

CONTROL OF IMPURITIES IN CONTROLLED FUSION MACHINES*

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Keywords: Impurities; Controlled FusionCompounds: Sputtered atoms, ions and moleculesABSTRACT

Recent advances in Tokamak research have given promise that the next generation of machines may approach break even conditions. Nonetheless, calculations show that quasi-steady state fusion reactors may be plagued by high Z impurities causing intolerable radiation losses. The present state of knowledge concerning impurity release rates and mechanisms resulting from plasma-materials interactions as well as impurity transport and detection diagnostics, is reviewed. Various impurity control methods are discussed which either are being currently used or have been proposed and are in the development stage.

The paper attempts to convey to the non-specialist an impression of the magnitude and importance of the impurity control problem and points to areas where plasma chemical insights can aid in the development of better approaches to impurity control.

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1. INTRODUCTION

In the quest for inexhaustible, economical and environmentally acceptable energy sources, certain aspects of plasma chemistry seem destined to play an important role. This turn of events has come about because improvements in the performance of magnetically confined fusion devices depend in large measure on better control of impurities resulting from plasma-materials interactions.

It will become apparent in the discussion to follow that important mechanisms of impurity release and transport are strongly influenced by plasma chemical processes. Effective control methods can therefore be fully developed only as a result of a better understanding of the chemical parameters involved in the generation of impurities. In a D-T fusion plasma, impurities not only dilute the fuel but also cause direct energy loss by line, recombination and bremsstrahlung radiation as well as by increasing particle diffusion rates and heat conduction. Furthermore, the ionization of impurity atoms and consequent addition of cold electrons contribute to plasma radiation losses.

The significance of impurity radiation in Tokamak plasmas is well established. Moderate and high-Z impurities from the wall and limiter were observed for example by Hinnov, et al, on the ST Tokamak (1). Radiation from such impurities accounts for a large fraction of the energy loss from present Tokamaks and is expected to be one of the limiting factors in the performance of break-even fusion devices and future reactors (2-4).

Calculations of impurity radiation in hydrogen plasmas have been published in recent years (5-11). Such calculations were examined recently by Vernickel and Bohdansky (12) for quasi-stationary fusion reactor plasmas (corona equilibrium) and were found by them to be expressible in terms of a relatively simple relationship valid for temperatures in the range 1-100 Kev. A plot of the critical impurity concentration, f_c , as a function of Z, the atomic number is shown in Fig. 1 for temperatures of 12 and 35 Kev. It can be seen that the critical impurity concentration, defined as that concentration at which the power radiated by hydrogen bremsstrahlung plus impurity radiation just equals the power gained from fusion alphas, must be kept below $\sim 1\%$ for $Z \geq 20$ and below $\sim 0.1\%$ for $Z \geq 50$ in order for the fusion reaction to be sustained for an extended period of time.

Using the presently available data base, a dynamic simulation of the burn-cycle in an experimental power reactor was performed (13). This study, concluding that the burn was quenched immediately by radiative power loss from impurities when a bare stainless steel first wall was used, highlighted the importance of impurity control for Tokamak fusion reactor operations.

It was recognized by Stacey, et al, (13) and by other workers in this field that the mathematical models developed for particle fluxes to the first wall, for impurity sources to the plasma and for relative impurity concentrations in the plasma at equilibrium, are based on inadequate factual information concerning most of the important phenomena governing the fate of impurities. A sizable effort is under way at many fusion

energy research centers around the world to rectify this situation. The present paper attempts to summarize this work under three different headings:

- Impurity release rates and mechanisms
- Impurity detection and transport
- Impurity control

It is hoped that increased understanding of these topics will lead to rational solutions to the "impurity problem" in Tokamaks and thus make a contribution to bringing about the era of fusion energy.

In this paper, only terse summaries of the subject matter can be given. For more detailed information, the reader is referred to several review papers, and proceedings of symposia devoted to plasma-wall interactions (14).

2. Impurity Release Rates and Mechanisms

We take as a basis for discussion a beam driven D-T Tokamak (TFTR) (15) or an ignited Tokamak reactor (UWMAK III) (16) which derive their energy from the reaction



The plasma parameters and power balances expected for these machines are listed in Table I. The ranges and energies of particle and photon fluxes on surfaces exposed to the plasma will determine impurity release rates but these quantities can only be estimated at the present time (17) because they are strongly dependent on the details of machine operation. Nonetheless, in order to obtain some impression of the magnitude of the problem, expected fluxes are listed for a reactor grade plasma as follows: $10^{18} - 10^{20}/\text{m}^2/\text{sec}$ D° , D^+ , T° and T^+ at energies of a few volts to a few kilovolts; $10^{16} - 10^{18}/\text{m}^2/\text{sec}$ $\text{He}^+(1-3.5 \times 10^6 \text{ ev})$; $10^{15} - 10^{17}/\text{m}^2/\text{sec}$ impurities ($1-10^4 \text{ ev}$); $10^{17} - 10^{19}/\text{m}^2/\text{sec}$ electrons ($1-10^5 \text{ ev}$); $\sim 100 \text{ W}/\text{cm}^2$ photons ($10^{-3} - 10^4 \text{ ev}$). The flux of D° and T° particles with energies below 1 ev can reach $10^{22}/\text{m}^2/\text{sec}$ and the 14 Mev neutron flux will be $\sim 10^{18}/\text{m}^2/\text{sec}$.

In order to obtain reliable numbers for impurity release rates, it will be necessary to have detailed information on the energy spectra and fluxes to plasma exposed surfaces of particles and photons so that yield data for impurities originating from a wide variety of bombarded surfaces can be determined. Synergistic effects on sputtering yields due to simultaneous bombardment of a surface by a variety of particle and photon fluxes need to be taken into account (18,19). Finally, fluxes have to be known during each phase of device operation including start-up, heating, burn, fueling, shutdown and failure modes.

Much has been done to improve the data base in these areas in the last ten years but it is clear that a great deal more work remains to be accomplished before quantitative impurity release rates can be determined.

Before discharge cleaning techniques came to be routinely used (20), impurities were constituted primarily of oxygen and carbon released by a variety of desorption processes. In clean Tokamaks, metal impurities presumably produced by sputtering, arcing, cracking and evaporation came

to the fore. It is thought that hydrogen isotope recycling is in part responsible for metal impurity release from walls and limiters. Indeed, surface analytic and spectroscopic studies have shown that trapping and subsequent re-emission of hydrogen isotopes from walls dominate the fuel balance in ungettered discharges (21). On the average, all plasma particles hit the first wall and are recycled into the plasma 5-10 times during one discharge. Part of the ions leaving the plasma are directly backscattered from the first wall into the plasma as neutrals with energies up to near the incident energy. Those ions not directly backscattered become neutralized and come to rest in the solid, thus contributing, for example, to the T-inventory. After slowing down, they generally occupy interstitial positions and may diffuse further. Depending on the solubility, the diffusibility and the barrier at the surface, they may either diffuse into the bulk of the solid, they may be trapped in the implanted layer or they may in part diffuse to the surface and be re-emitted into the plasma as cold hydrogen atoms or molecules. Re-emission and trapping processes must be quantified in first wall materials to establish how surface properties affect the phenomena.

Accurate measurements of sputtering yields from particles escaping the plasma and impinging on first-wall materials are required in order to assess the importance of physical sputtering to the impurity generation problem, to the long-term integrity of first-wall materials, and to provide data for plasma modeling calculations.

Information concerning interactive effects on sputtering, including sputtering of alloys and compounds, preferential sputtering, and the effects of near-surface radiation damage and diffusion on sputtering, is required. A more complete understanding is needed of the effects of surface structure and surface chemistry on the sputtering process. Finally, theoretical models suitable for use in predictive modeling codes need to be developed and verified, particularly as regards the theory of light ion sputtering.

To fully understand the influence of sputtering on plasma behavior one would need to study sputtering of realistic surfaces carrying absorbed, chemisorbed, and implanted impurities. One must monitor not only the gross material removal rate but also the nature of the molecular and atomic species which are ejected. It is particularly important to include sputtering by plasma impurity species. While their flux may be lower than that of hydrogen, their sputtering coefficients are much higher, so that their contribution is significant.

An operating CTR device produces an extremely reactive chemical environment, the most important aspect of which is the highly reducing atmosphere resulting from the active forms of hydrogen that are produced.

Chemical sputtering occurs when a bombarding species forms a volatile compound with the target material. An obvious example is the bombardment of carbon with hydrogen where at elevated temperatures (e.g., 600° C) formation of CH₄ occurs with a simultaneous large rise in sputtering yield (22,23). Similar effects have been found for silicon carbide and boron carbide; however, the surface becomes depleted in carbon as sputtering progresses at elevated temperatures, and chemical sputtering tends

to disappear (24,25).

Desorption of impurities adsorbed on the first wall and limiters may significantly contribute to the total impurity influx into the plasma during a discharge. In addition to thermal desorption, one must consider ion and neutral atom impact desorption, electron induced desorption and photon induced desorption (26-33).

Factors influencing the desorption cross sections of surface species are: 1) the composition, binding energy, and location of the adsorbate; 2) the composition, topography, and temperature of the substrate; and 3) the composition, energy, and direction of the ion or neutral flux at the surface.

Thermal vaporization of wall, limiter, and beam dump material could be a serious contributor to plasma impurity release. The situation is complicated by changes in surface topography and surface roughness due to sputtering, blistering and gas re-emission which could greatly alter the kinetics of the vaporization process from those derived from equilibrium vapor pressure measurements. The high power levels of photon radiation emanating from the plasma and its partial absorption by the near-surface regions of the wall is expected to raise the surface temperatures to levels which depend not only on the material, but also on its surface condition which may vary in different locations in the Tokamak.

Blistering has been found to occur in a variety of helium implanted metals (34-36). The simultaneous irradiation with hydrogenic and helium ions can also present a serious blistering problem because of synergistic effects. Although there is a paucity of data, a D-T fusion environment appears to be highly conducive to such synergistic effects.

Erosion rates associated with helium blister exfoliation may exceed the sputtering produced by energetic helium particles escaping from the plasma.

Unipolar arcing is being recognized as possibly a major source of plasma impurities (37). Evidence for the presence of arcs has been found on the torus wall, on fixed and movable limiters and on specially prepared probes which have been inserted into the vacuum vessel (38). Two types of arcs have been observed; one is fernlike, the other consists of narrow linear tracks.

All of the impurity release mechanisms mentioned and briefly described above will be operative in fusion reactors. Their combined effects on impurity release rates are continuously being studied and assessed. In the following section, the fate of impurities, once created in a fusion machine, will be discussed.

3. Impurity Transport and Detection

Certain theoretical models predict that impurity ions do not recycle along with the hydrogenic particles, but rather continuously accumulate in the plasma (39,40). However, experiments are contradictory in that some results have been interpreted as showing no evidence for appreciable peaking while others indicate neoclassical behavior, including

inward diffusion at a rate close to that predicted by theory (41). The situation in next generation Tokamaks will be such as to decouple MHD and neoclassical processes. Theoretical calculations of impurity transport will therefore have to be done in both the collisionless and the plateau regimes as well as in a variety of mixed regimes. The theoretical problem is to calculate the diffusion mechanisms and to predict the spatial and temporal evolution which should be observed given certain impurity production characteristics.

In the absence of a generally applicable theory of impurity transport, the experimental approach has been to define first the chemical composition of the plasma and to measure the confinement properties of the impurities that are found. This requires knowing (a) the production rate of impurities at the wall or limiter; (b) measuring their temporal and spatial evolution in the discharge; (c) determining the nature as well as the temporal and spatial redeposition of the impurities. The impurity cycle is illustrated schematically in Fig. 2. Impurities are born at surfaces (wall, limiter, beam dump, etc.) exposed to the plasma as a result of the various release processes discussed in the previous section. They travel toward the plasma edge, are stripped of electrons and become part of the plasma. Finally, in part during and in part after the termination of the discharge, impurities are implanted or deposited on Tokamak surfaces.

Early in the development of magnetically confined fusion machines, techniques were developed for measuring the effective Z 's of plasmas and more specifically the ionic composition of plasmas. Only later were surface analytical techniques employed to study impurities in the plasma edge and particularly the redeposition of impurities. The development of suitable diagnostic methods for studying the creation of impurities at surfaces before they are ingested by the plasma is still in its infancy. Clearly, a history of the life cycle of impurities requires all three diagnostic disciplines to work in concert so as to develop a complete picture against which to test theories of impurity transport and confinement. In the following, a brief description will be given first of the methods for determining impurities in plasmas; next of the surface analysis of redeposited impurities and finally of the laser fluorescence technique and its possible use in the determination of impurity fluxes at walls.

Impurities can be divided into two classes: "light" which are completely ionized and "heavy" which are not completely stripped in the plasma center. Since Tokamak plasma have central electron temperatures of a few Kev, the impurity lines are emitted in the VUV and soft x-ray region. Emission lines of the light ions are well known up to the last ionization stage. Unfortunately, this situation does not apply to heavy metallic impurities (42,43,44) where little information is available, for example, on highly ionized Mo or W. Nonetheless, spectroscopic measurements make very important contributions to an understanding of plasma behavior. Oxygen is usually the most abundant impurity ($\sim 1-10\%$). The actual concentration in a given discharge depends primarily on the previous history of the machine with little dependence on discharge parameters. Metallic impurities have lower concentrations (0.1-0.01%) but are still sufficiently abundant to contribute to plasma resistivity and radiation losses. It should be noted however, that after discharge cleaning, the oxygen

concentration decreases and in some experiments this appears to be accompanied by an increase in metallic impurities. The reason for this effect is far from clear (49).

The most desirable way of measuring Z_{eff} of a plasma would be through a complete inventory of impurity ion concentrations, preferably spatially and temporally resolved, via spectroscopy. In part because of the paucity of spectroscopic data, such a goal is probably unrealistic. Some indirect methods for measuring Z_{eff} , such as plasma resistivity, beam attenuation, angular scattering of fast ions and collective laser scattering have been developed (44) but their discussion is beyond the scope of this paper.

Impurity transport rates and the origin of surface impurities have been important questions to which quantitative answers are beginning to be obtained by surface analytical techniques as embodied in QWASS (45), SAS (46) and SXAPS (47) diagnostics. In general, results from these experiments show a build up of wall and limiter material on the surface probes implying a continual redistribution of surface materials inside the Tokamak vacuum chamber. The plasma edge diagnostic developed by Cohen and Dylla (48) is a material probe inserted into the plasma edge used to measure the flux and energy distribution of impurity ions which impact on and inbed in it. The probe, a continuous moving metal belt allows 1 ms time resolution. After a discharge, the tape is translated back to an analysis area where the surface concentration of the implanted atoms are measured by Auger electron spectroscopy. This is converted to the flux by taking into account the angle of impact and the time resolution. The energy distribution is unfolded from the departure of the implantation profile from geometric optics. Time resolved fluxes of C and O to the tape, obtained during beam heated discharges have shown that the oxygen is in synchronism with the beam heating.

Perhaps the most elusive part of the life cycle of impurities is their birth at a surface and subsequent transport to the plasma edge. The lack of knowledge concerning the quantitative aspects of impurity release behavior in present day Tokamaks is due to the lack of a diagnostic tool for measuring impurity fluxes, and for determining the nature of sputtered species, their energies, angular distributions, charge and excited state fractions and the dependence of these quantities on plasma and surface conditions. Effective impurity control however may hinge on a detailed knowledge of the condition of the surface from which sputtering occurs during the discharge as well as a precise determination of the characteristics of the sputtered species at the instant they leave the surface and before they reach the plasma edge or are redeposited on another surface. The recent successful use of laser fluorescence spectroscopy for studying the velocity distribution, density and flux density of sputtered atoms (50,51,52) has led to a consideration of this technique as a Tokamak diagnostic.

The laser fluorescence technique is sensitive ($\sim 10^5$ sputtered atoms/cm³ can be detected), versatile (by choosing appropriate laser techniques, most of the elements in the periodic table could be analyzed) and flexible (laser optics allow focused beams to interrogate very well defined segments of walls, limiters and protective plates).

A high intensity light beam generated by a tunable dye laser would be introduced either parallel to the wall surface or perpendicular to it through small optical ports in the wall. The densities of the sputtered neutral atoms or ions in an arbitrary velocity interval can be determined by excitation of fluorescence at the Doppler shifted wavelength by proper tuning of a narrow laser line. The determination of the velocity distribution perpendicular to the wall surface is particularly important for the calculation of impurity ionization cross sections in scrape-off layers and divertor chambers and allows one to obtain the density and flux density of impurities at the boundary of Tokamak plasmas. The total sputtered particle density, measured by choosing a sufficiently broad bandwidth for the laser radiation, could in principle be measured with high particle detection sensitivity.

4. Impurity Control

The goal of the study of impurity release rates, and mechanisms, their detection and transport is, ultimately, the development of methods for reducing the level of impurities that find their way into Tokamak plasmas.

The present state of knowledge in this field gives only a partial understanding of the many subtle factors that govern plasma-materials interactions. Consequently, the methods used today to control impurities are to a degree empirical in nature and cannot yet be precisely defined. It is likely that in the end a variety of approaches will be used to keep plasma impurities at minimal levels.

The techniques are conveniently divided into divertor and non-divertor methods. The latter depend on modifications of one sort or another of the composition or structure of the surfaces facing the plasma. Methods for enhancing the ion fraction sputtering yield of surfaces can be expected to make their greatest contribution to impurity control in divertor operated machines. Therefore, divertor and non-divertor methods are to a degree interrelated.

The objective of a magnetic divertor, first suggested by Spitzer, (53) is to reduce the plasma wall interaction by magnetically channeling charged particles near the wall into a remote divertor chamber where they are trapped and/or pumped away. Impurities leaving the wall as ions or ionized in a scrape-off layer before reaching the magnetic surface called the separatrix are swept into the divertor chamber. A strong reduction of plasma core radiation by heavy ions has been demonstrated by all divertor experiments performed so far (54).

Discharge cleaning methods of one kind or another have come to be an important aspect of Tokamak operation. They tend to be very effective in decreasing low Z impurities such as O and C by removing them in the form of H₂O, CH₄, CO and CO₂. Relatively low power hydrogen discharges are used for this work and different groups have explored a variety of techniques (55-59). It is possible that a better understanding of the surface chemical processes underlying the discharge cleaning procedures could lead to the development of more effective methods.

Still another impurity control approach that is currently being pursued

in a number of different laboratories is the development of protective, generally low-Z coatings, which appear to be desirable even for near term machines such as TFTR on limiters, protective plates and beam dumps.

Among the possible candidates, graphite, tungsten, molybdenum and copper may serve as substrate materials with carbides (e.g., SiC and B₄C), borides (e.g., TiB₂) nitrides and silicides as candidate coatings. Conventional techniques such as high temperature CVD and plasma spraying could be used to apply the coatings. Their use in TFTR and other plasma devices will depend on the outcome of a variety of materials testing procedures (60).

The need to control plasma recycling has led to the use of trapping surfaces, such as evaporated Ti. Recent dramatic improvements in PLT performance (61) have been ascribed in part as due to Ti gettering action. This subject is of great importance to impurity control since sputtering, which may become the dominant high-Z impurity release mechanism in reactors appears to be closely linked to plasma recycling. However, before the concept of gettering can be applied to D-T devices such as TFTR, a technique for removing the trapped tritium from the Tokamak must be devised. Titanium must be heated to > 500° K before the hydrogen isotopes are rapidly released, a temperature which may be too high for in-situ regeneration. Gettering by bulk getters such as Zr-Al alloys also suffer from the drawback of high regeneration temperatures. There would appear to be a need for the development of high efficiency bulk getters for hydrogen isotopes with relatively low regeneration temperatures. The development of such getters will be contingent on a better understanding of gettering action in a plasma environment.

A novel approach to impurity control is to select wall materials in such a way as to maximize the fraction of atoms which are ejected from the wall as ions (62). Three possible fates of particles ejected from a Tokamak surface facing the plasma are shown in Fig. 3. If the particle ejected from the surface is neutral, it will penetrate the scrape-off region (in a divertor operated Tokamak) to a depth determined by the kinetic energy and trajectory of the particle, and density of the gas in this region. If the particle becomes ionized in the scrape-off region, it will be swept into the divertor. Otherwise, it will penetrate the plasma (a). If, on the other hand, the particle is ejected as a low energy ion, it may simply return to the wall (b). This mechanism of impurity removal would be operative in Tokamaks with and without divertors. If the ion has high kinetic energy, and small ejection angle, it will penetrate to the edge of the scrape-off region and then be swept into the divertor (c). From Fig. 3, it may be seen qualitatively, that the influx of impurities could be strongly affected by the charge state, kinetic energy, and angle of emission of the sputtered particles.

A variety of techniques leading to increased ion fractions are under investigation with a view to assessing the potential of this approach for impurity control in Tokamaks (63-65). For example, oxygen forms an ionic bond with most metals, so that a metal atom ejected from an oxygen covered surface frequently escapes as an ion. High ion fractions achieved in this way could be exploited for impurity control in Tokamaks (67-70).

Another approach to increasing secondary ion fractions makes use of a technique analogous to high energy discharge cleaning to alter the chemical composition of the near surface region, to a depth of several tens of microns. Such in-situ discharge-induced ion implantation techniques could be used to modify Tokamak surfaces in such a way as to lead both to increased ion fraction yields in sputtering and to lower effective-Z than that of the pure metal.

Ion and plasma nitriding are examples of this approach. The nitriding can be easily performed using a low pressure discharge either in pure nitrogen or in a mixture of nitrogen with other gases, generally with hydrogen. The sample to be nitrided can either form the cathode of a D.C. discharge ("ion nitriding") (71) or it can be simply immersed in the plasma at a floating potential (72).

Since adequate plasma confinement and heating seems promising now, impurity evolution and control may turn out to be one of the critical remaining obstacles on the way to economic Tokamak reactors. Which impurity control technique or combination of techniques will be selected for a Tokamak reactor remains an open question.

Clearly this field is a fertile one for the exercise of ingenuity and imagination. New and more effective methods and approaches are sure to emerge as the wider scientific community becomes acquainted with and takes up the challenges inherent in the area of plasma-materials interaction chemistry.

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Table I. Plasma Parameters and Power Balance for a Beam-driven D-T Tokamak and an Ignited Tokamak Reactor.

<u>Plasma Parameters</u>		<u>TFTR</u> ⁽¹⁵⁾	<u>UWMAK III</u> ⁽¹⁶⁾
Discharge Duration	(s)	.5	1900
Time Between Discharges	(s)	300	50
B(O)	(kG)	52	40
I	(MA)	2.5	15.6
R	(cm)	250	810
a	(cm)	85	400
T _e (O)	(keV)	6	23
N _e (O)	(cm ⁻³)	1x10 ¹⁴	2.1x10 ¹⁴
T _i (O)	(keV)	6	18
Z _{eff}		2	1
Dominant Ions in Plasma		T,D,	
Ions in Plasma		(Fe,O)	1
<u>Power Balance</u>			
Fusion Events	(MW)	25	25,000
Ohmic Heating	(MW)	.18	.9
Auxiliary Heating	(MW)	32(.1 s	200(1.4 s
		duration)	duration)
(Neutral Beams - TFTR;RF-UWMAK)			
Loss to Wall Surface	(MW)	47	440
Charge Exchange (E < 300 eV)	(W/cm ²)	.05	0.01
Charge Exchange (E < 300 eV)	(W/cm ²)	3	0.5
Radiation	(W/cm ²)	8	4
Conduction	(W/cm ²)	15	.01
Alpha Particles (c.5MeV)	(W/cm ²)	1	.1*
Neutrons (14 MeV)	(W/cm ²)	20	250
Loss to Limiter	(MW:W/cm ²)	10:2000*	0
or Divertor	(MW:W/cm ²)	9	725:600
*Estimated			

FIGURE LEGENDS

- Fig. 1. Critical impurity concentrations f_c as function of atomic number Z .
 --- $T = 35$ KeV; -·-·- $T = 12$ KeV
 (Adapted from Fig. 3 of Ref. 12)
- Fig. 2. Schematic representation of impurity release processes;
 impurity transport and impurity detection diagnostics.
- Fig. 3. Schematic cross section of a Tokamak with divertor showing
 some of the possible life-cycles of particles released
 from a surface as a result of plasma-materials interactions:
- a neutral atom or molecule
 - a low energy ion
 - a high energy ion

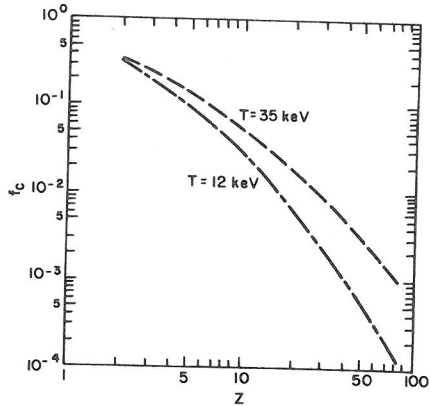


Fig. 1

PLASMA-MATERIALS INTERACTIONS

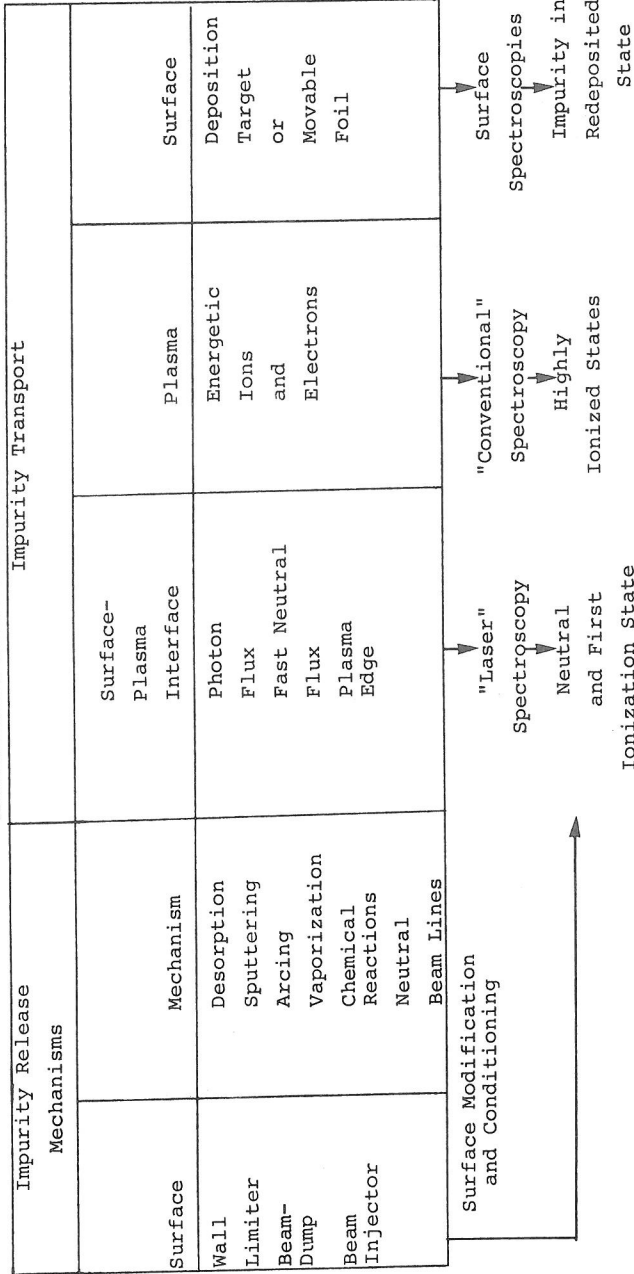


Fig. 2

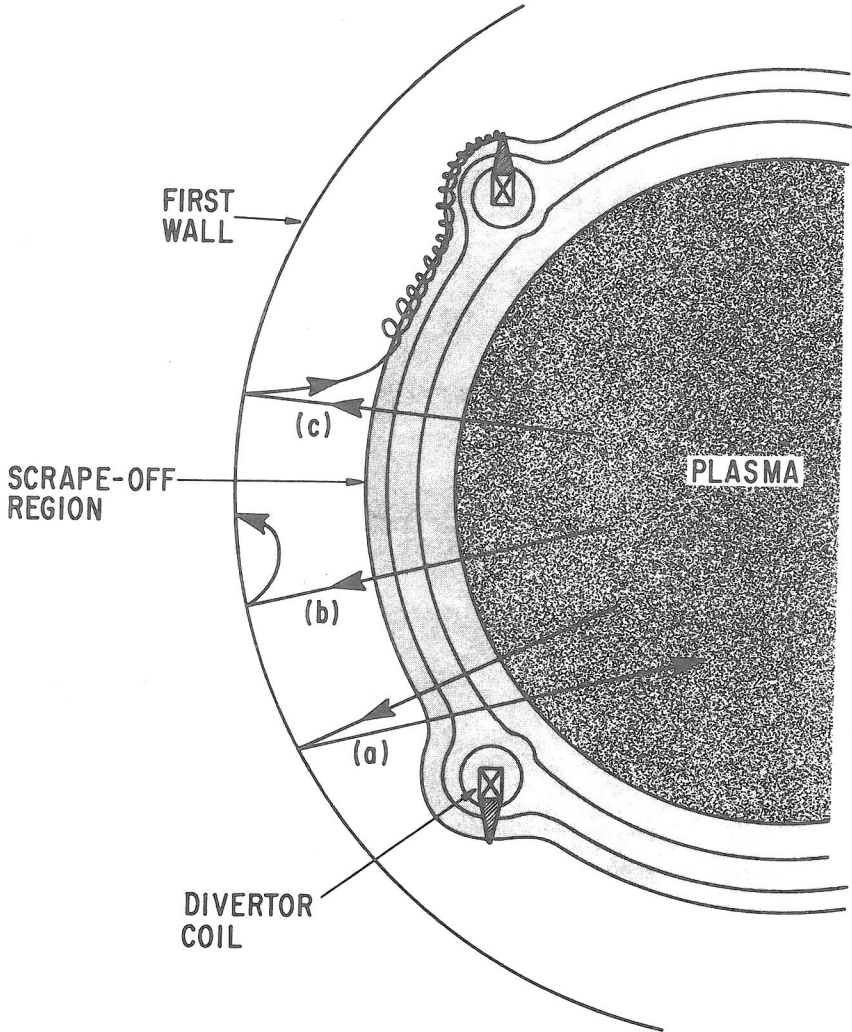


Fig. 3