On the Density Clamping of Tokamak Plasmas with Neutral Beam Injection

by

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In the ISX experiments\(^{(1)}\) with neutral beam injection, the phenomenon called density clamping has been observed. When the beam is injected, the plasma density does not increase as anticipated. The density can be increased by more intense gas puffing. Apparently the particle confinement time becomes shorter when the beam is injected. The purpose of this note is to offer a simple model to explain the phenomenon.

We make two observations. Firstly, the beam injections in these experiments are co-injection. That is, the beam is injected in the direction parallel to the ohmic electric field. Secondly, although the physical process responsible for the density buildup by gas puffing is not well understood, a likely process is wave pinch effects.\(^{(2)}\) The banana orbits of trapped electrons drift inward under the influence of the ohmic electric field. The ions follow the electrons to prevent a large ambipolar potential buildup.

We consider the interaction between beam ions and trapped electrons. The electrons receive a force \(F\) through collisions. It is given by

\[
F = \nu_{eb} m_e v_b
\]  

(1)

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where \( v_{eb} \) is the collision frequency of an electron with the beam ions, \( m_e \) is the electron mass and \( v_b \) is the velocity of the beam ions. If the injection is co-injection, the force is in the direction of the ohmic current and is in the opposite direction of the force that an electron receives from the ohmic electric field. As a result, the banana orbits drift with the radial velocity \( v_r \) given by

\[
v_r = \frac{v_{eb} m_e v_b}{e B_p}.
\]  

The density \( n_b \) of the beam ions may be estimated by calculating the slow down time. It is given by

\[
n_b \approx \frac{I_o m_i}{e V m_e v_{be}}
\]  

where \( V \) is the plasma volume, \( m_i \) is the mass of the beam ions, \( I_o \) is the injection current, and \( v_{be} \) is the collision frequency of a beam ion with electrons. The effects of the beam ion collision with the plasma ions has been neglected.

Since we have

\[
v_{eb} \approx v_{be} \left( \frac{n_b}{n} \right)
\]  

Equation 2 becomes

\[
v_r \approx \frac{m_i v_b I_o}{e B_p e n V}.
\]  

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The average electron density change due to the beam injection is then given by

\[ \frac{\partial n}{\partial t} \sim -\sqrt{c} \left( v_r \frac{n}{a} + I_0/(eV) \right) \]  

(6)

where \( a \) is the radius of the hot core of the plasma.

By using Equation 5 into Equation 6, we obtain

\[ \frac{\partial n}{\partial t} \sim \left( \frac{I_0}{eV} \right) \left( 1 - \frac{\sqrt{c} n_i}{eB a p} \right). \]  

(7)

The second term is the ratio of the banana size of the beam ions and the plasma radius. If the plasma radius is interpreted as the radius of the plasma where the beam is trapped, the ratio may be larger than unity for some experiments. An example is the experiments on ISXB, where the density clamping has been observed.

In the above model, interaction between the beam ions and the plasma ions has been neglected. The beam imparts the momentum to the plasma ions and the plasma acquires rotational momentum in the toroidal direction, as has been observed in PLT(3) and Dite(4) experiments. The force trapped electrons receive is given by

\[ F = \frac{m_e}{n_i} \int v_{ei} f_i v_{i\phi} \, dv^3 \]  

(8)

where \( n_i \) is the total ion density, \( v_{ei} \) is the electron ion collision frequency, \( f_i \) is the ion distribution function including beam ions and
\( v_{i\phi} \) is the ion velocity in the toroidal direction. If we assume that the electron thermal velocity is much larger than the ion velocity, \( v_{ei} \) depends only on the electron temperature. Also, the impurity ions interact strongly with hydrogen ions and they have the same average velocity as hydrogen ions. Equation 8 becomes

\[
F \approx \frac{m_{e} v_{ei} j_{i} Z_{\text{eff}}}{e n_{i}}
\]

(9)

where \( j_{i} \) is the current carried by ions and \( Z_{\text{eff}} \) is the effective charge number. The net radial velocity is then given by

\[
v_{r} \approx -\frac{n Z_{\text{eff}} j_{i}}{B_{p}} + \frac{m_{e} v_{ei} Z_{\text{eff}} j_{i}}{e^{2} B_{p} n_{i}}
\]

(10)

where \( n \) is Spitzer resistivity and \( j \) is the ohmic current density. By using

\[
v_{ei} \approx \frac{2 e^{2} n}{m_{e}}
\]

(11)

we obtain

\[
v_{r} \approx -\frac{n j_{i} Z_{\text{eff}}}{B_{p}} \left[ 1 - \frac{2 j_{i}}{j} \right].
\]

(12)

In the PLT experiments, the rotational velocity of \( 10^{5} \) msec\(^{-1} \) at the center of the plasma has been observed. By assuming the value of the central density of \( 6 \times 10^{19} \) m\(^{-3} \), the ion current density is roughly \( 10^{6} \) amp m\(^{-2} \). This value is comparable with the ohmic current density.

The above equation shows that the plasma rotation of this magnitude leads
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to the density clamping. The density clamping can be overcome by stepping up the gas puffing. We may speculate that this is due to increased charge exchange and plasma viscosity leading to reduction of the rotational velocity.

The above model can be tested experimentally by comparing the density clamping phenomenon in the co-injection case and the counter-injection case. According to the model, the counter-injection should avoid the density clamping. There has been an indication that the choice of injection direction affects the particle transport. The level of impurities observed in PLT is much higher with the counter-injection alone. The addition of the co-injection reduces the impurity level. The counter-injection enhances the were pinch as discussed in this note. Since the impurity ions are more susceptible to the ambipolar potential, they are more likely to follow the electrons than protons and are transported inwards. The addition of the co-injection reduces the pinch velocity, thus decreases the impurity level.

If the above model is correct, it opens up an interesting possibility; a beam driven, pellet fueled steady state tokamak without a divertor. The entire current is carried by ions and the trapped electrons are transported outward.

The impurity ions follow the electrons and transports outward. The hydrogen ions are supplied near the plasma center by the high speed pellet injection.
REFERENCES