Dust Particles as a Possible Source of
Impurities in Tokamaks

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A model is proposed where the dust particles are the source of impurity atoms that are present in the early phase of a Tokamak discharge. The model seems to fit the optical observation of the Doublet IIA discharge. Also it explains the relative cleanliness of Alcator compared with the other tokamaks. The direct observations are needed to confirm the hypothesis.

I. INTRODUCTION

Many tokamak experiments show that impurity ions are present in the plasma even at early phases of the discharge. The species of impurity atoms are not limited to the volatile gases but include atoms from nonvolatile sources such as metals. The source may be particulates that might have been produced by blistering or abrasion of walls in previous discharges. We shall consider the conditions in which the impurity atoms start from the wall and reach the center of the chamber.

II. FORCES ON DUST PARTICLES BEFORE THE START OF DISCHARGE

There are many forces acting on particulates in the chamber. We shall make estimates assuming that a particle is a sphere of radius r and density ρ .

a. Gravitational Force F_G

The force is given by

$$F_G = \frac{4\pi}{3} r^3 \rho g \quad (1)$$

where g is the gravitational acceleration.

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b. Electrostatic force F_E

A particle made of an insulator such as metal oxide may cling to the metal wall electrostatically. The force is given by

$$F_E = \frac{(Ne)^2}{4\pi\epsilon_0 4r^2} \quad (2)$$

where Ne is the charge on the particle.

The condition that the electrostatic force is larger than the gravitational force is given by

$$r < \left[\frac{3N_e^2}{(4\pi)^2 \epsilon_0 4\rho g} \right]^{1/5} \quad (3)$$

The charged particles with radius smaller than the value given by Eq. (3) can stick to the wall against the gravity. By using $\rho = 8 \times 10^3 \text{ kg m}^{-3}$, Eq. (3) becomes

$$r < 1.7 \times N_e^{2/5} \times 10^{-7} \text{ m} \quad (4)$$

It is weakly dependent on the number of charges. Only small particles are affected by the electrostatic field.

c. Magnetic Force F_M

If the particulates are of magnetic materials, such as iron, nickel and their oxides, they receive magnetic force while the toroidal magnetic field is on. Since the toroidal field is strong enough, they are magnetized to saturation. The saturation induction B_m is 0.5 to 2 Tesla. The magnetic force is in the direction of the gradient of the toroidal field strength, i.e., towards the major axis of the torus.

It is given by

$$F_M = \pi r^3 \frac{B_m}{\mu_o} \frac{B_t}{R} \quad (5)$$

where B_t is the toroidal magnetic field strength and R is the major radius. The condition that the magnetic force is larger than the gravitational force is given by

$$\frac{B_t}{R} > \frac{3\mu_o \rho g}{4B_m} \quad (6)$$

It is interesting that the quantity B_t/R determines the condition. The plasma current density and the plasma density in tokamaks are proportional to this parameter and set Alcator apart from the other tokamaks. For iron particles, we have $B_m \sim 2T$ and Eq. (6) becomes

$$\frac{B_t}{R} > 3 \times 10^{-2} \quad (7)$$

For iron oxide $B_m \sim 0.6$ and $B_t/R > 0.1$. If the particle consists of a fraction δ iron, then we have

$$\frac{B_t}{R} > 3 \times 10^{-2} \delta^{-1} \quad (8)$$

d. Force Due to Gas Flow F_W

A particle placed in a gas flow with velocity v_o receives a force given by

$$F_W = 4\pi r^2 v_o n \sqrt{2mT} \quad (9)$$

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where n is the gas number density, m is the mass of gas molecules, T is the temperature of the gas, and a long mean-free path for gas molecules is assumed.

For this force to be larger than the gravitational force, we have

$$r < \frac{3v_o n}{\rho g} \sqrt{2mT} \quad . \quad (10)$$

The chamber is usually filled with hydrogen gas at about 10^{-4} Torr. The mean-free path of gas molecules is larger than the minor diameter of the chamber. If the gas is stagnant, the long mean-free path means absence of turbulence and $v_o = 0$. If the gas is continuously fed and pumped, the flow velocity is given by the pumping speed of the toroidal chamber, assuming there is a large enough pumping port. The velocity is given by

$$v_o \approx \sqrt{\frac{2T}{m}} \left(\frac{d}{2\pi R} \right) \quad . \quad (11)$$

By combining Eqs. (10) and (11), we obtain

$$r < \frac{3nT}{\rho g} (d/\pi R) \quad . \quad (12)$$

With a set of parameters : $n = 10^{19} \text{ m}^{-3}$, $T = 300^\circ\text{K}$, $d/R = 1/2$, and $\rho = 8 \times 10^3 \text{ kg m}^{-3}$, Eq. (12) becomes

$$r < 1.5 \times 10^{-7} \text{ m} \quad . \quad (13)$$

When gas or plasma becomes strongly turbulent, the flow velocity approaches the thermal velocity of the molecules or the ions. By reuniting Eq. (9), the force on the particles is given by

$$F_W = 4\pi r^2 \epsilon nT \quad (14)$$

where ϵ is the relative strength of turbulence and $0 < \epsilon < 0.5$. This force is larger than the gravitational force, if

$$r < \frac{3nT\epsilon}{\rho g} \quad (15)$$

With the values of parameters; $n = 3 \times 10^{19} \text{ m}^{-3}$, $\rho = 8 \times 10^3 \text{ kg m}^{-3}$, and $\epsilon = 0.2$, we have

$$r < 4 \times 10^{-5} \text{ (T/e) meter} \quad (16)$$

If the turbulence force is compared with the magnetic force, we obtain

$$r < \frac{4nT\mu_o \epsilon R}{B_t B_m} \quad (17)$$

By using the same set of numbers as in Eq. (16) and also $B_t = 5\text{T}$, $B_m = 2\text{T}$, and $R = 0.5 \text{ m}$

$$r < 2 \times 10^{-7} \text{ (T/e) meter} \quad (18)$$

It takes much more turbulent force to overcome the magnetic force.

e. Other Forces

The adhesive force due to sticky materials such as oil film is not considered here assuming that the discharge cleaning is effective eliminating the contaminants.

III. SIZE AND QUANTITY OF PARTICULATES

We do not have information on the size and quantity of the particulates. Impurity atoms that show up in the plasma are at most 10^{18} atom m^{-3} . The total number is given by $10^{18} \times 2\pi R \pi (d/2)^2$. If they originate from solid state, the volume of the solid is roughly $10^{-11} (\pi^2/2) R d^2 m^3$. For $R = 0.5$ m, $d = 0.2$ the volume is $10^{-12} m^3$ and the mass is about 100 μg .

The distribution $f(r)$ of the size of particulates is not known. We make an assumption that the distribution is given by $f \sim \exp [-r^2/r^{*2}]$ and further that r^* is of the order of surface roughness. The mass distribution is then proportional to $r^3 f(r)$ and therefore has a peak around $(3/2)r^*$. The value of r^* for a typical metal surface is about a micron.

IV. TIME SCALE

After the discharge is initiated, the particulates are lifted from the wall, heated and ablated. Several time scales are important in determining whether the impurity atoms reach the central part of the plasma.

a. Transit Time of Particles

The plasma is very nonuniform and turbulent in the early phase of the discharge. Further the outside region is hotter than the interior due to the skin effect. We assume that there is a large scale turbulence and a particle is accelerated by the "wind" flowing towards the center. The equation of motion of a particle is given by

$$\frac{4}{3} \pi r^3 \rho \frac{dv}{dt} = 4\pi r^2 nT e \quad (19)$$

The time τ_t for the particle to reach the center is given by

$$\tau_t \approx \left(\frac{\rho r d}{6nT_e} \right)^{\frac{1}{2}} \quad (20)$$

With $n = 3 \times 10^{19}$, $\rho = 5 \times 10^3 \text{ kg m}^{-3}$, $\epsilon = 0.2$, and $d = 0.2 \text{ m}$, we obtain

$$\tau_t \approx 13 r^{\frac{1}{2}} (T/e)^{-\frac{1}{2}} \text{ sec.} \quad (21)$$

b. Heating Time and Ablation Time

The particle is first heated by gas and then by plasma as ionization of gas proceeds. The vapor pressure of iron becomes significant at around 1500°C . The vaporization rate is determined by the heat of evaporation and by the heat input rate.

We assume that the heat input per unit area P is given by

$$P = nT \sqrt{2T/m} + \kappa n T_e v_1 + \kappa n \sqrt{2T/m} W_R \quad (22)$$

where κ is the degree of ionization, T_e is the electron temperature, W_R is the effective recombination energy, and v_1 is the effective electron flow velocity. The radiation has been neglected. The velocity v_1 is between the sound wave velocity and the electron thermal velocity depending on the secondary electron emission from the particle. In a low temperature plasma, the gas cloud around the particle is of a low density and the plasma electron can reach the particle surface. Also the metal surface at high temperature can emit thermionic electrons. Thus we assume $v_1 \sim v_e$ (electron thermal velocity). Then the second term is almost always larger than

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the third term and becomes larger than the first term as soon as the degree of ionization reaches a few per cent.

$$P \sim \kappa n T_e \sqrt{2T_e/m_e} \quad (23)$$

where m_e is the electron mass.

The metal particulates have a large heat conductivity, for example, the value for iron is $5 \times 10^2 \text{ W m}^{-1} \text{ }^\circ\text{K}^{-1}$. Therefore the particles are heated uniformly. The heating time τ_H is given by

$$\tau_H = \frac{r T_1 C}{3P} \quad (24)$$

where P is the heat input per unit area, T_1 is the temperature at which vapor pressure becomes significant and C is the specific heat per unit volume. By using $T_1 \sim 1500^\circ\text{C}$, $H_1 = 3.4 \times 10^6 \text{ J m}^{-3} \text{ }^\circ\text{K}^{-1}$, $n = 3 \times 10^{19} \text{ m}^{-3}$, and P given by Eq. (23) we obtain

$$\tau_H \approx 6 \times 10^2 r \kappa^{-1} (T/e)^{-3/2} \quad (25)$$

For $T = 4 \text{ eV}$, $\kappa = 0.1$, and $r = 10^{-6} \text{ m}$, τ_H is $7 \times 10^{-4} \text{ sec}$. This time scale is not very small compared with the plasma temperature change. When the plasma temperature reaches 15 eV and $\kappa = 1$, the time scale becomes very short.

The ablation rate is calculated from the equation given by

$$\frac{d}{dt} \left(\frac{4}{3} \pi r^3 H \right) = 4\pi r^2 P \quad (26)$$

or

$$dr/dt = P/H$$

where H is the heat of evaporation per unit volume and its value for iron is $5 \times 10^{10} \text{ J m}^{-3}$.

The upper limit of the ablated gas density n' may be estimated by assuming that the minimum velocity of the gas is given by the sound velocity at about 2000°K .

$$n' \approx \frac{P}{H} \quad 2.5 \times 10^{-26} \text{ m}^{-3} \quad (27)$$

By using $P \sim n T_e \sqrt{2T_e/m_e}$ and $n \sim 3 \times 10^{19}$, we have

$$n' \sim 10^{22} (T_e/e)^{3/2} \text{ m}^{-3} \quad (28)$$

For a low temperature plasma $T_e < 10 \text{ eV}$, the electrons can penetrate the cloud around a particle of a few micron size. The ablation time τ_A may be calculated from Eq. (26)

$$\begin{aligned} \tau_A &\approx \frac{H}{P \cdot r} \\ &= 6 \times 10^{23} \text{ rn}^{-1} (T_e/e)^{-3/2} \kappa^{-1} \quad (29) \end{aligned}$$

At density of $3 \times 10^{19} \text{ m}^{-3}$, it becomes

$$\tau_A \approx 2 \times 10^4 r (T_e/e)^{-3/2} \kappa^{-1} \text{ sec} \quad (30)$$

c. Mean-Free Path and Transit Time of Ablated Atom

The mean-free path of the neutral atom collision with hydrogen atom is long enough for it to reach the center. The transit time τ_2 is given

$$\tau_2 \sim d/2v' \sim 2 \times 10^{-4} \text{ sec} \quad (d \sim 0.1 \text{ m}) \quad (31)$$

The atom may charge exchange with protons and become ionized. The charge exchange cross-section is of the order of 10^{-19} m^{-2} . The mean-free path λ_{ex} is given by

$$\lambda_{\text{ex}} \sim \frac{v'}{\kappa n 10^{-19} \sqrt{2T/m}} \quad (32)$$

$$\sim \frac{4 \times 10^{17} (T/e)^{1/2}}{\kappa n}$$

The mean-free path for the electron impact ionization λ_{ion} is given by

$$\lambda_{\text{ion}} \sim \frac{1.2 \times 10^{12} v'}{\kappa n} \frac{(T_e/e)^{3/2}}{h(W_i/T_e)} \quad (33)$$

where $h(x) = e^{-1} \int_x^\infty e^{-z} dz/z$ and W_i is the ionization energy of the atoms. The mean-free path λ_{ion} becomes shorter than λ_{ex} , when the temperature reaches about 4 eV, assuming $W_i = 7 \text{ eV}$.

The neutral atoms can reach the center of the plasma, if $\lambda_{\text{ion}} > d/2$ and $\lambda_{\text{ex}} > d/2$. With $n = 3 \times 10^{19} \text{ m}^{-3}$ and $W_i = 7 \text{ eV}$, this corresponds to $T_e < 4 \text{ eV}$ and $\kappa < 0.1$.

e. Experimentally Observed Time Scale

Figure 1 shows the time dependence of some of the emission light in the early phase of discharge in Doublet IIA elliptic discharge. The ionization of hydrogen is complete after about 0.8 msec. The neutral chromium line is present after about the same time. Also there is about 0.4 msec delay between the hydrogen neutral line peak and that of the chromium line.

The data indicate that the process of bringing the metallic atoms in must be fast enough to take less than a msec for the metallic line to appear.

Also it suggests that there is a process which causes a delay between the excitation of hydrogen atoms and metallic atoms.

VI. SEQUENCE OF EVENTS

We shall attempt to construct a model that fits the experimental observation.

We shall consider particulates of which size is $10^{-7} \sim 10^{-5}$ m. The particles smaller than 10^{-7} m do not contain enough numbers of atoms to be important. Also the continuous flow of the filling gas may clean the system of these small particles except the ones electrostatically bound on the wall.

Before the discharge is initiated, the nonmagnetic particles are resting at the bottom of the chamber and the magnetic particles are on the inner (smaller major radius) side of the chamber.

When the discharge is initiated and the plasma reaches 1 eV temperature, all the nonmagnetic particles are lifted from the wall as indicated by Eq. (16). The behavior of the magnetic particles depends on their size and the machine parameter B_t/R . For Doublet IIA where $B_t = 0.7$ T and $R = 0.7$, the particles with radius smaller than

$$r < 2 \times 10^{-6} \text{ (T/e) meter} \quad (34)$$

are lifted. For Alcator where $B_t = 7$ T and $R = 0.5$, the critical radius is

$$r < 1.5 \times 10^{-7} \text{ (T/e) meter.} \quad (35)$$

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Thus the effect of the magnetic field in Doublet IIA is minor but for Alcator, the major part of the magnetic particulates are not able to come into the plasma.

Since the transit time of the particulates given by Eq. (21) is much longer than the observed time scale, the impurity atoms have to reach the central part of the plasma as individual atoms. Further, the mean-free path consideration dictates that the plasma is partially ionized and at a temperature of a few eV. From Eq. (25), the heating time of 1 msec corresponds to a particle size of 1.5 micron. Thus the observed delay time of 0.5 msec can be interpreted as heating time and the particulate size of about one micron may be inferred.

The ablation time is longer than the heating time. Therefore, the evaporation continues as the plasma temperature further increases. However, the impurity atoms will be ionized locally because of the much shorter mean-free path. Since the plasma temperature is already above the first ionization potential, the neutral line intensity should be decreased by this time.

To summarize the sequence, (1) the particulates are lifted off the wall by plasma turbulence early in the discharge. (2) They are heated and vaporized. (3) The neutral atoms can reach the central part of the plasma, while the plasma is cold and partially ionized. (4) To fit the experimental observation, the size of the particle is of the order of one micron. (5) The magnetic particles; iron or iron oxide are affected by the toroidal magnetic field. In a device with a strong field and a small major radius, such as Alcator, the magnetic particulates with a micron radius are inhibited from coming into the plasma.

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VII. DISCUSSION

It is important to test the above hypothesis by further experimental observations. The population and the size spectrum of the particulate should be measured. It may be done by filling the chamber with a gas at a high pressure (1 atm for example) and measure the scattering of the low power laser light. Or a particulate trap may be placed at the end of the bottom port and the size spectrum may be measured under the microscope after many shots. It is also interesting to find out what fraction of particulates is magnetic.

If further observation confirms the hypothesis, then a method of getting rid of particulates should be developed. It may be done by periodic cleaning of the chamber by a gas flow or by designing a wall with a grid or a perforated plate in front of it to prevent the dust particulates from entering the plasma region.

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Fig. 1--Neutral atom emission line intensities as a function of time in the Doublet IIA discharge