https://doi.org/10.46813/2025-160-064

STABILITY OF KLYSTRON PARAMETERS IN THE ELECTRON LINAC LU-10

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The output parameters of a linear electron accelerator depend significantly on the stability of its microwave power supply system, which is based on a high-power klystron. This paper presents an analysis of the KIU-12 klystron, used in the output stage of the «LU-10» accelerator's microwave power supply, and develops a numerical model for it, taking into account operation in pulsed mode. The model is adapted for the development of an automatic control system based on a high-speed microcontroller.

PACS: 29.20.Ej; 84.80.F; 07.05.Dz

INTRODUCTION

To ensure stable operation of the linear electron accelerator microwave power supply system, it is necessary to develop a klystron control system that will monitor key parameters (voltage, current, input and output power) and compensate for disturbances in real time. Such a system is based on a numerical model that reflects the physical processes in the klystron and allows for the adaptation of control algorithms to a specific device. The main goal of this work is to develop a control system for the KIU-12 klystron based on a numerical model that describes its characteristics in pulsed mode.

1. OPERATING PARAMETERS OF THE KLYSTRON

The KIU-12 klystron is a high-power pulsed four-cavity amplifier designed to operate at a frequency of 2797.0 ± 7.0 MHz. The device employs a coaxial input for the RF drive signal and a waveguide output for the extracted RF power, providing reliable matching with the accelerator high-frequency transmission lines.

The klystron operates in pulsed mode with pulse durations of approximately 2…6 µs and a pulse repetition frequency ranging from 5 to 250 Hz (depending on the experimental conditions). To dissipate heat during operation at high average power, forced liquid cooling is employed for both the collector and the resonator block.

The main monitored parameters of the klystron are:
- anode voltage U_a;
- anode current I_a;
- focusing current I_f;
- input RF power P_{in};
- output RF power P_{out};
- power gain G;
- efficiency η.

These parameters are necessary for the development of an automated control system.

2. METHODS OF PARAMETER MEASUREMENT

Due to the pulsed operation of the klystron, measurement methods can be divided into electrical and calorimetric approaches.

2.1. ELECTRICAL MEASUREMENTS

Oscillograms of anode voltage *U(t)* and anode current *I(t)*, recorded with a digital oscilloscope, are used to analyze dynamic processes. These data make it possible to calculate instantaneous and peak the beam parameters, as well as to determine the beam resistance:

$$R_{\text{beam}} = \frac{U_{\text{a}}}{I_a}. \qquad (1)$$

Data in CSV format is transferred to a computer via a flash drive or a local network and is used to process and plot graphs of measured and programmatically calculated parameters (Fig. 1).

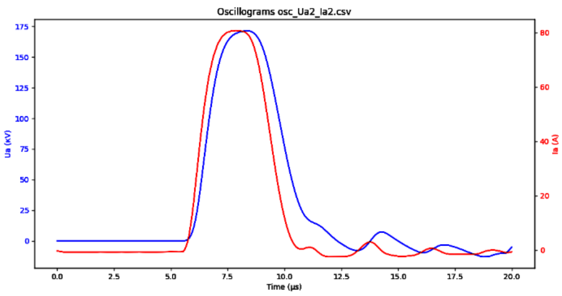

Fig 1. Graphs of anode voltage and current with calculation of beam resistance and pulse duration

2.2. CALORIMETRIC MEASUREMENTS

The average output power of the klystron can be determined using the calorimetric method. According to the technical documentation of the KIU-12:

$$P_{out,\,avg} = Q \cdot 4.18 \cdot (t_2 - t_1), \qquad (2)$$

where Q is the cooling water flow rate (cm³/s), and $t_2 - t_1$ is the temperature difference (°C) at the calorimeter outlet and inlet. To relate calorimetric average power to the pulse domain, the average power during the pulse is defined as:

$$P_{out,pulse} = \frac{1}{T_{Pulse}} \int_0^{T_{Pulse}} P_{out}(t)dt \cdot \quad (3)$$

Pulse-averaged power can be expressed via the calorimetric average as:

$$P_{out,pulse} = \frac{P_{out,avg}}{F \cdot T_{pulse}} \,, \quad (4)$$

where T_{pulse} – is the pulse duration and F – is the pulse repetition frequency.

2.3. MANUAL DATA INPUT

Under experimental conditions, some parameters (e.g., average output power obtained by calorimetry) may be entered manually by the operator into the data acquisition system. This enables integration of both automated and manual measurement methods.

Thus, the combination of electrical and calorimetric measurements provides a complete dataset for constructing an adequate mathematical model of the klystron. This forms the basis for further problem formulation and the development of control methods (Section 3).

3. PROBLEM STATEMENT

The primary task of control is to maintain stable output RF power under variations of supply parameters and external conditions.

The following requirements are imposed on the klystron control system:

- **Output power stability** – minimization of deviations of P_{out} from the specified level when the anode voltage or input power changes.
- **Disturbance compensation** – the ability to correct the effects of instabilities in the power supplies, as well as drift in the parameters of the cathode and focusing systems.
- **Pulse dynamics consideration** – the need to analyze the actual shape of the voltage and current pulses, which have a bell-shaped form rather than a constant level.

An important limitation in model development is the pulsed operating mode of the klystron: the pulse duration is 2…6 µs, while the repetition rate ranges from 5 to 250 Hz. This determines both the measurement methodology and the data processing algorithms. Not all parameters can be directly measured in real time; some characteristics (for example, the average output power obtained by the calorimetric method) are entered by the operator.

The KIU-12 klystron operates at high anode voltages (up to 270 kV), which significantly complicates the design of its high-voltage power supply system and the achievement of the specified parameters for modulating pulses longer than 4…5 µs [1]. At the same time, the output power pulse of the klystron does not have a rectangular shape, even if the waveform of the driving high-voltage pulse is close to rectangular [2]. The non-uniformity of RF power pulses supplied to the accelerator leads to significant degradation of the linac's output characteristics, particularly in terms of spectral uniformity [3].

One approach to compensate for this effect is the use of high-precision devices for control and synchronization of accelerator subsystems. For example, the authors have developed a device capable of generating synchronization pulses for several (up to five) accelerator subsystems with the required time delays, an adjustment step down to 10 ns, and programmable logic [4]. However, instability and parameter variations among different units of the same klystron model reduce the effectiveness of such solutions.

Currently, it is not technically difficult to develop systems for stabilizing individual electrical parameters. However, for such a complex device as a high-power RF klystron, a comprehensive approach is required to assess and regulate its operating modes in terms of both DC and RF input power.

The implementation of such a control system is possible through the use of modern high-speed microcontrollers with control software developed on the basis of a numerical model of a specific klystron unit.

Thus, the problem statement reduces to the creation of a numerical model describing the dependence of the output power on the anode voltage, beam current, and input RF signal, while taking into account the real pulse shape. This model should be suitable for integration into a hardware–software complex for klystron control (Fig. 2).

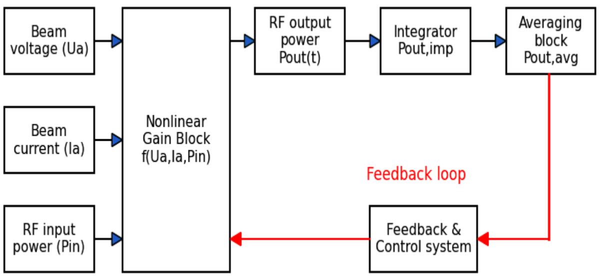

Fig. 2. Structural diagram of the KIU-12 klystron, reflecting the main relationships between its parameters and output power in pulse mode

4. CREATING OF THE PRELIMINARY MODEL

4.1. INITIAL EXPERIMENTAL DATA

Available oscilloscope traces of anode voltage $U_a(t)$ and anode current $I_a(t)$, recorded in CSV format, characterize pulsed processes in the electron gun. Input power P_{in} and output power P_{out} are fixed manually: input – from the excitation source, output – from calorimetric measurements or calculations. Thus, $U_a(t)$ are directly available, while RF powers are scalar parameters at this stage [5].

4.2. TRANSFORMATION OF OSCILLOGRAMS TO AVERAGED CHARACTERISTICS

Since $U_a(t)$ are close to bell-shaped, integral indicators are used:

- peak values U_{max}, I_{max};
- average values over the pulse duration:

$$\bar{U} = \frac{1}{T_{pulse}} \int_0^{T_{pulse}} U_a(t)dt, \quad (5)$$

$$\bar{I} = \frac{1}{T_{pulse}} \int_0^{T_{pulse}} I_a(t)dt, \quad (6)$$

- beam impedance:

$$R_{beam} = \frac{U_{max}}{I_{max}} \quad \text{or} \quad R_{beam} = \frac{\bar{U}}{\bar{I}}. \quad (7)$$

This forms the first block of the model – description of beam parameters.

4.3. NONLINEAR "BEAM → RF POWER" CONVERSION

The relation between beam parameters and RF output power is described by an empirical function:

$$P_{out} = f(U_a, I_a, P_{in}). \quad (8)$$

A practical approximation:

$$P_{out} = G_0 \cdot \frac{P_{in}}{1 + P_{in}/P_{sat}} \cdot \left\{\frac{U_a}{U_0}\right\}^{\alpha} \cdot \left\{\frac{I_a}{I_0}\right\}^{\beta}, \quad (9)$$

where G_0, P_{sat}, α, β are determined experimentally. This expression ensures transition from linear regime (small P_{in}) to saturation at high drive.

4.4. AVERAGING OVER PULSE AND REPETITION PERIOD

Since the klystron operates in pulsed mode, instantaneous power values must be converted to integral parameters:

- average power in pulse:

$$P_{out,pulse} = \frac{1}{T_{pulse}} \int_0^{T_{pulse}} P_{out}(t)dt; \quad (10)$$

- average power per operation period:

$$P_{out,avg} = P_{out,pulse} \cdot F, \quad (11)$$

where F is the pulse repetition rate.

4.5. FINAL MODEL STRUCTURE

Thus, the preliminary model includes:

- block converting $U_a(t), I_a(t)$ oscillograms into averaged beam parameters $\bar{U}$, $\bar{I}$, R_{beam};
- nonlinear gain block linking input power and beam parameters with output RF power;
- averaging block over pulse and repetition frequency, forming $P_{out,pulse}$ and $P_{out,avg}$ [6, 7].

4.6. PROSPECTS FOR MODEL DEVELOPMENT

With the availability of input and output RF power oscillograms, the model can be extended to a dynamic one, where $P_{in}(t)$ and $P_{out}(t)$ are treated as time functions. This will allow describing not only scalar parameters but also pulse shapes, including envelopes and transient processes.

4.7. TRANSITION FROM NONLINEAR TO LINEAR MODEL

For simplified analysis near the operating point, the model can be linearized:

- expansion of nonlinear dependencies $P_{out}(U_a, P_{in})$ into a Taylor series around nominal values;
- construction of a local transfer function suitable for stability analysis of the control system;
- subsequent use of the linear model in adaptive regulation algorithms.

Thus, the general model remains nonlinear, but for control analysis and tuning, a locally linearized version is applied.

CONCLUSIONS

The proposed approach to the development of a numerical model of the klystron differs from traditional methods in that it is focused on the practical use of available data and experimental measurements, rather than relying on complex and expensive licensed software packages (COMSOL, CST, MAGIC, KARAT, etc.). Although these systems allow detailed simulation of electrodynamic processes, they have significant limitations: high license costs, restricted access due to sanctions or political barriers, and substantial requirements for computing resources.

Instead, we create a model of the specific KIU-12 klystron available to us, which makes it possible to verify and adjust the model against experimental data. This approach provides an adequate description of the dynamics and operating modes of the klystron, which can be directly applied in the development of a control system.

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Article received 20.11.2025

СТАБІЛЬНІСТЬ ПАРАМЕТРІВ КЛІСТРОНА В ЛІНІЙНОМУ ПРИСКОРЮВАЧІ ЕЛЕКТРОНІВ LU-10

В.О. Мац, С.К. Романовський, Ю.О. Тітаренко, В.Ю. Титов, Р.М. Дронов, С.О. Ванжа

Вихідні параметри лінійного прискорювача електронів суттєво залежать від стабільності системи мікрохвильового живлення прискорювача, побудованої з використанням потужного клістрона. Представлено аналіз використання клістрона KIU-12 у вихідному каскаді системи мікрохвильового живлення прискорювача «LU-10» та розроблено його числову модель із урахуванням роботи в імпульсному режимі. Модель адаптована для створення системи автоматичного керування на базі високошвидкісного мікроконтролера.