

A Shielding Element for Shielding a Device from Electromagnetic Noise

Technical Field

The present disclosure relates to a shielding element for shielding a magnetically sensitive device, such as a quantum device, from electromagnetic noise. The disclosure also relates to a shielding device comprising a shielding element in accordance with the present disclosure, and to an assembly comprising a plurality of shielding devices, and to a shielded quantum processing unit, as well as a quantum apparatus, such as a quantum computer, comprising such a shielding assembly.

Technical Background

Magnetically sensitive devices, such as quantum devices, need to be shielded from electromagnetic noise because they are extremely sensitive to their environment. Such noise can be present in the form of an electromagnetic field, and/or in the form of radiation and, without adequate shielding, can interfere with the state of these devices, leading to errors, loss of information, and reduced performance.

For example, a class of magnetically sensitive devices are quantum devices, and for example superconductive devices that require particularly efficient shielding from noise. In accordance with the prior art, it is known to provide a shielding packaging for such quantum devices, or even a double shielding packaging.

US 2021/0068320 A1 describes shielding assemblies including a multilayer enclosure that comprises a superconducting material with a thickness that reduces the penetration of magnetic fields into the multilayer enclosure.

US 2023/0130402 A1 describes multilayer shielding assemblies with cylindrical outer walls.

US 5,466,885 A describes further shielding structures comprising a superconductor cylinder as a shell and a high permeability shield member inside thereof.

Despite the advances in terms of shielding assemblies for quantum devices, there is a need for further improvements. For example, shortcomings are associated with volumetric sizes. The sizes are larger than desirable and/or associated with difficulties concerning maintenance (too time consuming, etc.).

Moreover, efficient shielding often requires producing large quantities of metal plates, and the manufacturing is time consuming and costly, as well as resulting in heavy shielding devices.

There is, hence, a need for an improved shielding that addresses at least one of the above-mentioned shortcomings. It would also be desirable to have improved shielding assemblies comprising a plurality of shielding elements, as well as quantum processing units and quantum computers improved in terms of their shielding with respect to noise.

Summary

Aspects of the above-mentioned object are achieved by a shielding element for shielding a magnetically sensitive device from electromagnetic noise in accordance with the present disclosure.

One aspect of the present disclosure relates to a shielding element for shielding a magnetically sensitive device, in particular a quantum device, from electromagnetic noise. The

shielding element comprises a wall section that surrounds an opening extending through the shielding element in a first direction.

The wall section may have a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m).

The opening may in particular fully extend through the shielding element in the first direction, i.e., it may penetrate the shielding element. The shielding element may have a ring-like structure that surrounds the opening. The ring-like structure may have any cross-sectional shape (e.g., circular, asymmetric, with any number of corners, etc.).

The arrangement of the shielding element with the opening may allow placing one or several (additional) shielding devices that provide a shielding effect in the first direction such that these latter shielding devices are laterally (i.e., in directions perpendicular to the first direction) surrounded by the shielding element. This may in turn allow simplifying the structure of an outer main shield body in which a magnetically sensitive device as well as the shielding element are placed. In particular, it may suffice that the outer main shield body comprises a superconductive material layer that is superconductive when cooled below a critical temperature. In contrast, a layer of highly permeable material may not be necessary, although the overall shielding effect of the main shield and the shielding element may nevertheless be just as good or even superior as compared to the case in which the shielding element is omitted and the outer main shield body comprises several layers including, in particular, a superconductive material layer as well as a highly permeable material layer. Thus, material savings and thus weight savings on the main shield body may be possible due to the provision of the shielding element in accordance with the present disclosure.

An average dimension of the opening in a plane perpendicular to the first direction is larger than an average dimension of an extension of the wall section in the first direction. In particular, an average width of the opening in a plane perpendicular to the first direction is larger than an average length of an extension of the wall section in the first direction.

This may allow minimizing the amount of the high permeability material needed, as the shielding element is shortened in the length direction compared to prior art solutions. Thus, the price and weight of the shielding element according to the invention is reduced compared to a full shielding element being provided in a shielding assembly.

The widths are to be understood to be defined through the centroid of the cross-sectional shape of the wall section in the plane perpendicular to the first direction, i.e., through the geometrical center. If the cross-sectional shape is circular, then the centroid is the center of the circle. If the cross-sectional shape is a regular triangular shape, then the centroid is the center of the cross-section, etc.

An aspect ratio of the wall section may be 1.0 or less. The aspect ratio is in this context to be understood as an average length of an extension of the wall section in the first direction divided by an average width of the opening in a plane perpendicular to the first direction. Optionally, the aspect ratio may be in a range of 0.1 to 0.5.

The wall section may comprise at least one tubular section.

The wall section may be a lateral cylindrical surface.

The wall section may have a circular cross section. Additionally, or alternatively thereto, the opening may have a circular cross section.

An average wall thickness of the wall section may be 10 mm or less. A lightweight shielding element can thus be obtained compared to prior art solutions. This may promote light weight construction of an entire assembly comprising the shielding element.

An average wall thickness of the wall section may be 3 mm or less. An average wall thickness of the wall section may be 2 mm or less. An average wall thickness of the wall section may be between 0.8 mm and 1.7 mm. This may allow saving material costs and promoting a lightweight construction.

The wall section may comprise at least two segments that are welded together. This may be associated with convenient and/or efficient manufacturing.

The wall section may be an integral piece.

At least one of a first end and a second end opposite to the first end in the first direction may comprise a protrusion from the wall section in a direction perpendicular to the first direction. The protrusion may promote structural support.

The protrusion may extend outward and/or inward with respect to the wall section.

The relative electromagnetic permeability of the wall section may be in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries.

The relative electromagnetic permeability of the wall section may be in a range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries.

This disclosure also relates to a shielding device for shielding a magnetically sensitive device, in particular a quantum device, from electromagnetic noise.

The shielding device may comprise a main shield body that partially encapsulates an interior space and is provided with an opening that provides access to the interior space. A part of the interior space may be an accommodating space for accommodating a magnetically sensitive device, in particular a quantum device.

The shielding device may comprise at least one shielding element, in accordance with any one or several of the aspects described above, and provided in the interior space.

An average distance between opposing sections of the wall section is in a range of 0.7 to 0.99 times an average width of an interior wall of the interior space.

The wall section may fit inside the interior space without touching the interior wall. The wall section may be separable from the interior space. This may promote better accessibility to components of an assembly in the interior space. In particular, this may facilitate maintenance works and/or the replacement of parts. Moreover, it may in particular promote maintenance of the magnetically sensitive device.

The wall section and the interior wall may be at least partially lateral cylindrical surfaces.

The shielding element and the main shield body may have a common central axis. Put differently, the shielding element may be oriented in the main shield body such that a straight line passing through the through hole connects the opening and the accommodating space runs from the opening through the through hole to the accommodating space.

The shielding device may comprise at least one shield member that is located in the interior space and between the opening and the accommodating space.

The location between the opening and the accommodating space may promote the shielding effectivity, as the opening or, in particular, the lid opening, is where noise, which is headed towards the accommodating space, primarily stems from.

The at least one shield member may be structurally distinct and/or separable from the main shield body. Being structurally distinct from the main shield body in this context means not being integrally formed together with the main shield body as to be one and the same structure with the rest of the main shield body. Being structurally distinct means that the at least one shield member was manufactured in its own right and independently from the main shield body.

A structurally distinct shield member may be built into the interior space of the main shield body and may remain there for the lifetime of the entire shielding device, or, for other cases, it may be reversibly removed or replaced, i.e., it may be separable from the main shield body. The expression "separable from" in this context means that the shield member can be separated from the main shield body (e.g., taken out of the main shield body) without any substantial damage.

The at least one shield member may be separable and may in particular be reversibly separable from the main shield body. Moreover, the at least one shield member may be separated from the main shield body or not separated therefrom when built into the interior of the main shield body.

The separability of the at least one shield member from the main shield body may further improve the maintenance of the shielding device and/or a magnetically sensitive device mounted in the accommodating space of the shielding device.

The shield member may comprise at least a high permeability layer with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a low permeability layer that

is superconductive when cooled below a critical temperature, wherein the high permeability layer is provided between the opening and the low permeability layer.

Electromagnetic fields and/or radiation entering the interior space and propagating towards the accommodating space will be exposed to the at least one shield member due to the location between the opening and the accommodating space. In addition, as the high permeability layer is provided between the opening and the low permeability layer, the fields and/or radiation may be diverted efficiently by the high permeability layer. In other words, the high permeability layer may extract a flux and re-direct it away from the accommodating space.

The superconductive material layer may in turn prevent flux from transitioning deeper inside of the interior space and towards the accommodating space.

The low permeability layer that is superconductive when cooled below a critical temperature may also be referred to as a superconductive material layer.

The wall section of the at least one shielding element may at least partially surround at least one of the at least one shield members. Said at least shielding element may in this case exert its function locally where it is important. This may allow saving on material costs by not having a shielding element extend over other regions. This means that the weight of the assembly may be reduced.

A part of the wall section that forms part of a half of the shielding element that is closer to the opening may surround the at least one shield member.

The portion of the wall section that surrounds the at least one shield member may belong to the closest 25%, 15%, or 5%, of the shielding element. An edge portion of the wall section

may in particular surround the at least one shield member.

There may be a gap, in particular, a clearance gap, between the at least one shield member and the wall section.

The gap may have a width in a range of 0.1 mm to 5 mm, or 0.1 mm to 2 mm, or 0.1 mm to 1 mm. With these ranges, increasingly with the smaller ranges, space efficiency may be increasingly promoted.

The shielding device may comprise a plurality of shield members located in the interior space and between the opening and the accommodating space.

A plurality of shield members may be two shield members or more than two shield members. A plurality of shield members may, for example, be from 2 to 8 shield members or from 3 to 7 shield members.

Additional shield members may further promote the shielding effect against electromagnetic field flux and/or radiation penetrating further into the shielding device and towards the accommodating space.

However, openings may permit field and/or radiation flux to enter deeper into the interior space of the shielding device. To prevent this, each shield member may comprise a high permeability layer that extracts some field and/or radiation flux. In other words, each high permeability layer may extract some flux and re-direct it away from the accommodating space inside the interior space of the shielding device. Moreover, every superconductive material layer, following a neighboring high permeability layer, may prevent flux from transitioning further inside the shielding device. An alternating arrangement of high and superconductive material layers may, hence, be particularly effective in preventing flux from

penetrating further inside of the interior space and towards the accommodating space of the shielding device.

The wall section of the shielding element may at least partially surround at least one of the shield members, in particular several or all of the shield members, of the plurality of shield members. This may simplify the structure and/or save material and/or promote space efficiency.

One, two or more, optionally all, of the plurality of shield members may comprise a respective high permeability layer with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a respective superconductive material layer that is superconductive when cooled below a critical temperature.

Pairs of high and superconductive material layers in accordance herewith may particularly efficiently promote shielding against fields and radiation reaching the accommodating space.

For each of the plurality of shield members comprising the high permeability layer and the superconductive material layer, the respective high permeability layer is provided between the opening and the respective superconductive material layer of the respective shield member. In other words, the plurality of shield members may be arranged together to comprise alternating pairs of high permeability layers and superconductive material layers.

The high permeability layer and the superconductive material layer of any one or several (or all) of the plurality of shield members may be separated by a (respective) gap.

Alternating pairs of the high and superconductive material layers may particularly efficiently promote shielding against fields and radiation reaching the accommodating space.

The high permeability layer and the superconductive material of a shield member (of one of them, or two or more, or of all of them) may be provided on top of one another. Alternatively, a gap may be provided between them. Another alternative is that one or several other layers are provided in-between.

The high permeability layer and the superconductive material layer of any one or several (or all) of the plurality of shield members may be held together, fixed together, e.g., glued together and/or screwed together.

Adjacent shield members may be connected by a mechanical support.

When the shielding device comprises a plurality of shield members, a field and/or radiation flux may be reduced at each shield member.

The shield members may have openings permitting wire connectivity and mechanical structures to go through. This way, wire connectivity and/or mechanical support may be provided to the device located in the accommodating space in a convenient way for the accommodating space and for other parts of the interior space of the shielding device.

At least two shield members of the plurality of shield members may structurally differ from one another. Put differently, at least two shield members may not be structurally identical. For example, they may differ in terms of the number of and/or the composition of layers, or they may have layers with different thicknesses, or their size may differ. The structural differences may reflect a finetuning of the compositions and functionalities of the shield members for different locations within a shielding device.

At least two shield members of the plurality of shield members may structurally differ in terms of the high permeability layer

and the superconductive material layer of the shield member. In other words, the high permeability layer of one shield member may be different from the high permeability layer of another shield member. In addition, or alternatively thereto, the superconductive material layer of one shield member may be different from the superconductive material layer of another shield member.

At least two shield members of the plurality of shield members may be structurally the same.

Several or all of the plurality of shield members may be structurally the same.

A relative electromagnetic permeability of the high permeability layer of the at least one shield member may be in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries.

A relative electromagnetic permeability of the high permeability layer of the at least one shield member may be in a range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries.

A relative electromagnetic permeability of the high permeability layer of at least one of the plurality of shield members may be in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries.

A relative electromagnetic permeability of the high permeability layer of at least one of the plurality of shield members may be in a range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries.

A relative electromagnetic permeability of the high permeability layer of several of the plurality of shield members may be in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries.

Thereby, in each of these aforementioned cases, the relative electromagnetic permeability of each of the several high permeability layers of the several of the plurality of shield

members may be the same, or some or all of them may mutually differ.

A relative electromagnetic permeability of the high permeability layer of several of the plurality of shield members may be in a range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries. Thereby, the relative electromagnetic permeability of each of the several high permeability layers of the several of the plurality of shield members may be the same, or some or all of them may mutually differ.

A relative electromagnetic permeability of the high permeability layer of all of the plurality of shield members may be in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries. Thereby, the relative electromagnetic permeability of each of the high permeability layers of all of the plurality of shield members may be the same, or some or all of them may mutually differ.

A relative electromagnetic permeability of the high permeability layer of all of the plurality of shield members may be in a range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries. Thereby, the relative electromagnetic permeability of each of the high permeability layers of all of the plurality of shield members may be the same, or some or all of them may mutually differ.

The plurality of shield members may consist of from 2 to 7 shield members. The plurality of shield members may consist of from 3 to 6 shield members. The plurality of shield members may consist of from 3 to 5 shield members. The increasingly narrower ranges of total numbers of shield members may offer increasingly desirable compromises between limiting the volumetric size and the gain in shielding efficiency by adding shield members.

A distance between adjacent shield members may be in a range of three times the diameter of the hole for letting the mechanical structure and/or cables pass through or less.

Optionally, the distance may be twice the diameter or less.

The term adjacent refers to the property of being direct neighbors. In particular, shield members may be provided one after another in a direction starting from the opening of the shielding device and heading towards the accommodating space. The shield member closest to the opening is, hence, adjacent to the shield member 2nd closest to the opening. The shield member furthest away from the opening is adjacent to the shield member 2nd furthest from the opening. All of the shield members in-between are adjacent to the two shield members between which they are sandwiched in terms of position when looking in the direction from the opening to the accommodating space.

A thickness of the high permeability layer of the at least one shield member may be in a range of 0.2 mm to 3mm, in particular, sufficient to not saturate with the magnetic field. It may be in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

A thickness of the high permeability layer of any of the plurality of shield members may be in a range of 0.2 mm to 3 mm. It may be in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

A thickness of the high permeability layer of several of the plurality of shield members may be in a range of 0.2 mm to 3 mm. It may be in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

A thickness of the high permeability layer of all of the plurality of shield members may be in a range of 0.2 mm to 3 mm. It may be in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

A thickness of the superconductive material layer of the at least one shield member may be in a range of 0.2 mm to 3mm. It

may be in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

A thickness of any one or several, or optionally of all of the plurality of shield members may be a range of 0.2 mm to 3mm, optionally in a range of 0.2 mm to 1.5 mm or 0.7 mm to 1.3 mm or 0.8 mm to 1.2 mm.

The at least one shield member of the plurality of shield members may comprise an additional layer, in particular, a mechanical support layer, on which the superconductive material layer is at least partially fixed.

Any one or several, or all of the plurality of shield members may comprise an additional layer, in particular, a mechanical support layer, on which the superconductive material layer is at least partially fixed.

Any one or several of the additional layer(s) may be provided between the high permeability layer and the superconductive material layer.

Any one or several, or all of the additional layer(s) may comprise copper.

Any one or several, or all of the additional layer(s) may be a mechanical support plate.

A surface of the high permeability layer of the at least one shield member and/or of any one or several, or optionally all, of the plurality of shield members may be oriented towards the opening.

Being oriented towards the opening means does not necessarily mean directly facing the opening, but it can also mean indirectly facing the opening. For example, one shield member may be oriented towards the opening, but another shield member

(or several shield members or other components) may be in-between the one shield member and the opening.

When a high permeability layer of the shield member is plate-shaped, being oriented towards the opening implies that the main surface (a plate-shaped surface) of the high permeability layer of the shield member faces the opening. It may face the opening at 90 degrees or at another angle. For example, a high permeability layer (e.g., a high permeability plate) may be parallel to the opening, or it may be angled with respect to a surface in which the opening lies.

In contrast a high permeability layer that is oriented such that its main surfaces extend away from an opening in which the surface lies at an angle of 90 degrees would not be oriented towards the opening. Being oriented towards the opening may be referred to as facing the opening or indirectly facing the opening (when there are one or several other component in-between) with a surface (a main planar surface of the high permeability layer when the latter is plate-shaped).

The high permeability layer may be parallel to the opening.

A surface of the superconductive material layer of the at least one shield member and/or of any one or several, or optionally all, of the plurality of shield members may be oriented towards the opening.

Being oriented towards the opening means does not necessarily mean directly facing the opening, but it can also mean indirectly facing the opening. For example, one shield member may be oriented towards the opening, but another shield member (or several shield members or other components) may be in-between the one shield member and the opening.

When a superconductive material layer of the shield member is plate-shaped, being oriented towards the opening implies that

the main surface (a plate-shaped surface) of the superconductive material layer of the shield member faces the opening. It may face the opening at 90 degrees or at another angle. For example, a superconductive material layer (e.g., a superconductive material plate) may be parallel to the opening, or it may be angled with respect to a surface in which the opening lies.

In contrast a superconductive material layer that is oriented such that its main surfaces extend away from an opening in which the surface lies at an angle of 90 degrees would not be oriented towards the opening. Being oriented towards the opening may be referred to as facing the opening or indirectly facing the opening (when there are one or several other component in-between) with a surface (a main planar surface of the superconductive material layer when the latter is plate-shaped).

The superconductive material layer may be parallel to the opening.

The shielding device may comprise an outermost shield member that comprises at least an outermost high permeability layer with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and an outermost superconductive material layer that is superconductive when cooled below a critical temperature. The outermost high permeability layer may form the lid or a part of the lid of the shielding device.

The outermost shield member may be the shield member amongst the plurality of shield members that is the farthest located from the accommodating space.

The outermost high permeability layer may be located at a boundary of the interior space or outside of the interior space.

The location at the boundary of the interior space refers to a location where the interior space of the shielding device ends. Thus, the outermost high permeability layer may be located partially or fully inside of the interior space, and it may be located partially or fully outside of the interior space.

The outermost high permeability layer may at least partially close the opening.

A clearance gap may be present between the at least one shield member and the main shield body. The clearance gap may be in a clearance range, meaning the at least one shield member and the main shield body may be considered slightly touching so that sliding may be possible without scratching / damaging the materials. The clearance gap may have a width of around 1.5mm, but the width may, more generally, be of the order of 3mm or less.

Any one or several, or all of the plurality of shield members may not contact the main shield body, wherein a respective clearance gap may have a width of up to 3 mm, optionally up to 1.5 mm.

The at least one shield member and/or of any one or several, or optionally all, of the plurality of shield members may comprise(s) at least one opening to allow for a supporting structure, and/or a cable to pass through the at least one shield member, or any one or several, or all, of the plurality of shield members.

For example, shield members may be plate-shaped and may comprise openings located at mutually different locations or at mutually same locations, e.g., centrally in the plate or at a different position, such that a cable or a supporting structure can consecutively pass through every shield member or plate. This way, a cable or a supporting structure or both

can pass from the opening to the accommodating space and, e.g., support a quantum device and/or transmit signals thereto and therefrom and/or supply the quantum device with energy. This way, support and cable supply may be provided while minimizing any detrimental effects on the shielding of fields and/or radiation reaching the quantum device.

The at least one shield member may comprise a metal-containing plate and a superconductive plate, wherein the metal-containing plate of the at least one shield member may comprise the high permeability layer, and the superconductive plate of the shield member may comprise the superconductive material layer.

Optionally, the metal-containing plate of the at least one shield member consists of the high permeability layer.

Optionally, the superconductive plate of the at least one shield member consists of the superconductive material layer.

Optionally, any one or several, optionally all, of the plurality of shield members comprise a respective metal-containing plate and a respective superconductive plate, wherein, for any one or several, optionally all, of the plurality of shield members, the respective metal-containing plate comprises the high permeability layer and the respective superconductive plate comprises the superconductive material layer.

For any one or several, optionally all, of the plurality of shield members, the respective metal-containing plate may consist of the high permeability layer.

For any one or several, optionally all, of the plurality of shield members, the respective superconductive plate may consist of the superconductive material layer.

The superconductive layer of the at least one shield member may comprise any one or more than one of the materials selected from the list consisting of: indium, rhenium, yttrium barium copper oxide, tin (Sn), aluminum (Al), titanium nitride (TiN), titanium (Ti) and Nb.

When the shielding device comprises a plurality of shield members, the superconductive layer of any one or several, or optionally all, of the plurality of shield members may comprise any one or more than one of the materials selected from the list consisting of: indium, rhenium, yttrium barium copper oxide, tin (Sn), aluminum (Al), titanium nitride (TiN), titanium (Ti) and Nb.

The superconductive layers of two shield members may comprise the same materials. Alternatively, the superconductive layers of different shield members may differ in terms of material. For example, the superconductive layer of a first shield member may comprise different materials than the superconductive layer of a second shield member, or the superconductive layer of a first and the superconductive layer of a second shield member may partially comprise the same materials and partially different materials.

The high permeability layer of the at least one shield member may comprise any one or more than one of the materials selected from the list consisting of: Cryophy, Cryperm, Tokin R, A4K, other cryogenic compatible high permeability materials, typical of hi Ni-iron alloys ("hi" stands for high content).

When the shielding device comprises a plurality of shield members, the high permeability layer of any one or several, or optionally all, of the plurality of shield members may comprise any one or more than one of the materials selected from the list consisting of: Cryophy, Cryperm, A4K, Tokin R, and other cryogenic compatible high permeability materials, typical of hi Ni-iron alloys.

The main shield body may comprise or consist of a superconductive material layer that is superconductive when cooled below a critical temperature. It may not be necessary to also include any high permeability layer in the main shield body due to the presence of the shielding element. This may allow reducing the weight of the entire assembly. It may allow reducing the material costs.

The main shield body may comprise side walls and a bottom wall and the opening may be provided on an end of the shielding device that is remote from the bottom wall. The bottom wall being located at an end side of the shielding device, a top wall may be provided at the other end side of the shielding device, and the opening may be provided in the top wall. Alternatively, the shielding device may not comprise such a top wall, and the opening may be provided by virtue of the absence of the top wall so that the shielding device is open at the end side that is opposite to the one end side where the bottom wall is provided.

The main shield body may be cylindrically shaped, and the shielding device may be open on one side, either on the top side or on the bottom side. Alternatively, a side surface of the shielding device may comprise the opening.

The main shield body may comprise a superconductive material layer that is superconductive when cooled below a critical temperature. The main shield body may not comprise a high permeability layer. This may allow saving material and weight.

The main shield body may comprise a high permeability layer with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m).

Any side wall or other part of the main shield body may comprise a high permeability layer with a relative electromagnetic

permeability of at least 10^5 Henries per meter (H/m).

Any side wall or other part of the main shield body may comprise a superconductive material layer that is superconductive when cooled below a critical temperature. Different walls and/or parts of the main shield body may comprise the same materials or they may mutually differ in terms of material composition. The side wall or other part of the main shield body may not comprise a high permeability layer. This may allow saving material and weight.

A superconductive material layer, optionally, a superconductive layer, may be provided on at least one of the inside walls of the side walls and/or bottom wall of the main shield body that is exposed to the interior space on at least a part of the inside wall, optionally on the entire inside wall. This may particularly efficiently promote the shielding by the shielding device.

The superconductive material layer may be provided on at least one of the inside walls of the side walls and/or a bottom wall of the main shield body and may be provided in at least a part of the accommodating space.

There may be no superconductive material layer provided on at least a part of the inside walls and/or a part of the bottom wall of the main shield body.

Another aspect of the present disclosure relates to a shielding assembly that comprises a plurality of shielding devices, wherein only one of the shielding devices is in accordance with any of the shielding devices described above. The other shielding devices may be the same or they may differ.

The outermost shielding device may be a shielding device in accordance with any one or several features of a shielding device described above (i.e., a shielding device in accordance

with the present disclosure).

The plurality of shielding devices may be at least partially inserted into one another, from an outermost shielding device to an innermost shielding device.

The outermost shielding device may be provided with a lid member configured to close off an opening of the outermost shielding device. The lid member may comprise at least one lid member opening for letting a component, such as a cable or a stabilizing structure, pass.

At least one inner shielding device may comprise an inner lid member configured to close off an opening of the inner shielding device. The inner lid member may comprise at least one inner lid member opening for letting a component, such as a cable or a stabilizing structure, pass.

Another aspect of this disclosure relates to a shielded quantum processing unit comprising a shielding device in accordance with any one or several features described above or a shielding assembly in accordance with any one or several features described above, as well as a quantum processing unit provided in the accommodating space.

The combination of the shielding element with other shielding components, such as one or several shielding members and/or an main shield body may provide a particularly efficient shielding effect, while promoting material savings and a light weight construction.

Another aspect of this disclosure relates to a quantum device comprising a shielding device in accordance with any one or several features described above and/or the shielding assembly in accordance with any one or several features described above and/or the shielded quantum processing unit described above. The quantum device is, for example, a quantum computer.

Additional advantages and features of the present disclosure, that can be realized on their own or in combination with one or several features discussed above, insofar as the features do not contradict each other, will become apparent from the following description of particular embodiments.

The combination of the shielding element with other shielding components, such as one or several shielding members and/or an main shield body may provide a particularly efficient shielding effect, while promoting material savings and a light weight construction.

Brief Description of the Drawings

For a better understanding of the present disclosure and to show how the same may be carried into effect, reference will now be made, by way of example only, to the accompanying figures:

Fig. 1 depicts a shielding element in accordance with the present disclosure;

Fig. 2A depicts a shielding device in accordance with the present disclosure;

Fig. 2B depicts a shielding device in accordance with the present disclosure;

Fig. 2C depicts a shielding device in accordance with the present disclosure;

Fig. 2D depicts a shielding device in accordance with the present disclosure;

Fig. 3 shows experimental results concerning the shielding effect achieved at different locations surrounding and inside a shielding device in accordance with the present disclosure; and

Fig. 4 shows experimental results concerning the shielding effect achieved at different locations surrounding and inside the shielding device of Fig. 3.

Fig. 1 shows a schematic three-dimensional view of a shielding element 1 in accordance with the present disclosure. The shielding element 1 is for shielding a magnetically sensitive device from electromagnetic noise.

The shielding element 1 comprises a wall section 10. As shown in Fig.1, this shielding element has a shape of a cylindrical side surface. However, the shape of the shielding element can also not be cylindrical, but for example have a rectangular side surface.

The wall section 10 surrounds an opening 11 that extends through the shielding element 1 in a first direction. The first direction is in this case an axial direction extending through the center of the cross-sections of the wall section 10. In the case of Fig. 1, the first direction is parallel to the cylinder axis of the cylinder, of which the wall section 10 is a side circumferential surface section. The first direction is shown by an arrow in Fig. 1.

The wall section 10 has a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m). In fact, in the case of Fig. 1, the relative electromagnetic permeability may be in the range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries, but it may take on value outside of this latter range for other examples.

An average dimension of the opening 11 in a plane perpendicular

to the first direction is larger than an average dimension of an extension of the wall section in the first direction. In the case of the shielding element 1 of Fig. 1, the average dimension is an average width which corresponds the diameter of a cross-sectional surface in the plane perpendicular to the first direction, i.e., the direction of extension in axial direction of the wall section 10. In the case of the shielding element 1 of Fig 1, the statement that the average width is larger than the average length means that the cylindrical side surface has a height smaller than the width of the enclosed cylindrical space.

The aspect ratio of the wall section 10 of Fig. 1 is between 0.1 and 0.5, wherein the aspect ratio is defined as the average length of an extension of the wall section in the first direction (which is in this case the height of the cylinder enclosed by the cylindrical side wall surface constituting the wall section 10) divided by an average width of the opening 11 in the plane perpendicular to the first direction, wherein the first direction is in this case the axial direction of the cylindrical space.

The average wall thickness of the wall section 10 of the shielding element 1 of Fig. 1 is 1.5 mm or 1.0 mm. However, for other examples. It may take on different values in a range of 10 mm or less, or 3mm or less, 2 mm or less, or between 0.8 mm and 1.7 mm.

At the two axial ends of the cylindrical side-surface shaped wall section 10 of the shielding element 1 of Fig. 1, there are a first end 12 (shown at the top side in Fig. 1) and a second end 13 (shown at the bottom side in Fig. 1).

At the first end 12, the shielding element 1 comprises a protrusion 14 from the wall section 10 in a direction perpendicular to the first direction (i.e., in the radial direction which is perpendicular to the axial direction in the

case of Fig. 1). The protrusion 14 extends outward (in the radial section) with respect to the wall section 10.

Also at the second end 13, the shielding element 1 comprises a protrusion 15 from the wall section 10 in a direction perpendicular to the first direction (i.e., in the radial direction which is perpendicular to the axial direction in the case of Fig. 1). The protrusion 15 extends outward (in the radial section) with respect to the wall section 10.

In the case of other examples, the protrusions may not be present or they may only be present at one of the two ends. Moreover, the protrusions at one end or the other end or at both ends may extend inward from the wall section 10 in other cases.

Fig. 2A depicts a shielding device 20 for shielding a magnetically sensitive device 50.

First and foremost, the shielding device 20 comprises a shielding element 1 in accordance with the present disclosure, for example, the shielding element 1 of Fig. 1.

The shielding device 20 comprises a main shield body 21 that, together with a lid (not shown), encapsulates an interior space 22. The shielding device 20 comprises an opening 23 that provides access to the interior space 22. The lid (not shown) may cover the opening 23, but itself has a central opening which allows cables and a support structure 60 to pass through.

The shielding element 1 is provided in the interior space 22.

A part of the interior space 22 is also specifically referred to as an accommodating space 24 for accommodating an electromagnetically sensitive device 50 that is to be shielded, e.g., a quantum device. In other words, the electromagnetically

sensitive device 50 may be provided in the accommodating space 24.

The main shield body 21 of the shielding device 20 of Fig. 2A may be cylindrically shaped and comprise side walls and a bottom wall, while there may be no upper wall or surface. The open top may, hence, in this case constitute the opening 23 that may provide access to the interior space 22. As mentioned above, the shielding device 20 may optionally comprise a lid (not shown) comprising an opening or openings for cables and/or support mechanical structure. A support structure 60 enables to connect the sensitive magnetic device 50 to external components of the shielding device 20, in particular being a vertical mechanical connection to elements located on the top and outside of the shielding device 20.

A magnetically sensitive device 50 that may be placed in the accommodating space 24 may, for example, be a quantum device. The magnetically sensitive device 50 is then shielded by the shielding device 20.

The magnetically sensitive device may, for example, be a Traveling Wave Parametric Amplifier (TWPA). A quantum device is a device using principles of quantum physics to, for example, perform a computational, informational, communication or measurement task. A quantum device may, e.g., be one of a quantum computer, a quantum processor, a quantum sensor, a quantum limited amplifier, a quantum key distribution system, a quantum random number generator, a quantum communication system, a quantum annealer, a quantum simulator, and a quantum cryptography device.

In Fig.2A, two shield members 30 and 40 are located in the interior space 22. They are connected to a mechanical support 60, for example, bolted to a main axis of the support (which may include wire guides) of the shield device 20, so that it is stably mounted and held in place.

The shield members 30 and 40 are both located inside of the shielding element 1 and are thus surrounded by the latter. In other words, the shielding element 1 at least partially surrounds the shield members 30, 40, so that the shielding element 1 is positioned between the main wall of the shielding device and the shield members 30, 40. A clearance gap may be present between the shielding element 1 and the shield members 30 and 40. The clearance gap may be in a clearance range, meaning the shielding element 1 and the shield members 30, 40 may be considered slightly touching so that sliding may be possible without scratching / damaging the materials. The clearance gap may have a width of around 1.5mm, but the width may, more generally, be of the order of 3mm or less. This provides a particular shielding effect which allows avoiding the formation of the main shield body 21 of both a low permeability layer as well as a highly conductive (in particular: a superconductive) layer. The shielding effect can be provided more specifically by the shielding element 1 at one specific location within the accommodating space of the shielding device where the shield members are located. In Fig. 2A, one shielding element 1 surrounds both shield members 30 and 40.

The shielding element 1 and the shield members 30 and 40 are structurally distinct from the main shield body 21. They may also be separable from the main shield body 21. They may namely be built in and out. That is, the shielding element 1 and the shield member 30 and 40 may be removed from the interior space 22 without being damaged and without damaging the main shield body 21. The shield members 30 and 40 may also be referred to as a baffle.

As reflected by Fig. 2A, the shielding element 1 and the shield members 30 and 40 may not touch the main shield body 21. The shielding element 1 and the shield members 30 and 40 may be located at a distance of the side walls of the main shield

body 21. This may further prevent the penetration of electromagnetic field deeper into the shielding device 20. A clearance gap may be present between the shielding element 1 and the main shield body 21, the distance being a clearance gap. The clearance gap may be in a clearance range, meaning the shielding element 1 and the main shield body 21 may be considered slightly touching so that sliding may be possible without scratching / damaging the materials. The clearance gap may have a width of around 1.5mm, but the width may, more generally, be of the order of 3mm or less, or of 1.5mm or less.

In the case of the embodiment of Fig. 2A, the shield members 30 and 40 are baffles. The term baffle, as used herein, refers to a plate or screen that is for deflecting, directing or blocking a flow of a flux, in particular, a magnetic flux.

The shield member 30 comprises a high permeability layer 31 with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a low permeability layer 32 that is a superconductive material layer that is superconductive when cooled below a critical temperature.

The shield member 40 comprises a high permeability layer 41 with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a low permeability layer 42 that is a superconductive material layer that is superconductive when cooled below a critical temperature.

The shield members 30 and 40 may also comprise a respective mechanical support layer (not shown) on which the low permeability layers 32 and 42 is fixed. The mechanical support layer may be plate-shaped and may primarily be made of copper.

The shield members 30 and 40 may be provided between the opening 23 of the shielding device 20 and the accommodating space 24. This means that they exert a shielding effect at a location in-between the opening 23 and the bottom wall of the

main shield body 21, and, in other words, where the magnetically sensitive device 50 is placed in the accommodating space 24. Therefore, the shield member 30, 40 may prevent electromagnetic field flux and/or radiation from reaching the accommodating space 24 of the shielding device 20, i.e., from reaching the magnetically sensitive device 50. Thereby, the shield member 30, 40 may shield off the electromagnetically sensitive device 50 located in the accommodating space 24 from electromagnetic noise.

According to Fig. 2A, the shield members 30, 40 may comprise a high permeability layer 31, 41 with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m). In particular, the high permeability layer 31, 41 may be metal-containing layers.

The shield members 30 and 40 may also comprise respective low permeability layers 32, 42 that are superconductive when cooled below a critical temperature. In particular, the low permeability layers 32, 42 may be superconducting layers.

According to Fig. 2A, the high permeability layer 31 may be provided between the opening 23 and the low permeability layer 32. Likewise, the high permeability layer 41 may be provided between the opening 23 and the low permeability layer 42. Thus, electromagnetic field flux or radiation propagating towards the inside of the shielding device 20 may be diverted away from a propagation direction towards the accommodating space by the high permeability layers 31 and 41. Any remaining electromagnetic field and/or radiation that gets past the respective metal-containing plate may be blocked by the respective low permeability layers 32 and 42.

Alternatively, one or several other layers (e.g., one or several plates) may be provided in-between, and the shield member 30, 40 may, hence, comprise further layers/plates, etc. For example, a thermalization layer may be provided between

the high permeability layer 31, 41 and the low permeability layer 32, 42. The thermalization layer may be made of copper.

Maintenance of the shielding device 20 or of a device placed therein may be carried out particularly conveniently and efficiently. As the shielding element 1 and the shield member 30 and 40 may be taken out of the interior space 22, it may be possible to access the accommodating space 24 very easily.

Fig. 2A illustrates an embodiment wherein the high permeability layer 31 and the low permeability layer 32, as well as the high permeability layer 41 and the low permeability layer 42, are provided with a gap in-between, respectively. There are other examples without a gap in-between. The high permeability layer 41 and the low permeability layer 42 may, e.g., be glued to each other or screwed together.

In a variant, the shield members 30 and 40 each comprise only one baffle or plate.

An average distance between opposing sections of the wall section 10 of the shielding element 1 is in a range of 0.7 to 0.99 times an average width of an interior wall of the interior space 22. Thus, the wall section 10 may fit inside the interior space 22 without touching the interior wall and is separable from the interior space. In the case of Fig. 2A, the wall section 10 and the interior wall are lateral cylindrical surfaces.

The shielding element 1, the main shield body 21 and the shield members 30, 40 have a common central axis as shown in Fig. 2A.

The main shield body 21 comprises a superconductive material layer that is superconductive when cooled below a critical temperature. Due to the presence of the shielding element 1, which may in this case of Fig. 2A also be referred to as a shielding ring, it is not necessary to also include a low

permeability layer in the main shield body 21, as the shielding effect on the sides is provided highly specifically in the zone surrounding the shield members 30 and 40.

In a variant, one shielding element 1 may surround only one shield member or may surround more than two shield members.

Fig. 2B shows a configuration in which a plurality of shielding devices 20, 20A and 20B are inserted into one another. The outermost shielding device 20 comprises a shielding element 1 in accordance with the present disclosure. The shielding element 1 is located such that it surrounds and shields off a shield member 30 including a high permeability layer 31 (a superconductive layer) and a low permeability layer 32, analogous to what was described above.

The shielding device 20A is inserted into the interior space 22 of the shielding device 20. In turn, the shielding device 20B is inserted into the interior space 22A of the shielding device 20A. In other words, the main shield body 21B of the shielding device 20B is inserted into the interior space of the main shield body 21A of the shielding device 20A, and the main shield body 21A of the shielding device 20A is inserted into the main shield body 21 of the outermost shielding device 20.

In the case of Fig. 2B, only the outermost shielding device 20 is provided with a shielding element 1, but the two inner shielding devices 20A and 20B do not comprise additional shielding elements.

Figure 2B illustrates a situation in which two additional shielding devices 20A, 20B comprising their respective shield members 30A, 30B are located inside of the outermost shielding device 20. However, other total numbers of shield members 30, 30A and 30B are possible as well. In particular, the total number of shield members 30, 30A and 30B may be from 2 to 7,

and in particular from 3 to 5. In particular, 3 to 5 shield members may be suited to keep the volumetric space small while providing very efficient shielding. The additional shielding devices 20A and 20B comprise a main shield body 21A, 21B respectively and a shield member 30A and 30B respectively and do not comprise a shielding element.

A plurality of shield members (baffles) 30, 30A and 30B can thus work together to reduce, in each iteration (for each baffle), the magnetic flux into the system so that the (QPU) performance is equivalent to a fully contained shield. There may be a maximum number of shield members (baffles), for example 4 - 5 baffles, as adding more baffles will have no further practical reduction (diminishing return).

The uppermost part of the shielding device 20A (that is, the middle shielding device which is placed in the outermost shielding device 20 and which comprises the innermost shielding device 20B) is surrounded by a part of the shielding element 1. In particular, the shield member 30A of the shielding device 20A is shielded laterally by the shielding element 1. The shield member 30A is in the case of the embodiment of Fig. 2B comprising a high permeability layer 31A (optionally, a superconductive layer), and a low permeability layer 32A, analogous to what was described above for the shield member 30.

The innermost shielding device 20B comprises a shield member 30B comprising a high permeability layer 31B (optionally, a superconductive layer), and a low permeability layer 32B, analogous to what was described above for the shield members 30 and 30A.

A magnetically sensitive device 50, such as a quantum device, may in particular be placed inside the accommodating space 24B of the innermost shielding device 20B. This is a particularly efficiently magnetically shielded space.

The mutually inserted configuration of the shielding devices 20, 20A, 20B, combined with the provision of a single shielding element 1 (in this case: a shielding ring) allows for a light-weight construction. The main shield bodies 21, 21A, 21B of all three shielding devices 20, 20A, 20B may comprise a high permeability layer, but may not comprise a low permeability layer.

The shielding devices 20A, 20B may be built in and out of the shielding device 20. That is, they may be removed from the interior space without being damaged and without damaging the main shield body 21. Likewise, the shielding device 20B may be built in and out of the shielding device 20A. That is, it may be removed from the interior space without being damaged and without damaging the main shield body 21A.

All of the three shield members 30, 30A, and 30B may be provided between the opening 23 and the accommodating space 24. They may exert shielding effects in-between and may thus prevent electromagnetic field flux and/or radiation from reaching the accommodating space. Thereby, the shield members 30, 30A, 30B may shield off the quantum processing unit (or a different quantum device provided in the accommodating space 24) from electromagnetic noise.

Fig. 2C relates to a configuration in which a first shielding element 1 as well as a second shielding element 1A are provided in a shielding device 20. Moreover, three shield members 30, 30A, and 30B are provided inside of the main shield body 21 of the shielding device 20.

Each of the three shield members 30, 30A, 30B may comprise a respective high permeability layer 31, 31A, 31B with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m). In particular, any one or two of or each of the high permeability layers 31, 31A, 31B may be a metal-containing

layer.

Each of the three shield members 30, 30A, and 30B may also comprise a respective low permeability layer 32, 32A, 32B that is superconductive when cooled below a critical temperature. In particular, one or two or each of the low permeability layers 32, 32A, 32B may be a superconducting layer.

Fig. 2C shows a configuration in which a plurality of shield members 30, 30A and 30B are provided in series between the opening 26 and the accommodating space 24, along the mechanical structure 60. Thus, electromagnetic fields and/or radiation may be prevented from approaching the accommodating space 24 very efficiently due to the alternating encounters with a diverting high permeability layer 31, 31A, 31B (through which flow is diverted towards the sides and away from the direction towards the accommodating space 24) and the respective low permeability layer 32, 32A, 32B (that shields off and prevents noise from passing).

For each of the three shield members 30, 30A, 30B, their high permeability layer 31, 31A, 31B may be provided between the opening 26 and the respective low permeability layer 32, 32A, 32B. Thus, electromagnetic field flux or radiation heading towards the inside of the shielding device 20 may be respectively diverted by the high permeability layer 31, 31A, 31B. Electromagnetic field flux or radiation which nevertheless passes a respective high permeability layer, may be blocked by the corresponding superconductive plate, i.e., by the respective low-permeability layer. This may be successively repeated for what respectively leaks past a pair of high and low permeability layers through. Three to five serially arranged shield members may provide particularly good shielding effects, and the gain in shielding effect may be particularly high until reaching the total number of shield member of 3 to 5. The increase in shielding efficiency may merely be incremental when adding further plates, so that

saving costs and space may outweigh the benefit of additional shield members beyond a total of 3 to 5.

Maintenance of the shielding device 20 or of a quantum device placed therein (e.g., the quantum processing unit) may be carried out particularly conveniently and efficiently. As the shield members 30, 30A, and 30B may be taken out of the interior space, it is possible to access the accommodating space 24 very easily.

The respective high permeability layers 31, 31A, 31B and the low permeability layers 32, 32A, 32B, forming a respective pair belonging to a shield member 30, 30A, 30B of Fig. 2C are adhered together. Alternatively, such a pair may be separated by a gap, in line with what was discussed above. In other variants, with gaps present, the gap between the high permeability layer 31, 31A, 31B and the low permeability layer 32, 32A, 32B can be different for each shield member 30, 30A, 30B. In a variant, the two layers may be provided directly in contact without a gap in-between. They can be glued to each other or screwed together. Alternatively, one or several other layers (e.g., one or several plates) may be provided in-between, and the respective shield member 30, 30A, and 30B may, hence, comprise further layers/plates, etc. For example, a thermalization layer may be provided between the high permeability layer 31, 31A, 31B and the low permeability layer 32, 32A, 32B. The thermalization layer may be made of copper. Each of the shield member 30, 30A, and 30B of the plurality of shield member may have a different design for the combination of the high and low permeability layers 31, 31A, 31B 32, 32A, 32B.

Moreover, adjacent shield members 30, 30A, and 30B may also be separated by respective gaps d. The gaps d may all be the same or they may differ. The gaps d between the adjacent shield members 30, 30A, and 30B may be larger than the gaps d between

the high and low permeability layers 31, 31A, 31B, 32, 32A, 32B of each shield member 30, 30A, 30B.

Each of the high permeability layer 31, 31A, 31B and the low permeability layer 32, 32A, 32B of each of the three shield members 30, 30A, and 30B may be provided with an opening (not shown) through which a cable can pass. It connects the quantum processing unit (or another quantum device) with another unit outside of the shielding device 20. The openings in the plates can also be used to let a supporting structure penetrate.

The three shield members 30, 30A, and 30B may all be structurally the same or two may be the same and one may differ from two of them. Alternatively, they may all three be structurally different from one another, e.g., in terms of thickness and/or material composition and/or layers, distribution of materials, etc.

In particular, the high permeability layer 31, 31A, 31B of each of the three shield members 30, 30A, and 30B may have a relative electromagnetic permeability which is comprised in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries. However, different ranges (in accordance with what is disclosed above) may be possible. Moreover, all three shield members 30, 30A, and 30B may in this regard be the same, or they can mutually differ.

The three shield members 30, 30A, and 30B may each comprise a mechanical support layer (not shown) on which the low permeability layer 32, 32A, 32B may be fixed. The mechanical support layer may be plate-shaped and may primarily be made of copper.

The top shield member 30 in Fig. 2C may be the outermost shield member, whereas the bottom shield member 30B in Fig. 2B may be the innermost shield member.

The first shielding element 1 (in this case: an annular shielding ring) may shield off the first shield member 30 laterally. The second shielding element 1A (in this case: an annular shielding ring) may shield off the third shield member 30B laterally. Moreover, the first shielding element 1 and the second shielding element 1A may together also shield off the second shielding element 1A laterally in the case of the configuration of Fig. 2C.

The main shield body 21 of the shielding device 20 of Fig. 2C may comprise low permeability layer that may be superconductive when cooled below a critical temperature. There may be no need to provide the main shield body 21 with a high permeability layer, due to the presence of the shielding element 1 and the shielding element 1A. the latter provide a lateral shielding effect locally, where it is most useful. This may allow an overall weight and/or size reduction of the configuration.

The shielding device 20 of Fig. 2C together with a magnetically sensitive device 50, in particular, provided therein is an example of a shielded magnetically sensitive (in particular: quantum) processing unit in accordance with the present disclosure.

Fig. 2D shows three shielding devices 20, 20A, and 20B which are inserted into one another, starting from the outermost shielding device 20 to the innermost shielding device 20B, wherein each of the shielding devices 20, 20A, 20B comprises a main shielding body 21, 21A, 21B, a shield member or baffle 30, 30A, 30B, and is provided with its own shielding element 1, 1A, 1B (in this case, the shielding elements 1, 1A, 1B are provided in the shape of shielding rings).

Inside the innermost shielding device 20B, a magnetically sensitive device 50, such as a quantum device, may be provided in the accommodating space 24B.

The respective baffles 30, 30A, 30B each comprise a high permeability layer 31, 31A, 31B, in accordance with the high permeability layers described above, and a low permeability layer 32, 32A, 32B, as described above.

According to the embodiments of Figs. 2A, 2B, 2C, and 2D, the uppermost shield member 30 (i.e., the one located closest to the opening 26 of the shielding device 20) may be located well inside of the interior space 22 of the shielding device 20. Well inside in this context may be understood to mean distanced from the opening 26 of the shielding device 20, i.e., placed at a certain distance from it, so that it may not block the opening 26 of the shielding device 20. In an alternative, a shield member 30, 30A, 30B may be located within the opening 26 of the shielding device 20. This means it will be located at a boundary of the interior space 22 (this would be adjacent to the upper ends of the side walls of the main shield body 21). In another alternative, a shield member 30 could also be located slightly outside of the interior space 22 of the shielding device 20.

The respective main shield bodies of all of the shielding devices 20, 20A, 20B illustrated in Figs. 2A-2D may respectively comprise a high permeability layer facing the inside, with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m). Namely, all the side walls and the bottom wall may comprise a high permeability layer 15 with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m).

In each of the embodiments of Figs. 2A-2D, the respective shield member 20 may comprise a mechanical support layer (not shown) on which the high permeability layer is fixed. The mechanical support layer may be plate-shaped and may primarily be made of copper.

Fig. 3 depicts simulation results concerning the shielding effect of the magnetic flux achieved by using the shielding device 20 in accordance with the present disclosure. The simulation results show the shielding effect at different locations inside the shielding device 20.

The shielding device 20 for which the shielding of magnetic flux in terms of electromagnetic fields and radiation was simulated, comprises three shield members as described above. The shading in the different parts inside of the shield device show that the shielding effect is gradual within the shielding device. Starting from the top opening of the shielding device, the shielding effect becomes stronger and stronger as one moves further inside the shielding device towards the bottom of the shielding device. The combination of a shielding element in accordance with the present disclosure with the shield members results in a very strong reduction of the magnetic flux within the accommodating space of the shielding device at this location. The magnetic flux is further reduced where the magnetically sensitive device is located. While only one shielding element is used within the shielding device at a different location to where the magnetically sensitive device is located, the magnetic flux shielding is still strongly reduced at the position of the magnetically sensitive device. Thus, a localized use of a shielding element in combination with a shield member enables to obtain a strong magnetic field shielding of a magnetically sensitive device located within an accommodating space of the quantum apparatus. It is thus not necessary to have a shielding element present over the whole surface of the inner wall of the shielding device 1, the use of a local shielding element at a specific location, namely next to a shield member, is enough to result in an efficient magnetic field shielding.

Fig. 4 is a graph that shows simulation results concerning the shielding effect of the magnetic flux achieved by using the shielding device 20 according to the invention. The shielding

effect can be seen at different locations inside the shielding device 20 to which also the results of Fig. 3 relate to.

The simulated magnetic flux density (measured in Tesla) on the y-axis is shown in function of the z-coordinate on the x-axis, wherein the z-direction is the height direction of the shielding device. In other words, the z-coordinate extends from the bottom to the top, i.e., from the bottom side of the shielding device to the accommodating space, past the shield members and towards the opening of the shielding device.

Looking at Figs. 3 and 4, one can see that the opening of the shielding device 20 is associated with a z-coordinate of around 70, the shielding element 1 is associated with z-coordinates between around 30 to 40, and the shield members are then associated with z-coordinates around 40, 30, and 20. The flux density decreases significantly when moving from the z-range of around 70 to around 20 in Fig. 3. Fig. 4 shows all three 3D vector components of the flux density as a vector quantity as well as the norm (i.e., an absolute value of the strength) of the flux density.

In Fig. 4, the shielding device extends from around $z=-5$ to $z=70$, as a comparison to Fig. 3. At around $z=0$, a magnetically sensitive device, in particular a quantum device such as a quantum processing unit, is positioned within the accommodating space of the quantum apparatus. The shielding element or skirt extends between $z=40$ and $z=30$, being positioned next to a shield member positioned at $z=40$. This combination of shielding element and shield member results in a reduction of magnetic field of about two orders of magnitude, from around $4 \cdot 10^{-6}$ T to $3 \cdot 10^{-8}$ T. Further below is located a shielding device, also called traditional can, which also leads to a further reduction in the magnetic field. As can be seen in Fig. 4, each component comprised in the shielding device act to improve the total shielding provided by the shielding device. Namely the presence of a shielding element, shielding

members and shielding device, also called can, results in an overall shielding device with a good efficiency.

Fig. 4 shows extremely good shielding against the magnetic flux. The magnetic flux density norm takes on values around 10^{-12} T where the device is placed inside the shielding device 20. It is around 7 orders of magnitude lower than outside of the shielding device 20. This enables the magnetically sensitive device to operate in an environment with minimal electromagnetic field interference.

It will be apparent to those skilled in the art that various modifications and variations can be made in the disclosed devices and systems without departing from the scope of the disclosure. Other aspects of the disclosure will be apparent to those skilled in the art from consideration of the specification and practice of the features disclosed herein. It is intended that the specification and examples be considered as exemplary only. Many additional variations and modifications are possible and are understood to fall within the framework of the disclosure.

Claims

1. A shielding element for shielding a magnetically sensitive device (50), in particular a quantum device, from electromagnetic noise,
the shielding element (1) comprising a wall section (10) that surrounds an opening (11) extending through the shielding element (1) in a first direction,
wherein the wall section (10) has a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m)
wherein an average dimension of the opening (11) in a plane perpendicular to the first direction is larger than an average dimension of the wall section (10) in the first direction.
2. The shielding element of claim 1, wherein an aspect ratio of the wall section is 1.0 or less, optionally in a range of 0.1 to 0.5,
with the aspect ratio being defined as an average length of an extension of the wall section (10) in the first direction divided by an average width of the opening (11) in a plane perpendicular to the first direction.
3. The shielding element of claim 1 or 2, wherein the wall section (10) comprises at least one tubular section, in particular, the wall section (10) being a lateral cylindrical surface, in particular the wall section and/or the opening have a circular cross section.
4. The shielding element of any one of the preceding claims, wherein an average wall thickness of the wall section (10) is 10 mm or less, optionally 3mm or less, 2 mm or less, or between 0.8 mm and 1.7 mm.

5. The shielding element of any one of the preceding claims, wherein at least one of a first end and a second end opposite to the first end in the first direction comprises a protrusion (14, 15) from the wall section in a direction perpendicular to the first direction, wherein the protrusion (14, 15) optionally extends outward or inward with respect to the wall section (109), and/or
wherein the relative electromagnetic permeability of the wall section (10) is in a range of $1.5 \cdot 10^5$ to $2.5 \cdot 10^5$ Henries, optionally in the range of $1.8 \cdot 10^5$ to $2.2 \cdot 10^5$ Henries.
6. A shielding device for shielding a magnetically sensitive device (50), in particular a quantum device, from electromagnetic noise, the shielding device (20) comprising:
a main shield body (21) that partially encapsulates an interior space (22) and is provided with an opening (23) that provides access to the interior space (22), with a part of the interior space (22) being an accommodating space (24) for accommodating a magnetically sensitive device (50), in particular a quantum device; and
at least one shielding element (1) of any one of the preceding claims provided in the interior space (12).
7. The shielding device of claim 6, wherein an average distance between opposing sections of the wall section (10) is in a range of 0.7 to 0.99 times an average width of an interior wall of the interior space (22), wherein the wall section (10) optionally fits inside the interior space (22) without touching the interior wall and is separable from the interior space (22), wherein optionally the wall section (10) and the interior wall are at least partially lateral cylindrical surfaces, and/or

wherein the shielding element (1) and the main shield body (21) have a common central axis.

8. The shielding device of claim 6 or 7, comprising:
 - at least one shield member (30, 40) that is located in the interior space (22) and between the opening (23) and the accommodating space (24), and that is structurally distinct and/or separable from the main shield body (10);
 - wherein the at least one shield member (30, 40) comprises at least a high permeability layer (31, 41) with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a low permeability layer (32, 42) that is a superconductive material layer that is superconductive when cooled below a critical temperature, and
 - the high permeability layer (31, 41) is provided between the opening (23) and the low permeability layer (32, 42).
9. The shielding device of claim 8, wherein the wall section (10) of the at least one shielding element (1) at least partially surrounds at least one of the at least one shield members (30, 40), and/or wherein the wall section (10) of one shielding element (1) at least partially surrounds two shield members (30, 40).
10. The shielding device of any one of claims 6 to 9, wherein there is a gap, in particular a clearance gap, between the at least one shield member (30, 40) and the wall section (10), wherein the gap optionally has a width in a range of 0.1 mm to 5 mm, or 0.1 mm to 2 mm, or 0.1 mm to 1 mm.
11. The shielding device of any one of claims 6 to 10, comprising a plurality of shield members (30, 30A, 30B) located in the interior space (22) and between the opening (23) and the accommodating space (24), wherein the wall

section (10) at least partially surrounds at least one of the shield members (30, 30A, 30B), in particular several or all of the shield members (30, 30A, 30B), of the plurality of shield members (30, 30A, 30B),

wherein, two or more, optionally all, of the plurality of shield members (30, 30A, 30B) comprise a respective high permeability layer (31, 31A, 31B) with a relative electromagnetic permeability of at least 10^5 Henries per meter (H/m) and a respective superconductive material layer (32, 32A, 32B) that is superconductive when cooled below a critical temperature, and

the respective high permeability layer (31, 31A, 31B) of the shield member (30, 30A, 30B) is provided between the opening (23) and the respective superconductive material layer (32, 32A, 32B) of the respective shield member (30, 30A, 30B).

12. The shielding device of any one of claims 6 to 11, wherein a clearance range is provided between the shielding element (1) and the main shield body (21), respectively, and the clearance gap has a width in a range of up to 3 mm, optionally up to 1.5 mm, and/or

wherein the main shield body (21) comprises a superconductive material layer that is superconductive when cooled below a critical temperature.

13. A shielding assembly comprising a plurality of shielding devices, wherein at least one of the shielding devices (20) is the shielding device (20) according to any one of claims 6 to 12, and wherein the shielding devices of the plurality of shielding devices (20) are at least partially inserted into one another.

wherein, optionally, only one of the shielding devices (20) is according to any one of claims 6 to 12, and wherein the shielding devices of the plurality of shielding devices (20, 20A, 20B) are at least partially inserted into one another, from an outermost shielding

device (20) to an innermost shielding device (20B), and/or wherein the outermost shielding device (20) is the shielding device (20) according to any one of claims 6 to 12.

14. A shielded quantum processing unit comprising the shielding device (20) according to any one of claims 6 to 12 or the shielding assembly according to claim 13 and a quantum processing unit provided in the accommodating space (24).
15. A quantum apparatus comprising the shielding device (20) according to any one of claims 6 to 12 and/or the shielding assembly of claim 13 and/or the shielded quantum processing unit according to claim 14, wherein the quantum apparatus optionally is a quantum computer.