FOCUSING OF RELATIVISTIC ELECTRON BUNCHES AT THE WAKE-FIELD EXCITATION IN PLASMA.

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Abstract

Analytical and numerical investigations of the trajectories of probing beam electrons in a two dimensional wake-field, generated in a plasma by a dense bunch of relativistic electrons with Gaussian longitudinal and transverse distributions of density have been carried out. Based on the calculations of probing beam deviations, the diagnostic instruments are developed for the parameters of experiments conducted at NSC KIPT. The diagnostic instruments include an electron gun generating a $10keV$ electron beam with a current of $10\mu A$ and $2mm$ in diameter, which passes through the chamber of interaction and falls on the collector of $10mm$ diameter. The collector (screen) is placed in front of the first plate of a microchannel amplifier which consists of three microchannel plates (MCP) with sizes between 20 and $30mm$. The $3kV$ voltage was applied to each plate. The total amplification of MCP amplifier is 10^4 to 10^5 depending on the number of particles incident on the first plate. As a result of probing beam deviations due to the excited wake-field, the electrons fall on the first plate of the amplifier and are registered by its anode located behind the third plate. The calculated probing beam deviations and the amplification attained with the MCP amplifier permit one to detect and investigate the electrical wake-fields excited by a sequence of relativistic bunches (number of particles in a bunch is $2 \cdot 10^9$, energy is $14MeV$) in a plasma of $10^{11} - 10^{13} cm^{-3}$ density . The intensity of the fields registered by this technique is no less than $2kV/cm$.

1. INTRODUCTION

Measurements of HF-electric oscillations in a plasma is the currently central problem. So, high-intensity HF-fields are excited in a plasma during penetration of intense laser pulses and relativistic electron bunches. Such fields can be used for acceleration of charged particles [1]. For successful experimental realization of charged particle acceleration in a plasma it is nessary to elaborate simple and reliable methods of electric-field measurements in the plasma. This paper proposes such a method that is based on using a probing electron beam and microchannels plates [2]. This diagnostics is alternative to the well-known methodical procedure of plasma wake-field investigation using a streak-camera [3]. By way of example we consider the proposed method for measurements of wake-fields excited by a sequence of relativistic electron bunches.

2. SPATIAL STRUCTURE OF PLASMA WAKE-FIELDS

Let us determine the spatial distribution of wake-fields in a plasma excited by a relativistic electron bunch. We shall consider the bunch with Gaussian longitudinal and transverse profiles:

$$\vec{j}_0 = j_m e^{(-t_1^2/t_b^2 - r^2/\sigma_r^2)} \vec{z}. \tag{1}$$

where $\vec{j}_0$ is the current density of the bunch, $j_m = I_0/\pi\sigma_r^2$ is the maximum current density, I_0 is the peak current, $t_1 = t - z/c$, t_b is the bunch duration, σ_r is the transverse size of the bunch, $\vec{z}$ is the unit vector along the bunch motion, z, V are the longitudinal and radial coordinates, c is the light velocity in vacuum. We neglect the difference between bunch and light velocities, this is quite justified in the case of ultra-relativistic limit consideration.

The axial bunch of current density (1) excites in a plasma the electromagnetic field whose components are described by the expressions:

$$E_z = -\frac{4I_0}{\sigma_r^2 \omega_p} \Pi_{\|}(\eta) Z_{\|}(\tau) \tag{2}$$

$$E_r = -\frac{4I_0}{\sigma_r^2 \omega_p} \Pi_{\perp}(\eta) Z_{\perp}(\tau) - \frac{4I_0}{\sigma_r^2 \omega_p} \Pi_{\perp}(\eta) e^{(-\tau^2/\tau_b^2)}. \tag{3}$$

$$H_{\varphi} = \frac{4I_0}{\sigma_r^2 \omega_p} \Pi_{\perp}(\eta) e^{(-\tau^2/\tau_b^2)}. \tag{4}$$

Here $\tau = \omega_p(t - z/c)$, $\eta = \omega_p r/c$, ω_p is the plasma frequency,

$$\begin{aligned}
\Pi_{\|}(\eta) &= K_0(\eta) \int\limits_0^{\eta} I_0(\eta_0) e^{(-\eta_0^2/\eta_b^2)} \eta_0 d\eta_0 + \\
&\quad I_0(\eta) \int\limits_{\eta}^{\infty} K_0(\eta_0) e^{(-\eta_0^2/\eta_b^2)} \eta_0 d\eta_0, \\
\Pi_{\perp}(\eta) &= -\partial \Pi_{\|}/\partial \eta \\
Z_{\|}(\tau) &= \int\limits_{-\infty}^{\tau} e^{(-\tau_0^2/\tau_b^2)} \cos(\tau - \tau_0) d\tau_0, \\
Z_{\perp}(\tau) &= \int\limits_{-\infty}^{\tau} e^{(-\tau_0^2/\tau_b^2)} \sin(\tau - \tau_0) d\tau_0,
\end{aligned}$$

$\tau_b = \omega_p t_b$, $\eta_b = \omega_p \sigma_r / c$.

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At large distances behind the bunch $(z-\tau) >> \sigma_z^2, \sigma_z = c\tau_b$ being the longitudinal bunch size, the wake-field has the form of a harmonic wave with electric field components

$$E_z = -\frac{4\sqrt{\pi}\tau_b I_0}{\sigma_r^2\omega_p} e^{-\tau_b^2/4}\Pi_{\|}(\eta)\cos\tau \tag{5}$$

$$E_r = -\frac{4\sqrt{\pi}\tau_b I_0}{\sigma_r^2\omega_p} e^{-\tau_b^2/4}\Pi_{\perp}(\eta)\sin\tau \tag{6}$$

As it follows from expressions (2)- (6) the longitudinal component of electric field E_z is described by the function $\Pi_{\|}(\eta)$, and the transverse components E_r and H_φ are determined by the function $\Pi_{\perp}(\eta)$.

3. PROBING ELECTRON BEAM DYNAMICS IN WAKE-FIELDS

In the proposed method, a nonrelativistic probing electron beam is injected perpendicularly to the direction of relativistic bunch motion (longitudinal axis z) at a distance from the axis (impact parameter). The electric wake-field intensity is determined by the value of beam particles deflection for the given length L (base). For simplicity we neglect the transverse size of the probing beam, assuming it infinitely thin. As the probing beam injection continuously occurs in the periodic HF-field with components (5), (6), then in the plane being perpendicular to $x = L$ the thin probing beam depicts closed curve.

The probing beam particle dynamics in the axial wake-field (5- 6) is described by a set of equations of motion that take the following forms in the Cartesian coordinate system

$$\begin{aligned} U_x\frac{dU_x}{dX} &= -\epsilon\frac{X}{\eta}\Pi_{\perp}(\eta)\sin\tau, \\ U_x\frac{dU_y}{dX} &= -\epsilon\frac{Y}{\eta}\Pi_{\perp}(\eta)\sin\tau, \\ U_x\frac{dU_z}{dX} &= -\epsilon\Pi_{\|}(\eta)\cos\tau, \\ \frac{d\tau}{dX} &= \frac{1}{\beta_0 U_x}(1-\beta_0 U_z), \\ \frac{dY}{dX} &= \frac{U_y}{U_x}, \end{aligned} \tag{7}$$

where $\vec{U} = \vec{V}/V_0$ is the dimensionless velocity, V_0 is the initial velocity of the probing beam, $(X, Y, Z) = (\omega_p/c)(x, y, z)$ are the dimensionless Cartesian coordinates, $\beta_0 = V_0/c$, $\epsilon = \frac{4\sqrt{\pi}I_0\tau_b}{\beta_0^2\eta_b^2 I_A}e^{-\tau_b^2/4}$ is the dimensionless wake-field amplitude, $I_A = mc^3/e = 17kA$ is the Alfven current.

The set of equations (7) was solved by numerical methods for the following parameters of the plasma, relativistic electron bunch and probing beam: plasma density $n_p = 2\cdot 10^{11}cm^{-3}$,
plasma frequency $\omega_p = 2.5\cdot 10^{10}s^{-1}$,
transverse size of a bunch $\sigma_r = 7\cdot 10^{-2}cm$,
longitudinal size of a bunch $\sigma_z = 7\cdot 10^{-1}cm$,
bunch current $I_0 = 12A, 24A, 36A$,
corresponding wake-field amplitude $\epsilon = 19.5, 39, 58.5$.

Simulation was performed for 100 particles uniformly distributed in input phases relative to the wake wave $2\pi > \tau_0 > 0, \tau_0$ is the initial phase value.

If the bunch current increases or the number of bunches grows, then the maximum displacement of probing electrons becomes greater. So, for a single bunch of $36A$ or for 3 bunches with a $12A$ current in each bunch the displacement increases up to $2.1cm$.

4. EXPERIMENTAL FACILITIES

For intensity measurements of the wake-field excited in a plasma by short bunches of relativistic electrons we have elaborated diagnostic facilities based on the displacement of a $10keV$ probing electron beam current between 10 and $50\mu A$, and $2mm$ diameter, which was produced in a three-electrode electron gun. This beam passed across the interaction chamber perpendicularly to the axis of relativistic bunch motion. The choice of probing beam energy was dictated by the fact that the time of flight of the probing electron over the wake-field excitation zone ($\sim 1cm$) should be commensurable with a half of the excited wave period (for $n_p = 10^{11}cm^{-3}$ $T/2 \sim 150ps$). The scattering of probing electrons in the plasma due to elastic collisions is not essential. Indeed, the collisional length of probing electrons with the chosen energy is greater than the interaction region $l_e = V_e\nu_e = 100cm$, where $\nu_e^{-1} = \frac{2.5\cdot 10^4}{\Lambda/10}\frac{T_e^{3/2}}{Zn_p}$ is the collision frequency, V_e is the electron velocity, $T_e \simeq 3eV$ is the plasma temperature, $n_p = 10^{12}cm^{-3}$ is the plasma density, Λ is the Coulomb logarithm, Z_e is the plasma ion charge.

According to the calculations presented above, we have constructed the facilities for measuring the excited wake-field intensity. At about $3kV/cm$ the probing beam of $10kV$ should be displaced by $0.1cm$ in the interaction region. With the base length $L = 11cm$ to the registration place the probing electrons are displaced by $1cm$. This geometric configuration was modelled by using two deflecting plates fed by pulse voltage.

As a registration system for deflected probing beam an MCP amplifier [2] was used. It consists of three rectangular plates, each of $20 * 30mm$ size and $1mm$ thickness, with holes of $15\mu m$ in diameter and a structure step of $17.4\mu m$. A voltage of $3kV$ was applied to the current-carrying planes of the plates. Behind the third plate a collector was placed.

The signal from the collector was sent to the oscillograph through the emitter follower. The rate of amplification was 10^4 to 10^6 depending on the number of electrons incoming to each hole of the first plate. The amplifier has an individual vacuum pump, because the pressure in the amplifier chamber should be lower than $10^{-6}torr$.

Before the first plate of the amplifier there was a copper circular collector of $10mm$ diameter that registered the probing beam current. Being deflected by the excited wake-field the probing electrons get to the first plate, and after amplification the current is registered by the main collector. With the availability of a sectional collector the magnitude of probing beam displacement can be measured, and hence, the intensity of the excited wake-field can be evaluated.

5. CONCLUSIONS

The plasma wake-field diagnostics consisting of a probing electron beam and microchannel plates for current registration is proposed. For the same experimental arrangement the topography of excited wake-field has been obtained and evaluated. The trajectories of probing electrons in this field have been studied. Experimental facilities have been elaborated that allow one to measure the wake-field intensity of several kV per cm, excited by a relativistic bunch of $15MeV,\ 12A$, by using the probing beam of $10keV$ energy and 10 to $50\mu A$ current.

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6. REFERENCES

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