Experimental plasma wakefield acceleration project
at the VEPP-5 injection complex

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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. In search of a good regime that meets these requirements, several beam configurations were proposed and studied. One of them is the blowout regime in which all the plasma electrons are ejected off the beam propagation channel, and an electron-free region (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 ("strong beam" regime [2]) 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 Almost all this energy can be withdrawn from the plasma at a relatively high electric field within the witness beam.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 [3].

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.

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.

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 $\cdot$ cm
y-emittance	$0.5 \cdot 10^{-3}$ mrad $\cdot$ cm
energy spread, $\delta W/W_0$	0.05%
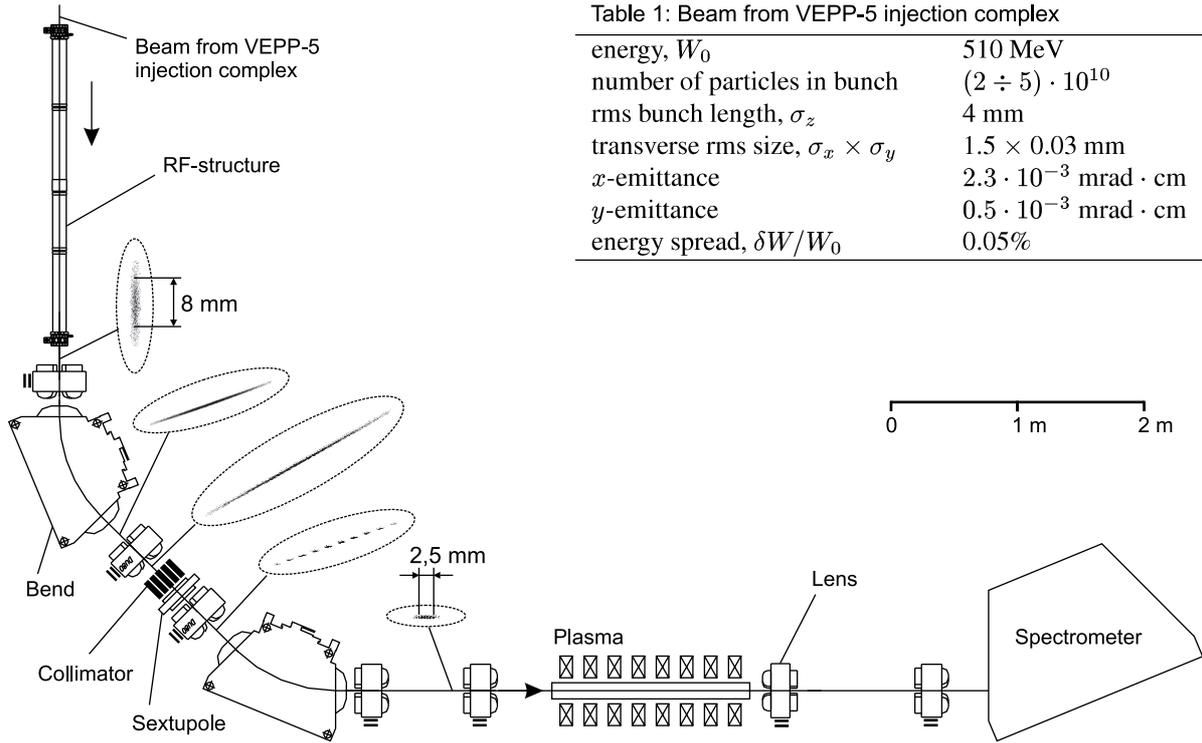
Figure 1: Layout of the designed facility. Insets show the beam portraits at different positions.

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

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

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 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 wake-field $\lambda_p \sim 2\,\delta z$ and the maximum required plasma density $n \sim 10^{16}\,\mathrm{cm}^{-3}$. 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 [4].

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

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, various plasma lens regimes, etc. Here we describe only the efficient two-bunch regime [3] 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 [5] 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 distribution (Fig. 2a). After passage of 95 cm in the plasma of density $1.7 \cdot 10^{15}\mathrm{cm}^{-3}$, the first bunch ($10^{10}$ electrons) loses 54% of its energy and decelerates, in average, from 510 MeV to 240 MeV (Fig. 2b). The second bunch takes 63% of the plasma energy and accelerates to 1.1 GeV. This corresponds to 34% bunch-to-bunch efficiency and the acceleration rate of 600 MeV/m. The final energy spread of the witness is 9% (Fig. 2b), the angular spread is lower than 0.3° (Fig. 2d).
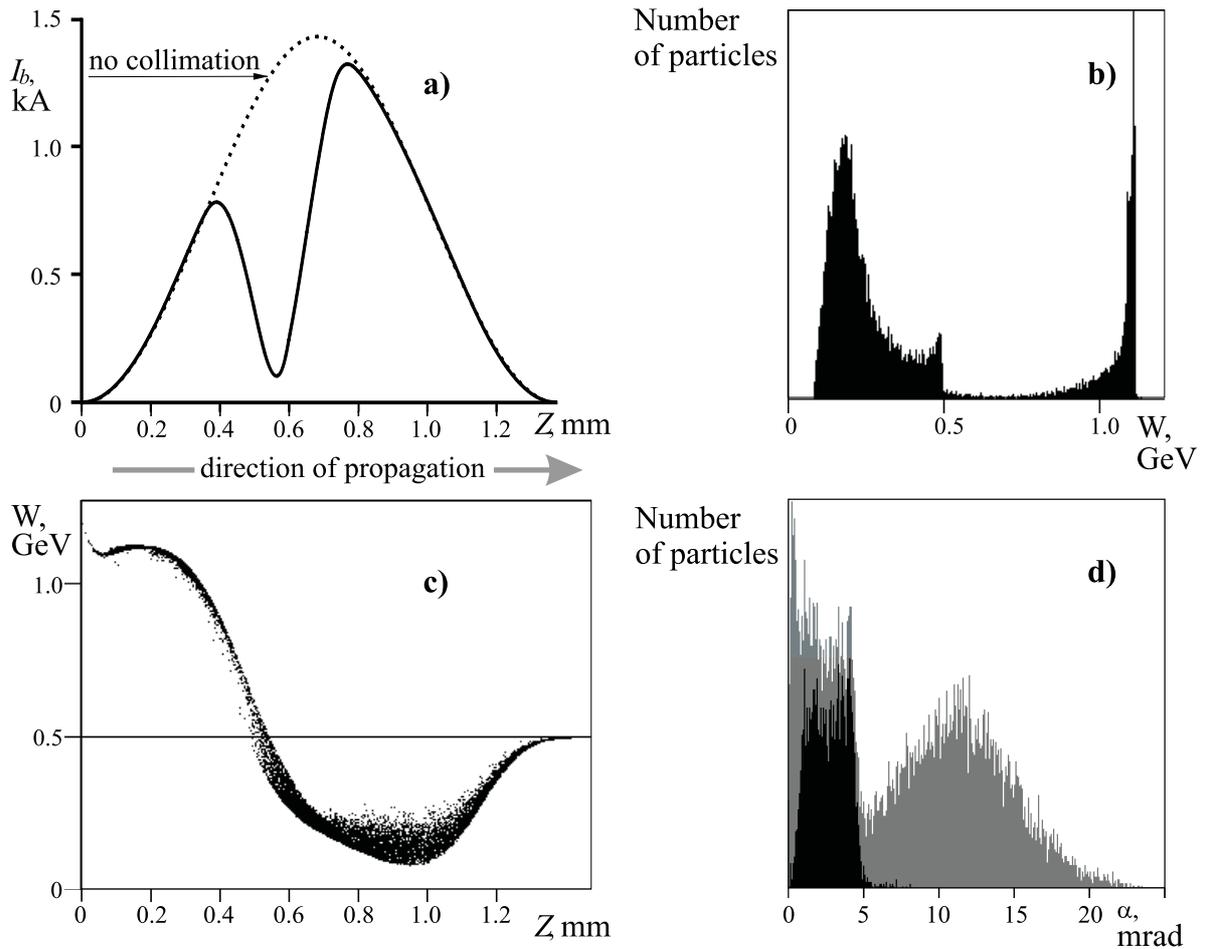
Figure 2: Results of simulations: a) beam profile before the entrance to the plasma; b) energy spectrum, c) portrait on the plane "energy – longitudinal coordinate", and d) angular distribution of the beam after the plasma; accelerated particles are shown by darker shading in d).

References

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