INDUSTRIAL PROTOTYPE OF COMPACT CW LINAC*

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Abstract

A compact continuous-wave linear accelerator for industrial applications with an output electron energy of 1 MeV and design average beam current of 25 mA is described. The results of beam dynamics, accelerating structure, and RF system simulation are presented, accelerator construction and first results of its commissioning are described.

INTRODUCTION

1 MeV RF CW electron accelerator [1] with a maximum beam current of 25 mA for radiation technologies is being developed at SINP MSU. Accelerator commissioning started in the falls, 2013. At present accelerator is being operated for testing radiation influence at the materials properties and for investigating the radiation degradation of solar cells and circuit boards properties, designed for space operation.

ACCELERATOR DESCRIPTION

The accelerator scheme is shown in Fig. 1.

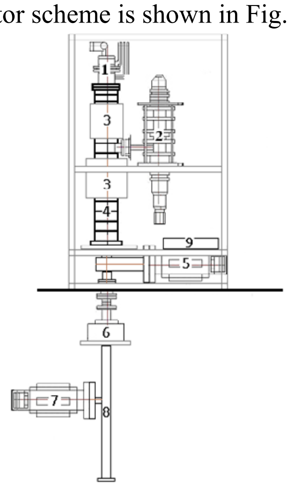

Fig. 1. The accelerator scheme.

An electron gun (1 in Fig. 1) with two focusing electrodes and an operating cathode voltage of -15 kV is located directly at the input flange of the accelerating structure (4). Focusing electrode voltage controls an output gun current from 0 to 250 mA. On-axis coupled biperiodic accelerating structure operates at a frequency of 2450 MHz. A klystron with a maximum output power of 50 kW [2] supplies the accelerating structure with RF power through the central accelerating cavity. Similar high voltage allows to use a common power supply for the klystron and the electron gun. The klystron operates in a self-oscillating mode provided by a low-power RF system (9) which fixes out a positive feedback loop between the klystron and accelerating structure. Magnetic shielding (3) is installed above the structure. Steering coils and solenoidal lens are located in between the structure and magnetic shielding. The accelerator vacuum is provided by an ion pump (5) and a sputter-ion pump of the electron gun. Depending on beam applications different systems can be installed at the output of the accelerating structure. To measure high power beam parameters a Faraday cup with water cooling is placed at the output, provided with vacuum system comprising a rough pump and a turbomolecular pump. The beam scanning system, consisting of a beam divergence camera (8), bending magnet (6) and an ion pump (7) is used for materials irradiation. The bending magnet is powered by the voltage with an amplitude and shape required for the formation of a uniform radiation field over the entire surface of the output window with 5x70 cm^2 dimensions. Accelerator operating volume is separated from atmosphere by 50 microns titanium foil fixed at the beam divergence camera output flange. The accelerating structure and the klystron are cooled with distilled water. A total water consumption of accelerator cooling system is 120 l/min.

The accelerator operation is managed by the control system based on programmable microcontrollers (PMC). The system provides control of all accelerator systems via the remote terminal and information on their operation status. The control system is equipped with a set of emergency – red buttons, and operational interlocks - accelerator hall open door, poor ventilation level, bad vacuum, insufficient structure and klystron water flow, unlocked accelerator case, as well as klystron beam and body overcurrents.

Accelerator photo with the beam scanning system is shown in Fig. 2.

Fig. 2. Photo of the accelerator with the beam scanning system.

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ACCELERATOR SYSTEMS CALCULATION

Accelerating Structure Simulation

Since we have used a common power supply for the gun and the klystron, our electron gun beam energy is 15 keV. To make our accelerator compact, we eliminated the traditional bunching system, drift space, and focusing elements and mounted the gun directly to the accelerator structure. Injecting a 15 keV direct current gun beam into the accelerating structure cells places large demands on the beam dynamics [3]. Electron velocities significantly vary in consequent structure cells, therefore the cells lengths vary too. Besides, to provide high capture efficiency, I_{out}/I_{gun}, we use the initial structure cell as a pre-buncher. To accomplish this we must provide the maximum bunching parameter at the second cell (the first accelerating cell) center.

Electromagnetic fields and beam dynamics in the accelerating structure were calculated with SUPERFISH [4] and PARMELA [5] codes. Electron gun calculations were carried out with EGUN [6] code for different focusing electrodes voltages. An example of particle trajectories for focusing electrodes voltages 500 V and 2500 V with respect to the cathode potential for beam current 53 mA is shown in Fig. 3 Calculated beam spot and phase space at the structure output with 19.1 kW RF power dissipated in the walls are shown in Fig. 4. In this case the capture efficiency, I_{out}/I_{gun}, is 38%.

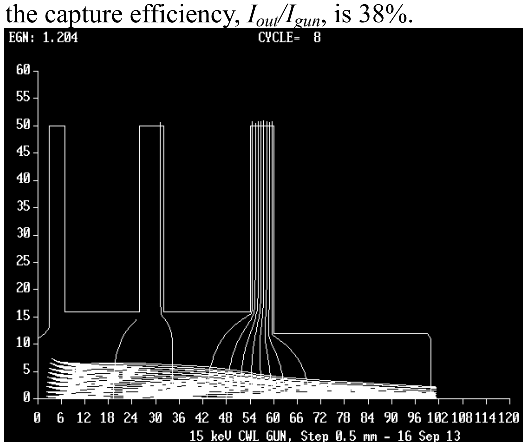

Fig. 3. Calculated particle trajectories in the electron gun for focusing electrodes voltages 500 V and 2500 V with respect to the cathode potential.

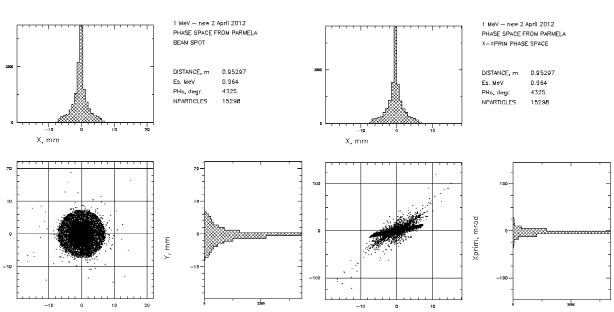

Fig. 4. Calculated beam spot and phase space at the structure output.

RF System Design

Accelerator RF system schematic is shown in Fig. 5.

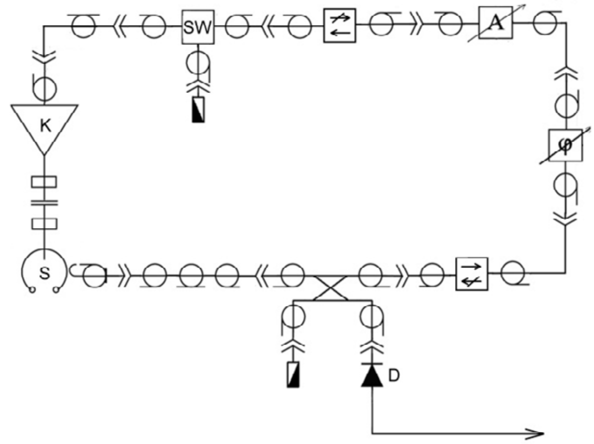

Fig. 5. Accelerator RF system schematic.

We use a 50 kW CW klystron (*K*) to drive the accelerating structure (*S*). Some 22 kW of the klystron power is dissipated in the structure walls providing the accelerating field and, depending on beam current, up to 25 kW goes into the beam. When operating in the self-excited mode, the system oscillates at the structure resonant frequency, which the klystron frequency automatically follows. A RF probe provides the structure signal that passes through electrically driven phase-shifter (φ) and attenuator (*A*), and then enters the klystron. The self-excitation phase conditions are chosen by the phase-shifter while the feedback attenuator regulates the klystron output power and, consequently, the accelerating field amplitude. This amplitude is controlled by a diode (*D*). To start/stop oscillations a RF switch (*SW*) is used.

To define optimum attenuation of the feedback we made calculations of accelerator parameters on beam loading for different values of feedback attenuation.

RF power dissipated in the structure walls P_w and beam energy E are connected with structure coupling β, beam current I, output klystron power P_{kl}, effective shunt impedance Z_{ef} and structure length L by relations [7]:

$$P_w = \frac{4P_{kl}\beta}{(1+\beta)^2}\left(1-\sqrt{\frac{I^2 Z_{ef} L}{4P_{kl}\beta}}\right)^2$$

$$E = \frac{\sqrt{4P_{kl}\beta Z_{ef} L} - I Z_{ef} L}{1+\beta}$$

Reflected power P_r is defined as $P_r = P_{kl} - P_b - P_w$, where $P_b = EI$.

Amplitude characteristics of the klystron was approximated by the square of the 1-st order Bessel function, normalized in such a way, that maxima of the Bessel function and of amplitude characteristics of the klystron approximately coincided.

Results of the calculation for optimum feedback attenuation of 39 dB, 1.22 coupling value, 53 MΩ/m effective shunt impedance, and 0.84 m structure length are shown in Fig. 6.

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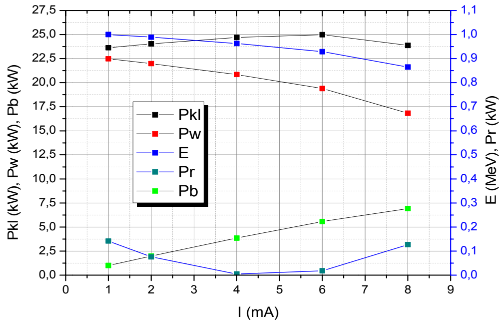

Fig. 6. Results of the RF system calculation.

BEAM SPECTRA MEASUREMENTS

To determine beam energy, current, and power dependence on RF power losses in the structure walls, spectra measurements using a magnetic spectrometer were carried out. Magnetic spectrometer includes a 45^0 bending magnet with its power supply, slit collimator, fixed in the focal plane of the magnet at an angle of 45^0, two isolated beam collectors - Faraday cups, placed at the angles 0^0 and 45^0, and its own vacuum system. The collectors are connected to ground through precise ground resistors for measuring the collectors electron currents.

Measurements were made at a beam current of 500 mA for different values of RF power losses in structure walls. Figure 7 shows measured and calculated spectra for 19.1 kW RF power losses. Figure 8 shows measured dependence of spectrum peak energy on different values of RF power losses in the walls.

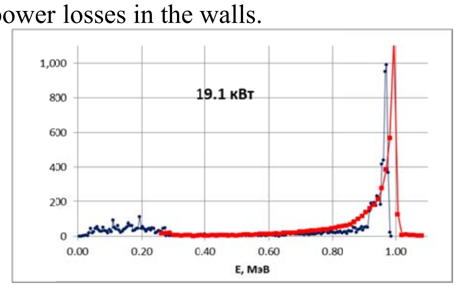

Fig. 7. Measured (red) and calculated (blue) beam spectra for 19.1 kW RF power losses in the walls.

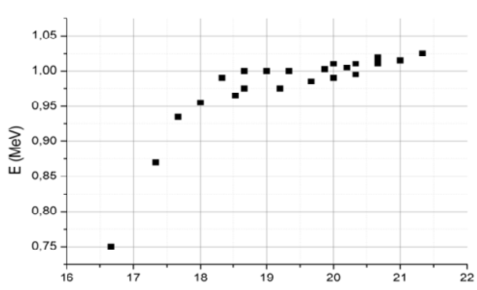

Fig. 8. Spectrum peak energy dependence on RF power losses in the walls.

Beam energy varies slightly when RF power losses in the structure walls are above 18.5 kW. Changing a magnitude of the electromagnetic field in the structure in this range mainly affects the capture efficiency.

HIGH POWER BEAM EXPERIMENTS

The accelerating structure was tuned to a coupling value of 1.22. It corresponds to the minimum of the reflection from the structure at a beam current of ~ 4.3 mA. In the absence of a circulator between the klystron and the structure a deviation from the optimal current affects the reflected wave influence on the klystron output cavity, reducing its operation stability and efficiency.

To obtain and measure a high power beam we installed a copper collector with water cooling at the output of the accelerating structure. The cooling circuit of the collector was connected with a measuring system, which allowed to measure electron beam power by temperature difference between the cooling water input and output temperatures and its flow. For pumping beam line at high beam currents a vacuum system, comprising a rough pump and a turbomolecular pump, was installed at the collector input. In such a configuration, currents up to 6.1 mA with RF power losses in the walls of 19.5 kW were obtained.

CONCLUSION

We have constructed the compact and reliable CW LINAC with 1 MeV output electron energy, thereby validating our design goals. In the first beam tests, our accelerator has provided a 1 MeV, 6 mA, 6 kW electron beam at a 18 mA gun current, thus demonstrating 30% capture efficiency and design beam energy. The accelerator tests are now in progress. Increasing the beam current to 25 mA and capture efficiency to 50% will require tuning the coupling between the structure and the klystron, some modification of the beam collector and vacuum system to improve vacuum conditions in the accelerator.

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