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in Magnetically Confined Hot Plasmas. ***

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Capillary hydrogen jetting is generally used for introducing fuel particles into the plasma interior in magnetic confinement fusion experiments. The spatial and time evolution of the initially low-temperature high-density particle clouds forming around such pellets are considered here, with particular attention being given to such physical processes as heating of the cloud by the energy fluxes carried by incident plasma particles, dynamic expansion with $\gamma \approx 1$, deceleration in the transverse direction, finite-rate ionization and recombination processes, and magnetic field convection and diffusion. While the dynamic processes associated with the ionization and radial confinement processes are characterized by the relatively short Alfvén time scale (μ s range), the subsequent phase of axial expansion is associated with a notably larger hydrodynamic time scale defined by the heat input and gasdynamic expansion rates (ms range). Data stemming from experimental measurements in toroidal confinement machines are compared with results of model calculations. Some similarities with space plasmas are briefly discussed.

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EVOLUTION OF PARTICLE CLOUDS AROUND ABLATING PELLETS IN MAGNETICALLY CONFINED HOT PLASMAS

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Abstract

Cryogenic hydrogen isotope pellets are being currently used for introducing fuel particles into the plasma interior in magnetic confinement fusion experiments. The spatial and time evolution of the initially low-temperature high-density particle clouds forming around such pellets are considered here, with particular attention being given to such physical processes as heating of the cloud by the energy fluxes carried by incident plasma particles, gasdynamic expansion with $\vec{j} \times \vec{B}$ -produced deceleration in the transverse direction, finite-rate ionization and recombination processes, and magnetic field convection and diffusion. While the dynamic processes associated with the ionization and radial confinement processes are characterized by the relatively short Alfvén time scale (μs range), the subsequent phase of axial expansion is associated with a notably larger hydrodynamic time scale defined by the heat input and gasdynamic expansion rates (ms range). Data stemming from experimental measurements in toroidal confinement machines are compared with results of model calculations. Some similarities with space plasmas are briefly discussed.

I. Introduction

1.1 Why pellets?

The objectives of pellet injection into fusion plasmas are manifold: replenishment of particle losses, control of density and, to a certain extent, temperature profiles, and, in some cases, creation of certain preferred distributions such as centrally peaked density profiles. Injection of impurity or tracer pellets for diagnostic purposes is another important application of this fuelling method. In future reactor-grade machines, pellet injection is one of the primary candidates for introducing fuel particles into the plasma beyond the edge layer and for producing special scenarios such as sudden density ramp-up and ignition of a preheated but not sufficiently dense plasma.

The characteristics of typical cryogenic pellets currently used are as follows: $T_{pel} = 5$ to $10^0 K$, $n_{D_2} \approx 6 \times 10^{28} m^{-3}$; equivalent (spherical) diameter ≈ 0.5 to $2.5 mm$. The injection velocities applied are of the order of $700 m/s$ (centrifuge-type injectors, repetitive pellet injection) to $\approx 2000 m/s$ (pneumatic guns, injection of single pellets per barrel). Pellet velocities of up to $\approx 4000 m/s$ have already been obtained (envisaged up to $10000 m/s$) with two-stage shock-tube-type injectors. Typical pellet lifetimes in current fusion plasma experiments are of the order of $500 \mu s$.

1.2 Why cloud physics?

A pellet injected into a hot plasma is exposed to the energy fluxes carried by the plasma species present (electrons, ions, both thermal and nonthermal) and erodes or "ablates" at a rate that is defined by the balance between the energy flux available and the flux that is required to remove the particles from the pellet surface and dissociate, ionize, and accelerate them. It was noted already at an early stage of pellet investigations that the cloud formed by the ablated particles around the pellet plays a decisive role in shielding it from the incident energy carriers, thus prolonging its lifetime. There are three types of shielding mechanisms of particular interest: (a) gasdynamic - neutral gas and/or plasma - shielding associated with collisions between the energetic plasma particles and the cold cloud particles [1, 2, 3]; (b) magnetic shielding caused by the partial expulsion of the magnetic field from the cloud interior by the expanding plasma, and the associated reduction of the flux of energy carriers [4]; (c) electrostatic shielding due to a possible negative charge excess of the cold cloud with respect to the hot

background plasma [5, 6]).

The magnitude of these shielding effects determines what fraction of the energy flux carried by the background plasma particles reaches the pellet surface and, consequently, the local ablation rate, the pellet penetration depth, and/or the pellet lifetime. The particle deposition profile plays an essential role in the resulting output characteristics of the fusion machines considered. Hence a thorough understanding of the physical processes that define the cloud evolution is essential from the point of view of reliable ablation theories and predictive models.

There exists some similarity between the physical processes observed in pellet clouds and those found in space plasmas. The mass-loading of the jovian atmosphere by the volcanically active satellite Io [7] induces motion, fields, and currents that may find their counterpart in pellet clouds (see Fig. 1). The magnetospheric barium release experiments produce cloud patterns [8] produce cloud patterns characteristic also for pellet clouds, as can be seen from Fig. 2. Common for all these cases is that a massive source of neutral particles is active in a magnetic field or in a magnetically confined plasma. As soon as the particles become ionized, they interact with the field and perturb or modify the ambient plasma.

II. Pellet Cloud Characteristics

2.1 What has been measured?

The diagnostics hitherto applied to pellet clouds in fusion experiments can be summarized as follows: (a) fast framing camera pictures and time-integrated photography (CCD cameras, etc.) with information on the morphology of the cloud, its shape and expansion rate, and on the evolution of the cloud structure as the pellet moves along; (b) line emission intensity measurements, primarily $H_\alpha(t)$, $H_\beta(t)$ lines but also impurity ion lines; (c) line (Stark) broadening, scattering diagnostics, laser interferometry or laser holography for the measurement of electron density.

In the case of hydrogenic pellets, owing to the approximate constancy of the cross-sections for photon emission and ionization events in certain electron temperature and density ranges, the H_α intensity is often used for determining the local ablation rate.

Figure 2a [9] shows the time development of the visible, i.e. not yet fully ionized,

part of the cloud around an ablating D_2 pellet. The pellet moves with a velocity of ≈ 700 m/s across the plasma. The background electron temperature and density corresponding to this case are $T_e = 500$ eV and $n_e = 3 \times 10^{19} \text{ m}^{-3}$. The exposure time used is $0.2 \mu\text{s}$, the delay between the subsequent exposures is $1 \mu\text{s}$ (the shift of the pellet position within $7 \mu\text{s} : \approx 5 \text{ mm}$). As can be seen, the transverse (B-perp) dimension of the cloud is well defined, apparently by the ionization length. The field-aligned dimension is determined by the unimpeded (practically vacuum) expansion of the ablatant along the field lines. The mass fraction that is not yet completely ionized emits in the visible range. Figure 2b [10] is a time-integrated (CCD camera) picture of a pellet trace. In this case, a D_2 pellet traverses the view field, moving from the bottom towards the top of the picture. A cloud structure consisting of alternating bright and dark stripes which extend along the magnetic field lines can be observed. The wake is slightly curved to the right, which, in the given case, is the direction of the electron drift in the current-carrying background tokamak plasma, and may be due to the asymmetry of the electron fluxes affecting the cloud on the e-drift and i-drift sides. Figure 2b is typical of the vast majority of time-integrated pellet cloud photographs. For the sake of comparison, the visible image of a barium cloud released at a height of $H = 6R_{\text{earth}}$ is shown in Fig. 2c [11]. The picture was taken 2 min after the moment of barium release. The similarity with the pellet clouds shown in Figs. 2a-2b - cigar-shaped elongated structures along the field lines - is apparent.

A typical photodiode signal representing the time history of the H_α emission of the cloud surrounding an ablating pellet, as recorded in the Princeton Large Tokamak, is shown in Fig. 3 [12]. The periodicity of the signal modulation roughly corresponds to the dark-bright striation pattern observed in Fig. 2b. Recordings of the H_α , H_β line emission and the electron temperature that can be deduced from the ratio of the two line intensities, as measured in Texas Tokamak [9], is displayed in Fig. 4. The flying pellet "sees" an environment with a temperature fluctuating between 2 and 6 eV. The maximum electron density in the cloud, recorded in the same experiment, was $\approx 2 \times 10^{23} \text{ m}^{-3}$.

Further results of temperature and density measurements pertaining to the ablatant cloud are available from a number of different tokamaks (TFTR Princeton, TFR Cadarache, ISX-B Oak Ridge, ASDEX Garching; see, for example, [13]). The reported electron temperature and density values in the cloud range from 1.5 to 6 eV and $\approx 2 \times 10^{23}$ to $\approx 10^{25} \text{ m}^{-3}$, respectively. The temperature and density of the recipient plasmas ranged from 0.5 to 2.0 keV and 10^{19} to $5 \times 10^{19} \text{ m}^{-3}$ (central values).

Hence the ablatant cloud constitutes a massive low-temperature high-density transient disturbance for the background plasma.

2.2 What has been calculated?

The initial analyses pertaining to pellet shielding and pellet ablation were based on steady-state, spherically symmetric, transonic expansion flow models, with complete neglect of the presence of a magnetic field [1, 2]. The aim of these approximations was to gain information on the magnitude of gasdynamic shielding and the resulting ablation rates. Most of the ablation models now in use derive from these analyses [3, 14, 15]. The problem reduces to determining the value of the line integral $\int n \times dl$ along the path of the energy carriers, which, for the collisional processes considered, determines the magnitude of energy flux depletion. In the first generation of these models, only electron-neutral collisions were taken into account ("neutral gas shielding" ablation models). On the whole, the models yielded ablation rates that were in agreement with values deduced from H_α line emission recordings - as long as the energy carriers were assumed to be a beam of monoenergetic particles. Attempts to include the effect of realistic (for example, Maxwellian) energy distribution functions yielded ablation rates that were considerably higher than the measured ones. An ad hoc increase of the line integral value by a factor of up to 10 was necessary to re-establish the agreement between the calculated and observed ablation rates. For this reason, in the next generation of ablation models, which still retains some of the basic characteristics of the spherical model, an ad hoc magnetic constriction of the ablatant flow was assumed and energy depletion by electron-electron collisions was also taken into account ("neutral-gas-plasma-shielding" ablation model, [3]).

Following some early estimates pertaining to the effect of magnetic confinement on the ablatant cloud characteristics [4], a self-consistent zero-dimensional time-dependent Lagrangian model was developed on the basis of the full set of magnetohydrodynamic conservation equations and Maxwell's equations [16]. A non-trivial problem in these calculations is the definition of the energy fluxes affecting the cloud in the directions parallel and perpendicular to the magnetic field.. The parallel heat flux may be approximated as $q_{\parallel} \approx \frac{1}{4} f_f n_{e\infty} v_{eth\infty} (2kT_{e\infty})$, where f_f represents a flux-limiting parameter and is of the order of 0.5 to 1.0. More difficult is the determination of the magnitude of the transverse heat flux $q_{\perp}$ at the cloud boundary $r = R_{cld}$. Indeed, in the case of a rather cold high-density cloud, all plasma electrons confined to flux surfaces within one

gyro-radius from the lateral cloud surface transfer practically all of their energy to the cloud upon dipping into it. This quenching process may successively affect a number of neighbouring flux surfaces as well. The lost energy is rapidly replenished, partially or totally, by fresh plasma electrons moving along the same flux surfaces, as long as fresh electrons are available. Furthermore, as the cloud expands, it sweeps a hot plasma volume, thus gaining additional internal energy and contacting new flux surfaces with energetic electrons. Hence the energy transfer to the cloud in the transverse direction is not a purely diffusive process. For the sake of simplicity, it was assumed in the above analyses that $q_{\perp}$ can be represented as $q_{\perp} = \chi_{\perp} n k \partial T / \partial r$. In the series of calculations here considered, the *ambient plasma density*, $n_{e\infty}$, was used for defining the value of $q_{\perp}$ at the cloud boundary. This is apparently the lower limit of the transverse heat flux affecting the cloud. The sum of $q_{\perp}$ and the local ohmic heating associated with the deceleration phase were sufficient to produce peripheral ionization and an inward-bound ionization wave. In some calculations [15], an anomalously high value of $q_{\perp}(r = R_{cld})$ was used by using the *average density* value at the plasma-cloud interface, $(n_{e\infty} + n_{cld})/2 \approx n_{cld}$, in the expression for $q_{\perp}$. The value of $q_{\perp}$ thus obtained was flux-limited to a maximum of 0.05-times the free-flux or $q_{\parallel}$ value. The model was tested with the help of the results of earlier magnetospheric barium cloud release experiments [11]. In spite of the rough approximation used in simulating the photoionization process, the measured data pertaining to the cloud dimensions, expansion rates, the lifetime of the magnetic cavity in the cloud, etc., were reproduced with sufficient accuracy (see, for example, Fig. 5 taken from [16]). The characteristic times and dimensions pertaining to the expansion of barium clouds in the magnetosphere are measured in *min* to *hr* and in *km*, respectively.

The time history of some typical pellet cloud characteristics, computed with the same model and corresponding to the instantaneous deposition of 10^{20} particles (D_2) into a plasma reservoir with $T_e = 1 \text{ keV}$, $n_e = 10^{20} \text{ m}^{-3}$, and $B = 4 \text{ tesla}$ are shown in Fig. 6. Here the characteristic time scale is determined by the ionization time (μs range); the overdamped oscillations observable on the curves have a frequency given roughly by the ratio of the Alfvén velocity and the cloud radius.

The computational model [16] was extended into a $1\frac{1}{2}$ -D Lagrangian model with nested annular cells [17]. The aim of this model was to follow up the transverse expansion and deceleration dynamics in detail and to study the resulting radial structures by allowing, at the same time, for the axial expansion and its effects (flow work, etc.) Calculations were made for scenarios in which a continuously operating source of cold particles of

given strength and given radial extent was placed at the centre of the cloud. The results exhibit a strong dependence on the combination of three basic parameters: the total heat flux ($q_{\parallel} + q_{\perp}$) available, the intensity of the cold particle source, and the strength of the applied magnetic field. The combination of the three parameters defines the ionization and confinement radii, which turns out to be the most relevant result of the calculations. The rest of the resulting flow parameters (temperature, density, etc.,) strongly depend on the cross-section of the "channel" (magnetic flux tube) confining the flow.

The cloud evolution undergoes two clearly distinguishable phases: a short transient associated with the ionization and radial flow confinement processes (μs time scale) and a subsequent quasi-steady period associated with the axial expansion and magnetic field rediffusion processes (ms time scale). Typical initial expansion rates are a few $10^4 m/s$, which is an order of magnitude higher than pellet injection velocities presently in use. Thus the pellet traverses its own shielding cloud. Some typical radial parameter distributions in the cloud corresponding to the set of background plasma parameters $T_{e0} = 5 keV$, $n_{e0} = 10^{19} m^{-3}$, $B_0 = 2.5 tesla$, a D_2 source strength of $\dot{N} = 3.5 \times 10^{23} s^{-1}$, and a source size of $r_{src} = 5 mm$ are given in Figs. 7a and 7b for a time instant $5 \mu s$ after the source of cryogenic particles has been turned on. The distributions correspond to the $q_{\perp} \propto n_{e\infty}$ case. The results show the existence of hollow temperature profiles with $T_{cntr} \approx 2$ to $4 eV$, while $T_{bndr} \approx 30 eV$ for $q_{\perp} \propto n_{e\infty}$ and $300 eV$ for anomalously high $q_{\perp}$ (see [17]). The corresponding transverse density profiles are peaked all the time: $n \approx 10^{24} m^{-3}$ at the centre and $\approx 10^{22}$ at the radial boundary. These profiles, with the ionization or confinement radii as characteristic wavelength, may be the cause of the striated structures seen on the cloud photos. Also the flutes, caused by Rayleigh-Taylor instability, developing at the cloud surface may contribute to this structure. If one assumes classical magnetic diffusivity (Spitzer conductivity), as has been done in these calculations, a large transient reduction of the magnetic field strength, by almost an order of magnitude, in the cloud interior results. The corresponding magnetic shielding effect is significant.

Remarkable is the evolution of the radial flow field, as shown in Fig. 8. Following a short initial acceleration of the neutral gas to supersonic velocities in both the axial and transverse directions, the transverse velocity rapidly reduces to rather low subsonic values as soon as ionization sets in. Analogous results were reported by Pilipp [18], who simulated earlier barium cloud release experiments by means of 1-D and multi-D approximations. According to his results, owing to the rather low magnetic field

strength in the magnetosphere, first a pronouncedly supersonic flow field develops, and, after the peripheral cloud region becomes stopped, a shock wave propagates back to the cloud interior, reducing the velocities to subsonic values. The expansion along the field lines is unimpaired. In a quasi-steady (asymptotic) approximation it can be represented by a constant-area channel flow with heat addition. As is known, such a flow is Mach-1-limited and may become choked. Although the present $1\frac{1}{2}$ -D Lagrangian system is inadequate for modelling truly two-dimensional phenomena and effects, and its results are therefore not conclusive in this respect, they seem to be indicative of the absence of quasi-steady supersonic spherical flow fields in pellet clouds. Hence one of the fundamental assumptions of the existing ablation models, viz. the existence of steady-state spherically symmetric supersonic flow domains in pellet clouds [19] may need supporting evidence.

III. Problems of current interest

In addition to the phenomena described in the previous sections, the following problems are currently being addressed at Garching and elsewhere.

3.1 Field-aligned expansion of the ablatant

3.1.1 Cloud structure in the B-parallel direction

Accurate estimation of the ablation rate requires a knowledge of the energy fluxes carried by field and test particles confined to magnetic field lines, with expansion, ionization, and other effects taken into account (see Fig. 9). In the Lagrangian model discussed in Sect. 2.2, the field-aligned expansion was approximated in a rather simple way: the expansion rate was calculated according to the momentary value of the pressure difference on the two sides of the end-faces of the Lagrangian cells. Within each cell, all cloud parameters were assumed to be uniform. An accurate treatment of the details of heat transfer to the cloud and the pellet along the field lines, i.e. the stopping length and/or non-local heat transfer calculations with simultaneous, most likely anomalous, conductive heat transfer in the transverse direction, require self-consistent calculation of the evolution of the cloud parameters along the field lines as well.

Figure 10 displays preliminary results, stemming from such a system [22], on the evolution of the temperature and density profiles in a flux tube with a cold particle source specified at the left-hand boundary ($\dot{N} = 10^{23}$ in case (a) and 10^{24} in case (b), flux tube cross-section 1 cm^2 in both cases), and a plasma with a temperature of

10 keV and a density of 10^{20} m^{-3} at the right-hand boundary of the expanding slug. In these calculations, only thermal conduction parallel to the magnetic field lines and finite-rate ionization and recombination processes were taken into account. The curves of different lengths correspond to different time instants: 5, 10, 15, and 20 μs in case (a), and 1, 2, and 3 μs in case (b). The z coordinate is directed along the magnetic field lines. The $n(z)$ and $T(z)$ distributions are "floating": their spatial and temporal variations are uniquely defined by the given particle and energy fluxes. The mass present in the system is steadily increasing: the heat source represented by the undisturbed plasma at the right-hand end of the slug is shifted further and further from the cold-particle source. The transverse energy flux was assumed to be zero in these calculations. Modifications of this computational model are to be used in analyses aimed at polarization effects (see previous section) and electrostatic shielding (see next section).

3.2.2 Electrostatic shielding

In early ablation models, it was assumed that the incident flux of energetic electrons is automatically balanced by an outwardly directed flux of cold electrons created in the cloud by collisional ionization. However, owing to thermal conduction in the partially ionized and neutral gas regions, the domain where cold electrons are created does not necessarily coincide with the region in which the energy carriers are stopped. Furthermore, at the interface of the cold high-density cloud and the hot low-density background plasmas a double layer may form. It was shown in [5] that, if the ion dynamics is neglected (pressure equilibrium, absence of ion motion), an electrostatic potential difference $e\Delta\Phi \approx 10 kT_{\text{cold}}$ may develop at the interface, with the gradient pointing to the hot side (see Fig.11). Rozhanskii [6] found approximately the same shielding potential in the case of pellet clouds, but neglecting again the ion dynamics and assuming homogeneous conditions on each side of the interface. It is of interest to see what shielding potential, if any, builds-up when the expansion of the cloud along the magnetic field lines is taken into account in a self-consistent manner (see previous section).

3.2 Effect of pellet motion across the magnetic field

3.2.1 Modification of the cloud structure

Note that while all experimental data available on pellet clouds stem from moving pellets, all analyses and computational models are based on the assumption of stationary

pellets.

Since the average expansion velocity of the ablatant cloud is much larger than the pellet injection velocity, the pellet traverses its own shielding cloud, as is shown schematically in Fig. 12. Obviously, in the case of a homogeneous plasma and in the absence of any magnetic field, an observer moving with a frame of reference attached to the pellet sees a steady-state flow pattern which, if the pellet velocity exceeds the gas expansion velocity, becomes Mach-cone-shaped. Depending on the combinations of the particle source strength, the plasma parameters, and the magnetic field strength considered, the presence of a magnetic field may introduce a periodic modulation of the distributions seen by the observer, with the ionization radius as characteristic wavelength.

The measurements of Durst [9] (see Fig. 2a) seem to indicate that, at least at low pellet velocities, the cloud structure is not very sensitive to the exact location of the pellet in the cloud interior, as long as the pellet is not in the immediate vicinity of the cloud boundary. As soon as the pellet exits from its own shielding cloud, a new "bubble" develops around it and the process is repeated. The same conclusion may be arrived at on the basis of Wurden's time-integrated picture; see Fig. 2b. It is of practical interest to determine the modification of the ionized and confined portion of the shielding cloud by the moving pellet as it approaches and crosses the boundary of its cloud. The locally emitted cold particles most likely change the local cloud parameters and, by means of a self-regulatory feedback mechanism, the local ablation rate as well.

3.2.2 Motion-induced polarization effects

The problem considered here is analogous to the one analyzed by M. Scholer in connection with the polarization drift of barium clouds [20], or to the one treated by C. Goertz [7], who considered the motion of the satellite Io in the plasma torus surrounding Jupiter. With respect to pellet clouds, Rozhanskii was the first to address the problem [21]. His model was thoroughly discussed in the course of a recent Soviet-German meeting at Garching.

The model proposed by Rozhanskii is schematically shown in Fig. 12. The translatory motion of the pellet in the applied magnetic field induces an electromotive force (emf) given by $\vec{v}_{pel} \times \vec{B}$ which produces charge separation in the cloud. Under open-circuit conditions, a polarization field $\vec{E}$ is created which is equal in magnitude but opposite to the induced emf. As a result, the ionized cloud is subject to an $\vec{E} \times \vec{B}$ drift with the drift velocity equal to the pellet velocity. In the other limiting case, i.e. under short-circuit conditions, one has $\vec{E} = 0$ and the resulting force $\vec{j} \times \vec{B} = -\vec{v}_{pel} \sigma B^2$ retards the ionized gas and confines it to local flux surfaces. The polarization charges are free

to spread along the magnetic flux surfaces at which the positive and negative charges accumulate. Hence an electric field is created which is also spread along the magnetic field lines into the initially undisturbed plasma. As a result of the time-dependent (rising) electric field, a polarization current is produced. The perturbations propagate along the magnetic field lines as Alfvén waves carrying field-aligned currents. The fundamental problem here is to identify the currents (conductive, inductive, etc.) induced in the various parts of the domain, define their path through the cloud and/or the background plasma, determine the equivalent loop, and the effective circuit parameters. The ultimate purpose of this analysis is obviously the calculation of the current density $\vec{j}$ and the associated force $\vec{j} \times \vec{B}$, which retards the ionized portion of the cloud. The problem is complicated by the fact that the plasma slug is strongly nonuniform along the magnetic field lines (see next section), and that there exist a second emf in the cloud in the poloidal direction, $\vec{v}_r \times \vec{B}$, which is associated with the radial expansion of the ablatant. This emf is short-circuited: the resulting poloidal currents are responsible for the radial deceleration and confinement of the ablatant. As is known, any anisotropy in any of the emf induce eddy currents, which may have a complex 3-D structure and may, partially or completely, short out the polarization fields.

It should be noted that there is no conclusive evidence available yet on the existence of polarization-induced drift in pellet clouds. The fast-framing photographic recordings of hydrogenic pellet clouds, as shown in Fig. 2a, do not reveal whether or not the cloud drifts with the pellet: both possibilities are open. On the other hand, the striated structure seen in time-integrated cloud photographs, which is the pattern seen by an observer moving with the pellet, seem to indicate the presence of periodicity in the dynamics of cloud formation and thus the absence of any substantial cloud drift. Note that, in the case of hydrogenic pellets, line radiation comes from excited atoms. Only impurity pellets emitting ion lines, such as carbon, may yield conclusive information, if at all, on the existence of cloud drift in tokamak plasmas. From the point of view of pellet shielding, it is important to know what fraction of the cloud drifts with the pellet, i.e. to have information on the modified value of the line integral $\int n \times dl$ along the field lines.

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Figure 1 Similarity between the mass-loading of Jupiter's magnetosphere by the satellite Io and the cloud formation around a pellet in a tokamak field.

Figure 2. Photographic images of particle clouds in magnetically confined plasmas: (a) fast-framing-camera pictures of a pellet cloud in the TEXT tokamak [7], (b) time-integrated picture of the cloud trace in the ASDEX tokamak [8], (c) barium cloud expanding in the magnetosphere at a height $H = 5R_{\text{earth}}$ [9].

Figure 3 Time history of the H_{α} line radiation emitted by an ablating hydrogen pellet in the PLT tokamak [12].

Figure 4 Time histories of the H_{α} and H_{β} traces recorded in TEXT and of the corresponding electron temperature deduced from the ratio of the signal intensities . [7].

Figure 5 Results of test calculations pertaining to barium cloud expansion in the magnetosphere: (a) $B = 160\gamma$, $H = 5R_{earth}$, (b) $B = 10\gamma$, $H = 9.5R_{earth}$ ($1\gamma \approx 10^{-9}$ tesla), [14]. Measured data: (a) $R_{max} \approx 25$ km, $R_{eq1} \approx 12$ km, (b) $R_{eq1} \approx 400$ km [9].

Figure 6 Time evolution of pellet cloud parameters following the instantaneous deposition of $N = 5 \times 10^{18}$ deuterium atoms in a target plasma with $n_e = 5 \times 10^{19} \text{ m}^{-3}$, $T_e = 500 \text{ kV}$, and $B = 2.5 \text{ tesla}$ [11].

Figure 7 Cloud parameter variations in the radial direction $5 \mu\text{s}$ after the moment of turn-on of a continuous source of cryogenic D_2 particles with $\dot{N} = 3.5 \times 10^{23} \text{ s}^{-1}$ in a plasma with $T_{e0} = 5 \text{ keV}$, $n_{e0} = 10^{19} \text{ m}^{-3}$, and $B = 2.5 \text{ tesla}$. Source size: $r_{src} = 5 \text{ mm}$; $q_{\perp}(r = R_{\text{cld}}) \propto n_{e\infty}$. (a) Temperature, density, ionization degree, and magnetic field strength variation; (b) collision frequencies, electron cyclotron frequency, and $\omega\tau$ values.

Figure 8 Time evolution of the radial-flow Mach-number: (a) $q_{\perp} \propto n_{\text{cld}}$ [15], (b) for the conditions of Fig. 7

Figure 9 A Lagrangian scheme for calculating the field-aligned expansion of the ablatant and the resulting distributions.

Figure 10 Calculated cloud parameter variations along the magnetic field lines. Continuous D_2 particle source given at the left-hand boundary ($z=0$): (a) $\dot{N} = 10^{23} \text{ s}^{-1}$, (b) $\dot{N} = 10^{24} \text{ s}^{-1}$, channel cross-section = 1 cm^2 . Steady-state plasma reservoir at the right-hand boundary (moving cloud-plasma interface): $T_{e0} = 10 \text{ keV}$, and $n_{e0} = 10^{20} \text{ m}^{-3}$. The curves of different lengths correspond to different time instants: 5, 10, 15, and 20 μs in case (a), and 1, 2, and 3 μs in case (b).

Figure 11 Schematic view of a pellet traversing its shielding cloud.

Figure 12 Schematic representation of the polarization field and the resulting current pattern in an ablatant cloud.

Figure 13 Formation of double layer at the interface of the ablatant with the background plasma (see also [5]).