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(54) X-RAY TUBE

(57) The present invention relates to an X-ray tube (10) comprising a cathode (20), the cathode comprising:
- an electron emitter filament (30);
- a first pair of grids (40); and
- a second pair of grids (50).

The first pair of girds are located at opposite sides of the electron emitter filament. The second pair of girds are located at opposite sides of the electron emitter filament closer to the electron emitter filament than the first pair of grids. The cathode is configured such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids.

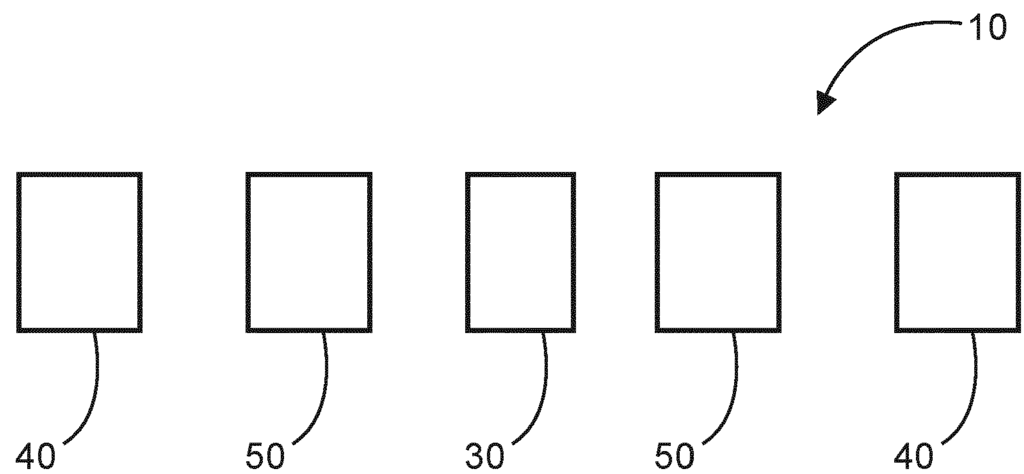

FIG. 1

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to an X-ray tube and an X-ray generation system.

BACKGROUND OF THE INVENTION

[0002] Some X-Ray tubes for medical CT imaging use electrostatic electron beam forming in combination with temperature limited emission. The emission current depends on the filament temperature and electrical heating is typically used to control the emission current. The electron beam is steered by electrical grids for focal spot sizing and positioning. The control of the emission via the temperature of the filament is a relatively slow process because the heating and cooling of the filament requires a certain amount of time. This slow emission, via control of the current flowing through the filament, is a problem for some applications. Although the emission is controlled via the filament temperature, the tube voltage and the voltage of the grids also impact the emission.

[0003] Slow emission current control is a severe burden for rapid kVp switching (kVp-S) where the tube voltage is switched between consecutive acquisition intervals (e.g. 80kV and 140kV). The X-Ray generation is much more efficient for high voltages. The difference of the X-Ray output dose between 80kV and 140kV of a tube at the same filament temperature may easily become as large as a factor of 7. For spectral imaging the flux of the low kV and high kV intervals should be roughly the same to obtain good spectral material separation. The imbalance of the flux between low and high kV can be partly compensated with longer integration periods for low tube voltages. However, it is not possible to rapidly increase the emission current to lead to an associated increase in filament temperature and emission current, because such filament heating is too slow.

[0004] There is a need to resolve this issue.

SUMMARY OF THE INVENTION

[0005] It would be advantageous to have an improved X-ray tube for rapid KVp switching between different high voltages. The object of the present invention is solved with the subject matter of the independent claims, wherein further embodiments are incorporated in the dependent claims.

[0006] In a first aspect, there is provided an an X-ray tube comprising a cathode, the cathode comprising:

- an electron emitter filament;
- a first pair of grids; and
- a second pair of grids.

[0007] The first pair of girds are located at opposite sides of the electron emitter filament. The second pair of girds are located at opposite sides of the electron emitter filament closer to the electron emitter filament than the first pair of grids. The cathode is configured such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids.

[0008] In this manner a new design of cathode of an X-ray tube has been developed, where an extra set of grids are provided inside of a normal pair of grids around filament that can be held at a different potential to the normal grids. In this way, the voltages of the grids can be optimised, with respect to a high voltage between the cathode and an anode of the X-ray tube, to increase the electron emission from the filament. This means that when switching between a first high voltage of the X-ray tube (for example 140KV) to a second high voltage of the X-ray tube (for example 80KV) the electron emission from the filament can be increased over that normally achievable during the 80KV operation, without increasing heating current flow through the filament to increase the thermal emission (that would incur a time lag). This means that voltage switching of the grids around the filament in combination with switching of the voltage between the cathode and anode can be utilized to provide a closer match between the X-ray flux produced by the X-ray tube during both the 80KV mode of operation and the 140KV mode of operation, because the electron emission during the 80KV operation can be boosted.

[0009] In an example, the grids of the first pair of grids are configured to be at different voltages to each other.

[0010] In an example, the grids of the second pair of grids are configured to be at the same voltage to each other.

[0011] In an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is greater than the voltage of the second pair of grids.

[0012] In an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is two times greater than the voltage of the second pair of grids.

[0013] In an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is ten times greater than the voltage of the second pair of grids.

[0014] In an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is thirty times greater than the voltage of the second pair of grids.

[0015] In a second aspect, there is provided an X-ray generation system, comprising:

- an anode;
- a cathode;
- a high voltage supply;
- a low-medium voltage supply; and
- a controller.

[0016] The cathode comprises:

an electron emitter filament;
a first pair of grids; and
a second pair of grids;

[0017] The first pair of girds are located at opposite sides of the electron emitter filament; and
The second pair of girds are located at opposite sides of the electron emitter filament closer to the filament than the first pair of grids; and
In a first mode of operation:

the controller is configured to control the high voltage supply to apply a first high voltage between the anode and the cathode;
the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
electrons emitted from the electron emitter filament are formed into ae electron beam and focused on the anode;

[0018] In a second mode of operation:

the controller is configured to control the high voltage supply to apply a second high voltage between the anode and the cathode that is greater than the first high voltage;
the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
electrons emitted from the electron emitter filament are formed into an electron beam and focused on the anode.

[0019] This enables ultra-fast dose (tube current) modulation and provides a significant improvement for fast kVp-Switching by boosting the flux for lower tube voltages

[0020] In an example, the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids.

[0021] In an example, the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids at a same average voltage to steer the electron beam.

[0022] In an example, the controller is configured to control the low-medium supply to apply a voltage of different magnitudes to the grids of the first pair of grids or an average voltage of different magnitudes to the grids of the first pair of grids.

[0023] In an example, the controller is configured to control the low-medium supply to apply a same voltage of different magnitudes to the grids of the second pair of grids.

[0024] In an example, a reduction in the magnitude of the voltage magnitude applied to the grids of the second pair of grids in both the first mode and second mode of operation for a fixed voltage or average voltage applied to the grids of the first pair of grids is configured to increase a current of the electron beam and increase a focal spot size.

[0025] In an example, the controller is configured to maintain a focal spot size between the first mode of operation and the second mode of operation through application of a voltage of different magnitudes between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and in the second mode of operation.

[0026] In an example, the controller is configured to control the low-medium supply to apply a first voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and to control the low-medium supply to apply a second voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the second mode of operation, wherein the second magnitude is less than the first magnitude.

[0027] The above aspect and examples will become apparent from and be elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] Exemplary embodiments will be described in the following with reference to the following drawing:

Fig. 1 shows a schematic representation of an example of an X-ray tube;
Fig. 2 shows a schematic representation of an example of an X-ray generation system;
Fig. 3 shows a conventional cathode of an X-ray tube, shown at the left in 3D, and at the right in cross section;
Fig. 4 shows a new cathode of an X-ray tube, shown at the left in 3D, and at the right in cross section;
Fig. 5 shows the emission current (top) and focal spot (FS) size (bottom) in a conventional cathode design of an X-ray tube as a function of X-ray tube voltage (KV);
Fig. 6 shows the emission current (top) and focal spot (FS) size (bottom) in a conventional cathode design of an X-ray tube as a function of inner grid voltage of the cathode with a fixed outer grid voltage of the cathode and a fixed X-ray tube voltage;
Fig. 7 shows the emission current (top) and focal spot (FS) size (bottom) in anew cathode design of an X-ray tube as a function of X-ray tube voltage (KV) for various inner grid and outer grid voltages of the cathode; and
Fig. 8 shows electron-track visualizations. On the left the inner grids and outer grids of the cathode have identical grid voltages (705V), the FS size is 1.2mm, and the emission current is 480mA. On the right the outer grids of the cathode are at a voltage of 1500V,

and the inner grids of the cathode are at 50V, the FS size is 1.2mm, and the emission current is 650mA.

DETAILED DESCRIPTION OF EMBODIMENTS

[0029] Fig. 1 shows an example of an X-ray tube 10 comprising a cathode 20. The cathode 20 comprises an electron emitter filament 30, a first pair of grids 40, and a second pair of grids 50. The first pair of girds are located at opposite sides of the electron emitter filament. The second pair of girds are located at opposite sides of the electron emitter filament closer to the electron emitter filament than the first pair of grids. The cathode is configured such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids.

[0030] According to an example, the grids of the first pair of grids are configured to be at different voltages to each other.

[0031] According to an example, the grids of the second pair of grids are configured to be at the same voltage to each other.

[0032] According to an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is greater than the voltage of the second pair of grids.

[0033] According to an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is two times greater than the voltage of the second pair of grids.

[0034] According to an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is ten times greater than the voltage of the second pair of grids.

[0035] According to an example, the cathode is configured such that the voltage or the average voltage of the first pair of grids is thirty times greater than the voltage of the second pair of grids.

[0036] Fig. 2 shows an example of an X-ray generation system 100. The system 100 comprises an anode 60, a cathode 20, a high voltage supply 70, a low-medium voltage supply 80, and a controller 90. The cathode comprises an electron emitter filament 30, a first pair of grids 40, and a second pair of grids 50. The first pair of girds are located at opposite sides of the electron emitter filament. The second pair of girds are located at opposite sides of the electron emitter filament closer to the filament than the first pair of grids.

[0037] In a first mode of operation:

the controller is configured to control the high voltage supply to apply a first high voltage between the anode and the cathode;
the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
electrons emitted from the electron emitter filament are formed into ae electron beam and focused on the anode;

[0038] In a second mode of operation:

the controller is configured to control the high voltage supply to apply a second high voltage between the anode and the cathode that is greater than the first high voltage;
the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
electrons emitted from the electron emitter filament are formed into an electron beam and focused on the anode.

[0039] According to an example, the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids.

[0040] According to an example, the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids at a same average voltage to steer the electron beam.

[0041] According to an example, the controller is configured to control the low-medium supply to apply a voltage of different magnitudes to the grids of the first pair of grids or an average voltage of different magnitudes to the grids of the first pair of grids.

[0042] According to an example, the controller is configured to control the low-medium supply to apply a same voltage of different magnitudes to the grids of the second pair of grids.

[0043] According to an example, a reduction in the magnitude of the voltage magnitude applied to the grids of the second pair of grids in both the first mode and second mode of operation for a fixed voltage or average voltage applied to the grids of the first pair of grids is configured to increase a current of the electron beam and increase a focal spot size.

[0044] According to an example, the controller is configured to maintain a focal spot size between the first mode of operation and the second mode of operation through application of a voltage of different magnitudes between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and in the second mode of operation.

[0045] According to an example, the controller is configured to control the low-medium supply to apply a first voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and to control the low-medium supply to apply a second voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the second mode of operation, wherein the second magnitude is less than the first magnitude.

[0046] The new cathode of an X-ray tube and an X-ray generation system having such a cathode are now described in specific detail, where reference is made to Figs. 3-8.

[0047] It was realised that although the electron emission from a conventional cathode is controlled via the filament temperature, the tube voltage and the grid voltage also impact the emission, and that an introduction of two sets of grids of the cathode that can operate at different voltages would enable the electron emission to be increased. Thus, the electron emission at a lower switch voltage e.g. 80KV could be increased above that presently available, whilst that at 140KV could be kept at levels now achievable. The higher voltage electron emission could be increased, but by increasing just the lower switch voltage the resultant X-ray doses between the low voltage and high voltage of X-ray tube operation could be brought closer together.

[0048] To help explain the new cathode design, an existing typical cathode design is introduced. Fig. 3 shows a typical cathode design. The filament is embedded in a cup with steering grids on both sides. The grid voltages are used to position and size the focal spot (FS). The common part of the voltages defines the FS size. High voltages will constrict the emitted electron beam and form a small focal spot (and vice versa). A voltage difference between the grids can be used to position the focal spot. The common voltage will also impact the emission by changing the electrical field. In Fig. 3 GridVioltage 1 is represented by "A", and GridVoltage 2 is represented by "B". The grids can be at different voltages indicated by the A and B.

[0049] In the new cathode design, such an existing design is changed and another grid (actually two inner grids) are added close to the filament see Fig. 4. The voltage of this grid is used to control the emission current. The impact on the focal spot size is than compensated with the second set of grids (outer grids). Since the steering voltages can rapidly be changed, the new design allows for ultra-fast emission current control without impacting on the focal spot size. In Fig. 4 GridVoltage 1 is represented by "40 - A", and GridVoltage 2 is represented by "40 - B". The outer grids 40 can be at different voltages indicated by the A and B. In Fig. 4 GridVoltage 3 is represented by "50 - C". The inner grids 50 are generally held at the same voltage to each other indicated by the C.

[0050] Continuing with Fig. 4 this shows an embodiment where the inner grids are close to the filament and can efficiently control the emission even with relatively small voltages. The outer grids are mainly used to shape the focal spot and to correct for the focal spot impact of the inner grids.

[0051] For a desired focal spot size, there is a variety of grid voltage combinations that realizes the size but generate different emission currents. For kVp-S, this capability can be used to have a moderate emission current at high tube voltages and to increase the emission current for low voltages by maintaining the desired focal spot size.

[0052] Fig. 5 shows two emission current (mA) at the top and FS size (mm) at the bottom curves as a function of the X-ray tube voltage (KV) for one filament temperature using a conventional tube design. The two curves belong to two different grid voltages (705V, 1150V). These grid voltages have been selected to get the same focal spot size (1.2mm) at 80kV and 140kV in this example. As it can be seen the emission current goes down from about 570mA (@ 140kV, grid 1150V) to 480mA (@ 80kV, grid 705V). In atypical kVp-S protocol, the grid voltage may be switched forth and back during the tube voltage transition.

[0053] Fig. 6 shows the emission current (top) and focal spot size (bottom) for the new design of cathode. This shows what happens if the grid voltages for the inner grids 50 (GridVoltage3 "50 - C") is different form the outer grids 40 (Gridvoltage1 "40 - A" and GridVoltage2 "40 - B"). It can be seen how the emission current increases from about 480mA to 750mA for smaller voltages on the inner grids. However, at the same time the focal spot gets larger, where it is to be noted that the voltage on the outer grids 40 has been kept constant.

[0054] In Fig. 7 it is shown how this unwanted focal spot (FS) enlargement can be compensated with higher voltages on the outer grids 40. The outer grid voltages have been selected to maintain the desired FS size of 1.2mm at 80kVp (bottom). The emission currents however are very different. The maximal improvement of the current relative to the conventional cathode design is a gain of about 35% (from 480mA to 650mA). This is a significant improvement for kVp-S and it enables ultrafast dose modulation.

[0055] In Fig. 8 the differences can be visualized with an electron track simulation. It shows in effect the conventional setting (left) with all grids (outer and inner) at 705V to generate a FS size of 1.2mm - this then equates to the conventional design with only one pair of grids. The image to the right shows the improved case associated with the new cathode design with 50V on the inner grids 50 and 1500V on the outer grids. Although the same FS size is realized on the anode, the electron cloud is much larger close to the filament indicating the increased current.

[0056] Therefore, during kVp switching with the new design it is desired to change the emission current and at the same time to maintain the focal spot size. To do this, the common part (in effect the average voltage of the pair) of the outer grids 40 and the voltage of the inner grids 50 are switched to get the required combination of FS size and current.

[0057] Therefore, one can consider there to be two scenarios with different tube behaviors (80 and 140 kV). There are three controllable parameters for the new cathode design (the voltage of the outer grids 40, the voltage difference between the outer grids and the voltage of the inner grids 50). There, are then three relevant outputs: FS position, FS size and current. For each of the two operating scenarios (80/140kV) the 3 input parameters are set in order to get the desired outputs. This can be achieved in a similar process to that shown graphically in the figures described above for particular X-ray tube designs.

[0058] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive. The invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing a claimed invention, from a study of the drawings, the disclosure, and the dependent claims.

[0059] In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are re-cited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

Claims

1. An X-ray tube (10) comprising a cathode (20), the cathode comprising:

   - an electron emitter filament (30);
   - a first pair of grids (40); and
   - a second pair of grids (50);

     wherein the first pair of girds are located at opposite sides of the electron emitter filament;
     wherein the second pair of girds are located at opposite sides of the electron emitter filament closer to the electron emitter filament than the first pair of grids; and
     wherein the cathode is configured such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids.

2. X-ray tube according to claim 1, wherein the grids of the first pair of grids are configured to be at different voltages to each other.

3. X-ray tube according to any of claims 1-2, wherein the grids of the second pair of grids are configured to be at the same voltage to each other.

4. X-ray tube according to any of claims 1-3, wherein the cathode is configured such that the voltage or the average voltage of the first pair of grids is greater than the voltage of the second pair of grids.

5. X-ray tube according to claim 4, wherein the cathode is configured such that the voltage or the average voltage of the first pair of grids is two times greater than the voltage of the second pair of grids.

6. X-ray tube according to claim 4, wherein the cathode is configured such that the voltage or the average voltage of the first pair of grids is ten times greater than the voltage of the second pair of grids; or wherein the cathode is configured such that the voltage or the average voltage of the first pair of grids is thirty times greater than the voltage of the second pair of grids.

7. An X-ray generation system (100), comprising:

   an anode (60);
   a cathode (20);
   a high voltage supply (70);
   a low-medium voltage supply (80); and
   a controller (90);
   wherein the cathode comprises:

     an electron emitter filament (30);
     a first pair of grids (40); and
     a second pair of grids (50);

   wherein the first pair of girds are located at opposite sides of the electron emitter filament; and
   wherein the second pair of girds are located at opposite sides of the electron emitter filament closer to the filament than the first pair of grids; and
   wherein in a first mode of operation:

     the controller is configured to control the high voltage supply to apply a first high voltage between the anode and the cathode;
     the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
     electrons emitted from the electron emitter filament are formed into ae electron beam and focused on the anode;

   wherein in a second mode of operation:

     the controller is configured to control the high voltage supply to apply a second high voltage between the anode and the cathode that is greater than the first high voltage;
     the controller is configured to control the low-medium voltage supply such that a voltage or an average voltage of the first pair of grids is different to a voltage of the second pair of grids; and
     electrons emitted from the electron emitter

filament are formed into an electron beam and focused on the anode.

8. System according to claim 7, wherein the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids.

9. System according to claim 8, wherein the controller is configured to control the low-medium supply to apply different voltages to the grids of the first pair of grids at a same average voltage to steer the electron beam.

10. System according to any of claims 7-9, wherein the controller is configured to control the low-medium supply to apply a voltage of different magnitudes to the grids of the first pair of grids or an average voltage of different magnitudes to the grids of the first pair of grids.

11. System according to any of claims 7-10, wherein the controller is configured to control the low-medium supply to apply a same voltage of different magnitudes to the grids of the second pair of grids.

12. System according to claim 11, wherein a reduction in the magnitude of the voltage magnitude applied to the grids of the second pair of grids in both the first mode and second mode of operation for a fixed voltage or average voltage applied to the grids of the first pair of grids is configured to increase a current of the electron beam and increase a focal spot size.

13. System according to any of claims 8-12, wherein the controller is configured to maintain a focal spot size between the first mode of operation and the second mode of operation through application of a voltage of different magnitudes between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and in the second mode of operation.

14. System according to any of claims 8-12, wherein the controller is configured to control the low-medium supply to apply a first voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the first mode of operation and to control the low-medium supply to apply a second voltage magnitude between the grids of the first pair of grids and the grids of the second pair of grids in the second mode of operation, wherein the second magnitude is less than the first magnitude.

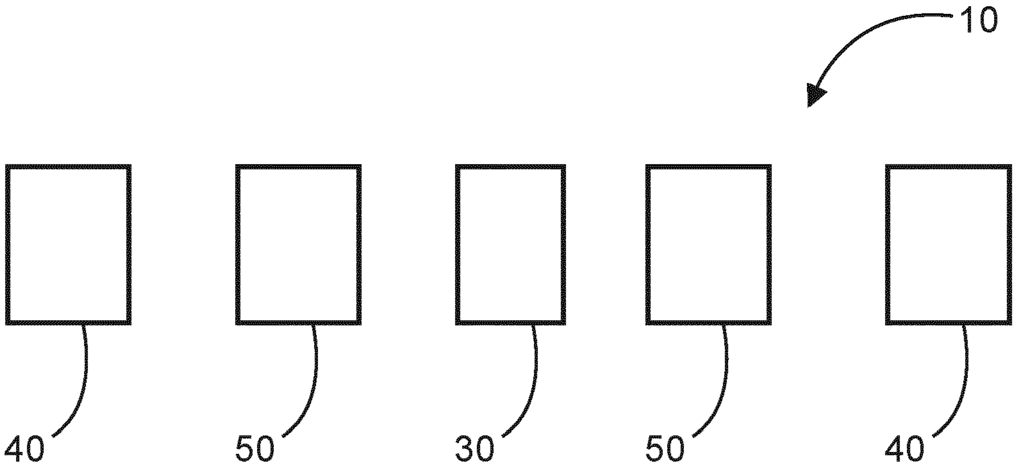

FIG. 1

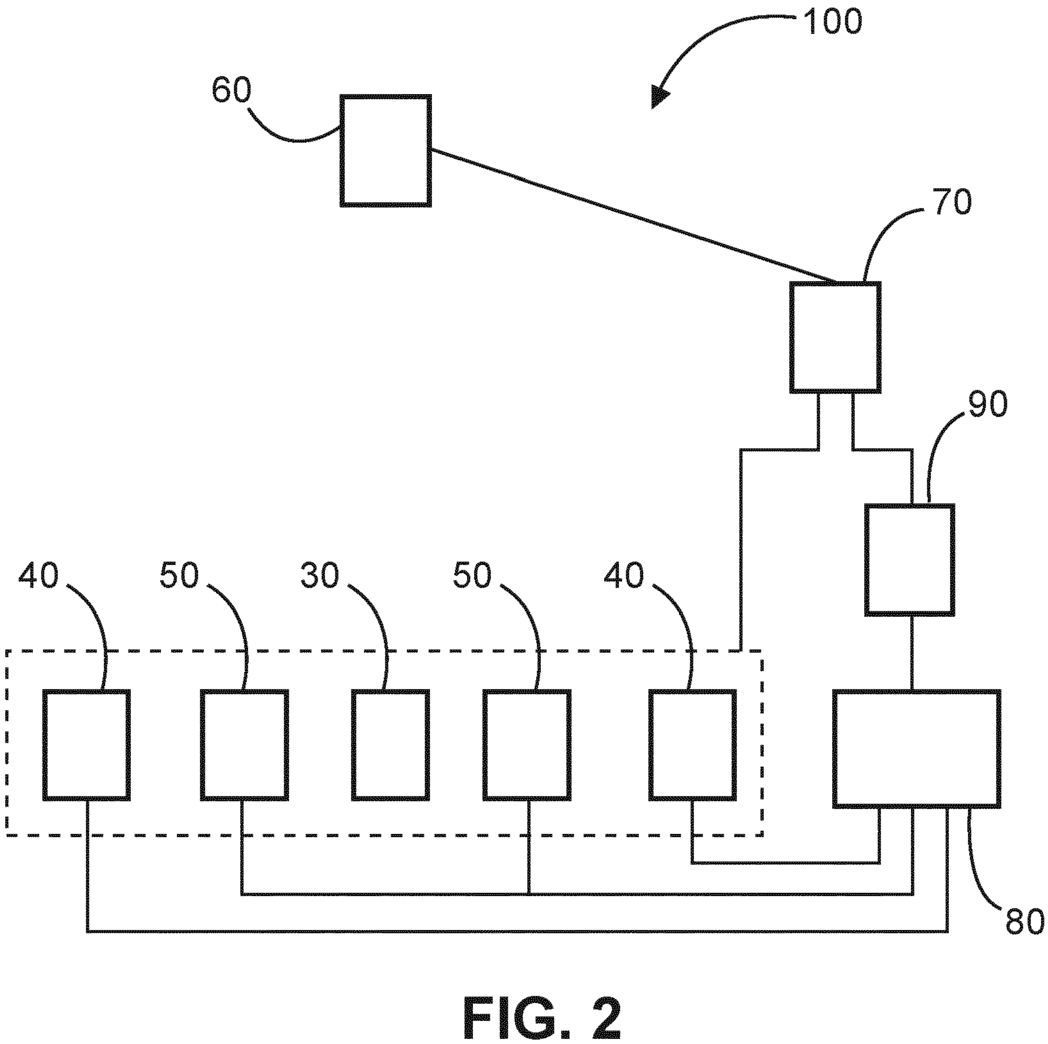

FIG. 2

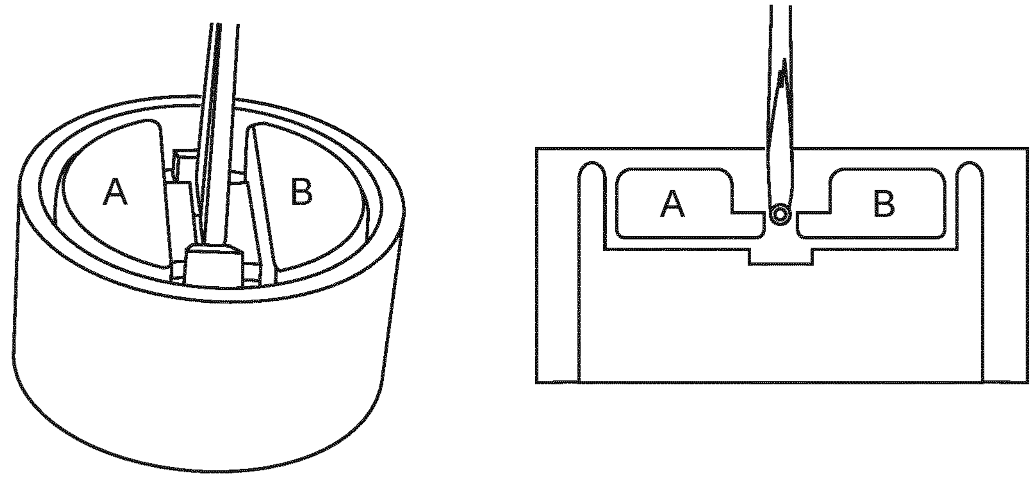

FIG. 3

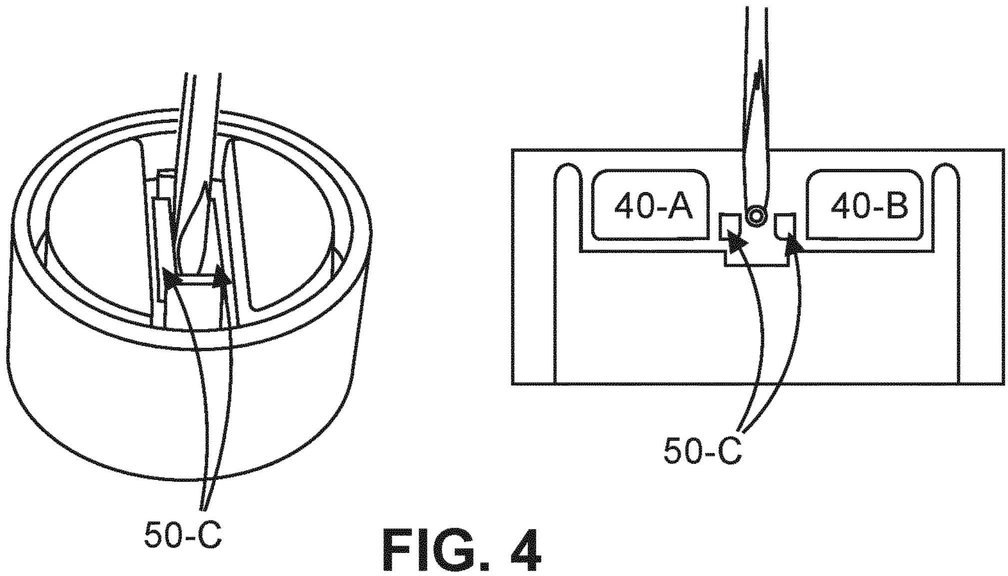

FIG. 4

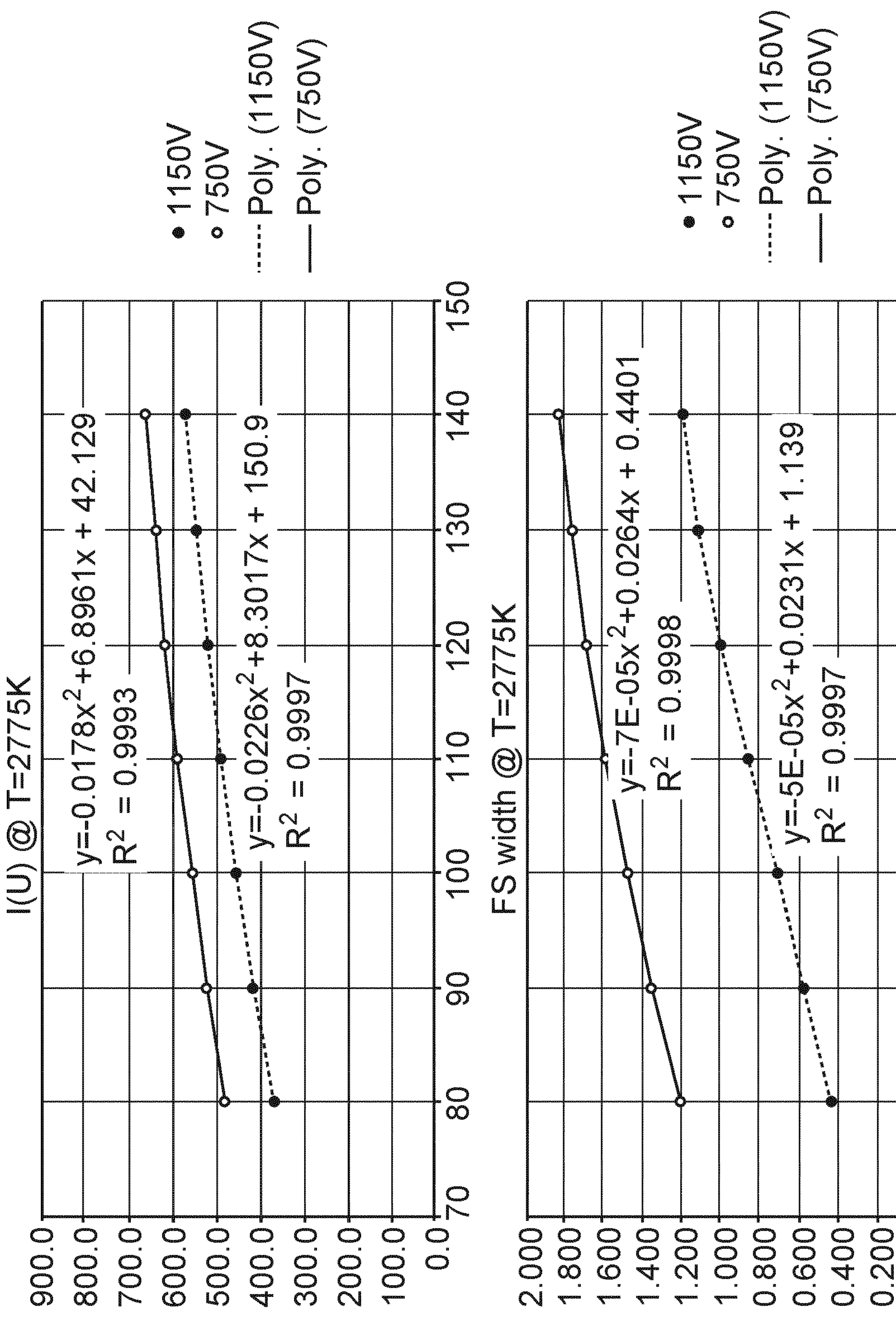
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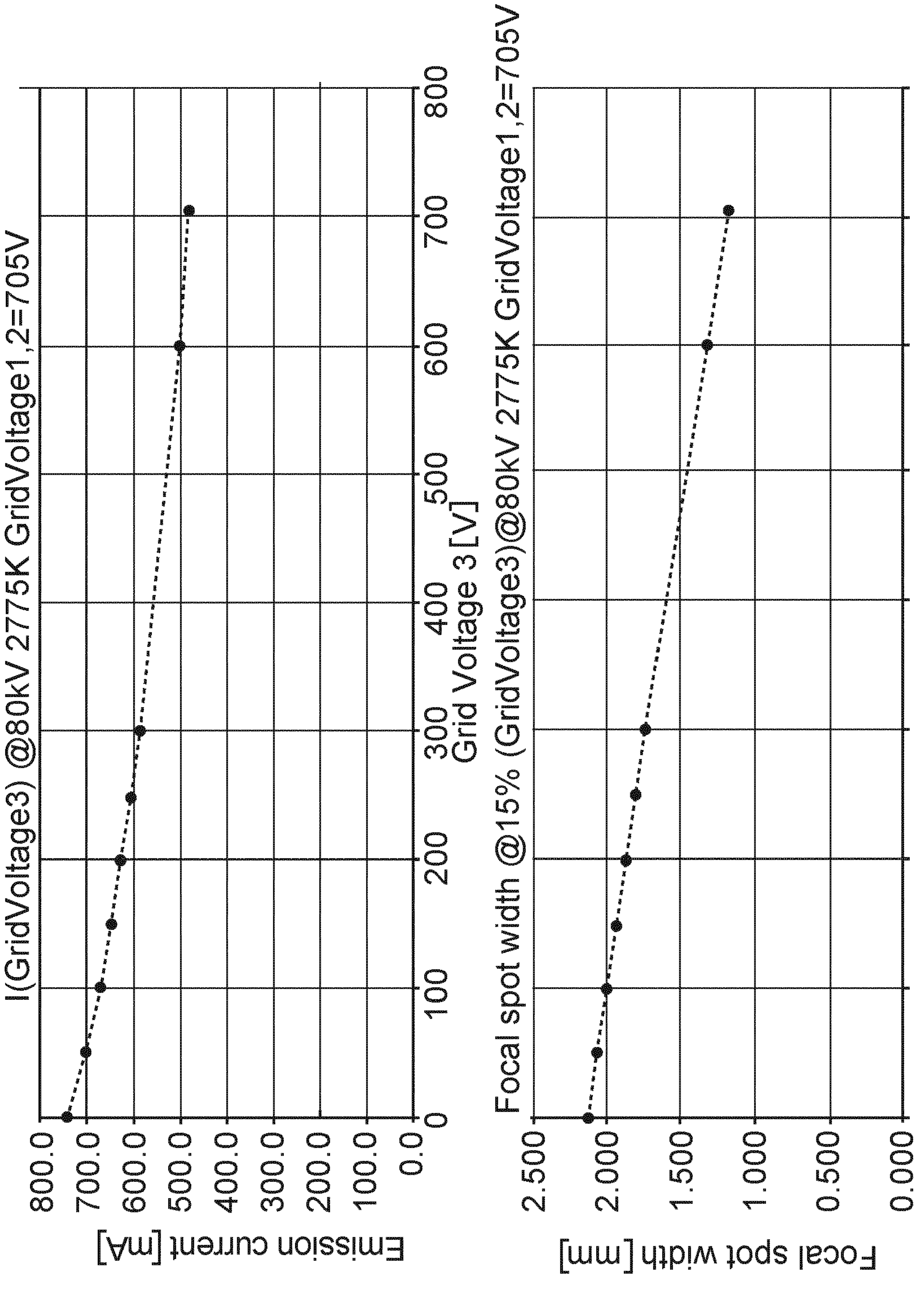
FIG. 5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100
200
300
400
500
600
700
800
Grid Voltage 3 [V]

FIG. 6

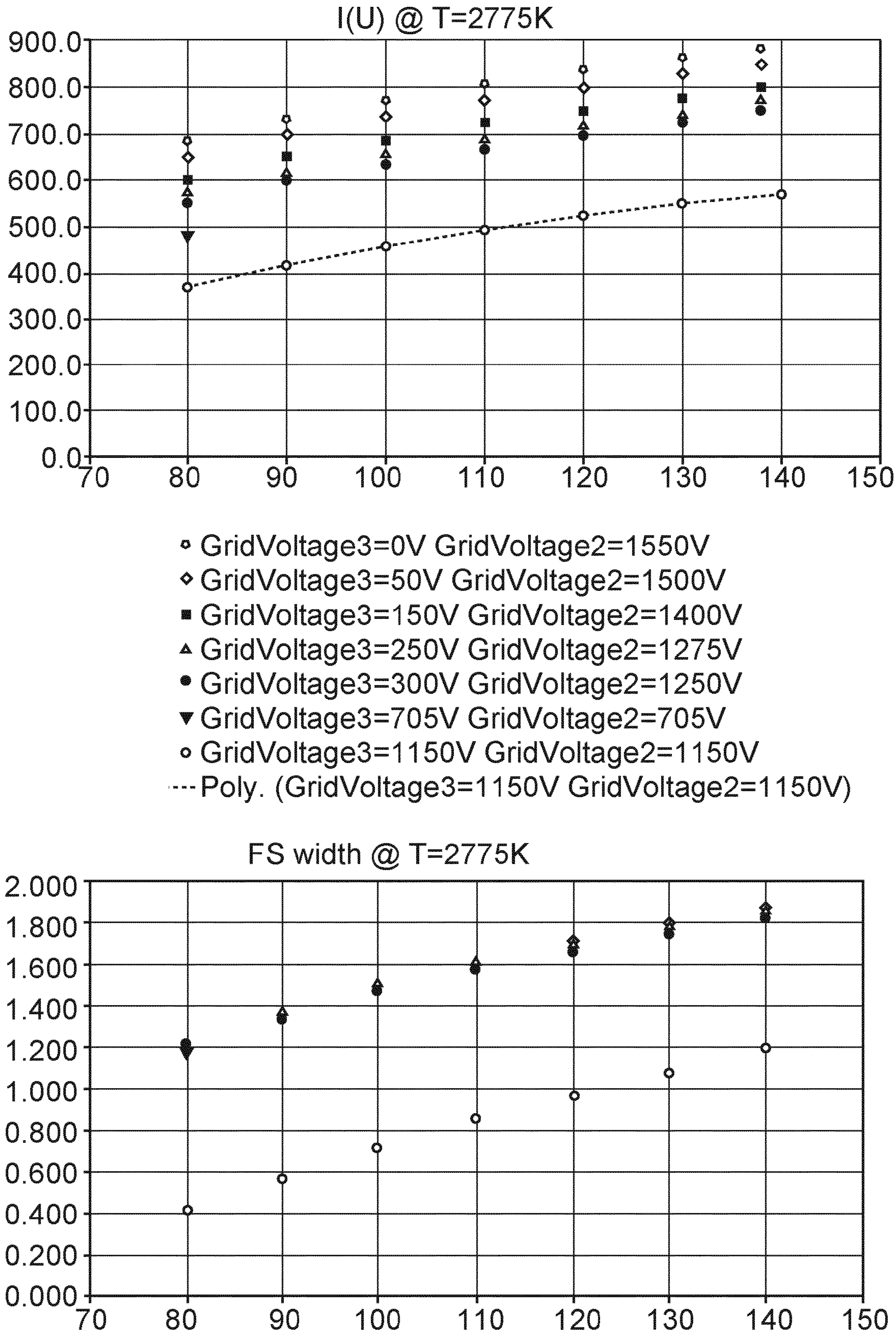
I(U) @ T=2775K
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
70
80
90
100
110
120
130
140
150
GridVoltage3=0V GridVoltage2=1550V
GridVoltage3=50V GridVoltage2=1500V
GridVoltage3=150V GridVoltage2=1400V
GridVoltage3=250V GridVoltage2=1275V
GridVoltage3=300V GridVoltage2=1250V
GridVoltage3=705V GridVoltage2=705V
GridVoltage3=1150V GridVoltage2=1150V
Poly. (GridVoltage3=1150V GridVoltage2=1150V)
FS width @ T=2775K
2.000
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
70
80
90
100
110
120
130
140
150

FIG. 7

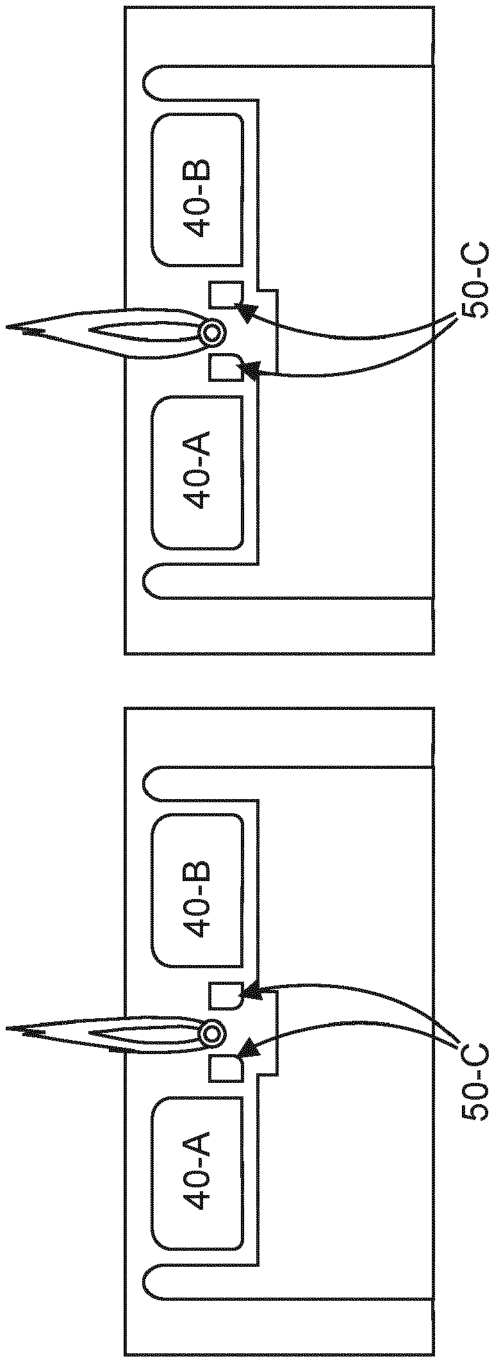

FIG. 8

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Place of search	Date of completion of the search	Examiner
Munich	19 April 2022	Krauss, Jan

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