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DAMPED ACCELERATION CAVITIES*

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ABSTRACT

Structures with slots to strongly damp higher-order longitudinal and transverse modes should allow the use of multiple bunches in linear colliders, and thus attain luminosities of over 10^{34} cm^{-2} sec^{-1}. Preliminary measurements on model structures suggest that such damping can be achieved.

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1. INTRODUCTION

The luminosity of a linear collider[1] is severely limited by the total beam power and thus, since wall power is limited, by the efficiency with which rf power is transferred to the beam. Of course, there are many other applications that would like high efficiency, so this is also a general problem.

The primary bound on the loading, and thus on the efficiency, comes from the fields, known as wakefields,[2] generated by the bunches themselves in the structure. These fields acting back on the bunches cause unacceptable distortion, momentum spread or deflection of the bunches. Those that cause momentum variations are referred to as longitudinal wakes and generate momentum variations. Those that cause deflections are referred to as transverse wakes. In this case, they are only generated if the bunch is itself off-center, but cause subsequent bunches to be deflected further off-center, thus leading to the possibility of an instability, known as beam breakup. If the beam is displaced, quadrupole and higher wakes will also be excited, but these will have little effect unless the displacement is large and the bunch broad.

In a linac loaded with many bunches each bunch sees fields generated by itself and by a sum of all previous bunches. The effects from the bunch itself, at least for short bunches, are dominated by the iris hole diameter. Besides using the largest possible iris, there is nothing much one can do about the fields themselves, although B.N.S. damping[3] can be used to reduce their effects. The maximum fraction of rf energy extracted by one bunch is then bounded to a few percent, the exact amount depending on detailed assumptions. If more efficiency is required it is imperative to use multiple bunches.

When there are many bunches, the fields seen by a particular bunch are a sum of those from all previous bunches. These wakefields have many different frequencies that are not in general multiples of the bunch spacing and will not add coherently. Thus for a large number of very small bunches, the contributions of the wakefields are relatively less and higher efficiencies can be obtained.

For colliders, unfortunately, we need both relative high individual bunch loading, plus multiple bunches for high efficiency, and in this case both momentum spread and beam breakup become unacceptable unless something is done. In this paper we study the possibility of damping the wakefields generated by each bunch before later bunches are introduced. Clearly this damping must be very rapid, i.e., very low Q's are required for all unwanted wakefields.

2. RF MODES

For these studies I have considered a traveling wave structure similar to that in the SLAC accelerator, except that I have chosen a relatively larger iris to wavelength ratio (.2 instead of .1) and, as a result, a larger group velocity (.07c instead of .007c). This choice was made[4,5] to reduce the single bunch wake fields. A multicell model of this structure was constructed at one-half SLAC scale. Figure 1 shows this structure. Its dimensions are given in Table 1.

Table 1. Cavity dimensions.

a =	1.0381 cm
b =	2.2291 cm
p =	1.7526 cm
t =	0.2286 cm

Figure 2 shows the measured mode frequencies as a function of phase advance, and Fig. 3 shows several examples of these modes. It will be noted that the deflecting modes are described as TE/TM or TM/TE, rather than simply TE or TM. The problem here is that such descriptions are only valid in a smooth waveguide. In a loaded guide, with phase advance other than zero or 180°, the modes are always mixed. When described as TE/TM the mode is pure TE at zero phase advance, and TM at 180°. It may also be noted that the TE/TM mode falls below the TM/TE. This is the opposite of the SLAC case, again as a consequence of the larger iris hole.

A beam passing through an infinite section of such a structure will only excite, or be perturbed by, modes with a group velocity equal to that of the beam. Assuming this to be c we can draw the straight line corresponding to this velocity on the figure. Modes will only be excited where they intersect this line; e.g., at A, B, C etc. The frequencies and character of each mode are listed in Table 2.

Table 2. List of synchronous modes.

	Frequency	Phase Adv	Mode	Type	Rel k
A	5.63	108°	TM_{01}	Accel	–
B	7.33	144°	TM_{11}	Deflec	3.5
C	9.87	158°	TE_{11}	Deflec	.13
D	10.25	151°	TM_{21}	Quad	–
E	11.75	115°	TM_{12}	Deflec	.52
F	12.40	101°	TM_{02}	Accel	–
G	13.00	86°	TE_{12}	Deflec	.22
H	13.40	79°	TM_{12}	Sext	–

We see that the fundamental accelerating mode has a frequency of 5.63 GHz, or approximately twice the SLAC frequency of 2.856 GHz. The phase advance per cell is 108° which is a little short of the usual 120°, but sufficiently close for this study. The first deflection mode is at 7.33 GHz, or 1.3 times the fundamental. This factor may be compared to the SLAC value of 1.5, and is lower as a consequence of the higher group velocity. One notes too that the loss factor k associated with this mode is far higher than that for any other transverse mode. This too is a characteristic that comes with the large iris high group velocity structures.

2.1 Wakefield Requirements

Current parameter lists of TeV linear colliders are limited to luminosities of the order of 10^{33}cm^{-2} sec^{-1}, for a wall power consumption of the order of 100 M Watts. But such designs employ only single bunches and use only from one[4] to a few[6] percent of the stored rf energy in the cavity. If multiple bunches can be employed, then as much as 25% of the energy could be extracted.[7] However, it has been shown[8] that with normal cavities and the required loading, beam breakup is unacceptable with more than one or two bunches. In addition, higher modes of longitudinal wakes will cause unacceptable momentum variations.[9]

If, however, the transverse modes can be strongly damped, then the beam breakup will be controlled; and if the higher longitudinal modes can also be damped, then the momentum variations will also be controlled. It should then be possible to extract of the order of 25% of the energy and obtain working luminosities of over 10^{34} cm^{-2} sec^{-1} with the order of 200 MW.

In principle, all transverse modes and longitudinal modes other than the first, i.e., all higher modes, should be damped to a negligible value between bunches. The requirement can be eased if we arrange that the bunch spacing is equal to an integer times a half wavelength of the most serious modes. If the bunch spacing is n cycles of the fundamental, f_0 is the frequency of the fundamental and f_i is that of the mode; then this requires that:

$$\frac{f_i}{f_0} = \frac{n}{m} \quad , \tag{2.1}$$

where m and n are integers. With the cavity being considered, $f_i/f_0 \approx 1.3$, so with some slight adjustment of dimensions, Eq. (2.1) will be satisfied for the first deflecting mode with $n = 4$ and $m = 3$; i.e., with one bunch every three cycles.

A study of the transverse wake problem[10] has shown that even with this condition, the wakefields for many bunches are still unacceptable. However, the study has shown that if the modes are damped, the effects can be controlled provided condition 2 is satisfied with some reasonable tolerance. For instance, with a Q of the first transverse mode of 20, then Eq. 2 must be satisfied within an error of 1%.

The longitudinal wake problem is less severe than that in the transverse direction, because no instability is involved. The wakes from each bunch simply add up, and since they have random phases, they add incoherently. Nevertheless, with the parameters being considered, they add to give an unacceptable momentum spread between bunches. A study of the problem[9] shows that the problem is controlled if all higher modes are damped with Q's less than about 80; and this will be taken as a requirement in this study.

3. STRUCTURES WITH HIGHER MODE DAMPING

Higher modes could, in principle, be damped by the introduction of resistive materials into the structure, but it would be hard in this way to damp one and not another mode. Instead we have studied damping by coupling the unwanted modes into a waveguide and damping the fields externally. Such coupling is accomplished by cutting into the basic cavity with slots leading to waveguides that can be chosen to have a cutoff higher than the fundamental. Thus, such slots will not damp this accelerating mode, but will allow all unwanted higher modes to propagate out of the structure. In placing the cuts to couple fields to a mode in the waveguide, we can place the slot so as to interrupt currents that would normally be flowing in the cavity wall, thereby inducing such currents to enter the waveguide and induce a traveling wave in the guide. Figure 4a these currents for the fundamental accelerating mode, and Fig. 4b for the first transverse mode. The dotted lines indicate two possible cuts that would interrupt the transverse mode currents. The circumferential cut is seen also to interrupt the currents of the accelerating mode, but the "radial cut" does not interrupt such currents, and would therefore not damp the accelerating mode. Because of their relative simplicity, we will first consider circumferential cuts. Then because of their lack of effort on the acceleration, we consider radial cuts. In all cases the measurements were made on a single aluminum cell, and only pi modes were examined. Future studies will be reported using multiple cavities. Also, in all cases, the fields in the waveguides were damped by inserting a cone of resistive plastic foam into the exits of the waveguides. When this was not done, the Q's of damped modes were, in general, a factor of two higher. This was because of the approximately 50% reflection of power at an open-ended waveguide.

3.1 Circumferential Slots

Slots were introduced as shown in Fig. 5. Two dimensions were tried, as shown in Table 3. In the first case, the cutoff was chosen to allow damping of all higher modes, including the important first transverse mode. In the second case, the cutoff is above this first mode and we can expect damping only of the higher modes, and in particular of the higher longitudinal modes, the first of which is at a frequency of 11.5 GHz. The observed Q's are also given in Table 3.

Table 3. Observed Q's with circumferential slots.

					Observed Q's		
	width (mm)	height (mm)	cutoff GHz	accel. GHz	accel.	1st trans. (7.33 GHz)	1st long. (11.5 GHz)
no slot				5.82	966	548	290
slot a)	23	5	6.56	5.66	435	50	20
slot b)	18	5	8.4	5.73	573	500	30
required Q's						20	80

We note that in neither case was the slot able to lower the Q of the first transverse mode to the required value of 20. But in both cases the Q of the first longitudinal mode was well below the required value of 80. An even wider slot would presumably achieve the required damping of the first transverse mode but then it would have to have a cutoff below the fundamental, and would damp this too. Even with the cutoff above the fundamental (as in the cases shown) a significant reduction in the Q of the fundamental is observed. However, it must be noted that even the initial value is far below that calculated for an ideal cavity. The losses are certainly coming from the relatively high resistance of the metal to metal joints, and it may be assumed that the lower Q's observed in the slotted cases come from the reduction of the area of these joints. Nevertheless, with such slots, some reduction of Q would be expected, even in a brazed cavity, due to the longer electrical path for the return currents. We note too that as the slot gets wider the frequency of the fundamental is perturbed, and it may be assumed that this is accompanied by some reduction of the elastance. Clearly, there are several arguments against wide circumferential slots.

A study was also made of the length of waveguide needed to assure that the fundamental mode Q was not further damped because of fields from that mode extending into the waveguide, even though it was beyond cutoff. Such fields will fall off as

$$E \propto e^{-pz} \quad , \tag{3.1}$$

where

$$p = \frac{2\pi}{c}(f_{\text{cutoff}}^2 - f_0^2)^{1/2} \quad , \tag{3.2}$$

and z is the distance down the waveguide. If resistive material is introduced at z then the contributed Q would be expected:

$$Q_{\text{slot}} \propto \frac{2}{E(z)^2} \propto e^{2pz} \quad . \tag{3.3}$$

The real Q will however be limited by other losses after some value of z is reached. The observed Q's in the two cases are shown in Fig. 6 together with an extrapolation using Eq. (3.3). We conclude that for a brazed copper cavity whose Q would be approximately 10,000 waveguide lengths of 3 cm, for case a, or 1.6 cm, for case b, would assure negligible further damping.

3.2 Longitudinal Slot

Since the circumferential slots described above were unable to obtain sufficient damping of the transverse mode, we also tried a longitudinal slot. Initially, a slot was tried without a cut through the iris, but as Fig. 4 suggests this was not effective for the first transverse mode (although it did damp some of the higher modes).

The longitudinal slot with cut iris is shown in Fig. 7. The length of the slot was chosen to have a cutoff about 7% above the accelerating mode, and was 15% below the first transverse mode. Its length was then 2.4 cm and thus longer than the individual cell length (of 1.75 cm). There is nothing obviously wrong with this, but it does mean that multiple cells cannot all have such slots at the same azimuthal angle (see the next section).

The width of the waveguide was 1 cm but, just prior to its entry to the cavity, this was reduced to a slot of only .5 cm, this being done to minimize the effect on the accelerating mode. The cut in the iris was only .27 cm. The object here was again to minimize the effect on the accelerating mode, and in particular, to minimize the increase in peak electric fields where the iris was cut.

We initially observed:

a) negligible effect on the accelerating mode, in frequency or Q.

b) negligible effect on the first higher longitudinal mode.

c) apparent disappearance of the first transverse mode.

A study was then undertaken to try and observe the first transverse mode as the gap width was gradually varied from closed to its full width of 2.7 mm. This revealed that as the gap was opened the transverse mode both widens and moves, and that its direction of motion is towards the undamped zero phase advance transverse mode at 8.1 GHz. Estimations of the final Q were then made both by observing the width and by tracking the amplitude of the resonance, extrapolating, in the case of the width observation, to the fully open case. Unfortunately, a fully consistent picture did not emerge. Both methods were complicated by the presence of the 8.1 GHz signal. We could only conclude that the Q of the mode was in the range between 10 and 20, with the width suggesting the higher value and the amplitude the lower. In either case the requirement of a Q less than or equal to 20 seems to have been achieved. Further measurements by other methods are needed.

3.3 A Combined Slot for Transverse and Longitudinal Modes

A basically longitudinal slot was tried whose length and cut iris was as described in Sec. 3.2, but the width of the slot was opened up to 1.4 cm (see Fig. 8). This width was chosen to have a cutoff in the lateral direction of 10.7 GHz, which is below the first longitudinal mode to be damped, although quite a bit narrower than even the smaller circumferential slots described in Sec. 3.1.

As expected the first transverse mode was again damped to a Q of between 10 and 20. The first longitudinal mode was observed to have a Q of 80. Note that in a linac one will wish to damp both horizontal and vertical transverse modes, and that there will thus have to be twice as many slots as in these model tests. As a result the longitudinal damping will be twice as strong; i.e., a Q of 40 would be expected (where we require 80), which is certainly okay.

The Q of the acceleration mode was lowered by 20%, which with double the number of slots would become 40% but, because of the bolted nature of the test cavity, this is presumably an overestimate. A preliminary study with the three-dimensional computer code "MAFIA" indicated a loss of only 2%.

We thus appear to have a solution that has required damping of both the first transverse and longitudinal modes. A brief look for higher modes suggested that these will also meet our requirements, although a more careful study is needed.

4. A PRACTICAL REALIZATION

The design of a multicell linac employing such damped accelerating cavities is not simple. Four slots per cell are required, and succeeding slots cannot be at the same azimuthal angles. Each slot should open out before exiting the structure, so as to minimize reflections at their outer ends. The entire structure would then be supported inside a larger vacuum chamber, which may have to contain rf damping resistors, or at least be made of a relatively high-resistance material. Since the structure is inside the vacuum container, water cooling would have to be integral to the structure. It should be noted that despite its complication, such a design will have the advantage of providing very good vacuum pumping to the inside of the cavities; something that is probably essential, and something that would be impossible to obtain without slots or holes of some kind. Figure 9 illustrates what one cell (a) and a multicell structure (b) might look like. But it should be clear from this preliminary paper that much work remains to be done.

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FIGURE CAPTIONS

1. Cross section of high group velocity accelerating structure.
2. Frequencies of modes in the accelerating structure as a function of the phase advance per cell.
3. Electric field lines of standing wave in the structure, for different modes. The modes shown correspond to the parenthesized letters in Fig. 2.
4. Sketch showing approximate directions of current flow in the iris and wall of a structure, a) for the first accelerating mode, and b) for the first transverse mode.
5. Diagram of test cell with slot in the circumference of the cell.
6. Measured Q's for the first accelerating mode as a function of the length of waveguide to the absorbing plug, a) for a waveguide 23 $\times$ mm, and b) for 18 $\times$ 5 mm.
7. Diagram of test cell with slot cut longitudinally in the cell wall and extending through the iris.
8. Diagram of test cell with rectangular waveguide entering the cell wall and with a cut extending through the iris.
9. Conceptual design of damped structure with a) a single cell and b) a stack of four such cells. Each cell is rotated 45° with respect to its neighbors.

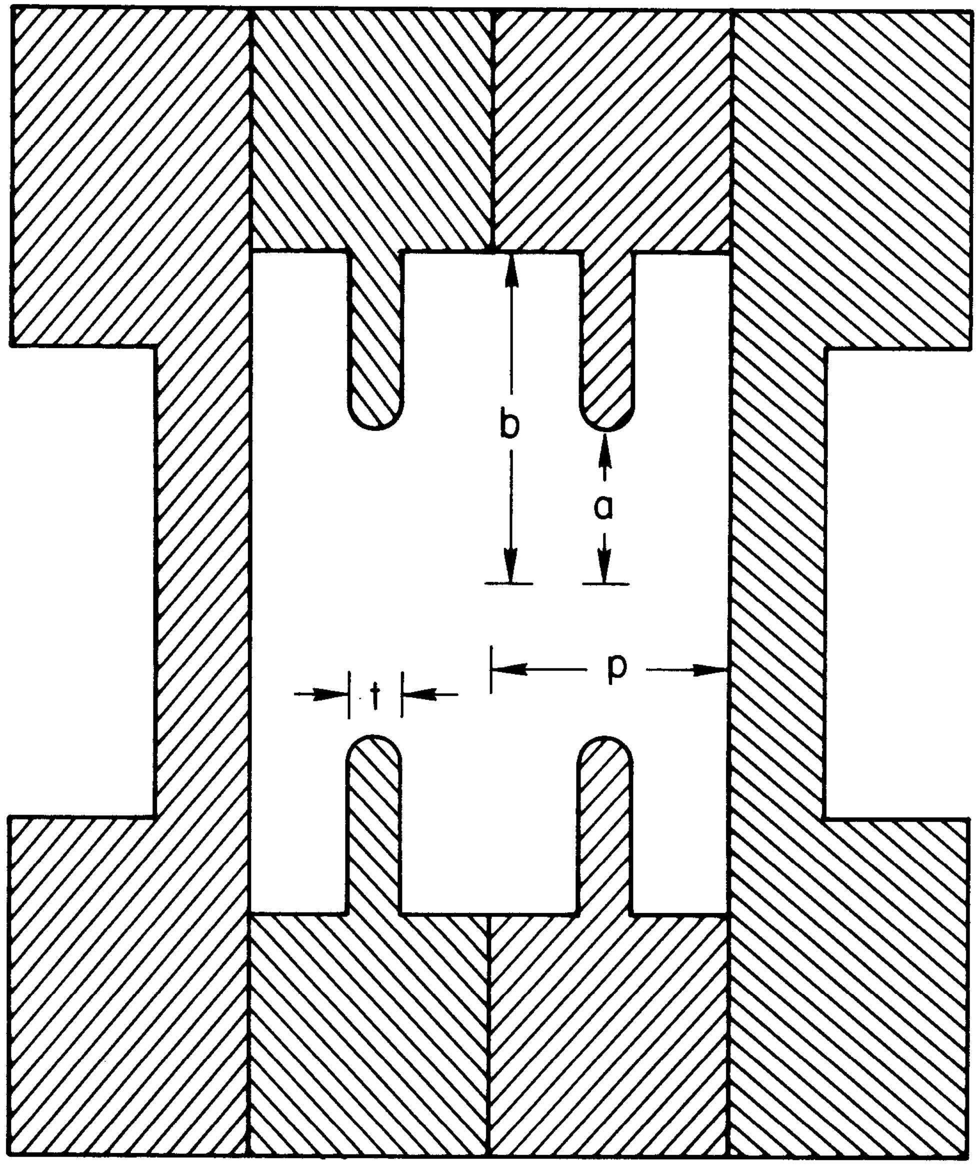

Fig. 1

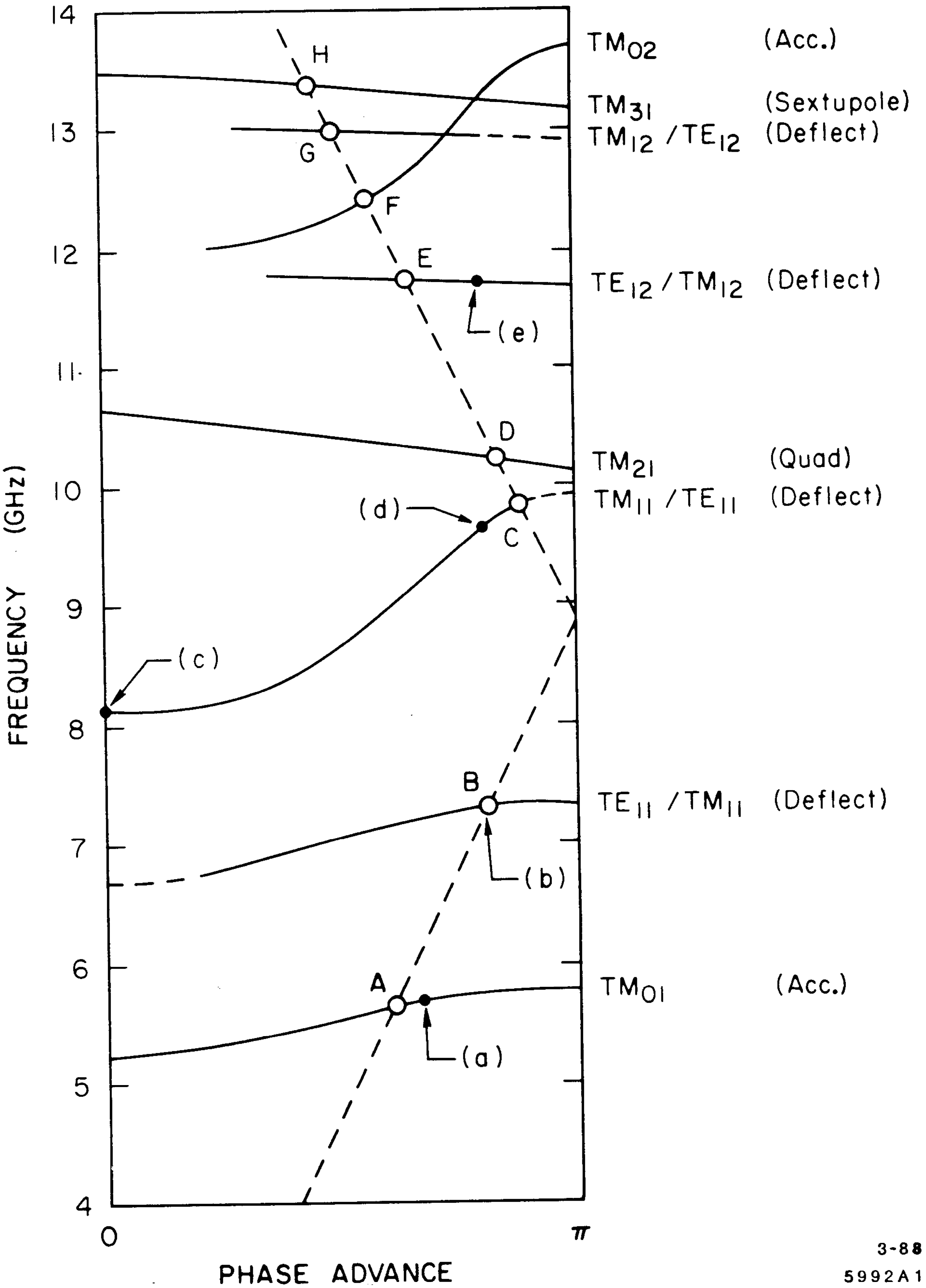

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Fig. 2

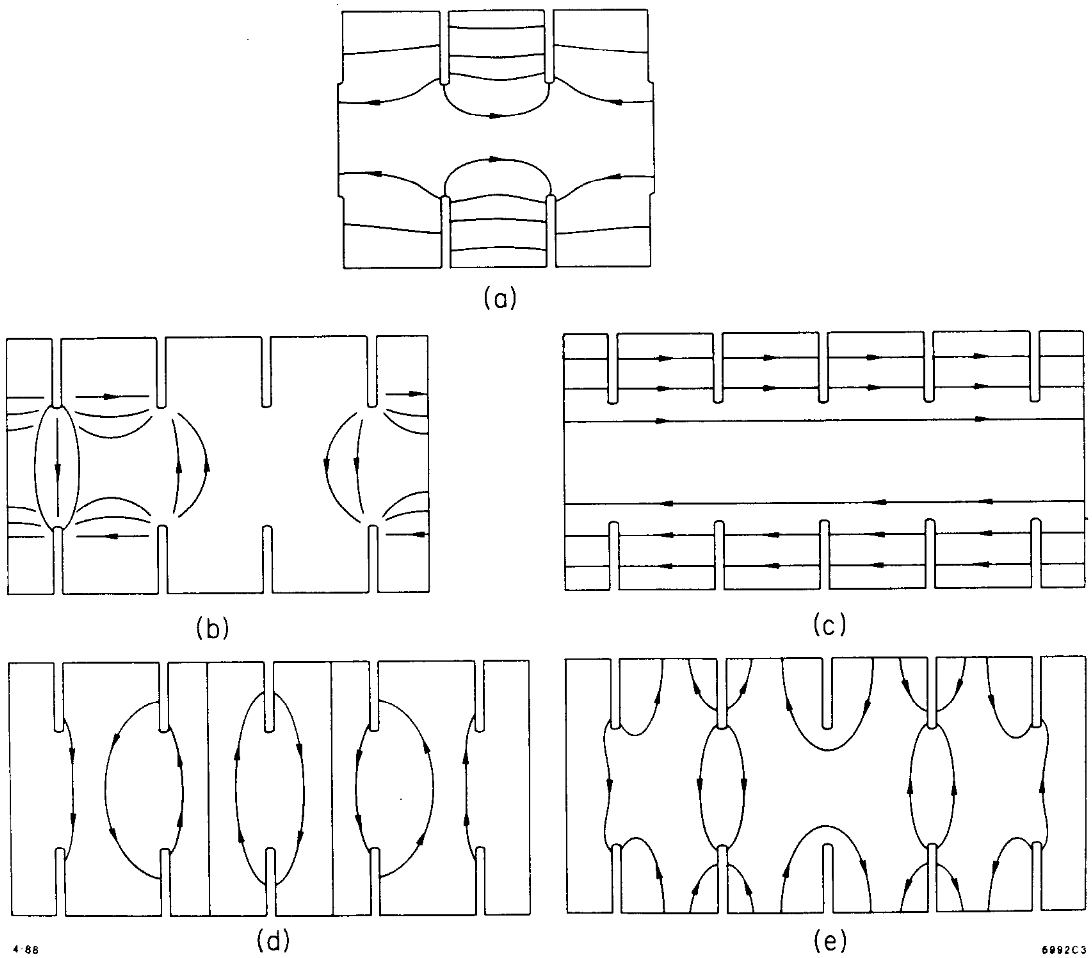

Fig. 3

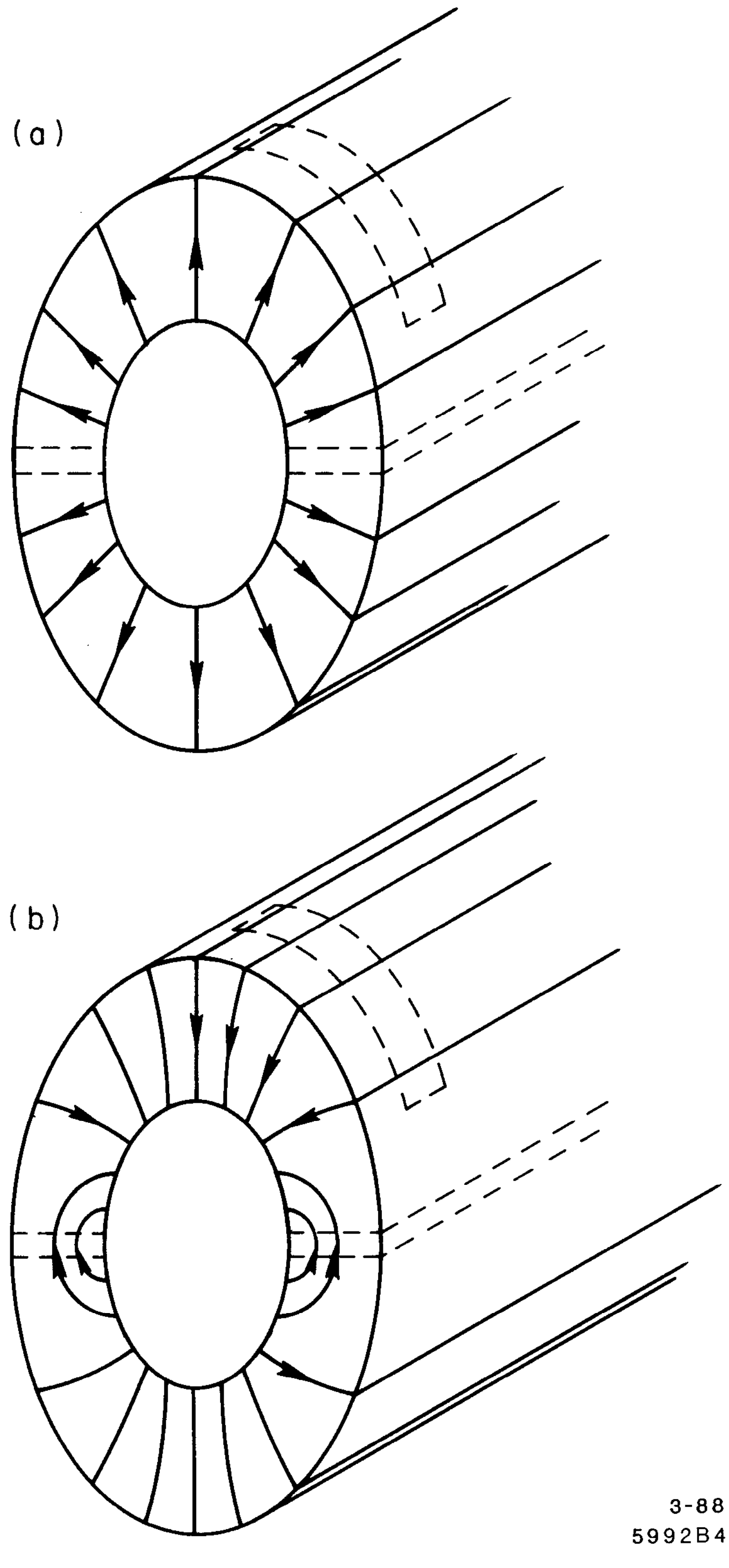

Fig. 4

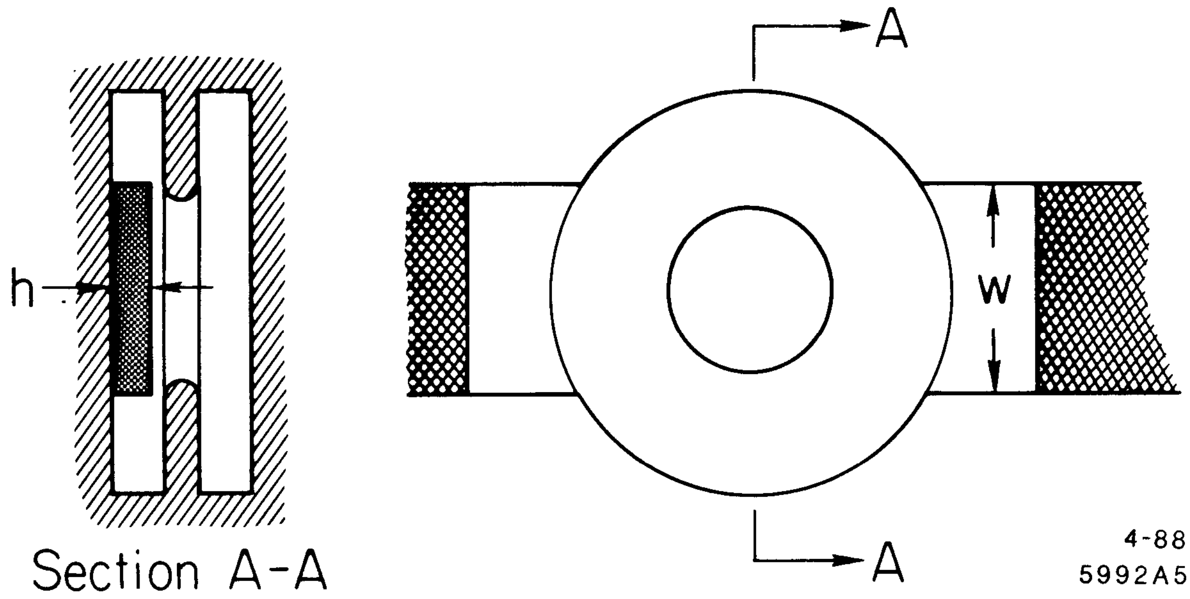

Fig. 5

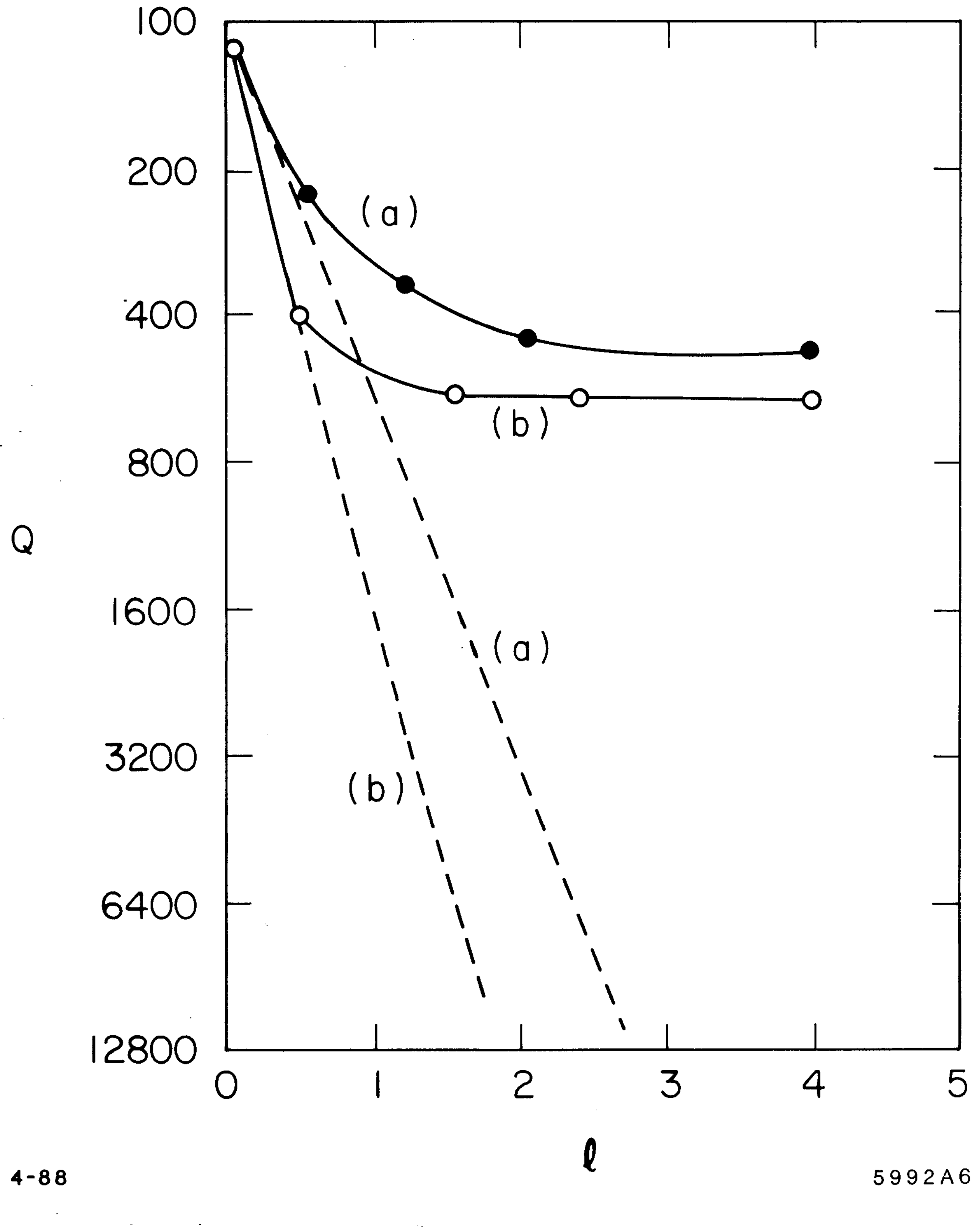

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Fig. 6

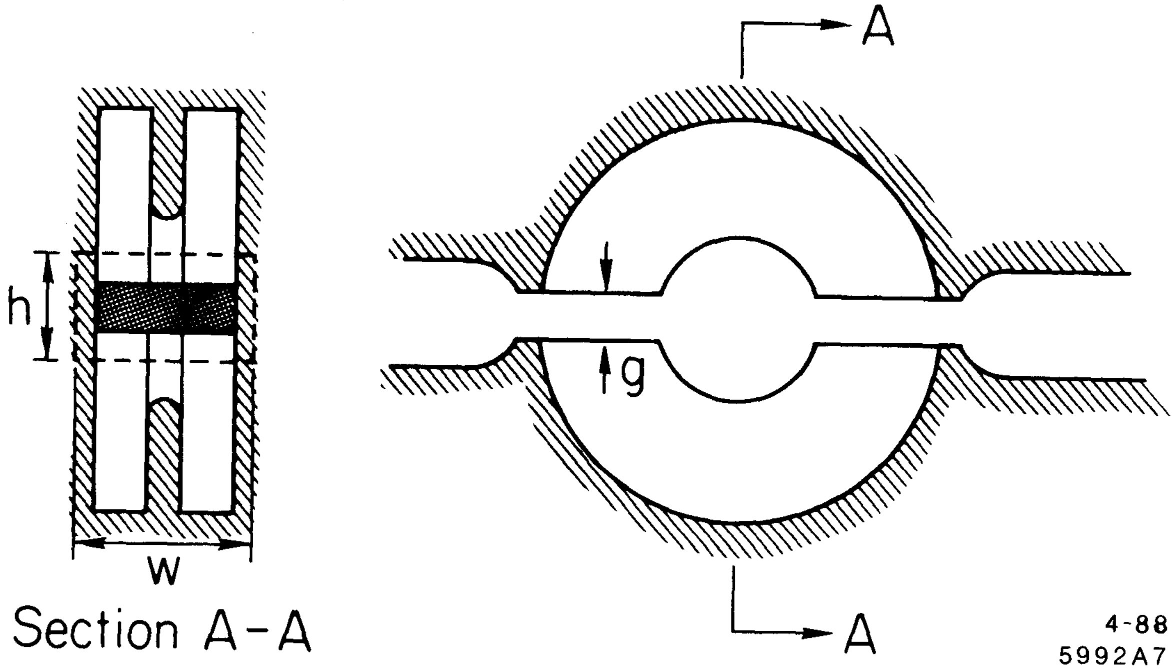

Fig. 7

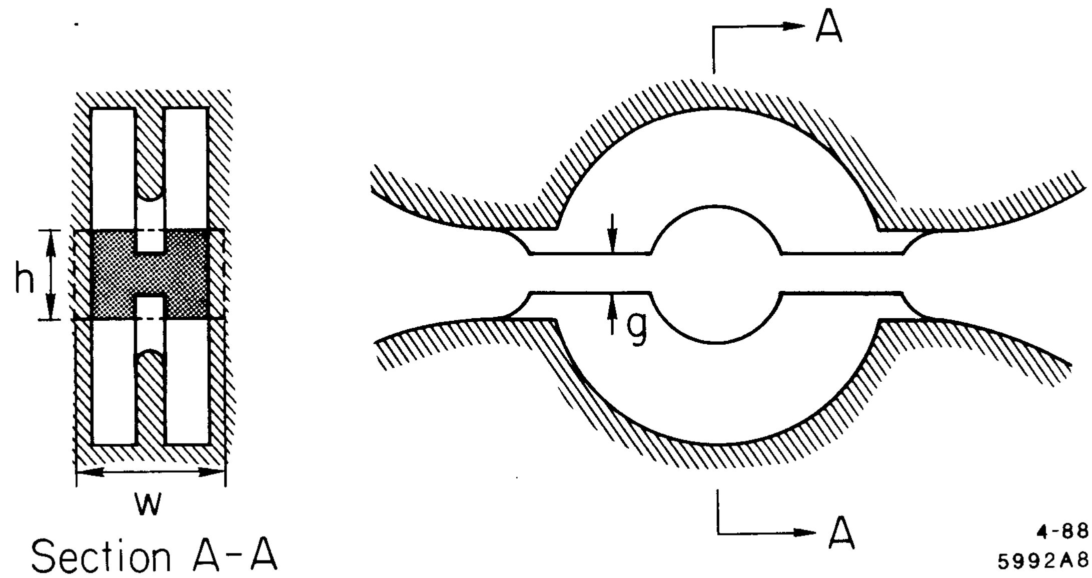

Fig. 8

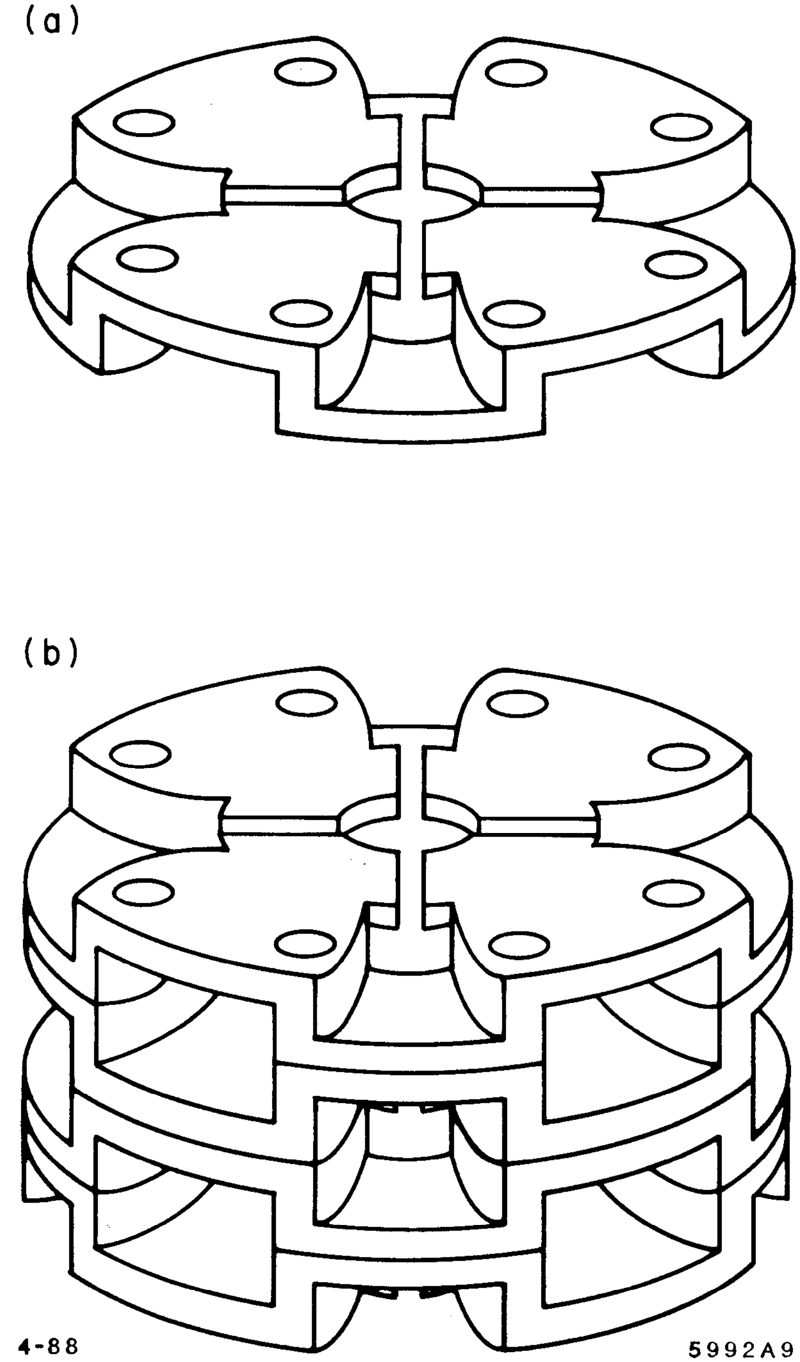

Fig. 9