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(12) # EUROPEAN PATENT SPECIFICATION

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(54) **Small diameter standing-wave linear accelerator structure.**

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NUCLEAR INSTRUMENTS AND METHODS, vol. 193, 1982, pages 437-444, North-Holland Publishing Co., Amsterdam, NL; J.-P. LABRIE et al.: "The coaxial coupled linac structure"
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, vol. NS-28, no. 3, June 1981, pages 3440-3444, IEEE, New York, US; S.O. SCHRIBER: "Accelerator structure development for room-temperature linacs"

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Description

The present invention relates generally to standing-wave linear particle beam accelerators and more particularly to charged particle beam accelerators and methods wherein a coaxial coupled structure is used to build a small-diameter efficient electron accelerator for radiation therapy and industrial radiography.

Electron linear accelerators with energies up to 50 MeV have been widely used for radiation therapy and industrial radiography since early 1960. Currently an emphasis is being placed on more efficient, compact, and cost-effective designs. For standing-wave, $\pi/2$ mode linear accelerators, the coupling cavities allow for a flexibility of design, since they are unexcited in steady state operation. Existing standing-wave accelerator coupling cavities can be placed in four general design types : on-axis, coaxial, side cavity, and annular ring structures. These four structures are shown schematically in Fig. 1.

Since the side cavity structures are off-axis, they do not influence the design of the accelerating cells, enabling side coupled accelerators to attain high efficiencies. Side coupled structures, however, have the disadvantages of increasing the effective diameter of the accelerator guide and the number of machining and assembly steps required.

Cylindrically symmetric cavities, the on-axis, coaxial, and annular ring designs, have the advantage of being machined directly into the opposite side of an accelerating cell, thereby eliminating multipiece assembly and prebrazing. Construction costs can be substantially reduced. Existing designs, however, all have disadvantages. The radius of an on-axis coupling cavity is comparable to the radius of the accelerating cavity. The structure is susceptible, however, to the excitation of parasitic and beam blowup modes, which reduce the overall accelerator efficiency and beam stability. (See J. P. Labrie and J. McKeown, « The Coaxial Coupled Linac Structure », Nuclear Instruments and Methods, No. 193, pp. 437-444, 1982). On-axis structures are also sensitive to thermal detuning, a result of the thermal deformation of the web between the accelerating cells. (See : J. McKeown and J. P. Labrie, « Heat Transfer, Thermal Stress Analysis and the Dynamic Behavior of High Power RF Structures », IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, pp. 3593-3595, 1983).

Coaxial structures eliminate the direct interaction of the electron beam with the coupling cavity, but designs of the prior art increase the effective guide diameter 60 % to 80 %. Prior art designs consist of narrow cylindrical cavities sandwiched between accelerating cells, which operate at a coaxial TM_{010}-like mode. (See for example : C. Fuhrmann et al, « Characteristiques de Dispersion et Impedances Shunt de Trois Structures Biperiodiques Acceleratrices en Bande S », Nuclear Instruments and Methods in Physics Research, No. 227, pp. 196-204, 1984 and R. M. Laszewski and R. A. Hoffswell, « Coaxial-Coupled Linac Structure for Low Gradient Applications », in Proceedings of the Linear Accelerator Conference 1984, pp. 177-179). Annular ring designs in the prior art have the same size disadvantage as the existing coaxial structures, along with increased machining complexity.

The invention is defined in Claim 1. In one example a coaxial coupling cavity extends the zero field region between adjacent accelerating cavities, thereby reducing the efficiency of the accelerator. Coaxially coupled structures, however, attain a higher percentage of theoretical shunt impedance. (See : S. O. Schriber, « Accelerator Structure Development for Room-Temperature Linacs », IEEE Trans. Nuclear Science, Vol. NS-28, No. 3, pp. 3440-3444, June 1981). Consequently, accelerator efficiencies comparable to that of side coupled structures can be obtained if the web between accelerating cells is not increased more than several millimeters. The size disadvantage of the annular ring and existing coaxial designs exemplifies the problem of developing a new coaxial design which 1) has a diameter comparable to an accelerating cavity, 2) does not significantly increase the web thickness, and 3) has strong nearest neighbor coupling with small next nearest neighbor coupling. In this invention, a new coaxial cavity design is disclosed.

The newly developed coupling cavity is located entirely within the copper web between the accelerating cells of a standing wave, linear, electron accelerator operated at the $\pi/2$ mode. The coupling cavity is isolated from the beam axis of the accelerator. The outer radius of the coupling cavity is approximately equal to that of the accelerating cavities resonating at the same frequency, distinguishing the design from prior art coupling structures not open to direct electromagnetic interaction with the accelerated electron beam. The regions of the cavity near the inner and outer radii are enlarged to form triangular sectioned volumes, while the middle region consists of a pair of narrowly separated parallel plates. Consequently, the magnetic and electric components of the fundamental mode electromagnetic field resonating in the cavity are separated, by concentrating the magnetic field in the inductive end regions of the coupling cavity and the electric field in the capacitive region between the parallel planes.

Coupling is accomplished through a pair of coupling slots 180° apart cut into the web between the coupling and accelerating cavities. This preserves symmetry about the beam axis, minimizing the beam perturbation. Because the magnetic field in the coupling cavity is concentrated in this region and the electric field is negligible, the magnetic coupling is maximized while the electric coupling is minimized. This is an optimum coupling situation for high efficiency operation. Relatively small slots intercept sufficient flux for coupling. This minimizes the effect of coupling on the electric field distribution of the accelerating cavities. Further, by rotating the coupling slots 90° at each half accelerating cavity, the coupling slots are at maximum separation, thereby further reducing the direct coupling between accelerating cavities through the slots. This reduction increases the power flow and stability of the accelerator. Also, because the cavity is isolated from direct interaction with the beam, transverse beam break-up modes and inefficient parasitic modes cannot be excited by beam-cavity interaction.

These and further constructional and operational characteristics of the invention will be more evident from the detailed description given hereinafter with reference to the figures of the accompanying drawings which illustrate preferred embodiments and alternatives by way of non-limiting examples.

Fig. 1 shows partial longitudinal cross-sections and end views of four general types of designs of standing-wave linear accelerators in the prior art : Fig. 1a on-axis coupled structure, Fig. 1b coaxial coupled structure, Fig. 1c side coupled structure, Fig. 1d annular coupled structure.

Fig. 2 shows a partial longitudinal cross-section in Fig. 2a and an end view in Fig. 2b of the standing-wave linear accelerator according to the invention.

Fig. 3 shows a section through a coupling cavity according to the invention in which the dotted lines represent the electric field vector.

Fig. 4 shows theoretical energy spectra for an accelerator according to the invention.

Fig. 5 shows a longitudinal cross-section of a complete accelerator according to the invention.

Fig. 6 shows measured and theoretical dispersion curves for an accelerator according to the invention.

Referring now to the drawings wherein reference numerals are used to designate parts throughout the various figures thereof, there is shown in Fig. 2 a short section of the structure.

It consists of a small radius, coaxial structure 10 with coupling cavities 12 which are located in the webs 14 between accelerating cavities 16 and increase the magnetic induction in those regions near the inner and outer radii of the coupling cavity. In essence, the geometry enhances the intrinsic field distribution of a simple coaxial cavity in the TM_{010}-like mode, while reducing the cavity to smaller overall dimensions. The thin flattened regions 18 between the enlarged end regions 20 act as an effective capacitor and concentrate the electric field in the flattened regions 18 as shown in Fig. 3, away from the coupling slots 22. The concentration of the magnetic field in the enlarged regions 20 provides an ideal coupling opportunity. The shape of the enlarged regions 20 was selected to be in the triangular form shown in the drawings but enlarged shapes can be used, such as a hemispherical or oval type shape. Two slots 22 are cut 180° opposite each other about the beam axis into each accelerating cavity 16, thereby preserving symmetry about the beam axis. Relatively small slots can provide adequate nearest neighbor coupling, K_1, and the next nearest neighbor coupling, K_2, can be made negligibly small by rotating the slots 90° about the beam axis at the opposite side of each web 14 at each cell. The design also allows for a very high K_1 to be obtained while keeping K_2 to an acceptable value, by increasing the slot width and arc length.

The coupling cavity sits in the web between two accelerating cavities. Several dimensional constraints were imposed upon the prototype design for an S-band accelerator structure. First, the coupling cavity outer diameter was to be approximately equal to that of the accelerating cavity. Second, the parallel plate gap could not be less than 3 mm to maintain reasonable mechanical tolerances. Third, a minimum wall thickness of 3 mm for S-band cavities was to be maintained at all points for mechanical stability and thermal conduction.

Before the coupling cavity prototype was designed, an accelerating cavity with a 9 mm web thickness was optimized for maximum shunt impedance, using the cavity program LALA. (See : H. C. Hoyt et al, « Computer Designed 805 MHz Proton Linac Cavities », Review of Scientific Instruments, Vol. 37, p. 755, 1966.) A cavity with inner radius 3.58 cm and theoretical shunt impedance per unit length of 124 M-ohm/m was developed. The cavity cods LACC was then used to design the coaxial cavity, subject to the constraints listed above. (See : A. Konrad, « A Linear Accelerator Cavity Code Based on the Finite Element Method », Computer Physics Communications, No. 13, pp. 349-362, 1978.) The program was used to arrive at a cavity 5 % higher in frequency than the operation frequency, because of the anticipated effect of the coupling slots. The size and location of the coupling slots were determined using the LACC magnetic field values. A coupling slot 22 of arc length 45° and width 5 mm was selected and located along the outer edge of the accelerating cavity 16. Substantially smaller and larger slots are workable.

The prototype coupling cavity shown in Fig. 2 resonates at 3 160 MHz without the coupling slots and 3 015 MHz with the slots. In the assembled accelerator, however, the coupling slots are rotated 90° and this lowers the full cavity frequency to 3 000 MHz. Machine tuning to within ± .2 MHz of the desired frequency was easily accomplished by increasing the diameter to lower the frequency or the capacitive gap to increase the frequency.

The prototype accelerator was designed to match the performance characteristics of an existing side coupled structure for comparison, the L1000-A accelerator built by Varian Associates. It consists of 7-1/2 accelerating cavities and was designed for optimum performance at 4 MeV output energy. A beam simulation program was used to develop the buncher configuration for the guide, using the LALA field profiles. An injection voltage of 15 kV was used, with variable field gradients. A three-cell buncher with cell, length 44.8 mm was selected. The resulting output energy spectrums are given in Fig. 4. The overall length of the guide is 35.9 cm. RF power from a magnetron is inputted at the 4th full accelerating cavity. The peak rf power delivered at the guide is 2.3 MW, with a 4.3 microsecond pulse width. Table I summarizes the accelerator design parameters.

Table I

Performance Summary

Accelerator Length		35.9 cm
Number of Cavities		7 1/2
Frequency		2997 MHz
Coupling: Nearest Neighbor (K_1)		3.3%
Nearest Neighbor (K_2)		.03%
RF Peak Power		2.3 MW
RF Pulsewidth		4.3 microsecond
E peak/E_O		8.1
Transit Time Factor		.916
Theoretical Q_O		16,000
Theoretical ZT^2/L		124 M-ohm/m
	Design	Measured
Q_O	14,400	13,500
Q_{ext}	7,200	6,600
$Beta_O = Q_O/Q_{ext}$	2.0	2.05
ZT^2/L	111 M-ohm/m	104 M-ohm/m

Both the coupling and accelerating cells were accurately machined of oxygen-free high conductivity (OHFC) copper to make post-braze tuning of the guide unlikely. The accelerating cells were tuned in separate halves to within ± 1 MHz of the desired frequency. The desired frequencies were determined from the dispersion measurements of successive stacks of 2, 4, and 6 half cells. The coupling cavities were tuned in separate halves to within ± .2 MHz of 3 009 MHz, which gave full coupling cell frequencies of approximately 2 994 MHz. Because of the sensitivity of the large capacitive region of the coupling cavity to gap length, the effect of the braze had to be allowed for. The full coupling cavity frequency varies 240 MHz/mm of additional spacing between half cells. The braze process adds 20 μm (microns) of copper between cells on average, resulting in an approximately 5 MHz increase.

The prototype accelerator constructed to test the new coupling cavity is shown in Fig. 5. A series of identical half-cavity pieces 30 of OFHC copper are brazed together alternately back to back and front to front as shown. Slightly modified coupler half cells 32 are used to admit microwave energy. Slightly shorter buncher pieces 34 are used to increase the beam velocity to match the phase of the accelerating section. A beam source 36 inserts a beam into the buncher. The high energy beam strikes a target or window 38 at the end opposite to that of the beam source.

The measured and theoretical dispersion curves for the brazed guide are shown in Fig. 6. The theoretical curve assumes a biperiodic structure with $f_{accelerating}$ = 2 996.69 MHz and $f_{coupling}$ = 3 001.5 MHz. The bead drop data is shown in Figure 6. The guide had a measured Q_o of 13,500 and Q_{ext} of 6,580, with a VSWR ($Beta_o$) of 2.05. The nearest neighbor coupling, K_1 was 3.3 % and the next nearest neighbor coupling was .04 %. The coupling cavity frequencies were 3 001.5 MHz, ± 1.5 MHz. Before and after brazing length measurements of the guide indicated a greater than average increase per cell, approximately 30 μm (microns). This explains the high coupling cavity frequency, which is apparent in the dispersion curve. The accelerating cells remained tuned to within ± .1 MHz of a fixed frequency. These frequency variations were acceptable and no post-braze tuning of the guide was done.

This invention is not limited to the preferred embodiments heretofore described, to which variations and improvements may be made, without leaving the scope of protection of the present patent, the characteristics of which are summarized in the claims.

Claims

1. A linear standing-wave charged-particle beam accelerator for accelerating a beam of particles, said accelerator comprising :

plural cascaded standing wave accelerating cavities with approximately the same resonant frequency, said accelerating cavities being positioned so that a particle beam propagates longitudinally through them defining a beam axis, said accelerating cavities being figures of rotation around the beam axis having a cavity diameter, adjacent ones of said accelerating cavities being electromagnetically coupled,

coupling cavities located equidistant between said accelerating cavities and substantially within said cavity diameter, each said coupling cavity being in the form of a hollow flattened annular ring having an inner rim defining an inner diameter and an outer rim defining an outer diameter, said coupling cavities being coaxial with the beam axis, the gap of said flattened annulus at the mean of said inner and outer diameters being much less than the diameter of said outer rim with significantly increased gap at said inner and outer rims, means for coupling said accelerating cavities to said coupling cavities and said coupling cavity including means for isolating said coupling cavity from excitation by a beam.

2. The accelerator of claim 1, wherein said coupling means includes a first pair of slots connecting a first main cavity to a coupling cavity near said outer rim of said coupling cavity, each of said slots being in the form of an arc of a circle around said beam axis, said slots being generally 180 degrees from each other with respect to said beam axis, and a second pair of slots between said coupling cavity and a second main cavity, said second pair of slots being similar in shape and placement to said first pair of slots.

3. The accelerator of claim 1, wherein the gap at said outer rim of said coupling cavity is substantially increased over the gap at said inner rim.

4. The accelerator of claim 2, wherein each of said second pair of slots is 90 degrees from each of said first pair of slots with respect to said beam axis.

5. The accelerator of claim 1, wherein said coupling cavity in the form of a flattened annular ring includes in a section from a center to said inner and outer diameter sectional portions of generally triangular shape.

6. The accelerator of claim 5, wherein said triangular shapes are those of isocelles triangles defining apexes between equilateral sides of said triangles, said triangular shapes being oriented to place said apexes closest to a center of said section of said coupling cavity.

7. The accelerator of claim 1, including means for maintaining sufficient thickness of supporting walls to dissipate heat.

Patentansprüche

1. Stehwellen-Linearbeschleuniger für Ladungsteilchen zum Beschleunigen eines Strahles von Teilchen, gekennzeichnet

durch mehrfach kaskadierter Stehwellen-Beschleunigungskammern mit etwa gleicher Resonanzfrequenz, wobei die Beschleunigungskammern so positioniert sind, dass sich der Teilchenstrahl längs durch die Kammer ausbreitet und so die Strahlenachse definiert, die Strahlungskammern um die Strahlenachse angeordnete Rotationsfiguren sind, einen Kammerdurchmesser aufweisen, und wobei die nachfolgenden Beschleunigungskammern elektromagnetisch gekoppelt sind,

durch äquidistant zwischen den Beschleunigungskammern angeordnete Kopplungskammern mit im wesentlichen dem besagten Kammerdurchmesser, wobei jede der Kopplungskammern die Form eines hohlen, abgeplatteten, kreisförmigen Ringes besitzt mit einem inneren Rand, welcher einen Innendurchmesser festlegt und einem äusseren Rand, welcher einen Aussendurchmesser festlegt, wobei die Kopplungskammern koaxial zur Strahlenachse angeordnet sind, und wobei der am Mittel zwischen dem Innen- und dem Aussendurchmesser gelegene Spalt des besagten abgeplatteten Ringes viel kleiner ist als der Durchmesser des äusseren Randes mit deutlich grösserem Spalt an dem besagten inneren und äusseren Rand, durch Mittel zum Koppeln der besagten Beschleunigungskammer mit der besagten Kopplungskammer, wobei die besagte Kopplungskammer Mittel zum Freihalten der besagten Kopplungskammer von Strahlenanregung enthält.

2. Beschleuniger nach Anspruch 1, dadurch gekennzeichnet, dass die besagten Kopplungsmittel ein erstes Paar von Schlitzen zum Verbinden einer ersten Hauptkammer zu einer Kopplungskammer nahe des besagten äusseren Randes der besagten Kopplungskammer enthalten, und jeder der besagten Schlitze die Form eines Kreisbogens um die besagte Strahlungsachse aufweist, und die besagten Schlitze generell um 180°, bezogen auf die besagte Strahlungsachse gegeneinander versetzt sind, und dass ein zweites Paar von Schlitzen zwischen der besagten Kopplungskammer und einer zweiten Hauptkammer vorhanden sind, wobei das besagte zweite Paar von Schlitzen in bezug auf Gestalt und Anordnung dem ersten Paar von Schlitzen ähnlich ist.

3. Beschleuniger nach Anspruch 1, dadurch gekennzeichnet, dass der Spalt an dem besagten äusseren Rand der besagten Kopplungskammer gegenüber dem Spalt am inneren Rand vergrössert ist.

4. Beschleuniger nach Anspruch 2, dadurch gekennzeichnet, dass jedes der besagten zweiten Paare von Schlitzen gegenüber dem ersten Paar von Schlitzen in bezug auf die besagte Strahlungsachse um 90° versetzt ist.

5. Beschleuniger nach Anspruch 1, dadurch gekennzeichnet, dass die besagte Kopplungskammer in Form eines abgeplatteten, kreisförmigen Ringes in einem Schnitt zwischen dem Mittelpunkt und dem

besagten inneren und äusseren Durchmesser Querschnittsbereiche von grundsätzlich dreieckiger Gestalt besitzt.

6. Beschleuniger nach Anspruch 5, dadurch gekennzeichnet, dass die besagten dreieckförmigen Querschnitte so beschaffen sind, dass sie gleichzeilige Dreiecke sind und einen Scheitel zwischen gleichseitigen Kanten der besagten Dreiecke bilden, und dass die dreieckförmigen Querschnitte so orientiert sind, dass die besagten Scheitel dem Zentrum des Schnittes der Kopplungskammer nächstgelegen sind.

7. Beschleuniger nach Anspruch 1, dadurch gekennzeichnet, dass Mittel zum Beibehalten einer ausreichenden Dicke der tragenden Wände vorhanden sind zum Abführen von Wärme.

Revendications

1. Un accélérateur de faisceau de particules chargées, linéaire à onde stationnaire, pour l'accélération d'un faisceau de particules, le dit accélérateur comprenant :

une pluralité de cavités d'accélération à onde stationnaire en cascade, avec approximativement la même fréquence de résonance, les dites cavités d'accélération étant positionnées de manière à ce qu'un faisceau de particules se propage longitudinalement à travers elles, définissant un axe de faisceau, les dites cavités d'accélération étant des figures de rotation autour de l'axe de faisceau, ayant un diamètre de cavité, adjacentes à certaines des dites cavités d'accélération, étant couplées électromagnétiquement,

des cavités de couplage disposées de façon équidistante entre les dites cavités d'accélération et substantiellement à l'intérieur du dit diamètre de cavité, chacune des dites cavité de couplage étant de la forme d'un anneau circulaire creux et plat, ayant un bord intérieur définissant un diamètre intérieur et un bord extérieur définissant un diamètre extérieur, les dites cavités de couplage étant coaxiales avec l'axe de faisceau, le vide du dit anneau plat, à la moyenne des dits diamètres intérieur et extérieur étant beaucoup plus faible que le diamètre du dit bord extérieur, avec un vide augmentant significativement aux dits bords intérieur et extérieur, des moyens pour coupler les dites cavités d'accélération aux dites cavités de couplage, et les dites cavités de couplage incluant des moyens afin d'isoler la dite cavité de couplage de l'excitation par un faisceau.

2. L'accélérateur selon la revendication 1, dans lequel les dits moyens de couplage incluent une première paire de rainures connectant une première cavité principale à une cavité de couplage, à proximité du dit bord extérieur de la dite cavité de couplage, chacune des dites rainures étant de la forme d'un arc de cercle autour du dit axe de faisceau, les dites rainures étant généralement à 180 degrés de chaque autre par rapport à l'axe de faisceau, et une seconde paire de rainures entre la dite cavité de couplage et une seconde cavité principale, la dite seconde paire de rainures étant similaire en forme et disposition à la dite première paire de rainures.

3. L'accélérateur selon la revendication 1, dans lequel le vide au dit bord extérieur de la dite cavité de couplage est substantiellement plus grand que le vide au dit bord intérieur.

4. L'accélérateur selon la revendication 2, dans lequel chacune des dites secondes paires de rainures est à 90 degrés de chacune des dites premières paires de rainures par rapport au dit axe de faisceau.

5. L'accélérateur selon la revendication 1, dans lequel la dite cavité de couplage de la forme d'un anneau plat circulaire inclut dans une section, depuis un centre des dits diamètres intérieur et extérieur, des portions sectorales de forme généralement triangulaire.

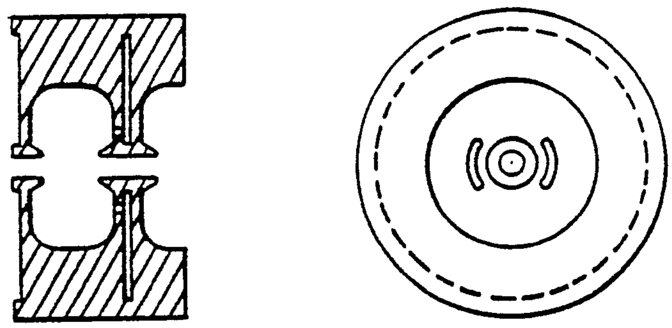
6. L'accélérateur selon la revendication 5, dans lequel les dites formes triangulaires sont celles de triangles isocèles définissant des sommets entre les côtés équilatéraux des dits triangles, les dites formes triangulaires étant orientées afin de placer les dits sommets le plus prés d'un centre de la dite section de la dite cavité de couplage.

7. L'accélérateur selon la revendication 1, incluant des moyens pour maintenir une épaisseur suffisante des parois support, afin de dissiper la chaleur.

FIG.1A
PRIOR ART

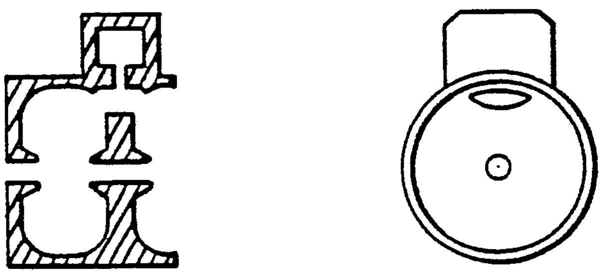
ON-AXIS COUPLED STRUCTURE

FIG.1B
PRIOR ART



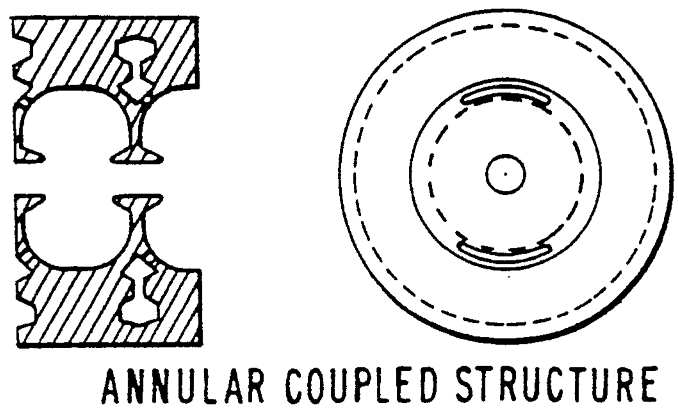
COAXIAL COUPLED STRUCTURE

FIG.1C
PRIOR ART



SIDE COUPLED STRUCTURE

FIG.1D
PRIOR ART



ANNULAR COUPLED STRUCTURE

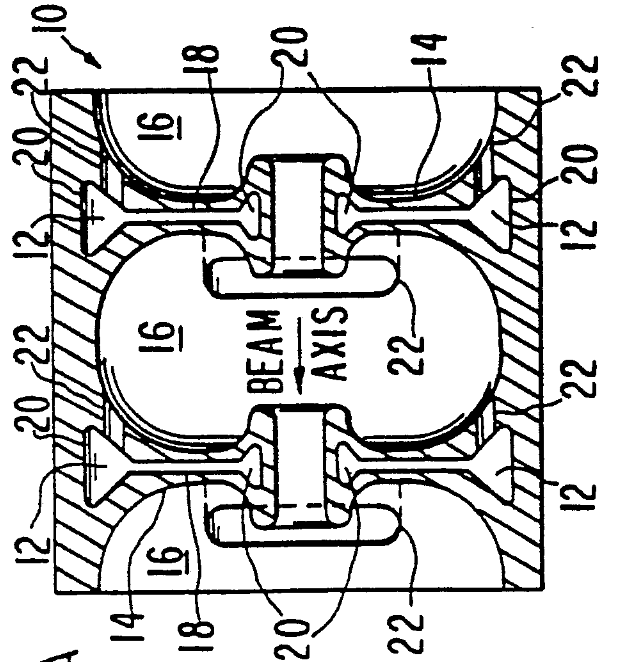


FIG.2A

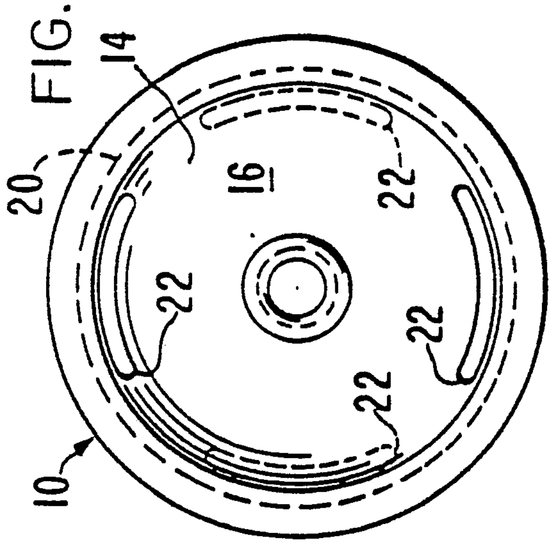


FIG.2B

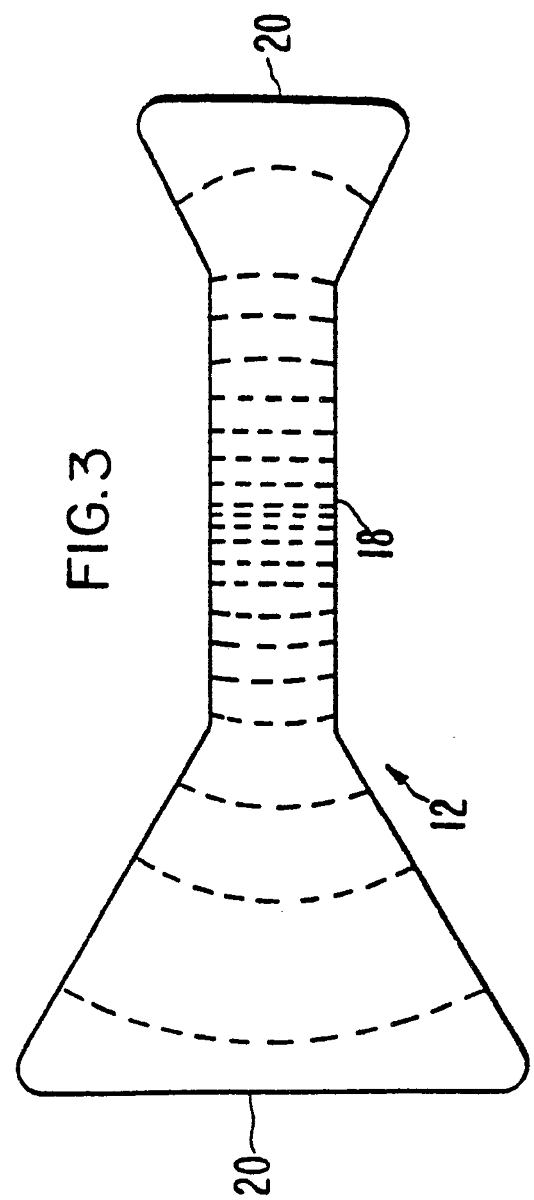
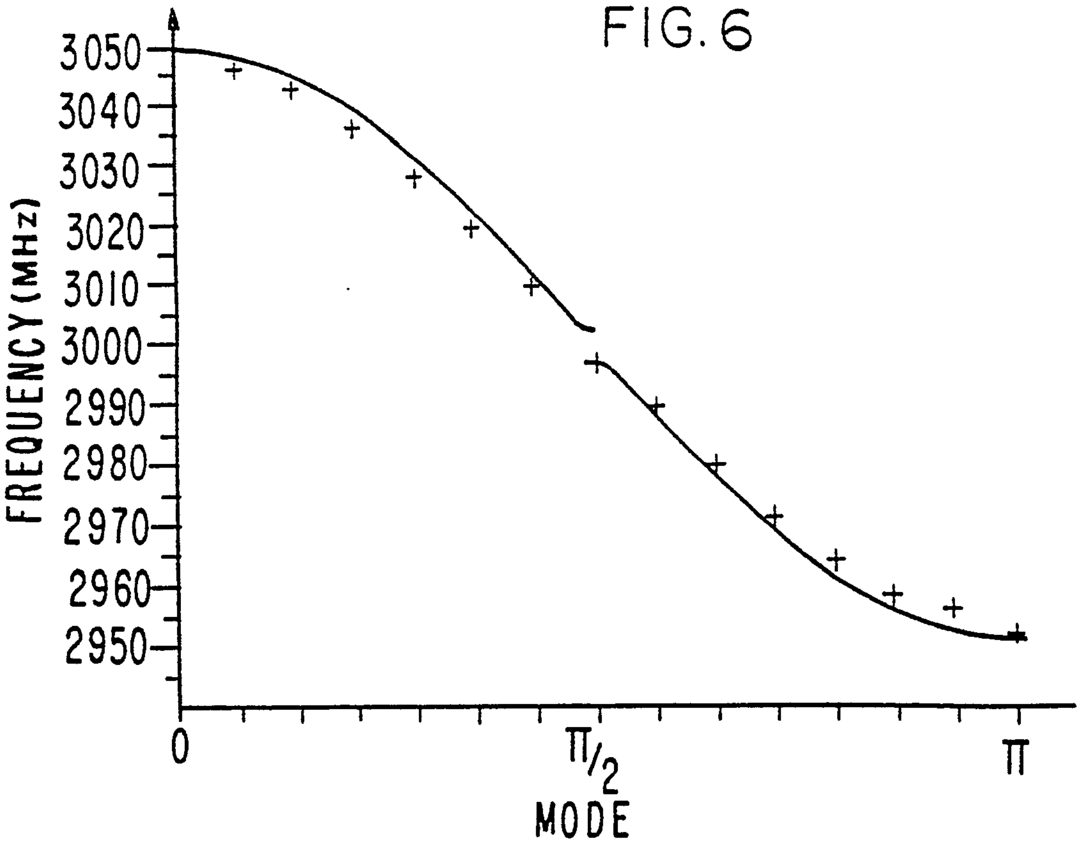


FIG.3

FIG. 6


3050
3040
3030
3020
3010
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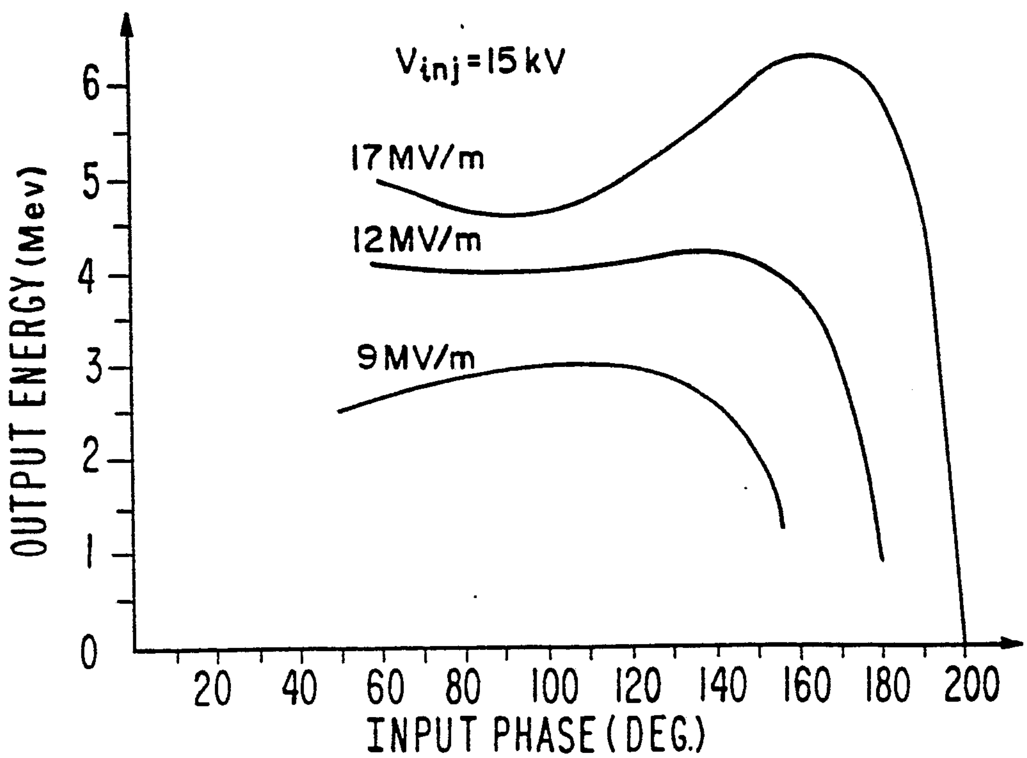
2990
2980
2970
2960
2950
FREQUENCY (MHz)
0
π/2
π
MODE

FIG. 4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17 MV/m
12 MV/m
9 MV/m
6
5
4
3
2
1
0
OUTPUT ENERGY (Mev)
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180
200
INPUT PHASE (DEG.)

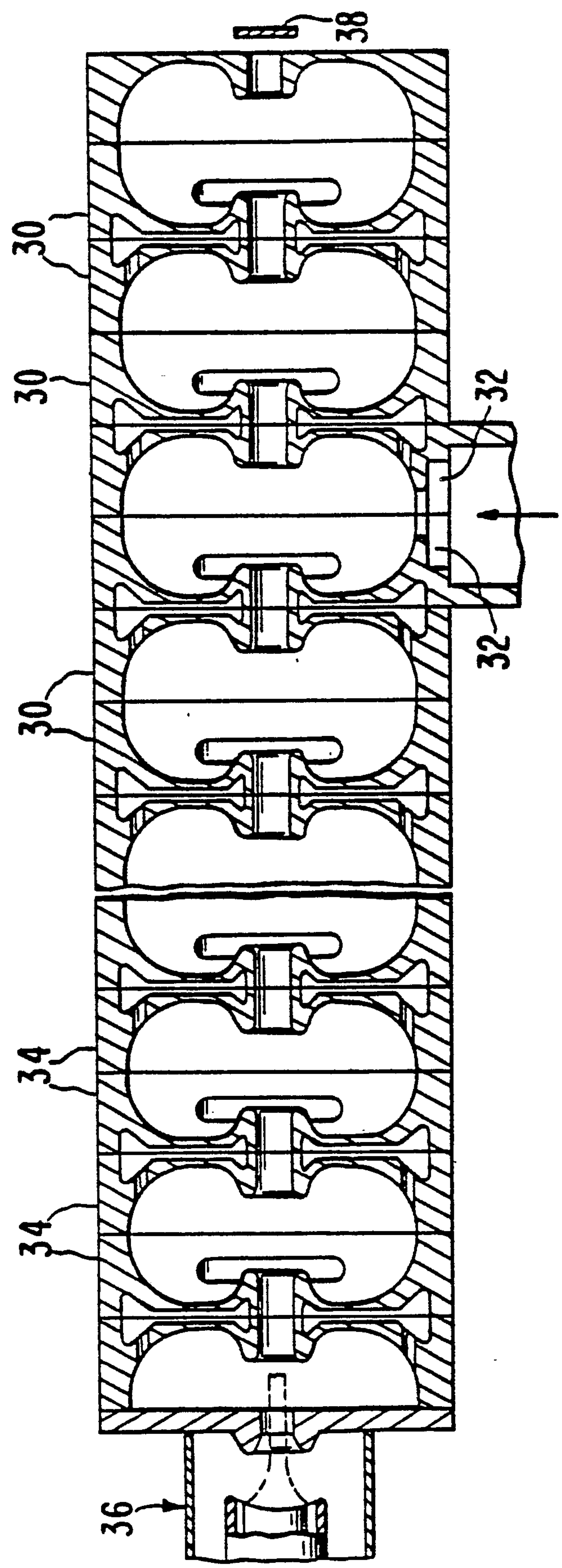

FIG.5