PROPERTIES AND POSSIBLE APPLICATIONS OF MULTIPLE BEAM COUPLED CAVITY STRUCTURE*

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1. BACKGROUND AND INTRODUCTION

Beam current is restricted by physical aperture size due to space charge limitation and, in commonly used structures, it is difficult to exceed this limitation of approximately 10^9 1/cm^3 without affecting structure efficiency and energy gain. Multiple or hollow beam concept for microwave structure design is proposed [1] to expand range of beam current which could propagate through the structure. The coupled circuits model and microwave theory was used to analyze one of the simple realization of the proposed concept. A cavity was designed which is capable of accelerating four parallel beams, the tuning procedure was refined and microwave properties of the structure were studied. The study could be considered successful as our analysis confirmed predictions made at the very early stage of development. The proposed design concept could be used for a number of applications.

2. PROPERTIES OF FOUR BEAM STRUCTURE (FBS)

2.1 Coupled Circuit Model and Modes of Resonantly Coupled FBS

To study MBS properties, we decided to start with a simlified version of FBS resonator [1]. The resonator is shown on Fig.1. Two "rings" of four cavities, coupled through a central coupling cavity have formed the complete resonator.

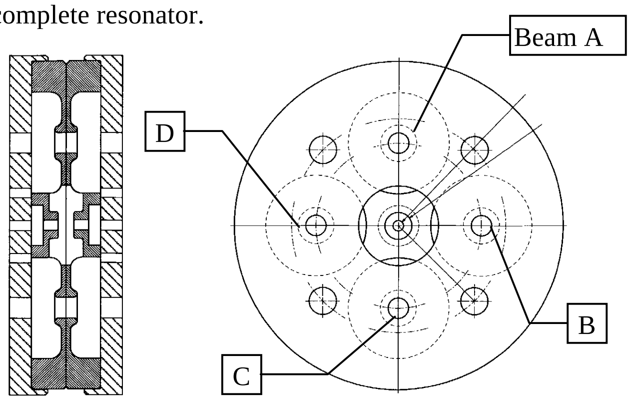

Fig.1 One-period FBS Resonator Analyzed By Means of Coupled Circuit Model.

Schematic for two rings of coupled half cells, coupled together through a single coupling resonator is illustrated in Fig.2. This element represents a period of the four-beam accelerator structure. The modes of resonantly coupled, multibeam structure were analyzed by establishing the notation and normalization for the simple structure so that the impedance matrix of the more complicated multibeam structure can be written by inspection.

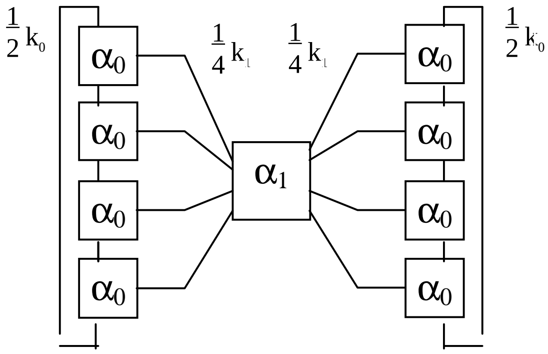

Fig. 2. Schematic representation of two "rings" of FBS cavities coupled through a single coupling cavity.

Without presenting the complete analysis for the simplified circuit, we will write down the final normalized impedance matrix for the circuit shown on Fig.2:

$$
Z=\begin{vmatrix}
\alpha_0 & -\kappa_0/2 & 0 & -\kappa_0/2 & -\kappa_1/4 & 0 & 0 & 0 & 0. \\
-\kappa_0/2 & \alpha_0 & -\kappa_0/2 & 0 & -\kappa_1/4 & 0 & 0 & 0 & 0. \\
0 & -\kappa_0/2 & \alpha_0 & -\kappa_0/2 & -\kappa_1/4 & 0 & 0 & 0 & 0. \\
-\kappa_0/2 & 0 & -\kappa_0/2 & \alpha_0 & -\kappa_1/4 & 0 & 0 & 0 & 0. \\
-\kappa_1/4 & -\kappa_1/4 & -\kappa_1/4 & -\kappa_1/4 & 2\alpha_1 & -\kappa_1/4 & -\kappa_1/4 & -\kappa_1/4 & -\kappa_1/4 \\
0 & 0 & 0 & 0 & -\kappa_1/4 & \alpha_0 & -\kappa_0/2 & 0 & -\kappa_0/2 \\
0 & 0 & 0 & 0 & -\kappa_1/4 & -\kappa_0/2 & \alpha_0 & -\kappa_0/2 & 0. \\
0 & 0 & 0 & 0 & -\kappa_1/4 & 0 & -\kappa_0/2 & \alpha_0 & -\kappa_0/2 \\
0 & 0 & 0 & 0 & -\kappa_1/4 & -\kappa_0/2 & 0 & -\kappa_0/2 & \alpha_0.
\end{vmatrix}
$$

The modes of one period can be determined by finding the frequencies for which the determinant of Z vanishes. The mode equation is:

$$\mathrm{Det}\,[Z]= 2\,\alpha_0^4(\alpha_0-\kappa_0)\,(\alpha_0+\kappa_0)^2\,[(\alpha_0-\kappa_0)\alpha_1-\kappa_1^2/4]=0,$$
$$\text{where } \alpha_i=1-(\omega_i/\omega)^2.$$

This immediately shows that there are a total of 9 modes, four modes corresponding to $a_0=0$, two modes

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corresponding to a_0=-k_0 , one mode corresponding to a_0 = k_0 , and two modes that depend on a_1 and k_1 .

The eigenvectors are readily determined. The modes for a_0 = 0 correspond to the doubly degenerate π/2 mode of the four accelerating cell resonators which are coupled in a ring. Of course, since the modes are degenerate, any orthogonal linear combination of the eigenvectors can be used. A possible set of two eigenvectors for the a_0 = -k_0 correspond to the p mode of the ring of four resonators. None of the preceding modes involve propagation of rf power through the central coupling cavity since their net coupling to the central cavity is zero.

The a_0 = k_0 mode corresponds to the 0 mode of the four resonator ring. This could be the desired operating mode, where the structure is in the π/2 mode for longitudinal waves and is resonantly coupled if the coupling resonator is correctly tuned.

The remaining two modes also involve the 0 mode of the four resonator ring, but with the two rings in phase, which requires stored energy in the central coupling resonator. The coupling resonator can either be in phase or out of phase with the two adjacent four resonator rings. The amplitude of the excitation of the coupling resonator depends on the coupling resonator frequency and the ring to coupling resonator coupling factor, k_1.

The simple model presented above does not have the next-nearest-neighbor coupling factors usually included in the mode analysis of coupled cavity linac structures. However, the conclusions regarding the mode spectrum are only slightly affected. With next-nearest-neighbor coupling between adjacent accelerating cells, the degeneracies would split and narrow passbands would be formed about the a_0 = -k_0 and a_0 = 0 modes. The passband about the a_0 = k_0 mode would only be slightly modified by the additional coupling factor. If the modes are identified according to the internal modes of the accelerating cells, the modes corresponding to the azimuthal zero mode (all gaps in phase in a particular accelerating cell) can be analyzed using the standard biperiodic structure model to determine the standard five parameters, accelerating cell frequency, coupling cell frequency, nearest neighbor coupling factor and next nearest neighbor coupling factors.

The analysis shows that the structure behaves like a normal biperiodic coupled-cavity linac structure with coupling factor k_1 , with the addition of the non-propagating modes due to the internal resonances of the multiple gap accelerating cells. Since the internal modes don't propagate only if the cells and coupling apertures are perfectly symmetrical, the coupling factor k_0 should be kept large to keep the internal modes away from the operating frequency to reduce the likelihood of coupling microwave energy to these modes.

2.2 Experimental Study of Test Resonator.

Test resonator was made by combining the cells, shown on Fig.3.

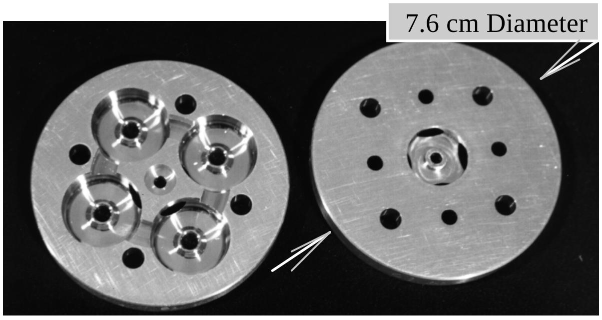

Fig.3 Manufactured X-band Cavity

Coupling between the cavities in the rings was introduced and changed during the measurements to study theoretical predictions, which were in a good agreement with experimental results.

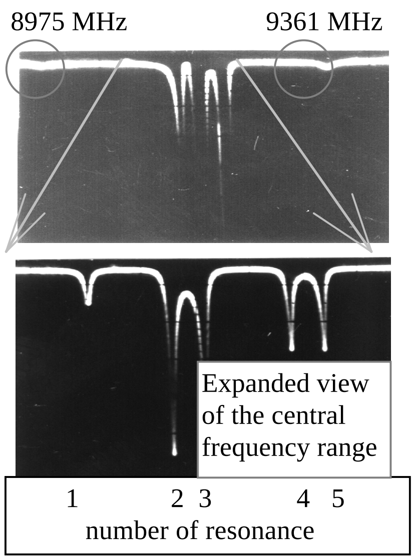

Fig. 4 Resonator with two full cavity "rings" coupled through central coupling cavity (as shown on Fig.1).

Fig.4 presents the oscillograms for the resonator with two full cavity "rings" excited by probe located in A beam centerline and read by probe in C beam centerline, correspondingly. "Bead pull" was done for every resonance in axial and radial direction and field patterns were analyzed. The interpretation of experimental data is summarized in the following Table 1 ("n" is integer).

Table 1

Number	f., MHz	Longit. Θ, Rad	Azim. Θ, Rad	Acc.Cav excited
1	8900	π/2	πn	All
2	8971	π/2	π/2	except B,D
3	8982	2πn	π/2	except B,D
4	9050	π/2	2πn	All
5	9060	2πn	2πn	All

Introduced azimuthal coupling caused some difference in the frequency readings, shown on Fig.4 (9156, 9179, 9188, 9210, and 9220 MHz) and in Table.1. However, it has not affected the analysis. Two weak resonances at the end of the structure bandwidth on Fig.4 (8975 and 9361 MHz) supposedly represent 0 and π modes for the structure when the coupling cavity is excited and does not present any interest for our study. Mode separation (bandwidth is approximately 160 MHz) and Q (10,000) are large enough for practical use. Prediction that the structure should in general behave as a side coupled structure is confirmed.

3. POSSIBLE APPLICATIONS OF MBS

We have started to discuss some applications of the proposed design and concept in [1]. MBS permits exceeding the space charge limitations due to reduction of aperture size at high frequency observed, for example, in X-band. The proposed structure could also be used to increase energy gain for the same linac length in a mode of multiple pass operation. Fig.5 shows the system with double pass operating mode.

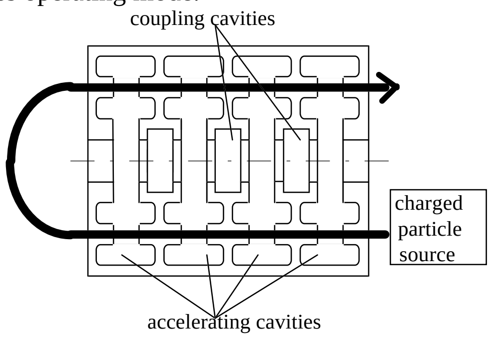

Fig. 5 Multiple pass beam section (two-pass on this drawing)

Energy gain will be increased in proportion to $N^{1/2}$, where N is number of beam passes, assuming that we use the same power source and structure volume grows proportionally to N. Therefore, with four passes, energy gain would be two times higher, with 16 - four times higher, etc. Bending magnets could be used to bend the beam 180 degrees.

Potential application of the proposed structure could be found in many areas where accelerators are used.

1.<u>Accelerators for various commercial applications</u>, such as non-destructive testing, sterilization, etc. In the proposed accelerator concept, beam is physically distributed over a larger area and easier to extract.

2. <u>Microwave amplifier tubes.</u> Hollow beam instabilities have been studied and observed by Kyhl and Webster at low energies (<100 keV) for TWT[2] applied to traditional structures with beam concentrated in the center.

3. <u>Injectors for free electron lasers</u> (FEL). One of the ideas, expressed in the accelerator physics community is to develop a "table-top" FEL for commercial applications with an acceptable price range. X-band accelerator for 9 - 13 MeV is a potential source for that application [3,4].

4. <u>"Beam-beam" interaction systems</u>. The proposed system seems to be attractive for this class of devices [1] due to its mechanical design and principle of operation. Presently, the plan is to build a working prototype which will deliver 1.2 MeV electron beam at 1 A current in four beams in 12 cm long X-band structure [5], which is a natural result of Phase I research, which we consider successful. The goal is to achieve 1 kW average power stored in four beams at 0.001 duty factor and 70 percent beam efficiency.

4. CONCLUSIONS

FBS was studied as an example of MBS concept, described in [1]. The proposed technical study appears to be successful and might help to solve the problem of beam current limitation or increase energy gain by using mulripass operating mode. The proposed concept seems to be a new technical approach in accelerator structure construction and has a number of various practical realizations. It does not seem possible to have every proposed design studied in details in a reasonable period of time. However, we are hoping to continue our study of various types of the proposed structure design during Phase II, if supported by DOE.

4. REFERENCES

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