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(54) ELECTROMAGNETIC PUMPS IN LIQUID METAL JET X-RAY SOURCES

(57) A liquid metal jet X-ray source is disclosed, comprising an electromagnetic (EM) pump for pumping liquid metal and for forming the metal jet by forcing the liquid metal through a nozzle. The X-ray source comprises one or more sensors configured to provide a value indicative of a flow of liquid metal through the EM pump; a pressure generated by the EM pump; and/or an electrical resistance of the EM pump. A control-

ler is provided for monitoring the sensor output. The flow of liquid metal through the EM pump is reversed if the sensor output deviates from a nominal value. The reversal of the flow can be effected automatically by the controller, or manually by an operator following an alert provided by the controller. A corresponding method for operating a liquid metal jet X-ray source is also disclosed.

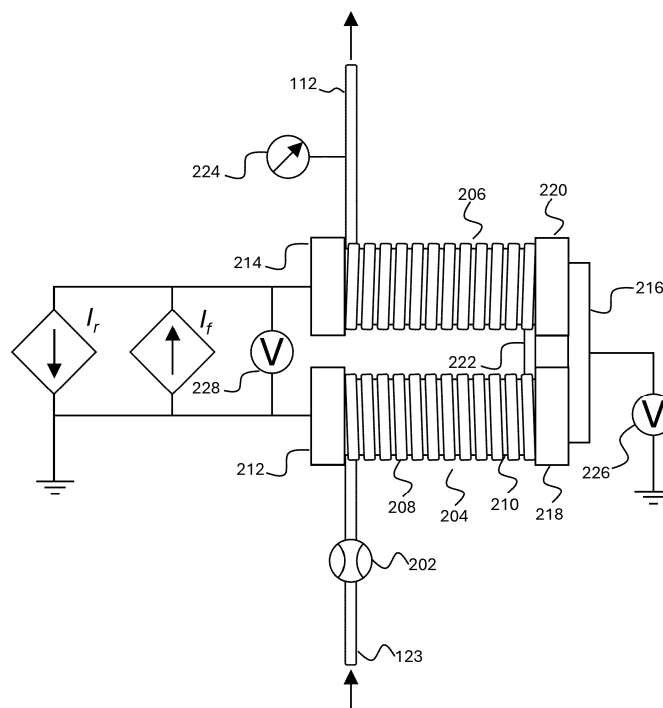


Fig. 2

Description

Technical field

[0001] The present disclosure relates to electromagnetic (EM) pumps. In particular, the disclosure relates to electromagnetic pumps used in liquid metal jet X-ray sources.

Background

[0002] X-ray sources using a liquid metal jet as an electron beam target for generating X-ray radiation are generally known in the art. Advantages of this kind of X-ray sources include improved thermal handling and reduced spot sizes for the generated radiation. It has been proposed to use EM pumps for circulating the liquid metal in the X-ray source. EM pumps lead to reduced pressure variations in the liquid metal, which in turn provides improved uniformity of the jet. Further, EM pumps typically require less maintenance than traditional piston-based pumps, which may lead to decreased operational costs and improved system up-time.

[0003] When a current flows in a conductor through a magnetic field, the conductor experiences a Lorentz force given by $d\vec{F} = I \cdot d\vec{L} \times \vec{B}$, where F is the force, I is the electrical current, L is the length of the conductor within the magnetic field, and B is the magnetic field. This effect is utilized in EM pumps, where an electrically conductive liquid is pumped using a magnetic field and an electrical current flowing through the liquid. The cross product in the expression above for the force indicates that in order to maximize the Lorentz force for a given electrical current and magnetic field, both the electrical current and the magnetic field should be perpendicular to the intended flow direction of the liquid.

[0004] Aspects of EM pumps and the use thereof in liquid metal X-ray sources are discussed, for example, in WO 2020/225333 and WO 2022/258641.

[0005] There is a general need for improved functionality of EM pumps, particularly for use in liquid metal jet X-ray sources. In particular, it would be desirable for liquid metal jet X-ray sources using EM pumps to have functionality to detect and handle issues that may occur in the circulation of the liquid metal.

Summary

[0006] This disclosure relates to liquid metal jet X-ray sources including electromagnetic (EM) pumps for circulating liquid metal, wherein the X-ray sources are provided with monitoring capabilities for the metal circulation system. Fault states or operational issues, such as clogging or cavitation, inside of an EM pump or elsewhere in the metal circulation system can be detected and, in some implementations, also remedied.

The monitoring capabilities are also useful for identifying whether a pump is partially filled with conductive liquid, intentionally or not as the case may be. Procedures for filling liquid into and emptying liquid from EM pumps are also discussed.

[0007] The invention is defined in the appended claims.

[0008] In one aspect, there is provided a liquid metal jet X-ray source, comprising an electromagnetic pump configured to force a liquid metal through a nozzle to produce a liquid metal jet; a sensor configured to provide a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, and (iii) an electrical resistance of the EM pump; a power supply arranged to provide a current through the EM pump, wherein the power supply is configured so that the current provided by the power supply can be altered from a forward direction to a reverse direction corresponding to pumping liquid metal in a first direction, towards the nozzle, and a second direction, opposite to the first direction, respectively; and a controller coupled to the sensor, the controller being configured to monitor the output from the sensor as a function of time; wherein the controller is further configured to automatically alter the current provided by the power supply from the forward direction to the reverse direction in response to the output from the sensor deviating from a nominal value.

[0009] In another aspect, a liquid metal jet X-ray source is provided, comprising an electromagnetic pump configured to force a liquid metal through a nozzle to produce a liquid metal jet; a sensor configured to provide a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, and (iii) an electrical resistance of the EM pump; a power supply arranged to provide a current through the EM pump, wherein the power supply is configured so that the current provided by the power supply can be altered from a forward direction to a reverse direction corresponding to pumping liquid metal in a first direction, towards the nozzle, and a second direction, opposite to the first direction, respectively; and a controller coupled to the sensor, the controller being configured to monitor the output from the sensor as a function of time; wherein the controller is further configured to alert, in response to the output from the sensor deviating from a nominal value, an operator that the current supplied by the power supply should be altered from the forward direction to the reverse direction. The controller may further be configured to automatically turn off the current supplied to the EM pump when one or more of the sensor outputs deviates from the nominal value.

[0010] The current from the power supply may be restored from the reverse direction to the forward direction based on various criteria. For example, the current may be restored to the forward direction when the output from the sensor fulfills a predetermined criterion,

e.g. that the resistance of the EM pump has increased to a predetermined value indicating a corresponding fill factor for liquid metal inside the pump. The current may also be restored to the forward direction after a pre-set time.

[0011] The EM pump is preferably comprised of at least two pump units and at least two sensors, wherein one sensor is arranged to provide a value indicative of the electrical resistance of one pump unit and the other sensor is arranged to provide a value indicative of the electrical resistance of the other pump unit.

[0012] The electrical currents used for driving the EM pump can be considerable, which may make it difficult to use a switchable (i.e. a single polarity-reversing) power supply. Therefore, the power supply may conveniently comprise a first current source for providing current in the forward direction, and a second current source for providing current in the reverse direction.

[0013] In a further aspect, there is provided a method for operating a liquid metal jet X-ray source in which a liquid metal jet target is provided by forcing liquid metal through a nozzle using an electromagnetic pump, the method comprising: measuring, using one or more sensors, a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, (iii) an electrical resistance of the EM pump; monitoring, using a controller, the measured value as a function of time; determining, using the controller, whether the measured value deviates from a nominal value; and if it is determined that the measured value deviates from the nominal value; reversing a flow direction of the liquid metal through the EM pump from a forward direction to a reverse direction.

[0014] The reversing of the flow direction from the forward direction to the reverse direction may be effected automatically by the controller when it is determined that the measured value deviates from the nominal value.

[0015] Alternatively, the reversing of the flow direction from the forward direction to the reverse direction may be performed by an operator following an alert provided by the controller to do so. In implementations where the flow direction is reversed by an operator, it may be preferred to have the controller automatically stop the EM pump if the measured value deviates from the nominal value. It is conceivable, for example, that a deviation from the nominal value has been noted in the output from a sensor and that continued operation of the X-ray source may lead to fatal failure. In such case, it may be preferred to stop the EM pump until the flow direction is manually reversed. In other situations, the deviation from the nominal value may only be minor, so that continued operation can be allowed, but flow reversal should nevertheless be performed eventually. If the deviation increases from minor to more severe, the EM pump can be stopped by the controller awaiting manual flow reversal.

[0016] The nominal value(s) with which the sensor output(s) is/are compared will typically be values that directly or indirectly indicate that the flow path is free from obstructions for the liquid metal. One or more thresholds may be set at which the measured value may be caused by an obstruction of the flow of liquid metal, e.g. by blockage or cavitation. For example, a blockage of the flow path may cause an increased pressure in some parts and a decreased pressure in other parts and/or a reduced flow rate; or cavitation may cause rapidly changing measurement values or increased electrical resistance due to formation of voids. As will be understood, the principles disclosed herein involving a reversal of the flow of liquid metal are particularly useful for mitigating problems relating to obstructions of the metal flow through the system.

[0017] Several modifications and variations are possible within the scope of the invention. In particular, radiation sources comprising more than one liquid metal jet, or more than one electron beam are conceivable within the scope of the present inventive concept. Furthermore, X-ray sources of the type described herein may advantageously be combined with X-ray optics and/or detectors tailored to specific applications exemplified by but not limited to medical diagnosis, non-destructive testing, lithography, crystal analysis, microscopy, materials science, microscopy surface physics, protein structure determination by X-ray diffraction, X-ray photo spectroscopy (XPS), critical dimension small angle X-ray scattering (CD-SAXS), and X-ray fluorescence (XRF).

Brief description of the drawings

[0018] In the detailed description below, reference is made to the accompanying drawings, on which:

Fig. 1 schematically shows an overview of a liquid metal jet X-ray source;

Fig. 2 schematically shows an EM pump arrangement according to the principles disclosed herein;

Fig. 3 schematically shows an EM pump arrangement similar to that of Fig. 2, including also a pre-pump;

Fig. 4 schematically shows an arrangement in which two pump units are mounted to a base plate; Figs. 5a and 5b schematically show a configuration for an EM pump suitable for a pre-pump;

Figs. 6a-6c schematically show various implementations of flow meters;

Fig. 7 is a flow chart illustrating a method according to the principles disclosed herein.

Detailed description

[0019] Fig. 1 shows a schematic overview of an exemplary liquid metal jet X-ray source 100. A liquid metal jet 107 is created by forcing liquid metal through a

nozzle 106. The liquid metal jet is received by a jet receiver 108, where the liquid jet impacts a slanted surface directing the liquid metal towards a reservoir 122 for the liquid metal. Liquid metal is transported from the reservoir to a pump box 110 by means of a conduit 123. The pump box comprises an electromagnetic pump arrangement as disclosed herein to raise the pressure of the liquid metal and to supply pressurized liquid metal to the nozzle 106 through a conduit 112. An electron beam generator 104 is arranged to provide an electron beam 105 directed towards an electron beam dump 114, where the absorbed electrical current may be measured using an ammeter 118 connected to electrical ground at 120. The electron beam may be focused and/or deflected using an electron optic arrangement 103. During operation, the electron beam interacts with the liquid metal jet 107 in an interaction region 115 to create X-ray radiation in the form of characteristic line emission and bremsstrahlung. X-ray radiation is emitted from an enclosure 102 of the X-ray source 100 through an X-ray transparent window (not shown). The generated X-ray radiation may conveniently be emitted through the X-ray transparent window in a direction that is generally orthogonal to both the electron beam 105 and the liquid jet 107. To facilitate filling of the system with liquid metal, a port 124 in fluid communication with the reservoir can be provided. During operation of the X-ray source, the enclosure 102 is evacuated to provide a reduced pressure environment, e.g. vacuum. A filter (not shown) may be provided along conduit 123, i.e. between the reservoir and the pump box, to prevent solid particles in the liquid metal from entering the pump. The filter is advantageously placed so that gravity induced pressure in the liquid metal is sufficient to force the liquid metal through the filter.

[0020] Fig. 2 shows a schematic exemplary embodiment of the pump box 110. During operation, liquid metal flows in to and out from the pump box through an incoming conduit 123 and an outgoing conduit 112. A flow meter 202 may be provided to measure the flow of liquid metal through the system. It should be noted that a flow meter may be connected either to the incoming conduit 123 (as shown) or to the outgoing conduit 112, or to both the incoming conduit 123 and the outgoing conduit 112. Pumping of the liquid metal is in this example performed by two pump units, a first pump unit 204 and a second pump unit 206, which are connected in series to successively increase the pressure in the liquid metal from the incoming conduit 123 to the outgoing conduit 112. Each pump unit comprises a conduit (indicated at 208 for the first pump unit 204), carrying the liquid metal, wound around a core (indicated at 210 for the first pump unit 204). The incoming conduit 123 may have a larger inner diameter than the conduit comprised in the pump unit 208, to facilitate sufficient feeding of liquid metal to the pump unit. Permanent magnets (not shown) are arranged concentrically with the core and the wound conduit to provide a magnetic field

perpendicular to a cross section of the conduit. An outer yoke (not shown) completes the magnetic circuit. A current generator I_f is connected to a first current terminal 212 of the first pump unit and a first current terminal 214 of the second pump unit. The circuit is completed by a bus bar 216 connecting a second current terminal 218 of the first pump unit and a second current terminal 220 of the second pump unit. Electrical current is provided in a direction through the pump units that is perpendicular to the cross section of conduit 208 and to the direction of the magnetic field, to thereby generate a Lorentz force that drives liquid along the conduit. In the illustrated example the current is coaxial with the core 210 of each pump unit, and the magnetic field is radial with respect to the core. An intermediary conduit 222 provides a flow path for the liquid metal from the first pump unit 204 to the second pump unit 206. Pressurized liquid metal is delivered from the pump box to the nozzle (106 in Fig. 1) via the outgoing conduit 112. A pressure meter 224 may be provided, for example on the outgoing conduit 112, to monitor the performance of the electromagnetic pump units. A first voltmeter 226 may be connected between the bus bar 216 and electrical ground. Since the current terminal 212 is also connected to electrical ground, readings from the first voltmeter 226 will be proportional to the electrical resistance of the first pump unit 204. Readings from the first voltmeter 226 may thus be used as an indicator of the amount of liquid metal present in the first pump unit. It will be appreciated that a minimum electrical resistance of the pump unit will occur when the conduit of the pump unit is completely filled with liquid metal, and that the electrical resistance of the pump unit will increase with a decreasing fill factor (degree of filling) of the conduit due to formation of non-conducting voids. Other factors, such as contact resistance between the liquid metal and the conduit, may also influence the measurement. A second voltmeter 228 may be connected between the first current terminal 214 of the second pump unit and electrical ground. Readings from the second voltmeter 228 will be proportional to the combined electrical resistance of the first pump unit 204 and the second pump unit 206. Thus, a difference between values registered by the second voltmeter 228 and first voltmeter 226, respectively, may indicate a degree of filling of the second pump unit 206 with liquid metal. Sudden changes in values measured by either of the voltmeters may indicate bubbles/voids appearing in the conduits.

[0021] Further, a second current generator I_r is provided, which is configured to drive current through the first pump unit and the second pump unit in the opposite direction compared to the first current generator I_f . With this arrangement, using both a first and a second current generator as described, the flow direction of the liquid metal may be conveniently reversed.

[0022] Fig. 3 illustrates another exemplary embodiment similar to the one in Fig. 2, the difference being

the inclusion of a pre-pump 300. The pre-pump according to this embodiment is an electromagnetic pump connected in series with the first pump unit and the second pump unit. Current is provided via first and second current terminals 302 and 304 of the pre-pump, wherein the first and second current terminals 302 and 304 are in electrical contact with one side of the conduit 123. The electrical circuit is completed by a bus bar 306 provided on the opposite side of the conduit relative to terminals 302 and 304. Electrical current is supplied to the pre-pump from current generator I_f in series with the first pump unit and the second pump unit by means of a bus bar 308. The electrical current thus traverses the cross section of the incoming conduit 123 twice, namely going from current terminal 304 to bus bar 306, and from bus bar 306 to current terminal 302. As mentioned above, the conduit 123 may have a larger inner diameter than conduits comprised in the pump units. In such a case, a filter (not shown) may be placed between the pre-pump and the pump units (i.e. downstream of the pre-pump; the pre-pump may then contribute to forcing the liquid metal through the filter) to prevent solid particles carried by the liquid metal from entering into the pump units. Furthermore, a filter may also, or instead, be placed upstream of the pre-pump, where such a placement may enable easier maintenance and/or exchange of the filter, and/or at other locations in the flow path of the liquid metal. Permanent magnets (not shown) are arranged so as to provide a magnetic field for the pre-pump directed perpendicular to the current and to the cross section of the conduit. A more detailed example of such a pump is presented below with reference to Fig. 5. Since the direction of the electrical current between terminal 304 and bus bar 306 is different from (opposite to) the direction of the current between bus bar 306 and terminal 302, the magnetic field must also change direction accordingly in order to produce a force that drives the liquid metal through the conduit. This may be accomplished by arranging pairs of magnets with alternating polarity along the length of the conduit. A third voltmeter 310 may be connected between the bus bar 308 and electrical ground. The readings from this third voltmeter will be proportional to the electrical resistance of the pre-pump and may be used as an indicator for the amount (fill factor) of liquid metal present in the pre-pump.

[0023] Blockage in the pre-pump may lead to cavitation in and mechanical collapse of the inlet pipe to the main EM pump. To have an early warning of this, controlled variations of the inlet pressure may be introduced by varying the driving current for the pre-pump while monitoring the outlet pressure. The pre-pump is preferably designed not to be the limiting factor for the flow from the main pump. Thus, in normal operation, the changes in outlet pressure from the main pump units will be negligible if the current through the pre-pump is changed only by a small amount, such as less than 10%. On the other hand, if the pre-pump is partly

blocked it may become the limiting factor for the flow from the pump, and in this case the changes to the outlet pressure in response to current changes through the pre-pump may be significant. The intention is to discover this type of blockage before it actually causes cavitation. Once cavitation starts to occur it may be detected in a number of ways, e.g. as rapid variations in the generated pressure, intermittent resistance increase in the conduits, or as vibrations in the conduits.

[0024] A decrease in the observed flow rate and/or generated pressure may be due to partial clogging or blockage somewhere along the flow path connecting the liquid metal reservoir with the nozzle. A method of clearing such a clog comprises setting the current I_f to zero and increasing the current I_r , thus reversing the flow in the pump, i.e. transporting liquid metal from the electromagnetic pump arrangement to the liquid metal reservoir. Such reverse of the flow may, for example, effectively provide backwashing of one or more filters provided in the liquid metal flow path. By monitoring a quantity indicative of the electrical resistance of the pump, an indication of the amount of liquid metal transported to the reservoir may be estimated since the electrical resistance of the pump will increase when the amount (fill factor) of metal in the pump decreases. In case the electrical resistance over the pump or a pump unit does not change during reverse pumping an error state may be indicated as this could be caused by pump malfunction or persistent clogging somewhere along the conduits. The expected effect of reversing the flow of liquid metal in the pump is that the resistance over the pump increases as parts of the pump closest the outlet is emptied of liquid metal. Reverse pumping may proceed until some limiting condition is fulfilled, e.g. that the pump unit closest to the outlet is emptied as indicated by the resistance in the next pump unit starting to increase. Once such a limiting condition is fulfilled the reverse current may be set to zero and the forward current may be applied again to resume pumping in the forward direction. The state of the system may again be monitored by observing the resistance over the pump units. As they are again filled with liquid metal the resistance is expected to decrease and approach a value corresponding to a filled state. If this behavior is not observed another fault state may be indicated.

[0025] Reversing the flow in the pump may be automatically initiated by a controller when a predetermined condition is fulfilled, or an operator may initiate the procedure in response to an alert. The alert may be implemented in a number of ways. A basic level of alert may comprise showing a number or indicator based on the measured value indicative of at least one of a flow through the pump, the pressure generated by the pump, and an electrical resistance of the pump. The alert may be augmented by the use of color, e.g. the displayed current value can be continuously updated and when some condition is fulfilled the display color

could be changed. An alternative may be to graphically display how the value develops over time and mark the limiting value with a line. Further levels of alert may include warning (e.g. blinking) lights, sounds, messages sent over a computer network, or the like.

[0026] A method for operating a liquid metal jet X-ray source in which a liquid metal jet target is provided by forcing liquid metal through a nozzle using an electromagnetic, EM, pump according to the invention is schematically illustrated in Fig 7. The method comprises measuring 700 a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, (iii) an electrical resistance of the EM pump; monitoring 702 the measured value as a function of time by means of a controller; determining 704, using the controller, whether the measured value deviates from a nominal value; and if it is determined that the measured value deviates from the nominal value reversing 706 a flow direction of the liquid metal through the EM pump from a forward direction to a reverse direction.

[0027] When filling the system with liquid metal, a syringe or similar may be connected to port 124 (see Fig. 1) for injecting the metal. A forward current may be applied to the pump arrangement to transport liquid metal towards the nozzle to facilitate injection of the metal into the system. The resistance over the pump units may be measured to confirm the expected filling of the system. Preferably, the enclosure 102 is evacuated during the filling procedure. Filling may continue until a predetermined time has elapsed, until a predetermined volume has been injected, until a desired pressure has been established, or until some similar criterion is fulfilled. When the filling is completed, the port 124 is closed, and the syringe is removed. Depending on the type of valve (or similar) used to close the port it may be advantageous to let ambient atmosphere into the enclosure 102 before removing the syringe.

[0028] When emptying the system, the enclosure 102 is preferably at atmospheric pressure. A syringe may be connected to the port 124 or, as an alternative, the conduit 123 connecting the pump 110 to the reservoir 122 may be opened and the liquid metal collected in some suitable container. A reverse current may be applied to the pump arrangement to empty the conduit between the nozzle and the pump and the pump itself. The electrical resistance over the pump units may be monitored to ensure that the process progresses smoothly.

[0029] In embodiments with multiple pump units, the pump units may be assembled on a common base plate. Nominally no current should flow through the base plate. However, in case of a short circuit e.g. between a conduit in one of the pump units (like 208 in Fig. 2) and an outer magnetic yoke mounted on the base plate, at least some of the current may flow through the base plate. Fig. 4 illustrates such an embodi-

diment with two pump units 402 and 404 mounted on the base plate 406. Liquid metal flows into the first pump unit 402 through conduit 408, continues to the second pump unit 404 through intermediate conduit 410 and is output through conduit 412. A current source I_f supplies a current to the first pump unit in series with second pump unit. The current source is connected to a ground potential at 414. The base plate is connected to ground potential via a resistor R . Provided the resistance of R is large compared to the resistance of the pump units, a voltmeter V connected over R will record the electrical potential where a short circuit has occurred. Since there is a known, or expected, voltage drop along the circuit from the current source, through the first and second pump unit, and back to the current source, the voltage measured over the resistance R will provide an indication of where, along this circuit, that a short circuit has occurred. Thus, the measured voltage may be used to pinpoint where a fault has occurred and assist an operator in alleviating such a fault. One may note that the electrical resistance of the pump units is typically of the order of $m\Omega$ and thus the resistor R may be realized by e.g. stainless-steel screws (having a comparatively high resistance compared to the pump units) used for fastening the base plate. The arrangement according to Fig. 4 is advantageous in that relatively small current leaks may be detected. A complete short circuit where all current goes through the base plate instead of through the pump units may be detected in other ways, e.g. by monitoring the electrical potential of each pump unit as described in connection with Fig. 2 and Fig. 3. However, a small leakage current of a few percent of the total current may go undetected in those scenarios and be detected as a change in the voltage measured over R in Fig. 4.

[0030] Fig. 5a depicts a cross section of an electromagnetic pump in which liquid metal is pumped through a conduit 502. Such pump configuration is conveniently used for a pre-pump, as described elsewhere herein. A first electrode 504, a second electrode 508, and a bus bar 506 are provided. A current I that is supplied to the first electrode 504 passes through a first cross section of conduit 502 from the first electrode 504 to the bus bar 506, from which the current is returned through a second cross section of the conduit 502 to the second electrode 508. In a direction perpendicular to the current, through the cross sections of the conduit, a magnetic field is provided by means of permanent magnets 510 and 512, shown as broken contours in Fig. 5a. Fig. 5b offers a view of the same pump as in Fig. 5a along a cross section perpendicular to the cross section shown in Fig. 5a. Permanent magnets 510 and 512 arranged on one side of the conduit have matching counterparts 511 and 513 respectively arranged on the opposite side of the conduit. The magnets are arranged so that the field direction through the first cross section of the conduit is opposite to the field direction through the second

cross section of the conduit so that the cross product between the current and the magnetic field, and hence the force exerted on the liquid metal, has the same direction along the conduit for the first and the second cross section. First electrode 504 and second electrode 508 which are not in the plane of the cross section shown in Fig. 5b are indicated as broken contours.

[0031] An exemplary embodiment of an electromagnetic flow sensor suitable for usage in devices and methods according to the invention is schematically illustrated in Fig. 6a. Liquid metal flows through a conduit 602 perpendicular to the plane of the drawing in Fig. 6a and in the plane of the drawing in Fig. 6b and Fig. 6c. A pair of magnets 604 and 606 are provided on opposite sides of the conduit 602, thus applying a magnetic field across the conduit cross section. Two electrodes 608 and 610 are provided on opposite sides of the conduit so that a voltage perpendicular to the applied magnetic field may be measured by means of a voltmeter V. Flow of liquid metal through the cross section will induce a voltage that is indicative of the flow rate.

[0032] However, in a liquid metal jet X-ray source according to the invention a leakage current may be carried by the conduit and the liquid metal flowing therein. If the electrodes are not perfectly aligned along the length of the conduit (i.e. if the electrodes are not exactly opposite each other) this current will create a voltage drop between the electrodes that will influence the measurement. By providing bypass connections according to Fig. 6b such an influence may be avoided or at least greatly reduced. A first bypass connection is provided wherein a bypass resistance R_2 is provided between two points 612 and 614 on opposite sides of the electrodes along the length of the conduit. A second bypass connection is provided between two other points 616 and 618 on opposite sides of the electrodes along the length of the conduit wherein a bypass resistance R_3 is provided. The resistance of the conduit filled with liquid metal as measured between the connection points for R_2 and R_3 on the respective sides of the electrodes are R_1 and R_4 respectively, i.e. the resistance between points 612 and 616 is R_1 , and the resistance between points 614 and 618 is R_4 . By selecting the values of R_2 and R_3 , and the positions of the connection points so that $R_1/R_3 = R_2/R_4$ the potential at points 614 and 616 will be equal, and thus no current will flow along the part of the conduit between these points and there will be no contribution to the voltage measured between the two electrodes despite these not being perfectly aligned.

[0033] An alternative solution to the problem with leakage current contributing to the measured flow rate is illustrated in Fig. 6c where two electrodes 610a and 610b are provided on the opposite side of the conduit from electrode 608. One of the electrodes 610a and 610b are placed upstream of electrode 608 whereas the other is placed downstream of electrode 608. A

potentiometer R_p is connected between the electrodes 610a and 610b. The potentiometer is adjusted so that the potential of the wiper 620 is equal to the potential of the electrode 608 when a current is flowing along the conduit. A voltmeter connected to the wiper 620 and the electrode 608 will thus measure a voltage that is not influenced by a current flowing along the conduit.

[0034] Since the liquid metal may be at an elevated temperature when flowing through the conduit care must be taken to avoid thermal gradients and Seebeck effect contributions to the measured voltage. One way of doing this is to contact the conduit using wires of the same material as that comprised in the conduit itself, e.g. stainless steel, and to make connections to the voltage sensor at a location where it can be ensured that there is no temperature gradient between the connection points, e.g. by clamping the connections to a water-cooled metal block.

[0035] Another way to handle spurious contributions to the measured voltage may be to alter the direction of the magnetic field and take an average measured voltage as indicative of the flow rate, since such contributions may be independent of field direction. This however comes at a cost of providing for electromagnets with alternating current directions and readout of the voltage synchronized with the alternations.

Conclusion

[0036] A liquid metal jet X-ray source is disclosed, comprising an EM pump for pumping liquid metal and for forming the metal jet by forcing the liquid metal through a nozzle. The X-ray source comprises one or more sensors configured to provide a value indicative of a flow of liquid metal through the EM pump; a pressure generated by the EM pump; and/or an electrical resistance of the EM pump. A controller is provided for monitoring the sensor output. The flow of liquid metal through the EM pump is reversed if the sensor output deviates from a nominal value. The reversal of the flow can be effected automatically by the controller, or manually by an operator following an alert provided by the controller. A corresponding method for operating a liquid metal jet X-ray source is also disclosed.

Claims

1. A liquid metal jet X-ray source, comprising:

- an electromagnetic, EM, pump configured to force a liquid metal through a nozzle to produce a liquid metal jet;
- a sensor configured to provide a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, and (iii) an electrical resistance of the EM pump;

- a power supply arranged to provide a current through the EM pump, wherein the power supply is configured so that the current provided by the power supply can be altered from a forward direction to a reverse direction corresponding to pumping liquid metal in a first direction, towards the nozzle, and a second direction, opposite to the first direction, respectively; and
a controller coupled to the sensor, the controller being configured to monitor the output from the sensor as a function of time;
wherein the controller is further configured to automatically alter the current provided by the power supply from the forward direction to the reverse direction in response to the output from the sensor deviating from a nominal value.
2. A liquid metal jet X-ray source, comprising:
- an electromagnetic, EM, pump configured to force a liquid metal through a nozzle to produce a liquid metal jet;
a sensor configured to provide a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, and (iii) an electrical resistance of the EM pump;
a power supply arranged to provide a current through the EM pump, wherein the power supply is configured so that the current provided by the power supply can be altered from a forward direction to a reverse direction corresponding to pumping liquid metal in a first direction, towards the nozzle, and a second direction, opposite to the first direction, respectively; and
a controller coupled to the sensor, the controller being configured to monitor the output from the sensor as a function of time;
wherein the controller is further configured to alert, in response to the output from the sensor deviating from a nominal value, an operator that the current supplied by the power supply should be altered from the forward direction to the reverse direction.
3. The X-ray source according to claim 2, wherein the controller is further configured to automatically turn off the current to the EM pump in response to the output from the sensor deviating from the nominal value.
4. The X-ray source according to any one of the preceding claims, wherein the controller is configured to restore the current from the reverse direction to the forward direction when the output from the sensor fulfills a predetermined criterion.
5. The X-ray source according to any one of the preceding claims, wherein the controller is configured to restore the current from the reverse direction to the forward direction after a pre-set time.
6. The X-ray source according to any one of the preceding claims wherein
the EM pump is comprised of at least two pump units; and
at least two sensors are arranged to provide at least two values, each value indicative of the electrical resistance of a respective one of the at least two pump units.
7. The X-ray source according to any one of the preceding claims wherein the power supply comprises:
a first current source arranged for providing current in the forward direction; and
a second current source arranged for providing current in the reverse direction.
8. A method for operating a liquid metal jet X-ray source in which a liquid metal jet target is provided by forcing liquid metal through a nozzle using an electromagnetic, EM, pump, the method comprising:
measuring, using one or more sensors, a value indicative of at least one of (i) a flow of liquid metal through the EM pump, (ii) a pressure generated by the EM pump, (iii) an electrical resistance of the EM pump;
monitoring, using a controller, the measured value as a function of time;
determining, using the controller, whether the measured value deviates from a nominal value; and
if it is determined that the measured value deviates from the nominal value:
reversing a flow direction of the liquid metal through the EM pump from a forward direction to a reverse direction.
9. The method of claim 8, wherein the step of reversing the flow direction of the liquid metal through the EM pump from the forward direction to the reverse direction is automatically performed by the controller.
10. The method of claim 8, wherein the step of reversing the flow direction of the liquid metal through the EM pump from the forward direction to the reverse direction is performed by the controller alert-

ing an operator and the controller receiving an instruction from the operator to reverse the flow direction.

11. The method claim 10, further comprising stopping the EM pump, by means of the controller, if the measured value deviates from the nominal value while awaiting the instruction from the operator. 5
12. The method according to any one of claims 8-11, further comprising resetting the flow direction through the EM pump to the forward direction when the measured value fulfills a predetermined criterion. 10
13. The method according to any one of claims 8-12, further comprising resetting the flow direction through the EM pump to the forward direction after a pre-set time. 15
14. The method according to any one of claims 8-13, wherein the EM pump comprises at least a first pump unit arranged in series with a second pump unit, wherein the second pump unit is arranged downstream of the first pump unit in the forward flow direction, and wherein the method further comprises 20
 - measuring a first value indicative of the electrical resistance of the first pump unit; 30
 - measuring a second value indicative of the electrical resistance of the second pump unit;
 - monitoring the first value and the second value as a function of time by means of the controller reversing the flow direction through the EM pump from the forward direction to the reverse direction if the first value indicates that the electrical resistance of the first pump unit has increased above a predetermined first level. 35
15. The method of claim 14 comprising resetting the flow direction through the EM pump to the forward direction if the second value indicates that the electrical resistance of the second pump unit has increased above a predetermined second level. 40 45

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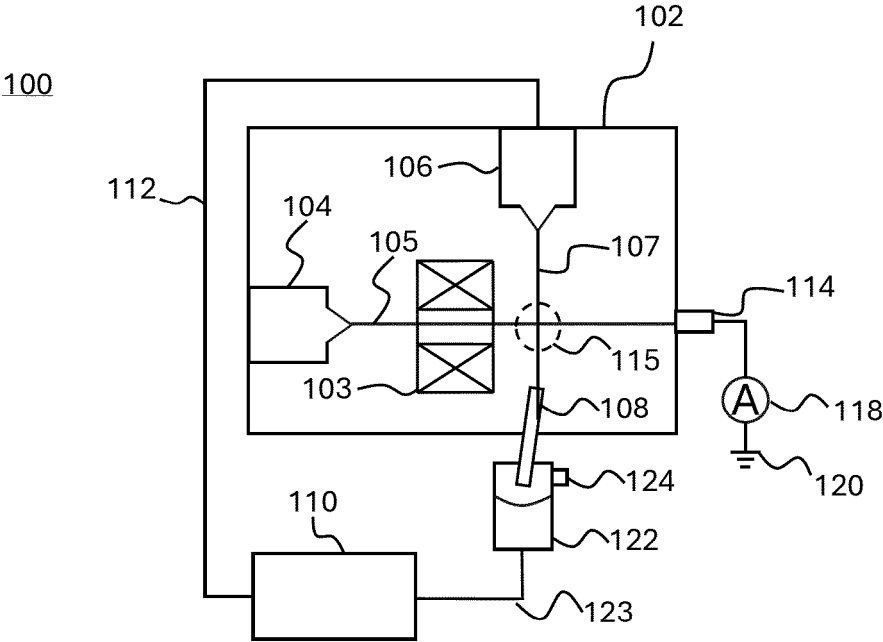


Fig. 1

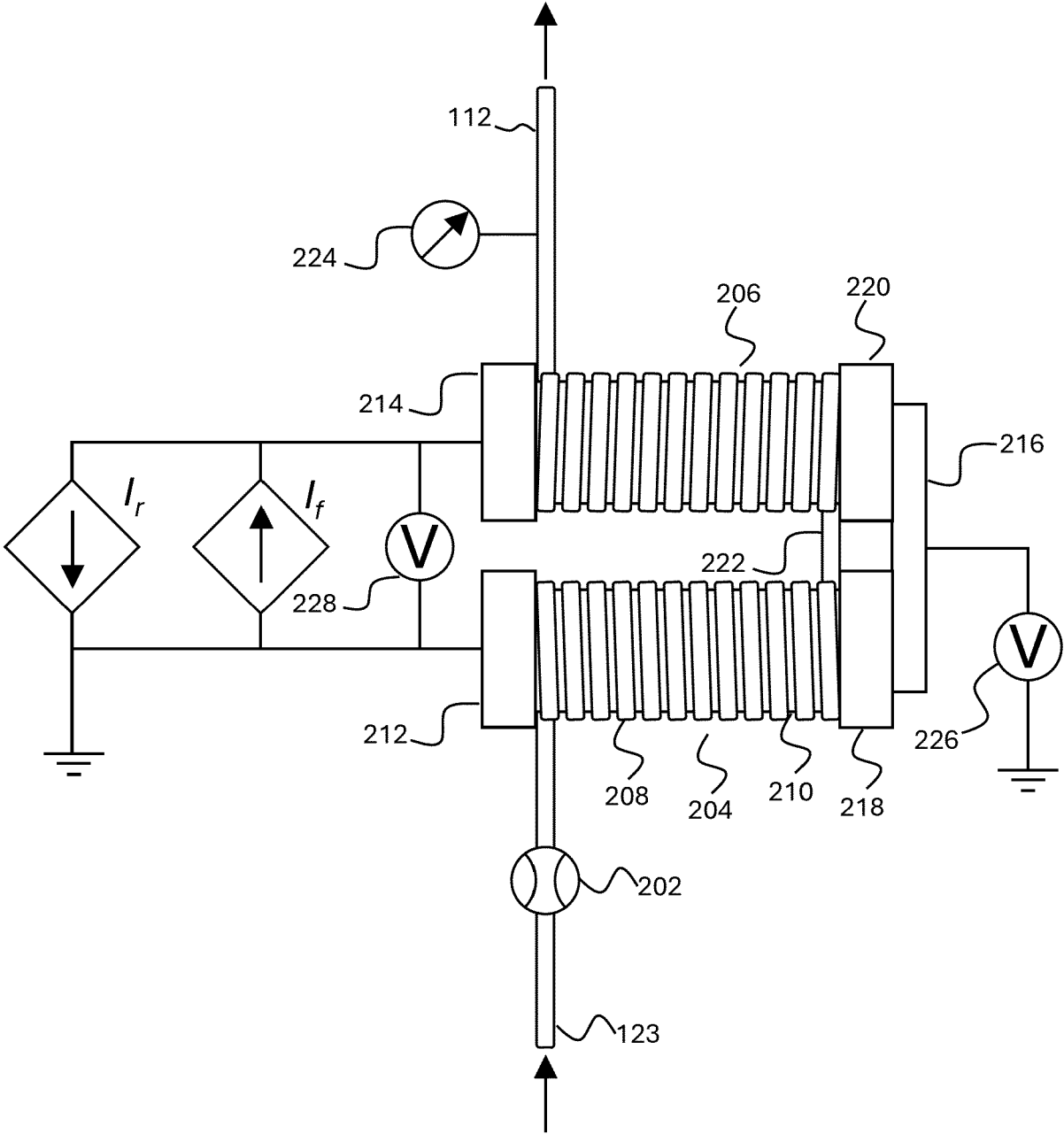


Fig. 2

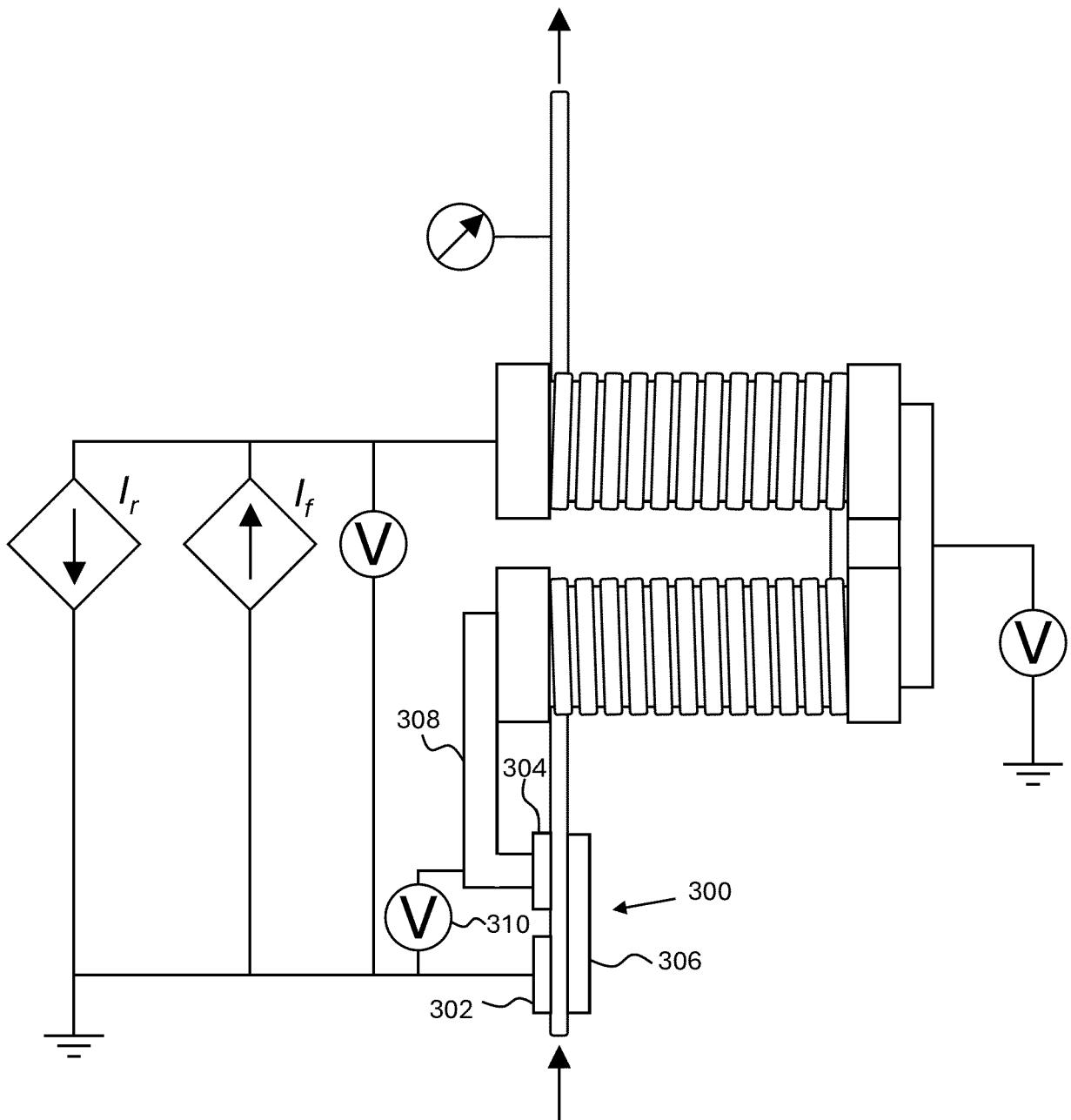


Fig. 3

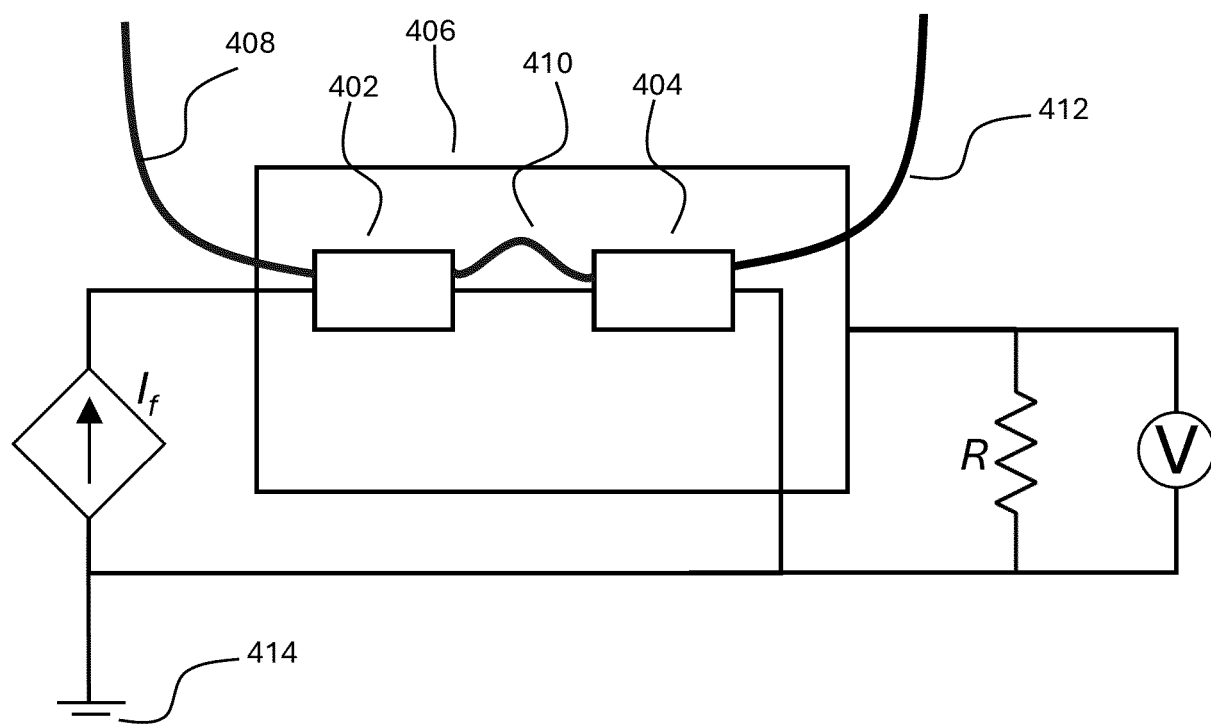


Fig. 4

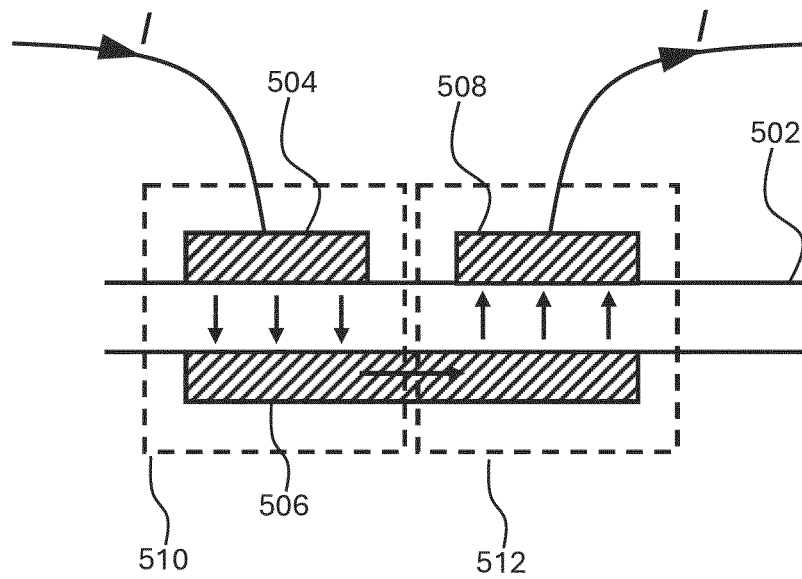


Fig. 5a

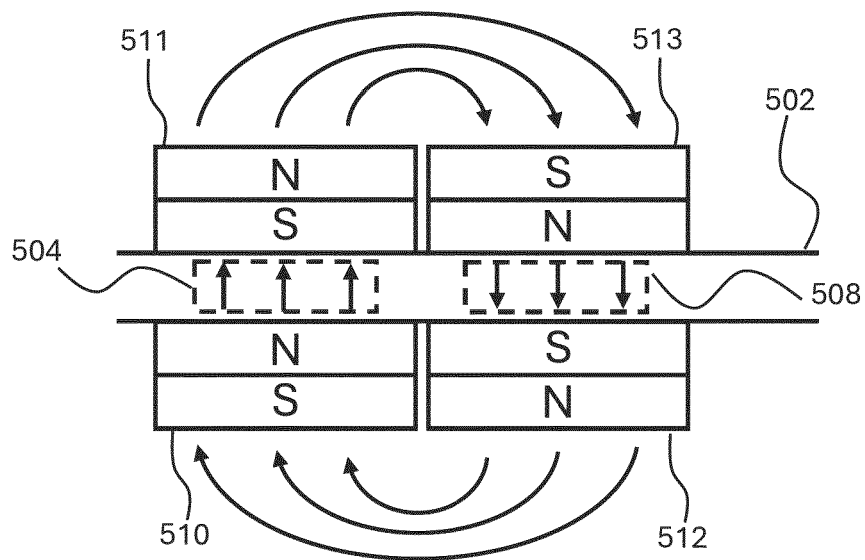


Fig. 5b

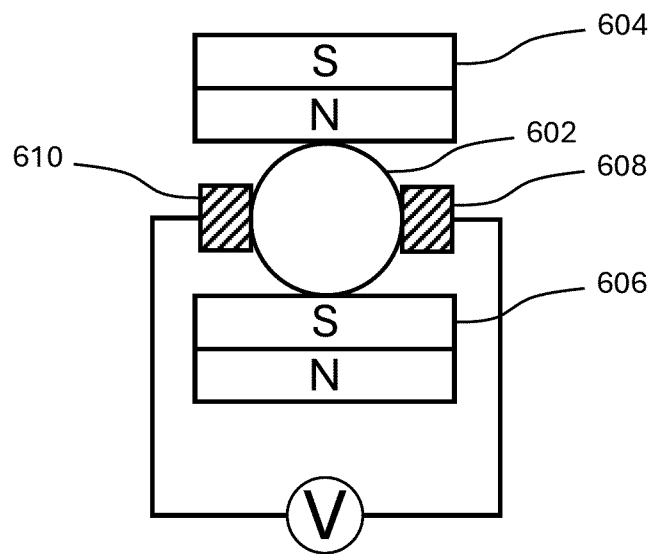


Fig. 6a

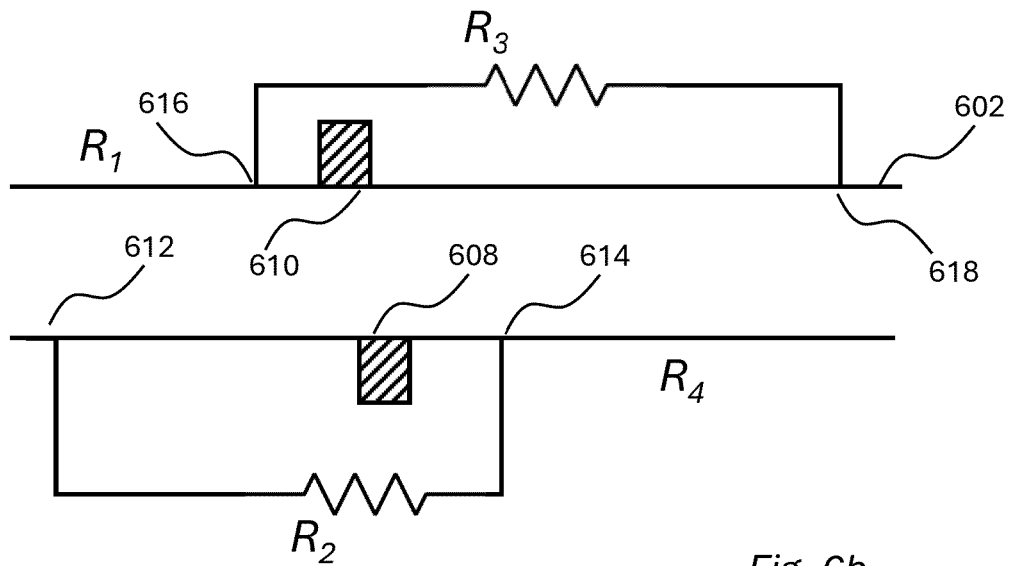


Fig. 6b

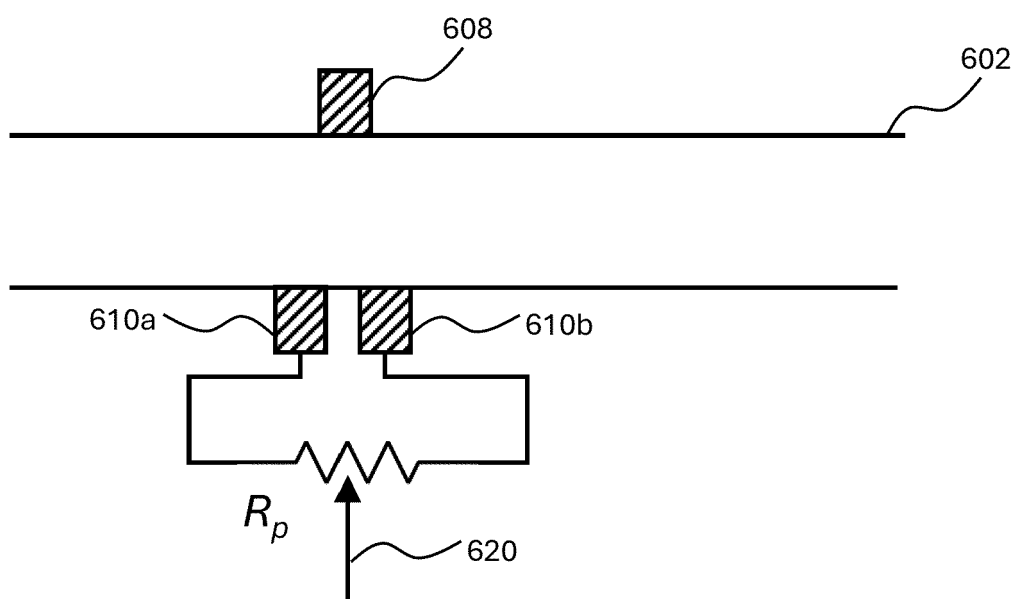


Fig. 6c

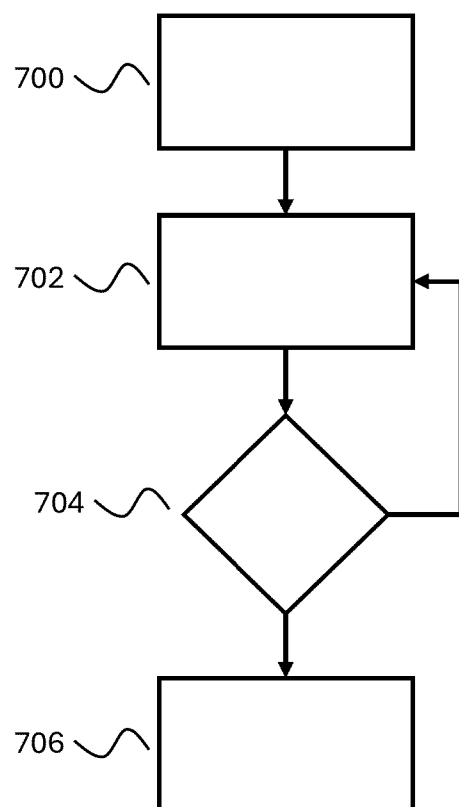


Fig. 7



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Application Number

EP 25 17 0949

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The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
Munich		22 September 2025	Oestreich, Sebastian
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