is set up to prevent instantaneous equilibration. The protons are attracted and impurity ions flow against the proton gradient; thus, there is an electrostatic sheath prohibiting further penetration of the argon injected from the outside.

At present, although a detailed model is lacking, it appears that neoclassical theory with MHD effects can explain the features of impurity transport in tokamaks. In each experimental situation, however, there are key unknowns in the atomic physics areas: ionization rates for electron impact and charge exchange of hydrogen in the 0-1-keV energy range with multicharge impurity ions.

4.2 DIVERTOR/SCRAPEOFF PLASMA

Serious experimentation with divertor plasmas is now under way. The DITE bundle divertor and DIVA divertor showed beneficial effects of divertors on plasma properties.²⁰ The major results of the DITE experiment illustrate the role which divertors will play in a reactor: by reducing the ion-induced desorption of cold gas trapped on the wall, the plasma particle balance could be controlled. By ionizing metallic impurities and sweeping them into the divertor chamber, the scrapeoff layer could serve as a shield for the plasma. Plasma energy was, in fact, coupled to the divertor plates, and this raises a concern with divertors: the energy flux may be too severe. Besides the multiple roles of recycle control, shield for impurities, and energy absorber, the divertor must pump the helium produced by D-T reaction products in a reactor.

The atomic physics role in determining divertor properties is similar to that in analyzing the conventional limiter.²¹ Essentially one is balancing the parallel flow along field lines to the divertor box (or limiter) against the cross-field transport. The plasma models for parallel flow are still being worked out. The usual assumption is that ions flow at the sound speed into the divertor chamber if charge exchange with neutrals is unimportant:

$$u_{\parallel} \sim \sqrt{2(T_e + T_i)/m_i} = c_s . \quad (16)$$

Under these circumstances, however, the product $\bar{n}_e \Delta$ of the scrapeoff layer may be insufficiently large to ionize the impurities produced at the first wall. In that case, neutral gas puffing will be introduced to build up the scrapeoff density. However, charge exchange will balance the parallel pressure gradient, and the flow to the collector will be reduced:

$$u_{\parallel} \sim \frac{D}{n} \Delta P; \quad D = \frac{1}{m_i n_o \langle \sigma v \rangle_{cx}} . \quad (17)$$

The optimum scrapeoff design will have three major physical features: ion parallel flow into the divertor, hydrogen gas puffing at a large enough rate to keep up the $\bar{n}_e \Delta$, and impurity production. The ionization rates will be determined by T_e , and it, in turn, will be determined by flow and radiative losses. Further, the radiative losses will be strongly influenced by the $H_0 + A^{NT}$ charge exchange reactions. Thus, charge exchange cross sections for the 0-100-eV range for H_0 with low ionization stages of Fe, Cr, Ni, and Ti are most crucially needed because even crude estimates are lacking. Moreover, the electron impact ionization rates require better calculation measurement.

There is an important surface-related factor as well. As ions flow to the collector plate, an electrostatic sheath is built up. The magnitude of this potential barrier depends in a critical way on the secondary electron emission that occurs in the divertor box. Assuming no secondary emission, present models give a parallel heat flux.

$Q_{||} = 6 T_e \Gamma_{||}$, with $\sim 7 T_e \Gamma_{||}$ recorded on the DIVA experiment. However, 100 times this value is needed to explain the DITE experiments; thus, there is some room for improvement in the models.

4.3 NEUTRAL BEAM DEPOSITION

The neutral beam heating technique has been successfully proven. In view of the large role it will play in future tokamak experiments, we will describe the major physical processes.

The neutral atoms emerge from the beam line and are trapped in the plasma by charge transfer with plasma ions, by electron impact ionization, or by impact ionization on the plasma ions. Once charged, these energetic injected particles are confined by the tokamak magnetic field. For the case of injection nearly tangential to the magnetic field shown in Fig. 4, the particles follow trajectories that also lie nearly along the fields. However, a projection of their orbits onto a plane perpendicular to the toroidal axis shows that there are important drift motions; their orbits are displaced outward from the axis of symmetry for particles injected nearly parallel to the plasma current and inward for those particles that are nearly antiparallel. By calculating the resulting drift after trapping and averaging the densities of the fast

Fig. 4. Neutral beam deposition processes. The beam enters the plasma chamber (see top left) and neutrals are ionized. Seen in cross section, particles travelling in the direction of the plasma current are displaced outward, and those travelling in the opposite sense are shifted in (see top right). Resulting deposition profiles for co- and counter-injection (see bottom).

ions over the tokamak radial flux surfaces, the deposition of fast ions is finally characterized by the function $H(r)$ shown in Fig. 4. It is the normalized density of deposited fast ions as a function of plasma minor radius. Various radial deposition profiles are shown as a function of a/λ (a is the plasma minor radius, λ the mean free path against trapping by all the processes mentioned). That is,

$$\frac{a}{g} = \int \left(\sum n_e \langle \sigma_e v_e \rangle + n_H \sigma_{x0} v_0 + n_Z \sigma_{xz} v_0 + n_H \sigma_{i0} v_0 + n_Z \sigma_{iz} v_0 \right) ds. \quad (18)$$

The integral is taken along the path of the beam from entrance to a point on the vacuum chamber wall opposite the injector.

Once deposited, the energetic ions interact with the background confined plasma. Many possible collective thermalization processes have been considered, but the model of successive distant binary encounters, as described by the Fokker-Planck drift-kinetic equation, is thought to be the most accurate. The injected fast neutrals, now fast ions, thus transfer momentum and energy to the plasma and finally join the background, increasing the plasma number density. Calculations with the Fokker-Planck equation yield estimates for these processes that are consistent with the rates observed in a number of present experiments.

The chief effect of contemporary injection experiments is to transfer energy to the background plasma, and thus to heat it to temperatures impossible to obtain by ohmic heating alone. The beam particle input is small by comparison with the particle sources from the walls and aperture limiters.

In some present experiments the beam energy transfer to the plasma is degraded by charge exchange of the thermalizing ions with residual low energy hydrogenic neutrals in the plasma. Although the ratio of hydrogenic neutral/hydrogenic ion densities is typically 10^{-5} , the resonance charge exchange cross section is large enough to produce a significant loss of beam ions during the time (of the order of 10 msec) required for thermalization.

Figure 5 shows a typical computed distribution of fast ions in velocity space. (This is a solution of the Fokker-Planck equation.) There is an empty region in the space of particles traveling counter to

INJECTION / COMPRESSION

CO INJECTED IONS

Fig. 5. A typical distribution of fast ions in velocity space ($v_{\parallel} \equiv \mathbf{v} \cdot \mathbf{B}/B$). The loss region occurs for those values of pitch angle producing orbits that intersect the chamber wall.

the current. This so-called "loss region" is characterized by particle drift orbits whose spatial trajectories cause them to leave the machine and strike the wall. Perpendicular injection, such as will be done on the PDX, also produces such a loss region, especially at low plasma current. The rate at which the beam ions are lost through this gap in velocity space is characterized by the rate of diffusion in the angle made by the ion velocity with the magnetic field. This "pitch angle" diffusion rate is proportional to the rate of momentum exchange with the background electrons and is directly proportional to the plasma Z_{eff} .

The cross sections and the rate coefficient needed for Eq. 18 are obvious examples of atomic data needs. The charge transfer and impact ionization cross sections are needed for quite a large number of species and over a fairly wide range of energies. These quantities are also needed for plasma diagnostics and for estimates of plasma cooling caused by impurity ions. One wishes to ascertain, largely from spectroscopy, the chemical composition (i.e., the n_k) and the charge state distribution (i.e., the Z_k) for the positive ion species in the plasma. Estimates of the plasma cooling processes will require knowledge of the dielectronic and radiative recombination rates for the impurity ions. These topics will be discussed elsewhere in the Institute.

Because these latter processes are important to the overall plasma energy balance and are not unique to the neutral injection process, we will focus on the deposition cross sections in our discussion.

Making reference once more to Fig. 4, we note that the beam deposition profile ceases to be peaked in the center and becomes flat for $a/\lambda \sim 4$. In present tokamaks, the energy confinement is better in the center of the device than at the edge; thus, the peaked profiles in Fig. 4 will produce an efficient plasma heating, and those peaked outwardly will produce poor heating. Not only that, but such outwardly peaked profiles will also produce a stronger interaction with the wall. Thus, $a/\lambda \sim 4$ represents the lower limit of adequate beam penetration; larger values are deemed unsuitable.

A very effective cooperative atomic physics/fusion effort has succeeded in the past few years in finding the charge exchange cross section for interaction of impurities and injected ions in the range of

25 keV < $E_0/\text{nucleon}$ < 60 keV. This is the range of interest for experiments up to TFTR. It is found that the electron loss cross section scales as $Z^{1.4}$, and thus $\lambda^{-1} \sim \bar{n}_e \sigma_H$. Hence, the increased capture rate when impurities are present just balances the deficit of scattering centers. Thus, previous estimates of neutral beam heating in impure plasmas turn out to be fortuitously correct! Moreover, a previously feared coupling between impurity production and beam trapping is diminished. If the cross-section scaling had been worse, say $\sim Z^2$, then $\lambda^{-1} \approx n_e Z_{\text{eff}}$. As more impurities are created, the beam would be trapped closer to the wall, creating even more impurities, and so on.

Although this instability will not occur when charge exchange is the dominant trapping reaction, it should be noted that work is still needed for impact ionization. The International Tokamak Reactor (INTOR) design study jointly conducted by the U.S., U.S.S.R., CEC, and Japan through the IAEA presently considers the use of 400-keV beams to provide auxiliary core heating. Recent measurements of H_2 impact ionization on multicharged impurities suggest that scenarios requiring long pulse operation of 400-keV beams may well revive concern about the beam deposition instability.

4.4 PLASMA FUELING

As noted previously, the puffing of neutral gas is used to increase the density. The density evolution is determined by

$$\frac{\partial n_e(r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D \frac{\partial n_e}{\partial r} \right) + n_o n_e \langle \sigma v \rangle_{\text{ion}} + \sum_{\text{impurities}} \quad (19)$$

Given the gas inlet rate and the rate at which gas is recycled from the walls, it follows that the net ionization input will depend on the neutral density inside the plasma. Figure 6 shows the dependence of calculated neutral density profiles on the scaling of the $O^{n+} + H^0 \rightarrow O^{(n-1)} + H^+$ charge exchange reaction in the range of 0-1 keV. Order of magnitude changes are seen in the central density, which is calculated to result from a given edge density.

DEPENDENCE OF $n_0(0)$ ON OXYGEN CHARGE EXCHANGE

ASSUME CROSS-SECTION FOR $O^{n+} + H^0 \rightarrow O^{(n-1)+} + H^+$ IS $\sigma = z^\alpha \sigma_{H^0+H^+}$

MINOR RADIUS 20 cm

$$T_e(r) = 1880 (1 - r^2/a^2)^{2.5} \text{ eV}$$

$$T_p(r) = 1000 (1 - r^2/a^2) \text{ eV}$$

$$n_e(r) = 8.10^{13} (1 - r^2/a^2) \text{ cm}^{-3}$$

$$n_p(r) = n_e(r) - \sum_{k=2}^9 (k-1) n_{oxy}^{(k)}(r)$$

$$n_{oxy}^{(k)}(r) = C^{(k)}(r) n_{oxy}^T(r)$$

$$C^{(k)}(r) \rightarrow \text{CORONAL EQUILIBRIUM}$$

$$n_{oxy}^T(r) = n_{oxy}(0) (1 - r^2/a^2) + 10^9 \text{ cm}^{-3}$$

Fig. 6. Effects of hydrogen impurity cross section on calculated neutral densities. For typical TFR parameters, a discrepancy of nearly two orders of magnitude can be produced by varying the scaling of the cross section.

Isler and Crume²² have recently reported an experiment in which certain spectral lines of O^{5+} and O^{6+} appear too anomalously intense to have been produced solely by electrons. Estimates from the calculated $C^{4+} + H^0 \rightarrow C^{3+} + H^+$ reaction allowed these authors to speculate that the emission from $n = 4$ states of O^{4+} and O^{5+} and the $n = 5$ (and possibly 4) states of O^{6+} were enhanced by charge exchange. The anomalous oxygen lines (115 Å for O^{5+} and 81.9 Å for O^{6+}) originate from levels that could be populated by charge exchange.

The fusion significance of this result is that radiative losses from oxygen are much larger than those that would be calculated neglecting charge exchange. As a result, the "anomalous" transport needed to explain the observed behavior is reduced.

5. CASE HISTORY: CHARGE EXCHANGE CROSS SECTIONS

As an example of the way in which specific new atomic physics information is used in fusion, we retrace the influence that calculation and measurement of beam trapping cross sections have had on the understanding of neutral beam heating experiments.

Originally, several studies showed that impact ionization rate coefficient enhancement due to impurities in the 60-keV/amu energy range could prove fatal for neutral beam experiments such as TFTR. By curtailing the effectiveness of heating after ~300 msec, much of the research value of these experiments would be lost. This conceptual issue led to the identification of the need for knowledge of this cross section as a high priority atomic physics issue. Several theoretical and experimental groups contributed to the measurement of the cross sections,²³ and it was found that earlier predictions of a beam-dominated instability were too pessimistic. However, the effort has just begun to pay off in scientific terms. Prior to these measurements, a diagnostic beam experiment was under way on the TFR tokamak.²⁴ By measuring the attenuation of a low current, 10-20-keV beam, it was hoped to be able to extract the ratio n_p/n_e in a plasma with $Z_{eff} \sim 4-6$, which was rich in oxygen. Without detailed knowledge of the trapping cross section,

however, this experiment would have yielded n_p/n_e within limits that were too coarse. Once σ_{cx} was known, however, the experiment produced the first solid measurement of this ratio.

Direct observation of charge exchange trapping on impurities (O^{8+}) was reported on the ORMAK device.²⁵ Here there was some discrepancy with the detailed calculations as to whether the charge states that should be populated by this process were, in fact, those observed.

However, the most important result of this collaboration has been found by Abramov et al.²⁶ They point out that in intense neutral beam injection experiments, the recombination of highly stripped iron ions by charge exchange with H^0 is orders of magnitude higher than radiative or dielectronic recombination rates. Hence, the charge state is reduced and radiative output enhanced. Goldston et al. have shown that the neutral hydrogen produced by charge exchange of beam neutrals with thermal protons produces a neutral density $\sim 10^8 \text{ cm}^{-3}$ in PLT.²⁷ This neutral population is calculated to depress the ionization stage of iron by several states and may explain the large measured power loss from the center of PLT. The charge exchange of H^0 and multicharged ions thus has an important effect not originally considered: the recombination due to this process enhances the line radiation cooling of the plasma core. As beam power is raised, the neutral atom density is raised with it. Thus, higher beam power leads to a higher recombination rate, as well as a higher ionization rate, and not to a simple complete stripping of the impurity ion and the consequent diminution of radiative losses. The now known charge exchange cross sections have led to a more accurate picture of the energy loss processes and have refined our knowledge of the power input deposition.

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APPENDIX A — DEFINITIONS OF SYMBOLS

α	coefficients in expressions for neoclassical fluxes ¹⁵
α_2	
β	ratio of plasma to magnetic field pressure $2\mu_0 P/B^2$
Γ	flux of particles (number/cm ² /sec)
γ	neoclassical coefficient ¹⁵
Δ	width (cm) of radial extent of a magnetic island, width of scrapeoff
ϕ	toroidal angle
λ	mean free path
ψ	magnetic flux produced by the field due to the plasma current (poloidal flux)
ψ^*	helical poloidal flux ¹⁸
σ	cross sections: following are subscripts
	x charge exchange of injected H with plasma hydrogen
	xz charge exchange of injected H with impurities
	i impact ionization of injected H with plasma protons
	iz impact ionization of injected H with impurities
	e impact ionization of injected H with electrons
Σ	source of electrons from ionization of impurities
$\tau_{E,P}$	energy and particle replacement times
r	gyrofrequency $\frac{eB}{m}$
χ	thermal conductivity
a	plasma minor radius
$\underline{B}$	magnetic field
B_T	magnitude of the toroidal component of the magnetic field
c_o	neoclassical coefficient ¹⁵
c_i	neoclassical coefficient ¹⁵
D	particle diffusion coefficient
$\underline{E}$	electric field vector
e	electron charge
I	plasma current
m	mass, toroidal mode number
n	poloidal mode number

$\bar{n}$	average density
P	(scalar) pressure
$\underline{P}$	pressure tensor
q	stability safety factor $\frac{2\pi a^2 B_T}{\mu_0 R I}$
R	plasma major radius, rate coefficient for recombination
$\underline{R}$	friction force vector
r_o	minor radii for sawtooth oscillations
r_s	
S	ionization rate coefficient
T	temperature
$\underline{u}$	plasma flow velocity
v_a	Alfvén speed $\frac{mn}{\sqrt{B^2/2\mu_0}}$
Z	ionic charge
$\langle \rangle$	average over a poloidal flux surface

subscripts

e	electron
i	ion
p	proton
z	impurity

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58. W. R. Ellis, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545

59. H. K. Forsen, Exxon Nuclear Co., Inc., 777 106th Avenue, N.E., C-000777, Bellevue, WA 98009
60. Harold P. Furth, Princeton Plasma Physics Laboratory, Princeton University, Forrestal Campus, P.O. Box 451, Princeton, NJ 08540
61. Roy W. Gould, California Institute of Technology, Mail Stop 116-81, Pasadena, CA 91125
62. Robert L. Hirsch, Exxon Research and Engineering, P.O. Box 101, Florham Park, NJ 07932
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64. V. E. Ivanov, Physical-Technical Institute of the Ukrainian SSR Academy of Sciences, 310108 Kharkov, U.S.S.R.
65. A. Kadish, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
66. E. T. Karlson, Department of Technology, Box 534, S-75121 Uppsala, Sweden
67. Y. Kiwamoto, Research Institute for Energy Materials, Yokohama National University, Yokohama 232, Japan
68. R. N. Kostoff, Office of Fusion Energy, Department of Energy, Room 509, 401 First Street NW, Washington, DC 20545
69. L. M. Kovrizhnikh, Lebedev Institute of Physics, Academy of Sciences of the U.S.S.R., Leninsky Prospect 53, Moscow, U.S.S.R.
70. Guy Laval, Groupe de Physique Théorique, Ecole Polytechnique, 91 Palaiseau, Paris, France
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78. Oscar P. Manley, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
79. D. G. McAlees, Exxon Nuclear Co., Inc., 777 106th Avenue, NE, Bellevue, WA 98009
80. J. E. McCune, School of Engineering, Department of Aeronautics and Astronautics, Bldg. 37-391, Massachusetts Institute of Technology, Cambridge, MA 02139
81. A. T. Mense, Subcommittee on Energy Research and Production, B-374, Rayburn House Office Building, Washington, DC 20515
82. Claude Mercier, Service du Theorie des Plasmas, Centre d'Études Nucléaires, Fontenay-aux-Roses (Seine), France
83. K. Nishikawa, Institute for Fusion Theory, Hiroshima University, Higashisendamaichi, Hiroshima, Japan
84. Burnet Outten, Jr., Western Metal Products Company, 1300 Weber Street, Orlando, FL 32803

85. R. E. Papsco, Grumman Aerospace Corp., 101 College Road,
Princeton, NJ 08540
86. Octavian Petrus, Supervisor, C.T.R. Theory Group, Plasma
Physics Laboratory, AL. I. CUZA University, Iasi, ROMANIA,
6600
87. D. Pfirsch, Institute for Plasma Physics, 8046 Garching bei
München, Federal Republic of Germany
88. Plasma Physics Library, c/o Dr. Philip Rosenau, Department of
Mechanical Engineering, Technion-Israel, Institute of
Technology, Haifa, Israel
89. Plasma Physics Group, Department of Engineering Physics,
Australian National University, P.O. Box 4, Canberra A.C.T.
2600, Australia
90. A. Rogister, Institute for Plasma Physics, KFA, Postfach 1913,
D-5170, Jülich 1, Federal Republic of Germany
91. W. Sadowski, Office of Fusion Energy, G-234, Department of
Energy, Washington, DC 20545
92. V. D. Shafranov, I. V. Kurchatov Institute of Atomic Energy,
46, Ulitsa Kurchatova, P.O. Box 3402, Moscow, U.S.S.R.
93. Yu. S. Sigov, Institute of Applied Mathematics of the U.S.S.R.
Academy of Sciences, Miuskaya, Sq. 4, Moscow A-47, U.S.S.R.
94. W. M. Stacey, Jr., School of Nuclear Engineering, Georgia
Institute of Technology, Atlanta, GA 30332
95. V. I. Tereshin, Physico-Technical Institute of the Ukrainian
SSR Academy of Sciences, Kharkov, 310108 Kharkov, U.S.S.R.
96. J. B. Taylor, Culham Laboratory, United Kingdom Atomic Energy
Authority, Abingdon, Oxon, OX14 3DB, United Kingdom
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Tokai, Naka, Ibaraki, Japan
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Uji, Kyoto, Japan
99. Francisco Verdaguer, Director, Division of Fusion, Junta de
Energia Nuclear, Madrid 3, Spain
100. Office of Asry UC-20 g, Theoretical Plasma Physics
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