THEORY AND TECHNOLOGY OF PARTICLE ACCELERATION

SPECIFICITY OF SIMULATION OF LOW ENERGIES ACCELERATING STRUCTURES

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Parameters of the H-resonator: the resonant frequency, the distribution of phases and amplitudes of the high-frequency field in the accelerating gaps are mainly determined by the load that forms the acceleration channel. When creating applied accelerators based on H-resonators, it is necessary to determine not only the parameters of the accelerating channel, but also the electrodynamics characteristics of the resonator, which have influence on the efficiency of high-frequency power use. The paper presents an analysis of the methods for modeling the load of accelerating H-resonators taking into account the stated requirements.

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INTRODUCTION

Since the second half of the last century, the NSC KIPT has been studying accelerating structures on H resonators [1]. A feature of H-resonators is the absence of a longitudinal component of the electric field necessary to accelerate the beam. To create such a field component, a special load is placed in the resonator. Drift tubes forming the beam acceleration channel and tube mounting devices are used as loading. Two variants of H-resonators are being developed at the NFCC of the CPTI, which differ in the way of mounting of drift tubes. In the counter-pin structure, the drift tubes are mounted on separate oppositely located holders [2]. In the embodiment, the so-called "comb structure", the tubes are fixed on flat plates, installed in pairs on the element of cylinder of resonator opposite in diameter [3]. The load changes the topography of the field in the resonator and has a strong influence on its characteristics. The volume of H-resonators is 20...30 times smaller than that of resonators on E-wave at the same wavelength of excited oscillations. A significant advantage is also that the use of the π-type oscillation twice increases the acceleration rate and, accordingly, decreases the length of the resonator.

The small size of the H-resonators made it impossible to focus on the particles of devices similar to those used in E-wave structures – electromagnetic or solid-state quadrupole lenses. The only way to ensure steady acceleration of high current beams is to use a high-frequency field excited in resonators to accelerate particles [4, 5]. NSC KIPT has developed several variants of focusing field focusing: Modified Alternative Phase Focusing (MAPF) [6], Alternative Phase Focusing (APF) with floating bunch center, focusing with stepping phase synchronous phase [7], and combined elements of alternating phase focusing and quadrupole lenses [8].

A number of application ion accelerators have been created using MAPF [9]. On the basis of the H-resonator with comb-holders, a high-frequency deuteron accelerator – a driver of the neutron source of the complex for the study of impurities in the materials of the nuclear industry – was put into practice [10]. Work on improving the performance of such accelerators is ongoing.

1. H-STRUCTURES WITH MAPF

Two interrelated problems need to be solved in order to create accelerated structures on H-resonators with modified variable phase focusing. It is required to develop an accelerating-focusing channel (AFC), which provides stable beam dynamics with given parameters, and to create a resonator with RF field parameters that satisfy the conditions of stable beam dynamics. The algorithm for solving these problems is based on a combination of the stages of numerical simulation of the dynamics of a particle beam in a superposition of a high-frequency electric field and the own field of the beam and the stages of numerical or experimental modeling of the parameters of the H-resonator. The results obtained at each stage are taken into account when preparing the next one. Stages of simulations are carried out to achieve the most complete correspondence of the characteristics of the resonator to the data obtained in studies of particle dynamics (resonant frequency, amplitude distribution of the RF field in the accelerating periods). The ultimate goal of the simulation is to minimize the RF power in the resonator and to provide the estimated parameters of the acceleration channel. It is not possible to apply the traditional channel calculation method when creating an acceleration channel with MAPF. The law of distribution of synchronous phases and amplitudes of the RF field in the accelerating periods (AP) of the acceleration-focusing channel, which provides steady motion of the particles, cannot be specified in advance. It is necessary to simultaneously determine the size of the acceleration channel, the law of distribution of synchronous phases and amplitudes of the RF field in the accelerating periods and maintain the specified beam parameters at the output of the accelerator.

The peculiarity of the construction of the acceleration-focusing channel with MAPF, in contrast to the accelerating-focusing channel with APF is that the calculation of the acceleration structure is carried out not by on one equilibrium particle, but by a certain initial ensemble of particles, with accounting theirs geometry in phase volume. Moreover, the stability of the beam motion is ensured on average by the group of acceleration periods, which are grouped together under the name focusing period [11, 12]. Each AP in the focusing period, containing the drift tube and the gap between adjacent tubes, provides stability in only one plane of motion of the particles – phase (longitudinal) or radial. The acceleration periods into the focusing period with the MVPF are related to a consistent choice of particle motion stability. In other words, a particle in the phase space, having passed the period of focusing and receiving an increase in energy, should return to the initial point or close to it. And so on, until reaching a given energy. The parameters that ensure the stability of the motion of the beam particles are the phase of the synchronous particle and the field strength in the AP.

Analytical and numerical studies of the acceleration process have shown that optimal particle motion stability and consistent particle transition between focusing periods is achieved if it begins and ends with periods providing beam grouping in the longitudinal direction (phase). There are several radially focusing periods between the phasing periods. In order to increase the focusing rigidity, the number of radially focusing periods should exceed the number of phasing periods. The number of acceleration periods within the focusing period is not constant. It should increase with increasing particle energy. Increasing the number of acceleration periods in the focusing period allows you to more accurately optimize the movement of particles in the acceleration focusing channel. In order to limit the emission growth, it is necessary to select the values of synchronous phases inside acceleration periods so that the field distribution within the longitudinal length of the bank is linear.

At the initial stage of creating the acceleration-focusing channel, the dimensions of the acceleration channel are simulated, and at the same time, using a limited number of model particles, the dynamics of the particles in this channel is investigated. The channel parameters are then refined to take into account the full current load. Optimization of the distribution of the magnitude, sign of the synchronous phase and the electric field intensity, which achieves the required beam characteristics and acceleration rate, are attained, with the lowest possible emissance increase [13 - 15].

2. MODELING OF H-STRUCTURES

The results of a numerical study of particle dynamics during the development of the acceleration-focusing channel do not provide the complete data needed to create the accelerator. Missing data should be determined by numerical or experimental modeling of the H-resonator. To accelerate the particles in the H-resonator, a lower RF mode of oscillation is used, which, unless special measures are taken, has a field strength distribution that falls to the edges of the resonator. A field with this distribution cannot be used effectively to accelerate particles. It was shown [1] that it is possible to influence the field distribution and electrodynamic characteristics of the H-resonator by changing the configuration and dimensions of the load installed in the resonator: drift tubes, support plates and tube holders. Changing the capacitance and inductance of the load elements that form the resonant circuit causes a change in the characteristics of both the individual acceleration periods and the entire resonator. Increasing the capacitance between the elements of the load of the resonator, especially between the drift tubes reduces the quality factor and shunt resistance of the resonator. Thus, the most appropriate way to influence the characteristics of the resonator is to change the inductance of the elements of the resonant load and make the elements of additional inductive coupling. The software-hardware complex was used for modeling [17, 18]. The distribution of high-frequency fields was determined by the method of small perturbations [19]. The studies were performed on scale models of H-resonators. The sizes of the models corresponded to the sizes of full-scale resonators with a diameter of 0.5 m. The length, taking into account the scale factor, was determined by the magnitude of the acceleration period obtained from the calculations. The longitudinal section of a typical H-resonator is shown in Fig. 1. The figure shows the places where the geometry of the combs has changed in the process of the following studies.

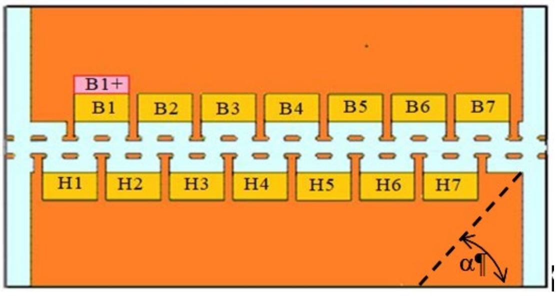

Fig. 1. A longitudinal section of a simulated H-resonator

It has been found that with the change of the length in the acceleration period, which occurs when the accelerated particle energy is increased; the electrodynamics characteristics have acceptable values in the energy field up to ~ 12 MeV/nucl. With increasing energy, the shunt resistance of the resonator Rsh decreases and at a particles energy of ~ 12 MeV/nucl. its value is ~ 85 MΩ/m. The quality factor from ~ 3000 in the energy of injection increases to ~ 15000 in the high-energy region. The obtained data indicate that in the studied energy range, the electrodynamics characteristics of the H-resonators ensure efficient use of RF power.

At a fixed RF power in the resonator in the case of simultaneous increase in the area of the cutouts on the plates (see Fig. 1), in the range of the ratio of the cutout area to the area of the longitudinal section of the resonator (0.01...0.35), 30% increases the field strength in periods located in the middle part of the acceleration – focusing channel. In extreme periods, the field strength decreases. The resonant frequency decreases by 20%. Shunt resistance and quality factor in the specified range of changes have a gentle maximum and beyond the specified range of their values are reduced by more than 30%. The nature of the field strength distribution on the axis remains unchanged.

As the cutout area increases, from period to period, towards one of the edges of the plate, the maximum of the field shifts to the edge of the plate where the cutout area is increased. In periods with increased cutout area, the absolute field strength increases. In Fig. 2 shows the shape of the plates and the values of the angles that determine the increase in the area of the cutouts. Black dotted line in Fig. 2 and in the following figures shows the initial field distribution in the H-resonator. The field's distribution is normalized to the magnitude of the field in the gap with maximum intensity.

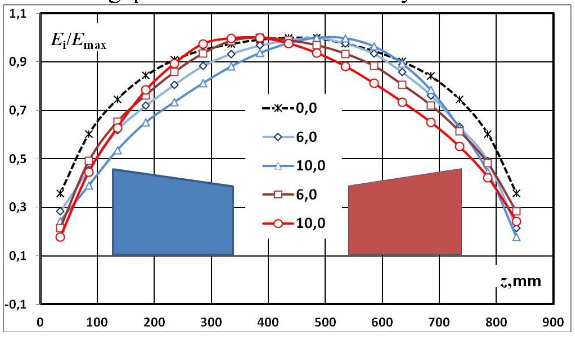

Fig. 2. Field distribution as the cutout area increases at the resonator edges

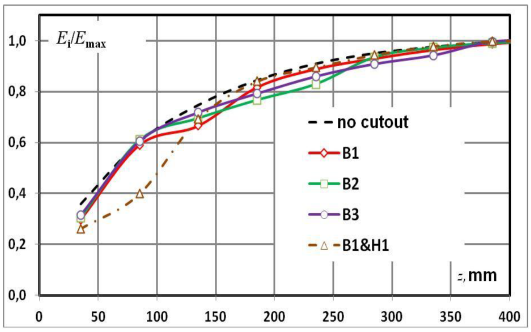

Fig. 3. The influence of cutouts B1, B2, B3 and (B1 & H1) on the field distribution on the axis of the resonator

To adjust the field strength in one or more AP, you can change the cutout area near the period. Fig. 3 shows the result of changing the cutout area in separate periods. The designation in Fig. 3 corresponds to the areas indicated in Fig. 1. Single cutout B1, located in periods 3 and 4, reduces the field in the third and does not affect the field in period 4. It slightly increases the field by 5 and decreases by 10. Cutout B2 in 5 and 6 periods reduces the field in 3, 4 and 5 periods and slightly increases the field in 6. Cutout B3 – opposite 7 and 8 periods reduces the field in five periods – 3...7. If the cutouts on the plates are symmetrical, their impact not only increases, but also changes the area of influence. The field decreases significantly in period 2 (see Fig. 3, line (B1 & H1)) and slightly in 1 and 3. As the depth of cutouts increases, the magnitude of the impact increases and the area of influence expand. As can be seen, the magnitude of the impact depends not only on the cutout area but also on the location on the plate. This effect is explained not only by the change in the inductance of the elements of the circuit – the acceleration period, but also by the change in the high frequency connection between adjacent circuits – the acceleration periods. Quality factor and shunt resistance in the measurements varied slightly less than 7%, and their average value was approximately 10.000 and 100.0 MW/m, respectively.

Changing the angle of inclination α at the edges of the plate, as shown by the dashed line for one of the plates in Fig. 1, has a significant effect on the field distribution along the axis of the acceleration – focusing channel. For several angles of inclination in Fig. 4 shows the distribution of the field with increasing angle of inclination on one plate, by the end of the acceleration periods. As the angle increases, the maximum of the field shifts to the side with a cutout, the field grows in periods at the cut and falls from the opposite side. The field distribution changes more if you increase the cuts at the same time on two plates. This case in Fig. 4 illustrates the dependencies denoted by 20×2, 45×2, 65×2, the graphs of which, for clarity, are rotated on 180°.

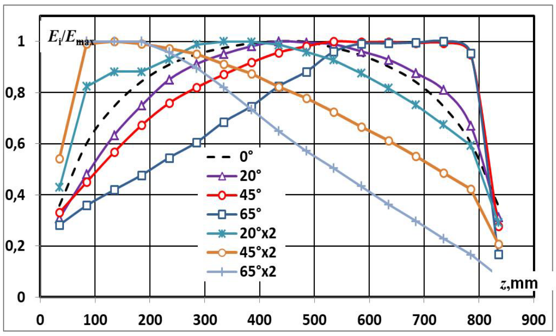

Fig. 4. The influence of the angle of inclination of the plate α on the distribution of the field on the axis of the resonator

If you increase the angle of the cuts at the same time on two plates on both sides, the longitudinal component of the field in periods by the slopes increases, as shown in Fig. 5. As the angle of inclination increases, the field grows in extreme periods – gaps on both sides of the plates. In the case of cuts with a 45° angle, the field distribution across the acceleration periods is almost uniform. If the inclination angle exceeds 45°, the field "sags" in the central gaps. The "sag" reaches ~10% at angle of inclination α = 60°. Intermediate field distribution values can be obtained using a combination of the number of cuts and the values of their angles. A positive factor in the use of cuts is the increase of the field in the initial and final periods from 0.3 relative units to 0.6 relative units. The "sagging" of the field in the middle periods can be compensated, for example, by changing the area of cutouts in these periods. As the angle of inclination increases, the resonant frequency decreases by 20% when the angle is 60° on one plate on one side, by 30% at the same angle of inclination at the same time on two plates on one side, and by 35% at the specified value of the angle of inclination on two sides on two plates. The electrodynamics characteristics (EDC) of the resonator vary but remain acceptable. The values of the angle of inclination providing the optimum electrodynamics characteristics of the resonator are in the range 30...50°. EDC of the resonator impairs on both sides of the specified range.

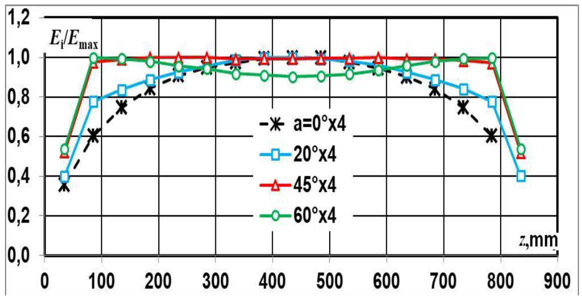

Fig. 5. The distribution of the electric field when the angle of inclination α is changed on two plates on both sides

Cutouts in the body of the plates change the distribution of the field just as it does when changing cutouts in the plates by the drift tubes. The notches affect on the distribution of current flowing in the plates and change the distribution of the electromagnetic field in the structure, depending on their location and magnitude. The distribution of the longitudinal component of the field strength on the axis of the acceleration-focusing channel for several positions of the cutouts is shown in Fig. 6.

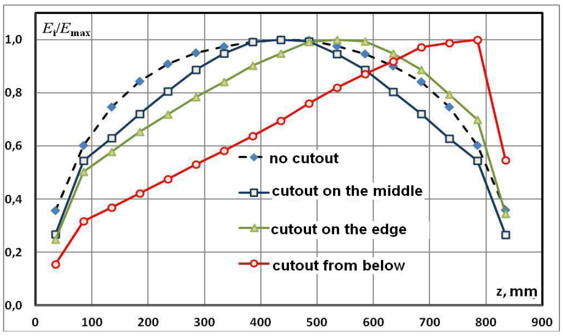

Fig. 6. The influence of cutouts in the plates on the distribution of the electric field

The figure shows the dependences of the field distribution on the location of the cutouts. The cutouts in the middle of the plates increase the level of the field strength in the middle gaps of the resonator and reduce it in the extreme gaps, similar to the action of cutouts by the tubes. If the hole is moved to one of the edges of the plate, then the maximum of the field also shifts in the direction of displacement just as it happens when the area of cutouts of the plate increases to the edge of the plate. This adjustment method allows you to apply the optimum ratio between the plate size and the height of the drift tube holder. This makes it possible simultaneously to adjust the field distribution to obtain acceptable energy characteristics of the resonator. Rectangular notches on the edge of the plates create a perturbation of the field, just as it does at the cuts of the ends of the plates. Such cutouts can be used to increase the magnitude and to extend the field distribution. The rectangular cutout can significantly increase not only the cutout area compared to the cutout, but also its dimensions along the plate. Quality factor and shunt resistance during these changes in the plates decreased by no more than ~15%.

To adjust the resonance frequency, you can change the diameter of the entire H-resonator or its individual parts. This method produces the necessary result, but it isn't technological. The slope of the lateral surface of the plates has a similar effect due to the expansion of the lower part of the plate at the junction of the plate with the lateral surface of the resonator. In this case, the cross-section of the resonant cavity decreases and the resonant frequency increases, as with the decrease in the diameter of the resonator.

In Fig. 7 shows the layout of the resonator that was used when changing the cross-section of the plates. The upper and lower plates in the resonator had the appearance of the upper plate shown in Fig. 7, when studying the dependence of the resonator parameters on the angle of inclination β of the side surface of the plate. It was found that with increasing angle β in the range 0...60° the resonant frequency increases by ~30%. The quality factor in such changes reduced by about 3%, shunt-wound resistance – about 10%. At the same time, the absolute value of the field strength in the middle gaps of the acceleration-focusing channel increases, in the same way as it does with a uniform increase in the area of cutouts on the plates on the side of the axis of the resonator. The variation of the lateral surface angle β have not influence on the field distribution in the resonator.

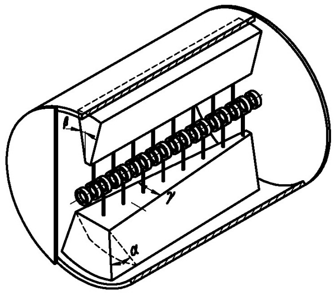

Fig. 7. General view of H-structure in experiments with cross-section change of plates

Changing the cross-sectional area of the plates along the resonator, at a fixed value of the angle of inclination of the lateral surface of the plate, have influence not only on the resonant frequency, but also the nature of the field distribution along the resonator, as shown in Fig. 8. In these measurements, both plates had the appearance of a lower plate, which was shown in Fig. 7.

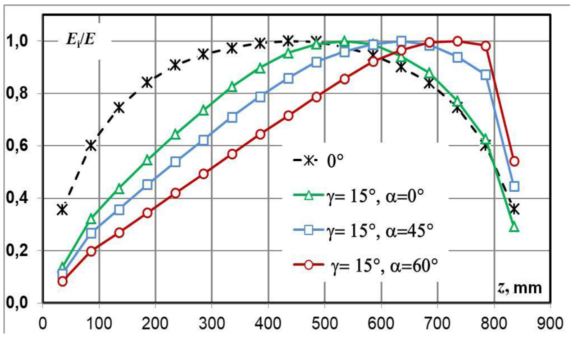

Fig. 8. The distribution of the field strength depending on the angle of incision α of the expanding plate

The maximum of the field strength shifts towards the expansion (see Fig. 8 line $\gamma = 15°$, $\beta = 0°$), with the expansion plate in the direction of the beam motion. The maximum of the field distribution shifts any longer in the direction of expansion and at the same time increases the field strength in recent periods, with the extension angle γ increasing. The resonant frequency increased by about 20%, with the angle γ varying from 0 up to 15°. The quality factor of the resonator and shunt resistance decreased by about 7 and 15%, respectively.

The maximum field strength is increasingly shifting to the plane of undercut when simultaneously changing the angle undercut α end surface of the plate. The distribution of the longitudinal component of the field strength depending on the angle α, with fixed values of the angles β and the extension γ, is shown in Fig. 8. The maximum field strength shifts in the 13th period, (line $\gamma = 15°$, $\alpha = 45°$) if the plates are cut at an angle $\alpha = 45°$. As the angle α to 60° increases, the maximum shifts to the last gaps 14...16 (line $\gamma = 15°$, $\alpha = 60°$). The increase in field strength becomes almost monotonous.

According to the presented research results, the change in the shape of the plates on which the drift tubes are placed makes it possible to influence the electrodynamics characteristics and the field distribution in the resonator. Changing the shape of the plates only slightly reduces the electrodynamics characteristics of the resonator. The parameters of the resonator can be changed by additional inductive coupling by a conductor that connects the plates inside the resonator. In Fig. 9 shows the distribution of the field on the axis of the accelerating-focusing channel when creating an additional induction connection with an arc with an average radius of 150 mm and a cross-section of 10×10 mm. The additional connection locations and corresponding field distributions are shown in the figure.

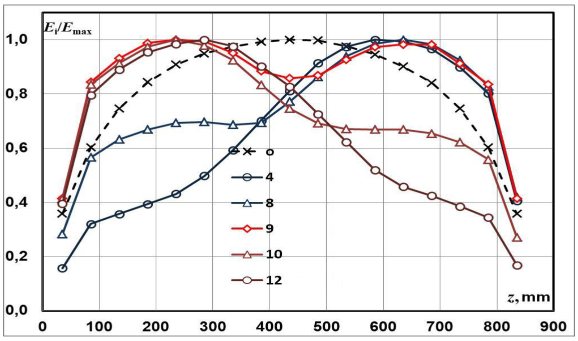

Fig. 9. The distribution of field strength depending on the location of the communication elements

The field strength near the location of the communication circuit decreases. The influence of the communication circuit increases with the shift of communication in the beginning or end periods. The field decreases in the middle periods (8...10) and increases in the finite periods, when the communication element is located in the region of the middle period.

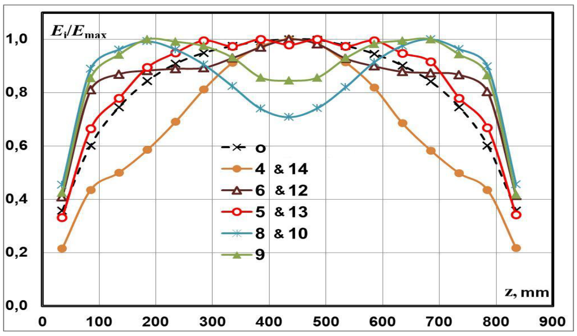

Fig. 10. The distribution of the field strength depending on the radius of the circuit

The impact on the parameters of the resonator provides not only the location of the connection, but the size of the communication elements. The effect on the field distribution near the installation site decreases by ~20% as the radius of the communication loop increases from 150 to 175 mm. Increasing the longitudinal length extends the area of influence in the longitudinal direction. The nature of the impact does not change. The installation of two communication loops simultaneously allows to affect on the field distribution, both in the initial and final periods. The distribution of the field is approaching uniform in the setting of the communication loops in the central periods, as can be seen in Fig. 10. Quality factor increases by about 20% when additional communication circuits are installed. Shunt resistance decreases slightly.

CONCLUSIONS

Methods settings using change of inductance elements and additional inductive coupling are quite effective. They provide the creation of resonators with the necessary electrodynamics characteristics. To achieve the fullest correspondence of the characteristics of the resonator to the results obtained from the calculations of the particles dynamics (resonant frequency, phase distribution and amplitudes of the RF field in the accelerating periods), it is possible to use a combination of the considered methods of influence on the electrodynamics characteristics of H-resonators.

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ОСОБЕННОСТИ МОДЕЛИРОВАНИЯ УСКОРЯЮЩИХ Н-СТРУКТУР В ДИАПАЗОНЕ НИЗКИХ ЭНЕРГИЙ

С.А. Вдовин, Е.В. Гусев

Параметры Н-резонатора: резонансная частота, распределение фаз и амплитуд высокочастотного поля в ускоряющих зазорах, главным образом, определяются устанавливаемой в резонаторах нагрузкой, образующей канал ускорения. При создании на базе Н-резонаторов ускорителей прикладного назначения необходимо определять не только параметры ускоряющего канала, но и поддерживать приемлемые электродинамические характеристики резонатора, влияющие на эффективность использования высокочастотной мощности. Представлен анализ способов моделирования нагрузки ускоряющих Н-резонаторов с учетом изложенных требований.

ОСОБЛИВОСТІ МОДЕЛЮВАННЯ ПРИСКОРЮВАЛЬНИХ Н-СТРУКТУР У ДІАПАЗОНІ НИЗЬКИХ ЕНЕРГІЙ

С.О. Вдовін, Є.В. Гусєв

Параметри Н-резонатора: резонансна частота, розподіл фаз і амплітуд високочастотного поля в прискорювальних періодах, головним чином, визначаються встановленим у резонаторах навантаженням, яке утворює канал прискорення. При створенні на базі Н-резонаторів прискорювачів прикладного призначення необхідно визначати не тільки параметри прискорювальних каналів, але й підтримувати прийнятні електродинамічні характеристики резонатора, які впливають на ефективність використання високочастотної потужності. Представлено аналіз способів моделювання навантаження Н-резонаторів з урахуванням викладених вимог.