Investigation of charge balance in ion accelerator TEMP-4M

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Abstract. The paper presents the results of a study on the balance of charge in accelerator TEMP-4M operating in double-pulse mode with resistance load and ion diode. Crucially, it was found, that during the switching there is no losses of accumulated charge. It means, that all accumulated charge transferred to the load. However when the charge is transferred from the Marx generator to Blumlein line the half of accumulated charge is lost. Calibration of diagnostic equipment showed a good agreement between the calculated and experimental values of voltage and current. It means, that our diagnostic system is correct for registration parameters of the ion accelerator.

A distinctive feature of the ion accelerators with self-magnetically insulated diode is that there is no need to use additional energy source for the creation of an external magnetic field. That’s why the efficiency of ion diodes with an external magnetic field is not more than 10-15%. The efficiency of energy conversion in self-magnetically insulated diodes will be determined by not only the efficiency of the diode, but the energy losses in the units of the accelerator. The aim of the researches is the analysis of the balance of charge in units of the ion beams pulsed generator and definition of the most significant channels of energy loss.

1. Experimental set-up and calibration of diagnostic equipment.

Investigations were conducted at the TEMP-4M accelerator [1, 2] set in a double pulse mode: the first pulse being negative (300–500 ns, 100–150 kV) and the second positive (150 ns, 200–250 kV). The accelerator consists of a capacitive storage—Marx generator, a nanosecond double forming line (Blumline line), and a vacuum ion diode with self-magnetically insulated of electrons and different.

The flowchart of the double-forming line of accelerator TEMP-4M is shown on picture 1.

![Flowchart of the double-forming line of accelerator TEMP-4M](image)

**Figure 1.** Flowchart of the double-forming line of accelerator TEMP-4M: 1 – main discharger (trigatron), 2 – the middle electrode, 3 – inner electrode, 4 – pre-discharger, 5 – airlock, 6 – cable delay line, R1 and R2 – resistance of the voltage divider and limiting resistor respectively.
The diode current and voltage were measured by a Rogowski coil [3], and a high frequency voltage divider, respectively. The shot-to-shot variation in the accelerating voltage for 100–200 pulses does not exceed 6–7% [4].

Analysis of the balance of the charge was made on the oscillograms of voltage and current, so the first stage of research was calibrated voltage divider and current sensors.

Figure 2 shows the results of the calibration of the voltage divider at the output of the double-forming line when the accelerator operating with resistance load resistive load - 40 cm long tube with an aqueous solution of K2CO3.

![Figure 2](image)

**Figure 2.** Experimental values of voltage (1, points) and current (2) on the output of Blumlein line and calculated values of the voltage (3, line)

Parasitic inductance of diode unit took into account in calculations (100 nH), which was determined in the short-circuit at the output of the double-forming line. The values of experimental and calculated voltage are in good agreement during the formation of the main voltage pulse and afterpulses. This confirms the correctness of measurement of current and voltage at the double-forming line output and the absence of parasitic leakage current in the diode unit.

2. Definition of capacity of Blumline line.

In the analysis of the energy balance in a double-forming lines we calculated energy in forming lines on the ratio \( E = 0.5CU^2 \). Therefore at the first stage of the research carried out calculation and measurement of the capacity of each forming line.

Actual capacity of Blumline line may differ from the calculated due to the error of calculation formulas, deviation of geometrical sizes along the length of the line, changes in the dielectric constant of water at high electric field intensity (70-80 kV/cm), etc. Therefore, the capacity of middle and inner lines were determined experimentally from the condition of balance of charge when Blumline line works in normal mode. While charging voltage of Blumline line was calculated by:

\[
U_{mg} = \frac{1}{C} \int I_{mg} \, dt; \quad (1)
\]

where \( U_{mg}, I_{mg} \) – charging voltage and current of DFL respectively, \( C \) – capacity of Blumline line.

Figure 3 shows the experimental and calculated values of the charging voltage of Blumline line[5].
Figure 3. Waveform voltage (1 point) and current (2) at the output of pulsed generator and the calculated value of the voltage at \( C = 16.5 \text{ nF} \) (3) and \( 30.5 \text{ nF} \) (4).

Before pre-discharger is breakdown \((t = 20 \text{ ns in Fig. 3})\) output voltage on pulsed generator coincides with the calculated ratio (1) with \( C = 16.5 \text{ nF} \). After the breakdown the parallel charging began in the inner and middle lines and output voltage of Marx generator (after completion of transition processes, \( t \approx 280 \text{ NS} \)) is equal with the calculated at \( C = 30.5 \text{ nF} \).

The capacitance value of forming lines can be determined experimentally from the analysis of transient processes for charging Blumlein line. To this end, the nitrogen pressure in both spark gaps has increased to levels above the pressure of self-breakdown. The equivalent circuit of the generator pulse voltage connected with Blumlein line is a serial oscillatory circuit, see figure 4.

![Figure 4](image)

Figure 4. The equivalent circuit of Marx generator + Blumlein line: \( C_1 \) - capacity of Marx generator, \( C_2 \) - capacity of middle forming line, \( L \) is own inductance of Marx generator, \( R \) is the resistance losses. The waveform of the current measured by Rogowski coil of Marx generator in mode without breakdown of dischargers (1 point) and calculated current of serial oscillations (2 line).

Current of nonsingular oscillations in a serial resonant circuit is equal to:

\[
I(t) = -I_0 \cdot e^{-\alpha t} \sin(\omega t)
\]  

(2)
где \( I_0 = \frac{U_0}{\sqrt{L/C}} \), \( \alpha = \frac{R}{2L} \), \( \omega_0 = \sqrt{(\omega_0^2 - \alpha^2)} \), \( \omega_0 = \frac{1}{\sqrt{LC}} \).

For the scheme on figure 4:

\[ C = \frac{C_1 \cdot C_2}{C_1 + C_2} \]

The best agreement between experimental and calculated values of the current of nonsingular oscillations obtained by \( LC = 9.3 \times 10^{-14} \), \( R = 4 \) Ohm, \( I_0 = 6.5 \) kA. These data help to determine the capacity of the middle forming line \( (C_m = 16.5 \text{ nF}) \) using the value of self-inductance of Marx generator obtained in the analysis of transient processes in Marx generator working in short circuit mode \( (L = 7.5 \text{ uh}) \). The obtained data allow us to calculate the reduction of tension in GIN for capacitors to discharge through the charging of resistance during charging double-forming line. The obtained data allow us to calculate the reduction of voltage in Marx generator due to capacitors discharging through the charging resistance during charging the Blumlein line. When the charging voltage of each stage 22.3 kV (for data Fig. 4) full output voltage of Marx generator (8 steps) must be 178 kV. Calculation of current of eigentones for a ratio (2) for these fig. 4 is executed at \( I_0 = 6.5 \) kA that there corresponds \( U_0 = 160 \) kV and a discharge of condensers for 10%.

To measure the capacities of the inner forming line the pressure was reduced in the preliminary gap. In this case current of a recharge of double-forming line is well described by a ratio (2) at \( C_2 = 16.5 \text{ nF} \) before preliminary gap is breakdown (\( t < 0.5 \) microsec) and \( C_2 = 30.5 \text{ nF} \) after breakdown, see figure 5.

![Figure 5](image)

**Figure 5.** The waveform of the current measured by Rogowski coil of high voltage pulsed generator operating in mode without breakdown of the main discharger (1 point) and calculated current of serial oscillations till the pre-discharger is breakdown (2 line) and after the breakdown (3 line). Curve 4 - current of Rogowski coil on output of double-forming lines after the preliminary discharger (first part)

Calculated and experimental values of the capacity of the internal forming line are the same. Middle forming line formed by body of accelerator and inner electrode. In the Blumlein line there is window for connection with Marx generator, therefore the experimental values of capacity of middle forming line there are less than calculated is executed.

**3. The analysis of balance of charge.**

At the first stage of researches calculation of an accumulated charge in Arkadyeva-Marx's generator on the following formula (2) was made:
\[ Q = C \times U \]  

(2)

Where \( C_{sp} = 50 \) nF, \( U = 300 \) kV.

Calculations showed that Marx's generator accumulates 15 mC.

Further the balance of a charge of Blumlein line was executed. Charge in Blumlein line counted by integration current from Marx generator to Blumlein line. Before the preliminary discharger is breakdown only inner forming line charging (\( C = 14 \) nF), so the charge in Blumlein line is equal to multiplication of capacity of the inner line on a charge voltage. After breakdown of the preliminary discharger, both forming line are charge. At the same charge in the Blumlein line is the multiplication of sum of two capacities (24 nF) on a charge voltage. The balance of a charge of double-forming line is shown on figure 6.

![Figure 6](image)

**Figure 6.** The oscillogram of a charge voltage of double-forming line (1), changing of a charge in Blumlein line at calculation for integral of charging current (2), multiplication of a charge voltage on capacity 14 nF (3) and 24 nF (4).

The figure shows, that in the double-forming line the stored charge is equal to 7 mC. Losses of charge during switching the dischargers was not observed.

At the last stage researches of balance of a charge during the accelerator operating on the diode were carried out. Researches are executed on the strip focusing diode with self-magnetically insulated [6]. The results of researchers are presented on figure 7.

![Figure 7](image)

**Figure.** 7. The oscillogram of a charge voltage of double-forming line (1), changing of a charge in Blumlein line at calculation for integral of charging current (2), multiplication of a charge voltage on capacity 14 nF (3) and 24 nF (4).
Conclusion.
The analysis of the balance of charge showed that double-forming line transmits the accumulated charge in a diode with a 100% efficiency, but a significant loss of charge occur during switching Marx generator. In this way, the main channel of loss of charge in the accelerator TEMP-4M is a Marx generator. Therefore, further work plan will be aimed at improving the transfer of charge from voltage impulse generator in the double line.

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