High-CURRENT Electron Accelerator Based on Pulse Generator with Vacuum Insulation

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Abstract – This report presents description of the electron accelerator on basis of the powerful small-inductive pulse generator with vacuum insulation. Using of the generator with vacuum insulation allows simplifying considerably a design of the accelerator having excluded from it an intermediate store. The accelerator tests results and the experimental results on obtaining of the large cross-section ribbon beams with the \( \sim 500–700 \) keV electron energy are reported. Distinctive feature of the accelerator configuration for the ribbon beam generation is the cathode arrangement in parallel to the generator column axis. It is shown that in such configuration it is possible to receive practically homogeneous ribbon beam with the current density of 25 \( \text{A/cm}^2 \) and the cross-section of 25 \( \times \) 100 cm\(^2\).

1. Accelerator Design

The accelerator consists of pulse generator cylindrical column 1 with vacuum insulation relative to the walls and diode 2, placed in total volume (Fig. 1) [1]. The accelerator body consists of two dismountable cylindrical tanks with the internal diameter of 880 mm and the total height of 1850 mm. The generator column body is formed by metallic screens 3 divided by polyethylene insulators 4. The distance between screens and internal tank wall is equal to 155 mm. For uniform potential distribution along the column at generator switching, the screens have contacts with corresponding electrodes of the discharge cavities. The column body hermetization is reached by pressing of the metal screens having sharp edges in the polyethylene insulators by means of two glass-textolite studs. Internal accelerator volume is pumped by turbo-molecular pump up to the residual pressure \((2–5) \times 10^{-5} \) Torr.

The pulse generator is assembled on Marx’s scheme and consists of nine stages. Each stage consists of three specially developed small-inductive 0.16 \( \mu\text{F} \) capacitors with charging voltage up to 100 kV. The capacitor charging is made on the generator high-voltage side through the resistors \( R_1 \), and on the low-voltage side through the \( R_2 \) ones. The hemispherical switches electrodes, \( Sw_1 – Sw_6 \), are directly built in capacitors bodies and connected to their sections. This allows considerable reduction of the discharge circuit inductance. The gaps in the first stage switches, \( Sw_1 \), are formed by the cylindrical electrodes connected to capacitors and holes edges in the bottom flange. The inter-electrode gap of these switches is \( \sim 20 \) mm. For switches operation and generator insulation, inside the column the mixture of dry air with \( \text{SF}_6 \) gas composing from 30 up to 45% from the total amount is used. At the 1.2–1.4 atm mixture pressure, the generator operation range is 70–100 kV. All two-electrode generator switches operate in self-breakdown regime, and their triggering is carried out by the discharging cable shortening with the help of a multi-gap switch. Voltage withdraws wave initiates breaking down of the switch in the second generator stage. Thereafter other switches are operating due to over-voltage. Multi-gap switch triggering is provided by thyatron pulse scheme. Thyatron triggering is made by signal from standard generator GI-1.

Vacuum insulation application has allowed excluding an insulator on full output voltage. This gives essential reduction of the inductance between generator and diode. For accelerator testing, the quasi-planar
cathode in diameter ~ 50 cm is established directly on the generator last stage. The emitting cathode surface is made of velvet. The axially symmetric beam collector is the metal disk in diameter ~ 850 mm.

For obtaining of rectangular cross-section beam, the cathode lengthy side is oriented in parallel with the generator axis. The cathode is established on console 5 (the left part in Fig. 1) which is lowered downwards along the column axis, or on screen 6 (the right part in Fig. 1). Experiments are carried out with the cathodes of 71 cm or 93 cm length. The cathode emitting part in the width of 18 cm is made from velvet, or carbon-graphite felt. The anodes are plates with the dimensions of 25 × 94 cm² or of 35 × 112 cm². The radius of anode curvature is equal to 43 cm. The cathode console is curved similar to the anode. The divided anode consisting of six or eight collectors with the dimensions of 11(15, 19) × 25 cm² is applied for current distribution measurement along beam cross-section. The cathode-anode gap is changed from 44 mm up to 56 mm. For exception of breakdowns from cathode holder towards the generator body, the column moved upon 50 mm relatively to the accelerator axis.

2. Accelerator Testing

Determined in short circuit experiment, the generator inductance and the internal resistance are equal to 630 nH and 2.5 Ohm. The accelerator testing has shown that the diode current repeats the voltage pulse and reaches the peak value for ~ 200 ns (Fig. 2). The pulse duration reaches ~ 1.5–2 μs and is limited by the generator discharge time. Waveforms conformity of current signals from Rogovskii coils, \( I_1 \) and \( I_2 \), and the current shunt, \( I_d \), is evidence of leakage current absence from the generator column towards the vacuum chamber walls.

The diode peak voltage, \( U_d \), and the peak beam current, \( I_d \), depending on the charging voltage are shown in Fig. 3. The tests data are coordinated with the calculated dependencies for the diode impedance \( R_d = (3 - 3.5)\rho \), where \( \rho \) is the generator characteristic impedance. For insulation reliability checking, the tests are run by the raised diode voltage. For this the cathode-anode gap is enlarged up to 10.3 cm. Thus, the diode voltage reaches 800 kV with the current beam of 25 kA. The greatest beam energy is equal to ~ 17 kJ in the diode with the 7.2 cm gap, the accelerator efficiency factor is ~ 65%.

![Fig. 2. Voltage (a) and current (b)–(d) waveforms](image)

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![Fig. 3. Voltage (a) and current (b) peak values as a function of charging voltage. Generator with (3) and without (4) screen. Calculated dependencies for \( R_d = \rho \) (1) and 3.5\( \rho \) (2)](image)

![Fig. 4. Peak voltage as a function of charging voltage. SF₆ amount: 30 (1), 45 (2), 100% (3)](image)

![Fig. 5. Beam energy as a function of charging voltage square. SF₆ amount: 30(1), 45 (2), 100% (3)](image)

The generator operating regime essentially depends on switches mixture composition. At the SF₆ gas concentration increasing in the mixture from 30–
45% up to 100%, the delay time between triggering pulse and accelerator operation increases approximately about 100 ns. Simultaneously the diode voltage (Fig. 4) and the beam energy (Fig. 5) are decrease.

3. Ribbon Beam Obtaining

Discriminating feature of the accelerator configuration for ribbon beam obtaining is the cathode arrangement in parallel to the column axis. Such approach allows creating multi-modular installations for generation of radially convergent electron beams. However, at such configuration there is problem of electron magnetizing in the magnetic field of the diode current. The accelerating electrons are exposed to action of magnetic fields both the diode current and the current along the cathode, and the generator column current. This effect influences on the anode current density in longitudinal and transverse directions, and on angles under which electrons get to the anode.

The current measurements with the help of the sectional anode have shown that the strongest effect on beam structure has the magnetic field along the cathode. The beam structure essentially depends on power supply from the generator to the diode. When the cathode fastens on the generator screen, current to the diode flows from the internal, turned to the generator column, screen part mainly to the cathode bottom part. Electrons emitted from the bottom cathode part in crossed magnetic field, which is parallel to the short cathode dimension, and accelerating electric fields are drifted upwards. This leads to additional beam compression along the cathode length and suppression of electron passage on the bottom collectors. Current shape on the bottom collectors has thus more overextended flat top in comparison with the upper collectors currents which traces coincides with the total beam current waveform.

Magnetic field influence of current feeding to the diode is become apparent greatly in the experiments with the cathode lowered along the column by means of console. In this case, the power is supplied to the diode through the strip of 25 cm width which is equal to the transverse console dimension. At the 50 kA current in the cathode top part, the magnetic field of ~1.3 kG arises. Such magnetic field value approximately four times more than the accelerating electric field. It can provide conditions for electron magnetic self-insulation and occurrence of parapotential electron stream along the cathode [2].

The collector measurements data (Table) indicate that current passage is impeded on two-five collectors. Collectors numbering goes in the direction from top to bottom along the generator axis. Current crosses basically on the bottom collectors. Current waveforms from the middle collectors have characteristic shape with distinct current failure (Fig. 6). Such shape differs from the generator current discharge waveform. Current failure testifies to electron stream self-insulation in the region opposite to the cathode middle part. Trajectories curvature of the electrons, emitted from the top cathode part, due to drifting in crossed electric and magnetic fields leads to emission suppression of the middle cathode part. Current increase in the anode lower part is connected with drifting of electron stream part in parallel to the cathode with its subsequent eruption on the bottom collectors due to magnetic self-insulation destruction. Meanwhile, the beam autograph has very non-uniform irregular form with intensive influence marks in the bottom part.

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<th>Table. Collectors currents, kA</th>
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1 – console \( l = 102 \text{ cm}, d = 45 \text{ mm} \),
II – console with ribs, \( d = 55 \text{ mm} \).

Fig. 6. Waveforms for fourth and fifth collectors. Console with (1) and without (2) ribs. Calibrating frequency is equal to 5 MHz

Magnetic field influence diminishing is reached by means of installation of the additional ribs connecting the generator potential electrode with the console. The ribs are denoted in Fig. 1 as \( a, b, c \). This is made for distribution of current feedback to the cathode. Thus, the collectors current waveforms becomes similar to the total diode current trace, the collector currents peak values are leveled (Table). The anode current density distribution becomes almost uniform (Fig. 7).

Fig. 7. Beam current density distribution

The current density is calculated by division of the collector peak currents into the beam irradiated collectors area which was determined from conformity of section anode arrangement with the beam autograph. The total collector current value has changed slightly despite of the accelerating gap increasing by 10 mm. In such a way, it is possible to receive practically ho-
mogeneous ribbon beam with the current density of \( \sim 25 \text{ A/cm}^2 \) and the cross-section of \( \sim 25 \times 100 \text{ cm}^2 \).

4. Conclusion
The developed high-current electron accelerator has demonstrated steady work in all available charging voltage range. Elimination of forming line in design simplifies the accelerator construction and made its rather attractive at operation and servicing. The accelerator efficiency reaches \( \sim 65\% \), the electron beam energy does \( \sim 17 \text{ kJ} \). The executed experiments have shown an opportunity of large-aperture ribbon beams obtaining along the accelerator body generatrices. It allows using it for multi-modular systems creation to obtain radially convergent electron beams.

References