US012387903B2

(12) **United States Patent**
**Van Veen et al.**

(10) **Patent No.: US 12,387,903 B2**
(45) **Date of Patent: *Aug. 12, 2025**

(54) **ABERRATION CORRECTION IN CHARGED PARTICLE SYSTEM**

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(72) Inventors: **Alexander Hendrik Vincent Van Veen**, Rotterdam (NL); **Willem Henk Urbanus**, Delft (NL); **Marco Jan-Jaco Wieland**, Delft (NL)

(73) Assignee: **ASML Netherlands B.V.**, Veldhoven (NL)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **17/824,831**

(22) Filed: **May 25, 2022**

(65) **Prior Publication Data**

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**Related U.S. Application Data**

(63) Continuation of application No. 15/985,763, filed on May 22, 2018, now Pat. No. 11,348,756, which is a

(Continued)

(51) **Int. Cl.**

| | |
|---|---|
| ***H01J 37/153*** | (2006.01) |
| ***H01J 37/02*** | (2006.01) |

(Continued)

(52) **U.S. Cl.**

CPC .......... ***H01J 37/153*** (2013.01); ***H01J 37/065*** (2013.01); ***H01J 37/09*** (2013.01); ***H01J 37/12*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC . G21K 1/02; G21K 5/04; B82Y 10/00; B82Y 40/00; H01J 2237/0213;

(Continued)

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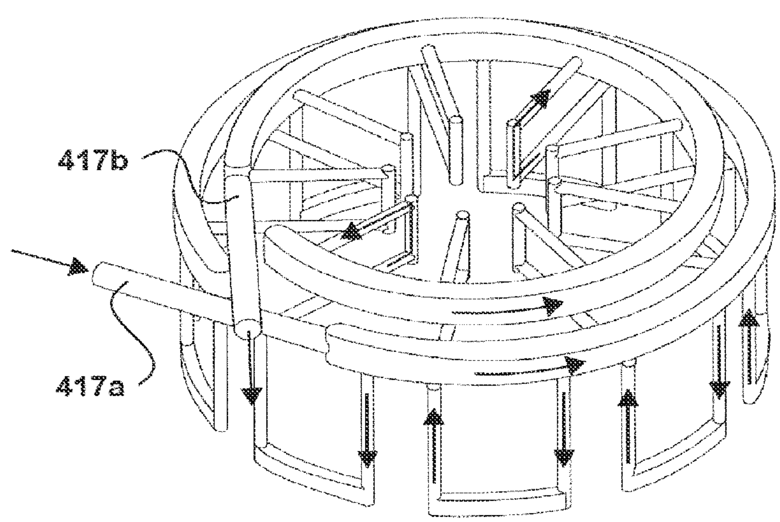
(74) *Attorney, Agent, or Firm* — FINNEGAN, HENDERSON, FARABOW, GARRETT & DUNNER LLP

(57) **ABSTRACT**

A lens element of a charged particle system comprises an electrode having a central opening. The lens element is configured for functionally cooperating with an aperture array that is located directly adjacent said electrode, wherein the aperture array is configured for blocking 5 part of a charged particle beam passing through the central opening of said electrode. The electrode is configured to operate at a first electric potential and the aperture array is configured to operate at a second electric potential different from the first electric potential. The electrode and the aperture array together form an aberration correcting lens.

**20 Claims, 13 Drawing Sheets**



## Related U.S. Application Data

continuation-in-part of application No. 15/594,712, filed on May 15, 2017, now Pat. No. 10,037,864, which is a continuation-in-part of application No. 14/400,569, filed as application No. PCT/EP2013/059963 on May 14, 2013, now Pat. No. 9,653,261, said application No. 15/985,763 is a continuation-in-part of application No. 15/493,159, filed on Apr. 21, 2017, now Pat. No. 10,586,625, which is a continuation-in-part of application No. 14/541,233, filed on Nov. 14, 2014, now Pat. No. 9,905,322, said application No. 15/493,159 is a continuation-in-part of application No. 14/400,569, filed as application No. PCT/EP2013/059963 on May 14, 2013, now Pat. No. 9,653,261.

(60) Provisional application No. 61/646,839, filed on May 14, 2012, provisional application No. 61/904,057, filed on Nov. 14, 2013.

(51) **Int. Cl.**

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|---|---|
| ***H01J 37/065*** | (2006.01) |
| ***H01J 37/09*** | (2006.01) |
| ***H01J 37/12*** | (2006.01) |
| ***H01J 37/317*** | (2006.01) |

(52) **U.S. Cl.**

CPC ......... *H01J 37/023* (2013.01); *H01J 37/3177* (2013.01); *H01J 2237/0213* (2013.01); *H01J 2237/0264* (2013.01); *H01J 2237/0453* (2013.01); *H01J 2237/1207* (2013.01); *H01J 2237/1534* (2013.01); *H01J 2237/1825* (2013.01); *H01J 2237/188* (2013.01); *H01J 2237/31774* (2013.01); *H01J 2237/31793* (2013.01)

(58) **Field of Classification Search**

CPC ....... H01J 2237/0264; H01J 2237/0453; H01J 2237/1207; H01J 2237/1534; H01J 2237/1825; H01J 2237/188; H01J 2237/31774; H01J 2237/31793; H01J 37/023; H01J 37/065; H01J 37/09; H01J 37/12; H01J 37/153; H01J 37/3177; H01J 2237/002; H01J 2237/0216; H01J 2237/024; H01J 2237/026; H01J 2237/0262; H01J 2237/032; H01J 2237/1215; H01J 2237/16; H01J 2237/182; H01J 2237/30472; H01J 37/147; H01J 37/16; H01J 37/3007; H01J 37/302; H01J 37/3174

See application file for complete search history.

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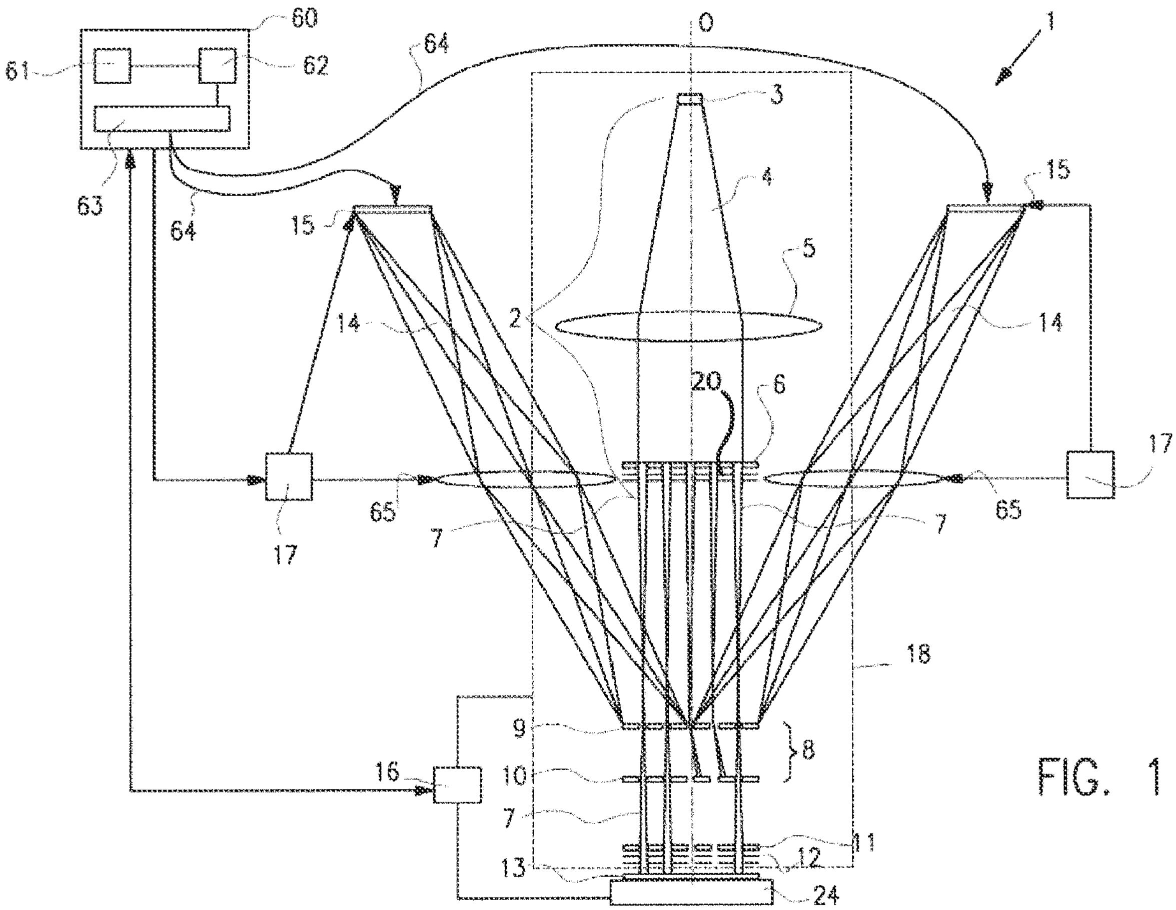
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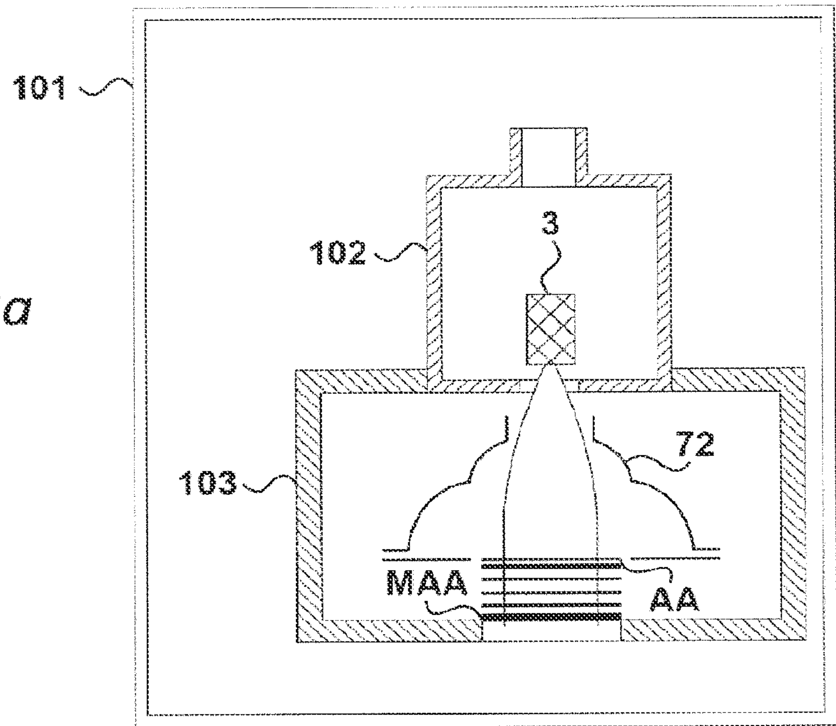
FIG. 1

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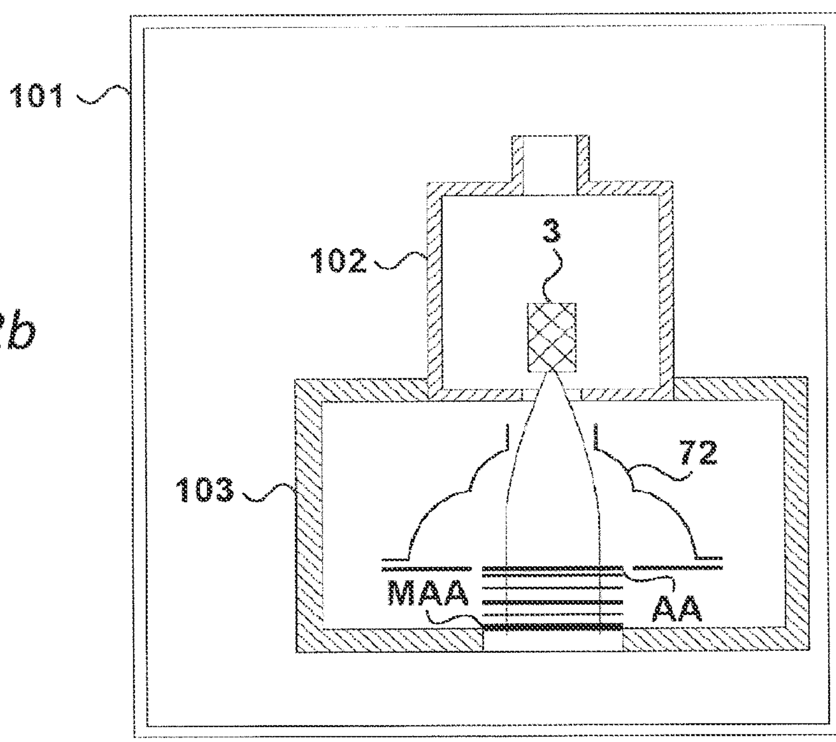


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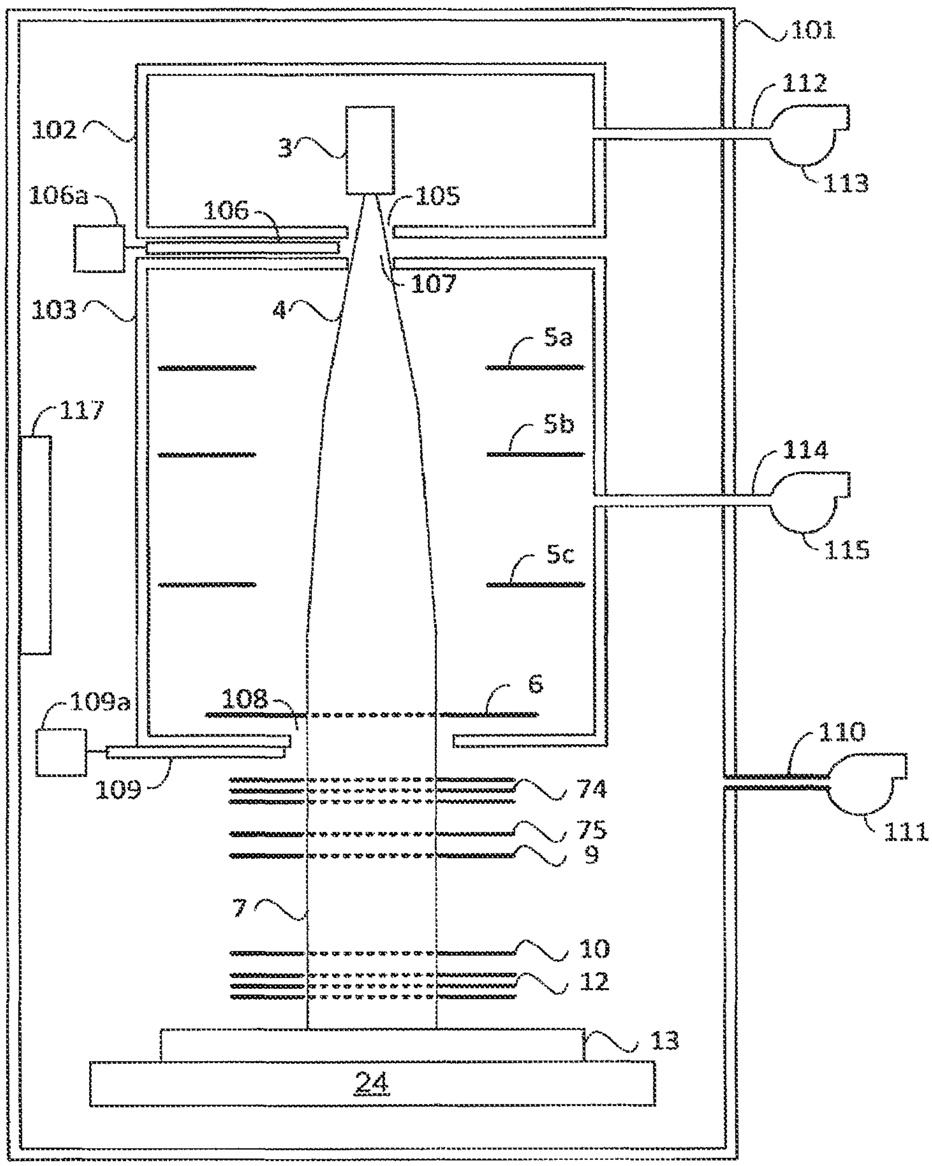
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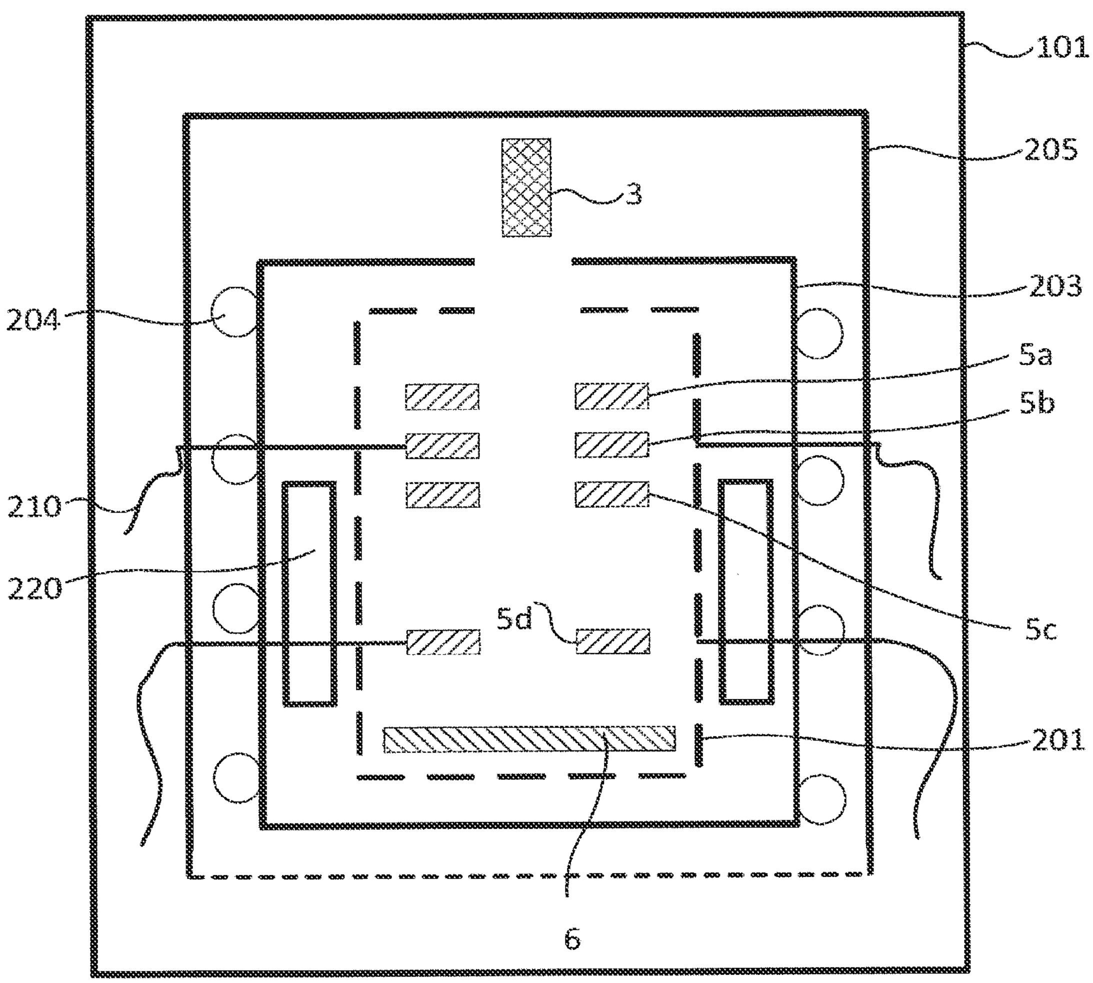
Fig. 3

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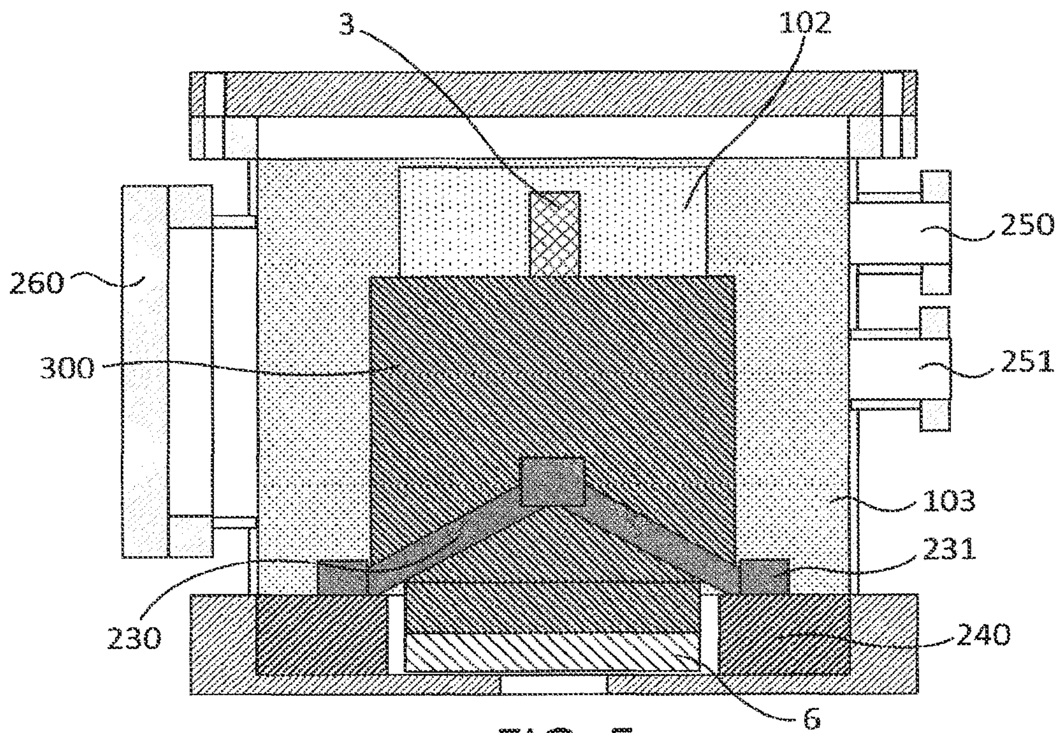
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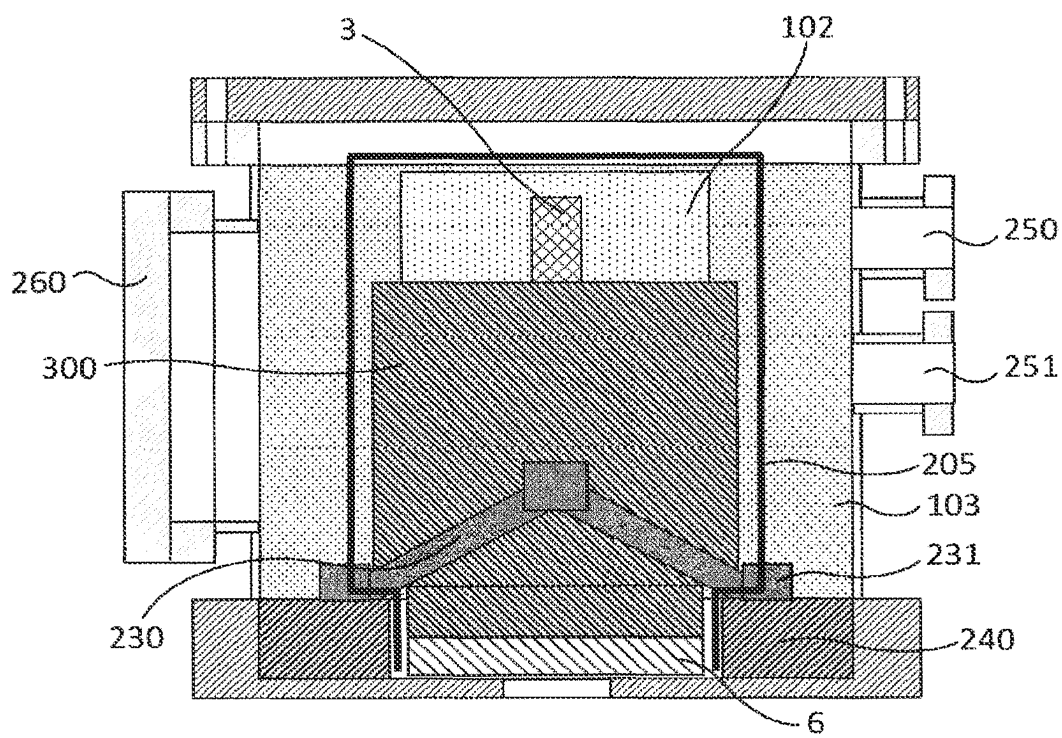
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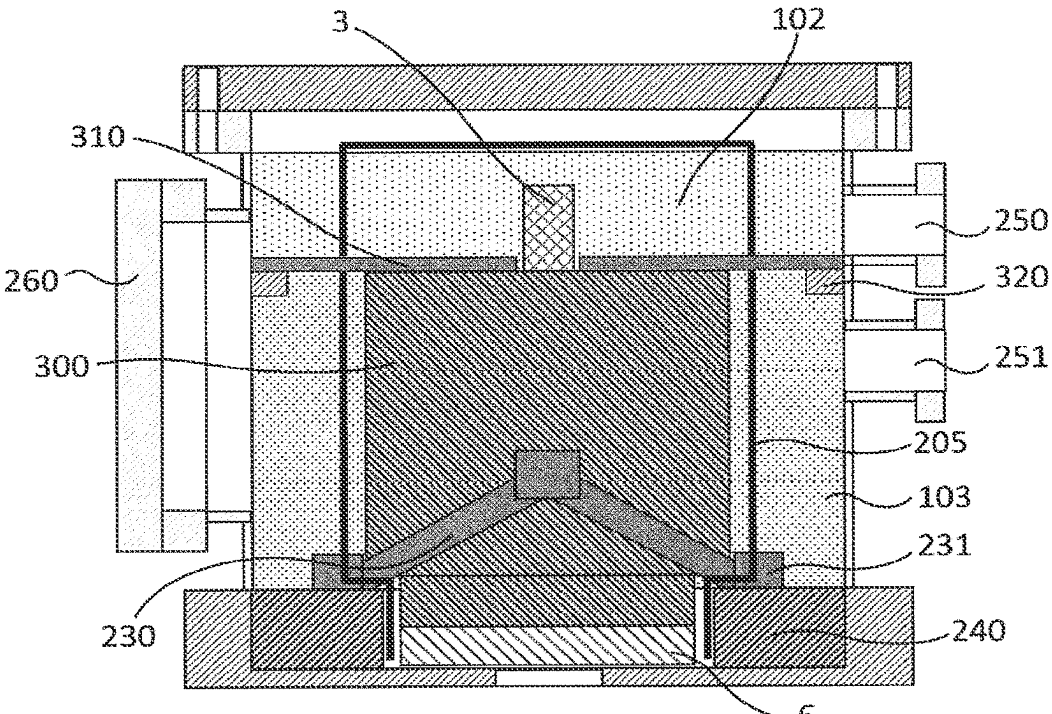
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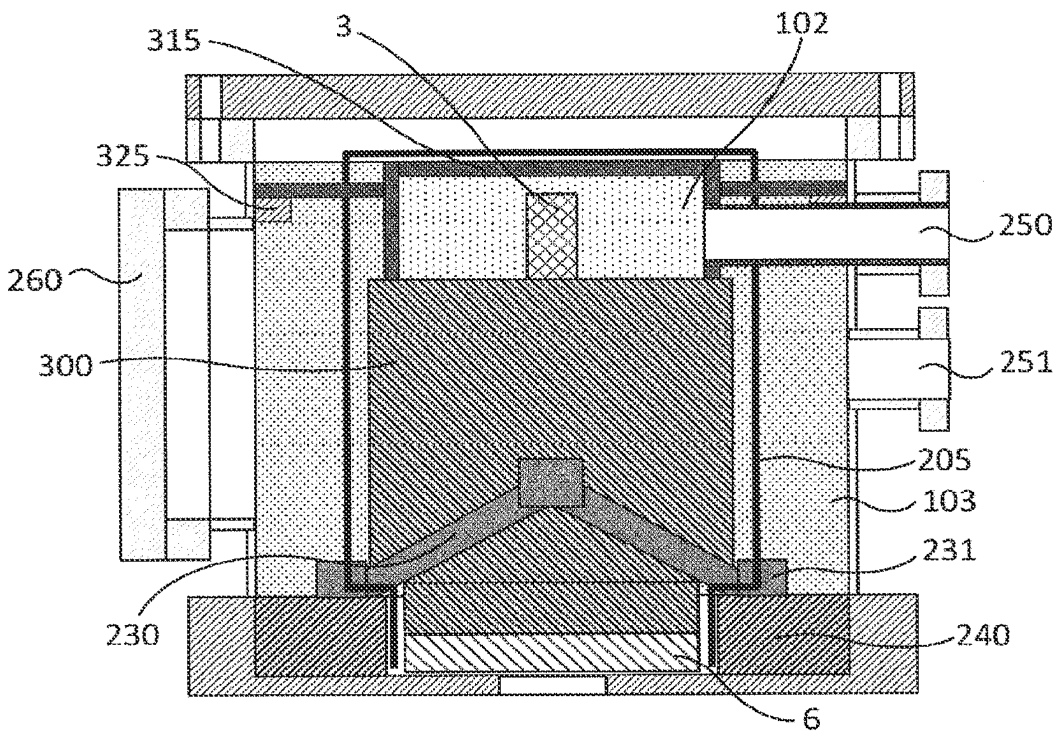
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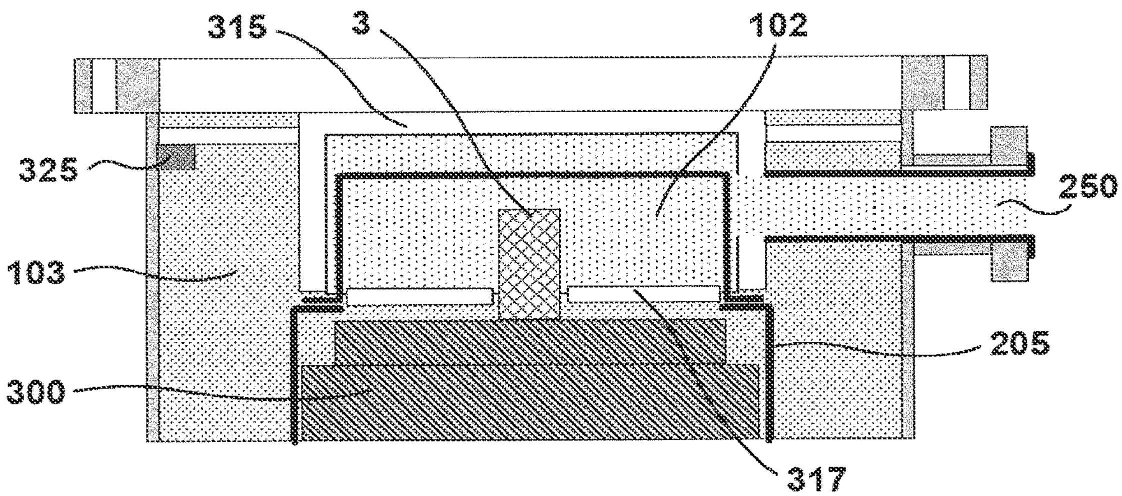


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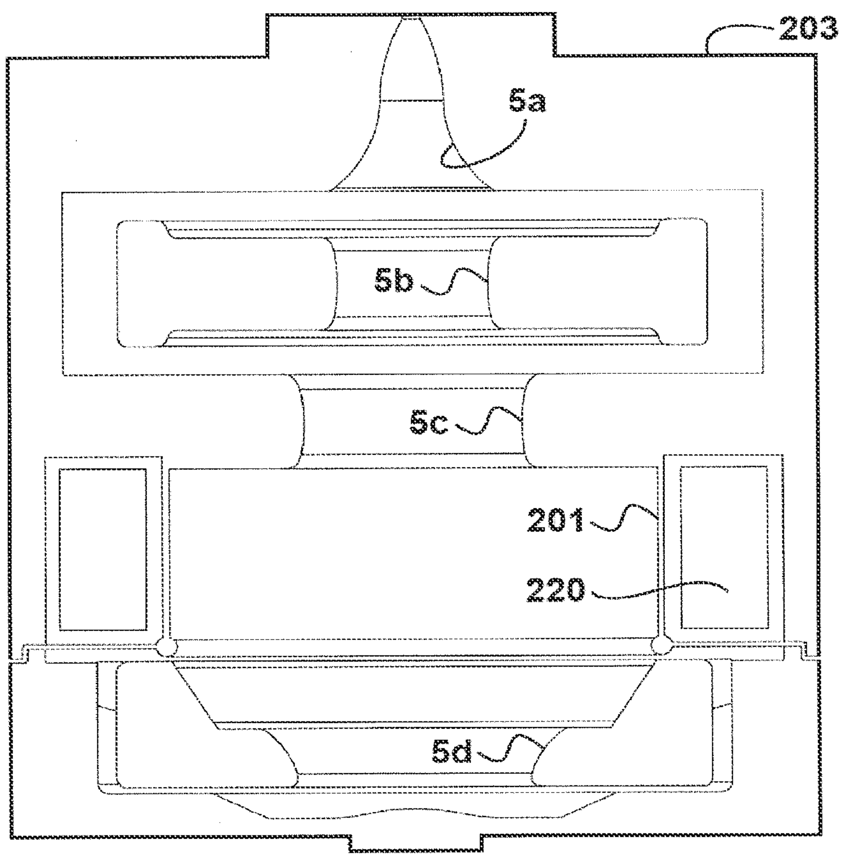


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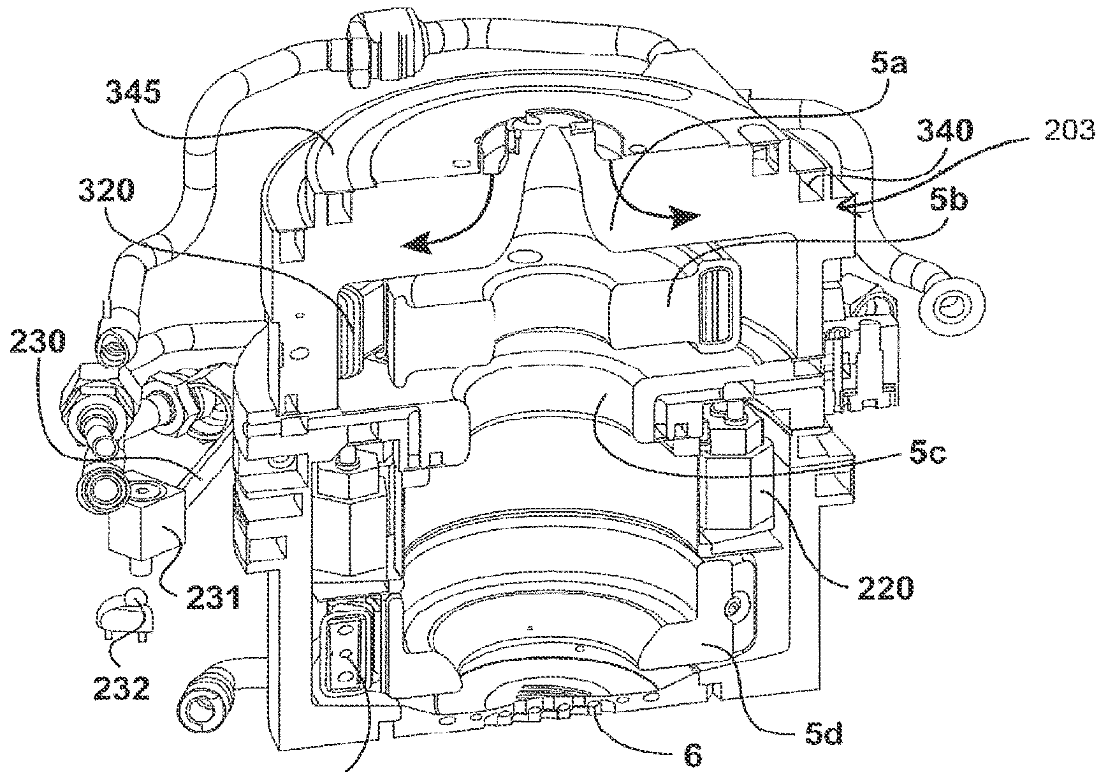


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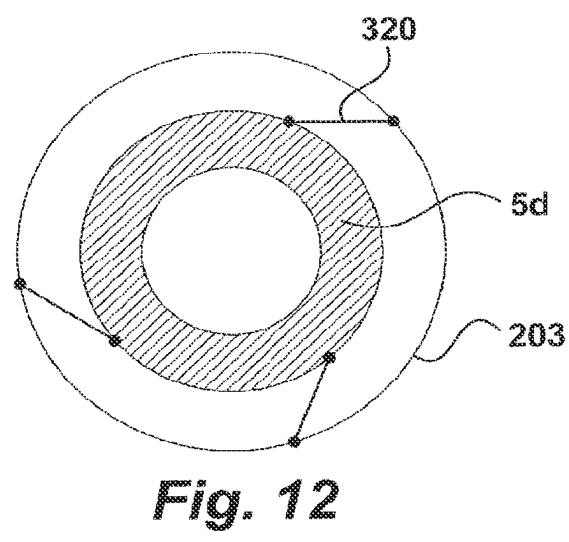
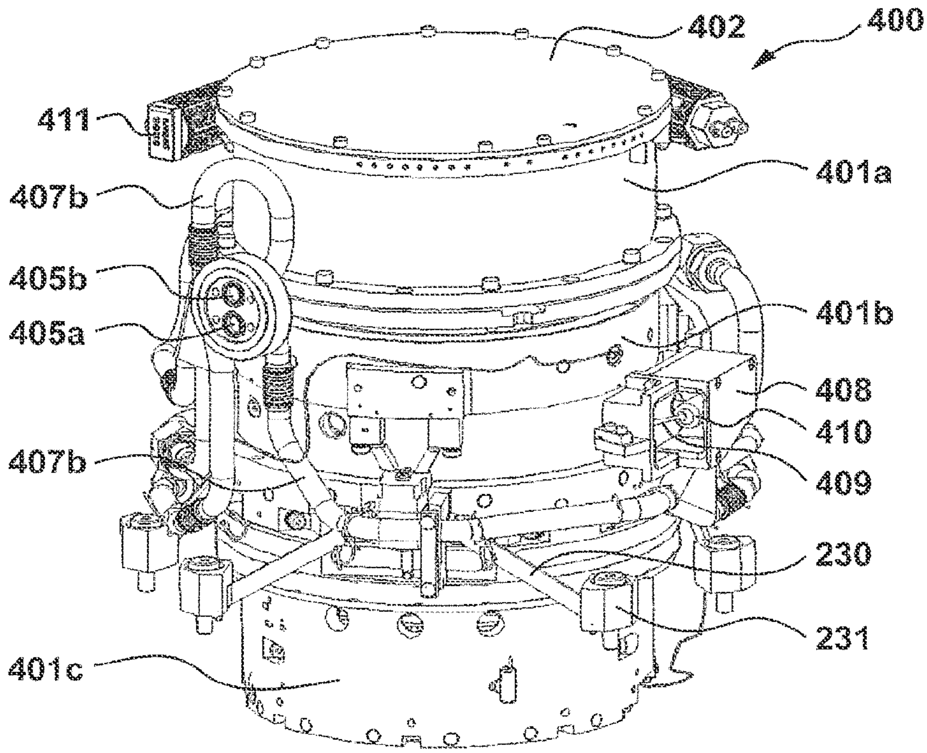



Fig. 12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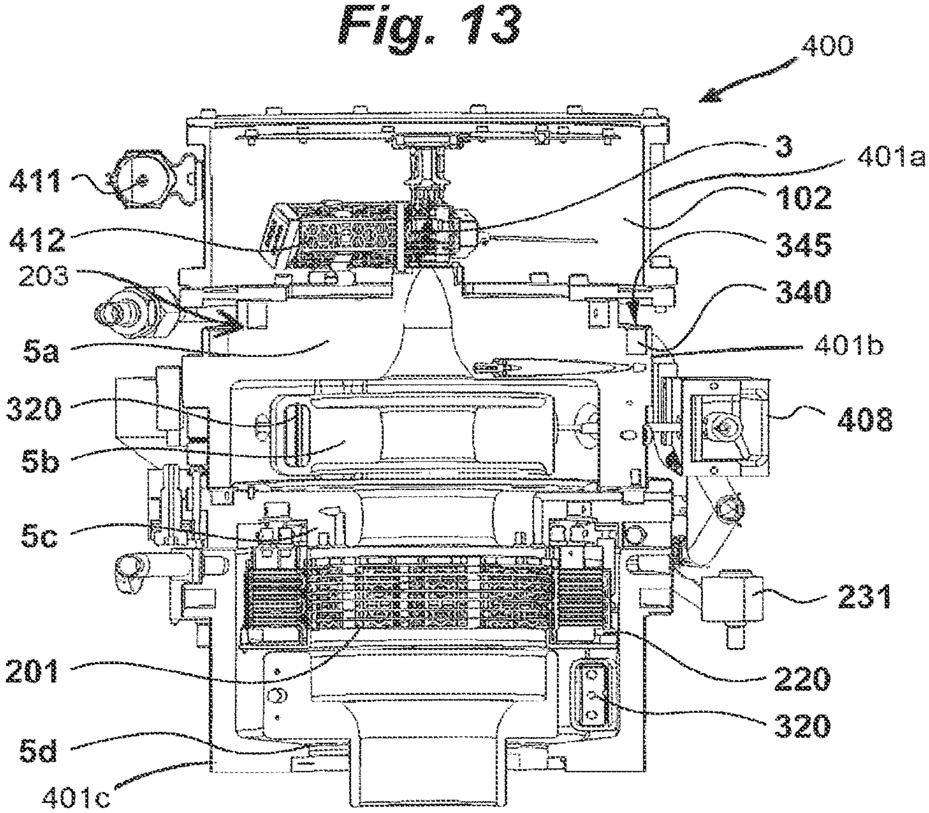
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Fig. 14

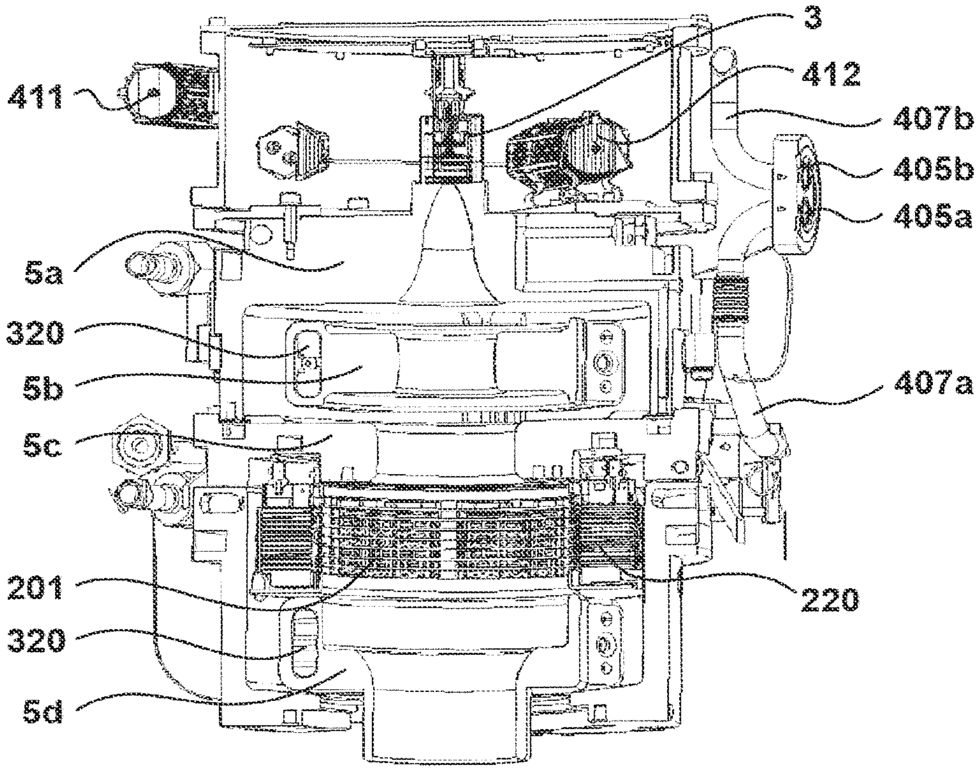



*Fig. 15*

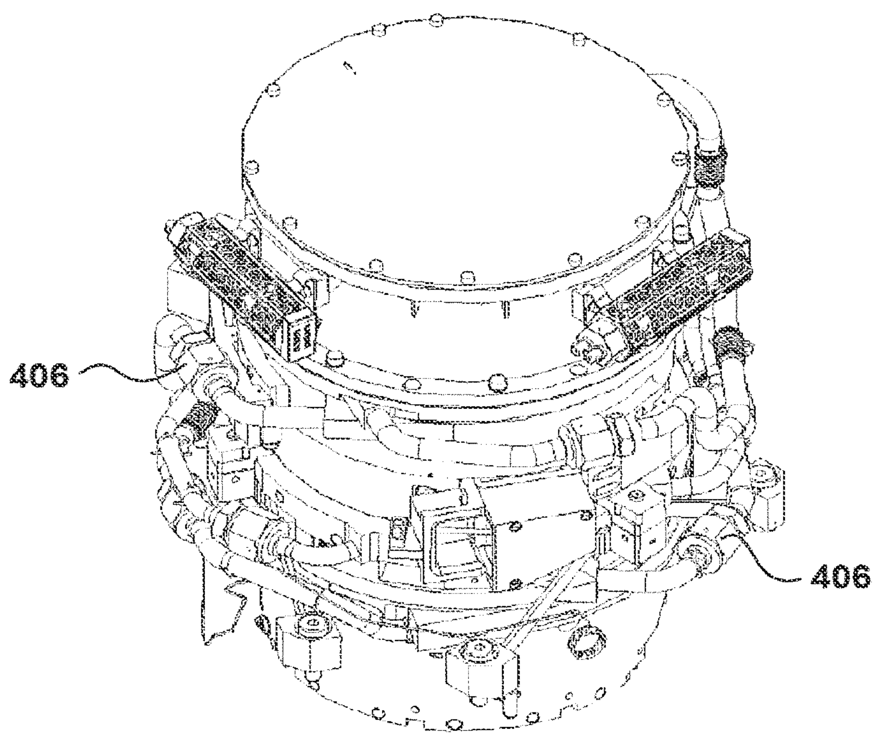
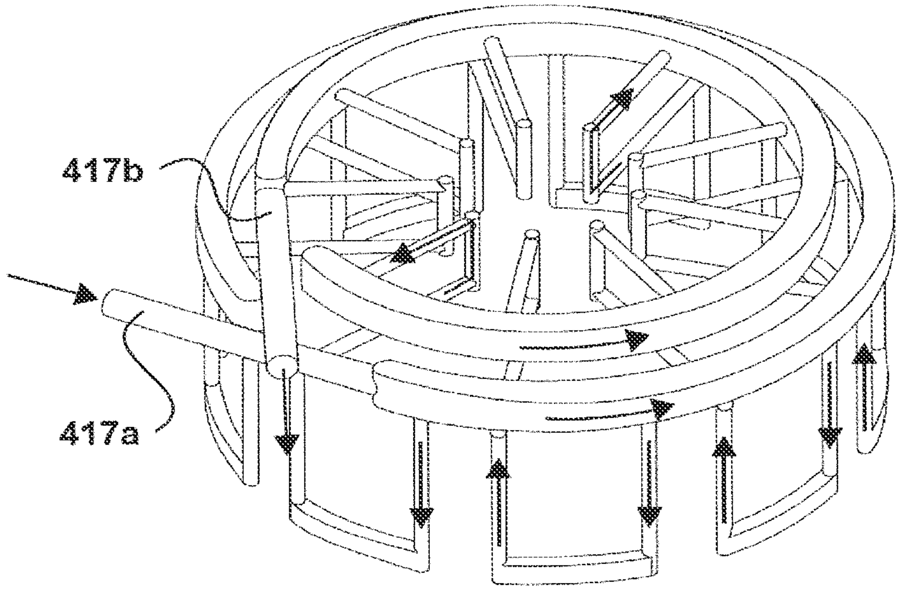



*Fig. 16*

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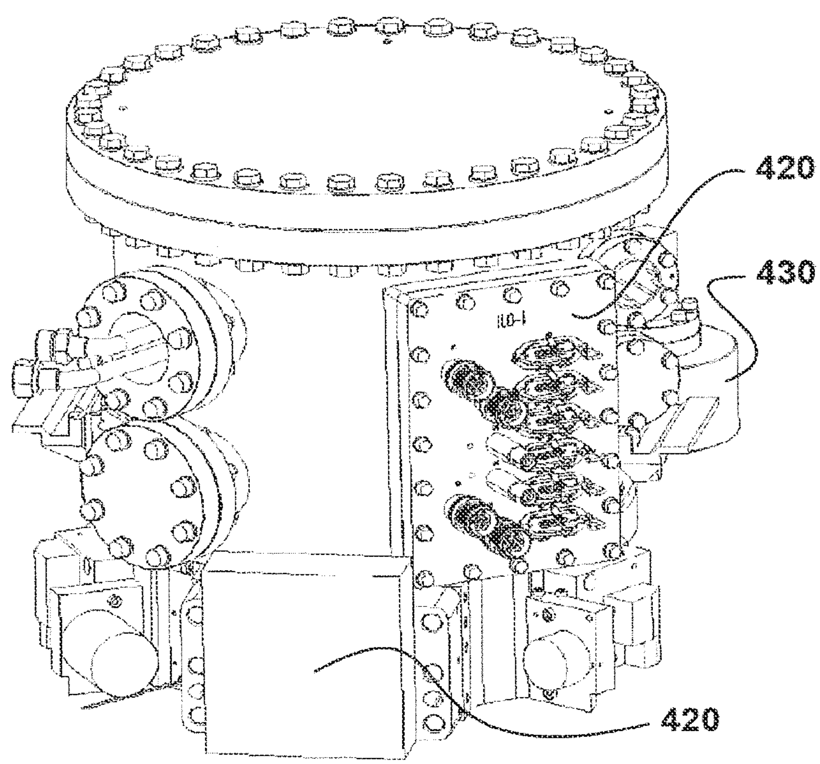


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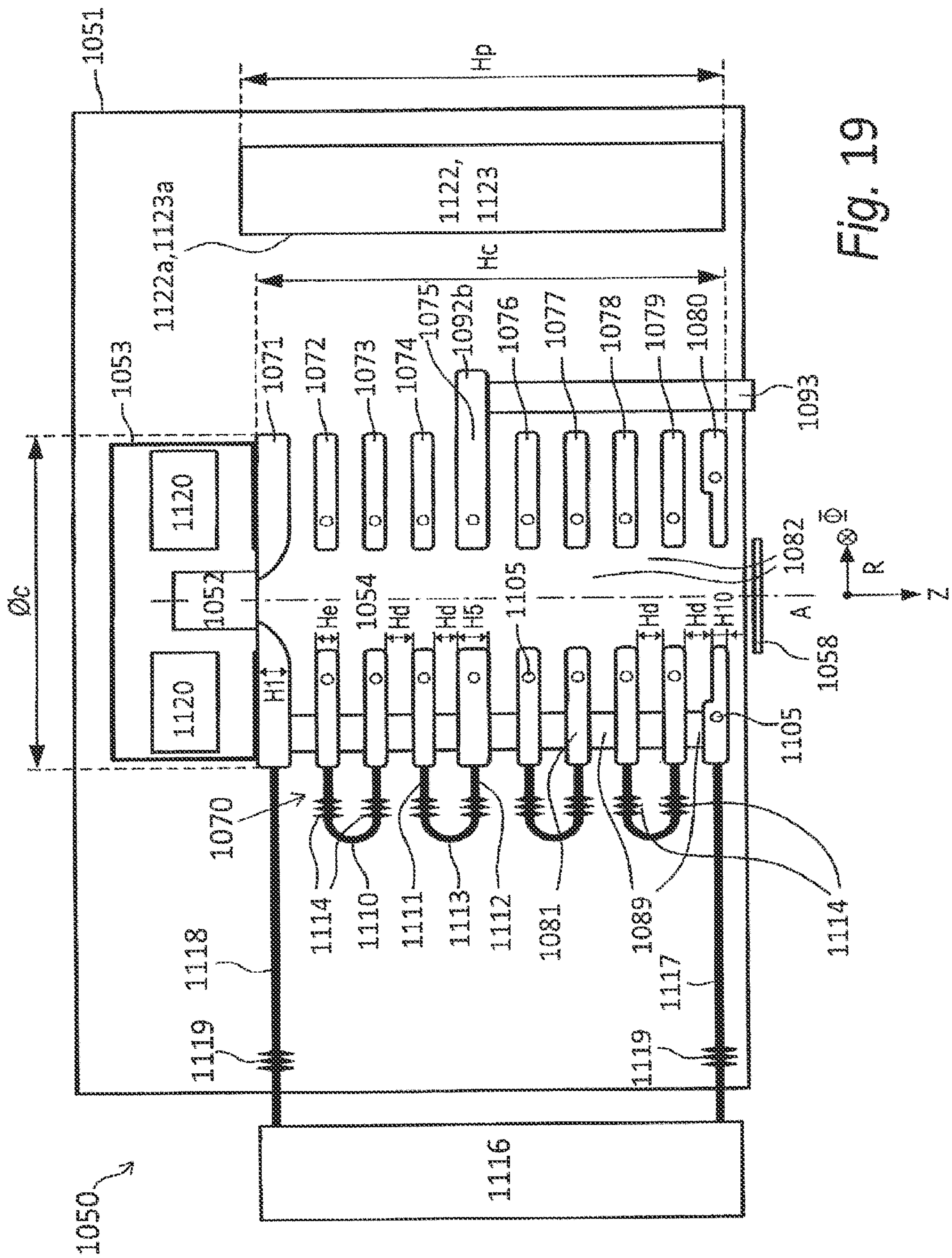

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Fig. 19

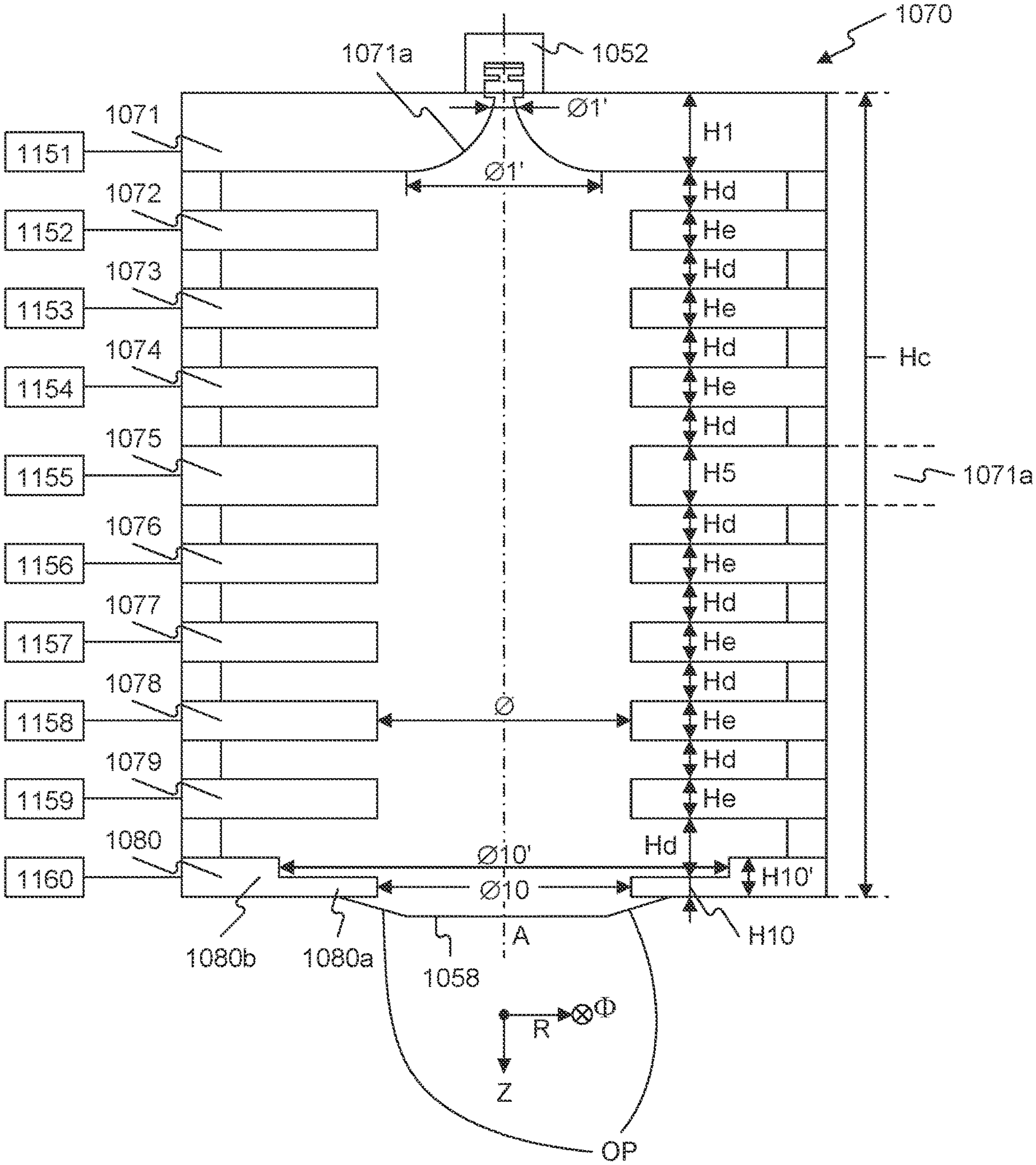
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FIG. 20

# ABERRATION CORRECTION IN CHARGED PARTICLE SYSTEM

This application is a continuation of U.S. Non-Provisional patent application Ser. No. 15/985,763, filed on May 22, 2018, which is a continuation in part of U.S. application Ser. No. 15/594,712 filed on 15 May 2017 (now U.S. Pat. No. 10,037,864), which is a continuation of U.S. application Ser. No. 14/400,569 filed on 12 Nov. 2014 (now U.S. Pat. No. 9,653,261), which is a national stage entry of PCT/EP2013/059963 filed on 14 May 2013, which claims priority to U.S. provisional application No. 61/646,839 filed on 14 May 2012. All these applications are hereby incorporated by reference in their entirety.

This application is a continuation of U.S. Non-Provisional patent application Ser. No. 15/985,763, filed on May 22, 2018, which is also a continuation in part of U.S. application Ser. No. 15/493,159 filed on 21 Apr. 2017, which is (i) a continuation in part of U.S. application Ser. No. 14/541,233 filed on 14 Nov. 2014, which claims priority to U.S. provisional application No. 61/904,057 filed on 14 Nov. 2013, and which is also (ii) a continuation in part of U.S. application Ser. No. 14/400,569 filed on 12 Nov. 2014, which is a national stage entry of PCT/EP2013/059963 filed on 14 May 2013, which claims 15 priority to U.S. provisional application No. 61/646,839 filed on 14 May 2012.

All the above related applications are hereby incorporated by reference in their entirety.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates to aberration correction on a charged particle beam in a charged particle systems.

### 2. Description of the Related Art

In the semiconductor industry, an ever increasing desire exists to manufacture smaller structures with high accuracy and reliability. Lithography is a critical part of such manufacturing process. Currently, most commercial lithography systems use a light beam and mask as a means to reproduce pattern data for exposing a target, such as a wafer with a coating of resist thereon. In a maskless lithography system, charged particle beamlets may be used to transfer a pattern onto such target. The beamlets may be individually controllable to obtain the desired pattern.

However, for such charged particle lithography systems to be commercially viable, they need to handle a certain minimum throughput, i.e. the number of wafer being processed per hour should not be too far below the number of wafers per hour that are currently processed with an optical lithography system. Furthermore, the charged particle lithography systems need to meet low error margins. The combination of a relatively high throughput in combination with the requirement to meet low error margins is challenging.

A higher throughput may be obtained by using more beamlets, and therefore more current. However, handling a greater number of beamlets results in the need for more control circuitry. Furthermore, an increase in the current results in more charged particles that interact with components in the lithography system. Both the circuitry and the impingement of charged particles onto components may cause heating of the respective components within the lithography system. Such heating may reduce the accuracy of the patterning process within the lithography system. In a worst case scenario, such heating may stop one or more components within the lithography system from functioning.



Furthermore, the use of a great number of beamlets increases the risk of unacceptable inaccuracy due to interaction between the beamlets, e.g. Coulomb interactions. Such risk may be reduced by shortening the path between source and target. The shortening may be achieved by using stronger electric fields along the charged particle path, which may be the result of applying higher voltages to certain electrodes in the charged particle lithography system. The use of high voltage induces the risk that components within the lithography system are accidentally charged, which would be a risk for the reliability of the system.

Finally, an increase in the current that would be caused by increasing the number of beamlets in the lithography system would increase the demands with respect to the pressure in the electron optical column.

## BRIEF SUMMARY OF THE INVENTION

It is an object of the invention to provide aberration correction to a charged particle beam in a charged particle system as described in this specification and defined in the claims.

It will be evident that the presently invented principle may be set into practice in various manners.

## BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of the invention will be further explained with reference to embodiments shown in the drawings wherein:

FIG. **1** is a simplified schematic drawing of an embodiment of a charged particle multi-beamlet lithography system;

FIGS. **2**A and **2**B are simplified diagrams showing certain components of a projection column in a main vacuum chamber.

FIG. **3** illustrates another embodiment of a charged particle lithography system with an intermediate vacuum chamber;

FIG. **4** schematically shows a charged particle beam generator;

FIG. **5** schematically shows an overview of the beam generator;

FIG. **6** shows the beam generator of FIG. **5** with a magnetic shielding arrangement provided therein;

FIG. **7** shows the beam generator of FIG. **6** with vacuum chamber separation;

FIG. **8** shows the beam generator of FIG. **6** with another way of vacuum chamber separation;

FIG. **9** shows a basic layout of a source chamber and a collimator together with a magnetic shielding arrangement;

FIG. **10** shows a cross-sectional view of an embodiment of a collimator system;

FIG. **11** shows an elevated cross-sectional view of the collimator of FIG. **10**;

FIG. **12** shows a cross-sectional top view of a possible connection between spring elements and a cavity within a cooling arrangement;

FIG. **13** shows an elevated side view of a beam generator according to an embodiment of the invention;

FIG. **14** shows a first cross-sectional side view of the beam generator of FIG. **13**;

FIG. **15** shows a second cross-sectional side view of the beam generator of FIG. **13**;

FIG. **16** shows another elevated side view of the beam generator of FIG. **13**;

FIG. **17** shows an elevated side view of an arrangement of channels used to cool a portion of the collimator system in the beam generator of FIG. **13**; and

FIG. **18** shows yet another elevated side view of the beam generator of FIG. **13**. FIG. **19** shows a schematic cross-sectional view of a beam generator module **1050** according to an exemplary embodiment. FIG. **20** shows a schematic cross-sectional side view of a collimator electrode stack **1070** according to an exemplary embodiment.

## DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The following is a description of various embodiments of the invention, given by way of example only and with reference to the drawings.

FIG. **1** shows a simplified schematic drawing of an embodiment of a charged particle lithography apparatus **1**. Such lithography systems are described for example in U.S. Pat. Nos. 6,897,458, 6,958,804, 7,019,908, 7,084,414 and 7,129,502, U.S. patent application publication no. 2007/0064213, and co-pending U.S. patent applications Ser. Nos. 61/031,573 and 61/031,594 and 61/045,243 and 61/055,839 and 61/058,596 and 61/101,682, which are all assigned to the owner of the present invention and are all hereby incorporated by reference in their entirety.

In the embodiment shown in FIG. **1**, the lithography apparatus **1** comprises a beamlet generator **2** for generating a plurality of beamlets, a beamlet modulator **8** for patterning the beamlets to form modulated beamlets, and a beamlet projector for projecting the modulated beamlets onto a surface of a target **13**. The beamlet generator **2** typically comprises a source **3** for producing a charged particle beam **4**. In FIG. **1**, the source **3** produces a substantially homogeneous, expanding charged particle beam **4**. Hereafter, embodiments of the invention will be discussed with reference to an electron beam lithography system. Therefore, source **3** may be referred to as electron source **3** and beam **4** may be referred to as electron beam **4**. It must be understood that a similar system as depicted in FIG. **1** may be used with a different type of radiation, for example by using an ion source for producing an ion beam.

In the embodiment shown in FIG. **1**, the beamlet generator **2** further comprises a collimator lens **5** for collimating the electron beam **4** produced by the electron source **3**, and an aperture array **6** for forming a plurality of beamlets **7**. The collimator lens **5** may be any type of collimating optical system. Before collimation, the electron beam **4** may pass a double octopole (not shown). Preferably, the aperture array **6** comprises a plate provided with a plurality of through holes. The aperture array **6** blocks part of the electron beam **4**, whereas a portion of the electron beam **4** passes the aperture array **6** through the holes so as to produce the plurality of electron beamlets **7**. The system generates a large number of beamlets, preferably about 10,000 to 1,000,000 beamlets.

The beamlet modulator or modulation system **8** in the embodiment of FIG. **1** comprises a beamlet blanker array **9** and a beamlet stop array **10**. The beamlet blanker array **9** comprises a plurality of blankers for deflecting one or more of the electron beamlets **7**. The deflected and undeflected electron beamlets **7** arrive at beam stop array **10**, which has a plurality of apertures. The beamlet blanker array **9** and beam stop array **10** operate together to block or let pass the beamlets **7**. Generally, if beamlet blanker array **9** deflects a beamlet **7**, it will not pass through the corresponding aperture in beam stop array **10**, but instead will be blocked. However, if beamlet blanker array **9** does not deflect a beamlet **7**, then it will pass through the corresponding aperture in beam stop array **10**. Alternatively, beamlets **7** may pass the beamlet stop array **10** upon deflection by corresponding blankers in the beamlet blanker array **9** and be blocked by the beamlet stop array **10** if they are not deflected. To focus the beamlets **7** within the plane of the blanker array **9** the lithography system **1** may further comprise a condenser lens array **20**.

The beamlet modulator **8** is arranged to provide a pattern to the beamlets **7** on the basis of pattern data input provided by a control unit **60**. The control unit **60** comprises a data storage unit **61**, a read out unit **62** and a data conversion unit **63**. The control unit **60** may be located remotely from the rest of the system, for example outside the clean room. The pattern data may be transferred via optical fibers **64**. The light transmitting ends of the optical fibers **64** may be assembled in one or more fiber arrays **15**. The pattern data carrying light beams **14** are then projected onto corresponding light receiving elements, such as photodiodes, provided on the beamlet blanker array **9**. Such projection may be done directly, or via projection system, in FIG. **1** schematically represented by projection lenses **65**. One or more elements in such projections system, such as projection lenses **65**, may be moveable under control of the control unit **60** via a positioning device **17** to enable proper alignment and/or focusing of the data carrying light beams **14** onto the corresponding light sensitive elements in the beamlet blanker array **9**.

The light sensitive elements are coupled to one or more blankers and are arranged to convert the light signal into a different type of signal, for example an electric signal. A pattern data carrying light beam **14** may carry data for one or more blankers within the beamlet blanker array **9**. The pattern data is thus sent via the pattern data carrying light beams towards the blankers to enable the blankers to modulate the charged particle beamlets **7** passing there through in accordance with a pattern.

The modulated beamlets coming out of the beamlet modulator **8** are projected onto a target surface of a target **13** by the beamlet projector. The beamlet projector comprises a beamlet deflector array **11** for scanning the modulated beamlets over the target surface and a projection lens arrangement **12** comprising one or more arrays of projection lenses for focusing the modulated beamlets onto the target surface. The target **13** is generally positioned on a moveable stage **24**, which movement may be controlled by a control unit such as control unit **60**.

For lithography applications, the target usually comprises a wafer provided with a charged-particle sensitive layer or resist layer. Portions of the resist film will be chemically modified by irradiation of the beamlets of charged particles, i.e. electrons. As a result thereof, the irradiated portion of the film will be more or less soluble in a developer, resulting in a resist pattern on a wafer. The resist pattern on the wafer can subsequently be transferred to an underlying layer, i.e. by implementation, etching and/or deposition steps as known in the art of semiconductor manufacturing. Evidently, if the irradiation is not uniform, the resist may not be developed in a uniform manner, leading to mistakes in the pattern. High-quality projection is therefore relevant to obtain a lithography system that provides a reproducible result.

The deflector array **11** and the projection lens arrangement **12** may be integrated into a single end module. Such end module is preferably constructed as an insertable, replaceable unit. The insertable, replaceable unit may also include the beamlet stop array **10**.

The deflector array **11** may take the form of a scanning deflector array arranged to deflect each beamlet **7** that passes through the beamlet stop array **10**. The deflector array **11** may comprise a plurality of electrostatic deflectors enabling the application of relatively small driving voltages. Although the deflector array **11** is drawn upstream of the projection lens arrangement **12**, the deflector array **11** may also be positioned between the projection lens arrangement **12** and the target surface **13**.

The projection lens arrangement **12** may thus be arranged to focus the beamlets **7** before or after deflection by the deflector array **11**. Preferably, the focusing results a geometric spot size of about 10 to 30 nanometers in diameter. In such preferred embodiment, the projection lens arrangement **12** is preferably arranged to provide a demagnification of about 100 to 500 times, most preferably as large as possible, e.g. in the range 300 to 500 times. In this preferred embodiment, the projection lens arrangement **12** may be advantageously located close to the target surface **13**.

The charged particle lithography apparatus **1** operates in a vacuum environment. A vacuum is desired to remove particles which may be ionized by the charged particle beams and become attracted to the source, may dissociate and be deposited onto the machine components, and may disperse the charged particle beams. A vacuum of at least $10^{-6}$ bar is typically required. Preferably, all of the major elements of the lithography apparatus **1** are housed in a common vacuum chamber, including the beamlet generator **2** including the charged particle source **3**, the beamlet modulator **8**, the beamlet projector system, and the moveable stage **24**. These major elements are also referred to as the electron-optical column, or simply as the column, and is schematically represented by the dashed box **18** in FIG. **1**.

In an embodiment the charged particle source environment is differentially pumped to a considerably higher vacuum of up to 10'10 mbar. In such embodiment, the source **3** may be located in a separate chamber, i.e. a source chamber. Pumping down the pressure level in the source chamber may be performed in the following way. First, the vacuum chamber and the source chamber are pumped down to the level of the vacuum chamber. Then the source chamber is additionally pumped to a desired lower pressure, preferably by means of a chemical getter in a manner known by a skilled person. By using a regenerative, chemical and so-called passive pump like a getter, the pressure level within the source chamber can be brought to a lower level than the pressure level in the vacuum chamber without the need of a 5 vacuum turbo pump for this purpose. The use of a getter avoids the interior or immediate outside vicinity of the vacuum chamber being submitted to acoustical and/or mechanical vibrations as would be the case if a vacuum turbo pump or similar would be used for such a purpose.

FIGS. **2**A and **2**B are simplified diagrams showing certain components of a projection column in a main vacuum chamber. FIG. **2**A indicates a preferred operating vacuum pressure in the system with the main chamber at about $2\times10^{-6}$ mbar, the intermediate chamber at about $4\times10^{-9}$ mbar, and the source chamber at about $10^{-9}$ mbar. FIG. **2**B shows a calculation of typical resulting partial pressure of hydrocarbon contaminants in the system, with hydrocarbon partial pressure in the main chamber of about $7\times10^{-8}$ mbar, in the intermediate chamber about $10^{-10}$ mbar, and in the source chamber about $10^{-11}$ mbar.

In the embodiment shown in FIGS. **2**A and **2**B the source **3** is located in a separate source chamber **102**, and in this embodiment the collimator **72** and aperture array elements from the first aperture array element (AA) to the multi-aperture array (MAA) are located in an intermediate chamber **103**. An alternative embodiment also includes the beamlet blanker array element in the intermediate chamber **103**, so that the much smaller apertures of the blanker array element form the opening between the intermediate chamber and the main chamber. In another embodiment the first aperture array element (AA) forms the opening between the intermediate chamber and the main chamber, with the remaining aperture array elements located in the main chamber.

FIG. **3** illustrates another embodiment of a charged particle lithography system with an intermediate vacuum chamber. The lithography system is enclosed in a main vacuum chamber **101**. The lithography system operates in a vacuum environment. A vacuum is desired to remove particles which may be ionized by the charged particle beams and become attracted to the source, may dissociate and be deposited onto the lithography system's components, and may disperse the charged particle beams. A vacuum of about $2\times10^{-6}$ mbar is preferred. In order to maintain the vacuum environment, the charged particle lithography system is located in a main vacuum chamber **101**. Note that FIG. **3** is a simplified diagram and many components of the lithography system are not shown that are normally located in the main vacuum chamber, e.g. the short stroke and long stroke wafer stages etc.

The charged particle source **3** is located in a source vacuum chamber **102** which is in turn located in the main vacuum chamber **101**. This enables the environment in the source chamber **102** to be differentially pumped to a considerably higher vacuum than the main chamber **101**, e.g. up to 10'10 mbar. Although only a single source **3** is shown in FIG. **3**, the source chamber **102** may accommodate more than one source. The high vacuum within the source chamber **102** may promote the life time of the source **3**, reduces the effects of gases in the source chamber interfering with the charged particle beam, and for some types of source may even be required for their functioning. The source is typically an electron source. A thermal dispenser type source may be used.

The high vacuum in the source chamber results in fewer free molecules circulating within the source chamber. Limiting free molecules in the source chamber limits contaminants from the main chamber such as water vapor and hydrocarbons outgassed from the resist-coated wafer being exposed can be limited, and reduces electron beam induced deposition (EBID) onto components in the source chamber.

The system of FIG. **3** also includes an intermediate chamber **103** located in the main chamber **101**. In this embodiment, the intermediate chamber houses the collimating system (which may be e.g. a single collimator electrode or one or more collimator lenses **5**_a_, **5**_b_, **5**_c_ as depicted in FIG. **3**) and first aperture array element **6**. Additional aperture array elements may be included in the intermediate chamber, such as in the embodiment shown in FIG. **2**A.

The source and intermediate chambers may be constructed as a single vacuum chamber with a wall dividing the chamber into a top section for the source and bottom section comprising the intermediate chamber. Typical dimensions for the distance from the source **3** to the first aperture array **6** is about 300 mm.

The environment in the intermediate chamber **103** is differentially pumped to an intermediate pressure, between the vacuum level of the main chamber and the source chamber. For example, the system may be operated with the main chamber at about $2\times10^{-6}$ mbar, the intermediate chamber at about $4\times10^{-9}$ mbar, and the source chamber at about $10^{-9}$ mbar. Similarly to the source chamber, this high vacuum results in fewer free molecules circulating within the intermediate chamber, limiting contaminants from the main chamber such as water vapor and outgassed hydrocarbons, and reducing EBID on the components in the intermediate chamber.

The source chamber **102** is provided with an opening **105** in the wall of the source chamber **102** to permit transmission of the charged particle beam **4** into the intermediate chamber **103** and main chamber **101**. The source chamber may be provided with a valve **106** for closing the opening **105** if needed, that is if the pressure level within the source chamber needs to be maintained at a much lower pressure level than the pressure level in the vacuum chamber. For example, the valve **106** may be closed if the vacuum chamber is opened, for example for servicing purposes. In such a case a high vacuum level is maintained within the source chamber, which may improve downtime of the lithography apparatus. Instead of waiting until the pressure level within the source chamber is sufficient, now only the vacuum **10** chamber needs to be pumped down to a desired pressure level, which level is higher than the level needed in the source chamber. The valve **106** is controlled by an actuation unit **106*a*** that may comprise a piezo-electric actuator, for example Physikinstrumente model N-214 or N-215 NEXLINE®.

The opening **105** in the source chamber **102** to permit transmission of the charged particle beam **4** needs to be relatively large to emit a large beam. The size of this opening amounts to a substantial fraction of the round beam needed for a 26 mm×26 mm lithography system column, and this large opening is too large to maintain the large pressure drop from the main chamber **101** to the source chamber **102**, i.e. a pressure differential from $10^{-9}$ mbar in the source chamber to $2\times10^{-6}$ mbar in the main chamber. The intermediate vacuum chamber **103** creates an intermediate pressure environment which enables this large pressure differential to be maintained.

The intermediate chamber has an opening **107** corresponding to the source chamber opening **105**, for admitting the charged particle beam, and an opening **108** between the intermediate chamber and the main chamber permitting transmission of the charged particle beamlets into the main chamber. A valve **109** may be provided for closing the opening **108** if needed, e.g. if the main vacuum chamber is opened for servicing purposes. A high vacuum level can be maintained within the intermediate (and source) chamber, which may improve downtime of the lithography apparatus by reducing pump down time because only the main vacuum chamber needs to be pumped down to the desired pressure level, which is higher than 30 the level needed in the intermediate and source chambers. The valve **109** is controlled by an actuation unit **109*a*** that may comprise a piezo-electric actuator.

The intermediate chamber **103** may be constructed so that the opening **108** between the intermediate chamber and the main chamber is formed by the first aperture array element. This can be achieved by forming a portion of the wall of the intermediate chamber to fit closely with the first aperture array element **6**. For example, a recess may be formed in the intermediate chamber wall to accommodate the outer edge of the first aperture array. In this way, the size of the opening **108** is greatly reduced, the area of the opening comprising the plurality of very small apertures of the first aperture array. This greatly reduced size of the opening **108** permits a much larger differential pressure to be maintained between the intermediate chamber **102** and the main chamber **101**.

The lithography system is preferably designed in a modular fashion to permit ease of maintenance. Major subsystems are preferably constructed in self-contained and removable modules, so that they can be removed from the lithography machine with as little disturbance to other subsystems as possible. This is particularly advantageous for a lithography machine enclosed in a vacuum chamber, where access to the machine is limited. Thus, a faulty subsystem can be removed and replaced quickly, without unnecessarily disconnecting or disturbing other systems. In the embodiment shown in FIG. **3**, these modular subsystems may include a beam switching module including condenser lens arrays **74**, multi-aperture array **75**, beamlet blanker array **9**, and a projection optics module including beam stop array **10** and projection lens arrays **12**. The modules are designed to slide in and out from an alignment frame. Each module requires a large number of electrical signals and/or optical signals, and electrical power for its operation. The modules inside the vacuum chamber receive these signals from control systems which are typically located outside of the chamber. The vacuum chamber includes openings or ports for admitting cables carrying the signals from the control systems into the vacuum housing while maintaining a vacuum seal around the cables. Each module preferably has its collection of electrical, optical, and/or power cabling connections routed through one or more ports dedicated to that module. This enables the cables for a particular module to be disconnected, removed, and replaced without disturbing cables for any of the other modules.

The main vacuum chamber **101** is provided with an outlet and vacuum pumping system **111**. The source chamber **102** may be provided with its own outlet **112** and pump **113**, and intermediate chamber **103** may also be provided with an outlet **114** and pump **115**. The pumps **113** and **115** are shown schematically exhausting externally of the main chamber. This may result in vibrations being fed through to the lithography system. Given the level of the vacuum in chambers **102** and **103**, a chemical or getter pump may be used for catching molecules in these chambers without exhausting outside the main chamber. A cryogenic pump may also be used for these chambers, but may be precluded due to the small size of the chambers.

Pumping down the pressure level in the system may be performed in the following way. First, the main chamber **101** and intermediate chamber **103** and source chamber **102** are pumped down to the level of the main chamber **101**. This may be accomplished completely or primarily by the pumping system **111** of the main vacuum chamber **101**. The pumping system **111** may have one of more dedicated vacuum pumps for the main chamber, or one or more vacuum pumps may be shared between several main vacuum chambers for several separate lithography systems. Each main chamber may have a small vacuum pump, and share a larger vacuum pump. The ability to use more than one pump to realize a vacuum in the main vacuum chamber creates a vacuum pump redundancy that may improve the reliability of vacuum operation. If a vacuum pump malfunctions, another vacuum pump can take over its function.

The vacuum in the main vacuum chamber can be generated by turbo vacuum pumps, and a cryopump system may also be used. A water vapor cryopump, for example in the form of one or more cryopump shields **117**, may be included in the main vacuum chamber **101** to capture water vapor in the main chamber to assist in forming the vacuum in the main chamber. This reduces the size of the vacuum pumps needed to produce an adequate vacuum and reduces pump down time, and uses no moving parts so that it does not introduce vibrations typically caused by other types of low temperature (<4K) systems. Preferably, the vacuum pump(s) are activated first followed by activation of the cryopump system. Activation of the vacuum pump system prior to the cryopump system may lead to a more efficient vacuum pumping procedure, and to further enhance efficiency, the vacuum pump(s) may be isolated from the main vacuum chamber after a certain period, e.g. the time needed to obtain a pressure value below a certain predetermined threshold value. After isolation of the vacuum pump(s), the cryopump system may continue to operate to complete generation of the vacuum.

Then the intermediate chamber and source chamber are additionally pumped to a desired lower pressure, preferably by means of a chemical getter in a manner known by a skilled person. By using a regenerative, chemical and so-called passive pump like a getter, the pressure level within the intermediate chamber and source chamber can be brought to lower levels than the pressure level in the main chamber without the need of a vacuum turbo pump. The use of a getter avoids the interior or immediate outside vicinity of the vacuum chamber being submitted to acoustical and/or mechanical vibrations as would be the case if a vacuum turbo pump would be used for this a purpose.

The main chamber is initially pumped down by pumping away the air inside the chamber. The pump down continues by catching as many as possible of the molecules left in the chamber using the cryopump shield or similar methods. This results in "catching" molecules circulating in the main chamber and preventing these molecules from entering the intermediate chamber and the source chamber. By using the apertures of one of the aperture arrays to form the opening between the main chamber and the intermediate chamber, thereby reducing the size of the opening, the chance of the (relatively many more) molecules in the main chamber from entering in the intermediate chamber is also reduced. In the same way the opening between source and intermediate chamber limits the chance of the further reduced amount of molecules from entering the source chamber. The use of an aperture array to separate the main chamber and the intermediate chamber permits a higher pressure differential between the chambers and reduces contaminant molecules moving from the main chamber into the intermediate chamber, and onwards to the source chamber.

The main chamber is much larger than the intermediate and source chambers, and contains many components that be a source of outgas sing hydrocarbons, water and other contaminant molecules. The most intensive source of outgassing of hydrocarbons is from the resist-coated wafer exposed by the lithography system. These hydrocarbons interact with the charged particles and form EBID (electron beam induced deposition) deposits. The dominant growth of contamination is typically on the apertures, the contamination grown by an EBID process. The current density on the electrodes is much lower than on the apertures.

The intermediate chamber assists by limiting aperture deterioration due to contaminants and EBID growth, especially at the edges of apertures. Although the contamination problem, i.e. EBID growth in the apertures causing reduced aperture diameter, is more severe at the beam stop (which is closer to the source of the hydrocarbon outgassing) than at the aperture arrays, the effect of hydrocarbon partial pressure and EBID growth is also noticeable on the aperture array located further form the wafer, and may necessitate cleaning of the apertures. By having the opening **108** between the intermediate chamber **103** and the main chamber **101** formed by the apertures of one of the aperture array elements, a large pressure differential can be maintained between the source and intermediate chambers and 30 the main chamber. Furthermore, the hydrocarbon partial pressure in the intermediate chamber is reduced very significantly to a very low level, and in the source chamber to an even lower level, as indicated in FIG. **2**B. This lower hydrocarbon partial pressure greatly reduces EBID growth on the aperture arrays and other components located in these chambers.

The idea of the present invention is to combine the two aspects into one design, such that each of the two aspects meets a minimum specification, i.e. a maximum pressure. These two aspects are maintaining the required pressure differential between the source chamber and the main chamber, and reducing incidence of contaminants in the intermediate and source chambers, in particular by reducing the hydrocarbon partial pressure in these chambers and reducing EBID growth. With the use of the intermediate chamber, contamination of components in the intermediate and source chambers due to contaminants such as hydrocarbons is expected to drop by a factor of **100** according to preliminary calculations.

FIG. **4** schematically shows a charged particle beam generator. The beam generator comprises a charged particle source **3** for generating a diverging charged particle beam, a collimator system for refracting the charged particle beam, and an aperture array **6**. The collimator system comprises an Einzel lens comprising three lenses **5***a*, **5***b*, **5***c* and a further lens **5***d*. The aperture array **6** is arranged for forming a plurality of charged particle beamlets from the beam generated by the source **3**. Additionally, the beam generator comprises one or more openings of a pumping system, such as a pumping system as depicted in FIG. **3** with respect to the intermediate chamber **103**. The opening may take the form of an inlet used as an outlet such as outlet **114** depicted in FIG. **3** for connection to a (vacuum) pump **115**. The one or more openings may form an integrated part of the pumping system, or the one or more openings may be connectible to one or more pumps within the pumping system. In some embodiments, such as the embodiment depicted in FIG. **4**, the one or more openings are part of one or more pumps **220**, the pumps **220** being included by the beam generator. The pumps may be getter pumps or sublimation pumps, such as titanium sublimation pumps. Hereafter, embodiments will be discussed in which one or more pumps **220** are included in the beam generator.

One or more lenses within the collimator system, typically lens **5***b* and **5***d*, operate at a high voltage, e.g. a voltage that is higher than 500 eV. Electrode **5***b*, i.e. the center electrode of the Einzel lens arrangement, may be used to refract the charged particle beam. A suitable voltage for this lens may be 15-25 kV, for example about 20 kV. Lenses **5***a*, **5***c* may be kept at 0V. Further lens **5***d* may be used to correct aberrations, as will be discussed later. Lens **5***d* may operate at a much lower voltage, for example about 1 kV.

The presence of high voltages on non-designated components within the system is undesired, for example because such voltages create additional fields that would influence the charged particle beam in an undesirable, and often unpredictable way. Therefore, the lenses **5***a*-**5***d*, and in this embodiment also the aperture array **6** are located within a high voltage shielding arrangement **201** for shielding components outside the arrangement **201** from high voltages that are present within the shielding arrangement **201**. Furthermore, the charged particle beam that is present during use will be shielded from fields originating from locations outside the high voltage shielding arrangement **201**, which may negatively influence the uniformity of the beam and/or may introduce additional aberrations. Preferably, the shielding arrangement **201** comprises a wire mesh structure. The use of a wire mesh structure instead of a closed structure with some small openings therein is that the volume within the shielding **10** arrangement **201** can be more easily pumped down to obtain a suitable vacuum pressure.

The one or more pumps **220** are placed outside the shielding arrangement **201** to avoid that the one or more pumps would be charged. The charged particle beam generates heat, in particular as a result of charged particles back-scattering from the aperture plate **6**. As a result, the one or more pumps **220** are heated as well, which could affect their efficiency. The operation of other components may also be negatively influenced by heating. Therefore, the beam generator further comprises a cooling arrangement **203** for removing heat, such as heat generated within the collimator system. The cooling arrangement **203** surrounds the high voltage shielding arrangement **201** and the one or more pumps **220**. As a result, the one or more pumps **220** are located between the high voltage shielding arrangement **201** and the cooling arrangement **203**. The cooling arrangement **203** may comprise one or more cooling channels **204** through which a cooling liquid, such as water, may flow. The use of active cooling by means of cooling channels with a cooling liquid flow therein enhances heat transfer as compared to a heat sink made of a heat conductive material.

Preferably, a magnetic shield arrangement **205** surrounds the cooling arrangement **203**. The use of a magnetic shield arrangement **205** blocks external magnetic fields which could influence the charged particle beam. Preferably, the magnetic shield arrangement **205** comprises one or more walls comprising a magnetic shielding material with a magnetic permeability greater than about 20,000. Preferably, the magnetic shielding material has a magnetic permeability greater than about 300,000. Most preferably, the magnetic shielding material also has a low remanence. Examples of magnetic shielding materials, include, but are not limited to a type of mu-metal and Nanovate™-EM.

The magnetic shield arrangement **205** does not block magnetic fields generated by wiring within the arrangement **205** to interfere with the charged particle beam. Such wiring is for example present to charge the electrodes **5***b*, **5***d*. For this reason, the wires within the magnetic shield arrangement **205** are straight and oriented in a radial direction with respect to the center of the collimator system. Furthermore, the wiring may be in such a way that the magnetic fields of different wires cancel each other out as much as possible. Outside the magnetic shield arrangement **205**, the orientation of the wires is of less importance, because **5** magnetic fields generated by the wires at these locations may be blocked by the arrangement **205**. Note that the magnetic shield arrangement **205** does not necessarily need to be a closed structure. In particular at the bottom, the arrangement **205** may be open, in FIG. **4** denoted by the dashed line.

All components including high voltage shield arrangement **201**, cooling arrangement **203** and magnetic field shield arrangement **205** may be placed within a vacuum chamber **101**. The use of a separate vacuum chamber for a portion of a lithography apparatus may be useful in a modular design. All components within the vacuum chamber may then for example be aligned with respect to each other and being tested prior to shipment towards a manufacturing environment.

FIG. **5** schematically shows an overview of the beam generator. Preferably, the source **3** is located in an area **102** with a higher vacuum than the area **103** in which the collimator resides. In FIGS. **5**-**8**, the collimator is schematically depicted as a block with reference number **300**. The collimator is supported by a support structure **230** with feet **231**. Preferably, the support structures **230** take the form of so-called A-structures. The support structure **230** may be connected to a frame **240**. To establish a vacuum, the beam generator comprises one or more ports **250**, **251** for initial pump-down. Reference number **260** refers to a flange that may be arranged for coupling in cooling fluid and/or wiring.

FIG. **6** shows the beam generator of FIG. **5** with a magnetic shielding arrangement **205** provided therein. The shielding arrangement **205** may take the form of a cylindrical box around the source **3** and the collimator **300**, and may be closed at the top and open at the bottom. As can be seen, the mere use of a shielding arrangement **205** would form a blocking structure for more than just magnetic shielding. For example, wires and cooling fluid tubes may not be able to pass. Furthermore, the shielding arrangement **205** is preferably mounted in such a way that components can be easily replaced and/or maintained.

FIG. **7** shows the beam generator of FIG. **6** with vacuum chamber separation. In particular, a plate **310**, preferably a metal plate, creates a first vacuum chamber **102** and a second vacuum chamber **103**, where the first vacuum chamber **102** preferably contains a lower pressure than the second vacuum chamber **103**. Port **250** may now be used to pump down vacuum chamber **102**, whereas port **251** may be used to pump down vacuum chamber **103**. The plate is supported by a ring **325**.

FIG. **8** shows the beam generator of FIG. **6** with another embodiment of vacuum chamber separation. In this case a structure **315** are mounted around the source **3** to create the first vacuum chamber **102**. The structure **315** may also be supported by a ring **325**.

In the embodiments of the beam generator shown in FIGS. **7** and **8**, the shielding structure of the magnetic shield arrangement **205** is interrupted. FIG. **9** shows a basic layout of the source chamber **102** and the collimator **300** together with the shielding arrangement **205** arranged in such a way that the vacuum leak between the first vacuum chamber **102** and the second vacuum chamber **103** is limited, i.e. its negative influence is acceptable. Note that the structure **315** now comprises a further wall **317** between first vacuum chamber **102** and the second vacuum chamber **103**. Furthermore, at locations where the shielding is interrupted, the shielding plates are formed in such a way that they run parallel to each other over a certain distance.

FIG. **10** shows a cross-sectional view of an embodiment of a collimator system. In the embodiment depicted in FIG. **10**, the collimator system comprises a body with a cavity therein, wherein the cavity is structured in such a way that the surface of the cavity serves as the outer electrodes **5***a*, **5***c* of the Einzel lens. The center electrode **5***b* of the Einzel lens may be kept in position within the cavity by means of spacers, for example by means of three or more spring elements as will be discussed with reference to FIGS. **11** and **12**. Preferably, the body forms the cooling arrangement **203**. In such case, preferably, the body comprises one or more cooling channels (shown in FIG. **11**) for accommodating a flow of cooling fluid, e.g. water.

In the embodiment depicted in FIG. **10**, the upper electrode **5***a* is further shaped in such a way that the source **3** that is located upstream is effectively shielded from the electric field generated by the center electrode **5***b* of the Einzel lens. The center electrode **5***b* is used to refract the charged particle beam generated by the source. In some embodiments, the central aperture being formed in the upper electrode **5***a* is therefore substantially conically shaped, or, as depicted in FIG. **10**, substantially bell-shaped.

The cross-sectional view farther shows the presence of the high-voltage shield **201** and the one or more pumps **220**. Finally, in the embodiment depicted in FIG. **10**, at a lower position within the cavity, a further electrode **5***d* is present. This further electrode **5***d* may be used for aberration correction. The shown shape of this electrode **5***d* may further provide a repulsive force for low energy electrons that backscatter from the aperture array. Consequently, less electrons re-enter the cavity, which reduces EBID. Similar to the center electrode **5***b* of the Einzel lens, the further electrode **5***d* is connected to the cavity by means of spacers, for example by means three or more spring elements, as will be discussed with reference to FIGS. **11** and **12**.

FIG. **11** shows an elevated cross-sectional view of the collimator system of FIG. **10**. The cooling arrangement **203** comprises one or more cooling channels **340** for accommodating a flow of cooling liquid. In the embodiment of FIG. **11**, the cooling channels are grooves provided with a cover **345** using laser drilling and laser welding. Alternatively, cooling channels may be manufactured by one or more other techniques known in the art such as brazing. The cooling channels preferably also cool in a vertical direction, as denoted by the arrows.

FIG. **11** further shows that the support structure **230** for supporting the collimator may be provided with feet **231** that match with balls **232** that are located at predetermined positions. The use of such balls **232** enables alignment of different modules in a lithography system with respect to each other.

Furthermore, FIG. **11** shows spring elements **320** for connecting the center electrode **5***b* of the Einzel lens and the further electrode **5***d* with the surface of the cavity. A cross-sectional view of such arrangement showing a possible orientation of the spring elements **320** is schematically depicted in FIG. **12**.

FIG. **13** shows an elevated side view of a beam generator **400** according to an embodiment of the invention. The beam generator comprises a housing, which in this embodiment comprises three parts **401***a*, **401***b* and **401***c* connected to each other by means of flanges **402**. Housing part **401***a* accommodates a source **3**, housing part **401***b* accommodates an Einzel lens having three electrodes **5***a*, **5***b* and **5***c*, and housing part **401***c* accommodates a further electrode **5***d* for aberration corrections.

At the outside of the housing connections are available for accommodating supply and removal of cooling fluid to be used by a cooling arrangement. A suitable cooling fluid is water. A supply unit, such as a supply tube, for supply of cooling fluid may be connected to an inlet **405***a* of a fluid supply conduit **407***a*. Similarly, a fluid removal unit, such as a tube, for removal of cooling fluid, may be connected to an outlet **405***b* of a fluid removal conduit **407***b*.

The housing further accommodates support of a high voltage supply unit **408**. The high voltage supply unit **408** contains a wire **409** via which a high voltage is applied to the middle electrode **5***b* of the Einzel lens. Additionally, a high voltage may be applied to the further electrode **5***d*. The wire is suitable insulated by means of a insulating structure **410** to avoid discharges.

The beam generator **400** is placed in a vacuum chamber. The pressure in the vacuum chamber may be reduced by means of pumps **411** that are connected to the housing of the beam generator **400**.

As already discussed with reference to FIG. **11** support structures **230** and feet **231** may be used to support the beam generator **400**.

FIG. **14** shows a first cross-sectional side view of the beam generator of FIG. **13**. The source **3** is placed in a separate source chamber **102**. The pressure in the source chamber **102** may be regulated by means of one or more pumps **412**. The shape and size of the Einzel lens electrodes **5***a*, **5***b* and **5***c* is similar to the electrodes shown in and described with reference to FIG. **11**. The beam generator comprises multiple pumps **220** that are arranged in circumference of the cavity through which the beam passes during use behind a high voltage shielding arrangement **201**. The high voltage shielding arrangement **201** in this embodiment comprises a wire mesh structure. The use of a wire mesh structure provides sufficient shielding from high voltages, while simultaneously allowing the pumps **220** to have sufficient access to the space within the high voltage shielding arrangement **201** to create a suitable vacuum pressure.

The pumps **220** effectively regulate the pressure within a chamber formed within the housing parts **401***b* and **401***c*, which may be qualified as an intermediate chamber as discussed with reference to FIGS. **2***a*, **2***b* and **3**. The difference compared to the intermediate chamber **103** of FIG. **3** is that the aperture array **6** is not placed within the intermediate chamber formed by the interior of housing parts **401***b* and **401***c*.

FIG. **15** shows a second cross-sectional side view of the beam generator of FIG. **13**. In this cross-sectional view, portions of the cooling arrangement of the beam generator are depicted. In particular, FIG. **15** shows inlet **405***a* and a portion of a fluid supply conduit **407***a* for accommodating a supply of cooling fluid, as well as outlet **405***b* and a portion of a fluid removal conduit **407***b* for removal of cooling fluid after it has absorbed heat in the beam generator.

Heat is not only generated by the presence of a high field within the Einzel lens. In particular in cases where the aperture array **6** is placed in close proximity of the Einzel lens, for example directly below or above the further electrode **5***d*, backscattered charged particles will cause heat generation within the system. Such heat generation will not only be limited to the lower electrode **5***c* of the Einzel lens, but may also seriously affect the upper electrode **5***a* of the Einzel lens. An embodiment of an arrangement of channels for cooling a portion of the collimator system in the beam generator will be described with reference to FIG. **17**.

FIG. **16** shows another elevated side view of the beam generator of FIG. **13**. In this view, tube splitters **406** are shown, which divide the streams of cooling fluid to different portions of the cooling arrangement. In some embodiments, the cooling arrangement is divided in three segments. An upper segment of the cooling arrangement may then be arranged for cooling the upper electrode **5***a* of the Einzel lens. A middle segment of the cooling arrangement may then be arranged for cooling the lower electrode **5***c* of the Einzel lens. Finally, a lower segment of the cooling arrangement may be used for cooling the further 20 electrode **5***d*. It will be understood that in embodiments where a further electrode **5***d* is absent, fewer segments may be used.

In the presently shown embodiment, the middle electrode **5***b* of the Einzel lens is not actively cooled by means of a cooling fluid.

FIG. **17** shows an elevated side view of an arrangement of channels used to cool a portion of the collimator system in the beam generator of FIG. **13**. This channel arrangement is particularly suitable for use as the upper segment in a cooling arrangement having three segments as discussed earlier. Although FIG. **17** appears to depict tubes, the infrastructure for cooling is preferably formed by channels formed within a solid structure with a suitable heat conduction.

Cooling fluid, such as water, is supplied via channel **417***a*. The cooling fluid progresses in a substantially horizontal direction in circumference of the cavity formed within the body of the collimator lens. Along the circumference, side channels arrange for transfer of a portion of the cooling fluid supplied via channel **417***a* subsequently in downwards in a substantially vertical direction, substantially horizontal in a direction substantially opposite to the flow direction in the channel **417***a*, upwards in a substantially vertical direction, radially inwards in a substantially horizontal direction, upwards in a substantially vertical direction, and radially outwards in a substantially horizontal direction. Finally, the side channels terminate in a channel **417***b* which progresses along the circumference of the cavity formed within the body of the collimator lens and flows out of the arrangement. The shown channel arrangement is suitable for absorbing a great amount of heat. The extent of heat absorption along the vertical direction, in particular with respect to the upper electrode **5***a* of the Einzel lens, may largely determine the optimal thickness of the upper electrode **5***a* of the Einzel lens.

FIG. **18** shows yet another elevated side view of the beam generator of FIG. **13**. In this view, a patch panel **420** is shown for arranging a connection of wiring. Additionally, this view shows the presence of contra weights **430**. The contra weights **430** may be used to adapt the center of mass of tire beam generator so as to allow a stable structure with more predictable characteristics.

In some embodiments, such as the embodiment discussed with reference to FIGS. **13-18**, a cavity within the collimator lens forms an chamber with a mostly closed nature, i.e. the housing surrounding the collimator lens has limited openings. As a result, one or more pump outlets, in some embodiments part of pumps **220**, may create a relatively low vacuum pressure within the cavity, e.g. a pressure in the order of $10^{-6}$ bar, but lower pressures up to $10^{-10}$ bar are achievable. A low pressure within the collimator lens reduces ionization of residual molecules which could not only negatively affect the charged particle beam, but also may lead to actual impingement of ions onto the source **3**. Such impingement could seriously limit the lifetime of the source **3**, and is therefore undesirable.

FIG. **19** shows a schematic cross-sectional view of a beam generator module **1050** according to an exemplary embodiment. The cross sectional view is defined in an axial-radial plane i.e. which is spanned by the axial direction Z and the radial direction R.

Shown in FIG. **19** is a beam generator chamber **1051**, which encloses elements, components and/or modules that make up the beam generator **1050**. The beam generator **1050** comprises a charged particle beam source **1052**, a collimator stack **1070**, and vacuum pumps **1122**, **1123** for creating a vacuum inside the beam generator chamber **51** (only vacuum pump **1122** is shown).

The beam source **1052** is accommodated within a beam source vacuum chamber **1053**, which in turn is located within the beam generator chamber **1051**. The beam source **1052** is fixed to a top side of the collimator stack **1070**, and configured to generate a charged particle beam **1054** along optical axis A. The beam source chamber **1053** encloses source vacuum pump units **1120**, which allow an ultra-low vacuum to be created locally near the beam source **1052**, to improve its radiation emission efficiency and prolong its effective radiation lifetime.

The charged particle beam **1054** generated by the charged particle source **1052** may initially have radially outward diverging properties while travelling along the optical axis A. The collimator electrode stack **1070** may then serve to refract portions of the charged particle beam **1054** selectively, thereby collimating the beam i.e. making the various parts of the beam distribution travel downstream with greater co-linearity along the optical axis A.

Collimator stack **1070** comprises an axially arranged stack (i.e. sequence) of collimator electrodes **1071-1080** that are mutually displaced along the axial direction Z by means of spacing structures **1089**, which are made of an electrically insulating material. The collimator electrodes **1071-1080** are formed by flat ring-shaped bodies **1081**, each of which comprises an electrode aperture **1082**. In the shown embodiment, the ring-shaped bodies **1081** are displaced at equal distances Hd along the optical axis A, and the electrode apertures **1082** are coaxially aligned along the optical axis A. The electrode bodies **1081** are preferably made of an electrically conducting and mechanically rigid material. Sufficient electrical conductivity enables easy application of a homogeneously distributed electrical charge onto each respective surface of the collimator electrodes **1071-1080**. Sufficient mechanical rigidity allows the collimator electrodes **1071-1080** to retain a fixed spatial configuration and hence to sustain steady electric potential differences during generation of the particle beam **1054**. Preferably, the electrodes **1071-1080** are made from aluminum. Aluminum is a light-weight material with good electrical conductance and non-magnetic properties, and which furthermore provides sufficient thermal conductance for dissipating thermal energy that is accumulated during charged particle beam generation.

The formation of a plurality of collimator electrodes **1071-1080** and spacing 30 structures **1089** into a coaxially aligned electrode stack **1070** provides the possibility to optimize the electric field distribution within the collimator stack **1070** at different positions along the optical axis A. The use of a plurality of separated collimator electrodes **1071-1080** allows for a relatively lightweight design.

Thicknesses HI, H**5**, He of the collimator electrodes **1071-1080** along the vertical direction Z may be sufficient for accommodating a liquid conduit **1105** on an inside of respective electrode bodies **1081**, while ensuring sufficient structural integrity of the electrode body **1081** during beam generation, even under considerable thermal stresses.

An uppermost collimator electrode **1071** in the collimator stack **1070** (i.e. the collimator electrode **1071** that is encountered and traversed first by the charged particle beam **1054** upstream of the stack **1070**) comprises a diverging curved aperture. A last collimator electrode **1080** in the collimator stack **1070** (i.e. the collimator electrode that is encountered last by the charged particle beam **1054** downstream along the optical axis A) has a relatively small inner thickness H**10**. Electrode properties of the stack are further discussed with reference to FIG. **20**.

The collimator electrodes **1071-1080** may be spaced with respect to each other by means of the electrically insulating spacing structures **1089**. The spacing structures **1089** define a minimal distance Hd between the electrodes **1071-1080**, which prevents the occurrence of electrical discharge between adjacent electrodes, even at relatively large electrical potential differences that are to be applied between the electrodes during beam generation (potential differences in the order of kilovolts per millimeter).

The spacing structures **1089** are made of an electrically insulating material that also has a high resistance to mechanical compression, to keep the distances between the electrodes fixed, and to avoid the electrodes from becoming electrically connected (i.e. becoming electrical equipotential surfaces). The spacing structures **1089** may for example be made of a ceramic. Preferably, each spacing structure **1089** is provided between a pair of adjacent collimator electrodes. Three such spacing structures **1089** are provided between each pair of adjacent collimator electrodes, to provide two stable **3**-point support planes, one for each adjacent collimator electrode, while maintaining a well-defined inter-electrode spacing Hd.

The collimator stack **1070** is suspended within the beam generator chamber **1051** by means of support protrusions **1092***b* and support legs **1093** that surround the stack **1070** on three sides. The support legs **1093** are used to fix the collimator stack **1070** with respect to an external reference frame (e.g. a carrier frame).

FIG. **20** shows a schematic cross-sectional side view of a collimator electrode stack **1070** according to an exemplary embodiment. The collimator electrode stack **1070** comprises ten collimator electrodes **1071-1080**, wherein the fifth collimator electrode **1075** constitutes the middle collimator electrode. The shown cross-section only schematically depicts several characteristic dimensions of this embodiment of the collimator electrode stack **1070**. Many construction details of this embodiment are omitted for simplicity (for example, detailed shapes of collimator apertures, electrode support portions, and spacing structures are not shown)

In general, the use of multiple collimator electrodes **1071-1080** separated by spacing structures **1089** so as to form a coaxially arranged collimator electrode stack **1070** provides the possibility for optimizing the electric field distribution in the collimator stack **1070** at different positions along the optical axis A. The step-wise variation of the electric potential differences between at least five adjacent collimator electrodes results in a relatively smoothly varying electric field distribution along the axial direction A. An electrode stack comprising five or more collimator electrodes allows generation of an electric field distribution that may have a plurality of negative electric field minima as well as a plurality of positive electric field maxima, and hence yields sufficient degrees of freedom for generating electric fields that may both collimate a charged particle beam **1054** as well as reduce spherical aberrations in the charged particle beam **1054**. Finding preferred beam characteristics for a particular application is achieved easily with the multi-collimator electrode stack via variation of the applied electrical potential values.

The inventors noted that, in one particular embodiment, the use of ten collimator 20 electrodes **1071-1080** in a collimator stack **1070** provides a good balance between the degrees of freedom for creating a relatively gradual electrical potential distribution along the axial direction Z on one hand, and obtaining sufficient inter-electrode spacing Hd for providing a good line of sight with vacuum pumps **1122**, **1123**, sufficient electrode cooling, and constructional simplicity on the other hand.

In the embodiment of the collimator electrode stack **1070** shown in FIG. **20**, the intermediate electrode thicknesses He of all the intermediate collimator electrodes **1072**, **1073**, **1074**, **1076**, **1077**, **1078**, **1079** are substantially identical. The term "substantially identical" herein refers to intermediate electrode thicknesses He that have the same value within achievable manufacturing tolerances. For collimator electrodes made from aluminum, 30 the intermediate electrode thickness He may be in the range of 10 millimeters to 20 millimeters, preferably in the range of 12 millimeters to 15 millimeters, and more preferably equals 13.6 millimeters. Using intermediate electrodes of equal thickness allows mass production of the electrode bodies and simplifies the assembly of the intermediate collimator electrodes into a collimator stack. In alternative embodiments, all of the electrodes may have identical thicknesses. Yet in other embodiments, some or all of the electrode thicknesses may be different.

An uppermost collimator electrode **1071** in the collimator stack **1070** (i.e. the collimator electrode **1071** that is encountered and traversed first by the charged particle beam **1054** upstream of the stack **1070** and along the optical axis A) comprises a smaller upper aperture diameter 01, followed by a divergently curved aperture bore **1071***a*. The small upper aperture diameter 01 and curved aperture bore **1071***a* allow a charged particle beam **1054** generated by the beam source **1052** to experience a gradual electric field change. A first electrode thickness HI of the first collimator electrode **1071** is in a range defined by 1.5·He≤HI≤2.5·He. A first collimator electrode **1071** having a thickness in the specified range allows the upstream end (i.e. the top) of the collimator stack **1070** to have a smooth transition from a relatively small beam source aperture, to the relatively larger collimator apertures, and allows the first electrode to have sufficient strength for directly supporting a weight of the beam source **1052** that is mountable thereon. The term "smooth" is used herein to indicate that a surface (here, the aperture surface) has no abrupt changes in curvature (i.e. sharp ridges, corners, or crevices) at a macroscopic scale. Abrupt curvature changes would generate undesirably large local variations in the electric field.

A middle collimator electrode **1075** is provided between the first collimator electrode **1071** and the last collimator electrode **1080**. The intermediate collimator electrodes **1072**, **1073**, **1074**, **1076**, **1077**, **1078**, **1079** are located between the first collimator electrode **1071** and the last collimator electrode **1080**, and on both sides of the middle collimator electrode **1075**. A middle electrode thickness H**5** of the middle collimator electrode **1075** is in a range defined by 1.5·He<H**5**<2.5–He. Preferably, the middle electrode thickness H**5** lies in a range between 22 millimeters to 26 millimeters, and more preferably equals 24 millimeters. A middle collimator electrode **1075** having a thickness H**5** in the specified range allows the center region **1075***a* of the collimator stack **1070** to have sufficient strength and bending stiffness for preventing the collimator electrode stack **1070** from vibrating e.g. about transversal axes (perpendicular to the axial direction Z).

In alternative embodiments, the middle electrode **1075** may have a thickness H**5** that is substantially equal to the thickness He of the intermediate electrodes **1072-1074**, **1076-1079**. This may for example be achieved by the use of mechanically stronger materials, or in the case that the stack support structure engages other and/or more electrodes in the collimator stack.

The last collimator electrode **1080** in the collimator stack **1070** (i.e. the collimator electrode that is encountered last by the charged particle beam **1054**) has a radially inner portion **1080***a* with a last electrode inner thickness H**10**. The inner thickness H**10** lies in a range defined by H**10**<He/3. The inner thickness H**10** of the last electrode **1080** preferably has a relatively small value to effectively sustain an electric potential with opposite polarity with respect to the charged particle beam **1054** while extending over only a small axial distance. This produces a highly localized attractive E-field near the aperture perimeter. The thin last electrode **1080** with opposite polarity produces negative spherical aberration for a beam of charged particles, to compensate for positive spherical aberrations in the beam that have been generated in the preceding part of the collimator stack **1070**.

The last collimator electrode **1080** has a last electrode outer thickness H**10'** at a radially outer portion **1080***b*. The last electrode outer thickness H**10'** preferably equals the intermediate electrode thickness He, to make the last electrode **1080** mechanically stronger, and also to provide sufficient height for accommodating a cooling conduit inside the outward portion. As shown in FIG. **20**, the transition from the inner portion **1080***a* to the outward portion **1080***b* may involve an axial stepwise increase from inner thickness H**10** to outer thickness H**10'**. This creates an inner aperture diameter Ø**10** for the radially inner portion **1080***a*, and an outer aperture diameter Ø**10'** for the radially outer portion **1080***b*. According to a preferred embodiment, the inner body thickness H**10** of the last collimator electrode **1080** is in a range of 5 millimeters or smaller, the outer body thickness HI O' is in a range of 10 millimeters or larger, the inner aperture diameter Ø**10** is 60 millimeters, and the outer aperture diameter Ø**10'** is 100 millimeters.

Downstream of the last electrode **1080**, there is provided an aperture array **1058** for forming a plurality of beamlets from the charged particle beam **1054**. The aperture array **1058** may be a structural component of the collimator electrode stack **1070**. Alternatively, the aperture array **1058** may form part of a condenser lens module **1056** that is arranged in the projection column **1046** directly downstream from the beam generator module **1050** (as viewed along the optical axis A). The aperture array **1058** comprises a lower central surface and slanted lateral surfaces OP. During operation, the aperture array **1058** is preferably kept at ground potential. The shape of the aperture array **1058** creates sufficient distance between the inner perimeter of the (relatively) thin radially inner electrode portion **1080***a* of the last collimator electrode **1080**, to avoid electrical discharging between the (sharp edges of the) charged last collimator electrode **1080** and the aperture array **1058**. The shape of the aperture array **1058** also ensures that the spacing between the aperture array **1058** and the radially outward electrode portion **1080***b* of the last collimator electrode **1080** is kept small, to preserve the vacuum inside the collimator electrode stack **1070** with respect to the region outside the beam generator module **1050** and/or outside the condenser lens module **1056**.

FIG. **20** helps to illustrate exemplary methods for operating this embodiment of the collimator electrode stack **1070** during beam generation and processing. In this embodiment, **10** the collimator electrodes **1071-1080** are positioned at equal distances Hd along the optical axis A in a coaxial arrangement.

In other embodiments, the collimator electrodes may be positioned at different interelectrode distances.

Different electrostatic potential values (i.e. voltages) are applied to the collimator electrodes **1071-1080**. The collimator electrode stack **1070**, the charged particle beam generator **1050**, or the charged particle lithography system may comprise a set of distinct voltage sources **1151-1160**. Each voltage source **1151-1160** comprises an output terminal for applying a selected electric potential to a respective collimator electrode **1071-1080**. An electric connection is provided between the output terminal of each voltage source **1151-1160 20** and the electrical contact **1109** of a corresponding collimator electrode **1071-1080**. Preferably, the voltage sources **1151-1160** are independently and dynamically adjustable during operation of the beam generator **1050**. Alternatively, the voltage sources **1151-1160** may be formed as a single power supply with suitable adaptors and dividers to convert its output(s) to distinct selected voltage values to be applied to the corresponding collimator **25** electrodes **1071-1080**.

Below, is a table of two numerical simulations (one per column), which corresponds to a preferred arrangement for the collimator electrodes, and to two preferred electric potential distributions applied to the electrodes **1071-1080**. The sequence of electrode numbers in the table corresponds to the sequence of collimator electrodes **1071-1080** as used in the description with reference to e.g. FIG. **20**.

| Electrode # | V-distribution 1 (along Z) | V-distribution 2 (along Z) |
|---|---|---|
| 71 | 0 V | 0 V |
| 72 | −3165 V | −3649 V |
| 73 | 5577 V | 3907 V |
| 74 | 23160 V | 19140 V |
| 75 | 29590 V | 21990 V |
| 76 | 17400 V | 9651 V |
| 77 | 4870 V | 1525 V |
| 78 | 698 V | −313.5 V |
| 79 | 52 V | −491.9 V |
| 80 | 1023 V | 702.2 V |

The listed electric potential values for the various electrodes correspond to potential differences with respect to ground potential. Each of the electric potential values may be applied to the collimator electrodes **1071-1080** by the corresponding voltage source **1151-1160**. During operation, the aperture array **1058**, which is located directly downstream of the last collimator electrode **1080**, is preferably kept at ground potential. A method for operating a charged particle beam generator **1050** may comprise:—generating an electron beam **1054** with the beam source **1052**;—projecting the generated electron beam along an optical axis A through the apertures **1082** of the collimator electrode stack **1070**;—applying electrical **10** potentials onto the collimator electrodes **1071-1080**, comprising:—keeping a first collimator electrode **1071** at ground potential;—keeping a middle collimator electrode **1075** at a highest positive electric potential, and—keeping a last collimator electrode **1080** at a low positive electric potential.

The electric potential differences applied across the collimator electrodes serve to produce a homogeneous transversal electron beam surface current density, while reducing the angular error. During beam generation, the electron beam **1054** emanates from the beam source **1052** with a locally diverging contour as viewed in a cross section in a radial-axial plane.

The strongly increasing electric potential values applied to the third, fourth, and fifth collimator electrodes **1073-**

**1075** creates a local electric field distribution that acts as a positive lens on the traversing electron beam **1054**. This serves to refract the local contour of the electron beam **1054** in the radial-axial cross-section towards the optical axis A, and causes the distribution of the electron beam **1054** to converge. Due to the radial variation of the electric field strength in the radial-angular plane, the positive lens effect may cause the electrons in the electron beam **1054** to obtain a non-uniform axial speed distribution as viewed in the radial-angular plane (which causes for spherical aberration effects).

The strongly decreasing electric potential values applied to the sixth, seventh, eighth, and ninth collimator electrodes **1076-1079** create a local electric field distribution that acts as a negative lens on the traversing electron beam **1054**. This also refracts the local contour of the electron beam **1054** in the radial-axial cross-section, but now away from the optical axis A. The variations in the radial distributions of the electron beam and the electric field may again contribute to spherical aberration effects.

A positive electric potential (with respect to a grounded reference) applied to the last collimator electrode **1080** produces negative spherical aberration in the traversing electron beam **1054** (or for a beam of negatively charged particles in general). The generated negative spherical aberrations will (at least partially) compensate any positive spherical beam aberration that has been generated in the preceding part of the collimator stack **1070**.

The voltage sources **1151-1160** are preferably set to create electric potentials on the collimator electrodes **1071-1080** so that a final local contour of the electron beam **1054** is properly collimated as it emanates downstream from the beam generator **1050** (i.e. the beam is made parallel in the radial-axial cross-section, at least as much as possible). The electric potentials created by the voltage sources **1151-1160** may be dynamically adjusted, in order to alter the distribution of the electrical potential values along the axial direction and/or to alter the local amplitudes of the electric fields. The axial centers of the positive and negative lenses may thus be moved along the axial direction, and/or the field amplitudes changed. The independent adjustability of the electric potentials applied to the collimator electrodes **1071-1080** during operation facilitates reconfiguration and optimization to changing operational conditions (e.g. beam current, vacuum conditions, shielding conditions, etc.)

The method may further comprise:—keeping a second collimator electrode **1072** preceding the middle electrode **1075** at a negative electric potential. In addition, the method may also comprise—keeping at least one of two intermediate collimator electrodes **1078**, **1079** directly preceding the last collimator electrode **1080** at low negative electric potentials. Applying a negative electric potential at one or two of the last intermediate collimator electrodes **1078-1079** preceding the last collimator electrode **1080** helps to deflect secondary electrodes and/or backscattered electrodes originating from a region downstream of the collimator electrode stack **1070**. Secondary electrons may for example be created during collisions of primary electrons in the electron beam **1054** with the aperture array **1058**. The local negative electric potential helps to reduce the number of electrons that impact on the strongly positively charged middle collimator electrode **1075**.

According to the above mentioned specific numerical examples, further embodiments of the method for operating a beam generator **1050** may comprise:—keeping at least one of two intermediate collimator electrodes **1078**, **1079** directly preceding the last collimator electrode **1080** at a fixed electric potential with a value of −300 Volts to −500 Volts;—keeping the second collimator electrode **1072** at a fixed electric potential with a value 10 of −3 kilovolts to −4 kilovolts;—keeping the middle collimator electrode **1075** at a fixed electric potential with a value of +20 kilovolts to +30 kilovolts, and—keeping a last collimator electrode **1080** at a positive potential in a range of +500 Volts to +1100 Volts.

The invention has been described by reference to certain embodiments discussed above. It will be recognized that these embodiments are susceptible to various modifications 15 and alternative forms well known to those of skill in the art without departing from the spirit and scope of the invention. Accordingly, although specific embodiments have been described, these are examples only and are not limiting upon the scope of the invention, which is defined in the accompanying claims.

The invention claimed is:

**1**. A lens element of a charged particle system, comprising:

a body having a cavity formed therein for a path of a charged particle beam; and

a cooling arrangement comprising multiple segments for cooling the lens element, wherein:

an upper segment of the multiple segments is disposed at an upper portion of the body;

the body is structured to receive the charged particle beam into the cavity via the upper portion;

the upper segment comprises one or more channels configured to accommodate a fluid flowing around the path of the charged particle beam to cool the upper portion of the body,

the one or more channels are formed within a solid structure of the body at least part of which forms the lens element,

the one or more channels at the upper segment have a side channel arranged for fluid flow and having at least one section that extends substantially parallel to the path of the charged particle beam.

**2**. The lens element of claim **1**, wherein the cooling arrangement comprises one or more lateral channels extending in a substantially rotational direction around the path of the charged particle beam in circumference of the cavity.

**3**. The lens element of claim **2**, wherein the side channel is connected to at least two of the one or more lateral channels.

**4**. The lens element of claim **3**, wherein the side channel has at least one section that extends in a radial direction to the path of the charged particle beam.

**5**. The lens element of claim **3**, wherein the side channel has a section arranged for fluid flow in a substantially opposite direction of fluid flow via the lateral channels.

**6**. The lens element of claim **1**, wherein the upper portion of the body is an electrode.

**7**. The lens element of claim **1**, wherein the cavity is structured to serve as an electrode of the lens element.

**8**. The lens element of claim **1**, wherein the lens element is an Einzel lens.

**9**. The lens element of claim **1**, wherein the lens element is included in a collimator system comprising a plurality of collimator lenses.

**10**. A charged particle system, comprising:

a beam source for generating a charged particle beam;

a body having a cavity formed therein for a path of the charged particle beam; and

a cooling arrangement comprising multiple segments, wherein:

an upper segment of the multiple segments is disposed at an upper portion of the body;

the body is structured to receive the charged particle beam into the cavity via the upper portion;

the upper segment comprises one or more channels configured to accommodate a fluid flowing around the path of the charged particle beam to cool the upper portion of the body,

the one or more channels are formed within a solid structure of the body for cooling the body at least part of which forms a lens element of the charged particle system,

the one or more channels at the upper segment have a side channel arranged for fluid flow and having at least one section that extends substantially parallel to the path of the charged particle beam.

**11**. The charged particle system of claim **10**, wherein the cooling arrangement comprises one or more supply channels extending in a substantially rotational direction around the path of the charged particle beam in circumference of the cavity.

**12**. The charged particle system of claim **11**, wherein the side channel is connected to at least two of the one or more supply channels.

**13**. The charged particle system of claim **11**, wherein the side channel is arranged for transferring a portion of the fluid supplied via the supply channels in a direction substantially parallel to the path of the charged particle beam.

**14**. The charged particle system of claim **13**, wherein the side channel has a first section and a second section that both extend parallel to the path of the charged particle beam, and the first section being arranged for fluid flow in a substantially opposite direction of fluid flow via the second section.

**15**. The charged particle system of claim **10**, wherein the cooling arrangement comprises one or more side channels having at least one section that extends in a radial direction to the path of the charged particle beam.

**16**. The charged particle system of claim **10**, wherein the cavity is structured to serve as an electrode of the lens element.

**17**. A cooling arrangement of a lens element, comprising: multiple segments, wherein:

an upper segment of the multiple segments is disposed at an upper portion of a body of the lens element;

the body is structured to receive a charged particle beam into a cavity of the body via the upper portion;

the upper segment comprises one or more channels configured to accommodate a fluid flowing around a path of a charged particle beam to cool the upper portion of the body,

the one or more channels are formed within a solid structure of the body at least part of which forms the lens element,

the one or more channels at the upper segment comprise a first channel arranged for fluid flow and having at least one section that extends substantially parallel to the path of the charged particle beam.

**18**. The cooling arrangement of claim **17**, wherein the one or more channels comprise one or more second channels extending in a substantially rotational direction around the path of the charged particle beam in circumference of a cavity that is formed in the body.

**19**. The cooling arrangement of claim **18**, wherein the first channel is arranged for transferring a portion of the fluid supplied via the second channels in a direction substantially parallel to the path of the charged particle beam.

**20**. The cooling arrangement of claim **17**, wherein the one or more channels are formed within the body using a laser drilling, laser welding, or brazing.

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