Z-Pinch Study with Discharge Initiation by an Electron Beam

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Abstract. We study the gas discharge process under conditions when a relativistic electron beam is injected into the discharge tube after applying a high-voltage pulse. As a result, a plasma channel is created, a breakdown occurs, and a discharge develops. Comparative experiments were performed at different gas pressures under discharge conditions with and without electron beam initiation. They showed significant differences, especially during pinching and further development of the discharge.

1. Introduction
The study of breakdown processes, discharge development, and Z-pinch formation are the most important areas of plasma research. Usually, the discharge process after applying a high voltage to the discharge tube begins with a breakdown on the surface of the tube. But it is also possible to initiate a discharge by injecting a beam of electrons along the axis of the discharge tube. This work is related to previous studies of plasma-beam breakdown [1], but under specific conditions of a high-voltage discharge with the formation of a Z-pinch. The work uses an experimental setup that includes an electron beam source with an energy of 250 keV at a current of up to 100 A with a duration of up to 100 ns [2,3]. Studies are performed in a wide range of gas pressures, from 0.1 to 10 mbar. The difficulty is that the gas pressure in the electron gun should not exceed 0.03 mbar. For research in the field of low pressure in the discharge tube, up to 0.1 mbar, the problem is solved by applying a differential pumping system. At higher pressure, a separation film must be installed. When the electron energy of the beam used is 250 keV, the thickness of the Mylar film should be less than 1 μm.

2. Z-pinch discharge camera and diagnostic equipment
To separate the Z-pinch discharge chamber by vacuum from the electron beam focusing channel, a dynamic carousel-type separation system was created (Fig. 1). The system consists of a disk with Mylar windows rotating in a vacuum chamber. The electrons pass through the upper window located on the beam axis. Each window is a plastic shell ring covered with 0.5 μm thick Mylar film (Fig. 2). The film of this thickness does not have its own rigidity and it is difficult to apply it to a hole with a diameter of 2 cm. The vacuum seal of the film is provided by rubber rings that encircle it. A metal mesh is installed on the low-pressure side of the window. The window installed on the beam axis is clamped on both sides by passing bellows. This system provides a pressure drop between the electron gun and the discharge chamber from ~ 0.02 mbar to ~ 10 mbar.
Plasma flowing from the discharge tube burns through the film. After the shot is fired, the rotary device sets a new window. One can fire 21 shots during the session. Replacement of the windows is made through a special. This procedure, together with pumping, can be performed in 2 hours.

Experimental study of the dynamics of Z-pinch was performed by registering the plasma's own radiation in the visible light and near ultraviolet regions using a streak camera BIFO K-008, both in frame-by-frame mode and in the mode of temporal scanning of the glow from a thin plasma layer in the middle cross-section of the discharge tube. A quartz tube was used (Fig.3) with a length of 20 cm, an internal diameter of 3.9 cm, and a wall thickness of 3 mm. In this case, it is possible not only to study the dynamics of the discharge in one cross-section, but also to observe the entire discharge at a certain time (frame-by-frame shooting). In particular, it is possible to observe the electron beam itself.

3. Observation of the electron beam passing through the discharge tube
The efficiency of discharge initiation depends on both the amplitude of the electron beam current and dimensions. The beam propagation through the discharge tube is accompanied by the loss of electrons and their scattering on gas atoms, which leads to an increase in the transverse size of the beam. To estimate the latter effect, special experiments were performed on the passage of the beam through a tube filled with argon of different pressures. Figures 4 and 5 show the luminosity of the beam track in argon at a pressure of 0.5 and 3 mbar, as well as current waveforms (the lower curves are at the inlet to the tube, the upper curves are at the outlet). The current amplitude of the beam passed through the discharge tube at a pressure of 0.5 mbar is 15 A. At a pressure of 3 mbar, as can be seen, the beam current amplitude drops by ~ 2 times and the beam fills the entire tube section, which is the result of scattering. Thus, for our electron energy, the efficiency of the breakdown initiation beam will probably decrease when the gas pressure is more than a few mbar.
4. The discharge with initiation and without initiation by the electron beam

In these experiments, the tube was filled with oxygen at a pressure of 0.2 mbar. The duration of the sinusoidal half-wave of the discharge is 3.5 microseconds. The beam parameters: current ~ 10 A, duration-50 ns, beam diameter ~1.5 cm. The discharge current amplitude was ~40 kA. Figures 6 and 7 shows the oscillograms and the time scans of the discharge luminosity for a traditional a beam initiated discharges. Figures 8 and 9 show the corresponding radial distributions of plasma radiation density.

The beginning of the scan corresponds to the moment when the discharge current occurs. At the same time, the voltage on the discharge tube fall sharply due to the breakdown initiated by the electron beam. The surge and dip on the voltage and current curves display the features of the pinching process visible in the luminosity pictures.

The discharge process, as can be seen from experimental data, is quite complex. Several interesting features should be highlighted.

Without the beam, almost the entire tube "flares up" just before the maximum compression of the discharge plasma. Most likely this happens due to the sudden heating of the wall caused by a bright flash of pinch radiation. It is reasonable to assume that the radiation occurs after this and in the "volume", which is possible in the presence of a relatively dense and cold vaporized plasma outside the pinch. It is
possible that a breakdown without a beam, occurring primarily along the surface of the tube, is accompanied by a noticeable dispersion of the substance of the tube wall, which is a source of gas and plasma. The outer layers of the plasma (gas) are only gradually involved in the compression process. It should be noted that the MHD calculations [4] have not yet been able to reproduce this feature. There are three processes that are difficult to calculate using the MHD code:
- near-threshold evaporation of the chamber wall (first weak, then strong);
- electric "breakdown" of gas outside the main current channel (at the beginning of the discharge) due to an induction electric field;
- "stimulation" of wall evaporation by pinch radiation a little before the moment of pinching.

5. Discharge with and without beam initiation at different pressures
The Figures 10÷13 show the time scan of the discharge plasma luminosity at different gas pressures.
The experiments were performed in an atmosphere of oxygen. In each of the pairs of images, the lower one is obtained without the electron beam. The beginning of the scan corresponds to the moment when the discharge current occurs. The duration of the discharge luminosity scan is equal to 6 μs. The voltage and discharge current waveforms are similar to those shown in figures 6 and 7.

One can see from the pictures above that the effect of electron beam breakdown initiation decreases with increasing initial gas pressure. The main reason for this is probably the swelling of the beam due to scattering, which increases with the density of the gas.

6. Conclusion
The developed vacuum system that separates the accelerator section from the discharge tube allows conducting research at a gas pressure in the discharge tube of up to 10 mbar.

Experiments on the passage of a beam through a tube filled with a gas of various pressures have determined that for effective use of an electron beam with an energy of about 250 keV, the pressure must be less than 1 mbar. For high pressures, it is necessary to create a focusing axial magnetic field in the area of the discharge tube.

Comparative experiments with the initiation of electron-beam discharge and without initiation showed significant differences, especially with pinching and further development of the discharge.

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