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(54) **INTERRUPTED PARTICLE SOURCE**

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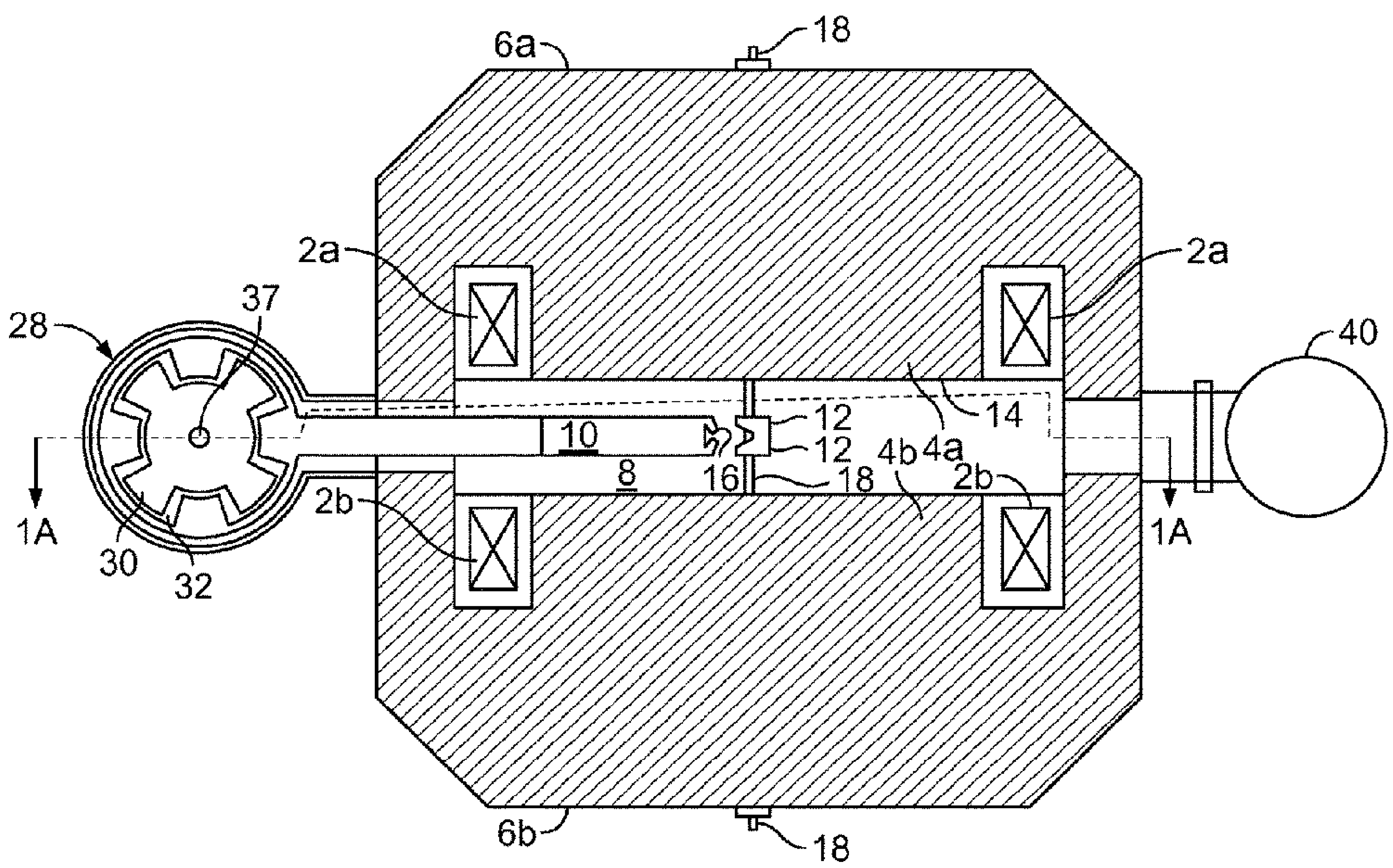
(57) **ABSTRACT**

A synchrocyclotron includes magnetic structures to provide a magnetic field to a cavity, a particle source to provide a plasma column to the cavity, where the particle source has a housing to hold the plasma column, and where the housing is interrupted at an acceleration region to expose the plasma column, and a voltage source to provide a radio frequency (RF) voltage to the cavity to accelerate particles from the plasma column at the acceleration region.

62 Claims, 9 Drawing Sheets



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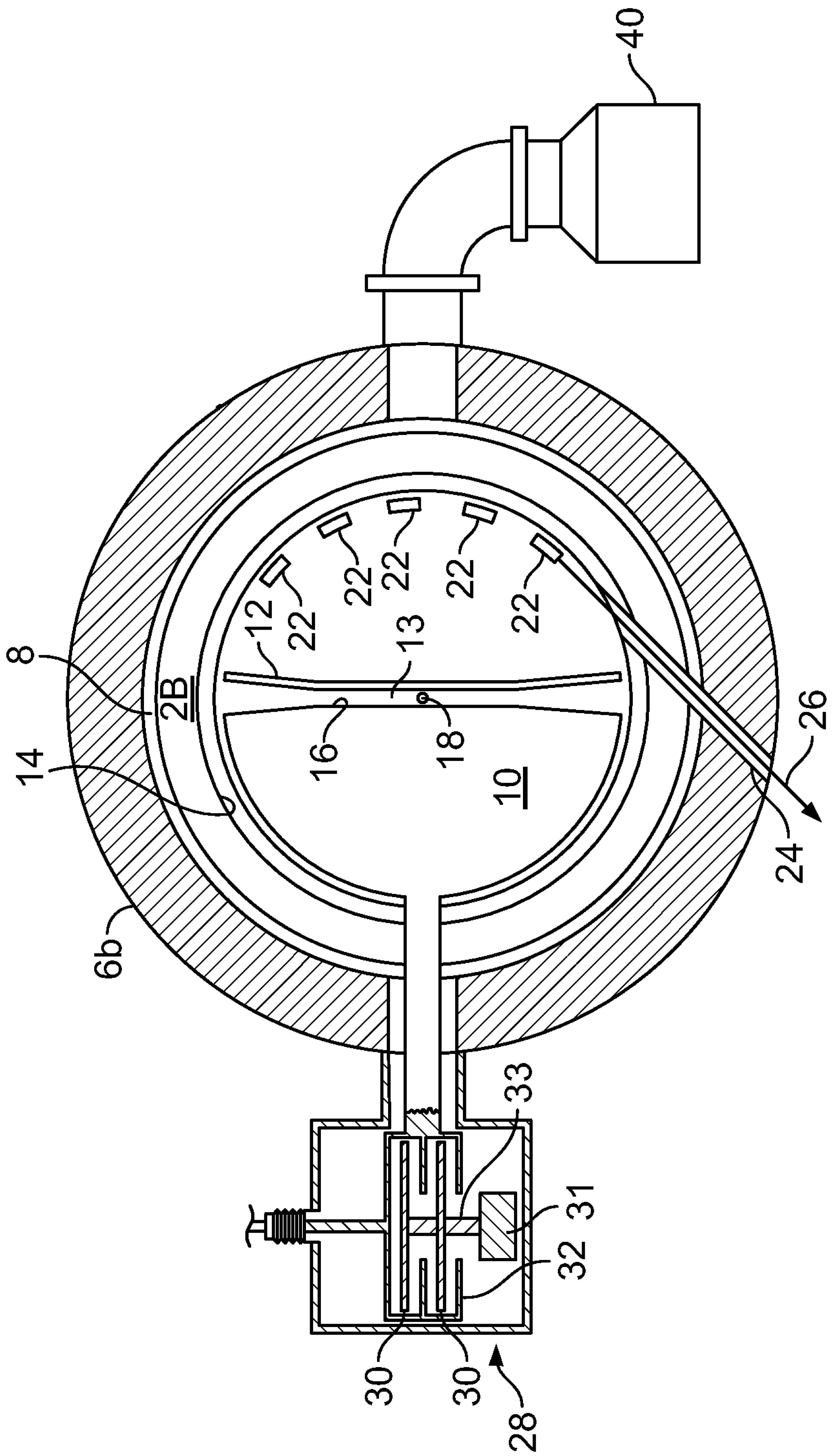


FIG. 1A

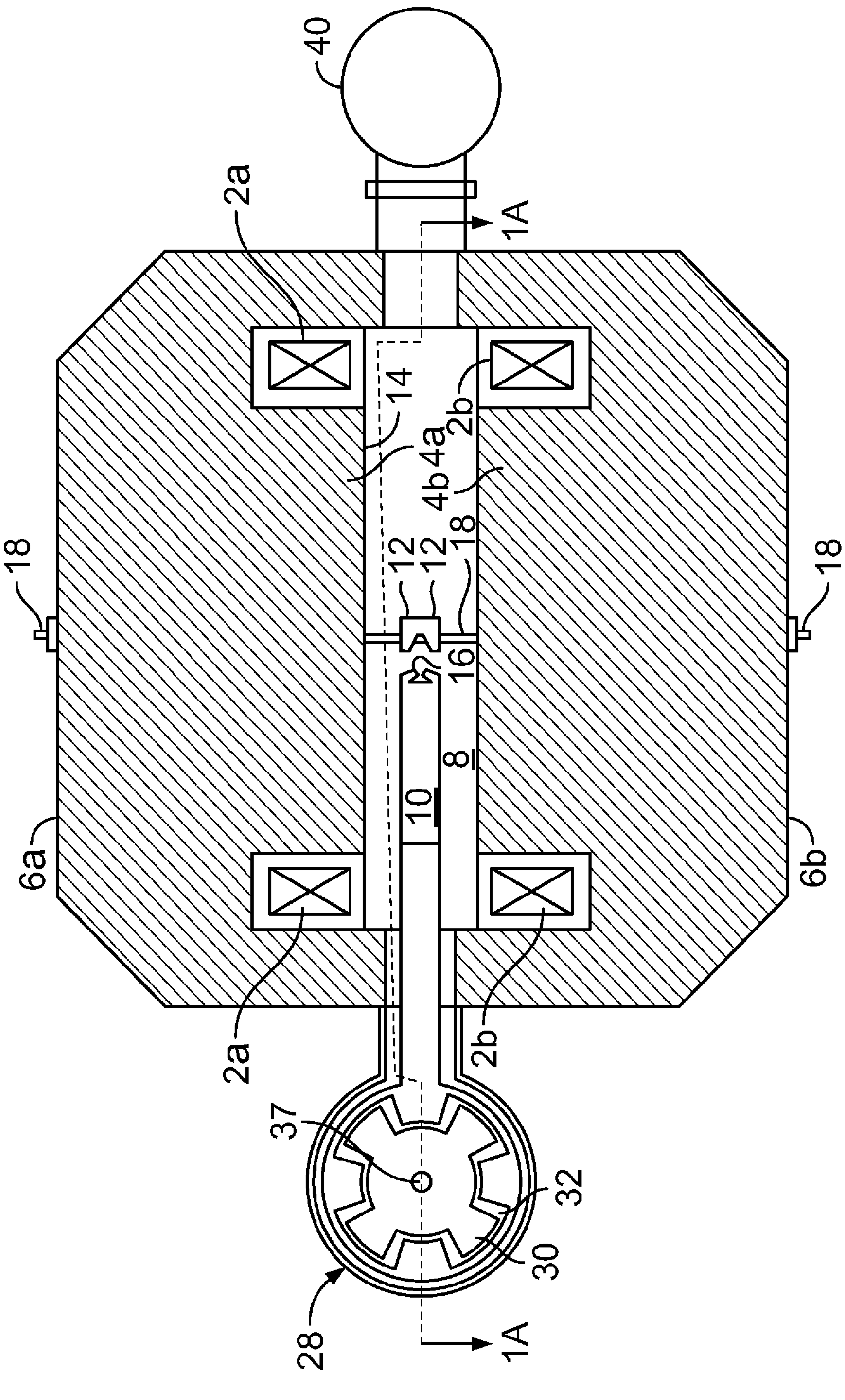
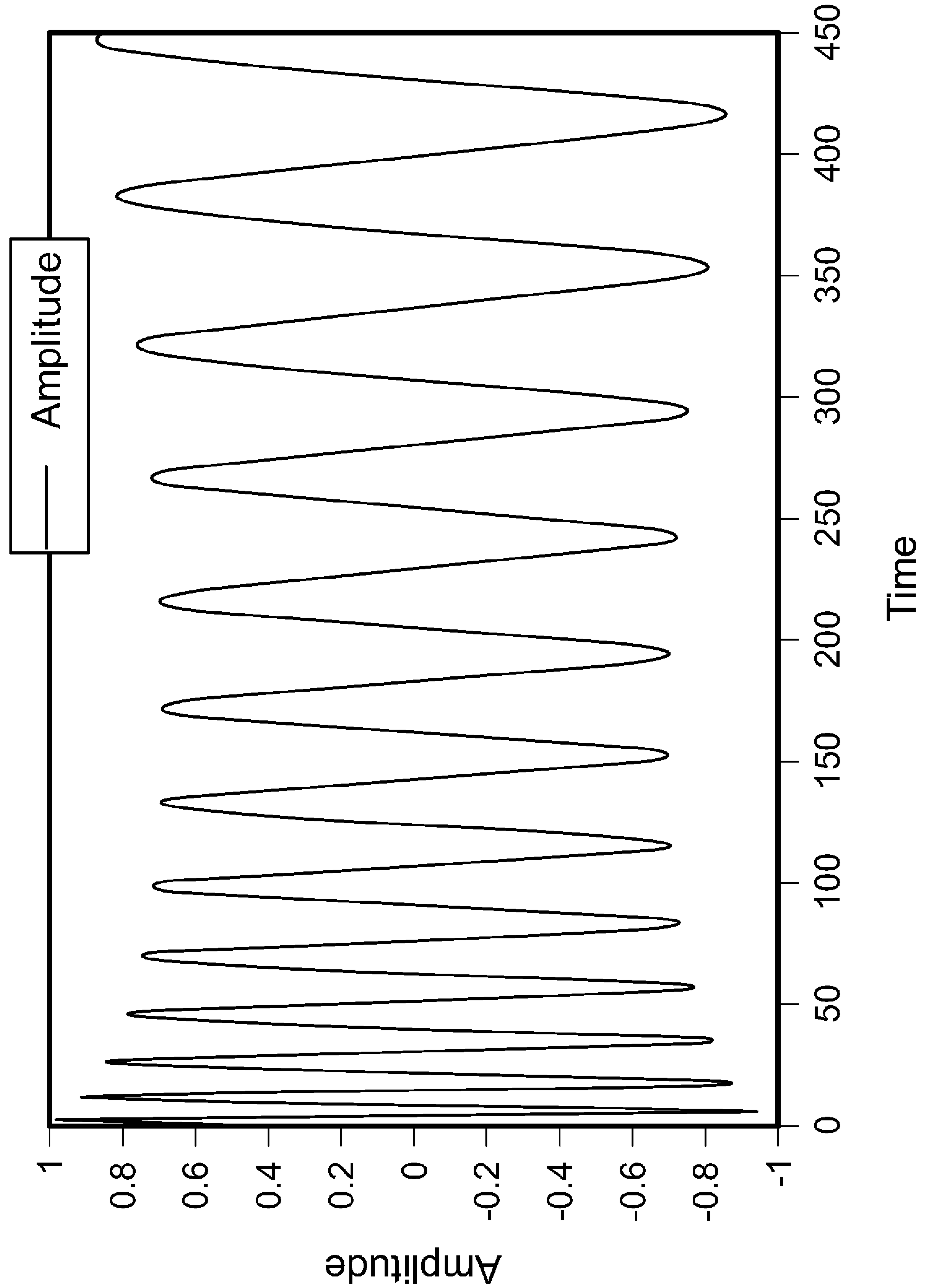


FIG. 1B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Amplitude
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0.4
0.2
0
-0.2
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-1
0
50
100
150
200
250
300
350
400
450
Time

FIG. 2

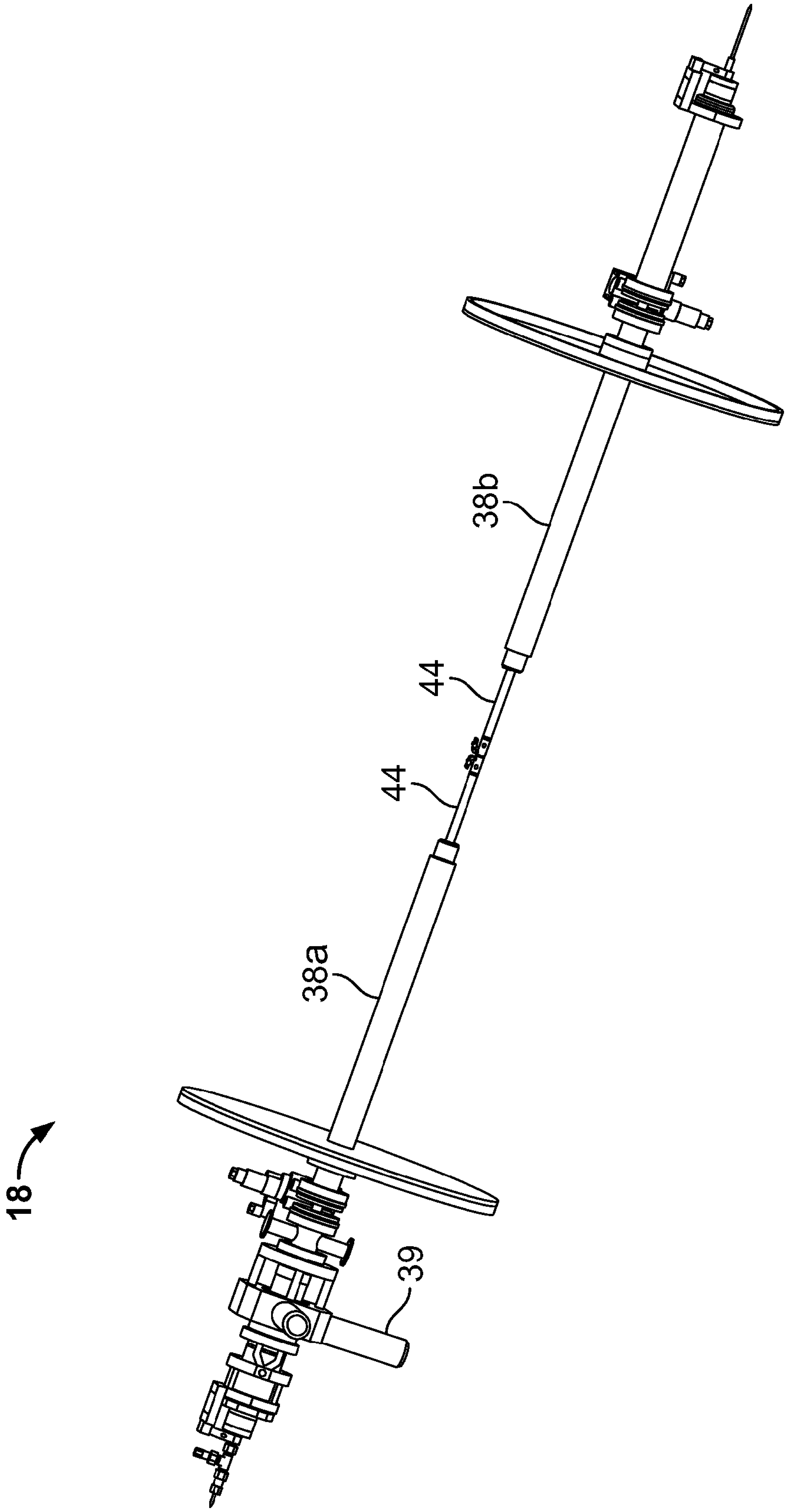

FIG. 3A

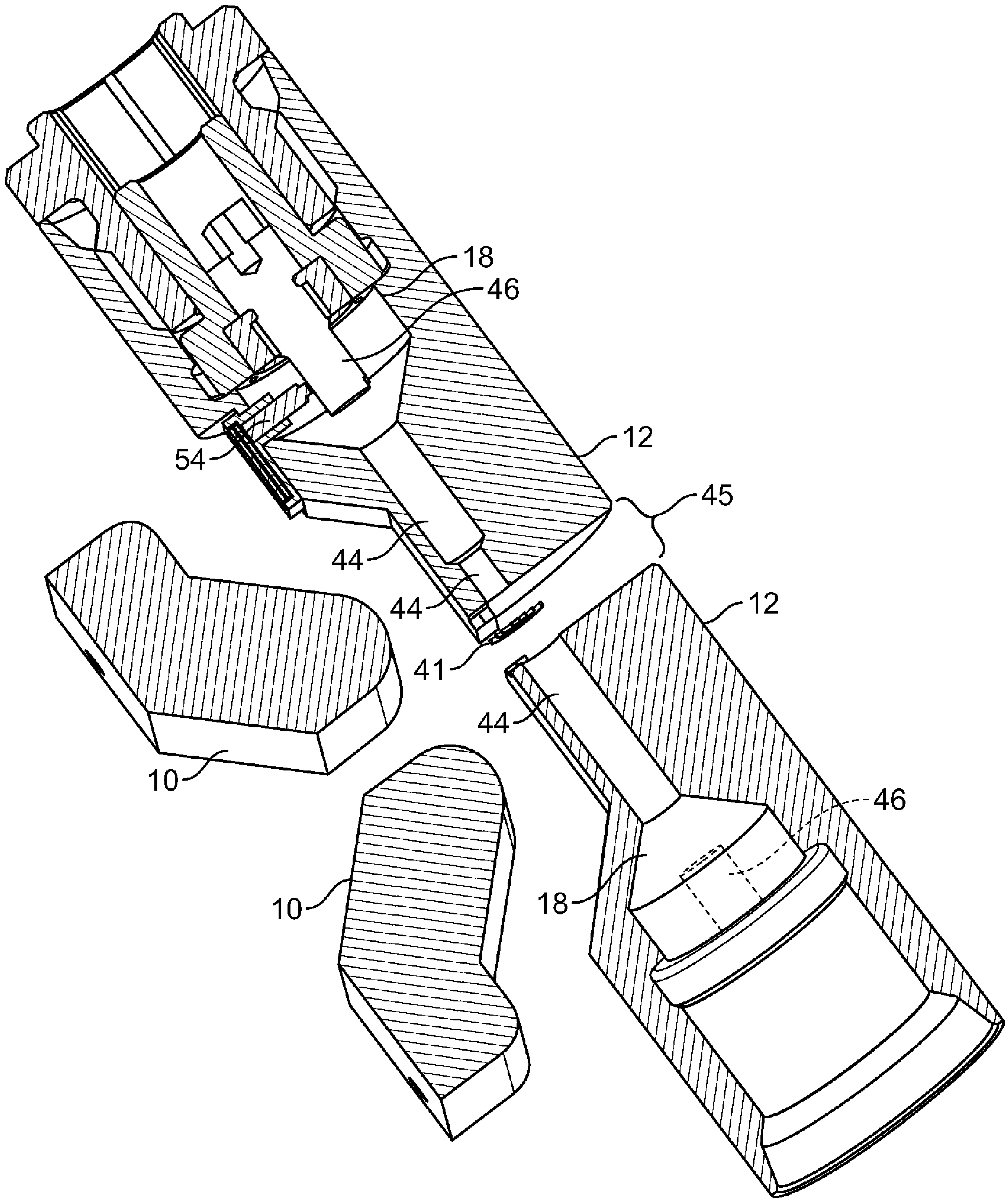

FIG. 3B

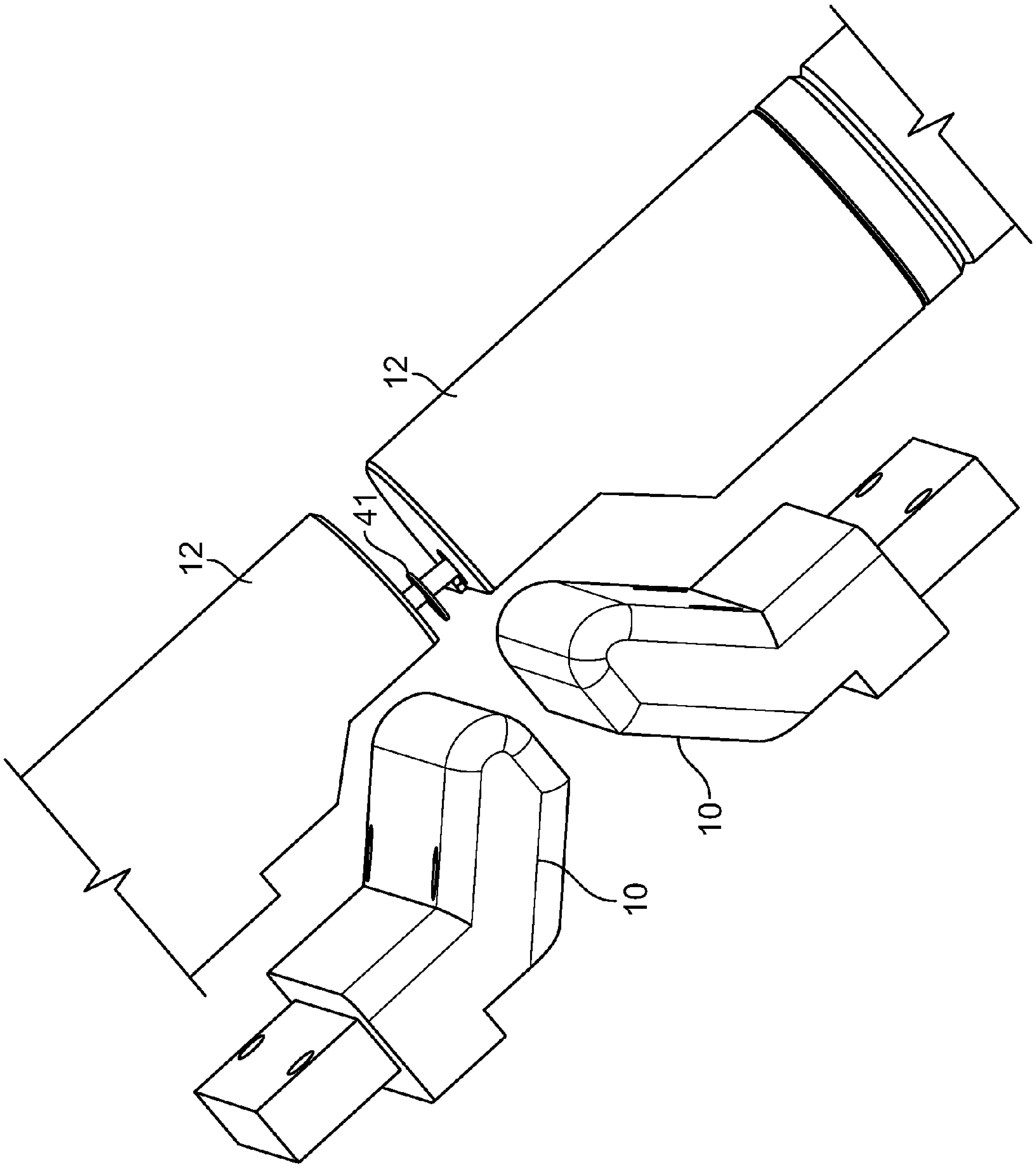

FIG. 4

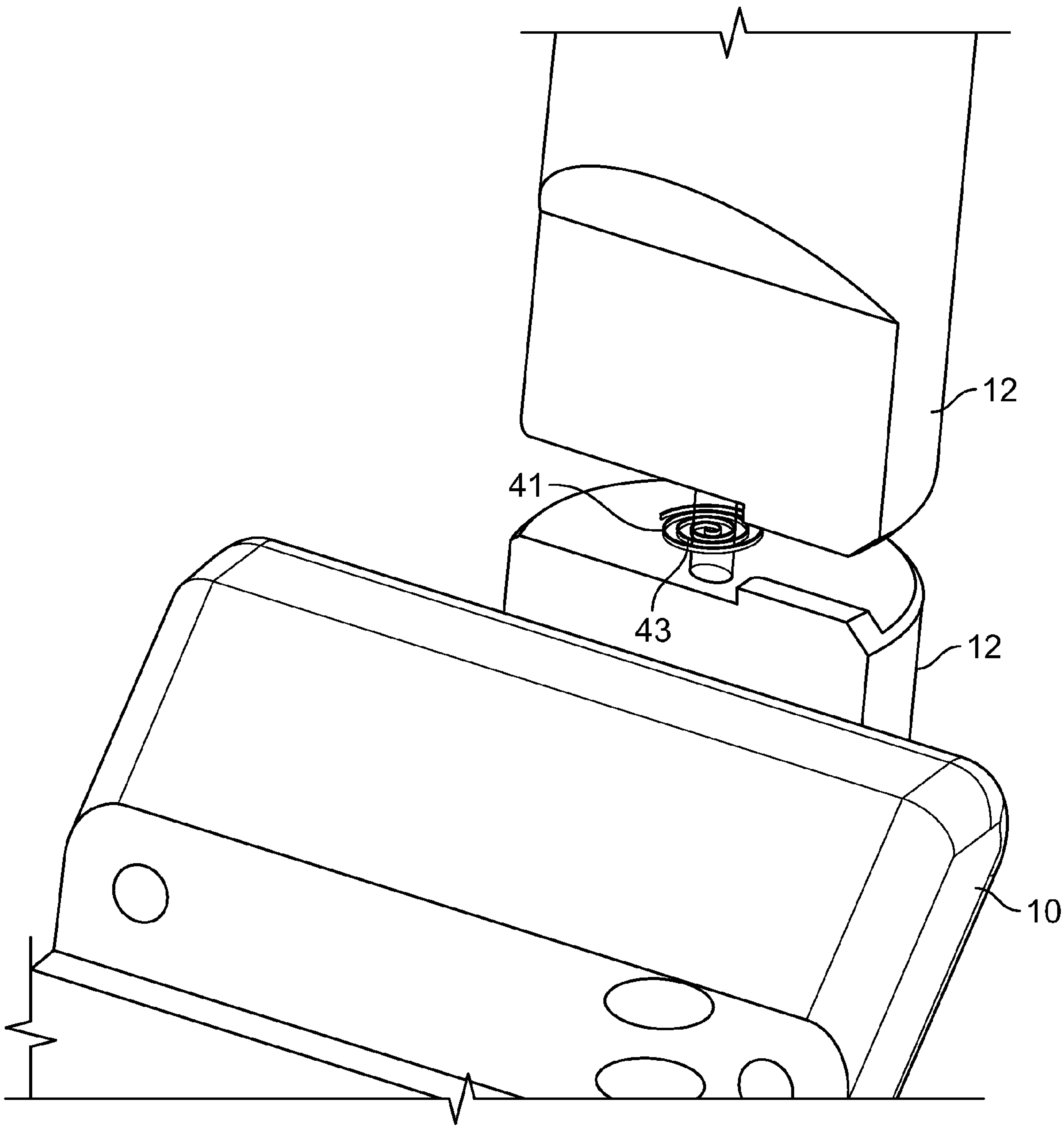

FIG. 5

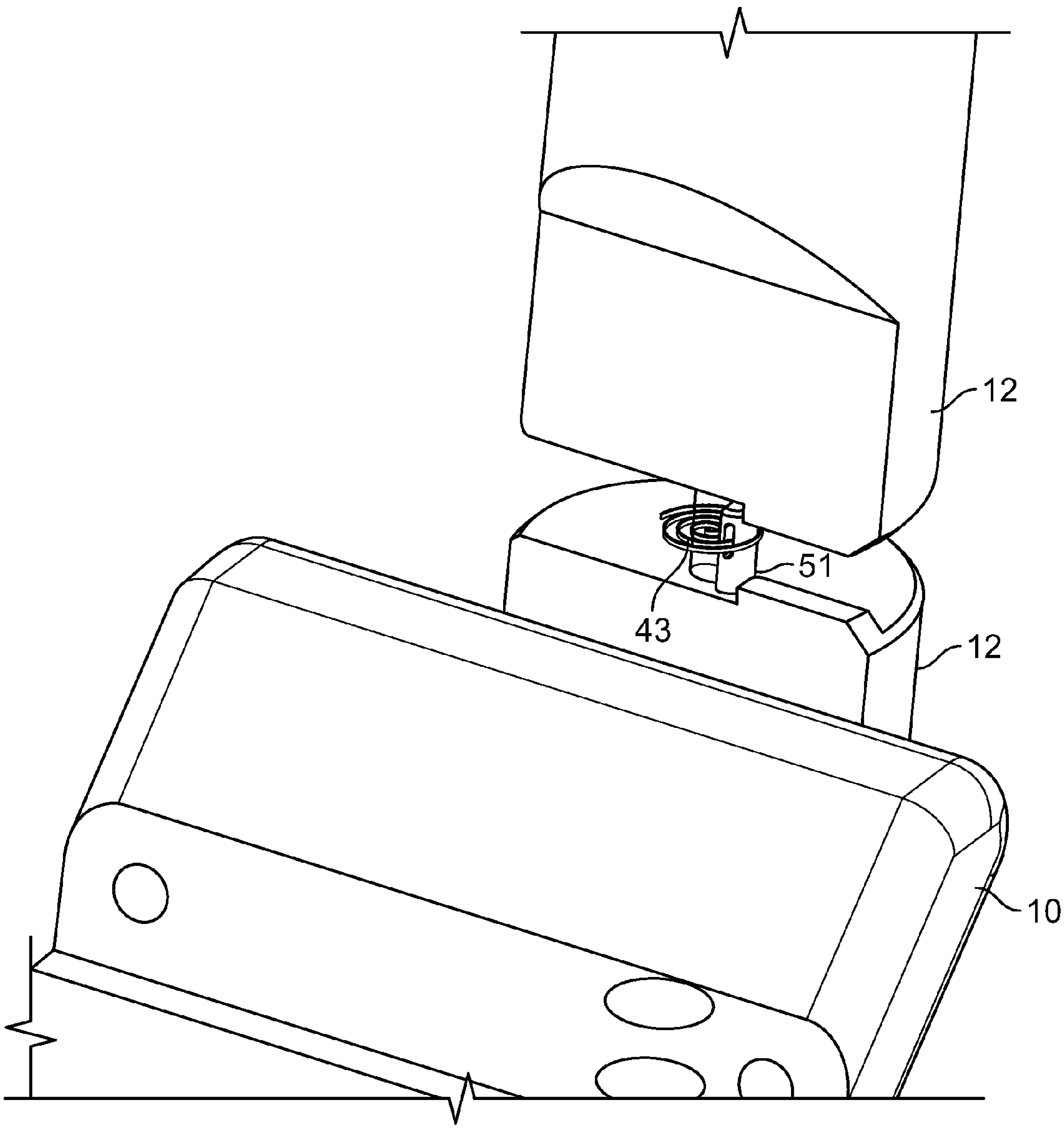

FIG. 6

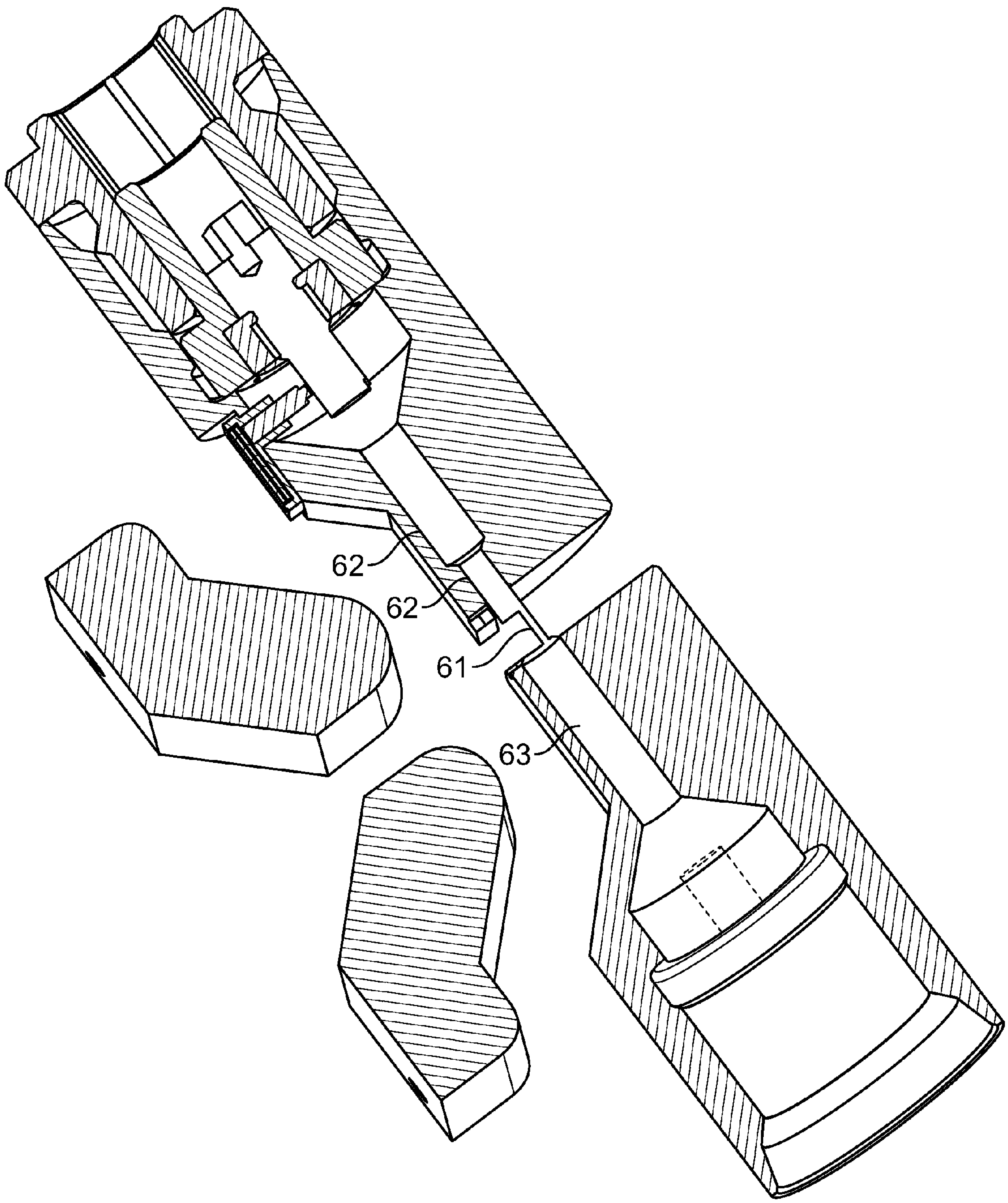

FIG. 7

INTERRUPTED PARTICLE SOURCE

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS-REFERENCE TO RELATED APPLICATION

This [patent] application *a reissue application of U.S. application Ser. No. 14/075,261 filed on Nov. 8, 2013 now U.S. Pat. No. 8,970,137, which* is a continuation of U.S. application Ser. No. 11/948,662, which was filed on Nov. 30, 2007 [and which is scheduled to issue as] *now* U.S. Pat. No. 8,581,523 [on Nov. 12, 2013]. The contents of U.S. application Ser. No. 11/948,662 are incorporated herein by reference.

TECHNICAL FIELD

This patent application describes a particle accelerator having a particle source that is interrupted at an acceleration region.

BACKGROUND

In order to accelerate charged particles to high energies, many types of particle accelerators have been developed. One type of particle accelerator is a cyclotron. A cyclotron accelerates charged particles in an axial magnetic field by applying an alternating voltage to one or more dees in a vacuum chamber. The name dee is descriptive of the shape of the electrodes in early cyclotrons, although they may not resemble the letter D in some cyclotrons. The spiral path produced by the accelerating particles is perpendicular to the magnetic field. As the particles spiral out, an accelerating electric field is applied at the gap between the dees. The radio frequency (RF) voltage creates an alternating electric field across the gap between the dees. The RF voltage, and thus the field, is synchronized to the orbital period of the charged particles in the magnetic field so that the particles are accelerated by the radio frequency waveform as they repeatedly cross the gap. The energy of the particles increases to an energy level greatly in excess of the peak voltage of the applied RF voltage. As the charged particles accelerate, their masses grow due to relativistic effects. Consequently, the acceleration of the particles varies the phase match at the gap.

Two types of cyclotrons presently employed, an isochronous cyclotron and a synchrocyclotron, overcome the challenge of increase in relativistic mass of the accelerated particles in different ways. The isochronous cyclotron uses a constant frequency of the voltage with a magnetic field that increases with radius to maintain proper acceleration. The synchrocyclotron uses a decreasing magnetic field with increasing radius to provide axial focusing and varies the frequency of the accelerating voltage to match the mass increase caused by the relativistic velocity of the charged particles.

SUMMARY

In general, this patent application describes a synchrocyclotron comprising magnetic structures to provide a magnetic field to a cavity, and a particle source to provide a plasma column to the cavity. The particle source has a housing to hold the plasma column. The housing is interrupted at an acceleration region to expose the plasma column. A voltage source is configured to provide a radio frequency (RF) voltage to the cavity to accelerate particles from the plasma column at the acceleration region. The synchrocyclotron described above may include one or more of the following features, either alone or in combination.

The magnetic field may be above 2 Tesla (T), and the particles may accelerate from the plasma column outwardly in spirals with radii that progressively increase. The housing may comprise two portions that are completely separated at the acceleration region to expose the plasma column. The voltage source may comprise a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground. At least part of the particle source may pass through the second dee. The synchrocyclotron may comprise a stop in the acceleration region. The stop may be for blocking acceleration of at least some of the particles from the plasma column. The stop may be substantially orthogonal to the acceleration region and may be configured to block certain phases of particles from the plasma column.

The synchrocyclotron may comprise cathodes for use in generating the plasma column. The cathodes may be operable to pulse a voltage to ionize gas to generate the plasma column. The cathodes may be configured to pulse at voltages between about 1 kV to about 4 kV. The cathodes need not be heated by an external heat source. The synchrocyclotron may comprise a circuit to couple voltage from the RF voltage to the at least one of the cathodes. The circuit may comprise a capacitive circuit.

The magnetic structures may comprise magnetic yokes. The voltage source may comprise a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground. The first dee and the second dee may form a tunable resonant circuit. The cavity to which the magnetic field is applied may comprise a resonant cavity containing the tunable resonant circuit.

In general, this patent application also describes a particle accelerator comprising a tube containing a gas, a first cathode adjacent to a first end of the tube, and a second cathode adjacent to a second end of the tube. The first and second cathodes are for applying voltage to the tube to form a plasma column from the gas. Particles are available to be drawn from the plasma column for acceleration. A circuit is configured to couple energy from an external radio frequency (RF) field to at least one of the cathodes. The particle accelerator described above may include one or more of the following features, either alone or in combination.

The tube may be interrupted at an acceleration region at which the particles are drawn from the plasma column. The first cathode and the second cathode need not be heated by an external source. The first cathode may be on a different side of the acceleration region than the second cathode.

The particle accelerator may comprise a voltage source to provide the RF field. The RF field may be for accelerating the particles from the plasma column at the acceleration region. The energy may comprise a portion of the RF field provided by the voltage source. The circuit may comprise a capacitor to couple energy from the external field to at least one of the first cathode and the second cathode.

The tube may comprise a first portion and a second portion that are completely separated at a point of interruption at the acceleration region. The particle accelerator may comprise a stop at the acceleration region. The stop may be used to block at least one phase of the particles from further acceleration.

The particle accelerator may comprise a voltage source to provide the RF field to the plasma column. The RF field may be for accelerating the particles from the plasma column at the acceleration region. The RF field may comprise a voltage that is less than 15 kV. Magnetic yokes may be used to provide a magnetic field that crosses the acceleration region. The magnetic field may be greater than about 2 Tesla (T).

In general, this patent application also describes a particle accelerator comprising a Penning ion gauge (PIG) source comprising a first tube portion and a second tube portion that are at least partially separated at an acceleration region. The first tube portion and the second tube portion are for holding a plasma column that extends across the acceleration region. A voltage source is used to provide a voltage at the acceleration region. The voltage is for accelerating particles out of the plasma column at the acceleration region. The particle accelerator described above may include one or more of the following features, either alone or in combination.

The first tube portion and the second tube portion may be completely separated from each other. Alternatively, only one or more portions of the first tube portion may be separated from corresponding portions of the second tube portion. In this latter configuration, the PIG source may comprise a physical connection between a part of the first tube portion and the second tube portion. The physical connection may enable particles accelerating out of the plasma column to complete a first turn upon escaping from the plasma column without running into the physical connection.

The PIG source may pass through a first dee that is electrically connected to ground. A second dee that is electrically connected to an alternating voltage source may provide the voltage at the acceleration region.

The particle accelerator may comprise a structure that substantially encloses the PIG source. The particle accelerator may comprise magnetic yokes that define a cavity containing the acceleration region. The magnetic yokes may be for generating a magnetic field across the acceleration region. The magnetic field may be at least 2 Tesla (T). For example, the magnetic field may be at least 10.5 T. The voltage may comprise a radio frequency (RF) voltage that is less than 15 kV.

The particle accelerator may comprise one or more electrodes for use in accelerating the particles out of the particle accelerator. At least one cathode may be used in generating the plasma column. The at least one cathode used in generating the plasma column may comprise a cold cathode (e.g., one that is not heated by an external source). A capacitive circuit may couple at least some of the voltage to the cold cathode. The cold cathode may be configured to pulse voltage to generate the plasma column from gas in the first tube portion and the second tube portion.

Any of the foregoing features may be combined to form implementations not specifically described herein.

The details of one or more examples are set forth in the accompanying drawings and the description below. Further features, aspects, and advantages will become apparent from the description, the drawings, and the claims.

DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a cross-sectional view of a synchrocyclotron.

FIG. **1**B is a side cross-sectional view of the synchrocyclotron shown in FIG. **1**A.

FIG. **2** is an illustration of an idealized waveform that can be used for accelerating charged particles in the synchrocyclotron of FIGS. **1**A and **1**B.

FIG. **3**A is a side view of a particle source, such as a Penning ion gauge source.

FIG. **3**B is a close-up side view of a portion of the particle source of FIG. **3**A passing through a dummy dee and adjacent to an RF dee.

FIG. **4** is a side view of the particle source of FIG. **3** showing spiral acceleration of a particle from a plasma column generated by the particle source.

FIG. **5** is a perspective view of the particle source of FIG. **4**

FIG. **6** is a perspective view of the particle source of FIG. **4** containing a stop for blocking one or more phases of particles.

FIG. **7** is a perspective view of an alternative embodiment, in which a substantial portion of the ion source is removed.

DETAILED DESCRIPTION

A synchrocyclotron-based system is described herein. However, the circuits and methods described herein may used with any type of cyclotron or particle accelerator.

Referring to FIGS. **1**A and **1**B, a synchrocyclotron **1** includes electrical coils **2**a and **2**b around two spaced apart ferro-magnetic poles **4**a and **4**b, which are configured to generate a magnetic field. Magnetic poles **4**a and **4**b are defined by two opposing portions of yokes **6**a and **6**b (shown in cross-section). The space between poles **4**a and **4**b defines vacuum chamber **8** or a separate vacuum chamber can be installed between poles **4**a and **4**b. The magnetic field strength is generally a function of distance from the center of vacuum chamber **8** and is determined largely by the choice of geometry of coils **2**a and **2**b and the shape and material of magnetic poles **4**a and **4**b.

The accelerating electrodes are defined as dee **10** and dee **12**, having gap **13** between them. Dee **10** is connected to an alternating voltage potential whose frequency is changed from high to low during an accelerating cycle in order to account for the increasing relativistic mass of a charged particle and radially decreasing magnetic field (measured from the center of vacuum chamber **8**) produced by coils **2**a and **2**b and pole portions **4**a and **4**b. Accordingly, dee **10** is referred to as the radio frequency (RF) dee. The idealized profile of the alternating voltage in dees **10** and **12** is show in FIG. **2** and will be discussed in detail below. In this example, RF dee **10** is a half-cylinder structure, which is hollow inside. Dee **12**, also referred to as the "dummy dee", does not need to be a hollow cylindrical structure, since it is grounded at the vacuum chamber walls **14**. Dee **12**, as shown in FIGS. **1**A and **1**B, includes a strip of metal, e.g., copper, having a slot shaped to match a substantially similar slot in RF dee **10**. Dee **12** can be shaped to form a mirror image of surface **16** of RF dee **10**.

Ion source **18** is located at about the center of vacuum chamber **8**, and is configured to provide particles (e.g., protons) at a center of the synchrocyclotron for acceleration, as described below. Extraction electrodes **22** direct the charged particles from an acceleration region into extraction channel **24**, thereby forming beam **26** of the charged particles. Here, ion source **18** is inserted axially into the acceleration region.

Dees **10** and **12** and other pieces of hardware included in a synchrocyclotron define a tunable resonant circuit under an oscillating voltage input that creates an oscillating electric field across gap **13**. The result is a resonant cavity in vacuum chamber **8**. This resonant frequency of the resonant cavity can be tuned to keep its Q-factor high by synchronizing the frequency being swept. In one example, the resonant frequency of the resonant cavity moves, or "sweeps", within a range of about 30 Megahertz (MHz) and about 135 MHz (VHF range) over time, e.g., over about 1 millisecond (ms). In another example, the resonant frequency of the resonant cavity moves, or sweeps, between about 95 MHz and about 135 MHz in about 1 ms. Resonance of the cavity may be controlled in the manner described in U.S. patent application Ser. No. 11/948,359, entitled "Matching A Resonant Frequency Of A Resonant Cavity To A Frequency Of An Input Voltage", the contents of which are incorporated herein by reference as if set forth in full.

The Q-factor is a measure of the "quality" of a resonant system in its response to frequencies close to the resonant frequency. In this example, the Q-factor is defined as

$$Q=1/R\times\sqrt{(L/C)},$$

where R is the active resistance of the resonant circuit, L is the inductance, and C is the capacitance of the resonant circuit.

The tuning mechanism can be, e.g., a variable inductance coil or a variable capacitance. A variable capacitance device can be a vibrating reed or a rotating capacitor. In the example shown in FIGS. **1**A and **1**B, the tuning mechanism includes rotating capacitor **28**. Rotating capacitor **28** includes rotating blades **30** that are driven by a motor **31**. During each cycle of motor **31**, as blades **30** mesh with blades **32**, the capacitance of the resonant circuit that includes dees **10** and **12** and rotating capacitor **28** increases and the resonant frequency decreases. The process reverses as the blades unmesh. Thus, the resonant frequency is changed by changing the capacitance of the resonant circuit. This serves the purpose of reducing, by a large factor, the power required to generate the high voltage applied at the dee/dummy dee gap at the frequency necessary to accelerate the particle beam. The shape of blades **30** and **32** can be machined so as to create the required dependence of resonant frequency on time.

The blade rotation can be synchronized with RF frequency generation so the frequency of the resonant circuit defined by the synchrocyclotron is kept close to the frequency of the alternating voltage potential applied to the resonant cavity. This promotes efficient transformation of applied RF power to RF voltage on the RF dee.

A vacuum pumping system **40** maintains vacuum chamber **8** at a very low pressure so as not to scatter the accelerating beam (or to provide relatively little scattering) and to substantially prevent electrical discharges from the RF dee.

To achieve substantially uniform acceleration in the synchrocyclotron, the frequency and the amplitude of the electric field across the dee gap is varied to account for the relativistic mass increase and radial variation of magnetic field as well as to maintain focus of the beam of particles. The radial variation of the magnetic field is measured as a distance from the center of an outwardly spiraling trajectory of a charged particle.

FIG. **2** is an illustration of an idealized waveform that may be required for accelerating charged particles in a synchrocyclotron. It shows only a few cycles of the waveform and does not necessarily represent the ideal frequency and amplitude modulation profiles. FIG. **2** illustrates the time varying amplitude and frequency properties of the waveform used in the synchrocyclotron. The frequency changes from high to low as the relativistic mass of the particle increases while the particle speed approaches a significant fraction of the speed of light.

Ion source **18** is deployed near to the magnetic center of synchrocyclotron **1** so that particles are present at the synchrocyclotron mid-plane, where they can be acted upon by the RF field (voltage). The ion source may have a Penning ion gauge (PIG) geometry. In the PIG geometry, two high voltage cathodes are placed about opposite each other. For example, one cathode may be on one side of the acceleration region and one cathode may be on the other side of the acceleration region and in line with the magnetic field lines. The dummy dee housings **12** of the source assembly may be at ground potential. The anode includes a tube extending toward the acceleration region. When a relatively small amount of a gas (e.g., hydrogen/H_2) occupies a region in the tube between the cathodes, a plasma column may be formed from the gas by applying a voltage to the cathodes. The applied voltage causes electrons to stream along the magnetic field lines, essentially parallel to the tube walls, and to ionize gas molecules that are concentrated inside the tube, thereby creating the plasma column.

A PIG geometry ion source **18**, for use in synchrocyclotron **1**, is shown in FIGS. **3**A and **3**B. Referring to FIG. **3**A, ion source **18** includes an emitter side **38**a containing a gas feed **39** for receiving gas, and a reflector side **38**b. A housing, or tube, **44** holds the gas, as described below. FIG. **3**B shows ion source **18** passing through dummy dee **12** and adjacent to RF dee **10**. In operation, the magnetic field between RF dee **10** and dummy dee **12** causes particles (e.g., protons) to accelerate outwardly. The acceleration is spiral about the plasma column, with the particle-to-plasma-column radius progressively increasing. The spiral acceleration, labeled **43**, is depicted in FIGS. **5** and **6**. The radii of curvature of the spirals depend on a particle's mass, energy imparted to the particle by the RF field, and a strength of the magnetic field.

When the magnetic field is high, it can become difficult to impart enough energy to a particle so that it has a large enough radius of curvature to clear the physical housing of the ion source on its initial turn(s) during acceleration. The magnetic field is relatively high in the region of the ion source, e.g., on the order of 2 Tesla (T) or more (e.g., 8 T, 8.8 T, 8.9 T, 9 T, 10.5 T, or more). As a result of this relatively high magnetic field, the initial particle-to-ion-source radius is relatively small for low energy particles, where low energy particles include particles that are first drawn from the plasma column. For example, such a radius may be on the order of 1 mm. Because the radii are so small, at least initially, some particles may come into contact with the ion source's housing area, thereby preventing further outward acceleration of such particles. Accordingly, the housing of ion source **18** is interrupted, or separated to form two parts, as shown in FIG. **3**B. That is, a portion of the ion source's housing is removed at the acceleration region **41**, e.g., at about the point where the particles are to be drawn from the ion source. This interruption is labeled **45** in FIG. **3**B. The housing may also be removed for distances above, and below, the acceleration region. All or part of dummy dee **12** at the acceleration region may, or may not, also be removed.

In the example of FIGS. **3**A and **3**B, the housing **44** includes a tube, which holds a plasma column containing particles to be accelerated. The tube may have different diameters at different points, as shown. The tube may reside within dummy dee **12**, although this is not necessary. A portion of the tube in about a median plane of the synchrocyclotron is completely removed, resulting in a housing comprised of two separate portions with an interruption **45** between the portions. In this example, the interruption is about 1 millimeter (mm) to 3 mm (i.e., about 1 mm to 3 mm of the tube is removed). The amount of the tube that is removed may be significant enough to permit particle acceleration from the plasma column, but small enough to hinder significant dissipation of the plasma column in the interrupted portion.

By removing the physical structure, here the tube, at the particle acceleration region, particles can make initial turn(s) at relatively small radii—e.g., in the presence of relatively high magnetic fields—without coming in to contact with physical structures that impede further acceleration. The initial turn(s) may even cross back through the plasma column, depending upon the strength of the magnetic and RF fields.

The tube may have a relatively small interior diameter, e.g., about 2 mm. This leads to a plasma column that is also relatively narrow and, therefore, provides a relatively small set of original radial positions at which the particles can start accelerating. The tube is also sufficiently far from cathodes **46** used to produce the plasma column—in this example, about 10 mm from each cathode. These two features, combined, reduce the amount of hydrogen (H_2) gas flow into the synchrocyclotron to less than 1 standard cubic centimeter per minute (SCCM), thereby enabling the synchrocyclotron to operate with relatively small vacuum conductance apertures into the synchrocyclotron RF/beam cavity and relatively small capacity vacuum pump systems, e.g., about 500 liters-per-second.

Interruption of the tube also supports enhanced penetration of the RF field into the plasma column. That is, since there is no physical structure present at the interruption, the RF field can easily reach the plasma column. Furthermore, the interruption in the tube allows particles to be accelerated from the plasma column using different RF fields. For example, lower RF fields may be used to accelerate the particles. This can reduce the power requirements of systems used to generate the RF field. In one example, a 20 kilowatt (kW) RF system generates an RF field of 15 kilovolts (kV) to accelerate particles from the plasma column. The use of lower RF fields reduces RF system cooling requirements and RF voltage standoff requirements.

In the synchrocyclotron described herein, a particle beam is extracted using a resonant extraction system. That is, the amplitude of radial oscillations of the beam are increased by a magnetic perturbation inside the accelerator, which is in resonance with these oscillations. When a resonant extraction system is used, extraction efficiency is improved by limiting the phase space extent of the internal beam. With attention to the design of the magnetic and RF field generating structures, the phase space extent of the beam at extraction is determined by the phase space extent at the beginning of acceleration (e.g., at emergence from the ion source). As a result, relatively little beam may be lost at the entrance to the extraction channel and background radiation from the accelerator can be reduced.

A physical structure, or stop, may be provided to control the phase of the particles that are allowed to escape from the central region of the synchrocyclotron. An example of such a stop **51** is shown in FIG. **6**. Stop **51** acts as a obstacle that blocks particles having certain phases. That is, particles that hit the stop are prevented from accelerating further, whereas particles that pass the stop continue their acceleration out of the synchrocyclotron. A stop may be near the plasma column, as shown in FIG. **6**, in order to select phases during the initial turn(s) of particles where the particle energy is low, e.g., less than 50 kV. Alternatively, a stop may be located at any other point relative to the plasma column. In the example shown in FIG. **6**, a single stop is located on the dummy dee **12**. There, however, may be more than one stop (not shown) per dee.

Cathodes **46** may be "cold" cathodes. A cold cathode may be a cathode that is not heated by an external heat source. Also, the cathodes may be pulsed, meaning that they output signal burst(s) periodically rather than continuously. When the cathodes are cold, and are pulsed, the cathodes are less subject to wear and can therefore last relatively long. Furthermore, pulsing the cathodes can eliminate the need to watercool the cathodes. In one implementation, cathodes **46** pulse at a relatively high voltage, e.g., about 1 kV to about 4 kV, and moderate peak cathode discharge currents of about 50 mA to about 200 mA at a duty cycle between about 0.1% and about 1% or 2% at repetition rates between about 200 Hz to about 1 KHz.

Cold cathodes can sometimes cause timing jitter and ignition delay. That is, lack of sufficient heat in the cathodes can affect the time at which electrons are discharged in response to an applied voltage. For example, when the cathodes are not sufficiently heated, the discharge may occur several microseconds later, or longer, than expected. This can affect formation of the plasma column and, thus, operation of the particle accelerator. To counteract these effects, voltage from the RF field in cavity **8** may be coupled to the cathodes. Cathodes **46** are otherwise encased in a metal, which forms a Faraday shield to substantially shield the cathodes from the RF field. In one implementation, a portion of the RF energy may be coupled to the cathodes from the RF field, e.g., about 100V may be coupled to the cathodes from the RF field. FIG. **3**B shows an implementation, in which a capacitive circuit **54**, here a capacitor, is charged by the RF field and provides voltage to a cathode **46**. An RF choke and DC feed may be used to charge the capacitor. A corresponding arrangement (not shown) may be implemented for the other cathode **46**. The coupled RF voltage can reduce the timing jitter and reduce the discharge delay to about 100 nanoseconds (ns) or less in some implementations.

An alternative embodiment is shown in FIG. **7**. In this embodiment, a substantial portion, but not all, of the PIG source housing is removed, leaving the plasma beam partly exposed. Thus, portions of the PIG housing are separated from their counterpart portions, but there is not complete separation as was the case above. The portion **61** that remains physically connects the first tube portion **62** and the second tube portion **63** of the PIG source. In this embodiment, enough of the housing is removed to enable particles to perform at least one turn (orbit) without impinging on the portion **61** of the housing that remains. In one example, the first turn radius may be 1 mm, although other turn radii may be implemented. The embodiment shown in FIG. **7** may be combined with any of the other features described herein.

The particle source and accompanying features described herein are not limited to use with a synchrocyclotron, but rather may be used with any type of particle accelerator or cyclotron. Furthermore ion sources other than those having a PIG geometry may be used with any type of particle accelerator, and may have interrupted portions, cold cathodes, stops, and/or any of the other features described herein.

Components of different implementations described herein may be combined to form other embodiments not specifically set forth above. Other implementations not specifically described herein are also within the scope of the following claims.

What is claimed is:

1. A synchrocyclotron comprising:

magnetic structures to provide a magnetic field to a cavity;

a particle source [to provide] *comprising cathodes for generating* a plasma column [to] *in* the cavity, the particle source having a housing to hold the plasma column, the housing being interrupted at an acceleration region to expose the plasma column, wherein the housing is interrupted such that the housing is completely separated at the acceleration region [or such that a part of the housing is physically connected at the acceleration region]; and

a voltage source to provide a radio frequency (RF) voltage to the cavity to accelerate particles from the plasma column at the acceleration region[;

wherein, in a case that part of the housing is physically connected, the part of the housing has structure that allows particles accelerated from the plasma column to perform at least one turn without impinging on the part of the housing].

2. The synchrocyclotron of claim **1**, wherein the magnetic field is above 2 Tesla (T)[, and the particles move from the plasma column outwardly in spirals with radii that progressively increase].

3. The synchrocyclotron of claim **1**, wherein the housing comprises two portions that are completely separated at the acceleration region to expose the plasma column.

4. The synchrocyclotron of claim **1**, wherein the voltage source comprises a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground; and

wherein at least part of the particle source passes through the second dee.

5. The synchrocyclotron of claim **1**, further comprising a stop in the acceleration region, the stop for blocking acceleration of at least some of the particles from the plasma column.

6. The synchrocyclotron of claim **5**, wherein the stop is substantially orthogonal to the acceleration region and is configured to block certain phases of particles from the plasma column.

7. The synchrocyclotron of claim **1**,[further comprising:

cathodes for use in generating the plasma column,] *wherein* the cathodes [being] *are* operable to pulse a voltage to ionize gas to generate the plasma column; *and*

wherein the cathodes are not heated by an external heat source.

8. The synchrocyclotron of claim **7**, wherein the cathodes are configured to pulse at voltages between about 1 kV to about 4 kV.

9. The synchrocyclotron of claim **7**, further comprising:

a circuit to couple voltage from the RF voltage to the at least one of the cathodes.

10. The synchrocyclotron of claim **9**, wherein the circuit comprises a capacitive circuit.

11. The synchrocyclotron of claim **1**, wherein the magnetic structures comprise magnetic yokes, wherein the voltage source comprises a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground, wherein the first dee and the second dee form a tunable resonant circuit, and wherein the cavity comprises a resonant cavity containing the tunable resonant circuit.

12. A synchrocyclotron comprising:

a tube containing a gas;

a first cathode adjacent to a first end of the tube; and

a second cathode adjacent to a second end of the tube, the first and second cathodes applying voltage to the tube to form a plasma column from the gas;

wherein particles are available to be drawn from the plasma column for acceleration; and

a circuit to couple energy from [an external] *a* radio frequency (RF) field to at least one of the cathodes;

wherein the tube is interrupted at an acceleration region where the particles are accelerated to expose the plasma column, wherein the tube is interrupted such that the tube is completely separated into two parts at the acceleration region [or such that a part of the tube is physically connected at the acceleration region where the particles are accelerated;

wherein, in a case that part of the tube is physically connected, the part of the tube has structure that allows particles accelerated from the plasma column to perform at least one turn without impinging on the part of the tube].

13. The synchrocyclotron of claim **12**, wherein the first cathode and the second cathode are not heated by an external source.

14. The synchrocyclotron of claim **13**, further comprising:

a voltage source to provide the RF field, the RF field for accelerating the particles from the plasma column at the acceleration region where the particles are accelerated.

15. The synchrocyclotron of claim **14**, wherein the energy comprises a portion of the RF field provided by the voltage source.

16. The synchrocyclotron of claim **13**, wherein the circuit comprises a capacitor to couple energy from the [external] RF field to at least one of the first cathode and the second cathode.

17. The synchrocyclotron of claim [**13**] *12*, wherein the tube comprises a first [portion] *part* and a second [portion that are completely separated at the acceleration region where the particles are accelerated] *part that are separated by a space that is between 1 mm and 3 mm.*

18. The synchrocyclotron of claim **13**, further comprising:

a stop at the acceleration region, the stop to block at least one phase of the particles from further acceleration.

19. The synchrocyclotron of claim [**13**] *12*, further comprising:

a voltage source to provide the RF field to the plasma column, the RF field for accelerating the particles from the plasma column at the acceleration region where the particles are accelerated, wherein the RF field comprises voltage that is less than 15 kV; and

magnetic [yokes] *structures* to provide a magnetic field that crosses the acceleration region where the particles are accelerated, the magnetic field being greater than about 2 Tesla (T).

20. The synchrocyclotron of claim **12**, wherein the first cathode is on a different side of the acceleration region than the second cathode.

21. A synchrocyclotron comprising:

a Penning ion gauge (PIG) source comprising a first tube portion and a second tube portion, the first tube portion *having a first cathode* and the second tube portion *having a second cathode, the first cathode and the second cathode* for [holding] *generating* a plasma column that extends across an acceleration region from which particles are accelerated from the plasma column; and

a voltage source to provide a voltage at the acceleration region, the voltage for accelerating particles out of the plasma column at the acceleration region;

wherein the first tube portion is completely separated from the second tube portion at the acceleration region [or a connection exists between the first tube portion and the second tube portion at the acceleration region;

wherein, in a case that the connection exists, the connection has structure that allows particles accelerated from the plasma column to perform at least one turn without impinging on the connection].

[22. The synchrocyclotron of claim **21**, wherein the PIG source comprises a physical connection between a part of the first tube portion and the second tube portion, the physical connection enabling particles accelerating out of the plasma column to complete a first turn upon escaping from the plasma column without running into the physical connection.]

23. The synchrocyclotron of claim **21**, wherein the PIG source passes through a first dee that is electrically connected to ground, and wherein a second dee that is electrically connected to an alternating voltage source provides the voltage at the acceleration region.

24. The synchrocyclotron of claim **21**, further comprising: magnetic [yokes] *structures* that [define] *border* a cavity containing the acceleration region, the magnetic [yokes] *structures* for generating a magnetic field across the acceleration region.

25. The synchrocyclotron of claim **24**, wherein the magnetic field is at least 2 Tesla (T).

26. The synchrocyclotron of claim **25**, wherein the magnetic field is at least 10.5 T.

27. The synchrocyclotron of claim [**26**] *21*, wherein the voltage comprises a radio frequency (RF) voltage that is less than 15 kV.

28. The synchrocyclotron of claim **21**, further comprising one or more [electrodes for use in accelerating] *structures to direct* the particles out of the particle accelerator.

29. The synchrocyclotron of claim **21**, [further comprising:

at least one cathode for use in generating the plasma column, the at least one cathode comprising] *wherein the first cathode comprises* a cold cathode *and the second cathode comprises a cold cathode*; and

a capacitive circuit to couple at least some of the voltage to [the] at least one cathode.

30. The synchrocyclotron of claim **21**, wherein the [at least one cathode is] *first cathode and the second cathode are* configured to pulse voltage to generate the plasma column from gas in the first tube portion and the second tube portion.

31. A particle accelerator comprising:

a tube containing a gas;

a first cathode adjacent to a first end of the tube;

a second cathode adjacent to a second end of the tube, the first and second cathodes applying voltage to the tube to form a plasma column from the gas;

wherein particles are available to be drawn from the plasma column for acceleration;

a circuit to couple energy from [an external] *a* radio frequency (RF) field to at least one of the cathodes; and

magnetic structures to provide a magnetic field that crosses an acceleration region where the particles are accelerated, the magnetic field being greater than about 2 Tesla (T);

wherein the tube is interrupted at the acceleration region where the particles are accelerated to expose the plasma column, and wherein the tube is interrupted such that the tube is completely separated into two parts at the acceleration region [or such that a part of the tube is physically connected at the acceleration region where the particles are accelerated;

wherein, in a case that part of the tube is physically connected, the part of the tube has structure that allows particles accelerated from the plasma column to perform at least one turn without impinging on the part of the tube].

32. The particle accelerator of claim **31**, wherein the first cathode and the second cathode are not heated by an external source.

33. The particle accelerator of claim **32**, wherein the circuit comprises a capacitor to couple energy from the [external] RF field to at least one of the first cathode and the second cathode.

[**34**. The particle accelerator of claim **32**, wherein the tube comprises a first portion and a second portion that are completely separated at the acceleration region where the particles are accelerated.]

35. The particle accelerator of claim [**32**] *31*, further comprising:

a stop at the acceleration region where the particles are accelerated, the stop to block at least one phase of the particles from further acceleration.

36. The particle accelerator of claim [**32**] *31*, further comprising:

a voltage source to provide the RF field to the plasma column, the RF field for accelerating the particles from the plasma column at the acceleration region where the particles are accelerated, wherein the RF field comprises voltage that is less than 15 kV; and

[where] *wherein* the magnetic structures comprise magnetic yokes.

37. The particle accelerator of claim **31**, wherein the first cathode is on a different side of the acceleration region where the particles are accelerated than the second cathode.

38. The particle accelerator of claim **37**, further comprising:

a voltage source to provide the RF field, the RF field for accelerating the particles from the plasma column at the acceleration region where the particles are accelerated.

39. The particle accelerator of claim **33**, wherein the energy comprises a portion of the RF field [provided by the voltage source].

40. The particle accelerator of claim **31**, wherein the magnetic field is greater than 8 T.

41. The particle accelerator of claim **31**, wherein the magnetic field is greater than 10.5 T.

42. A synchrocyclotron comprising:

ferromagnetic pole pieces that border a cavity containing an acceleration region;

electrical coils adjacent to the ferromagnetic pole pieces to produce a magnetic field of at least 2 Tesla (T) within the cavity; and

a Penning ion gauge (PIG) source comprised of a first part and a second part that are completely separated at the acceleration region to allow extraction of charged particles from a plasma column for acceleration, the first part having a first cathode and the second part *having a second cathode, the first cathode and the second cathode for generating the plasma column.*

43. The synchrocyclotron of claim 42, wherein the magnetic field is at least 8 T.

44. The synchrocyclotron of claim 42, further comprising:

a voltage system to provide radio frequency (RF) voltage to the cavity, the voltage system comprising a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground;

wherein at least part of the PIG source passes through the second dee.

45. A synchrocyclotron comprising:

ferromagnetic pole pieces that border a cavity containing an acceleration region;

electrical coils adjacent to the ferromagnetic pole pieces to produce a magnetic field of at least 2 Tesla (T) within the cavity;

a Penning ion gauge (PIG) source comprised of a first part and a second part that are completely separated at the acceleration region to allow extraction of charged particles from a plasma column for acceleration; and

a stop in the acceleration region, the stop for blocking at least some of the charged particles.

46. The synchrocyclotron of claim 45, wherein the stop is substantially orthogonal to the acceleration region and is configured to block certain phases of the charged particles.

47. The synchrocyclotron of claim 42, wherein the first cathode and the second cathode are operable to pulse a voltage to ionize gas to generate the plasma column; and

wherein the first and second cathodes are not heated by an external heat source.

48. The synchrocyclotron of claim 47, wherein the first and second cathodes are controllable to pulse at voltages between about 1 kV to about 4 kV.

49. The synchrocyclotron of claim 48, further comprising:

a circuit to couple voltage to at least one of the first and second cathodes.

50. The synchrocyclotron of claim 49, wherein the circuit comprises a capacitive circuit.

51. A synchrocyclotron comprising:

ferromagnetic pole pieces that border a cavity containing an acceleration region in which charged particles are accelerated, the cavity containing a magnetic field of at least 2 Tesla (T);

a particle source comprising a first part and a second part, the first part having a first cathode and the second part having a second cathode, the first part and the second part being completely separated at the acceleration region;

accelerating electrodes to provide a radio frequency (RF) voltage to the acceleration region to extract the charged particles, the RF voltage sweeping over a frequency range; and

circuitry to couple energy from the RF voltage to at least one of the first cathode or the second cathode.

52. The synchrocyclotron of claim 51, wherein the cavity contains a magnetic field that is at least 8 T.

53. The synchrocyclotron of claim 51, wherein the cavity contains a magnetic field that is at least 10.5 T.

54. The synchrocyclotron of claim 51, further comprising:

a voltage system to provide radio frequency (RF) voltage to the cavity, the voltage system comprising a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground;

wherein at least part of the particle source passes through the second dee.

55. The synchrocyclotron of claim 51, further comprising a stop in the acceleration region, the stop for blocking at least some of the charged particles.

56. The synchrocyclotron of claim 55, wherein the stop is substantially orthogonal to the acceleration region and is configured to block certain phases of the charged particles.

57. The synchrocyclotron of claim 51, wherein the first and second cathodes are controllable to pulse at voltages between about 1 kV to about 4 kV.

58. The synchrocyclotron of claim 51, wherein the circuitry comprises a capacitive circuit.

59. A synchrocyclotron comprising:

ferromagnetic pole pieces that border a cavity containing an acceleration region;

a voltage system to provide radio frequency (RF) voltage to the cavity,

electrical coils around part of the ferromagnetic pole pieces to produce a magnetic field having a magnitude of at least 2 Tesla (T) within the cavity; and

a particle source that is completely separated at least at the acceleration region to allow extraction of charged particles from a plasma column for acceleration in response to the RF voltage, the particle source comprising a first part and a second part, the first part having a first cathode and the second part having a second cathode, the first and second cathodes for generating the plasma column.

60. The synchrocyclotron of claim 59, wherein the magnetic field is at least 8 T within the cavity.

61. The synchrocyclotron of claim 59, wherein the voltage system comprises a first dee that is electrically connected to an alternating voltage and a second dee that is electrically connected to ground; and

wherein the RF voltage provided to the cavity is less than 15 kV.

62. The synchrocyclotron of claim 59, wherein the first part and the second part are separated for distances above and below the acceleration region.

63. The synchrocyclotron of claim 59, wherein the plasma column is produced from a gas, and wherein flow of the gas into the synchrocyclotron is less than one standard cubic centimeter per minute (SCCM).

64. A synchrocyclotron comprising:

ferromagnetic pole pieces that border a cavity containing an acceleration region;

a voltage system to provide radio frequency (RF) voltage to the cavity,

electrical coils around part of the ferromagnetic pole pieces to produce a magnetic field having a magnitude of at least 2 Tesla (T) within the cavity;

a particle source that is interrupted at least at the acceleration region to allow extraction of charged particles from a plasma column for acceleration in response to the RF voltage; and

one or more stops at the acceleration region, the one or more stops to block at least one phase of the charged particles extracted from the particle source from further acceleration.

* * * * *