CRYOGENIC SUPPLY FOR THE GERDA EXPERIMENT

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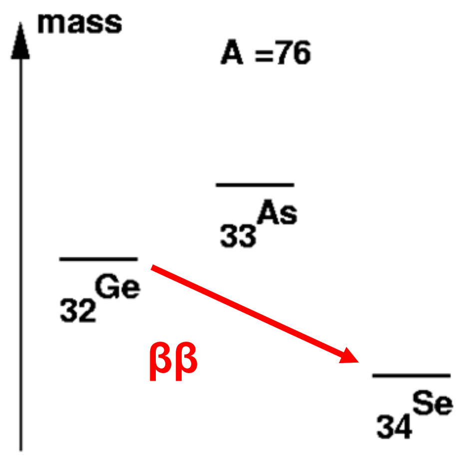
ABSTRACT

In the GERDA experiment (GERmanium Detector Array for the search of neutrinoless double beta decay of ^{76}Ge) germanium diodes are suspended in a superinsulated cryostat filled with 70 m³ of liquid argon. The cold medium is required since the diodes have to be operated at low temperatures, and furthermore for shielding against background radiation. For the same reason the whole experiment will be placed in the underground laboratories in the Gran Sasso mountains, Italy. In order to avoid any detrimental perturbation inside the dewar vessel, the liquid-argon (LAr) inventory in the main tank will be kept in a subcooled state at a working pressure of 0.12 MPa absolute at the surface. At the TU Dresden an appropriate cryogenic arrangement was designed to match these requirements. Liquid nitrogen (LN_2) is used as a cooling fluid. Special care was taken to cope with the narrow temperature span between the LAr boiling temperature and triple point. In the proposed solution a subcooler located close to the cryostat neck provides a stable LAr convection inside the main tank. The working pressure is adjusted with a controlled, slightly elevated temperature level at the liquid-vapor interface.

KEYWORDS: GERDA experiment, double-beta decay, subcooled liquid argon

INTRODUCTION

The GERDA experiment was proposed in 2004. The aim is to study the nature of neutrinos by observation of a neutrinoless double beta decay of Ge-76 isotopes [1, 2]. The process is shown in FIGURE 1a. Whereas a cascade of two consecutive β decays is energetically forbidden, double beta decays, i.e. two simultaneous decays, are allowed and observed from a number of isotopes. Normally by this decay of two neutrons n, a pair of protons, p, electrons, e^-, and anti-neutrinos, ν, are generated and observed. A neutrinoless double beta decay with mere generation of p and e^- pairs is possible only if both neutrinos



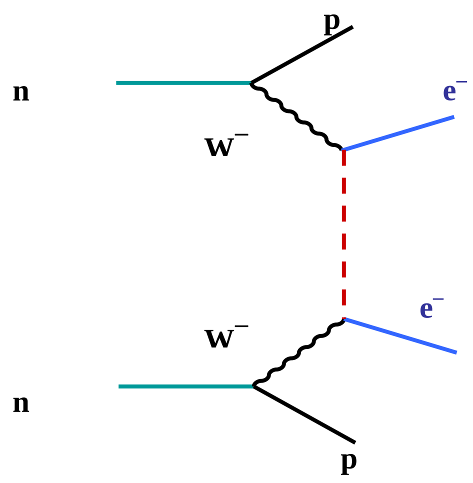


FIGURE 1. a) nuclear decay scheme of a double beta decay of a $^{76}{}_{32}$Ge nucleus. b) Feynman graph of the neutrinoless double beta decay: two neutrons n simultaneously transmute into a proton p and, via W–Boson, an electron e^- each. The neutrinos necessarily generated at both decays are directly annihilated (dashed line).

annihilate (dashed line in FIGURE 1b). In other words, if the neutrino is identical with the anti-neutrino. This is expected by most of the extensions of the Standard Model of particle physics, but could not be experimentally verified irrefutably up to now. The doubtless observation of a neutrinoless double beta decay, thus would have a large impact on our understanding of the evolution of the universe. The non-observation of anti-matter, although produced in equal amount to matter in the big bang, could be related to the nature of the neutrino. Moreover the observation would reveal not only the so called Majorana nature of the neutrino, but also provide a measurement of its effective mass.

The GERDA collaboration comprises about 80 nuclear physicists from 13 different institutions in five different countries. Responsible for the cryogenics herein is the MPIK at Heidelberg/Germany. The present work reflects additional contributions from the TU Dresden.

GERDA SET-UP

In the past, the search for this decay using Ge diodes made from material enriched in the Ge-76 isotope was a most sensitive investigation. These diodes were operated in copper cryostats and the sensitivity was limited by radioactive contamination in the close vicinity of the diodes, e.g. the copper. In GERDA a new approach is pursued: almost all construction material is replaced by LAr, which can be produced with extremely low content of radioactive contaminations (most important: radon).

The ββ0υ events can be identified by a peak in the energy spectrum at 2039 keV, the Q value of the decay. Since the decay is extremely rare, shielding against external radioactivity is of paramount importance. For this reason the whole GERDA experiment will be installed in the underground laboratories at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy. Cosmic background rays are widely absorbed there by hundreds of meters of rock above.

Measurements must be performed at cryogenic temperatures for an essential reduction of the thermal noise. Additionally, cryogenic liquids like LN_2 or LAr, due to their radiopurity, do not contribute to the background radiation and serve as a shield against ex-

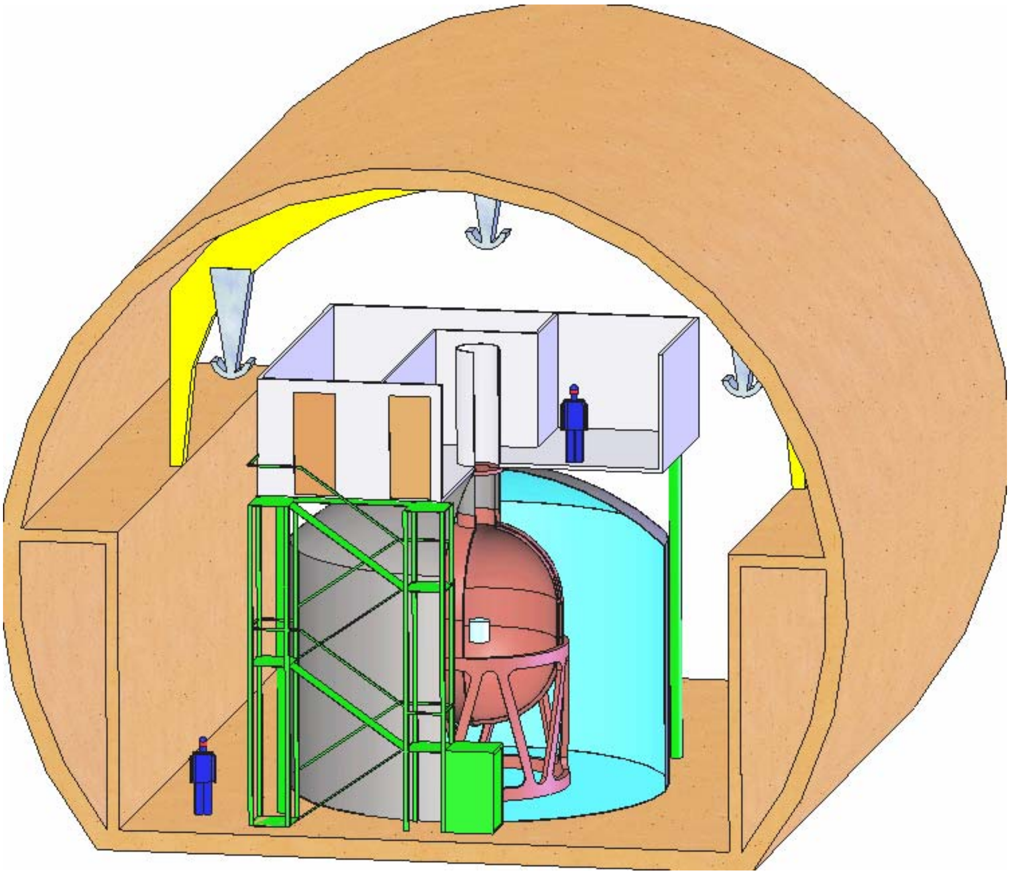


FIGURE 2. Artist's view of the GERDA set-up in the Gran Sasso underground laboratories (LNGS) in Assergi, Italy. The 70 m³ cryostat with the diode arrays suspended in its center is placed inside a water tank. On top of the cryostat are mounted the lock and cleanrooms..

ternal radioactivity. Further shielding is provided by a huge water tank (650 m³) surrounding the cryostat. In FIGURE 2 the arrangement in the LNGS underground tunnel is visualized.

The cryostat has a capacity of 70 m³. Its total height will be 8.9 m, and the inner and outer vessels are made of stainless steel. Thermal insulation will be accomplished by vacuum superinsulation. The inner vessel is supported by 8 Torlon pads at the bottom. A stainless steel bellow in the neck counterbalances the thermal contractions during cool-down. The only opening of the cryostat is the neck with an inner diameter of 800 mm. A lock containing the diode suspension and instruments is mounted on top of the cryostat, beneath clean rooms and instrumentation. In order to avoid any radioactive contamination, cryostat and lock will be hermetically sealed. All materials used for the cryostat or for the inventory must pass a very stringent test on their intrinsic radioactive impact (here: Th-228 is most relevant). Best values can be realized with pure LN_2 or LAr (~ 0 µBq/kg), water (~ 1 µBq/kg), pure copper or lead (~ 20 µBq/kg) or special batches of stainless steel (~ 1000 to 5000 µBq/kg). Most materials, especially compound materials of rock / concrete (~ 300000 µBq/kg) must be kept away from the diodes as far as possible.

The cryostat will be designed for maximum of 0.25 MPa absolute pressure, whereas the normal working pressure will be about 0.12 MPa absolute. For a number of reasons the experiments will be performed exclusively with LAr.

CRYOGENIC CASE

Heat Loads

The heat load estimate included the residual heat transfer via superinsulation (~ 1 W/m^2), heat transfer via Torlon pads (64 W in total), radiation down the neck despite baffles (~ 20 W), and heat conduction down the neck wall and along the vapour column (~ 26 W, calculated with CRYOCOMP). This totals up to about a 200 W heat load. This figure was multiplied with a safety factor of 1.5, and some additional margin added for transient states and cool-down, respectively.

Requirements on the Cryogenic Supply

Due to the quite sensitive measurement conditions required to investigate this decay, quite stringent restrictions are imposed on the cryogenic cooling system:

- exact compensation of the heat load on the LAr inventory (i.e. assuring zero boil-off conditions)
- avoidance of pool-boiling inside the main vessel (i.e. assuring a subcooled state of the liquid)
- avoidance of any perturbation or vibration inside the tank
- adjustment of a pressure level (in the gas phase) of typically 0.12 MPa absolute.

Thus the peripheral cryogenic system has to cover the following tasks:

- initial cool-down of the inner tank and filling procedure
- further cooling of the 70-m^3 LAr content down to the subcooled operating state
- pressure and temperature control inside the tank.

Additional cryogenic installations (LAr purification unit, sensor equipment, control), as well as safety issues, are the responsibility of other collaborators and not discussed here.

CRYOGENIC CONCEPT

The proposed flow scheme for cryogenic supply is sketched in FIGURE 3. It comprises separate systems for LAr and LN_2.

LAr System

The LAr system comprises a standard LAr storage tank of about 10 m^3 capacity, a superinsulated LAr transfer line, a LAr phase separator of about 200 l capacity and a filling line. The phase separator is kept with a slight overpressure of about 0.15 MPa absolute.

The initial filling (and rare cases of re-fill during the later operational phase, despite normally adhered to zero boil-off regime) is done via V1, V2, V3 and the central blow-off line of the tank that includes V4. The main task of the intermediate phase separator is to prevent undue overpressure passing from the storage tank to the vulnerable 70 m^3 dewar, which has safety valves and rupture discs set to 0.19 MPa and 0.2 MPa absolute, respectively. To accommodate the zero boil-off regime, this refilling system will be only rarely in use. Thus during most of the time this part of the cryogenic system is allowed to warm up. The level is measured by three independent systems supplied separately.

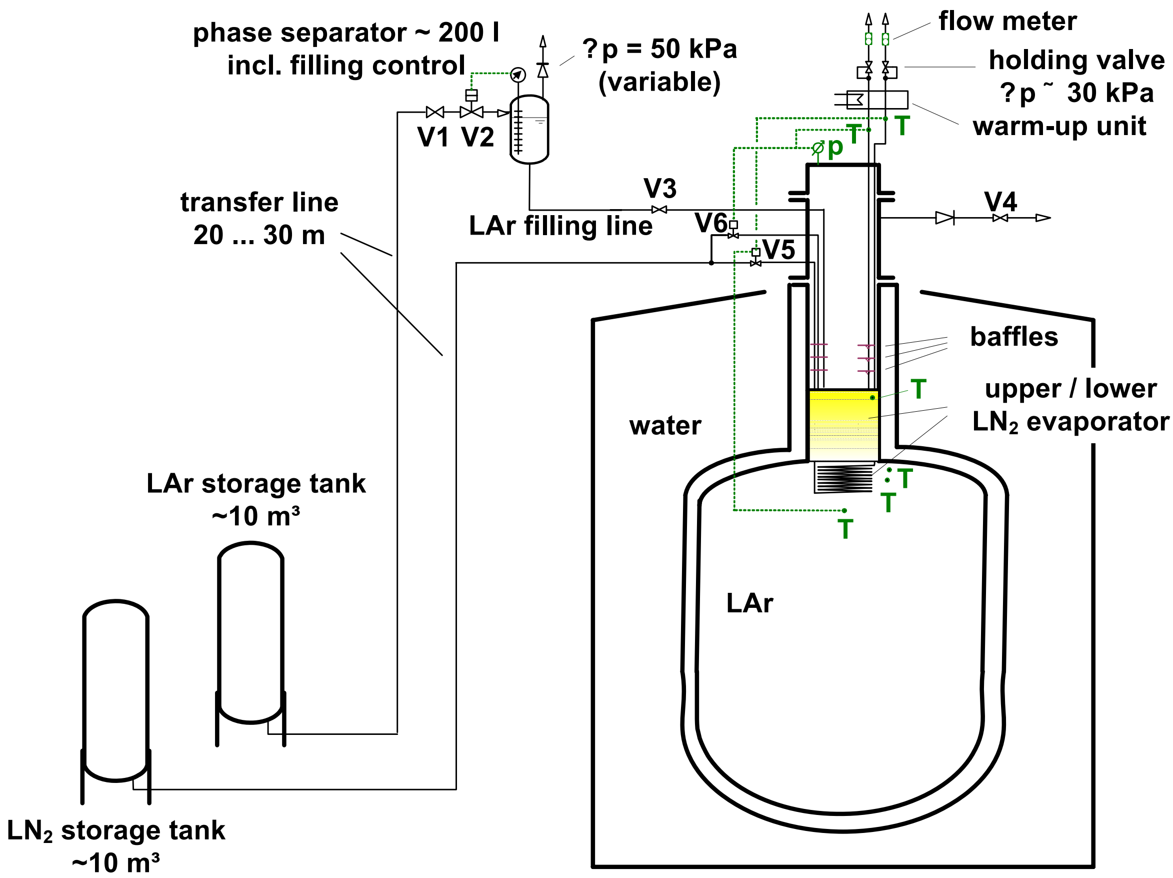


FIGURE 3. Simplified flow scheme of the cryogenic supply of the GERDA cryostat. T and p denote locations for temperature and pressure sensors, respectively. Control loops are indicated by dashed lines.

In case the cryostat must be emptied for any reason, an electrical heater will be inserted through the neck to evaporate all the contents. The necessary heat input can be estimated as follows:

$$163.4 \text{ kJ/kg} \cdot 98350 \text{ kg} \approx 1.6 \cdot 10^7 \text{ kJ} \approx 4464 \text{ kWh} \qquad (1)$$

Thus a 10 kW heater will have to be activated for more than 18 days!

A draining of the liquid-argon inventory is not possible since no additional dumping line at the bottom of the tank can be accepted. Pumping or blowing out fails for hydrostatic reasons, or since it requires exceeding the maximum operational pressure of the cryostat.

LN_2 Cooling System

The LN_2 system comprises a standard LN_2 storage tank of about 10 m³ capacity, a superinsulated transfer line of about 30 m (including ~ 9 m vertical level difference), inlet control valves, two evaporators of different size and at different levels, outlet lines, a warm-up unit for the cold nitrogen gas, holding valves (differential pressure for opening at about 50 kPa) and flow meters for better control.

The active cooling of the liquid-argon inventory is achieved by the two liquid-nitrogen evaporators. A larger one is mounted in the main LAr volume directly below the neck; the major part of the nitrogen is evaporated there. LAr passing the evaporator will be recooled. Subsequently this cooler and denser fluid sinks downwards.

The smaller evaporator is mounted inside the neck, with its windings concentrated below the liquid-vapour interface. With a minor amount of evaporating nitrogen the LAr content inside the neck and the baffles are cooled.

Liquid nitrogen is taken from the storage tank, operating at typically 0.5 MPa absolute pressure. Due to the level differences, a first pressure reduction of 20 to 80 kPa occurs in the transfer line, thus some appreciable vapour fraction will be present already before passing through the inlet control valves V5 and V6. After throttling down to the pressure level of about 0.15 MPa absolute in the evaporators, the significant volumetric vapour fraction is dominates the flow, thus continuously transporting the volumetrically small fluid fraction. Collection of fluid in the lower parts of the evaporator with subsequent geysering and uneven transport is thus avoided.

The nitrogen will be evaporated completely, and the cold vapour is warmed up outside the cryostat to nearly ambient temperatures (for easy handling and simple controls and instruments). By means of the holding valves the boiling temperature inside the evaporator is kept at ~ 79.5 K. For later optimization, the set points of the valves should be adjustable between 5 and 100 kPa differential pressure to atmosphere, corresponding to a nitrogen boiling temperature between 77 K and 84 K, respectively.

Subcooled State of the Liquid Argon Inventory

The basic idea is to use the comparative large LAr density and thus the large hydrostatic pressure occurring with increased depth below the LAr surface, as sketched in FIGURE 4. The level of the vapor-liquid interface is defined as zero. In the vapor space above a working pressure of e.g. 0.12 MPa absolute is established. Thus the liquid in the neck directly at the interface is at boiling conditions at 88.9 K, tolerable in terms of perturbation for the experiment placed below. At the lower end of the neck, a temperature of about 87 K is achieved by active cooling, thus creating a clearly subcooled state of the fluid. At lower levels, the degree of subcooling appreciably increases.

As indicated in FIGURE 4, the lower evaporator will cool the LAr in the main volume close to the neck from about 87 K to 86 down to 84 K. This results in an appreciable increase in fluid density:

87.0 K / 0.16 MPa: $\rho = 1397.4$ kg/m³
86.0 K / 0.16 MPa: $\rho = 1403.6$ kg/m³
85.0 K / 0.16 MPa: $\rho = 1409.7$ kg/m³
84.0 K / 0.16 MPa: $\rho = 1415.8$ kg/m³

In effect a convective motion inside the main volume is initiated as indicated in FIGURE 4. It can be calculated that a heat load of 200 W can be transferred by a LAr mass flow of 90 g/s (324 kg/h) with a temperature reduction at the evaporator of 2 K. Considering an area of about 0.28 m² below the evaporator for the main descending current, a flow velocity of about 0.2 mm/s can be estimated. In other words, for the necessary heat transfer extremely low flow velocities are sufficient due to the large dimensions of the cryostat.

In reality the flow conditions, of course, will adjust themselves by the equilibrium between convective and viscous forces. It is expected that the flow velocities will be typically at least one order of magnitude higher compared to the minimum estimated above. The density differences and thus the convective forces depend to a large degree on the flow velocity and thus on the heat transfer at the evaporator. A low heat load results in reduced convection and low heat transfer rates at the evaporator. On the other hand, large temperature differences will provoke a vigorous convective circulation. Hence, the system will self-adjust within a wide range of heat loads.

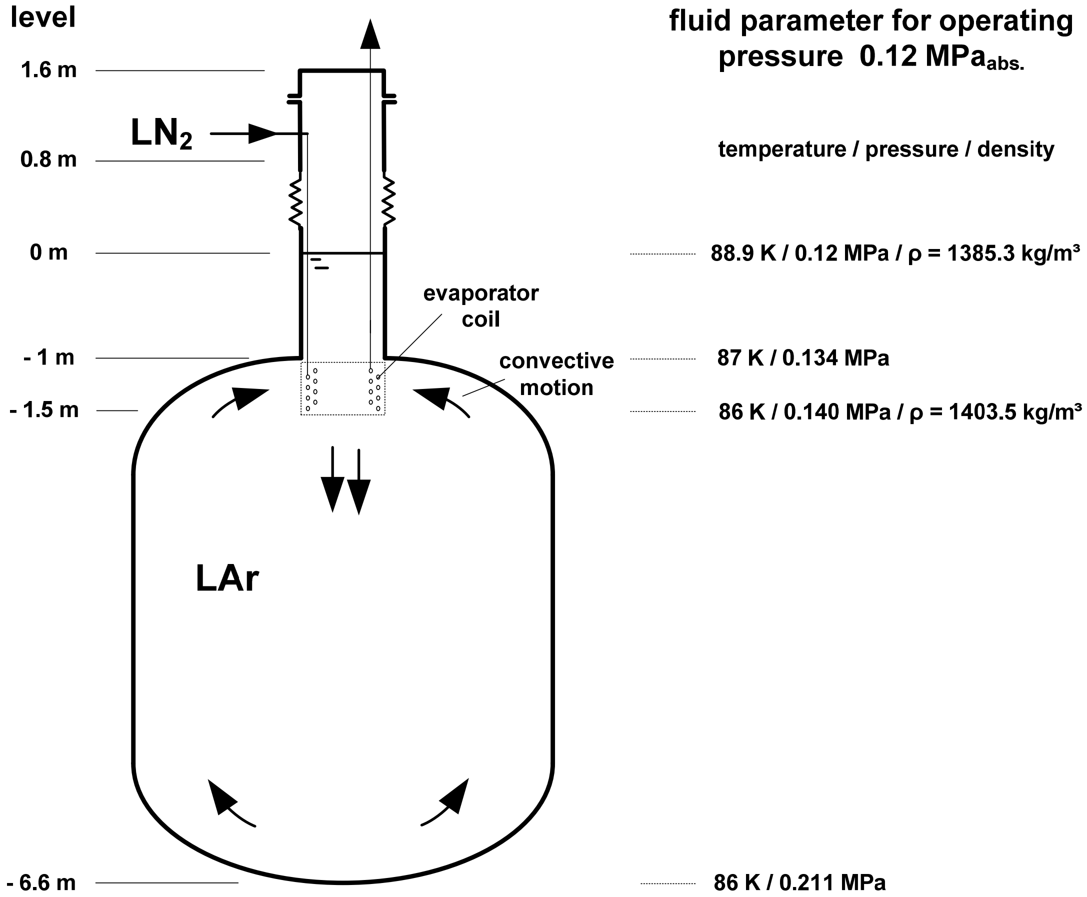


FIGURE 4. Pressure and temperature levels inside the 70 m³ LAr cryostat due to active cooling and hydrostatic pressure, with convective flow in the main volume.

Evaporators

The evaporators are made of standard copper tube (about 18 x 1 mm) coiled up in large spirals. The required length is given by the heat transfer at the outer surface. A heat flux was calculated according to corresponding equations. For a temperature difference of 0.6 K and a cross-flow LAr velocity of 10 mm/s, a heat flux of about 0.1 kW/m² was obtained. This leads to an outer surface area for the lower evaporator of 2 m², considered to be sufficient to handle the 172 W heat load at the main part of the LAr tank calculated for the design point. Since temperature differences of up to 4 K seem feasible at the evaporator, plenty of margin is given.

As indicated in FIGURE 4, the lower evaporator should be realized with nine spiral layers, 0.7 m in diameter and another nine spiral layers, 0.6 m in diameter. Both the vertical and the horizontal distance between neighboring tubes is 50 mm, forming a wide heat exchanger grid.

Some complication is given by the fact that argon will freeze out at temperatures below 83.8 K. Thus forced cooling might give rise to an argon ice crust at the evaporator tubes. Due to the relative large distance between single evaporator tubes mentioned above, a blockage of the passages is avoided. A temporary ice formation generally can be tolerated. In case of need the evaporation temperature can be increased by modifying the holding-valve working pressure.

Control Loops for Active Cooling

According to the elaborated concept, no additional fluid like helium or neon is introduced to maintain the working pressure inside the cryostat. Therefore, the pressure level above the surface solely depends on the LAr temperature near the surface. This is controlled by the nitrogen mass flow inside the upper evaporator. Therefore, the inlet valve V6 is controlling to the pressure inside the vapor phase as indicated in FIGURE 3.

By means of V5 the degree of subcooling in the main tank is adjusted. This is done according to the reading of the temperature sensors placed close to the evaporator. Due to the slow velocities in the convective flow, time constants will be in the range of hours.

Moreover, the nitrogen temperature at the outlet lines of both evaporators is observed. If here temperatures close to the nitrogen boiling temperature are detected, thus indicating an incomplete evaporation of the cooling fluid with incomplete use of its cooling power, further increase of the respective nitrogen mass flow is prevented.

TIMETABLE

The GERDA project is scheduled as follows:

2004	Proposal; formation of collaboration
2005	Approval, layout and technical studies
2006	Detail planning
2007	Construction of cryostat
2008	Construction of water tank and peripheral devices
2009	Start of data taking.

ACKNOWLEDGMENT

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