Production of hot plasmas in a mirror system by means of a gas-discharge arc source

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A hot plasma with a density $n \simeq 3 \times 10^{13}$ cm^{-3}, an ion temperature $T_i \sim 1$ keV, and an electron temperature $T_e \geqslant 50$ eV has been produced by filling the AMBAL–YuM mirror system with plasma from a quasisteady gas-discharge source. No auxiliary heating methods were used.

An approach to producing a steady-state hot plasma in an open magnetic confinement system involves first producing a plasma target[1] with comparatively modest properties. Fast atomic beams would then be captured in this plasma. When a plasma jet from a gas-discharge arc source [2] is used as this plasma target, the resulting target is usually characterized by temperatures $T_i \simeq T_e \sim 10$ eV, a density $n \geqslant 10^{14}$ cm^{-3}, and a flow velocity $V \sim V_t$, where V_t is the ion thermal velocity. A distinctive property of this plasma jet is that a Kelvin–Helmholtz instability sets in as the jet is transported in a magnetic field.[3] As a result of drift in the magnetic field crossed with the transverse electric field generated by the anodic potential drop across the discharge, which is carried off in the plasma jet, some of the energy ($\sim 10\%$) evolved in the arc is converted into energy of differential rotation of the plasma column. Under certain conditions this rotation is unstable and is accompanied by the excitation of low-frequency electrostatic waves in the plasma jet, which propagate across the magnetic field at a phase velocity $\omega/k \leqslant V_t$. The frequency of these waves satisfies $\omega < \omega_{ci}$, where ω_{ci} is the ion cyclotron frequency. Electrostatic waves of this sort are effectively absorbed by the plasma ions. In the course of collisions these ions transfer energy to the cooler electrons; some of the energy transferred to these electrons is returned to the arc by electron heat conduction, and some of it is carried out to the plasma receiver. Under our conditions the power density evolved in the plasma ions is on the order of 10 W/cm^3. This power is sufficient to heat the ions to a temperature $T_i \simeq 50$ eV. This temperature is limited by heat transfer to the cool, temperature-regulated electrons.

The situation changes radically when a thermal potential barrier for electrons forms between the confinement system proper and the plasma source. The production of a thermal barrier $\varphi \sim 2T_e$ in the AMBAL-YuM confinement system resulted in a decrease in the electron thermal conductivity by a factor of about[4] $\exp(e\varphi/T_e) \sim 10$. At the same power density, this reduction should be accompanied by an increase in T_e by a factor of $10^{2/3} \simeq 5$ in the confinement system. This increase was indeed confirmed by measurements of the electron temperature from an x-ray emission spectrum recorded with a photoelectron spectrometer (Fig. 1). Since the equilibrium ion temperature is determined by the rate at which the ions exchange energy with the electrons, a fivefold increase in T_e led us to expect an increase in T_i by

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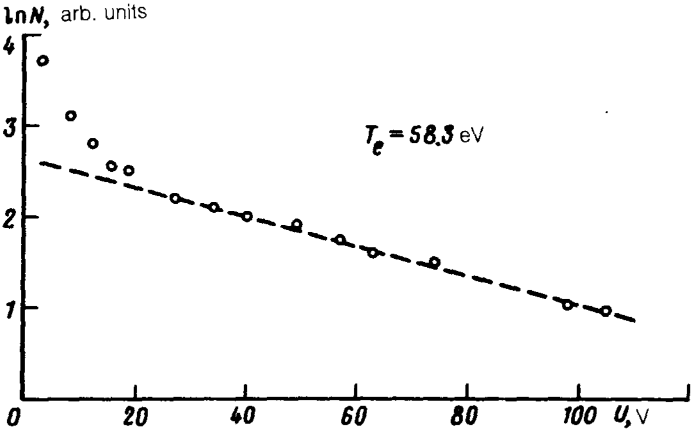

FIG. 1. Semilogarithmic spectrum of the x-ray photoelectrons.

an order of magnitude ($T_i \propto \tau_e \propto T_e^{3/2}$). In an effort to check this point, we carried out some experiments which are described below.

The ion temperature in the confinement system was determined by measuring the Doppler broadening of the emission by charge-exchange atoms in the *Hα* line (656.3 nm).[5] An image of the plasma was projected by a system of objective lenses onto the entrance slit of an MDR-2 monochromator. At the exit from this monochromator, the *Hα* lineshape was detected through an optical collector by an array of photomultipliers. This optical collector provided a resolution of 0.12 nm/channel, so an accuracy of 10% could be achieved in measurements of the ion temperature of a hydrogen plasma in the interval 0.5–1.0 keV. Figure 2 shows the results found from measurements of the broadening of the *Hα* spectral line. For the particular parameters of the confinement system, the Stark broadening does not exceed 0.1 nm, and the Zeeman splitting in the magnetic field of the confinement system is less than 0.03 nm. We thus see that the Doppler broadening of the *Hα* line is predominant and that this broadening can be used with confidence to determine the ion temperature. The value found for T_i through an analysis of the spectrograms represents only a certain average ion temperature in the confinement system. The lineshape found experimentally has a "hot" wing of Gaussian shape due to the plasma temperature and also a "cold" central peak, due to the emission by Franck–Condon atoms at the plasma periphery. The lineshape is symmetric with respect to its center. The temperature of the hydrogen ions was determined from the hot wing, through a comparison with a model Gaussian profile. The typical ion temperature found was $T_i \simeq 620$ eV.

In addition, a 90° magnetic analyzer was installed in the end plasma receiver in order to analyze the emitted ions. This analyzer detected ions with energies from 200 eV to 6 keV with an energy resolution $\simeq 20\%$. In the gasdynamic regime of the plasma flow out of the confinement system, the average ion energy in the expander is related to the ion temperature in the mirror system by $\bar{E} = (5/2)T_i(T_e \ll T_i)$. For adiabatic

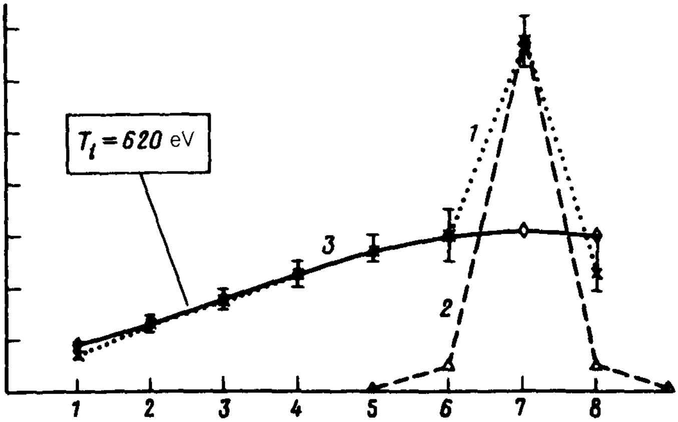

FIG. 2. Results of measurements of the broadening of the *Hα* spectral line. *1*—Reconstructed *Hα* lineshape; *2*—instrumental function of the measurement system; *3*—inscribed Gaussian profile. The numbers 1–8 on the abscissa scale are the channels of the measurement system. The width of one channel is $\Delta\lambda = 0.12$ nm. The seventh channel goes through the *Hα* line at 656.5 nm.

expansion, on the other hand, we would have $\bar{E} = 2T_i$. In this experiment, the flow is in a transitional regime. By choosing a coefficient of 5/2 we thus obtain a lower estimate of the ion temperature: $T_i \geqslant 0.65$ keV (see the spectrum in Fig. 3).

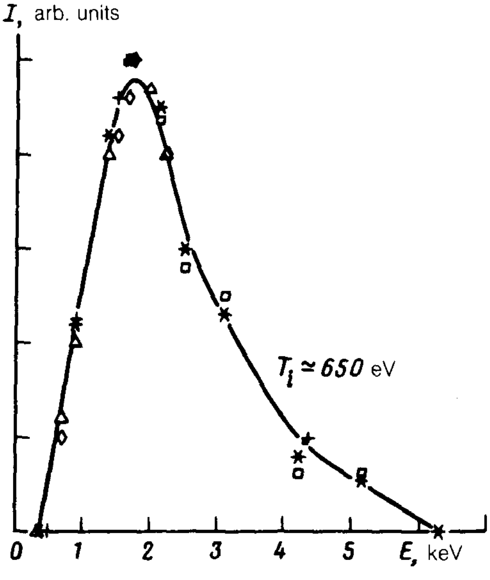

FIG. 3. Ion energy spectrum in the plasma receiver (the symbols of different shapes correspond to different series of measurements).

The plasma source used in the present experiments was designed in such way that the sign of the radial electric field carried out in the plasma jet could be changed.[6] In this case, the Kelvin–Helmholtz instability does not occur, so there is no stochastic heating of the ions.[7] Experiments carried out with the source in this operating regime also revealed that there was no ion heating. One way to increase the ion temperature further might be to increase the radial electric field in the plasma jet. This field, which drives the Kelvin–Helmholtz instability, is due primarily to the geometric anodic potential drop in the arc ($\Delta\phi_a \simeq 120$ V). As a result of a decrease in the area of the annular anode,[2] the overall potential drop across the discharge increases by 27%. The ion temperature of the deuterium plasma in the confinement system increases by a factor of 1.5 to 930 eV.

In experiments with deuterium, the following well-known nuclear fusion reactions occur in the plasma:

$$D+D\rightarrow {}^3\mathrm{He}\ (0.82\ \mathrm{MeV})+n(2.45\ \mathrm{MeV}),$$

$$D+D\rightarrow T(1.01\ \mathrm{MeV})+p(3.02\ \mathrm{MeV}).$$

At a deuteron temperature $T\simeq 1$ keV the rates of these reactions are[8] $\langle\sigma v\rangle \simeq 1.5\times 10^{-22}$ cm^3/s. The total number of neutrons obtained in one working pulse of the apparatus ($\tau\simeq 2$ μs) in the volume of the mirror system is estimated to be $N\sim (n^2/2)\langle\sigma v\rangle V_\tau \sim 10^5$. A polystyrene neutron scintillation detector was used outside the vacuum chamber to detect neutrons. For the particular position and efficiency of this detector, it should detect 30–40 neutrons in one shot of the apparatus. This prediction is completely supported by the experimental data. The corresponding statistical base was built up over 400 shots with deuterium.

In summary, the onset of the Kelvin-Helmholtz instability when there is a thermal barrier in the confinement system makes it possible to produce a plasma with a density $n\simeq 3\times 10^{13}$ cm^{-3} at the center of the confinement system, with an ion temperature $T_i\sim 1$ keV and an electron temperature $T_e\geqslant 50$ eV, from quasisteady gas-discharge sources, without the help of auxiliary heating. In experiments with a source of a deuterium plasma the yield of fusion neutrons was $\sim 10^8$ neutrons/s. The use of a plasma of this sort as a target for intense atomic beams would dramatically simplify the effort to achieve quasisteady operation, since the lifetime of the hot ion population which is captured is not determined by the stopping by cold electrons. It is instead limited by the natural mirror-system time scales for scattering into the loss cone and the lifetime with respect to charge exchange with the atomic beams and the residual gas.

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