FREQUENCY PLASMA OPENING SWITCHES AND THEIR
APPLICATION IN THE TECHNOLOGY OF HIGH-POWER
ACCELERATORS

N. U. Barinov, G. S. Belen'kii, G. I. Dolgachev,
L. P. Zakatov, M. S. Nitishinskii,
and A. G. Ushakov

UDC 621.316.543

The main results reported here were obtained in a cycle of studies on plasma opening switches (POSs) and their application in frequency-pulse accelerators; those studies were carried out at the Russian Research Center, Kurchatov Institute from 1986 to 1997. That research was the basis for the development of frequency-pulse generators based on POS technology for quasi-constant generation of an electron beam and bremsstrahlung radiation. Several generators have been built for use in commercial radiation processing technologies. We give the parameters and basic circuit designs and discuss the prospects for further development of generators using POSs. The competitiveness in comparison with existing accelerating systems is examined.

INTRODUCTION

Effective peaking of the power of high-current pulsed voltage generators (PVGs) by means of plasma opening switches (POSs) [1] has led to high-power x-ray generators [2] that operate in a single-pulse mode as well as frequency-pulsed electron-beam and bremsstrahlung generators for production technologies [3]. Experiments on the development and applications of POSs were undertaken at the Russian Research Center, Kurchatov Institute in 1986 and were subsequently continued on a number of installations. The parameters of those installations had the following ranges: conduction time $t_{con} \sim T/4 = 0.6-5 \mu$sec, PVG voltage $U_0 = 0.04-2$ MV, amplitude of current in the PVG-POS circuit $I_0 = 40-400$ kA, wave resistance of the circuit is $\rho = 0.2-20 \Omega$, and the load ranged from low-inductance $L \sim 0.1L_0$ (where $L_0$ is the inductance of the circuit) to high-resistance $R \sim 3-10 \rho$, including the "no-load" mode $R \gg \rho$.

The various POS circuits were compared by using the following main indicators of the quality of their operation:
- voltage multiplication factor $k = U_{POS}/U_0 = -R_{POS}/\rho$, where $R_{POS}$ is the POS resistance when the current is cut off;
- the efficiency $\eta$ with which the PVG energy is converted to energy in the load; and
- the relative decrease in current $i = \Delta I/I_0$, where $\Delta I$ is the amount by which the current decreases during the cutoff, characterizing the POS dielectric strength.

Five kinds of POS can be distinguished (Fig. 1), depending on the relative positive of the current lines and the self-magnetic field [1] cathode, 2) anode, 3) direction of the current: a) the self-magnetic field of the current is on the outside of the plasma neck, i.e., the POS resembles a Z pinch or a disk pinch, $k = 1-1.5$, $\eta = 1$, $i = 0.5$; b) the magnetic field is inside the plasma neck, "inverse pinch," $k = 1-1.5$, $\eta = 1$, $i = 0.5$; c) ordinary coaxial POS, $k = 1-5$, $\eta = 0.3$, $i = 0.5$; d) "reflecting system" with transparent anode for suppressing the electron component of the current, $k = 2-2.5$, $\eta = 0.3$, $i = 0.8$; e) POS external insulating magnetic field, generated by an auxiliary source. A longitudinal, azimuthal magnetic field or a radial field orthogonal to the electric field was used, $k = 2-10$, $\eta = 0.3$, $i = 1$ (for an azimuthal field $i = 0.6$).
1. RESULTS

1.1. There is a limiting plasma density \( n_{\text{lim}} \) at which current cutoff can occur. If the density is higher an oscillatory mode exists in the PVG–POS circuit, i.e., current cutoff does not occur. That result is reproduced on all the installations used in the experiments. An estimate gives the value \( n_{\text{lim}} \sim 10^{14} \text{ cm}^{-3} \). For \( n \sim n_{\text{lim}} \) there is a limiting (maximum) charge density such that its passage results in current cutoff. That density was determined as the density per plasma gun \( q_1 = (5-10) \times 10^{-3} \text{ C/gun} \), per unit of circumferential length of the outer electrode \( q_2 = (2-5) \times 10^{-3} \text{ C/cm} \), or per unit of surface area of that electrode \( q_3 = (1-3) \times 10^{-3} \text{ C/cm}^2 \) [4-7]. Those values do not depend on the polarity of the electrodes; when the guns were arranged on the inner electrode the number of guns was determined from \( q_1 \) [8, 9]. For a planar system the number of guns and the area of the electrodes were determined from \( q_1 \) and \( q_3 \) [10, 11].

1.2. The existence of a limiting charge allows the operation of parallel-connected POSs to be synchronized: as the resistance of one POS increases an additional part of the charge flows through the other parallel-connected POS and accelerates its triggering. If the additional charge flowing from one POS to the other constitutes 1-2% of the total charge (~20% of the current), the accuracy of synchronization of two identical POSs is 50 nsec [4, 12]. On this basis we propose a circuit for parallel-serial connection of POSs to create powerful generators [5, 12, 13]; this is possible if the parallel POSs are not closed when the current is transferred to the final POS. Reclosing can be prevented if there is a longitudinal magnetic field on the POS [14].

1.3. An appreciable increase in voltage \( (k > 2) \) is possible only when the magnetic field in the POS gap is 3-5 times the critical value for the given gap and voltage. In low-impedance installations with \( \rho = 0.2-2 \, \Omega \) [6, 7, 12, 15] the self-magnetic field is sufficient for obtaining \( k > 2 \). In high-impedance installations with \( \rho = 10 \, \Omega \) [14, 16, 17] the maximum voltage multiplication factor \( k = 2.5-3 \) is attainable only when an external insulating magnetic field or other measures are employed to suppress the electron component of the current [9, 18]. Without the magnetic field \( k = 1-1.5 \). Under our conditions application of a longitudinal magnetic field is effective only for positive polarity of the inner electrode. Otherwise, magnetic insulation of the high-voltage electrode cannot be ensured because of the high electron leakage from it to the vacuum chamber walls along the divergent lines of forces of the external magnetic field. In low-impedance installations \( \rho = 0.5-2 \, \Omega \) the application of a longitudinal [6, 7, 19], azimuthal [8], or radial [20, 21] magnetic field also causes the voltage multiplication factor to increase. It increases by a factor of 1.5-2, reaching a value of 5-15.

1.4. The ionic currents in POSs were measured in installations with [13, 19] or without [10] an external longitudinal magnetic field under a high-resistance load. The ionic currents begin long before the cutoff, when the current reaches about 20% of the maximum, with 10-20% of the VPG voltage entering the POS. The density of the ionic currents is 30-100 A/cm².