PLASMA DYNAMICS IN ACCELERATOR WITH PLASMA OPENING SWITCH

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Plasma propagation in the pulse electron accelerator chamber with a plasma opening switch is investigated. Output beam and X-ray radiation parameters are shown to vary depending on the plasma channel location at the moment of current breaking. Experiments showing plasma compression into channels during the conductive phase of the plasma opening switch operation have been performed.
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INTRODUCTION

Accelerators with inductive energy storage and plasma current interrupters are used to build terawatt power sources with pulse width of 10…100 ns [1].

Energy density of inductive storage is tens of times higher than that of capacitance storage which is a decisive advantage of such schemes. Plasma opening switch (POS) is a main element of them. In this paper we consider the role of POS's plasma.

1. EXPERIMENTAL SETUP

Experiments were conducted on the DIN 2K accelerator [2, 3]. Current through the POS reached 20 kA with acceleration diode voltage estimated up to 300 kV when the IKM-50 capacitor was charged to 25 kV and the circuit inductance was 250 nH. Before the current interruption POS resistance reached about 0.4 Ω.

Fig. 1 shows the accelerator layout. Two Rogowski coils (RC) (2 and 5) are placed at either side of the plasma gun assembly (4). After the circuit powering plasma guns is turned on, RC 2 measures the total current through the accelerator chamber while RC 5 measures only the current that goes through the front section of accelerator chamber.

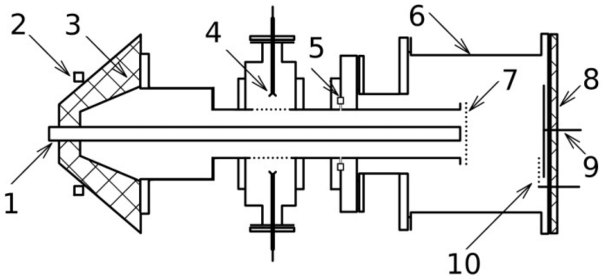

Fig. 1. Experimental setup:
1 – cathode; 2, 5 – Rogowski coil; 3 – insulator; 4 – plasma guns; 6 – device frame; 7 – grid anode; 8 – PMMA flange; 9 – collector; 10 – grid electrode for measuring plasma velocity

Fig. 2 shows the movable anode assembly which enables changing anode-cathode distance with 0.1 mm accuracy. By turning the handle 5, the mesh anode 1 can move in axial direction both ways in relation to PMMA flange 2 of accelerator's vacuum chamber. Copper laminated fiberglass-epoxy collector 4 and a steel mesh electrode for plasma velocity measurements 3 are situated on the flange 2.

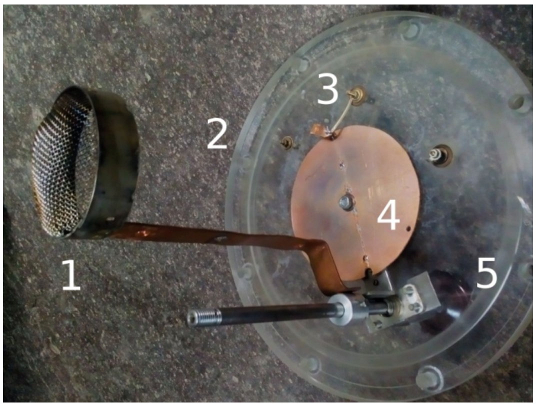

Fig. 2. Movable anode assembly

Vacuum diode impedance Z depends on the distance between anode and cathode d as: $Z \propto d^2$. It is imperative to match impedances of the current generator and diode in order to get the highest voltage multiplication possible.

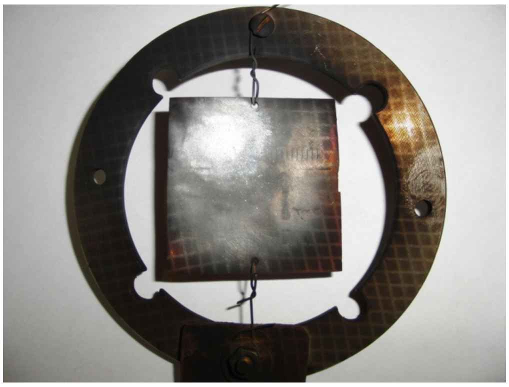

Fig. 3. Electron beam imprint on the collector

Fig. 3 shows an imprint of electron beam that passed through the mesh anode on a collector.

The plasma gun module is an important part of the accelerator construction. Plasma properties in the accelerator vacuum chamber must allow for POS current interruption at the amplitude of the current pulse with the highest rate possible.

Surface breakdown plasma guns were used in many studies including those conducted on DIN 2K accelerator (Fig. 4).

Fig. 4. Surface breakdown plasma gun

However after multiple breakdown discharges the copper layer evaporates. Breakdown distance increases and plasma guns go out of order. To avoid it, coaxial plasma guns (Fig. 5) based on Rk-50 cable were made which ensured stable operation of the plasma gun module.

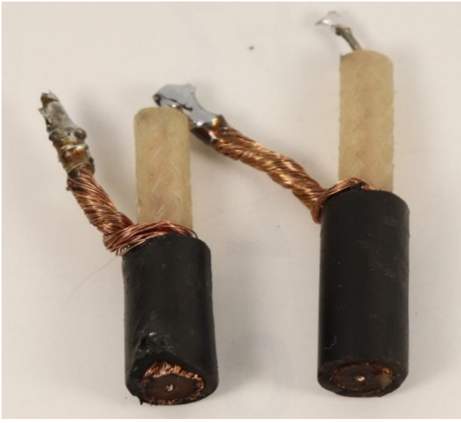

Fig. 5. Coaxial plasma guns

A concentric breakdown gap during the discharge generates plasma with the concentration up to 10^{13} 1/cm^3.

On the accelerator output a copper laminated fiberglass-epoxy 10 cm disc collector was installed (see 9 on Fig. 1). Distance between the central plane of the plasma gun module and the collector plane was 54 cm.

12 plasma guns were evenly placed along the circumference of the accelerator chamber 2 cm from the coaxial line anode mesh. Pulse current generator (PCG) fires a few microseconds after the synchronized firing of plasma guns. Electric current goes through plasma and the energy stored in PCG capacitor is pumped into the vacuum coaxial line inductance. This process goes on until the critical current [4] is reached:

$$I = 1.36 \cdot 10^4 \cdot \sqrt{\gamma^2 - 1} \cdot r / x,$$

where $\gamma = 1 + 1.96 \cdot 10^{-6} \cdot U$, U is the PCG voltage, r is the cathode radius, and x is the erosion gap.

When the number of charge carrying particles in plasma becomes insufficient to support the current a break in the plasma switch occurs. Its resistance grows with the rate of $10^8 \ldots 10^9$ Ω/s. This creates a high voltage pulse $U = -L \cdot \dfrac{dI}{dt}$ on the cathode leading to explosive electron emission. Electrons then undergo acceleration in the vacuum diode electric field and form a beam which goes through the anode mesh hitting the target (see Fig. 3).

2. EXPERIMENT RESULTS

Fig. 6 shows a number of current interruption oscillograms. It is evident that after about 1μs the current increasing through plasma drops rapidly. This generates a voltage pulse about 100 ns long. Then the plasma bridge reestablishes itself and PCG capacitor discharge continues. The rate of resistance increase $\dot{R}$ is deduced from the slope of current drop when it is interrupted.

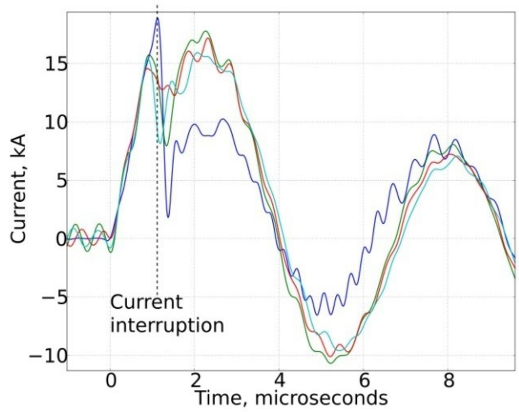

Fig. 6. Current interruption oscillogram

When the plasma bridge is formed it inflates and fills the whole vacuum chamber. After PCG fires, the plasma bridge moves in crossed electric and magnetic fields as the current through it grows accelerating in the load direction and pinching into a filament. This leaves a definite arc spot trace on the cathode surface (Fig. 7) and causes cathode material to sputter adding to plasma in the accelerator chamber.

Fig. 7. Arc spot traces on the cathode

Mesh electrode 10 (see Fig. 1) was placed on the butt flange 8 in front of collector 9 for plasma velocity measurements. This electrode, the collector and a charged high voltage capacitor attached to them, formed a plasma sensible circuit. Current signal was generated in this circuit when the gap between electrode 10 and collector 9 was filled with plasma. Plasma propagation time was measured from the moment of plasma guns discharge to the appearance of signal in the plasma sensible circuit. Plasma inflation speed turned out to be 7.3 cm/μs.

Fig. 8 shows an oscillogram of currents picked up by Rogowski coils.

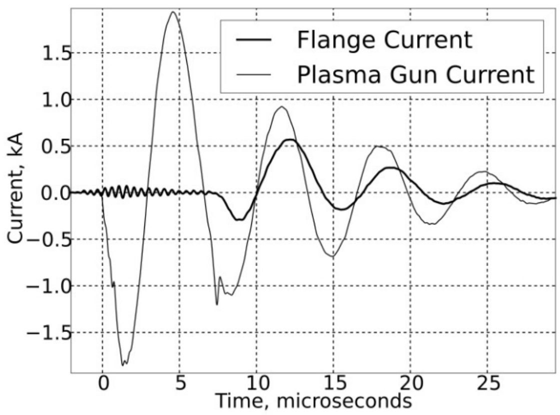

Fig. 8. Plasma gun current and plasma sensible current oscillograms

A pulse of positive voltage up to 100 V in amplitude was observed on the cathode used as the collector (without firing the PCG) after plasma guns power supply capacitor discharged. It might be attributed to heavy ions arriving on the collector (Fig. 9).

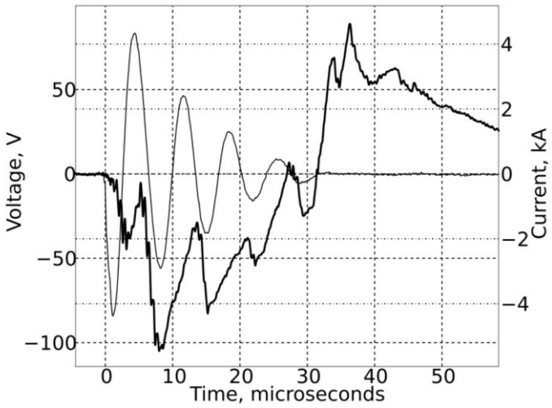

Fig. 9. Collector signal

Fig. 10 shows the relation of output X-ray radiation to diodes parameters. Accelerator parameters were: PCG charge voltage was 25 kV, PCG current amplitude was 20 kA. An optimum diode gap was 5 mm. Delay time between firing plasma guns and PCG was 5 μs.

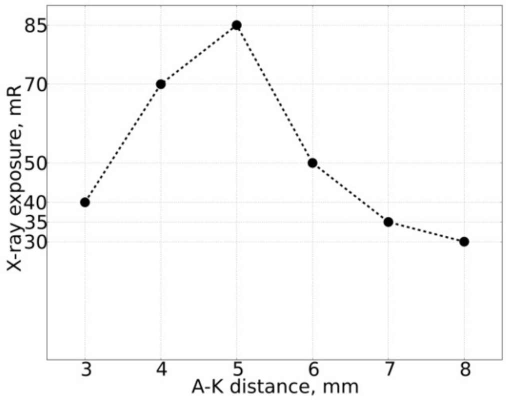

Fig. 10. X-ray dose against cathode-anode distance

Delay time also plays an important role in the accelerator operation because plasma bridge parameters are time-dependent. Fig. 11 shows the output X-ray dose relative to delay time without changing other accelerator parameters.

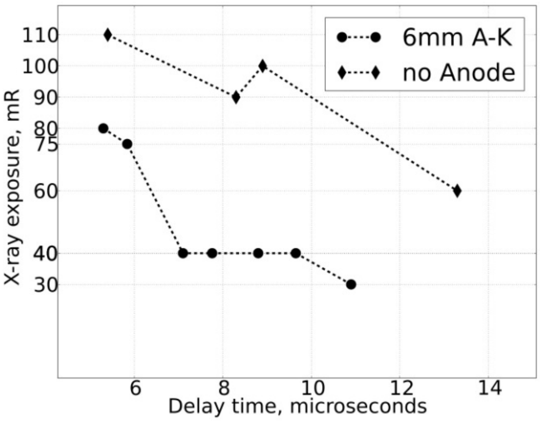

Fig. 11. X-ray exposure against delay time

Doses of X-ray radiation obtained when the cathode-anode distance was 6 mm are marked with circles. Diamonds mark X-ray doses obtained when there was no anode mesh present.

Different modes of operation possible for the accelerator depending on plasma bridge placement in the chamber are theoretically studied in [5].

1. Plasma bridge itself is the PCG load. I. e. The load in form of an axial diode is absent. In this case peak voltage of $V = I \cdot \sqrt{\frac{\dot{R} \cdot L}{e}}$ is reached during current interruption and the power sent into the load is maximum $p = \sqrt{\frac{\dot{R} \cdot L}{2 \cdot e}} \cdot I^2$, here I is PCG current, $\dot{R}$ is the growth rate of the plasma switch resistance L is the cathode inductance, e is Euler's number. On the output of DIN 2K accelerator, X-ray radiation of 100…110 mR per pulse was recorded in this mode of operation.

2. The switch opens while dividing cathode in two parts (Fig. 12).

Fig. 12. Cathode spots traces left on the middle of the cathode after plasma bridge breaking

If the inductance values of parts are equal, L1=L2, the maximum voltage on the POS is 1.4 times lower than in the case 1 and the diode pulse power is:

$$P = 0.13 \cdot \sqrt{L_1 \cdot \dot{R}} \cdot I^2 .$$

In this mode 60…70 mR/pulse was recorded on the output flange.

3. In case when the plasma bridge breaks on the end of the cathode (see Fig. 8) voltage pulse amplitude is 1.5 times lower, than in the case 1. X-ray dose registered was at about 60 mR/pulse.

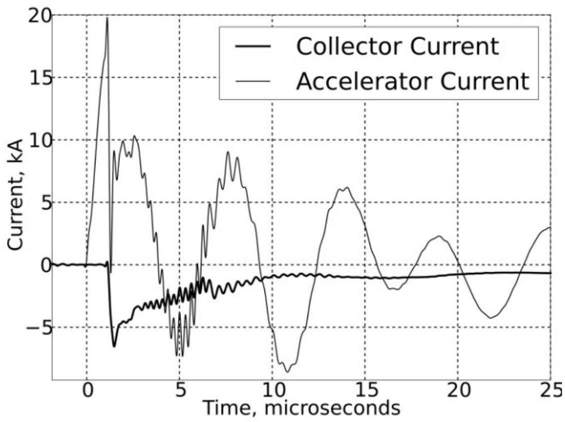

Fig. 13. Accelerator current oscillograms when the diode is filled with plasma

4. If the diode is filled with plasma when the POS is opened explosive electron emission causes the electron beam to form. But then emission from the plasma continues and the beam current is registered by the Rogowski coil in the span of a few microseconds

(Fig. 13). I. e. nanosecond accelerator emits microsecond electron beam pulses. If the diode is not filled with plasma, electron beam pulse is less than one microsecond long.

Therefore accelerator output parameters change depending on the plasma bridge placement in the accelerator coaxial line during its breaking and on the delay time between plasma gun and PCG firing.

Plasma properties and its composition influence the POS speed of opening and need further study.

CONCLUSIONS

Reliable POS opening parameters were found.

Plasma bridge compression into current channels and cathode surface evaporation from cathode spots adding metallic plasma into accelerator chamber was observed.

Dependence of accelerator output parameters on plasma bridge placement in the accelerator vacuum chamber is illustrated with experimental data.

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ДИНАМИКА ПЛАЗМЫ В УСКОРИТЕЛЕ С ПЛАЗМЕННЫМ ПРЕРЫВАТЕЛЕМ ТОКА

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Рассматривается влияние на работу ускорителя распространение плазмы в камере импульсного ускорителя электронов с плазменным размыкателем. Показано, что в зависимости от положения плазменной перемычки в момент размыкания меняются параметры выходного пучка и рентгеновского излучения. Экспериментально показано сжатие плазмы в токовые каналы в фазе проводимости работы плазменного размыкателя тока.

ДИНАМІКА ПЛАЗМИ В ПРИСКОРЮВАЧІ З ПЛАЗМОВИМ ПЕРЕРИВАЧЕМ СТРУМУ

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Розглядається вплив на роботу прискорювача поширення плазми в камері імпульсного прискорювача електронів з плазмовим розмикачем. Показано, що в залежності від положення плазмової перетинки в момент розмикання змінюються параметри вихідного пучка та рентгенівського випромінювання. Експериментально показано стиснення плазми в струмові канали у фазі провідності роботи плазмового розмикача струму.