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RADIAL DYNAMICS OF PARTICLES IN SMALL SIZE ELECTRON ACCELERATOR WITH CONSIDERATION FOR SPACE FORCES

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ABSTRACT

Charged particle beams with high current density are applied more and more frequently. Obtaining of such particles is characterized by certain peculiarities which are stipulated by interaction between charged particles, the so-called effect of spatial charge. While calculating travelling of electron beams it is insufficient to take into account only external electromagnetic field, since the beam electrons create their own electric and magnetic fields with influence significantly on electron travelling at high current densities. Numeric simulation of intensive beams of charged particles is an important constituent in studies of processes occurring in various electrophysical devices of scientific and engineering purposes. Numerical simulation assumes performance of researches in three main fields: development of mathematical model, development of numerical algorithms, and development of software on the basis of the developed algorithms. Calculation of dynamics of intensive beams of charged particles is reduced to solution of non-linear self-consistent problem which is comprised of the equations of motion of charged particles, the Poisson equation for electric field potential, and equation of continuity.

Keywords: dynamics of particles, simulation of charged particle beam, macroparticle, standing wave accelerator, spatial charge.

INTRODUCTION

Nowadays charged particle beams are used in industry, in particular, for non-destructive quality control of materials [1], for treatment of various materials, in medicine [2], in exploration and scientific researches.

Almost all important properties of vacuum devices and assemblies used for fabrication and diagnostics of materials of nuclear engineering depend on quality of formation, spatial configuration, and microstructure of charged particle beams, as well as on physics of wave processes upon their interaction with electromagnetic fields which propagate in various materials [3]. Such researches make it possible to develop new electrophysical devices for diagnostics and fabrication of materials, to improve existing numerical and experimental methods of formation and diagnostics of charged particle beams.

Charged particle beams are used in numerous electrophysical devices, including cyclic and linear accelerators. Intensive development of accelerators for fundamental physical researches in the field of high energy physics and advances in other fields of science and engineering provided practical application of accelerators in industry and medicine [4].

Accelerators significantly improve efficiency of commercial production in such fields as radiation chemistry, non-destructive testing, sterilization of medical preparations, tools and food products, elemental activation analysis [5]. Application of accelerators in geology for radiation survey of wells is economically efficient.

Accelerators are applied more and more frequently in medicine [6]. X-ray therapy makes it possible to combine high treatment efficacy with possibility of mass services [7]. The interest to application of linear electron accelerators in industry and medicine can be attributed to their numerous advantages: simplicity of input and output of accelerated particles, thus obtaining strictly oriented beams of fast electrons and braking radiation; simplicity of adjustment of energy and power of dose; high power of dose of braking radiation even at moderate energies.

While calculating paths of electron beams it is insufficient to consider only for external electromagnetic field [8] since the beam electrons create their own electric and magnetic fields which influence significantly on motion of electrons at high current densities. The beams are considered as intensive when it is impossible to neglect the Coulomb repulsion forces created by own spatial charge. Such beams are a working element in electron and ion-optical systems and accelerators of charged particles which are widely applied, for instance, for melting and cutting of metals, spraying of materials and other practical purposes.

In general case the dynamics of charged particle beams is described by self-consistent set of equations. Solution of such equations involves significant computations, thus, in practice; low amount of exactly solvable models is applied in practice. While considering current problems of physics and equipment of high current beams, it is necessary to apply and develop new mathematical models for simulation of beam dynamics with high spatial charge. At present the macrotparticle method is frequently applied [9].

Numerical simulation of intensive beams of charged particles is an important constituent in investigation into processes in various electrophysical scientific and engineering appliances. Numerical simulations assume researches in three main trends: development of mathematical model, numerical algorithms and software complexes on the basis of the developed algorithms [10].

METHODS

Consideration for forces of spatial charge in analysis of dynamics of electrons will be exemplified by two-resonator standing wave electron accelerator with the energy of $1\ MeV$ and current up to $500\ mA$ in pulse used for application purposes. Portable design of accelerator does not permit to apply conventional and well recommended magnetic coils of aluminum foil for radial motion of electrons. Focusing of electron beam can be provided by small focusing coils rolled with copper tube. Cooling water flows inside the tube, thus providing passing of high currents in the winding and to obtaining of sufficient reserve of magnetic field intensity on the accelerator axis.

Schematic view of accelerator injecting, accelerating and focusing systems are illustrated in Figure-1. The assembly is comprised of electron injector, injector lens, drift space AB, two accelerating resonators and two focusing coils located at both sides of accelerating unit. The injector lens is armored, wound with copper wire and permits to obtain magnetic field intensity on the axis up to $1000\ Oe$. The injector lens and each focusing coil are activated independently of each other, thus facilitating variation of relative distribution of external magnetic field along the accelerator axis in wide range.

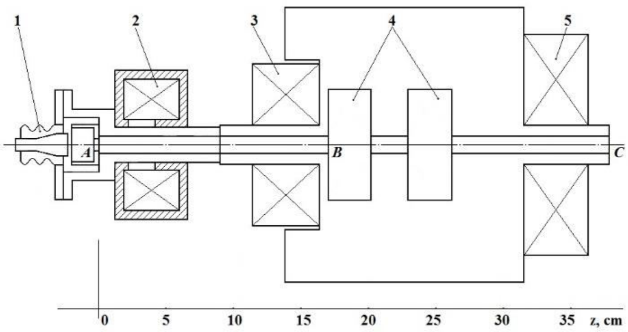

Figure-1. Schematic view of accelerating part of two-resonator accelerator: 1- injector, 2- injector lens, 3- the first focusing coil, 4-accelerating resonators, 5- the second focusing coil.

The accelerating system is comprised of two similar hollow cylindrical resonators with intensity of accelerating electric field of $200\ kV/cm$ at nominal current load. The resonators are not connected with each other and are powered by high frequency via three-decibel oriented couples with determines phase shift between high frequency fields of resonators. The injector is the Treneva electron gun with actually parallel beam, energy of $40\ keV$ and current up to $5\ A$ in pulse.

Preliminary analysis of longitudinal dynamics with regard to energy gain by electrons in this flowchart made it possible to determine longitudinal sizes of accelerating resonators and distance between them. While analyzing radial dynamics of particles in this accelerator it should be mentioned that at such high intensity of accelerating electric field already in the first accelerating resonator a particle bunch is formed, that is, the resonator cuts out and accelerates certain regions of continuous beam from injector. These regions of capture into acceleration are strictly limited and interchange with the period equaling to the wavelength of activating high frequency generator. Then, the space forces can be calculated by approximation of bunch by uniformly charged ellipsoid of revolution.

On the basis of actual physical pattern of acceleration let us assume that in the segment AB (Figure-1) the beam is continuous particle flow and in the segment BC is consists of alternating bunches with the same uniform charge density in the form of ellipsoids of revolution. Continuous beam in the segment AB will be also approximated by ellipsoid of revolution extended along the axis z. With certain ratio of ellipsoid semi-axes, it is possible to believe that the space force acting on peripheral particle in the ellipsoid center corresponds to the force acting on peripheral particle of infinitely long parallel beam.

On the basis of these assumptions the radial motion of particles in two-resonator accelerator was calculated. These calculations were aimed at selection of external magnetic fields for harness wiring in aperture not exceeding $10\ mm$ in diameter. Thus, it is necessary to determine the influence of each focusing element on envelope of beam of magnetic field particles and to determine optimum distribution of intensity of external magnetic field along the accelerator axis. The optimum variant is the case when upon passing of focusing element the flow only slightly varies its radius, that is, we will pursue parallel alignment of flow along overall accelerator.

It is known that in one operation mode the beam radius at the injector outlet is $2\ mm$ and the divergence does not exceed 1^0, herewith, the beam current is $1\ A$ and the energy is $40\ keV$. Since the lens magnetic field does not fall onto the injector cathode, it is possible to assume that the initial angular speed of particles actually equals to zero. The performed analysis revealed dependence of beam radius and radial speed at inlet to the first accelerating resonator on intensity of lens magnetic field for two values of initial radial speed corresponding to the initial beam divergence of 0^0 and 1^0. Minimum of radius and radial beam speed corresponds to the intensity $500\ Oe$ of lens magnetic field, herewith, the beam radius at the inlet to the first accelerating resonator is $3.2\ mm$ and its divergence is 1^0.

Figure-2 illustrates the influence of the first focusing coil on beam envelope without accelerating field in resonators. Even at sufficiently low intensities of magnetic field of about $400\ Oe$ the beam is refocused which leads to its destruction. This result does not contradict with previous data where optimum magnetic field for capture of the same beam is $500\ Oe$. This is attributed to the fact that in the first case magnetic field of armored magnetic lens of injector is concentrated in the main break point of armored core and occupies slightly

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lower space of beam pass channel in comparison with regular focusing coil. Since the beam speed is the same in both cases, then the influence of the injector magnetic lens will be lower than the influence of the focusing coil. Hence, the beam can be confined in beam channel aperture by higher value of magnetic field.

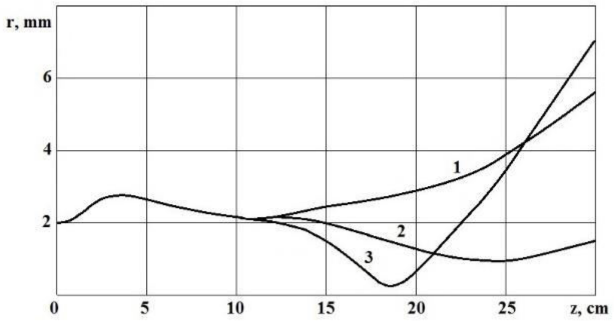

Figure-2. Beam envelope without accelerating field in resonators for various intensities of magnetic field of the first focusing coil: $(1)-H=200\ Oe, (2)-H=300\ Oe, (3)-H=400\ Oe.$

Figure-3 illustrates beam envelopes at various intensities of magnetic field of the second focusing coil. The influence of this coil is lower in comparison with the first focusing coil since the beam has already passed accelerating resonators and is rigid now. The beam confinement in beam channel aperture requires for magnetic field with intensity of 900 Oe and higher.

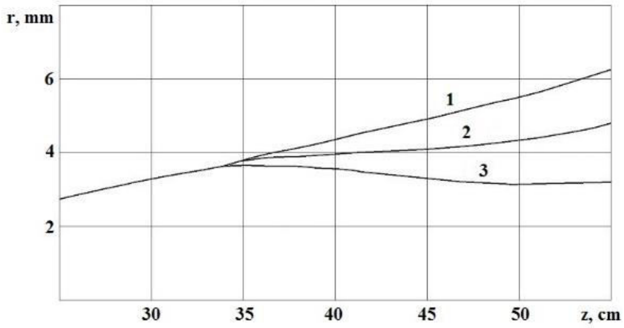

Figure-3. Beam envelope without accelerating field in resonators for various intensities of magnetic field of the second focusing coil: $(1)-H=0, (2)-H=600\ Oe, (3)-H=900\ Oe.$

RESULTS AND DISCUSSIONS

Therefore, as demonstrated by the analysis of beam radial motion, optimum intensities of magnetic field of injector lens of the first and second focusing coil are 500, 300, and 900 Oe, respectively. Such fields provide harness wiring via overall accelerator without radial motion losses.

Final results obtained by approximation of particle bunch by uniformly charged ellipsoid of revolution [11] are illustrated in Figure-4 in the form of beam envelope along overall accelerator (curve 1). Dashed line shows relative distribution of intensity of magnetic field on accelerator axis.

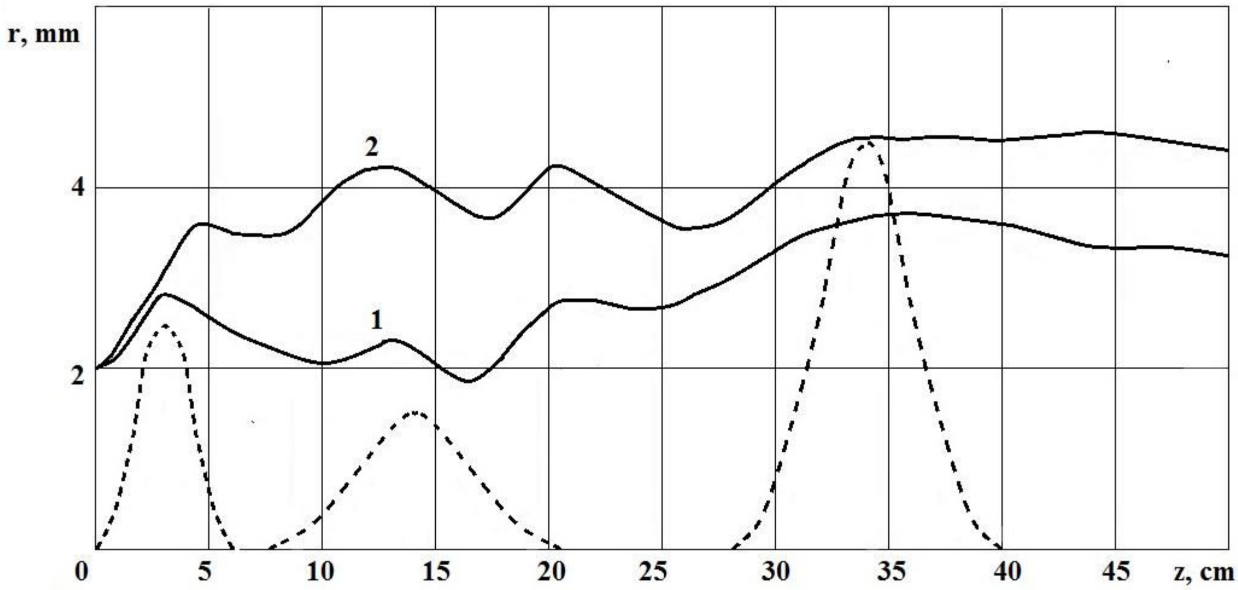

Figure-4. Beam envelope along overall accelerator. Curve (1) is obtained using approximation of particle bunch by uniformly charged ellipsoid of revolution, curve (2) - using numeric solution of the Poisson equations. Dashed line shows relative distribution of intensity of external magnetic field on accelerator axis.

Figure-5 illustrates the influence of space forces on outlet beam diameter with consideration for motion of all particles involved into acceleration with the capture coefficient of 33%.

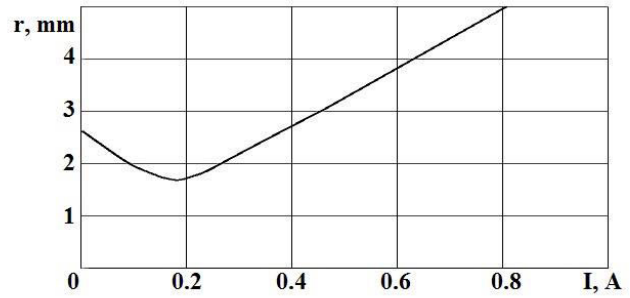

Figure-5. Output beam diameter as a function of injection current upon optimum distribution of external magnetic field for current I = 1A and capture coefficient of 33%.

Distribution of external magnetic field on the axis was set to optimum for radial motion of 25% beam core upon injection current of $1\,A$, the beam diameter was considered at outlet upon decrease in injection current. Such accelerator mode is desirable during operation, hence, the obtained dependences of outlet beam radius on injection current are important.

The results demonstrate that decrease in injection current improves conditions of harness wiring and leads to decrease in outlet radius, minimum corresponds to the current of $0.2\,A$. At lower current beam is defocused, and its radius slightly increases.

Space forces during analysis of electron dynamics were considered according to two procedures [12] for the case study of two-resonator standing wave electron accelerator with the energy of $1\,MeV$ and current up to $500\,mA$ in pulse. Portable design of accelerator does not permit to apply conventional and well recommended magnetic coils of aluminum foil for radial motion of electrons. Focusing of electron beam can be provided by small focusing coils rolled with copper tube. Cooling water flows inside the tube, thus providing passing of high currents in the winding and obtaining of sufficient reserve of magnetic field intensity on the accelerator axis.

The assembly is comprised of electron injector, injector lens, drift space AB, two accelerating resonators and two focusing coils located at both sides of accelerating unit. The injector lens is armored, wound with copper wire and permits to obtain magnetic field intensity on the axis up to $1000\,Oe$. The injector lens and each focusing coil are activated independently of each other, thus facilitating variation of relative distribution of external magnetic field along the accelerator axis in wide range.

The accelerating system is comprised of two similar hollow cylindrical resonators with intensity of accelerating electric field of $200\,kV/cm$ at nominal current load. The resonators are not connected with each other and are powered by high frequency via three-decibel oriented couples, which determines phase shift between high frequency fields of resonators. The injector is an electron gun with actually parallel beam, energy of $40\,keV$ and current up to $5\,A$ in pulse.

Final results obtained by approximation of particle bunch by uniformly charged ellipsoid of revolution are illustrated in Figure-1 in the form of beam envelope along overall accelerator (curve 1). Dashed line shows relative distribution of intensity of magnetic field on accelerator axis.

Determination of space forces by approximation of particle bunch by uniformly charged ellipsoid of revolution does not completely correspond to real physical pattern of beam motion in accelerator. From this point of view more exact was consideration for space forces on the basis of numerical solution of Poisson difference equation on rectangular grid [13]. Using this method the radial particle dynamics was calculated in the same accelerator with experimentally determined distribution of external magnetic field. The results are illustrated in Figure-1 (curve 2).

While comparing the results of calculations obtained on the basis of two different procedures of determination of space forces, it is possible to see that the maximum difference corresponds to the accelerator region where continuous particle beam moves (segment AB in Figure-1). Obviously, approximation of such beam by ellipsoid of revolution least of all corresponds to real physical pattern exactly in this point. After grouping of beam into bunches both methods provide similar results.

On the basis of the obtained results it is possible to conclude that with the determined intensities of magnetic fields of focusing elements the harness wiring is possible along overall accelerator with outlet diameter of not higher than $8 \div 9\,mm$ and divergence close to zero. These conclusions agree well with experimental data obtained on operating accelerator. The diameter of beam dent at accelerator outlet does not exceed $8\,mm$ and the beam itself can be successfully transported in vacuum without noticeable increase in its diameter.

The data in Figure-4 correspond to the 25% coefficient of particle capture into acceleration with consideration for radial motion. These particles form the core of accelerating electrons, which determines radial properties of beam.

The calculations demonstrate that decrease in injection current improves conditions of harness wiring and reduces beam outlet diameter, the minimum corresponds to $0.2\,A$. At lower current beam is refocused, which slightly increases its radius.

CONCLUSIONS

Determination of space forces based on approximation of particle bunch by uniformly charged ellipsoid of revolution is characterized by certain drawbacks resulting in variances of the obtained calculations of particle radial motion from actual physical pattern of beam motion in accelerator. From this point of view, more exact was consideration for space forces on the basis of numerical solution of Poisson difference equation on rectangular grid. Using this method, the radial particle dynamics was calculated in the same accelerator with experimentally determined distribution of external magnetic field. The calculations were performed with the model consisting of 50 big particles on 32×16 grid. The obtained results are illustrated in Figure-4 (curve 2).

The main conclusion based on the obtained results is that with the determined intensities of magnetic fields of focusing elements the harness wiring along overall accelerator is possible, herewith, the beam outlet diameter does not exceed $8 \div 9\ mm$ and the divergence is close to zero. This conclusion agrees well with the experimental data obtained on operating accelerator. The diameter of beam dent at accelerator outlet does not exceed $8\ mm$ and the beam itself can be successfully transported in vacuum without noticeable increase in its diameter.

Taking into account the ever-increasing interest to linear accelerators with intensive beams for application purposes, we propose to continue the researches in the field of radial dynamics of charged particle flows with high density of spatial charge. Special attention will be paid to possibility of application of focusing properties of accelerating high frequency field [14] and beam outlet properties [15].

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