United States Patent

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[33] France
[31] 129070

[54] ACCELERATOR FOR RELATIVISTIC ELECTRONS

13 Claims, 7 Drawing Figs.

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[51] Int. Cl. H01j 23/10, H01j 25/10, H01j 29/76, H05h 9/00
[50] Field of Search 313/62; 328/232-238, 230, 253; 315/5.18, 5.42, 5.13, 5.69, 5.25, 5.27, 5, 5.39

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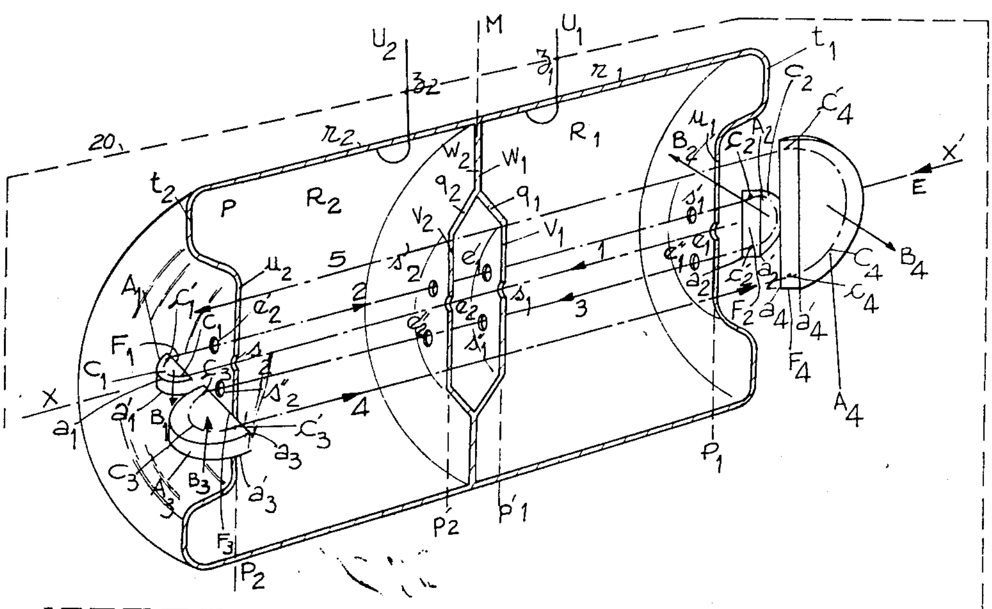
ABSTRACT: An electron accelerator supplied with H.F. energy comprising one or more resonators in series through which an electron beam is propagated several times, along parallel trajectories with deflection by 180° at each end of the accelerator.



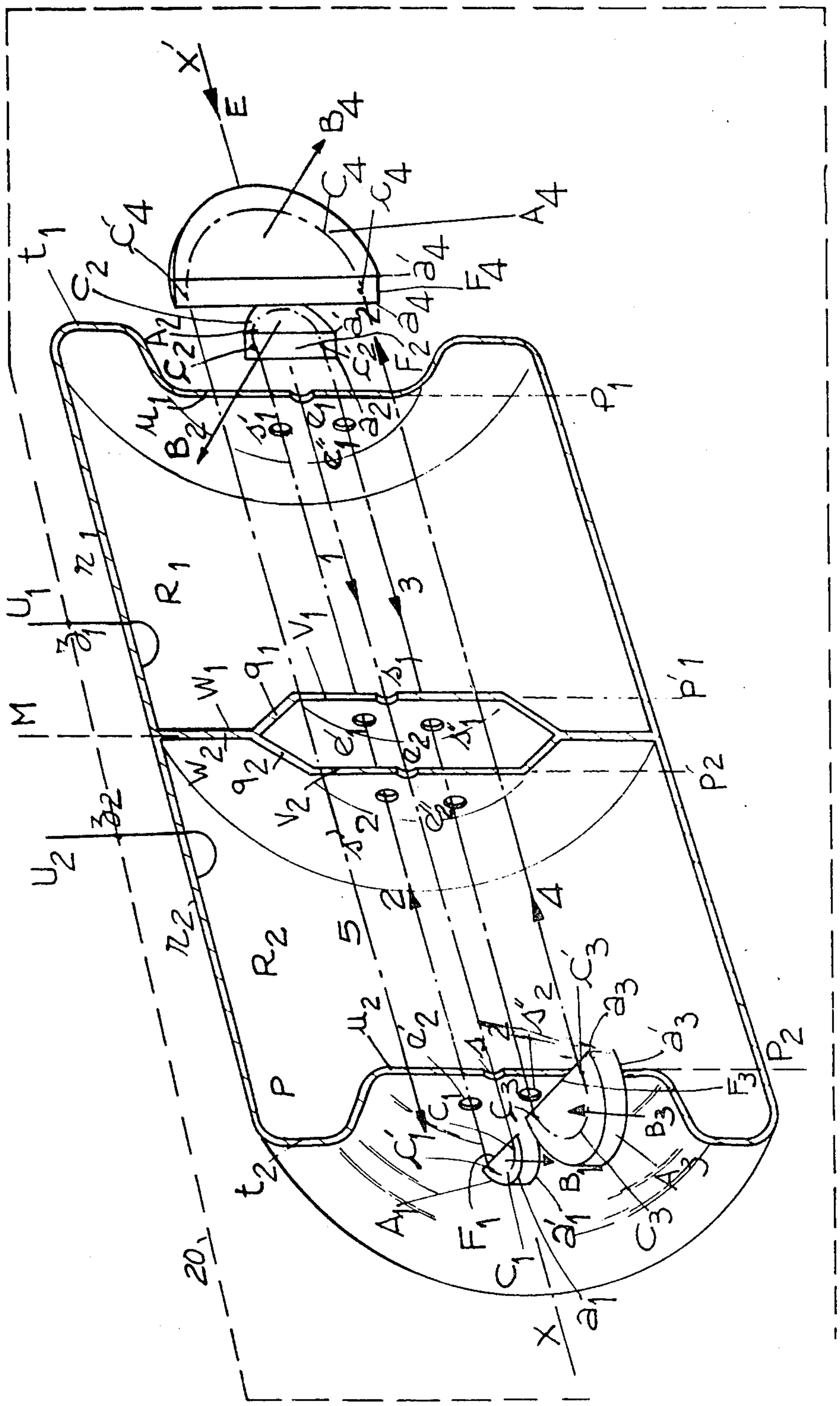
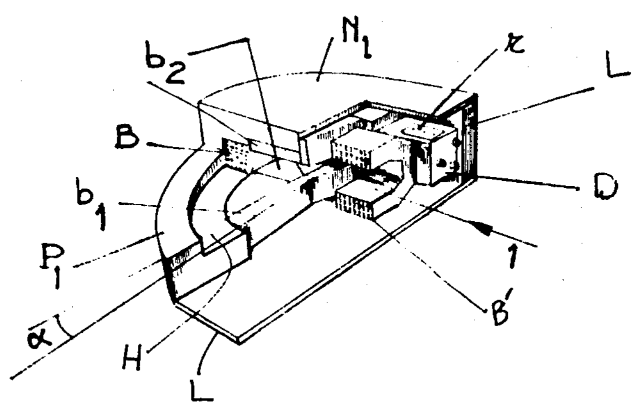


Fig. 1

Fig.7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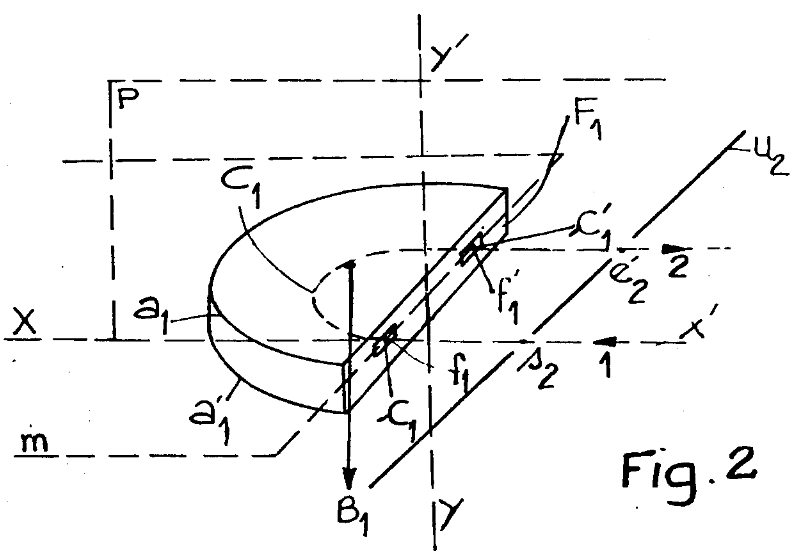
b_2
B
b_1
P_1
α
H
L
L
D
1
B'


y'
P
F_1
u_2
C_1
C'_1
e'_2
2
f'_1
X
a_1
x'
f_1
s_2
1
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C_1
m
B_1
Y

Fig. 2

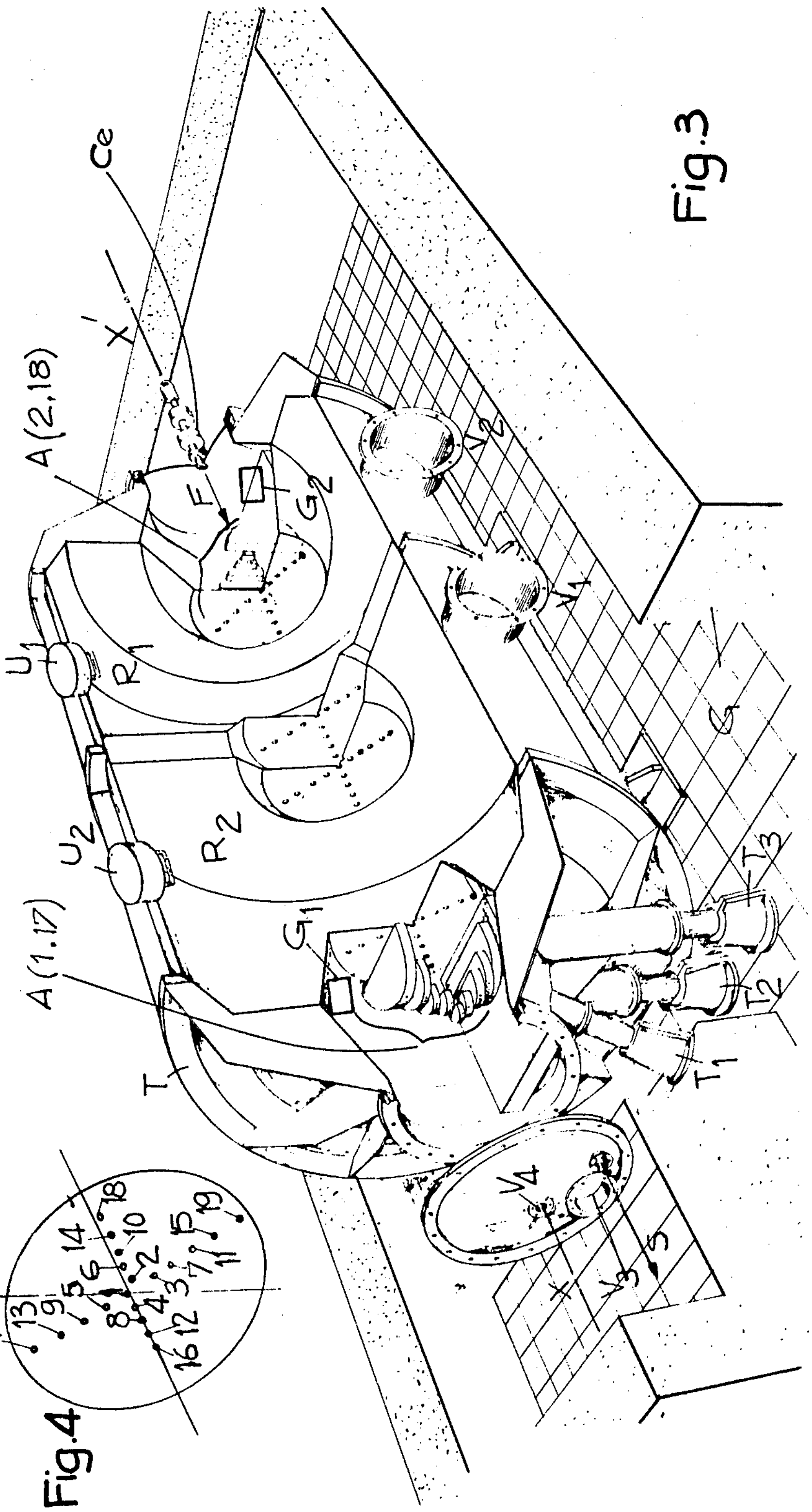
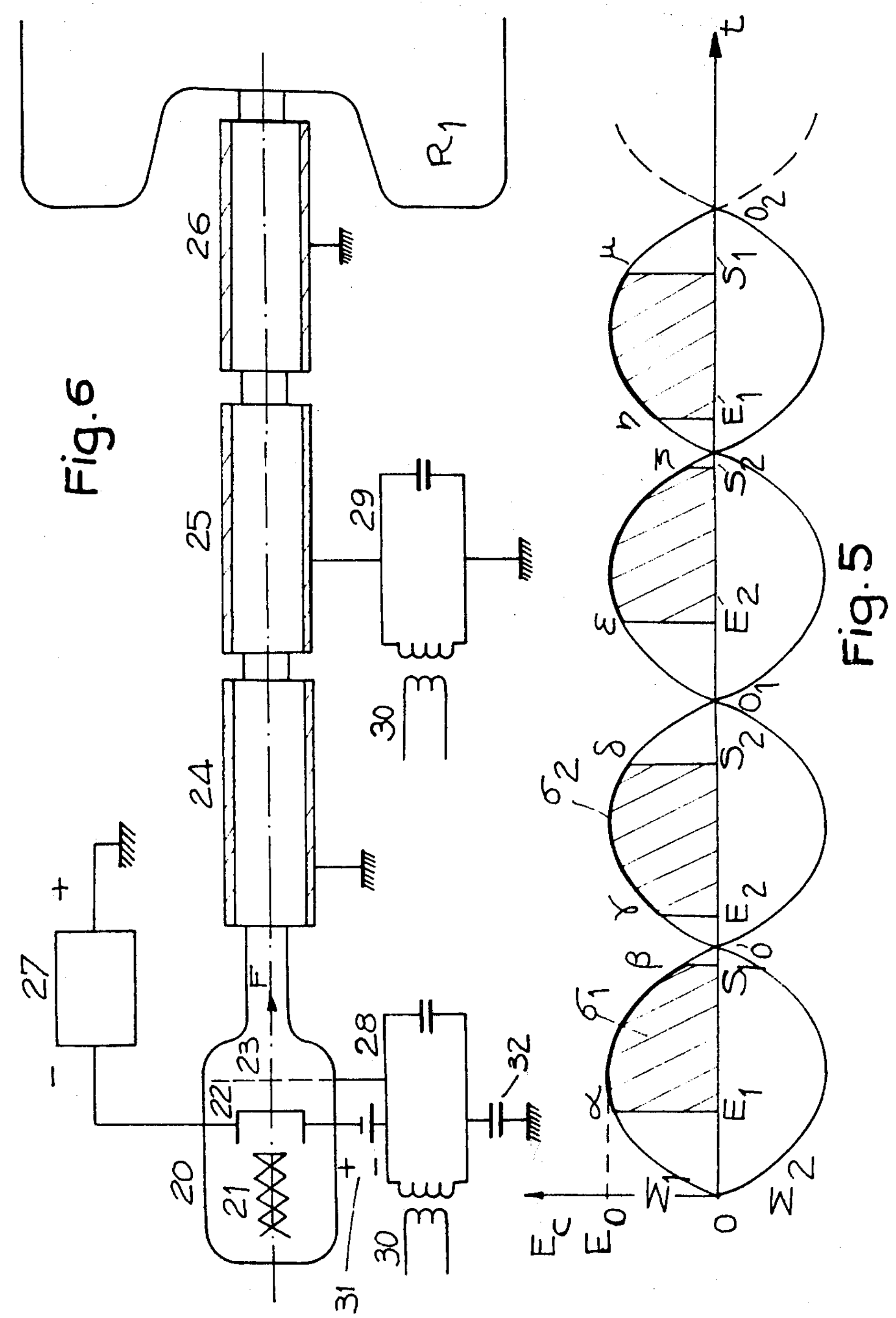

Ce
X'
A(2,18)
F
G_2
R_1
U_1
V_2
V_1
G
R_2
U_2
T_3
G_1
A(1.17)
T
T_2
T_1
V_4
V_3
S
X
17 13 9 5 6 14 18 10 8 1 4 2 3 15 19 7 11 16 12

Fig.3

Fig.4


R1
26
25
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27
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28
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20
21
22
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F
31
32
t
O2
S1
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S2
E2
O1
S2
E2
S1
O
E1
Ec
E0
O

Fig. 6

Fig. 5

ACCELERATOR FOR RELATIVISTIC ELECTRONS

The present invention relates to electron accelerators. More precisely it is an object of the invention to provide an electron accelerator which is capable of permanent operation at a level in the order of 100 mev.

A variety of physical investigations require the use of particles with a very high duty factor and even of permanent beams.

Such beams can be produced at low (20 mev.) and mean (100 mev.) energies, in the case of heavy particles such as ions, for example by means of an isochronous cyclotron.

Unfortunately, this approach cannot be employed in the case of electrons because the latter become relativistic beyond 1 mev. and isochronous devices can no longer be employed beyond this energy level.

In so far as present-day electron accelerators are concerned, it should be noted that electrostatic Van de Graaff-type accelerators are limited to around 10 mev. and continuously operating linear accelerators, because of the low level of the accelerated current and the losses in the cavities, have very poor efficiency indeed.

It is true that attempts have been made to improve the efficiency by reducing the losses in the cavity walls by rendering the latter superconducting, It is possible to reduce these losses in a ratio of around 10^4 by operating at 1.8° K. and it has been possible to accelerate some tens of μ μa. to 6 mev. (Stanford).

Nevertheless, this kind of approach comes up against very considerable problems, such as the efficiency of the cooling system, the compatibility of such systems with the magnetic focusing, the production of a great number of cavities with a high Q factor, service life, reliability, etc. All these factors have so far prevented a viable accelerator of this kind from being produced.

Also research work, carried out notably in the U.S.S.R., on a cyclotron design operating at ultrahigh frequency, would appear to have encountered a variety of difficulties, such as those associated with the injection, absence of horizontal and vertical focusing, need to use very strong ultrahigh frequency fields (50 mev./m.), very high H.F. power.....etc. Although practical embodiments of this kind of design would appear to have reached levels of 30 mev. in operation, these are in fact figures reached only in pulsed operation.

According to the invention, there is provided an electron accelerator comprising an arrangement including n cavity resonators associated in series for electron beam propagation therein, n being an integer, means for feeding an electron beam into said arrangement at one end thereof, means for propagating said beam a plurality of timeout and back along different rectilinear, parallel trajectories throughout said arrangement and means for feeding high frequency energy to said arrangement.

For a better understanding of the invention and to show how the same may be carried into effect, reference will be made to the drawing accompanying the following description and in which:

FIG. 1 is a schematic perspective view in axial longitudinal section along the plane of symmetry P of an accelerator according to the invention showing some initial trajectories of the beam:

FIG. 2 shows a detail of the accelerator of FIG. 1;

FIG. 3 is a partially cutaway perspective view of an accelerator in accordance with the invention;

FIG. 4 is an enlarged view of a detail of FIG. 3;

FIG. 5 is an explanatory diagram showing the passage of the beam through the accelerator 1;

FIG. 6 is a diagrammatic sectional view of an electron gun used in the accelerators in accordance with the invention, and

FIG. 7 is a perspective view of one of the deflecting systems employed in an accelerator according to the invention.

Similar symbols designate similar elements throughout all the figures.

The embodiment of the accelerator according to the invention shown in FIG. 1, comprises two resonators R_1 and R_2 of the small-gap rhumbatron type having a common axis of revolution XX'.

The two resonators R_1 and R_2 are identical. They have respectively cylindrical walls r_1 and r_2 and inwardly dished terminal walls q_1, t_1 and q_2, t_2. The recessed portions of the dished walls have flat bottoms u_1, v_1 and u_2, v_2 respectively in the planes p_1, p'_1 and p_2, p'_2

The resonators R_1 and R_2 abut each other, the nonrecessed portions w_1 and w_2 of their respective end walls q_1 and q_2 being applied to each other.

The recessed wall portions u_1, v_1, u_2 and v_2 have holes $e_1 s'_1$, e''_1—s_1, e'_1, s''_1—s_2, e'_2, s''_2—e_2, s'_2, $3''_2$ for the passage of the electron beam.

The resonators R_1 and R_2 are supplied with high frequency energy by means of respective antennae U_1 and U_2, coupled to a source (not shown).

Five of the trajectories **1**,**2**,**3**,**4**, and **5**, followed by the electron beam through the accelerator, are shown in FIG. **1**.

FIG. **1** also shows, very diagrammatically, two of the deflecting elements of each of the deflection systems, namely magnets (or electromagnets) A_1 and A_3 at the left and A_2 and A_4 at the right.

The assembly shown in FIG. **1**, is enclosed in an evacuated tight enclosure represented by the broken line **20** with the tight lead-throughs z_1 and z_2 for the antennae U_1 and U_2.

All the deflection elements of the deflection system are of the same type. They are well known to those skilled in the art and take, for example, the form of flattened semicylinders of revolution, whose axes are parallel to the plane P and perpendicular to the axis XX' at the left-hand end of the accelerator, and perpendicular to the plane P at the right-hand end thereof.

One of the elements, pertaining to the cavity R_2 of FIG. **1**, has been schematically shown in FIG. **2** as a semicylinder, limited by a plane F_1 parallel to its axis of revolution YY', and the faces a_1 and a'_1, perpendicular to this axis. The face F_1 is perpendicular to the plane P. In the case of all the deflecting elements situated at the right hand end of the accelerator of FIG. **1**, this face is perpendicular to the axis XX'.

In FIG. **2**, f_1 and f'_1 represent sections of the airgap of the element, which is, as is known, an essential part of a deflecting element, in the plane of the face F_1 and c_1 and c'_1 are the respective centers of these sections; m designates the median plane of the sections f_1 and f'_1. The point c_1 is located in the plane P on the axis XX'.

By referring to FIGS. **1** and **2** the trajectory of the electron beam through the accelerator, may be readily followed.

The electron beam enters at E, in the accelerator and propagates along the axis XX'. It enters the cavity R_1 through the orifice e_1 to follow the trajectory **1**, leaves it through the orifice s_1, enters the cavity R_2 through the orifice e_2, and leaves it through the orifice s_2.

At the output of the resonator R_2, still following the rectilinear trajectory **1**, it is taken up by the deflecting element A_1, as shown in FIG. **2**, at a point which there prevails a constant, uniform flux B_1, parallel to the plane P and directed downwards in the figure.

The electron beam is then deflected, following the circular trajectory C_1, as is well known in the art. This reflection is backwards of the plane P in FIG. **1**, due to the fact that the magnetic field is the reflecting elements A_1 is directed downwards, as indicated by the arrow B_1.

The beam then leaves the deflecting element to follow a rectilinear trajectory, tangentially to the semicircular are C_1 and parallel to but in the opposite direction of the trajectory **1**. It enters the resonator R_2 through the orifice e'_2. It leaves it through the orifice s'_2, then entering the resonator R_1 at e'_1 and leaving it at s'_1.

At the output of the resonator R_1, it follows the rectilinear trajectory **2** and penetrates into the deflecting element A_2. The latter is positioned normally to the element A_1, as above specified.

The magnetic field of the deflecting element A_2 is constant, uniform, perpendicular to the plane P and directed from front to rear of the FIG. **1**, as indicated by the arrow B_2.

The electron beam is deflected by the deflecting element A_2 in the same manner as by the element A_1. but in a plane normal to that in which is was deflected in the latter. Upon leaving it, it follows the trajectory 3 which is parallel to the trajectory 2 but of opposite direction and is located below it.

The beam then propagates again towards the resonators R_1 and R_2, through the orifices $3''_1$, s''_1, and e''_2, s''_2. At the output of the resonator R_2, it is deviated by the deflecting element A_3, positioned beneath the element A_1 in FIG. 1. The beam is then deflected to follow the rectilinear trajectory 4. This trajectory is parallel to the trajectory 3, and is located in front of it in FIG. 1.

Following the trajectory 4, the beam once again propagates through the resonators R_1 and R_2, at points not shown in FIG. 1, since the forward half of the resonators has been out away in this figure, the trajectory 4 being forward of the plane P.

After having left the resonator R_1 the beam enters the deflecting element A_4, which is geometrically similar to the element A_2, oriented in the same manner and is situated in front of the element A_2 in FIG. 1.

Accordingly, the beam is deflected in the airgap of the magnet element A_4 as it was in element A_2, although in the opposite direction, i.e. upwards in FIG. 1, in view of the direction B_4 of the magnetic field of the deflecting element A_4.

After having followed the trajectory 5, the electron beam is again taken up by a deflecting element similar to elements A_1 and A_3 (not shown). Two successive deflections are thus made in opposite directions, towards the front of towards the rear of the figure, in the cause of the elements A_1, A_3..., and downwards or upwards, in the case of the elements A_2, A_4.... Each of these deflections has an amplitude such that the trajectory followed by the beam upon its leaving one of the deflecting elements is always behind all the preceding trajectories in the event that the last deflection is experienced took place towards the rear, of the figure, is always in front of the preceding trajectories when the last deflection took place towards the front of the figure, and is always above or below all the preceding trajectories according to whether the last deviation which it experienced was upwards or downwards in the figure.

As is known, when an electron travelling along a straight line enters a space within which there prevails a constant, uniform magnetic flux perpendicular to the direction of its velocity, it is subjected to a deviation along a circular trajectory, the radius of which is given by the formula:

$$B\,R=U1300, \qquad (1)$$

wherein, considering a relativistic electron, U represents the energy of the electron in mev., B the magnetic flux, in Tesla units and R the radius of the circle of deflection in meters.

In the case of the beams occuring in the accelerator of the invention, which is aimed at transferring energy to the beam, this energy increases with each transit through the resonators. In the case of the accelerator of FIG. 1, the beam gains the same energy amount, substantially 5 mev., with each transit, including the first one, one and the magnetic flux strength is the same in the airgaps of all the deflecting elements. It will thus be seen that, in accordance with formula (1), the radii of the arcs, C_1, C_2, C_3, C_4 described by the beam during deflections, and accordingly the dimensions of the deflecting elements, will increase from one to the next by a fixed amount. By way of example, one would have for U=5 mev. and B=0.45 Tesla, $U/300\,B$=0.037 m. or 3.7 cm.

This explains the relative positions of the rectilinear trajectories followed by the beam in the accelerator of FIG. 1, as described hereinbefore.

The electron beam is also subjected to certain phase conditions. These conditions are the conditions which it has to satisfy in order that its energy may increase with each transit. For this to happen, it is necessary on the one hand for the phase of the high frequency field in each resonator, at the instant the beam enters it, i.e., its input phase, to have a predetermined value or one which is at least comprised within certain limits, and the transit time of the beam within the resonator should also fall within certain limits.

The accelerator in accordance with the invention is devised for a continuous mode of operation. The phase condition is that experienced by a observer connected to the beam and travelling with the electrons of a given section thereof. This section will be chosen in accordance with considerations which will be dealt with in more detail hereinafter.

In accordance with one feature of the invention, the input phase of the beam, lags by a fixed amount, comprised between 0 and one-fourth of the period of the high frequency wave, in relation to the phase zero. The phase zero is that phase of the high frequency field in the resonator for which this field grows in the direction of propagation of the beam.

Considering a relativistic beam, this characteristics is expressed, both in the case of a single resonator and in the case of several resonators, by the following relationship:

$$L+D+\pi R=k\lambda/2 \qquad (2)$$

wherein,

—L designates the length of one of the rectilinear trajectories followed by the electron beam, in one direction, from the input of the first resonator to the output of the last;

—D is the sum of the distances travelled by the electron beam from the output of the last cavity traversed, to the input of the deflecting magnet element disposed beyond same and, after deflection in said element, from the output thereof to the input of the same cavity;

—R is the radius of the semicircular arc described by the electron beam inside the deflecting element:

—λ is the length of the operating high frequency wave; and

—k is the number of cavities.

In accordance with another feature of the invention the input phases of the beam, lag in relation to the zero phase aforesaid, by an amount which may vary from one transit to the next but in all cases is less, for each transit, than a quarter of a period of the operating high frequency wave:

$$n\times\Phi+\sum_1^n \Phi'+\varphi-nk\times\pi<\frac{\pi}{2}, \qquad (2')$$

this expression being valid, whatever the number n of transits, and in which:

— Φ is the phase shift experienced by the beam during a transit from the input of the first resonator to the output of the last resonator;

—Φ' is the phase-shift experienced by the beam between its exit from the last resonator and its return thereto after a deflection through 180°;

—$\Sigma_1{}^n$ is intended to indicate the summing of the phase shifts Φ'aforestated, over the n transits considered;

—Φ is the phase shift of the beam at the input to the first resonator at the beginning of the first transit, in relation to the zero phase as defined; and

—k is the number of resonators.

The length of the arcs described by the beam in the deflecting elements increases from one to the next in the manner explained hereinbefore in accordance with the condition (1), and the condition (2) means that, on the other hand, the sum of the distances covered by the electron beam between its exit from the resonators and a deflection element, i.e. the distance $s_2\,c_1$ in FIG. 2 in the case of the deflecting element A_1, and after deflection in the same element, between the latter and the resonator which it has just left, i.e. the distance $c'_1\,e'_2$ (these distances being equal in the case of magnets arranged as in FIG. 1 for example) will be smaller and smaller as the radius of the beam trajectory in the deflecting magnet, increases.

This explains the stepped arrangement of the deflecting elements, as it appears in FIG. 3.

This figure is a perspective, partly cutaway view, showing an embodiment of an accelerator according to the invention for operation in accordance with the phase condition defined by equation (2). The accelerator of FIG. 3 is similar in all respects to that shown in FIG. 1, except that it has been assumed that the first deflection undergone by the beam is from the rear towards the front of the FIG. 3 instead of being from the front towards the rear as in the case of FIG. 1.

In FIG. 3, an electron gun Ce supplies a beam directed, as shown by the arrow F, along the axis XX'.

The beam propagates through the resonators R_1, R_2 which are provided with holes for the passage of the beam. There are two deflecting systems, each comprising nine elements A (1 to 17) and A (2 to 18). The position of these systems can be varied in the resonators by means of two arrangements symbolically illustrated by G_1 and G_2.

The arrangements also comprises the antennae U_1 and U_2, which supply the high frequency energy to the resonators R_1 and R_2 respectively, a shielding enclosure G, vacuum connections V_1, V_2, V_3, V_4, an envelope T and cooling ducts T_1, T_2, T_3.

The resonators R_1 and R_2 are tuned as well known in the art.

As FIG. 3 shows, in the left-hand deflecting system the deflecting elements have a vertically stepped disposition on both sides of the deflecting element in which the first deflection takes place; similarly, the right-hand deflecting system has a horizontally stepped disposition. In each system the largest magnet, that is to say that in which the radius of the semicircular trajectory followed by the beam is the greatest, is nearest to the resonator wall, in accordance with the considerations set out hereinbefore.

It may be mentioned, at this juncture, that the use of magnetic deflecting systems gives the accelerators in accordance with the invention an additional advantage:

When a relativistic beam, made up of electrons of different energies, is subjected to a circular deflection in a magnetic field, the trajectory followed by a given electron is the smaller the lower its energy. Since all these trajectories are followed at the same speed by the relativistic electrons, it is the electron of lowest energy which takes the shortest time to travel through its deflection path.

Now, it is well known that in accelerators, the electrons of the beam, because of the energy they receive, are grouped together in "bunches," the energy of which decreases from the center towards the edges, the energies of the different electrons of which the bunch is made up depending upon the phase with which these electrons entered the different sections of the accelerator.

In the case of the accelerator in accordance with the invention, when one of these "bunches" traverses a deflecting magnet, the low energy electrons, therefore, have a tendency to overtake the maximum energy electrons located at the center of the bunch and preceding them, and, therefore, arrive at the input of the first resonator, ready for the next transit, with a lower phase shift with respect to the latter, than it was at the end of the previous transit, prior to entering the deflection element.

The presence of the deflecting system thus has the effect that with each passage of the beam through one of them, the electron "bunches" present in the beam are shortened, that is to say the electron grouping inside the bunches is improved, and this is something which is always desirable in accelerators.

The invention presents various other advantages which will be listed hereinafter:

Continuous operation is made possible due to the use of resonators whose resonance frequency in the principal mode, which is the only one to be considered, is sufficiently low to keep the wall losses low. It is well known that these losses reduce as the square root of the resonance frequency. By way of example, operation is carried out at a resonance frequency of 30 mc./sec. (λ=10m.) at which the loss impedance, or shunt impedance, can easily obtain value of some tens of megohms.

In addition, the ultrahigh frequency energy is the easier to generate, the longer is its wavelength, the maximum power output attainable with ultrahigh frequency generators being a steeply rising function of the wavelength.

Another advantage of the present invention resides in the fact that the dimensions of the resonators increase, other things being equal, in proportion with the wavelength of resonance, so that the section presented by the resonators for passage of the beam increases too, enabling the beam to traverse the section several times at different points in each case.

The overall result is a very substantial improvement in terms of size, as far as the length is concerned, with respect to what is possible in linear accelerators where the different trajectories are all disposed end to end. Of course, in the case of accelerators according to the invention, there has to be added to the length of the trajectories, not only the length occupied by the electron gun, which is in the same order as in known accelerators, but also that of the deflection systems. However, even taking this factor into account, the saving in terms of length is quite substantial indeed and is a major factor in facilitating the exploitation of the system.

A still further advantage of the invention resides in the fact that, in view of the trajectory followed by the beam in the accelerators in accordance with the invention, the point of injection and the point of extraction are spaced apart from one another and may even be arranged at different ends of the system.

The problem of extraction is thus readily solved, quite unlike what happens in the case of cyclotron-type accelerators for example.

FIG. 4 illustrates the arrangement of holes in one of the sections u_1, u_2, v_1 or v_2 of the resonators R_1 and R_2 of FIG. 3. These holes carry the reference numbers of the rectilinear trajectories traversing them respectively. In the case of FIG. 3, the beam covers 19 trajectories from the input F of the trajectory 1 to the end S of the trajectory 19.

The diagram of FIG. 5 indicates, in the case of the accelerator of FIG. 1, the passage of the beam through the resonators in relation to the phase of the H.F. field therein, for a beam obeying the phase condition (2) (constant input phase in the first resonator, in respect of all the transits).

The diagram of FIG. 5 relates to a given section of a continuous beam, this beam section entering the accelerator at the moment the applied H.F. field has the phase E_1.

In FIG. 5, the sinusoidal curve Σ_1 illustrates as a function of time the H.F. wave in the principal mode in the resonator R_1, for example, and the sinusoidal curve Σ_2, symmetrical with the former in relation to the time axis, the H.F. wave of the principal mode in the resonator R_2, which is in phase opposition with that of the resonator R_1 in accordance with one feature of the invention. The H.F. field is in each resonator uniform and parallel to the trajectories of the beam.

Let, for example, the electron beam following the trajectory 1 be considered. It enters the resonator R_1 through the orifice e_1, at the time E_1, which precedes that at which the H.F. electric field in this resonator reaches its peak value, by about one-twelfth of a cycle. At this instant, the strength of the H.F. electric field in the resonator R_1 is that plotted along the ordinate of the point α on the sinusoid Σ_1.

The electron beam propagates through the resonator R_1 from the point e_1 to the point s_1 situated in the plane p'_1, which it reaches at the instant S_1. The strength of the H.F. electric field in the resonator R_1 is at this instant equal to the ordinate of the point β of the sinusoid Σ_1, the time taken by the beam to propagate from e_1 to s_1 being, in accordance with another feature of the invention, less than half a cycle of the H.F. wave applied to the resonators. In the diagram of FIG. 5, the time S_1 precedes the end of the half-period O', by around one-twentieth of a period.

The electron beam then follows the trajectory 1 through the distance s_1e_2, where there is no H.F. field and which separates the plane p'_1 in which the beam leaves the resonator R_1, from the plane p'_2 in which it enters the resonator R_2. It enters the resonator R_2 at an instant E_2 the strength of the ultrahigh frequency electric field in the resonator R_2 being then equal to the ordinate of the point γ on the sinusoid Σ_2.

On the diagram of FIG. 5, the instant E_2 is later by about one-fifteenth of a cycle than the end of the first half-period.

The electron beam then passes along the trajectory 1 through the resonator R_2, leaving the latter at s_2 at the time S_2, at which time the H.F. field in the resonator R_2 has a strength equal to the ordinate of the point δ on the sinusoid Σ_2.

The electron beam is then deflected through 180° and returns in the direction of the arrows 2 towards the resonator R_2, which, it reaches at the instant E'_2, one cycle after having entered the resonator R_1. The beam then continues its propagation, as shown in FIG. 1 and as indicated in FIG. 5 at E_2 and ϵ, S'_2 and ζ, E'_1 and η, S'_1 and μ, the arcs ϵ ζ and η μ being derived respectively from the arcs α, β and γ, δ, by a translation equivalent to one cycle, O—0_1, O_1—O_3, etc., in FIG. 5, all in accordance with the phase condition (2), , this being true also for the following trajectories.

In FIG. 5, these sinusoidal arcs have been shown in full line.

The energy supplied to the beam by the two resonators R_1 and R_2 during the course of its transit through them, depends of course upon the transit time of the beam through these resonators.

The same applies to all the transits, given that the resonators are symmetrical with respect to the plane M, that they operate in antiphase, and that the beam phase condition is defined by the expression (2).

In respect of every electron in the beam, with the exception of a factor e (e being the electron charge), this is equal to the integral of the H.F. field considered between the planes p_1 and p'_1 in the case of the resonator R_1, and between the planes p_2 and p'_2 in the case of the resonator R_2.

This integral is written $\int_E^S E_c \, d\rho$, ρ being the distance traversed by the beam through the resonator between the instant E at which it enters the same, and the instant S at which it leaves it, E_c being the H.F. field strength of the fundamental oscillation in the resonator. S at which it leaves it, E_c

Considering a relativistic beam, one may write also:

$$\int_E^S E_0 \sin 2\pi \frac{l}{\lambda} al,$$

E_0 being the peak value of the H.F. field and λ the wavelength of the fundamental oscillation.

The energy is given by the crosshatched area σ_1 (FIG. 5) in the case of the resonator R_1, and by the crosshatched area σ_2 (FIG. 5) in the case of the resonator R_2.

By way of example, this energy is in the order of 5 mev. for each transit, considering an H.F. peak field in the resonator of around 1 megavolt per meter and a transit time through the resonators of around three-tenths of the cycle time.

This has the effect of producing within the beam energy bunches, or quanta, characteristic of accelerator beams, this feature having been discussed earlier.

This modulation is preceded by density modulation of the beam at the electron gun, where the only voltage applied to it being the continuous acceleration voltage, it does not yet achieve the relativistic condition. A conventional technique is then used, which consists in modulating the direct voltage applied to the beam to achieve drift modulation of the beam. The phase considered in the foregoing, is that of the central section of each bunch.

The gun is shown schematically in section in FIG. 6.

This figure shows a tight insulating envelope **20**, a filament **21**, a cathode **22** and an accelerator grid **23**, three drift tubes **24**, **25**, **26** and the input of resonator R_1. The direct acceleration voltage, in the order of a few kv., is supplied from the source **27** to the bean which is travelling in the direction F. Oscillatory circuits **28** and **29** are coupled to an ultra high frequency source **30**, tuned to the frequency of operation of the accelerator. They feed respectively the grid **23** and the central drift tube **25**. The grid is biased by a source **31**. The oscillatory circuit **28** is earthed across a capacitor **32**.

The grid which is class C operated, produces a first modulation in the beam which results in the formation of bunches of about 60° length, at the end of the tube **24**.

A further modulation applied to the tube **25**, the length of which is preferably made equal to $\lambda/2$, enchances the formation of bunches, whose length after drift through the tube **26** is around 5 °at the input to the resonator R_1.

In so far as the deflecting elements are concerned it should be noted that, as such, magnetic deflectors do not exert any concentrating action on the electron beam they deflect.

FIG. 7 shows, in perspective and partly in section a deflecting element which, while deflecting the beam, insures a certain amount of focusing of the latter.

The deflecting element shown in FIG. 7 comprises two pole pieces N_1 and P_1. A coil is positioned between these pole pieces in a groove H formed therein and is spread out at B' on the outer faces of the pole pieces to provide room for the passage of the beam on entering the deflecting element and leaving it after having described a semicircular trajectory in the space limited by the pole pieces N_1 and P_1 and the coil B.

The normal to the front vertical faces of the pole pieces N_1 or P_1 forms an acute angle α with the direction 1 of the beam. To this end, tapered elements b_1 may be applied on the frontal face of semicircular pole pieces P_1 and N_1.

Other tapered elements b_2 are applied on the opposed horizontal walls of the pole pieces, the inclination being in the direction of propagation of the beam. A shield L surrounds the whole assembly. r is the coil junction box and D the cooling system connector.

It is also possible to cause the beam to propagate outwardly of the deflecting element, the propagation path surrounding then this element.

In addition, in designing the magnets it must be borne in mind that during its passage through the resonator, the beam undergoes a radial deflection due to the high frequency magnetic field, however weak, prevailing inside said resonators in the zone traversed by the beam.

Whatever the case, given the trajectory followed by the beam in the accelerators in accordance with the invention, which trajectory has been described hereinbefore, correct orientation and centering of the beam are indispensable to the proper operation of the system. For this reason, means must be provided to permit of possible centering and alignment of the beam.

These means may take a variety of forms. They may consist, quite simply, of the deflection coils of the deflecting electromagnets, in the case where the deflector systems use electromagnets, of auxiliary electromagnets in the case where the deflector systems are made up of permanent magnets, or of mechanical devices G_1 and G_2 (FIG. 3), which enable slight displacements to be effected within the deflector systems, or of any other known system.

These means may also be required for other reasons.

With a given accelerator and a fixed operating wavelength λ it is possible to switch from the operation in accordance with the phase condition (2) to the operation in accordance with the condition (2'), i.e.

—either, with a fixed flux in the magnets, by displacing said magnets using devices G_1 and G_2 (FIG. 3) as already mentioned, so as to vary the distance D;

—or, for fixedly located magnets, by controlling the flux they produce, so as to vary R; it goes without saying, of course, that when using this second approach one is limited to variations of small amplitudes, since airgaps of a given size do not, with the wavelength employed according to the present invention, allow but very restricted possibilities in this direction.

On the other hand, outside the fundamental mode of oscillation which is the only one which has been considered in the foregoing, other oscillation modes actually develop in the resonators, whose frequency is generally very much higher than that of the fundamental mode. Although they cannot basically disturb the operation of the accelerator (because of their very low amplitude in relation to that of the fundamental mode), these modes exert parasitic effects upon the beam and in particular have a deflecting effect, the existence of which is well known in ultrahigh frequency accelerators. The influence of these deflecting wave modes, can be eliminated by selectively loading them so that it is virtually impossible for them to be excited at all.

To give some idea of the performance characteristics which it is possible to achieve with an accelerator in accordance with the invention, there are listed hereinafter the principal data for a two-resonator system of the kind shown in FIGS. 1 and 3 for example, accelerating a beam current of 1 ma.:

Operating frequency	30 MHz. (λ=10 meters)
Length of one transit: distance between the utmost points of two successive deflections	10 meters
Impedance of the cavities	approx.: 55 megohms
Cavity diameter	7 meters
Width of cavities on axis	4 meters
Peak accelerating field	1 mv./m.
Energy gain per single transit	5.3 mev.
Total number of deflecting elements	18
Total number of transits	19
Total energy gain	101 mev.
Beam current	1 ma.
H.F. power consumption:	
—in the beam	101 kw.
—in the resonator walls	280 kw.
Conversion efficiency (ratio of beam power consumption to total power consumption)	26%
Installed H.F. power	450 kw.
Deflection:	
—field strength of each magnet	0.45 Tesla units
—diameter of the trajectory in the first magnet	7.4 cm.
—diameter of the trajectory in the last magnet	140 cm.
—overall thickness of a magnet	15 cm.
—thickness of the airgap	5 cm.
Requisite stability:	
—magnetic field	better than 1/1000
—H.F. field	<3/1000
Thickness of bunches	<5°
Spectral width	in the order of 1%.

The energy level which can be attained with the accelerators in accordance with the invention, depends essentially upon the size of the magnets. This size, for a given flux in the airgap of the magnets (and the flux density cannot exceed certain values in the present state of the art), limits the beam energy in accordance with the formula (1) which states that, for a given flux, the beam energy and magnet size are proportional: $U/R=300\,B$.

The size of the magnets is itself limited by that of the cavities, the manufacture of which in the seize envisaged in accordance with the invention, creates problems in view of the great loads they have to support once evacuated. Accordingly, it is the size of the cavities which appears to be the essential factor in limiting the energy which it is possible to attain in accelerators in accordance with the invention.

It should be noted that a given accelerator according to the invention offers several possibilities of operation.

For example, it is possible, using the above-described accelerator, to achieve a level of 180 mev. by raising the flux in the airgap of the magnets from 0.5 to 0.8 Tesla units, this obviously inferring a corresponding increase in the power injected into the cavities, which will be in the order of around 1 mw. for a figure of 180 mev.; and of course all the levels intermediate of 100 and 180 mev. can be achieved in each case by an appropriate adaptation of magnetic field and injected power.

It is also possible, using the same accelerator, retaining the same supply arrangement and the same mean level of injected H.F. power and the same mean power transfer to the beam, to reduce the duty factor of the beam progressively as the magnetic flux of the magnets is increased; thus, the accelerator being designed to have a duty factor of 100 percent at 100 mev., this factor can be reduced to 38 percent at 180 mev.

Of course, the invention is not limited to the embodiments described and shown which were given solely by way of example.

What is claimed is:

1. An electron accelerator comprising an arrangement including n cavity resonators associated in series for electron beam propagation therein, n being an integer, means for feeding an electron beam into said arrangement at one thereof, magnetic means for propagating said beam a plurality of times out and back along different rectilinear, parallel trajectories throughout said arrangement and means for feeding high frequency energy to said arrangement.

2. An electron accelerator as claimed in claim 1, wherein said beam-propagating means comprise deflecting means including a first and a second beam-deflecting system, respectively positioned at the two ends of said arrangement, said first and second systems each comprising a plurality of deflecting elements, each element of one plurality being positioned for deflecting said beam through 180° towards one element of said other plurality.

3. An electron accelerator as claimed in claim 2, wherein said deflecting elements are magnetic elements having a semicircular gap through which said beam propagates and wherein the magnetic flux density is constant, uniform and normal to the common direction of said rectilinear trajectories for causing semicircular deflections of said beam.

4. An electron accelerator as claimed in claim 3, wherein said flux in said deflecting elements of one of said systems is directed normally to the direction of said flux in said elements of said other system.

5. An electron accelerator as claimed in claim 3, wherein said flux in said deflecting elements of each system is directed in a direction opposite to that in which it is directed in the elements of the same system adjacent thereto.

6. An electron accelerator as claimed in claim 1, wherein said arrangement of cavity resonators comprises two identical resonators having a common axis of revolution and abutting symmetrically each other.

7. An electron accelerator as claimed in claim 6, having means for feeding thereto said electron beam along said common axis.

8. An electron accelerator as claimed in claim 6, wherein said resonators are small-gap cavity resonators having a cylindrical body and opposed dished end walls.

9. An electron accelerator as claimed in claim 6, further comprising means for feeding ultrahigh frequency energy to said resonators in phase opposition.

10. An electron accelerator as claimed in claim 1, wherein means for feeding said electron beam into said resonators comprise means for bunching said electron beam prior to entering the first resonator.

11. An electron accelerator as claimed in claim 3, wherein said deflecting elements of each of said two magnetic systems are disposed stepwise with respect to each other on both sides of the deflecting element in which takes place the first deflection.

12. An electron accelerator as claimed in claim 3, wherein the pole pieces of said deflecting elements are tapered to provide an acute angle α between the direction of the beam, and the normal to the outer face of said pole pieces.

13. An electron accelerator as claimed in claim 3, wherein the pole pieces of said deflecting elements are tapered to provide a slope between the pole pieces of said deflecting elements so that the distance between said pole pieces of said deflecting elements so that the distance between said pole pieces increases in the direction of propagation of the beam.