CRYOSTAT FOR TESTING HIE-ISOLDE SUPERCONDUCTING RF CAVITIES

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Abstract

The High Intensity and Energy ISOLDE (HIE-ISOLDE) project is a major upgrade of the existing ISOLDE and REX-ISOLDE facilities at CERN [1], with the objective of increasing the energy and intensity of the delivered radioactive ion beams (RIB). This project aims to fill the request for a more energetic post-accelerated beam by means of a new superconducting (SC) linac based on Quarter Wave Resonators (QWR). A research and development (R&D) programme looking at all the different aspects of the SC linac started in 2008 and continued throughout 2010. The R&D effort has particularly focused on the development of the high β cavities (β = 10.3%) for which the Nb sputtered on Cu substrate technology has been adopted.

Two prototype cavities were manufactured and are undergoing RF cold tests. The pre-series cavity manufacturing is under way using 3D forged Cu billets.

A single vacuum cryostat was designed and built to test these cavities at liquid helium temperatures. This paper details the main design concepts of the test cryostat as well as the results of the cryogenic behaviour of the complete set-up including the cryostat, RF cavity, tuner, and main coupler.

INTRODUCTION

HIE-ISOLDE's activity aims to construct a superconducting linac based on 101.28 MHz niobium sputtered QWRs. The current design considers two basic cavity geometries (geometric β0 = 6.3% and 10.3%).

The present design of the accelerator lattice features housing for five high-beta cavities in a common cryomodule. A total of twenty high-beta cavities will be installed, grouped in four cryomodules. At a later stage of the project, two additional cryomodules will house twelve low-beta cavities.

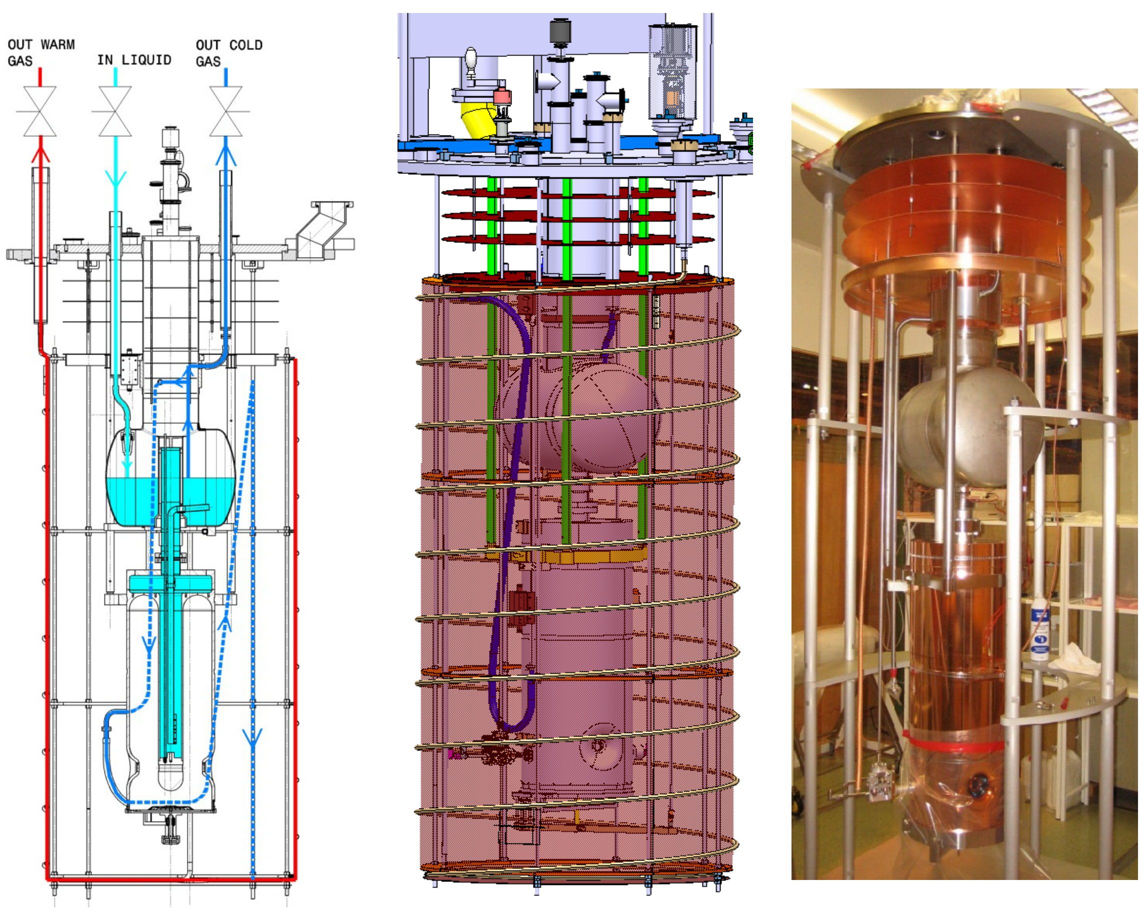

Figure 1: Cryogenic working principle, cryostat design and cryostat insert manufactured.

Two prototype high-beta cavities were manufactured, niobium sputtered, and RF cold tested. The pre-series cavity fabrication is under way using 3D forged Cu billets.

A concept design study of the cryomodules was performed at CERN and several design options were analysed [2]. In most of the existing low-energy heavy-ion installations worldwide, a single vacuum system was chosen both for the beam and thermal insulation of the cryomodules, essentially because it leads to a simpler mechanical design and assembly of the cryomodules. But, as a consequence, in order to preserve the superconducting surface from contamination, a high level of cleanliness of all internal surfaces is needed. The choice of a single vacuum carries a number of drawbacks, the main one being the risk of contamination in case of accidental break of the insulation vacuum leading to particulate contamination of the cavity surface. The separate vacuum concept is nevertheless technically more complex, necessitating additional feedthrough passages to the cavities for the tuners (externally operated), coaxial cables of the couplers, and electrical feeding of the solenoid. Also, the beam vacuum vessel needs a dedicated pumping system and appropriate overpressure protection. Cold-to-warm transitions between the beam vessel and room temperature insulation of the vacuum vessel are also needed. For HIE-ISOLDE cryomodules, the common vacuum solution was considered to provide the best compromise.

Each cavity will be tested at 4.5 K in order to validate the RF performance prior to its installation into the cryomodule. During the development phase of the project it was considered essential that at least one cryogenic test stand be available at CERN. A test cryostat has been developed for this purpose.

DESIGN

General Principle

A cryostat was designed and manufactured at CERN to test the cavities, integrating the cryogenic facility of the SM18 area. The cryostat was aimed at testing one cavity equipped with its tuning system, power coupler, and pickup, while applying some of the same basic concepts chosen for the future machine cryomodules: common vacuum, cooling the cavity by saturated He I at 4.5 K.

The working principle is schematised in Fig. 1: the cryogen is delivered to the cryostat where the helium level is kept constant in a reservoir. From the reservoir, liquid helium fills the cavity and the heat exchange with the cavity is increased by a thermosyphon mechanism (Fig. 2). The principle is based on natural convection which circulates liquid without needing a mechanical pump, increasing the heat exchange coefficient, thus cooling the cavity more efficiently. The evaporated helium gas is evacuated by a "warm line" after passing through the thermal shield and a "cold line" directly linked to the reservoir.

An actively cooled thermal shield reduces the radiation heat load to the cavity and allows a stable temperature of the cavity to be reached. The remainder of the enthalpy from the reservoir's evaporated helium gas is used to cool down the thermal screen.

Passive radiation screens are also installed in the common vacuum on the upper part of the insert, to decrease the heat load from the upper flange to the helium bath. Screens are also installed in reservoir's neck to reduce the radiation heat load from the upper flange but also to stratify the helium gas contained in the neck to avoid ice forming on the cryostat flange. The space between the shield and the neck's wall is minimized to increase wall thermalisation thus reducing conduction through the wall in the lower part close to the liquid surface.

The cavities' technology lies in the use of the niobium sputtered on a thick copper substrate [3]. One of the advantages of the thick copper substrate is that the cavity can in fact be cooled only by pool boiling He I within the inner stem and over the top part, the thick external copper wall ensuring an adequate heat transfer by conduction. Thermal calculation (FEA and analytical) showed that, with the expected power dissipation, the temperature difference between the lower and the upper part of the cavity external wall should not be more than 1 K.

The gas circuit from the reservoir to the thermal shield is first used as thermalisation for the coupler line, as close as possible to the connection of the coupler to the cavity.

The residual particles in the common vacuum are cryo-pumped on the surfaces reaching cryogenic temperature. To keep the cavity internal surface (RF side) as clean as possible, it is essential for the cavity to be cooled at the final stage, after the thermal shield and the reservoir have reached their nominal cryogenic temperature. The particles are thus cryo-pumped on the thermal shield and the reservoir. The reservoir is cooled before the cavity by keeping a low liquid level in the reservoir hence not allowing helium into the thermosyphon. Gas evaporates from the reservoir and starts cooling the thermal shield. The liquid level in the reservoir is then increased until it starts filling the thermosyphon which cools the cavity.

In steady state operation, the helium gas mass flow through the circuit cooling the thermal shield is kept constant enabling stable temperature operation. The pressure of the reservoir is kept constant at about 1.3 bar via a regulation valve allowing the helium gas to be extracted through the cold line. A safety relief-valve limits the maximum pressure in the cryostat at 1.8 bar. During the RF tests, any flow-induced vibrations have to be avoided. The supply of the liquid helium is then closed during the measurements.

Thermosyphon

Two-phase natural circulation loops commonly called thermosyphons, are thermofluid-dynamic systems mainly used to refrigerate a heat source by using the buoyancy driven motion of a fluid in a loop, instead of mechanical pumping [4-6].

Natural convective movement of the liquid starts when liquid in the loop is heated, causing it to expand and become less dense, and thus more buoyant than the cooler liquid at the bottom of the loop. Convection moves heated liquid upwards in the system as it is simultaneously replaced by cooler liquid returning by gravity, generating larger circulation rates than single-phase loops and therefore larger heat transfer rates.

The thermosyphon design principle for the cavity cooling in the test cryostat is schematised in Fig. 2.

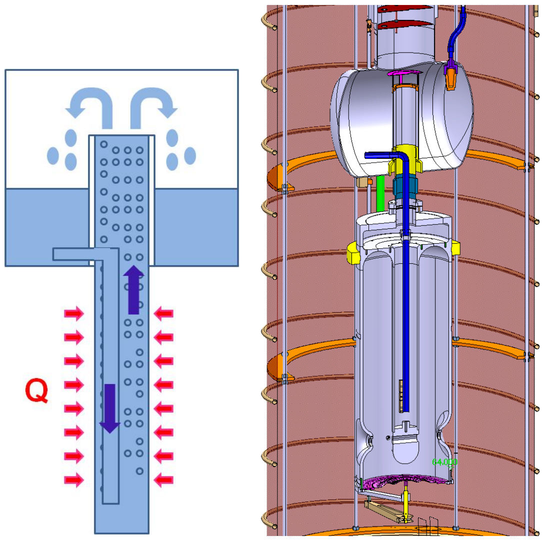

Figure 2: Thermosyphon cooling principle of the cavity.

A helium mass flow of about 30 g/s was estimated circulating by natural convection into the circuit for the nominal dynamic heat load during RF tests.

TESTS

One cryostat has been manufactured and successfully used several times to test sputtered niobium cavities, fully validating the design principle of the test cryostat as well as the foreseen cryogenic behaviour of the cavity, coupler, and tuner, including the thermosyphon mechanism.

Some incidents degrading the insulating vacuum resulted in time-consuming leak detection and repair. This confirmed that common vacuum solutions induce an additional risk during the accidental break of the insulation vacuum.

However, except for the incidents, the entire system including the cavity, coupler, and tuner installed in the test cryostat performed well. The common vacuum level obtained at cryogenic temperature was better than 10^{-7} mbar.

The thermal gradient established on the external cylinder of the cavity was measured and confirmed the expected values. The nominal RF power deposition is about 7 W. The thermal gradient between the upper part of the cavity in contact with the helium bath and the lower part cooled by conduction, was measured to be lower than 0.5 K.

The thermalisation of the coupler was confirmed to be essential.

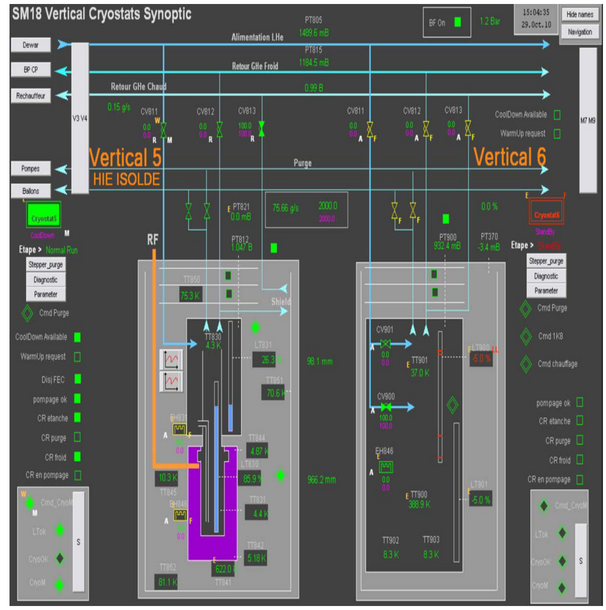

Figure 3: Tests at cryogenic temperature.

The static losses of the cryostat were determined by the measurement (Fig. 3) of the stabilized mass flow of the helium gas through the fully opened warm line. The static losses of 4.5 K liquid helium are of 3.5 W which is well within specifications.

SUMMARY

A cryostat was designed and manufactured at CERN to test the RF cavities for the HIE-ISOLDE project. The cavities were cooled by saturated He I at 4.5 K and the cryostat design fulfilled the future cryomodule principle of common vacuum. The cavity cooling efficiency was increased using a thermosyphon principle. The tests of the cryostat equipped with the cavity, its coupler and tuner validated all the design principles, including the cryogenic behaviour of the cavity and its equipment.

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