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DESIGN OF NEW BUNCHER CAVITY FOR RELATIVISTIC ELECTRON GUN FOR ATOMIC EXPLORATION – REGAE

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Abstract

The Relativistic Electron Gun for Atomic Exploration, REGAE, is a small electron accelerator build and operated at DESY. Its main application is to provide high quality electron bunches for time resolved diffraction experiments. The RF system of REGAE contains different parts such as low level RF, preamplifier, modulator, phase shifter, and cavities. A photocathode gun cavity to produce the electrons and a buncher cavity to compress the electron bunches in the following drift tube. Since the difference between the operating mode of the existing buncher and its adjacent mode is too small, the input power excites the other modes in addition to the operating mode which affects the beam parameters. A new buncher cavity is designed in order to improve the mode separation. Furthermore the whole cavity is modeled by a circuit which can be useful especially during the tuning process. Beam dynamics simulations have been performed in order to compare the new designed cavity with the old one which declare that the effects of the adjacent modes on the beam parameters are decreased.

INTRODUCTION

The REGAE buncher is formed from four coupled pillbox cavities and so it has four fundamental $TM010$ normal modes which are named as 0-Mode, $\frac{\pi}{3}$-mode, $\frac{2\pi}{3}$-mode, and π-mode [1]. The measurement and simulation results for the frequencies of these four $TM010$ normal modes with Microwave Studio (MWS) and Superfish are shown in Table 1 [2]. According to this table the difference between the π-mode which is the operating mode and its adjacent $\frac{2\pi}{3}$-mode is only 2 MHz. This very close mode might affect on the REGAE operation and its stability. In fact the input power excites the other normal modes of the buncher in addition to the π-mode that leads to some problems in low level RF operation of the system which might cause unwanted effects on the beam that is going to be bunched. Fig. 1 for example shows the amplitude of the RF power in the buncher in which some fluctuations are added to the main signal. The frequency of these fluctuations is exactly equal to the difference between the π-mode and the $\frac{2\pi}{3}$-mode and the origin of this parasitic signal is the poor mode separation in the buncher [2]. The main goal in designing the new buncher is to improve the mode separation in order to remove or at least reduce the effects of other modes on the buncher operation as much as possible.

Table 1: Measured and Simulated Frequencies of the Buncher Modes in MHz

	0-Mode	$\frac{\pi}{3}$-mode	$\frac{2\pi}{3}$-mode	π-mode
MWS	2983	2988	2993	2995
Superfish	2984.2	2989.4	2994.6	2996.8
Measured	2985	2991	2996	2998

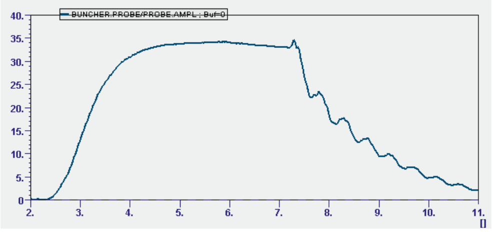

Figure 1: The RF power amplitude in the REGAE buncher.

DESIGN PROCESS AND SIMULATION RESULTS

In order to improve the mode separation in the buncher one should increase the coupling between adjacent cells which is strongly dependent on the geometry of the cavities such as radius and thickness of the disks between them. It is possible to achieve a better mode separation by changing the physical parameters of the buncher. Parameters that have been investigated are depicted in Fig. 2. In this figure rA, rB, and rC are representing half of the thicknesses of the disks between the cells while yA, yB, and yC represent the radii of these disks openings. Furthermore yD, rD and yE, rE determine the corresponding parameters related to the input and output cells respectively.

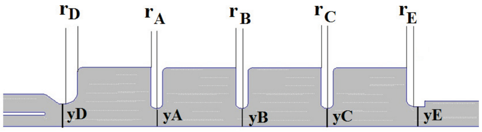

Figure 2: The physical parameters of the buncher.

To find the effects of each parameter it is varied between reasonable end values while the other parameters are kept constant. After simulation and finding the frequencies of the buncher normal modes, the dependency curves of these frequencies on the buncher parameters are drawn. As an example Fig. 3 shows the dependency of δf_3 on the mentioned physical parameters, where δf_3 is difference between the π-mode and the $\frac{2\pi}{3}$-mode. Similar curves are extracted

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for the other modes. Analyzing the curves results that in order to improve the mode separation the radii of the disks openings between cavities should be increased and despite of their radii the thickness of the disks should be decreased. These results are in agreement with the basic expectation as increasing the radius of a disk opening or decreasing its thickness will fortify the coupling between the cells which are located at the sides of the disk. Considering these results the optimum values of the parameters can be chosen, however some other limitations should be considered. The absolute value of the operating frequency should be 2998 MHz, while by changing the physical parameters of the cavity this frequency will vary and it is necessary to shift it back to its operating point. Also one requirement is flatness of E-field across the cells. In other words the maximum of the electric field inside the cells should be equal in order to achieve the best efficiency of the buncher. It is required to find a way to solve these two problems at once. It is possible to shift the π-mode frequency back to its operating point and simultaneously make the peak of the electric field profile flat by adjusting the cell's diameter. Decreasing one cell diameter results in two phenomena. First, an increase of the π-mode frequency and second, an increase of the electric field of the corresponding cell. Considering these changes a guideline could be extracted to find the appropriate amounts for the radii of the cells. Considering all the mentioned issues the optimum values of the physical parameters of the cavity in order to have the desired mode seperation were selected. The simulation results for the fundamental modes of the buncher based on these parameters are shown in Table 2.

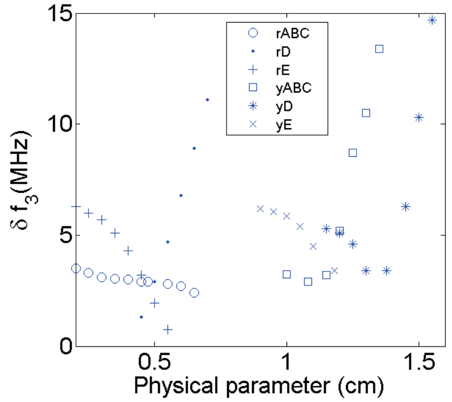

Figure 3: δf_3 dependency on the physical parameters of the buncher.

Table 2: Simulated Frequencies of the Optimized Buncher Modes in MHz

	0-Mode	$\frac{\pi}{3}$**-mode**	$\frac{2\pi}{3}$**-mode**	π**-mode**
MWS	2940	2964	2989	2998
Superfish	2939.5	2964	2988.6	2998.1

As it can be seen from this table and table 1 the differences between the operating frequency and the other modes have been increased from 2, 7 and 12 MHz to about 9, 35 and 59 MHz respectively.

DEVELOPING A CIRCUIT MODEL FOR THE BUNCHER

In the following a circuit model of the buncher cavity is developed to get an understanding into the effects of different parts of the buncher on determining the normal mode frequencies.The key point is to consider a precise model which covers all the properties of the buncher. REGAE buncher includes four pillbox cavities that could be modeled by LC resonance circuits and the interaction of the adjacent cells can be represented by the mutual inductances of the LC circuits [1]. Such model is shown in Fig. 4. The coupler is modeled with a transmission line with characteristic impedance of Z_0 and an inductor which is coupled to the first cell and the RF input is modeled with a voltage source. On the other hand the end tube has to be modeled by a transmission line with short circuit termination because of negligible power loss at the end of the tube. Since the length of the end tube is 5cm which is half of the wavelength its input impedance is equal to zero [3].

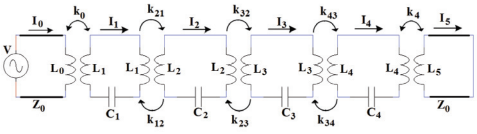

Figure 4: The circuit model of the REGAE buncher.

The Kirchhoff equation of this circuit should be written in order to find the fundamental modes frequencies. Such equations can be written in matrix form, after some algebra as follow:

$$LX = \frac{1}{\Omega^2}X \tag{1}$$

where L is the network matrix:

$$L = \begin{bmatrix} \frac{1}{\omega_{01}^2} & \frac{k_{12}}{2\omega_{01}^2} & 0 & 0 \\ \frac{k_{21}}{2\omega_{02}^2} & \frac{1}{\omega_{02}^2} & \frac{k_{23}}{2\omega_{02}^2} & 0 \\ 0 & \frac{k_{32}}{2\omega_{03}^2} & \frac{1}{\omega_{03}^2} & \frac{k_{34}}{2\omega_{03}^2} \\ 0 & 0 & \frac{k_{43}}{2\omega_{04}^2} & \frac{1}{\omega_{04}^2} \end{bmatrix} \tag{2}$$

here ω_{0n} is the resonant frequency of the individual resonators if they were uncoupled, Ω is the assumed frequency of a steady-state oscillation (normal mode), and X is the vector of the loops current which actually represent the amounts of the electric field inside the cells. So in order to find the normal mode frequencies of the cavity it is sufficient to calculate the eigenvalues of the network matrix, λ, considering that $\Omega = \frac{1}{\sqrt{\lambda}}$. Also the ratio of the maxima of the electric field inside the cells can be found by simply calculating the eigenvectors of the network matrix which is very useful during the tuning process of the cavity.

Validation of the Circuit Model

As declared before it is critical to have a precise model in order to exploit the benefits of the circuit model. To find out how exact is the proposed model one can make some comparisons between simulation results and the results obtained from the circuit model. Fig. 5 shows such comparisons. In this figure the two upper curves are the model results which display the difference between adjacent normal modes as a function of individual resonant frequencies of the first and the second cell while the lower curves are the Superfish results that display the difference between adjacent modes versus cell diameters. A decrease in one cell diameter and consequently decrease in its volume leads to an increase in the resonant frequency of the respective cell. Hence in order to have a better comparison the horizontal axis of the Superfish results are set to show the values in reverse order. In each series of the curves, from left to right the individual resonant frequency of the specified cell is increasing. As it can be seen the characteristics of changes are similar to each other.

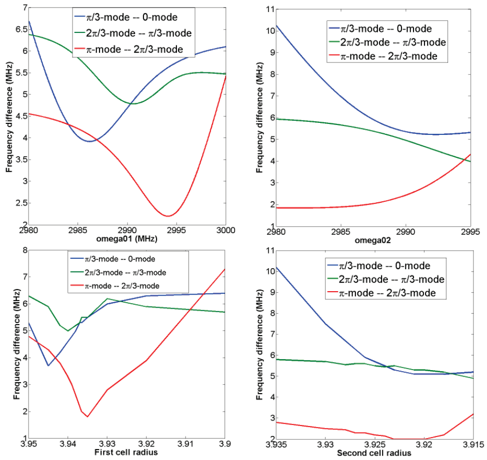

Figure 5: Comparison between the circuit model results (top) and Superfish simulation results (bottom).

BEAM DYNAMIC SIMULATIONS

As mentioned in the first section, the input RF power excites the non-operating normal modes of the buncher in addition to the π-mode and so some contribution of these modes exist in the total electric field inside the cells which can influence the transverse and longitudinal beam parameters such as bunch length and beam emittance. It seems to be necessary to perform some beam dynamic simulations in order to find the effects of different modes on the electron beam. For beam dynamic simulation the tracking program ASTRA (A Space Charge Tracking Algorithm) has been used [4]. First, the bunch length variations in a drift behind the buncher cavity is simulated both for the existing buncher and the new design. In these simulations the electric field component due to the $\frac{2\pi}{3}$-mode has been translated into the amplitude of the electric fields in the ASTRA input which reversely proportional to the difference between π-mode frequency and the other normal modes frequencies and can be calculated from the resonance curve. Simulation results declare that by changing the phase of the π-mode the minimum achievable bunch length will vary and also the distance in which this minimum occurs can be moved by changing the phase of the π-mode. The minimum achievable bunch length for the existing and the new designed buncher are compared in Fig. 6. The beam emittance at the end of the buncher is also simulated for both, the existing cavity and the new buncher. To calculate the effect of the $\frac{2\pi}{3}$-mode, the emittance result in absence of the $\frac{2\pi}{3}$-mode is subtracted from the emittance result with the $\frac{2\pi}{3}$-mode. All the possible phases have been simulated and the maximum value of the emittance has been considered as the total emittance in the presence of the $\frac{2\pi}{3}$-mode. Fig. 7 displays the contribution of the $\frac{2\pi}{3}$-mode to the beam emittance for the new designed buncher and for the old one. As for the bunch length the effects of the $\frac{2\pi}{3}$-mode on the emittance is much lower for the new design than for the existing cavity which is a result of the better mode separation.

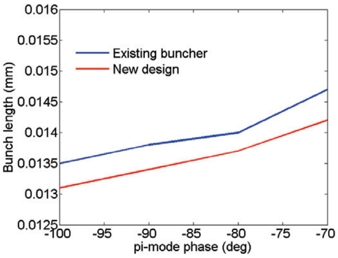

Figure 6: Comparison of the effect of $\frac{2\pi}{3}$-mode for the existing cavity and the new design.

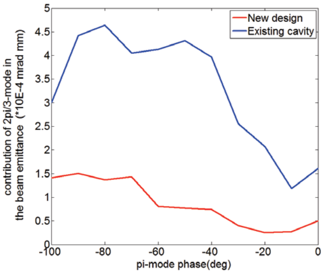

Figure 7: The contribution of $\frac{2\pi}{3}$-mode in the beam emittance.

CONCLUSION

A new buncher cavity has been designed for REGAE in order to improve the mode separation and overcome the consequences of small difference between the adjacent modes. The beam dynamic simulations show that the beam parameters such as bunch length and beam emittance will be improved by the new design. Furthermore a circuit model is developed to model the cavity buncher and its behavior regarding to change of the physical parameters.

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