(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 3 364 440 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
22.08.2018 Bulletin 2018/34

(21) Application number: **17156494.1**

(22) Date of filing: **16.02.2017**

(51) Int Cl.:
H01J 23/34 *(2006.01)* ***H01J 25/04*** *(2006.01)*
H05H 7/02 *(2006.01)*

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
MA MD

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(54) IOT BASED POWER SYSTEM

(57) A system for powering an accelerator component, comprising
an inductive output tube (10), including a thermionic cathode (11) and an anode (13) spaced therefrom, the anode (13) and cathode (11) being operable at a high voltage therebetween to form and accelerate an electron beam, as well as a grid (15) arranged between the cathode (11) and anode (13) and accepting a high frequency control signal to density modulate the beam,
a tube power supply (30) for supplying the high voltage between said anode (13) and cathode (11), the tube power supply (30) comprising a cathode line (31) and an anode line (33) connected to the cathode (11) and anode (13), respectively,
a grid power supply (40) for supplying a bias voltage between the grid (15) and cathode (11), the grid power supply (40) comprising a grid line (45) and a cathode line (41) connected to the grid (15) and cathode (11), respectively, and
a filament power supply (50) for supplying current to heat the cathode (11), the filament power supply (50) comprising a circuit (51) connected to the cathode (11).

The cathode (11) is connected to ground and the tube power supply (30) is configured to supply a positive high voltage between said anode and cathode.

The tube power supply (30) can be configured to supply said high voltage in a pulsed manner.

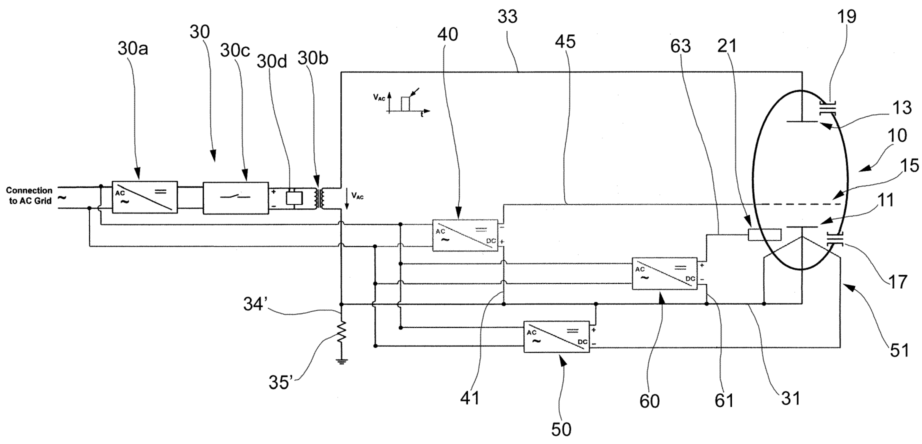

FIG.2

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Description

Background of the Invention

[0001] The present invention relates generally to RF powering systems for particle accelerators.

[0002] RF powering systems are used to generate radio frequency (RF) power to feed accelerating structures. A particular concern is related to powering of radio frequency quadrupoles (RFQ).

[0003] In order to produce RF power (>1kW) there are currently two options: RF tubes and solid state amplifiers. When accurate phase and frequency is required the tubes that could be used are klystrons and IOTs (Inductive Output tubes, also known as klystrodes due to their nature in between a klystron and a triode). It is difficult to find klystrons available in the market for certain frequencies. This means that it would require the custom design of a new klystron, which would be by all means extremely expensive. Available solutions alternative to klystrons are IOTs and solid state amplifiers. Right now solid state technology is still too expensive and bulky for pulsed applications. Current equivalent solution using IOT is more cost-effective and compact.

[0004] IOT tubes are mostly used in TV broadcasting and industrial heating applications. They are also used in accelerators to produce RF power, but it represents an extremely low percentage in comparison.

[0005] In broadcasting and heating the tubes are used in a continuous way, in DC. The classical topology used to power it is, therefore, DC. The required high voltage ratings require a high voltage deck (high voltage cage), to provide protection against the high voltage equipment and floating power supplies and electronics, as shown in Figure 1.

[0006] Figure 1 shows a schematic layout of a conventional IOT based powering system. An inductive output tube (IOT) is designated with 10. The IOT 10 includes a thermionic cathode 11 and an anode 13 spaced therefrom. The anode 13 and cathode 11 are operable at a negative high voltage between, for example -40 kV, to form and accelerate an electron beam. The IOT 10 further comprises a grid 15 arranged between the cathode 11 and anode 13 and accepting a high frequency control signal to density modulate the electron beam. This control signal is supplied by a control unit (not shown) through a RF input 17 of the IOT 10. The kinetic energy of the electron beam is transformed to electromagnetic energy and supplied to a user system, such as an accelerator component, through a RF output 19 of the IOT 10. For the sake of simplicity, further common components of IOTs, such as drift tube, output cavities and collector are not shown in the drawings. The IOT 10 may also comprise an ion pump 21 for monitoring residual gases within the tube.

[0007] The powering system is connected to the AC utility grid, and comprises a tube power supply 30 for supplying a high voltage, for example 40 kV, between the anode 13 and cathode 11. The tube power supply 30 is configured to convert the AC supply from the AC supply grid into a high voltage DC supply. The tube power supply 30 comprises a cathode line 31 and an anode line 33 connected to the cathode 11 and anode 13, respectively. The anode 13 is connected to ground, at 34. An optional ground resistance is designated with 35 to monitor the body current. Such ground resistance is of few ohm.

[0008] The powering system further comprises a grid power supply 40 for supplying a bias voltage, for example a voltage comprised between -150V and -50V, between the grid 15 and cathode 11. The grid power supply 40 is configured to convert the AC supply from the AC supply grid into a DC supply for the grid 15. The grid power supply 40 comprises a grid line 45 and a cathode line 41 connected to the grid 15 and cathode 11, respectively. On the other side, the grid power supply 40 is connected to the AC supply grid through an isolation transformer 47.

[0009] The powering system further comprises a filament power supply 50 for supplying current, for example a current of 25A at 13V, to heat the cathode 11. The filament power supply 50 comprises a circuit 51 connected to the cathode 11, through which current is supplied to the cathode 11 in order to heat the cathode 11 and cause electrons to be emitted therefrom by thermionic effect. The filament power supply 50 is connected to the AC supply grid through the isolation transformer 47.

[0010] The powering system further comprises a ion pump power supply 60 for supplying a voltage, for example a voltage of 3.5 kV, between the ion pump 21 and the cathode 11, the ion pump power supply 60 comprises a ion pump line 63 and a cathode line 61 connected to the ion pump 21 and cathode 11, respectively. On the other side, the ion pump power supply 60 is connected to the AC supply grid through the isolation transformer.

[0011] A high voltage deck 70 contains the grid power supply 40, isolation transformer 47, filament power supply 50 and ion pump power supply 60.

[0012] Furthermore, an IOT based powering system is disclosed in M. Marks et al, "CPI's 1.3 GHz, 90 kW Pulsed IOT Amplifier", Proceedings of IPAC'10, Kyoto, Japan, p. 4011-4013 (http://www.cpii.com/docs/related/30/thpeb061proceedings%20.pdf). In this known system, the grid voltage is pulsed between two voltage levels to reduce the power dissipated in the collector.

[0013] In linear accelerator applications, the RF power is only required during short periods of time and at a certain repetition rate, where the repetition rate is defined by the design of the linear particle accelerator and possibly also by the needs of the application requiring the accelerated particle output.

[0014] In view of the above, a problem of the invention is to develop a RF powering system architecture for particle accelerators which is relatively inexpensive and compact.

Summary of the Invention

[0015] Accordingly, the invention proposes a system for powering an accelerating structure, comprising

an inductive output tube, including a thermionic cathode and an anode spaced therefrom, said anode and cathode operable at a high voltage therebetween to form and accelerate an electron beam, as well as a grid arranged between said cathode and anode and accepting a high frequency control signal to density modulate said beam,
a tube power supply for supplying said high voltage between said anode and cathode, said tube power supply comprising a cathode line and an anode line connected to the cathode and anode, respectively,
a grid power supply for supplying a bias voltage between said grid and cathode, said grid power supply comprising a grid line and a cathode line connected to the grid and cathode, respectively, and
a filament power supply for supplying current to heat said cathode, said filament power supply comprising a circuit connected to the cathode,
wherein said cathode is connected to ground and the tube power supply is configured to supply a positive high voltage between said anode and cathode.

[0016] Consequently, the electronics and the power supplies are not floating on an approximately - 40kV potential, but instead referenced to ground. This reduces the complexity of the system, avoids the need for a high voltage cage/deck, and allows the use of inexpensive standard off-the-shelf power supplies, etc.

[0017] According to an embodiment, the system further comprises an ion pump for monitoring gas within the inductive output tube, and an ion pump power supply for supplying a voltage between said ion pump and cathode, said ion pump power supply comprising an ion pump line and a cathode line connected to the ion pump and cathode, respectively.

[0018] According to a particularly preferred embodiment, the tube power supply is configured to supply said high voltage in a pulsed manner.

[0019] In particular, said tube power supply may comprise AC to DC converting means for converting an AC supply to a DC supply, and pulse forming means for generating a pulse from the DC supply.

[0020] According to an embodiment, said AC to DC converting means are configured to supply the pulse forming means with a voltage lower than said high voltage, and wherein said pulse forming means are configured to generate a high voltage pulse from the lower voltage supply.

[0021] However, it is preferred that said AC to DC converting means are configured to supply the pulse forming means with a voltage lower than said high voltage, and wherein said tube power supply further comprises step-up transforming means for transforming a lower voltage pulse generated by the pulse forming means into a high voltage pulse.

[0022] The use of a step-up pulsed transformer reduces the size of the system, minimizing the risks of arcing, making possible to stop in case of overvoltage or overcurrent in less than 1μs, etc.

[0023] According to a further preferred embodiment, the grid power supply is configured to supply said bias voltage in a pulsed manner.

Brief Description of the Drawings

[0024] Some preferred, but non-limiting, embodiments of the invention will now be described, with reference to the attached drawings, in which:

- Figure 1 shows a schematic layout of a IOT based powering system according to the prior art,
- Figure 2 shows a schematic layout of a IOT based powering system according to an embodiment of the invention, and
- Figure 3 shows a schematic layout of a IOT based powering system according to a further embodiment of the invention.

Detailed Description

[0025] Figure 2 shows a schematic layout of an IOT based powering system according to the invention. Elements corresponding to those of Figure 1 have been designated with the same reference numbers.

[0026] An inductive output tube (IOT) is designated with 10. The IOT 10 includes a thermionic cathode 11 and an anode 13 spaced therefrom. The anode 13 and cathode 11 are operable at a high voltage therebetween, for example 40 kV, to form and accelerate an electron beam.

[0027] The IOT 10 further comprises a grid 15 arranged between the cathode 11 and anode 13 and accepting a high frequency control signal to density modulate the electron beam. This control signal is supplied by a control unit (not shown) through a RF input 17 of the IOT 10. The kinetic energy of the electron beam is transformed into electromagnetic energy and supplied to a user system, such as an accelerator component, through a RF output 19 of the IOT 10. The accelerator component is, in particular, a RFQ, but - depending on the application - could be another kind of accelerating structure, such as for example a Side Coupled Drift Tube Linac (SCDTL) or Coupled Cavity Linac (CCL). For the sake of simplicity, further common components of IOTs, such as drift tube, output cavities and collector are not shown in the drawings. The IOT 10 may also comprise an ion pump 21 for monitoring residual gases within the tube.

[0028] The powering system is connected to the AC utility grid, and comprises a tube power supply 30 for supplying a positive high voltage, for example 40 kV, between the anode 13 and cathode 11. The tube power supply 30 is configured to convert the AC supply from the AC supply grid into a high voltage DC supply. The tube power supply 30 comprises a cathode line 31 and an anode line 33 connected to the cathode 11 and anode 13, respectively. The cathode 11 is connected to ground, at 34'. An optional ground resistance to monitor the tube body current is designated with 35'. Such ground resistance is of few ohm. Referencing the IOT cathode to ground potential allows to have a ground reference for the filament, ion pump and grid power supplies; this avoids the need to have a high voltage cage/deck and/or using expensive power supplies with high voltage isolation ratings.

[0029] According to the example shown in Figure 2, the tube power supply 30 comprises a low voltage capacitor charger (for example <1kV), which is used to charge an intermediate energy storage capacitor 30a that is connected to a step-up pulse transformer 30b to produce a voltage pulse between the IOT anode 11 and cathode 13. This connection or pulse shaping is performed in a pulse forming system module 30c, consisting for instance in semiconductor power electronics switches. The pulse repetition rate is defined by the design of the linear particle accelerator and possibly also by the needs of the application requiring the accelerated particle output. This parameter has a direct impact on the dimensioning of the capacitor charger (for example as pulse repetition rate increases the J/s output ratings will increase) and the step-up transformer (for example an increase in pulse repetition rate will require a faster demagnetization of the pulse transformer). The pulse transformer 30b is connected to a demagnetizing system 30d (such as a demagnetization circuit or bias power supply) to demagnetize the pulse transformer between pulses.

[0030] Alternatively, the high voltage pulse can be achieved in different ways: multilevel topologies, resonant converters, Marx generators, etc. All these topologies could generate high voltage pulses, however in this case the utilization of a step-up pulse transformer is the most convenient, due to its reduced size and corresponding cost advantage. Use of a step-up pulse transformer allows for the creation an overall smaller system.

[0031] According to a further alternative embodiment, it would be possible to avoid stepping-up the voltage and use an expensive 40kV high voltage charger. In addition to this a high voltage switch stack would be required (also very expensive).

[0032] The powering system further comprises a grid power supply 40 for supplying a bias voltage, for example a voltage comprised between -150V and -50V, between the grid 15 and cathode 11. The grid power supply 40 is configured to convert the AC supply from the AC supply grid into a DC supply for the grid 15. The grid power supply 40 comprises a grid line 45 and a cathode line 41 connected to the grid 15 and cathode 11, respectively. On the other side, the grid power supply 40 is connected to the AC supply grid without any isolation transformer.

[0033] The powering system further comprises a filament power supply 50 for supplying current, for example a current of 25A at 13V, to heat the cathode 11. The filament power supply 50 comprises a circuit 51 connected to the cathode 11, through which current is supplied to the cathode 11 in order to heat the cathode 11 and cause electrons to be emitted therefrom by thermionic effect. The filament power supply 50 is connected to the AC supply grid without any isolation transformer.

[0034] The powering system further comprises a ion pump power supply 60 for supplying a voltage, for example a voltage of 3.5 kV, between the ion pump 21 and the cathode 11, the ion pump power supply 60 comprises a ion pump line 63 and a cathode line 61 connected to the ion pump 21 and cathode 11, respectively. On the other side, the ion pump power supply 60 is connected to the AC supply grid without any isolation transformer.

[0035] The above described solution is relatively inexpensive, compact, and it does not require a high voltage deck, as all the electronics and power supplies are referenced to a common ground and no high-voltage is present in the vicinity. According to a further embodiment, it can be applied to a continuous, i.e. not-pulsed, RF power supply, by omitting the pulse forming system.

[0036] Figure 3 shows an embodiment wherein the grid voltage can also be pulsed. Elements corresponding to those of Figure 2 have been designated with the same reference numbers, and will not be further disclosed.

[0037] In the embodiment of Figure 3, the grid line 45 of the grid power supply 40 is connected to a pulse transformer 40a, pulse forming system 40b and low voltage capacitor charger 40c in order to transform a continuous bias voltage supply provided by the grid power supply 40 into a pulsed bias voltage supply for the grid 15.

Claims

1. A system for powering an accelerating structure, comprising
an inductive output tube (10), including a thermionic cathode (11) and an anode (13) spaced therefrom, said anode (13) and cathode (11) being operable at a high voltage therebetween to form and accelerate an electron beam, as well as a grid (15) arranged between said cathode (11) and anode (13) and accepting a high frequency control signal to density modulate said beam,
a tube power supply (30) for supplying said high voltage between said anode (13) and cathode (11), said tube power supply (30) comprising a cathode line (31) and an anode line (33) connected to the cathode (11) and anode (13), respectively,
a grid power supply (40) for supplying a bias voltage between said grid (15) and cathode (11), said grid power supply (40) comprising a grid line (45) and a cathode line (41) connected to the grid (15) and cathode (11), respectively, and
a filament power supply (50) for supplying current to

heat said cathode (11), said filament power supply (50) comprising a circuit (51) connected to the cathode (11),
characterised in that said cathode (11) is connected to ground and the tube power supply (30) is configured to supply a positive high voltage between said anode and cathode.

2. A system according to claim 1, further comprising a ion pump (21) for monitoring gas within the inductive output tube (10), and a ion pump power supply (60) for supplying a voltage between said ion pump (21) and cathode (11), said ion pump power supply (60) comprising a ion pump line (63) and a cathode line (61) connected to the ion pump (21) and cathode (11), respectively.

3. A system according to claim 1 and 2, wherein the tube power supply (30) is configured to supply said high voltage in a pulsed manner.

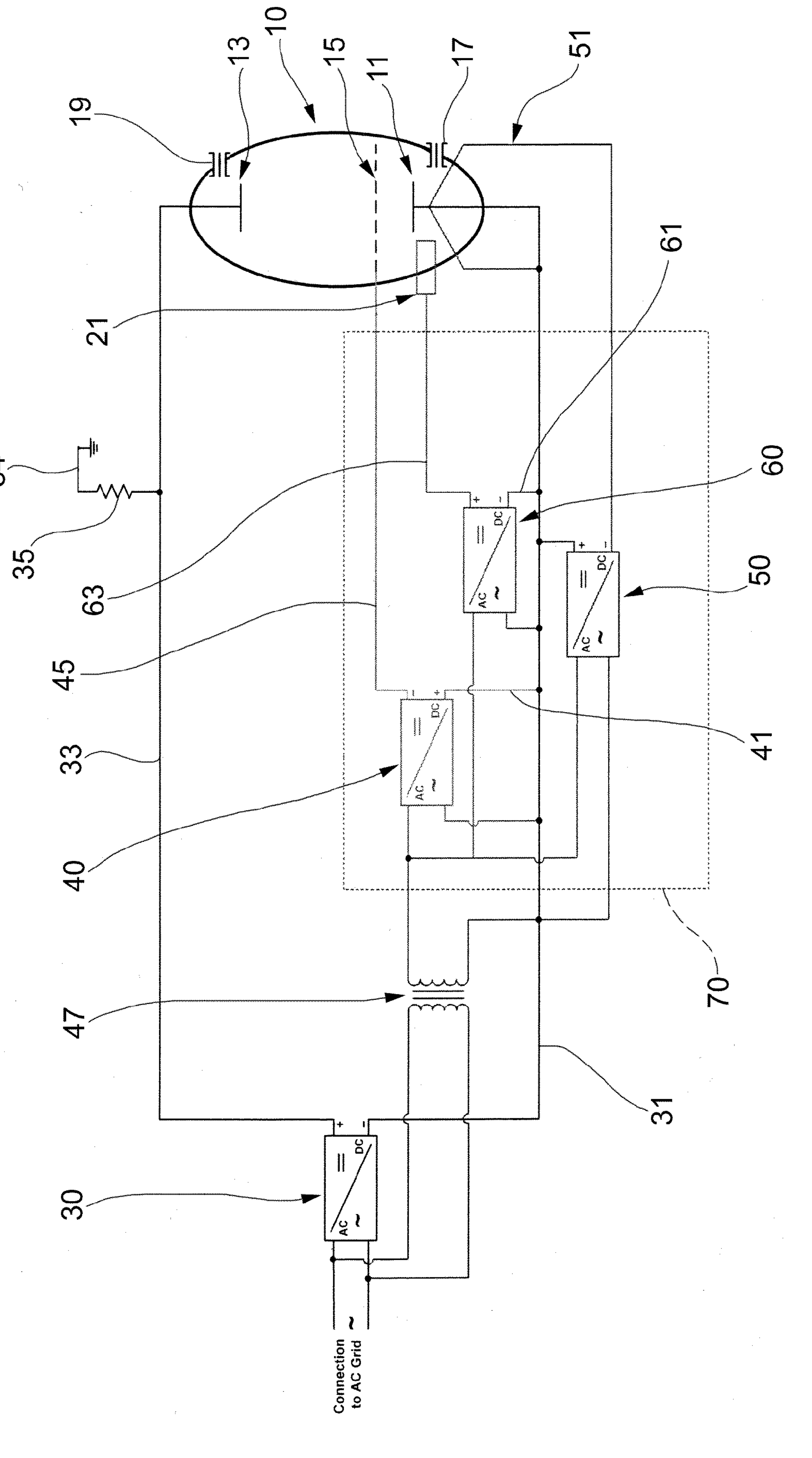
4. A system according to claim 3, wherein said tube power supply (30) comprises AC to DC converting means (30a) for converting an AC supply to a DC supply, and pulse forming means (30c) for generating a pulse from the DC supply.

5. A system according to claim 4, wherein said AC to DC converting means (30a) are configured to supply the pulse forming means with a voltage lower than said high voltage, and wherein said pulse forming means are configured to generate a high voltage pulse from the lower voltage supply.

6. A system according to claim 4, wherein said AC to DC converting means (30a) are configured to supply the pulse forming means (30c) with a voltage lower than said high voltage, and wherein said tube power supply (30) further comprises step-up transforming means (30b) for transforming a lower voltage pulse generated by the pulse forming means (30c) into a high voltage pulse.

7. A system according to any of claims 3 to 6, wherein the grid power supply (40) is configured to supply said bias voltage in a pulsed manner.

8. A system according to any of the preceding claims, wherein said tube power supply (30) comprises a low voltage capacitor charger (30a), a pulse forming system (30c) and a step-up pulse transformer (30b), said low voltage being lower than said high voltage.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AC
DC
Connection to AC Grid

FIG.1

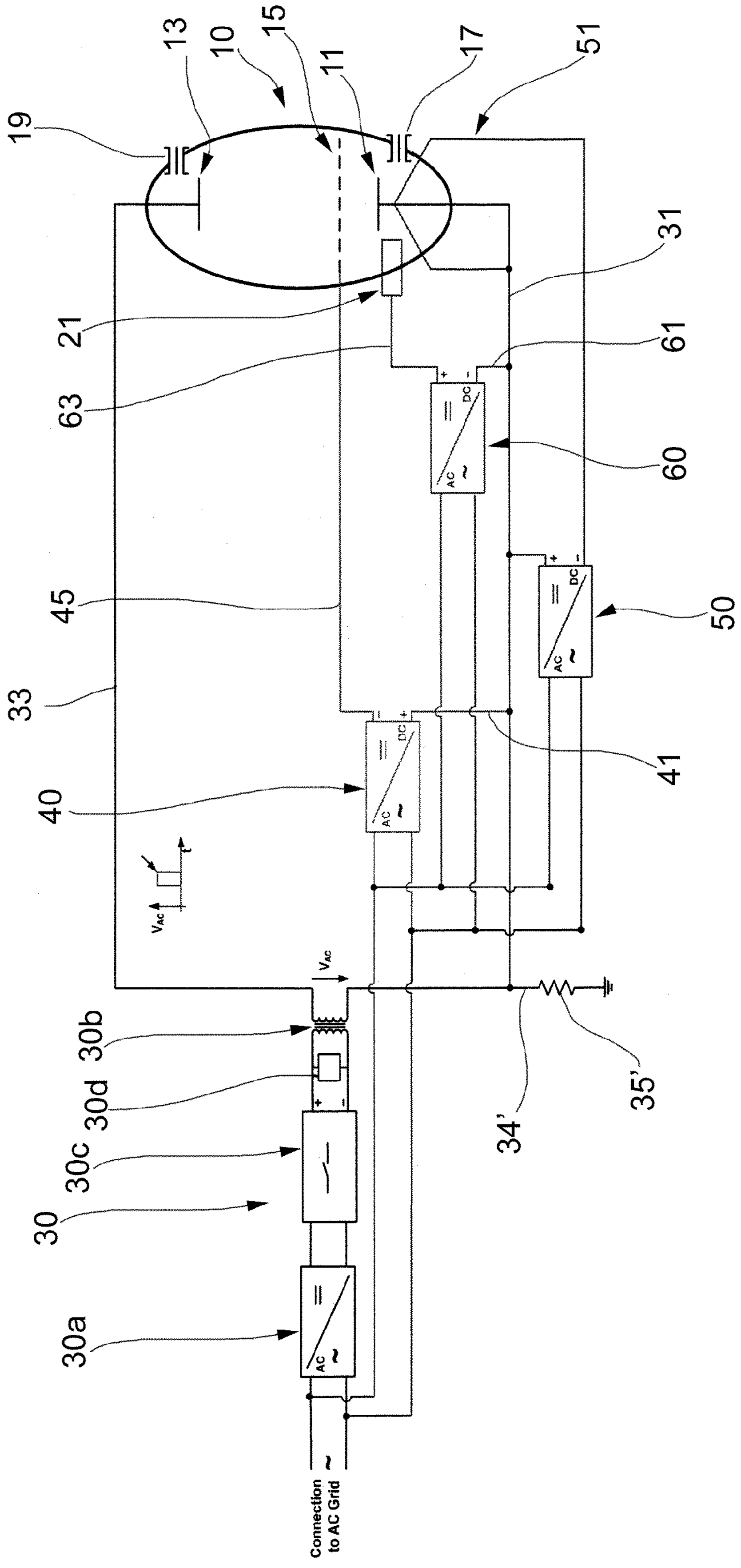
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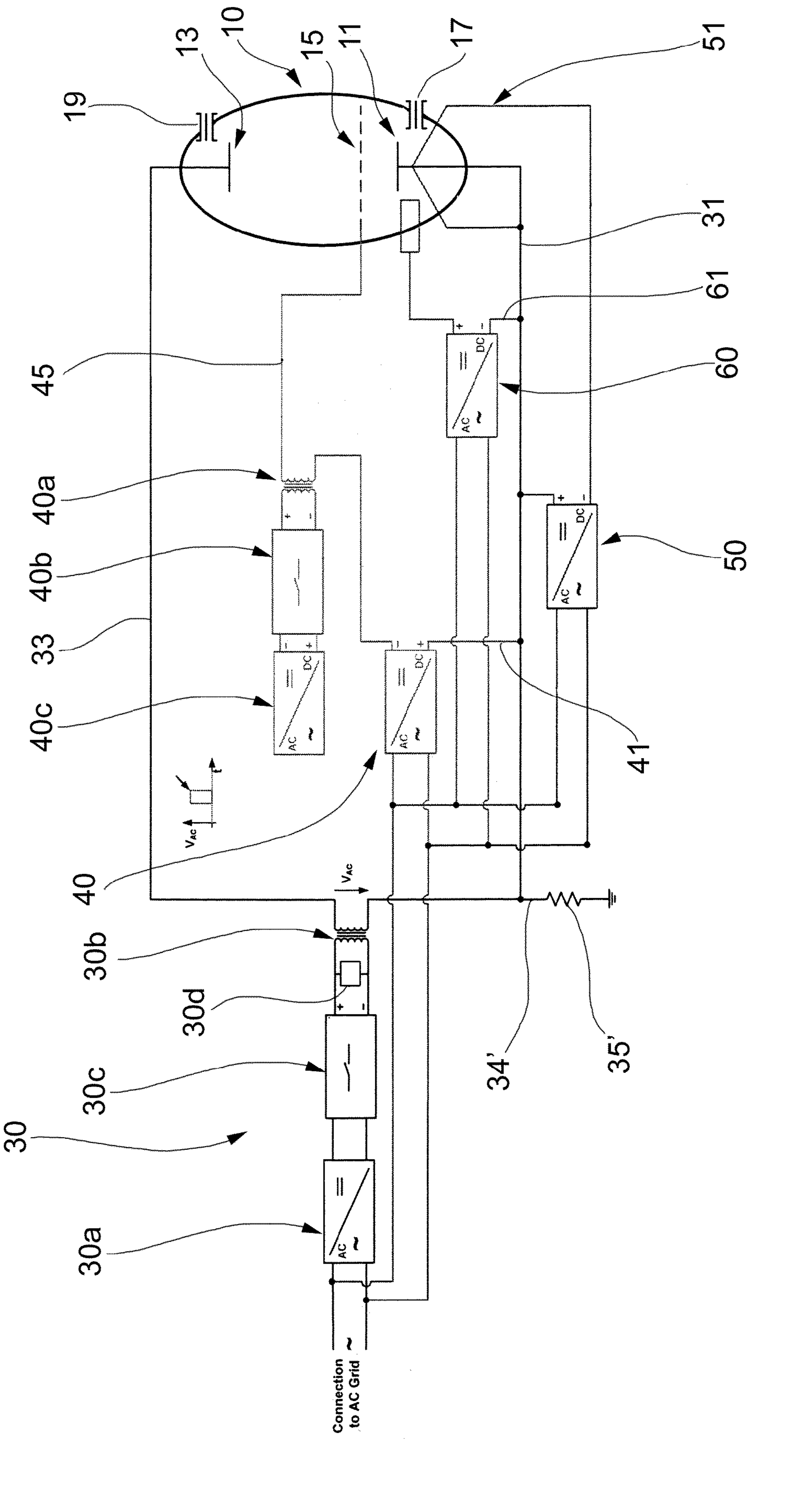
FIG.2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30a
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Connection to AC Grid

FIG.3

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EUROPEAN SEARCH REPORT

Application Number
EP 17 15 6494

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	US 2 452 318 A (NERGAARD LEON S) 26 October 1948 (1948-10-26) * column 1, line 10 - column 3, line 53; figures 1-4 *	1 2-6,8	INV. H01J23/34 H01J25/04 H05H7/02
Y	US 5 418 427 A (CIPOLLA JOHN C [US] ET AL) 23 May 1995 (1995-05-23) * abstract * * column 3, lines 4-34; figure 1 *	2	
A	DE 23 62 202 A1 (PHILIPS PATENTVERWALTUNG) 26 June 1975 (1975-06-26) * page 3, line 15 - page 4, line 3 *	2	
Y	US 6 300 715 B1 (CLERC GUY [FR]) 9 October 2001 (2001-10-09) * abstract * * column 1, line 5 - column 6, line 50; figure 3 *	3-6,8	
Y	ALLRED D A ET AL: "Space power experiments aboard rockets", PULSED POWER CONFERENCE, 1991. DIGEST OF TECHNICAL PAPERS. EIGHTH IEEE INTERNATIONAL, IEEE, 16 June 1991 (1991-06-16), pages 249-254, XP032151230, DOI: 10.1109/PPC.1991.733279 ISBN: 978-0-7803-0177-1 * abstract * * page 250, paragraph 1; figure 2 * -/--	3,8	TECHNICAL FIELDS SEARCHED (IPC) H01J H05H

The present search report has been drawn up for all claims

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Place of search	Date of completion of the search	Examiner
Munich	2 November 2017	Lang, Thomas

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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D : document cited in the application
L : document cited for other reasons
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EUROPEAN SEARCH REPORT

Application Number
EP 17 15 6494

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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TECHNICAL FIELDS SEARCHED (IPC)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	2 November 2017	Lang, Thomas

CATEGORY OF CITED DOCUMENTS

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Application Number
EP 17 15 6494

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

- [ ] Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

- [ ] No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

- [X] All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

- [ ] As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

- [ ] Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

- [ ] None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

- [ ] The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).

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LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 17 15 6494

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 1, 2

A system for powering an accelerating structure, comprising an inductive output tube, including a thermionic cathode and an anode spaced therefrom, said anode and cathode being operable at a high voltage therebetween to form and accelerate an electron beam, as well as a grid arranged between said cathode and anode and accepting a high frequency control signal to density modulate said beam, a tube power supply (30) for supplying said high voltage between said anode and cathode, said tube power supply comprising a cathode line and an anode line connected to the cathode and anode, respectively, a grid power supply for supplying a bias voltage between said grid and cathode, said grid power supply comprising a grid line and a cathode line connected to the grid and cathode, respectively, and a filament power supply for supplying current to heat said cathode, said filament power supply comprising a circuit connected to the cathode, wherein said cathode is connected to ground and the tube power supply is configured to supply a positive high voltage between said anode and cathode (claim 1),
further comprising a ion pump for monitoring gas within the inductive output tube, and a ion pump power supply for supplying a voltage between said ion pump and cathode, said ion pump power supply comprising a ion pump line and a cathode line connected to the ion pump and cathode, respectively (claim 2).

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2. claims: 3-8

A system according to claim 1, wherein the tube power supply is configured to supply said high voltage in a pulsed manner (claims 3-7); or a system according to claim 1, wherein said tube power supply comprises a low voltage capacitor charger, a pulse forming system and a step-up pulse transformer, said low voltage being lower than said high voltage (claim 8).

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 17 15 6494

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02-11-2017

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **M. MARKS et al.** CPI's 1.3 GHz, 90 kW Pulsed IOT Amplifier. *Proceedings of IPAC'10,* 4011-4013, http://www.cpii.com/docs/related/30/thpeb061proceedings%20.pdf **[0012]**