The RF-power upgrade systems with RF-field energy compression are intended for accelerating wave power increase in order to increase an accelerated beam energy or decrease the feeding RF-generators power. At present a number of energy compression system (ECS) types and designs with various properties are known [1]. Among these a system with a resonant load presents the certain interest for practical use. The main difference of such ECS from the other types is that here a resonant load is an essential part of the system that influence significantly on its parameters. They can be named as systems with connected resonators also.

I. THEORY

A. The main principles of work and a system characteristics

The main principle of the system with resonant loading operation is based on the following: for certain parameters of a system formed by two connected resonators all energy primarily stored in one resonator passes by terns from one resonator to another. For the first approximation it may by considered that a maximum value of equivalent RF-power in each resonator is determined by expression:

\[ P_1 / P_2 = Q_2 / Q_1 \]  

where \( P_1 \) and \( P_2 \) - equivalent RF-wave power in the first and second resonators; \( Q_1 \) and \( Q_2 \) - the first and second resonator quality factors. From expression (1) it follows that the higher resonators q-factor relation the more equivalent power increase can be achieved. The resonators can be with standing or travelling waves. In case of resonators with travelling waves (TWR) the equivalent power is the quite certain power of RF-wave circulating in resonator ring.

The variant of ECS with a resonant load is submitted on fig.1 [2]. Here accelerating structure 4 is a part of a TWR. The switched coupler 2 transfers the system operation mode from storing energy to its use. During the energy storing period (state A) the coupler 2 connects generator 1 output to storing resonators 3 and the acceleration structure 4 output - to an absorbing load 5. To use the stored energy (state B) the coupler 2 is switched in such way that the acceleration structure output becomes connected to storing resonators, forming TWR.

The system works as following. In state (A), an energy storing in resonators 3 occurs. The wave, reflected from storing resonators (SR), passes through a TWR and arrives in a load 5. When the energy storing process ends the coupler

Fig. 1. An RF-energy compression system with a resonant load (1 - RF-generator; 2 - switched coupler; 3 - storing resonators; 4 - accelerating structure; 5 - absorbing load).

transformed in state B. So the wave coming to SR is a wave leaving from accelerating structure. A wave phase shift in a TWR is chosen so that the wave coming on SR has the same phase as the wave irradiated from them. Then after each turn-over the amplitude of a wave circulating in TWR ring will grow so long as all accumulated in SR energy will not pass completely in TWR. And after this the return swapping of energy from TWR to SR will begin. The qualitative graph of the circulating in TWR wave average amplitude variations are shown on fig.2. If the energy losses in TWR are insignificant, the factor of wave power increase \( K_p \) in such system can be evaluated on following expression:

\[ K_p = P_w / P_o = W_s / (T \times P_o) \]  

Fig. 2. The RF-wave average amplitude variations in a system with a resonant load (\( E_o \) - generator wave amplitude; \( E_w \) - wave in TWR ring).

RF-POWER UPGRADE SYSTEM WITH RESONANT LOADING

A.Shalnov, B.Bogdanovich, A.Ignatyev, V.Senyukov

Moscow State Engineering-Physics Institute, MEPhI, Moscow, 115409, Russia.
where $P_w$ and $P_o$ - the power of RF-waves in TWR and on a generator output, accordingly; $W_s$ - energy stored in resonators; $T$ - time (duration) of one turn-over of a wave in a TWR. Practically the achievable values of factor $K_p$ in such system can make $150 \ldots 200$ (for SR with self q-factor $Q_o = 10^5$ and more (for superconductor resonators). The time of the high power wave existence in TWR appears to be about an order higher, than for the case when RF-pulse is formed on active load.

B. Field calculation equations

Let’s consider a system shown in fig.1. After a generator switching-off and TWR forming the wave, emitted from the SR is added to a wave circling in the TWR. In this case the amplitude of a summarised wave at the acceleration structure entrance during the energy use period is described by a following expression:

$$E_W(t) = \begin{cases} 
\left(-\frac{2\beta}{1+\beta}\right)(1-e^{-t/T}) + 1 \cdot E_0, & \text{for } 0 \leq t < t_0 \\
\sum_{n=0}^{N} E_{WN}(t), & \text{for } t \geq t_0
\end{cases}$$

(3)

where:

$$E_{WN}(t) = \frac{-2\beta}{1+\beta} \cdot E_0 \cdot (1-e^{-t_0/T}) \cdot e^{-\alpha \cdot t_0} \cdot e^{-\frac{t-t_0-T}{\tau}} \cdot F(-n,1,A)$$

$$F(-n,1,A) = \sum_{k=0}^{n} \frac{c_k^n}{k!} (-1)^{n} A^n$$

$$A = \frac{2\beta}{1+\beta} \cdot \frac{t-t_0-nT}{\tau}$$

$N = \lfloor (t-t_0)/T \rfloor$ - number of wave revolutions in TWR.

C. Calculation results

The graph of dependence of wave amplitude at an accelerating structure entrance on time $t$ for $t > t_0$ is indicated in fig.3. Calculations were made for a system with following parameters: $Q_o = 100.10^3$; $\beta = 5$; $t_0 = 2.5 \ \mu$s; $T = 40 \ \text{ns}$; $\alpha = 0.01$. One can see, that the wave amplitude changes are executed by inherent steps, the duration of which is equal for a wave turn-over time in a TWR (it is supposed, that changing of the system operation mode is executed instantly).

On fig.4 the graphs of a maximum normalized wave amplitude at an acceleration section entrance averaged for a time of one turn-over in a ring dependence on a duration of turn-over period $T$ for various values of attenuation in a ring are given for the same system parameters.

The results presented show, that the attenuation in a TWR appreciably influences on the wave amplitude $E_W$ (and, hence, and on $K_p$ value) only for small magnitudes of the turn-over time ($T < 50 \ \text{ns}$). Also researches have shown, that the optimum value of a coupling factor $\beta$ (for a maximum wave amplitude $E_w$) is determined only by a duration of an energy storing period $t_0$.

Theoretical researches of an accelerated beam energy changes within a stored energy using period have shown, that in difference from time dependence of wave amplitude in TWR (see fig.2) the time dependence of beam energy is smooth and has no any steps.

II. EXPERIMENTAL RESULTS

The experimental researches of a ECS with resonant load were conducted at RF-generator pulsed power up to 100
kW in S-band. For energy storing there were used a copper cylindrical cavities with $H_{015}$ mode. This cavities had an unloaded $q$-factor $Q_0 = 90 \times 10^3$ and coupling factor $\beta = 6$. For changing the system operation mode a waveguide discharge switches were used. The experiments were conducted at two values of a wave turn-over duration in a ring: 40 ns and 24 ns. The summary energy losses in a ring in both cases were about 0.05.

The typical RF-wave normalized power variations in a TWR within the energy using period is shown in fig.5.

![Fig. 5. The RF-wave normalized power variations in a TWR within the energy using period $P_w/P_o$.](image)

The results of measurements and calculations (on expression (3)) of a maximum wave amplitude $E_{wm}$ in TWR dependence for considered parameters of a system on an energy storing period duration are shown in fig.6. The measurements and accounts were made for a ring with a one turn-over duration $T = 40$ ns and RF-generator output pulsed power up to 10 kW. A measured values of a maximum power increasing factor $K_P$ for $t_0 = 2.5 \mu s$ are the following: for a ring with $T = 40$ ns $K_P = 15.0 \pm 0.5$ dB ($\sim 32$ times); for a ring with $T = 24$ ns $K_P = 17.0 \pm 0.5$ dB ($\sim 50$ times). The calculated values are 14.9 dB and 16.8 dB, accordingly. A number of experiments on a system work research was also conducted at an RF-generator power up to 100 kW in a pulse. In these experiments the high-voltage switch modulator was used only for initialization of discharge, and the formation of a plasma in a switch was executed at the expense of a dropping RF-wave power. In this case a system was capable to work also. As it was expected, there occur a little decrease of a power increasing factor $K_P$ (at the expense of losses in the switches while plasma formation). At source power about 100 kW the measured value of $K_P$ was about $14 \pm 0.5$ dB ($\sim 25$ times). Further increase of source power resulted in appearing of RF-discharges in a TWR waveguides, since the path was under atmospheric pressure, and the maximum wave power in a waveguide for this conditions is about the permissible one (corresponded to electrical strength for used waveguide: $72 \times 34$ mm$^2$), i.e. about $2 - 2.5$ MW.

As far as in a given system a mode transfer switching is executed at a high power level there is a necessity to use the discharge switches, that limits to some extend an opportunities of such systems application. However, as a positive fact it should be noted, that here the switches in an opened state (i.e. in absence of discharge) operates only at a feeding generator power level. In the other type systems with storing resonators (for example, the system with variable resonator parameters [1]) a switch in opened state should maintain the power levels equal to those of an output RF-wave. This permits a considerable simplifying of constructions of a switch and a managing high-voltage modulator, and in a number of cases (at not so large power levels) to use for switching a solid-state devices.

III. REFERENCES
