COMPACT LOW ENERGY CW LINAC WITH HIGH BEAM CURRENT

A.Alimov, A.Chepurnov, O.Chubarov, D.Ermakov, K.Gudkov, B.Ishkhanov, I.Piskarev, V.Shvedunov, A.Shumakov, Institute of Nuclear Physics, Moscow State University, 119899, Moscow, Russia.

I. INTRODUCTION

Up till now the main sources of electrons with high average power at low energies were DC accelerators and pulsed linear accelerators. Development of new technologies requires an increase of electron beam energies up to 10 MeV and beam powers up to hundreds kW. For these aims a CW mode of operation is more preferable. However, development of powerful CW linacs faces a number of problems.

1. Because of relatively low values of accelerating fields in a CW mode and a high average power of an electron beam, effective capturing of the particles into acceleration and further acceleration without losses present a serious problem.

2. Powerful accelerators require RF klystrons with high average power and, as a rule, can be designed only as multi-section accelerators, each section being supplied by a separate klystron.

3. Characteristics of the accelerator structures are to be optimised to reach maximum characteristics of CW linacs.

The present paper deals with the experimental investigation of electron capturing, design of a simple RF power system for multi-section accelerator, and beam acceleration at the prototype accelerator with two accelerator sections.

II. ACCELERATOR DESCRIPTION. ACCELERATOR STRUCTURE PARAMETERS

The block-diagram of a prototype two-section accelerator 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 normalised transverse emittance 5 mm*mrad enters the buncher cavity (B). As a buncher we use a cylindrical copper cavity with TM_{010} mode at a frequency of 2450 MHz. The

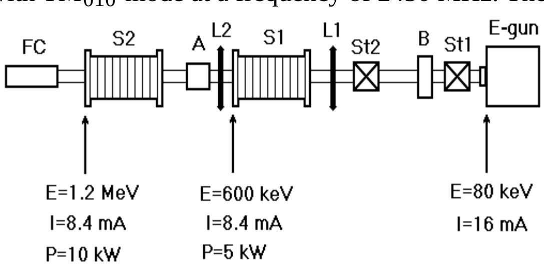

Fig.1. Block-diagram of the accelerator.

buncher has a probe for power supply and a probe for field control. Fine frequency tuning of the buncher is made by a tuning plunger in the range of 2450±2 MHz. Loaded quality factor of the cavity Q_l = 3500 with a coupling constant 1.0. The calculated value of intrinsic quality factor Q_0 = 9000, shunt impedance R = 1.4 MΩ. After the buncher the beam enters the first accelerator section with graded-β (S_1), which accelerates the beam up to 600 keV. The output beam of the first section passes through a cooled aperture (A) with a diameter of 10 mm, which serves as a low- energy filter, and enters the second accelerator section (S_2) with tapered-β which accelerates the beam up to the energy of 1.2 MeV. 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.

The accelerator was constructed with two accelerator sections first designed for the injector linac of Moscow CW RTM [2,3]. Both sections are made on the basis of on-axis coupled accelerator structure with effective shunt impedance 78 MΩ/m (for β = 1) and operation frequency 2450 MHz. The first section consists of 9 accelerating cells with β from 0.582 (1^{st} cell) to 0.869 (9^{th} cell). The second section consists of 7 accelerating cells - first three cells have β = 0.945, next three cells have β = 0.975. Both sections have circumferential cooling only [3]. Loaded quality factors for both sections are Q_l = 7000, and the coupling constant with a feeding waveguide is 1.2 (overcoupling).

III. RF POWER SUPPLY SYSTEM

One of the problems of CW operation of accelerator structures is a shift of a resonant frequency resulting from thermal deformations of the structure during start-up. This frequency shift depends on a level of RF power losses and on cooling efficiency. For our accelerator structure with circumferential cooling the frequency shift can exceed a bandwidth of a resonant curve at a moderate level of RF losses (20 kW/m at RF frequency 2450 MHz) [3]. Dependence of the structure resonant frequency on the dissipated RF power results in an asymmetry of a resonant curve which can be interpreted as a non-linear resonance.

Under these conditions the most simple and reliable method of operation of a single-section accelerator is a self-excited mode in a positive feedback loop between klystron and accelerator section. In this mode of operation the system oscillates at a section's resonant frequency and a klystron's frequency follows it automatically.

A transition from one accelerator section to two accelerator sections complicates the structure of a RF system. The complication arises from the necessity to phase the sections and from a presence of different frequency shifts of the sections. As a result the second section can not operate in a self-excited mode, and should be driven by a reference signal of the first section.

The block-diagram of the accelerator RF system is shown in Fig.2. 22 kW CW klystrons (K_1 and K_2) at the frequency 2450 MHz [3] are used to drive the accelerator sections. The klystrons are isolated from the sections by T-circulators (C_1 and C_2). The first section (S_1) operates in a self-excited mode and forms a reference signal for the second section (S_2) and the buncher (B). The signal of the first section which is taken from the RF probe passes through the electrically driven coaxial phase-shifter (φ_2) and p-i-n attenuator (A_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. Reflected power level is controlled by a diode D_1, the accelerating field

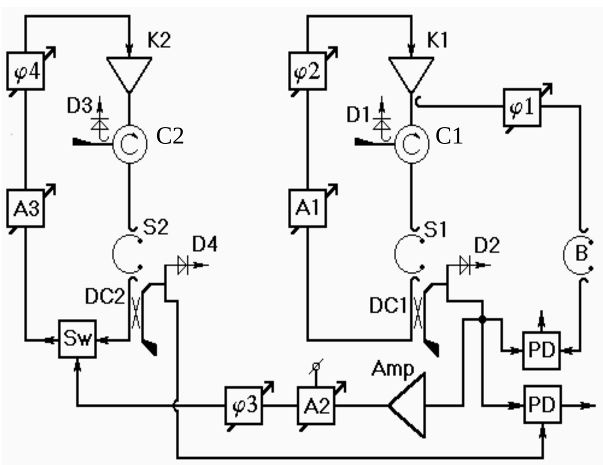

Fig. 2. Block-diagram of the accelerator RF system.

amplitude, by a diode D_2. D_2-signal is used by the system of amplitude stabilisation, which controls a p-i-n attenuator (A_1) current stabilising the amplitude of the accelerating field in the first section at the level of 10^{-3}. Such a stabilisation is very essential for our system with high beam loading. A part of the klystron's power (~ 60 W) is used to drive the buncher. The signal is taken from a probe, located in the output waveguide of the klystron. A part of the output section's signal from the directional coupler (DC_1) is used for monitoring phase differences between the first and the second sections, the first section and the buncher, for frequency measurements, and as a reference signal for driving the second accelerator section.Start-up of the second section (S_2) is carried out in a self-excited mode [3]. A positive feedback loop of S_2 contains the p-i-n attenuator (A_3) and the phase-shifter (φ_4). The positive feedback loop is being closed with a help of the RF switch (Sw) which has two input connectors and one output connector. The attenuator and phase-shifter adjust the phase and amplitude of self-excited oscillations, providing the RF power to reach the operating level. When the section's resonant frequency coincides with that of the first section, the klystron's (K_2) drive is switched from the feedback loop to the reference signal of the first section. Phase and amplitude of the reference signal are adjusted by the 4-W RF amplifier (Amp), p-i-n attenuator (A_2), and phase-shifter (φ_3). Reflected power level is controlled by a diode D_3, the accelerating field amplitude, by a diode D_4. D_4-signal is also used for amplitude stabilisation at the level of 10^{-3}. A part of the output section's signal from the directional coupler (DC_2) is used for monitoring the phase difference between the first and the second sections and for frequency measurements.

The sources of frequency instability, such as cooling water temperature and flow, change practically in the same way for both sections and do not destructively influence the system operation.

IV. BEAM ACCELERATION EXPERIMENTS

Beam acceleration experiments were carried out in three stages. At the first stage the buncher was switched off and we chose the phase difference between sections 1 and 2 to obtain maximum current and maximum beam power at the Faraday cup. Dependence of the beam current on the phase difference between the accelerator sections is shown in Fig.3.

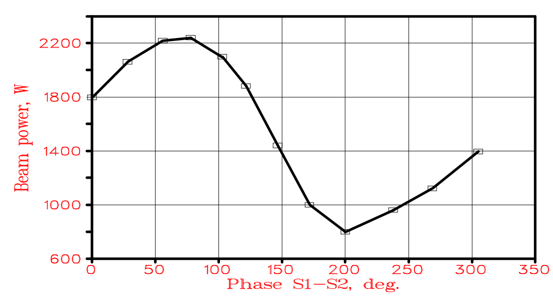

Fig. 3 Dependence of the beam power on the phase difference between the sections.

The measurements were made at gun voltage U = 80 kV, cathode current I_{cath} = 6.5 mA. Maximum output parameters of the accelerator obtained without the buncher were as follows: beam energy 1.2 MeV, beam current 5.5 mA (cathode current 16 mA), beam power 6.6 kW.

At the second stage we switched on the buncher and chose the buncher phase (respective to the phase of section 1) and the buncher amplitude (in these measurements section 2 was switched off). Dependence of the output beam current on the buncher phase is shown in Fig.4.

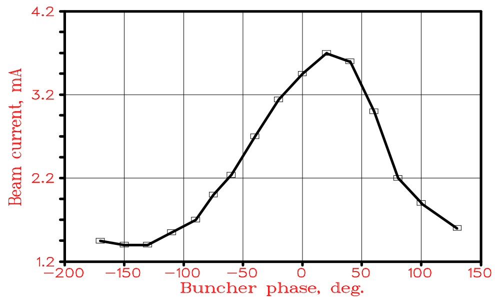

Fig. 4. Dependence of the output beam current on the buncher phase.

The dependence has the expected sinus form and makes it possible to choose the optimal phase of the buncher. It was measured at gun voltage U = 80 kV, cathode current I_{cath}= 7.0 mA, section power P_{S1}= 10 kW, and buncher power P_B = 60 W. The output beam energy was 600 keV. Fig.5 shows the dependence of the output beam current after the first section on the power, dissipated in the buncher. The measurements were made at the optimal value of buncher phase. The buncher power was regulated from 0 to 66 W. This dependence was measured at gun voltage U = 80 kV, cathode current I_{cath}= 6.8 mA; beam energy after the first section was 600 keV. With our experimental layout (Fig.1) the electrons which were not captured into acceleration by the first section can not reach the Faraday cup because the focusing length of the lens L_2 for low energy electrons is several centimetres, and these electrons cannot pass through the aperture. Hence, the capture efficiency

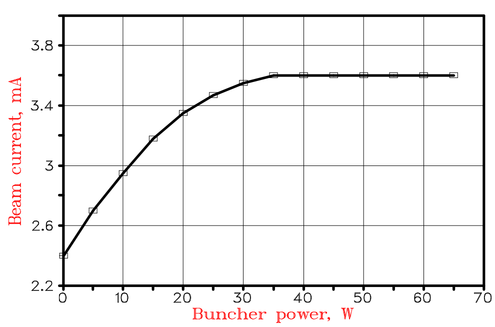

Fig. 5 Dependence of the output beam current on the buncher power.

can be estimated as a relation of the current at the Faraday cup to the cathode current of the gun. Beam energy was estimated using a relation of the measured beam power to the measured beam current. From Fig.5 the capture efficiency is equal to 35% when the buncher is switched off, and increases up to 53% at the optimal level of buncher power 40 - 66 W.

At the third stage we carried out beam acceleration experiments with two accelerator sections and the buncher for optimal values of RF phases and RF amplitudes. The maximum value of beam current was limited by the parameters of the gun power supply and amounted to 16 mA. Dependence of the beam power on the cathode current up to 16 mA was linear. This means that space charge effects have no essential influence at these currents. With the cathode current of 16 mA, capture efficiency of 53%, the output beam current was equal to 8.4 mA at beam energy of 1.2 MeV. This corresponds to beam power of 10 kW. The value of beam power, measured by the Faraday cup, was also 10 kW. The accelerator operated under these conditions for several hours without additional tuning of its parameters.

V. SUMMARY

The prototype two-section CW linear accelerator with a simple RF power supply system was constructed. The electron beam with the energy of 1.2 MeV and beam power of 10 kW was obtained.

CW linear accelerator of this type, to our opinion, has the following advantages and perspectives:

1. The accelerator is rather compact. The weight of the two-section accelerator with radiation shielding is ~2000 kg (without electron gun and klystrons power supply). The length of the accelerator itself (without the gun and the buncher) is ~1 m, so, the power gradient is ~10 kW/m and the energy gradient 1.2 MeV/m. As it was mentioned above, the beam current in our experiments was limited by the gun power supply. A reserve of klystrons power (maximum power 22 kW) makes it possible to accelerate beam currents of 20 mA with the same energy gradient 1.2 MeV/m. Preliminary PARMELA calculations with space charge show that this current can be accelerated without compensating the space charge influence. Accounting for the 53% capture efficiency a beam current of 20 mA corresponds to a reasonable value of a cathode current ~40 mA. In this case the power gradient increases up to ~24 kW/m with the same energy gradient of 1.2 MeV/m.

2. Beam energy and beam power can be increased by adding accelerator sections with β=1. RF power supply system for each new accelerator section will be quite similar to the RF system of the second section of the described accelerator.

V. REFERENCES

[1] B.S. Ishkhanov et al. "100 keV Electron Gun for Moscow CW RTM", Pribori i Technica Experimenta, 3 (1987), pp. 24-26 (in Russian).

[2] A.S.Alimov et al. "Beam Acceleration Experiments in the Capture Section of CW Race-Track Microtron". INP MSU-89-61\128 (1989), 28 pp.

[3] A.S.Alimov et al. "Operational Experience with Room Temperature Continuous Wave Accelerator Structures", Nucl.Instr. and Meth. A328 (1993) pp. 385-397.