

Experimental Investigation of Plasma Formation at Dielectric Rod's Surface within the Annular Electron Beam Generated and Transported in the Magnetic Field¹

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Abstract – In the course of the development of the X-band antenna-amplifier [1], the experiments on annular relativistic electron beam generation and transport in the guiding magnetic field with a dielectric rod inside have been carried out. The experiments were aimed at estimating the density of plasma that can appear at the surface of dielectric. The beam was generated in the compact module of linear induction accelerator; as a rod material, plexiglass, polyethylene, and quartz were tested. It was found that the critical place for plasma formation at the rod surface was at the tapered region between the coaxial magnetically insulated diode and beam-wave interaction space. The dependences of plasma density on the value of guiding magnetic field, beam-rod gap, and accelerating voltage were studied. It follows from the results obtained that one can avoid plasma formation to the degree inadmissible for an X-band device, when the density much exceeds 10^{12} cm^{-3} . Thus, the concept of the antenna-amplifier can be considered realizable.

1. Introduction

An antenna-amplifier, relativistic Cherenkov device with a rod slow-wave structure operating in the fundamental HE_{11} mode of a dielectric rod antenna, seems promising as a compact, controllable, high-power microwave source. The annular electron beam in the antenna-amplifier is generated in the linear induction accelerator (LIA) with the hollow knife-edge cathode and cathode holder, through which the RF drive signal excites the dielectric rod. For the development of the antenna-amplifier, an important issue is plasma-related studies. Indeed, the plasma can appear at the surface of the rod located within the hollow high-voltage electrode and annular beam moving near and along, and too dense plasma could prevent a Cherenkov interaction between the beam and HE_{11} mode of the rod.

The plasma in the beam-wave interaction space can be produced due to such processes as dielectric flashover (under the voltage applied or under the electric field induced at the propagation of the beam head

near the rod surface), direct electron bombardment of dielectric, or the breakdown of residual and desorbed gases. In this work, the model experiments on beam generation and transport by the guiding magnetic field with the dielectric rod inside were conducted. Their goal was to study plasma formation at different conditions in the absence of an external microwave signal and estimate its density. If the density, by its order of magnitude, does not exceed 10^{12} cm^{-3} (that means the plasma frequency is less than the operating frequency of the X-band), the presence of plasma does not significantly affect the electrodynamic characteristics (dispersion and RF field pattern) of the HE_{11} mode in the X-band, so that an X-band antenna-amplifier can be realized.

2. Experimental setup and evidences of plasma presence

Investigations were performed on the compact LIA module. The LIA accelerating voltage was varied from 250 to 340 kV; for the used configuration of coaxial magnetically insulated diode, this corresponded to the beam current variation range of 0.9 to 1.5 kA. Detailed geometry of the experiments is presented in Fig. 1. It includes the LIA vacuum chamber (with its insulator, high-voltage flange, and cathode holder), the diode (60 mm anode and 20 mm cathode edge diameters), the tapered buffer section (26 mm length), and the drift tube (40 mm diameter). The cathode holder alignment unit is at the high-voltage flange; the magnetic field axis was aligned by means of adjusting bolted joints between the solenoid flange and the vacuum chamber. The cathode edge was located in the region of uniform magnetic field (52 mm from the drift tube entrance). The guide field magnitude was up to 2.6 T.

Dielectric rods were inserted through the hollow cathode into the hollow end section of the cathode holder as a tight fit. Rods of different length and diameter were used in the experiments; the maximum length was 270 mm from the cathode edge to the rod end, and the diameters were 10 and 12 mm. Three different materials were employed for rods: plexiglass, polyethylene, and quartz.

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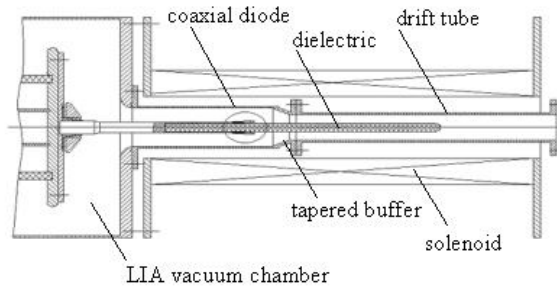


Fig. 1. Schematic of experimental geometry (circle marks the cathode)

Initial evidences of the plasma presence were obtained from images produced on witness plates within the drift tube downstream of the rod end. First, we studied the possibility of plasma formation inside the cathode. The details of the cathode design are shown in Fig. 2. It is seen that for the initial design, the triple point circle, where the rod contacts the cathode inner surface, was rather close to the cathode edge. This resulted in a very dense plasma production, as one can see from the image presented in Fig. 2. There are two concentric circles of, in fact, the same brightness; one corresponds to the cathode edge diameter, and another one corresponds to the rod diameter. Similar images were obtained with long, extending into the drift tube, and short, just slightly sticking out of the cathode, plexiglass rods at the given witness plate position. This proves that the inner trace is originated from inside the cathode. The same brightness means that the plasma density at the triple point region is as high as the density of explosive emission cathode plasma. Such plasma would certainly prevent RF fields of an X-band drive signal from coupling to the electron beam outside the rod; this is not acceptable.

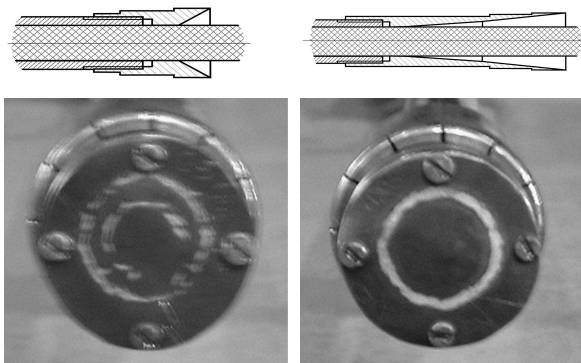


Fig. 2. Initial (left) and modified (right) designs of the cathode and images produced with these cathodes on witness plates downstream of $\varnothing 12$ mm plexiglass rods. The rod lengths are, respectively, 25 mm (left) and 12 mm (right) from the cathode edge to the end

Then the cathode design was modified in order to "hide" the triple points inside, much farther from the

cathode edge. As a result, plasma production from this place was eliminated. The image obtained on the copper foil in case of the short rod inserted into the modified cathode shown in Fig. 2 is the same as one produced by the electron beam without dielectric at all. However, the trace on the witness plate within the trace produced by the main beam appeared in case of the long dielectric rod extended into the drift tube. The corresponding image is presented in Fig. 3. It is seen that the inner trace is less bright than the main beam trace, in difference of Fig. 2, i.e., the plasma produced at the rod surface is not so dense. As the inner trace appeared only when the rod extended into the drift tube, one can conclude that the critical place for plasma formation at the rod surface is at the tapered buffer region. After many shots done, we got another evidence for that: the traces of surface breakdown appeared on the rod namely at the location of tapered region. This was observed only for plexiglass and polyethylene rods.

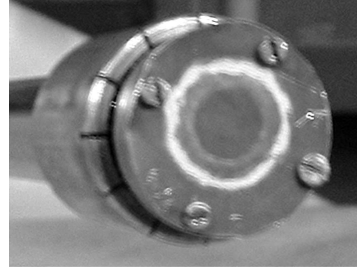


Fig. 3. Same as in Fig. 2 (bottom right) for the long rod (240 mm from the cathode edge to rod end)

3. Estimation of plasma density

The diagnostics implemented for estimations of the plasma density was based on measuring the current transferred by the inside of annular beam, which produces this less bright trace on the witness plate seen in Fig. 3. We assume that the source of this current is the plasma at the rod surface; hence, considering it as the electron saturation current, one can estimate the plasma electron density n from the formula $j \approx nev_t$, where j is the measured current density and v_t is the thermal velocity. Assuming then that the electron plasma temperature is a few eV (this is typical for surface discharge plasma), one can calculate the electron saturation current for the characteristic plasma density of 10^{12} cm^{-3} mentioned above and obtain $j \sim 20 \text{ A/cm}^2$. So, an acceptable value of current density measured in the beam inside would be some 20-40 A/cm^2 (for comparison, the current density of the beam as its own is of the order of 1-2 kA/cm^2).

We employed the special composite Faraday cup with two collectors capable of measuring both the main beam current and the current transferred inside the beam. It was placed downstream of the rod end at the distances of 52 and 200 mm (the rods of maximum 270 mm length were used in these experiments). The design of the Faraday cup is shown in Fig. 4.

The main beam current is delivered to the outer collector 1. The inner collector 2 is made changeable, so that its diameter could be varied; maximum diameter was anyway less than the inner diameter of the beam. The added pieces to the outer collector and the diaphragm 5 protected the insulator 4 of inner collector from the plasma produced by the beam. On the other hand, molybdenum diaphragms were used to reduce plasma production under the beam, and the hole was shut in by 12 μm aluminum foil. Also, the diaphragms served as witness plates showing the degree of beam-rod alignment. The collet 6 provides a contact with the drift tube wall, and registration cables go outside through the hollow supporting stick 7.

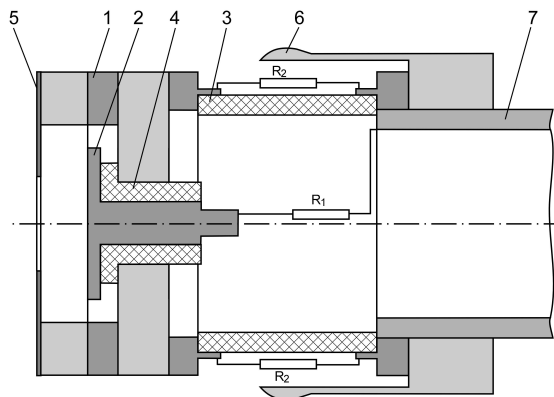


Fig. 4. Schematic of the composite Faraday cup. 1 – outer collector, 2 – inner collector, 3 – insulator of outer collector, 4 – insulator of inner collector, 5 – diaphragm (witness plate), 6 – collet, 7 – grounded stick (support)

Using diaphragms of different diameters and obtaining dependences of the current delivered to the inner collector on the size of the hole allows for estimating the plasma density radial profile. We used the diaphragms of 11 to 15 mm diameter with the step of 1 mm and statistically processed measurements data to get the current differences, from which the current densities were calculated.

Typical oscilloscope traces from the series of LIA shots processed for obtaining the current density profiles presented in the next Section are shown in Fig. 5. It should be noted here that the current delivered to the Faraday cup inner collector strongly depended on the degree of beam-rod alignment. Non-satisfactory alignment resulted in its significant increase. In addition to getting the main beam autograph on molybdenum diaphragms, we placed plastic for tracking detection before the diaphragm hole in order to check the concentricity of rod shadow and diaphragm circumferences. In Fig. 6, the images of beam on the diaphragm and plasma on the plastic are presented showing an acceptable degree of beam-rod alignment. For statistical processing, the data obtained at satisfactory alignment were used.

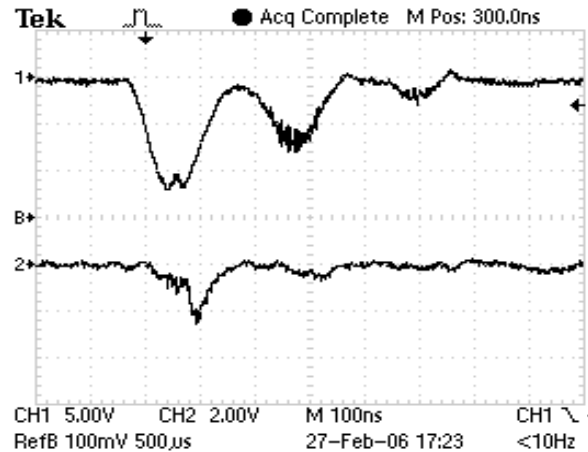


Fig. 5. Current delivered to the outer (450 A/div., channel 1) and inner (25 A/div., channel 2) collectors of the Faraday cup. $\varnothing 12$ mm quartz rod, $\varnothing 14$ mm diaphragm, ~ 280 kV LIA voltage, ~ 2.6 T guide field



Fig. 6. Images produced by the main beam (left) and plasma (right)

4. Results and discussion

First, experiments were performed with the rods of organic materials: plexiglass and polyethylene. It should be noted, at once, that after many shots made in the course of experiments, these rods exhibited traces of surface breakdown along all their length from the buffer section to the rod end. This can be seen from Fig. 7 where the photo of the plexiglass rod employed in the experiments is presented. In addition, for the plexiglass rod, with which a greater number of shots were made, a small "waist" under the cathode edge (0.3 mm reduction of diameter) was observed. It is caused, most likely, by the UV radiation from the cathode plasma heating the rod up to material transfer off, since plexiglass softening point is as low as 90°C .



Fig. 7. Plexiglass rod after many shots made

Evidently, plastic rods are rather not appropriate for an operating device, and materials with high softening (melting) temperature like quartz, ceramics, or titanium silicate glass should be employed. The main part of our experiments was carried out with the quartz rods, and for the quartz, neither breakdown traces, nor

waist were observed. So, the most of the data processed to get radial profiles of current density inside the beam were obtained with the quartz rods.

In the series of experiments with two quartz rods, of 12 and 10 mm diameters, the current delivered to the Faraday cup inner collector was measured at different accelerating voltages, values of guiding magnetic field. Respectively, two different beam-rod gaps were realized (4 and 5 mm counting from the mean beam radius). Some results of data processing are shown in Figs. 8 and 9. In Fig. 8, the current density radial profiles are presented in the case of rather high guide magnetic field. It is seen that the near-surface current density is higher for the smaller beam-rod gap and increases with increasing beam voltage and current. Also, there is rather a maximum in the profiles near the rod surface; so that one can associate the following big increase (for $\varnothing 10$ mm rod) with inner periphery electrons of the main beam.

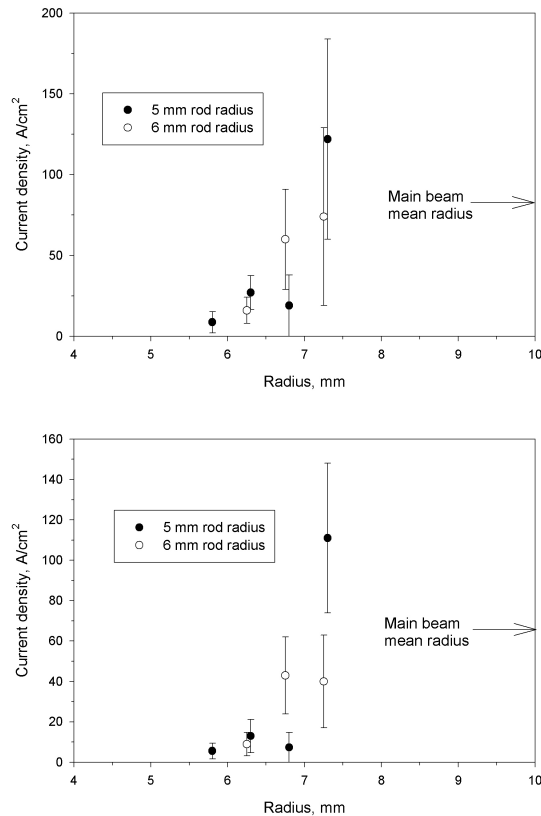


Fig. 8. Radial profiles of current density inside the main beam obtained for $\varnothing 12$ and $\varnothing 10$ mm quartz rods at ~ 2.6 T guide field. The LIA voltage is ~ 280 kV for the top plot (~ 1.1 kA beam current) and ~ 250 kV for the bottom plot (~ 0.9 kA beam current).

As to the absolute value of the current density, one can conclude that the abovementioned characteristic $20\text{--}40$ A/cm² is achieved here, so that the plasma formation is rather acceptable in this case as its density is not too high. Though, the current density considerably increases with decreasing guide magnetic field and at

a higher LIA voltage as seen from Fig. 9. It should be noted here that the influence of such important factor as vacuum conditions on the plasma formation has not been properly investigated. The dispersion of measured data in series of LIA shots at given parameters significantly changed for different series, and causes of these changes remain unclear.

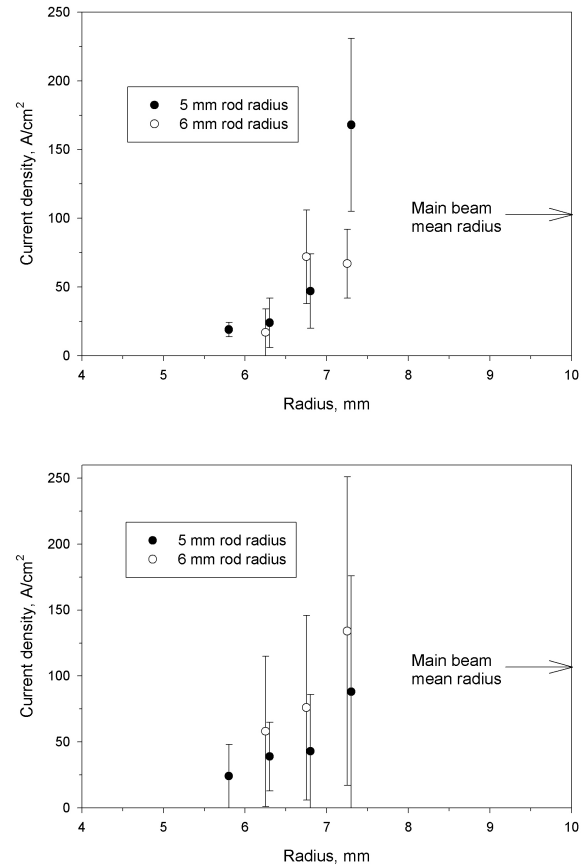


Fig. 9. Same as in Fig. 8 for ~ 320 kV LIA voltage (~ 1.35 kA beam current). The guide magnetic field is ~ 1.9 T for the top plot and ~ 0.9 T for the bottom plot.

5. Conclusion

Our studies have shown that the plasma formation at the dielectric rod surface within the beam can be rather acceptable, i.e., plasma density can be low enough, so that the concept of the antenna-amplifier can be considered realizable. Further investigations are needed with improved vacuum conditions to achieve acceptable plasma densities over a wider range of LIA voltage and to get better shot-to-shot stability. The authors acknowledge A. V. Petrov for original designing and fabricating the composite Faraday cup.

References

- [1] A.S.Shlapakovski, S.N.Artemenko, et al., in *Proc. 14th Symposium on High-Current Electronics*, 2006 (this issue).