Tokamak Fuelling with Pellets: Effect of Transport Phenomena on the Injection Requirements

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Results of calculations on pellet-plasma interaction that take into account transport phenomena inherent in tokamak plasmas are analyzed. It is shown that the results obtained by different authors on the optimum pellet penetration depth and required pellet injection frequencies, which are partly contradictory, can be explained by means of the different transport processes taken into account or neglected in the calculations concerned.

Introduction

The injection of hydrogen isotope pellets produced at cryogenic temperatures (typical condensed deuterium pellet temperatures being $T \lesssim 8\,\mathrm{K}$) in to hot plasmas is considereed to be a promising method for increasing the plasma density or for replenishing the particle losses in magnetic confinement devices. The method may also prove to be useful for controlling, or at least for affecting, the current and plasma parameter distributions in such machines. The immediate applications of this method include replenishment of particle losses in large tokamaks (the ASDEX axisymmetric divertor experiment at Garching [1], the ISX-B tokamak at Oak Ridge [2]). A future application envisaged is the refuelling of tokamak fusion reactors by means of periodic pellet injection.

A cryogenic pellet exposed to a hot plasma evaporates at a rate defined by the intensity of the energy flux incident on the pellet surface and is affected by certain shielding mechanisms. The major part of the incident energy flux is transported to the pellet by the hot plasma particles, particularly by the plasma electrons [3, 4, 5]. In the free flux limit, the incident energy flux is given by $\Phi \approx \Phi_e = \frac{1}{4} n_e \langle v_{eth} \rangle (2\,k\,T_e)$, where a Maxwellian energy distribution is assumed. Here n_e, T_e and v_{eth} denote the density, temperature, and the thermal velocity of the electrons. As a result of the severe vaporization taking place at the pellet surface on being exposed to a hot plasma, the pellet almost immediately becomes covered with a relatively cold high-density, partially ionized gas blanket. The subsequent quasi-stationary vaporization process, particularly the ablation rate, is thus affected by a number of shielding phenomena such as gas-dynamic shielding (the high-density gas blanket covering the pellet surface intercepts most of the incident plasma particles before they reach the pellet surface), electrostatic shielding (if the pellet and the gas blanket surrounding it assume a potential that is different from the plasma potential), and magnetic shielding (since the motion of the incident plasma particles is confined to or affected by the magnetic flux lines present, partial expulsion of the magnetic field from the ablation cloud may reduce the energy flux impinging on the pellet). The shielding phenomena and their effect on the ablation rates have been considered in some previous studies (see, for example [3–5], and the references cited therein). It is, in general, possible to express the ablation rate as a function of the temperature and density of the surrounding plasma and of the instantaneous pellet radius: $\dot{r}_p = f(n_e, T_e, r_p)$. Typical ablation rates for pellets of 0.3 to 1 mm in diameter are a few 10 μs to a few 100 μs. Note that the characteristic transport times that define the particle and energy confinement characteristics of present tokamak plasmas are measured in the ms interval.

A pellet injected into a plasma is first exposed to a medium with the original (undisturbed) plasma parameters. However, since the rate at which energy is transported to the pellet surface is proportional to the thermal velocity of the incident plasma particles, whereas the rate of mass transport from the pellet surface is defined in the immediate neighborhood of the pellet by the thermal velocity of the ablated particles and, further away from the pellet, by the dominant transport process, the plasma parameters in the region around the pellet are strongly

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affected by the ablation products. Hence the plasma temperature and density "seen" by the pellet are quite different from the original, undisturbed plasma parameter values, and a self-consistent calculation of the ablation rate and pellet penetration depth requires computations in which the ablation and the change of the plasma parameter distributions are simultaneously taken into account. Owing to the difference between the ablation and transport time scales, these computations are inherently time-dependent. A quasi-steady approximation to this problem can be constructed by assuming steady-state particle source and sink distributions (simulating pellet injection and particle losses to the wall and divertor, respectively) and by calculating the resulting density distribution. The objective of these calculations is a relatively accurate determination of the optimum pellet penetration depth and of the initial pellet velocity required for injecting the pellet into the plasma.

There is as yet only a limited number of studies available in which ablation models are combined with transport calculations ([6 – 8, see also 9]), and the results of these calculations are in part contradictory. Haas et al. [6, 9] conclude, on the basis of a steady-state solution of the ion diffusion equation, that shallow fuelling (i. e. pellet ablation restricted to the outer plasma layers) is sufficient, the pellet injection velocities required for fuelling present tokamaks are a few 100 m/s. Mense et al. [7] performed calculations with the help of a transport code for reactor plasma conditions and suggest that deep fuelling (i. e. pellet injection into the central plasma region) is not only unnecessary but also undesirable since it may impair the particle confinement characteristics. On the other hand, the results of calculations performed by Lengyel and Düchs [8] for present-day tokamak conditions (see also Pt. B in [9]) indicate that shallow fuelling is accompanied by substantial particle losses and may even overload the divertor pumps in divertor tokamaks. As will be seen, the different conclusions are due to the assumptions underlying the respective calculations. Let us now consider in somewhat greater detail some of the models used.

Steady-state diffusion model of Haas et al. [6]

In these calculations, the pellet plasma interaction was approximated by the steady-state solution of the ion diffusion equation for a cylindrical plasma column:

$$\frac{1}{r}\frac{d}{\mathrm{d}r}\left(r\,D_i\frac{\mathrm{d}n_i}{\mathrm{d}r}\right) = -S_i(r) + \frac{n_i}{\tau_{\|}}, \qquad (1)$$

where $S_i(r)$ is a source function for the plasma ions (related to the ablation rate), $\tau_{\|}$ is the mean lifetime of the ions in the scrape-off layer (a given quantity), and D_i is the ion diffusion coefficient. The plasma conditions used in these calculations were given in terms of the ASDEX parameters: $R = 1.65$ m, $a = 0.4$ m, $T_0 = 2$ keV, $n_0 = 5 \times 10^{19}$ m^{-3}. The temperature profile was prescribed and kept constant during the calculations. In a following analysis (see Pt. A of [9]), a term taking the Ware pinch effect into account was included in the above equation. The refuelling rate necessary for maintaining a given plasma density at the torus axis (n_0) was found by varying the sizes of the injected pellets and/or their velocities until the desired density value was reached. The steady-state H_2 molecule source distribution was calculated with the help of the ablation model of Milora and Foster [10]. The H_2 influx thus specified was assumed to undergo locally dissociation, ionization, and charge exchange collisions. The charge exchange neutrals were limited to one generation: their outflux was calculated by integrating, for a given source distribution, over the surface of an inifinitely long cylinder. The charge exchange neutrals that remained (i. e. did not escape from the plasma volume) were assumed to be distributed over the plasma cross-section in proportion to the local plasma density and to be ionized there. The ion source distribution $S_i(r)$ was thus defined. The results obtained show that pellet injection in the outer plasma layers suffices to provide reasonable bulk plasma densities without overloading the divertor pumps. The pellet injection velocities required for maintaining the projected plasma density in ASDEX were found to be under 500 m/s.

However, as can readily be seen from Eq. (1) by integrating it once with respect to r, in those regions where no sources or sinks are present (i. e. in the central plasma region in the case of shallow fuelling), $\mathrm{d}n_i/\mathrm{d}r$ vanishes and $n_i \equiv$ const. However, the ion density profiles computed by Haas et al. [6] in this steady-state approximation increase monotonically towards the plasma centre, reaching a value at $r = 0$ that, at low pellet injection velocities, is approximately twice as high as the density in the ablation zone. These results incidate that in this model the ion source distribution is practically decoupled from the neutral particle source location, the latter being defined by the site of pellet ablation. Indeed, the ad hoc distribution of the charge exchange neutrals over the plasma cross-section proportional to the local ion density provides an effective particle transport to the plasma centre, irrespective of the location of the ablating pellet. The ion source strength may even increase in this model with increasing distance from the neutral particle source.

Reactor Transport Considerations of Mense et al. [7]

The effect of particle fuelling profiles on the particle and energy transport characteristics of an ignition-sized divertor tokamak (TNS, $R = 5$ m, $a = 1.25$ m, $T_0 \approx 12$ keV, $n_0 \approx 10^{20}\,\mathrm{m}^{-3}$) was investigated by Mense et al. [7] with the help of a one-dimensional multi-fluid transport code supplemented by the ablation model of Milora and Foster [10]. In the transport code two ionic species (H, D) and a thermal alpha component are taken into account. The alpha particles were assumed to be thermalized at the magnetic flux surface where they were born, finite orbit effects were neglected. Also the energy deposition from the electron beams applied was assumed to be local (on the flux surfaces where the neutrals are ionized, thermalization by Coulomb collisions). Ohmic heating was assumed to be small compared with the neutral beam injection power and heating by fusion alpha particles. The current density profile was given and fixed in time. Hence possible MHD activities, particularly the modification of the $q(r)$ profile, could not be taken into account in this approximation. The poloidal divertor was assumed to act as a perfect pump for the particles diffusing from the system and to prevent impurities from entering the plasma. Recycling of cold gas, cold plasma, or impurities was not taken into account. Hence the radiation losses were restricted to bremsstrahlung and synchrotron radiation. The particle and energy transports were modelled by three basic processes which were assumed to be additive: neoclassical transport, pseudoclassical transport, and trapped particle microinstability transport processes (with two collisionality regimes for the trapped electrons).

With the help of this model, two basic phenomena were investigated: (a) The effect of particle fuelling (fuelling depth) on thermally stable ignited states during steady-state burn; (b) The effect of particle fuelling profiles on the ignition requirements, particularly on the required neutral beam power. In part of the calculations, a linear fuelling profile (gas injection) was used, but many of the conclusions obtained with this model can be applied to the cases with pellet injection as well.

Regarding the steady-state burn calculations the results showed that, within the framework of the assumptions made, a reduction of the fuelling depth at the same average density is accompanied by an increase in the fusion power produced. Furthermore, reducing the penetration depth reduces the average density required for maintaining fusion, lowers the average temperature and increases the particle confinement time. Clearly, this result is a direct consequence of assuming the ∇n-driven trapped particle modes to be dominant ($\nabla n \approx 0$ in the bulk of the plasma at shallow fuelling) and of neglecting transport processes that play a substantial role in present tokamaks (recycling, charge exchange collisions in the boundary layer, impurity effects, enhanced collisionality, possibly Bohm diffusion, etc.). Regarding the results pertaining to ignition requirements, the authors conclude that a highly peaked particle source at the plasma edge produces a uniform-density central region not subject to trapped particle modes. The alpha power generated and the pressure profile do not appreciably change. The low edge temperatures associated with the massive local supply of cold particles tend to reduce sputtering and associated effects. To maintain the average density above $10^{20}\,\mathrm{m}^{-3}$, it was necessary to inject a pellet every 45 ms ($f \approx 22\,\mathrm{s}^{-1}$). No attempt was made in these calculations to optimize the pellet injection velocity. However, reducing the fuelling depth to very small values resulted in rapidly increasing "convective" particle losses, and the neutral beam power required for ignition increased. Hence the authors conclude that there is an optimum fuelling depth yielding the minimum beam power required for ignition. No such minimum was found to exist when only neoclassical transport was taken into account. In this case the predicted losses were found to be so minimal that the particles supplied by a 25 MW, 200 KeV, 2 s beam injector system were found to be sufficient to produce ignition and to replace all particle losses without any additional particle supply for a discharge duration of 8 s. The inclusion of pseudoclassical effects did not substantially change the results, which indicates that in the temperature range considered (the minimum temperature in the boundary layer is about 1 keV, the ion temperature in the plasma centre is of the order of 50 keV) the trapped particle modes are the only ones that affect the transport processes. This is, of course, quite a different collisionality range from that encountered in present tokamaks.

Tokamak Transport Calculations for ASDEX [8]

In the computations reported by Lengyel and Düchs a multi-regime transport code [11] was combined with two different ablation models [4, 10]. The objective of these computations – besides checking the effect of the different ablation models – was to investigate the effect of the pellet size and pellet velocity on the confinement characteristics of the plasma. Furthermore, for checking the effect of the ionization degree of the ablation products on the plasma confinement, the ablating pellet was considered either as a source of neutral particles or as a source of cold ions injected into the plasma. (Note that most of the ablation models available provide no information on the ionization state of the high-density cloud surrounding the pellet. An estimate of the ionization degree was given in [4].)

The transport code [11] includes three regimes of collisional drift instabilities: Bohm diffusion, an intermediate (Kadomtsev-Pogutse) regime, and pseudoclassical regime, and four regimes of collisionless trapped particle modes (trapped electron and trapped ion instabilities, each with two collisionalities). The transition from the collisional regime to collisionless trapped particle modes is modelled by an appropriately defined collisionless drift regime. An upper bound is defined for the transport coefficients in terms of the Bohm diffusion term both for the collisional and the trapped particle regimes. The transport coefficients appearing in the conservation equations are computed as linear combinations of the terms corresponding to these regimes. In the case of the ion thermal conductivity, the neoclassical contribution, which may be greater than the anomalous term, is also taken into account.

The poloidal magnetic field and thus the current distribution is calculated by this code in a self-consistent manner. The total discharge current is given; it may be a function of time. Enhanced transport due to possible MHD modes is taken into account by adding a Bohm-like term to the particle diffusion coefficient and electron thermal conductivity in the region where the safety factor $q(r)$ is less than unity.

The presence of neutral hydrogen in the discharge is accounted for by a group of "cold" ($T < 10$ eV) neutrals and up to ten generations of "hot" neutrals. The cold neutrals may suffer charge exchange or ionization collisions. Charge exchange collisions of cold neutrals with plasma ions produce the first generation of hot neutrals. The second generation of hot neutrals (and higher ones) is produced by charge exchange collisions of the first generation of hot neutrals (and higher ones) with plasma ions. A temperature equal to the local ion temperature is assigned to the hot charge exchange neutrals. In divertor operation it is assumed that the neutral particles returning from the wall are recycled; the charged particles are pumped off by the divertor. Allowance is made for an energy spectrum of the incoming cold neutrals.

The local density of the impurity ions (up to 8 oxygen groups in these calculations) is calculated in a self-consistent manner. The model for impurity transport consists of a neoclassical inward diffusion (in the direction of ∇n_i) and a superimposed anomalous diffusion (in the direction of $-\nabla n_{\text{imp}}$). The impurities are assumed to have the same temperature as the hydrogen ions.

Typical penetration depths (ablation lengths) obtained by these calculations for typical ASDEX conditions are displayed in Table 1 for different injection velocities and pellet-to-plasma mass ratios. The upper numbers correspond to the ion source approximation (i. e. the ablated particles are introduced as cold ions into the plasma), while the lower numbers correspond to the neutral source approximation. The values in parentheses were computed with the ablation model of Milora and Foster [10], those without parentheses by means of the ablation rate estimates of Lengyel [4]. As can be seen, as far as the penetration depths are concerned, it does not make any significant difference whether the ablated particles interact as charged particles or as neutrals with the background plasma. The difference caused by the different ablation models is noteworthy: at an injection velocity of 500 m/s the ablation model of Milora and Foster yields penetration depths that are

$\frac{m_{pe}}{m_{pl}}$		U_p 500 m/s	1000 m/s	2000 m/s	5000 m/s
0.1	Ion source	3.00 (6.86)	5.73 (10.34)	10.86 (15.84)	25.2 (29.06)
	Neutr. source	2.82 (5.46)	5.40 (9.03)	10.42 (15.0)	24.92 (28.38)
0.2	Ion source	4.26 (9.36)	8.20 (13.96)	15.50 (21.26)	37.0 (43.56)
	Neutr. source	4.10 (7.42)	7.86 (12.16)	15.34 (19.8)	36.6 (38.90)
0.49	Ion source	6.62 (13.67)	12.46 (20.0)	23.66 (30.8)	58.95
	Neutr. source	6.36 (10.45)	12.10 (17.21)	23.55 (28.1)	58.62 (62.95)

Table 1. Penetration depth of pellets l_p (cm) (calculations with ASDEX plasma parameters).

Values in parentheses ( ) correspond to calculations with the ablation model of Milora and Foster. Upper numbers: ion source approximation; Lower numbers: neutral source approximation.

about twice as large as those corresponding to the ablation rates given in [4]. With increasing injection velocity (i. e. increasing effective plasma temperatures sensed by the pellets) the difference between the results corresponding to the two ablation models considered decreases.

The time evolution of the ASDEX discharge characteristics computed in [8] and [9] shows an abrupt change at the time of the pellet vaporization: the total number of particles in the torus abruptly increases whereas the mean particle confinement and energy confinement times decrease accordingly. However, after a time Δt the discharge characteristics return to their reference level, i. e. to their undisturbed values that would prevail if no pellet had been injected. If the discharge is to be maintained at a certain average density level, a new pellet would have to be injected at the end of this Δt interval. Hence the value of Δt is a measure of the "quality" of the pellet injection. The time increment Δt is tabulated in Table 2 as a function of the pellet size and injection velocity for the two ablation models used (numbers without and with parentheses) and for the ion source and neutral source (upper and lower numbers, respectively) approximations. As can readily be seen, the effect of the ablation models used is not so pronounced as in the previous case: the response of the plasma on the presence of a cold pellet does not significantly depend upon the details of the ablation models involved. However, it makes a great difference whether the ablated particles are introduced to the plasma as cold ions or neutral particles (compare the upper and lower numbers), particularly at low injection velocities, in which case the difference in the respective Δt values may be of an order of magnitude. While cold ions interact with the surrounding plasma by means of Coulomb collisions and are affected by the confining magnetic field from the moment of their birth, a significant portion of the neutral particles undergo charge exchange collisions and the resulting hot neutrals may leave the plasma and interact with the wall particularly at shallow penetration depths. The ionization state (ionization time, etc.) of the ablated particles is thus of crucial importance as far as the confinement characteristics of the discharge and the required fuelling rates are concerned. Unfortunately, this aspect of the ablation dynamics is not considered in most of the ablation models available. Note that the Δt value may also be estimated by assuming that the ablating pellet represents a local perturbation of the density distribution and using the equation $\partial n/\partial t \approx \langle n \rangle/\tau_p$, where τ_p is the local particle confinement time. Hence $\Delta t \approx (\Delta n/\langle n \rangle)\tau_p$. Since for present tokamaks τ_p is rather low at the plasma edge [12], this expression predicts rather pour confine-

$\frac{m_{pe}}{m_{pl}}$		U_p 500 m/s	1000 m/s	2000 m/s	5000 m/s
0.1	Ion source	8.2 (8.2)	8.2 (8.35)	8.6 (9.75)	10.0 (11.6)
	Neutr. source	1.0 (1.0)	1.0 (1.5)	1.1 (3.8)	2.6 (3.7)
0.2	Ion source	12.6 (13.3)	12.6 (14.9)	14.6 (17.9)	20.6 (21.4)
	Neutr. source	1.5 (2.2)	1.7 (3.65)	3.6 (5.1)	5.6 (5.35)
0.44	Ion source	21.6 (24.6)	23.6 (31.6)	29.6 (37.6)	39.6
	Neutr. source	3.4 (5.4)	5.2 (8.5)	12.0 (13.0)	17.0 (16.0)

Table 2. Discharge time increment Δt (ms) resulting from pellet injection (calculations with ASDEX plasma parameters).

Values in parentheses ( ) correspond to calculations with the ablation model of Milora and Foster. Upper numbers: ion source approximation; Lower numbers: neutral source approximation.

ment characteristics for shallow fuelling (the Δt values computed with the help of this simplified expression and the τ_p data given in [12] are of the same order of magnitude as those given in Table 2). Note that the Δt values corresponding to $v = 10^3$ m/s are much lower than the typical value computed by Mense et al. (45 ms, see [7]) for a mass ratio $m_{pe}/m_{pl} < 0.1$. Taking the Δt values obtained for small pellets and low injection velocities, the neutral source approximation predicts injection frequencies (required for maintaining a constant quasi-stationary density level) of the order of 1 kHz. Since the pumping capacity of the ASDEX divertor system is about 5×10^{21} H_2/s, practically all of the fuelling rates appearing in the upper left half of Table 2 and corresponding to the neutral source approximation would cause overloading of the divertor pumps. The response of the plasma to the injection of large pellets ($N_{pe}/N_{pl} \approx 0.44$) was found to be not much different from that observed for smaller pellets. It may thus prove possible to inject larger pellets, thus relaxing the injection speed requirements. The distribution of the safety factor $q(r)$ did not show any change on injection of single pellets. The plasma pressure profile (and hence β) also remained unaffected. The behaviour of $q(r)$ and $\beta(r)$ under continuous refuelling conditions is still to be seen.

It should be noted that the calculations presented by Lengyel and Düchs [8] were performed with a fixed mesh size originally designed to handle field gradients inherent in normal tokamak discharges. Since pellet ablation produces local gradients, particularly at shallow penetration depths associated with low injection velocities, that are very much larger than those for which the transport code [11] was developed, the accuracy of the results obtained for shallow penetration depths is unknown. Further computations are needed (with finer or variable mesh size) to clarify this question.

Conclusions

A comparison of the results of calculations available on pellet-plasma interaction permits the following conclusions:

(1) The ionization state of the particles leaving the ablation zone is of major importance in defining the confinement properties of the resulting plasma. Ions interact with the recipient plasma by means of Coulomb collisions and are captured by the confining magnetic field, whereas neutral particles produce primarily charge exchange collisions, thus causing substantial particle losses and enhanced impurity influx from the wall, particularly with shallow fuelling. Since most of the ablation models available do not treat the process of ionization (ionization time, ionization radius) in sufficient detail, the corresponding transport code calculations can only be used for estimating the upper and lower limits of the respective particle loss rates (uncertainties brought about by the transport models used are not included here). The sensitivity of the confinement properties on the ionization state of the ablatant may require integrated ablation-transport models.

(2) A comparison of the computations of Mense et al. [7] and those performed by Lengyel and Düchs [8] show that the results of combined ablation-transport calculations depend decisively on the transport processes taken into account and/or neglected in the respective codes. The boundary conditions used in the calculations play an equally important role. Since there is some uncertainty regarding the relative importance of the various transport modes envisaged (according to Furth [13], the recent PLT results can best be approximated by a transport code that only includes the neoclassical regime, Alcator-empirical scaling, and trapped ion effects with an appropriately chosen weighting factor), great care should be exercised in defining the transport model used and in selecting the respective boundary conditions. It should be born in mind that the resulting confinement properties, and hence the required fuelling rates, are practically determined by the transport processes assumed. Hence the experimental verification of the assumptions made is also of great relevance.

(3) Owing to the important role that pellet-plasma interaction plays in the determination of the ablation rate and confinement properties of the recipient plasma, the fuelling characteristics such as the fuelling rate, the optimum pellet size, injection frequency, and injection velocity combinations, etc., can only be determined from properly posed transport computations and/or experiments. The maximum pellet size admissible under quasi-steady fuelling conditions, i.e. under the conditions of periodic pellet injection, deserves special attention since it may reduce the technical requirements imposed on the injector system.

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