The role of the rotation in the correlated transient change of the density and confinement

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We draw attention to the possible unifying connection between a wide class of regimes where it has been noted a correlation between the density change and the improvment of the confinement. This connection may be due to the fact that the change of density via ionization (of a pellet of gas puff) produces a torque which sustains poloidal rotation against magnetic pumping, thus reducing or suppressing the turbulence and enhancing the confinement. Pellet Enhanced Performace (PEP at JET), high confinement obtained with increasing the density (DIII-D), etc. may be manifestations of the effect of strong space dependence of the ionization rate.

The drift of the newly born particles is imposed by the toroidal geometry, with the difference that the electrons are drifting much less than the ions. The newly born ions will move to place themselves on the periodic trajectories, banana or circulating. We first discuss the case of trapped ions. A fraction of $\sqrt{\varepsilon}$ of the new ions (produced by ionization) is trapped.

The *trapped* ions that are produced by ionization take trajectories that are composed of two parts: (1) first there is a motion of the ion such as to reach the "virtual center" of the banana; (2) second, there is periodic bounce "around this virtual center", whose radial projection is zero.

Therefore the trapped ion produces a radial current arising from only the first, unique and transitory, part of their trajectory. This part which is transient and non-periodic, *i.e.* the part that carries the current, is half of the width of the banana. The speed of the ions on this transient part of its motion is the neoclassical drift velocity $\mathbf{v}_{Di}$ which we take constant and positive. It can have both orientations on the radial "segment" of ionization process and a sign will be given according to the motion of the ions.

We consider *first* the trapped ions that have, at the moment of ionization, parallel velocity in the same direction with the magnetic field and we note that their banana is formed outside of the magnetic surface on which the ionization has taken place. It results a radial displacement toward the edge. This is one of the elementary components of the radial current. The part of the current is build up of a succession of such elementary events consisting of motion of a positive charge on the length, $\delta r =$ half of the outer ion banana and only on the time interval of this displacement $\delta t = \frac{\delta r}{v_{Di}}$. A large number of such events build up a continuous radial current of ions, $j^{t(+\|)}$. From this shift it results a charge imbalance and its electric field, a purely geometrical effect.

For new ions with the initial velocity anti-parallel to $\mathbf{B}$ the banana is formed fully inside the magnetic surface and the transitory displacement of the new ion, until the "virtual center" of this smaller banana, is to the left, towards smaller r radius, $\delta r < 0$. This discrete event is second type of contribution to the radial current.

In addition there are circulating new ions, *i.e.* on untrapped orbits. Those that have at the initial point a momentum directed parallel to **B** make a circle which fully include the magnetic surface on which the ionization has taken place. The effective displacement to the virtual center is to the left, towards smaller radius, $\delta r < 0$.

The last type consists of ions that are circulating but with their velocity at the inital point anti-parallel to the magnetic field. For them the closed orbit is fully inside the magnetic surface and it is equivalent to the displacement of the average position of the new ion from the magnetic axis to a positive r, towards right ($\delta r > 0$, towards the edge).

The radial current results as a composition of events of displacement on finite-size intervals. At the end of this displacement on the finite-size intervals (along the radius r) the motion becomes periodic (either on bananas or on closed circulation orbits) and the average eliminates any contribution to a radial current. The process involves several time scales with wide separation. The creation of a new population of ions takes place at a rate given by the ionization τ_{ioniz}. The motion of the newly created ions (after ionization) in the transitory part of their evolution toward the stationary "virtual center" takes place with the drift velocity and the distance of displacement is $|\delta r|$ as explained. This defines a second time scale, τ_{drift}. The motion of ions builds up electric charge with nonuniform profile and, as an instant manifestation of the Gauss law, an electric field with time variation $\partial \mathbf{E}/\partial t$ on this same time scale. The response by polarization drifts (of mainly the ions) takes place on a time scale $\tau_{pol} \sim \tau_{drift}/\left(1+c^2/v_A^2\right)$. The new ions produced by ionization are $n^{ioniz}(x,t)$ and we calculate how many new ions arrive at time t in the point x: (1) the ions created by ionization on trapped orbit and going parallel to **B**, contribute with $n_i^{t(+\|)}(x,t) = n^{ioniz}\left(x-\delta r^t, t-\frac{\delta r^t}{v_{di}}\right)$; they come from the left (smaller radius) to the right (larger radius); δr^t is by definition a positive quantity, with magnitude equal to half the width of the banana. (2) the ions created by ionization on trapped orbits and going anti-parallel to **B**, are $n_i^{t(-\|)}(x,t) = n^{ioniz}\left(x+\delta r^t, t-\frac{\delta r^t}{v_{di}}\right)$; they are coming from the right (large radius) to the left (smaller radius), δr^t is taken for simplification as above. (3) the ions created by ionization on circulating particles and going parallel to **B**, are $n_i^{c(+\|)}(x,t) = n^{ioniz}\left(x+\delta r^c, t-\frac{\delta r^c}{v_{di}}\right)$; they have an orbit that encloses the magnetic surface on which they are born, therefore they have a shift to the left, from larger radius to smaller radius. δr^c is positive, a length equal to the distance between the center of the magnetic surface and the center of the closed circulation orbit. (4) the ions created by ionization on circulating particles and going anti-parallel to **B** , are

$n_i^{c(-\|)}(x,t) = n^{ioniz}\left(x-\delta r^c, t-\frac{\delta r^c}{v_{di}}\right)$; they have a closed orbit (circulating) that is fully inside the magnetic surface where the ion has been created. Then they have a shift δr^c of their center from the center of the magnetic surface to the right, i.e. their displacement is toward the right, to larger radius. This is why they originate at $x-\delta r^c$. The total number of ions arriving at time t in the point x during an interval τ^{ioniz} is

$$\delta n_i(x,t) = n_i^{t(+\|)}(x,t) + n_i^{t(-\|)}(x,t) + n_i^{c(+\|)}(x,t) + n_i^{c(-\|)}(x,t)$$

The number of pairs per unit volume produced by ionization in the current point, $n^{ioniz}(x,t)$, in a time interval τ^{ioniz} on the time scale of ionization is $S(x,t)\,\tau^{ioniz} n^{bg}$. The density of electric charge due to the *incoming ions* is

$$\begin{aligned}\rho^{in}(x,t) &= |e|\left(n_i^{t(\|)} + n_i^{t(-\|)} + n_i^{c(\|)} + n_i^{c(-\|)}\right)\\ &= |e|\,n^{bg}\tau^{ioniz}\left[4S(x,t) + \frac{\partial S}{\partial t}\left(\frac{-2\delta r^t - 2\delta r^c}{v_{di}}\right)\right]\end{aligned}$$

and the density of electric charge due to the lost, or *outgoing* (from (x,t)) *ions* is

$$\rho^{out}(x,t) = |e|\,n^{ng}\tau^{ioniz}\left(4S(x,t)\right)$$

The charge density $\rho(x,t) = \rho^{in}(x,t) - \rho^{out}(x,t) - |e|\,n^{bg}\tau^{ioniz}S(x,t)$ is

$$\rho(x,t) = |e|\,n^{bg}\tau^{ioniz}\frac{\partial S}{\partial t}\left(\frac{-2\delta r^t - 2\delta r^c}{v_{di}}\right) - |e|\,n^{bg}\tau^{ioniz}S(x,t)$$

and $\frac{\partial E}{\partial x} = -\frac{1}{\varepsilon_0}\rho(x,t)$,

$$\frac{\partial E}{\partial t} = \left(-\frac{1}{\varepsilon_0}|e|\,n^{bg}\tau^{ioniz}\right)\int_0^x dx'\left[\left(\frac{-2\delta r^t - 2\delta r^c}{v_{di}}\right)\frac{\partial^2 S}{\partial t^2}(x',t) - \frac{\partial S(x',t)}{\partial t}\right]$$

The current of *polarization* of the *BULK* ions $j_i^{bulk} = |e|\,n_i^{bulk}v_{Di}^{(pol)}$ is $j_i^{bulk} = \varepsilon_0\left(1+\frac{c^2}{v_A^2}\right)\frac{\partial E}{\partial t}$. The new term is

$$J^{new} = \left(1+\frac{c^2}{v_A^2}\right)|e|\,n^{bg}\tau^{ioniz}\left(\frac{2\delta r^t + 2\delta r^c}{v_{di}}\right)\int^x dx'\frac{\partial^2 S}{\partial t^2}(x',t) \qquad (1)$$

This will provoke the *torque*.

We calculate the electric current that traverses a surface placed transversarly on the radial "segment" (where the ionization occurs) at point x.

$$J(x,t) = v_{Di}\tau^{ioniz}n^{bg}\left(\frac{\partial S}{\partial x}\right)\left[\left(\delta r^t\right)^2 + \left(\delta r^c\right)^2\right]$$

The equation of continuity is $\frac{\partial \rho}{\partial t} + \nabla\cdot\mathbf{J} = 0$, or

$$\frac{\partial \rho}{\partial t} = -\frac{\partial J}{\partial x} = -v_{Di}\tau^{ioniz}n^{bg}\left[\left(\delta r^t\right)^2 + \left(\delta r^c\right)^2\right]\left(\frac{\partial^2 S}{\partial x^2}\right)$$

The electric field $\partial E/\partial x = (-1/\varepsilon_0)\,\rho\,(x,t)$. Then

$$J\,(x,t) = \varepsilon_0\left(1+\frac{c^2}{v_A^2}\right)\frac{\partial E}{\partial t} = \left(1+\frac{c^2}{v_A^2}\right)v_{Di}\tau^{ioniz}n^{bg}\left[\left(\delta r^t\right)^2+\left(\delta r^c\right)^2\right]\left(\frac{\partial S}{\partial x}\right) \tag{2}$$

Using the equation of continuity of the new density, the two expressions are shown to be compatible, within the approximations adopted here.

The second expression, Eq.(2), is easier to comment. The importance of the space variation of the source should not be underestimated. A pellet or a gas puss from the high field side can produce high values of the radial current via the space variation of their ionization rate. Even the gas puff at the low field side, crossing strong gradients of temperature and background density, can produce a high value of the radial current of the ions and substantial poloidal torque. This should be checked by replacing in the particle codes the condition $J_r + J_i^{return} = 0$ by an accurate representation of the finite ion displacements that further induce the ion polarization response.

We also draw attention on the instability that can grow, due to the form of the Eq.(2): when the torque produces sheared poloidal rotation the suppression of the turbulence enhances locally the gradient of the background density (which we here adopted constant n^{bg} for simplification) and temperature, making the rate of ionization to have an even stronger space dependence, and so creating a positive feedback process.