July 10, 1962 I. PODLIASKY **3,043,986**

PARTICLE ACCELERATORS

Filed March 13, 1957 4 Sheets-Sheet 1

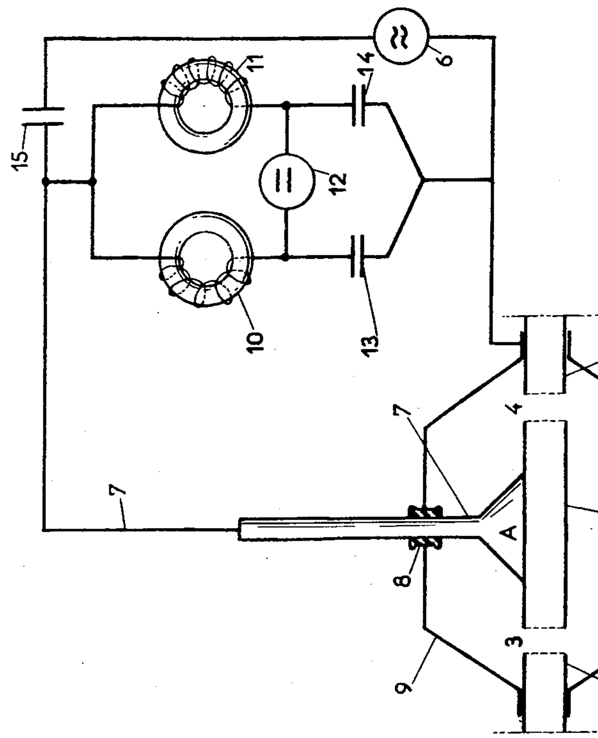

Fig. 1

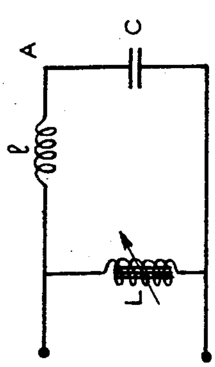

Fig. 2

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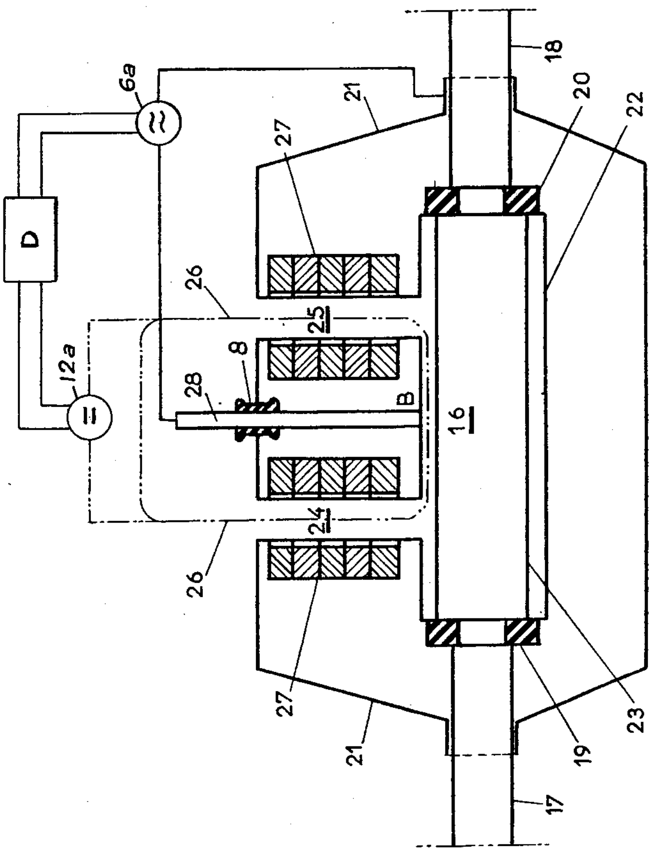

Fig. 3

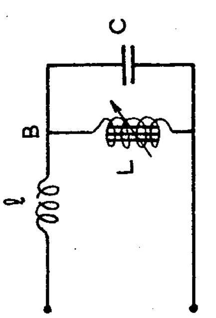

Fig. 4

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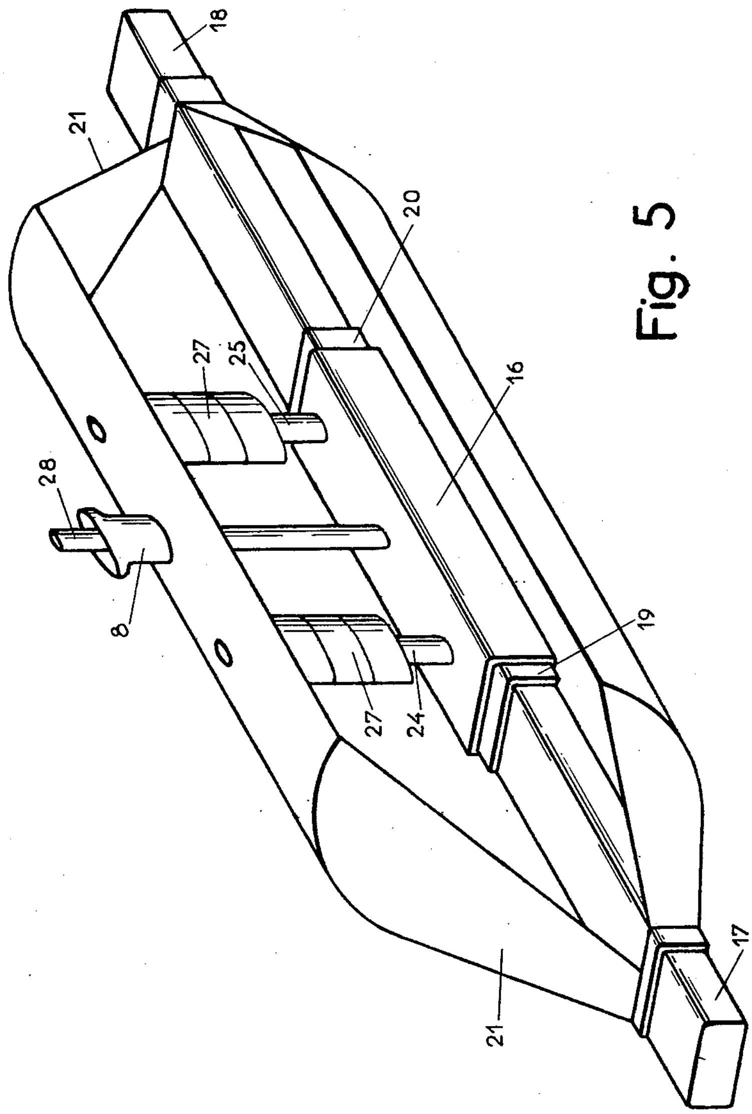

Fig. 5

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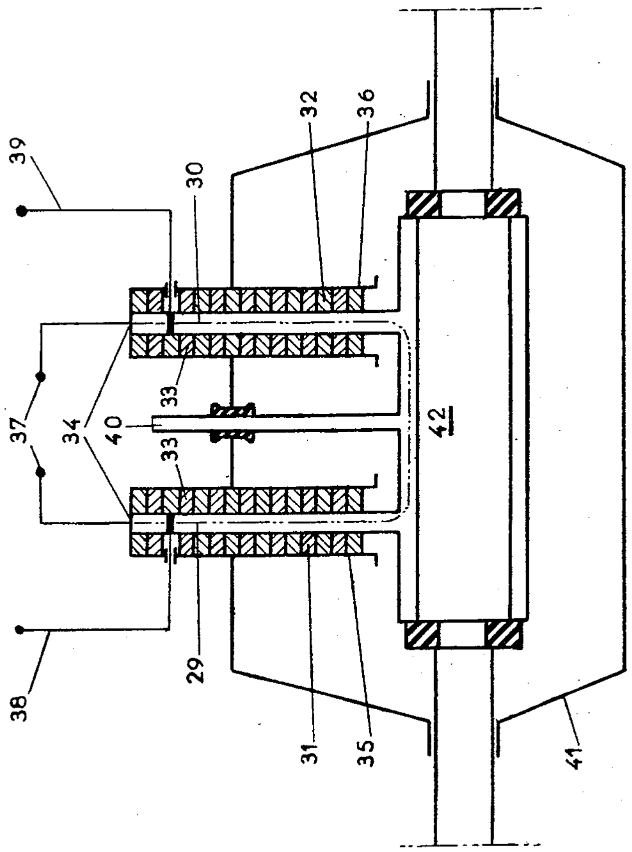

Fig. 6

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3,043,986

PARTICLE ACCELERATORS

Ilia Podliasky, Asnieres, France, assignor to Commissariat a l'Energie Atomique, French State Administration, Paris, France, a society of France

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5 Claims. (Cl. 315—5.46)

The present invention relates to particle accelerators of the type of proton synchrotrons, for the obtainment of very high energies (several billions of electron-volts or several tens of billions of electron-volts).

Such accelerators include accelerating tubes capable of creating a high frequency field which supplies one or several impulses to the particles as they are passing at a given point of a tore-shaped vacuum-chamber. Said impulses are produced by the electric field existing between the edges of said accelerating tubes.

As an example of such tubes, I may indicate the arrangement called "drift tube," diagrammatically shown on FIG. 1 of the appended drawing. On FIG. 1, I have shown, at **1** and **2**, passages formed by suitably metallized portions of the vacuum chamber. The particles which follow the longitudinal axis of said vacuum chamber (shown in dot-and-dash lines) are in Faraday cage, except when they pass through the gaps **3** and **4** existing between drift tube **5** and passages **1** and **2**. A high frequency voltage, supplied by an electronic generator **6** of variable frequency, is applied between tube **5** and elements **1** and **2** by means of a connection **7** which passes through an insulating plug **8**. The whole of the device is enclosed in a metallic casing **9** which is electrically connected with elements **1** and **2** and is intended to avoid radiation and electro-magnetic inductions to the outside.

The system constituted by tube **5** on the one hand, elements **1** and **2** and the whole of chamber constituted by casing **9** on the other hand, acts as a capacitor which is automatically tuned to the varying frequencies of generator **6** (which is frequency modulated) by means of self-inductance elements **10** and **11** mounted in shunt relation to said capacitor, so as to form a resonant circuit. The windings of self-inductance elements **10** and **11** are mounted on ferro-magnetic cores having low losses at high frequencies and generally constituted by ferrites. In addition to the high frequency which is flowing therethrough, they receive from an external source **12** a slowly varying current serving to "polarize" the cores (slow magnetizing thereof).

The differential (or incremental) permeability of said cores, which is varied by this polarization action, varies the self-inductance of elements **10** and **11** so as to comply constantly with the resonance condition in accordance with the variation of frequency of generator **6**. Capacitors **13**, **14** and **15** serve to separate the high frequency currents from the polarization currents which vary gradually.

FIG. 2 shows the electrical lay-out corresponding to the arrangement of FIG. 1. On said FIG. 2, L designates the variable self-inductance of elements **10** and **11**, C is the capacitance of the system including 1, 2, 9 on the one hand and 5 on the other hand, and *l* is the self-inductance of the high frequency intake conductor **7**.

With such a lay-out, and account being taken of particular requirements (such as the use of harmonics of the frequency of rotation of the particles), it becomes necessary to give higher and higher values to the frequency of generator **6**. In these conditions, several drawbacks are met with, these drawbacks being the more serious as the frequency is higher:

(*a*) Drift tube **5** is acted upon by generator **6**, through conductor **7**, at a low impedance point A (FIG. 2) since the capacitance between tube **5** on the one hand and the whole of parts **1** and **2** and chamber **9** on the other hand, is relatively high and varies in inverse ratio to the linear dimensions on chamber **9**. Chambers having dimensions which correspond to several meters already give rise to substantial capacitances. It follows that the self-inductance of conductor **7** itself has a detrimental action in that it lowers the potential of tube **5** as the frequency of generator **6** is increasing more and more in the course of the acceleration cycle and the particles are getting nearer to the target. At the same time and for the same reasons, there is produced, between the voltage of generator **6** and that of drift tube **5**, a phase difference which it is hardly possible to control;

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(*b*) When the frequency increases, separation between the high frequency currents and the polarization currents by means of capacitors **13**, **14** and **15** becomes more and more difficult and a greater amount of high frequency currents passes to generator **12**, which is undesirable;

(*c*) The arrangement of FIG. 1 makes it necessary to pass the high frequency currents and the core polarization currents through the same windings **10** and **11**. The number of turns of these windings is necessarily small (in order to avoid the so-called "coil effects" at the high frequency, the production of uncontrollable stationary waves, etc.), the polarization source **12** must, most often, supply a high intensity current (several thousands of amperes) under a low voltage. This is a source of constructional difficulties, and generator **12** becomes difficult to control for the production of variable currents. This generator often becomes more complicated and more expensive than the high frequency generator **6** itself.

The object of the present invention is to obviate the drawbacks.

For this purpose, according to the essential feature of my invention, the self-inductanc means, which are to be varied in accordance with the variations of frequency of the high frequency source, are inserted directly between the tubular electrode and the wall of the chamber.

Furthermore, preferably, said electrode subjected to the high frequency is provided with a double wall the external element of which is connected, through at least two hollow conductors surrounded by ferrite rings, with the wall of the chamber, a ferrite polarization winding being housed in the hollow space including said conductors and the inside of the double wall of the electrode. The system constituted by said conductors, their ferrite rings and the polarization winding, constitutes the above mentioned self inductance means.

As, in the circuit including the capacity constituted by said chamber and said electrode and the self-inductances of the hollow conductors, resonance is maintained during the whole acceleration cycle, the system constituted by the accelerating tube and the ferrite surrounded conductors, seen from the high frequency generator, is equivalent to a high resistance. Therefore the influence of the individual inductance of the intake conductor becomes negligible even at high frequencies.

Furthermore, the above indicated arrangement of the polarization winding is such that said winding is wholly protected against the electrical and magnetic inductions of the field existing in the chamber. In other words, the mutual inductance between the polarization circuit and the high frequency circuit is zero.

The hollow conductors surrounded by the ferrite rings may constitute the secondary of a high frequency transformer the primary of which is constituted by some turns of a winding extending around the ferrites and passing between them and the hollow conductors. The primary turns carried by the two ferrite assemblies may be connected in the series together and serve to excite the tubular electrode through a symmetrical high frequency amplifier (push-pull amplifier).

It should be well understood that the arrangement according to my invention is not limited to the use of drift tubes. It applies also in the case of accelerating tubes of another type (for instance of inductive type, where the tube no longer constitutes an element of a capacitor, but an element of a self-inductance unit where, in case of relatively high frequencies, difficulties such as above mentioned arise.

Preferred embodiments of my invention will be hereinafter described with reference to the accompanying drawings, given merely by way of example and in which:

FIG. 3 is an axial sectional view of a first embodiment of my invention.

FIG. 4 shows the lay-out of the high frequency electric circuit corresponding to the construction of FIG. 3.

FIG. 5 is a perspective view of the system of FIG. 3, a portion of the front wall of the chamber being cut away.

FIG. 6 shows a second embodiment of my invention.

In the embodiment of FIGS. 3 to 5, the accelerating tube is a drift tube. This drift tube **16** is insulated from two metallized tubular elements **17** and **18** of the vacuum chamber by means of insulating rings **19** and **20**. The joints between tubular parts **17, 19, 16, 20** and **18** are gas-tight so that a vacuum can be preserved inside said parts, whereas the pressure in chamber **21** is the atmospheric pressure. Said vacuum averages 10^{-5} millimeters of mercury. According to my invention, drift tube **16** has a double wall the external and internal elements of which are designated by reference numerals **22** and **23** respectively. The particles to be accelerated pass through the space limited by the internal wall element **23**.

Tube **16** carries two hollow conductors **24** and **25** extending between the external element **22** of said tube **16** and the wall of chamber **21**. These hollow conductors **24** and **25** have a double function. First they constitute self-inductances for the high frequency circuit and secondly they serve to shield the polarization windings passing therein and a single wire of which is shown at **26** for the sake of simplicity.

Conductors **24** and **25** are surrounded by ferrite rings **27** juxtaposed so as to cover most of the height of said conductors. The differential permeability of these ferrite rings is varied by magnetic polarization thereof by means of winding **26**.

A slowly varying current, supplied by a source **12***a*, flows through said winding **26**. This source **12***a* may be at least partly controlled by a discriminator D responsive to the phase difference between the high frequency current and the voltage supplied to chamber **21** by generator **6***a*. A device of this kind is disclosed in the following document: "The R.F. System of the Bevatron" by C. Norman Winningstad of June 4, 1954 (U.C.R.L. 2,593, Berkeley, California). This generator has one terminal connected to the end portion of said chamber, on the one hand, and its other terminal connected to the outer element **22** of chamber **16** through a conductor **28**, on the other hand.

I may feed to the polarization winding **26** a suitably filtered portion of the current flowing through the electromagnet of the synchrotron. This is particularly advantageous when this current is filtered by means of an electronic device and includes only very weak harmonics in the frequency band which can excite the vibrations of the ionic beam passing along the axis of tube **16**.

Winding **26** runs along the inside of hollow conductors **24** and **25** and in the space between the elements **22** and **23** of the drift tube **16**. Provided that the thickness of said wall elements **22** and **23** and also that of hollow conductors **24** and **25** exceeds the penetration thickness of the flux thereinto (corresponding to the high frequency skin effect), that is to say, for practical purposes, provided that the thickness of wall elements **22, 23, 24** and **25** is greater than one millimeter if these elements are made of aluminum, copper and the like, winding **26** is wholly shielded with respect to the electro-magnetic field existing in chamber **21**, and this is one of the main advantages of my invention.

The high frequency current fed through conductor **28** is distributed between the capacity formed between elements **22—23** on the one hand and elements **17—18—21** on the other hand and two self-inductance elements in parallel, constituted by conductors **24** and **25**, surrounded by ferrite rings **27**. FIG. 4 shows the high frequency electric lay-out corresponding to the construction of FIG. 3. L, *l* and C correspond respectively to the variable self-inductance of conductors **24** and **25**, the individual self-inductance of the intake conductor **28** and the capacity of the system constituted by tube **16** on the one hand and elements **17, 18** and **21** on the other hand.

As the value of the self-inductances depends upon the value of the polarization current, this last mentioned current is made to vary so that, for every value of the high frequency, resonance is obtained by tuning between the whole of the self-inductances and the capacity of the system including the drift tube. Under resonance conditions, the whole of the device between conductor **28** and chamber **21** acts as a high resistance. In this case, the action exerted through conductor **28** takes place at the point B of FIG. 4 where the impedance is maximum. Therefore the value of the separate self-inductance of conductor **28** has very little influence upon the high frequency voltage of acceleration of the particles between elements **17** and **18** and drift tube **16**, and also upon the phase difference between this voltage and that of the high frequency generator. This is an important advantage of the present invention.

It should be noted also that the mean line of the magnetic field in the ferrites which surround conductors **24** and **25** is much shorter than in the case of a conventional construction. This permits a great reduction of the ampere turns of polarization supplied through winding **26** and contributes in simplifying the means which constitute the polarization source.

According to a modification, the hollow conductors **24** and **25** may be made to act as high frequency transformer secondaries, so as to increase the reactance of the tube seen from the high frequency source. In this case, the ferrites are surrounded by some turns (not shown on FIG. 3), extending parallel to conductors **24** and **25**, respectively on the inside and the outside of the ferrite rings **27**. Connection **28** is then dispensed with and replaced by the ends of the primary windings. These primary windings may then be connected in series together and be fed through a symmetrical high frequency source with respect to the ground.

This source may for instance be output of a push-pull amplifier, which is particularly interesting for various reasons (elimination of even harmonics, high efficiency). In opposition with the usual arrangements including a conventional drift tube, the arrangement according to my invention may therefore be fed from a symmetrical amplifier.

In the other embodiment of my invention, illustrated by FIG. 6, the accelerating tube is still a drift tube, but the self-inductance means are constituted by stationary wave coaxial cables packed wth ferrite rings.

The ferrite stacks are lined on hte outside with conductor tube forming the external armature of the coaxial cables. The length of these cables is such that a transverse stationary wave takes birth therein and contributes in increasing the input inductance of the columns. Furthermore, the polarization current is placed under control of the frequency in such manner that the "electric length" of the coaxial cables and their natural wave-length remain constant within a large band of frequencies.

On FIG. 6, I have shown hollow conductors **29** and

30 surrounded by coaxial cables 31 and 32 filled with ferrite rings 33. With a loing sheath of ferrite rings of particularly small dimensions, this arrangement permits of obtaining high inductances and may constitute a substantial economy.

The construction of FIG. 6 is little different from that of FIG. 3, but in this case the elements 29 and 30 have a height such that the electric length of the coaxial cables filled with ferrite rings is close to 90°. These cables, short-circuited at their end 34, cause the formation of a purely transverse stationary wave working close to quarter wave conditions.

This can easily be obtained, even at relatively low frequencies, averaging one megacycle per second, when the wavelength in air is close to 300 meters. Therefore it is still more easily obtained at higher frequencies. As a matter of fact, if the initial permeability and the permitivity of the ferrites that are used average 900 and 16 respectively (case of some ferrites found on the market), their "refractive index" is $\sqrt{900 \cdot 16}$, that is to say 120 and the wavelength in the ferrites will be 120 times shorter than in air (that is to say 250 cm. for the megacycle frequency). A coaxial cable with ferrites having a length of 62 cm. already constitutes a quarter wave line. As this line is provided at its end with a capacity (one half of that existing between the drift tube, the two portions of the vacuum tube and the earth), the length of every coaxial cable must be lower than one quarter of a wavelength or an odd multiple thereof.

The characteristic impedance and the phase velocity in the coaxial cable may be adjusted by providing annular air spaces between the ferrite rings and the metallic tubes which form the armatures of the coaxial cable. It may be domonstrated that these annular spaces contribute in reducing the dielectric losses and magnetic losses due to (hysteresis carrying effect, Foucault currents). In opposition with this, they increase the phase velocity and make the cables less easy to saturate. This is due to the fact that the permeability of these air spaces does not depend upon polarization and their presence requires a supplement of polarizing ampere-turns. This is but a small counterpart to the advantage of the arrangement according to my invention, since said ampere-turns may be created by a low amperage in a coil having a great number of turns, instead of being obtained, as in the systems used up to now, by means of a very high current flowing through a small number of turns.

In the case of particularly high frequencies, it may be advantageous in some cases to give the ferrite cables a length higher than that of one quarter of a wavelength but still somewhat lower than an odd number quarters of a wavelength. These cables are still short-circuited at their end opposed to that connected with the drift tube and thus have the properties of the self-inductance with respect to the drift tube.

On FIG. 6, the conductors are constituted by thin tubes 29 and 30 and they form the internal conductors of the coaxial cables. The ferrites that surround them are shown at 33. The inner conductors 29 and 30 and the outer conductors 35 and 36 are short-circuited at the end 34. Short-circuiting ring 34 is provided with a hole for the passage of the wires 37 of the polarization winding. This winding is, from the high frequency point of view, at the ground potential.

It can be shown that, by giving the polarization current a law of variation such that the product of the incremental permeability (thus controlled) by the square of the frequency remains constant, the cables contain a stationary wave the length of which becomes independent of the frequency. If every cable works for instance as a line corresponding to one fifth of wavelength at the lowest frequency of the high frequency generator, it will keep working in this way for the whole spectrum of this generator and will maintain the properties of a self-inductance within a range of frequencies which may vary from one to ten. This may seem extraordinary but is explained by the fact that the frequency depends upon the refractive index of the ferrites.

In a modification of this construction, the coaxial cables are (or only one of them is) provided with connections 38 and 39 passing between the ferrite rings 33 and extending to the conductors 29 and 30. The input connection 40 can then be dispensed with and the high frequency generator is connected on the one hand to conductors 38 and 39 interconnected with each other, and on the other hand to the earth (wall 41). In this case, drift tube 42 is fed with high frequency through cables which act as transformers, thus permitting a better utilization of a given electronic generator. With such an arrangement, I may make use of only one of the connections 38 and 39, the other coaxial cable, which is not provided with an intermediate current connection, then acting as a shock coil.

In a general manner, while I have, in the above description, disclosed what I deem to be practical and efficient embodiments of my invention, it should be well understood that I do not wish to be limited thereto as there might be changes made in the arrangement, disposition and form of parts without departing from the principle of the present invention as comprehended within the scope of the accompanying claims.

What I claim is:

1. In a particle accelerator, the combination of a tubular drift tube, a casing made of a conductive material surrounding said drift tube, out of contact therewith, two tubular elements made of a conductive material in coaxial line with said drift tube at either end thereof and insulated therefrom, said tubular elements being in direct electric contact with said casing, the cylindrical space for the travel of particles that extends through said tubular elements and said drift tube being evacuated, variable self-inductance means directly interposed between said drift tube and the wall of said casing, the whole of said drift tube, casing, tubular elements and variable self-inductance means forming an oscillatory circuit, a source of cyclically varying high frequency voltage, means, distinct from said self-inductance means, for connecting one terminal of said source with said casing, means, distinct from said self-inductance means, for connecting the other terminal of said source with said drift tube, and means responsive to the cyclical variation of frequency of said source for automatically varying the self-inductance of said self-inductance means to maintain resonance in said circuit.

2. In a particle accelerator, the combination of a tubular drift tube having a double wall over at least a portion of its length, a casing made of a conductive material surrounding said drift tube, out of contact therewith, two tubular elements made of a conductive material in coaxial line with said drift tube at either end thereof and insulated therefrom, said tubular elements being in direct electric contact with said casing, the cylindrical space for the travel of particles that extends through said tubular elements and said drift tube being evacuated, two hollow conductors at a distance from each other directly interposed between said drift tube and the wall of said casing, juxtaposed ferrite rings surrounding said conductors, the whole of said drift tube, casing, tubular elements, hollow conductors and ferrite rings forming an oscillatory circuit, a source of cyclically varying high frequency voltage, coupled with said circuit, and means, including a winding extending inside said hollow conductors and between the two wall elements of the double wall of said drift tube in the portion thereof located between said hollow conductors, for varying the self-inductance of said circuit in accordance with the frequency of said source to maintain resonance in said circuit.

3. A particle accelerator according to claim 2 further including around said hollow conductors, conductor tubes forming the external portions of coaxial cables short-circuited with said hollow conductors at their end farther from the drift tube.

4. A particle accelerator according to claim 3 in which said coaxial cables have a length such that a transverse stationary wave is produced therein and increases the self-inductance in these cables.

5. In a particle accelerator, the combination of a tubular drift tube, a casing made of a conductive material surrounding said drift tube, out of contact therewith, two tubular elements made of a conductive material in coaxial line with said drift tube at either end thereof and insulated therefrom, said tubular elements being in direct electric contact with said casing, the cylindrical space for the travel of particles that extends through said tubular elements and said drift tube being evacuated, variable self-inductance means directly interposed between said drift tube and the wall of said casing, the whole of said drift tube, casing, tubular elements and variable self-inductance means forming an oscillatory circuit, a source of cyclically varying high frequency voltage, means for coupling the terminals of said source with said casing and said drift tube, respectively, across said self-inductance means, the portion of said coupling means which has a substantial inductance being on the other side of said self-inductance means from said drift tube and said casing and means

responsive to the cyclical variation of frequency of said source for automatically varying the self-inductance of said self-inductance means to maintain resonance in said circuit.

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