INVESTIGATION OF PLASMA LENSES IN NSC KIPT

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The results of carried out at NSC KIPT theoretical and experimental studies of focusing electron and ion beams with using plasma lens are presented. Several mechanisms of beam focusing in plasma are considered: plasma compensation of defocusing space charge field of the beam, focusing by electric and magnetic fields of charged current-carrying plasma, ejected from the plasma gun, and focusing by high-frequency wakefield excited in plasma by a sequence of short relativistic electron bunches.

PACS: 41.85.Ne; 41.85.Lc

INTRODUCTION

Plasma lens (PL) as a device for focusing charged particle beams has a long and abundant history. Arising of PL began from electrostatic focusing of low-energy electron beams by the beam-generated plasma in cathode ray tubes [1] and positive ion beams by pure electron cloud in Penning trap (Gabor lens [2]). Based on plasma optic principles [3] the uniform plasma density was created that generates a radially linear electric field within the column, which was used to electrostatically focus heavy ion beam [4]. A current carrying neutral plasma column was used to magnetically focus a 350 MeV proton beam [5]. The focusing force of this lens is due to an azimuthal magnetic field generated by the externally driven axial plasma current. Direct experiments with focusing heavy ions by PL of this type were conducted at GSI (Germany) on the SIS-18 accelerator. A 300 MeV/u beam of neon ions (Ne^{10+}) and a beam current of up to 350 kA were focused onto a 300 μm spot [6]. Efficient focusing of intense heavy ion beams is an important issue for heavy-ion driven inertial confinement fusion and for investigations of high energy densities in matter produced by heavy ion beams. The description and the results of performance investigation of a PL designed for the heavy-ion accelerator–accumulator facility TWAC-ITEP (Russia) are presented in [7] (discharge current of 200 kA was achieved with spatial distribution suitable for ion beam focusing).

In contrast to these two type of PL with externally generated electric or magnetic field in plasma (so called "active" PL), a "passive" PL based partially on Bennett's concept of magnetic self-focusing [8] was proposed in [9, 10]. In the "passive" PL, a preformed, current-free, neutral plasma either partially or completely charge neutralizes a relativistic particle beam, allowing the azimuthal, self-magnetic field of the beam to pinch the beam. For SLC bunch (1 nC, σ_r=2 μm, σ_z=1.2 mm) the self-magnetic field at the edge of the bunch is 5 T that corresponds to a focusing gradient of 250 MG/cm. When the beam radius is less than plasma skin depth ($r_b<c/\omega_p$, ω_p is plasma frequency), since most of the plasma return currents flow outside of the beam, the self-magnetic field is not reduced significantly within the beam. For under-dense PL ($n_p<n_b$) [9, 10] the strong electric field created by the space charge of the electron beam ejects the plasma electrons from the beam region entirely, leaving a uniform ion column. In this case spherical aberration is eliminated. For over-dense PL ($n_p>n_b$) [11-13] electric field is neutralized, self magnetic field is pinching the beam.

In this work PL of various types investigated and applied in NSC KIPT are presented.

1. VERIETY OF PLASMA LENSES IN KIPT

1.1. PRODUCTION OF DENSE MICROBUNCHES OF RELATIVISTIC ELECTRONS [14]

Use of dense microbunches in radiation investigations makes it possible to improve the ecological conditions of many experiments due to the decrease of produced radioactive volumes. New possibilities are opened for solving many problems: simulation of radiation damages of materials and biota; transmutation alloying of semiconductors and high pure materials; radioactive waste reprocessing; high luminosity of colliding beams etc.

On the high-current universal injector complex UIC and linac LUE-300 owing to the precision short-focusing magnetic compression the pulsed density of microbunch $j_{pulse}=10^6$ A/cm^2 was obtained at E_0=300 MeV and $\tau=3\cdot10^2$ s. Interaction with Uranium target gives the production of neutron intensity $S\sim10^{16}$ n/s. This "illumination" is quite sufficient for ignition of overdense nuclear targets with inertial confinement.

In order to improve radiation-ecological conditions of experiment with a set of high fluencies ($F=10^{22}\ldots10^{23}$ e$^-$/cm^2) in reactor materials we succeeded in obtaining electron flux density $n_e=10^{17}$ e$^-$/cm^{2}s at average current 2 μA instead of 40 μA, i.e. decreased more than one order the radioactivity level of material microsamples.

The scheme of increasing by several orders the electron bunch density by means of underdense plasma lens focusing is proposed. Plasma focusing is equivalent to the external magnetic focusing by quadrupoles with strength gradient $H/r=3\cdot10^{-9}\,n_p$, i.e. for bunch density in the crossover $n_b\sim n_p=10^{14}$ cm^{-3} the expected gradient of focusing field is $H/r=3\cdot10^5$ G/cm, that is more than one order higher comparatively to the gradient in the duplet of quadrupole lenses $H/r=10^4$ G/cm.

1.2. FOCUSING OF MEV MULTI-CHARGED MOLYBDENUM ION BEAM [16]

Multi-charged Mo ion beam was produced at the heavy ions accelerator of «UTI-1» [15]. Scheme of experimental installation for this ion beam focusing by electrostatic plasma lens is shown in Fig. 1. Ion sources produced the strip beam (5 cm×0.4 cm) of multi-charged ions of various metals and gases. The quadruple lens was used to form cylindrical ion beams of diameter 2 cm from the strip one. Ions were accelerated through two stages – firstly to the energy $E_1=ZU_1$ in ion optic system and secondary in accelerating tube to the energy $E_2=ZU_2$, where Z is ion charge, U_1 and U_2 are accelerating voltages of ion source and accelerating tube, correspondingly. The total energy of accelerated ion is $E=Z(U_1 +U_2)$. Magnetic separation was performed at low ion energy U_1=25…125 kV. The accelerating tube voltage was U_2=200 V. In particular the maximum energy of Mo^{4+} reached 0.9 MeV and current 25 μA. The gas amount was chosen such (0.5…2 cm^3/min) that the beam current had a maximum value.

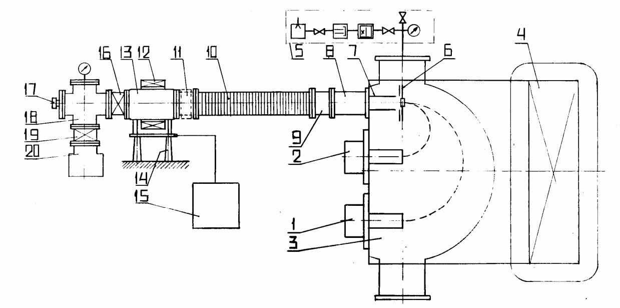

Fig. 1. Scheme of the installation: 1, 2 – ion sources of metals and gases; 3 – vacuum chamber of mass-analyzer; 4 – mass-analyzer; 5 – system for vacuum measuring; 6 – unit for beam current measuring; 7 – system of beam declining; 8 – quadruple lens; 9,11 – sylphons; 10 – accelerating system of UTI-1; 12 – magnetic field coil; 13 – plasma lens chamber; 14 – insulator; 15 – rectifier on 200 kV; 16, 19 – vacuum valves; 17 – target complex; 18 – vacuum chamber; 20 – magnetic discharge pump

During ion beam propagation through the hydrogen the gas ionization and plasma production takes place. In magnetic field 0.8 kOe plasma ions are not magnetized and they leave the system. Plasma electrons are confined in magnetic field and create plasma lens as an electron cloud or noncompensated plasma. Its electric field is focusing one for ion beam.

At hydrogen leak-in 1 cm^3/min and more, and for Mo^{4+} ion energy less 350 keV, the current decreasing in several times and changing of charge state and energy spectrum were observed. It can be explained by recombination and charge exchange processes of multi-charged Mo ions on hydrogen atoms. At ion energy growth to 1 MeV and gas leak-in of 1 cm^3/min the capture cross-section decreases considerably and the probability of charge exchange falls down. Under these conditions the ion beam current increasing and its transversal size lessening was observed.

For this case the changing of the beam cross-section shape was measured on the beam imprint at the collector of diameter 3 cm that was placed at a distance 30 cm from plasma lens and 45 cm from accelerator exit.

The dependence of the beam cross-section lessening on the magnetic field value is represented in Fig. 2. It is seen that in process of beam focusing by electron cloud its diameter decreases with magnetic field growth and for 0,8 kOe it is 0,8 cm.

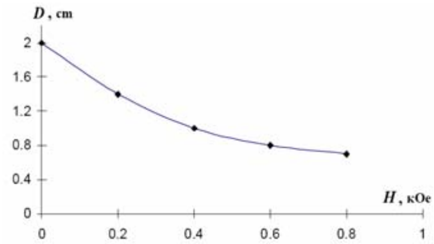

Fig. 2. Dependence of ion beam diameter on magnetic field value in plasma lens region

Simultaneously with beam cross-section measurements the beam current density were measured by Faraday micro-cup with inner diameter 3 mm. In Fig. 3 the dependence of the beam current on this micro-cup on magnetic field value is shown. During focusing the beam current grows in 2 times. It is additional evidence of focusing process. However incomplete correspondence of these two measurements is probably connected with considerable decreasing of the total beam current under beam charge exchange on gas target.

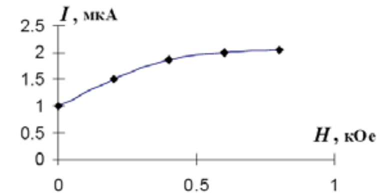

Fig. 3. Dependence of ion beam current on magnetic field value in plasma lens region

Thus the experimental investigations have shown that multi-charged heavy ions of metals and gases can be focused by plasma lens, which is created during ion beam penetration in gas with magnetic field applying for electrons confinement.

1.3. PLASMA FOCUS AS AN ACTIVE PLASMA LENS FOR INTENSE ION BEAM FOCUSING

Plasma lens for focusing of the proton beam of energy 5 MeV and current 10 mA produced by the accelerator “Ural-5” with RFQ radial-phase focusing is investigated [16-18]. The scheme of the experimental set-up is shown in Fig. 4.

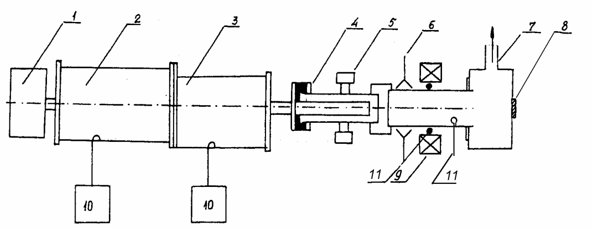

Fig. 4. Experimental set-up: 1 – proton injector; 2 – initial stage of accelerator; 3 – final stage; 4 – plasma gun; 5 – gas valve; 6 – horn antenna; 7 – vacuum chamber; 8 – luminescence screen; 9 – solenoid; 10 – RF sources; 11 – magnetic field probes

Plasma lens was created by injection of plasma from coaxial plasma gun into short coil magnetic field 500 Oe. Parameters of the plasma flow are followings: density $10^{11}…10^{15}$ cm^{-3}, temperature 1…3 eV, velocity 10^7 cm/s, time duration 500 μs. Glass tube for plasma containment is of length 100 cm and diameter 10 cm.

The changing of plasma diameter and value of amplitude of azimuth magnetic field B_φ, measured on the distance 3 cm from the end of the plasma source in dependence on electrode voltage, is shown in Fig. 5.

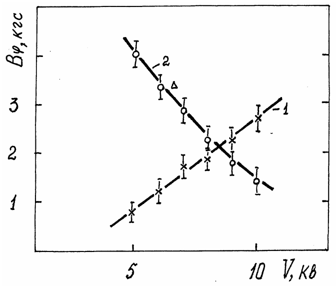

Fig. 5. Dependence of azimuthal magnetic field B_φ and plasma diameter d upon electrode voltage

In Fig. 6 the beam portraits on luminescent screen at bombardment by ion beam of energy 5 MeV are shown at several voltages on plasma gun electrode. At plasma absence the beam portrait is shown in Fig. 6,a. The luminescent screen and Faraday cylinder were placed at the same distance from the end of the plasma source. One can see from Fig. 6 that for the voltage U=9 kV the focusing coefficient, which was determined by ratio of beam diameter in plasma absence to beam diameter after passing through the plasma $K=d_1/d_2\approx10$. It is equal to value of relative growth of the currents for these two cases, which was measured by Faraday cylinder.

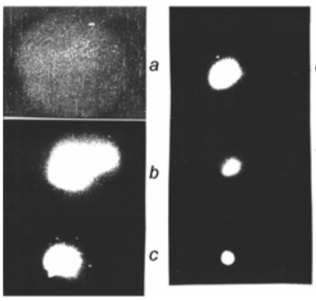

Fig. 6. Photos of beam portraits *in absent of plasma (a) and after passing through the plasma at several voltages on electrodes of plasma gun: b – U = 5 kV; c – U = 6 kV; d – U = 7 kV; e – U = 8 kV; f – U = 9 kV*

The obtained focusing is 10 times decreasing of ion beam diameter at the distance of 30 cm, where plasma focus is formed. It was revealed that the main focusing effect was caused by the azimuthal magnetic field of the current carried by the plasma

4. FOCUSING BY PLASMA WAKEFIELD AND OVERDENSE PLASMA LENS [19-22]

The device for measuring intensity of wakefield, excited in plasma of density $5\cdot10^{11}$ cm^{-3} by a sequence of 1500 needle electron bunches (each bunch $2\cdot10^9$ electrons, length 10 mm, diameter 1.5 mm, energy 14 MeV) was elaborated. Wakefield amplitude is determined by measuring the deflection of a probing electron beam (10 keV, 50 μA, 2 mm diameter), which is injected perpendicularly to the direction of bunches movement. The scheme of the experimental installation is shown in Fig. 7.

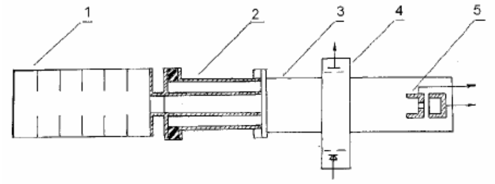

Fig. 7. Scheme of the installation: 1 – linac; 2-coaxial plasma gun; 3 – interaction chamber; 4 – unit of probing beam; 5 – double Faraday cup

The effect of focusing relativistic bunches was registered by double Faraday cup located after the interaction chamber. It consists of two consecutive cups; in the bottom of the first cup there was an aperture in diameter 3 mm through which the part of bunch electrons passed into the second cup (Fig. 8). Increase of bunch current on the second cup at plasma presence evidences the focusing effect. The maximal increase in a current at the second cup and corresponding current reduction on the first cup were observed at plasma density $n_p=5\cdot10^{11}$ cm^{-3}, when frequency of bunches repetition coincides with plasma frequency ω_p, that is when maximal wakefield was excited.

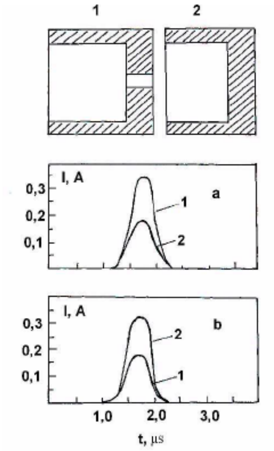

Fig. 8. Double Faraday cup and oscillograms of current of a sequence of relativistic electron bunches from the first cup (1) and from the second cup (2): in vacuum (a); with plasma of density $n_p = 5\cdot10^{11}$ cm^{-3}(b)

For measurement of wakefield intensity the probing electron beam of diameter 2 mm energy 10 keV and current 50 μA, was used.

The deflection of a probing beam in wakefield depends on value of aimed parameter (distance between axes of relativistic and probing beams [6]).

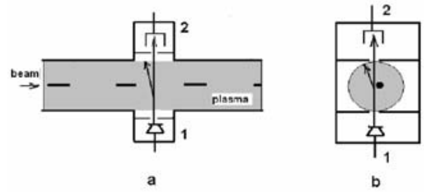

*Fig. 9. Scheme of wakefield measurement: of longitudinal view (a); of transversal view (b) (1 – gun; 2 – Faraday cu*For determination of aimed parameter the diagnostic system was made, one element of which was the thin metal string, located horizontally under the angle 45° to both directions of movement of driver relativistic beam and probing beam.

The string can be moved vertically with sylphon by means of distantly controlled electromotor. It allows to determine the position of both beams in space, and to measure the aimed parameter, determining the radial place of the maximal value of transversal component of excited wakefield. Movement of the probing beam for changing of aimed parameter was carried out with the help of the focusing coil and the adjustors located at exit of the electron gun producing the probing beam.

The calibration of probing beam deflection upon electric field intensity was carried out by means of deflecting plates of length 10 mm and gap between them 1 cm, to which a pulsed voltage 3 kV of duration 0.5 μs, equal to relativistic beam pulse duration. Measurements have shown, that at intensity of field E=3 kV/cm the deflection of the probing beam was 0.3 cm.

Results of measurement of probing beam deviation by wakefield are shown in Fig. 10.

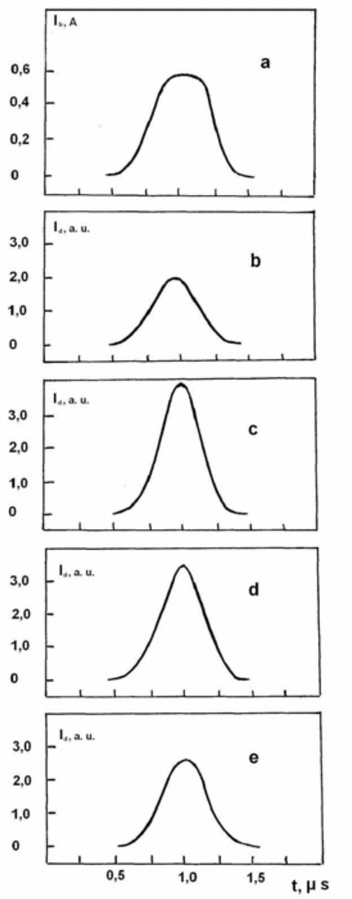

Fig. 10. Oscillograms: macropulse of a sequence of relativistic electron bunches (a); pulse of rejected current of the probing beam (b, c, d, e); $n_p=10^{12}$ cm^{-3}, ρ=4 mm (b); $n_p=5\cdot10^{11}$ cm^{-3}, ρ=4 mm (c); $n_p=10^{11}$ cm^{-3}, ρ=4 mm (d); $n_p=10^{11}$ cm^{-3}, ρ=6 mm (e)

The maximal deflection when the probing beam completely falls outside the limits of diaphragm aperture in diameter 2.5 mm, was observed at plasma density of $n_p=5\cdot10^{11}$ cm^{-3} and at the value of aimed parameter ρ=4 mm (see Fig. 6,c). Intensity of wakefield thus makes E=2.5 kV/cm. The maximal amplitude of excited wakefield is observed at density of plasma when plasma frequency ω_p, is equal to frequency of repetition of relativistic electrons bunches (resonant case). In this case all bunches coherently participate in wakefield build-up. At reduction or increase in plasma density the magnitude of probing beam deflection decreases (see Fig. 6,b,d). The oscillogram in Fig.6,e shows, that at increase in aimed parameter (ρ=6 mm) the magnitude of probing beam deflection decreases, as one would expect [19].

As it was already marked, relativistic electron bunches are focused at passage through plasma, both by wakefield and self azimuthal magnetic field at space charge neutralization. Obviously, both focusing processes take place in our case. However dependence of magnitude of probing beam deflection upon plasma density and observed maximal transversal wakefield in the resonant case testifies that focusing relativistic electron bunches in our experiment mainly by transversal wakefield.

5. FOCUSING/DEFOCUSING OF BUNCHES AT NONRESONANT EXCITATION OF PLASMA WAKEFIELD [23]

In the nonresonant case at detuning between the frequency of bunches repetition and the frequency of the excited wakefield bunches are periodically spaced both in focusing and defocusing phases. Detuning was achieved by changing plasma density. Scheme of experiment is shown in Fig. 11.

For enhancement of the role of radial component of wakefield for focusing/defocusing the bunches were put into elongated shape by aperturing, so the length of the bunch 17 mm essentially exceeded its diameter 4 mm (instead of initial 10 mm). Besides, increase of the wakefield amplitude was achieved by use of the plasma resonator.

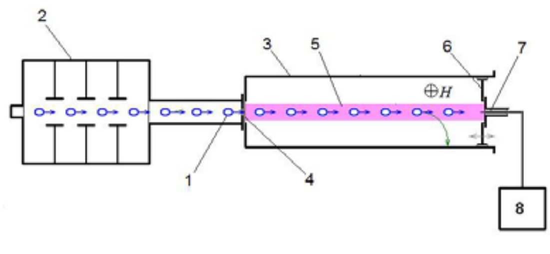

Fig. 11. Scheme of setup: 1 – sequence of bunches; 2 – linac; 3 – interaction chamber; 4 – aperture; 5 – plasma; 6 – movable plug; 7 – RF-probe; 8 – oscilloscope

Fig. 12 shows black central regions (imprints of the focused bunches) and grey halos (imprints of the defocused bunches). For resonator case (bottom) this picture is more expressed, as expected for higher wakefield intensity.

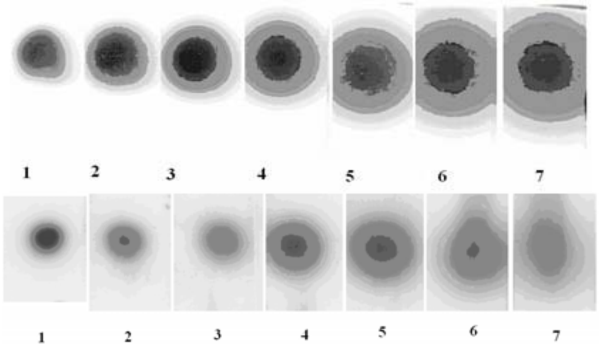

Fig. 12. Imprints of bunches on glass plates for semi-infinite waveguide (upper) and resonator (bottom) cases at distances from the exit foil: 1 – 0 cm; 2 – 5 cm; 3 – 7 cm; 4 – 9 cm; 5 – 1 cm; 6 – 13 cm; 7 – 15 cm

CONCLUSIONS

Several types of plasma lenses used in various applications were investigated. Physical principles of focusing by plasma lens were proved. Some applications of focused electron and ion beams (bunches) were demonstrated. Promising use of plasma lens for intense focusing in IP of conventional colliders and advanced colliders based on plasma wakefields was confirmed.

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Article received 07.09.12

ИССЛЕДОВАНИЯ ПЛАЗМЕННЫХ ЛИНЗ В ННЦ ХФТИ

И.Н. Онищенко

Представлены результаты проводимых в ННЦ ХФТИ теоретических и экспериментальных исследований фокусировки электронных и ионных пучков плазменной линзой. Рассмотрены несколько механизмов фокусировки пучков в плазме: плазменная компенсация дефокусирующих полей пространственного заряда пучка, фокусировка электрическими и магнитными полями заряженной токонесущей плазмы, эжектируемой из плазменной пушки, и фокусировка высокочастотными кильватерными полями, возбуждаемыми в плазме последовательностью коротких релятивистских электронных сгустков.

ДОСЛІДЖЕННЯ ПЛАЗМОВИХ ЛІНЗ В ННЦ ХФТІ

І.М. Онищенко

Представлені результати проведених у ННЦ ХФТІ теоретичних і експериментальних досліджень фокусування електронних та іонних пучків плазмовою лінзою. Розглянуто декілька механізмів фокусування пучків у плазмі: плазмова компенсація дефокусуючих полів просторового заряду пучка, фокусування електричними і магнітними полями зарядженої струмонесучої плазми, эжектуємої з плазмової пушки, та фокусування високочастотними кільватерними полями, збудженими в плазмі послідовністю коротких релятивістських електронних згустків.