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Role of Impurities in Magnetically Confined High Temperature Plasmas *

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In the late 1950's there was overwhelming optimism in controlled fusion research that high temperature plasmas could be achieved and fusion energy would be a reality. This optimism gave way to a period of pessimism in the 1960's when all plasmas were beset by instabilities, including a universal instability. Beginning in 1970 theoretical studies indicated that most of these instabilities did not exist or ways could be found to reduce the instabilities to an acceptable level. These studies, along with the success of the tokamak plasma experiments, have initiated a period in which extrapolations have been made to thermonuclear type reactors. In 1976 the cycle has been completed and a high degree of optimism exists. Since the tokamak approach has been chosen as the most likely method to achieve thermonuclear type plasmas using magnetic confinement, the role that impurity atoms and ions play in limiting the plasma temperature has been studied intensely during the past few years. This paper summarizes the atomic physics concerned with plasma cooling by impurities and the limiting effect that impurities may have on heating of plasmas by neutral injection.

A general description is given of the tokamak concept and the present and next generation experiments are described. The time and spatial behaviour of O and Mo multicharged ions in present hydrogen plasmas is presented. This is followed by a discussion of the power loss from a plasma containing one per cent Fe. Finally, the limitation of plasma heating by energetic H or D injection is summarized.

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9/16 = 97%

Shown in Fig. 1 is a schematic diagram of a tokamak plasma. The toroidal field coil generates a magnetic field B_T of 25-50 kg around the torus. H_2 gas at a pressure of approximately 10^{-4} torr is admitted to the torus and the application of a rf voltage produces a glow discharge. Applying a pulsed voltage to the ohmic heating coil induces a voltage around the torus of 400-500 V which drives the plasma current I_p . A large iron core yoke increases the coupling between the ohmic heating winding and the plasma. As the plasma conductivity increases due to the heating by I_p , the induced torus voltage decreases to a few volts. To prevent the shorting out of the induced voltage, a ceramic break must be inserted in the liner or the liner must be made of very thin SS with a high resistivity. Since the magnetic field decreases with the major torus radius, a vertical field coil creates a B_z field which centers the plasma in the liner. Also, since a cylindrical plasma tends to expand radially, a conducting shell is placed around the plasma to force the plasma inward. The large current flow I_p creates a magnetic field B_p when combined with B_T results in a helical magnetic field that gives the plasma its dynamic stability. Not shown is a 1-2 cm annular W or Mo ring, known as the limiter, that prevents the plasma from coming into direct contact with the walls.

In Table I the parameters of the present generation tokamak plasmas are tabulated. Without neutral particle injection heating, the maximum ion temperature has been less than 1 keV. The higher temperatures have been obtained with this additional heating. Table II tabulates the anticipated parameters of the next generation of machines which are designed to use D-T as a fuel and produce power but not economically. The JET experiment is the joint European tokamak, TFTR is to be constructed and installed at Princeton, T-20 is the Soviet facility and the JT-60 is the Japanese entry into the field.

Plasma impurities arise from electromagnetic radiation and energetic neutral particles impinging on the confining walls which are usually fabricated of SS or Au. Adsorbed gases and the wall materials are either sputtered or desorbed and flow into the plasma where they are immediately ionized. In addition to this source of impurity, the plasma comes into direct contact with the limiter and sputters or evaporates W or Mo into the plasma. Table III lists the impurities that have been found in the Oak Ridge ORMAK. The most abundant impurities are C and O. These impurities have been identified by measurements of line radiation. At the present time the energy levels of Au and W multicharged ions are not known with sufficient accuracy to be used to identify these elements in the complicated spectra usually observed in these high temperature plasmas.

In the interpretation of optical radiation and the modeling of plasma dynamics, the assumption is usually made that corona equilibrium exists in the plasma. In steady state corona equilibrium the assumptions usually made are:

1. Instead of each collisional process being balanced by its inverse process, as in local thermodynamic equilibrium, the balance is between collisional ionization and excitation and recombination, including both radiative and dielectronic recombination, and spontaneous decay.
2. Plasma is optically thin.
3. Free electrons have Maxwellian distribution.
4. Only a negligible number of plasma ions in excited states.

Using this corona model, optical radiation has been used to study the time and radial distributions of impurities. Figs. 2-4 are measurements of oxygen and molybdenum impurities found in the plasma of the French tokamak, FTR.¹ In Fig. 2 are shown the OIII to OVI profiles as a function of time at the beginning of the discharge. During the first few msec of the discharge higher charge states of oxygen appear. At an electron temperature of 100 eV most of the O is in charge states greater than O^{5+} . Lines of OVII - OVIII are difficult to measure due to background interference. The time dependence of some highly ionized Mo lines are shown in Fig. 3 along with the time dependence of the plasma current. Lines of Mo^{30+} and Mo^{31+} were observed only after 50 msec indicating the time necessary for step-by-step ionization. The radial profiles of O ions are shown in Fig. 4 at a discharge time of 200 msec which was sufficient time for plasma equilibrium to be established. Each charge state exists in a shell within a few cm of the periphery of the plasma where the electron temperature was approximately 100 eV. Fig. 5 indicates the radial distribution of iron ions as calculated by Hogan² for coronal equilibrium. The ratio of the ionic charge species to the total Fe present is plotted as a function of the plasma radius for a central electron temperature of 750 eV. at this temperature approximately 30% of the ions in the central core are in charge state 13.

In understanding the operating characteristics of present plasmas and in modeling future machines, a detailed knowledge of atomic physics of the plasma ions is required. Merts, Cowan, and Magee³ have made computations of the power loss from a hydrogen plasma seeded with 1% iron for relatively low electron temperatures up to temperatures of 10 keV. Atomic processes they included in the calculation were collisional excitation and ionization, both radiative and dielectric recombination, and free-free or

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bremsstrahlung radiation. Since experimental cross sections are not known for the multicharged Fe ions, they relied on theoretical predictions. For ionization the ionization rates given by Lotz⁴ were used; electron excitation cross sections were those predicted by Bely⁵ and Van Regemorter⁶; dielectric recombination rates from Burgess⁷ and Jordan⁸; and radiative recombination rates from Kramer's formula⁹. The results of these calculations are tabulated in Table IV. The total power radiated from the plasma varies from 4.1 w/cm³ for a low temperature plasma down to 0.42 w/cm³ for a reactor-type plasma with an electron temperature of 10 keV. These power losses can be compared to 1 w/cm³ power production rate in a D-T reactor. In the table collisional excitation refers to the radiative de-excitation following collisional excitation. For plasma electron temperatures below 2 keV the dielectronic recombination loss is greater than the radiative recombination loss. The cross sections and reaction rates used have large uncertainties, such that the radiated power is known no better than a factor of two. Raymond et al.¹⁰ have performed similar calculations with the predicted power loss being a factor of two higher than the results of Merts et al. Computations such as these illustrate the serious need for atomic data to accurately predict the feasibility of economic power production from a thermonuclear reactor with impurities present.

In a tokamak plasma the plasma ions are heated by coulomb collisions between electrons and ions. As the plasma electron temperature approaches 1 keV, the collision cross section becomes small, resulting in inefficient heating of the ions. To overcome this difficulty, plasma heating to higher temperatures is accomplished by injecting large currents of energetic H or D neutrals which are trapped by ionizing collisions. These trapped energetic ions transfer their energy to the cooler plasma ions again through coulomb collisions. During the past few months theoretical studies have indicated that if the impurity ions in the plasma have a large H or D ionization cross section, a beam-deposition instability will develop. The H or D atoms will be trapped at the plasma edge where the ion will be readily lost to the plasma confining walls by charge exchange, since the neutral pressure is high in the plasma periphery. These particles will desorb and sputtering more impurities which flow into the plasma boundary. This process of impurity buildup near the edge may cascade and lead to no plasma penetration or reflection of the injected neutral beam.

The mean free path of a neutral particle injected into the plasma is given by

$$1/\lambda_0 = \frac{n_e \langle \sigma n \rangle_{ion}}{v_0} + n_i \sigma_{cx} + n_i \sigma_i + \sum_k n_k \sigma_k$$

where the trapping or ionization is due to electron impact, charge exchange, and impact ionization on plasma protons, respectively. The last term is the impact ionization by impurity ions. The assumption was made that σ_k is given in terms of the impurity charge Z_k such that $\sigma_k = Z_k^2 \sigma_i$ where σ_i is the proton impact ionization cross section. Ionization of the neutral by charge exchange with impurity ions has been neglected. In plasma physics the impurity concentration is denoted by Z_{eff} which is equal to $(n_i + \sum_k n_k Z_k^2) / n_e$ such that

$$1/\lambda_0 = \frac{n_e \langle \sigma v \rangle_{ion}}{v_0} + \frac{n_i}{n_e} \sigma_{ex}(v_0) + Z_{eff} \sigma_i(v_0)$$

where v_0 is the injected neutral velocity. Using this expression we may calculate the fast ion density profile $H(r)$ in the plasma. The results of the calculation by Hogan¹¹ are shown in Fig. 6 where the fast beam profile and plasma ion temperature profile are plotted as a function of the radius for the proposed TFTR facility. The different curves are for the effective Z which in present plasmas varies between 2 and 10. As Z_{eff} becomes greater the fast ion profile peaks near the plasma edge, the peak ion temperature moves outward. Application of these results to present and future experiments indicate that the present small machines have no penetration problems; the PLT machine being placed into operation at Princeton may have problems; and the future machines will have serious problems even for low effective Z .

The curves in Fig. 6 were obtained under the assumptions that charge exchange cross sections were negligible and the impurity ionization trapping cross sections were equal to the ion charge squared times the proton impact ionization cross section of H atoms. Cross section data pertinent to neutral beam trapping are shown in Fig. 7. Cross sections are plotted as a function of the H ion or atom energy. Shown are the cross sections for trapping by resonant charge exchange; electron ionization of H^0 in plasmas whose electron temperatures are 1 and 10 keV; ionization of H^0 by H^+ ; and ionization or stripping of H^0 by oxygen atoms. These cross sections have been known for several years. Also, plotted in Fig. 7 are some recent unpublished preliminary charge exchange cross sections of Kim, Bayfield and Steison¹² for the reaction $H + Fe^{10+} \rightarrow H^+ + Fe^{9+}$ at equivalent H energies of 70 and 250 keV. The large cross section of $6.6 \times 10^{-15} \text{ cm}^2$ for Fe^{10+} indicates that charge exchange trapping of H cannot be ignored in considering beam penetration into plasmas. On this graph the planned injection D^0 energy of 120 keV for the Princeton PLT plasma experiment would be at 60 keV. To indicate the magnitude and importance of the cross sections involving multi-charged ions, some recent data are also shown at the lower energies. Bayfield at this conference has reported on measurements of light ions in

atomic H. At an equivalent energy of 2.5 keV the charge exchange cross section of O^{5+} in H was 10^{-14} cm^2 . The data for O^{5+} in H_2 are from some recent unpublished work of Crandall et al¹³. The large sketchy cross section data of multi-charged ions clearly indicate the future difficulties of heating plasmas by neutral injection and the increased plasma cooling by charge exchange which has been ignored in the past.

With the available experimental data and theoretical predictions, the future of obtaining high temperature plasmas is doubtful unless some way is found to eliminate impurities or to maintain a low impurity level.

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Table I

TOROIDAL PLASMA PARAMETERS

T_e (Electron Temperature)	1-2 keV
T_i (Ion Temperature)	0.5-2.0 keV
N_e (Electron Density)	10^{14} cm^{-3}
a (Minor Torus Radius)	10-45 cm
R (Major Torus Radius)	0.5-1.5 m
I_p (Ohmic Heating Current)	100-1000 kA
τ_e (Energy Containment Time)	5-60 msec
T (Pulse Time)	50-400 msec
P_H (Power of Injected Neutrals)	100-400 kW

Table II

NEXT GENERATION TOROIDAL MACHINES

	<u>JET</u>	<u>T-2R</u>	<u>T-20</u>	<u>JT-60</u>
R (m)	2.96	2.48	5.0	3.0
a (m)	1.25	0.85	2.0	1.0
I _p (MA)	4.8	2.5	6.0	3.3
T _i (keV)	5.0	6.0	7-10	5-10
T _e (keV)	5.0	6.0	7-10	5-10
N _e (cm ⁻³)	5 x 10 ¹³	4 x 10 ¹³	5 x 10 ¹³	2-10 x 10 ¹³
N τ _e (cm ⁻³ sec)	5 x 10 ¹³	1.5 x 10 ¹³	1 x 10 ¹⁴	2-6 x 10 ¹³
T (sec)	15	1.0	5-20	10
Neutral Injection Power (MW)	3-25	12-40	60	10-20
D ⁰ Energy (keV)	160	120	160	100

Table III

IMPURITIES FOUND IN ORMAK PLASMA

<u>Element</u>	<u>% Abundance</u>
He	trace
Be	< 1.0
C	1.0 - 5.0
N	trace
O	1.0 - 2.0
Na, Cl, Ca	< 0.1
Si	< 1.0
S	~ 0.1
Cr, Mn, Ni	unknown
Fe	< 1.0
Cu, Ag, W, Pt, Au	unknown

Table IV

POWER LOSS FROM FE-SEEDED PLASMA

$N_e = 10^{14} \text{ cm}^{-3}$

$N_{Fe} = 10^{12} \text{ cm}^{-3}$

T_e (keV)	Total Power Loss w/cm ³	Coll. Excit		Recombination		Free- Free
		$\Delta n = 0$	$\Delta n \neq 0$	Diel.	Rad.	
0.8	4.1	2.2	1.1	0.78	0.04	0.02
1.5	1.5	1.1	0.20	0.12	0.09	0.04
2.0	0.76	0.46	0.12	0.05	0.08	0.04
5.0	0.42	0.05	0.17	0.02	0.11	0.07
10.0	0.42	0.004	0.14	0.01	0.16	0.1

FIGURE CAPTIONS

- Fig. 1: Schematic diagram of the tokamak fusion plasma experiment.
- Fig. 2: The evolution of charge states of O with time for the FTR plasma experiment. Also shown is the plasma electron temperature during the formative stage of the discharge.
- Fig. 3: The appearance of highly ionized states of Mo during the FTR discharge. Shown as I_p is the time dependence of the plasma current used to ohmically heat the ions.
- Fig. 4: Radial profile of O ions in the FTR plasma. These profiles were taken at 200 msec after the initiation of the discharge.
- Fig. 5: Calculated radial profile of Fe ions in a 750 eV plasma assuming corona equilibrium.
- Fig. 6: The radial profile of the fast ion density and ion temperatures in the proposed TFTR as the impurity effective charge changes.
- Fig. 7: Atomic cross sections pertinent to the trapping of a neutral H beam in high temperature plasmas.

TOKAMAK

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