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GENERATION AND TRANSPORT OF 140 kJ RIBBON ELECTRON BEAM

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ABSTRACT

Generation of a microsecond ribbon electron beam with a strongly elongated cross section $4\cdot140$ cm in a magnetically insulated diode at 1 MV voltage and its transport at the distance 2 m in a slit vacuum channel with a guiding magnetic field about 1 T are described. High efficiency of the ribbon beam generation and transport at the total energy about 140 kJ is experimentally proved.

Our experimental studies of high power microsecond electron beams with a strongly elongated cross section are aimed to achieve on this way a total energy in a beam pulse about 1 MJ at high current density and small angular spread. The improvement of the beam parameters in the case of a ribbon shape is associated with a generation of such beams in a foilles magnetically insulated diode in which the influence of an anode plasma can be practically eliminated. The above mentioned beam parameters allow using the ribbon beam for a number of applications, e.g. for plasma heating in long solenoids [1] and microwave generation at a wavelength 1÷10 mm [2].

Our experimental studies on ribbon beam generation with total energy of tens of kilojoules and transport in a slit vacuum channel with a guiding magnetic field [3] show that, for keeping a cross section shape invariable, the beam thickness should be larger than half width of the channel and, for stabilizing this equilibrium at the beam current density about 1 kA/cm^2, the magnetic field strength should be larger than 0.4 T. These results have formed a basis of the development of the ribbon beam technique at the total energy content up to a few hundreds of kilojoules in a beam pulse. In this paper we describe the ribbon beam experiments carried out on the U-2 device at the energy in a storage about 200 kJ.

A schematic of the experiments is shown in Fig. 1. A megavolt pulse comes from a LC-generator to a steel holder

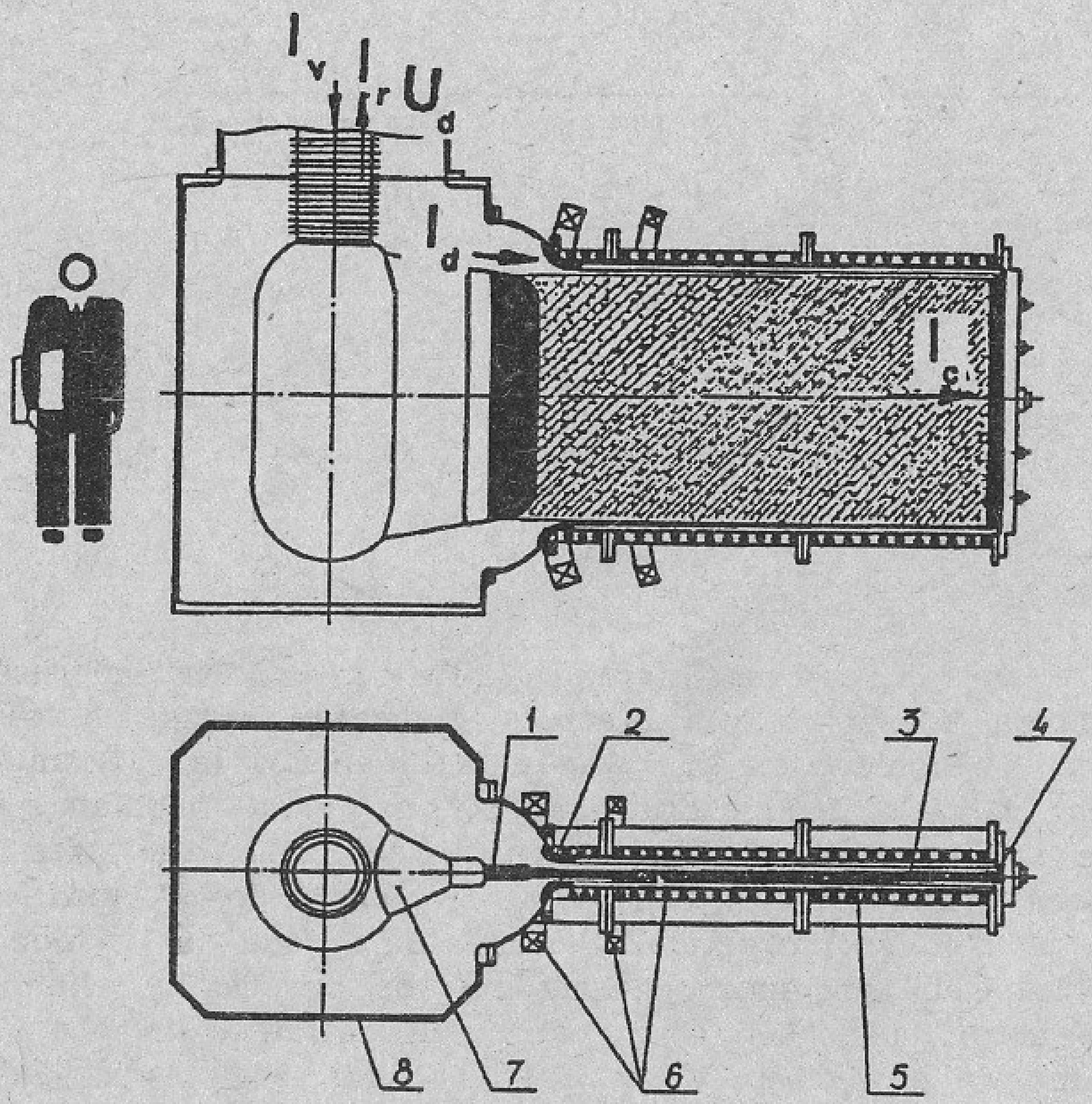

Fig. 1. Schematic of the ribbon beam experiment.

(7) which is placed in a vacuum chamber (8) and keeps a cathode (1). The strongly elongated cathode (1) made of KARBOTEXTIM (fibrous graphite material) has the length 140 cm and the width 4.5 cm. A slit with sizes 5·140 cm sawn in a graphite plate, is operated as an anode (5) of a magnetically insulated diode. An electron flow (3) emitted from the cathode, comes through the anode slit and passes to a vacuum channel with dimensions 6·145 cm. These dimensions are limited by walls of a copper liner (5). A residual gas pressure in the vacuum channel is about $5\cdot10^{-5}$ Torr. A special configuration of the computer design magnetic coils (6) gives a required structure of the magnetic field lines. The magnetic field strength in a homogeneous part of the transport channel may be varied from 0 to 1.0 T. The electron beam passing through the vacuum channel with the length 2 m, is absorbed by a graphite collector (4) operated as a calorimeter. A voltage on the accelerator diode U_d is measured by a resistive divider, input vacuum chamber current I_v and accelerator diode current I_d - by Rogowsky coils, calorimeter beam current I_d - by a shunt. Electrical energy and energy of the beam in various parts of the device are calculated by integration over the time of a product of the diode voltage and an appropriate current. In addition, the total energy of the beam at the exit of the channel is measured by the collector-calorimeter (4). This collector is divided in four sections and a temperature of each section is measured individually by thermocouples. A shape of the beam cross section is determined by an imprint of the beam on thin aluminum and titanium foils and plastic films.

The signals characterizing the microsecond ribbon beam generation and transport, and an imprint of the cross section shape are given in Fig. 2. First of all, we would like to point out that during all time of the beam generation all currents follow the time behavior of the diode voltage U_d. It points out that the ribbon magnetically insulated diode with so large sizes may be operated during 5-10 μs at the magnetic field about 0.5 T without any break-downs in the cathode-anode gap. A waveform of the diode resistance R is shown in Fig. 2. The second fact which can be seen on Fig. 2, is that the diode current I_d is close to the vacuum current I_v. Only a small part (about 3-4 kA) of the vacuum current is lost as a current I_r flowing through an active resistance of the high voltage insulator and as an electron leakage from the steel holder. The current I_r may be determined from the signal of the diode voltage U_d and a known resistance (r = 520 Ohm) of the high voltage insulator. The waveform of I_r obtained by this way, is also shown in Fig. 2 . A comparison of a sum I_d+I_r with the vacuum current I_v shows that the leakage current from high voltage electrodes are negligibly small. So small leakages have been achieved by a special adjustment of the .optimum geometry of the electrodes for decreasing of an electric field strength on their surfaces down to 50 kV/cm.

As far as a difference between the beam current I_c and the diode current I_d is concerned, it is more considerable (See Fig.2). Measurements of the beam parameters by the same graphite collector which has been used at the end of the channel, immediately after the anode slit have given the analogous result. The experiments have shown that the difference between these two currents essentially depends on a relative position of the cathode and the anode slit as well as on the configuration of the magnetic field lines. As a result of the experiments one can say that this difference is associated with a loss of some part of the beam in the graphite plate around the anode slit and there is no visible loss of the beam in the channel. The increase of the difference between I_d and I_c currents during the time of the beam generation may be explained by an expansion of a plasma generated on the cathode surface. The expansion of an electron emission surface leads to an increase of the thickness of the ribbon beam in the diode and as a result to the additional loss of the beam electrons in the graphite plate around of the anode slit.

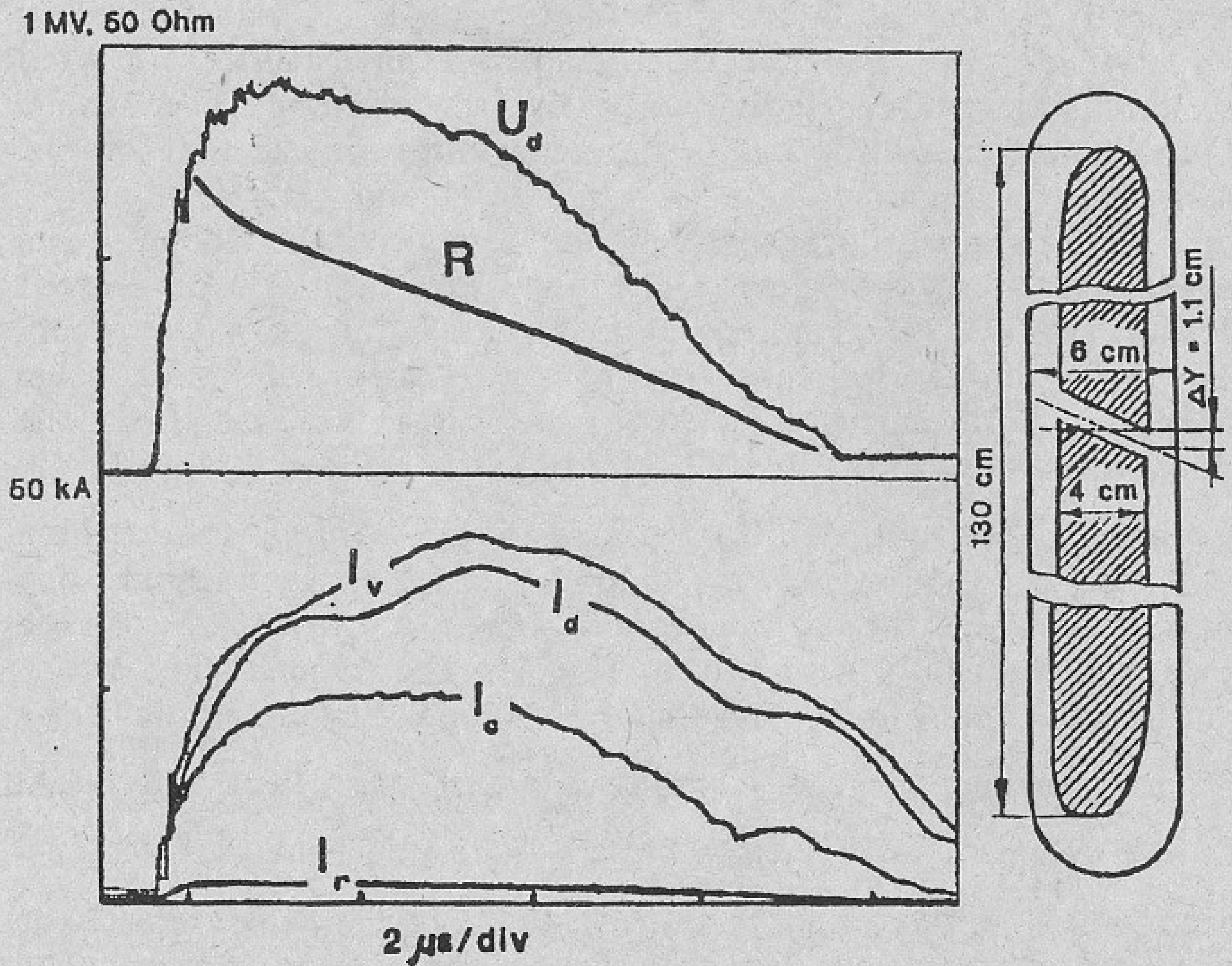

Fig. 2. Waveforms of the signals and imprint of the beam at the magnetic field in the channel B_0 = 0.7 T.

It should be pointed out that some error in the measurements of the beam current by virtue of the graphite collector is caused by the current from the collector to the liner through a plasma produced near the collector.

A gap between the electron beam and the walls of the vacuum channel is demonstrated by the imprint of the beam cross section shape in Fig. 2. A shaded region is the area where a 50 μm Ti-foil is melted down and evaporated. This beam shape practically coincides with one at the entrance of the channel. It confirms that the beam equilibrium is actually stabilized by the conducting walls and guiding magnetic field. Furthermore, in the central part of the imprint an inclined strip of the undestroyed titanium is clearly seen. This is a shadow of the graphite bar of the thickness 0.4 cm that has been deliberately placed at the distance ΔZ=65 cm upstream of the foil, perpendicularly to the channel wall. The fact that the shadow of the bar is turned with respect to the bar's orientation, indicates a presence of a drift motion of the electrons. A displacement of the band ends ΔY=1.1 cm allow one to estimate a factor f of a charge neutralization of the beam in the vacuum channel. Indeed, a perpendicular velocity of the electrons in the channel $\vec{V}$ is given by the following expression:

$$\vec{V} = (1-f)\,\frac{\vec{E}_b \cdot \vec{B}_0}{B_0^2}\,C + \frac{\vec{B}_b}{|\vec{B}_0|}\,\beta C\,,$$

where B_0 is a magnetic field strength in the channel, E_b and B_b are the self electric and magnetic fields of the beam, respectively, βC is the velocity of the beam electrons along the magnetic field lines. Taking into account the relation $\Delta Y/\Delta Z=|\vec{V}|/\beta C$ one may obtain $f=\frac{B_0}{B_b}\,\beta^2\,\frac{\Delta Y}{\Delta Z} + \frac{1}{\gamma^2} \simeq 1$. So, the charge neutralization of the beam is close to 100%.

As to an angular spread of the beam electrons it should be about 10^{-2} at the magnetic field strength in the diode B_d=0.5 T and decreases with an increase of the field strength [4].

To obtain an efficiency of the energy transfer from the capacitor storage to the beam the energies passing through the different parts of the U-2 device during the beam generation, have been compared. This comparison is shown in Fig. 3. When 72 capacitor banks of the pulse generator are charged up to the voltage U_c=43 kV they accumulate the electric energy Q_{pq}=185 kJ (shadow region). In this case the energy coming into the vacuum chamber, has a value $Q_v=\int I_v \cdot U_d \cdot dt \simeq$ 155 kJ (triangles), the energy picked out in the accelerator diode - $Q_d= \int I_d \cdot U_d \cdot dt \simeq$ 145 kJ (circles) and at least the energy of the beam measured by the calorimeter at the exit of the channel - $Q_c \simeq$ 115 kJ (crosses). As a result an efficiency of the U-2 device at the beam generation is the following: Q_v/Q_{pg} = 84%, Q_d/Q_{pg} = 78%, Q_c/Q_{pg}=62%. Value of Q_c/Q_{pg} may be somewhat increased by more accurate choice of the cathode-anode geometry and configuration of the magnetic lines. As to the total energy of the beam it will be increased by charging the capacitor

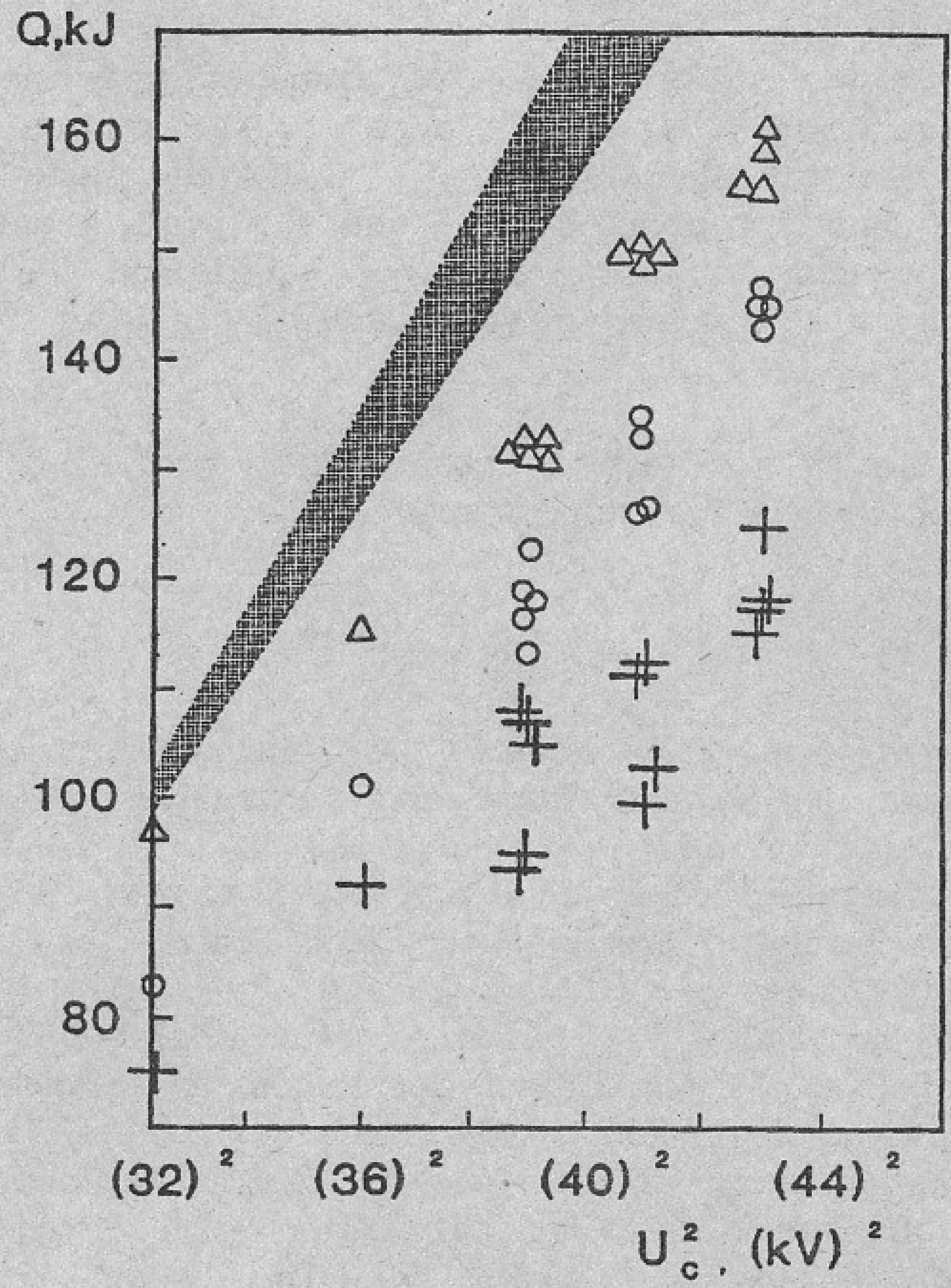

Fig. 3. Dependences of the energies passing through the different parts of the beam generator on the squared voltage of the storage capacitor banks. Shadow region shows the energy in the capacitor storage, triangles - in the vacuum chamber, circles - in the accelerator diode, crosses - at the end of the channel (B_0 = 0.7 T).

banks up to 48 kV and then more considerably by connecting to the operated pulse generator another one with the twofold energy content [5].

The main results of our experiments are the highly efficient generation of the large cross section ribbon electron beam in the magnetically insulated diode at the total energy content about 140 kJ and the beam transport in the slit vacuum channel at the equilibrium which is stabilized by the conducting walls and the guiding magnetic field.

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