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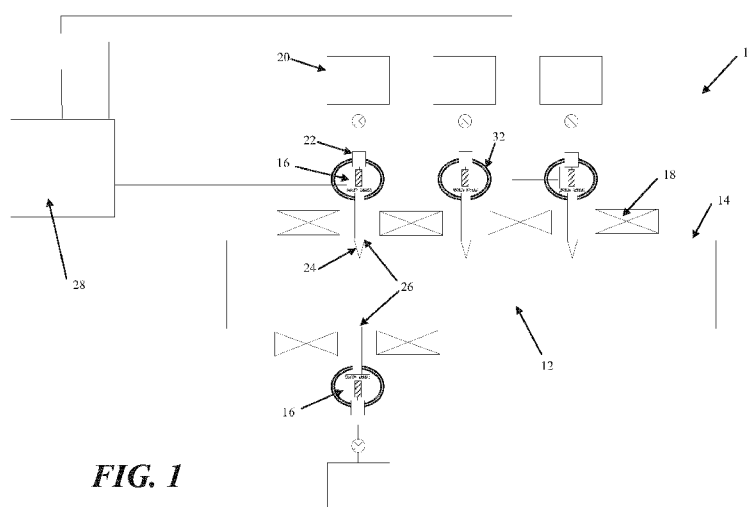


FIG. 1

(57) Abstract: Examples of systems and methods for gas injection and control are described. In some examples, an electromagnetically actuable valve can be triggered by applying a voltage to a valve's coil. The gas can be injected uniformly through an injection system that comprises one or more valves designed to simultaneously inject a quantity of gas. Temperature at the one or more valves can be maintained at a pre-determined reference value. In some cases, two or more sequential gas injection pulses can be used. The uniform gas density is injected within a chamber configured to receive the gas. The injection through the one or more valves is controlled by a valve control system.

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SYSTEMS AND METHODS FOR GAS INJECTION AND CONTROL

Technical Field

5 The present disclosure generally relates to methods and systems for injecting gas, and more particularly relates to methods and systems for providing uniform gas density within a chamber and a control system for synchronizing and/or controlling such gas injection.

Background

10 Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

In various systems such as plasma processing systems, plasma injectors, neutron generators, X-ray sources etc., gas may be injected into a chamber and then ionized. The gas can be injected into such systems through a fast acting gas valve, e.g. electromagnetic valve or piezoelectric valve. In some valves, when a voltage is applied to the valve, an electromagnetic force pulls a plunger away from a valve seat, thereby opening the valve. When the current stops flowing in the valve, the valve is de-energized, the electromagnetic force is reduced, and the valve can close against the valve seat.

20 **Summary**

In one aspect, a gas injection system is provided. The gas injection system comprises a plurality of gas injection valves designed to simultaneously inject a quantity of gas. The quantity of gas may be a predetermined quantity in some implementations. The plurality of gas injection valves are designed to provide a

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uniform gas density and a uniform gas distribution within a chamber configured to receive the gas injected through the valves.

In one aspect, a gas injection system for use in a plasma generator is provided. The gas injection system comprises a plurality of electrically actuated gas injection valves. Each of the plurality of valves comprises a current driver to open the valve. The plurality of gas injection valves are in gaseous communication with a plasma generation chamber. A valve control assembly that is in communication with the current driver of each of the valves is provided to control the opening time of the valves. The valve control assembly comprises a memory with a time schedule being encoded thereon. The time schedule comprises a valve opening time delay value for each valve in the plurality of gas injection valves. A processor is programmed to use the time schedule to coordinate a timing of the plurality of gas injection valves during a gas injection operation.

The gas injection system further comprises a means for maintaining a temperature at the plurality of gas injection valves at a pre-determined reference value in order to facilitate timely opening of the one or more valves. The means for maintaining the temperature comprises at least one of a cooler or a heater in thermal communication with the plurality of valves and that is configured to maintain the temperature at the valves at the reference value.

The means for maintaining temperature further comprises a temperature sensor for measuring the temperature at each of the plurality of gas injection valves. The sensor is in communication with a temperature controller that receives signals from the sensors and triggers the cooler/heater to maintain the valve's temperature at an operating reference value.

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In one aspect, the valve control assembly comprises a current detector configured to measure a rate of current change as a function of time for each of said plurality of valves. The current detector measures a rate of current change as a function of time for each valve for gas injected at a first pressure (HREF) and
5 measures a rate of current change as a function of time for gas injected at a second pressure (LREF) that is lower than the first pressure. The processor is configured to receive the HREF and the LREF measurements for each of said plurality of valves to determine a divergence point wherein the HREF and the LREF measurements diverge and to determine a time delay for each of the plurality of
10 valves from the determined divergence points. The processor is programmed to trigger the current driver of each of the plurality of valves according to the time schedule in order to coordinate the timing of the plurality of gas injection valves during a gas injection operation.

In one aspect, the processor of the valve control assembly is further
15 programmed to inject the gas into the plasma generation chamber in a sequence of at least two sequential gas injection pulses. A first gas injection pulse is injected ahead of a next sequential gas injection pulse that is injected at a pre-determined time delay from the first gas injection pulse. Gas ionization is triggered immediately after injection of a last gas injection pulse in the sequence. The
20 plurality of gas injection valves comprises a first set of valves and at least one additional set of valves. The processor is further programmed to inject the first gas injection pulse through the first set of valves, and to inject at least one additional gas pulse through the additional set of valves.

In one aspect, a means for generating an external magnetic field within the
25 chamber in which the gas is injected is provided. The gas injection system includes a magnetic field shielding means for reducing an effect of the external

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magnetic field on the opening/closing of the plurality of valves. The magnetic shielding means includes a shielding circuit that comprises a controller that is in communication with an external coil driver. The controller is configured to receive a timing schedule for triggering an external coil from the external coil driver in order to synchronize an initial current flow through the plurality of gas injection valves so that the initial current flow through the plurality of gas injection valves happens simultaneously with the triggering of the external coil. The magnetic shielding circuit controller is also in communication with the valve control assembly to send an output signal to the current driver of the plurality of gas injection valves to reverse a direction of the current flow through the valves when opening of the valves is required.

In one aspect, the magnetic field shielding means includes a ferromagnetic shield positioned around a valve's body so that the magnetic field lines are deflected to go through the ferromagnetic shield instead of through the valve.

In yet another aspect, a valve control assembly for controlling a plurality of valves is disclosed. The valve control assembly comprises a current detector configured to measure a rate of current change as a function of time for each of the plurality of valves at a first pressure (HREF) and measures a rate of current change as a function of time for each of the plurality of gas injection valve at a second pressure (LREF) that is lower than the first pressure. A valve processor that is in communication with a current driver of each of the plurality of valves is configured to receive the HREF and the LREF measurements for each of said plurality of valves to determine a divergence point wherein the HREF and the LREF measurements diverge and to determine a time delay for each of the plurality of valves from the determined divergence points. The processor comprises a memory encoded with a time schedule comprising the valve opening

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time delay value for each valve in the plurality of gas injection valves that is used to coordinate the timing for triggering the current driver of the plurality of gas injection valves during a gas injection operation.

5 In another aspect, a method for calibrating valve timing for a plurality of gas injection valves of a gas injection system is provided. The method comprises measuring a rate of current change as a function of time for each of a plurality of gas injection valves operating at a first pressure (HREF), measuring a rate of current change as a function of time for each of the plurality of gas injection valve at a second pressure (LREF) that is lower than the first pressure, determining a
10 divergence point for each of the plurality of gas injection valves wherein the HREF and the LREF measurements for each of the plurality of gas injection valves diverge, determining a time delay for each of the plurality of gas injection valves from the determined divergence points, and encoding a time schedule comprising an identifier and the associated time delay for each of the plurality of
15 gas injection valves onto a memory of a valve control assembly of the gas injection system.

In addition to the aspects and embodiments described above, further aspects and embodiments will become apparent by reference to the drawings and study of the following detailed description.

20 **Brief Description of the Drawings**

Throughout the drawings, reference numbers may be re-used to indicate correspondence between referenced elements. The drawings are provided to illustrate example embodiments described herein and are not intended to limit the scope of the disclosure. Sizes and relative positions of elements in the drawings
25 are not necessarily drawn to scale. For example, the shapes of various elements

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and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility.

FIG.1 is a schematic cross-sectional view of a gas injection system according to one non-limiting embodiment.

5 FIG. 2 is a schematic cross-sectional partial view of an example of a plasma generator employing one non-limiting embodiment of a gas injection system.

FIG. 3 is a perspective view of an example of a plasma generator with a ring of plurality of valves of the gas injection system arranged around a housing
10 of the plasma generator.

FIG. 4 is a graph illustrating an example of voltage and current signals in a pre-ionization phase and ionization phase.

FIG. 5 is a schematic illustration of one non-limiting embodiment of a magnetic shielding circuit of the gas injection system.

15 FIG. 6 is a schematic illustration of one non-limiting embodiment of a system for valve control of valves in the gas injection system.

FIG. 7 is a flowchart illustrating an example of a method for determining a schedule of triggering time for a plurality of valves in the gas injection system.

20 FIG. 8 is a graph schematically illustrating an example of rate of change of current as a function of time (di/dt) waveforms for an embodiment of a valve. A solid black curve shows an example when an injected gas is at higher pressure, and a dashed black curve shows an example when an injected gas is at lower pressure.

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FIG. 9 is a graph schematically illustrating an example of a di/dt waveform at higher gas pressure (HREF - solid black curve), a di/dt waveform at lower gas pressure (LREF - dashed black curve) and a DIFF waveform (dot-dashed curve) obtained by subtracting the LREF waveform from the HREF waveform for an embodiment of a valve. The graph also shows an example of an ACCEL waveform obtained from an accelerometer that measures the acceleration of the valve's plunger.

FIG. 10 is a graph schematically illustrating an example of a divergence point (vertical solid line) determined by a maximum peak of a derivative (acceleration) waveform DIFF_D2 (dot-dashed curve).

FIG. 11 is a graph schematically illustrating an example of a DIFF waveform (dashed curve), a derivative waveform (solid line curve) and a threshold (horizontal line) obtained according to one example of a method for determining a divergence point for a valve used in the gas injection system.

FIG. 12 is a graph schematically illustrating an example of a DIFF waveform (dashed curve), a projected sloped line and a zero crossing point corresponding to a divergence point and opening time of one example of a valve.

Detailed Description

In some implementations such as plasma generation, in order to inject a gas in a substantially uniform fashion into a chamber using a plurality of electrically-actuated gas injection valves, the opening of the plurality of valves may need to be achieved substantially rapidly and/or substantially simultaneously. Because of the inductance of a solenoid in solenoid-type gas injection valves, current can build up over a current rise time so, there may be a time delay between the time the voltage is applied and the time the valve starts to open. In

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addition, the valve opening may vary for a given valve depending on for example, a condition of the valve, temperature, external magnetic field, length of time the particular valve has been closed, material(s) making up the plunger and/or valve seat (e.g., in some valves the plunger can be stuck to a valve seat), applied
5 voltage, etc. In order to obtain a uniform gas density and gas distribution within the chamber, it can be important to control the quantity of the injected gas and/or the timing of the gas injection.

Some of the known gas injection systems provide gas flow that is not directional and the gas diffuses quickly thus providing poor control over plasma
10 density. Embodiments of the systems and methods disclosed herein can be used to address at least some of the foregoing, as well as other, challenges.

Accordingly, embodiments of systems and methods for gas injection are disclosed that accurately control the timing of gas injection through one or more electrically-actuated valves, such as electromagnetic valves or piezoelectric
15 valves as well as uniform distribution of the gas within an enclosure. Embodiments of the methods and systems may be used for controlling and/or synchronizing opening and/or closing of a plurality of valves.

The present disclosure provides examples of a gas injection system capable to accurately control opening time of one or more valves for injecting a
20 gas within a chamber and to provide uniform gas density and gas distribution within such chamber. The injection system can be used to inject gases such as for example, one or more isotopes of light elements e.g., isotopes of hydrogen (e.g., deuterium and/or tritium) and/or isotopes of helium (e.g., helium-3) or any other gas or gas mixture. For example, in some implementations, a 50% deuterium-50%
25 tritium gas mixture can be used.

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A gas injection system can release the gas within a very short increment of time. The gas may be injected through a plurality of valves. FIG. 1 schematically illustrates an example of a gas injection system 10 through which a gas is injected into a chamber 12. The gas injection system 10 may inject gas through a plurality of spaced valves 16. The chamber 12 has an outer wall 14 and can be cylindrical, rectangular, spherical or any other shape. For example, there can be 25 to 200 valves 16 through which the gas can be injected into the chamber 12. More or less valves 16 can be used for injecting gas into the chamber 12 without departing from the scope of the invention. The valves 16 can be arranged evenly and uniformly along the length of the chamber 12 or around the chamber 12. The plurality of valves 16 can be in fluid communication with one or more gas reservoirs 20. The quantity of gas injected through each of the plurality of valves 16 can be determined by the size of a plenum chamber 22. The plenum chamber 22 is positioned close to and is in direct fluid communication with the valve 16. The plurality of plenum chambers 22 are filled with a desired quantity of gas at specified pressure. The gas from the gas reservoir 20 is fed into the plenum 22 and once the valve 16 is opened such gas is quickly injected within the chamber 12. The plurality of gas plenums 22 can be in fluid communication with a plurality of gas reservoirs 20. The quantity of gas injected in the chamber 12 can be changed by changing the size of the plenum chamber 22 or by changing the gas pressure. In one implementation, some or all of the plurality of gas plenums 22 can be in fluid communication with a single gas reservoir 20.

In certain implementations, the plenum 22 can be formed by placing a restrictor (not shown) within a channel leading to the valve 16. The restrictor may form a capillary channel (not shown) through which the plenum 22 can communicate with the one or more gas reservoirs 20. The capillary channel formed by the restrictor can be sufficiently restricted in size so that during the

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time the valve 16 is opened the gas flowing through the restrictor is insignificant compared with the gas released from the plenum 22. However, during the time the valve 16 is closed, sufficient gas can pass through the restrictor to fill the plenum 22. The quantity of the injected gas can be changed by moving the restrictor
5 closer to or farther away from the valve 16.

In one implementation, the gas injection system 10 may comprise a nozzle 24 positioned in front of the valve's exit 26. The nozzle 24 may be configured to control the direction of the injected gas. In various implementations, the nozzle 24 can be a de Laval, or converging-diverging nozzle, e.g. a small rocket nozzle, so
10 that when the gas expands to a vacuum, it gives more momentum in the direction of the nozzle and the gas stays in a small location near a point of injection instead of expending like a sphere. Any other type of nozzles or jets configured to control the direction and/or the speed of the gas injection can be used without departing from the scope of the invention. In one implementation, the nozzle 24 can be
15 oriented perpendicularly to the longitudinal axis of the chamber 12. In another implementation, the nozzle 24 can be angled with respect to the longitudinal axis of the chamber 12.

In one implementation, the gas injection system 10 can be configured so that the gas is injected into the chamber 12 in two or more sequential pulses of gas
20 introduced through one or more sets of valves. For example, some of the valves 16 (a first set of valves) can be actuated prior to the opening of the rest of the valves 16 (a second set) so that the gas injected by the first set of valves 16 can reach the opposing wall of the chamber 12 just as a second pulse of gas is injected through the second set of valves 16 into the chamber 12. More than two sets of
25 valves can be provided for injecting gas into the chamber 12.

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In one implementation, the gas injection system 10 may comprise only a single valve 16. For example, the gas can be delivered through the valve 16 to a manifold (not shown) which feeds a number of ports in the chamber 12. For example there can be 25 to 200 ports spaced evenly around the chamber 12. The
5 ports may feed into nozzles which may be perpendicular or angled to direct the gas radially and inwardly toward the center of the chamber 12. In one embodiment more than one valve 16 may be provided to feed the manifold with a plurality of ports. For example, the gas injection system 10 may comprise four valves separated at 90 degrees, feeding gas to a manifold with a plurality of ports.
10 Less or more than four valves can be provided for feeding gas to a manifold with plurality of ports.

The gas injection system 10 may further comprise a valve control assembly/system 28 configured to accurately control opening time of the plurality of valves 16. An example of the valve control assembly 28 in more details is
15 described below with reference to FIGS. 6 to 10.

In one implementation, the gas injected into the chamber 12 may be ionized to form plasma. The gas can be ionized by applying a voltage of several kilovolts between two electrodes or by subjecting it to a strong electromagnetic field applied with a laser or microwave generator or by subjecting it an externally
20 applied radio frequency field, etc. One or more external coils 18 can be provided around the chamber 12 to produce an external magnetic field within the chamber 12 for confining the plasma formed by ionization of the gas injected within the chamber. The one or more coils 18 can be energized by providing a current from a power source. In one embodiment, an inner region of the chamber 12 may be
25 evacuated with a pumping system forming a vacuum region. In some implementations, the chamber 12 can be at least partially evacuated.

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The operation of the plurality of valves 16 in the chamber 12 can be affected by the environmental conditions to which the valves are exposed. For example, environmental conditions, such as a heat/cold exposure can play a large part in a control of the opening time of the valves. For example, temperature can affect thermal expansion properties of piezo ceramics in piezo-electric valves or stickiness of the valve seat in solenoid valves. In order to provide highly controllable gas injection the temperature at the valves 16 should be controlled and maintained at a certain desired reference point. In one implementation, the gas injection system 10 can comprise a temperature controller (not shown). The temperature controller can comprise a temperature sensor (not shown) positioned in proximity to the plurality of valves 16 to detect the temperature at the plurality of valves 16. The temperature sensor can be a thermocouple or any other suitable thermo sensor such as an infrared thermo sensor, bimetallic sensor, etc. The signal detected by the temperature sensor is transmitted to the temperature controller. A heater (and in some implementations a cooler) can also be provided to maintain the temperature of the plurality of valves 16 at the reference point. The temperature reference point can be preselected in advance depending on the working gas that should be injected by the valves, pressure of such injection gas, applied voltage for opening the valves, type of valve, material of the valves etc. For example, the valves 16 can be controlled at reference temperature of 15 - 20 °C. In one implementation, one or more fluid ports can be provided in the valve 16 for a heating or a cooling fluid to flow maintaining the temperature of the valve at the reference temperature. Liquid cooling/heating ports can be included in the valve's body (not shown) or around valve's body. In another implementation, a heater or a cooler connected to a power source can be provided to maintain the temperature of the valves at the reference value. The temperature reference value can be selected to be higher than 15 - 20 °C, e.g. 20 - 40 °C or

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lower, such as 5 - 15 °C without departing from the scope of the invention. The temperature sensor monitors the temperature of the valves and provides the information of the measured temperature to the temperature controller. The controller implements a control algorithm to control operation of the cooler/heater in order to maintain the valve temperature close to the predetermined reference temperature point. As an example, the control algorithm could be a simple low-temperature/high-temperature trigger. In this example, when the temperature is low (below the reference value), the controller triggers the heater to increase the temperature up to the pre-determined reference temperature value. When the temperature is higher than the predetermined reference value the temperature sensor sends a signal to the controller which turns the heater off and/or turns the cooler on in some implementations. Persons skilled in the art would understand that any other known temperature control systems can be used without departing from the scope of the invention. For example, the temperature control algorithm can comprise a proportional-integral-derivative control. In one embodiment, the temperature controller maintains the temperature at the valves 16 within a range of $\pm 0.2^{\circ}\text{C}$ from the reference temperature point. The temperature reference point can have any value and the controller can be set-up to maintain the temperature within a bigger or lower range than the mentioned $\pm 0.2^{\circ}\text{C}$ temperature range without departing from the scope of the invention. In one embodiment, each of the plurality of the valves 16 can be provided with a temperature sensor and a heater/cooler so that the temperature of each valve can be independently monitored and controlled. In one implementation, the signal obtained from each of the temperature sensors can be stored in a memory unit. The temperature controller can be integrated with the valve control assembly 28 or can be a separate unit.

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FIG. 2 schematically illustrates a part of a plasma generator 100, as an example of one implementation of the gas injection system 10. This is intended to be illustrative and not limiting and the gas injection system 10 can be employed in any other type or configuration of plasma generator without departing from the scope of invention. In one implementation, the gas injection system 10 can be used for uniform and/or synchronized injection of a gas in any other systems, devices or engines where uniform and/or synchronized gas injection is desired.

The plasma generator 100 can include a pair of concentric electrodes such as an inner electrode 110 and an outer electrode 120. The gas is injected in an annular formation space 130 defined by the inner electrode 110 and the outer electrode 120. The gas is injected through a ring of plurality of equally spaced valves 16, radially oriented and arranged uniformly around the periphery of the outer electrode 120. An example of the ring of plurality of valves 16 arranged around the outer wall of the generator 100 is illustrated in FIG. 3. In one implementation, a set of a plurality of inner valves (not shown) can be provided within the inner electrode 110 to inject gas from the inner electrode 110. A back plate 140 closes one end of the generator 100. An insulating ring 160 can be used to insulate the inner electrode 110 from the outer electrode 120 and to insulate the electrical transmission line from the back plate 140. Before the gas is injected in the space 130, an inner region of the generator 100 can be evacuated with a pumping system (not shown). In some implementations, the vacuum region can be at least partially evacuated. One or more coils 18 can be provided to produce a magnetic field within the formation space 130 for confining plasma formed by ionization of the gas injected between the electrodes 110 and 120.

One method for generating plasma is to pass a current through the gas injected in the formation space 130. Once certain parameters are met, the gas is

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ionized forming plasma. For example, plasma can be generated by applying a voltage of several kilovolts between the electrodes 110, 120 using a power source 200. The power source 200 can be a pulse power source. In some embodiments, the plasma can be formed into a toroidal plasma configuration, such as, e.g., a
5 spheromak or a Field Reversed Configuration (FRC), or any other plasma configuration or shape.

Once the gas is injected into the generator 100 and passes across the space 130 to the inner electrode 110, breakdown discharge can occur ionizing the gas. The breakdown discharge needs electrons and ions to carry the current. The gas
10 can diffuse axially so that more gas can be required to be injected for a breakdown to occur or the breakdown may occur with delay depending on the time required for the gas to reach the opposing inner electrode 110. When the gas is injected only from outside, through the valves 16, the concentration of the gas tends to be higher in proximity to the outer electrode 120, so the discharge may
15 use surface contamination of the inner electrode 110 as a source of electrons and ions, which may make the discharge less stable and may put impurities in the plasma. In one implementation, the plasma injection system 10 may comprise a plurality of inner valves 16' arranged uniformly around the inner electrode 110, for injecting gas in the space 130 from within the inside of the generator 100.
20 Injecting gas simultaneously through the valves 16 and 16' may overcome potential problems associated with discharge stability and/or plasma impurities. In addition, injecting gas from both sides may shorten the time for a sufficient quantity of gas to be injected for a breakdown to occur.

In another implementation, the gas injection system 10 can be configured
25 so that the gas is injected into the formation region 130 by providing two or more sequential pulses of gas. For example, a first number of valves (first set) can be

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opened first so that a first amount of gas is injected into the formation region 130. The first number of valves in the first set is such to allow a symmetrical gas injection into the formation region 130. Then a second number of valves (second set) can be opened and a second amount of gas can be injected into the formation region 130. The first and/or second amounts of gas can be selected, in some implementations, to provide predetermined amounts of gas into the formation region 130. In one embodiment, the first set of valves can include 5 – 15% of the total number of valves. For example, if the total number of valves is 200 valves arranged uniformly around the periphery of the outer electrode 120, the first set of valves can comprise about 10-30 valves spaced evenly around the outer electrode 120 while the second set of valves can comprise about 170-190 valves. The first set of valves can provide the predetermined amount gas to be symmetrically distributed in the formation region 130 that can expend radially toward the inner electrode. The second set of valves can be fired with a delay after the firing of the first set of valves so that the gas from the second set of valves can be injected into the formation region as the gas from the first set of valves reaches the inner electrode 110 and the gas breakdown can occur as soon as the second pulse of gas is injected in the formation region. In some implementations, the delay can be predetermined based at least partly on the time it takes for the gas from the first set of valves to reach the inner electrode 110.

A possible advantage of certain implementations using two or more sequential pulses of gas is that such use can shorten the time for the breakdown to occur and can provide less dense initial plasma and more reliable and consistent gas breakdown and thus more stable plasma formation. Higher gas density implies that less energy goes into each injected particle and conversely, if lower density gas is injected into the plasma generator 100 then there is more energy per ion and the ions may get hotter. For example, in some embodiments around 20% to 30%

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less dense plasma can be formed by injecting the gas in a two sequential gas pulses. Experiments have shown that, for a particular magnetic field (stuffing field) configuration, temperature of a formed plasma (as it bubbles out) measured by Thomson scattering was around 20-21 eV when the gas is injected in one pulse
5 through a plurality of valves, while for the same magnetic field configuration, the temperature of the formed plasma has increased to 26-27 eV when the gas is injected in at least two pulses. The delay of the second set of valves can be determined based at least partly on size of the chamber (e.g. a distance between the outer and inner electrodes) at the point of gas injection and gas properties (e.g.
10 gas pressure). For example, the second set of valves can be fired with a delay of about 50 – 250 μ s (depending on a gas pressure). The timing of the opening of the valves of the first and second set can be synchronized and controlled by the control system 28. The number of valves in the first and the second sets of valves can vary in different embodiments depending on the total number of valves, size
15 of the chamber, gas pressure, and so forth. In one implementation, a small amount of gas can be first injected using all valves 16 and then after a delay time a larger amount of gas can be injected through all valves 16 by, for example, moving the restrictor farther and enlarging the size of the plenum chamber 22. In another implementation, more than two sets of valves can be fired sequentially with
20 various delays so that the gas can be injected in two or more pulses of gas and the breakdown can occur concurrently as the first pulse of gas reaches the further end of the chamber (i.e. inner electrode) and the last pulse of gas is injected into the chamber (e.g. into the formation region 130 close to outer electrode 120).

The gas flow rate may be a linear function of the pressure of the gas in the
25 plenum, thus a gas at higher pressure will come out faster, so that enough gas can be injected between the electrodes to cause its ionization before the gas has time to spread axially in the vacuum chamber. The pressure of the injected gas may be

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sufficient so that the current discharge completely ionizes the injected gas. For certain chamber sizes (space 130 in FIG. 2) and a certain pressure of the injected gas, there is a minimum voltage required for a complete ionization of the gas (Paschen curves).

5 For example, the gas pressure in the plenum 22 may be 50 psig (pounds per square inch gauge) however, gas at lower pressures, such as e.g. 20 – 40 psig, or higher pressures e.g. 60 – 150 psig may also be used. If the injected gas is at higher pressure then the gas will be released at higher velocity and will more quickly cross the space 130 between the electrodes 110 and 120. Hence, less gas
10 may be injected in the space 130 for the gas to reach the wall of an inner electrode and for a breakdown to occur. The timing of the voltage pulse can be synchronized with the gas injection, so that the least amount of gas can be used for initiating the discharge. In one embodiment, the voltage may be applied to the electrodes 110 and 120 after the gas is injected into the generator 100. In another
15 embodiment, a voltage may be applied before the gas injection.

 After the gas is injected into the space 130 of the plasma generator 100, it can spread at approximately a thermal speed of the particles (e.g., atoms or molecules) injected. For example, at room temperature (e.g., about 20°C), the thermal velocity of a deuterium molecule is about 1700m/s. The gas injected into
20 the plasma generator may stay in the formation space 130 (e.g., about 0.5 m around the injection point in some cases), so that when an electrical discharge is triggered, the gas can be ionized and a plasma can be generated. The gas may be injected through each valve within a time approximately equal to the size of the space 130 divided by the thermal velocity of the particles in order to reduce or
25 prevent spreading of the gas beyond the desired region. This time may be about 300μs in some cases (e.g., $0.5 \text{ m} \div 1700 \text{ m/s} \approx 300\mu\text{s}$). Therefore, the gas can be

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injected in the space 130 through the plurality of valves 16 and/or 16' within a time that is less than 300 μ s in some such implementations.

For increasing the uniformity and density of the plasma, the gas can be injected symmetrically in the vacuum chamber and the gas breakdown may occur as fast as possible after a voltage is applied to the electrodes. Increasing the voltage applied to the injected gas can increase the uniformity and density of the plasma however, increasing the voltage between the electrodes may also increase the probability of an undesirable electrical discharge (electrical arcing) in the vacuum chamber of the generator 100. Thus in one implementation, a system for pre-ionizing the injected gas may be provided. The pre-ionization system may comprise a circuit for applying a pre-ionization pulse at lower voltages and then applying ionization pulse at higher voltages. So, the injected gas can be initially pre-ionized by applying a pulse at lower voltage as e.g. 8 – 16kV pulse. The lower voltage may be applied to trigger a discharge and partially ionize the injected gas. Then a higher voltage pulse (e.g. 25 – 45kV) can be provided for complete gas ionization. The lower voltage pulse may be provided by a separate power source or the same power source 200 can be used for providing a pre-ionization (plasma pre-formation) pulse and the ionization (plasma formation) pulse. In one example of operation, the pre-ionization system may trigger a pre-formation discharge to the injected gas in duration of about 2-10 μ s. This causes a partial ionization of the injected gas that may be detected by a current detector (not shown) as a current signal. Once a current signal is detected, the pre-ionization system can trigger a formation pulse of 25-45kV to cause a complete ionization of the gas forming plasma. For example, once the current detector (such as for example a Rogowski coil) detects a current signal occurring after the pre-ionization pulse discharge is triggered, it can send a signal to a controller of the power source 200 to trigger the

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formation pulse. The temporal length of the formation pulse may be in a range of about 25-50 μ s.

FIG. 4 shows an example of a voltage signal 402 and a current signal 404 during the pre-ionization and ionization phases. The partial ionization can be
5 detected by a small current signal 410.

In some implementations, the pre-ionization may be conducted with one or more ultraviolet (UV) light sources, such as e.g. UV lamps 170 shown in FIG. 2. The UV lamps 170 can be arranged around a housing of the generator 100. The UV lamp 170 can be coupled to a suitable power source to generate a UV light
10 beam (schematically shown by a dashed arrow in FIG. 2) which may be directed toward the gas injection region near the gas injection port (e.g. valve exit port 26). The housing of the generator 100 may comprise one or more transparent portions, e.g. a window 180, which are configured so that the UV light may pass through the window 180 and impinge on the injected gas causing at least partial ionization
15 of such gas. The window 180 may be transparent to the type of energy generated by the selected energy source, e.g. UV lamp 170. In one implementation, the transparent portion 180 may be configured as a lens to focus the energy generated by the lamp 170 to the gas injection point or region. In other implementations, other types of energy sources (e.g. lasers, corona discharges, radio-frequency (RF)
20 systems etc.) can be used for the excitation and pre-ionization of the injected gas.

In some cases the ionized gas formed in the chamber may flow into a channel which is positioned between the valve seat and valve's exit port 26. This may cause a current leakage or voltage breakdown which might affect the valve's performance, for example, it may melt the valve seat and result in gas leakage. To
25 inhibit or prevent damages to the valve 16, a solenoid 30 may be provided to generate a magnetic field that will inhibit or prevent the ionized gas from the

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generator 100 to flow into the valve's channel. In one implementation, one or more coils can be provided to generate a magnetic field into the valve's channel. In addition, a mesh designed as a fine grade filter can be provided in the valve's channel to prevent dust particles that may be present or have emerged from the walls of the injector to enter the valve and cause damage to the valve's seals and thus cause valve leakage.

Experiments have shown that the valve opening time is influenced by an external magnetic field produced by the one or more external coils 18 that produce the magnetic field into the chamber 12. There can be two components of the external magnetic field that have an effect on the valve opening, such as, 1) an axial component, which acts in direction of plunger's moving path, and 2) a transverse component. The transverse component of the externally applied magnetic field can be such that it does not physically apply a force on the valve plunger, but instead saturates the valve solenoid and changes the inductance of the solenoid circuit. The effect of the externally modified inductance is such that the solenoid current waveform will change. In order to observe current waveforms at different gas pressures, the external transverse magnetic field can be kept constant. The external magnetic field can be controlled and kept constant by accurately controlling the amount of current flowing through the coils 18.

At a high external magnetic field in the chamber at the valve location, the magnetic field may tend to keep the valves 16 opened (or closed depending on the direction of the magnetic field) at all times. In order to avoid or reduce the effect of the external magnetic field on the opening/closing operation of the valve 16, the valve can be shielded from the effects of such magnetic field. It has been observed that when a current flows through the solenoid of the valve 16 the current creates a magnetic field which, depending on the direction of the current,

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can be in the same direction as the axial component of the external magnetic field or in the opposite direction of such external magnetic field. If the magnetic field created by the current flow in the solenoid of the valve is in the same direction as the external axial magnetic field generated by coils 18, it will add to the external magnetic field, but if the current in the solenoid of the valve flows in opposite direction, then the generated magnetic field can be in the opposite direction of the external magnetic field and will subtract/reduce the external axial magnetic field.

A valve magnetic shielding circuit can be employed to reduce the effect of the external magnetic field on the opening operation of the valves 16. An example of valve shielding circuit 500 is illustrated in FIG. 5. In an example of operation of the valve shielding circuit 500, the circuit 500 can control the direction of the current flow in the solenoid of the valve 16 and thus the direction of the magnetic field generated by the current flow. The direction of current flow in the solenoid can be adjusted by the circuit 500 so that the magnetic field generated by the current flow adds to or subtracts from a magnetic field (e.g., generated by the coils 18). As one example, if the direction of the external magnetic field induced by the coils 18 is such as to urge the valve to open, then the valve shielding circuit can direct the flow of the current through the solenoid of the valve in a direction to generate a magnetic field that will keep the valve closed (assuming it is desired that the valve remains closed). Once an opening of the valve is desired, the valve shielding circuit can reverse the direction of the current flow in the valve solenoid so that the generated magnetic field is in the direction of the external magnetic field and the valve can open. In an opposite case, when the direction of the external magnetic field is such as to keep the valve 16 closed, then the current flowing through the solenoid of the valve will be such that the generated magnetic field can be in the direction of the external magnetic field until an opening of the

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valve is desired, when the current can be reversed to generate a magnetic field that will subtract from the external magnetic field and will open the valve.

In operation, the one or more coils 18 can be energized before the injection of the gas into the chamber. A coil power source (not shown) can send a
5 current pulse through the one or more coils 18 in order to generate a magnetic field in the chamber such as chamber 12 (FIG.1) or formation space 130 (FIG. 2). At the same time a current pulse can be send to the valves so that the direction of the initial flow of current through the solenoid of the valve keeps the valve closed. When valve opening is directed, the current flow through the solenoid of the valve
10 is reversed in the opposite direction and the valve is opened.

The shielding circuit 500 may trigger a valve's current driver 510 to initiate a current flow through the valve 16 and/or to reverse the direction of the current flow through the valve 16 when an opening of the valve is desired. Initially, the driver 510 sends a current signal to the valve 16 so that such current
15 generates a magnetic field that keeps the valve 16 closed. In one implementation, the timing of the initial current flow is synchronized with the timing of the current pulse through the coils 18 so that the effect of the external magnetic field on the opening/closing operation of the valve is avoided or reduced. The timing synchronization can be done by employing a controller 520 that can receive a
20 signal from a coil driver 530 on the timing of a current pulse to the coils 18 and is programmed or otherwise configured to send a signal to the driver 510 to trigger the initial current flow through the solenoid of the valve 16 simultaneously with the triggering of the current pulse through the coils 18. The controller 520 can be integrated with the valve control 28 or can be separate unit.

25 In another implementation, a small amount of current can be set up to flow through the solenoid of the valve all the time. The amount of such current is low

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so it cannot trigger opening of the valve but can reduce the effect of the external magnetic field generated once the coils 18 are energized. In this case, synchronization of the timing of the current pulse through the coils 18 and/or the triggering of the initial current flow through the valve 16 may not be used (e.g.,
5 the controller 520 may not be used in such cases).

Once an opening of the valve 16 is desired, the driver 510 receives a signal of a valve triggering time from a valve control system 28 (described in detail with respect to FIG. 6) and sends a signal to the valve reversing the direction of the current flow to open the valve. In one embodiment, the valve
10 shielding circuit 500 may be integrated with the valve control system 28.

In another implementation, the valve 16 may be shielded by utilizing a ferromagnetic shield 32 (FIG. 1). For example, a tube of ferromagnetic material, such as cobalt or iron alloy (e.g., mumetal, hematite, magnetite), can be shaped so to enclose the valve 16. When a current flows through the coils 18 to generate a
15 magnetic field, the lines of such magnetic field go through the ferromagnetic tube but not through the valve. Any other ferromagnetic material with Curie temperatures higher than the temperature in the chamber 12 or any other shape/design of the shield can be used to shield the valve 16. The ferromagnetic shield can comprise one or more layers of ferromagnetic material divided by one
20 or more insulating layers. The one or more layers of ferromagnetic material can attract flux lines and can divert the magnetic field away from the valves 16. Enclosure of the valve 16 by the magnetic shield 32 can be as complete as possible in some implementations. For example, the magnetic shield 32 can be shaped as open-ended cylinder, five-sided box, U or L shaped brackets, etc.

25 When a voltage is applied to a plurality of valves 16, the valves do not necessarily open instantaneously. A time delay, e.g., the difference between the

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time the voltage is applied and the time valve 16 is opened, can occur and the time delay can vary from valve to valve. In some embodiments, the time delay can vary from valve to valve by up to about 2ms. The time delay can also vary for a given valve by about 10 μ s - 100 μ s in some valve embodiments. Accordingly and as will be discussed in detail below, embodiments of the disclosed systems and methods for valve control can be used to control the timing of the opening of one or more valves 16, including synchronizing the timing of the opening of the valves 16 so that gas can be injected into a desired chamber in less than 300 μ s and more particularly in less than 100 μ s.

It has been observed that for solenoid-type valves, the current in the valve rises at a certain rate depending at least in part on the applied voltage V and the inductance of the solenoid $V=L \, dI/dt$, where L is the inductance of the solenoid and I is the current in the solenoid. When the valve's plunger starts lifting up to open the valve, the inductance of the solenoid may change, which may change the current. The current through the valve can be measured to determine a rate of current change as a function of time (e.g., dI/dt). The valve 16 may be designed so that the plunger's orientation is such that the gas pressure constrains the plunger's movement. Thus at higher pressures the opening of the valve may be delayed as it takes more time for such valve to open. At some gas pressures, such as pressures higher than 200 psig, some of the valves 16 may not be able to open at all. By observing the waveform of the rate of current change (dI/dt) in the solenoid of each valve 16 at higher gas pressures (when the valve does not open or the opening is delayed) and comparing it with the rate of current change (dI/dt) waveform in the solenoid of such valve when the gas pressure is lower (e.g., when the valve opens more quickly), the time when the valve starts to open can be accurately determined. The divergence between the higher pressure dI/dt waveform and the lower pressure dI/dt waveform is thought (but not required) to

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occur because the plunger physically moves at different time points due to the pressure differences between the two measurements. The rate of current change waveform at higher gas pressure can be used as a reference. Such reference is then compared to the waveform of the rate of current change at lower pressures to
5 determine a divergence point between the high pressure and low pressure waveforms. This feature of the electromagnetic valves may be used to determine the time delay for each valve 16 and then develop a valve opening timing schedule to control and/or synchronize the opening of the one or more valves 16 in a gas injection operation.

10 FIG. 6 schematically illustrates an example of the valve control assembly/system 28 configured with a valve opening timing schedule to accurately control opening times of one valve (shown in FIG. 6) or a plurality of valves. In the illustrated embodiment, one or more of the valves 16 can be opened by applying a voltage to the valves through one or more current drivers 602. The
15 valves 16 can open and/or close sufficiently rapidly to inject the gas from the gas plenum into the plasma generator. The speed of the valve's opening operation can be regulated, at least in part, by a supplied voltage from the current driver 602. In some embodiments, a voltage of about 24 V can be supplied to the valves. In other embodiments, the valves 16 can be briefly overvoltage to accelerate the
20 opening speed of the valves. In some cases, the valves 16 may be overvoltage only for a relatively short time to reduce or prevent damage to the valves 16. In some implementations, different voltages, overvoltages, times for applying the voltage or overvoltage, etc. can be applied to the valves 16.

In this example system, the current driver 602 can include an input
25 terminal 603 for receiving valves' timing schedule from a valve controller 605, and an output terminal 604 for producing a drive triggering signal to each of the

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valves 16. In some implementations, the current driver 602 may include electrical-to-optical converting circuits to avoid electromagnetic interference that may occur in the chamber 12 or the plasma generator 100. The valve controller 605 is configured to control and/or synchronize the opening time of the valve 16.

5 The valve controller 605 may comprise a processor 608, a memory 610, an input/output (I/O) interface 612, and/or a media reader 614. The memory has encoded thereon the valve opening timing schedule of the valves 16, and program code executable by the processor to access the timing schedule and control the operation of the valves 16 in accordance with the timing schedule. The processor

10 608, the memory 610, input/output (I/O) interface 612, and the media reader 614 can be integrated as a single device or as separate devices. The I/O interface 612 includes an input that receives a signal from a current detector 606 that measures the current flowing through the solenoid of the valve 16 and an output to convey a control signal in accordance with the valves' timing schedule to the current driver

15 602. The valve controller 605 may further include analog to digital and/or digital to analog (D/A) conversion circuitries. In one implementation, the valve controller 605 can receive signals from the temperature sensors as an input and can send an output signal to the temperature maintaining means such as for example the heating/cooling means. In another implementation, the controller 605

20 can receive a signal from the external coil driver 530 (FIG. 5).

In the illustrated embodiment, the memory can include program code executable by the processor 608 for calibrating the timing of each of the controlled valves 16. When this calibration operation is executed, the processor 608 receives the current signal from the current detector 606 and processes the

25 rate of current change (dI/dt) waveform of each of the valves 16 at a higher gas pressure and the rate of current change (dI/dt) waveform of such valves at a lower gas pressure. Then, the processor 608 determines the divergence point between

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the two waveforms and thus find a time delay for each valve 16. Based on these time delays, the processor produces the timing schedule of a triggering signal for each valve 16. The timing schedule comprising a valve opening time delay value for each valve in the plurality of gas injection valves is encoded in the memory 5 610. The processor 608 can be programmed to use the timing schedule to coordinate the timing of the plurality of gas injection valves during the gas injection operation. In some implementations, the processor 608 can comprise an electronic circuit. In other embodiments, the components of the valve controller 605 may be rearranged or combined differently than shown in FIG. 6 and/or 10 components or functionalities may be merged or separated.

FIG. 7 is a flowchart schematically illustrating one example of a method for determining the valve opening timing schedule that is used by the gas injection system to controll and synchronize an opening time for a plurality of valves 16. Various actions of the method may be encoded in the memory 610 (or 15 other non-transitory computer-readable storage) for directing the processor 608 to produce a schedule of a triggering time for each valve 16. The external magnetic field can be set to, for example, an operational magnetic field of the plasma generator 100, as e.g. $\sim 0.1 - 3\text{T}$. A temperature at each of the valves 16 can be set to a predetermined reference point (e.g. $15 - 35^{\circ}\text{C}$). A temperature control 20 algorithm can be implemented to maintain the temperature at the valves 16 at the desired temperature reference point.

As shown at block 710 and during the calibration operation, a rate of current change waveform at higher gas pressure (HREF) is acquired for each valve in the gas injecting system 10 (a reference waveform). In some 25 implementations, the HREF reference waveform may be obtained when a gas at pressure of about $100 - 250\text{ psig}$ is introduced in the plenum 22 and the driver

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602 applies voltage to the valve. The gas pressure for the reference waveform can be at least 50 psig above an operational gas pressure in some implementations. For example, if the operational gas pressure is chosen to be 50 psig than the reference, high, pressure may be at least 100 psig or higher, or if the operational
5 gas pressure is 100 psig then the reference, high pressure may be at least 150 psig or higher. Block 720 then directs obtaining the rate of current change waveform at an operational gas pressure (LREF). This is done by feeding a gas at lower, operational, pressure in the plenum 22 and the driver 602 applies a voltage to the valve.

10 An example of an HREF waveform and an LREF waveform for one example valve is schematically illustrated in FIG. 8. The solid curve 810 shows an example of di/dt waveform at higher gas pressure (HREF) when the opening of the valve is delayed, and the dashed curve 820 shows an example of the di/dt waveform at operational gas pressure (LREF) when the valve opens faster. As can
15 been seen there is a difference between these two curves which is based on the time of inductance change due to the travel of the plunger. The actions represented at blocks 710 and 720 may be repeated every time the external magnetic field is changed.

Returning to the example method shown in FIG. 7, at block 730, the
20 beginnings of the HREF waveform and the LREF waveform are shifted so that the beginning of each waveform lines up. At Block 740, a divergence point between the HREF and LREF is determined. The divergence point for each of the plurality of valves can be determined by performing some or all of the following actions a) to e) in some embodiments of the method.

25 a) The LREF waveform is subtracted from the HREF waveform to obtain a difference (DIFF) waveform. FIG. 9 schematically

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illustrates an example of the DIFF (dot-dashed curve) waveform 930 obtained by subtracting the LREF (dashed curve) 920 waveform from the HREF (solid curve) 910 waveform. As can be seen from FIG. 9, the DIFF waveform generally tracks an ACCEL waveform (dotted curve) 940 obtained from an accelerometer (not shown) that measure the acceleration of the valve's plunger. The ACCEL waveform 940 can be used to validate the accuracy of the control algorithm. The accelerometer and the ACCEL waveform 940 are optional. In one implementation, the DIFF waveform 930 can be normalized by dividing it by a maximum height (value) of the reference (HREF) waveform.

b) With reference to the examples schematically shown in FIG. 10, first and second derivatives of the DIFF waveform 930 are numerically generated, obtaining a velocity (DIFF_D) waveform 1010 (FIG. 10) and an acceleration (DIFF_D2) waveform 1020 (FIG. 10), respectively.

c) A window of data (e.g., data to be analyzed by the algorithm) can be generated. The window may be generated by ignoring data in the first 350 μ s of the obtained waveforms, because the valves typically do not open that early. Also any signal that comes after the valve's plunger lifts completely up can be ignored in some cases. After the plunger lifts to its maximum distance from the valve seat, it may oscillate based on the mass of the plunger and the stiffness of the detention spring. The window of acceptable data can vary depending on the detector's characteristics. For given characteristics of the detector 606 a window threshold can be determined manually and provided as an input value to the processor 608, or it can be determined automatically by the processor

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608 (e.g., based on one or more of the HREF, LREF, DIFF, DIFF_D, and DIFF_D2 waveforms). Each time the characteristics of the detector 606 are changed, the window threshold value may be determined again.

5 In some implementations, the window of data can be determined by conducting a number of experiments on valves opening. During the experiments the exact time of valve opening could be determined based on the motion waveform obtained from the accelerometer, e.g. the ACCEL waveform 940 (FIG. 9). Then the magnitudes of HREF and LREF waveforms for all valves were normalized and a value of maximum peaks
10 of derivatives DIFF_D and DIFF_D2 were analyzed. In some such implementations, the threshold was selected as a value that was below the maximum peak $1010_{\max}$ of the derivative DIFF_D waveform and such threshold value can be inputted into or determined by the controller 605. For example, the threshold value may be approximately 5%, 10%, 15%,
15 20% or more of the maximum peak $1010_{\max}$ of the DIFF_D waveform. In some implementations the window threshold may be determined automatically by the controller 605 (or some other computing device). In some implementations, all the data is used, and windowing is not performed.

20 d) Once the data window is generated (if windowing is used), for each valve 16 the maximum peak $1010_{\max}$ of the velocity derivative (DIFF_D) waveform (FIG. 10) can be detected by searching for the highest point of the DIFF_D waveform within the generated window of data.

25 e) A divergence point 1030 (FIG. 10) between the HREF and LREF waveforms can be determined by identifying the maximum peak

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1020_{max} of the acceleration derivative (DIFF_D2) waveform that is in proximity to the DIFF_D maximum peak 1010_{max}. This maximum peak 1020_{max} of the DIFF_D2 waveform may be in a range of about 100μs on either side of the DIFF_D maximum peak 1010_{max}. The maximum peak 5 1020_{max} of the acceleration (DIFF_D2) waveform may correspond to the divergence point 1030 between the HREF and LREF waveforms and may indicate the time the plunger of the valve starts lifting up (T_{open}). For example, T_{open} can correspond to the divergence point between the HREF and LREF waveforms and is schematically shown by a vertical solid line 10 1040 in FIG. 10.

FIGS. 11 and 12 illustrate examples of graphs that can be used with another method for determining the divergence point between the reference (HREF) waveform and operational (LREF) waveform for each of the valves 16. In FIG. 11, the difference (DIFF) waveform (dashed curve) 1110 can be obtained 15 as previously explained and can be normalized by dividing the DIFF signal by a maximum height of the reference (HREF) signal. A threshold (solid horizontal line) 1120 can be selected as a value based on the maximum height of the difference (DIFF) waveform. For example, the threshold value may be a percentage of the maximum height of the DIFF waveform. For example, the 20 threshold value can be approximately 5%, 10%, 15%, 20% or more of the maximum height of the DIFF waveform based on the signal to noise ratio of the reference (HREF) and operational (LREF) signals. The divergence point between the reference (HREF) waveform and operational (LREF) waveform can be found by determining a point (crossing point 1130) at which the difference (DIFF) 25 waveform 1110 crosses the threshold line 1120. Then a derivative waveform DIFF_D (solid curve) 1140 can be used to determine an instantaneous slope of the difference DIFF waveform 1110 at the crossing point 1130. Based on a projection

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of the slope when the DIFF waveform 1110 crosses the threshold 1120, a sloped line 1150 (FIG. 12) can be determined. A zero crossing point 1160 of the DIFF waveform can be determined based on the projected sloped line 1150 as illustrated at FIG. 12. Time of the projected zero crossing 1160 can correspond to the divergence point between the reference (HREF) waveform and operational (LREF) waveform and therefore can correspond to the opening time (T_{open}) of such valve.

Once the divergence point for each valve is determined, the valve control method at block 750 (FIG. 7) directs finding a time delay (e.g., a time difference between the time the voltage is applied to the valve and the time valve actually opens) for each of the one or more valves 16. At block 760, the time delay for the slowest valve is identified. Such valve is appointed to have a trigger delay “0” and the triggering time of all other valves can be aligned to open the valves at the same time as the slowest valve. Block 770, directs setting up the timing schedule, i.e. a table of trigger time for each valve 16 so that all valves 16 can open at the same time as the slowest valve, thereby synchronizing the opening of the plurality of valves 16.

For example, the opening time of the slowest valve T_0 may be used as a desired time for each valve to open. The triggering time for each valve $T_{trigger}$ (e.g., the time when voltage or current is applied to the valve) can be determined for each valve as $T_{trigger} = T_0 - \Delta t$, where T_0 is the opening time of the slowest valve and Δt is the time delay of the particular valve.

The example method of FIG. 7 may be implemented, partially or totally, by computer hardware capable of executing instructions such as, e.g., a general or special purpose computer, a programmable logic device or controller, an application-specific integrated circuit, etc. The example method of FIG. 7 may be

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implemented by embodiments of the system of FIG. 6 and may be used to control the valves 16 of embodiments of the gas injection system 10 of FIG. 1 during a gas injection operation. The timing schedule can be stored in a memory (volatile or non-volatile), for example as a look-up table (LUT). The valve controller 605
5 may output a signal to the current driver 602 with information relating to the triggering time of each valve so that the current driver 602 can provide a signal (e.g., a current or a voltage) to each valve to open according to the time schedule. In some implementations, the accuracy of the valve control system of the present invention is about 5 - 30 μ s.

10 In some implementations, the time delay for each valve can be determined and can be repeated after each cycle of valve opening, i.e. the calibration operation can be executed after each cycle of valve opening. The timing schedule may be tuned on a cycle-to-cycle basis, for example, by re-measuring the time delays of some or all valves after each cycle or after a certain number of cycles.
15 In other implementations, the time schedule of each valve is determined and then re-measured from time to time by the calibration operation, such as for example, once an hour, once a day, or once every few days. The time delays (and time schedule) may be re-determined after maintenance on the system has been performed or modifications to the system have been implemented (e.g. if an
20 external magnetic field generated by coils 18 has been modified). In some implementations, the process for determining a time schedule for triggering the valves can be repeated in any suitable sequence.

As an illustrative example of the synchronization of three valves, if divergence point for valve 1 occurs at 450 μ s, at 600 μ s for valve2, and at 500 μ s
25 for valve3 (e.g., the time delays are 450 μ s for valve1, 600 μ s for valve2, and 500 μ s for valve3). The desired opening time for all three valves is 600 μ s (e.g.,

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the opening time of the slowest valve2). Then the triggering voltage can be applied to valve1 with a delay of 150 μ s (600 μ s - 450 μ s), to valve2 with no delay, and to valve3 with 100 μ s delay, so that all three valves open at approximately the same time. Accordingly, in this example, the current driver 602 could apply the triggering voltage (or current) to valve2 first, then 100 μ s later apply the triggering voltage to valve3, and then 50 μ s later apply the triggering voltage to valve1. A timing schedule for any number of valves may be determined using embodiments of the disclosed systems and methods.

Although various embodiments have been described with reference to measurement of a current or rate of change of the current supplied to a coil in the valve, in other embodiments the systems and methods may measure voltage, rate of change of voltage, impedance, rate of change of impedance, resistance, or rate of change of resistance, or any other electrical property of the valve. Some embodiments may measure more than one electrical property to provide a more accurate estimate of valve time delays.

The methods and systems for valve control disclosed herein may be used in a variety of applications such as, e.g., controlling or synchronizing the opening and/or closing of valves in an engine. For example, embodiments of the methods and systems may be used to control intake and/or exhaust valves in an internal combustion engine. Embodiments of the methods and systems can be used to control valves used to inject fluid into pneumatic or hydraulic piston drivers such as used in stamping or machine presses. The methods and systems can also be used for controlling or synchronizing injection of a fluid (e.g., a gas) through one or more valves into a target chamber. In some implementations, the gas in the target chamber can be ionized to form a high energy plasma, which can be used in the fields of nuclear physics and astrophysics, for example, in a neutron source, in

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an x-ray radiation source, in a nuclear fusion device, or used for production of medical isotopes, etc.

While particular elements, embodiments and applications of the present disclosure have been shown and described, it will be understood, that the scope of the disclosure is not limited thereto, since modifications can be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings. Thus, for example, in any method or process disclosed herein, the acts or operations making up the method/process may be performed in any suitable sequence and are not necessarily limited to any particular disclosed sequence. Elements and components can be configured or arranged differently, combined, and/or eliminated in various embodiments. The various features and processes described above may be used independently of one another, or may be combined in various ways. All possible combinations and subcombinations are intended to fall within the scope of this disclosure. Reference throughout this disclosure to “some embodiments,” “an embodiment,” or the like, means that a particular feature, structure, step, process, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of the phrases “in some embodiments,” “in an embodiment,” or the like, throughout this disclosure are not necessarily all referring to the same embodiment and may refer to one or more of the same or different embodiments. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, additions, substitutions, equivalents, rearrangements, and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions described herein.

Various aspects and advantages of the embodiments have been described where appropriate. It is to be understood that not necessarily all such aspects or

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advantages may be achieved in accordance with any particular embodiment. Thus, for example, it should be recognized that the various embodiments may be carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other aspects or advantages as may be taught or suggested herein.

Conditional language used herein, such as, among others, "can," "could," "might," "may," "e.g.," and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or steps. Thus, such conditional language is not generally intended to imply that features, elements and/or steps are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without operator input or prompting, whether these features, elements and/or steps are included or are to be performed in any particular embodiment. No single feature or group of features is required for or indispensable to any particular embodiment. The terms "comprising," "including," "having," and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. Also, the term "or" is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term "or" means one, some, or all of the elements in the list. Further, the articles "a" or "an" mean one or more in the foregoing description and the following claims.

Any of the processes, methods, and algorithms described herein may be embodied in, and fully or partially automated by, code modules executed by one or more computers, computer processors, or machines configured to execute computer instructions. The code modules may be stored on any type of non-

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transitory computer-readable medium or computer storage device, such as hard drives, solid state memory, optical disc, and/or the like. The systems and modules may also be transmitted as generated data signals (e.g., as part of a carrier wave or other analog or digital propagated signal) on a variety of computer-readable transmission mediums, including wireless-based and wired/cable-based mediums, and may take a variety of forms (e.g., as part of a single or multiplexed analog signal, or as multiple discrete digital packets or frames). The processes and algorithms may be implemented partially or wholly in application-specific circuitry. The results of the disclosed processes and process steps may be stored, persistently or otherwise, in any type of non-transitory computer storage such as, e.g., volatile or non-volatile storage.

The example calculations, simulations, results, graphs, values, and parameters of the embodiments described herein are intended to illustrate and not to limit the disclosed embodiments. Other embodiments can be configured and/or operated differently than the illustrative examples described herein.

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Claims:

1. A gas injection system for use in a plasma generator, the system comprising:

5 a plurality of electrically actuated gas injection valves, wherein each valve comprises a current driver;

a plasma generation chamber in gaseous communication with the plurality of gas injection valves, the plurality of gas injection valves being arranged at a periphery of the chamber; and

10 a valve control assembly communicative with the current driver of each valve in the plurality of gas injection valves and comprising a memory having encoded thereon a time schedule comprising a valve opening time delay value for each valve in the plurality of gas injection valves, and a processor programmed to use the time schedule to coordinate a timing of the plurality of gas injection valves during a gas injection
15 operation.

2. The gas injection system of claim 1, further comprising means for maintaining temperature, said means for maintaining temperature comprising at least one of a cooling means or a heating means in thermal communication with the plurality of gas injection valves.

20 3. The gas injection system of claim 2, further comprising a temperature sensor positioned in proximity to each of the plurality of gas injection valves and a temperature controller being in communication with the sensor to receive an input signal from the sensor and provide an output signal to the means for maintaining the temperature at each of the plurality of gas injection valves.

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4. The gas injection system of claim 3, wherein the temperature controller is integrated with the valve control assembly.

5. The gas injection system of claim 1, further comprising a magnetic field shield configured to envelop a housing of each of the plurality of gas injection valves to deflect field lines of an external magnetic field in the chamber and to reduce an effect of the external magnetic field on the plurality of gas injection valves, the magnetic field shield being made of ferromagnetic material.

6. The gas injection system of claim 1, further comprising a magnetic shielding circuit in communication with the current driver of each of the plurality of gas injection valves, the shielding circuit configured to provide a signal to the current driver to initiate a current flow through the plurality of gas injection valves to generate a magnetic field to keep the plurality of gas injection valves closed and to reverse a direction of the current flow through the valves to open the plurality of gas injection valves.

7. The gas injection system of claim 6, wherein the magnetic shielding circuit comprises a controller communicative with an external coil driver and configured to receive an input signal therefrom, the input signal comprising a timing schedule for triggering an external coil and synchronizing an initial current flow through the plurality of gas injection valves so that the initial current flow through the plurality of gas injection valves happens simultaneously with the triggering of the external coil, the magnetic shielding circuit controller being in communication with the valve control assembly to send an output signal to the current driver of at least one valve in the plurality of gas injection valves to reverse a direction of the current flow through the at least one of the gas injection valves when opening of the at least one of the gas injection valves is required.

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8. The gas injection system of claim 7, wherein the magnetic shielding circuit controller is integrated with the valve control assembly.

9. The gas injection system of claim 1, wherein each of the plurality of gas injection valves has a channel in gaseous communication with the plasma generation chamber, and at least one valve in the plurality of gas injection valves includes a solenoid connectable to a power source for generating a magnetic field in the channel of the at least one valve to prevent ionized gas from entering the at least one valve.

10. The gas injection system of claim 9, further comprising a fine grade particulate mesh filter positioned in the channel configured to prevent entry of any dust particles flowing along with the ionized gas.

11. The gas injection system of claim 1, wherein the valve control assembly further comprises

a current detector configured to measure a rate of current change as a function of time for each of said plurality of gas injection valves,

wherein the processor of the valve control assembly is communicative with the current detector to receive therefrom a rate of current change as a function of time measurement at a first pressure (HREF) and a rate of current change as a function of time measurement at a second pressure (LREF) that is lower than the first pressure for each of said plurality of valves and wherein the processor is further programmed to determine a divergence point wherein the HREF and the LREF measurements diverge for each of the plurality of gas injection valves, to determine the valve opening time delay for each of said plurality of gas injection valves from the determined divergence points, and to trigger the

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current driver of each of the plurality of valves according to the time schedule to coordinate the timing of the plurality of gas injection valves during a gas injection operation.

12. The gas injection system of claim 1, wherein the processor of the
5 valve control assembly is further programmed to synchronize opening of the plurality of gas injection valves to inject the gas into the plasma generation chamber in a sequence of at least two sequential gas injection pulses, wherein a first gas injection pulse is injected ahead of a next sequential gas injection pulse, the next sequential gas injection pulse being at a pre-determined time delay from
10 the first gas injection pulse, and wherein a gas ionization is triggered immediately after injection of a last gas injection pulse in the sequence.

13. The gas injection system of claim 12, wherein the plurality of gas injection valves comprise a first set of valves and at least one additional set of valves, wherein the processor is further programmed to inject the first gas
15 injection pulse through the first set of valves, and to inject at least one additional gas pulse through the additional set of valves.

14. A valve control assembly for controlling a plurality of gas injection valves in a gas injection system of a plasma generator, the assembly comprising:

20 a current detector configured to measure a rate of current change as a function of time for each of said plurality of gas injection valves,

a controller communicative with the current detector and configured to receive therefrom a rate of current change as a function of time measurement at a first pressure (HREF) and a rate of current change as a function of time measurement at a second pressure (LREF) that is
25 lower than the first pressure for each of said plurality of valves, the

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controller also communicative with a current driver of each of the plurality of gas injection valves and programmed to determine a divergence point wherein the HREF and the LREF measurements diverge for each of the plurality of gas injection valves, to determine a valve opening time delay for each of said plurality of gas injection valves from the determined divergence points, and to trigger the current driver of each of the plurality of gas injection valves according to a time schedule comprising the determined valve opening time delays, thereby coordinating the timing of the plurality of gas injection valves during a gas injection operation.

15. A method for gas injection into a plasma generator through a plurality of gas injection valves, the method comprising:

setting and maintaining a temperature at the plurality of gas injection valves at a pre-determined reference point;

setting an external magnetic field at a pre-determined configuration in the plasma generation chamber that is in gaseous communication with the plurality of gas injection valves;

determining a time schedule of a valve opening time for each of the plurality of gas injection valves, wherein the time schedule comprises a valve opening time delay for each of the plurality of gas injection valves; and

coordinating a triggering of the opening of the plurality of gas injection valves according to the time schedule thereby injecting gas into the plasma generation chamber.

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16. A method for calibrating valve timing for a plurality of gas injection valves of a gas injection system for use in a plasma generator, the method comprising:

5 measuring a rate of current change as a function of time for each of a plurality of gas injection valves operating at a first pressure (HREF), and measuring a rate of current change as a function of time for each of the plurality of gas injection valves at a second pressure (LREF) that is lower than the first pressure;

10 determining a divergence point for each of the plurality of gas injection valves wherein the HREF and the LREF measurements for each of the plurality of gas injection valves diverge, and determining a valve opening time delay for each of the plurality of gas injection valves from the determined divergence points; and

15 encoding a time schedule comprising an identifier and the associated valve opening time delay for each of the plurality of gas injection valves, onto a memory of a valve control assembly of the gas injection system.

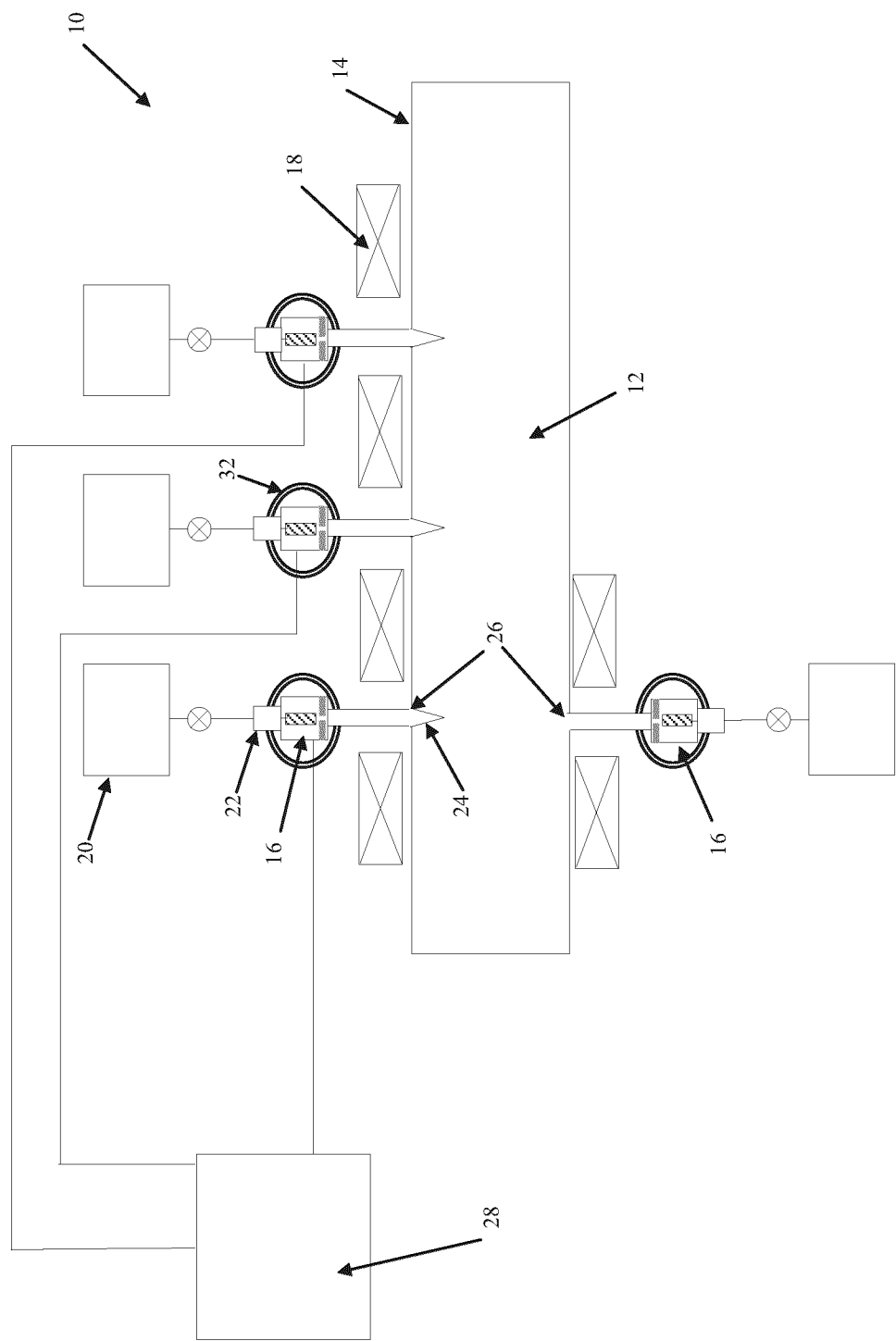


FIG. 1

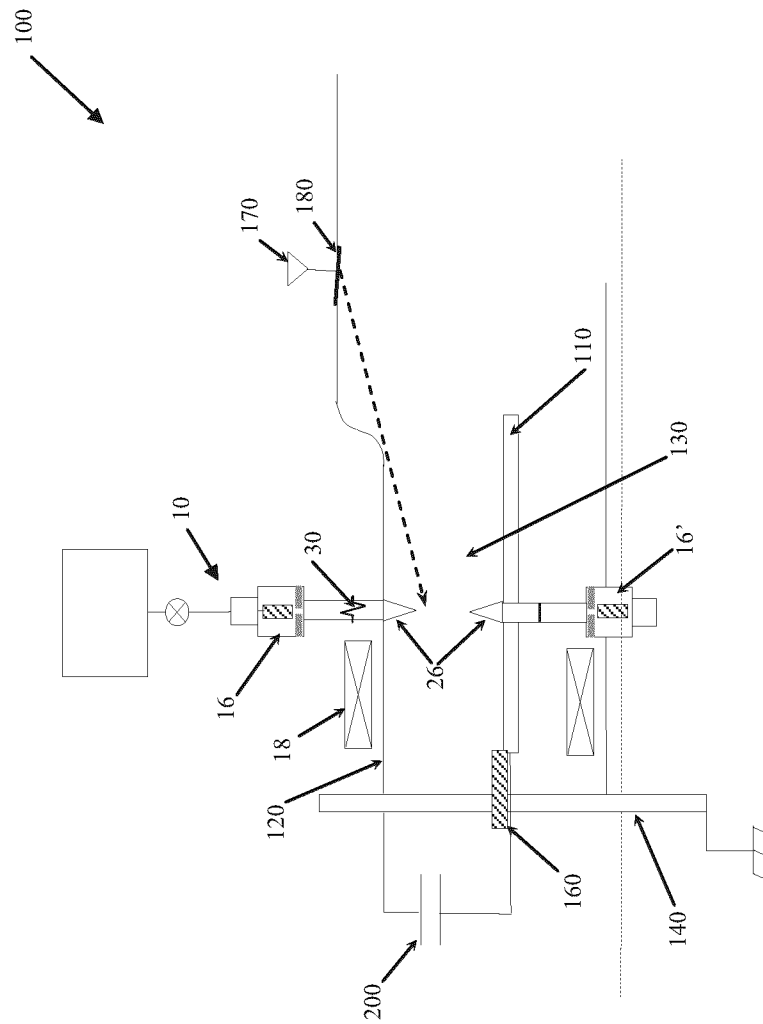


FIG. 2

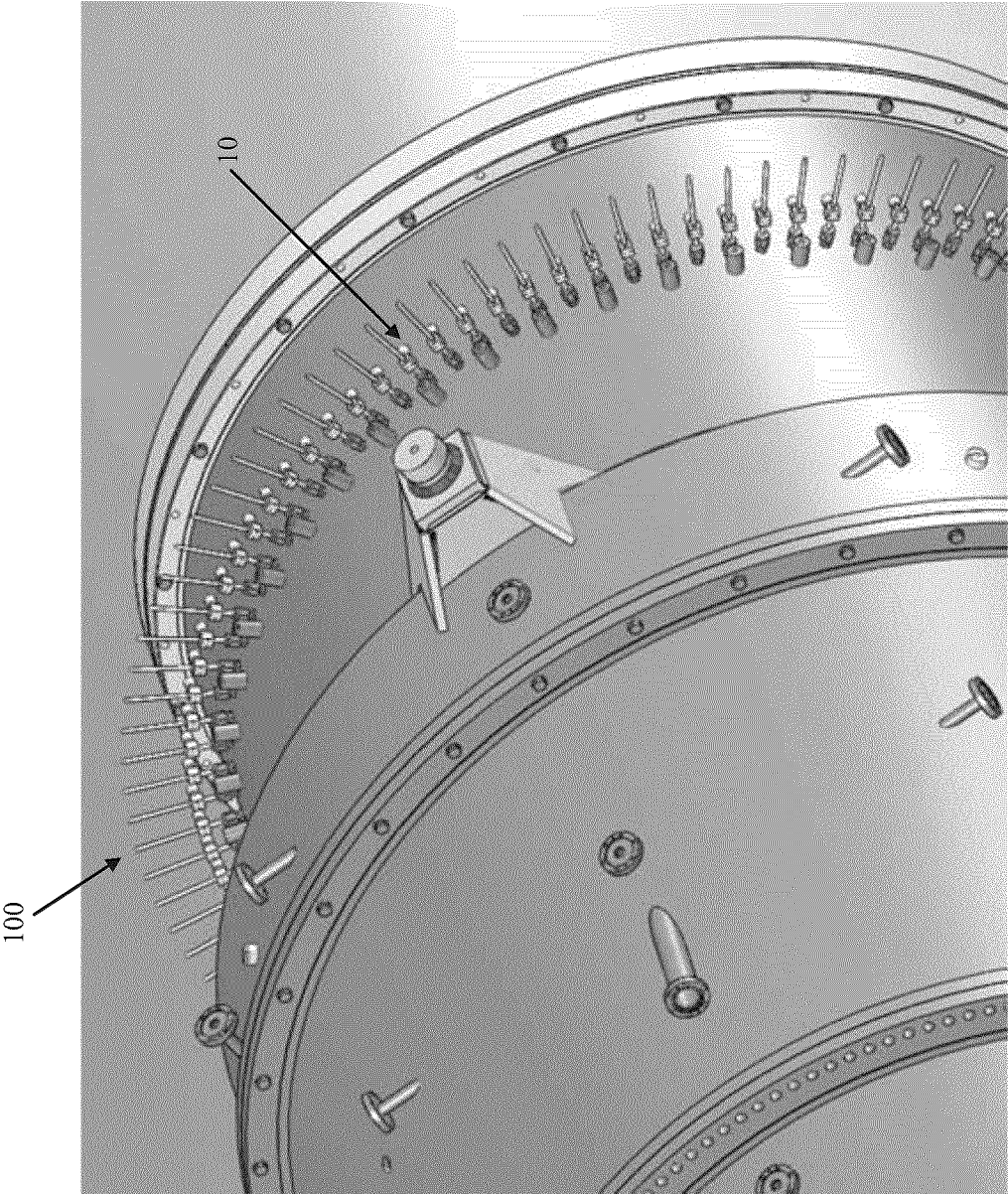


FIG. 3

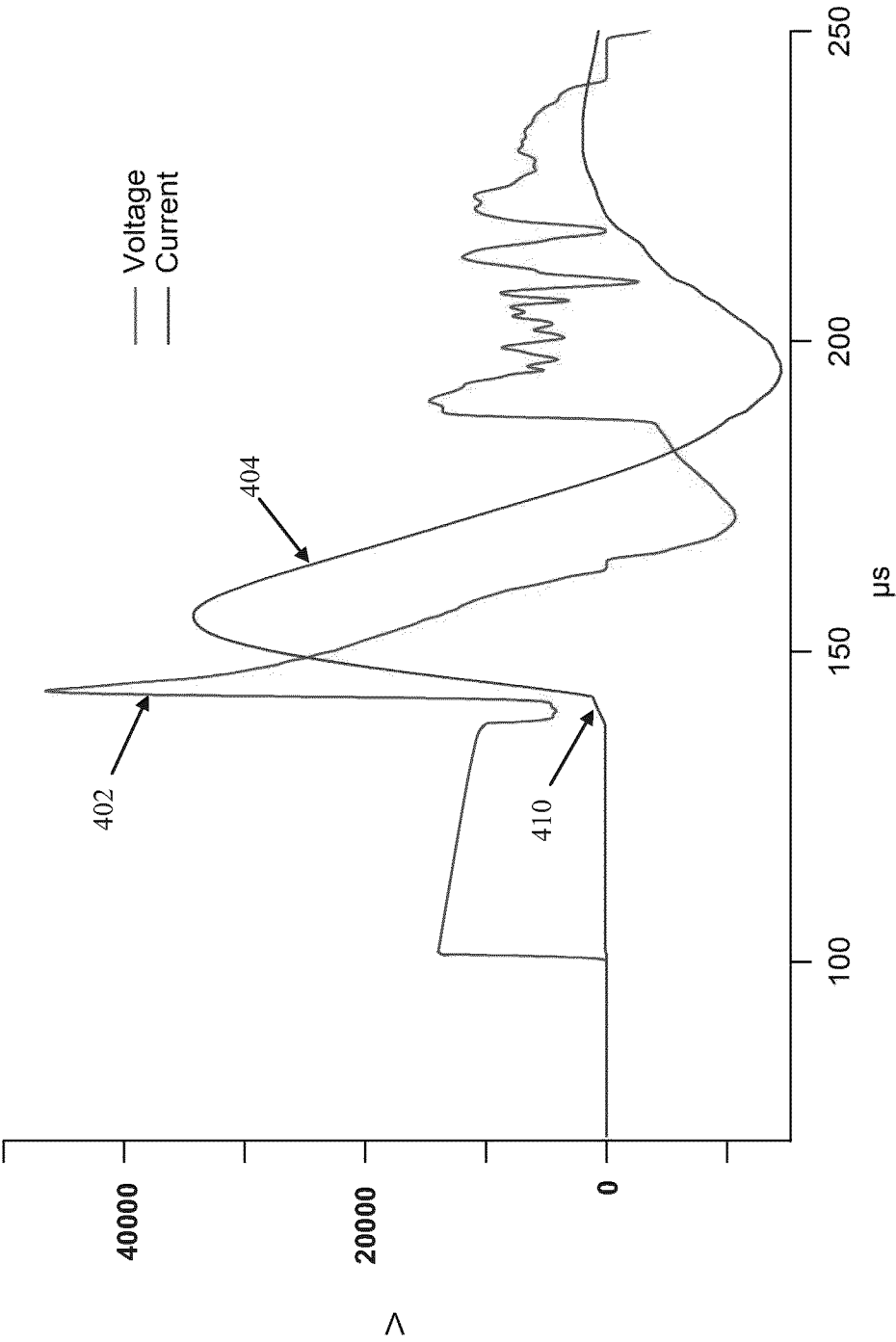


FIG. 4

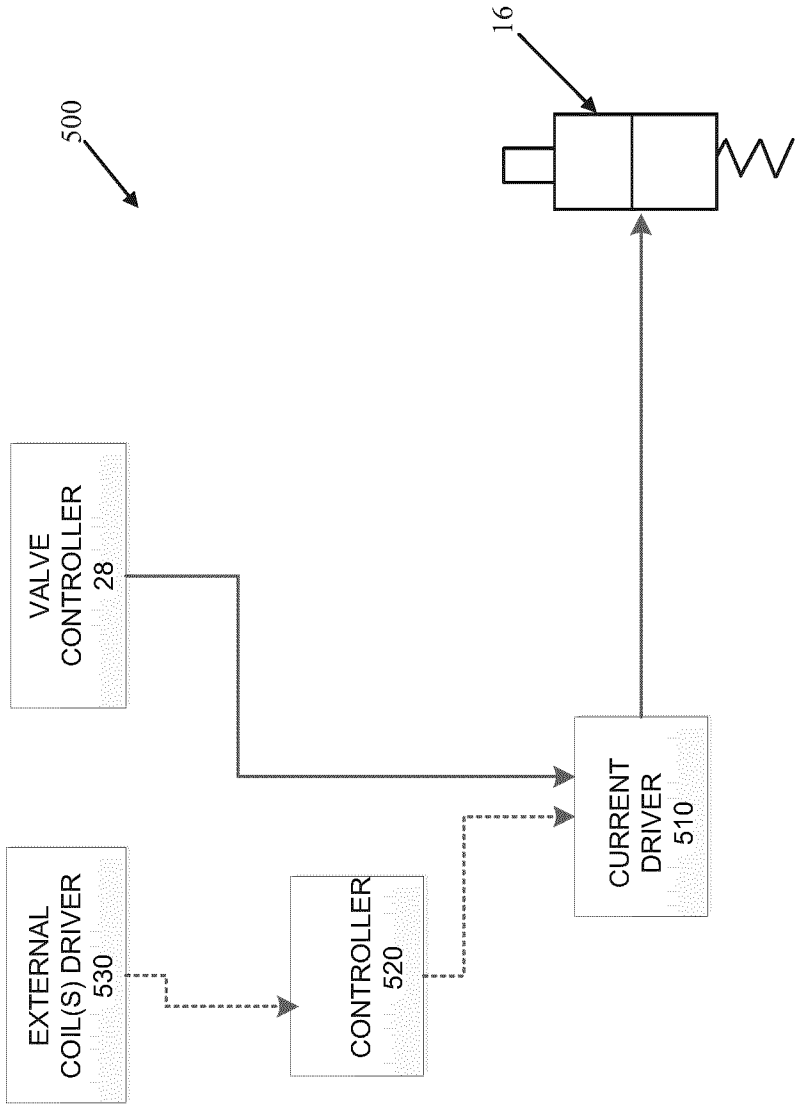


FIG. 5

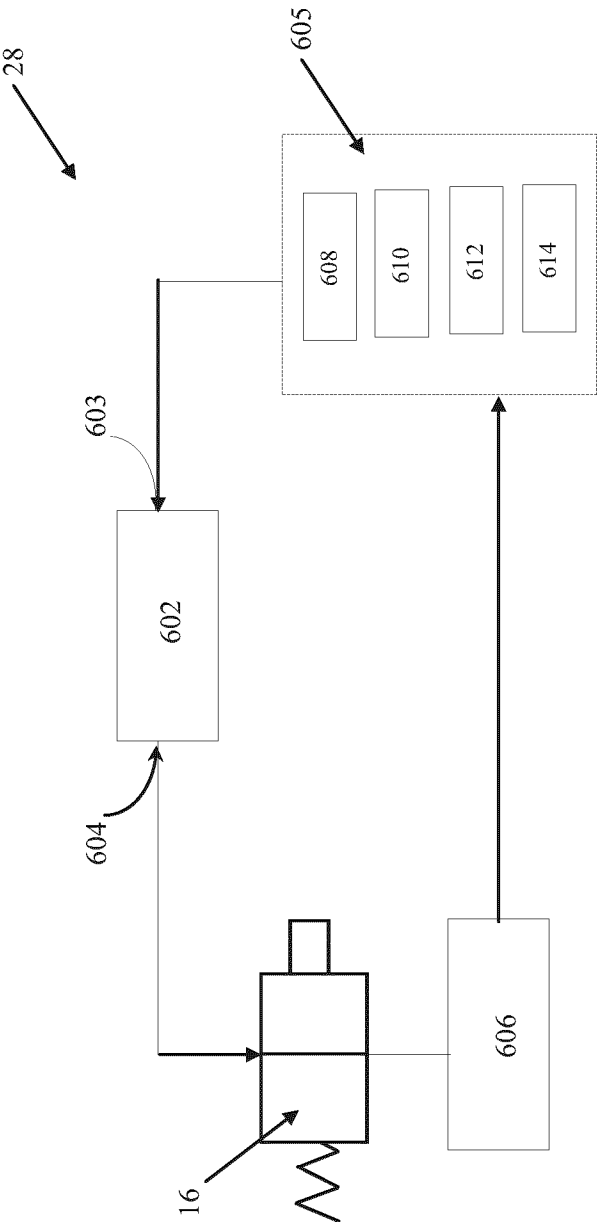
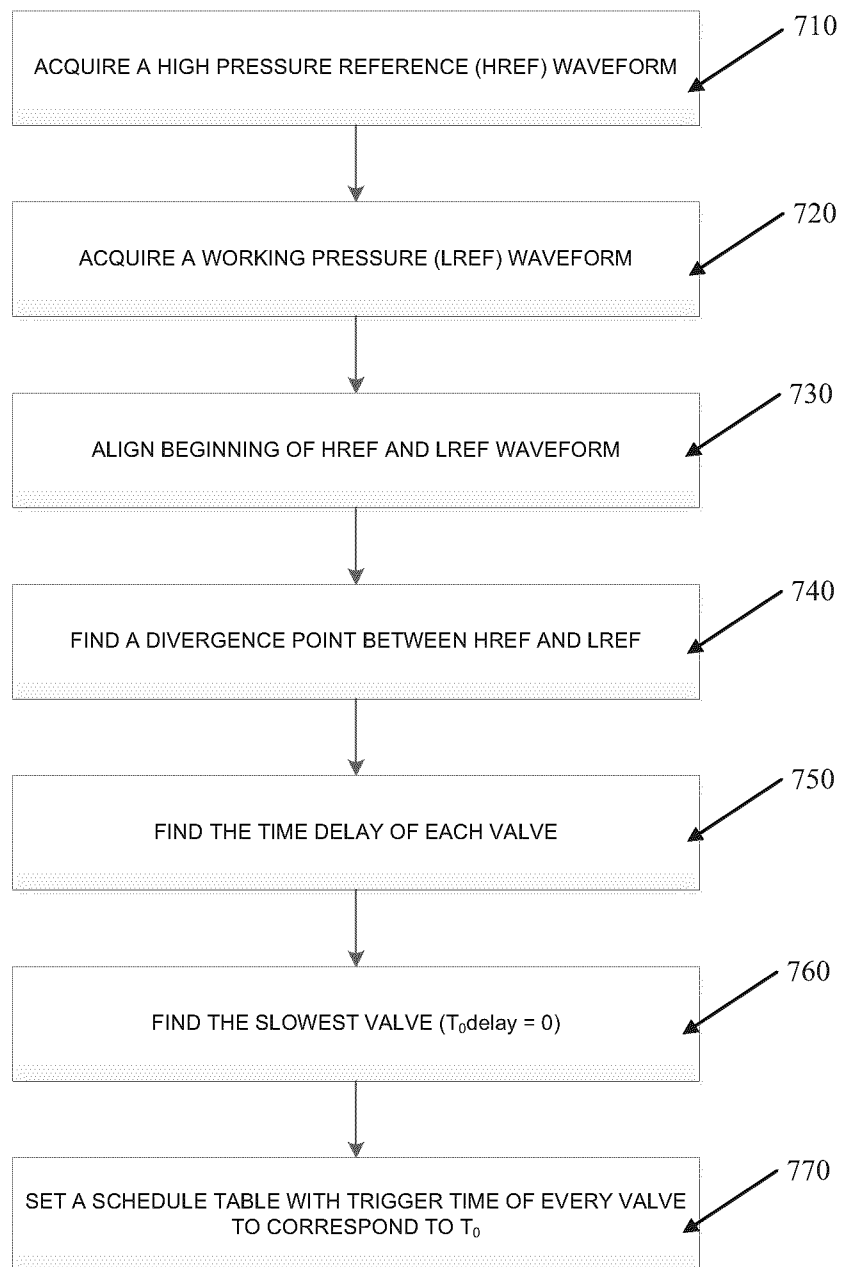


FIG. 6

**FIG. 7**

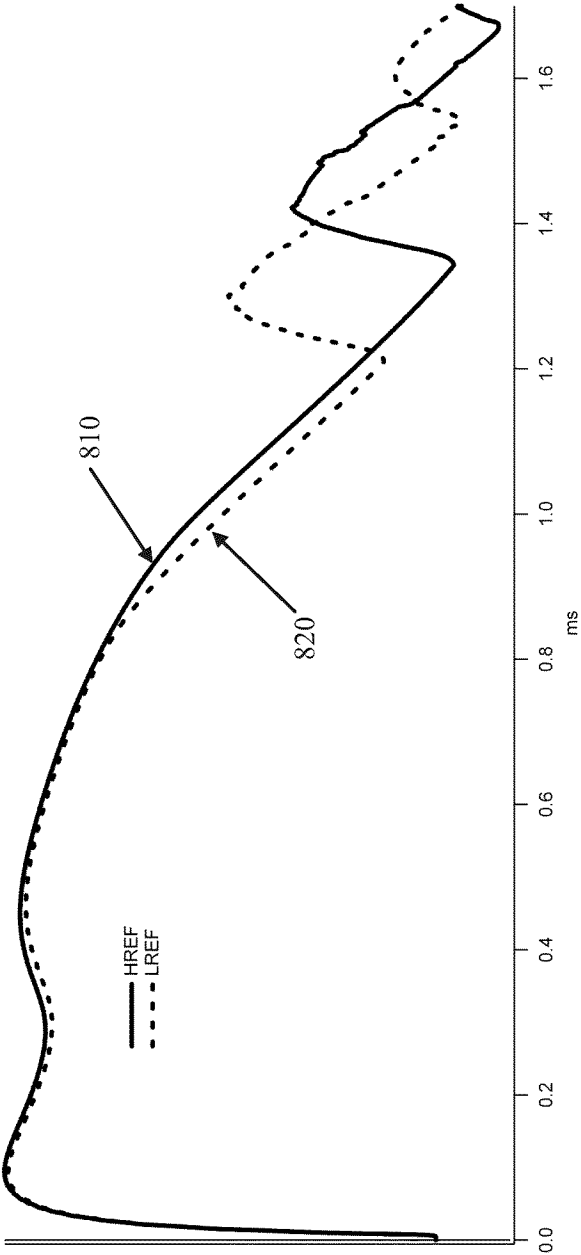


FIG. 8

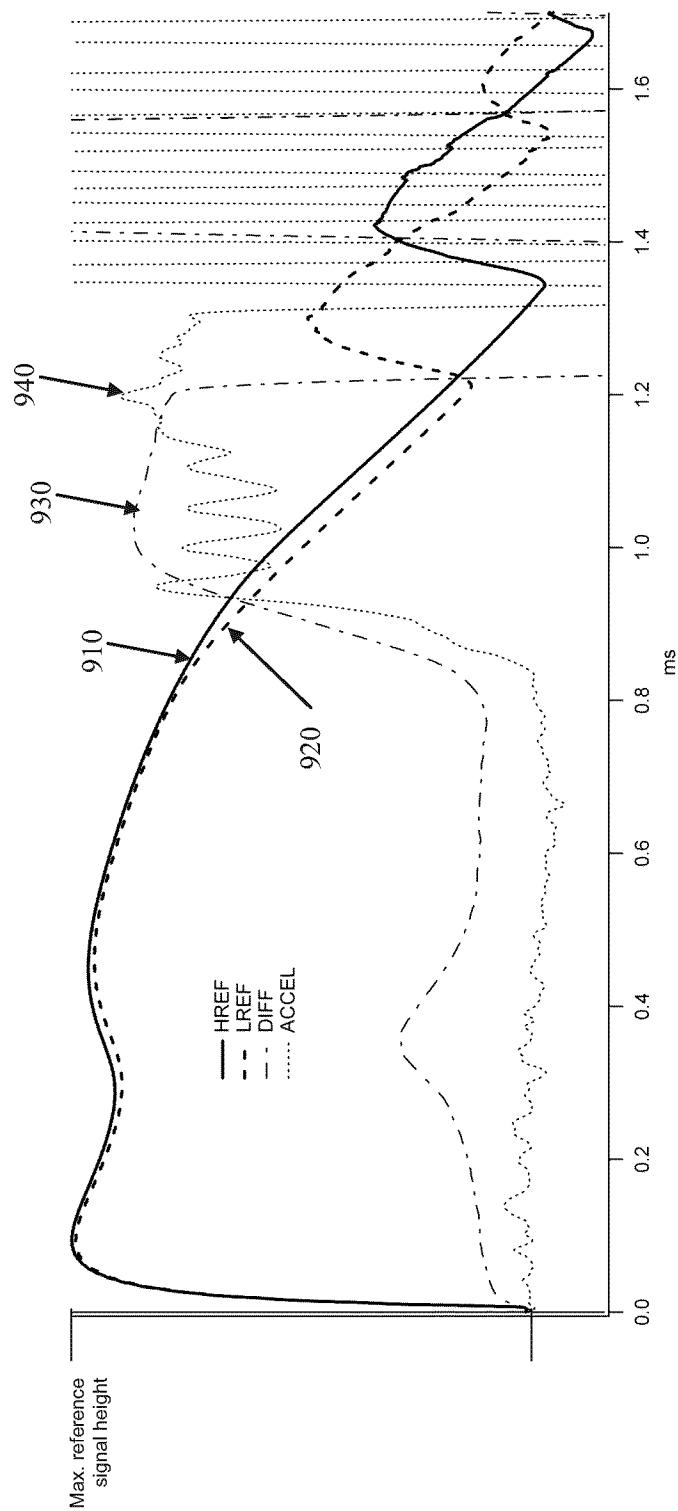


FIG. 9

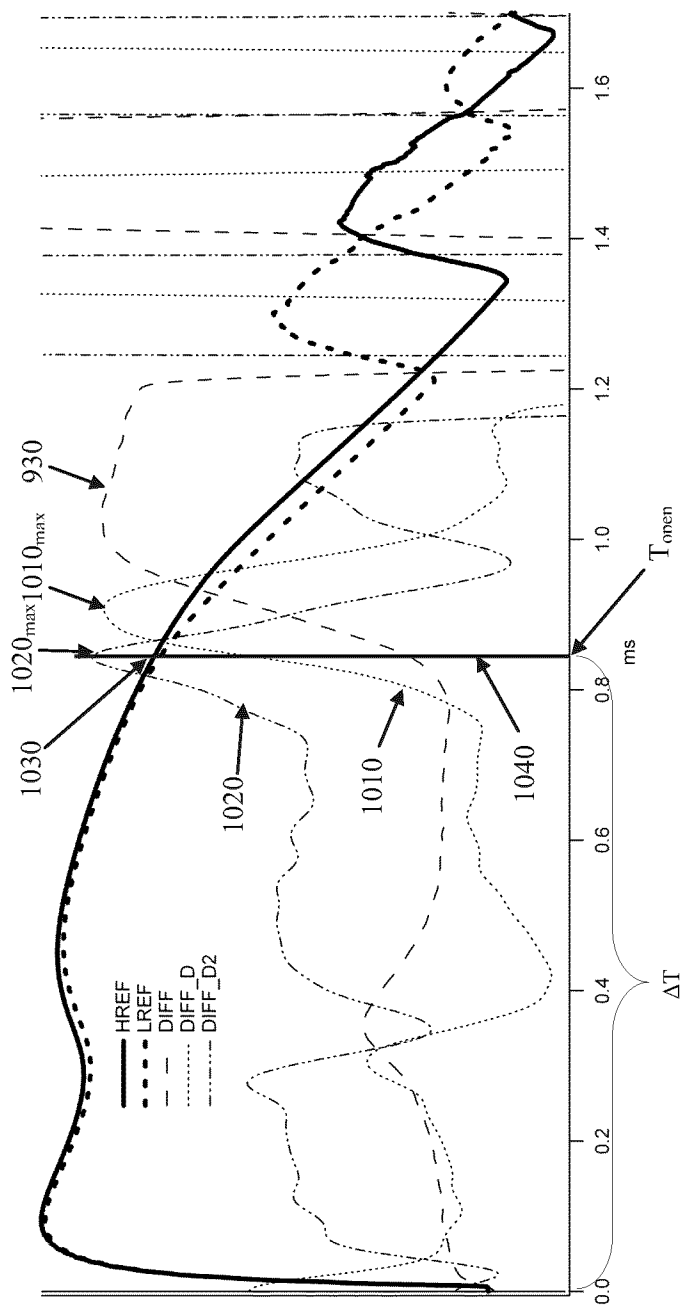


FIG. 10

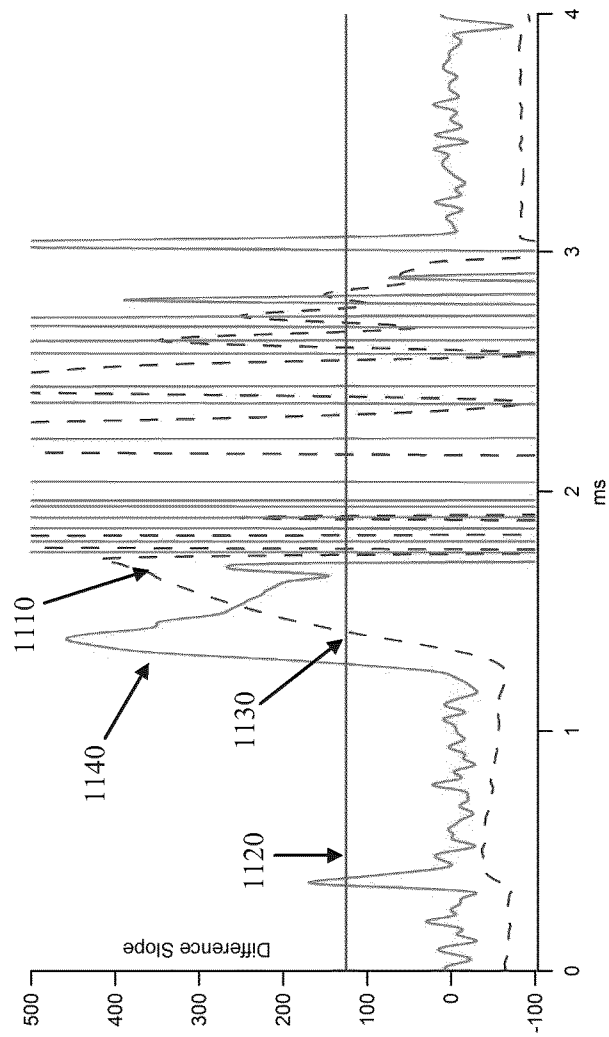


FIG. 11

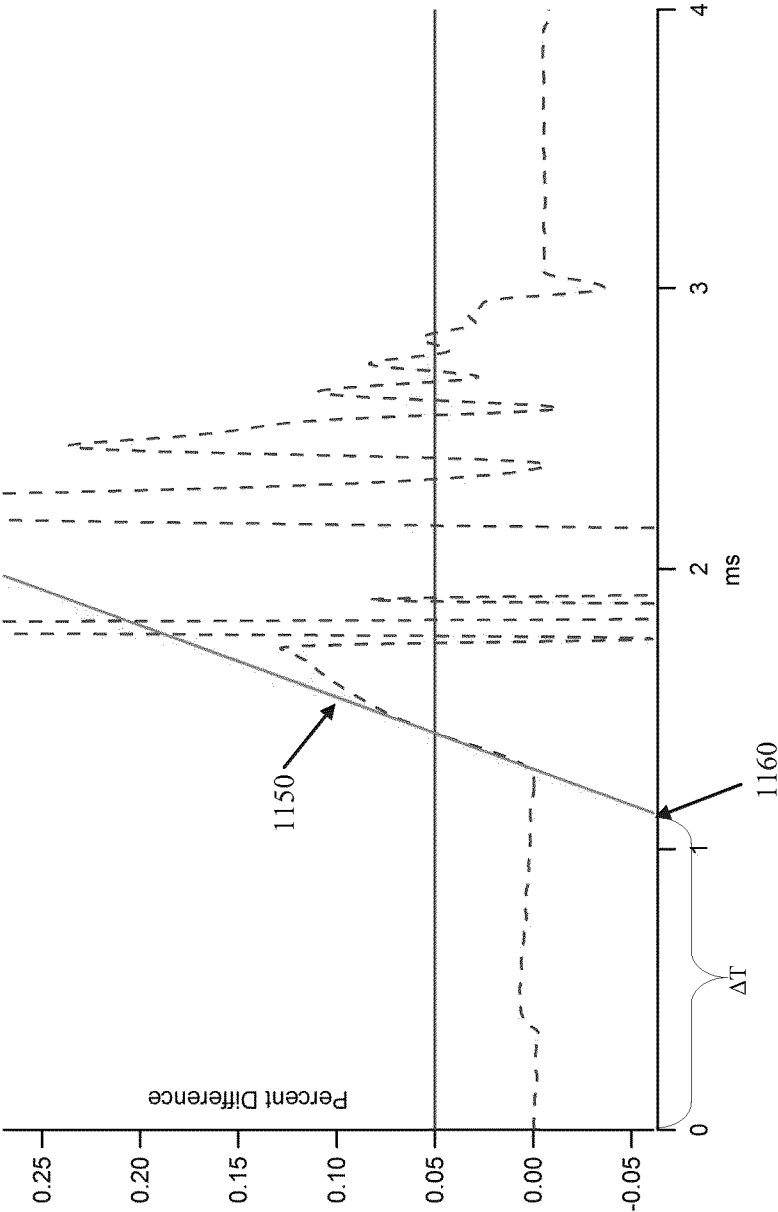


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CA2014/051243

A. CLASSIFICATION OF SUBJECT MATTER

IPC: **H05H 1/00** (2006.01), **H05H 1/24** (2006.01), **H05H 1/42** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H05H 1/00 (2006.01), H05H 1/24 (2006.01), H05H 1/42 (2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Databases used: Questel Orbit, WEST, Canadian patent database

Keywords used: plasma, generation, creation, gas, injection, valve, piezoelectric, electromagnetic, solenoid, filter, temperature, current, time, delay, controller, mfc, mass flow controller, high, low, pressure, schedule, memory, processor, computer, sensor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8 053 254 B2 (Tsuda et al.) 8 November 2011 (08-11-2011)	1 and 5
Y	see column 5, lines 60-65, column 6, lines 30-43, column 8, lines 17-27, and column 8, line 46 – column 9, lines 4 and Figure 1	2-4, 6, 9, 10, and 12
Y	US 2012/0305188 A1 (Kato et al.) 6 December 2012 (06-12-2012) see paragraph [0068] and Figures 1 and 2	2-4
Y	US 3 822 679 (Hobo et al.) 9 July 1974 (09-07-1974) see column 3, line 36 – column 4, line 24	6
Y	US 2009/0095364 (Itoh et al.) 16 April 2009 (16-03-2009) see paragraph [0049] and Figure 4	9 and 10

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* “A” “E” “L” “O” “P”	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance earlier application or patent but published on or after the international filing date document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) document referring to an oral disclosure, use, exhibition or other means document published prior to the international filing date but later than	“T” “X” “Y” “&”	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art document member of the same patent family
Date of the actual completion of the international search 04 March 2015 (04-03-2015)		Date of mailing of the international search report 11 March 2015 (11-03-2015)	
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 001-819-953-2476		Authorized officer Kristina Bodnar (819) 934-5146	

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