# High-current magnetized REB generated by a field-emission cathode, with the geometry and angular spectrum invariable during microsecond intervals.

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High-current relativistic electron beams (REB) are usually generated with the help of field-emission cathodes: plasma acts as electron emitter. In the majority of applications REBs are generated and used in a strong magnetic field where electrons move along helical trajectories around the field lines. It is very desirable to preserve all the parameters of the REB constant throughout the pulse, namely, to preserve the beam geometry and so called pitch-angle of electron trajectories, e.g., the angle between electron velocity and the guiding magnetic field.

If the pulse duration of the REB is of the order of microsecond or more then at least two problems arise. The first one is: how to avoid the cathode plasma propagation across magnetic field lines and the concurrent increase of REB transverse dimension with the rate of several mm/μs? The second problem is: how to be sure that the electron trajectories have invariable pitch-angles, especially if they have to be small, not more than several degrees?

The mechanism of cathode plasma expansion is schematically presented in Fig. 1. Plasma (dotted area) covers the surface of the field-emission cathode (hatching below) immersed in strong magnetic field **B**. The source of plasma is the cathode surface. The plasma does not move parallel to the cathode surface because the pressure $\mathbf{p}_{pl}$ of the similar plasma areas is equal from the left and right. From the top the plasma is exposed to the magnetic field pressure: $\mathbf{p}_B \sim B^2$. The cathode surface, which restricts plasma from the bottom, jets new and new portions of matter during all the pulse, increasing plasma density and, consequently, its pressure. So, the pressure from the bottom **p** grows, overcoming the opposite $\mathbf{p}_B$, and plasma expands upward tending to diminish its density. The more the magnetic pressure $\mathbf{p}_B$ is, the slower plasma intersects magnetic field lines. Unfortunately, in real experiments it is difficult to obtain **B** exceeding a few Tesla, so the problem of microsecond REBs with changing geometry was on the agenda during decades.

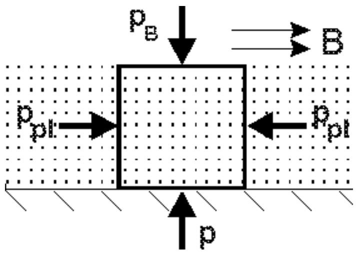


**Fig. 1.** Mechanism of cathode plasma expansion.

The way to avoid this effect of plasma expansion was proposed in [1]. The idea is simple: let us avoid the situation where plasma is forced to propagate across magnetic field. Let *all* created plasma propagate freely *along* magnetic field (with the speed ~ 10 cm/μs, i.e. much faster than across the field). Then plasma density will be insufficient to impel plasma to intersect the magnetic field lines. With this aim in view, *the entire* emitting surface of the cathode must be perpendicular to the magnetic field.

Fig. 2 demonstrates the implementation of this idea. Both front (right) and back (left) sides of the cathode are (almost) normal to the magnetic field. The circular cathode has a very sharp edge, so there are no areas on the cathode surface where the situation resembles Fig. 1. The cathode plasma may freely propagate

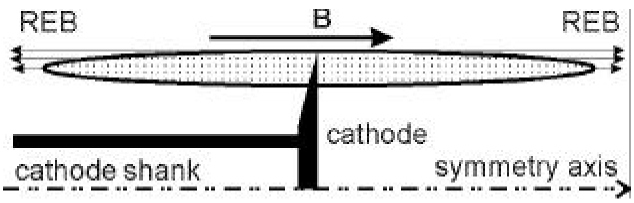


**Fig. 2.** Explosive cathode for microsecond REB with stable geometry. Dotted area — plasma.

along the magnetic field without radial expansion. The result is the annular REB (500 keV, 2 kA) with absolutely stable geometry (diameter 3 cm, thickness 0.3 cm) during 1000 ns.

Hence, the long-term electron beam preserves its shape, but the other above indicated question remains: does the REB also preserve the pitch-angles of electron trajectories? Of course, a diamagnetic probe may be used, but it cannot present the distribution over pitch-angles, only a mean value. Moreover, it is very difficult to apply this method when the pitch-angles are comparatively small (e.g., a few degrees) and the magnetic field is strong (> 1 T), as it takes place in many microwave oscillators.

There are many other methods, whose main idea is the following: to cut out a little portion of the REB using a small diaphragm and then to analyze it. The electron flux density ~ 1 kA/cm$^2$ is usual for high-current REBs, and the consequences of this approach are well known: plasma immediately appears on the surface of the diaphragm and begins to propagate opposite to the REB with the velocity 10 – 100 cm/μs. If the pulse duration is ~ 1 μs then the electrons have to move to the analyzer through long plasma channel, and their measured parameters may strongly differ from those before the interaction with plasma.

At first sight it seems possible to diminish the density of electrons diminishing the magnetic field, to carry out the measurements and then to recalculate the results. Nevertheless, the space charge of the high-current beam perverts the information about the pitch-angles obtained in such a procedure. Indeed, electrons drift in the crossed electric field of the space charge and the external magnetic field, so the value of the pitch-angle has an inevitable spread. It is easy to show that the "relative error", i.e., the ratio of this spread to the "true" pitch-angle, vary inversely proportional to the magnetic field if it diminishes along the axis. So, following this method with high-current electron beam deprive the measurements of any sense. So, the measurements must be conducted immediately in strong magnetic field.

Two methods (with different modifications) are mostly in use for measurements of pitch-angles of electron trajectories of a high-current REB in strong magnetic field. They are the method of cylindrical channels (or "wells") [2] and the method of "pinhole" [3]. In the method of "wells" on the way of REB they install a specific diaphragm, namely, a cylindrical channel with the axis parallel to the magnetic field and the radius comparable with Larmor radius of electrons. The number of electrons registered at different distances from the channel entrance characterizes the distribution over pitch-angles. This method was useful to measure the angle spread $\vartheta \sim 10°$ in the magnetic field 4.2 T. The drawbacks are, first, the sensitivity to the reflections of electrons from the channel wall, especially significant at little angles, and second, the sensitivity to the parallelism of the channel axis and the magnetic field. And, of course, the plasma creating at the entrance of the channel is the common disadvantage for both the methods of "wells" and "pinholes".

The "pinhole" method is presented schematically in Fig. 3. Electrons, which penetrate through a small diaphragm (pinhole) into the chamber, are registered on the monitor at certain radii **r** from the axis. The axis is parallel to the magnetic field **B**. The pitch-angle $\vartheta$ may be found if the distance L is sufficiently small, less than ¼ of the step of the helical electron trajectory in the magnetic field. Different monitors may be used: scintillators, multi-collector receivers, etc. If a scintillator (with the following photo camera) is used then the method does not depend on the parallelism of the axis and the magnetic field. Along with other advantages the method has the main drawback, namely, it is unsuitable for measurements in strong magnetic field. E.g., for electrons with the energy 500 keV and B = 1 T the analyzer length L < 3 mm, and an electron with $\vartheta = 10°$ has to be registered at r ≅ 0.5 mm from the axis. So, the only obstacle on the way of appli-

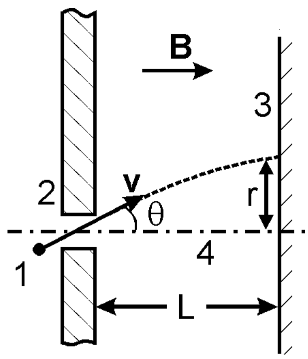


**Fig. 3.** "Pinhole" method. 1 — electron; 2 — diaphragm; 3 — monitor; 4 — axis.

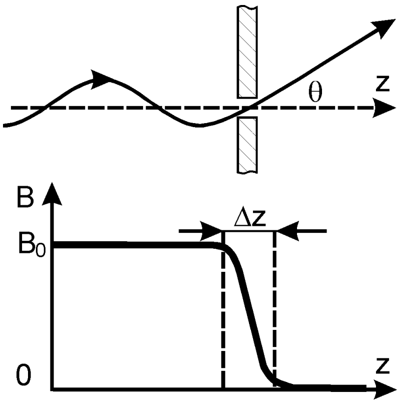


**Fig. 4.** *Top* — electron trajectory; *bottom* — longitudinal distribution of the magnetic field B.

cation of the “pinholes” is the presence of strong magnetic field between the diaphragm and the monitor.

If the distribution of the magnetic field along the axis B(z) were as shown in Fig. 4 and the intermediate area $\Delta z$ were sufficiently short, then an electron could preserve its pitch-angle $\vartheta$ and propagate directly to a monitor of some kind. This distribution B(z) may be obtained if a homogeneous field $B_0$ is added to a field which compensates $B_0$ in the analyzer.

Fig. 5 shows a cone surface with the angle $\alpha$, so the radius R changes as: $R = z \cdot \mathrm{tg}\,\alpha$. Let the surface be covered with circular currents distributed along z axis so that the magnetic field inside is constant $-B_0$ (later we will show that it is possible). It is easy to estimate that in front of the cone ($z \le 0$) the magnetic field $-\delta B$ is $\left(1 + ctg^2 a\right)^{3/2}$ times less than inside the cone: $\delta B < B_0 \cdot \left(1 + ctg^2 a\right)^{3/2}$. For $\alpha = 20°$ this ratio is 25, so the cone does not affect significantly the behavior of electrons before entering the analyzer.

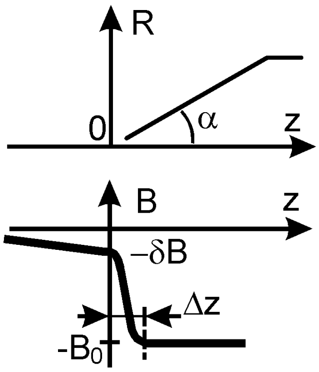


**Fig. 5.** *Top* — profile of the cone; *bottom* —distribution of the magnetic field B.

Let the cone surface to be the body of the analyzer. Then the profile of the magnetic field should be as shown in Fig. 6: the lines are parallel in front of the device and then skirt the cone. The length $\Delta z$ of the intermediate area is comparable with the diameter of the pinhole, which may be as little as the sensitivity of a particular type of the monitor permits.

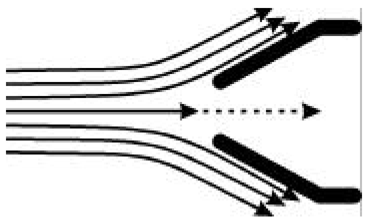

**Fig. 6.** Profile of magnetic field lines. Bold-faced line denotes the conic body of the pitch-angle analyzer.

Note that the magnetic field is strong near the analyzer surface, so the majority of electrons (“frozen” into the field) avoid striking with the surface and in doing so prevent intensive plasma creation. Only those electrons, which flow immediately near the axis, penetrate into the device. Of course, there are electrons bombarding the diaphragm, but their amount is much less than it could be if the magnetic field were homogeneous.

The magnetic configuration shown above may be obtained using skin-effect in “fast” fields. If the magnetic field pulse is sufficiently short-term, and the body of the analyzer is a good conductor, then the magnetic field inside the body is negligible. The magnetic field in the other areas (the diode, etc.) may be long-term, the only requirement on it is to equal zero at the site where the analyzer is installed, as shown in Fig. 7.

Let the total magnetic field to be a superposition of the two fields: $B_1$ is a steady-state field with zero magnitude to the right from a certain z-coordinate, $B_2$ is the short-term pulse field (a few μs), it is “switched on” when the REB propagates. The sum $B_1 + B_2$ provides more or less homogeneous field. The conic body of the analyzer is made of copper, it resides in the area where $B_1 = 0$. The "fast" field $B_2$ cannot penetrate inside the analyzer, so when $B_2$ is “switched on” the profile of the magnetic field lines is as presented in Fig. 6.

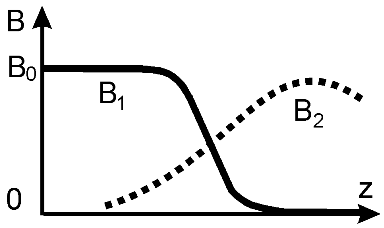


**Fig. 7.** Magnetic field along the axis. $B_1$ — steady-state field, $B_2$ — “fast” field.

The analyzer designed according to the described above technology comprised solenoids for creation magnetic fields $B_1$ and $B_2$, ~1 T each one, the conic metal body (upper limit of measured pitch-angles $\alpha = 20°$) with the pinhole (diameter 1 mm) and the monitor (diameter 50 mm). For the calibration of the device we used the multi-collector monitor resembling [3]: seven coaxial collectors installed at $\approx 2.3°$ from each other. The monitor allowed to follow the temporal changes of electron trajectories. The calibration was conducted using a flux of 500-keV electrons with pitch-angles $\vartheta < 2°$ during 1 μs. These electrons passed through 20-μm aluminum foil installed at ~ 0.5 m from the monitor.

The spread of electrons on a foil is well studied, the distribution of electron current I over coaxial collectors installed at angles $\vartheta$ is: $I(\vartheta) \sim \sin\vartheta \cdot e^{-\frac{\vartheta^2}{\vartheta_0^2}}$, where $\vartheta_0$ depends on the foil and electron energy. For the chosen parameters $\vartheta_0 \approx 10°$. Fig. 8 demonstrates good accordance between the measured signals from the collectors and the calculated values.

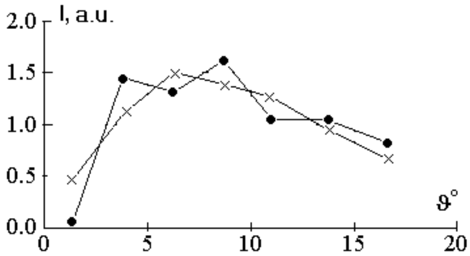


**Fig. 8.** Current of electrons with different **J** : × — calculation, • — experiment.

The least squares method permits to calculate the spread angle $\vartheta_0$ for the exponential function $I(\vartheta)$ indicated above for every particular moment. The result is presented in Fig. 9. The curve 1 was obtained using the waveform of cathode voltage, which was almost constant during the pulse, and the parameters of the foil. The curve 2 is the result of treating the signals from the collectors. These two curves are in good accordance in spite of the fact that the sum of the currents to all 7 collectors (bottom in Fig. 9) changed significantly during the pulse.

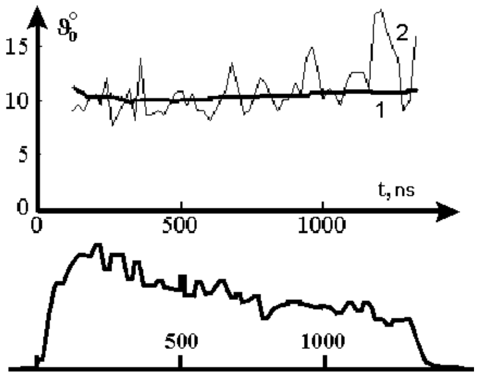


**Fig. 9.** *Top* — spread angle $\theta_0$ during the pulse: 1 – prediction, 2 – measurements. *Bottom* — total electron current in the analyzer.

Therefore, the calibration has shown that the analyzer is suitable to measure the parameters of electron trajectories in a REB of microsecond duration. Note that by moving the monitor farther from the pinhole it is easy to increase the angular resolution of the method.

The described time- and spatially-resolving analyzer was used to investigate an annular REB with electron energy 500 keV, total current 2 kA, radius 1.5 cm, thickness ~ 3 mm during 1-μs pulse. The beam was generated on the field-emission cathode shown in Fig. 2 in the magnetically-insulated diode. The beam propagated in homogeneous magnetic field 1 T. The measurements have shown that during 1 μs the electron beam preserves both its annular shape and all pitch-angles of electron trajectories < 4°. Such a REB may be used in high-power microwave devices of microsecond pulse duration, and the electron beam properties can not be considered as the reason for the known effect of "high-power microwave pulse shortening".

## References


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