EXPERIMENTAL STUDY OF CHARACTERISTICS OF INTENSE ELECTRON BEAM INJECTOR

M.I. Aizatskyi, I.V. Khodak, V.A. Kushnir, V.V. Mytrochenko, S.A. Perezhogin, D.L. Stepin, V.F. Zhiglo
National Science Center “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine
E-mail: khiv@kipt.kharkov.ua

Application of low voltage electron source requires the use of steep change of on-axis RF field along the buncher for electrons to be bunched and accelerated efficiently. The paper presents the results of studies of the characteristics of the S-band injector based on such buncher. The injector consists of the 25 kV diode electron gun with current of 1.5 A, the toroidal cavity prebuncher as well as the three cavity buncher with the coaxial to rectangular waveguide transition for the RF power feeding and the sectional solenoid. The RF tests of the manufactured injector have shown its sufficient reliability and lack of multipactoring. Results of studies of the beam parameters at the injector output correlate well with the calculated data.

PACS: 29.25.Bx, 29.27.-a, 29.27.Ac

INTRODUCTION

It is necessary to provide valuable average current of accelerated electrons for series of nuclear physical investigations and especially for investigations of methods of medical radioisotopes production. It is well known that this task is provided by an electron beam injector mainly. Powerful linear electron accelerator of the radio-chemical division in NSC KIPT [1] is equipped by the injector that requires the electron beam shaping structure to be upgraded to minimize its spatial-energy performances. In this context we have studied the new manufactured injector of intense electron beam that has to be replaced in the accelerator mentioned above.

The prototype of the investigated injector is the injector system based on five-cavity resonance system with evanescence oscillations [2]. This system permits to shape electron beam with required performances but can be unstable in case of intense electron beam operation. Therefore the one of the main purposes of the new injector experimental research is the approving of its stable operation for the intense electron beam shaping with current 1 A.

1. INJECTOR PERFORMANCES

Preliminary numerical simulation of the injector operation stability has shown that the electron bunching is stable for the pulse beam current up to 2.5 [3]. Injector parameters and results obtained during self-consistent beam dynamics simulation according to the method described in paper [4] are summarized in the table.

Simulated injector performances

Parameter	Value
Electron gun output current, A	1.5
Injector output beam current, A	1.34
Operating frequency, MHz	2797.15
RF power supplying the prebuncher, W	570
RF power supplying the buncher, MW	1.8
RF power pulse duration, μs	2.9
Beam pulse duration, μs	2.4
Normalized emittance, $\varepsilon_{rms\ x,y}$, π·mm·mrad $(1\cdot\sigma)$	12
Beam size $(4\sigma_{x,y})$, mm	2.8
Bunch phase space (for 70% of particles), degree	18

Main units of the injector system: solenoid, resonance cavity system, coaxial-waveguide transition for RF power feeding has been manufactured during the design-engineering stage of the injector developing. Sectional view of the injector is shown on the Fig. 1.

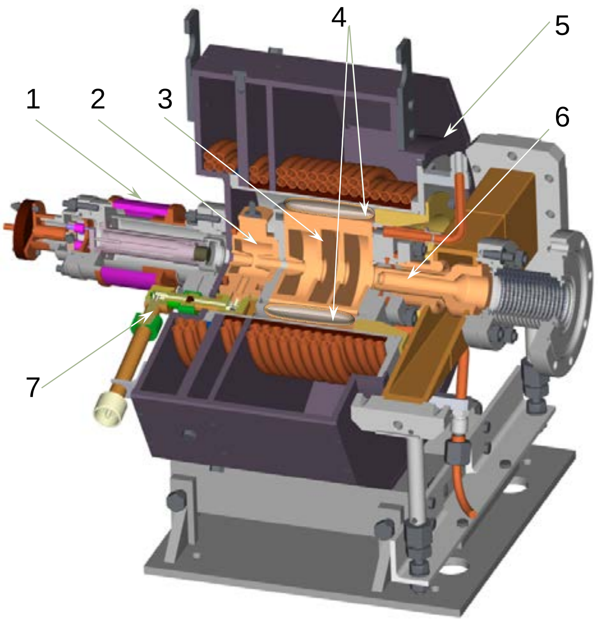

Fig. 1. Injector sectional view

The injector assembly consists of the diode electron gun (1) with 25 kV anode voltage [5], the cylindrical pre-buncher (2) with coaxial waveguide (7), the buncher (3) with coaxial-waveguide transition (6) for RF power supplying and the magnetic system (5) designed as a sectional solenoid with beam position correctors (4) added. The injector is mounted on the platform that may be aligned.

The radio-frequency tuning of the injector bunching system allowed establishing the axial electric field distribution (Fig. 2) and the axial magnetic field distribution (Fig. 3) that correlates to the simulated ones respectively. Values of *Z* axes on Fig. 2 and Fig. 3 correspond to the same longitudinal axes of symmetry of the injector. Position *Z*=0 mm on the Fig. 3 corresponds to the emitting surface of the cathode.

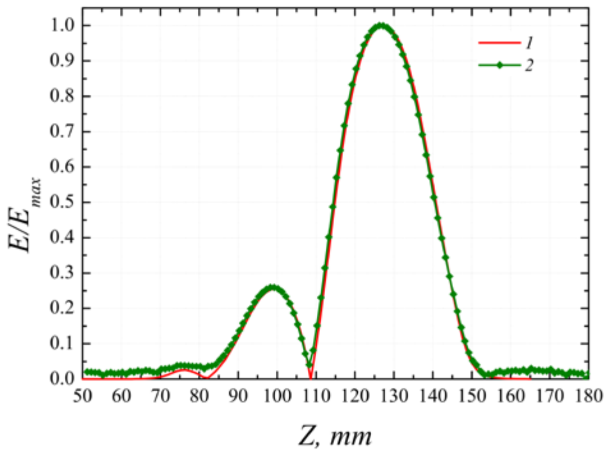

Fig. 2. Simulated axial electric field distribution (red) and measured on the operating frequency (green)

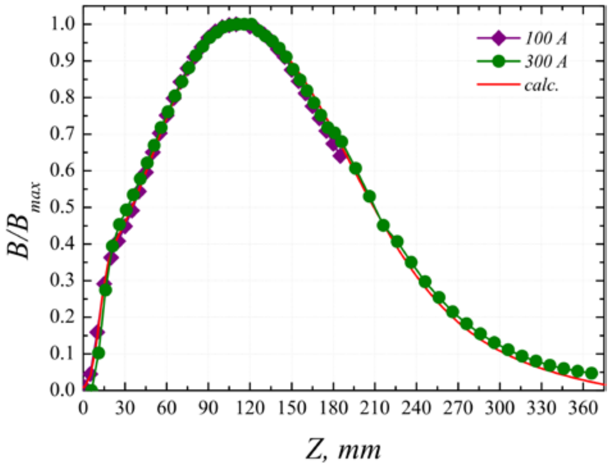

Fig. 3. Simulated and measured axial magnetic field distribution for the excitation current 100 and 300 A

Experimental research of thermal and hydraulic test operation modes approved the validity of the applied numerical simulated models and chosen assumptions for the solenoid design. The results of the tests are presented in the paper [6] more detailed.

2. EXPERIMENTAL SET-UP

The injector parameters and electron beam performances at its output have been researched experimentally on the special experimental set-up. The set-up (Fig. 4) purposed for measuring of beam parameters at the output of an injector system with electron energy up to 1 MeV [7].

RF power feeding system of the set-up is based on the application of an amplifying klystron KIU-12AM that operates in self-exited generator mode and on the RF waveguide transmission lines with diagnostic probes of RF signals. The output of the RF waveguide transmission line is equipped with two directional couplers (see Fig. 4, pos. 3, 4) purposed to feed the resonance system of the injector by the corresponding RF power. With RF power of 10 MW at the klystron output the couplers permits the prebuncher and buncher to be supplied with RF power of 1 kW and 1 MW respectively. The waveguide transmission line of the prebuncher is equipped by the attenuator and phase shifter (is not shown on Fig. 4). RF measuring system parameters permits to monitor amplitude phase and temporal dependencies of all RF signals.

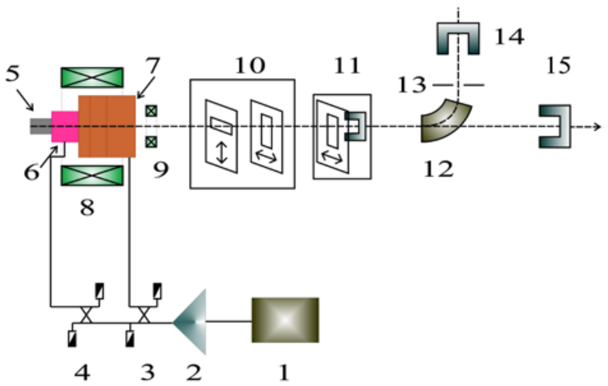

Fig. 4. Set-up block diagram: 1 – klystron modulator; 2 – klystron; 3, 4 – directional coupler; 5 – electron gun; 6 – prebuncher; 7 – injector; 8 – solenoid; 9 – induction beam current monitor; 10 – system of slit collimators; 11 – measuring movable collimator with Faraday cup; 12 – magnetic spectrometer; 13 – collimator; 14, 15 – Faraday cups

Electron energy and energy spread are measured using magnetic spectrometer with resolution 1%. Induction beam current monitor (see Fig. 4, pos. 9) and Faraday cups (see Fig. 4, pos. 11, 14, 15) are used to measure electron beam current.

The experimental set-up was equipped for a long time by the emittance measuring system based on “three-gradient” technique [8]. In case of 1 A beam current emittance measurement this method has errors due to space charge effects on a long enough distance between quadrupole lens and collimating slit. Therefore, we applied another well known “double slit” technique [9] for the emittance measurement. According to the main principle of this technique space charge effects is eliminated during measurement due to beam cutting into “beamlet” by the first slit seeing the beam. The second slit seeing the beamlet cuts it into a “sub-beamlet”. By scanning both slits throughout the whole beam area, a beam distribution in the transverse phase can be restored. Since the total charge in the beamlet would be very small, the space charge effect is small as well. For this technique implementation, the set-up has been reassembled and the new designed emittance measuring system has been added. The system includes three movable slit collimators and two Faraday cups [10]. Such composition permits to measure beam profiles both horizontal and vertical and electron distribution in transverse phase space as well. The system (see Fig. 4, pos. 10, 11, 15) is mounted directly after the injector to reduce the beam loss. The movement of slits is actuated by step drivers with minimal resolution 0.1 mm per step and is controlled by the microcontroller system approached by the same one that described in the paper [11]. The system has also ADC converter connected to the PC that makes the emittance measurement to be automatic.

3. MEASURED BEAM PARAMETERS

After the injector has been mounted on the experimental set-up, it was pumped down up to high vacuum pressure $p = 2.6 \cdot 10^{-7}$ Torr during several calendar days. The cathode of the electron gun was activated after this.

The injector resonance system was RF commissioned by the RF power increasing step-by-step up to 1 MW that can be maximum supplied by the RF system of the set-up. For the supplying RF power of 1 MW, the standing wave rate VSWR is 4.8, maximum on-axis electric field strength and on cavity walls of the buncher is 39 and 65 MV/m respectively. The RF commissioning was continued during 8 hours at vacuum pressure 10^{-6} Torr and less. Radio-frequency tests of the injector resonance system by the applying RF power up to 1.05 MW elicited its high electric field resistance and multipactor absence for the operating RF power values.

The main beam parameters: energy, energy spread, beam emittance and beam intensity are interrelated and dependent from many factors. The beam of the injector is most affected by the RF power value and phase difference of RF power feeding the prebuncher and the buncher, by the magnetic field value of the solenoid and the high and heating voltage values of the cathode of the electron gun. The detailed research of beam parameters is complicated also by the absence of the temporal stability of all above factors that grows into valuable errors during long-term measurements. The measurement results are also affected by the errors in alignment of the electron gun, the resonance system and solenoid and by the presence of electromagnetic noise from the operating powerful high-voltage equipment.

We researched the injector for different electron gun current in the range of 0.5…1 A. Beam parameter oscillations featured for unstable operating mode and typical for five-cavity resonance system was not observed.

According to the numerical simulation, the RF power feeding the buncher should be of 1.8 MW for generation of electron beam with pulse current 1.3 A. But the most of below described results was researched with electron beam current of 0.7 A due to maximum RF power of 1 MW that can supply RF system of the set-up.

The beam emittance was measured at the distance 20 cm from the injector output. It was established that the emittance value is the most affected by the axial magnetic field value of the solenoid and by the displacement between the solenoid magnetic axis and the injector geometric axis. The existence of the last factor was established experimentally (Fig. 5) while researching the beam current dependence on the solenoid current value and on its polarity in the injector that was not fed by RF power.

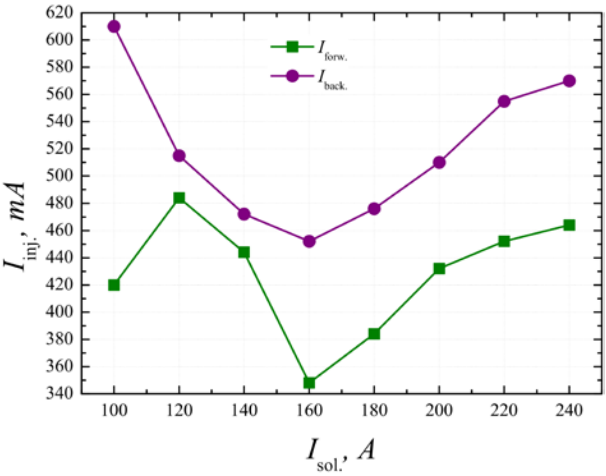

Fig. 5. Beam current at the injector output vs polarity of the solenoid current

Beam axis position was corrected by special lengthwise coils that are placed between the solenoid and the resonance system of the injector. It should be noted, if the beam axis is not coincide with both the solenoid magnetic axis and the injector geometric axis the emittance may be increased due to electron interaction with both constant magnetic field and RF field components. Therefore, evidently, transverse momentum value seen by electrons and beam emittance should be dependent appreciably on the transverse magnetic field of the corrector. Really, it was observed in the research the variation of normalized rms beam emittance value in the range 16…53 mm·mrad dependently on the magnetic field value of the corrector. Phase space distribution for the optimal corrector operating mode is shown on the Fig. 6.

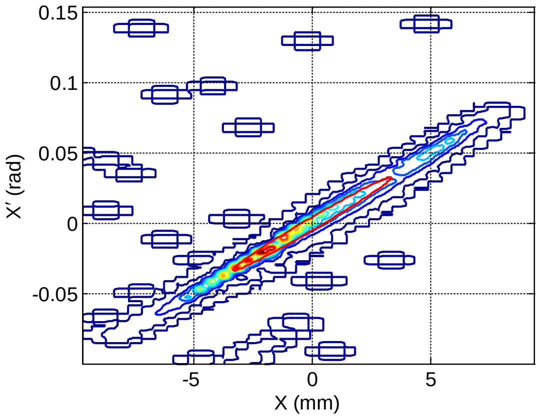

Fig. 6. Beam phase space for normalized rms emittance of 16 mm·mrad

Results of beam emittance measurement are affected by noises of different genesis and peripheral electrons that composes a beam halo. These factors only increase emittance value.

Electron energy spread of the beam was measured for the electron gun current of 660 mA and dependently on RF field phase in the prebuncher (Fig. 7). It was established that in the phase range 50…90° the injector output current was unvaried of 540 mA and the energy spread value was in the range 6…7% for steady-state mode.

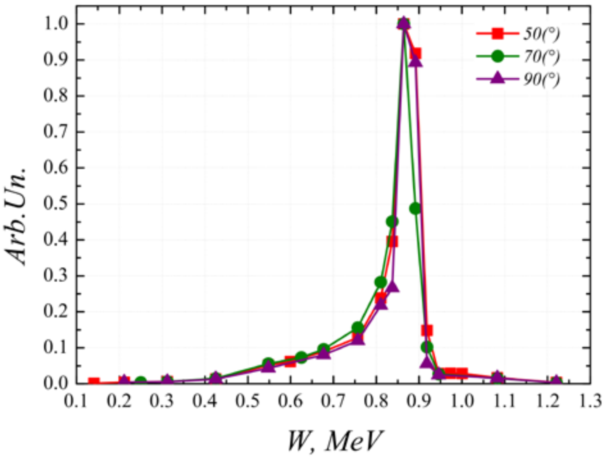

Fig. 7. Energy spread vs rf phase in the prebuncher for the electron gun current of 660 mA

Optimal amplitude and phase tuning of RF field in the prebuncher permitted the electron energy spread of the beam to be more narrow (Fig. 8). The energy spread value in this case is 4.2% for the maximum electron energy of 860 keV and the injector output current of 750 mA.

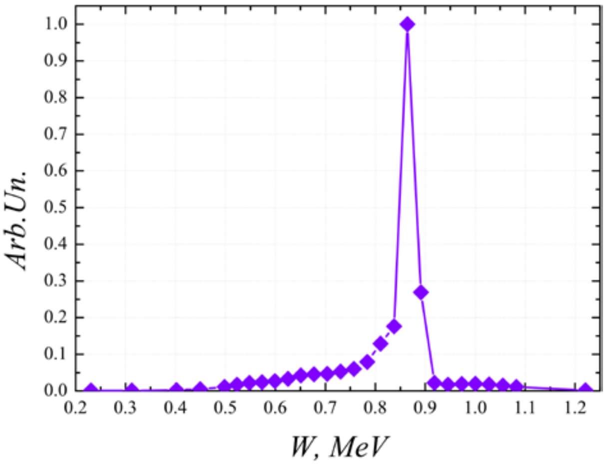

Fig. 8. Energy spread for the optimal injector tuning

Beam parameters dependences on RF field phase and on initial injection energy of electrons into the resonance system (the same as high voltage of the electron gun) were researched more detailed when the electron beam current at the gun output was increased up to 1.2 A. As it follows from the results of the measurements, there is the sufficient wide phase range (more then 80°) for which the electron capture factor (the relation of the injector output current to the gun output current) does not depend sufficiently on RF field amplitude (Fig. 9).

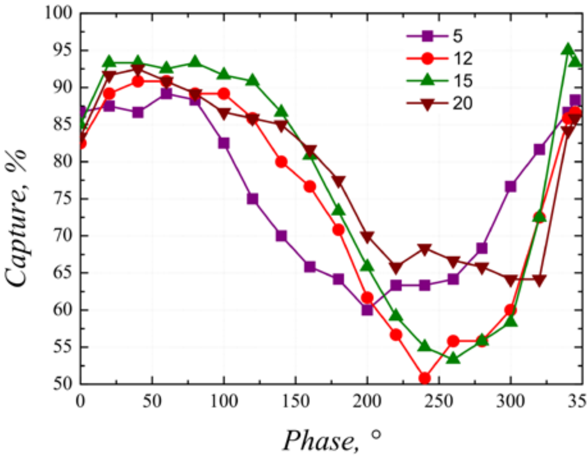

Fig. 9. Electron capture factor vs rf phase in the prebuncher. Digits are rf field amplitude in arbitrary units

In this context the RF amplitude and phase in the prebuncher, according to the numerical simulation, should affect an electron phase space distribution. Thus, the optimization of RF field amplitude in the prebuncher and the injector system phasing should be performed synchronously with measurement of an energy spread or a bunch phase length.

Beam energy spreads for different phase values and identical electron gun output current of 1.2 A are shown on Fig. 10. The optimal phase of 22° is featured by the energy spread ≅ 8% and by the energy of 740 keV in the maximum of the energy spread. The injector output current is 1.1 A in this case. In case of non-optimal phase (φ =300° on the Fig. 9) the injector output current is not higher than 0.7 A.

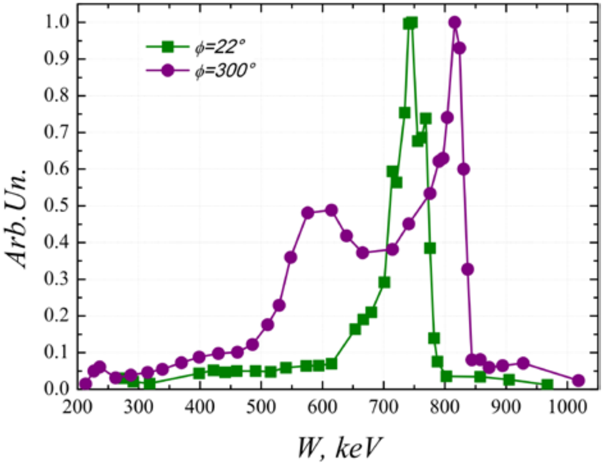

Fig. 10. Energy spread vs rf phase in the prebuncher for the electron gun current of 1.2 A

Beam energy spreads depend on energy of electron beam injected into the prebuncher i.e. on anode voltage of the electron gun. The Fig. 11 presents energy spreads for the different anode voltage 26.5 kV ($\Delta W/W$ = 13%), 25.5 kV ($\Delta W/W$ = 6%), 23.5 kV ($\Delta W/W$ = 14%). The RF field phase in the prebuncher was tuned up to the maximum beam current for the each anode voltage value. The injector output current in this case was 1 A, 1 A, 0.85 A respectively. As one can see from the Fig. 11 the optimal value of the anode voltage for a bunch shaping is the voltage of 25.5 kV that corresponds to the results of the numerical simulation.

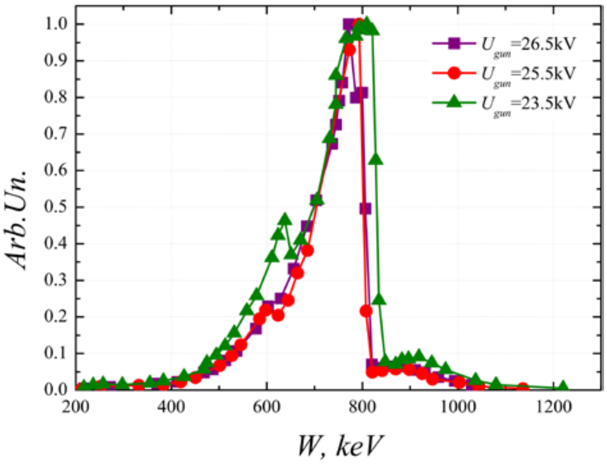

Fig. 11. Energy spread vs anode voltage of electron gun

CONCLUSIONS

Experimental research of the injector did not identify its any unstable operation while generating intense electron beam with the pulse current up to 1 A. The obtained values of the beam current, electron energy of the beam, its emittance and energy spread are matched sufficiently with simulated values for the available RF power feeding the resonance system of the injector. It should be noted that conditions for the optimal beam shaping requires RF power value higher that it was in the research. Just this fact explains the considerable amount of electrons with low energy in energy spreads.

REFERENCES

1. M.I. Aizatskyi, V.I. Beloglazov, E.Z. Biller, et al. High-power 40 MeV Electron Linac // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (49).* 2008, №3, p. 25-29.
2. M.I. Aizatskyi, P.G. Gurtovenko, V.M. Kodyakov, et al. Compact Electron Injector for S-Band Linac // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (49).* 2008, №3, p. 68-72.
3. M.I. Aizatskyi, V.F. Zhiglo, V.A. Kushnir, et al. Development of Intense Electron Beam Injector // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (54).* 2010, №3, p. 22-25.
4. V.V. Mytrochenko, A. Opanasenko. Study of transient self-consistent beam dynamics in RF linacs using a particle tracing code // *Nuclear Instruments and Methods in Physics Research (A558).* 2006, p. 235-239.
5. I.V. Khodak, V.A. Kushnir, V.V. Mitrochenko, et al. Electron Gun for Technological Linear Accelerator // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (36).* 2000, №2, p. 86-88.
6. M.I. Aizatskyi, V.A. Kushnir, V.V. Mytrochenko, et al. The Results of Tuning of Intense Electron Beam Injector // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (80).* 2012, №4, p. 11-14.
7. M.I. Aizatskyi, E.Z. Biller, K.Yu. Kramarenko, et al. The investigations of the beam characteristics in the electron injector based on resonance system with evanescent oscillations // *Proceedings of RuPAC XIX.* 2004, p. 444-446.
8. V.I. Artemov, S.A. Dobromirov, F.A. Peev, et al. Beam emittance definition using a profile set // *Instruments and Experimental Techniques (Pribory i Tekhnika Eksperimenta).* 1989, №4, p. 42-44.
9. Masanori Ikegami, Masaki Kando, Hideki Dewa, et al. Double-slit Emittance Monitor for Pulsed Proton Beams // *Bull. Inst. Chem. Res.* Kyoto Univ. 1995, v. 73, №1, p. 1-10.
10. I.V. Khodak, V.A. Kushnir, V.V. Mitrochenko, D.L. Stepin, V.F. Zhiglo. Measurement system of a beam spatial transverse performances of electron injectors for linacs // *Thesis of the X Conference on high energy physics, nuclear physics and accelerators.* NSC KIPT, Kharkov. 2012, p. 79.
11. I.V. Khodak, V.A. Kushnir, V.V. Mitrochenko, D.L. Stepin. Stabilization of a Klystron Anode Voltage of a Linac RF Power System by Microcontroller Based feedback // *Problems of Atomic Science and Technology. Series «Nuclear Physics Investigations» (80).* 2012, №4, p. 46-50.

Article received 16.10.2013

ИССЛЕДОВАНИЕ ХАРАКТЕРИСТИК ИНЖЕКТОРА ИНТЕНСИВНОГО ПУЧКА ЭЛЕКТРОНОВ

Н.И. Айзацкий, И.В. Ходак, В.А. Кушнир, В.В. Митроченко, С.А. Пережогин, Д.Л. Степин, В.Ф. Жигло

Применение низковольтных источников электронов требует использования группирующих систем с неоднородным нарастающим СВЧ-полем для эффективной группировки и ускорения электронов. Приведены результаты исследования характеристик инжектора десятисантиметрового диапазона, использующего такую систему. Инжектор состоит из диодной 25 кВ электронной пушки с током до 1,5 А, торроидального резонатора предварительной группировки, трехрезонаторной группирующей системы с коаксиально-волноводным переходом для ввода СВЧ-мощности и секционированного соленоида. Высокочастотные испытания изготовленного инжектора показали достаточную надежность его работы при рабочих режимах уровня мощности СВЧ-питания, достаточную электрическую прочность и отсутствие мультипакции. Результаты исследований параметров пучка на выходе инжектора хорошо соотносятся с расчетными данными.

ДОСЛІДЖЕННЯ ХАРАКТЕРИСТИК ІНЖЕКТОРА ІНТЕНСИВНОГО ПУЧКА ЕЛЕКТРОНІВ

М.І. Айзацький, І.В. Ходак, В.А. Кушнір, В.В. Митроченко, С.О. Пережогін, Д.Л. Стьопін, В.Ф. Жигло

Застосування низьковольтних джерел електронів вимагає використання групуючих систем з неоднорідним наростаючим НВЧ-полем для ефективного групування і прискорення електронів. Приведені результати дослідження характеристик інжектора десятисантиметрового діапазону, що використовує таку систему. Інжектор складається з діодної 25 кВ електронної пушки зі струмом до 1,5 А, тороїдального резонатора попереднього групування, трьохрезонаторної групуючої системи з коаксіально-хвилеводним переходом для вводу НВЧ-потужності і секціонованого соленоїда. Високочастотні випробування виготовленого інжектора показали достатню надійність його роботи при робочих режимах рівня потужності НВЧ-живлення, достатню електричну міцність і відсутність мультипакції. Результати досліджень параметрів пучка на виході інжектора добре співвідносяться з розрахунковими даними.