COMMISSIONING OF HIGH EFFICIENCY STANDING WAVE LINAC FOR INDUSTRIAL APPLICATIONS

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Abstract

We present the results of the commissioning of the pulsed linear electron accelerator with beam energy of 10 MeV, developed with the participation of scientists and engineers of the SINP MSU, LEA MSU Ltd. and JSC "RPE "Toriy". The source of RF power for accelerator is a multibeam klystron KIU-147A operating at 2856 MHz with pulse output power 6 MW and an average power of 25 kW. As a result of commissioning we received at the output of accelerator scanning system an electron beam with an energy of 10 MeV and an average power of more than 15 kW. Capture ratio and electronic efficiency of 1.24 m long accelerating structure are greater than 60% and 75%, respectively.

INTRODUCTION

Described in this paper a prototype of industrial electron linear accelerator for beam energy and average power of 10 MeV and 15 kW is based on our previous studies [1,2].

We describe the main accelerator systems: accelerating, RF, high-voltage power supply, beam scanning and diagnostic. Finally, a description of methods and results of measurements of the basic beam parameters is given.

ACCELERATING SYSTEM

Our linear accelerator is based on a standing wave bi-periodic on-axis coupled accelerating structure. In the process of the accelerating structure optimization we chose sufficiently large beam hole diameter and large webs thickness, thus increasing the vacuum conductivity, reducing the beam losses and increasing the limit of average RF losses in the walls. These features of accelerating structure are reason of a moderate value of the effective shunt impedance $Z_{eff} \approx$ 70 MOm/m. High overall efficiency of the accelerator is achieved by high value of accelerated pulse current.

The next relations provide rough estimation of accelerator parameters. Pulsed RF power required to get beam energy E = 10 MeV is:

$$P_w = \frac{E^2}{Z_{eff}L} \approx 1.14 \text{ MW} \quad (1)$$

for accelerating structure electrical length L = 1.25 m. With maximum klystron pulsed RF power $P_{kl} = 6$ MW, taking into account losses in the waveguide system, about $P_b =$ 4.5 MW pulsed beam power can be reached which corresponds to pulsed beam current $I_b = 450$ mA and average beam power 18 kW with maximum duty cycle of klystron KIU-147A D_{max} = 0.4 % [3].

Electronic efficiency of accelerating structure thus is:

$$\eta = \frac{P_b}{P_b + P_w} \cdot 100\% = 80\ \%, \quad (2)$$

which is obtained with optimal coupling coefficient of the accelerating structure with waveguide:

$$\beta = 1 + P_b/P_W = 4.94. \quad (3)$$

Detailed computer simulation of accelerating structure and beam dynamics was done in [4]. Parameters of the first three accelerating cells were optimized to provide high capture efficiency and proper beam focusing with space charge forces taken into account. The rest 21 accelerating cells are β = 1. With total electric length of the accelerating structure is L = 1.24 m, RF power losses in the walls necessary to reach 10 MeV are 1.5 MW.

About 60% of nominal 750 mA electron gun current is accelerated to final energy within energy spread of ±0.3%. Beam current losses take place mainly in the initial part of accelerating structure, so beam power losses in the structure do not exceed 1.4% of accelerated beam power.

Two more features of our accelerating structure should be mentioned. First, if a focusing coil is installed at the initial part of accelerating structure, then the beam energy can be changed in the range 5 – 10 MeV by regulation of accelerating field level within 70%, wherein the capture efficiency is varied in the range 45 – 60% (for energy spectrum width ±0.3 MeV).

Second, for pulsed RF power losses in the walls 1.5 MW and duty cycle 0.4%, average RF power losses per unit of accelerating structure length are 4.8 kW/m. Due to large webs thickness cooling channels can be drilled in them as described in [1]. In this case, the limit for RF power dissipation is about 200 kW/m [5] and maximum possible average beam power with appropriate RF source is above 700 kW.

Three electrodes electron gun operating at -50 kV cathode voltage is used as an injector. Injected beam current can be regulated between 200 – 900 mA by changing control electrode voltage in the range 2 – 15 kV with respect to cathode.

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TEST STAND

The accelerator commissioning was done at a stand shown in Fig. 1. Besides the accelerating structure with electron gun, manufactured by JSC "RPE "Toriy" [6], the stand included low and high power RF systems, high voltage klystron modulator and gun power supply, vacuum system, cooling system, beam scanning, beam diagnostic and control systems.

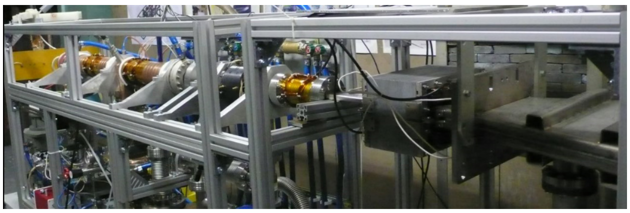

Figure 1: Test stand photo.

High power RF system consisted of klystron, ferrite isolator, directional coupler and isolating gas system.

Two variants of low power RF systems were tested: one based on an autooscillation principle with the accelerating structure in the klystron feed-back loop [7], and another with external excitation by master oscillator with adjustable frequency, and with a p-i-n attenuator followed by a solid state amplifier at klystron RF input.

To power klystron we used solid-state modulator [8] with pulsed/average power supplied to klystron 13.2 MW/60 kW, high voltage pulse length regulated in the range 6 - 12 μs and pulse repetition rate regulated from 10 to 400 Hz. Photo of modulator pulses is shown in Fig. 2.

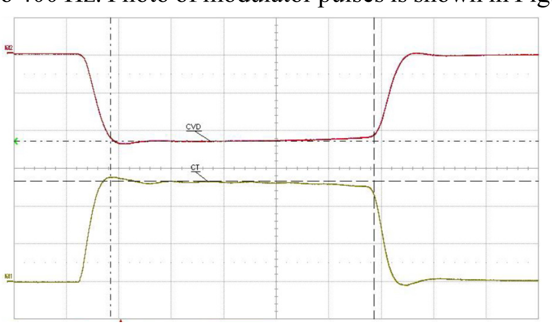

Figure 2: Modulator high voltage (upper trace) and current pulses with amplitudes 50 kV/270 A, respectively. Time scale is 2 μs/div.

Electron gun was powered by -50 kV DC power supply, current pulses were produced by providing regulated in the range 2 – 15 kV pulsed voltage to control electrode. Gun current pulse duration and position with respect to RF pulse can be regulated in a wide range.

Two configurations of the stand we used during the accelerator commissioning: one with cooled high power Faraday cup (FC) at accelerator exit (Fig. 3) and another with scanning magnet and scanning horn with 50 μm Ti foil window followed by cooled beam dump.

We used two methods to control accelerating field level: measurement of RF signal from antenna, installed in coupler cell, and measurement of average power losses in accelerating structure walls. To estimate pulsed RF power dissipated in the wall via antenna signal, the average power measured by power meter was divided by duty cycle, determined with RF diode, and multiplied by known attenuation factor of antenna and RF cable.

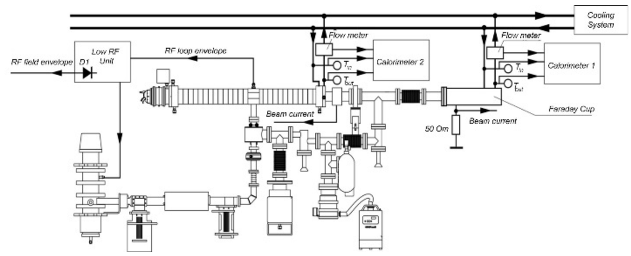

Figure 3: Stand configuration with FC at exit.

To estimate pulsed RF power dissipated in the structure walls by another method we measured average power using data from temperature sensors installed at structure cooling circuit inlet and outlet and from flowmeter. Pulsed power value was obtained by dividing average power by duty cycle. The results obtained by two methods were in good agreement and were used to estimate beam energy via a calibration curve found in beam dynamics calculations.

We controlled pulsed accelerated beam current also by two methods (Fig. 3): by beam current transformer (BCT) with sensitivity about 5 V/A, installed at accelerating structure exit, and by current of FC (or beam dump) loaded by 50 Ohm resistor. Example of signals from BCT and from FC, corresponding to about 430 mA current, is given in Fig. 4.

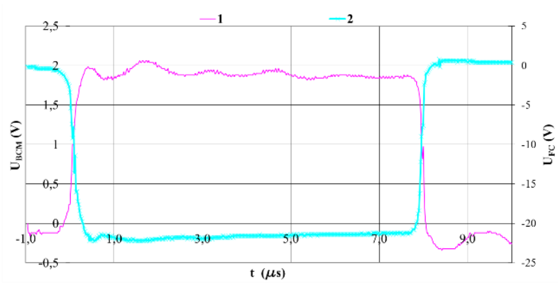

Figure 4: BCT (read curve) and FC (blue) pulses. Time scale is 2 μs/div.

We measured average beam power absorbed by FC or by beam dump using precise calorimeter consisting of inlet and outlet water temperature sensors, flowmeter and power calculator. The beam power measured by this method is somewhat underestimated (up to 10%) due to power escaped via bremsstrahlung radiation.

Average beam power, $\bar{P}_b$, and average beam current, $\bar{I}_b$, were used to estimate average beam energy:

$$\bar{E}_b = \bar{P}_b/\bar{I}_b \qquad (4)$$

Beam scanning along the horn exit window following a saw-tooth law with a frequency in the range 0.5 – 30 Hz and scanning width, regulated in the range 400 – 600 mm, was reached by powering the scanning magnet by a fast four-quadrant programmable power supply. We controlled current density distribution at the horn exit by measuring average current from 20 mm diameter cooled cylinder

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remotely movable along the exit window. Finally, to check the beam spot dimensions and form during the scanning we covered the beam dump wall by luminophore, tilted it for 450 and registered moving beam image with CCD camera synchronized with the beam pulses.

THE MAIN RESULTS

After accelerating structure training with FC at exit and reaching the average beam energy, estimated with expression (4), in the range 9.8 – 9.9 MeV for average beam power of a few kW, we installed scanning horn and did following measurements of beam power with the beam dump. Keeping constant average beam energy, we gradually increased the duty cycle by increasing the pulse length and pulses repetition rate. Dependence of the beam power on the duty cycle is shown in Fig. 5. To get the project value of beam power 15 kW it took about 16 hours of accelerator operation. Given value of maximum beam power does not include more than 1 kW of power escaped with bremsstrahlung radiation.

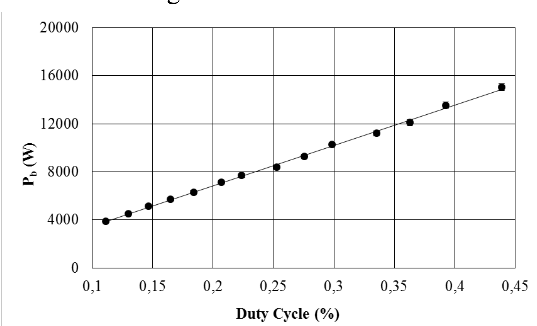

Figure 5: Dependence of measured beam power on the duty cycle.

In Fig. 6 we show results of measurement of the beam current distribution along the scanning horn exit window at 10 cm from the exit for two amplitudes of scanning magnet coils current. Current distribution uniformity is about ±3%.

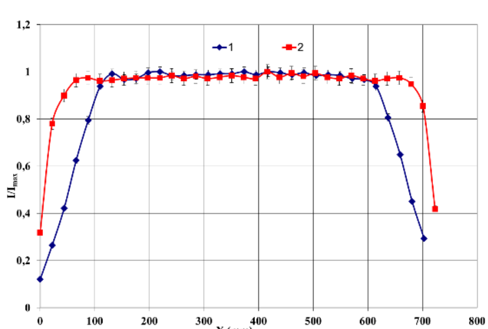

Figure 6: The beam current distribution at the scanning horn exit for two amplitudes of scanning magnet coils current.

Instantaneous beam images registered during the scanning at three positions along the exit window are shown in Fig. 7. Central image corresponds to about zero scanning magnet field. Two symmetrical images at upper and lower pictures correspond to beam position at exit window of about ±150 mm with respect to center. One can clearly see the beam dispersion due to energy spread. The dispersion, which can influence on the dose distribution during irradiation process, can be decreased by decreasing the energy spread. The energy spread is defined in part by specific of beam dynamics in accelerating structure, but the main contribution is due to variation of accelerating field at front and rear edges of the RF pulse. This contribution can be decreased by proper positioning of the gun current pulse with respect to RF pulse.

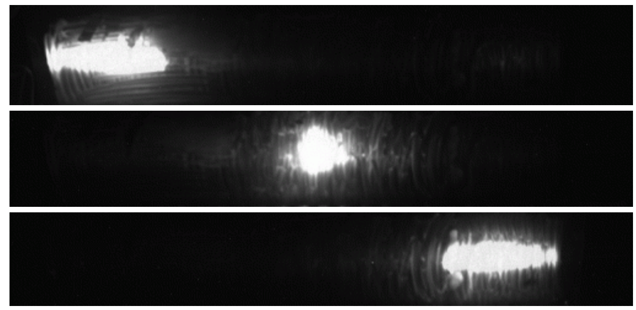

Figure 7: The moving beam spot images during the scanning.

CONCLUSION

The design accelerator parameters: beam energy of 10 MeV and average beam power of 15 kW have been reached during the accelerator commissioning. Electronic efficiency of accelerating structure of about 75 % have been obtained. Taking into account the efficiency of the klystron and modulator the overall efficiency of accelerator is close to 30% in nominal mode.

As the next series of experiments we plan to conduct beam parameters measurements in the range of energy regulation 5 – 10 MeV and to measure the beam energy spread depending on relative position of the gun current pulse with respect to RF pulse.

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