June 30, 1964 R. H. RHEAUME ETAL 3,139,591

AMPLIFIER APPARATUS FOR HIGH ENERGY PARTICLE ACCELERATORS

Filed Jan. 16, 1961 3 Sheets-Sheet 1

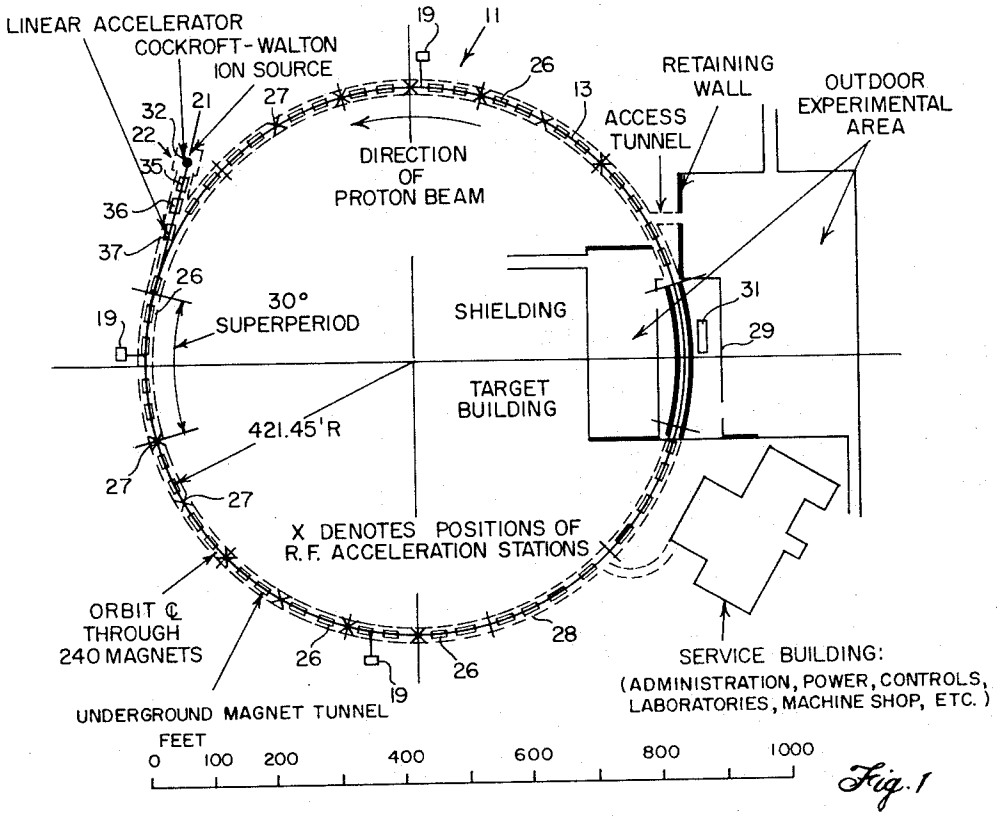


Fig. 1

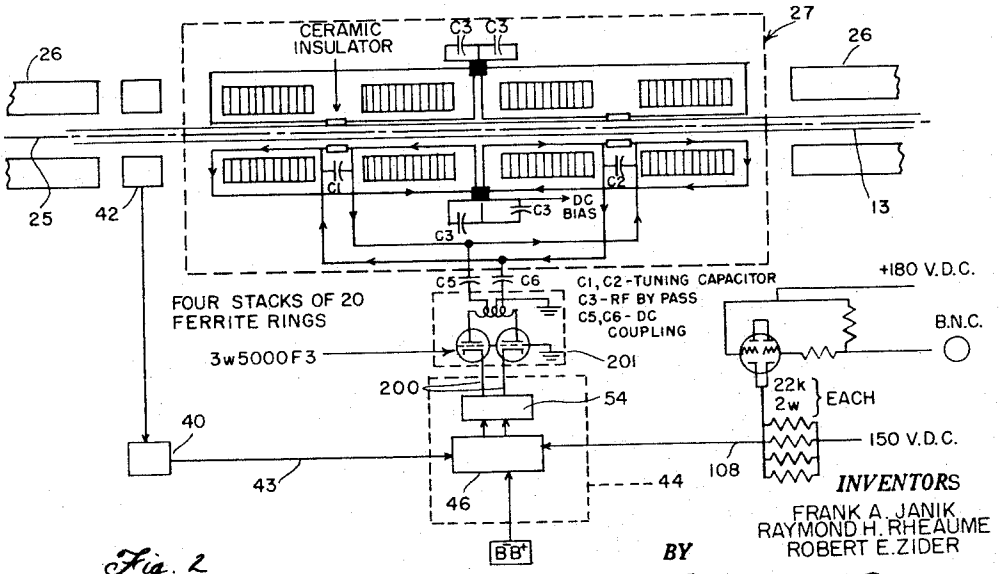


Fig. 2

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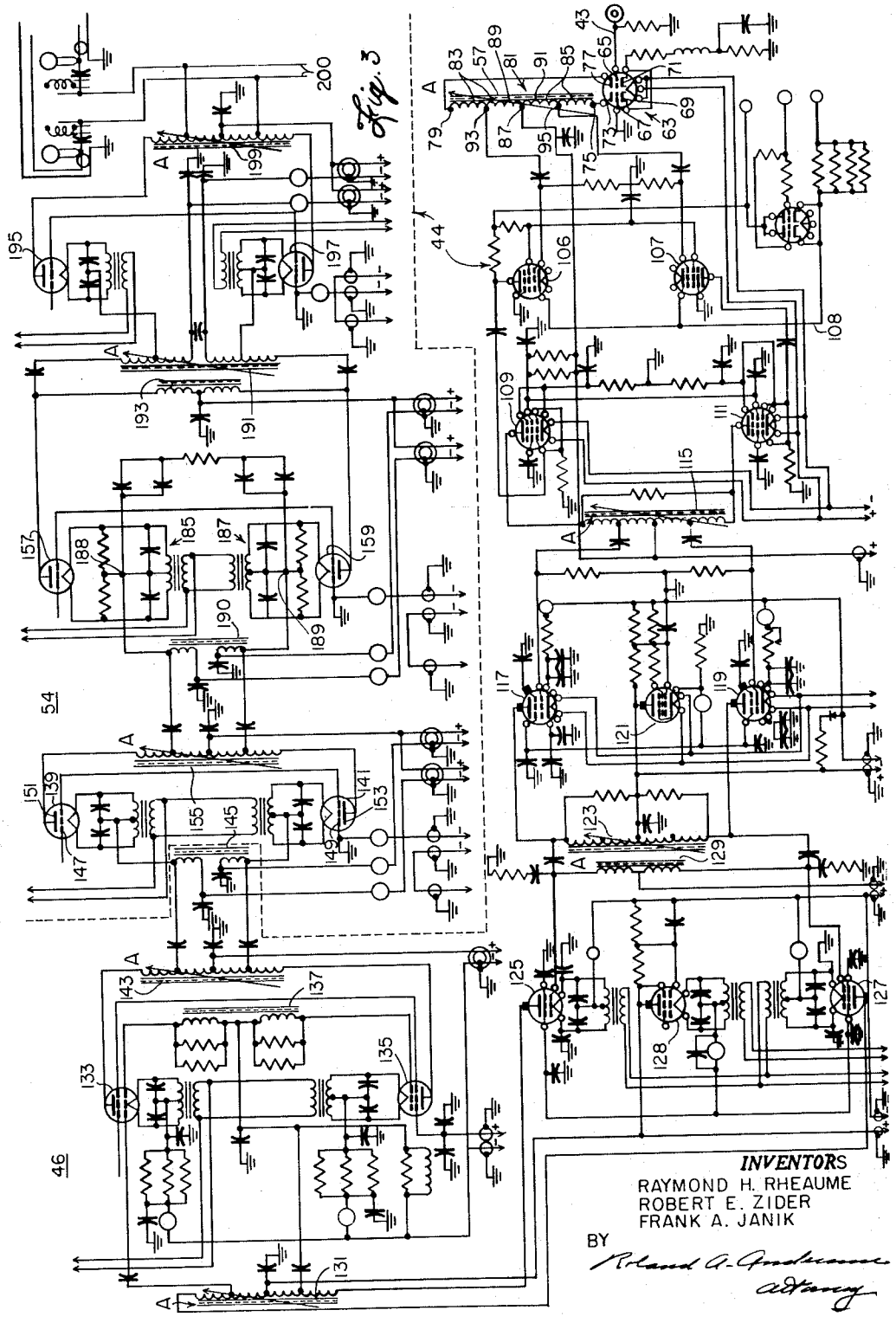


Fig. 3

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Filed Jan. 16, 1961 3 Sheets-Sheet 3

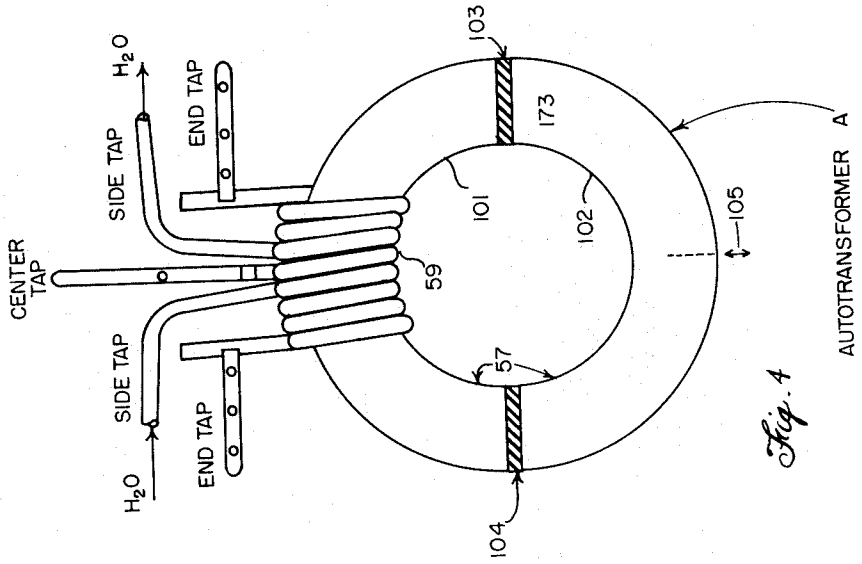


Fig. 4

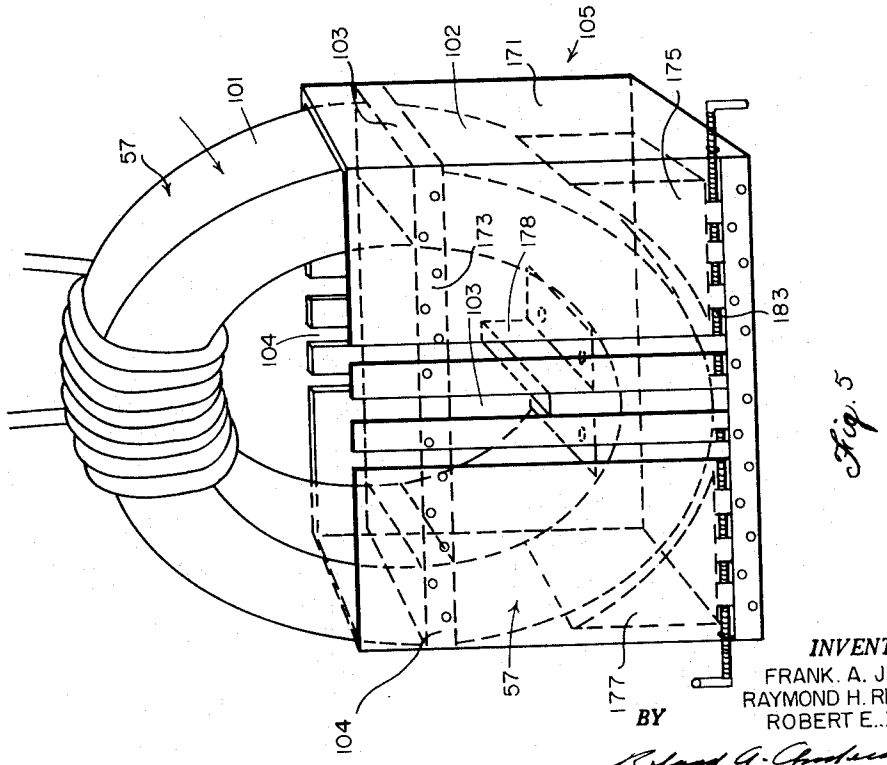


Fig. 5

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United States Patent Office 3,139,591 Patented June 30, 1964

3,139,591

AMPLIFIER APPARATUS FOR HIGH ENERGY PARTICLE ACCELERATORS

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Filed Jan. 16, 1961, Ser. No. 83,125
10 Claims. (Cl. 330—119)

This inventiotn relates to amplifiers and more particularly to the amplification of power in accelerators capable of accelerating atomic particles to high energy levels.

It has been discovered that atomic particles can be accelerated to high energy levels and directed at target atoms to produce momentarily many new particles such as mesons which are of intermediate masses between the electron and proton. Also, anti-matter or antiparticles have been produced in such a way and it has been believed that the production of such particles and materials may hold the key to the basic structure of the nucleons which make up an atomic nuclei.

It has been found that cosmic radiation has produced such particles as mesons but the mesons that have been studied from this source have been in existence for brief periods of time measured in millionths of a second or less. Moreover, the source of primary cosmic rays in space has made it difficult to study the mesons produced thereby. It has thus been universally recognized that high energy accelerators have been necessary to produce the mentioned particles and materials under controlled conditions.

An early high energy particle accelerator produced particles having up to about 80,000 electron volts energy. Later similar devices grew successively larger until multi-million electron volt particle energies were achieved. Still later devices, such as the Brookhaven Cosmotron and the CERN Synchrotron, have achieved multi-billion electron volt particle energies.

Conveniently, the high energy accelerators known heretofore have employed an evacuated hollow substantially torus shaped endless tube and particles have been accelerated therein by at least one radio-frequency accelerating means placed around the tube at an accelerating gap in a confining magnet. The magnet substantially encircled the tube along most of the length of the tube and has been adapted to guide the particles around the tube as the particles have been accelerated. Advantageously, the particles have been injected into the tube at relatively low energy levels and a radio-frequency low power command signal has been amplified and applied to the accelerating means to produce a travelling wave of radio-frequency electrical field that travelled with the speed of the injected particles as the particles orbited past the accelerating means. Thereupon the frequency of the command signal and signal amplified therefrom have been increased over a broad band of video-frequencies to increase the speed of the wave and the speed of the particles as they orbited past the accelerating means. For amplifying the command signal a radio-frequency amplifier has been required, that has been capable of good transient response and the production of broad band, high power, video frequency signals of pure wave form.

Conventional audio-frequency amplifiers known heretofore have been inadequate for amplifying the command signal and supplying the accelerating means of high energy accelerators. As an illustration the audio-frequency amplifiers known heretofore have not been capable of supplying high enough power levels (e.g. up to about 80 kilowatts peak power). Conventional high power radio-frequency amplifiers have also been inadequate. As an illustration, they have not been capable of supplying a broad band of video-frequency signals (i.e. frequency from 1 megacycle per second to 5 megacycles per second) at such a high power level. This has been true particularly with amplifiers having air-core solenoid interstage coupling networks. Also conventional amplifiers have been complicated and expensive. As an illustration, grounded cathode amplifiers have had a large number of expensive and large vacuum tubes, have required high direct current plate power input and have been subject to parasitic oscillations and undesirable instabilities such that complicated and expensive neutralization and series and shunt peaking have been required.

This invention contemplates the combination, in a high energy particle accelerator, comprising a multi-stage amplifier having low power push-pull grounded cathode operated tetrodes, high power push-pull, grounded-grid operated triodes, and interstage autotransformers for coupling the stages of said amplifier, comprising split ring-shaped ferrite cores formed with gaps that bisect said cores normal to the plane of said cores, said ferrite having a high permeability, a low power loss factor, and center-tapped voltage-step-down windings tightly encircling said cores and extending equal distances from a point on each of said cores equal distances from said gaps with small spacing between said windings.

The above and further novel features of this invention will appear more fully from the following detailed description when the same is read in connection with the accompanying drawings. It is to be expressly understood, however, that the drawings are not intended as a definition of the invention but are for the purpose of illustration only.

FIG. 1 is a partial top view of the high energy accelerator of this invention.

FIG. 2 is a partial schematic view of the energizing and control means for the apparatus of FIG. 1.

FIG. 3 is a detailed schematic of the amplifying means of FIG. 2.

FIG. 4 is a partial isometric view of the interstage autotransformer of FIG. 3.

FIG. 5 is a partial isometric view of the tuning means for the autotransformer of FIG. 4.

Referring to FIG. 1, accelerator **11** comprises generally non-magnetic endless tube **13**, means **19** for evacuating tube **13**, a particle source **21**, means **22** for accelerating and injecting energetic nuclear particles, advantageously protons, into tube **13**, magnetic means **26** partially shown schematically for ease of explanation for guiding the particles around tube **13**, particle accelerating means **27** capable of accelerating the particles to high speeds and high energies, a stable support **28** for the mentioned elements, and a target structure **29** where target atoms are bombarded by particles **25** after they are accelerated to high energies to produce reactant particles such as mesons, hyperons, neutrons, protons, anti-nucleons, and other products such as those mentioned above. Auxiliary

equipment for analyzing the reactants includes means 31 in the target building 29 such as bubble chambers photographic emulsions, and counters such as scintillation counters.

Advantageously, the particle source 21 has a small chamber filled with hydrogen gas and an electrical arc. The arc discharge ionizes the hydrogen by tearing electrons off the hydrogen atoms and produces hydrogen nuclei or protons with positive charges. The protons pass through a small aperture in the mentioned chamber and into means 22 for accelerating the protons.

Accelerating means 22 advantageously includes a pre-injector 32 comprising a conventional Cockcroft-Walton type generator in which a five stage voltage multiplier operating from a direct current transformer, builds up large potential differences and applies them across an evacuated accelerating tube so that protons travelling down the tube receive an amount of energy equivalent to the potential difference across the tube. The protons receive an energy of about 75 thousand electron volts and pass into a buncher cavity 35.

The buncher cavity 35 receives the accelerated protons from the pre-injector 32 and pre-bunches the protons received thereby to match the entrance requirements of the injector-accelerator 36. The accelerator 36 is conventional and advantageously is like the one described in United States Patent 2,874,326, comprising a radio-frequency structure approximately ninety centimeters in diameter, and thirty-three meters long, and twenty-four drift tubes through which the proton beam from the pre-injector 32 passes. Pulsed quadrupole magnets (not shown) located inside the drift tubes focus the proton beam and a 200 megacycle pulsed radio frequency source having a peak power of about five megawatts, a width of about 200 microseconds and a repetition rate of five peaks per second excites the accelerator 36 to increase the proton beam therein to about fifty million electron volts.

Thereupon a conventional debuncher 37, following the accelerator 36, reduces the energy spread of the proton beam and an injection system having a deflector, focuser and monitor inject the beam into tube 13 at closely controlled conditions, for example, at an energy of fifty million electron volts ± 0.2 percent at a speed of about one-third the velocity of light, at a pulse width of seven microseconds, at an angular spread less than $\pm$ two milli radians and at a proton content of about 10^{10}.

Magnetic means 26 bend the particles 23 into circular paths around tube 13 and prevents the particles from hitting the walls of tube 13. Advantageously, magnetic means 26 strongly focuses the beam of particles 25 in one plane and simultaneously defocuses in the other plane. This system, known as the alternating gradient synchrotron system, has been shown to yield a net strong focusing force and has required only about 4,000 tons of steel for the magnets. When the particles are injected into tube 13 the magnetic field produced by magnetic means 26 is about 120 gauss. The magnets thereof provide a field of uniform azimuth around tube 13, having a gradient of about 10% per inch, and maintain their field patterns from 120 gauss to about 13,000 gauss. Since the latter requirement cannot be met sufficiently well without correction auxiliary correcting magnets are included at sixty points around tube 13. Apparatus like magnetic means 26 and its auxiliaries is described in "The Brookhaven Alternating Gradient Synchrotron" by R. A. Beth and C. Lasky, in the December 5, 1958 issue of Science.

The particles injected into tube 13 and guided by magnetic means 26, are accelerated to energies as high as over thirty billion electron volts and to speeds of up to a few tenths of a percent less than the speed of light. To this end, there are advantageously twelve radio-frequency accelerating stations or means 27 at spaced intervals around tube 13. Each accelerating station 27 has a double tunable radio-frequency cavity that imposes accelerating electric forces on proton bunches at each passage of a station by means of a pair of accelerating gaps about four feet apart in the wall of tube 13. At each passage, each station advantageously accelerates the protons 8,000 volts and for this purpose high total peak radio-frequency amperes are required by accelerating means 27. As the energy of the particles increases the velocity of the particles increases rapidly at first and then more slowly as the protons approach the velocity of light. Due to the velocity increase, the transit time of each particle around tube 13 will decrease. Thus the frequency supplied to the accelerating stations 27 must be increased so that the protons will arrive at the gaps in the right phase to experience a forward accelerating impulse. Because the accelerating means 27 accelerate the particles from less than one-third of the velocity of light to within a fraction of a tenth of one percent of light velocity the frequency of the accelerating must increase over a broad range of frequencies, e.g., from 1.4 to 4.46 megacycles per second.

Referring to FIG. 2, the high power, broad band of video-frequencies required by accelerating means 27 must be regulated in phase and amplitude in order that the energization of the accelerating means 27 is synchronized with the movement of the particles in tube 13. To this end, a suitable low power, broad-band, video-frequency command signal source connected to an induction pick-up 42 around tube 13 supplies in cable 43 a command signal of the proper phase and amplitude that must be boosted in power level and supplied to accelerating means 27 while maintaining a substantially linear (coaxial-cable-like) amplitude and phase response to the input command signal in cable 43. For example, a charge is induced in pick-up 42 every time a bunch of protons passes the pick-up and this charge is supplied as a 1 watt, 2 volt, 1.4 to 4.46 megacycles per second command input in cable 43 properly synchronized in phase and amplitude e.g. by suitable lead length compensating means 40 when several leads are employed. The command signal must be amplified to about eighty peak kilowatts, 120 peak amperes and 1400 volts while maintaining a wave form that corresponds in phase and amplitude substantially perfectly with the input command signal. Then when the amplified signal is supplied to accelerating means 27 and the particles in tube 13 pass thereby, the accelerating means 27 bunch the particles in tube 13 and impart progressively greater and greater energies to the particles each time they pass an accelerating station 27.

Conventional amplifiers known heretofore have not been capable of supplying high enough power levels, have not been capable of supplying a broad-range of video-frequency signals, have been unduly inefficient, expensive, or complicated, have required a large number of expensive and large vacuum tubes, high direct plate power input and have been subject to parasitic oscillations and undesirable instabilities such that complicated and expensive neutralization and series and shunt peaking have been required.

Referring now to FIG. 3, this invention provides in high energy particle accelerator 11 the combination comprising a high power output amplifier 44 having push-pull grounded cathode connected tetrodes in a first section 46, push-pull connected triodes having grounded-grids in a second section 54, and interstage autotransformers A for coupling the stages of said amplifier 44, comprising a split-ring-shaped ferrite core forming gaps in a plane that bisects said core normal to said core and having a high permeability, a high quality factor and tightly wound, closely-spaced, center-tapped voltage-step-down windings extending equal distances from a point on said core equal distances from said gaps.

The first section 46 of amplifier 44 takes a low power, broad-band, video-frequency, single ended command input such as described above, in coaxial cable 43 and converts the single ended input into a double-ended push-

pull output balanced with respect to ground while boosting the power of the input and maintaining linear phase and amplitude response therewith. To this end coaxial cable **43** carries the input to a phase invertor **63** (FIG. 3) such as provided by a 12BH7A tube, having a grid **65** connected to input cable **43**. Advantageously, grid **65** is also grounded through a suitable resistor and an opposite grid **67** is also connected with ground. Cathodes **69** and **71** of invertor **63** connect with ground through a suitable resistor, coil and capacitor. Plate **73** connects with end tap **75** and plate **77** connects with opposite end tap **79** of autotransformer **81**.

In order to preserve the waveform of the command signal in this amplifier **44**, not only must the relative amplitude of the various frequency components be controlled, but the relative phase deviations of the various frequency components must be minimized and held essentially linear with frequency throughout the frequency band of interest. If there is substantial departure from linearity in phase vs. frequency response, the time of propagation of all frequency components through an amplifier will differ appreciably and synchrotron phase control difficulties will ensue. It is significant that for the range of frequencies which encompass a phase deviation from about 10 degrees leading to 20 degrees lagging, where the amplifier **44** and ferrite-cored autotransformer **81** of this invention are employed, even at high power levels, the phase deviation is essentially linear with frequency. In contrast, the extent of the range of phase deviation is a full 75 degrees leading to a full 75 degrees lagging when conventional air core autotransformers are used for the range of frequencies contemplated by this invention and the phase deviation is not linear with frequency. Thus, when waveshape fidelity, as determined by freedom from distortion, is required over a broad-band of frequencies, the air core autotransformer is not satisfactory.

The mentioned autotransformer **81** has high coupling coefficients. For example, the side-to-side coupling coefficient is 0.94 and the primary to secondary coupling coefficient is 0.98. Such high coupling coefficients have not been possible in autotransformers known heretofore, and are provided in accordance with the novel design and configuration of the autotransformer of this invention. To this end, autotransformer **81** is a center-tapped voltage step down transformer having primary windings **83** and **85** with a common center tap **87** and secondary windings **89** and **91** with respective side taps **93** and **95**. The windings have a suitable insulation such as a polyurethane insulation, minimum spacing between their coils, and low series leakage inductance, i.e., minimum voltage drop, without insulation break down at high frequencies or shunting at low frequencies. The windings are tightly wound on a first semi-circular section **101** (FIG. 4) of ferrite core **57** having a second semi-circular section **102** spaced from the first section **101** so as to form opposite gaps **103** and **104** equally spaced from the mentioned windings. Advantageously the gaps **103** and **104** are disposed 180° apart and normal to the plane of the vertical axis of core **57** so as to bisect the core and an adjustment means **105** equally adjusts the spacing therein. The gaps are not for impedance stability but are for tuning and to this end the windings have sufficient impedance so that varying the spacing of the gaps changes the autotransformer inductance. The inductance is changed in this manner without essentially changing the side-to-side and primary-to-secondary coupling coefficients.

The cross section of core **57** has a short vertical axis and a long horizontal axis normal to the center of the vertical axis to provide maximum ferrite essentially at a constant radius. A suitable cross-section that is easy to fabricate is a rectangular cross-section, but an elliptical cross section is also acceptable.

Conventional magnetic core materials with low resistivity, such as iron, steel, Alnico, molybdenum permalloy, permalloy, permivar, or iron powder imbedded in an insulating matrix are not suitable for core **57**. Likewise, non-magnetic materials, such as non-magnetic metal, plastic, ceramic, glass, and air or a combination thereof are not suitable core materials. Advantageously, the ferrite core **57** of this invention has a high radio-frequency permeability. For example, the permeability must be over 300 which permeability is in a range that is commercially available. When the radio-frequency permeability is measured as a constant times the ratio of the flux density to the magnetizing force and expressed as a value compared with the permeability of air, the permeability of the ferrite material suitable for the cores of this invention should be greater than 300. Although higher permeability is available, physical limitations for adjustment of gaps **103** and **104** make it undesirable to have permeabilities that are too high. Also, higher permeabilities in the range of 3000 to 4000 would offer slight incremental advantage over currently available ferrite having permeabilities of 300 to 400.

An additional requisite for the ferrite is a high quality factor or Q value of 20 or over, i.e., low radio-frequency losses and a low power loss factor. A Q value of 2 or lower creates severe heat losses in the ferrite and is inoperable in accordance with this invention. A ferrite having a Q value of 10 is still undesirable from this standpoint. However, with a ferrite having a Q of 20 or over, the ferrite can be cooled easily, e.g., with a 100 c.f.m. air blower even when the autotransformer is passing 80 kilowatts of video-frequency power. An advantageous ferrite for core **57** is the Ferroxcube IV H brand of ferrite made by Philips, Eindhoven.

The described variable-gap ferrite core autotransformer **81** has the advantage of a higher current gain and impedance match, for example between a high impedance of a driving anode and a low impedance of a driven cathode, than have been available heretofore. Thus, the autotransformer of this invention unexpectedly makes possible the advantageous use of smaller multi-grid tubes for amplifying video-frequency energy having smaller input energy and broader band widths. The smaller tubes offer more reliability, less harmonics in the output wave form and less parasitic oscillation. The autotransformer of this invention also is compact, easy to fabricate and requires less elaborate shielding than the autotransformers known heretofore, particularly air core autotransformers. This results from the fact that the tight windings and remoteness of the windings from gaps insures that the electromagnetic field is essentially enclosed within the ferrite core of the autotransformer of this invention. Consequently, the autotransformer of this invention makes possible a simple, inexpensive, and effective apparatus in combination with a multi-stage, broad band, video-frequency amplifier, as will be understood in more detail from the following.

As shown in FIG. 3 the output side of taps **93** and **95** of autotransformer **81** energize push-pull, multi-grid tubes **106** and **107** balanced to ground. Side taps **93** and **95** connect respectively with control grids of tubes **106** and **107** having suppressor grids that are grounded. The cathodes of the tubes are connected with an input signal through a line **108** having a suitable direct current source shown in part. The output of tubes **106** and **107** increases or decreases in power in a manner corresponding to the command of the input signal therefor from autotransformer **81** which in turn corresponds with the output from tube **63** and the input to tube **63** from line **43**. Thereupon the output of tubes **106** and **107** energizes push-pull, multi-grid tubes **109** and **111** balanced to ground through their screen grids and having low impedance inputs. Tubes **109** and **111** are advantageously class A1 operated 6CL6 pentodes having a high impedance output, with substantially linear amplitude and phase response to the input to tubes **109** and **111**.

The mentioned output of tubes **109** and **111** connects through an autotransformer **115**, like the autotransformer

81 with low impedance control grids of two push-pull, multi-grid power amplifying tubes 117 and 119 balanced to ground through their screen grids. Tubes 117 and 119 are advantageously class A1 operated type 4X250 B tetrodes having indirectly heated cathodes and suitable B+ and B— energy sources (not shown). Advantageously, tubes 117 and 119 have a suitable cathode follower screen grid potential feed such as provided by an 807 pentode 121. Tubes 117 and 119 produce a high impedance output having substantially linear amplitude and phase response with the input to tubes 117 and 119.

The outputs from tubes 117 and 119 connect through an interstage autotransformer 123, like the autotransformers described above, with low impedance control grids of two push-pull, multi-grid, power amplifying tubes 125 and 127. Tubes 125 and 127 are class A1 operated, 4–1000 A tetrodes having their cathodes directly heated by suitable high leakage inductance filament transformers. The filament transformers protect the free hung filaments of the tubes from collapse due to cold current inrush and have suitable power sources (not shown). Tubes 125 and 127 also have a suitable cathode follower screen grid potential feed provided by a 4–1000 A tetrode 128. Also, a ferrite cored center-tapped choke 129 advantageously cross-couples the inputs to the control grids of tubes 125 and 127 to clean up the wave form of the inputs by minimizing even-order harmonics, while simultaneously introducing D.C. grid bias potential. To this end, the windings of the choke 129 have closely spaced tightly wound turns on an annular ferrite core having a high permeability and a low power loss factor like the cores of the autotransformers described above. Thus the ferrite core of choke 129 is the same as the ferrite of the autotransformers described above and has a permeability of over 300 and a high Q of over 20.

The plates of tubes 125 and 127 have a high impedance and their output corresponds linearly with the input to their grids. The plates of tubes 125 and 127 connect through an interstage autotransformer 131, like the ones described above, with low impedance control grids of two push-pull, multi-grid, power-amplifying tubes 133 and 135. The tubes 133 and 135 are class AB2 operated standard commercial 4CW 10,000 A tetrodes having a suitable B+ power source (not shown) for their screen grids, and their cathodes are directly heated by filament transformers like those described above. A ferrite cored centertapped choke 137 like choke 129 connects the control grids of the tubes 133 and 135 and plates of the tubes 135 and 133 provide a high impedance output having an amplitude and phase corresponding linearly with the input to tubes 133 and 135.

The described multi-grid amplifying tubes of the first amplifying section 46 of amplifier 44 have the advantage that they are readily available, relatively inexpensive, durable and reliable at low power levels compared with the present low power triodes. Also the described multi-grid tubes act as a phase buffer to keep output cable termination phase perturbations from tailing back from the grounded grid tubes in the second section of amplifier 44 described in more detail hereinafter. The described autotransformers have the advantage that the tubes connected therewith have enhanced gain-band width capabilities at video frequencies, smaller and fewer tubes can be used therewith than in conventional amplifiers, and the interstage circuitry thereof provides substantially linear phase change with frequency with simpler interstage circuitry than in the amplifiers known heretofore. The autotransformer of this invention also provides means for making rapid and effective changes in inductance tuning in the autotransformers of this invention and their associated circuits without appreciably affecting the coupling coefficients of the autotransformers. Also high coupling coefficients can be obtained without disproportionately increasing the distributed capacitance.

The high impedance outputs from the plates of tetrodes 133 and 135 energize low impedance cathodes of two push-pull class B2 operated grounded-grid standard commercial power triodes 139 and 141 forming the beginning of the amplifying section 54. In this stage the high cross coupling coefficient provided by the ferrite autotransformer of this invention affords economy of high voltage plate D.C. input current and minimum anode dissipation without appreciably deteriorating the radio-frequency wave form from that of class A operation. To this end, a ferrite cored autotransformer 143, like the autotransformers described above, is interposed between the output plates of tetrodes 133 and 135 and the input cathodes of triodes 139 and 141. Also, two filament transformers like those described above, having a suitable power source (not shown) are interposed between the output side taps of the autotransformer 143 and the input cathodes of triodes 139 and 141. Additionally, a split ferrite cored cathode choke 145, like the chokes described above, in other respects, connects the push-pull outputs of the autotransformer 143 to maintain a clean wave form input to the mentioned filament transformers connected to the cathodes of triodes 139 and 141. Thus, it is understood that the input to the cathodes of triodes 139 and 141, and amplifying section 54 is a double-ended, push-pull, broad-band, video-frequency, relatively low impedance, balanced-to-ground, input signal of intermediate power level. It is also understood that this input signal to triodes 139 and 141 corresponds substantially linearly in amplitude and phase to the relatively low power input command signal in coaxial cable 43, the input command source for the first section 46 of amplifier 44 and thus the input to triodes 139 and 141 is also an input command signal.

Triodes 139 and 141 have their grids 147 and 149 connected to each other and locked to ground. The class B2 push-pull grounded grid operation herein was not possible heretofore with interstage air cored autotransformers or with other interstage coupling such as conventional series and shunt peaking. It is achieved in accordance with this invention with no grid bias source required because of the combination with the described ferrite autotransformer of this invention. The triodes 139 and 141 are advantageously of the ML–6424 type. The triodes 139 and 141 have high impedance output plates 151 and 153 connected through end taps of a center-tapped ferrite cored interstage autotransformer 155, like the ones described above, with subsequent low impedances provided by cathodes of stable ground-grid, push-pull connected, class B2 operated triodes 157 and 159. The center tap of the autotransformer is radio frequency grounded thru a suitable capacitor and has a suitable B+ source (not shown). This system in combination with the multi-grid tubes of section 46 described above, which act as buffers to keep output cable termination phase perturbations from tailing back from the triodes has the advantage of great stability and simple, low cost, reliable circuitry with readily available standard components for high power output, broad-band, video-frequency applications where good transient response is essential, such as in high energy accelerator 11.

In the present, as well as the succeeding amplification stages, amplification takes place in interstage, ferrite-cored voltage step-down autotransformers which are like those described above. The autotransformers of the present and succeeding stages have typically a 3:1 voltage step-down ratio in the same configuration as the above-described autotransformer windings. It is understood that succeeding autotransformers increase progressively in size and have larger tuning means. Additionally, the coils of at least the last autotransformer have cooling means such as are provided by hollow windings having means (not shown) for circulating a cooling fluid

therethrough. This is to offset skin effect heating in the copper coils rather than for cooling the ferrite.

The core of autotransformer **155** is like the autotransformer cores described above and in this regard is made of a ferrite that must possess high radio-frequency permeability and low radio-frequency losses, i.e., a high Q or quality factor. The form of the cores in the present and upper amplification stages is the same as the previously described autotransformers. Thus the autotransformers herein have split-ring, shaped cores forming gaps which bisect the core in a plane normal to the vertical axis of the core. The cores herein, additionally advantageously comprise a plurality of closely stacked coaxially adjacent semi-circular segments separated by 0.15 polytetrafluoroethylene wafers that protect the segments from the high turn-to-turn voltage and high transient voltage in the autotransformers. Advantageously, an insulating tape, such as polyester tape, having high mechanical and electrical insulating properties, ties six or more of the segments together, to form U-shaped semi-circular sections **101** and **102**.

The segments of this and later stages are large and the tuning means **105** therefor is substantially the same as the tuning means for the previously described autotransformers, and opens and closes the autotransformer gaps equally. Particularly, the tuning means **105** for the autotransformers of this and the next stages comprise a rectangular box shaped linen base phenolic housing **171** held together by nylon screws at its sides. A rectangular phenolic block **173** fastened inside of the housing near its top supports one of the semi-circular sections. The other section rests adjacent to the bottom inside of the housing. Phenolic vice jaws **175** and **177** on the bottom inside of housing **171** support the second section **102** and holds the open ends thereof facing upwardly adjacent the downwardly facing open ends of section **101** to form gaps **103** and **104**. Brass left and right threaded screw **183** rotates in a housing **171** and threads in opposite directions into vice jaw **175** and **177** so that rotation of the screw **183** in one direction, closes the jaws to raise second section **102** and reduce the distance across gaps **103** and **104** between sections **101** and **102**. Rotation of screw **183** in the opposite direction opens jaws **175** and **177** so that section **102** falls to increase the opening of the gaps. A pheolic key **178** secured to the inside curved portion of the second section and fitted into slots **184** on opposite sides of housing **171** guides the up and down movement of section **102** so as to maintain a spacing in gap **103** that always equals the spacing in gap **104**. The purpose of the prescribed adjustment means is to adjust the total inductance without essentially degrading the high coupling coefficients, and to tune the autotransformer such that full broad-band frequency response can be completely utilized. This variable gap spacing has the advantage that it permits tuning in a broad-band application whereas conventional tuning has been for tuning to a resonant frequency in a narrow-band application.

The windings of the autotransformer **155**, like those described above, are tightly wound on the core thereof with close spacing between the turns. As described above, the autotransformer of this and the other stages have a high primary-to-secondary coupling coefficient, and a high side-to-side coupling coefficient. Actual primary-to-secondary coupling coefficients (KPS) of up to 0.98 and side-to-side coupling coefficients K22 of up to 0.94 have been obtained at video-frequencies. Also, the coupling coefficients obtained, in accordance with this invention, are essentially independent of gap spacing.

Such high coupling coefficients are in contrast to those obtainable with air core and other conventional autotransformers in video-frequency applications. For example, the air core transformer would normally have primary-to-secondary coupling coefficients of only up to about 0.85 and side-to-side coupling coefficients of up to only about 0.75. Air core autotransformers are accordingly disadvantageous for class B2 push-pull operation and for providing sufficient impedance match between the high impedance driving anode and low impedance driven cathode contemplated with the broad-band, push-pull, grounded-grid configuration of this invention. Also, conventional air core autotransformers do not have the gain band width capabilities of the autotransformer of this invention. The autotransformer of this invention is also advantageous over iron core transformers because the latter cannot be used for video-frequency applications on account of high distributed capacitance and eddy current loss. The frequency band aspect ratio

$$\left(\text{FBAR}=\frac{\text{f max.}}{\text{f min.}}\right)$$

of the radio-frequency power amplifier stages, in which this invention is employed, is very large for such a high power level. For example, an AM broadcast station at 1 mc./s. carrier frequency has a ratio of only

$$1.005/0.995=1.01$$

Here, this ratio is

$$\frac{4.46}{1.40}=3.18$$

A preferred transformer-coupled power amplifier interstage circuit design is to regard such circuits as pseudo-low-pass LC ladder filter networks, where one or more of the series inductances and one or more of the shunt capacitances are contributed by the leakage inductances and distributed capacitances respectively of the transformer itself.

This particular ferrite autotransformer configuration permits more precise design of LC filter interstage networks because a greater proportion of the associated filter sections are external to, and hence more readily controlled, than in former designs.

The output side taps of interstage autotransformer **155** connect with the cathodes of the grounded-grid, push-pull, class B2 operated standard commercial power triodes **157** and **159**, which are triodes such as the ML–6696 type, through low capacitance high leakage inductance filament transformers **185** and **187**, like those described above. To this end, one side tap of the autotransformer **155** connects with a center tap **188** of filament transformer **185** and the other side tap of the autotransformer connects with a center tap **189** of the other filament transformer **187**. The transformers **185** and **187** have a suitable input power source such as a 460 v. A.C. power source as shown in FIG. 3. The outputs of the filament transformers connect with the cathodes of triodes **157** and **159**. To help maintain a clean wave form through optimized cross coupling, the center taps of the filament transformers connect with the opposite end taps of a split ferrite cored cathode choke **190**, like the ones described above.

Triodes **157** and **159** begin the next stage of amplification at their grids which are connected to each other and locked on ground. Triodes **157** and **159** are push-pull, class B2 operated triodes, such as the ML–6696 type, and their plates are connected to the cathodes of two more push-pull, class B2 operated triodes, such as F–6398 triodes, through an interstage autotransformer **191**, like those described above, and having a suitable radio frequency ground and B+ source (not shown). This stage of amplification is similar to the stage that preceeded it, and the output high impedance plates of tubes **157** and **159** connect through autotransformer **191** and suitable filament transformers with low impedance cathodes of two push-pull, class B2 operated triodes **195** and **197** having their grids connected to each other and to ground. Here, however, the plates of triodes **157** and **159** are connected through a ferrite cored choke **193** like those described above for D.C. energizing and suitable capacitors are provided between the plates and the end taps of autotransformer **191**.

The output plates of triodes 195 and 197 connect with the end taps of ferrite cored center-tapped autotransformer 199 like those described above. As mentioned, however, the windings thereof are hollow and have a cooling fluid circulated therein, as are the windings of 191. The center tap of autotransformer 199 of radio frequency grounded through a suitable capacitor and has a suitable B+ source. The output side taps are connected by coaxial cables 200 to suitable push-pull amplifiers such as amplifiers 201 (FIG. 2), which are connected with the accelerating cavity gaps of accelerating means 27, of the described high energy particle accelerator 11.

In operation atomic particles are injected into tube 13 at predetermined energies, speeds, pulse widths and angular spreads. Magnetic means 26 bends the particles into a circular beam and focuses the beam in tube 13 and accelerating cavity gaps 27 are energized to accelerate the particles. Since the frequency tolerances that must be met by the cavity gaps 27 are so exacting, the programmed cycle of conventional machines has been impractical. Accordingly, in the apparatus described herein, the proton beam in tube 13 provides the necessary information to control the frequency. To this end, a low level radio frequency system having an induction pick-up 42 around tube 13 which picks up an electrical signal each time a bunched beam of particles passes the pick-up, detects the correct frequency from the beam itself, means 40 corrects the phase so that the particles can be accelerated properly and supplies a low power command signal in cable 43 to amplifier 44. The amplifier 44 boosts the power of the signal and supplies the boosted signal to twelve accelerating stations, each having a twenty-five kw. push-pull amplifier 201 and a double tunable radio-frequency loaded ferrite cavity 27 having a pair of gaps as described above, which imposes accelerating forces on the proton bunches at each passage of the gaps to produce protons with up to over 31 billion electron volts.

Amplifier 41 provides stable, pure wave, broad-band, video-frequency signals for amplifiers 201 corresponding substantially linearly in amplitude and phase response to a relatively low power broad-band video-frequency command input signal in cable 43. For example, an output of 80 peak kilowatts, 120 peak radio-frequency amperes, and 1400 peak radio-frequency volts over a frequency range of from 1.4 to 4.46 megacycles per second is supplied to amplifiers 201 by amplifier 44 from a 1 watt 2 volt 1.4 to 4.46 megacycles per second input in cable 43. To this end, phase invertor 63 converts the single-ended input in cable 43 into a double-ended signal and supplies autotransformer 81. Autotransformer 81 energizes push-pull, pentodes 106 and 107 having cathodes with a suitable direct current source connected therewith through lead 108 and the output from the plates of tubes 106 and 107 is a low impedance, push-pull, balanced-to-ground, broad-band, video-frequency signal corresponding in phase and amplitude to the input from cable 43.

The output from tubes 106 and 107 energizes further amplification stages having cascaded push-pull, balanced-to-ground, low impedance input, high impedance output, multi-grid tubes 109 and 111, 117 and 119, 125 and 127, and 133 and 135, having interstage center-tapped ferrite cored autotransformers 115, 123, 131 and 143, like the described auto-transformer 81 with their center-taps energized from a suitable source (not shown) through connections as shown in FIG. 3. Tubes 117 and 119, and 125 and 127 have suitable cathode followers as described and ferrite chokes 129, 137 and 145 clean up the wave form in the last three stages of section 46. The output from amplifying section 46 thus is a double-ended, push-pull, broad-band, video-frequency, high impedance source which corresponds in amplitude and phase with the command input in cable 43 and the multi-grid tubes of the amplifying section 46 keep output radio-frequency cable termination phase perturbations of the section 54 from tailing back from the triodes of section 54.

In the amplifying section 54, the push-pull, grounded-grid triodes amplify the input thereto to high power levels and the output therefrom corresponds in amplitude and phase with the input. To this end, the high impedance plates of triodes 139 and 141 energize the low impedance cathodes of triodes 157 and 159 through autotransformer 155. The high permeability, low power loss factor and high coupling coefficients of the autotransformer 155 causes the described cascaded grounded-grid configuration to produce high power amplification in the autotransformer 155, with a pure wave form. Likewise, the outputs from triodes 157 and 159 are amplified further in autotransformer 191 which connects triodes 157 and 159 with triodes 195 and 197 and in autotransformer 199 which connects triodes 195 and 197 through leads 200 with amplifiers 201 which are like the described grounded-grid amplification stages. Also tuning means 105 is operable to adjust the impedance of the described autotransformers.

From the above, it will be understood that there are numerous applications in the fields of nuclear physics research and communications that require broad-band high power output, video-frequency amplifying systems and it will be understood from the above that the autotransformer of this invention can be used advantageously in such fields.

It is also understood that the foregoing has emphasized the utility of the autotransformer of this invention in balanced circuitry but the autotransformer of this invention is also useful in single-ended applications.

The system of this invention provides a simple, relatively inexpensive and effective means for supplying in a high energy accelerator a high power, broad-band, stable, video-frequency signal corresponding precisely in amplitude and phase with a relatively low power, broad-band video-frequency input. The system of this invention has the advantage of low cost, effective, simple, components, standard power triodes in the upper stages thereof, standard tetrodes in the lower stages thereof, and permits the use of a reduced number of commercially available high power electron tubes, relatively low direct current anode potential, minimized direct current anode power input, and minimized electrode dissipations. This invention additionally provides an autotransformer for interstage coupling in a truly broad-band video-frequency amplifier and provides an impedance match between a high impedance driving anode and a low impedance driven cathode that has not been possible heretofore so that the described combination with the described inherently stable grounded-grid configuration produces high power, broad-band, video-frequency amplification with good transient response.

I claim:

1. An amplifier for supplying high power, broad-band, video-frequency signals in a high energy particle accelerator having particle accelerating means connected to said amplifier, comprising an amplifying stage having push-pull connected grounded cathode tetrodes, an amplifying stage having push-pull connected triodes with grounded grids, and interstage autotransformer for coupling the stages of said amplifier having a ring-shaped ferrite core with a high permeability, low power loss factor, and tightly-wound, closely-spaced, center-tapped, voltage-step-down windings around said core for preventing output termination phase perturbations from tailing back from said triodes.

2. An amplifier for supplying high power, broad-band, video-frequency signals in a high energy particle accelerator having particle accelerating means connected to said amplifier, means for providing a low power single-ended signal corresponding in phase and amplitude to the speed of said high energy particles first amplifying stages for said signal having low power output push-pull connected grounded cathode multigrid tubes, second amplifying stages having high power output push-pull connected grounded-grid triodes, and interstage autotransformers for

coupling and amplifying the output of the stages of said amplifier for supplying said output to said accelerating means with linear phase and amplitude response to said low power signal, comprising a split-ring-shaped ferrite core forming gaps that bisect said core in a plane that is normal to the plane of said core and coincides with the axis of said core, said ferrite having a high permeability and a low power loss factor, and tightly-wound, closely-spaced, center-tapped, voltage-stepdown windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps.

3. An amplifier for supplying high power, broad-band, video-frequency signals in a high energy particle accelerator having particle accelerating means connected to said amplifier, comprising first amplifying stages having low power output push-pull connected grounded cathode tetrodes, second amplifying stages having high power output push-pull connected grounded-grid triodes, and interstage autotransformers for coupling the stages of said amplifier in a cascade, comprising a split-ring-shaped ferrite core forming gaps that bisect said core in a plane that is normal to the plane of said core and coincides with the axis of said core, said ferrite having a high permeability and a low power loss factor, means for equally varying the opening in said gaps in said core, and tightly-wound, closely-spaced, center-tapped voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps wherein said windings have a high side to side coupling coefficient and a high through coupling coefficient.

4. An amplifier for supplying high power, broad-band, video-frequency signals in a high energy particle accelerator having particle accelerating means connected to said amplifier, comprising amplifying stages having low power output, push-pull connected grounded cathode tetrodes, amplifying stages having high power output push-pull connected grounded-grid triodes, and interstage autotransformers for coupling the stages of said amplifier, comprising a split-ring-shaped ferrite core having adjacent coaxial semi-circular segments forming gaps that bisect said core in a plane normal to the plane of said core that coincides with the axis of said core, said ferrite having a permeability of over 300 and a quality factor of over 20 at 1.4 megacycles per second, means for equally opening and closing said gaps in said core, tightly-wound hollow closely-spaced, center-tapped, voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps, and means for circulating a coolant through said windings.

5. Apparatus for supplying broad-band, video-frequency high power output signals, comprising a broad-band, video-frequency low power energy source, a first amplifying section having low power output push-pull connected grounded cathode tetrodes connected to said source, a second amplifying section having high power output push-pull connected grounded-grid trodes, and interstage inductors for coupling the sections of said amplifier, comprising a split-ring-shaped ferrite core forming gaps that bisect said core in a plane normal to the plane of said core that coincides with the axis of said core, said ferrite having a permeability of over 300 and a quality factor of over 20 at 1.4 megacycles per second, means for equally opening and closing said gaps and tightly-wound closely-spaced, center-tapped voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps for connecting said stages through said inductors for providing high stage gain and smoothness of phase-frequency response.

6. Apparatus for amplifying broad-band, video-frequency high power signals, comprising at least two grounded-grid push-pull, high power output amplifying stages having triodes, and interstage inductor for coupling said amplifying stages in a cascade, comprising a split-ring-shaped ferrite core formed with gaps in a plane that bisects said core normal to the plane of said core, said ferrite having a high permeability and a low power loss factor, means for maintaining an equal opening in said gaps in said core, and tightly-wound, closely-spaced, center-tapped, voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps for connecting said stages through said inductors for providing high stage gain and smoothness of phase-frequency response.

7. Apparatus for supplying broad-band, video-frequency, high power output signals, comprising a broad-band, video-frequency, low power energy source, first amplifying stages having low power output, push-pull connected grounded cathode tetrodes connected to said source, second amplifying stages having high power output, push-pull connected grounded-grid triodes, and interstage inductor for coupling the stages of said amplifier in a cascade, comprising a split-ring-shaped ferrite core formed with gaps that bisect said core normal to the plane of said core, said ferrite having a high permeability, a low power loss factor, means for maintaining an equal opening in said gaps in said core, and tightly-wound, closely-spaced, center-tapped, voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps for connecting said stages through said inductors for providing high stage gain and smoothness of phase frequency response.

8. An interstage autotransformer for coupling amplifying stages in an amplifier operable to supply high power, broad-band, video-frequency outputs, comprising a split-ring-shaped ferrite core forming two opposite gaps that bisect said core in a plane normal to the plane of said core and coinciding with the axis of said core, said ferrite having a permeability of over 300 and a quality factor of over 20 at 1.4 megacycles per second, means for equally opening and closing said gaps, and tightly-wound, closely-spaced, center-tapped voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps.

9. An interstage autotransformer for coupling amplifying stages in an amplifier operable to supply high power, broad-band, video-frequency outputs, comprising a split-ring-shaped ferrite core formed with gaps in a plane that bisects said core normal to the plane of said core, said ferrite having a high permeability and a high power loss factor, means for maintaining an equal opening in said gaps in said core, and tightly-wound, closely-spaced, center-tapped voltage-step-down windings around said core and extending equal distances in opposite directions from a point on said core equal distances from said gaps.

10. In a power amplifier for use in a high energy particle accelerator requiring high power, broad-band, video-frequency signals and having cascaded push-pull connected grounded-grid triode amplification stages, prior push-pull connected, cascaded grounded-cathode tetrode amplification stages that are connected with said triode stages and are operable to keep output cable termination phase perturbations from tailing back from said grounded-grid triode stages, high permeability, low power loss factor ferrite cored interstage chokes for smoothing wave forms between said stages, and a low-power, broad-band, video-frequency command signal input for said stages, a ferrite cored interstage autotransformer between each of said stages, comprising an annular core having a permeability greater than 300, a quality factor of at least 20, tightly wound, center-tapped, voltage-step-down windings around said core, and opposite equally adjustable gaps equally spaced from said windings so that substantially all the lines of force produced by said windings remain in said core and said autotransformer has high through coupling

coefficients and high side-to-side coupling coefficients whereby a simple, easily cooled, easily shielded circuit having standard vacuum tubes is provided that supplies high power, broad-band, video-frequency signals that substantially linearly correspond with the phase and frequency of said command signal.

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