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Plasma opening switches in the inertial confinement fusion programs

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The research of the plasma opening switch (POS) operating in an externally applied magnetic field first proposed in 1986 in the Kurchatov Institute to sharpen the powerful pulses of inductive storage generators has demonstrated certain advantages over the plasma switches using only the generator current for the magnetic insulation. Externally applied magnetic field, which additionally magnetically insulates the POS gap helps to obtain maximum switching voltage and effective generator current interruption. It allows using a compact plasma crosspiece with a low expansion velocity toward the load. This approach is proposed for the *Baikal* generator (80 MA, 10 MV at the output) being a part of the Russian ICF program and also for other applications [1]. In our previous research, we introduced several methods of POS parameters evaluation [1,2] and of the POS and liner matching [3].

In the present report, the results obtained at the RS-20 generator [4] to prove the viability of the proposed concept to improve the POS effectiveness are demonstrated.

One of the important characteristics of the POS is its voltage in the switching state obtained in the open circuit regime with no load connected to the POS. In the experiment the energy of the inductance of the RS-20 (280 kJ) is deposited in POS electrodes within 100 ns, that constitutes high energy and power densities of 300 J/cm^2 and $3 \cdot 10^9$ W/cm^2 respectively.

A primary Marx type energy storage of the RS-20 (Fig.1) can use variable number of in-series and parallel stages producing same charge and current at the output. Experiments were performed with output voltages 360-840 kV. With 840 kV the POS can achieve 3 MV at the switching. The POS voltage measurements employed a photo-nuclear method to measure the short-wavelength border of the Bremsstrahlung spectrum to determine the energy of the electron beam striking the POS anode [5].

POS evaluation [2] is based on limitations of the POS performance established after many experiments, such as specific charge density transferred through the POS during the conduction phase $q_{s.}= (3\text{-}5)\ mK/cm$, charge density per plasma injector $q_{s.}=(5\text{-}7)\ mK/gun$ and a velocity of a longitudinal plasma expansion in the externally applied magnetic field $v_z \approx 10^6$ *cm/s*.

POS voltage is also depends on the energy density w_i, spent on ion acceleration in the POS (plasma erosion): $U_{POS} \propto w_i^{4/7}$. Note, that in the open circuit regime the voltage is maximal and can be estimated by an empiric equation:

$$U_{POS}(MV)=3.6[U_{Marx}(MV)]^{4/7} \quad (1)$$

The magnitude of the externally applied magnetic field needed for magnetic insulation of the POS is also empirically determined by a condition:

$$B_Z \geq 2max\{B_\varphi, B_c\}, \quad (2)$$

where B_φ is the magnetic field of the current and B_c – is the critical magnetic field.

For the given POS switching voltage the width of the electrode gap is determined as $\Delta R \geq U_{POS}/E$, where $E \approx (0.5\text{-}1)\ MV/cm$ – electrical field in the POS gap. With maximum Marx voltage (840 kV) POS dimensions are: $\Delta R=3\ cm$, $B_Z=1.6\ T$, number of plasma guns $N=78$, current amplitude in each plasma gun I_g=4 kA, and U_{POS}= MV in the open circuit regime.

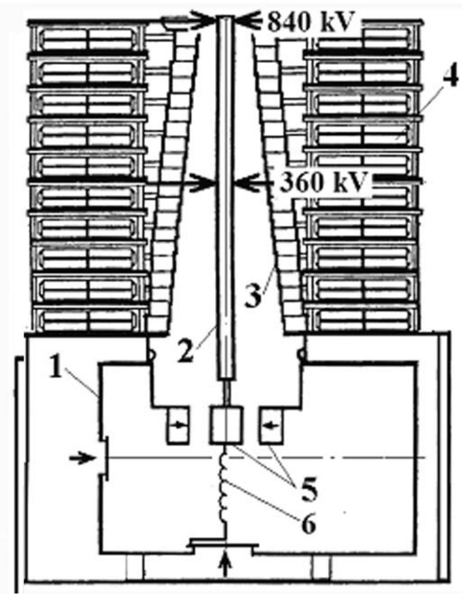

FIG.1. RS-20 generator, 1 – vacuum chamber, 2 – current drive, 3 – insulator, 4 – Marx, 5 – POS, 6 – load.

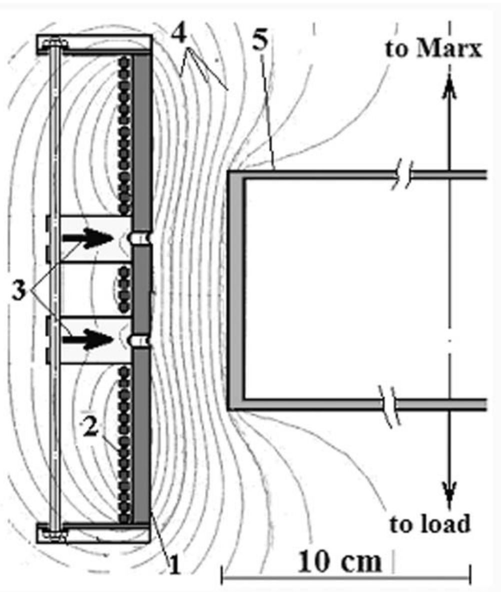

Fig. 2. POS scheme, 1–cathode, 4-solenoid, 5-plasma guns, 6 – magnetic field lines, 7 – anode

Experiments were performed both (i) in the open circuit regime and (ii) with the inductive load. In the latter case several inductances (L_{load}) were employed: $L_{load}/L_0=\{1.23, 0.92, 0.32\}$, being $L_0 = 1.62\ \mu H$ - the inductance of the electric circuit “Marx generator - POS”. To understand the characteristics, the POS input/output currents and POS voltages were measured.

Fig.3. is an integral photograph of the POS gap. It illustrates that plasma expands at short distance beyond the end of the cathode. Fig-4 illustrates the integral photo of uniform plasma luminescence during the current transfer through the POS. The orange line is an incandescent inductive load stainless steel wire conducting the load current.

Fig.5. illustrates typical waveform of current and voltage signals of the POS. The voltage in the open circuit regime is $U_{POS}=1.9\ MV$, with Marx voltage $U_{Marx}=0.36\ MV$ (fig. 5-a) ; $U_{POS}=3.2\ MV$ with $U_{Marx}=0.84\ MV$. The voltages were measured by the high-voltage monitor and verified with the photo-nuclear method. These results correspond to the Eq.(1) (see also points 1 and 2 in Fig. 6).

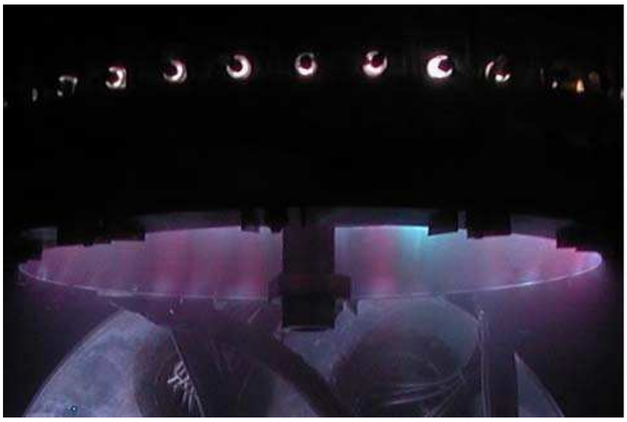

FIG. 3

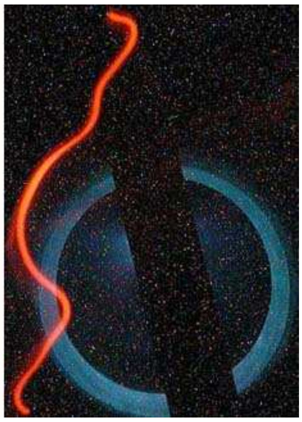

FIG. 4.

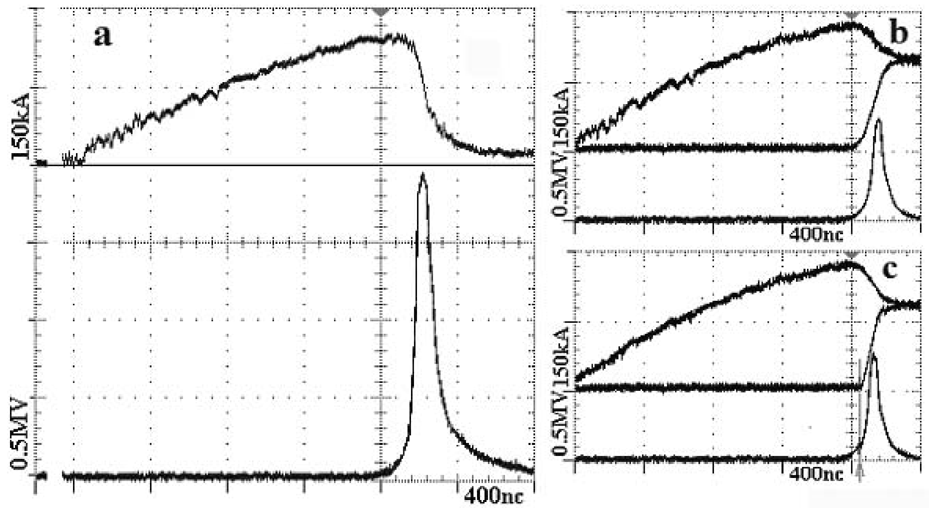

FIG. 5 signal waveforms, a – open circuit, b – current switching to the load $L_H=0.32L_0$, c – current switching to the load with separating switch.

For POS matching with the liner load it was proposed to use intermediate inductance or the separating vacuum closing switch placed in the load circuit [2, 6]. If the impedance of the liner remains low during the switching time then the L_i plays a role of the load and all energy deposited in the L_i can be transferred to the liner. The results of circuit simulations and the corresponding experimental points are shown in Fig.7. One can see a good agreement of calculated and experimental values of the electromagnetic energy pulse parameters. Note, that use of a separating switch (being a vacuum 1 mm wide gap between two point-to-plane electrodes [3,6]) is advisable with low load impedances.

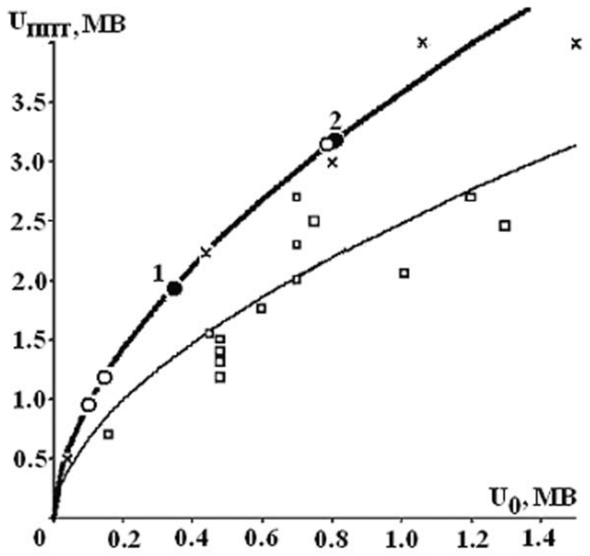

FIG. 6. Dependence of U_{POS} on U_{Marx} . Top curve (×,○,●) – for the POS in applied magnetic field, bottom curve (□) - for the experiments without magnetic field. Points «●» (1, 2) were obtained at RS-20, points «○» were obtained in the previous experiments.

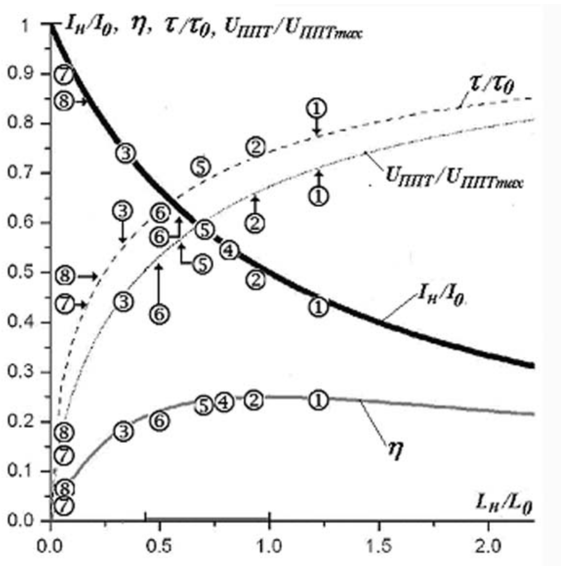

FIG. 7. Calculated and experimental values of the I_{load}/I_0, $\eta=L_{load}I_{load}^2/L_0I_0^2$, current front τ/τ_0, POS voltage ratio U_{POS}/U_{POSMax} as functions of arbitrary load inductance L_{load}/L_0.

Fig.5 (b)-(c) illustrate an influence of the separating switch when $L_{load}/L_0=0.32$. The moment of the separating switch triggering is shown with an arrow in Fig. 5 (c). One can see that the switch removes the a slowly rising part of the current front in the load having approx. 50 ns duration so that the amplitude of the current transferred to the load decreases 10%.

The experiments demonstrate that the scheme of the POS parameters evaluation proposed in [1, 2] is consistent and provides enough precision for practical needs. POS matching with the liner type low impedance load [3] is based on the use of a low-inductance load, which works as an inductive storage feeding the liner. The method to evaluate the parameters of the electromagnetic pulse transferred to the load produces results close to the experimental measurements. The liner can be driven with approximately 25% of the primary energy storage energy with duration of the current front in the liner being in the range of 100-150 ns (which is typical for liner experiments).

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