Applied calculations of accelerator characteristics for sterilization installation with local radiation shielding

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Abstract. The calculations of electron beam characteristics in the accelerator of sterilization installation with the local radiation shielding in relation to the use of a magnetron with a larger pulse power are made. It is shown that a simple method on the basis of "moving" of cathode-heating unit toward the anode plane of the injector may be used for increasing of current and power of accelerated beam.

1. Introduction
In relation to the use of magnetron MI-456AM with increased approximately to 3.5 MW pulse power, the possibilities of effective application the existing accelerating structure in the sterilization installation with the local radiation shielding the calculations [1] are made. The application of such self-shielded accelerators makes it possible to avoid construction of special buildings and makes less expensive the creation of radiation technology systems. This existing accelerating structure on a standing wave was developed and created using the magnetron MI-456A with a pulse power of about 2.5 MW. In this structure the electron beam is accelerated to an averaged, over the energy spectrum, energy of about 5 MeV, has a pulse current of 250 mA (up to 270 mA), i.e. the pulse power of 1.25 MW, the efficiency of the accelerating structure - 58%. The injected beam current is 1.6 amperes [2]. For effective use of microwave power from the upgraded magnetron it is necessary to increase the injection current. A simple way to achieve this purpose may be the "moving" of cathode-heating unit toward the anode plane of the beam injector. The calculations show the reality of this possibility. By means of variation of the new position of the cathode-heating unit, the optimal position of this unit is found.

2. Computer codes description
Several variants of computer codes DINA [1] were used for calculations.

DINA_RoZ is a 2.5-dimensional computer code to describe the processes of bunching and acceleration of electron beams in the accelerators in a steady-state, periodical in time, regime. It allows you to assign the initial parameters of the beam both with arbitrary distribution of different types and obtained in calculations of the electron injector with the help of specialized computer codes. 2D-distributions of radio-frequency (RF) fields in accelerating structures can also be set both as arbitrary ones and entered from calculations by specialized computer codes. The DINA_RoZ code calculates and takes into account the flow of electrons to the walls of the channel in accelerators with RF field focusing. This possibility allows explaining the power balance in linear accelerators of electrons on a standing wave. Only taking into account these power losses it is possible to significantly optimize the operation of such accelerators. In this code, to find the solutions of equations in the state with a given RF power, "pumped" into the resonator of the accelerating structure by an external RF generator, the method of "power balance" is used. It consists in calculating, first of all, the total cost of microwave power in the accelerating structure. Firstly, it is the microwave power transmitted to the accelerated beam, derived from the accelerator. Secondly, it is the power spent on the partial acceleration of the electron flow, which is not derived from the accelerator, but settles on the walls of the accelerating resonator. And, thirdly, it is
the power of ohmic losses of microwave energy in the walls of the resonator. Then this total amount of "spent" power is compared with the RF power "pumped" into the resonator by an external RF generator. The latter is the difference between the power of the RF generator and the loss of RF power in the microwave channel connecting the RF generator and the accelerating resonator. After a series of calculations of beam dynamics in the accelerator with different, but fixed at every calculation, values of the amplitude of the electric field generated by the microwave generator, and calculating the above amounts of "spent" microwave power, the code selects the regime in which the above "balance of power" is observed. This method determines the steady-state, periodic-in-time with the microwave field period, the state in the accelerating structure.

The computer code DINA_TIME simulates the 2.5-dimensional time evolution of electron beams in transient modes without the assumption of the periodicity of processes in time. In addition to the processes of bunching and acceleration, it describes the dynamics of reflected electrons moving in the direction to the injector. Such electrons appear in the regimes when the voltage on the injector is noticeably less than the voltages on the first accelerating gaps. In addition, it simulates the operation of the injector (in the regime with a given current) taking into account the own fields of these reflected electrons and calculates the power of the flux falling on the cathode of the injector. The characteristics of the flow of the injected beam distorted by these fields may be used in a self-consistent way to calculate the processes of bunching and acceleration. Calculation of the time interval in several times exceeding the electrons transit time of the accelerating structure leads to the establishment (if the effect of the field of the reflected electrons is small enough) of the periodic-in-time (with the frequency of the RF field) regime described by the code DINA_RoZ. The calculation time of such process is several times larger than the calculation time of the established process.

The computer code DINA_3D describes the three-dimensional dynamics of the electron beam in accelerators in periodic-in-time regime. It allows taking into account the non-alignment of the injected beam and the accelerating structure, azimuthal inhomogeneity of the beam self-fields and RF fields in the structure, and other three-dimensional effects.

The computer code DINA_RoZ_BL is created to describe the process of bunching and acceleration of electron beams with taking into account the effect of "beam loading". The general technique of describing the effect of "beam loading", i.e. the effect of excitation of electromagnetic waves in accelerating structure by electron bunches of the intense beam, has been developed by E. S. Masunov [3]. The equations describing the time evolution of the complex amplitude of the electric field radiated by a modulated electron beam in an accelerating structure with a known longitudinal field distribution of the resonator' own mode have been derived. The paper [4] describes a package of three-dimensional computer codes that use the solution of such equations to describe the beam loading effect in conjunction with the equations for the dynamics of the beam in the accelerator, taking into account the quasi-static fields of the beam' space charge and current. Taking into account the beam loading, the Masunov' equations describe the growth of the radiation field with the time calculated from the beginning of the beam current pulse. Given that this process is slow compared to the microwave field period, it is possible to find the quasi-stationary state of the accelerated beam at fixed radiation field characteristics at each such moment of time using, in our case, the DINA_RoZ code. As a result, either stationary, time-periodic solutions in the case of long beam current pulses or values at the end of short beam current pulses are determined. To find the total, taking into account the field emitted by the beam, the electromagnetic field in the accelerating resonator with a given, fixed microwave power, the equations for it are supplemented by two terms in the right side [5, 6]. First of them is a "source" that simulates the "pumping" of RF power into the resonator from an external microwave generator, a second term accounts the loss of microwave power in the resonator, taking place either because of its departure into the external waveguide, or due to ohmic losses in the resonator walls or in the absorber of microwave power. These two terms compensate each other in the absence of beam radiation, for example, at low injection current or in the absence (for any reason) of beam current modulation. The main result [7] of account for the effect of radiation of the electron beam (i.e., the effect of beam loading) is some frequency change of total microwave accelerating field (as compared with the case of absence of the beam radiation) under the condition of "pumping" in the accelerating structure of the same total microwave power. At the same time, there is no change (reduction) in the efficiency of the accelerator in this case.

3. Results of the calculations
Calculations of the beam formation processes in the injector with different positions of the cathode-heating unit relative to the anode plane have been carried out using computer code [8]. Calculations of
beam dynamics in the accelerating structure using information about the beam in the injector have shown the possibility of its effective acceleration. Provided that the previous energy, averaged over the energy spectrum, of about 5 MeV is maintained, the pulse accelerated current rises to a value of about 400 mA, which gives a pulse beam power of 2 MW and the efficiency of the accelerating structure 68% (figure 1).

Figure 1. Dependences on the injection current: of accelerated pulse current (curve 1) and pulse beam power (2), of efficiency of accelerating structure (3), of beam energies: averaged over the energy spectrum (4a), maximal energy in the spectrum (4b) and the energy found by using the coefficient of beam current transmission through the 6-mm aluminum plate in the method using Faraday cylinder (4c).

Figure 1 shows the dependences of the main characteristics of the accelerated beam on the injection beam current. In particular, it can be seen that there are optimal values of injection currents to achieve the maximum of different beam characteristics. Also can be seen, that the use of the method with a cylinder of Faraday of finding the energy by using the coefficient of beam current transmission through the 6-mm aluminum plate, allows enough accurately determine the averaged over the spectrum beam energy. Indeed, these energies, as can be seen from a comparison of curves 4a and 4c in the figure 1, are different not strong.

It is supposed in these calculations, that the part of lost microwave power in RF channel remains the same (about 14%, as with the old magnetron MI-456A), so the pulse power about 3 MW is entered to the accelerating structure.

In the above regime with the average, over the spectrum, energy of about 5 MeV, the injected beam current is equal to 2.5 amperes as can be seen from the curve 4a in the figure 1. To achieve this beam current, the offset of cathode-heating unit toward the anode plane of the injector must be equal to 7 mm.

Further increase of beam injection current by this method, as can be seen on figure 1, still more increases accelerated beam current - up to 500 mA, but it decreases the averaged over the spectrum energy - up to 4 MeV, which may be unacceptable for the practical use.

This method of increasing the injection current, in general, is not optimal, because, in particular, the beam characteristics at the entrance of the accelerating structure may be not optimal. Therefore, the above results are not optimal, but relate, we believe, to the simple method of utilizing the existing accelerating structure, leading to increase the accelerated beam current and the structure efficiency. It is probably that by some correcting the characteristics of accelerating structure a better result can be achieved, if, in
particular, to provide an improved conditions of beam entering to the accelerating structure. But the calculations with beam characteristics at the entrance from the injector to the accelerating structure, similar to the used in the calculations with applying to old magnetron MI-456A (which can be considered as optimal characteristics), show that the result is not improved practically.

Recall that in the sterilization installation with local radiation shielding, the use of a focusing magnetic field is unacceptable. Therefore, the focusing of the electron beam is realized by the radial component of the electric field of the microwave accelerating wave.

4. Conclusion
The calculations of electron beam characteristics in the accelerator of sterilization installation with the local radiation shielding in relation to the use of the upgraded magnetron MI-456AM with a larger, then in used magnetron MI-456A, pulse power are made. It is shown that the proposed simple method of increasing the injection current by means of “moving” the cathode-heating unit toward the anode plane of the injector is very promising.

References
[1] Rozanov N.E. 2002. Computer codes DINA for calculation of intense beams dynamics in linear accelerators. In: Proc. of MEPhI-2002, p.124.
[2] Belugin V.M., Pirozhko V.M., Rozanov N.E. 2009. Self-shielded electron linear accelerators designed for radiation technologies. Physical Review Special Topics - Accelerators and Beams 12, issue 9 (090101), pp.1-8.
[3] Masunov E.S. 1999. Beam loading effects in charged particle accelerators. MEPhI, 112 p.
[4] Bondarenko T.V., Masunov E.S., Polozov S.M. 2013. Computer codes BEAMDULAC-BL for three-dimensional simulation of electron beams with account of self electrostatic field and beam loading. Problems of Atomic Science and Technology. 6 (18), pp.114-118.
[5] Rozanov N.E. 2014. On the question of beam loading in standing-wave electron accelerators. In: Proc. of MEPhI-2014, 2, p.146.
[6] Rozanov N.E. 2015. Development of the theory of beam loading in standing-wave electron accelerators. In: Proc. of MEPhI-2015, 2, p.203.
[7] Rozanov N.E. 2016. An influence of beam loading in standing-wave electron accelerators. In: Proc. of MEPhI-2016, p.180.
[8] Vasiliev A.E., Vetrov V.V., Pikunov V.M., Smirnov V.S. Account of near-cathode phenomena in calculations of electron injector for TWT. Preprint of Lomonosov Moscow state University, 2005, №11, 10 p.