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Plasma Build-Up in W7–AS Stellarator by Neutral Beams Alone

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Abstract:

Plasma generation has been achieved in the stellarator W7–AS using only neutral beam injection. This became possible after the initial pressure in the vessel was sufficiently reduced. This process is elucidated using a zero–dimensional model. Only at low neutral gas pressure the slowing down of the fast ions heats the electrons such that further ionization can take place.

Introduction:

Whereas in tokamaks the initial plasma is created due to high ring voltage caused by the ohmic transformer, in helical confinement systems the plasma needs to be created by external means. Mostly these means are resonant or non–resonant absorption of RF waves. An example for resonant absorption is plasma generation using gyrotrons for electron cyclotron resonance heating. Since the gyrotron frequency is fixed the magnetic field is limited to the values for which the fundamental or harmonic electron cyclotron resonances are close to the plasma centre. On the stellarator W7–AS the available gyrotrons at 70 and 140 GHz allow plasma start–up at magnetic fields of 1.25 and 2.5 T. An example for non–resonant absorption of RF waves are lower hybrid systems. On W7–AS a low power (10 kW) system at 900 MHz is installed that allows plasma generation at other magnetic field strengths. Even at that low power the generated plasma is of sufficient electron temperature to serve as a target plasma for neutral beam injection. It is still desirable to generate plasmas simply with neutral beams alone in order not to have to rely on other systems and to be independent of the magnetic field strength.

After LHD reported successful plasma ignition by beams alone [1], the particle and energy balances for plasma start–up were reexamined at Garching. As a result it became apparent, that the key to plasma build-up is the participation of the electrons in ionization of the residual gas, and hence a sufficiently high electron temperature. The only source of heating power to the electrons is friction by fast ions. The main cooling process of the electrons is via collisions with neutral gas. Since the fast ion density and hence the heating power per electron is independent of neutral gas pressure, but the cooling power is inversely proportional to the neutral gas density, it was concluded, that the neutral gas density must be kept as low as possible, until T_e starts rising above ≈ 5 eV. As soon as the electrons start participating by thermal ionization, neutral gas can be added and the plasma density starts building up further. Obeying this recipe in the experiments was the key to successful plasma build–up in W7–AS. The paper first contains the analytical model for the formation of a cold plasma and electron heating. Then the experiments on W7–AS are described.

Analytical model:

When the neutral beam is injected into the gas-filled torus, some beam atoms are ionized by collisions with the gas molecules and with the cold ions produced. The hot ions are mainly lost by charge exchange (cx) with the gas, and within < 1 ms the hot ion density

n_h becomes constant (compare Riviere [2])

$$n_\mathrm{h} = \left(\frac{\sigma_\mathrm{ibg}}{\sigma_\mathrm{xhg}} + \frac{\sigma_\mathrm{xbc} + \sigma_\mathrm{ibc}}{\sigma_\mathrm{xhg}} \frac{n_\mathrm{c}}{n_\mathrm{g}} \right) \frac{P_\mathrm{n}\, l}{E_0\, V_\mathrm{p}\, v_\mathrm{h}} \tag{1}$$

(σ_ibg = cross-section for ionization of beam by gas, σ_xhg = c.-s. for cx of hot ions with gas molecules, σ_xbc = c.-s. for cx between beam and cold ions, σ_ibc = cross-section for beam ionization by cold ions, n_c = cold ion density, n_g = neutral gas density, P_n = neutral beam power, l = interaction length of beam and gas/plasma, E_0 = average energy of the neutral beam particles, V_p = plasma volume, v_h = hot ion velocity, $n_\mathrm{e} \approx n_\mathrm{c}$) Eq. (1) shows that the hot ion density does not depend on the absolute values of gas density or cold ion density. It only depends on their ratios. If the ratio $n_\mathrm{c}/n_\mathrm{g} > 10$ slowing-down of the fast ions becomes important and has to be included in the balance equation. The result of the combined equation is shown in Fig. 1 for $E_0 = 32.5\,\mathrm{kV}$ (= species average).

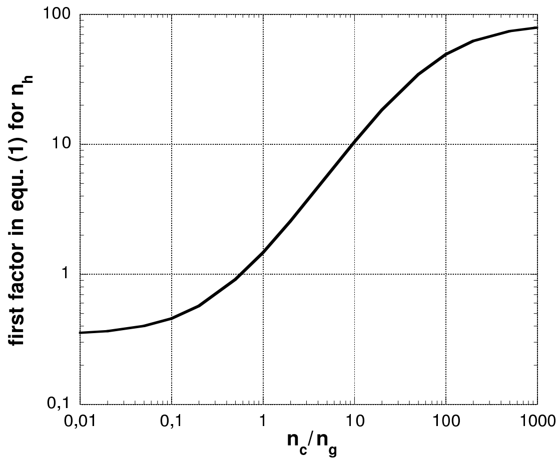

Fig. 1: Dependence of the normalized hot ion density on the ratio of cold-ion density to gas density. In contrast to eq. (1) electron friction of the hot ions is included here, which is important for $n_\mathrm{c}/n_\mathrm{g} > 10$.

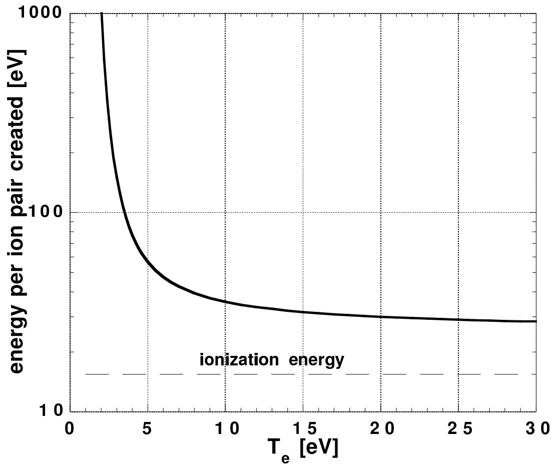

Fig. 2: Energy loss per electron-ion pair created by electron collisions in H_2. *All relevant excitation reactions described in Janev [8] are included with the energies given there. This curve is only a lower limit, compare ref. [9].*

The balance equation for the cold ion density (not distinguishing between different ion species, neglecting recombination and ionization by electrons) is ($n_\mathrm{h} \ll n_\mathrm{c} \approx n_\mathrm{e}$)

$$\dot{n}_\mathrm{c} = \frac{P_\mathrm{n}\, l}{E_0\, V_\mathrm{p}} (\sigma_\mathrm{igb}\, n_\mathrm{g} - \sigma_\mathrm{xbc}\, n_\mathrm{c}) + n_\mathrm{h}\, n_\mathrm{g}\, v_\mathrm{h}\, (\sigma_\mathrm{igh} + \sigma_\mathrm{xhg}) - n_\mathrm{c}/\tau \tag{2}$$

(σ_igb = cross-section for gas ionization by beam atoms, σ_igh = cross-section for gas ionization by hot ions, τ = confinement time).

The combination of eqs. (1) and (2) shows that as long as $n_\mathrm{c} \ll n_\mathrm{g}$ the ionization rate by hot ions is only of the same order as direct ionization by the neutral beam. The ionization rate can be increased dramatically as soon as $n_\mathrm{c} > n_\mathrm{g}$ as is shown in Fig. 1. Taking arbitrarily $n_\mathrm{c} = n_\mathrm{g}$ as a lower limit for the cold ion density to be reached for $\dot{n}_\mathrm{c} = 0$, these two equations together give a condition for the beam power

$$P_\mathrm{n} \geq \frac{E_0\, V_\mathrm{p}}{l\, \tau} \frac{1}{\sigma_\mathrm{ibc} + \sigma_\mathrm{ibg} + \sigma_\mathrm{igb} + \sigma_\mathrm{igh}(\sigma_\mathrm{ibg} + \sigma_\mathrm{xbc} + \sigma_\mathrm{ibc})/\sigma_\mathrm{xhg}} \,. \tag{3}$$

Taking for W7-AS $V_\mathrm{p} = 1.25\,\mathrm{m}^3$, $l = 2$ m, $\tau = 100$ ms (assumed) and for H beams $E_0 = 32.5$ keV, $\sigma_\mathrm{ibc} = 1.85$ [3], $\sigma_\mathrm{ibg} = 1.25$ [4], $\sigma_\mathrm{igb} = 1.7$ [5], $\sigma_\mathrm{igh} = 1$ [6], $\sigma_\mathrm{xbc} = 2.37$ [3], $\sigma_\mathrm{xhg} = 3.8 \times 10^{-20}\,\mathrm{m}^2$ [7], gives a minimum power of 500 kW.

For plasma generation it is important to increase the ionization degree to much more than $\approx 50\,\%$. Therefore the electrons have to be heated so strongly that they participate in gas ionization. The electrons loose power in inelastic collisions with the gas. The energy loss of the electrons per electron-ion pair created in H_2 depends strongly on the electron temperature T_e. As a first approximation for a quantitative treatment all the inelastic energy losses of electrons colliding with H_2 described in Janev [8] (vibrational and electronic excitation, dissociation, ionization) are summed up. This gives the following loss power density for the electrons

$$p_\mathrm{e,\,loss} = n_\mathrm{e}\, n_\mathrm{g} \textstyle\sum_i \langle \sigma_i\, v_\mathrm{e} \rangle\, \Delta E_i \tag{4}$$

where ΔE_i is the energy loss caused by the inelastic reaction i. Dividing the sum on the right-hand side of eq. (4) by the ionization rate gives the energy needed to create an ion pair in H_2 which is shown in Fig. 2 as a function of T_e. The figure shows the extreme energy loss of the electrons per created ion pair for $T_\mathrm{e} < 5\,\mathrm{eV}$. The evaluation of eq. (4) does not contain electron energy losses by eleastic collisions or by excitation of rotational energy levels. Therefore the curve of Fig. 2 represents only a lower limit. The electrons are heated by the hot ions with a power density

$$p_\mathrm{e,heat} = \frac{\pi\sqrt{2}}{(4\pi\epsilon_0)^2} \frac{e^4\lambda}{m} \frac{2m}{m_\mathrm{e}} \frac{n_\mathrm{e} n_\mathrm{h}}{\sqrt{E_0}} \tag{5}$$

(λ = Coulomb logarithm, m = fast-ion mass, m_e = electron mass). Solving the power balance yields the electron temperature which can be obtained by a certain population of hot ions which is shown in Fig. 3. If T_e should be raised to interesting values ($\geq 5\,\mathrm{eV}$) it follows from Fig. 3 that $n_\mathrm{h} > 2 \times 10^{-3} n_\mathrm{g}$. For a limited beam power the initial gas pressure and the gas release from the walls have to be reduced to such an extent that the electron power losses due to inelastic collisions are low enough.

Experiments:

On W7-AS usually some He gas is filled into the torus before the magnetic field is ramped up in order to avoid runaway electrons. During the flat-top there is a certain partial pressure of remaining helium of about 2×10^{-5} mbar. This helium gas together with the hydrogen gas accompanying the neutral beams is presumably the reason that former attempts for plasma generation by beams alone had no success. Therefore the torus is now filled with hydrogen gas for the magnetic field ramp. Hydrogen gas is pumped rather well by the injectors, and therefore the pressure in the torus is below 1×10^{-6} mbar before the beams start. Additionally, a glow discharge before the series of shots helps to minimize gas release from the walls. When the ion sources start there is a gas flow from the injectors into the torus because of imperfect pumping. So the hydrogen pressure in the torus is again raised to 2×10^{-5} mbar at the start of the beams.

Fig. 4 shows an example of these discharges. The beams start at $t = 100$ ms with a power of 1.6 MW. The electron density n_e rises at the beginning in accordance with eq. (2). After n_e has achieved a critical value of $n_\mathrm{e} \approx 5 \times 10^{17}\,\mathrm{m}^{-3}$ at $t = 135\,\mathrm{ms}$, the electron temperature T_e rises to $\approx 5\,\mathrm{eV}$. The additional gas ionization by the electrons leads to a sudden increase of n_e and also of the diamagnetic plasma energy W. Introduction of more gas at $t = 285\,\mathrm{ms}$ raises n_e, T_e and W. n_e, T_e and W decrease again after the gas flow is finished.

In further discharges the additional gas flow was introduced earlier, in order to shorten the duration of the very–low–density plasma where the beams hit the walls nearly undamped and release impurities. Further experiments are necessary in order to establish pure beam ignition as a standard method. Reduction of the beam power and faster ignition are necessary. It also remains to be shown that this method is applicable at smaller magnetic field strengths. A further reduction of the gas pressure at the beginning would be helpful.

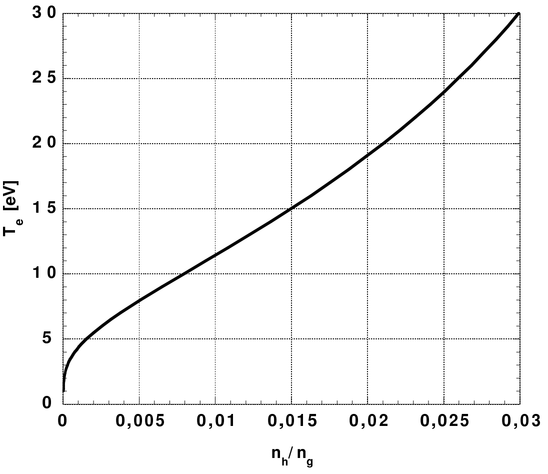

Fig. 3: T_e as determined from power balance (eqs. (4) and (5)) as a function of the ratio $n_\mathrm{h}/n_\mathrm{g}$.

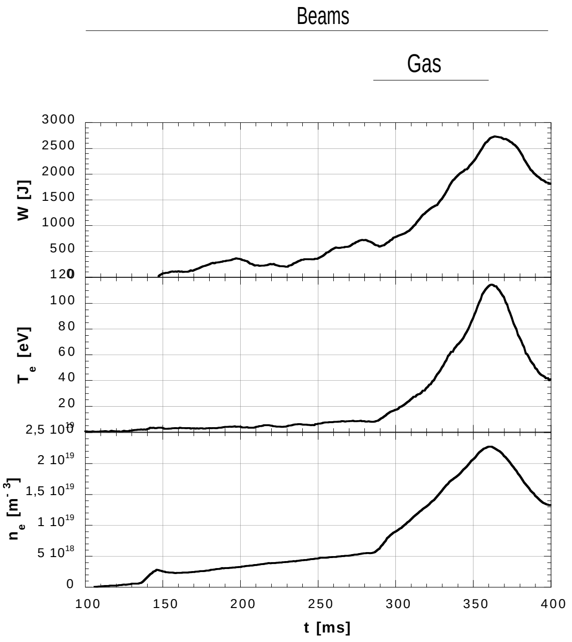

Fig. 4: #47682, plasma generation by beams alone: electron density n_e, electron temperature T_e and diamagnetic plasma energy W, see text.

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