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HOT ELECTRONS in BEAM-PLASMA DISCHARGE.

V.M.Atamanov[2]*, T.A.Biman*[1]*, L.I. Elizarov*[2]*, Al.A.Ivanov*[2]*, A.V.Pereslavtsev*[2]*, N.N.Shubin*[2]

[1]*Russian Friendship University, Moscow, Russia*

[2]*Russian Research Centre “Kurchatov Institute”, Moscow, Russia*

The possibility to obtain hot electrons for the X-ray generation on the base of beam-plasma discharge in mirror magnetic trap is considered. One can obtain the hot electrons with the temperature 40 - 200 keV in beam plasma discharge in mirror magnetic trap. The experimental programme on the X-ray generation is carried out on the “Oratoria-10” installation. The view on the possible variant of the X-ray source based on beam-plasma discharge in mirror magnetic trap is given.

1. Preconditions

It gets some interest to the possibility of X-ray generation by the electrons heating in plasma discharge and to create the X-ray sources on this basis for the practical application in the technology and medicine. The obtaining of X-ray generation in plasma by plasma discharge is more difficult than that by means of X-ray tubes. At the same time, the obtaining of high energy X-ray generation with the energy of 100 keV and higher by means of X-ray tubes is connected with the necessity of using power supply through the anode with the same voltages.

The series of experiments were executed at 60-th - 70-th. The works demonstrate the possibility to obtain the hot electrons in beam-plasma discharge. It is shown in work [1] that the high energy electrons are generated in a mirror magnetic trap with high mirror ratio at the interaction of electron beam with cold plasma with density 10^{12} cm^{-3} in volume of 20 litres. The temperature of high electron component was 200 keV, the plasma density was 2.10^{10} cm^{-3} . The plasma with electron temperature 550 keV and density of 10^{11} cm^{-3} in volume of 4,2 litres was produced in installation PN-2 by means of adiabatic plasma compression [2]. The intensive X-ray radiation in the experiments was up to 1 MeV. The hot plasma was confined by mirror magnetic field without decay for a few seconds in the experiment.

The powerful beam-plasma amplifier is described in work [3]. The amplifier is manufactured as a separate vacuum device. In the amplifier the accelerating voltage of electron beam was U_0=15 - 25 kV, the beam current was I= 3-5 A, the strength of magnetic field of a solenoid was 2 - 3 kOe, the pressure range of working gas (hydrogen) in the interaction space was 10^{-6}-10^{-3} Torr.

Thus, the existence of physical processes of electron heating up to relativistic energies in plasma of the beam-plasma discharge was experimentally tested at the end of 60-th - at the beginning of 70-th. At the beginning of 90-th the experimental researches were executed with the standalone device on the base of the beam - plasma discharge. The device parameters (the energy and the current of electron beam, the strength of magnetic field, the pressure of working gas) were sufficient for the generation of hot electrons. This experiment confirms the possibility of hot electron generation in the separate device, and consequently the possibility to create the device for the X-ray generation on the base of beam-plasma discharge in a mirror magnetic trap. One can assume that such devices will be competitive with X-ray tubes in the appropriate range of X-ray energies after the realisation of some programme of engineering researches.

The analysis of the experimental and theoretical researches of the beam heating of electrons in mirror magnetic trap is resulted in work [4]. When the electron beam is injected in a mirror magnetic trap [4] the strong beam-plasma interaction takes place and it results in the growth of the cross size of plasma and in the strong heating of the hot electrons confined by the trap. The electron beam excites the Langmuir oscillation at the interaction with plasma [5]. The heating of hot electrons takes place because of its interaction with the electron Langmuir oscillations $\omega_{pe}>\omega_{He}$. The width of the beam in the space of velocities Δv becomes to the initial velocity of the beam u at the distance of 20 - 30 cm from the beam input in the system.. The characteristic increment of instability is $\gamma\sim\omega_{pe}n_{0b}/n_0$. The electron beam excites the oscillations mainly with the wave vectors parallel to its axes. The spectrum of Langmuir oscillations is essentially non-isotropic. If the electrons at interaction with noise will not get in a cone of losses in the space of velocities, they will diffuse in usual space to the periphery of installation and its energy will slowly increase. The cone of losses in the space of velocities is the function of mirror ratio R. Thus to obtain hot electrons it is necessary to satisfy the series of conditions for the confinement of electrons in mirror magnetic trap and for its heating up to high energies, namely: $\omega_{pe}>\omega_{He}$, $\gamma\sim\omega_{pe}n_{0b}/n_0$ and $R>1/cos^2\theta_0$ (where $arctg\theta=k_\perp/k_{\parallel}$, and θ_0 is some limiting angle), the length L of beam interaction with plasma, the maximum radius r of plasma.

The experiments on the electron heating by beam-plasma discharge are carried out on the installation "Oratoria-10" with the parameters at $L\geq0,3$ m, $n_0\sim10^{12}$ cm^{-3}, $r>0,12$ m , $H\sim600$ Oe, $R\sim3,5$; $I_b\sim2$ A, $u\sim3\div6$ kV . For the above parameters: ω_{He} = $1,05.10^{10}$ s^{-1}, ω_{pe} = $5,64.10^{10}$ s^{-1} , n_b = $(1,54\div2,18).10^9$ cm^{-3}.

2. Experimental Programme

To create the autonomous X-ray generator as a separate device by the analogy to the beam-plasma amplifier [3] it is necessary to execute the series of experimental physical researches directed on the searching of optimal parameters of the device. At first we have to select the maximum intensity of X-ray radiation and the minimisation of dimensions of the device as a criterion of the optimisation of device.

From the above it follows the amount and the temperature of hot electrons are function of:

- the strength and the configuration of a magnetic field,
- the initial density of cold plasma,
- the current of an electron beam and the energy of electrons in the beam,
- the length and cross size of mirror magnetic trap.

One more parameter of the process is the initial gas composition in which the discharge is ignited.

We shall assume that the pulse mode of electron beam injection is more interesting than stationary one. At the same time, there is some part of hot electrons in the beam plasma discharge in a stationary mode. In this connection the program of experimental researches is directed to the creation of X-ray source and it is divided on three main stages:

- The study of X-ray generation in beam-plasma discharge in a stationary mode at the stationary injection of electronic beam.
- The study of X-ray generation in beam-plasma discharge in pulse mode at the pulse injection of electron beam.
- The study of X-ray generation in beam-plasma discharge in pulse mode at the pulse injection of electron beam with the following adiabatic compression of plasma.

At the first stage we shall execute the following researches:

- to investigate the dependence of energy and intensity of X-ray generation on the initial density of plasma and on the composition of the gas forming the plasma;
- to investigate the dependence of energy and intensity of X-ray generation on the strength of magnetic field (In some variant it is possible to investigate the dependence with the correlation through the composition of the gas forming the plasma);
- to investigate the dependence of energy and intensity of X-ray generation on the cross sizes of installation (by the introducing of diaphragms bounding the plasma) in the correlation with the strength of magnetic field;
- to investigate the dependence of energy and intensity of X-ray generation on the length of installation (the dependence of interaction of electron beam with plasma on the path by means of setting-up the cylindrical limiters).

The results at this stage will be laid in the basis of the research programme of the second stage. The dependencies of the obtaining of hot electrons will be experimentally clarified after the executing of the first stage of experiments. At the second stage it is necessary to determine the time dependencies of plasma formation in beam-plasma discharge and to obtain the time dependencies of formation of hot electron component in plasma. The experimental programme at the second stage include the following acts:

- the investigation of the formation of hot electron component in the dependence upon time of electron beam injection for various geometric parameters (the length and the cross size of installation), for the various values of the strength of magnetic field, for the various values of the initial density of cold plasma, for the various values of the current of electron beam and the energy of electrons in the beam;
- the investigation of the time dependencies of existence of hot electron component for the various geometric parameters of the installation, for the various values of the strength of magnetic field, for the various values of obtained temperatures of electrons;
- the determination of the operating regime of installation for the realisation the following adiabatic plasma compression taking into account the minimisation of the initial strength of magnetic field before the plasma compression because of the limiting of maximum strength of magnetic field (It is limited by the current in the solenoids of magnet system).

It is expedient at the second stage also to execute the researches directed to the creation of the standalone variant of X-ray generator. The first one is the obtaining of X-ray generation at the minimization of vacuum evacuation of installation. The second one is the obtaining of electron gun working conditions at the same pressure as the gas pressure in the working chamber.

It is supposed to demonstrate the heating of hot electron component up to relativistic energies at the third stage. The main task is to study the time dependencies of existence of relativistic electrons in mirror magnetic trap.

3. Experimental Installation

The installation “Oratoria-10” was selected for the executing of the research programme. Originally the installation “Oratoria-10” was intended for the plasma chemical researches. In this connection it was necessary to reconstruct the installation for the full realisation of the experimental programme directed on the X-ray generation in beam-plasma discharge.

The "Oratoria -10" installation enables to carry out the researches of nonequilibrum plasma with the density of 10^{10} – 10^{13} cm^{-3} produced in a beam-plasma discharge. The magnetic system of a "mirror-like magnetic trap" type produces magnetic field of maximum strength 800 Oe and magnetic mirror (max/min) ratio R~3.5 . System of the power supply of magnetic coils provides a possibility of short-duration (tens of seconds) increase of field-strength (~ by the factor 1.5) in the experiments on adiabatic compression of plasma. The electron beam of a cylindrical geometry of maximum diameter up to 4 cm is formed by means of an electron gun with a beam current of up to 2 A and of its energy up to 6 keV. The necessary vacuum-conditions are provided by diffusion vacuum pumps with liquid nitrogen-cooled traps. The residual pressure is not more than 5.10^{-7} Torr with the nitrogen cooled traps and not mor than 3.10^{-6} Torr without nitrogen cooling. The maximum working pressure is ~ 10^{-3} Torr.

The system of gas-feeding provides both continuous, and pulsing gas-supply. The scheme of the “Oratoria 10” installation is shown on the Fig. 1.

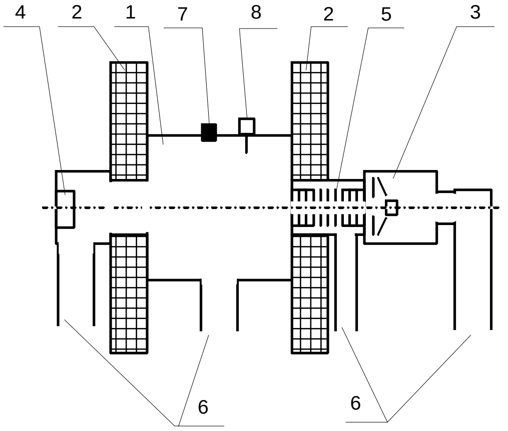

Fig. 1. The scheme of “Oratoria - 10” installation
1 - vacuum chamber: 2 - magnet coils; 3-electron gun; 4 - electron beam receiver; 5 - diafragms; 6 - vacuum pump; 7 - X-ray diagnostic; 8 - Langmuire probe

Now the first series of experiments on the electron heating in continuous mode is executed. The hot electrons with the energy higher than 40 keV are obtained

The possibility to obtain the X-rays with the energy higher than the energy of beam’s electrons is experimentally confirmed now in continuos mode on the “Oratoria-10”.

4. View of the X-ray Source

The possible view of the X-ray source based on beam-plasma discharge one can see on the Fig.2.

X-ray radiation is generated in the source by braking of high-temperature electrons on a metal diaphragm.

X-ray source (Fig. 2) consists of a chamber (1), electron gun (2), collector of electrons (3), magnetic system (4), diaphragms (5) of differential pumping system, getter elements (6) and working diagram (7).

The working pressure of hydrogen (~10^{-4} Torr) is supported by getter elements (6) in the chamber. The maintenance of given pressure is provided by the choice of equilibrium temperature of the getter (at the temperature, molecular hydrogen in the chamber is in equilibrium with atomic hydrogen, dissolved in getter).

The working pressure in the electron gun is supported by the differential pumping system with getter elements (6). This approach to the vacuum scheme is similar to that in work [3].

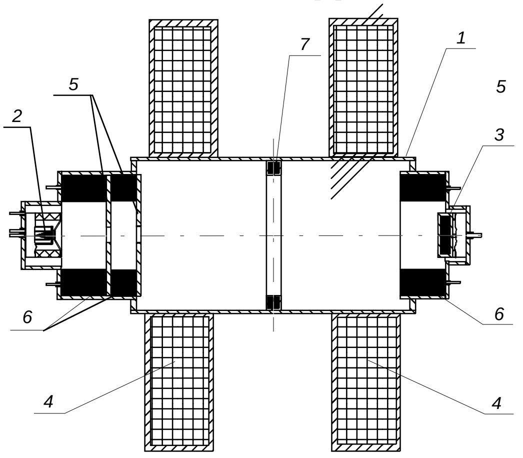

Fig. 2. X-ray source based on the beam-plasma discharge in mirror magnetic trap

Electron gun (2) is used for obtaining of the electron beam with a current 3 - 10 A, electron energy 6 - 20 keV The gun can operate both in continuous and pulsed mode (pulse duration is 100 - 250 μs). The electron current attains the collector (3).

The plasma produced as a result of electron beam interaction with working gas is confined by a mirror magnetic field. The magnetic system may be designed on the base of electromagnets (4) (Fig. 2) or on the constant magnets. The intensity of magnetic field at the centre of the axis of the system is about 0.6 - 1 kGs, the mirror ratio being about 2.5 - 4.

Beam-plasma instability due to the interaction of an electron beam with a plasma in the system causes significant increasing of plasma cross section and the appearance of hot electrons. The quasi-stationary state is established for about 100 μs and is decayed for about 100 ms after switch off the beam. The average energy of hot electrons depends on magnetic field intensity and trap radius. After having finished of beam injection the hot electrons are well confined by a mirror magnetic field configuration and generate X-ray radiation due to their interactions with diaphragm or walls. Distance between mirrors is about 15 - 30 cm, diameter of the chamber is 10 - 20 cm. The materials of the diaphragm and the chamber are determined to obtain the most effective generation of X-ray radiation.

One can use the intermittent regime of the electron gun operating for the obtaining of continuous X-ray generation in the source.

The working diagram of the X-ray source is described on Fig. 3.

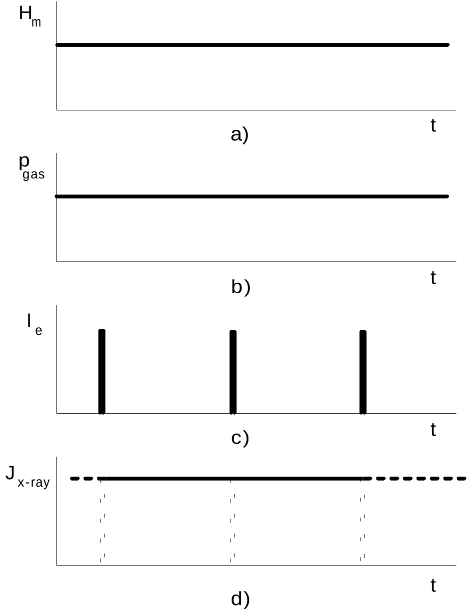

Fig. 3. Working diagram of the x-ray source on the base of beam-plasma discharge:
à) magnetic field intensity; b) working gas pressure;
c) electron beam current; d) x-ray radiation intensity

It looks as follows:

- magnetic field does not change;
- quantity of a gas in the system is supported constant;
- duration of electron beam pulse injection is 100 -

250 μs, the injection being repeated 100 ms;

Duty factor for the electron beam is of the order of ~ 400 - 1000.

X-ray generation is continues.

X-ray generation being after 100 μs of the start of beam injection and continues during the time about 100 μs after switching off the beam. The beam injection is switched on for 100 μs up to finishing of the X-ray generation.

To obtain more energetic X-ray radiation, it is necessary to increase the electron temperature. It could be achieved in the X-ray source based on beam-plasma discharge with adiabatic plasma compression. It is desirable to obtain the electrons with temperature more than 1 MeV.

The possible view of the X-ray source based on beam-plasma discharge with adiabatic plasma compression one can see on the Fig.4.

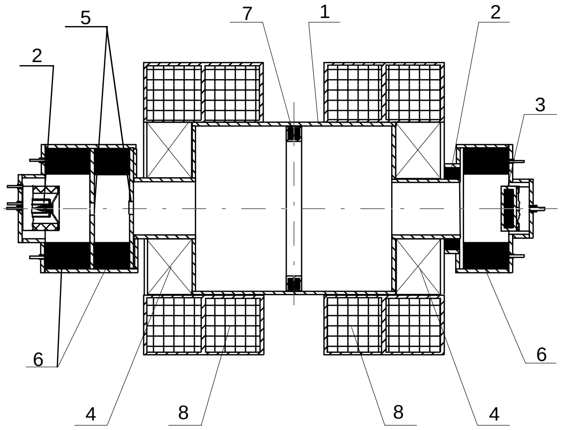

Fig. 4. X-ray source based on beam-plasma discharge with adiabatic plasma compression

Such source (Fig. 4) consists of a vacuum chamber (1), electron gun (2), collector (3), constant magnets (4), diaphragms (5) of differential pumping system, getter elements (6), working diagram (7) and compression magnetic system (8),

Additional electron heating can be provided by adiabatic plasma compression by magnets (8) after the establishing of the stationary state (after 100-250 μs). When the electromagnets are switch on the intensity of a magnetic field at the centre of a system is 6 - 10 kGs, mirror ratio can be reduced up to 1.2-1.5. Magnetic field growing time is determined by magnetic system properties.

The average energy of hot electrons is increased up to 1 - 2 MeV and is determined by both parameters of a initial plasma and the intensity of a magnetic field at the final stage of plasma compression (by ratio of initial field at which plasma is produced and final magnetic field value after compression). The hot electrons are well confined by a mirror magnetic field configuration and generate X-ray radiation due to the interaction with diaphragm or walls. The sizes of chamber are determined to optimise the source operation. Distance between mirrors, as well as in the previous case. The materials of the diaphragm and the chamber and the mutual position of the parts of the source are determined to obtain the most effective generation of X-ray radiation.

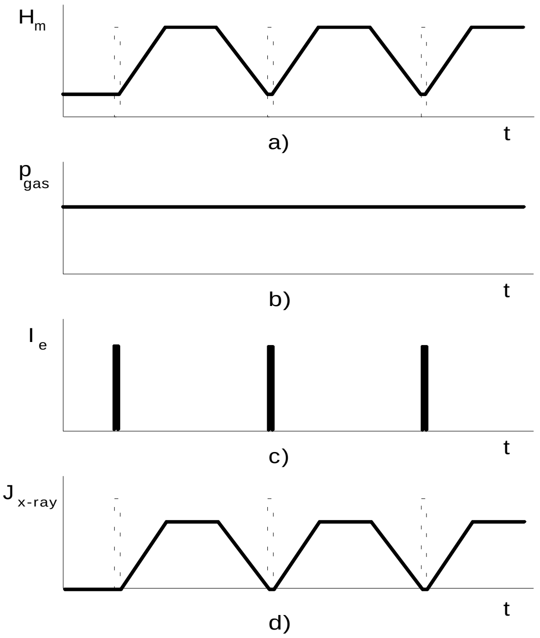

Fig. 5. Working diagram of x-ray source based onbeam-plasma discharge with adiabatic plasma compression: à) magnetic field intensity; b) working gas pressure; c) electron beam current; d) x-ray radiation intensity

Working diagram of X-ray source with adiabatic plasma compression is described on Fig.5. It looks as follows:

- initial magnetic field of magnets (4) does not vary;
- quantity of a gas in the system is supported constant;
- duration of electron beam pulse is 100 - 250 μs,
- adiabatic compression of a plasma by magnets (8) begins after 100 - 250 ms with the finishing of electron beam injection,
- compressed magnetic field of magnets (8) is supported constant during 0.5- 1 s, during this time x-ray radiation is generated with the X-ray energy up to 1 - 2 MeV;
- compressed magnetic field is decreased up to values mentioned above, and the system is returned to initial condition. Then the working cycle is repeated.

The duty factor of the electron beam may be about 2800 - 20000. The duty factor for the generation of X-ray radiation may be about ~1.2 - 3.

5. Acknowledgement

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