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(56) Documents Cited
EP 1056113 A2 **WO 2001/093646 A2**
JP 030179699 A **US 4667111 A**

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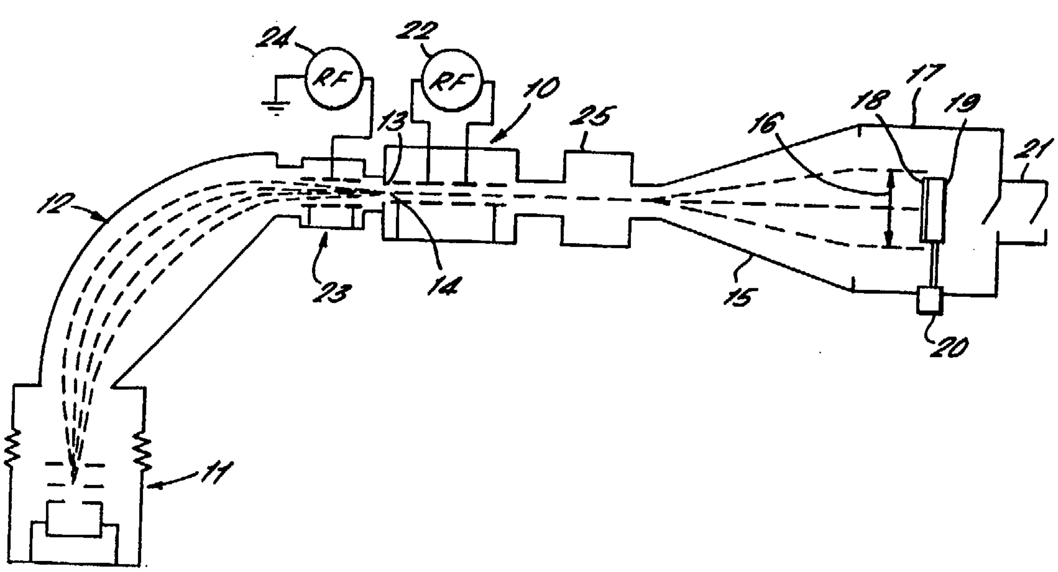
Other: **ONLINE: EPODOC, WPI, JAPIO, OPTICS**

(54) Abstract Title
Radio frequency linear accelerator

(57) The object of the present invention is to provide circuits and arrangements which can enhance the control of the resonant frequency of a resonator or resonant structure of the accelerator, thereby reducing the maximum power requirements of the rf amplifier energising the structure.

A radio frequency linear accelerator has an rf resonant structure with capacitance and an inductor arranged to provide a resonant circuit with a nominal resonant frequency. The rf structure is excited by an rf amplifier at the nominal frequency. A resonant detector provides a signal representing an error between the actual resonant frequency of the rf structure and the nominal resonant frequency. A resonance controller is responsive to the resonant error signal to vary the value of an electronically variable capacitance coupled to the resonant circuit, to return the resonant frequency of the rf structure towards the nominal resonant frequency.

FIG. 1.



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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

FIG. 1.

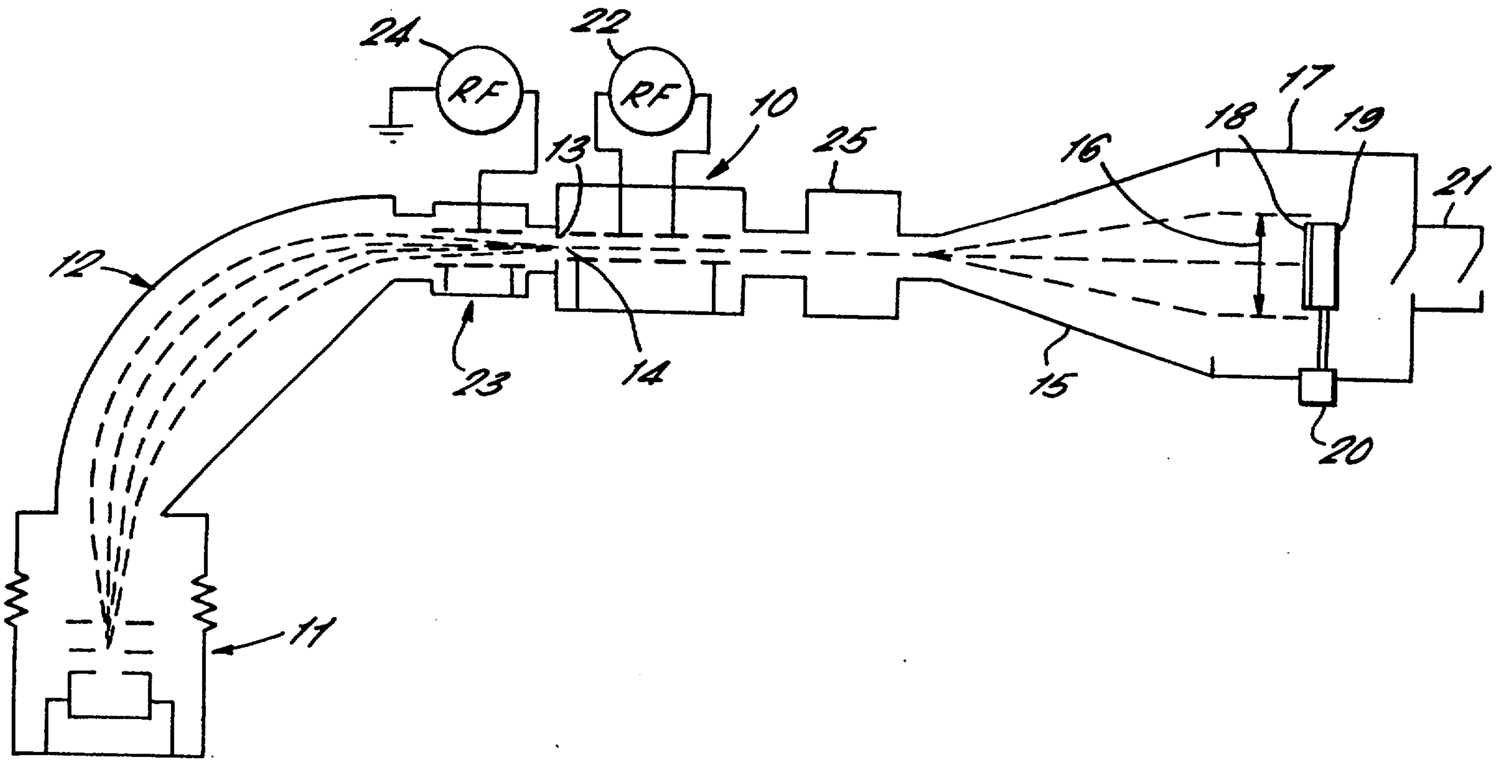


FIG. 2.

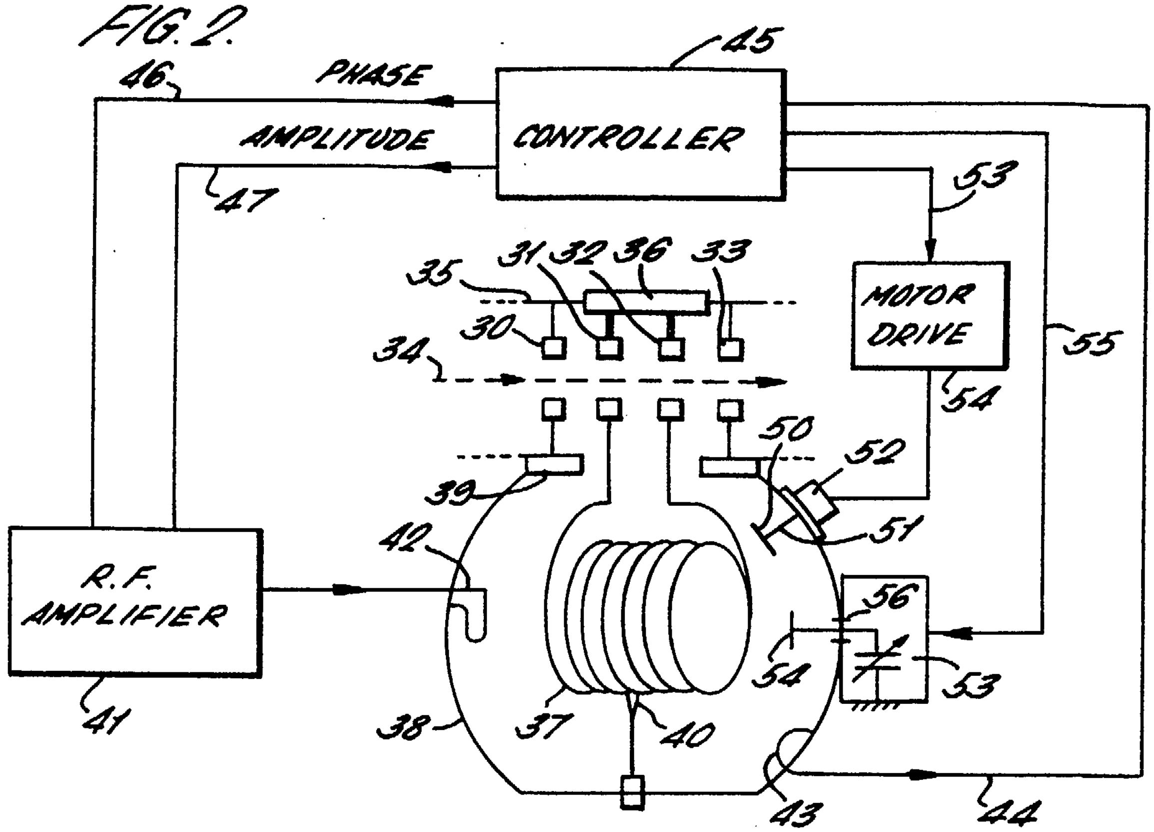


FIG. 4.

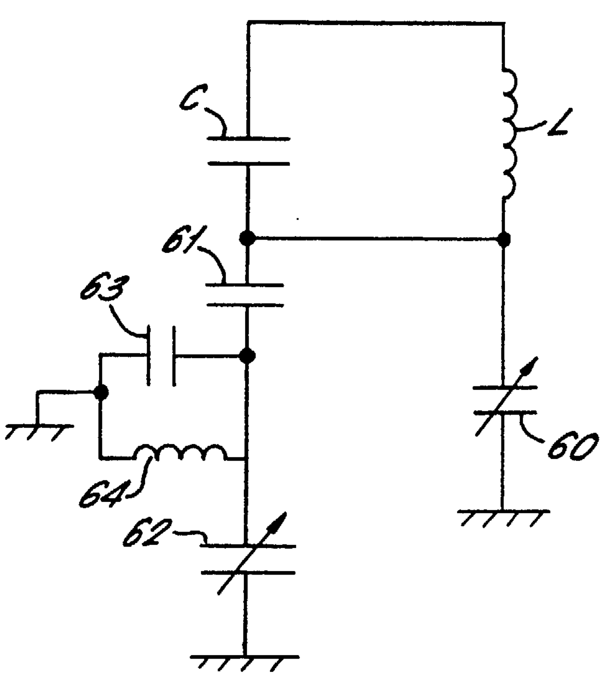
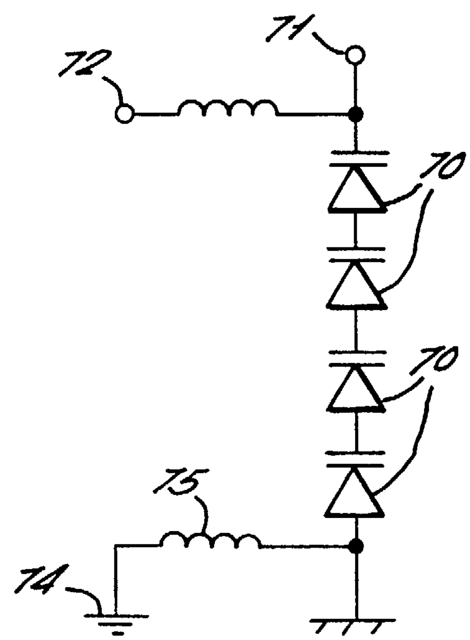


FIG. 3.



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RADIO FREQUENCY LINEAR ACCELERATOR

Field of the Invention

The invention is concerned with a linear accelerator, particularly but not exclusively for use in an ion implanter.

Background of the Invention

A linear accelerator structure accelerates charged particles of a specific mass/charge ratio which are injected into the accelerator at a specific injection energy. Radio frequency (rf) linear accelerators have been known for many years from the field of nuclear physics where they have been employed to accelerate heavy ions. More recently, rf accelerators have been used in semiconductor wafer processing. Typically, a beam of ions of a required species (such as boron, phosphorous, arsenic or antimony) is produced and directed at a wafer so that the ions become implanted under the surface of that wafer. Although electrostatic acceleration systems are suitable for producing beams of singly charged ions of 200keV or more, it has been recognised that the desirable characteristics (for certain applications) of relatively high beam current and relatively high beam energy can be achieved by including an rf accelerator in the ion implanter device.

Reference should be made to EP-A-1056113, the disclosure of which is incorporated herein by reference. This specification discloses an ion implanter incorporating an rf linear accelerator having two successive three gap resonant structures. Each resonant structure comprises a vacuum enclosure containing a coil providing inductance, connected to a central pair of the accelerating electrodes of the structure, so that the electrodes are energised by the rf potential with opposite polarity. The frequency, amplitude and phase of the energising rf voltage applied to the electrodes must be maintained at precise values for proper operation of the accelerator. Also, for efficient operation, the inductor and the capacitance of the structure constitute a resonant circuit having a resonant frequency at this desired operating frequency. The vacuum enclosure contains a movable plate electrode, driven by a motor, so as to adjust capacitance associated with the resonant circuit of the structure to maintain the resonant frequency of the structure accurately at the desired nominal resonant frequency.

Reference may also be made to United States Patent Application Serial No. 09/534,631, assigned to the Assignee hereof, the disclosure of which is incorporated herein by reference. This application discloses a controller responsive to a feedback signal monitoring the phase and amplitude of the rf field in the vacuum enclosure of the resonant structure of an accelerator to control the rf drive signal supplied to the structure, so as to maintain the amplitude and phase of the field within the enclosure accurately at desired values. The controller also monitors the current resonant frequency of the resonant structure and adjusts the movable electrode plate within the structure enclosure to maintain the resonant frequency at the desired nominal frequency.

The typical nominal frequency for accelerating heavy ions, such as those used for implanting desired species in semiconductor wafers, is about 20 MHz. Typically also, the accelerating electrodes of the resonant structure are energised with rf voltages up to 85 kV or more. A typical power drain on an rf amplifier providing the drive signal to energise the rf structure is 6 kW or more. It can be seen, therefore, that energising the resonant structure places considerable demands on the rf power amplifier used to provide the necessary drive signal.

These power demands are increased if the resonant frequency of the resonant structure is not accurately maintained at the nominal resonant frequency. Because the resonant structure has high Q, any deviation from nominal in the resonant frequency of the structure substantially increases the required rf power to be delivered to the structure in order to maintain the required rf voltage at the accelerating electrode.

Even with feedback control of the resonant frequency of the structure, using the movable plate electrode as disclosed in the above prior references, the rf amplifier providing the drive signal for the structure must be substantially over specified, in order to provide sufficient power to maintain the desired rf voltage on the accelerating electrodes during operation of the accelerator. If the amplifier is not sufficiently over specified, then there can be an unsatisfactory failure rate, resulting in extra cost and reduced productivity.

Summary of the Invention

An object of the present invention is to provide circuits and arrangements which can enhance the control of the resonant frequency of a resonator or resonant structure of the accelerator, thereby reducing the maximum power requirements of the rf amplifier energising the structure.

Accordingly, the invention provides a radio frequency (rf) linear accelerator comprising at least one rf resonant structure having capacitance and including an inductor arranged to provide a resonant circuit having a nominal resonant frequency, an electronically variable capacitance coupled to said resonant circuit, an rf amplifier arranged to produce an rf drive signal to excite the rf structure at said nominal resonant frequency, a resonance detector to provide a signal representing error between the actual resonant frequency of the rf structure and said nominal resonant frequency, and a resonance controller responsive to said resonance error signal to vary the value of said electronically variable capacitance to return the resonant frequency of the rf structure towards said nominal resonant frequency.

By using an electronically variable capacitance coupled to the resonant circuit of the resonant structure, controlled to maintain the resonant frequency of the structure close to the nominal frequency, the response of the feedback control to higher rate variations of the resonant frequency of the structure can be greatly improved. In fact, in arrangements of linear accelerator using relatively low rf frequencies (say 20 MHz) as are typically used for accelerating the ions in an ion implanter, errors in the actual resonant frequency of the rf structure can arise from two primary sources. The resonant frequency can drift at a relatively slow rate due to temperature changes in the vacuum enclosure containing the resonant structure, the inductor coil, or other beam line components including the accelerating electrode. Low rate of change error in the resonant frequency resulting from such drift processes are readily compensated by the movable plate electrode known in the prior art. However, mechanical vibration of the structure, particularly the inductor coil within the vacuum enclosure can result in periodic changes in the resonant frequency at rates too high for compensation by the movable plate electrode. Using an electronically variable capacitance, these high rate resonant frequency variations can be countered satisfactorily so that the actual resonant frequency of the structure is continuously maintained very close to the nominal resonant frequency. As a result, the power load on the rf amplifier energising the structure can be reduced while maintaining the same rf voltage amplitude at the accelerating electrodes of the accelerator.

Preferably, the electronically variable capacitance comprises at least one reverse biased varactor diode. Then, said resonance controller is preferable responsive to said resonance error signal to control a dc bias signal for said at least one varactor diode. Normally, at least one choke is connected to isolate said resonance controller from rf voltages across said at least one varactor diode.

The electronically variable capacitance may comprise a plurality of reverse biased varactor diodes connected in series, in order to provide the required voltage capability for the variable capacitance.

A load capacitance may be included coupling said electronically variable capacitance to said resonant circuit. This load capacitance may comprise an electrode plate providing a capacitive link to said inductor.

In a preferred embodiment, said electronically variable capacitance may have a maximum variable capacitance range effective to provide a corresponding first maximum frequency range of adjustment of the resonant frequency of the rf structure, and said resonance controller may have a first maximum response rate for adjusting said resonant frequency over said first range by varying the value of said electronically variable capacitance, and the accelerator may then further include a movable tuning member for varying a reactance value associated with the rf structure and an actuator to move the tuning member, said movable tuning member and said actuator providing a maximum variable reactance value range effective to provide a corresponding second maximum frequency range of adjustment of the resonant frequency of the rf structure and having a second maximum response rate, less than said first maximum rate, for adjusting said resonant frequency over said second range by moving said tuning member, said resonance controller being operative also to drive said actuator to varying said reactance value to keep a time average of the varying values of said electronically variable capacitance near the middle of said maximum variable capacitance range.

In this way, if said time average of the varying values of said electronically variable capacitance is taken over a relatively short time period, any variations in the resonant frequency over periods longer than this short period are countered by movement of the movable tuning member, leaving the electronically variable capacitance to counter the relatively short term variations in resonant frequency. The movable tuning member may vary either the capacitance, e.g. by means of a movable electrode plate, or the inductance, e.g. by means of a movable inductor core or movable coil elements.

The invention also contemplates an ion implanter having a radio frequency linear accelerator as described above, and further contemplates a method of implanting ions including the step of accelerating the ions using an rf linear accelerator and controlling the accelerator by the method described above.

Brief Description of the Drawings

Examples of the present invention will now be described with reference to the accompanying drawings in which:

Figure 1 is a schematic plan view of an ion implanter which may embody the present invention;

Figure 2 is a schematic view in combination with a block diagram, illustrating a resonant rf structure embodying the present invention;

Figure 3 is a diagram of a stack of series connected varactor diodes which may be used as the electronically variable capacitance in embodiments of the invention; and

Figure 4 is an equivalent circuit diagram illustrating an embodiment of the present invention.

Description of the Preferred Embodiments

Embodiments of the invention may be employed in many different kinds of ion implanters, including both implanters designed for simultaneously processing a batch of wafers, and single wafer implanters designed for processing single wafers one after the other. Figure 1 illustrates schematically a single wafer implanter incorporating a radio frequency linear accelerator assembly 10. In the simplified arrangement of Figure 1, the implanter comprises an ion source 11 directing a beam of ions at a predetermined energy E into an analyser magnet 12. Only ions of the required velocity times mass/charge (m/e) ratio pass through a mass selection slit 13 at the exit of the analyser magnet 12, and enter as a beam 14, still at energy E, into the radio frequency accelerator assembly 10. The beam exiting the rf accelerator assembly 10 then enters a beam scanning device 15 which is arranged to scan the ion beam to and fro in a direction 16 transverse to the beam direction. The scanning device 15 may be either electrostatic or electromagnetic. Electromagnetic scanning systems are preferred in applications especially for high current beams. A suitable electromagnetic scanning system is disclosed in U.S. Patent No. 5393984. The scanned beam then enters a process chamber 17 in which a semiconductor substrate 18 is held on a holder 19. The holder 19 is mounted on a mechanical scanning mechanism shown generally at 20 which can be actuated to reciprocate the wafer in a direction normal to the plane of the paper in Figure 1 and across the plane of the scanned beam. The combination of scanning of the beam and mechanical scanning of the wafer holder 19 allows the beam to scan over all parts of the wafer during an implant process. Processed wafers are removed from the holder 19 and passed out of the process chamber 17, and fresh wafers for processing are brought into the chamber 17 and mounted on the holder 19 one at a time, via a load lock 21, and using robot handling mechanisms which are not shown in this drawing for simplicity.

Further details of single wafer implanters can be determined from U.S. Patents Nos. 5003183 and 5229615, and of a preferred form of process chamber from International Patent Application WO 99/13488. The specific details of the ion source, the mass selection magnet and the scanning and processing mechanisms of the implanter are not crucial to aspects of the present invention, which concern solely the arrangement of an rf accelerator assembly which may be used to increase the energy of ions in implanters such as disclosed in the above prior art documents.

It should be understood that the invention is equally applicable to batch implanters, which typically rely solely on mechanical scanning to process a batch of semiconductor wafers simultaneously. The wafers are usually mounted around the periphery of a rotating wheel, which rotates to bring the wafers one by one across the line of the ion beam. Meanwhile, the axis of rotation of the wheel is reciprocated to and fro to complete the scanning in the orthogonal direction.

The earlier referred U.S. Patent No. 4667111 describes such a batch type implanter. Reference may also be made to U.S. Patent No. 5389793 for further details of a typical batch type implanter.

Referring again to Figure 1, the rf accelerator assembly 10 is schematically illustrated in the form of a three gap accelerator stage in which an rf voltage of opposite polarity is applied from a source 22 to respective ones of the two centre electrodes. Further details of the construction and design of the accelerator assembly will be apparent from EP-A-1056113 referenced previously.

It should be noted also that a buncher 23 would normally be incorporated in front of the accelerator assembly 10 to form and deliver bunches of ions at the injection energy to the accelerator to increase the proportion of ions from the unbunched beam which may be accelerated by the accelerator assembly. Such bunchers are known, and generally produce a controlled energy spread in beam ions so that the ions become physically bunched on entry into the accelerator assembly. Known bunchers are designed to capture for bunching a maximum proportion of unbunched beam ions, without providing any overall increase in average energy to the bunched ions. In Figure 1, the buncher 23 is illustrated as a two gap device having a central electrode energised from an rf supply 24. The purpose and operation of bunchers is described in Theory of Linear Accelerators, by A.D. Vlasov, Chapter 2.5, published in English translation in 1968. The buncher of a linear accelerator may also incorporate a resonant structure having capacitance and an inductor, and embodiments of the present invention are equally applicable to controlling the resonant frequency of the resonant structures of such bunchers.

It should also be noted that the rf accelerator assembly 10 would normally be followed, along the beam direction, by an energy filter, illustrated generally in Figure 1 at 25. The use of such an energy filter following an rf accelerator in ion implanters is well known, see for example "Production of High Energy Ion Implanters Using Radio Frequency Acceleration" by Glavish et al, Nuclear Instruments and Methods in Physics Research, B21(1987) 264-269. The energy filter is used to limit the range of energies of ions from the accelerator which proceed to be implanted in the semiconductor substrate.

The energy filter may take any known form such as an electrostatic inflector or an analyser magnet.

Figure 2 illustrates schematically a single resonant structure of a linear accelerator. The illustrated structure may, for example, take the form of one of the structures illustrated and described in greater detail in the above referenced EP-A-1056113. The structure comprises a three gap accelerator structure comprising four apertured electrodes 30, 31, 32 and 33 arranged along a beam path 34 within an evacuated beam line which is partly shown at 35. The first and last electrodes 30 and 33 of the structure are grounded and the two intermediate electrodes 31 and 32 are mounted in the beam line 35 by means of insulator 36 and are connected to opposite ends of an inductor coil 37 housed in a vacuum enclosure 38. The enclosure 38 is formed of an electrically conductive material, typically aluminium alloy, typically stainless steel, and is electrically connected to the beam line housing 35. The connections from the inductor coil 37 to the electrodes 31 and 32 pass through aperture 39 communicating between the interior of the beam line 35 and the interior of the enclosure 38. In the illustrated example, the inductor coil 37 comprises two coaxial coils having adjacent ends 40 connected to ground.

An rf drive signal is supplied to energise the structure from an rf amplifier 41 feeding an energising loop 42 within the enclosure 38.

As will be understood by those skilled in the art, and is further explained in the above referenced EP-A-1056113, the inductor coil 37, in combination with the capacitance of the structure, provide a resonant circuit with very high Q. The resonant circuit of the structure has a nominal resonant frequency at the desired operating frequency of the accelerator, which may be about 20 MHz in this example.

It is important, for proper operation of the accelerator structure, that the phase and amplitude of the rf voltages applied to the electrodes 31 and 32 are precisely controlled at predetermined values. A sense loop 43 within the enclosure 38 provides a signal on a line 44 representing the phase and amplitude of rf field within the enclosure 38, which is in turn representative of the phase and amplitude of the rf voltages applied to the electrodes 31 and 32. This sensed feedback amplitude and phase signal is supplied to a controller 45 which compares the detected phase and amplitude with desired phase and amplitude values and provides phase and amplitude control signals on lines 46 and 47 respectively, to control the output of rf amplifier 41.

As will be understood, if the resonant frequency of the described resonant structure is precisely at the desired operating frequency, that is the energising frequency delivered by the rf amplifier 41, the rf voltage appearing at the electrodes 31 and 32 can be maximised with minimum input power from the amplifier 41. In practice, however, the resonant frequency of the structure may require some adjustment so as to be accurately at the desired nominal resonant frequency, and furthermore in order to counter changes in the actual resonant frequency during operation of the accelerator.

In order to adjust the actual resonant frequency of the rf structure, a plate electrode 50 is mounted eccentrically on a shaft 51 driven by a stepper motor 52. The rotational position of the electrode plate 50 is controlled by signals from controller 45 delivered on a line 53 to motor drive unit 54. Rotating the position of the electrode plate 50 changes the capacitance associated with the resonant circuit of the rf structure, thereby controlling the resonant frequency. Further details of the construction and operation of an example of such movable plate type resonant frequency controller is provided in the above referred EP-A-1056113.

As mentioned above, it is important to maintain the actual resonant frequency of the rf structure at the nominal resonant frequency and the drive frequency from the rf amplifier 41, to provide maximum rf voltage amplitude at the electrodes 31 and 32 for minimum rf power delivery from the amplifier 41. Because of the high Q of the resonant circuit, a small frequency deviation from the nominal resonant frequency can require the amplifier to deliver substantially more power to the structure in order to maintain the required rf voltage amplitude at the accelerator electrodes.

The operation of the controller 45 in controlling the amplifier 41 to provide the appropriate rf drive to the structure to maintain the amplitude and phase at the accelerator electrodes 31 and 32 as required, is described in more detail in the above referred co-pending USSN 09/534,631.

The movable electrode plate system for adjusting the resonant frequency of the structure has a limited rate of response to changes in resonant frequency, corresponding to the speed with which the position of the electrode plate can be changed by the stepper motor and drive system. An additional high speed resonant frequency adjuster is provided by an electronically variable capacitance 53 coupled through a wall of the vacuum enclosure 38 to a fixed capacitor plate 54. The electronically variable capacitance 53 is controlled by a signal from controller 45 on a line 55. As illustrated, one end of the electronically variable capacitance 53 is connected to ground and the other end is fed through the wall of the enclosure 38 via a feedthrough 56 to the capacitance plate 54. The resulting series connected capacitors are effectively coupled to the resonant circuit of the resonant structure.

The electronically variable capacitance 53 is conveniently formed of a group of series connected varactor diodes as illustrated in Figure 3 at 70. One end terminal of the series connected diodes 70 is connected to ground and the other end terminal 71 is connected via the feedthrough 56 to the fixed capacitor plate 54. The value of the capacitance of the varactor diode 70 is controlled by a dc bias provided on the line 55 from the controller 45. The dc bias is connected to the terminal 71 from a terminal 72 via an rf decoupling choke 73. An additional connection to the grounded end of the diode stack 70 may be made to signal earth 74 via a further decoupling choke 75.

An equivalent electrical circuit of the resonant structure and resonant frequency adjusters is illustrated in Figure 4. The resonant structure has main inductance L and main capacitance C. The movable plate resonant frequency adjuster 50, 51 and 52 is illustrated by the adjustable capacitance 60 coupling between the above referred main reactance components C,L and ground. The coupling capacitor plate 54 is illustrated by the fixed capacitance 61 in Figure 4, connected in series with variable capacitance 62 representing the electronically variable capacitance 53 of Figure 2. The feedthrough 56 provides a parasitic capacitance 63 to ground, and unless this is very small compared to the values of capacitances 61 and 62, this parasitic capacitance 63 is preferably resonated out by a parallel connected inductor 64. The value of inductor 64 is selected to provide resonance with the parasitic capacitance 63 at the nominal resonant frequency of the rf structure.

With the above combination of variable plate resonant frequency adjuster 50, 51 and 52, together with the electronically variable capacitance arrangement illustrated in Figures 2 and 3, the resonant frequency of the resonant structure can be maintained accurately at the nominal frequency over a wide range of rates of change. For example, changes in the resonant frequency due to temperature drift can readily be accommodated by the movable plate 50 operating with a loop response of say 1 Hz. On the other hand, the electronically variable capacitor 53 can easily be made to operate with a loop response of 100 Hz or more, thereby countering fast rate changes in the resonant frequency of the rf structure, for example due to mechanical vibrations and shocks.

It has been found that the error amplitude of the resonant frequency at higher rates of change is smaller than the correction amplitude required for low rates of change, so that the dynamic range of correction of the electronically variable capacitance need not be as great as the range available from the movable plate 50. It is important, however, that the movable plate 50 is controlled to maintain the mean resonant frequency of the resonant structure at the nominal resonant frequency value, so that the electronically variable capacitance is normally operating in the middle of its adjustment range. This can be achieved by controlling the variable plate 50 in response to a signal representing the time average value of the electronically variable capacitance 53, so as to maintain this time average value near the middle of the dynamic range of adjustment of the electronically variable capacitance. On the other hand, the same effect can be achieved by ensuring that the electronically variable capacitance is not responsive to relatively slow rate changes in the resonant frequency of the rf structure, thereby ensuring that these slow rate changes are countered by adjustment of the movable plate 50. Generally, the movable plate system will have a maximum rate of response to changes in resonant frequency which is substantially less than the maximum rate of response of the electronically variable capacitance 53. However, the controller 45 may be arranged to provide a minimum response rate for the electronically variable capacitance, below the maximum response rate of the movable plate 50, to ensure that low rates of change of resonant frequency are countered by the movable plate.

Appropriate filtering and feedback systems may be provided in the controller 45 to achieve the desired results when responding to the feedback signal on line 44.

It will be understood that any deviation between the frequency of the rf drive signals supplied to energise the resonant structure and the actual resonant frequency of the structure will result in a phase difference between the electric field within the enclosure as sensed by the sensor 43, and the phase of the drive signal supplied by the rf amplifier 41. This phase difference is conveniently used by the controller 45 to monitor errors in the resonant frequency of the resonant structure and provide the appropriate control signals on lines 53 and 55. Other signals for monitoring resonant frequency error can be derived. For example the impedance of the resonant structure, as seen by the rf amplifier 41 may be monitored, e.g. by monitoring the standing wave ratio at the output of the amplifier.

In a practical arrangement, the electronically variable capacitance 53 may be required to have a tuning range of 10 kHz in terms of the resonant frequency of the structure. To achieve this, the total change in the value of capacitance loading the structure, that is the value of the series connected capacitors 61 and 62 in Figure 4, should be about 0.012 pF, centred about a capacitance value of about 0.094 pF. The value of the centre capacitance used should be as low as possible to minimise the total load on the resonant structure circuit, but must still be large enough to permit the required range of capacitance variation. It will be understood that if the coupling capacitor 61 has a value which is too small, it becomes difficult or impossible to achieve the required range of variation of capacitance by means of the series connected variable capacitance 62.

The parasitic feedthrough capacitance 63 may have a value of between 5 and 10 pF. Clearly this value is much higher than the load capacitance provided by capacitor 61 and 62 which is why it is important to resonate this capacitance out of the circuit by means of the inductor 64. If a feedthrough capacitance of much lower value can be achieved, then the cancelling inductor may be unnecessary.

The varactor diodes 70 used to provide the required electronically variable capacitance may be of type GC 15014 from Microsemi, Inc. The rf isolating chokes 73 and 75 should be high Q coils to minimise circuit losses. The overall effect of the electronically variable capacitance circuit on the Q of the resonant rf structure is minimised by using relatively low values for the capacitors 61 and 62.

In the above described example, the resonant structure is a three gap structure employing four electrodes. Examples of the invention are also applicable to other types of resonant structure in rf accelerators, including a two gap structure with three electrodes.

The arrangements described above and with reference to the drawings are only examples of embodiments of the invention as defined by the following claims.

CLAIMS

1. A radio frequency (rf) linear accelerator comprising at least one rf resonant structure having capacitance and including an inductor arranged to provide a resonant circuit having a nominal resonant frequency, an electronically variable capacitance coupled to said resonant circuit, an rf amplifier arranged to produce an rf drive signal to excite the rf structure at said nominal resonant frequency, a resonance detector to provide a signal representing error between the actual resonant frequency of the rf structure and said nominal resonant frequency, and a resonance controller responsive to said resonance error signal to vary the value of said electronically variable capacitance to return the resonant frequency of the rf structure towards said nominal resonant frequency.

2. An accelerator as claimed in Claim 1, wherein the electronically variable capacitance comprises at least one reverse biased varactor diode.

3. An accelerator as claimed in Claim 2, wherein said resonance controller is responsive to said resonance error signal to control a dc bias signal for said at least one varactor diode.

4. An accelerator as claimed in Claim 3, including at least one choke connected to isolate said resonance controller from rf voltages across said at least one varactor diode.

5. An accelerator as claimed in any of Claims 2 to 4, wherein said electronically variable capacitance comprises a plurality of reverse biased varactor diodes connected in series.

6. An accelerator as claimed in any preceding claim including a load capacitance coupling said electronically variable capacitance to said resonant circuit.

7. An accelerator as claimed in Claim 6, wherein said load capacitance comprises an electrode plate providing a capacitance link to said inductor.

8. An accelerator as claimed in any preceding claim, wherein said rf structure includes a conductive enclosure, said inductor being mounted within said enclosure, and said electronically variable capacitance being mounted exterior to said enclosure, and the accelerator including a feedthrough providing a coupling between said electronically variable capacitor and the interior of said enclosure, said feedthrough having a predetermined parasitic capacitance with said enclosure and including a cancelling inductor selected and connected to resonate with said parasitic capacitance at said nominal resonant frequency.

9. An accelerator as claimed in any previous claim, wherein said electronically variable capacitance has a maximum variable capacitance range effective to provide a corresponding first maximum frequency range of adjustment of the resonant frequency of the rf structure, and said resonance controller has a first maximum response rate for adjusting said resonant frequency over said first range by varying the value of said electronically variable capacitance, and the accelerator further includes a movable tuning member for varying a reactance value associated with the rf structure and an actuator to move the tuning member, said movable tuning member and said actuator providing a maximum variable reactance value range effective to

provide a corresponding second maximum frequency range of adjustment of the resonant frequency of the rf structure and having a second maximum response rate, less than said first maximum rate, for adjusting said resonant frequency over said second range by moving said tuning member, said resonance controller being operative also to drive said actuator to vary said reactance value to keep a time average of the varying values of said electronically variable capacitance near the middle of said maximum variable capacitance range.

10. An accelerator as claimed in Claim 9, wherein said resonance controller has a minimum response rate for adjusting said resonant frequency by varying the value of said electronically variable capacitance, whereby said resonance controller does not vary the value of the electronically variable capacitance to oppose variations of the resonant frequency at below said minimum rate, said minimum rate being less than said second rate.

11. An accelerator as claimed in Claim 9, wherein said resonance controller is operative to drive said actuator in response to said resonance error signal.

12. An accelerator as claimed in Claim 10, wherein said resonance controller is operative to drive said actuator in response to a signal representing changes in the detected phase of the field in the rf structure relative to the drive phase of the rf amplifier.

13. An accelerator as claimed in any preceding claim, wherein said rf drive signal has a drive phase and said resonance detector comprises a phase detector to provide a signal representing the phase of rf field in the rf structure relative to said drive phase, as said

resonance error signal.

14. A method of controlling a radio frequency (rf) linear accelerator comprising at least one rf accelerating structure having capacitance and including an inductor arranged to provide a resonant circuit having a nominal resonant frequency,

the method comprising the steps of

a) generating and applying an rf drive voltage to excite the rf structure at said nominal resonant frequency;
b) detecting error between the actual resonant frequency of the rf structure and said nominal resonant frequency;
c) and controlling the value of an electronically variable capacitance coupled to said resonant circuit in response to said detected resonant frequency error to return the resonant frequency of the rf structure towards said nominal resonant frequency.

15. A method of controlling a radio frequency (rf) linear accelerator as claimed in Claim 14, wherein said value of an electronically variable capacitance is controlled with a first maximum rate of response to correct errors in the resonant frequency, and the method includes the further step of adjusting the position of a movable tuning member to vary a reactance value associated with the rf structure, with a second maximum rate of response to correct errors in the resonant frequency, said second maximum rate being less than said first maximum rate, whereby relatively slow resonant frequency errors are corrected by moving said movable tuning member and relatively fast resonant frequency errors are corrected by controlling the value of said electrically variable capacitance.

16. A method as claimed in either Claim 14 or Claim 15, wherein said resonant frequency error is detected by detecting the phase of field in the rf structure relative to the phase of the rf drive voltage.

17. A method of controlling a radio frequency (rf) linear accelerator comprising at least one rf accelerating structure having capacitance and including an inductor arranged to provide a resonant circuit having a nominal resonant frequency,

the method comprising the step of

adjusting the value of an electrically variable capacitance coupled to said resonant circuit to maintain the actual resonant frequency of said resonant circuit of said rf structure at said nominal resonant frequency.

18. A method of controlling a radio frequency (rf) linear accelerator as claimed in Claim 17, wherein the actual resonant frequency of said resonant circuit is liable to a relatively high rate variation due at least to mechanical vibration, and is liable to a relatively low rate variation due at least to thermal drift, and said high rate variation is countered by said step of adjusting the value of said electronically variable capacitance, the method comprising the further step of adjusting the position of a movable tuning member to vary a reactance value of the rf structure, to counter said low rate variation.

Application No: GB 0123977.1
Claims searched: All

Examiner: Carol Ann McQueen
Date of search: 21 March 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): H1D (DAB4, DHC, DHX, DL)

Int Cl (Ed.7): H01J 37/30, 37/317, H05H 7/00, 7/02, 7/16, 7/18, 7/22, 9/00, 9/04

Other: ONLINE: EPODOC, JAPIO, WPI, OPTICS

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	EP 1056113 A2	(APPLIED MATERIALS) Whole document	1, 14 and 17
A, E	WO 01/93646 A2	(AXCELIS TECHNOLOGIES INC) Whole document	1, 14 and 17
A	JP 030179699 A	(KOBE STEEL LTD) Whole document	1, 14 and 17
A	US 4667111	(EATON CORPORATION) Whole document	1, 14 and 17

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		