THEORY OF PLASMA BUILD-UP IN STELLARATORS BY NEUTRAL BEAMS ALONE

W Ott and E Speth

Max-Planck-Institut für Plasmaphysik, IPP-EURATOM Association,
D–85748 Garching, Germany

Abstract

Successful plasma build-up in W7-AS stellarator by neutral beams alone has been described. A theoretical study is undertaken here in order to understand the problems of plasma generation and to predict conditions for easier and faster plasma ignition.

When a hydrogen beam is injected into a stellarator which is filled with hydrogen gas at low pressure a small part of the beam is ionized and leads to circulating hot ions. The gas is ionized by the beam as well as by the hot ions. The electrons produced loose energy primarily in inelastic collisions with the hydrogen molecules present and gain energy from the circulating hot ions. If the resulting electron temperature is too low recombination with H_2^+ molecules becomes so effective that a plasma cannot be ignited.

The particle balances and the electron energy balance are solved to describe plasma formation theoretically. The results show the somewhat surprising result that plasma generation by beams is easier when the neutral gas density is low. It is therefore necessary to start at low pressure and with well-conditioned walls.

1. Introduction

After plasmas could be generated by beams only in the W7-AS stellarator [1] it seemed necessary to look into the elementary processes of plasma formation more closely in order to get a guide for future improvements of the experiments. The results may be important not only for stellarators but also for tokamaks where beams may be used to save voltseconds during start up [2].

Section 2 describes the balance equations for the particle densities. In section 3 the electron energy balance equation is solved. These tools are applied in section 4 to the conditions on W7-AS where several conclusions are drawn. Section 5 compares two pulses of W7-AS which demonstrate the influence of the wall conditions.

2. Particle balances

In this section the balance equations are solved for the different kinds of ions which play a rôle in plasma formation. These ions are the hot ions formed by ionization of neutral beam atoms, slow molecular ions H_2^+ and slow atomic ions H^+. Slow molecular ions H_3^+ are omitted because there are not enough data available for them. They could slightly modify the results.

The low-density plasma formed at the beginning hardly decelerates the hot ions. They are mainly lost by charge exchange with neutral gas. Production and loss of hot ions approach an equilibrium much faster than the process of plasma generation. Therefore the hot ion density may be written as

$$n_\mathrm{h} = \left(\frac{\sigma_\mathrm{ibg}}{\sigma_\mathrm{xhg}} + \frac{\sigma_\mathrm{xb1} + \sigma_\mathrm{ib1}}{\sigma_\mathrm{xhg}} \frac{n_1}{n_\mathrm{g}} + \frac{\sigma_\mathrm{xb2} + \sigma_\mathrm{ib2}}{\sigma_\mathrm{xhg}} \frac{n_2}{n_\mathrm{g}} \right) \frac{P_\mathrm{n}\, l}{E_\mathrm{n}\, V\, v_\mathrm{h}} \,. \tag{1}$$

Here n_h, n_1, n_2 and n_g are the densities of hot ions, cold atomic and molecular ions and of gas molecules, respectively. The σ's are the cross-sections whose first index indicates the process (i = ionization, x = charge exchange), the second index the starting particle, the third index the collision partner (b = beam, g = gas, 1 = cold atomic ion, 2 = cold molecular ion, h = hot ion). The other variables are the neutral power P_n, the interaction length between beam and plasma l, the beam energy E_n, the plasma volume V and the velocity of the fast particles v_h.

The hydrogen gas in the vessel consists mainly of molecules. Only a few atoms may be present. The main ionization processes therefore produce H_2^+ and not H^+ ions. Two electron collision processes compete with each other in the destruction of H_2^+: dissociation into $\mathrm{H} + \mathrm{H}^+$ and dissociative recombination into two H atoms.

This gives the following balance equations for the cold-ion densities (assuming $n_\mathrm{h} \ll n_\mathrm{e} \approx n_1 + n_2$)

$$\begin{aligned}
\dot{n}_2 &= \frac{P_\mathrm{n} l}{E_\mathrm{n} V}(\sigma_\mathrm{igb} n_\mathrm{g} - \sigma_\mathrm{xb2} n_2) + (\sigma_\mathrm{igh} + \sigma_\mathrm{xhg}) v_\mathrm{h} n_\mathrm{h} n_\mathrm{g} \\
&\qquad + \langle \sigma_\mathrm{ige} v_\mathrm{e} \rangle n_\mathrm{g} n_\mathrm{e} - \left(\langle \sigma_\mathrm{rec} v_\mathrm{e} \rangle + \langle \sigma_\mathrm{diss} v_\mathrm{e} \rangle \right) n_\mathrm{e} n_2 - \frac{n_2}{\tau} && (2) \\
\dot{n}_1 &= -\frac{P_\mathrm{n} l}{E_\mathrm{n} V} \sigma_\mathrm{xb1} n_1 + \langle \sigma_\mathrm{diss} v_\mathrm{e} \rangle \, n_\mathrm{e} n_2 - \frac{n_1}{\tau} && (3) \\
n_\mathrm{e} &= n_1 + n_2 \, , && (4)
\end{aligned}$$

where τ is the particle confinement time.

The gas density is the sum of the original gas filling $n_{\mathrm{g},0}$ and that part of the beam which is not gettered in the walls. If α_beam gives the recycled beam fraction, the gas density develops as

$$n_\mathrm{g} = n_\mathrm{g0} + \alpha_\mathrm{beam} [P_\mathrm{n} / (2 E_\mathrm{n} V_\mathrm{v})] t - (V / V_\mathrm{v})(n_2 + n_1/2) \qquad (5)$$

(V = plasma volume, V_v = vessel volume).

3. Electron energy balance

Friction of the electrons with the hot ions gives the following heating power density

$$p_\mathrm{e,\,heat} \; = \; 5 \times 10^{-9} \frac{n_\mathrm{e} \, n_\mathrm{h}}{\sqrt{E_\mathrm{n}}} \qquad \left[\frac{\mathrm{eV}}{\mathrm{m^3 s}}, \frac{1}{\mathrm{m^3}}, \mathrm{eV} \right] \, . \qquad (6)$$

The electron cooling power density due to inelastic collisions with hydrogen gas is

$$p_\mathrm{e,\,cool} = n_\mathrm{e} \, n_\mathrm{g} \, L_{\mathrm{H}_2} \qquad \text{with the cooling rate} \qquad L_{\mathrm{H}_2} = \textstyle\sum_i \langle \sigma_i \, v_\mathrm{e} \rangle \, \Delta E_i \qquad (7)$$

(ΔE_i = energy loss connected with inelastic collision process i).

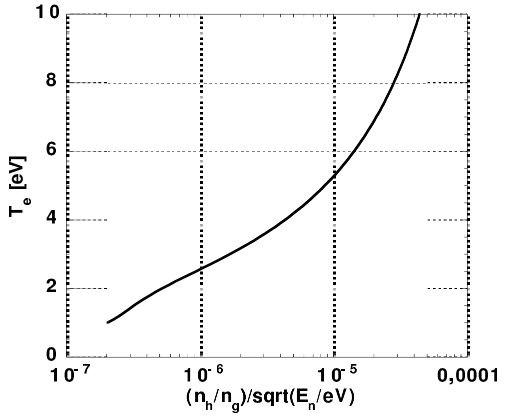

Fig. 1: T_e as determined from power balance (equation (8)) for hydrogen as a function of $E_\mathrm{n}^{-1/2} \, (n_\mathrm{h}/n_\mathrm{g})$.

The balance of heating and cooling power gives the relation

$$\frac{1}{\sqrt{E_\mathrm{n}}} \frac{n_\mathrm{h}}{n_\mathrm{g}} \; = \; 2 \times 10^8 \, L_{\mathrm{H}_2} \qquad \left[\mathrm{eV}, \frac{\mathrm{eV \, m^3}}{\mathrm{s}} \right] \, . \qquad (8)$$

The cooling rate L_{H_2} is calculated using all the relevant reaction rates listed in Janev [3]. L_{H_2} is a unique function of T_e. It is thus possible to determine $T_\mathrm{e} = T_\mathrm{e}(n_\mathrm{h}/n_\mathrm{g})$ for a given beam energy E_n. The result is shown in Fig. 1.

4. Results

The coupled balance equations are solved numerically. The importance of the participation of the electrons in the ionization process is shown in Fig. 2. A normal case is compared in this figure with a fictitious case where electron ionization is switched off.

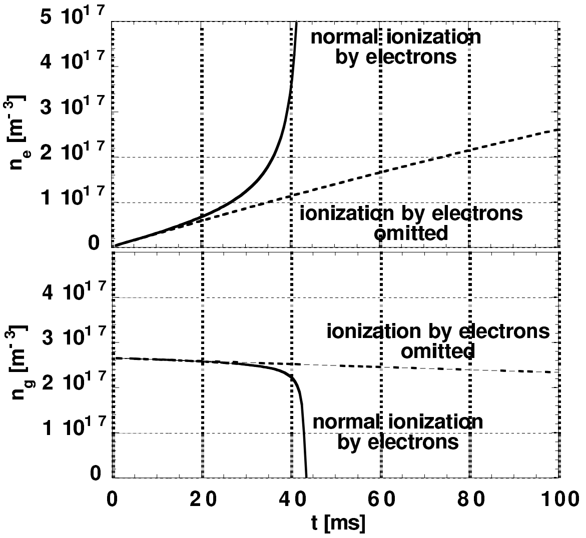

Fig. 2: Comparison of normal plasma generation by beams with a fictitious case where electron ionization is switched off. The parameters used are $P_\mathrm{n} = 1.6\,\mathrm{MW}$, $l = 2\,\mathrm{m}$, $E_\mathrm{n} = 32.5\,\mathrm{keV}$, $V = 1.25\,\mathrm{m}^3$, $V_\mathrm{v} = 5\,\mathrm{m}^3$, $p_0 = 1 \times 10^{-3}\,\mathrm{Pa}$, $\alpha_\mathrm{beam} = 0$, $\tau = 0.1\,\mathrm{s}$. *The two diagrams show the calculated developments of the electron density (upper diagram) and of the neutral gas density. Electron ionization leads to a strong reduction of* n_g *and hence to ignition in contrast to the other case.*

The figure shows that it is virtually impossible to generate a plasma without electron ionization. This calculation is done for the optimistic case $\alpha_\mathrm{beam} = 0$ which can certainly not be sustained during a longer beam pulse. The heat load on the walls would lead to outgassing.

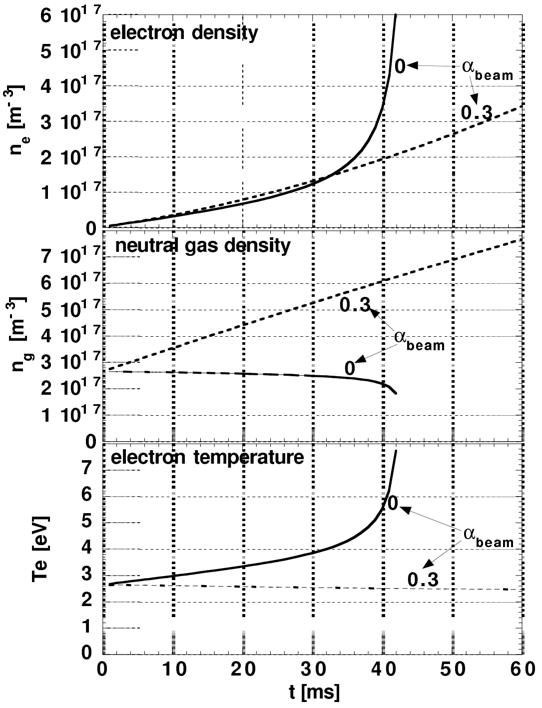

Fig. 3: Influence of the wall condition on plasma generation. The temporal developments of n_e, n_g *and* T_e *are compared for the cases* $\alpha_\mathrm{beam} = 0$ *and* $\alpha_\mathrm{beam} = 0.3$. *The other parameters are the same as in Figure 2. The case* $\alpha_\mathrm{beam} = 0.3$ *might resemble a usual wall, whereas* $\alpha_\mathrm{beam} = 0$ *may be obtained after a glow discharge.*

A comparison of two different wall conditions is made in order to see the effect of a cleaning discharge. The case of $\alpha_{\text{beam}} = 0.3$ is taken as a usual wall whereas $\alpha_{\text{beam}} = 0$ might resemble a freshly cleaned wall. The result is shown in Figure 3 which shows the temporal development of n_e, n_g and T_e for the two cases. The initial growth of n_e is very similar in both cases. The neutral gas density, however, develops rather differently, and so does the electron temperature. In case $\alpha_{\text{beam}} = 0$ the neutral gas density stays constant in the beginning, then decreases so that T_e rises, electron ionization becomes effective and the plasma ignites. In case $\alpha_{\text{beam}} = 0.3$ the neutral gas density rises so strongly that T_e stays low and a plasma is not formed. If in the experiment only n_e is measured, a reason for the different behaviour of the pulses cannot be recognized. If T_e is measured in addition, it will be seen that in the first case T_e rises, whereas in the second case it does not. If also n_g would be measured, the reason for the failure in the second case could be seen directly.

5. Experiment

An experimental verification of the influence of wall conditions on plasma ignition is shown in Fig. 4. This figure compares two pulses of W7-AS where it was tried to create a plasma with neutral beams alone. One shot was made before, the other one after discharge cleaning. It was possible to ignite a beam plasma only after the walls were well conditioned.

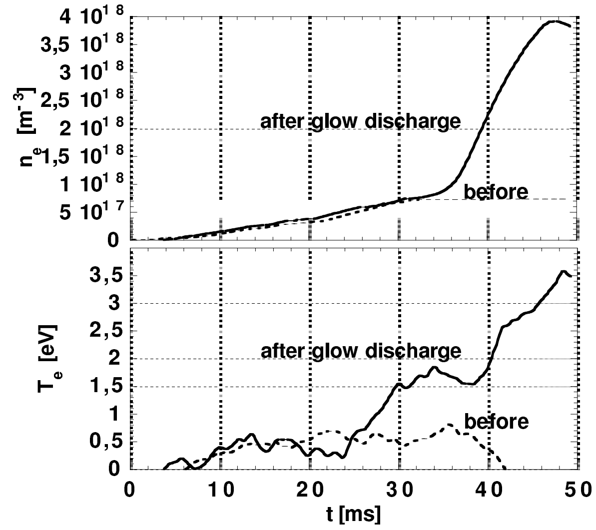

Fig. 4: Comparison of electron temperature and electron temperature of two pulses in W7-AS. One pulse was made before, the other one after discharge cleaning. The electron density and temperature rose very similarly during the first 30 ms. In the first case T_e *decreased afterwards whereas it rose in the second case. The plasma ignited only after the walls were well conditioned. The neutral gas density in the vessel would be an important experimental parameter according to Fig. 3. It could not be measured, however.*

References:

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