A klystron design is considered with a two-gap bunching resonator which provides interaction with electron beam by fields of multiple frequencies of two-gap resonator fundamental oscillations for increasing the klystron efficiency. That the two-gap resonator is tuned to anti-phase oscillation at operating frequency $f$ and to in-phase oscillation at the doubled frequency $2f$.

Such choice of frequency oscillation types allows to compact the resonator and provide optimal conditions for electron beam interaction with microwave fields of the two-gap resonator both in anti-phase and in-phase oscillation types. The relations are given for choosing two-gap resonator interaction area size providing klystron operation stability without self-excitation.

The compactness of the realized two-gap resonator with multiple frequencies allowed to locate it into klystron drift tube without increasing the klystron overall dimensions.

Experimental investigation of klystron with the two-gap resonator demonstrated significant increasing of klystron efficiency.

INTRODUCTION

In modern linear electron accelerators high-power sources of microwave energy are widely used which contain high stability driving oscillator, driver amplifier (solid-state or vacuum) and output device – klystron.

Klystrons provide high output power in a pulse (several dozens of MW), possess high gain and long life and to a large degree define main technical and operational characteristics of linear electron accelerators.

The present contribution gives the results of research in increasing the efficiency of the klystrons for accelerators using compact two-gap resonators operating at double frequency or at multiple frequencies of its fundamental oscillation modes – anti or in-phase ones.

TWO-GAP RESONATORS OPERATING AT MULTIPLE FREQUENCIES

The idea of designing a klystron with two-gap resonators operating at multiple frequencies of its fundamental oscillation modes was proposed in [1, 2].
oscillation the fields in resonator gaps are directed to one and the same side, at anti-phase mode of oscillation – to meet each other.

Figure 2 gives the dependencies of frequencies of in-phase and anti-phase modes of oscillation at angle $\beta$ of the connection slot between the resonators. From fig.2 one can see that the in-phase oscillation mode frequency depends weakly on connection slot whereas the anti-phase mode frequency changes greatly depending on connection slot angle. At the connection slot angle $\beta = 150^\circ$ it is possible to provide the multiplicity of frequencies of anti-phase and in-phase oscillation modes, i.e., $f_{in} = 2f_{anti} = 2f$.

Note, that the overall dimensions for two-gap resonator are chosen to obtain double operating frequency $2f$ for in-phase mode of oscillation, that makes klystron becomes compact. Such resonator can operate in the klystron in two modes:

- at double frequency of in-phase mode of oscillation;
- at multiple frequencies of in-phase and anti-phase modes of oscillation.

**KLYSTRON WITH TWO-GAP BUNCHING RESONATOR AT DOUBLED FREQUENCY AND AT MULTIPLE FREQUENCIES.**

Let’s consider why the frequency selection of oscillation mode is the optimal one for effective bunching of electron flow when in-phase mode is tuned to double operating frequency $2f$ and anti-phase mode of oscillation is tuned to frequency $f$.

To simplify the analysis consider gap factors [3, 4] for in-phase $M_{in}$ and anti-phase $M_{anti}$ modes of oscillation (fig.3 a,b) depending on complete transit angle $\theta_s + 2\theta_d$ in two-gap resonator at different transit angles between gaps $\theta_s$ ($\theta_s = \frac{2\pi f_s}{v_0}$, $\theta_d = \frac{2\pi f_d}{v_0}$ – a transit angle in the gap, $v_0$ – electron flow rate). Figure 3 demonstrates that the value scale for in-phase oscillation mode was chosen twice as larger as compared to that of anti-phase oscillation mode.

Figure 3 shows that gap factors for in-phase and anti-phase oscillation modes have maximal values simultaneously only when in-phase oscillation mode is tuned to double operating frequency $2f$ and anti-phase oscillation mode – to operating frequency $f$.

The dependencies of electron load conductance for in-phase $\frac{G_{in}}{G_0}$ and anti-phase $\frac{G_{anti}}{G_0}$ ($G_0$ – dc electron flow conductance) oscillation modes on complete transit angle in two-gap resonator given in fig.4 a, b show that at the selection of transit angles on the basis of relations

$$\theta_s + 2\theta_d = (1.35 \div 1.50)\pi$$

and

$$\theta_s = 1.8 \div 2.4$$

electron load conductances $\frac{G_{in}}{G_0}$ and $\frac{G_{anti}}{G_0}$ have positive values and electron gap factors are close to maximal ones (dashed areas in Fig. 3, 4). It means that the optimal interaction of electron flow with the fields of two-gap resonator multiple frequencies at the stable operation of the device is provided.

Note that one could choose modes with negative values of electron load conductances and maximal values of gap
factors, but in that case measures would have to be taken to avoid self-excitation of two-gap resonator.

Now let’s consider the case when two-gap resonator operates only in in-phase operation mode at double operating frequency $f_{in} = 2f$.

It is known that the klystrons use one-gap resonators at double frequency which allow to improve the klystron parameters.

As compared to the known solutions, more effective bunching of electron flow is realized in the considered two-gap resonator. It is connected to the fact that the bunching takes place in two interaction gaps and a two-gap resonator has a high wave resistance at doubled frequency $\rho \approx 100 \, \Omega$.

Such two-gap resonator was located in a drift tube between the second and the third resonators in existing 20 MW four-resonator klystron.

The results of experimental research showed that the efficiency increased from 36% to 45%.

Moreover, the overall dimensions, mass and focusing magnetic field remained without any changes. It is very important as the klystron is used in many accelerators and alterations of the customers’ installations are not desirable.

### Main klystron specifications:

- **Operating frequency**: 1818 MHz
- **Output pulse power**: 20 MW
- **Output mean power**: 18 kW
- **Anode pulse voltage**: 240 kV
- **Pulse duration**: 6 $\mu$s
- **Pulse repetition frequency**: 150 Hz
- **Efficiency**: 45%
- **Gain**: 37–40 dB

At present the work on using a two-gap resonator with multiple frequencies in the klystron is under way. Preliminary investigations showed that it is possible to reach 50% efficiency.

### CONCLUSIONS

The design of a compact two-gap resonator in which the interaction with electron flow is realized by fields of multiple frequencies of its fundamental oscillation modes is presented. It is shown that in-phase oscillation mode should be tuned to the double operating frequency and anti-phase oscillation mode – to operating frequency for effective bunching of electron flow.

The results of experimental investigations of the klystron showing the possibility of significant increase of the efficiency (from 36 to 50%) due to compact two-gap resonator with multiple frequencies in the klystron are given.

Two-gap resonator with in-phase oscillation mode at the double operating frequency allowed to increase the efficiency of the existing 20 MW klystron from 36 to 45% without changing the mass and overall dimensions of the klystron and focusing solenoid.

### REFERENCES