SUPERHIGH-POWER RF REGOTRON-TYPE GENERATOR FOR LINEAR ACCELERATOR WITH HIGH MEAN CURRENTS

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Theoretical principles and construction scheme of new-type super-power microwave relativistic electron-beam (REB) generator (Regotron) are discussed. Unlike other type of REB-generator, Regotron includes distributed power take-off system. To increase device efficiency the autophasing-principle is used. Such principles of device construction eliminate output power generator limitations. Theoretical basis of general generator construction principles is proposed; the results of mathematical simulations are presented; the different versions of construction scheme are discussed. It is shown that regotron efficiency can reach 70...80 % at output power levels up to 10 MW CW.

Due to recent development of large accelerating complexes (LEP, UNK, SSC, etc.), the RF amplifiers with high mean power become of ever increasing interest [1]. Reliability and efficiency requirements of such RF devices are increasing as well. This is specifically the case with the RF power-supply generators of proton linear accelerators which now under consideration for use in the burner-reactors. A total mean power of about 1 GW is necessary to accelerate a continuous beam in such accelerator. As preliminary investigation shows, the implementation of the devices has to be based on RF generators with at least 5...10 MW output power, 70 per cent efficiency and 20 dB gain. It stands to reason that the most powerful up-to-date devices, namely klystron amplifiers, are unable to meet the aforementioned power and efficiency requirements. An alternative RF system implementation with relatively modest generator parameters results in significant size and weight growth and increased maintenance problems.

A possible way out was outlined in the paper [2], where a new method of microwave generation was proposed. The method makes use of a bunched relativistic electron beam passing through a chain of N cavities and thus enables high efficiency to be obtained in the device with distributed RF power extraction system.

The peculiar feature of the device called "regotron" is the utilization of a number of uncoupled cavities in the power take-off system. The technique provides for the microwave power take-of which is N times that of a single cavity (which is the case with a klystron where the power taken off of the beam is limited by the ultimate dielectric strength). Implementation of the method enables one to place the output cavities in the vicinity of the load (e.g. near the accelerating sections of a particle accelerator) thus both simplifying the microwave system and decreasing its power loss.

The installation diagram is presented in Fig. 1. The generator involves high-voltage injector (I), buncher (B), distributed power take-off system (PS) and collector (C).

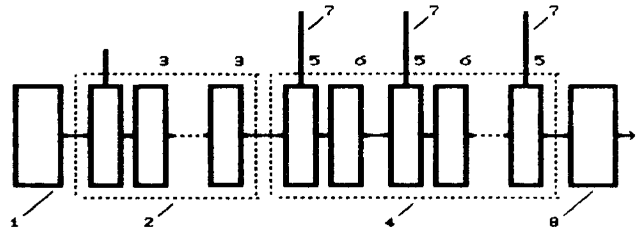

Fig.1. RF installation diagram.
1 - high-voltage injector (I) 2 - buncher (B)
3 - passive cavities of the buncher
4 - distributed power take-off system (PS)
5 - active cavities power take-off system
6 - bunching cavities of the power take-off system 7 - output cavities 8 - beam collector

The preferable design scheme of the electrostatic accelerator is that of Cockroft-Walton. In the continuous-beam accelerator one can also use an alternative high-voltage source in the form of dc high voltage transmission line ($U > 500$ kV). The latter simplifies both the generator design and accelerator RF system as a whole.

Quite a novel design approach is needed in the resonator part of the generator. The stretch of the power take-off system is limiting the perveance of the beam which has to reach the finite minimal energy after the deceleration in spite of the destructive action of the Coulomb forces. The perveance has to fall into the $(0.1 - 0.5) * 10$ A/V$^{3/2}$ range where effective beam deceleration is possible. This requirement is easily met with the 10 - 30 A relativistic beams.

If the generator design is based upon the klystron bunching then the initial beam energy has to be less than 700 keV - the limiting value for the klystron bunching to be still effective. If the initial energy W_o exceeds 1 MeV then the magnetic bunching is preferable.

The distributed nature of the power take-of system complicates the bunched beam dynamics problems. The device efficiency $\eta = 1 - W_k/W_o$, where W_k is the beam finite energy at the collector. To increase the efficiency and to decrease the collector power one has to organize the particle beam dynamics so as to preserve bunch configuration and hence the current harmonic through the whole deceleration process and to provide for the minimum possible value of W_k. The well-known principle of the acceleration theory - that of the autophasing - is used in the device to solve the problem. The most effective method of the autophasing implementation in the distributed power take-off system is based on the use of cavity pairs [3]. One of the two cavities (see (6) in Fig. 1) is passive. It's detuned to the higher frequencies with regard to the signal frequency while the another cavity (which is the active one, see (5) in Fig. 1) is tuned in to the resonant frequency and coupled with the load. Thus the voltage U_a which is excited in the active cavity, is in-phase with the first harmonic of the beam current I_1 whilst the phase lead of the voltage U_p in the passive cavity with regard to the first harmonic of the current is about $\pi/2$ (see Fig. 2). The beam is affected by the net voltage U_Σ with the phase lead with regard to the current first harmonic. This phase lead plays the role of the equilibrium phase and the bunches fall into the autophasing regime. If R_1 and R_2 are the shunt resistances of the cavity pair then the net effect of the pair on the beam is equal to that of a signal cavity with the shunt resistance $R_e = \sqrt{R_1^2 + R_2^2}$ and the detuning angle φ_e ($\cos\varphi_e = R_1/R_e$). Thus the autophasing regime with the desired equilibrium phase is realizable through the proper choice of the cavity parameters.

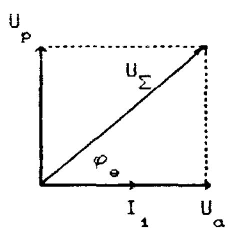

Fig.2.

Klystron bunching in the regotron has its specific features. Since the particles in the power take-off system are oscillating with regard to the equilibrium phase, the main problem of the bunching is to provide for the maximum capture into the stable oscillation domain. The boundaries of the domain are usually defined by the following inequalities $|\varphi - \varphi_e| \lesssim 60^o$, $|\Delta W/W| \lesssim 10\ \%$. In the case current harmonic at the entrance of the power take-off system doesn't define unambiguously the device efficiency. During the deceleration the value of current harmonic increases and the mean current harmonic over the whole take-off system exceeds the input value.

A computer simulations of bunching and power take-off processes was performed with the aim to investigate the beam dynamics to optimize the generator parameters over the wide frequency range [3-7]. The generator efficiency increase due to the autophasing was confirmed by the computer simulation results. A typical example is presented in Fig. 3. The calculated current harmonic variation is plotted against the relative bunch energy in the energy take-off system with (curve 1) and without (curve 2) the autophasing. The parameters were as follows : W_0 = 700 keV, $\Delta W/W$ = 0.08 per cavity, Equilibrium phase of the autophasing $\varphi_e = 60^o$. The autophasing clearly provides for the longer beam energy take-off feasibility and thus for the efficiency up to 80 per cent. The efficiency of the power take-off system without the autophasing is about 40 per cent.

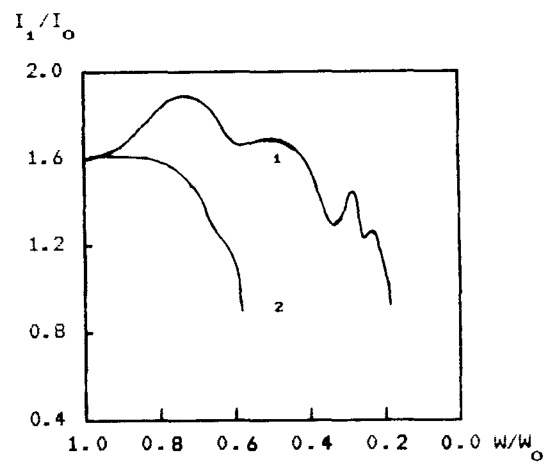

Fig.3.

The higher is the value of W_0, the higher are both the efficiency and the output power of the system.

The calculated performances of regotron with different operating frequencies are presented in Table I. The efficiency, dimensions of buncher L_b and power take-off system L_{ps} as well as the number of active cavities L_a were obtained through the optimization based on the calculation results of papers [3-6]. At present a pulsed regotron model with 3000 MHz operating frequency is being built in the Moscow Radiotechnical Institute of the USSR Academy of Sciences.

TABLE I

Calculated Performances of Regotron

f[MHz]	P[MW]	η[%]	I_0[A]	W_0[MeV]	L_b[m]	L_{ps}[m]	N_a
350	5÷10	70÷80	10÷30	0.5÷0.7	9÷12	4÷5	5÷10
600	5÷10	70÷80	10÷30	0.5÷0.7	6÷8	3÷4	6÷12
900	5÷10	70÷80	10÷30	0.5÷0.7	4÷4.5	1.5÷2	6÷12
3000*	3.5	70	10	0.5	2	1	7

* - pulsed regotron model

Main computer simulation results will be checked against the experiments with the model and different system will be tried out. The calculated performances of the regotron which is intended for the energy supply system of the burner-reactor's linear proton accelerator are given in Table II.

TABLE II
Calculated Performances of Regotron for burner-reactor's linac

Beam parameters	
Current, A	10
Initial energy, keV	500
Beam radius, cm	1.5
Buncher parameters	
Number of cavities	3
Input power, kW	2
Operating frequency, MHz	600
Cavity characteristic wave impedance, Ohm	130
Cavity Q-factor	10500
Length of the buncher, m	7
Power take-off system parameters	
Number of cavities	7
Cavity characteristic wave impedance, Ohm	206
Cavity Q-factors : active	22
passive	14000
Equilibrium phase, deg	60
Output power, MW	5.8
Efficiency, per cent	77
Length, m	3

The choice of the beam initial energy W_o = 500 keV enables the well developed dc energy supply system to be used. In Fig. 4 the beam current first harmonic variation along the device is presented (B - buncher, PS - power take-off system).

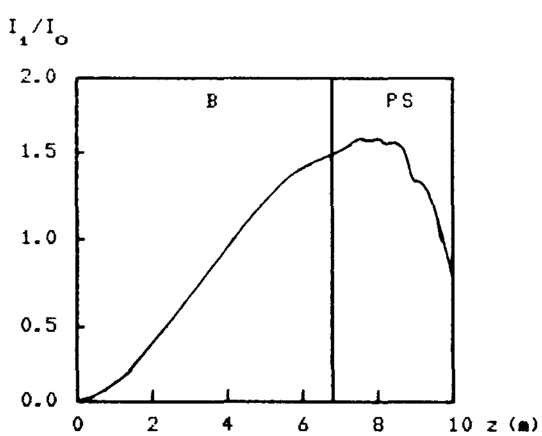

Fig.4.

The resonant part of the generator consists of the toroidal cavities with the TM_{010} wave. The focusing system involves a number of solenoidal lenses with magnetic induction which is less then 0.1 T. A constant magnet design is under consideration now.

This investigation shows that the proposed superhigh-power RF regotron-type generator is to produce 5 - 10 MW RF power in continuous mode with the 70 -80 per cent efficiency. The regotron-type generators should also be used in the energy supply systems of high-energy particle accelerators with high mean currents.

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