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CALCULATION OF ELECTROMAGNETIC FIELDS IN RESONATORS WITH A COMPLICATED SHAPE OF A BIPERIODIC RETARDING STRUCTURE

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ABSTRACT

The numerical modelling finds more and more various applications in the study of electrodynamic processes in accelerators for charged particles. The tendency to increase the current of charged particles and power of plants, in general, led to new requirements for the numerical modelling of electrodynamic processes. One of the essential requirements is the multimode property of the model – the possibility to analyze the interaction of beams of charged particles with a complex of electromagnetic oscillations that are excited in the displacement volume of power units. This article considers the method of calculation of electromagnetic fields in the resonators of a complicated shape, which are used in the linear electron accelerators with biperiodic retarding structure in a standing wave mode. The absence of an analytical solution to this problem makes it impossible to calculate radial dynamics in such structures. The results obtained by using numerical methods of calculation can be used when considering the motion of charged particles in general - both radial and longitudinal.

Keywords: linear accelerator, biperiodic retarding structure, a resonator with a complicated shape, method of finite differences, the iterative cycle

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1. INTRODUCTION

The wide application of linear electron accelerators (LEA) in industry and medicine is characterized by increasing requirements to the parameters of the accelerated beam. This is due to the expansion of the range of physical problems investigated with the help of charged particle beams. Therefore it is recommended to use the concept of beams with precision parameters. Such characteristics as narrow energy spectrum, small values of longitudinal and transverse emittance, high values of short-term and long-term energy and beam current stability must be realized under high energy and significant intensity of accelerated particles.

Along with the traditional application as a tool of experimental physics, the particle accelerators are widely used in the national economy [1] in recent years. The requirements for the accelerators applications are efficiency, reliability, and easy operation.

In this regard, a large practical importance is acquired by a numerical experiment that does not require large material costs. As practice has shown, the numerical experiment determines previously unknown processes and phenomena and is an instrument of subtle and comprehensive studies of the modeled object [2].

A lot of methods were developed and are applied to obtain accelerated beams with the required characteristics [3]. Among them is parametric stabilization of the characteristics of accelerator systems, the use of beam formation systems at different stages of acceleration - from injection to its output to the target. The accelerating system plays an important role in achieving the desired beam characteristics. The clusters are formed, accelerated, resized and shaped in the accelerating sections [4]. The study of the electrodynamic parameters of accelerating sections makes it possible to develop methods for beam quality improvement and to obtain its necessary characteristics [5].

It is possible to use the focusing of the electromagnetic field itself for beam conducting in linear electron accelerators (LEA) with a standing wave. This becomes possible due to the appearance of a biperiodic retarding structure (BRS) of the electric field radial component in the cells [6]. The use of the focusing properties of the own high-frequency field of the biperiodic retarding structure (BRS) significantly reduces the transverse dimensions of the accelerating section and facilitates the design of the accelerator in general. In addition, there is no need for enormous power sources of external focusing devices that create additional difficulties in the operation of accelerators and are especially important for use in geology, medicine, and flaw detection.

When considering the radial motion of particles, it is necessary to take into account the connection of longitudinal and radial dynamics of the particles and the fact that their equations must be solved consistently. When calculating the radial motion of particles in the LEA with a standing wave based on the BRS, it is necessary to take into account specific features. For the resonators, optimized with a shunt resistance, there are no analytical expressions for the components of the electromagnetic field that need to be calculated using special programs. The electromagnetic field components, which are distributed along the longitudinal coordinate and along the radius and are found by numerical methods must be given in the form of tables in the entire aperture of the passageway.

The presence of the far protruding spigots in the accelerating cells causes a strong curvature of the electric field force lines, which leads to the appearance of a significant transverse electric field of considerable magnitude in the part of greatest curvature. In addition, the protruding spigots screen a certain part of the passageway from the electromagnetic field, which leads to the appearance of periodically repeating areas free from the electromagnetic field in the accelerating structure.

2. METHODS

The overwhelming majority of numerical methods for solving wave equations is based on reducing the equation by discretization to a system of linear algebraic equations. As a rule, four basic methods are used for solving the boundary-value problem in hollow resonators: the finite difference method, the variational method, the integral method, and the finite element method, which has recently become widely used. Since the discretization can be considered as a projection of an infinite-dimensional functional space into a finite-dimensional space, then all the methods listed above are versions of the projection-grid method.

Improvement of accelerator technology and the use of complex physical processes in accelerating systems inevitably lead to the need for careful theoretical study of all the elements created by electrodynamic systems. A powerful and universal tool for such theoretical studies is a numerical modelling. The modelling in some cases is cheaper than a natural experiment, it does not require large material costs, allows collecting the necessary statistics in a short time and together with natural experiment helps significantly accelerate the development of new installations and devices.

When calculating the dynamics of particles in standing-wave accelerators based on the BRS, it is necessary to know the distribution of the components of the high-frequency field in the aperture of the passage channel of the entire structure. In turn, this task is reduced to the calculation of high-frequency fields and the proper parameters of the individual cells of BRS. The typical shape of them is shown in Figure 1.

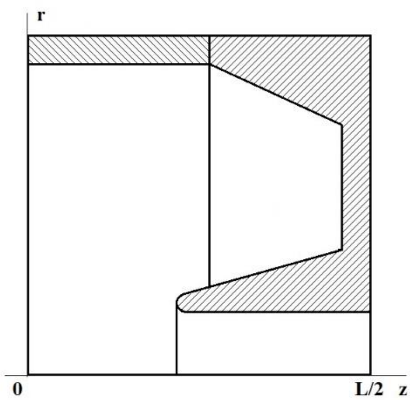

Figure 1 Profile of the BRS cell.

An agreement of the experimental and calculated results in the case of standing-wave LEA is achieved by considering the lowest mode of vibration (type E_{010}). When determining the electromagnetic fields in the BRS cell, let us assume that there is no current and no energy loss inside the cell. Then the calculation of the high-frequency fields of individual axially symmetric resonators can be reduced to a scalar problem with respect to the azimuthal component of the magnetic field $\boldsymbol{H}$.

$$\nabla^2 H_\varphi + k^2 H_\varphi = 0 \qquad (1)$$

with the boundary conditions $\partial H_\varphi / \partial n = 0$ on the conducting surfaces and $H_\varphi = 0$ on the axis of the resonator.

Equation (1) contains two unknown quantities: the eigenvalue $k = {}^{2\pi}/_{\lambda}$ (λ - the wavelength) and the azimuthal component of the magnetic field H_φ, and, therefore, must be supplemented by another equation that is an analog of the variational formulation of the problem

$$k^2 = \int_V (\nabla H_\varphi)^2 dv \Big/ \int_V H_\varphi{}^2 dv, \qquad (2)$$

where V is the cell displacement volume.

The solution of the problem was presented in [7, 8] in the calculation of the electrodynamic parameters of the proton accelerators cells of "meson facility". This method is quite labor consuming, therefore, to solve problems of optimization or synthesis of BRS cells for LEA with a standing wave, a simpler method is proposed, which makes it possible to significantly shorten the time for the necessary cell parameters calculation of the accelerating structure.

As in [7, 8], the finite-difference method [9] with a double iterative cycle on the magnetic field H_φ and the wave number k was chosen as the main solution method. To compile the difference scheme, a five-point approximation was used, and to solve this system of equations - the method of successive upper relaxation.

When implementing this algorithm, automatic mapping of the grid to an arbitrary boundary, the determination of boundary points and the automatic specification of boundary conditions are of particular importance. Solving this problem allows us to greatly reduce the time of preparation of the program to calculate for a particular resonator and to get rid of binding the program to a specific cell form.

The algorithm for automatic grid drawing and definition of boundary points is based on the fact that any boundary curve can be approximated by segments of lines and arcs of corresponding circles with a sufficient degree of accuracy. In the actual resonators of the considered BRS, the boundary contour of their longitudinal section is formed from the fragments listed above.

Thus, when specifying the geometry of the boundary, it is necessary to specify the coefficients in the equations of lines, the radii and centers of the arcs of circles, and also the boundaries of different regions along the coordinate. The only limitation in this method is the requirement for the generant of the side surface of the resonator to be unambiguous from the coordinate r. But this requirement is satisfied in almost all used resonators.

The described algorithm is implemented in the program, with the help of which the eigenvalues and other electrodynamic characteristics of axially symmetric resonators are calculated in the form of oscillations E_{010}.

The grid is applied to the specified area in rows from left to right. The key parameters that fully describe the applied grid are the number of internal nodes in each grid line, the total number of nodes in a row (the sum of internal and external nodes), and the number of internal grid lines. After defining these parameters, one must set the boundary conditions for each external grid node. These conditions are the slope of the normal to the boundary and the indices of the nodes that are present in the boundary equation for a given point.

If the grid step does not change during a program operation, then the boundary conditions for external nodes also do not change. They are used to calculate the value of the function H_φ in the boundary nodes, which allows increasing the speed of the program in comparison with the version when, at each calculation of H_φ in external nodes, the boundary conditions are also determined.

In addition, the program provides iterations on the sequence of grids, when the grid step decreases from one number of iterations to the next, and also the grid thickening, when the fields of strong field variation are covered with a thicker grid in advance. These two methods cannot be combined because of the difficulties associated with the appearance of new nodes on the boundary of regions with a different density of grids while reducing its step.

3. DISCUSSION AND RESULTS

As an initial approximation, the distribution of the magnetic field of a cylindrical resonator and its wave number is usually used. Then an iterative process is carried out along the field and the wave number is refined. The calculation stops after reaching the specified accuracy - usually $3 \cdot 10^{-4}$ by the wave number, which corresponds 10^{-2} by the magnetic field. In this case, the number of iterations over the field does not remain constant, amounting to about 10 at the beginning of the score and reaching 50 at the end. The number of iterations over the wave number is in the range of 20-25. The use of a sequence of grids increases the speed approximately twice.

Figure 2 shows the dependence of the wave number on the number of iterations with a coefficient of successive over relaxation equal to 0.4.

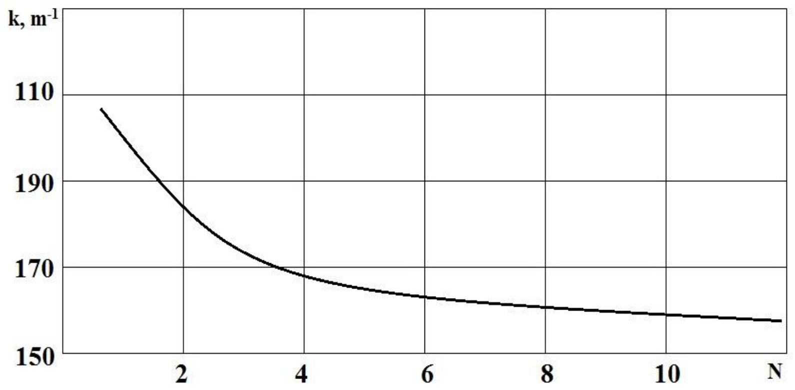

Figure 2 Dependence of the wave number on the number of iterations N.

Figure 3 shows the relative distribution of the longitudinal and transverse components of the electric field in the aperture of the transmission channel of the BRS cell at a distance from the axis at $r \neq 0$.

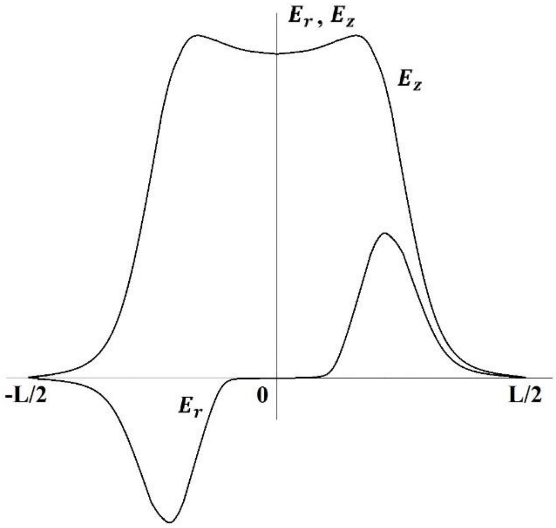

Figure 3 Relative distribution of the longitudinal and radial components of the electric field in the aperture of the passage channel at a distance $r \neq 0$ from the axis.

The results of the calculations, shown in Fig. 3, were used in developing the principles of high-frequency focusing in the LEA under consideration on the basis of the BRS [10]. The proposed method of conducting an electron beam in linear accelerators uses the focusing properties of the radial component of the electric field [11], which appears in the region of transmission tubes even in the lowest mode of oscillations in an ordinary cylindrical resonator near the axis of the passage channel. A similar effect arises from the curvature of the force lines of the electromagnetic field and can be used for proton or ion linear accelerators.

4. CONCLUSION

The need to increase the current of charged particles and the power of accelerating plants in general supposes new requirements for numerical modelling of electrodynamic processes. When creating a model of such processes one of the tasks of computational electrodynamics is the determination of the electrodynamic characteristics of the oscillation types, that can be excited in the volumes where the field interacts with the fluxes of charged particles [12].

Thus, one of the most significant requirements is the multimode property of the model - the possibility to analyze the interaction of charged particle beams with a complex of electromagnetic waves that are excited in the operating volumes of accelerator systems and to study the dispersion properties of structures in higher transmission bands.

The most promising is the electrodynamic model, which allows one to learn about the complete picture of electrodynamic processes in accelerating structures. The electrodynamic model can be based on the expansion of the desired electromagnetic fields over systems of eigenvector functions of resonators [13]. In this case, the problem is considered as two independent tasks, namely, the construction of systems of eigenvector functions of resonators and the determination of unknown coefficients of expansion.

The authors consider it necessary to continue work in the direction of selecting the optimal designs of accelerating structures, modernizing the existing and developing innovative accelerators of charged particles in order to minimize the effect of waves of higher types of oscillations on the characteristics of accelerated charged-particle beams. This problem is relevant for such accelerator complexes as powerful sources of synchrotron radiation based on linear electron accelerators with a large average power of the accelerated beam for the needs of industry, medicine and environmental protection [14, 15].

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