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A SINGLE-CAVITY DOUBLE-FREQUENCY BUNCHER

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Abstract

A single-cavity buncher has been developed that resonates at both the fundamental and twice the fundamental frequency to form a more nearly ideal bunching voltage waveform in the gap. The cavity utilizes the TM_{020}-like mode as the first harmonic of the fundamental TM_{010}-like mode. Field distributions on or near the axis, which are seen by the beam, are essentially identical for the two modes. Many beam bunching applications require two bunchers with the harmonic buncher being physically as close as possible to the fundamental frequency buncher - the buncher described here accomplishes this property with a single cavity and excitation of two modes. Calculated parameters for cavity designs with a fundamental frequency of 0.45 GHz are presented for different cavity lengths which represent a range of interest for accelerators and rf tubes. Means of tuning and fabrication are described. A geometry chosen for PIGMI is described in more detail.

Introduction

Many types of bunching systems are used between a dc source of charged particles and a system of rf cavities that accelerates or decelerates the bunched particle beam. Usual practice is to impart a small time-varying energy difference to the monoenergetic dc beam followed by a drift of the beam until the more energetic particles catch up with the less energetic particles - hence bunching action. The bunching system provides a reasonable interface between the dc source and the rf fields of the following rf cavity structure.

Some bunching systems employ two bunchers - the second at a harmonic of the first. In many instances it is advantageous to have the distance between the fundamental and the harmonic bunching cavity as small as possible. This paper discusses a novel way to minimize this separation - having the two frequencies excited in a single cavity.

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A family of buncher geometries has been determined using the computer code SUPERFISH.[1] The family can be used to select a single-cavity buncher design that requires specific relationships between the two modes. The fundamental mode is the usual TM_{010}-like mode employed in accelerating structures, and the harmonic at twice the fundamental frequency is TM_{020}-like. Electric field distributions in the region occupied by beam are essentially identical for both modes.

Cavity Geometry

The ratio of the TM_{020} and TM_{010} mode frequencies in a right circular cylinder is 2.3. Only small changes in the geometry should be required to make this ratio exactly two. However, for the buncher cavity to have a reasonably high effective shunt impedance, ZT^2, and to be of suitable length, a drift tube nose is required close to the beam axis. After studying various geometries, the one shown in Fig. 1 was selected. The radius at which the outer protrusion (with gap g_2) ends was found optimum at 0.6 R_C. This radius produces a maximum frequency shift as a function of g_2 for the TM_{020}-like mode while the TM_{010}-like mode experiences an almost maximum frequency shift of the opposite sign. A 30° drift tube nose was selected to improve rf efficiency.[2] For a 0.45 - 0.9 GHz cavity, R_1 was 0.15 cm.

Calculations with a representative cavity gave the following fractional frequency shifts of the (TM_{010}, TM_{020}) modes for the variables shown in Fig. 1.

$$\frac{\Delta f}{f} / \frac{\Delta g_2}{g_2} = (-0.2,\ 0.1) \quad ; \quad \frac{\Delta f}{f} / \frac{\Delta R_C}{R_C} = (-1,-1)$$

$$\frac{\Delta f}{f} / \frac{\Delta g_1}{g_1} = (0.1, 0.1) \quad ; \quad \frac{\Delta f}{f} / \frac{\Delta L}{L} = (-0.1,-0.3)$$

For half-cavity length, L, with beam bore hole, R_H, and gap, g_1, changes to the outer cavity radius, R_C, and g_2 produce the required resonance conditions.

Calculations

Tables 1 to 4 summarize some of the calculated results for different buncher geometries. A large range of geometries can be selected for the electron beam case, whereas choices are limited for low beta proton beams. Large L geometries do not have transit time factors listed for low beta proton beams because rf fields change sign as the proton beam traverses the cavity. Small R_H and L are desirable for low beta proton beams. Different ratios of ZT^2 between the TM_{010}-like and TM_{020}-like mode can be selected for different applications by inspection of the tables.

Geometrical parameters listed in the first few columns of the tables are defined in Fig. 1. Results of calculations for the rf properties are found in the last eight columns. The first four rf properties are resonant frequency in GHz, quality factor, Q, for the mode, shunt impedance, Z, in MΩ/m, and the ratio between the maximum electric field on the cavity metal surface to the average on-axis electric field, $E_{surface}/E_o$. Transit time factors given in the last four columns for particle betas of 0.0231, 0.04, 0.328 and 0.741 were determined using the calculated on-axis electric field distribution. ZT^2 for a particular velocity particle can be determined using the sixth last column with a transit time factor, T, from one of the last four columns. For example, to impart 16 keV at 0.2 GHz and 4 keV at 0.4 GHz to a 750 keV dc proton beam, peak powers of 319 and 29 watts, respectively, are required for a buncher with dimensions scaled from those given for L = 2 cm, R_H = 0.25 cm and g_1 = 0.08 cm in Table 3. The buncher would have a 1.13 cm beam bore hole diameter and would be 114 cm in overall diameter.

R_C and g_2/L are plotted as a function of g_1/L in Fig. 2 for various L and R_H combinations of an 0.45 – 0.9 GHz buncher. Figure 2 can be used to specify geometries not listed in the table by interpolation between the curves. A survey calculation showed that an axially symmetric mode at three times or at four times the fundamental frequency could not be excited for the geometries studied, hence these geometries are limited to double frequency operation. Electric field distributions for the TM_{010} and TM_{020} modes of an L = 8 cm, R_H = 1 cm and g_1 = 2 cm cavity are shown in Fig. 3.

While converging to the geometry with desired frequencies by adjusting g_2 and R_C for subsequent SUPERFISH calculations, fractional frequency shifts $\frac{\Delta f}{f}/\frac{\Delta g_2}{g_2}$ and $\frac{\Delta f}{f}/\frac{\Delta R_C}{R_C}$ were (-0.221, 0.0817) and (-0.939, -0.879), respectively, for the (TM_{010}, TM_{020}) modes.

PIGMI Buncher

A double-frequency aluminum buncher has been built for a Pion Generator for Medical Irradiation, PIGMI,[3] being prototyped at LASL, using a geometry similar to that given in Table 3. Figure 4 illustrates the geometry selected and field distributions for the two modes. The buncher is symmetrically loaded near the axis with a pair of 45° conical nose cones, instead of 30° shown in Fig. 1. The buncher, which has been built, tuned and mounted on the PIGMI beam line, was designed to bunch a 250 keV proton beam in an 80 cm drift distance. This requirement corresponds to a peak energy gain of 3.2 keV from the fundamental mode and 0.8 keV from the harmonic mode. With proper phasing between the two modes, the resultant rf wave will be almost linear over 220 degrees of phase space. Table 5 lists relevant parameters for the PIGMI buncher. Transit time factors were evaluated using the on-axis electric field distribution. Average rf powers were based on one percent duty factor.

The buncher design shown in Fig. 4 incorporated a pair of vanes for fine tuning. Each 2 cm wide vane is mounted on a radial rod that can be rotated for tuning purposes - the two vanes are strategically located to perturb the two modes differently. The lower or inner vane is centered at the TM_{020}-like mode electric field minimum. Rotation of this vane out of the buncher plane raises the TM_{020}-like mode frequency and lowers the TM_{010}-like mode frequency. The upper or outer vane is located to have virtually no effect on the TM_{020}-like mode frequency. Rotation of this vane out of the buncher plane increases the TM_{010}-like mode frequency. Perturbations from the vanes were studied using SUPERFISH - the mid-range position is illustrated in Fig. 4.

Discussion and Conclusions

A family of geometries has been determined for single-cavity double-frequency bunchers. Based on particular applications the data presented can be used to select an optimum geometry. Having two modes excited in the same cavity with virtually identical rf fields in the beam bore hole is a novel method for producing a double bunching scheme. Besides saving space on the beam line, the single cavity reduces fabrication.

A single-cavity double-frequency buncher has been built for PIGMI. Performance of the buncher with beam and high power rf will be determined shortly. Since the cavity can be excited exactly at twice the fundamental frequency, precautions have to be taken to isolate the rf drive properly from the resonant load.

An accelerating structure could be made from a chain of rf cavities using geometries determined for the single-cavity buncher. RF coupling between the cavities could be done on the web with slots located between 0.6 R_c and the drift tube nose. The structure could then be operated as a "harmonic accelerator"[4] with a fundamental mode frequency and a harmonic at twice the fundamental. With proper amplitude and phase control the rf accelerating wave could be linearized over a large range.

References

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TABLE 1

Parameters for a Single-Cavity Double-Frequency Buncher with L = 8 and 6 cm

									Transit Time Factors			
									Protons		Electrons	
L(cm)	R_H(cm)	g_1(cm)	g_2(cm)	R_C(cm)	Freq. (GHz)	Q	Z(MΩ/m)	$E_{surface}/E_o$	250 keV	750 keV	30 keV	[illegible]50 keV
8.0	1.0	0.5	3.35	20.69	0.45	19136	30.39	20.0			0.974	0.995
					0.9	19818	3.93	19.8			0.899	0.979
		1.0	5.04	22.06	0.45	23246	40.03	12.3			0.959	0.992
					0.9	24452	11.37	12.1			0.846	0.968
		2.0	6.15	23.96	0.45	26756	45.85	8.0			0.908	0.981
					0.9	28437	26.23	7.9			0.669	0.927
		3.0	6.19	25.22	0.45	27561	44.76	6.4			0.824	0.964
					0.9	31267	39.68	6.4			0.412	0.860
		4.0	5.84	26.44	0.45	27059	39.69	5.3			0.717	0.940
					0.9	33738	48.01	5.3			0.145	0.774
6.0	1.0	0.21	2.24	20.68	0.45	15931	27.95	29.8		0.282	0.977	0.995
					0.9	15781	2.98	29.5		0.021	0.911	0.982
		0.6	4.22	22.38	0.45	20842	37.69	13.3			0.971	0.994
					0.9	22940	14.00	13.2			0.891	0.977
		1.0	4.68	23.65	0.45	22422	40.58	9.9			0.960	0.992
					0.9	25236	23.95	9.8			0.850	0.968
		2.0	4.57	25.69	0.45	22667	35.68	6.1			0.910	0.982
					0.9	28607	39.21	6.0			0.677	0.929
		3.0	4.25	26.94	0.45	21813	31.01	4.6			0.829	0.965
					0.9	30323	44.43	4.6			0.426	0.864

TABLE 2

Parameters for a Single-Cavity Double-Frequency Buncher with L = 4 cm

								Transit Time Factors			
				Freq.				Protons		Electrons	
R_H(cm)	g_1(cm)	g_2(cm)	R_C(cm)	(GHz)	Q	Z(MΩ/m)	$E_{surface}/E_o$	250 keV	750 keV	30 keV	250 keV
1.0	0.16	2.92	21.53	0.45	15685	31.33	22.4	0.056	0.300	0.978	0.995
				0.9	17754	10.35	22.2	0.0001	0.028	0.916	0.983
	0.5	3.33	23.98	0.45	17456	32.16	10.8		0.210	0.974	0.995
				0.9	21088	25.98	10.7		0.0004	0.899	0.979
	1.0	3.04	25.90	0.45	16747	26.63	6.7			0.961	0.992
				0.9	22857	33.55	6.6			0.853	0.969
	1.5	2.86	26.86	0.45	16118	23.40	5.0			0.940	0.988
				0.9	23427	34.87	5.0			0.780	0.953
	2.0	2.75	27.44	0.45	15679	21.40	3.9			0.912	0.982
				0.9	23582	33.82	3.9			0.681	0.930
0.5	0.5	3.28	25.05	0.45	17442	29.67	10.1		0.475	0.989	0.998
				0.9	22245	35.82	10.0		0.009	0.957	0.991
2.0	0.5	2.77	23.09	0.45	15741	27.45	10.3			0.922	0.984
				0.9	18814	11.78	10.0			0.724	0.938
3.0	0.5	2.13	22.96	0.45	13839	21.31	10.0			0.871	0.973
				0.9	16137	5.78	9.3			0.560	0.897
4.0	0.5	1.68	23.09	0.45	12367	16.65	10.2			0.836	0.966
				0.9	13764	3.34	9.1			0.451	0.869
2.0	2.0	2.81	26.98	0.45	15923	22.36	3.8			0.871	0.974
				0.9	23300	30.79	3.7			0.558	0.897
3.0	2.0	2.78	26.76	0.45	15830	22.09	4.0			0.838	0.967
				0.9	22655	26.06	3.7			0.459	0.871

TABLE 3

Parameters for a Single-Cavity Double-Frequency Buncher with L = 2 cm

R_H(cm)	g_1(cm)	g_2(cm)	R_C(cm)	Freq. (GHz)	Q	Z(MΩ/m)	$E_{surface}/E_o$	Transit Time Factors Protons 250 keV	Protons 750 keV	Electrons 30 keV	Electrons 250 keV
1.0	0.08	1.76	22.82	0.45	10167	20.92	24.8		0.303	0.981	0.996
				0.9	12703	14.46	24.6		0.036	0.925	0.985
	0.25	1.57	25.65	0.45	9583	15.99	9.4		0.270	0.979	0.996
				0.9	13679	21.87	9.3		0.022	0.920	0.984
	0.5	1.42	27.05	0.45	8949	13.12	5.6		0.198	0.976	0.995
				0.9	13636	20.99	5.5		0.001	0.909	0.981
	0.75	1.37	27.59	0.45	8695	11.97	4.2			0.972	0.994
				0.9	13547	19.57	4.2			0.892	0.978
	1.0	1.34	27.89	0.45	8552	11.33	3.4			0.966	0.993
				0.9	13468	18.45	3.4			0.870	0.973
0.25	0.08	1.66	25.29	0.45	9865	17.70	25.0	0.662	0.869	0.998	1.0
				0.9	13595	27.57	24.9	0.213	0.581	0.992	0.999
	0.25	1.43	27.08	0.45	9002	13.46	9.4	0.507	0.799	0.997	0.999
				0.9	13753	23.93	9.4	0.034	0.400	0.987	0.997
	0.5	1.37	27.69	0.45	8675	12.00	5.8		0.634	0.994	0.999
				0.9	13580	20.76	5.8		0.086	0.975	0.995
	0.75	1.34	27.95	0.45	8525	11.33	4.5			0.989	0.998
				0.9	13463	19.05	4.4			0.955	0.991
	1.0	1.33	28.08	0.45	8466	11.00	3.6			0.981	0.996
				0.9	13425	18.11	3.6			0.927	0.985

TABLE 4

Parameters for a Single-Cavity Double-Frequency Buncher with L = 1 cm

								Transit Time Factors			
				Freq.				Protons		Electrons	
R_H(cm)	g_1(cm)	g_2(cm)	R_C(cm)	(GHz)	Q	Z(MΩ/m)	$E_{surface}/E_o$	250 keV	750 keV	30 keV	250 keV
0.5	0.08	0.73	26.90	0.45	4830	7.18	12.6	0.349	0.695	0.995	0.999
				0.9	7432	12.92	12.6	0.059	0.257	0.979	0.996
	0.15	0.69	27.52	0.45	4650	6.42	7.5	0.314	0.675	0.994	0.999
				0.9	7308	11.27	7.4	0.044	0.221	0.977	0.995
	0.3	0.67	27.98	0.45	4527	5.90	4.4	0.218	0.618	0.993	0.999
				0.9	7204	9.90	4.3	0.019	0.127	0.973	0.995
	0.5	0.66	28.18	0.45	4475	5.78	2.9			0.991	0.998
				0.9	7160	9.39	2.9			0.964	0.993
0.25	0.08	0.70	27.36	0.45	4696	6.88	12.5	0.667	0.872	0.998	1.0
				0.9	7343	12.71	12.5	0.217	0.586	0.992	0.998
	0.15	0.68	27.75	0.45	4590	6.36	7.6	0.611	0.847	0.998	1.0
				0.9	7267	11.21	7.6	0.141	0.519	0.990	0.998
	0.3	0.67	28.05	0.45	4510	5.96	4.4		0.775	0.996	0.999
				0.9	7197	9.97	4.4		0.342	0.985	0.997
	0.5	0.66	28.22	0.45	4469	5.74	2.9		0.639	0.994	0.999
				0.9	7159	9.30	2.9		0.087	0.975	0.995

Table 5

Properties of the Aluminum PIGMI Buncher

Mode	TM_{010}	TM_{020}
Frequency (GHz)	0.45	0.9
Shunt Impedance, Z (MΩ/m)	9.27	16.54
Quality Factor, Q	6602	9992
$E_{surface}/E_o$	11.2	11.2
Transit Time Factor, T	0.725	0.275
Effective Shunt Impedance, ZT^2 (MΩ/m)	4.87	1.25
Peak Energy Gain (keV)	3.2	0.8
Peak Gap Voltage (kV)	4.4	2.9
Peak Power (W)	52.5	12.8
Average Power (W)	0.525	0.128

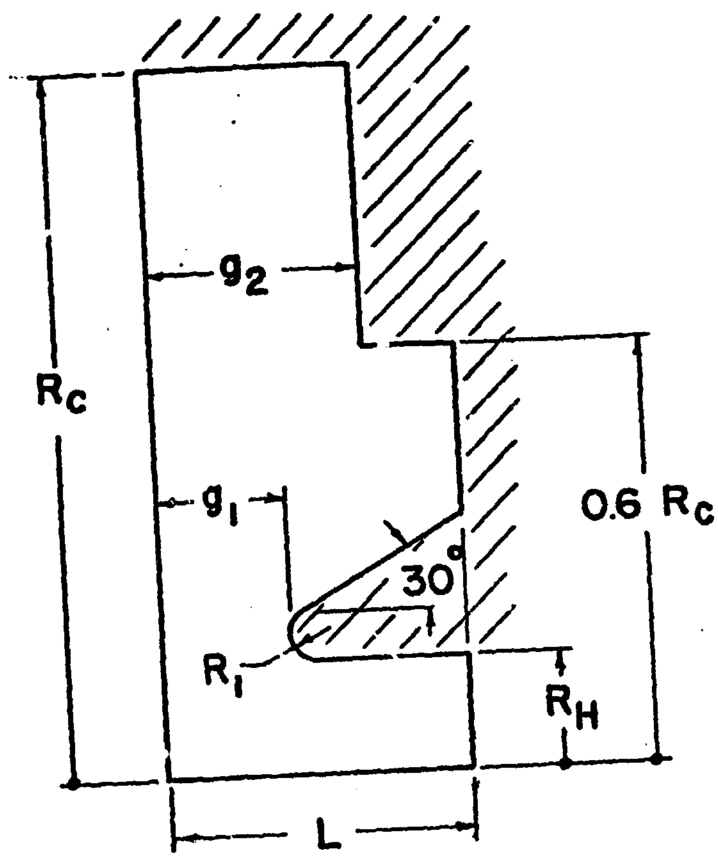

Fig. 1. Cavity geometry selected for the single-cavity double-frequency buncher. (One-quarter section of cavity.)

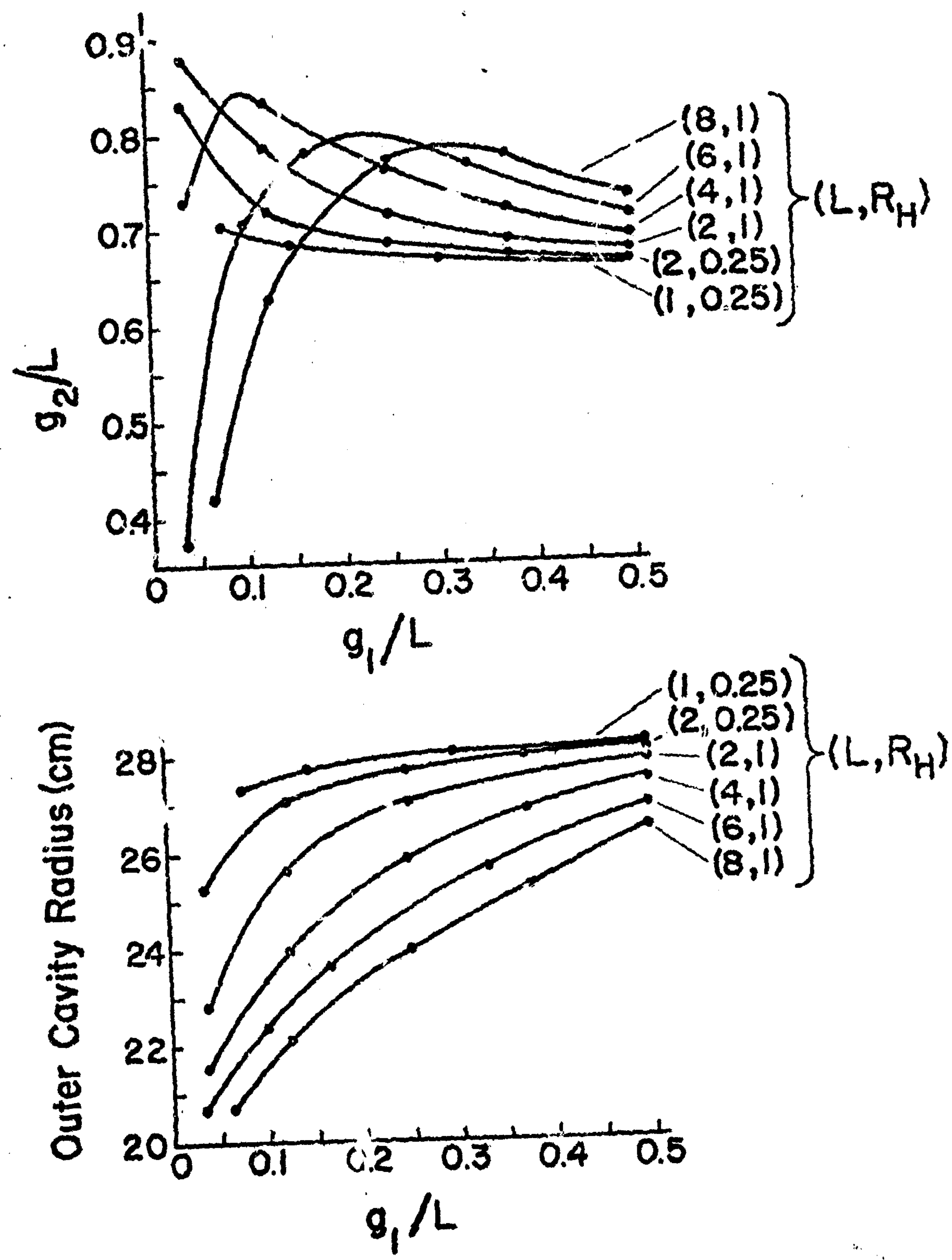

Fig. 2. Outer cavity radius, R_C, and g_2/L as a function of g_1/L for various L and R_H combinations.

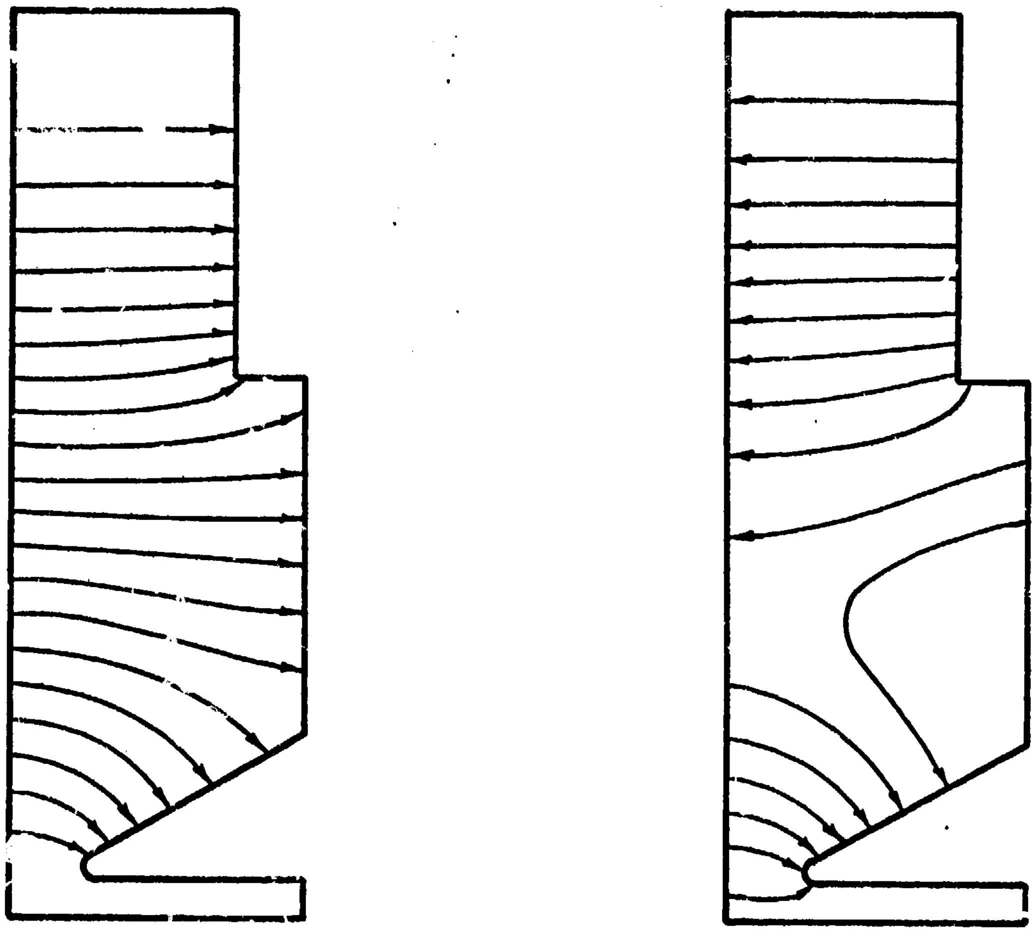

Fig. 3. Electric field distribution for a single-cavity double-frequency buncher with $L = 8$ cm, $R_H = 1$ cm and $g_1 = 2$ cm.

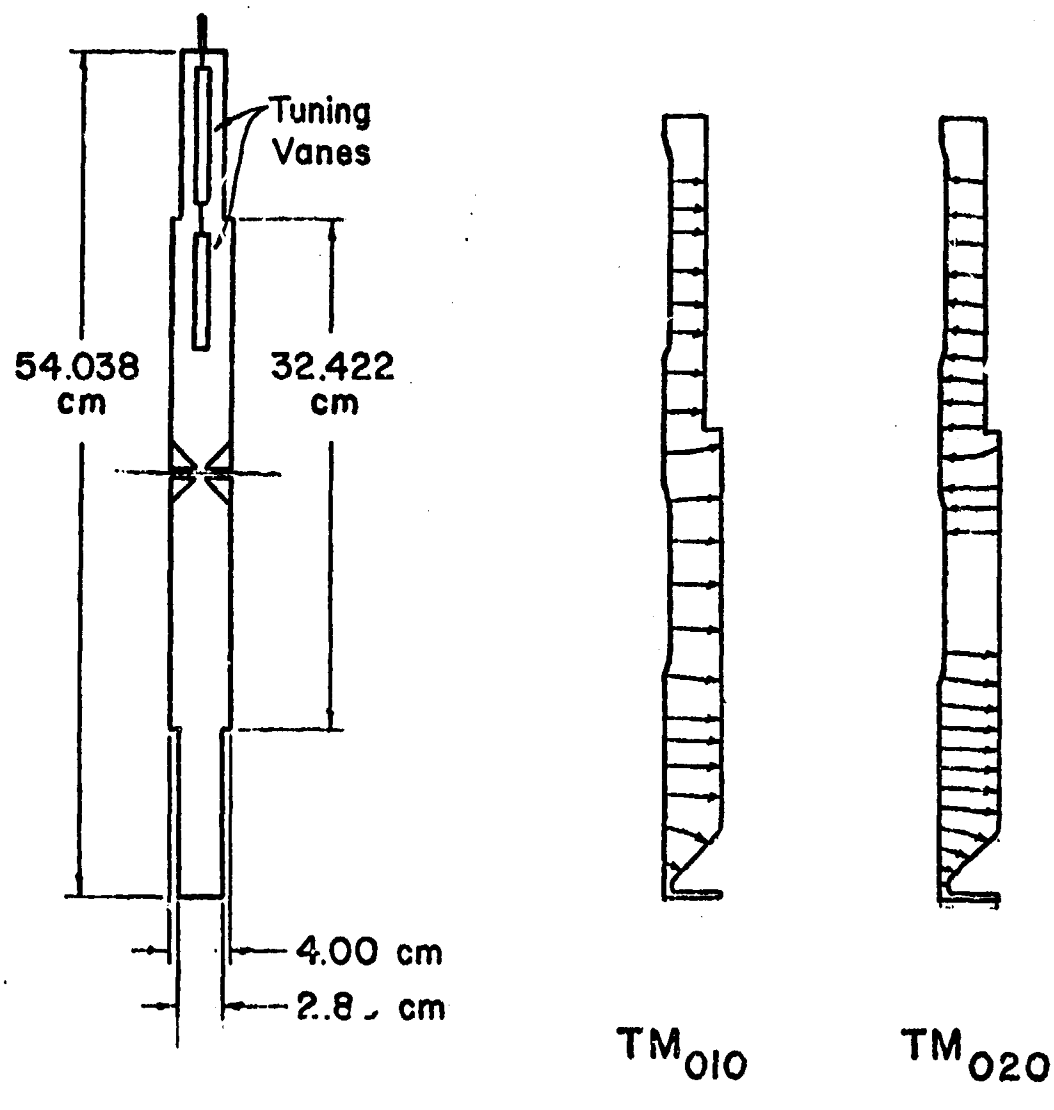

Fig. 4. Double-frequency buncher for PIGMI showing tuning vane locations and field distributions for the two modes with the vanes simulated by cylindrically symmetric perturbations.