NONLINEAR MECHANISM OF RUNAWAY ELECTRONS GENERATION DUE TO THE HALL EFFECT AND PLASMA DENSITY INHOMOGENEITIES

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Abstract

The nonlinear dynamics of magnetic field penetration into an inhomogeneous density plasma as a KMC wave is accompanied by a significant Joule heat release in the current layer and the generation of runaway electrons. In the frame of electron magnetohydrodynamic (EMHD) theory a particle in cell (PIC) modeling is carried out to study the process of self-consistent electron acceleration in the wave electromagnetic field. It is shown that the electron acceleration becomes possible due to a nonzero circulation of the Hall electric field component along the "cyclotron circles" of the electron trajectory.

Up-to the present time, the appearance of runaway electrons was considered as the consequence of their acceleration in some given external electric field. This model was proposed by Dreiser in [2] and was applied to Tokamak experiments. The dynamics of powerful pulsed discharges, such as Z-pinchs or plasma opening switches (POS), are also characterized by runaway electrons appearance. But the essential feature of the pulsed discharges is a self-consistent electron motion both in electric and in magnetic fields. The general direction of the electron motion in crossed fields is $[\mathbf{E} \times \mathbf{H}]$, which is perpendicular to the electric field. By this reason, in a potential field, an electron does not acquire energy.

Let us consider the real electron trajectory in crossed fields (Fig.1). The characteristic electron trajectory consists of a set of "cyclotron circles" linked by relatively "straight" intermediate lines. During the motion along the"cyclotron circle", the electron acceleration is possible only if the electromagnetic field is nonpotential, $\text{rot}\mathbf{E} \neq 0$. This situation realizes in the front of magnetic field penetration into an inhomogeneous plasma as a KMC wave [1]. In the wave front, the electron receives a main acceleration due to nonpotentiality of the Hall electric field component, and, during the "straight" lines, it receives some additional acceleration [3] due to the Ohm electric field component.

In the present paper, the phenomena of magnetic field penetration into inhomogeneous plasma density due to the Hall effect is discussed. This well-known phenomena was predicted in the work [1] and numerically shown in [4]-[6]. The fact itself of magnetic field penetration into the plasma, $\mathbf{H} = \mathbf{H}(t)$, demonstrates the nonpotential nature of the wave electromagnetic field. The essential reason for such nonpotentiality is the dependence of the Hall electric field component on the electron density. Let us suppose that an electron moves through a plasma region with increasing density (Fig.1). The upper and the lower part of each "cyclotron circle" lies in layers of different plasma density, and from this reason with different values of the Hall electric field components, $\mathbf{E}_{Hall} = [\mathbf{j} \times \mathbf{H}]/n_e ec$. The $\oint \mathbf{E_{Hall}}, \mathbf{dl} \neq 0$ (see formula 5), and the work produced by the Hall field at each "circle" is positive. Therefore, the electron acquires energy.

To demonstrate numerically the effect of an electron acceleration in the front of KMC wave, we run the EMHD code [3]. To do that, one can include the motion of some probe electron into the code. The EMHD part gives the electromagnetic field, which acts on the probe electron.

Basic equations.

The EMHD+PIC, present theory, considers the following equations:

1. equation for electric field:

$$\mathbf{E} = \frac{[\mathbf{j} \times \mathbf{H}]}{n_e ec} + \frac{\mathbf{j}}{\sigma}; \tag{1}$$

2. equation for magnetic field:

$$\frac{\partial \mathbf{H}}{\partial t} = \nabla \times [\mathbf{u} \times \mathbf{H}] - \nabla \times (\frac{c^2}{4\pi\sigma} \nabla \times \mathbf{H}); \tag{2}$$

3. Maxwell equation for current density:

$$\mathbf{j} = \frac{c}{4\pi} \nabla \times \mathbf{H}; \tag{3}$$

4. equation for particle momentum change:

$$\frac{d\mathbf{p_e}}{dt} = -e\mathbf{E} - \frac{e}{\gamma m_e c}[\mathbf{p_e} \times \mathbf{H}]. \tag{4}$$

here $\mathbf{u} = -\mathbf{j}/en_e$. e, m_e are the electron charge and mass at rest. σ is the plasma conductivity, $\mathbf{p} = \gamma m_e \mathbf{v}$ is the momentum and $\gamma^{-1} = \sqrt{1 - (v/c)^2}$.

Results of modeling.

The system (1)-(4) is modeled to study the influence of the KMC wave on the runaway electrons generation. The Fig.2a-2c present the results of modeling in the (x,y) plane geometry: $p = (p_x, p_y)$, $H = H_z(x, y)$, $n_e = n_e(y)$. On the left and on the right parts of each figure, distributions of the electron density and of the magnetic field are shown. Darker color corresponds to higher value. Plasma density is 10^{13} cm^{-3} at the top and is $2\,10^{13}$ cm^{-3} at the bottom . The inhomogeneity is shown as an intermediate layer of width $\lambda \approx 1$ mm. The magnetic field value is $H = 10^4$ [ers], the Hall parameter $(\omega\tau)_{ie} = 20$. The characteristic time of KMC wave evolution is $T = 4\pi e\lambda / cH \frac{\partial}{\partial y}\left(\frac{1}{n_e}\right) \approx 2\,10^{-12}$ sec. To analyse an electron acceleration in the front of KMC wave the energy interval is divided from 500 eV to 110 keV to a groups with energy-step 500 eV. Motion of an electron from each energy-group is modeled.

In the Fig.2a-2c, the trajectories of some probe electrons at time $2.8\,10^{-14}$ sec, $1.5\,10^{-12}$ sec and $1.9\,10^{-12}$ sec are given. The initial energy of the "1" electron is 500 eV, of the "2" is 30 keV, of the "3" and "4" ones are 60 keV and 90 keV. The fig.2a corresponds to the first moment of the magnetic field penetration into the plasma. This moment is more favorable for acceleration and for runaway of electrons. The beam accelerated

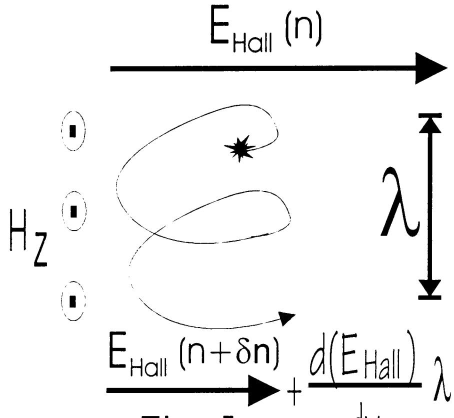

Fig.1

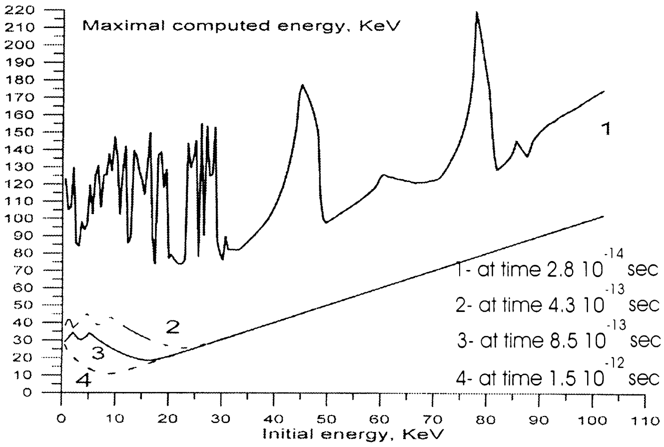

Fig.3

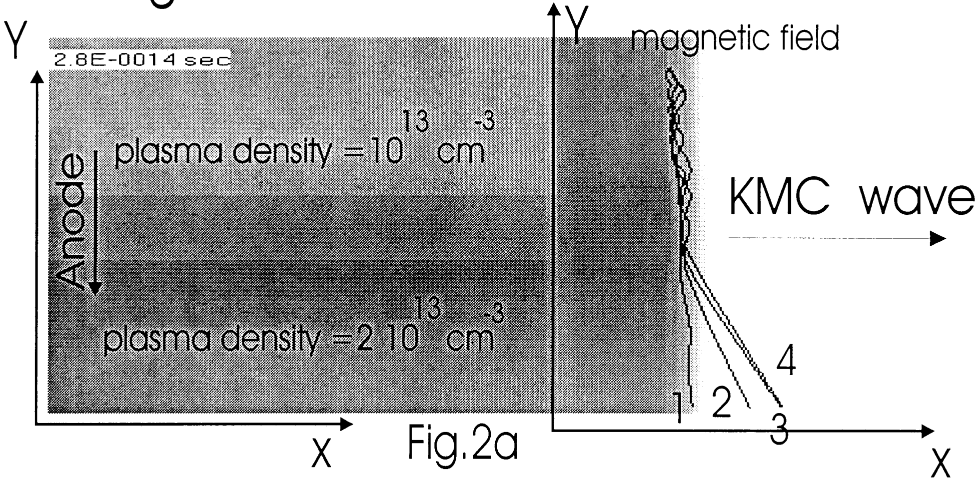

Fig.2a

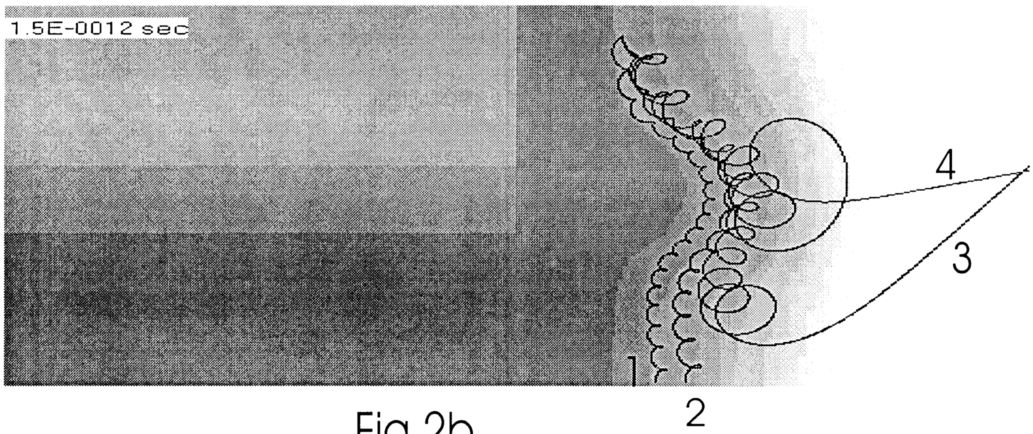

Fig.2b

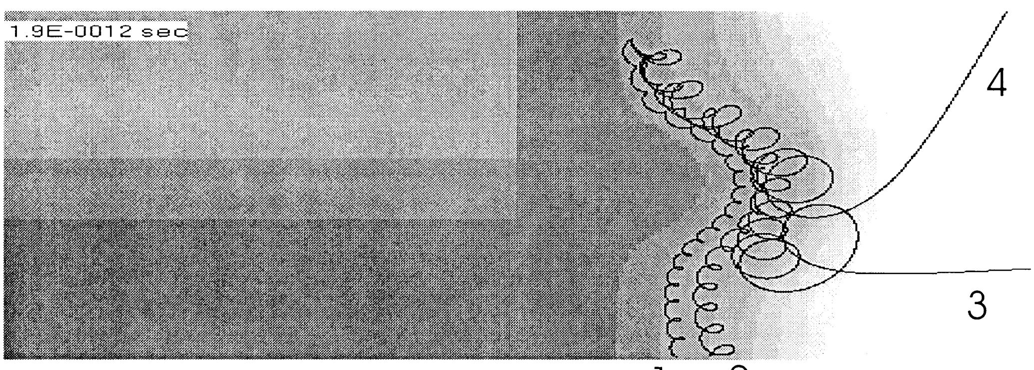

Fig.2c

electrons is directed to the anode under a small angle. We suppose, that at the initial moment of the magnetic field penetration into the inhomogeneous plasma the runaway electron beam is generated. The average electron energy increase for a length λ equals to

$$\mathcal{E}(\lambda) \approx -e \int \vec{\mathbf{E}}_{\mathbf{Hall}}, \vec{\mathbf{dl}} \approx \frac{H^2}{8\pi} \frac{\partial}{\partial y} \left(\frac{1}{n_e} \right) \lambda. \tag{5}$$

In Fig.3, the maximal kinetic electron energies for each energy-group versus the time of KMC wave evolution are given. One can see, that for fig.2a and for the parameters given above $\mathcal{E}(\lambda) \approx$ 110 keV.

Later moments of the KMC wave dynamics are shown in Fig.2b-2c. The magnetic field penetrates deeper into the plasma. The electrons "3" and "4" runaway from the front of the wave. In fig.3, one can see that the energies of these electrons do not change. The results of modeling show the exponential decrease of accelerated electrons quantity with time. Finally, we may propose the following scale dependence of maximal electron kinetic energy, $E_{\max}$, versus time, t, and versus initial energy, E_0:

$$E_{\max} \approx \begin{cases} \mathcal{E}(\lambda) * exp(-t/T), & \text{for } E_0 < \mathcal{E}(\lambda) * exp(-t/T); \\ E_0, & \text{for } E_0 > \mathcal{E}(\lambda) * exp(-t/T); \end{cases} \tag{6}$$

One of the important results of modeling is that the electrons of small energy, less than $500\, eV$, accelerate during all the calculated time up-to the energy $10 \div 30$ keV. If some heavy elements are present in the plasma, for example impurities, highly ionized ions (such as He-like ions) excited by medium energy accelerated electrons would radiate a polarized line spectra, which could be used as a diagnostic tool of the electron acceleration. When full accelerated electron reaches the anode, it produces hard X-rays emission.

In the present paper, we called runaway electron, high energy electron escaping from the magnetic field. Since the electron moves both in the magnetic field and in the electric fields of the wave, the condition for it to be runaway is the following : In the magnetic field the cyclotron radius, ρ_{Be}, of electron trajectory has to be greater, than the width of a current layer, δ. In the Hall electric field the kinetic electron energy, $m_e v^2/2$, has to be greater, than the "work of escape" from the magnetic field, $H^2/8\pi n_e$.

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