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Reduction of helium loss from a superconducting accelerating cavity during initial cool-down and cryostat exchange by pre-cooling the re-condensing cryostat

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ABSTRACT

A Zero-Boil-Off (ZBO) cryostat is designed to realize a compact, stand-alone cryogenic system for the AIST superconducting accelerator (SCA). Under normal operation there is no evaporative helium loss from the cryomodule and therefore operating costs associated with the supply of liquid helium can be eliminated. The only significant loss of helium from the module occurs during the initial cavity cool-down procedure or when the re-condensing cryostat is replaced. It takes about 3 h to cool down the cryostat head from room temperature (300 K) to 4 K. During this time around 100 L of liquid helium is lost due to evaporation. By pre-cooling the cryostat inside a low heat load vacuum tube before transfer to the cryomodule, this evaporative loss could be essentially eliminated, significantly reducing the volume of liquid helium required for the initial cryomodule cool-down. The pre-cooling system also provides an efficient method to test the cryostat prior to use.

1. Introduction

1.1. Background

Superconducting accelerators (SCA) with ultra-short pulses and high repetition rates are proposed to be ideal sources for very intense slow positron beams [1,2]. However, the cryogenic requirements for SCA has meant that these accelerators are limited to large research centers with suitable facilities and cryogenic expertise. If the accelerator module can be maintained at the required temperature (typically 4 K or 2 K) by a standalone compact cryogenic system then SCA technology could be introduced to smaller scale research centers or university laboratories. Also, the availability of liquid helium has been a cause for concern in recent years [3]. Previously, a Zero-Boil-Off (ZBO) cryostat was designed for the SCA modules at the Japan Atomic Energy Agency (JAEA) free electron laser (FEL) facility [4,5]. The ZBO cryostat realizes a standalone system in which a 4 K cryostat placed directly above the liquid helium tank provides continual re-condensing of evaporating helium enabling long term (> 1 year) operation of the accelerator without helium loss. Helium is lost from the cryomodule only during the initial cool-down procedure or when the 4 K cryostat is removed for regular maintenance (normally once per year) and replaced by a standby.

Recently, one of the JAEA FEL SCA modules was installed at AIST and is planned to form the basis of the next generation slow positron beam facility [1,6]. In this paper we report the development of a technique to reduce the helium loss during initial cool-down and cryostat exchange by pre-cooling the 4 K cryostat using a low heat load vacuum tube. During cool-down of the cryomodule, by using the pre-cooled cryostat we were able to maintain around 220 L of liquid helium in the tank after transfer of 400 L, an initial loss of around 180 L. Without using the pre-cooled cryostat the initial loss is typically around 300 L; thus the new method significantly reduces helium evaporation during cool-down, providing a significant cost saving. The pre-cooling system can also be used to test the performance of the 4 K cryostat, allowing us to quickly and efficiently confirm normal operation before using it on the main cryomodule.

1.2. AIST SCA cryomodule

The SCA module is composed of a central 5-cell niobium cavity with a resonant frequency of 500 MHz. This cavity is surrounded by a 400 L liquid helium tank. The tank is surrounded by a vacuum layer, which contains two copper shields surrounded by insulating material

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to reduce the thermal heat load on the liquid helium. The shield layers are cooled with a two stage closed cycle He gas refrigerator (Sumitomo Heavy Industries, model SRD220) using the G–M (Gifford–McMahon) cycle to around 40 K and 80 K. A second cryostat (Sumitomo Heavy Industries, model SRJ2008) is placed into the liquid helium tank to re-condense evaporating liquid helium and realize the ZBO system. This refrigerator utilizes the G–M cycle with a combined J–T (Joule–Thompson) valve and has a cooling power of around 8 W at 4 K. A schematic of the ZBO–SCA cryogenic system is shown in Fig. 1.

1.3. ZBO cryostat system

The ZBO cryostat involves the insertion of a re-condensing 4 K cryostat into the liquid helium tank. The cryostat re-condenses any liquid He which evaporates due to the heat load to the tank. With this system it is essential to maintain the tank pressure at a positive value to avoid the risk of atmospheric gases entering the cold tank. If such a situation occurs ice will be formed inside the tank, a potentially dangerous situation which must be avoided. To maintain an equilibrium positive pressure a small heater element is controlled with a feedback system. This heater turns on under conditions of low heat load to balance the 4 K cryostat cooling power and maintain a constant tank pressure ($\sim$0.02 MPa).

In the event of a failure of any component of the system the rate of helium evaporation will exceed the rate of liquefaction and the gas pressure in the tank will begin to rise. Using a safety blow value with a rating of 0.05 MPa the gas can be vented from the cryomodule. At AIST a central helium liquefaction facility (AIST Low Temperature Center) is in operation and we have connected the blow vent pipe from the cryomodule to this facility. In the case of a slow release of gas (e.g. cryostat failure) the helium gas can be collected by this facility and re-liquefied. In the case of a sudden evaporation event (e.g. sudden loss of vacuum) a large burst disk (0.15 MPa) allows for the rapid venting of helium gas in order to prevent damage to the cryomodule. In such a case the helium gas will be lost to the atmosphere.

2. Method

2.1. Initial cool down procedure for the cryomodule

During the cool down procedure the liquid helium tank is first cooled to 78 K by filling with liquid nitrogen. After maintaining this temperature for several days the nitrogen is then forced out of the tank and liquid helium is introduced. The tank and cavity are not further slowly cooled below 78 K by the cryostats in order to avoid flux-pinning and associated reduction in cavity *Q*-value which is reported to occur if the cavity is slowly cooled to 4 K [7,8]. Therefore, we introduce liquid helium directly after removal of all the liquid nitrogen in the tank. The cool-down from 78 K to 4 K causes the evaporation of most of the initial 200 L of liquid helium. It is necessary to introduce around 300 –400 L in order to see some liquid helium stored in the tank. Normally at this stage the 4 K cryostat is introduced and turned on. During the initial 3 h cool down time up to 100 L of liquid helium can be lost due to evaporation. It can therefore be extremely difficult to maintain any stored liquid helium using less than around 400 L of liquid helium. This loss can be eliminated by pre-cooling the 4 K cryostat as described below.

2.2. Pre-cooling the 4 K cryostat

The 4 K cryostat is pre-cooled by placing it inside a low-heat load vacuum tube, a simple vacuum tube which surrounds the refrigerator cold head. Heat loss is minimized by i) wrapping a layer of standard Al foil (thickness$\sim$15 μm) around the cold head to reduce the emissivity to around 0.04 and ii) surrounding the cold head with a thin (0.2 mm) cylinder of stainless steel. Once installed the vacuum tube is excavated to a pressure of around 10^{-3} Pa. With this system the cryostat can be typically cooled to 4 K within about 3 h. A calculation of the thermal heat load on the cryostat gives an estimate of around 0.5 W at 4 K, well within the capacity of the SRJ2008 refrigerator.

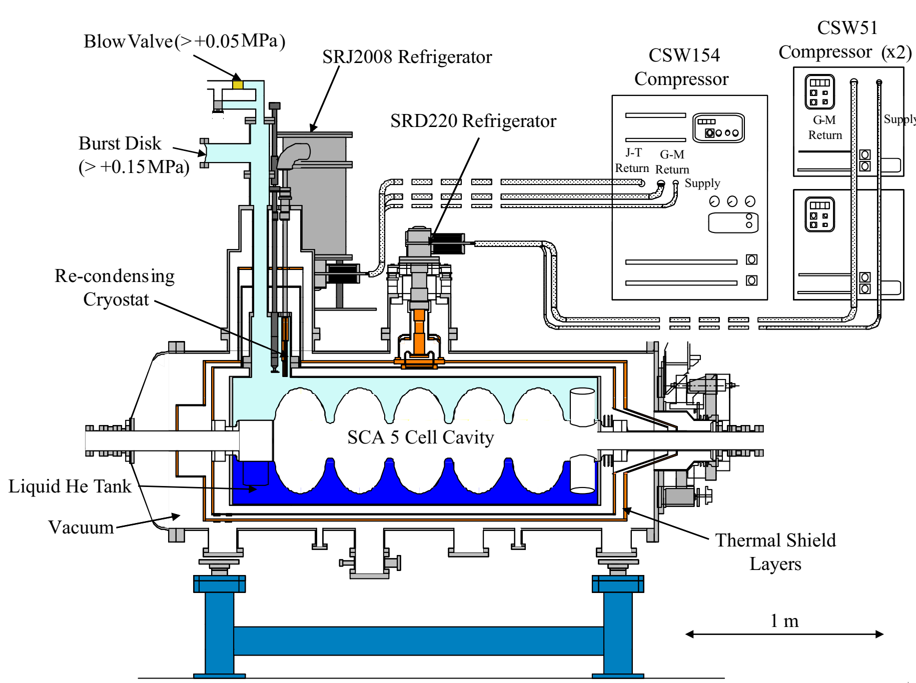

Fig. 1. A schematic of the ZBO-SCA system. The central 5-cell cavity is surrounded by a 400 L liquid helium tank. The tank is separated from the outer vessel by a vacuum layer which contains two copper shield layers covered with thermal insulating material. The shield layers are cooled by a closed cycle G–M helium refrigerator. A second 4 K cryostat is inserted into the liquid helium tank to re-condense evaporating helium. Under normal conditions no helium is lost from the system.