VOLTAGE INCREASE AT THE ACCELERATOR OF DIRECT ACTION BY SELECTION OF INDUCTION ENERGY STORAGE AND PLASMA OPENING SWITCH PARAMETERS

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The methods for determining the induced voltage based on experimental current oscillograms have been developed. Values of the voltage and current for the circuit of induction energy storage have been established to provide a maximum induced voltage. The effect of the charging voltage of the circuit of plasma gun and the number of guns on the voltage increase has been established. Optimal delay times between the switching on the voltages of plasma guns and the induction energy storage have been determined. The effect of the induction energy storage inductance and vacuum conditions on the voltage increase has been determined.

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INTRODUCTION

The direct-action electron accelerators with the inductive energy storage (IES) cell and plasma opening switch (POS) are used in the fields that require small overall dimensions and appropriate weight characteristics that ensure it maneuverability and the possibility of placement on moving platforms. A wide range of applications justify the demand for accelerators of this type and the global interest of scientists in such accelerators [1, 2].

The DIN-2K accelerator is a laboratory prototype of these system type. It is currently used for the study of electron beams, virtual cathodes, the combined effects of ionic and electron radiation on structural materials and other appropriate phenomena [3-12].

The induced in the IES with POS voltage due to plasma current interruption is the key factor providing the possibility for explosive emission from the cathode and, as a consequence, the electron beam. Thus, the determination of the factors influencing and enabling control of the value of induced voltage is an important task that ensures the successful implementation of many technological processes.

The objectives of this research are to establish the optimal ranges for parameters of the primary circuit of pulsed current generator and the plasma guns' circuit used by the high-current linear accelerator DIN-2K that guarantees the maximum values of the induced voltage.

1. DESCRIPTION OF THE SYSTEM OPERATION

The accelerator operation scheme with the main components and physical processes is shown in Fig. 1. The accelerator electrode system consists of a tubular cathode 1 with a diameter of 26 mm and a chamber wall 2, which is the anode. These are separated from each other by a high-voltage insulator 3. Plasma guns (PG) 4 inject plasma into the accelerator evacuated volume, forming a conductivity region with a density of about $n_e = 10^{13}…10^{14}$ cm^{-3}. On expiry of a set time, the current generator is triggered and the energy from it is feeded through the air discharger 5 to the accelerator electrode system. The pulse current generator (PCG) current I_{PCG} begins to flow through the plasma 6. A current-conducting channel 7 is formed. It moves in plasma towards the end of the cathode and according to calculations it has an S-shape [13-15]. The IES includes the coaxial accelerator chamber up to the POS plasma boundary 7, the PCG, the air discharger and connecting high-voltage cables (main circuit below). The change rate of the current in time determines the voltage multiplication factor, it can reach 1 kA/ns. During the POS operation, the plasma resistance is increased from 0.01…0.05 Ω by approximately two orders of magnitude, which results in an abrupt drop in current, but without a final violation of conductivity. The greater the current time derivative, the greater the induced voltage. A decrease in the IES inductance results in an increase in the main circuit current, and an increase of the rate of its change during the POS operation. The induced voltage is applied to the end of the tubular cathode and when its value exceeds 120…150 kV, the conditions appear for the formation of explosive emission and an electron beam 11, which forms a virtual cathode, propagating in the waveguide 8 and bypassing the metal grid 10. During its movement, the beam, interacting with the neutrals of the residual gas, ionizes them and, together with this plasma, moves to the walls of the waveguide and to the protective quartz glass 12 mounted in the plexiglass flange 13.

Thus, voltage multiplication is a determining factor for ensuring the sequence of many physical processes that have technological importance.

2. TECHNIQUE AND EXPERIMENTAL METHODS

Rogowski coils RB1 and RB2 were used for measurements of currents in the micro- and nanosecond time ranges (see Fig. 1).

The charging voltage of PGs was varying in the range of 6 to 20 kV. The charging voltage at the PCG was varying in the range of 20 to 45 kV.

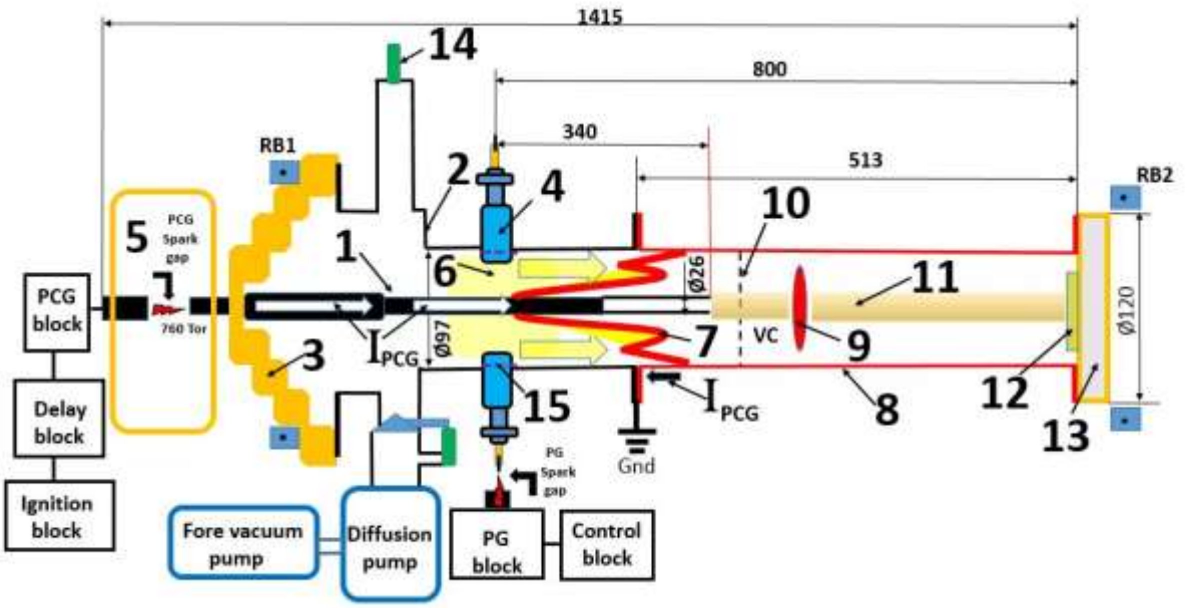

Fig. 1. DIN-2K electron accelerator schematic diagram. 1 is the tubular cathode; 2 is the grounded accelerator chamber body, anode; 3 is the vacuum insulator; 4 is plasma guns; 5 is the air gap; 6 is the POS; 7 is the S-shaped plasma current density in the POS [13 - 15]; 8 is the waveguide; 9 is the virtual cathode (VC); 10 is the anode mesh; 11 is the electron beam; 12 is the quartz protective glass; 13 is the plexiglass end flange; 14 is the vacuum tube; 15 is plasma guns; PCG is the pulse current generator; RB1, RB3 are Rogovsky belts

The induced voltage was determined based on experimental current curves. The calculation was made based on the change in current over time during the POS tripping. The beginning of the current decline and its termination allowed us to estimate the average values of the induced voltage, see Fig. 2, the section with a slope angle α1. Whereas, the flat sections with a sharper slope angle α2 allow us to estimate the possible maximum voltage values, which last for a much shorter period of time.

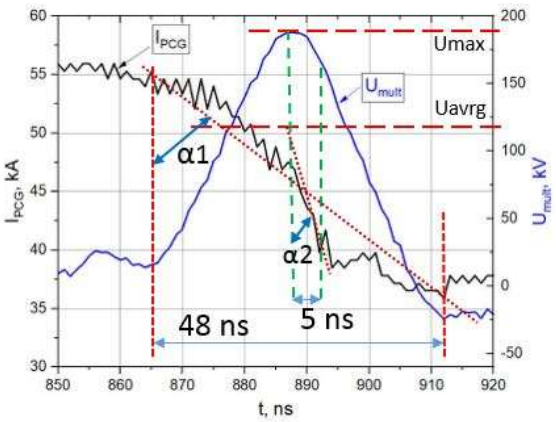

Fig. 2. The main circuit current dynamics in the POS operation time (current interruption time) and the calculated shape of the induced voltage curve

3. EXPERIMENTAL PART

To reveal the effect of the main circuit voltage (PCG charging voltage) on the POS opening rate, POS breaking current, POS opening time, voltage induced during the opening time, and voltage multiplication factor, all operating parameters were fixed. The plasma guns' capacitors were charged to 16 kV. The PCG was triggered with a delay of 3.6 µs. The vacuum conditions were not worse than $2 \cdot 10^{-5}$ Torr. The main circuit charging voltage was changed from 15 to 45 kV in steps of 5 kV. The pulses with fixed parameters were repeated at least 5 times. Figs. 3,4 shows the dependences of the main discharge circuit current dynamics for different PCG discharge voltages.

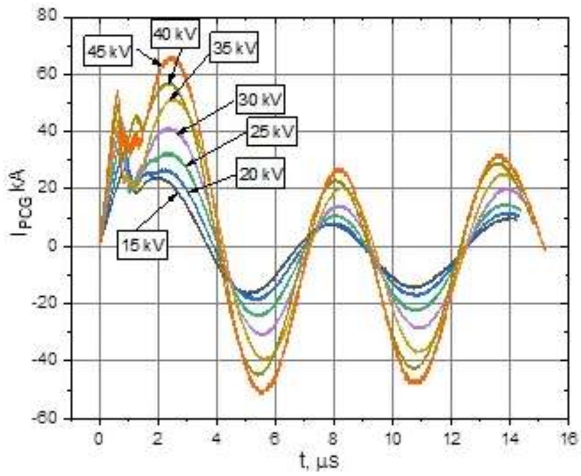

Fig. 3. Time dependence of the main circuit current for different PCG voltages

U_{PCG}/U_{PG} is a voltage on the capacitor bank of the PCG and plasma guns. The POS opening current is equal to ΔI, which is calculated by the difference between the upper and lower values of the current in the POS opening stage (see Fig. 4).

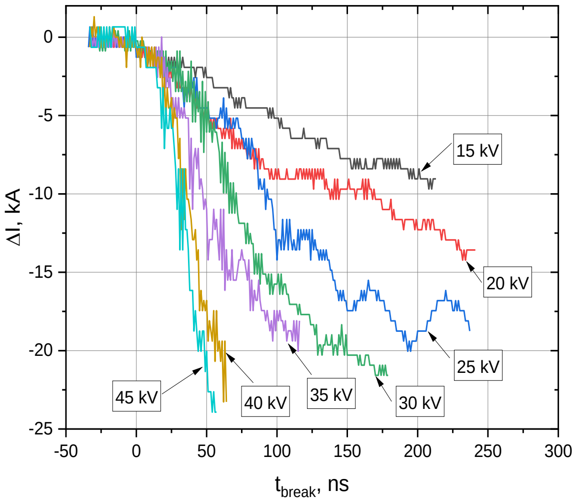

Fig. 4. Change rate of the POS current (in time of current interruption) for different PCG voltages

To do this calculation, a straight section of the current was chosen in the POS opening stage, where di/dt is maximum. ΔI kA is the value of the opening current, where di/dt is maximum. t_{break} is the opening time, where di/dt is maximum. $U_{average}$ is the calculated average induced voltage Ldi/dt and $k_{mult} = U_{average}/ U_{PCG}$ is the multiplication factor.

Representative current oscillogram at $5\cdot10^{-7}$ Torr is shown in Fig. 5.

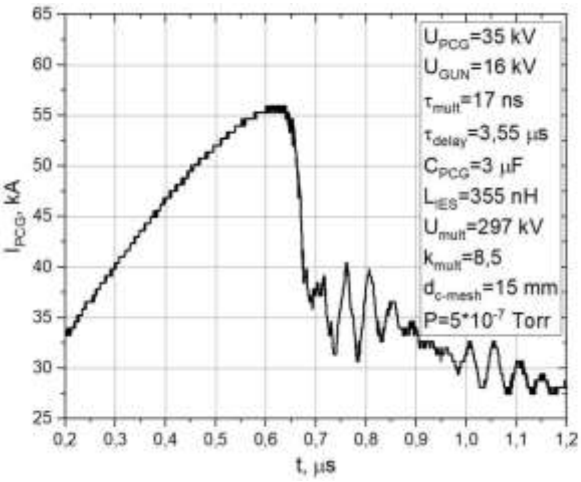

Fig. 5. Oscillograms of the main circuit current with the POS tripping

To obtain the maximum induced voltage, the parameters of the circuits are as follows: U_{PCG} = 47 kV, U_{PG} = 20 kV, delay time t_{delay} = 3.6 µs, p = $5\cdot10^{-7}$ Torr.

As can be seen from Fig. 6, increasing the charging voltage allows us to reliably obtain voltage multiplication factors k_{mult} = 6, and an induced voltage sufficient for the explosive emission from the cathode to take place.

Fig. 7 shows the dependence of the opening time of the POS on the voltage. The POS opening time is decreased significantly with an increase in voltage, according to the exponential tendency. Thus, at a voltage of 45 kV, the opening time is decreased almost threefold to 50 ns compared to that for a voltage of 15 kV.

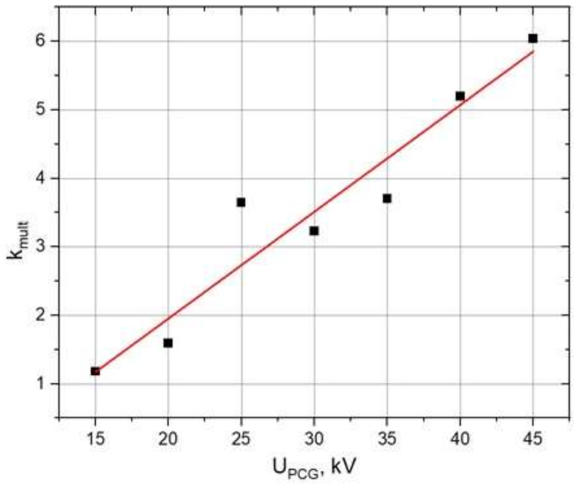

Fig. 6. Dependence of the multiplication factor on the main circuit voltage

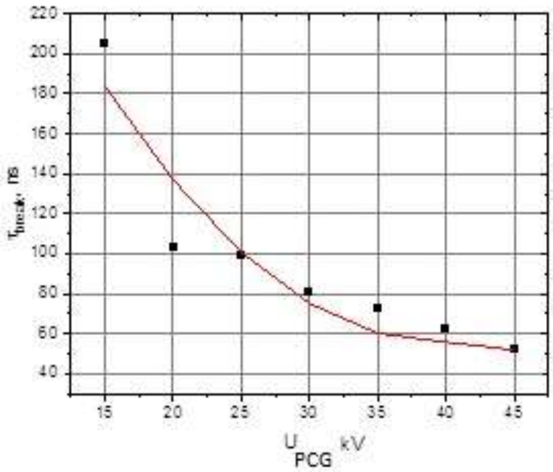

Fig. 7. Dependence of the POS opening time on the main circuit voltage

Fig. 8 shows that an increase in inductance due to the reduction of connecting power cables number (marked in Fig. 8 by 1, 2, ..., 6) results in an increased angle of inclination of the current on its decline during the operation of the circuit breaker and thus to a decrease in the induced voltage and the multiplication factor.

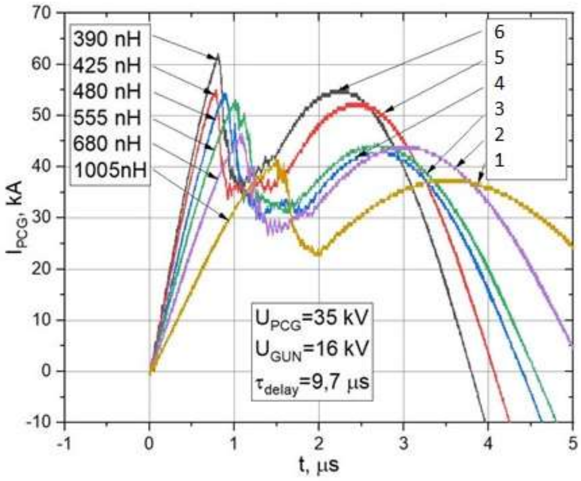

Fig. 8. The effect of inductance on the current value of the main circuit and the angle of the curve during POS operation

Fig. 9 shows a steady, almost linear decrease in the energy accumulation time, which is characterized by the front of an increase in the current of the main discharge circuit. A more rapid front reduction is possible due to an increase in the field strength both in the air discharger and in the coaxial system of the accelerator itself.

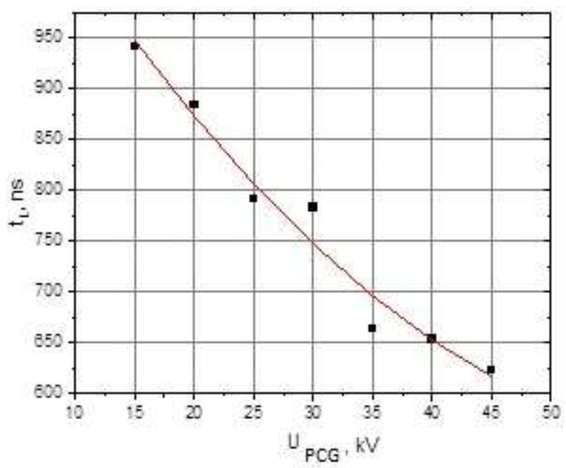

Fig. 9. Dependence of energy accumulation time on the charging voltage of the main circuit

Fig. 10 shows the dependences of the main circuit current during the operation of the POS on different values of the voltage on the plasma guns at a voltage on the PCG of 35 kV and other equal conditions.

Fig. 10 shows that the angle of inclination of the current curves during the tripping of the circuit breaker is almost the same for all values of the charging voltage except for 6 kV, which is indicative of the same values of the average induced voltage and the absence of a significant effect on the speed of the current tripping of the charging voltage of plasma guns.

Fig. 11 shows that the number of guns, their increase from one to six allows us to increase the amplitude of the main circuit current by 1.8 times. However, their number does not have a significant effect on the current change rate, except for the use of less than three guns.

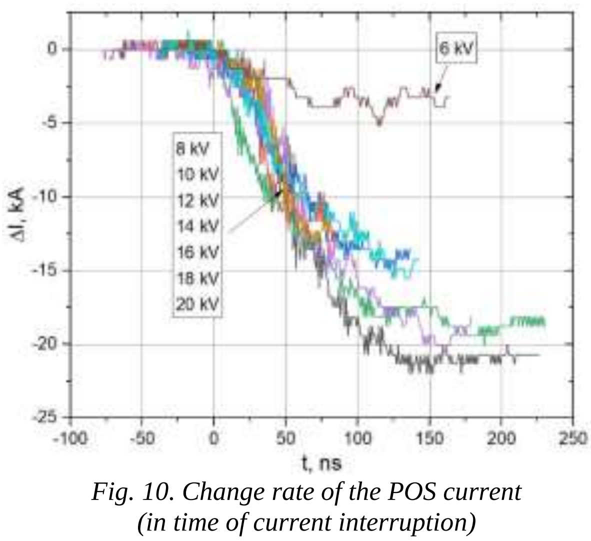

Fig. 10. Change rate of the POS current (in time of current interruption) for different plasma gun voltages

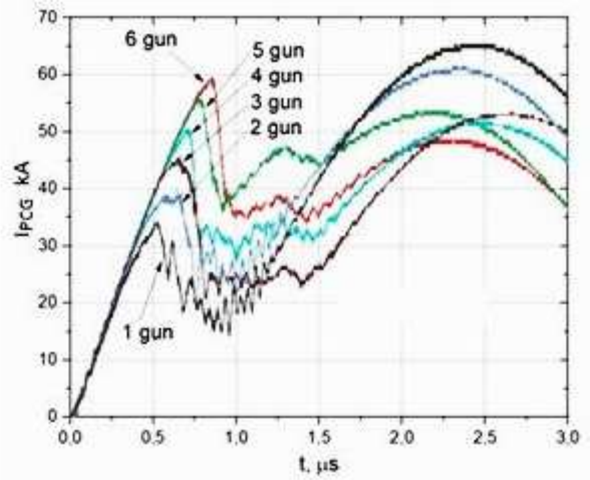

Fig. 11. Time dependence of the main circuit current for different plasma guns' number used to power the POS

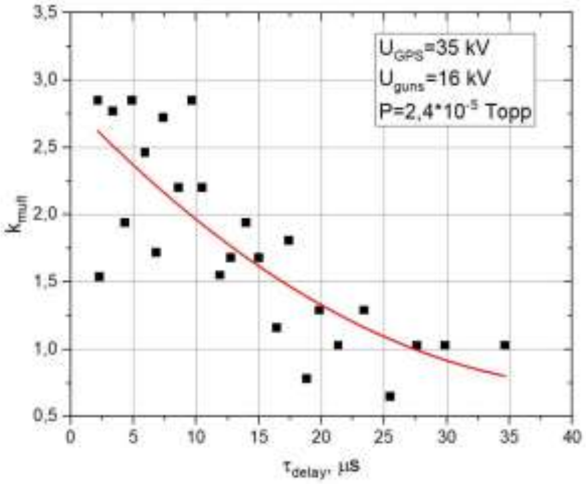

Fig. 12. The effect of delay time on the value of the multiplication factor

An experimental approximation curve of the influence of the delay time on the value of the multiplication factor was obtained, see Fig. 12. When changing the delay time between the operation of the plasma guns and the main discharge circuit of the PCG in the range of 2 to 30 μs with a step of 1 μs, it was determined that the highest multiplication factors are in the time interval not exceeding 10 μs.

CONCLUSIONS

The method of determinng the induced voltage from the current oscillograms during the operation of the plasma circuit breaker was improved using an increased resolution of the Rogowski belt integrator. Thus, it was possible to eliminate the need for the arrangement of the capacitive voltage divider plates in the internal volume of the chamber, which can be affected the studied physical processes.

A maximum multiplication factor is 8.5 at a voltage of the main circuit of 35 kV. In this case, the maximum currents of the main circuit are varied in the range of 70 to 100 kA, the POS opening currents are equal to 30 kA, and the induced voltage is 297 kV.

It has been established that it is possible to obtain the values of the induced voltage that will definitely result in the explosive emission and formation of an electron beam current exceeding the critical vacuum current by increasing the voltage of the main circuit and selecting the optimal voltage values of the circuit that feeds the plasma guns.

From the point of view of obtaining the maximum induced voltage, the optimal parameters for DIN-2K IES with POS are U_{PCG} exceeding 35 kV, U_{PG} = 20 kV, delay time less than 10 μs, and the vacuum not worse than $1\cdot10^{-5}$ Torr.

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