TWO METHODS OF PHASING THE ACCELERATOR RF SYSTEMS WITH SELF-EXCITATION

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1 INTRODUCTION

Driven by the needs of new industrial technologies, there is an increasing effort to raise the average beam power of proton and electron accelerators. These high beam power accelerators will most likely be linear and, out of necessity, have many structures, each of which will be driven by a separate RF source. One of the obstacles in constructing such machines is the availability of a simple and reliable RF power supply system.

Self-excitation in a positive klystron-structure feedback loop is the simplest and most reliable excitation mode for a high duty factor, single-structure accelerator. Here, the system oscillates at the structure resonant frequency with the klystron frequency following it automatically [1]. We suggest to use self-excited mode of klystron-structure operation for a multi-structure accelerator. The main problem which should be solved for this method of building the RF systems is phasing of the independent self-excited systems [2].

We suggest two methods of phasing the auto-oscillating systems, first - using the interaction of the accelerated beam with the accelerating structure, and second - using external signal of a master oscillator which is mixed into the positive feedback loop between klystron and accelerating structure.

2 MEASUREMENTS AND RESULTS

2.1 Experimental Layout

Experimental investigations of the proposed RF systems were made at a prototype two-structure CW electron accelerator [3] whose block-diagram is shown in Fig. 1. A DC electron beam of the gun (E-gun) [1] with the energy from 70 to 100 keV, current from 0 to 16 mA, and normalized transverse emittance 5 mm∗mrad enters the prebuncher cavity (PB), a cylindrical resonator with TM_{010} mode at a frequency of 2,450 MHz. After the prebuncher the beam enters the first accelerator structure with graded-β (S_1), which accelerates the beam up to 500 keV. The output beam of the first structure passes through a cooled aperture (A) which serves as a low-energy filter and enters the second accelerator structure (S_2) with tapered-β. This structure is used as a test-bed for investigations of beam phasing for auto-oscillating systems. Beam power and current at the accelerator output are measured by the Faraday cup (FC). To focus the beam solenoidal lenses L_1 and L_2 are used. Beam alignment is carried out by steerers St_1 and St_2.

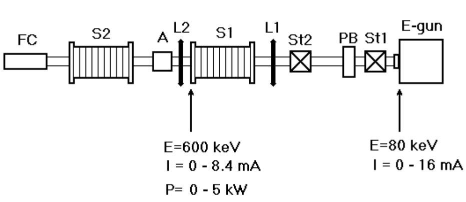

Fig. 1. Block-diagram of the accelerator.

2.2 RF Power Supply System I

Block-diagram of the RF power supply system for investigating beam phasing of self-excited systems is shown in Fig. 2. 22 kW RF klystrons (K_1 and K_2) at the frequency 2,450 MHz [1] are used to drive the accelerator structures. The first structure (S_1) operates in a self-excited mode and forms a reference signal for the prebuncher (PB). The signal of the first structure which is taken from the RF probe passes through the electrically driven p-i-n attenuator (A_1) and coaxial phase-shifter (φ_1) and enters the klystron. Phase conditions of self-excitation are chosen by the phase-shifter. The feedback p-i-n attenuator regulates the output power of the klystron and, consequently, the amplitude of the accelerating field.

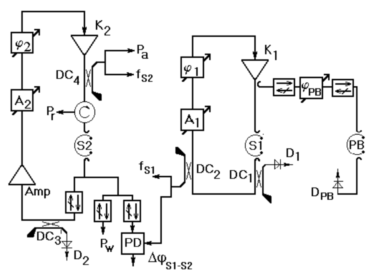

Fig. 2. Block-diagram of the RF power supply system I.

D_1-signal is used by the system of amplitude stabilization, which controls a p-i-n attenuator (A_1) current stabilizing the amplitude of the accelerating field in the first structure at the level of 10^{-3}. Such a stabilization compensates beam loading. A part of the klystron's power (~60 W) is used to drive the prebuncher. The klystron K_1 operates without a circulator.

The second structure (S_2) is used to test the process of beam phasing of self-excited systems. The structure is driven by the klystron (K_2) which operates in a self-excited mode at a power level approximately defined by the equation from [2]:

$$P_a = (i_b^2 Z) / (4\beta) \qquad (1)$$

We made the measurements at a value of average current i_b = 5 mA. For our accelerator structure with experimental values of shunt impedance Z = 14 MΩ and coupling constant $\beta \approx 1.0$, required operational level of the klystron power at a non-linear part of the amplitude characteristic is $P_a \sim 200$ W. To get about 300 W klystron output in saturation using a 22 kW klystron we introduce into the feedback loop a RF amplifier with strongly non-linear characteristic which limits RF signal amplitude at the klystron output.

RF system of the second structure is designed in a way which allows to measure the RF power balance in the system. Half of the RF signal of the structure taken from the RF probe is used to measure power dissipated in the structure walls (P_w) and phase difference between the structures ($\Delta\varphi_{S1\text{-}S2}$) via phase detector (PD). The rest of the structure's signal enters a 5-W amplifier (Amp), passes the electrically driven p-i-n attenuator (A_2), coaxial phase shifter (φ_2) and enters the klystron. Phase conditions of self-excitation are chosen by the phase shifter, output power of the klystron - by p-i-n attenuator. Klystron power (P_a) and operation frequency (f_{S2}) are measured from a waveguide directional coupler (DC_4). In the RF system of this structure we use a circulator, mainly for measuring reflected power (P_r) and beam induced power when the feedback loop is not closed. Diode D_2 is used to control accelerating field amplitude.

To change the resonant frequency of the second structure in the range of 500 kHz (and, hence, frequency detuning) we introduced thermoelectric heaters with the power 0 ÷ 14 kW into the cooling circuit of this structure.

2.3 RF Power Supply System II

Block-diagram of the RF power supply system for investigating phasing of self-excited systems with external signal is schematically shown in Fig. 3. RF signal of the master oscillator with regulated amplitude (A_{ex}) and phase for S_2 (φ_{ex}) is mixed into the feedback loop of the first and second accelerating structures through the 3 dB-couplers. Other elements of the RF system and their functions correspond to those used in method I (Fig. 2). RF parameters which can be measured in the experiments are -- operation frequencies (f_{s1}, f_{s2}), accelerating field amplitudes (D_1, D_2), phase difference

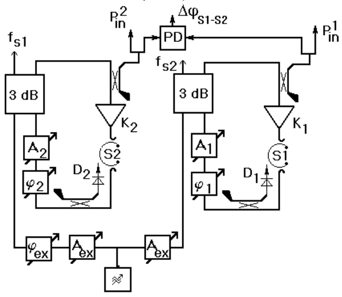

Fig. 3. Block diagram of the RF power supply system II.

between the structures ($\Delta\varphi_{S1\text{-}S2}$), and RF powers at klystron inputs (P_{in}^1, P_{in}^2).

2.4 Experimental Results and Discussion

In the experiments with RF power supply system I we measured dependencies of system parameters on feedback attenuation, feedback phase, and frequency detuning between structures S_1 and S_2.

To define parameters describing beam interaction with the accelerator structure we measured dependencies of power dissipated in the structure walls (P_w), reflected power (P_r), and phase difference ($\Delta\varphi_{S1\text{-}S2}$) on frequency detuning ($\delta = 2(f_{S1} - f_{S2})/ f_{S1}$) under the conditions when the klystron K_2 was switched off. From these dependencies we estimated loaded quality factor, Q_l = 8000 ± 500, coupling constant, $\beta = P_r / P_w = 0.9 \pm 0.1$, and shunt impedance, $Z \approx 14$ MΩ, of the structure.

At the next step we measured starting beam current when the self-excited oscillations at the resonant frequency of the second structure pass to the forced oscillations at a bunch frequency. These measurements were made at different values of frequency detuning in the range $-3{\cdot}10^{-4} \div +1.3{\cdot}10^{-4}$. Transition to the forced oscillations at different values of δ was observed at initial beam currents of 2.5 ÷ 3.0 mA for the klystron power of 200 ÷ 400 W. For further measurements we chose the beam current of 5 mA.

The question of particular interest for the proposed method of phasing the self-excited systems is experimental observation of beam acceleration and measurements of acceleration efficiency. To demonstrate the validity of our approach we measured power balance in the system depending on frequency detuning δ. Measured dependencies are shown in Fig. 4a. Two curves for the changes of beam power, ΔP_b^1 and ΔP_b^2, were obtained by two independent methods. The first dependence ΔP_b^1 was calculated from power balance in the system:

$$\Delta P_b^1 = P_a - P_w - P_r, \qquad (2)$$

and the second, ΔP_b^2, was calculated as a difference

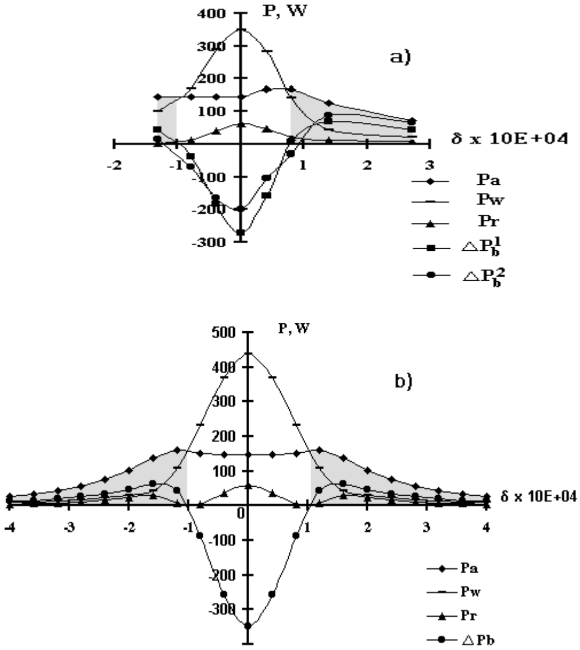

Fig. 4. Dependence of system parameters on frequency detuning: a) - experiment, b) - calculations.

between the measured beam power, P_b, and calibration value of beam power, P_b^{cal}, measured with second klystron switched off:

$$\Delta P_b^2 = P_b - P_b^{cal}. \quad (3)$$

Darkened areas in the figure show the range of frequency detuning where beam acceleration is experimentally observed, $\delta > 0.8 \cdot 10^{-4}$ and $\delta < -1.0 \cdot 10^{-4}$. Maximum increase of beam power is ΔP_b = 70 W $\pm$ 5 W (from power balance, eqn. (2)), which gives the acceleration efficiency:

$$\varepsilon = \Delta P_b / P_a \cdot 100\% = 58\% \pm 4\%.$$

Fig. 4b shows the same dependencies calculated using the model described in [2]. Experimental and calculated dependencies are practically similar and give the same values for the increase of beam power. Obtained results validate our approach and demonstrate predictive capabilities of the model.

In the experiments with RF power supply system II (Fig. 3) we measured dependencies of system parameters on feedback attenuation and phase, external signal amplitude and phase, and frequency detuning between the external signal and accelerating structures. First, we measured the range of frequency detuning and external signal amplitudes when the self-excited oscillations pass to the forced oscillations at the frequency of the external signal. This process takes place in a wide range of $\delta \sim 0 \div 10^{-3}$ for the amplitudes of the external signal 10 ÷ 100 mW (which is 2 ÷ 20% of the klystron input signal). The phase of the accelerating field in this system is defined by the phase of the mixed external signal. In our measurements the phase difference between the accelerating structures was regulated by changing the phase of the external signal mixed into the feedback of the second section (phase shifter φ_{ex} in Fig. 3). Measured dependence of beam power on phase difference $\Delta\varphi_{S1\text{-}S2}$ is shown in Fig. 5. The measurements were made at the average beam current 2 mA. It is seen from the figure that with mixed external signal the self-excited oscillations

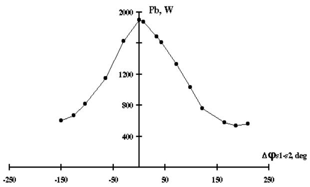

Fig. 5. Dependence of beam power on $\Delta\varphi_{S1\text{-}S2}$

in both accelerating structures become phased and provide full acceleration of the beam.

3 CONCLUSION

Two methods of phasing the self-excited systems using 1) - interaction of the accelerated beam with the accelerating structure, and 2) - external signal which is mixed into the positive feedback loop -- have been shown to provide efficient beam acceleration. Both methods considerably simplify the design of RF systems for multi-structure linacs making them simple, reliable, and inexpensive.

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REFERENCES

[1] A.S. Alimov, B.S. Ishkhanov, I.M. Piskarev, V.I. Shvedunov, and A.V. Tiunov, “Operational Experience with Room Temperature Continuous Wave Accelerator Structures”, *Nucl. Instrum. Meth.* **A328** (1993) p. 385.

[2] Chubarov, D. Ermakov, and V. Shvedunov, “Beam Phasing of Autooscillating Systems”, in *Proceedings of the 1994 European Particle Accelerator Conference*, vol. 3, p. 1969.

[3] Alimov, A. Chepurnov, O. Chubarov, D. Ermakov, K. Gudkov, B. Ishkhanov, I. Piskarev, and V. Shvedunov, “A Compact Low-Energy CW LINAC with High Beam Current”, in *Proceedings of the 1995 Particle Accelerator Conference*, v. 2, p. 1096.