DEVELOPMENT OF INHOMOGENEOUS DISK-LOADED ACCELERATING WAVEGUIDES AND RF-COUPLING

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Abstract

A description of different types of the accelerating structures that have been studied and constructed in NSC KIPT for electron linacs during last years is given in this paper. The accelerating structures consist of the inhomogeneous disk-loaded waveguides and input and output couplers. The disc-loaded waveguides operate at $f = 2797$ MHz in $2\pi/3$ mode and have different laws of variation of the disk apertures. Before brazing cups were tuned with using special method. This method is discussed in this paper.

Introduction

During development and tuning of linac accelerating sections, based on homogeneous disk-loaded waveguides, widely used are various cavity stacks, shorted at each end or at only one (plunger method) (see, for example, [1]). In case of homogeneous structures, the possibility of their employment for E-modes is based on the fact that in the infinite periodic waveguide there exists for E-modes an infinite number of symmetry planes whose replacement with metal planes does not affect the field structure. For such short-circuiting, despite the fact that only the finite number of cavities are involved in the cavity stack, the characteristics of the both traveling waves (into which the standing wave of the stack can be expanded) are completely identical to those of the wave propagating through infinite (or matched at the ends) waveguide.

A more complicated is the case of inhomogeneous disk-loaded waveguides for which the periodicity condition is violated and, strictly speaking, the grounds disappear not only for utilization of cavity stacks, but for existence of traveling waves which are synchronous with charged particles. If the disk-loaded waveguide parameters vary slowly along the waveguide, then, the amplitudes of reflected waves are small, and in the system there is a traveling wave with slow-varying parameters. Tuning of such waveguides, using cavity sets, is performed with a low systematic error which is proportional to the inhomogeneity value. As far as the possibility of using for acceleration (generation, amplification) purposes disk-loaded waveguides with highly variable parameters, in each specific case, there is necessity to analyze the types and structures of waveguide fields and, then, develop techniques for tuning the components of this slow-wave structure. In general case, there are no stringent laws which could guarantee one or another property of the inhomogeneous structure, as different from homogeneous ones.

One more requirement imposed on the cavity stacks is the possibility of a consecutive tuning (i.e., a selection the geometrical dimensions one way or another) of waveguide cells. In case of cavity stacks, which model the homogeneous disk-loaded waveguides, this requirement is fulfilled automatically: when one has tuned K cells he can tune (K+1)-cell. In case of inhomogeneous structures, such condition becomes realizable depending upon the degree of coupling between different resonators that form the disk-loaded waveguide.

The calculations performed by us on the base of a new disk-loaded waveguide model (coupled cavity chain) [2] indicate that for waveguides with the period $D \geq \lambda/3$, where λ is the free-space wavelength, the "remote" coupling influences weakly on the phase-shift per cell. For $\varphi = 2\pi/3$, taking into account the "cross-cavity coupling" ((i, i-1), (i, i+1), (i-1, i+1), i - is the cavity number) at $a/\lambda < 0.14$ (a - is the coupling hole radius), one can expect to achieve an accuracy of forming a phase-shift per cell of the order of $\Delta\varphi \leq 0.05°$. If one restricts oneself only "paired coupling" ((i, i-1), (i, i+1)), then, the accuracy of phase-shift per cell is getting worse - $\Delta\varphi \leq 0.5°$. Development of the techniques of disk-loaded waveguide cell tuning that should allow to make feasible the cross-cavity coupling is a difficult task, since during tuning of the i-th resonator one has to take into account, somehow, the effect from the (i+1)-th resonator which has not yet been tuned.

This paper presents the results of our research on the technique of cell-tuning in a strongly inhomogeneous disk-loaded waveguides which realizes paired coupling.

Underlying Theory

From the paper [2] it follows that an infinite chain of cylindrical cavities of the length d and the radii b_i, coupled through co-axial cylindrical holes with the radii a_i in the cavity dividing walls with the thickness t (inhomogeneous disk-loaded waveguide with the period $D = d + t$) at $D > \lambda/3$ can be, with a definite accuracy, described by a set of coupled equations

$$[\omega_n^2(1 + \alpha_n^{(+)} + \alpha_n^{(-)}) - \omega^2]\, u_n = \omega_n^2(\beta_{n,n-1}\, u_{n-1} + \beta_{n,n+1}\, u_{n+1}) \quad (1)$$

where u_n - are the amplitudes of E_{010}-modes in the n-th cavity, ω_n - is the n-th cavity eigen frequency, $\sqrt{\alpha_n^{(+)}}$, $\sqrt{\alpha_n^{(-)}}$ - are the relative n-th cavity eigen frequency shift due to coupling with (n+1) and (n-1) cavities, $\beta_{n,n+1}$, $\beta_{n,n-1}$ -are the coupling coefficients. If $\alpha_n^{(+)}$ and $\beta_{n,n+1}$ are determined by geometrical dimensions of only the n-th and (n+1)-th cavities, as well as by the coupling hole radius a_n ($\alpha_n^{(-)}$, $\beta_{n,n-1}$ are determined by geometrical dimensions of the n-th, (n-1)-th cavities and the hole radius a_{n-1}), then we shall say that the cavity coupling is paired. If these coefficients depend on geometrical dimensions of three cavities (n-th, (n+1)-th and (n-1)-th), as well as two coupling hole radii a_i , a_{i-1}, then, such coupling we shall call "cross-cavity coupling".

Let's find the conditions, when the set (1) at $\omega=\omega_*$ (ω_* - is the operating frequency) has the solution of such form $u_n = u_{n,0}\exp(in\varphi)$, where $u_{n,0}$ - is the real value. From (1) it follows that in order to achieve this, the following conditions is to be fulfilled $\beta_{n,n-1}\, u_{n+1,0} = \beta_{n,n-1}\, u_{n-1,0}$. For the n-th cavity (1) will take on the form

$$[\omega_n^2(1+\alpha_n^{(+)}+\alpha_n^{(-)})-\omega_*^2]\, u_{n,0} = 2\,\omega_n^2\, \beta_{n,n-1}\, u_{n-1,0}\cos(\varphi), \quad (2)$$

and for the (n-1)-th cavity

$$[\omega_{n-1}^2(1+\alpha_{n-1}^{(+)}+\alpha_{n-1}^{(-)})-\omega_*^2]\, u_{n-1,0} = 2\,\omega_{n-1}^2\beta_{n-1,n}\, u_{n,0}\cos(\varphi). \quad (3)$$

From (2) and (3) it follows that, if $\alpha_n^{(+)}$ is independent from the parameters of the (n+1)-th cavity, $\alpha_{n-1}^{(-)}$ - from the parameters of the (n-2)-th cavity and $\beta_{n-1,n}$, $\beta_{n,n-1}$ depend only upon the parameters of the n-th and (n-1)-th cavities, then, two equations (2) and (3) become closed and determine fully the relation of geometrical dimensions of the n-th and (n-1)-th cavity. In this case, having tuned the (n-1)-th cavity, one can find the conditions which must satisfy the geometrical dimensions of the n-th cavity, and, consequently, allow to consecutively tune all waveguides cavities. It can be shown that at the paired coupling $\beta_{n-1,n} = \beta_{n,n-1}$ and these coefficients are determined by the geometrical dimensions of the n-th and (n-1)-th cavities, only. Things are more complicated with the dependence of coefficients $\alpha_n^{(+)}$ on the parameters of the (n+1)-th cavity and $\alpha_{n-1}^{(-)}$ on the parameters of the (n-2)-th cavity. Even under the assumption of paired coupling such dependence exists. However, our calculations shown that this dependence is considerably weaker than the dependence on the parameters of the n-th ((n-1)-th) cavity, and can be neglected, as a result.

Cavity stacks for tuning inhomogeneous waveguides with $\varphi=2\pi/3$

From the equations (2) and (3) it follows that in order to achieve the traveling wave mode in an inhomogeneous disk-loaded waveguides with the mode type $\varphi=2\pi/3$ it is necessary that the parameters of the (n-1)-th and the n-th cavities be connected via the relationship

$$[\omega_{n-1}^2(1+\alpha_{n-1}^{(+)}+\alpha_{n-1}^{(-)})-\omega_*^2][\omega_n^2(1+\alpha_n^{(+)}+\alpha_n^{(-)})-\omega_*^2] = \omega_n^2\,\omega_{n-1}^2\beta_{n,n-1}\,\beta_{n-1,n}. \quad (4)$$

Suppose we have placed the n-th and (n-1)-th cavity into some sort of a cavity stack. It can be shown that the conditions (4) is fulfilled in the case, when in the cavities A and B (see Fig.1),adjoining the cells under consideration, the amplitudes of E_{010}-modes equal to zero. For cavity stacks, shorted at both ends, this condition can be accomplished by coupling the cavities A and B to terminal cavities, resonance-tuned at the frequency $\omega=\omega_*$ with taking into account the frequency shift due to the hole effect. Such cavity stacks have already been used for tuning separate parts of quasi-constant impedance sections for LIL accelerator [3]. However, there the cells were tuned not consecutively , i.e. beginning from the entrance (or exit), but in different stacks being then simply joined one-to-one.

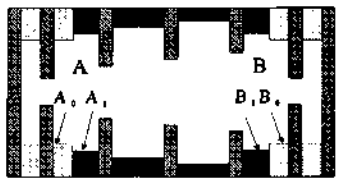

Fig.1. Cavity stack.

The above results indicate that it is possible to use a consecutive tuning of all cells for disk-loaded waveguides with an arbitrary law of the coupling hole radius variation. With that, at the operating frequency $\omega=\omega_*$ the traveling wave mode with the phase shift on the order of $2\pi/3$ with a certain accuracy is guaranteed in a waveguide. However, a quite natural question arises about the characteristics of such traveling wave, since the inhomogeneity in a disk-loaded waveguides is created with the purpose of optimizing its characteristics. Let's consider, for instance, a quasi-constant impedance section. Such a waveguide is supposed to consist of several homogeneous ($a_i = const$) segments with different radii of the coupling holes and transition sells which provide the matching of these segments. Our analysis indicates that fulfillment of such a requirement is realizable only under a certain law (unknown a priory) of hole radius variation. If one use the disks in the transition sells with some law of the hole radius variation (for instance, the linear one) and consecutive tune all cavities following the above technique, he can obtain a waveguide which will operate in a traveling mode at $\omega=\omega_*$, but its segments which are homogeneous relatively the hole radius will not be homogeneous relatively the waveguide inside diameter. Thus, under application of the above technique to the consecutive cell tuning in the case of the linear law of hole radius variation in the transition sells, the waveguide inside diameter will be periodically change within the second segment, i.e. the second segment of the section will be bi-periodic. For the subsequent "homogeneous" segments the law of the waveguide inside diameter variation will be more complicated. In the case of the linear law of hole radius variation in the transition sells two homogeneous segments cannot be matched together without violation of the condition $\varphi=2\pi/3$, and the precise matching is impossible and from the transition there occur certain reflection with a small phase jump. What is more expedient for the accelerating section: the traveling wave mode with cavity frequency variation along the length of the structure, and, consequently, with the acceleration amplitude variation causing a certain decrease in the energy gain or a joining of segments with a small phase jump and reflection that, also, leads to a certain decrease in the energy gain? There is no unambiguous answer to this question. In each case one will have to analyze the energy gain (or other characteristics) with taking into account the above factors. Our calculations indicate, for instance, that in the case of a structure with two homogeneous segments and for the linear law of hole radius variation in the transition sells more preferable would be the situation with the periodic cavity frequency variation in the second segment from the standpoint of energy gain.

Consecutive tuning feasibility is determined by stability of the technique, as well. The numerical analysis indicates that small errors in the tuning of individual cells should not lead to the exponential growth of subsequent deviations, i.e. the technique must be stable.

Inhomogeneous accelerating sections

The National Science Center "Kharkov Institute of Physics&Technology" (NSC KIPT) has created a technological base for building accelerating structures on the base of disk-loaded waveguides. The basic elements of a disk-loaded waveguides is asymmetric cell (disk and cup). The high-precision copper cups and disks are made on diamond tool lathers. Prior to brazing, the cups are tuned using different cavity stacks. Brazing a segment of cups and irises, segments and couplers are made in a vacuum RF-furnace at 779°C using the KIPT technology.

We have developed and manufactured four short inhomogeneous accelerating sections with $\beta_{ph}=1$ and $\varphi=2\pi/3$, three of which (S1, S2, S3) have quasi-constant law of coupling hole radius variation with a linear decrease of radii in transition cells, while in the fourth one (S4) the coupling hole radii decrease linearly from entrance to exit. Calculated characteristics of the first three sections are given in Table 1.

Prior to brazing the first section sells were tuned using the method completely coinciding with the one presented in [3]. Cavities in the second, third and fourth sections were consecutively tuned in the cavity stack using the above described method. While doing so, as compare with [3], the number of auxiliary cells was reduced to the minimum - we used only four auxiliary cells (see Fig.1). Cells A and B were composite ones ($A=A_l+A_n$, $B=B_l+B_n$, $A_n=B_n$) and during tuning process cells A_n and B_n were unchanged while the radii of cells A_l and B_l were changed according to a certain law. For sections S2 and S3 the radii of cells A_l and B_l were changed after tuning the transition sells, for section S4 - they were consecutively tuned together with the main sells. After brazing the sections cells were tuned by way of a small external deformation of the cups until the needed phase shift was achieved ($\delta\varphi=4\pi/3$) during the shorting plunger movement. Since such a tuning cleaned away all the errors of the first tuning (before brazing) we did not see the difference in the characteristics between sections S1, S2 and S3.

Table 1
Calculated characteristics of the S1, S2, S3 sections

	I=0 A	I=1.2A
Frequency, MHz	2797.2	2797.2
Input Power, MW	13	13
Energy Gain, MeV	17.8	9.5
Beam Power, MW		11.4
Gradient, Mev/m	14.3	7.6
Section Length, m	1.227	1.227
Filling Time, µsec	0.31	0.31
Field Attenuation, Nep/sect.	0.24	4.2
Output Power, MW	8	0.03
Number of Homogeneous Segments (Iris Diameters, mm)	4 (25.441, 23.630, 21.821, 19.620)	

During measurements of the after-brazing phase shifts it was found that the operating frequency of all sections was 150 to 200 kHz lower than the calculated one. It can be explained as errors of used cavity stack. Indeed, the above stacks are just for paired cavity coupling. According to the results of our calculations [2] the negligence of the "remote" coupling can produce errors during tuning about $\Delta\varphi\leq+0.5^0$ which agrees in value and sign with the obtained deviation of the operating frequency.

The section S1 was installed on KUT accelerator [4]. The results of beam characteristics measurements agreed with simulations.

Thus, our R&D has shown that the feasibility is there to tune (with a certain error) of disk-loaded waveguides with arbitrary law of hole radius variation. In order to achieve the necessary characteristics the choice of such law must be made with taking into account both the properties of inhomogeneous waveguides as the feasibility of tuning such waveguides. In view of all the above-said, a procedure should be worked out to optimize the structures considered. At present, based on the approach [2] we have begun to investigate this problem.

Acknowledgments

The authors wish to thank A.N.Dovbnya, V.A.Kushnir and V.V.Mitrochenko for discussions relating results of this work.

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