Electrodinamical Parameters of Bunchers, based on Quaterwave Coaxical Cavities

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1 ABSTRACT

Electrodinamical parameters of the double gap bunching cavities, based on quaterwave coaxical cavities, positioned perpendicular to the beam propagation, are considered. Methods of calculations is in reduction of the 3D Electrodinamical problem to the set of 2D problems and allows provide optimization of the RF parameters. Some reasons to choose cavity dimensions are considered. Comparisons with cylindrical cavities, exited with TM_{010} mode show, that coaxical buncher at least have smaller transverse dimensions. If distance more than $0.6\beta\lambda$ along beam axis is available, coaxical bunchers provide the same RF voltage with match smaller consumption of RF power.

2 INTRODUCTION

Application of the single gap cylindrical cavity with drift tubes, exited with TM_{010} mode, for bunching of the particle beam before acceleration is well known. In modern projects of the proton linear accelerators bunchers, based on coaxical cavities, are now under consideration (see, for example [1]). Correct electrodinamical simulation of this cavity is essentially 3D problem. Modern 3D codes are enough powerful to define the cavity dimensions, but direct 3D calculations with a lot of variants for optimization remain expensive procedure.
In this paper we describe method of optimization and some results for bunching cavities, developed for INR linac.

3 METHOD OF OPTIMIZATION

A schematic sketch of the cavity is presented in Fig. 1a. The cavity is a coaxical system consisting of outer conductor (1), inner conductor (2) and drift tube (3).

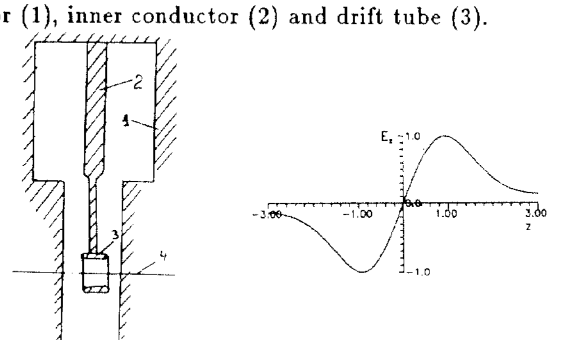

Fig. 1. Schematic sketch of the buncher cavity (a) [outer conductor (1), inner conductor (2), drift tube (3), beam line (4)] and electric field distribution along beam axis (b).

The electric field distribution along the beam axis in this cavity is presented in Fig. 1b.
This cavity may be considered as usual coaxical system loaded with end capacitance C_t - capacitance of the drift tube.
Consider evaluation of parameters for drift tube region. Taking into account small dimensions of this region in comparison with wavelength, we can successfully use electrostatic approximation. The distribution of the potential U (Fig. 2) and all parameters needed may be founded as a solution of the 2D simulation problem, considering beam axis as the axis of axial symmetry. We neglect here influence of the central conductor of the cavity. Capacitance of the drift tube is:

$$C_t = \frac{\int_S E_n dS}{\epsilon_0 U_t} = \frac{\int_S \frac{\partial U}{\partial n} dS}{\epsilon_0 U_t} \qquad (1)$$

where E_n is normal component of the electric field, S - surface of the drift tube, n - unit normal vector, U_t - voltage applied to the tube. If the beam hole radius is a, energy gain for the particle is:

$$\Delta W = \frac{2U_t T sin(\frac{l_c k}{2\beta})}{I_0(ka\sqrt{\frac{1}{\beta^2}-1})}, \qquad T = \frac{sin(\frac{l_g k}{2\beta})}{\frac{l_g k}{2\beta}}, \qquad (2)$$

where l_g is the length of the accelerating gap, l_c - distance between centers of accelerating gaps, β - relative velocity of the particle, $k = \frac{\omega}{c}$, T - transit time factor.

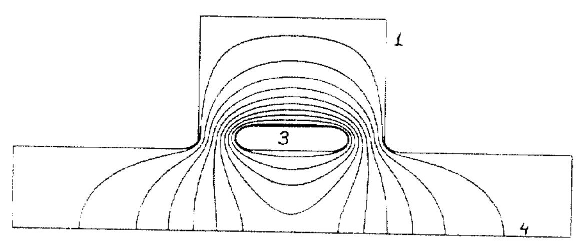

Fig. 2. Distribution of the potential in the beam aperture.

Let's consider coaxical part of the cavity. Suppose, for the simplification of the design and manufacturing, it consist of several longitudinally homogeneous parts. It is also well known, that electric field distribution in a coaxical system of arbitrary cross-section is like electrostatic. So, we can reduce problem of the electromagnetic field calculation to the simulation of the potential distribution in cartesian coordinates. For the outer conductor of rectangular form

and circular inner conductor the distribution of the potential is presented at Fig. 3.
Having the potential distribution, one can find electric field in usual way $\vec{E} = -gradU$ and the magnetic field components:

$$H_x = -\frac{k}{\mu_0}E_y, \qquad H_y = \frac{k}{\mu_0}E_x. \tag{3}$$

We don't consider here z-dependence of electric and magnetic fields. The wave resistance of the coaxical line is:

$$Z_w = \frac{\oint_L H_\tau dL}{U} = \frac{k}{\mu_0}\frac{\oint_L \frac{\partial U}{\partial n} dL}{U} \tag{4}$$

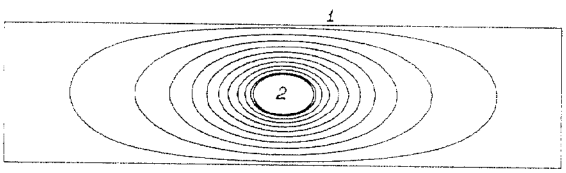

Fig. 3. Distribution of the potential in coaxical line.

If wave resistances of all parts of coaxical system are known, using usual formulas for resistance transformation in transmission lines and defining length for each part of the coaxical system, one can find wave resistance Z_t before drift tube (taking into account that opposite end of the line is shortened). Equation to find resonant frequency:

$$Im(Z_t + \frac{1}{i\omega C_t}) = 0, \tag{5}$$

or to find length of the cavity. As usual, operating frequency is given and problem is to find dimensions. When this problem is solved, using expressions 3 for magnetic field components, taking into account z-dependencies and phase shifts at places of connections of different parts, one find current and voltage distributions in the cavity. It means, that for energy gain needed (2) one can calculate RF power dissipated in surface and Q factor of the cavity. By using the method proposed we have reduced 3D problem to the set of 2D and simple calculations. Modern 2D codes for the simulation of the potential distribution, like POISSON or MASTER [2], allow for designer collect data library for different variants of the drift tube, and coaxical line crossections. It allow overlap in optimization large variety of variants in reasonably small time.
Comparison of results, obtained with the proposed method, and results of direct 3D simulation using RFC-3D code [4] exhibits fine coincidence in frequency and good (difference not more than 5%) in Q factor.

4 DISCUSSION

Some conclusions may be derived without numerical simulation. From (2) one see, that to have maximal energy gain at voltage given, one have fulfill condition $l_c = \frac{\beta\lambda}{2}$. If enough space along beam line is available, this condition is no problem. Length of the gap l_g have to be chosen (as usual) as compromise between transit time factor (small gap needed) and maximal electric field at the surface.
As a role, space for buncher is limited by focusing elements. Using soft dependence of the energy gain ΔW vrs l_c, we can reduce l_c, reducing total length of the buncher along beam line. For example, reduction in l_c from $0.5\beta\lambda$ to $0.4\beta\lambda$ leads to reduction in ΔW only at 5%.
The radius of the beam hole a has drastic influence at buncher RF efficiency, because term $I_0(ka\sqrt{\frac{1}{\beta^2} - 1})$ rises like $exp(\frac{2\pi a}{\beta\lambda})$, leading to increasing of RF power in $exp(\frac{4\pi a}{\beta\lambda})$ times. So, the beam hole radius have to be as small, as possible from bean dynamic requirements.
It should be mentioned here, that the drift tube capacitance have to be as small, as possible. Simplest shape of the drift tube - cylindrical with circular ends and outer diameter as small as possible seems the best. Reduction in dimensions for the drift tube is limited by two reasons. First one is the maximal electric field at the surface. Second one is the azimuthal ingomogenuity of the field in the beam aperture due to influence of the central conductor. To reduce it, diameter of the central conductor near drift tube have to be several $(3 \div 5)$ times less than length of the drift tube. Additional feature of the central conductor with small diameter near drift tube is small capacitance. It leads to reduction of the RF power.
The numerical optimization has shown for $\beta \approx 0.04$, that the gap length $l_g \approx 0.2\beta\lambda$ provides the best results. Total length of the buncher along beam line is $l_c + l_g = (0.7 \div 0.6)\beta\lambda$.
To reduce RF power losses by decreasing the current density, diameters of conductors near shortened wall have be enlarged. The investigation done has shown, that for $a = 10mm, \beta = 0.04, f = 198.2MHz, \Delta W = 100kV$ RF power $\approx 2.8kWt$ with the cavity Q factor $\approx 5 \times 10^3$ is needed. The length of the cavity in transverse direction is $\approx 0.2\lambda$. The same energy gain may be obtained with single gap cylindrical cavity, but with RF power needed 3 times more. The cylindrical cavity may be used only if space along beam axis is strongly restricted $(\approx (0.2 \div 0.4)\beta\lambda)$.
For the energy gain given coaxical cavity has approximately the higher maximal current density, than cylindrical one. But the surface square for coaxical cavity is match smaller and total RF power losses are less. The same magnetic field flow provides twice voltage along beam axis. The maximal current density is near shortened end of the cavity, far enough from beam axis, providing good conditions for placement of control and driving loops.

5 ACKNOWLEDGMENTS

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