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Note: Arc discharge plasma source with plane segmented LaB_6 cathode

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A plane cathode composed of close-packed hexagonal LaB_6 (lanthanum hexaboride) segments is described. The 6 cm diameter circular cathode is heated by radiation from a graphite foil flat spiral. The cathode along with a hollow copper anode is used for the arc discharge plasma production in a newly developed linear plasma device. A separately powered coil located around the anode is used to change the magnetic field strength and geometry in the anode region. Different discharge regimes were realized using this coil. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4950903]

Cathodes capable of producing high current density emission are required for many applications, such as plasma generators and ion sources. Devices for plasma-material interaction studies usually require a steady-state uniform plasma flow at the target over a spot of at least several centimeters in diameter, corresponding to a typical material sample size and a density of about 10^{13} cm^{-3} in an axial magnetic field of several kilogauss.[1] Such plasmas can be produced using large-area LaB_6 (lanthanum hexaboride) hot cathodes. However, large single-piece cathodes often suffer from cracking under thermal stresses, and therefore, need special care in operation. In plasma sources with large-area cathodes and hollow anodes, plasma density profiles are often hollow due to the self-screening of the discharge burning across the magnetic field. Therefore, it seems counterproductive to increase the plasma diameter in the source over ~10 cm in kilogauss magnetic fields. A disk cathode 7.6 cm in diameter with indirect tungsten filament heater at the PISCES plasma generator demonstrated good performance and capability of continuous operation.[2] At the same time, it was mentioned that the cathode disk was cracked by large fractures and the pieces were held in the frame by spring clamps on the edge of the disk. The fractures were reported not to deteriorate cathode performance. One of the solutions is to split the cathode into smaller pieces intentionally making it more fracture-resistant. This approach also allows one to develop the cathode area. A "honeycomb cathode" with ~22 cm diameter was developed at the MP[2] facility.[3] However, it was designed as a large diameter central disk surrounded by six disks of smaller diameter and did not have a close-packed emitting area. Although formally it is a large-area cathode, it is not evident if it would be capable of producing high-density homogeneous plasma stream. At the linear plasma device PSI-2, the plasma is produced by an arc discharge between a cylindrical LaB_6 cathode and a grounded hollow molybdenum anode.[4] The outer edge of the 7 cm diameter cylindrical cathode is mapped on to the inner surface of the anode along the magnetic field lines. In this area, the arc current flows along the magnetic field lines; therefore, most of the arc power in this configuration is released in the outer radial region resulting in a hollow plasma profile, which is inappropriate for the plasma-material interaction studies. Recently, a compact cathode made of a stack of 1.7 cm diameter LaB_6 washers alternated by a graphite foil was developed.[5,6] Unlike previously mentioned cathodes heated by radiation from a closely located graphite or tungsten heater, this one is directly heated by the current flowing through the assembly. Another discharge geometry is used at the LAPD device, where the plasma is produced in a direct arc discharge along the magnetic field between an 18×18 cm^2 square cathode consisting of four tiled LaB_6 pieces and a mesh anode.[7,8] This design with large cathode tiles proved to be very reliable in operation. However, applicability of the plasma source geometry to steady-state plasma-material interaction studies is questionable because of the difficulty with heat removal from a large-area mesh anode.

The aim of this work is developing and testing a large-area LaB_6 cathode resistant to cracking and capable of steady-state operation. Figure 1 shows the cathode drawing of the assembled cathode unit. The emitter consists of 61 identical LaB_6 segments, each of them being a hexagonal prism 15 mm long and 7 mm wide. Each segment is wrapped with a 0.15 mm thick flexible graphite foil, and all segments are clamped together by a circular skirt into a close-packed assembly to form a disc emitter. The graphite foil damps the mechanical stress from clamping and from thermal expansion during operation and serves as a current conductor between the segments. This segmented design prevents the emitter from cracking.

The emitter is indirectly heated by radiation from a flat spiral cut from a 0.5 mm thick flexible graphite sheet. The heater shape is stable at operating temperatures necessary to achieve the temperature of the cathode near 1600 °C required for the initial thermal emission current of several A/cm^2. The cathode and the heater are surrounded by heat shields made of 8 layers of tantalum foil and graphite foil. The heater current is supplied through an isolated feeder at the center of the

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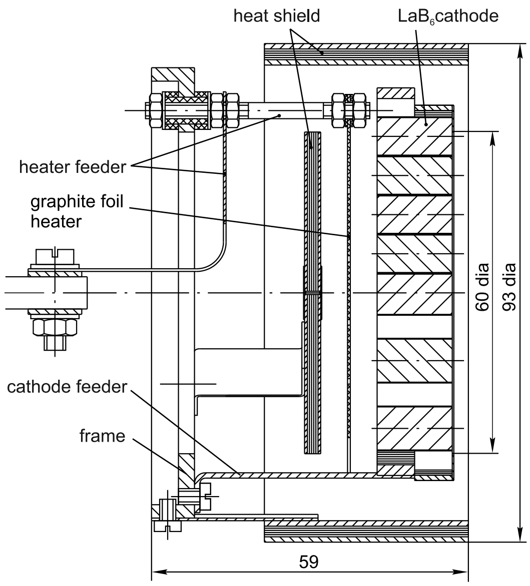

FIG. 1. Cathode arrangement.

water-cooled cathode flange and closes on the vacuum side of this flange.

The cathode voltage is applied directly to the same flange, which is electrically connected with the LaB_6 cathode. After about 30 min of gradual heater current ramp-up, the heater power reaches 2 kW (AC current 90 A, voltage ≈ 22 V), and the cathode produces a 100 A arc current at the start of the discharge pulse. The effective area of the front surface of the cathode (61 segments, 0.42 cm^2 each) is ≈ 25.6 cm^2 without account for partial shading of the edge segments by a circular skirt with the inner diameter of 60 mm at the front plane of the cathode. It gives an initial current density of 4 A/cm^2. When the discharge begins, the cathode is additionally heated by the impact of the plasma ions accelerated in the cathode sheath. As a result, the electron emission increases until the final steady-state is achieved in several hundred milliseconds. Depending on the operational mode of the discharge, the arc current can reach 400 A, which corresponds to an average current density of 16 A/cm^2.

A linear plasma device was developed for testing of the segmented cathode and investigations of different modes of plasma generation. Layout of the linear device with the plasma source based on the segmented cathode and a hollow copper anode with an inner diameter of 70 mm is shown in Fig. 2. The working gas (hydrogen in our case) is injected through the cathode flange by a valve. Gas feed rate variation in the range 25–200 sccm almost does not change the arc current. The background pressure in the vacuum chamber is $5\cdot10^{-5}$ Torr.

The arc pulse length was typically chosen 1.0 s which is sufficient for achievement of the quasi steady-state discharge conditions. At the same time, this pulse length limits the gas pressure in the vacuum chamber at the end of the pulse to about 10 mTorr allowing operation on a flowing gas without a spurious effect of neutral pressure growth in the vacuum vessel during the pulse. Depending on the initial cathode temperature determined by the heater power, it takes the arc current about 100–300 ms to rise to its steady-state value. The power supply works as a current generator up to a current of 200 A while the voltage is determined by the discharge resistance and has the upper limit of 200 V. When the current exceeds 200 A, the voltage starts to fall off from 200 V.

The almost uniform guiding magnetic field up to 1.25 kG is produced by a set of room-temperature copper coils. A molybdenum neutralizer disc terminates the magnetized plasma flow escaping from the linear device at the distance of 10 cm from the wall of the main vacuum vessel shown in Fig. 2. The neutralizer plate can be made either floating or biased negatively with respect to the anode. As a rule, we used the grounded anode and the floating neutralizer.

The segmented cathode has been operated in the linear device for plasma production in the pulsed regime for several months for an integral discharge time of about 1 h. During this period, there were about 20 vents. The cathode segment structure and its performance in terms of arc current dynamics and steady-state arc current in different discharge modes did not change during this period. The graphite foil spiral operated for about 200 h without any signs of wear.

The linear device is characterized by variable magnetic field geometry in the anode region, which is set by a special control coil with an inner diameter of 23.4 cm located around the anode (Fig. 2). The coil generates an additional magnetic field at the anode axis of up to 500 G; thus the axial magnetic field can be varied in the range 250–1250 G. It allows one to substantially change the discharge regime and consequently

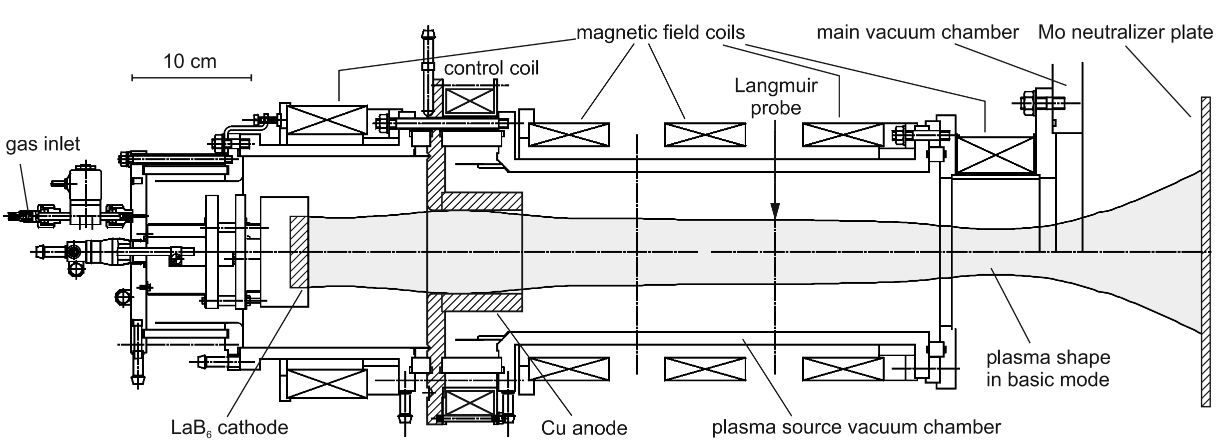

FIG. 2. Plasma source of the linear device.

the diameter and the density of the plasma stream. We mention here two distinct modes in terms of the projection of the outer edge of the cathode toward the inner surface of the anode along the magnetic field lines. When the control coil current is zero, we have a basic mode, where the field line from the edge of the hot cathode just touches the inner surface of the anode. When the current in the control coil adds to the field of the solenoid, we have a "magnetically insulated" discharge mode, which means that there appears a finite radial gap between the edge field line and the inner anode surface. In the opposite case, when the control coil decreases the solenoid field in the anode region, the magnetic field lines from a ring at the cathode edge intersect the anode surface. We call this case a "partially direct" discharge mode. The latter case is similar in the structure to the arc discharge with a cylindrical cathode and hollow anode in the plasma source of the steady-state PSI-2 facility.[4] However, this similarity is not complete, because in PSI-2, the magnetic field at the anode is approximately two times larger than at the cathode, reaching 1.7 kG, whereas in our plasma source, the field in the anode in this mode is 0.5 kG and is two times smaller than at the cathode. Another substantial difference is that our cathode is disc-like, providing electron emission over the whole area including the near-axis region, whereas at PSI-2, the cylindrical cathode generates electrons only at the periphery.

The radial profiles of the plasma density (for hydrogen $n_i = n_e$) in two operation modes are shown in Fig. 3. One can see that in the basic mode, the density is almost uniform up to $r \approx 25$ mm in the probe location where the magnetic field is 1.2 kG. In the partially direct discharge mode, the density profile becomes very narrow and the density reaches $2{\cdot}10^{13}$ cm^{-3}. Although this mode seems similar to the PSI-2 experimental conditions where the front surface of the cylindrical cathode is connected with the anode surface along the field lines, the results are quite different. In our case, the plasma stream is narrow and dense, and there is no deep well in the density profile near the axis. We attribute this difference in the plasma density profiles to the cathode shape which determines the magnetic flux tubes with high electron emission current density and thus with high ionization rate. In PSI-2, there is a lack of electrons near the axis, and the ionization takes place mainly in the annular channel connecting the cathode surface with the anode. These arguments will be studied in the following experiments.

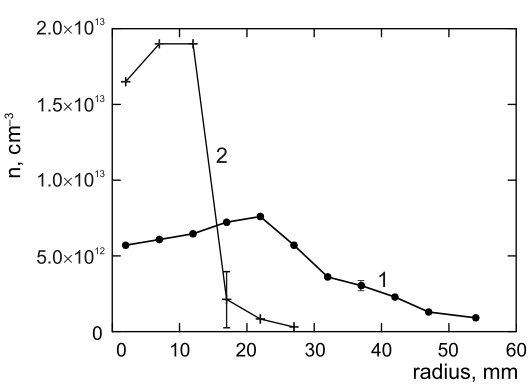

FIG. 3. Plasma density profiles in the basic operation mode (1) and in the partially direct discharge mode (2).

In summary, the electron emitter for high-current arc plasma generators based on the assembly of hexagonal LaB_6 segments has been developed and tested. The quasi-stationary plasma source with the segmented cathode has been reliably operated at an arc current of up to 400 A in a long-pulse mode with an integral discharge time of approximately 1 h.

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