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(54) **CRYOGENIC COOLING SYSTEM**
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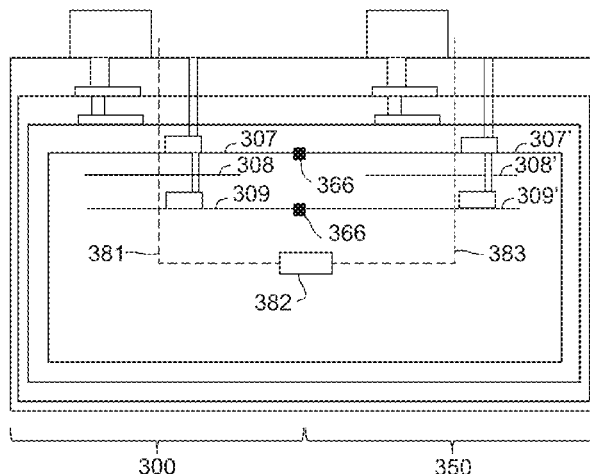
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(57) **ABSTRACT**
A cryogenic cooling system is provided comprising a cryogenic refrigerator assembly and two or more connected modules. The cryogenic refrigerator assembly comprises one or more cryogenic refrigerators. Each said connected module comprises: a housing defining an internal volume for the module, the housing having a plurality of side faces, and a plurality of stages arranged within the internal volume for the module, wherein one or more of the plurality of stages is thermally coupled to the cryogenic refrigerator assembly. The two or more said modules are mutually connected at
(Continued)



respective side faces, and a first said stage of a first said module is thermally coupled to a first said stage of a second said module.

26 Claims, 11 Drawing Sheets

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Fig. 1

Prior Art

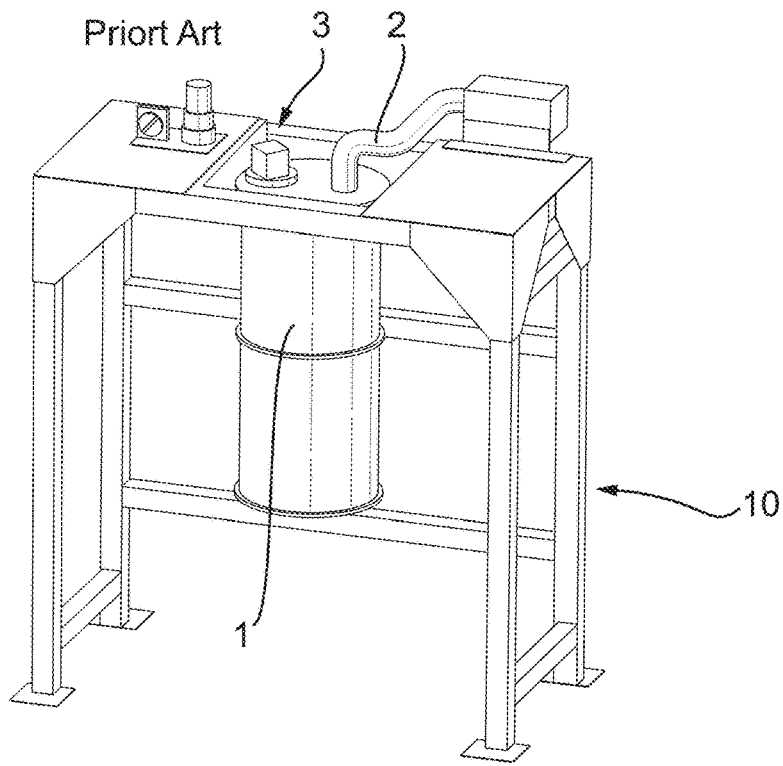


Fig. 2

Prior Art

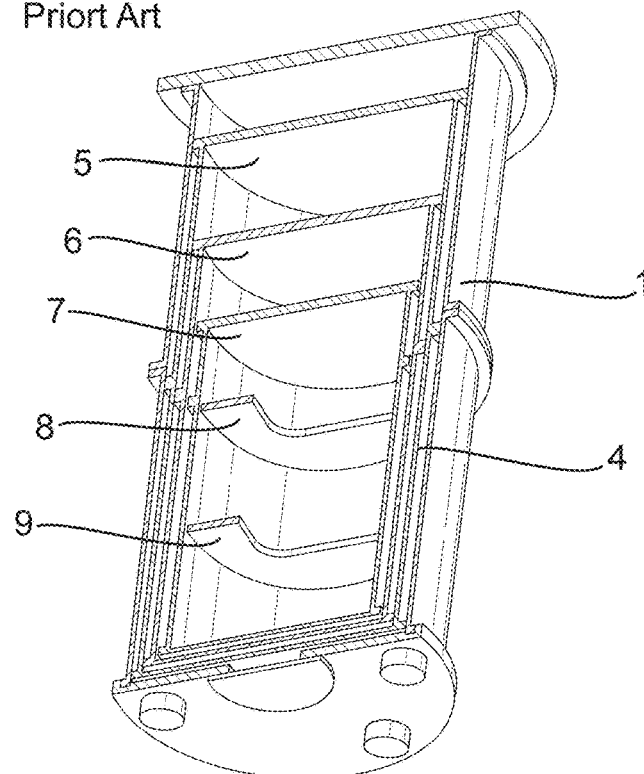


Fig. 3

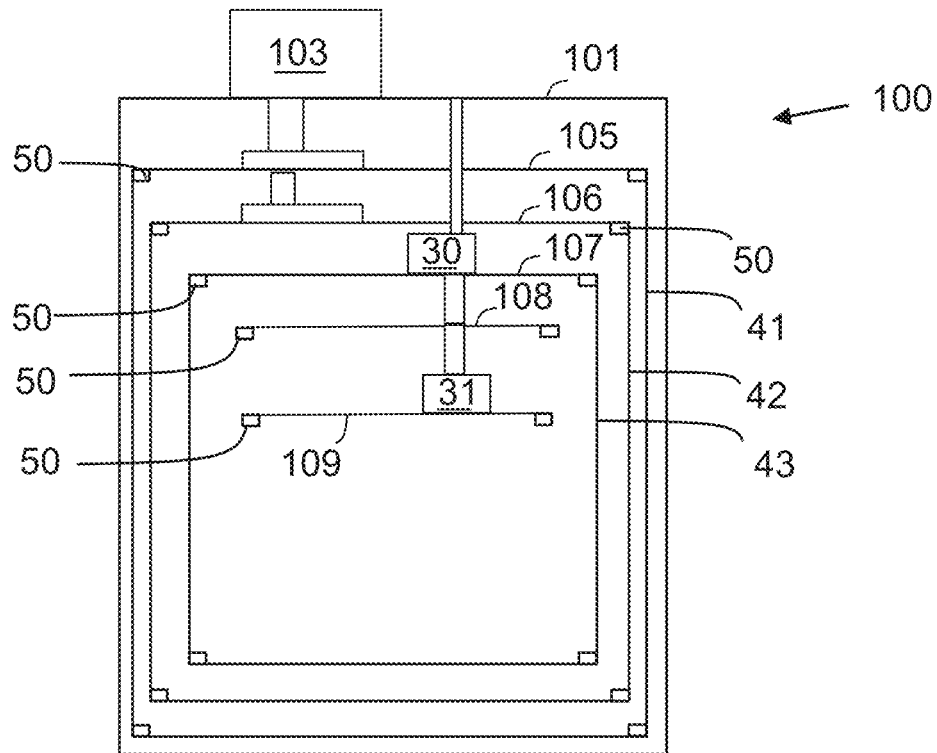


Fig. 4

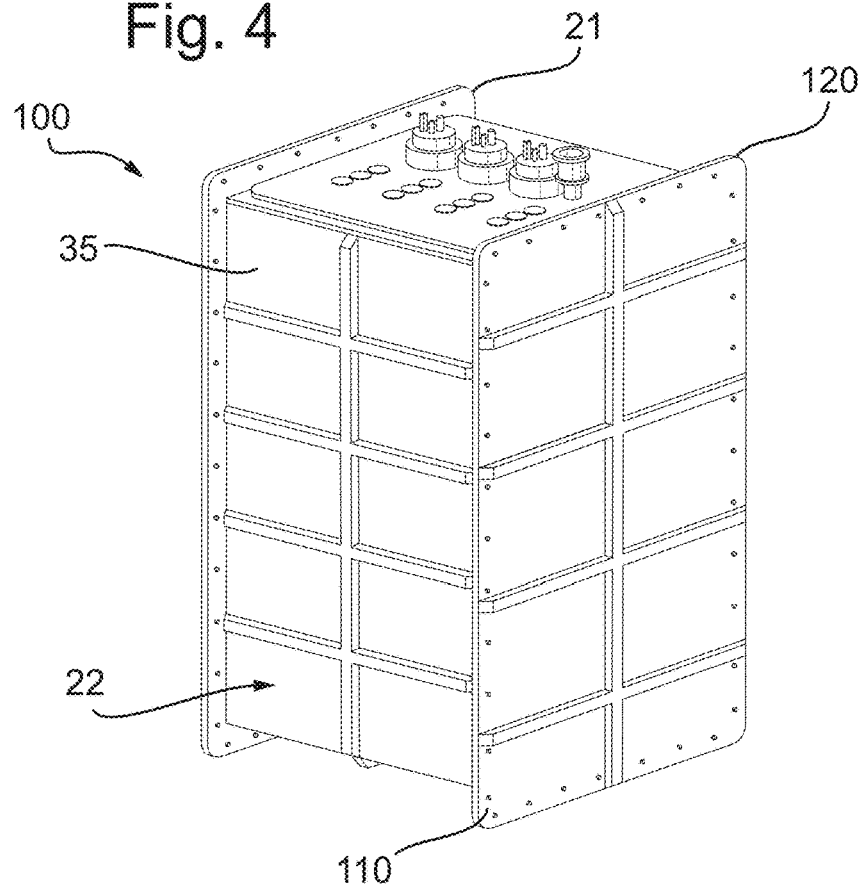


Fig. 5

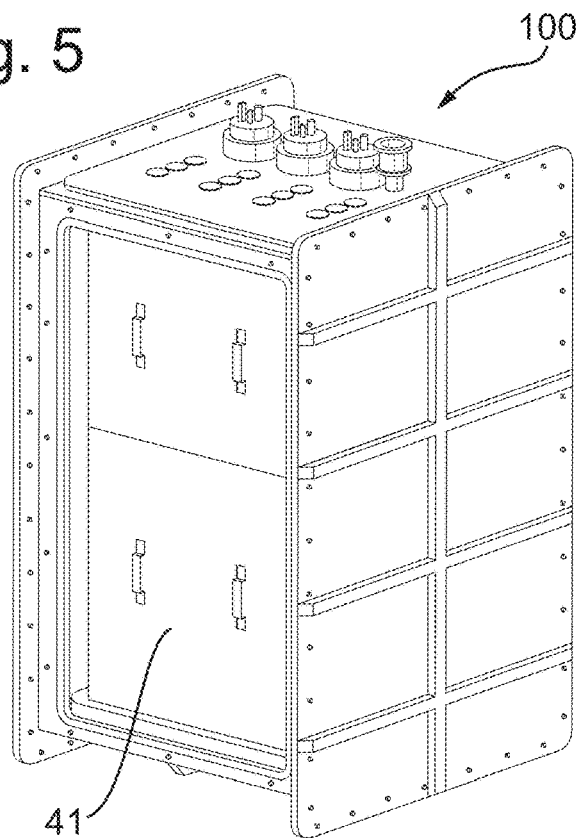


Fig. 6

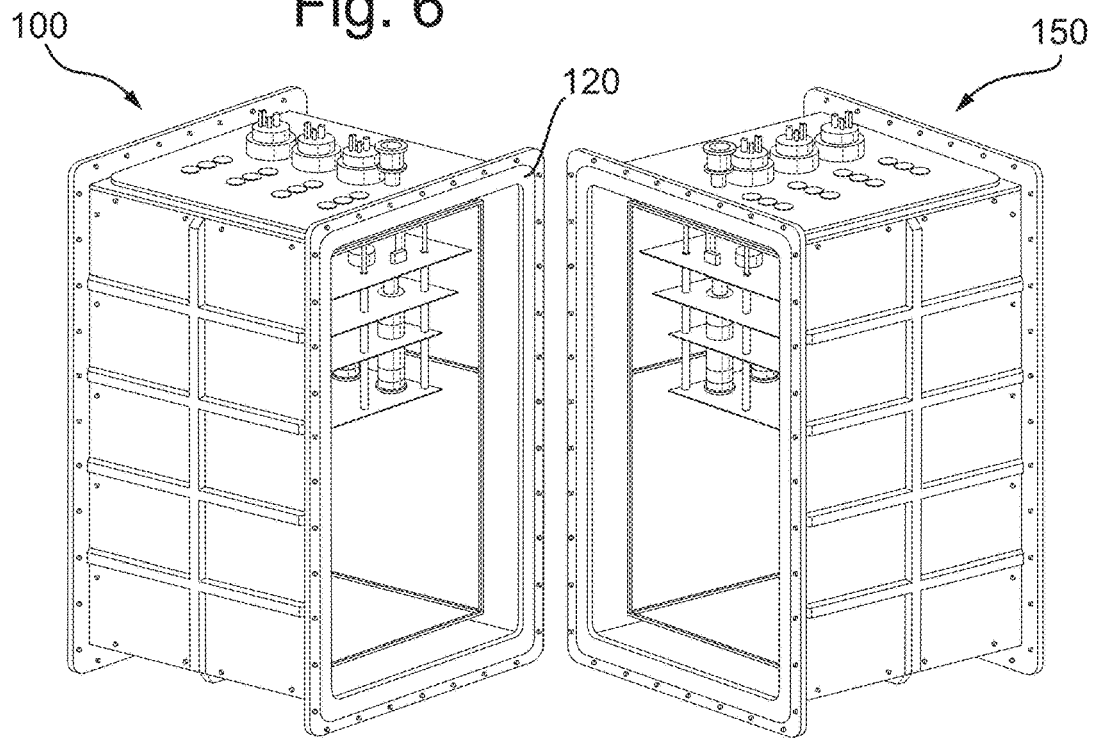


Fig. 7

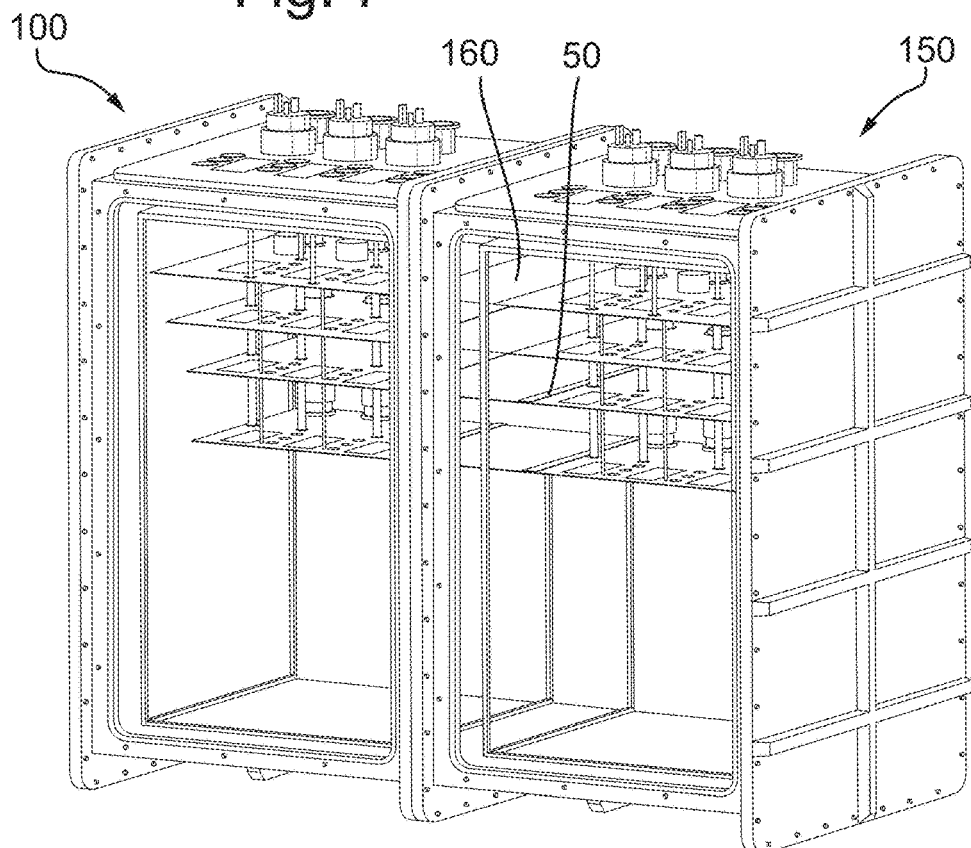


Fig. 8

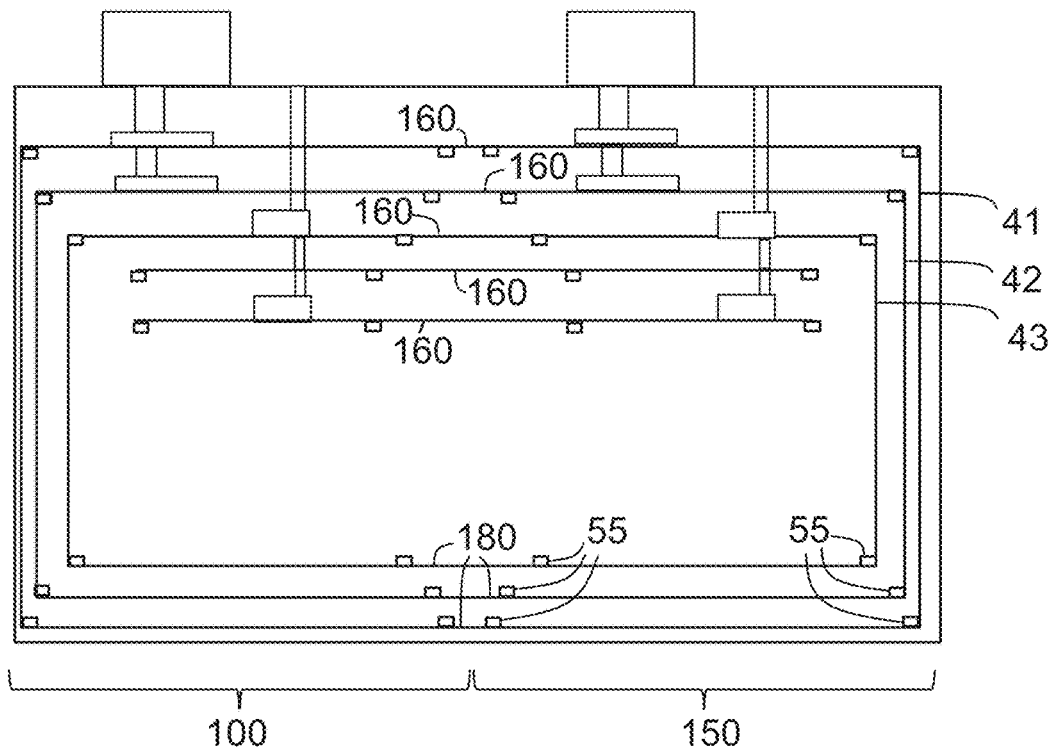


Fig. 9

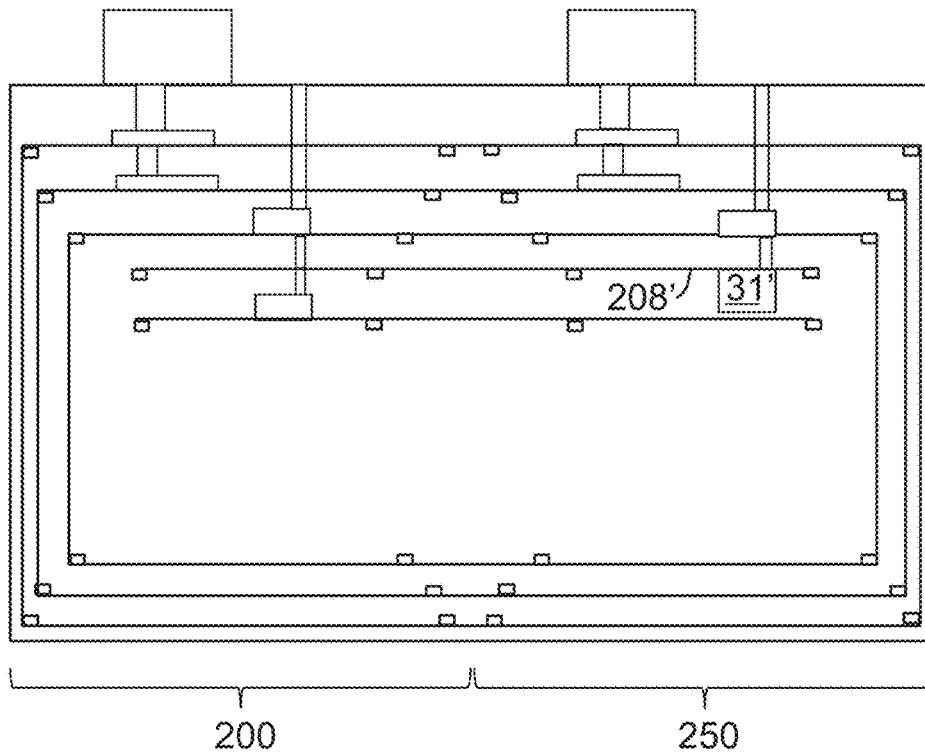


Fig. 10

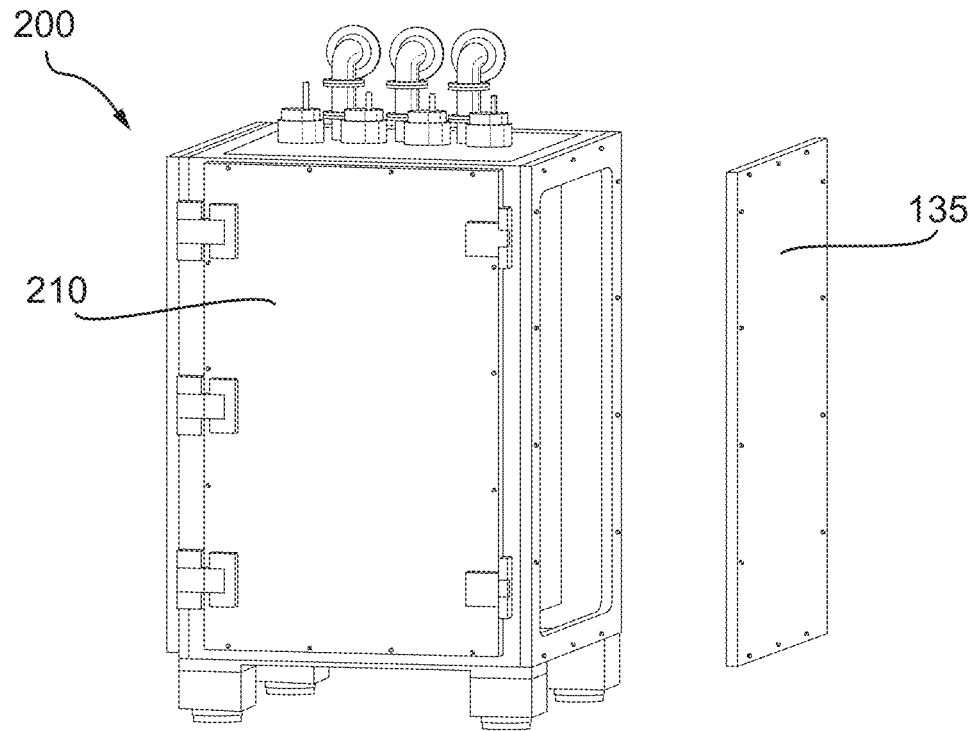


Fig. 11

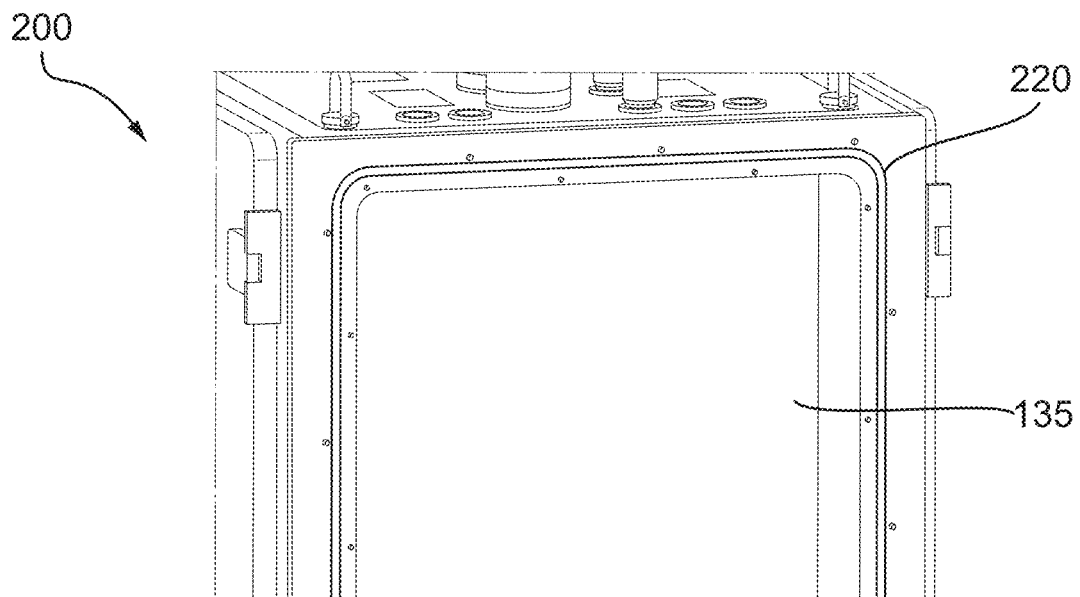


Fig. 12

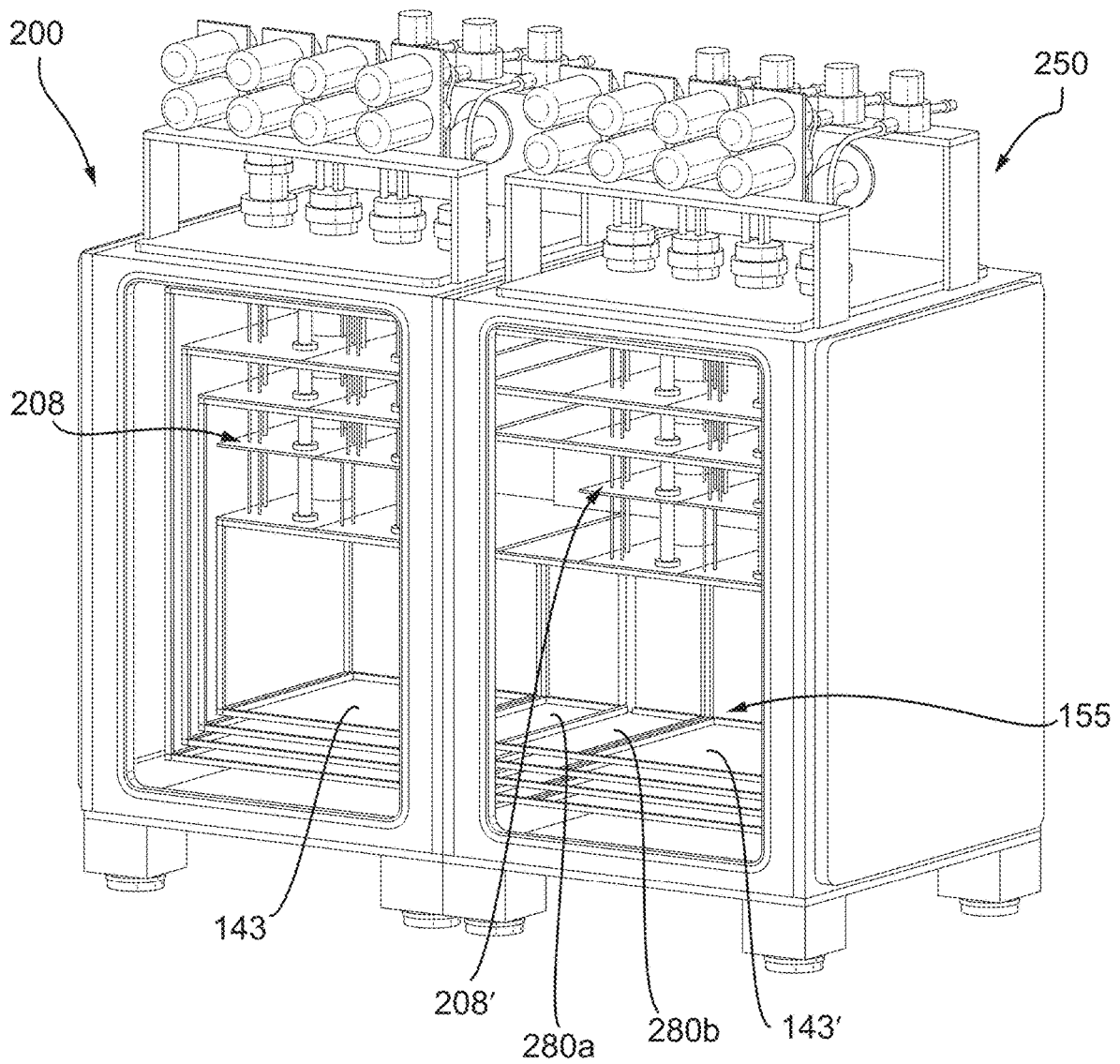


Fig. 13

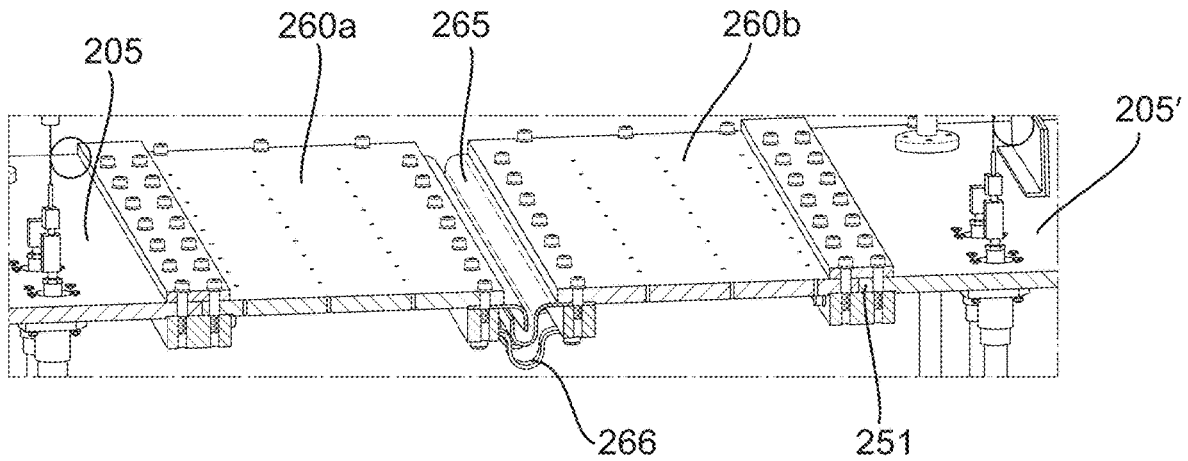


Fig. 14

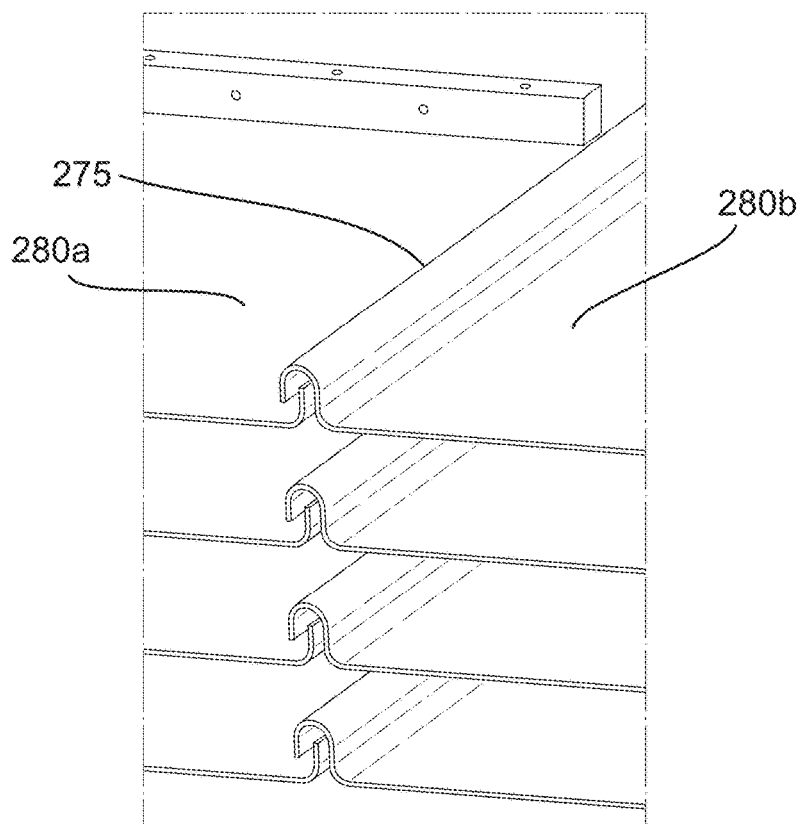


Fig. 15

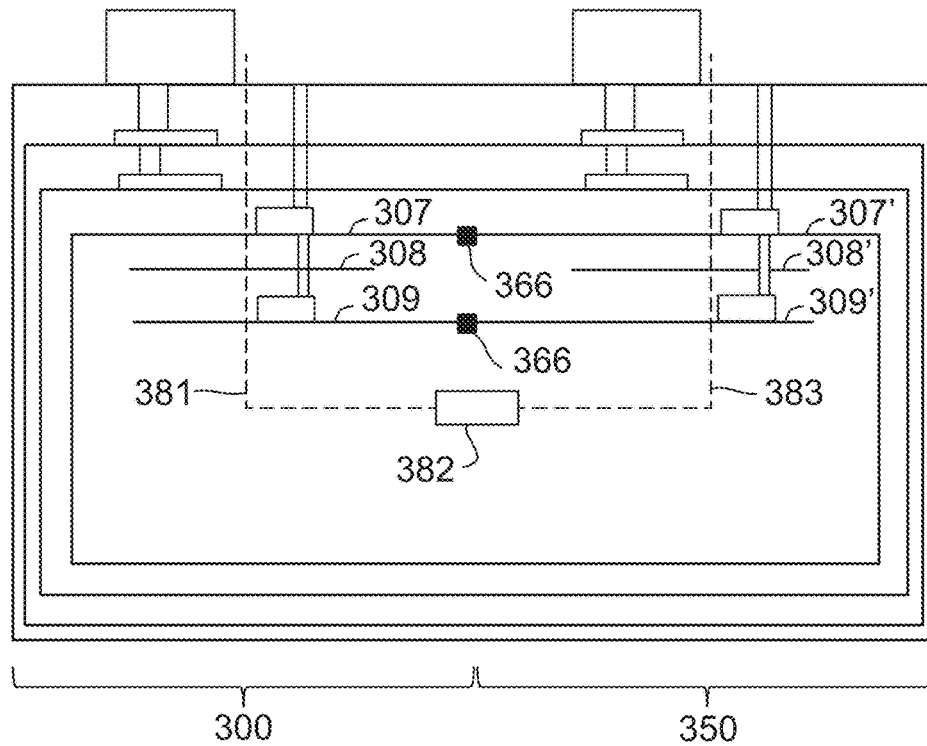


Fig. 16

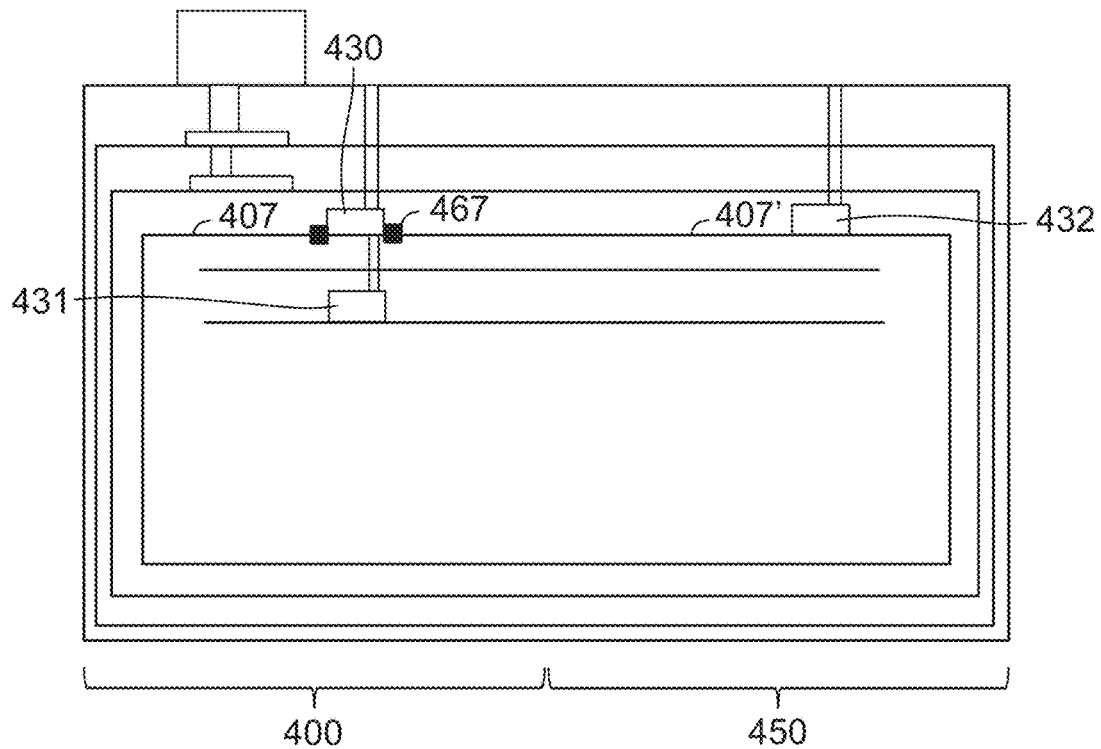


Fig. 17

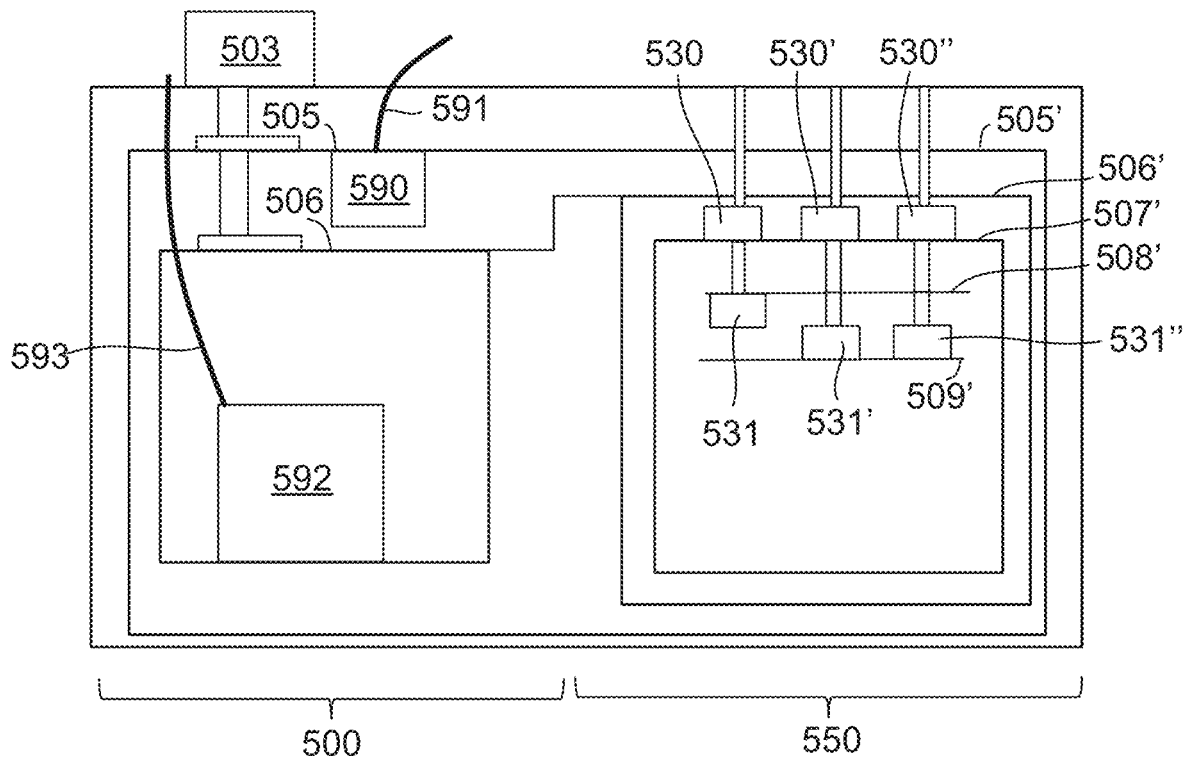
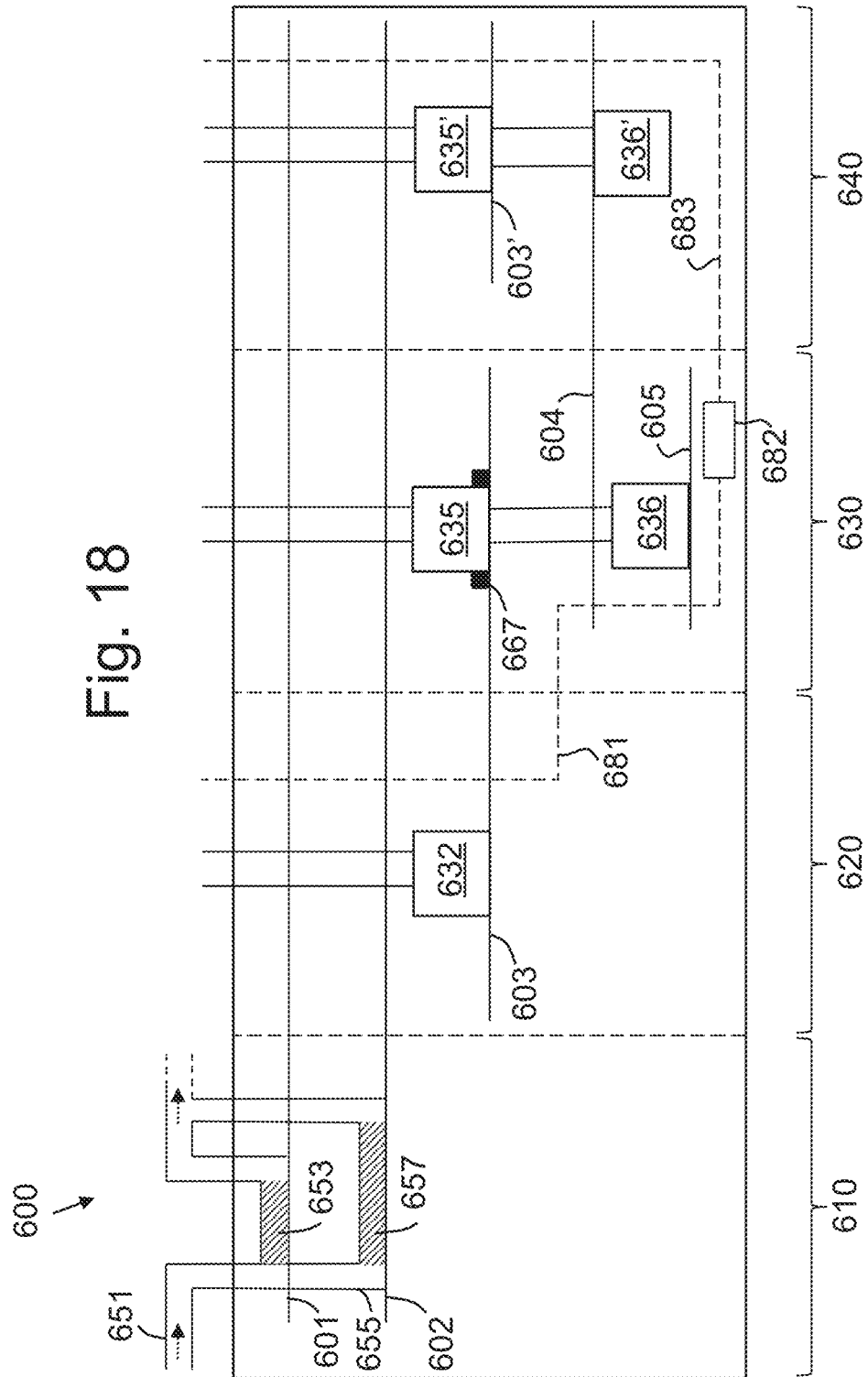


Fig. 18



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CRYOGENIC COOLING SYSTEM**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application is a continuation application based on and claims the benefit of International Application PCT/GB2023/051226, filed on May 10, 2023 (published on Aug. 24, 2023), which is itself based on and claims the benefit of Great Britain Application No. 2207170.8, filed on May 16, 2022, entitled "Cryogenic Cooling System", both of which are hereby incorporated by reference in their entirety.

FIELD OF THE INVENTION

The present invention relates to the field of cryogenic cooling systems. A particularly desirable application of the technology is commercial-scale superconducting quantum computing.

BACKGROUND TO THE INVENTION

The scale-up of quantum computing, based on superconducting quantum information processing (QIP) devices, will require a continuously low temperature on the order of 10-20 mK or less for QIP device operation. For this, it is envisaged that dilution refrigerators (DRs) will be essential. Today's industrial QIP companies use commercially-available cryogen-free ("dry") dilution refrigerators that follow a traditional form-factor: a series of vertically-spaced copper plates, with circular cross section, thermally isolated from each other, with a single dilution unit installed between the lower stage plates. Together with the pipework connected to the dilution unit inlet and outlet, and the pumping hardware, a closed cycle dilution refrigerator is created. Concentric, cylindrical radiation shields enclose each stage plate of the dilution refrigerator insert, to reduce the radiated heat load onto the dilution refrigerator stages (~0.8 K at the still stage, down to below 10 mK at the mixing chamber stage). The whole assembly is enclosed in a cylindrical vacuum vessel. The assembly is often frame-mounted to enable radiation shield and outer vacuum chamber (OVC) removal.

An example of a prior art dilution refrigerator, as discussed above, is shown by FIGS. 1 and 2. FIG. 1 shows a perspective view of a cylindrical outer vacuum chamber 1 supported by a cryostat support frame 10. External components of a helium gas handling system 2 and a cryogen-free refrigerator in the form of a pulse tube refrigerator (PTR) 3 are also visible. FIG. 2 is a perspective view of a cross-section taken through the outer vacuum chamber 1. The PTR and dilution unit are not shown in FIG. 2 for sake of clarity. There is a tiered arrangement of thermal stages 5-9, each in the form of a circular plate and being cooled to a respective temperature in use. A nested assembly of cylindrical radiation shields 4 is also visible, with each shield connected to a respective thermal stage. A first stage of the PTR 3 is mounted to a PT1 stage 5, and a second stage of the PTR 3 is mounted to a PT2 stage 6. A dilution unit forms part of the dilution refrigerator, the dilution unit comprising a still and a mixing chamber, connected by a set of heat exchangers. The still is mounted to a still stage 7 and the mixing chamber is mounted to a mixing chamber stage 9. An operational fluid formed of a helium-3/helium-4 mixture is circulated around the dilution unit during operation. The still and the mixing chamber cool the system as a result of a phase change or mixing of the operational fluid. Cooling is obtained at the mixing chamber from the enthalpy of mixing as helium-3 is

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diluted into helium-4. The mixing chamber is thereby operable so as to obtain the lowest temperature of any part of the dilution refrigerator. Helium-3 is boiled at the still, which removes energy due to the latent heat of vaporisation. A "cold plate" 8, forming a respective thermal stage, is arranged between the still stage 7 and the mixing chamber stage 9 and obtains an intermediate temperature in use. A cylindrical heat radiation shield is connected to each of the PT1 stage 5, PT2 stage 6 and the still stage 7 enclosing the lower temperature stages.

In low temperature applications such as QIP, various dissipative elements are installed across different stages of the dilution refrigerator to ensure adequate thermalisation of experimental wiring. Dissipated heat from resistive elements and conductive wiring adds to the heat load on the dilution refrigerator, which means that more cooling power is required in order to maintain a given base temperature for the system. Although the above form-factor (described with reference to FIGS. 1 and 2) has worked very well in the academic environment, where most dry DR systems have been installed, as QIP scales up in an industrial setting, this form factor starts to become limiting. Large radiation shields are cumbersome to handle. Such a system is fixed in size, which limits the maximum experiment size and the available cooling power at each stage. Whilst it is possible to design a very large vacuum chamber and cryogenic refrigerators as a way of providing physical space for upgradable experiments, the huge capital outlay makes such systems commercially unattractive for both manufacturer and customer. There is therefore a need for a cryogenic cooling system that is better adapted for an industrial or commercial setting. For example, there is a need to compensate for higher heat loads, as may result from the building of ever larger quantum computers, without incurring the above problems, and for facilitating new modes of operation.

SUMMARY OF THE INVENTION

A first aspect of the invention is a cryogenic cooling system comprising a cryogenic refrigerator assembly comprising one or more cryogenic refrigerators; and two or more connected modules, each said connected module comprising:

- a housing defining an internal volume for the module, the housing having a plurality of side faces; and
- a plurality of stages arranged within the internal volume for the module, wherein one or more of the plurality of stages is thermally coupled to the cryogenic refrigerator assembly;

- wherein the two or more said modules are mutually connected at respective side faces; and

- wherein a first said stage of a first said module is thermally coupled to a first said stage of a second said module.

In contrast to the prior art design of FIGS. 1 and 2, the cryogenic cooling system is modularised. This allows the system to be "scaled up" by connecting the interior of a first module to other similar modules, thereby increasing the shared internal volume and the total cooling power available. A user can build the size of their cryogenic cooling system incrementally by connecting additional modules, which addresses the concerns of the high capital expenditure associated with owning a large cryogenic cooling system. Modularising the design can also make it easier to service the system because any shields can be made smaller and a user may need only remove part of the housing for a given module to access the relevant experimental space within.

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Thermally coupling stages of different connected modules can enable the cooling power of the cryogenic refrigerators to be shared across the system. A user can hence include additional heat dissipating components to their system, typically on or between different cooled stages, and balance this heat load by connecting the module to other modules (for example an n^{th} number of times) rather than replacing the entire system with a larger one. New applications, such as the building QIP server farms, are therefore enabled through this technology.

The cryogenic refrigerator assembly may comprise a common cryogenic refrigerator, such as a liquid helium refrigeration plant, cooling respective stages of two or more modules within the system. Typically, however, the cryogenic refrigerator assembly is configured so that each said connected module comprises a cryogenic refrigerator thermally coupled to one or more of stages of the module. These cryogenic refrigerators may take a number of forms, including cryocoolers, helium-3 or helium-4 refrigerators and dilution refrigerators, as will be discussed. Each said module may have a cryogenic refrigerator mounted to a stage of the module by a high thermal conductivity connection.

One or each said module is preferably configured to operate in a first configuration as an independent cryogenic cooling system. Independent operation typically requires the internal volume of the module to be hermetically sealed by the housing and preferably still evacuated. A removable panel may therefore be fitted to the housing (and preferably a said side face) of the module in the first configuration to enclose the internal volume for the module. Each said module is preferably further configured to operate in a second configuration as a component of an integrated cryogenic cooling system comprising a plurality of said modules mutually connected at respective side faces to form a shared internal volume for the system in which the stages for each said connected module are arranged, wherein in the second configuration the removable panel is removed from the housing. The user may separate the modules and configure one or each in the first configuration, for example to perform different experiments using each module. Alternatively, the user can arrange the modules in the second configuration, for example if a larger total cooling power is required for a target apparatus inside the system. The housing for each said module typically comprises a framework supporting the plurality of side faces. Where provided, the removable panels may be fitted to framework in the first configuration and removed from the framework in the second configuration.

A side face of a said module (e.g. the first said module) is connectable to an opposing side face of another said module (e.g. the second said module), as earlier described. The housing (e.g. the framework) of each said module typically comprises one or more housing connectors for connecting the first said module to the second said module. The one or more housing connectors are typically arranged so that an outer surface of the housing of the first said module is configured to fit to an outer surface of the housing of the second said module in order to form the integrated cryogenic cooling system. This facilitates simple connection between different modules. For example a said housing connector on a first said side surface of the first said module may connect to a said housing connector on a second said surface of the second module, the second said side surface of each said module being opposite to the first said side surface respectively. This front-to-back geometry enables an indefinite number of modules to be connected together in the system. Alternatively two modules may be connected together by

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connecting a housing connector on a first said surface of a first said module to a housing connector on a similar first said surface of a second said module. A first said module may be connected to two modules (one either side) by connecting a housing connector on a first said surface of the first module to a housing connector on a second said surface of a second said module, and by connecting a housing connector on a second said surface of the first module to a housing connector on a first said surface of a third said module. The one or more housing connectors may comprise a flange, preferably surrounding or provided around the outside of a said removable panel. The housing connectors may further comprise fasteners, for example in the form of an array of bolts and holes, preferably around a sealing member (such as an O-ring seal), for coupling the flanges of different modules together.

A modularised cryogenic cooling system could have side faces that form a number of different tessellating or non-tessellating structures. However, a particular advantage is provided wherein the housing for each said module comprises four orthogonal side faces. This design allows for the modules to readily conform to the geometry of most rooms and for several such modules to be connected together in a space saving manner. More modules can then be connected together to increase the total cooling power of the system, before the available floor space is filled. The orthogonal symmetry also means that connected modules may be closely packed, for example without the need for spacers to couple adjacent modules together. A side face of the first said module is therefore preferably directly connected to a side face of the second said module. By bringing the adjacent modules close together, for example so that the modules directly connect to one another without the use of extension spacers, the total mass that is cooled decreases, which allows for higher cooling efficiencies and lower temperatures to be obtained.

One, more than one or potentially each thermal stage of the first said module may be thermally coupled to a corresponding stage of the second said module and optionally each said remaining module in the system. Typically, a second said stage of the first said module is thermally coupled to a second said stage of the second said module. The connected stages are typically arranged to obtain similar operational/base temperatures in use, for example to within 1-2 K. The system preferably further comprises one or more extension plates, each said extension plate arranged to connect adjacent stages of different modules in the system. The system may hence be arranged so that one or more stages of a first said module are thermally coupled to respective stage(s) of a second said module by one or more extension plates mechanically connecting the said thermally coupled stages. The extension plate(s) may hence enhance the thermal conductivity between stages of adjacent modules. In effect, this enlarges the thermal stages of the first said module, for example, so that experimental services may be shared between different modules. Similarly, the cooling power applied to a stage of a first said module may then be transferred to another stage of an adjacent second module in order to compensate for a higher heat load that may be applied to the second module by experimental services. This means that larger heat loads can be applied to the thermal stages, for example by incorporating more dissipative electrical cabling or elements, as may be desirable in some applications. For example, each said extension plate may be configured so that the effective thermal conductivity between the connected stages is above 5000 W/m K at a temperature of 20 K.

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The extension plate(s) may additionally perform a heat shielding function by blocking the direct radiative path between different temperature stages in adjacent modules. For example, the system may comprise a plurality of said extension plates, wherein one or more said extension plates is configured so that the effective thermal conductivity between the connected stages is above 5000 W/m K at a temperature of 20 K, and wherein one or more said extension plates is configured so that the effective thermal conductivity between the connected stages is below 50 W/m K at a temperature of 20 K. The lower thermal conductivity plate(s) may function to increase the structural rigidity of the assembly or the thermal shielding, without providing an effective thermal coupling between the connected stages. This may unlock new modes of operation and experiments that would otherwise be difficult to replicate using a traditional cryostat design.

The connected stages will usually be at a similar height across the different modules. The plurality of stages for each said module are typically arranged in a tiered arrangement, for example with a first said stage extending along a plane parallel to a second said stage and spatially dispersed from the second said stage along an axis normal to the first and second stages. Each said stage of a first said module is preferably then coplanar or substantially coplanar with a corresponding said stage of a second said module. The one or more extension plates are then typically arranged to mechanically connect one or more stages of a first said module to a respective coplanar stage of a second said module. The extension plate(s) are typically planar and may bridge the gap between coplanar stages of adjacent connected modules, effectively extending out these stages to form a common connected stage for the system. The extension plates may be included between any or all of the coplanar stages of connected modules, depending on the experimental need.

One or more of the plurality of stages typically comprise one or more stage connectors for connecting an extension plate between the coplanar or "respective" stages of the first and second said modules. For example, the stage connectors may comprise specific means for connecting to an extension plate, such as an array of fastening members or holes for fastening members provided at the periphery of the respective stages. At least one of the one or more extension plates preferably comprises an expandable joint. Such a joint may maintain mechanical connection between the connected stages during relative movement of said connected stages, for example as might arise from contraction and expansion of the components during thermal cycling. For example, at least one of the one or more extension plates may comprise a braided joint.

Each stage typically forms a platform onto which components of the cryogenic cooling system or heat dissipative elements in an electrical system (for instance) may be mounted. Each stage is typically a plate formed of a highly thermally conductive material at cryogenic temperatures, such as copper. Each stage is typically arranged to obtain a respective base temperature by operation of the cryogenic refrigerator, and so may also be referred to as a "thermal stage". The cryogenic refrigerator is typically configured cool each said stage to cryogenic temperatures in use (these being temperatures below 100 kelvin). The stages are generally arranged so that a longitudinal axis extends normal to the surface of each stage. The cryogenic refrigerator is typically configured to apply a thermal gradient across the stages, typically along the longitudinal axis. The stages are therefore typically arranged so that the base temperature for

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each stage becomes progressively colder in a direction extending between the plurality of stages.

The system is typically configured so that the plurality of stages for each said module share a common internal volume defined by the housings of the connected modules. The internal volume for the system is typically hermetically sealed from the surrounding environment and the region containing the stages for each module typically evacuated. This allows for operation of the system without the need for gas handling devices to expel any unwanted gases that might liquefy or solidify at low temperatures.

Radiation shields may be provided at each module and connected together to form a larger assembly of radiation shields surrounding the lower temperature components of the system. Each said module typically comprises one or more radiation shields, each said radiation shield being thermally coupled to a respective stage of the module and surrounding one or more remaining stages, each said radiation shield comprising one or more shield surfaces. The system may then further comprise one or more shield extension sections, each said shield extension section connecting coplanar shield surfaces of adjacent connected modules, typically held at the approximately the same temperature in use. For a module housing having four orthogonal side faces and being connected to another module in the system, each said radiation shield may comprises one, two or three orthogonal side surfaces extending perpendicular to the respective thermally coupled stage. It will be appreciated that the plurality of stages of each said module in the system are typically not fully surrounded by the radiation shields of that module because a space should be left for thermally connecting adjacent stages of different modules and/or running experimental services between the modules inside the internal volume.

The one or more radiation shields may further comprise shield connectors for connecting a shield extension section between adjacent radiation shields of a first said module in the second configuration and a second said module in the second configuration. The shield extension sections may be needed where there is a gap between coplanar side surfaces forming part of the radiation shields of adjacent modules, the shield extension sections being provided to bridge this gap so that the shields of adjacent connected modules combine together to surround the lower temperature components of the system.

Different cryogenic refrigerators could be used, including "wet" refrigerators and cryogen-free ("dry") cryocoolers (also referred to herein as mechanical refrigerators) or a combination of both. The use of cryocoolers, such as pulse tube refrigerator, Stirling refrigerators or Gifford-McMahon refrigerators is particularly cost-effective in smaller installations, for example where the system comprises up to three connected modules. For systems having over three modules it is often more efficient to cool stage(s) of one or more modules through thermal contact with a cryogen such as liquid nitrogen or helium. The cryogen may be stored internally within a or each said module, for example in a dewar/reservoir. Alternatively it may be stored in an external refrigeration plant and conveyed through the module(s) by conduits. The cryogenic refrigerator may hence comprise a conduit for circulating a cryogen through the module, the conduit comprising one or more heat exchangers thermally coupling the conduit to one or more stages of the plurality of stages. Such conduits can generally be used for obtaining temperatures below 4 kelvin, particularly where the cryogen is helium. The cryogenic cooling assembly may therefore comprise a helium refrigeration plant, the helium refrigera-

tion plant preferably arranged externally to the housing of each said module. In this case, one or more said modules preferably comprise a first helium heat exchanger thermally coupled to a said stage of the module, the helium heat exchanger arranged to receive a flow of liquid helium from the helium refrigeration plant. The one or more said modules preferably further comprise a second helium heat exchanger thermally coupled to a different said stage of the module, the second helium heat exchanger arranged to receive a flow of gaseous helium at a temperature below 100 K, preferably between 40-80 K, more preferably 50-70 K, from the helium refrigeration plant. Additionally, or alternatively, the cryogenic cooling assembly may comprise a nitrogen refrigeration plant, the nitrogen refrigeration plant preferably arranged externally to the housing of each said module. In this case, one or more said modules preferably comprise a nitrogen heat exchanger thermally coupled to a said stage of the module, the nitrogen heat exchanger arranged to receive a flow of liquid nitrogen from the nitrogen refrigeration plant. It will be appreciated that the nitrogen heat exchanger would be positioned on a different thermal stage from the first helium heat exchanger.

For sub-millikelvin cooling to be achieved, one or more modules of the system preferably comprise a dilution unit of a dilution refrigerator. A dilution unit comprises a still and a mixing chamber, as earlier discussed. In a particularly desirable implementation, the first said module comprises a first dilution unit and the second said module comprises a second dilution unit. For example, the first dilution unit may comprise a still mounted to a still stage of the plurality of stages for the first said module, and the second dilution unit may comprise a still mounted to a still stage of the plurality of stages for the second said module, wherein the still stages of the first and second modules are mechanically connected by an extension plate. The still stages are typically substantially coplanar, with the extension plate extending between the still stages. Depending on the application, it may be helpful to thermally couple the connected still stages by virtue of the extension plate, in which case it should have a relatively high thermal conductivity. However, there are some applications in which it may be desirable to have a low effective thermal conductivity between the connected still stages, for example so that a heat load applied to one still stage is not conducted to the other. In these circumstances, the effective thermal conductivity between the still stages of the first and second modules is preferably below 50 W/m K at a temperature of 20 K. This arrangement enables the two stills to be operated at different steady-state temperatures, as may be desirable for certain applications.

Similarly, the first dilution unit may comprise a mixing chamber mounted to a mixing chamber stage of the plurality of stages for the first said module, and the second dilution unit may comprise a mixing chamber mounted to a mixing chamber stage of the plurality of stages for the second said module, wherein the mixing chamber stages of the first and second modules are mechanically connected by an extension plate, the extension plate typically extending between coplanar mixing chamber stages. It may be desirable to physically connect the mixing chamber stages of the first and second modules without providing an effective thermal coupling, in which case the extension plate connecting the mixing chamber plates may be configured so that the effective thermal conductivity between the mixing chamber stages of the first and second modules is below 50 W/m K at a temperature of 20 K.

In one preferred implementation, the first said module comprises two or more dilution units, wherein the first

dilution unit is preferably arranged so that a first still is on a first stage and a first mixing chamber is on a second stage, wherein the second dilution unit is preferably arranged so that a second still is on the first stage and a second mixing chamber is on a third stage, the second stage arranged between the first stage and the third stage. Each of the first, second and third stages may therefore be provided with an active source of cooling (in particular a still or mixing chamber). The second stage, for instance, is therefore not reliant on the cooling power of the neighbouring stages first and third stages in order to compensate for any heat loads applied to the second stage.

The system may be configured to enable a variety of experimental services to be run between different modules. The system preferably comprises a target assembly comprising electrical circuitry (e.g. cabling) extending within the internal volume for the system between one or more stages of the first module to one or more stages of the second module. For example, the target assembly may form part of a quantum computer. Each module may hence form a scalable platform for supporting quantum information processing devices.

Different cryogenic refrigerators can be provided in the different connected modules. In a particularly desirable implementation, the first said module comprises a cryogenic refrigerator in the form of a dilution unit or helium-4 refrigerator having a 1K pot, and the second said module or a third said module having a stage that is thermally coupled to a corresponding stage from the first said module comprises a cryogenic refrigerator in the form of a cryocooler and/or a reservoir for liquid cryogen. The reservoir may take the form of a dewar or any suitable tank/container holding liquid cryogens. If the reservoir and cryocooler are provided within a module then the reservoir may be arranged to collect a cryogen that is liquefied by operation of the cryocooler. The reservoir may be operable to cool one or more stages of the first said module, for example by flow of a cryogen along a conduit that is thermally coupled to the one or more stages of the first said module. The reservoir can act as a failsafe mechanism to maintain cryogenic temperatures within the module in the event of a power failure, for example as may otherwise affect operation of any cryocoolers. Typically the reservoir cools the components of the system passively through conduction in the event of a power failure, for example by being fixed to one or more stages of the system. Alternatively, active control is envisaged. For example, the system may further comprise a controller configured to operate the reservoir to cool one or more stages of the first said module in response to a change of state of a said cryogenic refrigerator in the system. The controller is typically an electronic controller, which may be battery-operated. The controller is preferably configured to monitor the operation of one or more cryocoolers in the system and to operate the reservoir to cool the one or more stages of the first said module in response to detecting a failure of a said monitored cryocooler. The failure may be an unexpected interruption of operation for a compressor, such as may result from a lack of electrical power or mechanical part failure.

One, more than one or preferably each said module in the system preferably further comprises a heat switch assembly connected to one or more stages of the plurality of stages, the heat switch assembly operable to selectively thermally couple adjacent stages of the plurality of stages. For example, the heat switch assembly may comprise one or more gas gap heat switches and/or one or more heat pipes. The heat switch assembly is operable to control the thermal

conductivity across the assembly, for example to allow the stages to be in mutual high thermal conductivity during an initial cool down process from room temperature, and to thermally isolate the respective stages from each other at temperatures below 4 kelvin or during steady-state operation.

QIP systems may require a high cooling power applied to each of the lowest temperature stages. Therefore, in a particularly desirable implementation, the plurality of stages of the first said module comprise a still stage, a cold stage and a mixing chamber stage, the cold stage arranged between the still stage and the mixing chamber stage, the first said module further comprising three dilution units, each said dilution unit comprising a still thermally coupled to the still stage of the first said module, wherein the first dilution unit further comprises a mixing chamber thermally coupled to the cold stage, and wherein the second dilution unit and the third dilution unit each comprise a mixing chamber thermally coupled to the mixing chamber stage of the first said module.

One or more modules of the system is preferably configured to allow for convenient sample access and exchange by use of a secondary insert having experimental apparatus (typically including a sample) to be connected to the module. For example, one or more said modules may comprise a primary insert and a demountable secondary insert, the primary insert comprising a plurality of primary plates formed by respective stages of the module, the secondary insert comprising a plurality of secondary plates connected in a self-supporting structure, the system further comprising one or more adjustment members configured such that, when the secondary insert is mounted to the primary insert, the adjustment members cause the primary and secondary plates to be brought into conductive thermal contact.

The system design is particularly well suited for QIP applications and the building of server farms having 1000+ logical qubit systems with error correction. Such a large wiring requirement not only benefits from the increased experimental space achieved by connecting multiple modules but also the higher cooling power from, for example, connecting multiple dilution refrigerators within the same cryostat. The modularised design also enables a variety of cooling technologies to be implemented, spread across different modules, and facilitates new modes of operation, as discussed above. A second aspect of the invention is a quantum information processing device comprising a cryogenic cooling system according to the first aspect. Features discussed in connection with the first aspect of the invention are equally applicable to the second aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be discussed with reference to the accompanying drawings, in which:

FIG. 1 is a perspective outer view of a cryogenic refrigerator according to the prior art;

FIG. 2 is a perspective cross-sectional view of a cryogenic refrigerator according to the prior art;

FIG. 3 is a schematic illustration of a first module for forming part of a system according to a first embodiment;

FIG. 4 is a first perspective view of the first module according to the first embodiment;

FIG. 5 is a second perspective view of the first module according to the first embodiment;

FIG. 6 is a perspective view of first and second modules for forming a system according to the first embodiment

FIG. 7 is a perspective view of a cryogenic cooling system comprising the first and second modules according to the first embodiment;

FIG. 8 is a schematic illustration of a first arrangement of the cryogenic cooling system comprising the first and second modules according to the first embodiment;

FIG. 9 is a schematic illustration of a cryogenic cooling system according to a second embodiment;

FIG. 10 is an exploded perspective view of a first module forming part of the second embodiment;

FIG. 11 is a perspective view of a portion of the first module according to the second embodiment;

FIG. 12 is a perspective view of a cryogenic cooling system according to a third embodiment;

FIG. 13 is a perspective view of a first portion of the cryogenic cooling system according to the third embodiment;

FIG. 14 is a perspective view of a second portion of the cryogenic cooling system according to the third embodiment.

FIG. 15 is a schematic illustration showing a system according to a fourth embodiment of the invention;

FIG. 16 is a schematic illustration showing a system according to a fifth embodiment of the invention;

FIG. 17 is a schematic illustration showing a system according to a sixth embodiment of the invention; and

FIG. 18 is a schematic illustration showing a system according to a seventh embodiment of the invention.

DETAILED DESCRIPTION

A first module **100** for forming part of a cryogenic cooling system according to a first embodiment of the invention will now be discussed with reference to FIGS. 3-5. The module **100** comprises a generally cuboidal housing **110** with six orthogonal faces, which is in contrast to the traditional cylindrical design shown in FIGS. 1 and 2. The housing has a framework **21** (see FIG. 4) supporting four orthogonal side faces extending between an upper surface and a lower surface of the housing **110**. The upper surface supports a tiered assembly of cooled stages **105-109** and two cryogenic refrigerators. The first cryogenic refrigerator is a mechanical refrigerator (also referred to as a “cryocooler”/“cryogen-free refrigerator”) in the form of a pulse tube refrigerator (PTR) **103**. Alternative mechanical refrigerators that can be used include a Gifford McMahon (GM) refrigerator and a Stirling refrigerator. The second cryogenic refrigerator is a dilution unit, comprising a still **30** and a mixing chamber **31**, connected by a set of heat exchangers. The housing is configured to form a vacuum chamber **101** when fully assembled, with the interior of the chamber (containing the cryogenic refrigerators and the cooled stages **105-109**) being evacuated in use.

The assembly of cooled stages **105-109** comprises a PT1 stage **105** and a PT2 stage **106**. A first stage of the PTR **103** is mounted to the PT1 stage **105** for cooling the PT1 stage **105** to a base temperature of 50-70 K. A second stage of the PTR **103** is mounted to the PT2 stage **106** for cooling the PT2 stage **106** to a base temperature of 3-5 K. The assembly further comprises a still stage **107** and mixing chamber stage **109** that are thermally coupled to the still **30** and the mixing chamber **31** respectively. An operational fluid formed of a mixture of helium-3 and helium-4 is circulated around the dilution unit during operation through pumping lines. The still stage **107** and mixing chamber stage **109** obtain respective base temperatures of 0.5-2 K and 5-20 mK in use. A “cold plate” **108**, forming an additional thermal stage (and

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so also referred to herein as the “cold stage”), is arranged between the still stage **107** and the mixing chamber stage **109** and obtains a temperature between that of the still stage **107** and mixing chamber stage **109**, typically at 50-150 mK.

A heat switch assembly (not shown) comprising a plurality of gas gap heat switches selectively thermally couples each of the cooled stages **106-109** in use. The heat switch assembly is configured to allow thermal exchange between the cooled stages **106-109** during an initial cool-down procedure and to thermally isolate the different stages at low temperatures. Optionally one or more heat pipes may also be provided, for example between the PT1 stage **105** and PT2 stage **106**. The heat pipes may operate in conjunction with the PTR **103** and gas gap heat switches to further accelerate the pre-cooling process. A combination of the gas gap heat switches, heat pipes and low thermal conductivity support rods connected to the housing **110** holds the stages **105-109** in the tiered arrangement shown.

A nested assembly of heat radiation shields is provided within the module **100**, each heat radiation shield being connected to a respective thermal stage and surrounding the lower temperature components. A first heat radiation shield **41** is connected to the PT1 stage **105**, a second heat radiation shield **42** is connected to the PT2 stage **106**, and a third heat radiation shield **43** is connected to the still stage **107**, wherein the second heat radiation shield **42** is arranged between the first heat radiation shield **41** and the third heat radiation shield **43**. The first and second heat shields **41, 42** are typically aluminium whereas the third heat shield **43** is typically copper. The heat radiation shields **41-43** are configured to form a closed structure when fully assembled and mounted to the respective thermal stages, and will surround the components of the system that are configured to be cooled to a lower temperature. The heat radiation shields **41-43** have four orthogonal side surfaces, which are configured to fit together. In the present embodiment each side surface of each heat radiation shield comprises two coplanar removable panels for providing external access to the region contained by the heat radiation shield, as shown by FIG. 5. Handles are attached to the outside of the side faces for convenience during assembly and disassembly.

FIG. 4 provides an outer view of the module **100** in a first configuration with the housing **110** fully assembled. In the first configuration, the module **100** is configured to operate as an independent cryogenic cooling system in order to obtain cryogenic temperatures inside the module **100**. In the present embodiment each side face of the housing **110** has a removable panel that may be removed from the framework **21** to provide access to an internal volume for the module **100** defined by the interior of the housing **110**. In FIG. 5 a front removable panel **35** (visible in FIG. 4) is removed from a front side face **22** of the module **100** to expose a front side surface of the first heat radiation shield **41**, which may also be removed if needed, for example for servicing.

Another example of where a removable panel may be removed from a side face of the module **100** is for connecting the module **100** to an adjacent module. The module **100** is further configured to operate in a second configuration as a part of an integrated cryogenic cooling system comprising a plurality of such modules connected at respective side faces. An example is shown in FIGS. 6 and 7 in which two such modules according to FIGS. 3-5 are joined together to form an integrated cryogenic cooling system according to the first embodiment. A removable panel is removed from the right side face of a first module **100** and a removable panel is removed from the left side of a second module **150**, as shown in FIG. 6. The first and second modules **100, 150**

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are then arranged so that the right side face of the first module **100** abuts against the left side face of the second module **150**. The framework **21** for the first and second modules comprises housing connectors **120** comprising a flange on the exterior of the housing **110** and a sealing member arranged around the outside of the area for the removable panel. A said flange on the right side of the first module **100** is arranged fit to a said flange on the left side of the second module **150** by fastening members, such as bolts, coupling the flanges together.

Once connected, the first and second modules **100, 150** form a common cryogenic cooling system with an internal volume comprising the sum of the internal volume of the connected modules. This is shown in FIG. 7. The housings of the modules **100, 150** engage together to hermetically sealed internal volume of the system comprising the stages from each module can be evacuated. The heat radiation shield side surfaces on the right side of the first module **100** and the left side of the second module **150** are removed. Additional radiation shield side surfaces and side faces of the module housings may be removed during assembly of the system to provide access and then refitted. This arrangement creates a large sample space to run much larger experiments than can otherwise be run in a typical single-unit cryostat. This has the advantage of not only more space, but of much more cooling power because one or more neighbouring thermal stages of the different modules are thermally coupled together.

In the present embodiment, the first and second modules **100, 150** are configured so that when the first module **100** is connected to the second module **150** by the housing connectors **120**, each thermal stage of the first module is coplanar with a respective thermal stage of the second module **150**. This means that adjacent coplanar thermal stages can then be connected together by an extension plate **160** extending between adjacent coplanar thermal stages. The extension plate **160** may provide a structural benefit in increasing the rigidity of the assembly and have a heat shielding effect. The extension plate **160** may also be used for heat transfer purposes, for example to couple the cooling power from a cryogenic refrigerator on one of the modules across to a thermal stage on another module. In this case, a material of a high thermal conductivity, such as copper may be used to form the extension plate. Stage connectors **50**, in the form of an array of holes and bolts or any other suitable fastening means for connecting with an extension plate, are provided at the periphery of each stage **105-109**. These are shown schematically in FIG. 3, wherein the stage connectors **50** are provided at each end of each of the thermal stages to enable the stages to be extended in either direction for connection to an adjacent module on the left side or the right side of the module **100**.

As earlier discussed, the radiation shields **41-43** surround the lower temperature components of the system and are fitted to each of the PT1 stage **105**, PT2 stage **106** and still stage **107** respectively. The width of the PT2 stage **106** is therefore less than that of the PT1 stage **105**, the width of the still stage **107** is less than that of the PT2 stage **106**, the width of the cold plate **108** and the mixing chamber stage **109** is also less than that of the still stage **107**. Consequently, the lateral separation between coplanar thermal stages of the two adjacent modules is not the same for each of the stages. Different sized extension plates **160** are therefore used bridge the gap between the stage connectors **50** on each of the stages, as shown by FIG. 8.

In the first embodiment, the first, second and third radiation shields **41-43** are configured to surround the lower

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temperature components of the system. In the configuration shown in FIG. 3, each radiation shield has four orthogonal side surfaces, however when connected to another module in the system, at least one of these side surfaces is removed. This allows for experimental services, such as cabling, to extend between the different modules. A plurality of shield extension sections **180**, in the form of plates, are fitted for connecting coplanar surfaces of the radiation shields for connected modules. Direct physical contact between the adjacent radiation shields is not typically essential however shield connectors **55** are preferably provided at each end of each of the radiation shield to enable neighbouring shield extension sections **180** to interlock and preferably thermally couple. The shield connectors **55** may comprise any of interlocking features, a flexible joint, array of holes and bolts or any other suitable fastening means for connecting the shield extension sections **180**.

Although only two modules are coupled together in the first embodiment, it will be appreciated that any number of modules could be connected together to increase the size of the system. Furthermore, the system is not limited to a one-dimensional array of connected modules but that two-dimensional arrays are also envisaged. A particular benefit of the cuboidal module design is that it allows for modules to be fitted close together. This makes efficient use of the available floor space. It also means that the housings for the adjacent modules can be directly connected onto each other, thereby removing the need for any "spacers" between the module which increase the size and mass of the system, and which can therefore negatively impact on the cooling performance.

In the first embodiment of FIG. 8 two modules **100**, **150** are coupled together that have the same cryogenic refrigerator set-up in each. In particular, each module forms a cryogen-free dilution refrigerator with the PTR and dilution unit being arranged as discussed with reference to FIG. 3. However, a particular advantage offered by the modularised design is the flexibility to have different refrigerator setups in different modules of the system. FIG. 9 illustrates a second embodiment which is essentially the same as the first embodiment however the mixing chamber **31'** of the second module **250** is mounted on the cold plate **208'**. The cooling power applied to the cold plate **208'** is therefore significantly increased in comparison with the first embodiment. This cooling power is also transmitted through to the cold plate from the first module **200** by the copper stage extension plate thermally coupling the coplanar cold plates. The cold plate of the first and second module **200**, **250** therefore are not wholly reliant on the cooling power of the neighbouring stages but have a dedicated source of cooling. This means they have a greater capacity to tolerate heat loads, as may be applied by components of a QIP system for instance, without substantially raising the operational temperature of the system.

FIGS. 10 and 11 show perspective views of the first module **200** from the second embodiment. Similar to the first embodiment, a housing connector **220** is provided on each of the two opposing side faces for connecting the module **200** directly onto an adjacent module. The housing connector **220** comprises a sealing member **220** surrounded by an array of bolts and holes. In this embodiment the housing connector on the right side face of the first module **200** is configured to connect to a corresponding housing connector on the left side face of the second module **250**. A removable panel **135** may be fitted to each housing on the left and right side faces by bolts in order to enclose the internal volume for the module **200** and facilitate independent operation of the

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module **200**. The removable panel **135** is removed to allow for the connection of the module **200** to one or more adjacent modules. The sealing member **220** enables a vacuum-tight seal to be made between the connected housings. In this embodiment the sealing member **220** comprises an O-ring groove and an O-ring on the right side face of the first module **200**, which is configured to engage with an O-ring seal provided on the left side face of second module **250**. However other types of sealing members could be used, such as a knife-edge gasket seal.

The front face of the module **200** comprises a door **210** that is securely fitted to the housing by hinges and bolts so that a vacuum can be maintained inside the housing. The door **210** can be opened in order to provide access to the interior of the module **200**, for example during servicing and to adjust any bolts, such as those provided on the side faces of the housing or the radiation shields.

FIG. 12 shows a perspective view of the system according to a third embodiment in which the doors **210** of each module **200**, **250** are not shown in order to illustrate the various connections between the two modules **200**, **250**. The third embodiment is essentially the same as the second embodiment and uses the same general module design. However, in the third embodiment, the extension plate between the cold plates **208**, **208'** is removed so that the cold plate **208** of the first module **200** is disconnected and thermally decoupled from the cold plate **208'** of the second module **250**. In an alternative embodiment any of the thermal stages could be thermally decoupled without breaking their physical connection by use of an extension plate having a low thermal conductivity, for example being formed partially or fully of a material such as plastic or stainless steel. As an example, it may be desirable to thermally decouple adjacent coplanar stages so that heat from an electrical element on a thermal stage of a first module is not conducted across to the second module.

As each module of the system cools down from room temperature, the adjacent thermal stages will contract away from each other and may cool down at different rates depending on the exact configuration of each module. There will also be manufacturing tolerances to accommodate. To overcome these issues, thermal stages in each module may be joined 'indirectly' to each other by a flexible joint. An example of such a connection will now be discussed with reference to FIG. 13.

FIG. 13 shows the connection between coplanar thermal stages of the first and second modules **200**, **250** from the third embodiment. In particular, it shows the flexible mechanical connection that is made between the PT1 stage **205** of the first module **200** and the PT1 stage **205'** of the second module **250**. Similar connections are made between each of the remaining coplanar stages with the exception of the cold plates **208**, **208'** which are not connected (as earlier discussed). Stage connectors **251** are provided at the left side and the right side of each stage for allowing a connection between the coplanar stages by one or more intermediary extension plates. In this embodiment the PT1 stage **205** of the first module **200** is connected to the PT1 stage **205'** of the second module **250** by first and second extension plates **260a**, **260b**. The underside of the first and second extension plates **260a**, **260b** are joined together by an expandable joint **266** comprising soft braids of high thermal conductivity, for example made of copper. The expandable joint **266** allows good heat conduction between the neighbouring PT1 stages **205**, **205'** and relative movement between the stages, such as may occur during thermal cycling.

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A labyrinth structure **265** is provided to assist with radiative shielding in the region between the ends of the two extension plates **260a**, **260b**. The labyrinth structure **265** is formed by a downward pointing lip on the end of the first extension plate **260a** which is arranged inside an upward pointing lip on the adjacent end of the second extension plate **260b**. Additional light absorbing material may be applied to the interface between the two lips inside the labyrinth structure **265** to further assist with the heat shielding. The labyrinth structure **266** allows for relative movement between the first and second extension plates **260a**, **260b**, which may result in the lips coming into mutual contact. Other means for connecting adjacent thermal stages are envisaged including by using interlocking or interleaved parts that unroll when the connected stages contract, maintaining physical (and preferably also thermal) contact between the stages.

Similar structures to those shown in FIG. 13 can be used to connect the heat radiation shields. As shown in FIG. 12, each of the coplanar heat shields from the first and second modules **200**, **250** are coupled together by two shield extension sections. For example, a first shield extension section **280a** is mounted to the third heat shield **143** of the first module **200** by a shield connector **155** taking a similar form to the stage connector **251** shown in FIG. 13. A second shield extension section **280b** is mounted to the third heat shield **143** of the second module **250** by a similar shield connector **155**. The first and second shield extension sections **280a**, **280b** are coupled together as shown in FIG. 14, by a shield labyrinth structure **275**, which is similar to the labyrinth structure **266** discussed in connection with FIG. 13. In this case, the end of the first shield extension section **280a** forms a lip that is arranged inside another lip formed on the end of the second shield extension section **280b**. This engagement allows for some relative movement between the shield extension sections **280a**, **280b**, such as may occur during thermal cycling and allows for some misalignment due to manufacturing tolerances. Similar couplings are provided between each of the adjacent coplanar shield extension sections.

In effect, the system provides an extensible cryostat comprised of an extensible vacuum chamber and extensible temperature stages. This extensibility allows for a plurality of independent cryostats (or “modules”) to be strongly mechanically and strongly thermally coupled together and operated with the same or similar temperatures at corresponding/adjacent thermal stages of each cryostat, as discussed with reference to FIGS. 7-9. The extensibility also allows for a plurality of modules to be strongly (or weakly) mechanically coupled together, and operated as a single entity, with different temperatures at the corresponding/adjacent thermal stages of each module. FIG. 12 shows an example in which coplanar cold plates **208**, **208'** are separated and therefore thermally decoupled from each other. Another example will now be discussed.

FIG. 15 is a schematic illustration showing a system according to a fourth embodiment of the invention, the fourth embodiment having anisothermal connected stages. A first module **300** is connected to a second module **350** to form an integrated cryogenic cooling system. The arrangement is essentially the same as the first embodiment with the exception that the still stage **307**, cold stage **308** and mixing chamber stage **309** of the first module are not thermally coupled to the corresponding still stage **307'**, cold stage **308'** and mixing chamber stage **309'** of the second module **350**. All other coplanar stages are thermally coupled as before. A first stage extension plate mechanically connects the still

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stage **307** of the first module **300** to the still stage **307'** of the second module **350**, and a second stage extension plate mechanically connects the mixing chamber stage **309** of the first module **300** to the mixing chamber stage **309'** of the second module **350**. This improves the structural rigidity of the system and the thermal shielding. However, the first and second stage extension plates are configured to have a low thermal conductivity, preferably below 50 W/m K at a temperature of 20 K. This enables the coplanar connected stages to reach different operational temperatures, and may be achieved in a number of ways. For example, the first and second stage extension plates may be partially or wholly constructed out of a material having a relatively low thermal conductivity at the respective operational temperature, such as plastic, silicon or stainless steel. In this embodiment copper stage extension plates are used as before but they are connected together by a stainless steel expandable joint **366**. The cold stage **308** of the first module **300** is separated from the cold stage **308'** of the second module **350** by gap so that the adjacent cold stages **308**, **308'** are substantially thermally isolated from each other and may have different temperatures in use.

In this embodiment, the system forms part of a QIP system in which the first module **300** comprises the ‘input’ lines **381** and the second module **350** comprises the ‘output’ lines **383** (schematically represented). Electrical conductors in the form of input lines **381** and output lines **383** are thermally coupled to each of the cooled stages of the first and second modules **300**, **350** respectively. The input lines **381** transmit an electrical signal from a position exterior to the system to a QIP device **382** (e.g. a qubit processor), that is typically thermally coupled to the lowest temperature stage of the system. The output lines **383** transmit an electrical signal from the QIP device **382** to a position exterior to the system. Since the input lines are one of the biggest sources of heat generated a QIP experiment, via active and passive heat dissipation at the different stages of the refrigerator, it is beneficial to be able to operate the output lines at a lower temperature than that of the input lines. This preserves the signal to noise ratio in the output signals before those signals can be amplified. Typically the operational temperature of the still stage **307**, cold stage **308** and mixing chamber stage **309** of the first module **300** will exceed that of the still stage **307'**, cold stage **308'** and mixing chamber stage **309'** of the second module **350** respectively. Optionally additional cryogenic refrigerators may be thermally coupled to the input lines **381** relative to the output lines **383** so as to compensate for the higher heat load provided by the input lines **381**. For example, the arrangement shown in FIG. 15 could be modified so that two PTRs and two dilution units are provided in the first module **300**.

The ability to ‘split up’ the cooling stages by only weakly thermally coupling them together is also useful for applications where a high heat load is more effectively managed by a first cryogenic refrigerator on a cooling stage operating at one temperature, but where that temperature is not advantageous to the correct operation of another cryogenic refrigerator connected to the cooling stage. An example will now be discussed with reference to FIG. 16, which is a schematic illustration showing a system according to a fifth embodiment of the invention. A first module **400** is connected to a second module **450** to form an integrated cryogenic cooling system. The arrangement is similar to the first embodiment although components of a QIP system are not shown for clarity. The first module **400** has a pulse tube refrigerator and a dilution unit comprising a still **430** and a mixing chamber **431**, as before. However, the only cryogenic refrigerator

provided in the second module **450** is a helium-4 refrigerator, referred to in the art as a "1-K pot" **432**, configured to receive a flow of helium from an external location by pumping lines. The 1-K pot **432** is connected to a "1 K stage" **407'** that is thermally coupled to the still stage **407** by one or more stage extension plates, as earlier described. An additional difference is that the still **430** is connected to the still stage **407** by a weak thermal link **467**, such as a plastic or stainless steel collar.

The assembly may form part of a QIP system having any number of connected electrical elements that can provide a heat source. A large heat load applied to the still stage **407** can be effectively managed by the relatively high cooling power of the thermally coupled 1-K pot operating at 1-1.5 K or 1.2-2 K. The still of a dilution unit ideally operates in the 750-850 mK region. Therefore, the weak thermal link **467** advantageously allows the dilution unit to operate in a more optimum regime, independent of the temperature of the 1-K pot. This reduces the overall base temperature of the mixing chamber **431**, which may improve the performance of the QIP measurement.

Different types of modules serving different purposes can be connected together to form part of the integrated cooling system. FIG. 17 is a schematic illustration showing a system according to a sixth embodiment of the invention. A first module **500** is connected to a second module **550** to form an integrated cryogenic cooling system. In this embodiment the first module **500** comprises a pulse tube refrigerator **503** having a first cooling stage connected to a PT1 stage **505**, and a second cooling stage connected to a PT2 stage **506** (as before). In this embodiment the PT1 stage **505** and the PT2 stage **506** are thermally coupled to a first tank **590** and a second tank **592** respectively. The first tank **590** is mounted to the PT1 stage **505** and the second tank **592** is mounted to a radiation shield thermally coupled to the PT2 stage **506**. Each tank is configured to store a liquid cryogen in use. More specifically, the first tank **590** is configured to receive nitrogen which is introduced into the system along a first conduit **591** and which typically liquefies under thermal contact with the PT1 stage **505**. The second tank **592** is configured to receive helium-4 which is introduced into the system along a second conduit **593**. The second conduit **593** is thermally coupled to the PT1 stage **505** and the PT2 stage **506** by heat exchangers such that the helium may liquefy upon thermal contact with the PT2 stage **506** during low temperature operation. As well as allowing these fluids to enter the first module **500** into the respective tanks **590**, **592**, the conduits **591**, **593** provide a path for the gases to vent should the system need to warm up or the liquids boil off.

The second module **550** comprises a PT1 stage **505'** and a PT2 stage **506'** which are thermally coupled to the PT1 stage **505** and PT2 stage **506** of the first module **500** respective. Optionally, the second module **550** may further comprise a cryocooler to facilitate independent cooling of the second module (in particular the PT1 stage **505'** and PT2 stage **506'**) absent the connection to the first module **500**. Additionally, the second module **550** comprises three lower temperature thermal stages: a still stage **507'**, a cold plate **508'** and a mixing chamber stage **509'**, and three dilution units connected to the lower temperature stages. The first dilution unit comprises a first still **530** and a first mixing chamber **531**, the second dilution unit comprises a second still **530'** and a second mixing chamber **531'**, and the third dilution unit comprises a third still **530''** and a third mixing chamber **531''**. The first still **530**, second still **530'** and third still **530''** are each thermally coupled to the still stage **507'**. The second mixing chamber **531'** and the third mixing

chamber **531''** are thermally coupled to the mixing chamber stage **509'**, whereas the first mixing chamber **531** is thermally coupled to the cold plate **508**. The combination of three dilution units, one of which having a mixing chamber coupled to the intermediary cold plate, ensures that a high cooling power is provided to each of the lowest temperature stages **507'**, **508'**, **509'**. This arrangement for the second module **550** is particularly effective at managing the heat loads typically introduced by the electrical elements of a QIP system.

A particular advantage provided by the first module **500** in this embodiment is that it acts as a fail-safe mechanism for cooling the second module **550** if necessary. In particular, the first and second tanks **590**, **592** are configured to cool the PT1 stage **505'** and the PT2 stage **506'** of the second module **550** in the event of a failure of the PTR **503** or any cryocoolers in the system, such as may occur due to an interruption in the electrical power supply or a mechanical failure. In this embodiment, the first tank **590** (containing liquid nitrogen) is configured to maintain the temperature of the PT1 stage **505'** at around 70 K and the second tank **592** (containing liquid helium) is configured to maintain the temperature of the PT2 stage at around 4 K. The fail-safe mechanism operates passively by virtue of the thermal coupling between the tanks **590**, **592** to the remaining components of the system. In the absence of any electrical power, the temperature may gradually rise inside the system at a rate dependent on the insulation and the mass of the liquid cryogen in the tanks **590**, **592**. Typically, the temperature of the components inside the system would approach the boiling point of the liquid cryogen, and be fixed there whilst any external headloads are taken up by the latent heat of the liquid. If different tanks are provided for housing different cryogen then the temperature may settle at the higher boiling point of the cryogen. Only once the liquid has boiled away would the temperatures then start to increase further. Anticipated liquid volumes and heat loads should allow for 'hold times' of hours or days. The above system may therefore be capable of maintaining cryogenic temperatures below 100 K inside the system for at least 24 hours in the absence of any electrical power.

Alternatively, in some embodiments, the system comprises an electronic controller (typically battery operated) which is configured to detect a change in state of any cryocoolers in the system, such as may occur due to an unexpected power cut or mechanical failure. For example, the controller may monitor operation of a motor for the compressor in the PTR **503**. In response to detecting the change in state, the controller may operate one or more pumps (forming part of the controller) to convey a cryogen, typically in liquid form, along conduits so as to cool one or more thermal stages of the system. The cryogen may be conveyed from a position internal to the system (such as the first and second tanks **590**, **592** shown in FIG. 17) or from an external dewar.

The 4 K cooling power in dry dilution refrigerators has been historically provided by cryocoolers. The demand for these systems arose precisely because they are a dry technology. This simplified the supporting infrastructure and experience required to operate the system, making the systems more usable in the academic setting. For commercial-scale systems, however, there are reliability concerns associated with relying on multiple cryocoolers. As the experiment size grows, the available cooling power at 4 K also becomes inadequate very quickly. In a generous assumption, cryocoolers could realistically provide ~8 W of 4 K cooling power, assuming 4-off units each providing 2 W.

This already represents a significant investment, with a relatively short lifespan. There is a strict duty cycle for parts which, if neglected, leads to degradation of the performance of the cryocooler. In an industrial setting, cooling power at 4 K provided by a plant-scale 4He recirculating system is desirable (commercial suppliers include Air Liquide and Linde Kryotechnik). Such systems are implemented on medical installations (such as for a suite of MRI machines) or in large physics and engineering experiments (such as at CERN and ITER), where high reliability and large cooling powers are essential. Standard commercial liquefier units are easily capable of liquefying 280 l/hr of 4He, which translates into an available 4 K cooling power of 200 W (liquefiers are available with a capacity of >3500 l/hr, equating to a 4 K cooling power of >2.5 KW). The helium liquid may be circulated in heat exchanger pipework inside one or more of the modules to give the required thermal contact to the 4 K cooling bus of a QIP system. Plant-level 4 K cooling mechanisms enable a plurality of dilution refrigerators to be operated on the same 4 K cooling loop. This may include separate quantum computers that may be performing separate calculations, but sharing the same precooling system. These quantum computers could be in the same module or separate modules connected within a common vacuum chamber. An embodiment in which components of the system are cooled by liquid cryogen received from an external refrigeration plant will now be discussed.

FIG. 18 is a schematic illustration of a system 600 according to a seventh embodiment of the invention. The system 600 comprises a first module 610, a second module 620, a third module 630 and a fourth module 640. The modules are arranged as a one-dimensional array in which the second module 620 is connected to the first and third modules 610, 630 on opposing side faces, and the third module 630 is connected to the second and fourth modules 620, 640 on opposing side faces. The housings of the modules are connected together as described in the previous embodiments.

The first module 610 has a first conduit 651 for receiving a flow liquid nitrogen from a refrigeration plant (not shown) that is external to the modules. Alternatively, the first conduit 651 may receive a flow of cold helium gas tapped off from a helium refrigeration plant before the final liquefaction stage. The first conduit 651 is thermally coupled to a first stage 601 of the first module 610 by a first heat exchanger 653. The first module 610 also has a second conduit 655 for receiving a flow liquid helium from the refrigeration plant. The second conduit 655 is thermally coupled to a second stage 602 of the first module 610 by a second heat exchanger 657. In use, the first and second conduits are configured to cool first and second stages 601, 602 to around 50-70 K and 4 K respectively by the flow of the respective cryogens through the first and second heat exchangers 653, 657. This provides an alternative to the use of cryocoolers, which is particularly desirable in large-scale installations having over three connected modules, for the reasons discussed above.

A variant to this scheme is that the incoming liquid helium-4 stream is used to maintain a significant volume of liquid helium inside a reservoir tank, which is thermally connected to the second stage. The use of internal helium reservoirs would allow the system to continue running if the liquefier operation is interrupted for a period of time. It should be noted that a helium liquefying system using cryocoolers (as discussed in FIG. 17) could be used in the same way if the required cooling power at the second stage is only of the order of a few watts. In this case the use of

internal reservoirs would allow the system to continue running whilst the cryocooler liquefier was swapped for a standby unit, providing mitigation against cryocooler reliability concerns. For systems with low cooling power requirements where cryocoolers could be used instead of a plant scale helium-4 recirculating system, there are methods known in the art that could be used to mitigate against cryocooler reliability concerns other than cryocooler based liquefiers. However typically the number of cryocoolers fitted to the system would exceed what is strictly necessary for operation so that the system can operate with one or more cryocoolers inoperative.

Returning to the seventh embodiment, the first and second stages 601, 602 of the first module are thermally coupled to corresponding coplanar stages of the second, third and fourth modules 620, 630, 640 by stage extension plates (as earlier described) to form common isothermal stages across the system respectively. Optionally, the aforementioned first and second conduits 651, 655 may be connected to corresponding isothermal stage plates on each module by respective heat exchangers in a repeating manner, as indicated by the broken lines at the end of the first and second conduits 651, 655. Appropriate ports may be provided on the top surface of each module for facilitating this fluid flow into the modules and between the modules.

The second module 620 comprises a helium-4 refrigerator 632 (also referred to as a "1-K pot") configured to cool a third stage 603 to around 1 K. The third stage 603 is thermally coupled to a corresponding coplanar stage of the third module 630 however it is separated from a coplanar third stage 603' of the fourth module 640 by a gap. This enables the third stage 603' of the fourth module 640 to operate at a different temperature from the third stage 603 of the second and third modules 620, 630. This may be desirable in some instances, as earlier discussed with reference to the fourth embodiment.

The third module 630 has a fourth stage 604 that is thermally coupled to a corresponding thermal stage of the fourth module 640, and a fifth stage that forms the lowest temperature stage and which is not connected to any corresponding stages from connected modules. The third module 630 further comprises a first dilution unit having a first still 635 mounted to the third stage 603 by a weak thermal link 667 (as described in connection with the fifth embodiment of FIG. 16) and a first mixing chamber 636 mounted and thermally coupled to the fifth stage 605. The fourth module 640 comprises a second dilution unit having a second still 635' mounted to the third stage 603' of the fourth module 640 and a second mixing chamber 636' mounted to the fourth stage 604. This arrangement ensures that each of the thermal stages is thermally coupled to a respective cryogenic refrigerator, which can be particularly advantageous in compensating for heat loads, such as may be applied by any connected electrical apparatus.

Components of an optional QIP system are schematically represented in FIG. 18. The input lines 681 are sequentially connected to each of the first stage 601, second stage 602 and third stage 603 inside the second module 620. The input lines 681 then extend from the third stage 603 inside the second module 620 to the third module 630. The input lines 681 subsequently connect to each of the fourth stage 604 and fifth stage 605 inside the third module 630, and to a QIP device inside the third module 630, the QIP device being thermally coupled to the fifth stage 605. The input lines 681 are thereby cooled by each of the connected thermal stages and are arranged to transmit an electrical signal from a position exterior to the system 600 to the QIP device 682.

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Output lines **683** are arranged to transmit an electrical signal from the QIP device **682** to another position exterior to the system **600**. The output lines **683** extend from the QIP device **682**, into the fourth module **640**, and then are sequentially connected to each of the fifth stage **605**, fourth stage **604**, third stage **603**, second stage **602** and first stage **601** inside the fourth module **640**.

The seventh embodiment is illustrative of how the common internal volume to the system **600**, created by the connected modules, can be utilised for different parts of the QIP system. It also shows how cooled components from different modules can be utilised to compensate for heat loads applied by connected electrical apparatus (e.g. arising from operation of RF attenuators forming part of the input lines **681**). In the present case, the relatively large heat load provided by the input lines **681** at the third stage **603** is mitigated by the cooling power of a dedicated 1-K pot **632** rather than the still of a dilution unit which may have less cooling power. The first still **635** is thermally isolated from the input lines **681** and the 1-K pot **632** by using a low thermal conductivity link **667**. At the fourth stage **604**, the heat load from the input lines **681** is taken up by the second mixing chamber **636**, which forms part of a dedicated “cold stage dilution refrigerator”. This leaves the first dilution unit in the third module **630** otherwise ‘unloaded’ so that the first mixing chamber **636** can operate optimally to reduce the temperature of the QIP device **682** and lower the overall base temperature for the system **600**. In use, the fourth stage **604** typically obtains a base temperature of around 100-200 mK and the fifth stage **605** typically obtains a base temperature of around 10-20 mK or potentially lower depending on the heat load applied by any connected electrical apparatus.

It will be appreciated that the modularised approach described herein provides the user with flexibility to combine different modules having respective refrigerating arrangements according to the experimental need. For example, the operation of multiple closed loop (or open loop) refrigerators inside the cryostat (including dilution refrigerators, helium-3 or helium-4 refrigerators) allows the cooling power of several cooling systems to be combined, by mechanically strongly coupling and thermally strongly coupling their cooling stages together isothermally. This may be achieved by linking together the mixing chambers of multiple dilution units at the cold stage, using a material of high thermal conductivity. Alternatively the cooling power of several cooling systems may be separated, by mechanically strongly (or weakly) coupling, but weakly thermally coupling, their cooling stages together so that they are anisothermal. This may be achieved by having one mixing chamber of one dilution unit operating at one temperature and another mixing chamber of another dilution unit operating at a different temperature. Furthermore, the cooling at the PT2 stage (which generally has an operational temperature of approximately 4 K) may also be provided by any of (or any combination of) a cryocooler, a dry mechanical contact to the cold part of a helium recondensing system, or a connection to a liquid helium bath.

The stages of a module in the system may be considered to form a primary insert that is connectable to a secondary insert containing a target apparatus. The target apparatus may be conveniently loaded into the system and exchanged by the connection of the secondary insert to the primary insert, further increasing the customisability of the system. The secondary insert may comprise a plurality of secondary plates that are connected in a self-supporting structure, each secondary plate typically being connectable to a respective stage forming a primary plate of the primary insert. One or

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more adjustment members may be configured such that, when the secondary insert is mounted to the primary insert, the adjustment member(s) cause the primary and secondary plates to be brought into conductive thermal contact. For example, the adjustment member(s) may change the separation between the primary and secondary plates or they may comprise deformable member(s) forming part of a respective primary or secondary plate (as described in WO 2021/170,976 A1). A plurality of secondary inserts may be connectable to the primary insert, for example two or more secondary inserts may be connected on each of two opposing sides of the module (depending on the size and configuration of the module). Access to the secondary inserts may be conveniently enabled by a door on the side face of the housing, for example as shown in FIG. 10.

Each module may be considered to form a ‘unit cell’ of an extensible system. The modules may be configured to operate independently or coupled to adjacent modules to expand the cooling power of the system and the physical space inside, such that the modules operate as a single larger system as the experimental complexity grows. The connected modules in the system could serve different functions and may have a different size, shape or footprint from other modules in the system provided that the housings allow for mutual connection as earlier described. The extensible temperature stages facilitate the combination of a higher number of cryogenic cooling systems onto common temperature stages, for example to compensate for higher heat loads. The option to weakly thermally couple respective temperature stages allows for the stages to be sub-divided into different temperature regions, for example to allow optimal operation of the connected apparatus. Further preferred features and advantages are described above. Taken together, the system described herein provides a scalable cryogenic system that may be operable at millikelvin temperatures.

The invention claimed is:

1. A cryogenic cooling system comprising:

a cryogenic refrigerator assembly comprising one or more cryogenic refrigerators; and

two or more connected modules, each of the two or more connected modules comprising:

a housing defining an internal volume for the module, the housing having a plurality of side faces; and

a plurality of stages arranged within the internal volume of the module, wherein one or more of the plurality of stages is thermally coupled to the cryogenic refrigerator assembly;

wherein the two or more said modules are mutually connected at respective side faces;

wherein the system further comprises one or more extension plates; and

wherein a first stage of the plurality of stages of a first said module is thermally coupled to a first stage of the plurality of stages of a second said module by the one or more extension plates.

2. The cryogenic cooling system according to claim 1, wherein the cryogenic refrigerator assembly is configured so that each of said two or more connected modules comprises a cryogenic refrigerator thermally coupled to one or more of the plurality of stages of the module, the system further comprising a removable panel, wherein each said module is configured to operate in a first configuration as an independent cryogenic cooling system whereby the removable panel is fitted to the housing of the module in the first configuration to enclose the internal volume for the module, wherein each said module is further configured to operate in a second configuration as a component of an integrated cryogenic

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cooling system comprising a plurality of said modules mutually connected at respective side faces to form a shared internal volume for the system in which the stages for each said connected module are arranged, wherein in the second configuration the removable panel is removed from the housing.

3. The cryogenic cooling system according to claim 1, wherein a side face of the first said module is directly connected to a side face of the second said module.

4. The cryogenic cooling system according to claim 1, wherein a second stage of the plurality of stages of the first said module is thermally coupled to a second stage of the plurality of stages of the second said module.

5. The cryogenic cooling system according to claim 1, wherein the one or more extension plates comprises a plurality of extension plates, wherein two or more stages of the plurality of stages of the first said module are connected to respective stages of the second said module by the plurality of extension plates.

6. The cryogenic cooling system according to claim 5, wherein each extension plate of the plurality of extension plates is configured so that an effective thermal conductivity across the extension plate is above 5000 W/m K at a temperature of 20 K.

7. The cryogenic cooling system according to claim 5, wherein a first subset of the plurality of extension plates is configured so that the effective thermal conductivity across the plurality of extension plates of the first subset is above 5000 W/m K at a temperature of 20 K, and wherein a second subset of the plurality of extension plates is configured so that the effective thermal conductivity across the plurality of extension plates of the second subset is below 50 W/m K at a temperature of 20 K.

8. The cryogenic cooling system according to claim 1, wherein the one or more extension plates comprises an expandable joint configured to maintain a mechanical connection between the first stage of the plurality of stages of the first said module and the first stage of the plurality of stages of the second said module during relative movement.

9. The cryogenic cooling system according to claim 1, wherein the first said module comprises a first dilution unit and wherein the second said module comprises a second dilution unit, wherein the first dilution unit comprises a still mounted to the first stage of the plurality of stages for the first said module, and wherein the second dilution unit comprises a still mounted to the first stage of the plurality of stages for the second said module, wherein the first stages of the first and second said modules are mechanically connected by an extension plate of the one or more extension plates.

10. The cryogenic cooling system according to claim 9, wherein an effective thermal conductivity between the first stages of the first and second modules is below 50 W/m K at a temperature of 20 K.

11. The cryogenic cooling system according to claim 9, wherein the first dilution unit comprises a mixing chamber mounted to a mixing chamber stage of the plurality of stages for the first said module, and wherein the second dilution unit comprises a mixing chamber mounted to a mixing chamber stage of the plurality of stages for the second said module, wherein the mixing chamber stages of the first and second modules are mechanically connected by an extension plate of the one or more extension plates, wherein an effective thermal conductivity between the mixing chamber stages of the first and second modules is below 50 W/m K at a temperature of 20 K.

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12. The cryogenic cooling system according to claim 1, wherein the first said module comprises a cryogenic refrigerator in the form of a dilution unit or 1-K pot, and wherein the second said module, or a third said module having a stage that is thermally coupled to a corresponding stage from the first said module, comprises a cryogenic refrigerator comprising a cryocooler and a reservoir for liquid cryogen, wherein the reservoir is arranged to collect a cryogen that is liquefied by operation of the cryocooler, and wherein the reservoir is operable to cool one or more stages from the plurality of stages of the first said module.

13. The cryogenic cooling system according to claim 1, further comprising more than two said connected modules, wherein the connected modules are arranged to form a two-dimensional array of modules.

14. The cryogenic cooling system according to claim 1, wherein the plurality of side faces are arranged so that the system forms a tessellating structure.

15. The cryogenic cooling system according to claim 1, wherein one or more said modules comprise: a primary insert and a demountable secondary insert, the primary insert comprising a plurality of primary plates formed by respective stages of the module, the secondary insert comprising a plurality of secondary plates connected in a self-supporting structure, the secondary insert further comprising a target apparatus, the system configured such that, when the secondary insert is mounted to the primary insert, the primary plates are brought into conductive thermal contact with the secondary plates.

16. A quantum information processing device comprising the cryogenic cooling system according to claim 1, wherein the system further comprises a target assembly comprising electrical circuitry extending between the stages of two or more said connected modules.

17. The cryogenic cooling system according to claim 1, wherein the cryogenic refrigerator assembly comprises a liquid helium refrigeration plant connected to a plurality of heat exchangers for cooling one or more stages of the plurality of stages of the first said module and one or more stages of the plurality of stages of the second said module.

18. The cryogenic cooling system according to claim 1, wherein each stage of the plurality of stages for the first said module and each stage of the plurality of stages for the second said module is planar, wherein the first stage of the plurality of stages of the first said module is coplanar with the first stage of the plurality of stages of the second said module, wherein the first module comprises a first nested assembly of heat radiation shields, each said heat radiation shield of the first nested assembly being connected to a respective said stage of the plurality of stages of the first module, the system further comprising a second nested assembly of heat radiation shields, each said heat radiation shield of the second nested assembly being connected to a respective said stage of the plurality of stages of the second module.

19. The cryogenic cooling system according to claim 18, further comprising a first shield extension section connecting a first shield surface of the first nested assembly of heat radiation shields to a first shield surface of the second nested assembly of heat radiation shields, the first shield extension section comprising a flexible joint.

20. The cryogenic cooling system according to claim 1, wherein each said module forms a unit cell of an extensible system.

21. The cryogenic cooling system according to claim 1, wherein each said module comprises a side face having a door that can be opened to provide access inside the module.

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22. The cryogenic cooling system according to claim 1, wherein each said module comprises an aperture in a said side face of the housing, wherein the aperture extends around the plurality of stages, wherein said aperture is arranged at an interface between the two or more connected modules. 5

23. The cryogenic cooling system according to claim 22, wherein the interface further comprises a sealing member arranged around the aperture, the sealing member enabling a vacuum-tight seal to be made at the interface. 10

24. The quantum information processing device according to claim 16, further comprising electrical components mounted on at least one of the one or more extension plates and connected to the electrical circuitry extending between the stages. 15

25. The quantum information processing device according to claim 16, wherein the cryogenic refrigerator assembly comprises a dilution refrigerator, the dilution refrigerator comprising a still, and wherein the cryogenic refrigerator assembly further comprises a 1-K pot, wherein the still is thermally isolated from the 1-K pot, wherein the electrical circuitry comprises input lines and output lines, wherein the input lines are thermally coupled to the 1-K pot, and wherein the output lines are thermally coupled to the still. 20

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26. The cryogenic cooling system according to claim 1, wherein

the one or more extension plates comprises an expandable joint configured to maintain a mechanical connection between the first stage of the plurality of stages of the first said module and the first stage of the plurality of stages of the second said module during relative movement,

the plurality of side faces are arranged so that the system forms a tessellating structure,

wherein each said module forms a unit cell of an extensible system, each said module comprises a side face having a door that can be opened to provide access inside the module, and each said module comprises an aperture in a said side face of the housing,

wherein the aperture extends around the plurality of stages, wherein the aperture is arranged at an interface between the two or more connected modules, and

wherein the interface further comprises a sealing member arranged around the aperture, the sealing member enabling a vacuum-tight seal to be made at the interface.

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