BEAM PROBING DIAGNOSTICS OF THE PLASMA WAKE FIELDS

N. Ayzatsky, V. Balakirev, A. Dovbnya, Ya. Fainberg, V. Karas', V. Kiselev, V. Kushnir,
A. Linnik, V. Mitrochenko, **I. Onishchenko**, V. Stepin, A. Tolstoluzhsky and V. Uskov

NSC Kharkov Institute of Physics & Technology
Academic St. 1, Kharkov 310108, Ukraine

It is well known that high-intensity HF-fields can be excited in plasma by pulses or relativistic electron bunches. Such fields are appropriately used for acceleration and focusing of charged particles [1]. For successful experimental realization of charged particle acceleration in plasma it is necessary to elaborate simple and reliable methods of electric-field measurements in the plasma. On this paper a method is proposed that is based on using of a probing electron beam and microchannels plates [2]. This diagnostics connected with HF time resolution equipment is alternative to the plasma wake-field investigation using a streak-camera [3]. As one of examples we consider the proposed method for measurement of wake-fields excited by a sequence of relativistic electron bunches.

1. Theory

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:

$$\vec{j}_0 = j_m \exp(-t_0^2 / t_b^2 - r^2 / \sigma_r^2)\vec{z} , \qquad (1)$$

where $\vec{j}_0$ is the current density of the bunch, $\vec{j}_0 = I_0 / \pi\sigma_r^2$ is the maximum current density, I_0 is the peak current, $t_0 = t - z / c$, $t_b = \sigma_z / c$ is the bunch duration, $\sigma_{r,z}$ is the transverse and longitudinal size of the bunch, $\vec{z}$ is the unit vector along the bunch motion, z, r are the longitudinal and radial coordinates, c is the light velocity in vacuum

The axial bunch of current density (1) excites in plasma the wake field with the following components:

$$E_z = -(4I_0 / \sigma_r^2\omega_p)\,\Pi_\parallel(\eta)Z_\parallel(\tau) , \qquad E_r = -(4I_0 / \sigma_r^2\omega_p)(\Pi_\perp(\eta)Z_\perp(\tau) - \Pi_\parallel(\eta)T(\tau)),$$

$$H_\varphi = 4I_0 / \sigma_r^2\omega_p\,\beta_0\Pi_\perp(\eta)T(\tau) , \qquad (2)$$

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

$$\Pi_\parallel(\eta) = K_0(\eta)\int_0^\eta I_0(\eta_0)e^{(-\eta_0^2/\eta_b^2)}\eta_o d\eta_o + I_0(\eta)\int_\eta^\infty K_0(\eta_0)e^{(-\eta_0^2/\eta_b^2)}\eta_o d\eta_o , \qquad \Pi_\perp(\eta) = -\partial\Pi_\parallel / \partial\eta$$

$$Z_\parallel(\tau) = \int_{-\infty}^\tau e^{(-\tau_0^2/\tau_b^2)}\cos(\tau - \tau_0)d\tau_0 , \qquad Z_\perp(\tau) = \int_{-\infty}^\tau e^{(-\tau_0^2/\tau_b^2)}\sin(\tau - \tau_0)d\tau_0 , \qquad (3)$$

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

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

$$E_z = -4(\sqrt{\pi}\tau_b I_0 / \sigma_r^2\omega_p)e^{-\tau_b^2/4}\Pi_\parallel(\eta)\cos\tau , \quad E_z = -4(\sqrt{\pi}\tau_b I_0 / \sigma_r^2\omega_p)e^{-\tau_b^2/4}\Pi_\parallel(\eta)\sin\tau \quad (4).$$

As it follows from expressions (2)-(4) the longitudinal component of electric field E_z is described by the function $\Pi_\parallel(\eta)$, and the transverse components E_r and H_φ are

determined by the function $\Pi_\perp(\eta)$. In Fig.1 the functions $\Pi_\parallel(\eta)$ (curve 1) and $\Pi_\perp(\eta)$ (curve 2) are represented.

From these dependencies it follows that the function $\Pi_\parallel(\eta)$ monotonically decreases, while the function $\Pi_\perp(\eta)$ has a maximum in the region $\eta \sim \eta_b$. It should be noted that in the case of thin bunches $\eta_b \ll 1$, the transverse electric-field component exceeds the longitudinal one. Bunches of large transverse sizes, $\eta \geq 1$, excite mainly the longitudinal component.
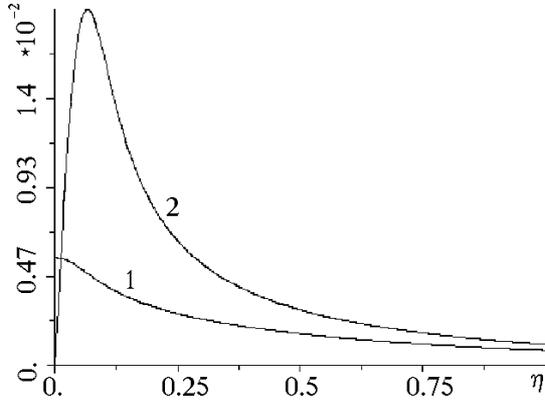

Fig. 1: *Plots of $\Pi_\parallel(\eta)$ (curve 1) and $\Pi_\perp(\eta)$ (curve 2) are given for dimensionless radius of the bunch $\eta_b = 0.059$.*

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 y_0 from the axis (impact parameter). The electric wake-field intensity is determined by the value of beam particles deflection for the fixed base L. As the probing beam injection continuously occurs in the periodic HF-field with components (4), 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 (4) was investigated 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 $\sigma_\tau = 7 \cdot 10^{-2}$ cm, longitudinal size of a bunch $\sigma_z = 7 \cdot 10^{-1}$ cm, bunch current I_0=12A, 24A, 36A, corresponding wake-field amplitude $\in$ =19.5, 39, 58.5. Simulation was performed for 100 particles uniformly distributed in input phases relative to the wake wave $2\pi > \tau_0 > 0$, τ_0 - is the initial phase value.

Fig.2 shows the intersection points of the plane at x =11cm by the trajectories of probing beam particles. The initial impact parameter value was chosen y_0 =0.07cm at the bunch current I_0 =12A. From Fig.2 it is seen that the maximum transverse displacement of probing electrons essentially exceeds the maximum longitudinal shift.

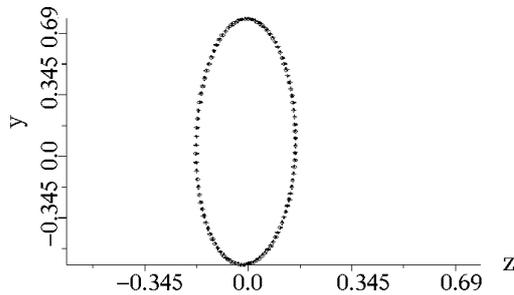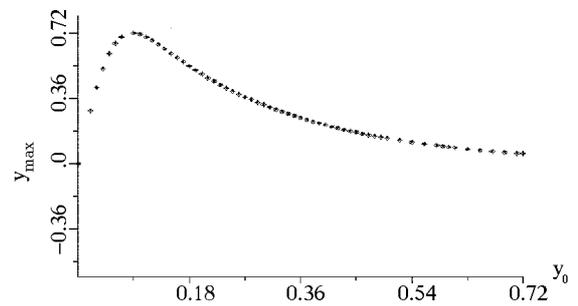**Fig. 2:** *Points of intersection of the plane by probing beam trajectories at x =11cm, impact parameter y_0 =0.07 cm.*

Fig. 3: *Maximum displacement y_{max} versus impact parameter at x =11cm.*

In Fig.3 the maximum displacement y_{max} at a distance of 11 cm is shown as a function of the impact parameter y_0. The maximum displacement is equal to 7 mm for y_0 =0.089 cm, and corresponds to the maximum transverse component of wake-field E_z =2.51kV/cm.

In Fig.4 the functions $y(x)$ and $z(x)$ for two particles that have experienced a maximum displacement in the wake-field are presented.
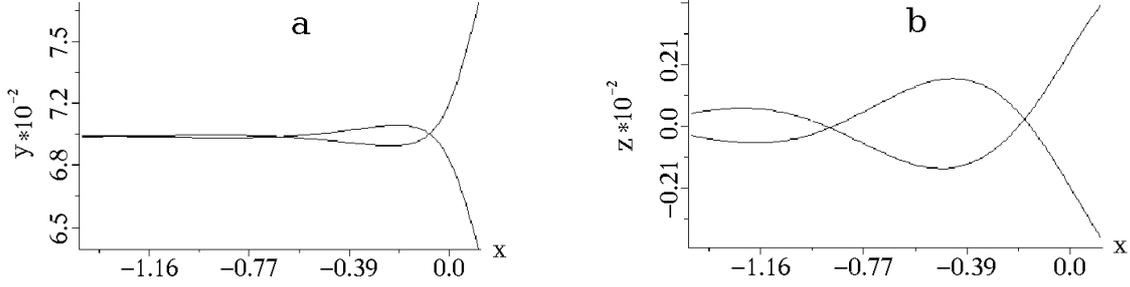

Fig. 4: Plot of trajectories of two particles hat have experienced maximum displacement: (a) y versus x; (b) z versus x.

For a single bunch of 36 A or for 3 bunches with a 12 A current in each bunch the displacement increases up to 2.1 cm.

To investigate the temporal evolution of probe beam particles density distribution at time scale 10ps at the a solely bunch the HF scanning of the probe beam in volume cavity can be applied. It is widely used in acceleration technique [4] for measurements of the electron bunch phase size.

The method concludes in transformation of the temporal (phase) distribution of the particles into transverse momentum distribution by means of cavity fields. After drifting for some distance particle are distributed in space. The mode TM_{110} of the cylindrical cavity is proposed for probe beam scanning. Maximum magnetic HF-field amplitude on axis is:

$H_{\perp max} = \sqrt{25PQ/\pi r R^2 h \omega \varepsilon_0}/\eta$ (A/m) where R, h are radius and height of the cavity, correspondingly P, ω are the HF-power and frequency, $\eta = \sqrt{\varepsilon_0/\mu_0}$. R is determined by the frequency, that was equal to operation frequency of accelerator, h is chosen so that the declining angle was close to π. For planned experiments parameters: wave length $\lambda = 10,7 cm$; probing beam energy $10 keV$; $R = 3,832 \lambda/\pi$ cm; $h = \beta \lambda/2 = 1,04$ cm; $H_{\perp max} = 2,8 \cdot \sqrt{PQ_0}$.

For cavity power $1kW$ and factor $Q_0 = 3 \cdot 10^3$ the declining value at distance 30 cm is 3,6 cm. The spot of the probing beam is a line for plane polarization and a circle for circular one. By moving the cavity along the declined beam the information about momentum distribution over particle-cavity field phase, correlated with their temporal distribution can be obtained.

2. Experiment

For intensity measurements of the wake-field excited in a plasma by a short bunch of relativistic electrons we have elaborated diagnostic facilities based on the displacement of a 10 keV 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 (~1 cm) should be commensurable with a half of the excited wave period (for $\eta_p = 10^{11} cm^{-3}$ $T/2 \sim 150$ ps). The scattering of probing electrons in the plasma due to elastic collisions is not essential. 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 $10\,kV$ should be displaced by 0.1 cm in the interaction region. With the base length $L = 11$ cm to the registration place the probing electrons are displaced by 1 cm. This geometric configuration was modeled by using two deflecting plates fed by pulse voltage.

As a registration system for deflected probing beam an microchannel plate amplifier [2] was used. It consists of three rectangular plates, each of $20*30$ mm size and 1 mm 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 in dependence on the number of electrons incoming to each hole of the first plate. Before the first plate of the amplifier there was a copper circular collector of 10 mm 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.

The measurements of a beam current by the double Faraday cup, mounted on an axis of system on distance 1,5 m from middle of interaction area, allowed to fix the focusing of a sequence of relativistic electron bunches at their passage through plasma. At density of plasma $n_p \approx 10^{11}$cm^{-3} the small Faraday cup registered increase of a current on 15-20% at the appropriate decrease of a current on the first cup. At density of plasma $n_p \approx 10^{13}$cm^{-3} the small Faraday cup registered increase of a current almost twice.

The power spectra of relativistic electron bunches, past through area of interaction were measured at density of plasma $n_p \approx 10^{11}$cm^{-3}. In fig.5 the «instant» energy spectra received everyone 100 ns, that corresponds to a package from 350 are shown.
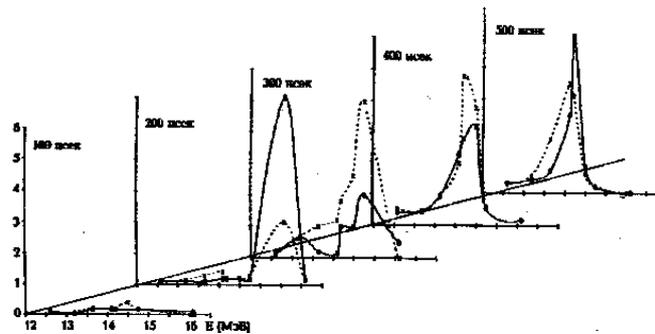

Fig. 5. *«Instant» power spectra of bunches without plasma (continuous curves) and passed through plasma (dotted curves) for the various moments of time*

From fig.5 follows, that appreciable displacement of power spectra showing the decelaration or acceleration of beam electrons in plasma is not observed. Taking into account, that accuracy of measurement of spectra displacement by the magnetic analyzer is of the order 150 KeV, it is possible to conclude that the amplitude of induced longitudinal wake-fields in plasma on length $\ell = 50$cm does not exceed 3 KV/cm. On the other hand, as it is visible from the figure, the head bunches do not undergo essential changes after passage through plasma: whereas the subsequent bunches, especially for $\tau = 300$ ns, give a spectrum with large intensity of electrons and smaller half-width. It evidence the bunches focusing.

References

[1] P. Chen, J.M. Dawson, R. Huff, T. Katsouleas: Phys. Rev. Lett. **54**, 692(1985).
[2] C.J. Armentrout: Rev. Sci. Inst. **5** 1179(1985).
[3] K. Nakajima, A. Enomoto, N. Kobayashi et al.: Nucl. Inst. and Methods in Phys. Res. **A292**, 12(1990).
[4] Z.S. Zlunitsin, A.I. Zykov, V.A. Kyshnir et al.: VANT **2**(28), 37(1986).