

EXPERIMENTAL PLASMA WAKE-FIELD ACCELERATION PROJECT AT THE VEPP-5 INJECTION COMPLEX

A. V. Petrenko, A. V. Burdakov, A. M. Kudryavtsev, P. V. Logatchov, K. V. Lotov*, and A. N. Skrinsky,
Budker INP, Novosibirsk, 630090, Russia

Abstract

The project of an experimental facility based on the VEPP-5 injection complex is described. Due to a good quality of electron or positron beams and special beam preparation system, the facility opens several possibilities for studies of the plasma wakefield acceleration: high peak beam currents, arbitrary beam profiles, long term beam-plasma interaction (up to the full driver depletion), and precise beam diagnostics. Various wakefield regimes can be experimentally demonstrated and studied: the efficient blow-out regime with a low energy spread and high acceleration rate (up to several GeV per meter); multibunch regime; long bunch instabilities; beam self-organization in plasma; plasma lens. If successfully realized, this experiment becomes a solid argument for feasibility of a high-energy collider based upon the plasma wakefield acceleration.

INTRODUCTION

Plasmas can sustain very large electric fields that are many orders of magnitude higher than those in conventional accelerating structures. This property is used in plasma wakefield accelerators (PWFA), in which one electron beam drives the high amplitude field in the plasma, and another beam (witness) is accelerated by this field (see review [1] and references therein). To compete with conventional accelerators, the plasma-based accelerators must have high efficiency, low energy spread of the accelerated beam, and high transformer ratio R (i.e., the ratio of longitudinal fields in two beams) at reasonable beam parameters and tolerances. In search of a good regime that meets these requirements, several beam configurations were proposed and studied. One of them is the blowout regime [2, 3] in which all the plasma electrons are ejected off the beam propagation channel, and an electron-free region (called the cavern) is formed around the drive beam.

For high beam currents and moderate beam lengths, a promising mode of the blowout regime is realized (so-called strong beam regime [4]) when the energy content of the plasma is very high. Almost all this energy can be withdrawn from the plasma at a relatively high electric field within the witness beam. Operating in the strong beam mode with properly shaped driver and witness opens the possibility to achieve high efficiency of the beam-to-beam energy exchange, high acceleration rate (with $R > 2$), and low energy spread simultaneously.

To demonstrate the efficient blowout regime, a high-quality high-energy electron beam from a conventional accelerator must be longitudinally compressed, properly shaped, and passed through a plasma section that is long enough to completely decelerate some parts of the driver. All this possibilities will be available at the experimental facility based on the VEPP-5 injection complex. The experimental project itself and the expected results obtained with computer simulations are reported in this paper.

THE PROJECT

VEPP-5 injection complex is currently under construction at Budker Institute of Nuclear Physics to provide VEPP-4 and VEPP-2000 colliders with high-quality electron and positron beams. The complex consists of 510 MeV linear accelerator followed by the damping ring. Beam parameters after the damping ring are shown in Table 1. These beams can be also used for experiments on plasma wakefield acceleration.

Being simply injected into a plasma, the beams will produce the electric field of the amplitude ~ 10 MV/m. For excitation of a higher amplitude plasma wave, the beam is to be compressed and shaped before the plasma chamber. These manipulations are to be made in the beam preparation system. Here, a linear correlation between energy and longitudinal position is induced in the beam by passing an RF structure at the zero-crossing phase (Fig. 1). Then follow two 45-degrees bending magnets where particles with different energies have different path lengths, so the bunch is compressed longitudinally.

The efficiency of such a technique is limited by the ratio of the initial (δW) to the induced (ΔW) energy spread which basically determines the minimum final length of the bunch δz . The maximum compression ratio in the proposed system is realized at $\Delta W/W_0 \approx 5\%$, whence we obtain

$$\delta z = \frac{\delta W}{\Delta W} \cdot 2\sigma_z \approx \frac{0.05\%}{5\%} \cdot 8 \text{ mm} \sim 0.1 \text{ mm}, \quad (1)$$

In the region of maximum dispersion, a collimator is placed to cut out some parts of the beam (Fig. 1). Since the dispersion function turns to zero after the second bending magnet, the transverse modulation of the beam after the collimator converts to an arbitrary longitudinal modulation of the beam current with the precision $\sim \delta z$.

Beam line tracing confirms the above estimates and shows that this system can produce electron or positron bunches of various shapes, for example, a single short bunch (0.2 mm-long) with peak current up to 6 kA, two

*K.V.Lotov@inp.nsk.su

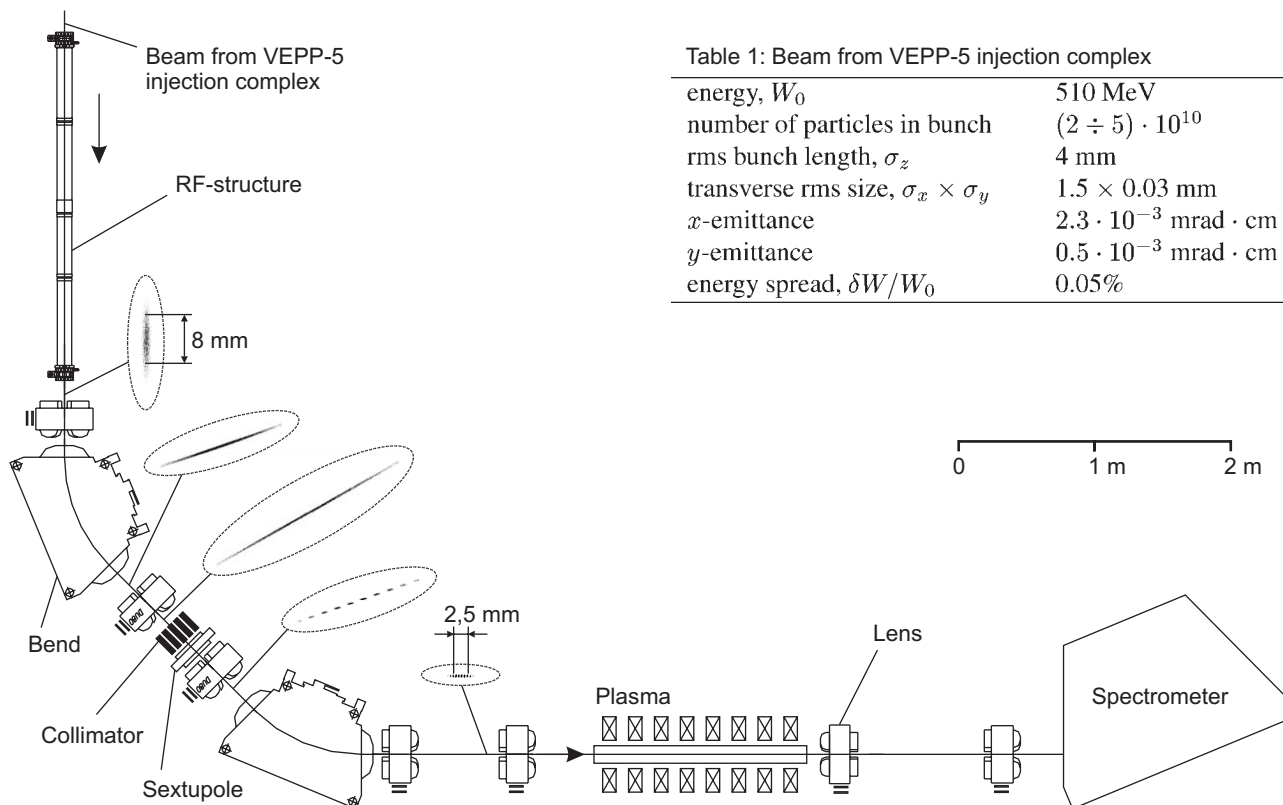


Table 1: Beam from VEPP-5 injection complex

energy, W_0	510 MeV
number of particles in bunch	$(2 \div 5) \cdot 10^{10}$
rms bunch length, σ_z	4 mm
transverse rms size, $\sigma_x \times \sigma_y$	1.5×0.03 mm
x -emittance	$2.3 \cdot 10^{-3}$ mrad · cm
y -emittance	$0.5 \cdot 10^{-3}$ mrad · cm
energy spread, $\delta W/W_0$	0.05%

Figure 1: General layout of designed facility. Insets show the beam portraits at different positions.

0.2 mm-long microbunches with peak currents of 1–2 kA, or a long train of microbunches with the peak current about 100 A.

The finest scale of beam modulation δz determines the minimum wavelength of the wakefield $\lambda_p \sim 2\delta z$ and the maximum required plasma density

$$n = \frac{\pi m c^2}{e^2 \lambda_p^2} \sim 10^{16} \text{ cm}^{-3}. \quad (2)$$

A plasma of this density and length $L \sim 1$ m can be created by a direct discharge in a magnetic field. A similar discharge is routinely used in Budker INP for creation of a dense target plasma at thermonuclear facility GOL-3 [5, 6].

The required plasma homogeneity is determined by the number of micro-bunches N in the modulated beam. The relative variation of the plasma wavelength $\delta\lambda_p/\lambda_p$ along the plasma column must not exceed $(3N)^{-1}$ [7]. Otherwise the particles from the beam tail will eventually fall into the defocusing phase of the wakefield and get lost.

The beam energy spectrum after the plasma will be measured by a dipole spectrometer. The angular distribution of beam particles will be registered also.

EXPECTED RESULTS

The designed facility will be flexible enough to study various regimes of plasma wakefield acceleration: the efficient blowout regime with a low energy spread and high

acceleration rate, resonant wakefield excitation by a train of short bunches, instability and self-organization of long bunches in the plasma, various plasma lens regimes, etc. Here we describe only the efficient two-bunch regime [8] which is of a prime interest for possible collider applications of PWFA.

In the efficient blowout regime, the plasma response to the beam is essentially nonlinear and allows no detailed analytical study. The account of beam dynamics complicates the problem further. Therefore, for optimization of the system we used two-dimensional hybrid code LCODE [9, 10] to make end-to-end simulations of beam propagation through the whole plasma section. The optimization involves the adjustment of several input parameters to maximize the witness energy gain and witness charge at moderate ($\lesssim 10\%$) energy spread. These parameters are: the longitudinal compression ratio of the beam, location of collimator plates, plasma length and density.

The result of optimization is shown in Fig. 2. The beam that initially comprises $2 \cdot 10^{10}$ electrons is to be compressed to $\sigma_z = 0.3$ mm, focused to $\sigma_r = 0.026$ mm, and collimated to create the double-hump density and current distribution (Fig. 2a). After passage of 95 cm in the plasma of density $1.7 \cdot 10^{15} \text{ cm}^{-3}$, the beam energy spectrum considerably changes (Fig. 2b). The first bunch (10^{10} electrons) loses 54% of its energy and decelerates, in average, from 510 MeV to 240 MeV. The second bunch takes 63% of the plasma energy and accelerates to 1.1 GeV. This cor-

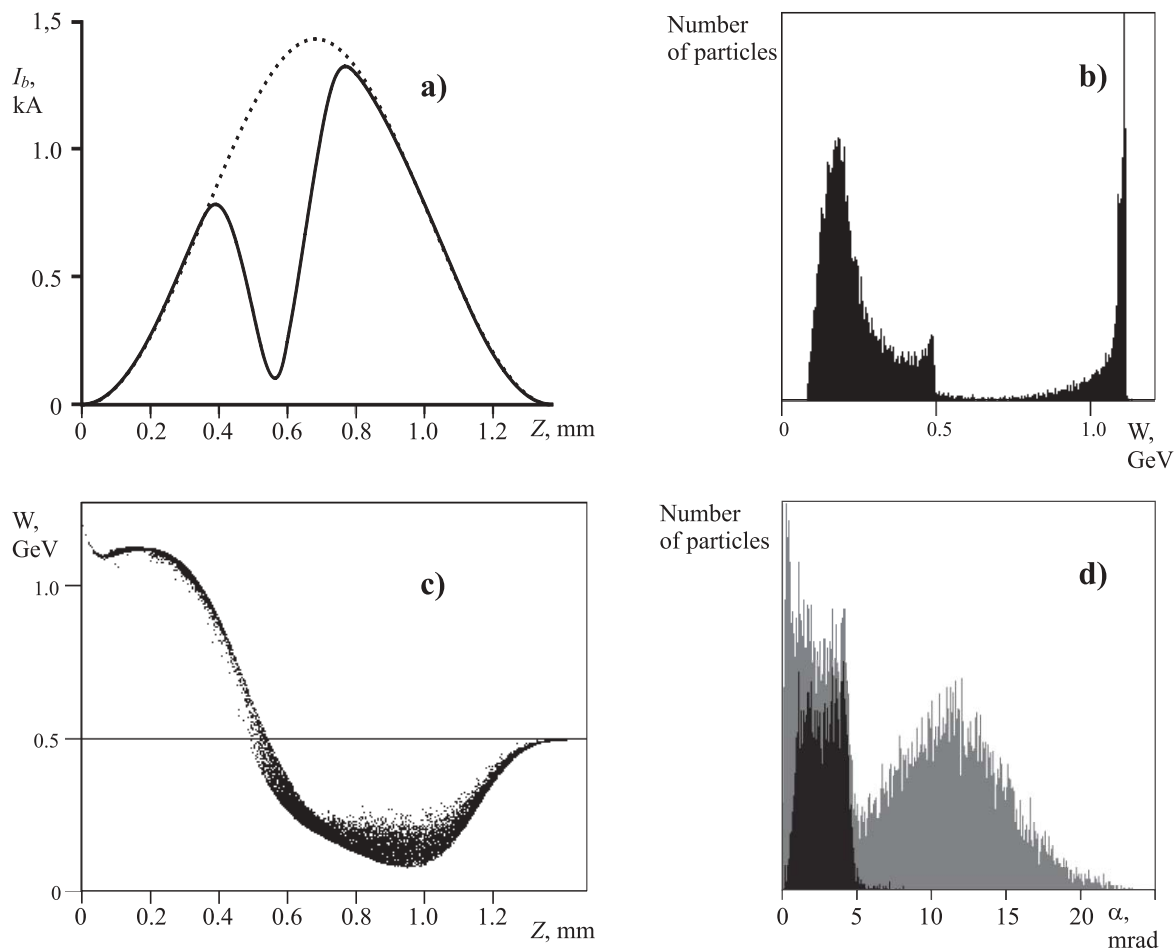


Figure 2: Results of simulations: a) the profile of beam current before the entrance to the plasma, dashed line shows the current profile with no collimation, the beam propagates toward positive z -direction; b) energy spectrum of the beam after the plasma; c) beam portrait on the plane “energy – longitudinal coordinate” after the plasma; d) angular distribution of the beam after the plasma, accelerated particles are shown by darker shading.

responds to 34% bunch-to-bunch efficiency and the acceleration rate of 600 MeV/m. The final energy spread of accelerated bunch is 9% (Fig. 2b), the angular spread is lower than 0.3° (Fig. 2d).

ACKNOWLEDGEMENTS

This work was supported by Science Support Foundation, SB RAS Lavrent'ev Grant for young researchers, Russian Foundation for Basic Research (grant 03-02-16160a), and Russian Ministry of Science (grant NSh-229.2003.2).

REFERENCES

- [1] E. Esarey et al., IEEE Trans. Plasma Sci. 24 (1996) 252.
- [2] J. B. Rosenzweig et al., Phys. Rev. A 44 (1991) 6189.
- [3] C. Joshi et al., Phys. Plasmas 9 (2002) 1845.
- [4] K. V. Lotov, Phys. Rev. E 69 (2004) 046405.
- [5] A. V. Burdakov et al., “Characterization of long magnetized linear discharge in a metallic chamber”, ICPIG'93, Bochum, 1993, p. 139.
- [6] R. Yu. Akentjev et al., Trans. Fusion Technol. 43 (2003) 30.
- [7] B. N. Breizman et al., AIP Conf. Proc. 396 (1997) 75.
- [8] K. V. Lotov, “Efficient Regime of the Plasma Wakefield Accelerator”, EPS'04, London, 2004.
- [9] K. V. Lotov, Phys. Rev. ST Accel. Beams 6 (2003) 061301.
- [10] K. V. Lotov, Phys. Plasmas 5 (1998) 785.