STABILITY OF THYRATRON OPERATION IN THE DISCHARGE CIRCUIT OF SELF-TERMINATING LASERS

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Received October 15, 1997

A range of stable thyratron operation in the discharge circuit of self-terminating lasers is qualitatively analyzed and the relations between this range and the basic electrophysical characteristics of the discharge circuit and the plasma are established. It is shown that the inverse voltage on the thyratron, rather than the voltage on a rectifier, is most critical for the stable thyratron operation.

Pulsed thyratrons filled with hydrogen have found the widest use in excitation circuits of self-terminating lasers. The fact that during the time over which an excitation pulse acts up to 40–50% of the energy stored in a storage capacity is lost is a distinctive feature of thyratron operation in laser excitation circuits (see Refs. 1–3). In its turn, according to Refs. 3 and 4, the losses of energy in the thyratron can be conventionally classified as starting, conductive, and afterpulsing. The afterpulsing losses of energy in the thyratron are caused by the discharge and wave impedance mismatch of the discharge circuit, when after the termination of the excitation pulse the storage capacitor charges to the negative voltage U_c^{inv} called the inverse voltage. For the significant mismatch, the increase of U_c^{inv} occurs which, in its turn, can lead to the significant increase of losses, back ignition of the discharge in the thyratron, and, as a result, to unstable thyratron operation. It then follows that the losses of energy in the thyratron have significant effect on the practical efficiency of lasers and the discharge and wave impedance mismatch of the discharge circuit determines their lifetimes and reliability of laser operation as a whole.

In spite of the fact that this problem is urgent, only Ref. 3 was devoted to it. There the dependences between the losses of energy in the thyratron and the parameters of the active medium and the conditions of excitation of the copper vapor laser (CVL) were clarified and the conditions of stable thyratron operation in case of significant mismatch between the discharge and wave impedance of the discharge circuit were determined when $U_c^{inv} \geq U_c^{max}$, where U_c^{max} is the maximum inverse voltage on the thyratron.

The regime of stable thyratron operation in case of matching between the discharge and wave impedance of discharge circuit is considered in the present paper. The urgency of the solution of this problem is determined not only by the necessity of clarifying the range of stable thyratron operation, but also by the fact that the maximum efficiency of the CVL active medium is achieved in case of matching (Refs. 5 and 6).

QUALITATIVE ANALYSIS OF THE RANGE OF STABLE THYRATRON OPERATION

Let us consider the operation of a circuit with resonance-diode charging of the storage capacity and its influence on U_c^{inv}.

Assuming that an ideal thyratron with zero internal impedance is used as a commutator and that the discharge impedance remains constant with time and equal to the impedance R averaged over the time during which the pulse acts, one can obtain

$$U_c^{inv} = -\,U_c^{o}\exp(-\alpha\pi/\omega)\ , \qquad (1)$$

where $\omega = (\omega_1^2 - \alpha^2)^{1/2}$, $\alpha = R/2L$, $\omega_1^2 = 1/LC$, L and C are the inductance and the storage capacitance of the discharge circuit, respectively. Considering U_c^{inv} , the maximum voltage to which the storage capacity is charged (under the assumption that the ohmic resistance of the discharge circuit is equal to zero), is equal to

$$U_c^{o} = 2U_{rect} + |U_c^{inv}|\ , \qquad (2)$$

where U_{rect} is the voltage on the rectifier. From Eqs. (1) and (2), it is easy to obtain the following relations:

$$U_c^{o} = 2U_{rect}/[1 - \exp(-\alpha\pi/\omega)]\ , \qquad (3)$$

$$U_c^{inv} = \frac{2U_{rect}\exp(-\alpha\pi/\omega)}{[1 - \exp(-\alpha\pi/\omega)]}\ . \qquad (4)$$

Proceeding from the rated characteristics of thyratrons (Ref. 6), they operate stable in the range $U_{lim}^{min} - U_{lim}^{max}$, where U^{min} and U^{max} are the minimum and maximum inverse voltages on the thyratron anode. For the stable thyratron operation, the conditions

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$$U_c^{inv} \le U_{lim}^{cr}, \quad (5)$$

$$|U_{lim}^{min}| \le |U_c^{inv}| \le |U_{lim}^{max}|, \quad (6)$$

must be satisfied, where U_{lim}^{cr} is the critical voltage on the thyratrone anode. From Eqs. (3) and (4) it can be seen that the increase of the discharge impedance leads to the decrease of U_c^o and U_c^{inv}. In case of the discharge and wave impedance matching in the discharge circuit, most critical for the stable thyratron operation is the fulfillment of the condition $|U_{lim}^{min}| \le |U_c^{inv}|$.

From Eqs. (3)–(6), it follows that

$$R > (2/\pi)\,(L/C)^{1/2} \ln[U_{lim}^{cr}/(U_{lim}^{cr} - 2U_{rect})] \quad (7)$$

$$(2/\pi)\,(L/C)^{1/2} \ln[(2U_{rect} + U_{lim}^{min})/U_{lim}^{min}] > R > $$
$$> (2/\pi)\,(L/C)^{1/2} \ln[(2U_{rect} + U_{lim}^{max})\,/\,U_{lim}^{max}]. \quad (8)$$

The resistance of the tube impedance is given by the equation

$$R = 1/\sigma\pi r^2 = m_e \nu l / n_e e^2 \pi r^2, \quad (9)$$

where e and m_e are the charge and mass of the electron respectively; l and r are the length and the radius of the active zone of the gas-discharge tube; n_e is the concentration of electrons; ν is the frequency of elastic collisions (mainly with atoms of buffer gas), $\nu = N_g \sigma_m \langle V \rangle$; N_g is the density of buffer gas (neon); σ_m is the cross-section of collisions between electrons and atoms of buffer gas (neon); $\langle V \rangle$ is the mean velocity of electrons. We can express N_g as

$$N_g = 3.5 \cdot 10^{16} (273/T_g)\, P_{Ne}\ (\mathrm{cm}^{-3})\,, \quad (10)$$

where T_g is the gas temperature and P_{Ne} is the pressure of neon. Combining all together, we obtain

$$3.5 \cdot 10^{16} (273/T_g)\, P_{Ne} \sigma_m \langle V \rangle l / n_e e^2 \pi r^2 >$$
$$> (2/\pi)\,(L/C)^{1/2} \ln[U_{lim}^{cr}/$$
$$/\,(U_{lim}^{cr} - 2U_{rect})]\,, \quad (11)$$

$$(2/\pi)\,(L/C)^{1/2} \ln[(2U_{rect} + U_{lim}^{min})/U_{lim}^{min}] >$$
$$> 3.5 \cdot 10^{16} (273/T_g)\, P_{Ne} \sigma_m \langle V \rangle l / n_e e^2 \pi r^2 >$$
$$> (2/\pi)\,(L/C)^{1/2} \ln[(2U_{rect} + U_{lim}^{max})/U_{lim}^{max}]\,. \quad (12)$$

The dependences between the change of the position of the stability boundary of thyratron operation and the voltage on the high-voltage rectifier are shown by curves *1–3* for the TGIZ–500/16 thyratron and *2–4* for the TGI 1–1000/25 thyratron, where $K_1 = \ln[(2U_{rect} + U_{lim}^{min})/U_{lim}^{min}]$, is shown by curves *1* and *2* and $K_2 = \ln[(2U_{rect} + U_{lim}^{max})/U_{lim}^{max}]$ is shown by curves *3* and *4*, respectively. Curves *5* and *6* are for the boundaries of stability ranges of thyratron operation as functions of the anode voltage, where $K = [U_{lim}^{cr}\,/\,(U_{lim} - 2U_{rect})]$. As can be seen from the dependences illustrated by Fig. 1, the value of the inverse voltage rather than the voltage up to which the storage capacity is charged is most critical for the stable thyratron operation. In addition, as the rectifier voltage increases the discharge voltage must grow and the ranges of variation of the plasma impedance must be shorten to stay within the range of the stable thyratron operation (see Fig. 2, $K = K_1/K_2$). This leads to the practical impossibility to keep the long-term stable thyratron operation at high rectifier voltages.

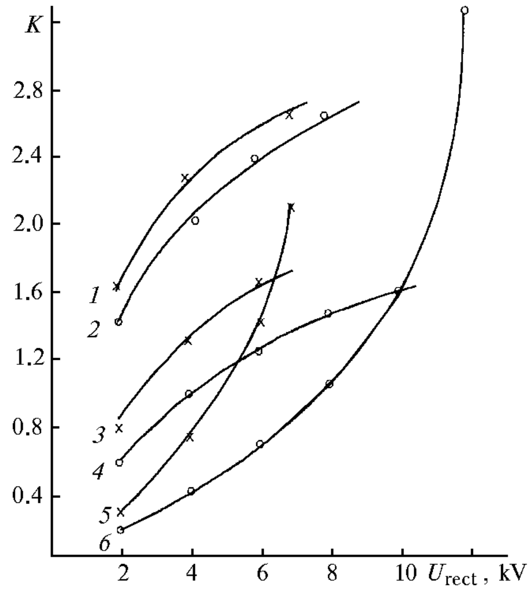

FIG. 1. Dependence between the range of the thyratrons TGIZ–500/16 (curves 1, 3, and 5) and TGI 1–1000/25 (curves 2, 4, and 6) stable operation and the rectifier voltage.

Our analysis shows that the GDT impedance linearly increases with the increase of the tube length and the pressure of neon. It is inversely proportional to the gas temperature and the density of electrons. For the GDT with large aperture, for which the resistance may be smaller than the reactance and the wave impedance, the elongation of the gas-discharge channel and the increase of the buffer gas pressure must lead to the improved matching and the increase of the lasing efficiency. The increase of the excitation energy or the pulse repetition frequency of excitation pulses for fixed mean excitation power, even for constant temperature of the wall, results in the increase of n_e, the decrease of the impedance, and possible in the decrease of the electron temperature. Our conclusions agree with the conclusions of Ref. 7. From the proceeding and the results reported in Refs. 5 and 6, we can conclude that the range of efficient pumping of the active

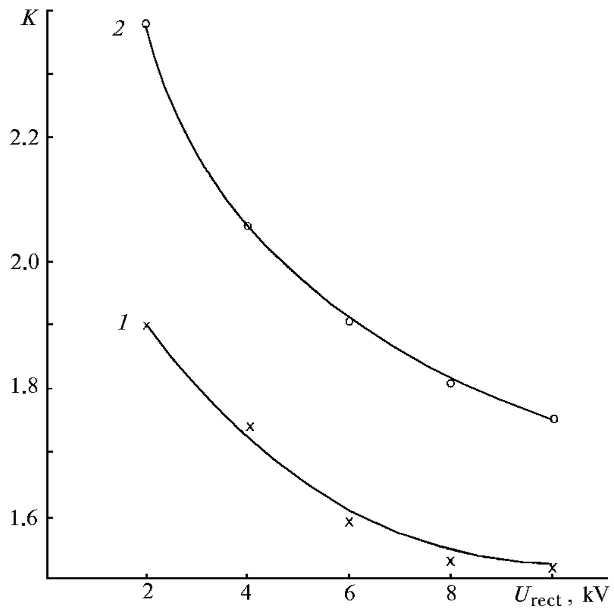

FIG. 2. Ranges of variation of the discharge impedance as functions of stable operation of the rectifier voltage within the ranges of the thyratrons TGIZ–500/15 (curve 1) and TGI 1–1000/25 (curve 2).

medium of self-terminating lasers with thyratron pumping lies beyond the range of the stable thyratron operation. The possibilities for optimization of the energy characteristics of self-terminating lasers are limited by the range of stable thyratron operation.

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