Generation of Fast Electrons in Reversed Field Pinches
by the Equilibrium grad $|B|$ Force.

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It is shown that a decreasing magnetic field profile in reversed-field pinch plasmas leads to formation of an anisotropic electron distribution function at the plasma edge. The mechanism is the conservation of the magnetic moment and the energy of electrons that collisionlessly travel outward in a stochastic magnetic field. As a result, the electrons have high parallel energies and low perpendicular energies at the edge. The details of the distribution function correspond well to experimental results.

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One of the striking features of the reversed-field pinch (RFP) confined plasma^{1,2} is the presence of so-called fast electrons at the plasma edge. The distribution function of the fast electrons is drastically different from the distribution function of the background electrons^{3,4}. First, the average energy of the fast electrons is much higher than the background temperature and is comparable to or higher than the central electron temperature. Second, the distribution function of the fast electrons is highly asymmetric in the direction parallel to the local magnetic field. The electron current and energy flux carried in one direction (referred herein as forward) is a several times higher than that in the opposite (backward) direction. The direction of the fast electron current at the edge is opposite to the direction of the applied electric field.

The results from different devices are qualitatively similar. For example, extensive studies of the fast electrons in the MST^{4,5,6} indicate (at reduced current) high parallel temperature $T_{e \text{ fast}} = 130$ eV (the central electron temperature $T_{e0} = 160$ eV), high asymmetry in the parallel direction varying from $J_{\text{forw}}/J_{\text{back}} = 2$ to 5 for the current flux, and from $Q_{\text{forw}}/Q_{\text{back}} = 3$ to 6 for the heat flux. In addition, a low perpendicular temperature about 30 eV (the central T_{e0} was 90 eV in this case) was measured.

A simple mechanism exists that can explain all these features of the fast electrons for a sufficiently collisionless plasma. The equilibrium magnetic field strength in the RFP decreases monotonically with the minor radius. The "mirror ratio" $R = B(0)/B(a)$ is about a factor of 2 for typical configurations (where subscript a denotes the plasma edge and 0 refers to the center).⁷ In the presence of a stochastic magnetic field (as a result of field fluctuations) a particle travels along the field line, down the field gradient, from the center to the edge. As a result it gains parallel energy and loses perpendicular energy, providing the "fast", anisotropic electrons as observed. For a collisionless particle, magnetic moment $\mu = mv_{\perp}^2 / 2B$ and energy conservation yield

$$v_{\perp a}^2 = v_{\perp 0}^2 / R \quad (1a)$$

and

$$v_{\parallel a}^2 = v_{\parallel 0}^2 + v_{\perp 0}^2 (R - 1) \quad (1b)$$

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Here, m is the electron mass, $v_{\perp}$ and $v_{\parallel}$ are the perpendicular and parallel electron velocity components. We ignore here the effect of the parallel electric field as well as the radial ambipolar electric field.

It is clear that equations (1a) and (1b) correspond to a decrease in the perpendicular energy and an increase in the parallel energy. In addition, the presence of a directed drift velocity at the center (which is necessary to carry the electron current) causes an additional distortion of the distribution function at the edge.

To demonstrate the effect a Monte-Carlo simulation was performed in which 32000 particles at the center were distributed according to the Maxwellian distribution $f = A \exp(-v_{\perp}^2 / 2v_{T0}^2) \exp(-(v_{\parallel} - v_{d0})^2 / 2v_{T0}^2)$, where $v_{T0} = (T_{e0} / m)^{1/2}$ is the electron thermal velocity, and v_{d0} is the drift velocity. The drift velocity was chosen according to $mv_{d0}^2 / 2 = 0.1 kT_{e0}$. After traveling to the edge the velocity components change according to Eq. 1. The mirror ratio was chosen $R = 2$.

Fig. 1 shows the perpendicular and parallel distribution functions $f_{\perp a} = \int_{-\infty}^{\infty} f(v_{\perp a}, v_{\parallel a}) dv_{\parallel a}$ and $f_{\parallel a} = 2\pi \int_0^{\infty} f(v_{\perp a}, v_{\parallel a}) v_{\perp a} dv_{\perp a}$ at the edge. From the perpendicular distribution we calculated the perpendicular temperature as $T_{\perp a} = \langle mv_{\perp a}^2 / 2 \rangle$, where the brackets denote the averaging over the distribution function. The perpendicular temperature is reduced by a factor of 2 from the center to the edge $T_{\perp a} = 0.5 T_0$.

The parallel distribution functions underwent a more substantial change. First, two groups of electrons appeared, with a clear asymmetry. (In the absence of a prescribed drift, the parallel distribution function is symmetric about the origin). The calculated current asymmetry is $J_{\text{forw}}/J_{\text{back}} = 3.3$, the heat flux asymmetry is $Q_{\text{forw}}/Q_{\text{back}} = 5.4$ which is close to experimental observations.^{5,6} The average kinetic energy of the forward electrons is $\langle mv_{\parallel a}^2 / 2 \rangle_{\text{forw}} = 1.3 kT_{e0}$, the average energy of the backward electrons is $\langle mv_{\parallel a}^2 / 2 \rangle_{\text{back}} = 0.8 kT_{e0}$. Were one to measure the temperature from the slope of the distribution function tails, then this effective temperature would be $T_{\text{eff}} = 1.3 T_{e0}$. The fitted Maxwellian distribution is shown by the dotted line. The parallel acceleration also causes an increase in the total parallel current, which was calculated as

$J_{\parallel} = \int_{-\infty}^{\infty} v_{\parallel} f_{\parallel} dv_{\parallel}$. The increase is $J_{\parallel a} / J_{\parallel 0} = 1.26$. This effect corresponds to the "dynamo". The direction of the current is parallel to the local magnetic field. Therefore, it is opposite to the applied electric field due to the magnetic field reversal.

FIG. 1. Fast electron perpendicular (top) and parallel (bottom) distribution function. The magnetic field strength decreases by a factor of $R = B(0)/B(a) = 2$ from the center to the edge. The dotted line is the Maxwellian fit to the edge distribution function.

Our model follows the kinetic dynamo theory (KDT)^{8,9,10} in relying upon the collisionless transport along a stochastic magnetic field. An extra ingredient is the grad $|\mathbf{B}|$ acceleration which adds three components beyond the standard KDT. First, it leads to a low perpendicular temperature. Second, it is an additional source of the high parallel temperature (beyond the electric field acceleration). Third, it is an additional source of dynamo current (the initial current distribution function asymmetry is enhanced by the grad $|\mathbf{B}|$ acceleration).

The applicability of the effect to experiment critically depends on the collisionality. The effect disappears at high collisionality. The criterion for the collisionality can be written as $\lambda_e > l$, where λ_e is the electron 90° scattering mean free path, and l is the path length along the stochastic magnetic field line that the electron travels along from the core to the edge. This length can be calculated¹¹ as $l = 2D_{st} / \langle (\Delta r)^2 \rangle$, where $\langle (\Delta r)^2 \rangle$ is the average squared field line radial displacement, and D_{st} is the diffusivity of magnetic field lines. We estimate the radial displacement as $\langle (\Delta r)^2 \rangle = 0.5 a^2$, which corresponds to the region of the maximum gradient of $|\mathbf{B}|$ from $r/a = 0.15$ to 0.85 .⁷ The magnetic field diffusivity can be estimated¹² as $D_{st} = L \tilde{b}_r^2$, where L is the parallel correlation length of the radial magnetic field fluctuations, and $\tilde{b}_r$ is the rms. of the relative amplitude of the radial magnetic field fluctuations. For typical MST conditions⁵ $\tilde{b}_r = 2\%$ and $L = 3a$. The collision mean free path is estimated as $\lambda_e = (2\varepsilon / m)^{1/2} / \nu_e$, where ε is the electron energy and $\nu_e = \nu_{ee} + \nu_{ei}$ is the sum of the electron-electron and electron-ion collision frequencies. As a result, $\lambda_e \propto \varepsilon^2$, and the collision criteria $\lambda_e > l$ can be written as

$$\varepsilon > (2\bar{n}a / 10^{13} \tilde{b}_r^2)^{1/2}, \quad (2)$$

where $\bar{n}$ is the line averaged plasma density (in cm^{-3}). For MST conditions ($\bar{n} = 0.7 \times 10^{13} \text{cm}^{-3}$, $a = 50 \text{cm}$, and $\tilde{b}_r = 2\%$) Eq. 2 yields $\varepsilon > 420 \text{eV}$. For the central electron temperature $T_{e0} = 160 \text{eV}$ this high energy tail constitutes about 7% of the of the central electron density. This criterion is easier to satisfy in higher temperature and smaller size machines, such as ZT-40M.

The importance of the magnetic moment conservation for a self consistent kinetic treatment was pointed out in Ref. 9, where the solution of the drift kinetic equation in the collisionless limit was written as a function of the magnetic moment and the energy. Our case corresponds to a trivial solution of the drift kinetic equation describing force free, ballistic motion of the electrons in a monotonically decreasing magnetic field. We have shown, though, that this solution alone reproduces all significant features of the fast electrons.

In conclusion, our simple calculations show that the magnetic field profile in reversed field pinches causes a change in the electron distribution function at the edge, effectively leading to formation of two anisotropic groups of electrons. These electrons represent the high energy tail of the central electrons that collisionlessly travel from the center to the edge in the stochastic magnetic field. The electrons are accelerated in the parallel direction by the $\text{grad } |\mathbf{B}|$ force and, simultaneously, they are cooled down in the perpendicular direction due to the magnetic moment conservation. This mechanism can be viewed as an extension of the KDT. Taken in isolation it is not self-consistent but it is very robust and it explains the experimentally measured fast electrons features. It seems that any self-consistent KDT must take this effect into account.

ACKNOWLEDGMENTS

The author wishes to acknowledge useful discussions with Dr. A. Jacobson, Dr. S. Prager, Dr. S. Hokin, and Dr. M. Stoneking.

This work was supported by the U.S. Department of Energy.

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