Journal of Research in Physics Vol.28, No. 3, 199-207 (1999)

Invited lecture

THE PROBLEMS OF PLASMA ACCELERATOR SPECTROSCOPY DIAGNOSTICS

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1. Introduction

The reliable data on distribution of basic gas- and thermodynamic parameters of plasma, as well as distributions of electric and magnetic fields in such systems are necessary for adequate description of physical processes in plasma accelerators. In examinations of plasma accelerators, various methods of diagnostics are applied, such as methods of high-speed photo-recording, interferometry and shadowgraphy, probe and calorimeter methods, corpuscular and microwave methods, photoelectric methods of recording of radiation, and also spectroscopic methods of diagnostics of plasma formations.

We shall consider the use of some of the listed above plasma diagnostic methods on an example of concrete experimental examinations of quasi-stationary plasma accelerators with their own magnetic field, which are carried out in Group of Plasma Accelerators at the Institute of Molecular and Atomic Physics of National Academy of Sciences of Belarus. It should be noted here, that a feature of plasma accelerators under investigation is that the acceleration of plasma along the axis of the discharge device is accompanied by pinching at the output of accelerating system. As a result, the compression plasma flow is formed behind the edge of interior electrode. The parameters of plasma in this flow are much higher, than that in interelectrode gap of the accelerator [1]. Three types of plasma accelerators were studied: magneto-plasmadynamic compressor (MPC) [2-5], the double-stage quasi-stationary high-current plasma accelerator (QHPA) P-50M [6,7], working in vacuum with pulse (valve) delivery of working gas, and erosive plasmadynamic systems [8,9], which are capable to generate (in air at atmospheric pressure) compression erosion plasma flows of designated composition, which is determined by material of an interior electrode.

2. Determination of basic gas-dynamic and electrical parameters of the discharge in plasma accelerators

Dynamics of plasma generation and the formation of compression plasma flows was studied by methods of high-speed photorecording. Photographic recordings of plasma luminescence were carried by high-speed photorecording installations SFR and VFU-1, which were working in streak mode or in frame mode. For time referencing of velocity photoscans and current and voltage oscillograms of the discharge, a simple method of synchronization by photodiode FD-10G (time resolution of the photodiode ~ 1,2 10^{-7} sec), which was introduced in one of the windows of lens insert (during frame mode operation) or in photorecording device film channel (during continuous scan operation), was used [2]. A signal from the photodiode was connected to the same beam of an oscilloscope, as one from Rogovsky coil.

Such examinations allow to study micro- and macrostructure of plasma flow and to determine characteristic velocities of plasma formations [2,4,6,8]. Summarizing results of the specified examinations, it is possible to present the following pattern of discharge development in the magneto-plasmadynamic compressor. After delivery of start pulse on a driving electrode of ignitron discharger, an electrical breakdown of an interelectrode gap is taking place at the point, where this gap has minimal value. The formed plasma is accelerated in the discharge device under action of electromagnetic (Ampere) force and is taken out behind the tip (edge) of the accelerator, where the compression plasma flow is formed on an axis of system. Under operating conditions, the plasma comes behind the tip of interior electrode (cathode) to ~ 15 μsec from the beginning of discharge current. As shown by continuous photoscans received with orientation of SFR slit normally to the axis of the discharge device, a compression flow in first 15 ÷ 20 μsec after coming of plasma to the tip of an interior electrode displays appreciable radial macro-oscillations, which get stronger as initial pressure of working gas is reduced. Approximately after 30 μsec from the beginning of discharge current, the flow becomes macro-stable, the diameter therewith comprises 0.3 ÷ 1 cm, and the length — 5 ÷10 cm (depending on the initial conditions of experiment). The time of stable existence of compression plasma flow makes ~ 40÷50 μsec (at total duration of the discharge of ~ 80 μsec).

The compression plasma flow during all the time of its existence evidently displays discrete (intermittent) microstructure, which is well visible on continuous photoscans under condition of orientation of the slit along the axis of the flow as alternation of light and dark stripes. The light stripes are projections of trajectories of motion of separate plasma formations onto the slit of moving-image camera. The frequency of following of plasma formations grows from 5 up to 15 MHz as initial pressure of working gas in the MPC camera increase from 133 up to 665 Pa. The presence of plasma sub-flow behind the tip of interior electrode, moving from compression region into divertor hole is evident. The demarcation of compression region and specified sub-flow of plasma is, in essence, "a zero point ", i.e. place, where the longitudinal velocity of plasma on an axis of system goes to zero.

In [7], the velocity of plasma formations generated by QHPA was estimated from continuous photoscans. At initial voltage of the store of the second stage of the accelerator $U_0 = 3$ kV, the velocity of plasma comprises ~ 7 $\cdot 10^6$ cm/sec. Experimentally, velocity of plasma flow reaches it's peak value at $U_0 = 4$ kV and makes ~ 1,7 $\cdot 10^7$ cm/sec, while at $U_0 = 5$ kV it makes ~ 10^7 cm/sec.

The basic electrotechnic characteri stics of the discharges in plasma accelerators, a discharge current I_d and voltage on electrodes U_d were measured by gauged Rogovsky coils with integration of the signal by RC-chain and by frequency compensated RC-voltage dividers. On the basis of received oscillograms of current and voltage of the discharge, an instantaneous power $P_i(t) = I_d(t) \cdot U_d(t)$, energy, which is put in the discharge, $W_c = \int P_i(t)dt$ and energy efficiency of the accelerator $\eta = W_c/W_0$ (here W_0 is energy reserved in the store) were determined. In MPC- and QHPA-type systems, η usually makes ~ 0.6-0.8 [2,6,8]. The volt-ampere characteristics, showing dependence between voltage on electrodes and current during one discharge of MPC during time since 20 till 60 μsec (when transients were finished and plasma flow is in stable state), are nonlinear and have power character with an exponent ~ 2.

3. Measuring electrical and magnetic fields

The studies of electric and magnetic field distributions in QHPA were carried out by probe methods [7,10]. Floating potential of plasma was measured by single Langmuir probe, and distribution of magnetic fields was studied by magnetic probe. The probes were inserted into the discharge device of QHPA perpendicularly to plasma flow between anode rods. The probe-induced perturbations were checked by investigation of integral performances (current and voltage) of the discharge, and by symmetry and stability of plasma flow in QHPA. For perturbation of plasma reduction, only one magnetic or electrical probe at a time was inserted into the channel. The insertion of probe does not render appreciable influence on the shape and values of discharge current practically in the whole volume of the channel, except for narrow layer (1-2 cm) near the surface of cathode transformer, where the influence of probe insertion on I_d could be appreciable. For example, the introduction of probes in near-cathode layer before critical section of the channel (10 cm from its inlet) is causing increase of discharge current amplitude on ~ 25% and diminution of duration of the first half-period by ~ 15%. If the probe is introduced into the channel behind critical section (40 cm from the inlet), the amplitude of current is rising by ~ 15%, the duration of a half-period thus decreases by ~ 10%. The study of frames of plasma luminescence received by VFU -1 have shown that the presence of probe in the channel does not influence symmetry and stability of plasma flow in QHPA.

The spatial-time pattern of distribution of isolines of current ($I=5HR=const$), which was constructed on the basis of measured azimuth component of magnetic field H_θ, has allowed to reveal, in addition to usually gained distribution of current with "slippage", two types of current distribution in the channel of QHPA: quasi-radial distribution and distribution with "antislippage" [7,10]. It was shown, that for receiving of any pattern of distribution of current in the channel of QHPA it is necessary to match in appropriate way quantities of a discharge current and rate of flux of ions in near-anode and near-cathode regions or, what is the same, to match an exchange parameters ξ_c and ξ_a. The quasi-radial distribution of a current is set, when $\xi_c = \eta\xi_a$. Here, η is a loss coefficient for current-carrying ions, depending on a construction of transformers and on interaction of specified ions with plasma in the channel of the accelerator; after matching of operation of first and second stages of QHPA this coefficient comes close to one. If $\xi_c > \eta\xi_a$, distribution of current with "antislippage" along cathode transformer (T_c) is observed. When $\xi_c < \eta\xi_a$, the distribution of a current with "antislippage" is implemented in the accelerating channel. It is obvious, that, having placed inside of cathode transformer an ion source (it could be plasma, which is filling interior volume of T_c), it is possible to move from a mode with "antislippage" of current to the mode with quasi-radial distribution or with "antislippage" one.

For classifying of patterns of potential distribution Φ in QHPA channel, the dimensionless coefficients χ_c and χ_a, were defined. This coefficients are showing accordingly the ratio of potential difference in narrow near-cathode and near-anode layer to potential difference between electrodes (transformers) as a whole [7,10]. It was shown, that when distribution of current in the channel of a QHPA with "antislippage" is taking place than $\chi_c < \chi_a$, while at "antislippage" of current and its quasi-radial distribution one have $\chi_c > \chi_a$. It should be noted, that χ_c at "antislippage" of current for appropriate moments of time always exceeds χ_c for quasi-radial distribution of current, but χ_a values for "slippage" of current, on the contrary, are always less than χ_a for its quasi-radial distribution. Hence, it is possible to make judgements about the character of distribution of discharge current in the channel of QHPA on the basis of relation of values χ_c and χ_a. The received relations allow to reduce essentially and to simplify procedure of diagnosing of modes of operations of the accelerator, that is especially important in operation with powerful and complex accelerating plasmadynamic systems.

4. Methods of definition of thermodynamic parameters of plasma in plasma accelerators

The use of traditional spectroscopic methods of diagnostics fo r studies of quasi-stationary plasma accelerators under conditions, when working gas is hydrogen, causes some difficulties. Under such conditions, temperature of plasma can be determined from results of experiments on supersonic compression flow incidence on thin wedge with sharp forward edge, which is a source of weak perturbations. In studies of plasma flows of QHPA a wedge was set under zero angle of attack to an axis of system, 35 cm apart from the tip of cathode transformer [10]. Visualization of Mach lines on forward edge of the wedge was carried out by shadow method with double passage of probing bundle of laser radiation through explored region. Recording of shadow pattern was carried out by high speed photographic camera working in a frame mode. The frame frequency of shadow pattern was equal to 245000 frame/sec. The time of exposure of each separate frame is defined by duration of spikes of laser radiation, it is less than 1 μsec.

As is known, the slope angle of Mach lines (Mach angle) depends on velocity of incident compression flow and on velocity of sound in plasma as follows : $sin\alpha = C_s/V$, where α is Mach angle; V is velocity of an incident plasma flow, C_s is velocity of sound. Then, from expression for velocity of sound in plasma $C_s^2 = (\gamma k(T_i+zT_e)/M_i$, where T_i and T_e are temperatures of ions and electrons; M_i is ion mass; z is ion charge; k is Boltzmann constant; γ — the exponent of Poisson adiabat, is possible to find temperature of plasma: $T_{pl} = (V \cdot sin\ \alpha)^2 \cdot M_i/\gamma k(1+z)$, where $T_{pl} \equiv T_i = T_e$. Under QHPA conditions, the temperature of plasma of compression flow, determined by specified method, comprises 10-15 eV [10].

Most informative, and at the same time most complex method of diagnostics of plasma accelerators, is interferometry method. Advantage of this method is the opportunity of reception of extensive and reliable information without entering perturbations into explored plasma. The application of an interferometer in combination with high-speed recording camera allows not only to visualize processes, which are not accessible for photographic recording, but also to determine spatial-time distribution of parameters in explored plasma with high accuracy.

The spatially and time-resolved electron concentration of plasma of compression flow in MPC and QHPA was determined by two-mirrors autocollimation interferometer [11] with visualization field, varied, depending on conditions of experiment, from 50 up to 200 mm. Interference figure recording was carried out by high-speed moving-image cameras SFR or VFU working in a frame mode, that allows to gain a series of interferograms for single experiment showing time change of phase refraction coefficient of studied plasma formation in the whole field of view.

For most symmetric interferograms, a definition of radial distribution of fringes shifts was carried out. In a symmetric case the radial distribution and registered quantities of fringe shifts at observation along a chord are interlinked through Abel equation. For the solution of this equation, a series of methods was designed, for example [12]. However, it is not always possible to receive required radial distribution by using simple computational methods, as the integral Abel equation belongs to a class of so-called ill-posed problems of mathematical physics. Tikhonov method of regularization was applied for determination of radial distribution of shifts of fringes [13], implementing computer build-up of stable approximate solution. The test checkouts have shown good precision of restoration of model radial distributions by used program and its considerable advantages in comparison to traditional methods such as Bokasten's.

The interferometric studies of MPC and QHPA P-50M were carried out with single wave length probing laser. Therefore as a preliminary, an opportunity of definition of electron concentration of plasma formations was analyzed, accounting for various factors influencing refraction of plasma in the range of parameters $T_e \sim 1 \div 15$ eV, $N_e \sim 10^{15} \div 10^{17}$ cm^{-3}, which is characteristic for MPC and QHPA. First of all, the contribution of heavy particles, i.e. atoms and ions of hydrogen, to a refraction of plasma was estimated. The calculations with use of value of a specific polarizability of hydrogen atoms have shown, that the contribution of heavy particles becomes comparable to the contribution of electrons at a degree of ionization ~ 0.03. At a degree of ionization more than ~ 0.3, contribution of atoms of hydrogen can be neglected, as it becomes comparable with an error of measurements. Let's note here, that the degree of ionization of plasma formations in MPC and QHPA is close to 1.

The shifts of interference fringe s caused by replacement of neutral gas from area, filled by compression plasma flow, was estimated too. Experimentally, it has appeared equal 0.02 fringes and was not taken into account in calculations. Then possible influence of "resonant" effect was analyzed. Wave length of $H\alpha$ ($\lambda = 656$ nm), having a half-width of about 5 nm, is nearest to probing laser wave length ($\lambda = 694$ nm) in spectrum of radiation of compression region. According to calculations, "resonant" influence of $H\alpha$ - line on an refraction coefficient is small (~ 0.03 fringes) and it was not taken into account at determination of N_e.

Further, at definition of density of charged particles by means of optical interferometry, some indeterminacy exists, which is caused by the lack of sharp transition between mobile electrons and electrons of the upper excited levels. However, the quantity of this indeterminacy for plasma formations with parameters, close to implemented in QHPA, does not exceed 1%.

At last, the passage of probing laser beam through e xplored plasma is accompanied by its diversion from a tentative direction owing to refraction of light on phase inhomogeneities, that can give in additional interferometry fringes shifts. However, this effect can be neglected in our case, because values of electron concentration ($10^{17} \div 10^{18}$ cm^{-3}) implemented even in compression region are at least three - four orders below critical density (~ 10^{21} cm^{-3}). Thus, as the analysis carried out shows, the refraction of plasma in MPC and QHPA contexts is defined mainly by mobile electrons.

Interferometric studies of MPC and QHPA executed in [14-17] have allowed to measure concentration of charged particles in the accelerating channel and to receive a spatial-time pattern of distribution of density of electrons in an output of the accelerator. The analysis of time change N_e in the accelerating channel shows, that there is some characteristic (boundary) range of values of electron density in QHPA (experimentally, it is equal to $\sim (1.5 - 2) \cdot 10^{15}$ cm^{-3}), in which quasi-radial distribution of current isolines is set at quasi-stationary stage of the discharge (after ~ 150 μsec). If electron concentration is higher than this range, the distribution of current with slippage is set. In the case, when density of electrons of plasma in the channel becomes below this boundary, the distribution of isolines of current with antislippage is observed.

The measuring of an electron concentration in the accelerating channel and in the output of accelerating system has enabled to determine the contraction ratio of compression flow, which, experimentally, varies from 20 up to 50.

5. Features of spectroscopic diagnostics of plasma in QHPA

The presence of areas of plasma with essentially different temperatures and densities of particles in discharge volume is characteristic for QHPA-type systems. Temperature of electrons can comprise ~ 1 eV in the drift channel and hundreds of eVs in compression flow, the electron concentration thus also varies for several orders ($10^{14} \div 10^{15}$ cm^{-3} in the channel and ~ 10^{17} cm^{-3} in compression region). It causes particular difficulties for spectroscopic diagnostics of QHPA, when working gas is hydrogen. Let's note also, that in the areas of QHPA, where the electron concentration reaches values ~ 10^{17} cm^{-3}, at temperatures exceeding 2 eV, hydrogen is practically completely ionized.

Under such conditions, procedures of definition of plasma parameters with the use of spectral lines of atoms and ions of inert gases, which are specially added as impurities into working gas of the accelerator [18] can be more convenient experimentally. The parameters of broadening for these lines are lower, and temperature interval, in which they are effectively excited, is wider in comparison to hydrogen lines. The addition in working gas of small portions of inert gas impurities with different potentials of ionization can allow not only to determine temperature and density of plasma, but also to visualize regions with various parameters in QHPA.

At the present time there are numerous data on parameters of Stark broadening, transition probabilities or oscillator forces and energy levels for many spectral transitions in Ar, Xe, Ne and especially He atoms and ions [19-21]. For spectroscopic diagnostics based on introduction of impurities of inert gases in hydrogen plasma, calculations of limits of applicability of concrete procedures using various spectral lines of atoms and ions of these gases for definition of parameters of plasma and calculations of limits of applicability of concrete procedures using various spectral lines are needed.

The tentative experiments on determination of parameters of plasma in QHPA P-50M by spectroscopic methods were carried out by addition of helium impurity in hydrogen, i.e. an intermixture of hydrogen and helium in the ratio 3:1 as working gas was used. The spectrums of emission filed were obtained with the help of time resolved spectrography (ISP-30 + SP-452). The time interval, in which radiation was registered, comprise ~ 40 μsec.

Electron concentration in plasma was determined by line broadening H_β 486.1 nm and *HeI* 587.5 nm caused by linear and square-law Stark effect accordingly. The precision of definition of density of electrons in plasma with the use of *HeI*-line 587.5 nm is not worse than at measuring N_e by broadening of H_β -line. Averaged through beam of sight values of electron concentration measured at line broadening H_β and *HeI* have made accordingly $\sim 3.5 \cdot 10^{15}$ and $\sim 3.6 \cdot 10^{16}$ cm^{-3} for section, which was ~ 35 cm apart from an edge of interior electrode [22]. The discrepancy of N_e, received with the use of specified lines, falls outside the measuring error limits and is due to spatial inhomogeneity of plasma flow in QHPA. It is clearly visible on spectrums of plasma luminescence slit, registered with orientation of spectrograph slit normally to compression flow axe, that the hydrogen Balmer series lines are displayed through all length of the chosen sections of plasma flow, while *HeI* lines with higher (in comparison to hydrogen atom lines) energies of the upper levels are emitting only from central, hotter region. The values of density of electrons received with use of helium atom lines correspond to this region.

6. Conclusion

As is known, distributions of electrical and magnetic fields in plasma accelerators are defined in the final by both the process of acceleration and by parameters of formed plasma flows. However use of probes can import essential contortions to real-life pattern of electrical and magnetic fields distribution in plasma accelerators. Therefore the studies, which are directed on development of non-contact methods of diagnostics, are very important. The spectroscopic methods using spectral lines of atoms and ions of inert gases purposely introduced as admixtures in the working gas can be useful for decision of those problems.

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Acknowledgements

This work was supported in part by the Belarus Foundation of Basic Investigation, grant F98-336.