Design and preliminary performance tests of the IFMIF-LIPAc Cryoplant

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Abstract. Special features of this Cryoplant are first given with operating purpose, main constraints, design choices for this cryoplant which will cool down a superconductive module (SRF Linac) of an accelerator currently under installation in Japan. The relationship between compliance with Japanese regulations and the successful hydraulic, electric and instrumentation tests are discussed. Measurements of refrigeration power and liquefaction rate were achieved inside the Dewar, and margin power was measured. Further functional and performance tests were conducted in order to demonstrate the correct operation of the cryogenic lines and distribution systems. These tests were performed successfully without the cryomodule, in anticipation to its installation and operation.

1. Introduction

The LIPAc’s (Linear Ifmif Prototype Accelerator) [1, 2] Cryoplant contains all necessary equipment to supply the IFMIF-EVEDA Superconducting RF Linear accelerator (SRF Linac) Cryomodule [3, 4] of the LIPAc with the different fluids used for its various operations. This paper describes the main requirements and special features of the cryogenic plant needed for the cryogenic cooling of the Cryomodule: helium refrigeration, distribution lines, cryogenic lines, valves, storage and accessories i.e. all the cryogenic equipment needed to perform all the operations requested by the Cryomodule.

Two main industrial contracts were awarded to Air Liquide-Advanced Technologies (AL-AT) for the detailed design, manufacturing, installation with QST support and commissioning of the Cryoplant at the IFMIF/EVEDA BA site in Rokkasho, Japan [5]. Multiple sub-contractors for the manufacturing of sub-components and for the installation on-site contributed to this industrial achievement, under the supervision of the Ifmif collaboration researchers and AL-AT experts.

2. Installation of the Cryoplant in anticipation to the Cryomodule installation

The Cryoplant is designed to be installed and tested before the presence of the Cryomodule in the accelerator vault. Interfaces were precisely defined using the 3-Dimensional Mock-up of the LIPAc Facility [6, 7], with flexibility to account for manufacturing and positioning tolerances of the Cryomodule. The cryogenic distribution loop was hence designed with a temporary test configuration and a future Cryomodule configuration. Installation operations were ordered rigorously:
• Laser alignment of dummy cap flange in the Cryomodule position
• Adjustment of dummy cap support and anchoring
• Adjustment of Valve Box supports and anchoring
• Installation of the Main Cryogenic Transfer Line (MCTL)
• Final positioning of the Dewar and cold box constrained by the fixed length of coaxial line
• Anchoring of Dewar and Cold Box according to seismic calculation note
• Installation of the single cryogenic lines and ambient temperature piping

Installation works had to fit within the schedule constraints of equipment deliveries from Europe, and of the accelerator first phase B maintenance windows, especially in the radiation control area: accelerator vault and pit that connects the vault to the RF area. Completion of civil work: perforations, foundation… was also required and the availability of utilities [8] in time for the commissioning.

Figure 1. Top view showing cold box above, Dewar left and valve panel on the bottom. The MCTL runs against the wall (left)

3. Radiation safety
The IFMIF/EVEDA particle accelerator brings ionizing radiation and creates a risk of material activation, malfunction of electronics and destruction of sensitive material over time [9].

• No nitrogen flow in and out of the vault is used. Cooling down, thermal barriers and thermal shielding must be performed with helium. LN2 precooling is only used by the cold box itself.
• Material of components installed near the Cryomodule must be radiation-resistant. Cryogenic valves were selected with radiation-hard properties although the level of radiation allowed to keep the controllers on the valves head. Materials used for joints must be chosen considering a list of forbidden materials, and electrical insulation must be halogen-free.
• Most sensors that can be displaced such as pressure sensors and mass flow rate sensors were deported to the RF area where there is no radiation hazard.
• For critical and inaccessible measurements that cannot be deported, such as Cryomodule bath level, a spare sensor and cable will be installed.
• No exhaust flow, exceeding the capacity of the air venting system, will be authorized inside the vault, even in the case of an accidental safety release of the Cryomodule. All scenarios of pressure rise in the cold mass helium circuits, thermal shield helium circuits, beam vacuum and insulation vacuum were analysed in order to define dimensioning accidents and their corresponding mass flow rates. Safety organs and safety chimneys were then dimensioned to evacuate the dimensioning accident mass flow rate out of the accelerator vault.
Figure 2. This vertical cut view of the building shows part of the accelerator vault on the left, with the valve box and dummy cap near floor level. Two exhaust chimneys slightly above are meant to collect accidental helium release from the Cryomodule helium circuits or vacuum volumes. The MCTL and the chimneys cross the pit under a radiation protection wall, and bring the fluids to the RF area on the right side.

4. Simplifications to reach more standardization

The Cryomodule cold mass ~2000 kg is bath cooled. The bath is supplied by two independent circuits for RF cavities and superconducting solenoids, allowing a separated cooling down or warming up. The gas boil-off from each cavity and solenoid is recovered inside a common upper phase separator vessel and collected towards the Cryoplant through the MCTL.

- The common outlet phase separator implies that one cooling circuit could fill the bath and cool down both circuits, which provides operational redundancy for the filling cryogenic valves.
- Cryomodule thermal shields will be cooled using a fraction of the gas boil-off, with a gas inlet around 5 K and a temperature rise up to ~50 K before returning to the MCTL thermal shield, where temperature further rises up to ~90 K, value that is regulated and can be adjusted.
- Because the MCTL is 35 m long including a siphon, a phase separator was installed on the Cryomodule LHe inlet, with control valves to reduce the number of cryogenic lines.
- As a consequence, the design of the main cryogenic transfer line is simpler and the refrigerator is more standard with only 4.5 K liquefaction and 4.5 K refrigeration duties.
- Acceptance tests are conducted with a dummy flange which is a bypass. The performances of the cryoplant are measured using a Dewar heater, to avoid the construction of a dummy load.
- For the Cryomodule LHe capacity of 0.4 m$^3$, a Dewar capacity of 1 m$^3$ would be sufficient but the oversized capacity of 2 m$^3$ has been selected to provide extra mass and power storage.
- While cryogenic power margin is 50% for prototype design, the margin has been reduced to 20% for industrial current leads and for dynamic heat loads that can benefit from load shedding.
- The high number of ambient temperature return from 48 current leads and 8 power couplers is reduced by grouping and hydraulically balancing current lead pairs down to 24 outlets. Small and easily replaceable control valves installed on the Cryomodule allow to bring only 5 DN15 collecting pipes from the Vault to the valve panel mass flow rates meters.
5. Compliance to EU and Japanese regulation

EU companies comply with EU regulation and safety laws. Additionally, all material and on-site intervention follow local safety rules [9, 10]. The licensing is based on equivalent equipment already installed in Japan under ASME standard with additional clarifications to comply with the Refrigeration Gas Regulation under the supervision of the Aomori prefecture. Licensing tests are performed at each step of the manufacturing:

- The Refrigeration Safety Regulations is used for gas pressure under 1 MPa above atmospheric pressure. The compressor high pressure regulation is hence modified to operate at 0.95 MPa.
- Compliance with seismic rules with an anchoring and structural calculation note is applicable to heavy, pressure and power equipment.

The helium circuit is subdivided into the following 4 categories of equipment under pressure:

- Piping for all diameters <160 mm: ASME standard accepted for equipment manufactured in Europe, while interconnection piping assembled on-site is compliant to JIS;
- Equipment (such as valves, measuring instrument etc.): Standard material certificates compliant with the temperature level, with pressure and leak tests performed by an in-house inspector;
- Pressure vessel for all diameters >160 mm. A third Party inspector must be involved in the design, inspection and manufacturing controls. ASME may be used with additional requirements for weld joint efficiency, wall thickness, welding coupons and tests;
- Safety organs. Their design and manufacturing is attested by the complete set of design calculation, drawings, material certificates, manufacturing, assembly and test reports.

Aomori prefecture approval was required before starting the installation. Final “as built” documentation and inspection must be complete for normal operation approval.

6. Preliminary performance tests

Controls or tests are performed at each step of manufacturing and installation, in order to repair or replace any non-conform piece. The tests described here are the cryoplant commissioning tests realized on-site to confirm the operational performances.

General controls:

- Check of Cryoplant safety devices and interlocks
- Leak tests of final helium connections with equipment better than $10^{-5}$ Pa.m$^3$/s for flanges;
- Buffer conditioning, check of helium purity;
- Cabling checks, continuity and range for all sensors
Exhaustive actuators integrity: Test of all logic control sequences

Compressor station commissioning:
- Checks, turbine installation
- Helium cryogenic lines vacuum tightness
- Cooling of the Dewar, MCTL, MCTL valve box and single cryogenic lines
- Cold box liquefaction performance resulting in 90 l/h above the required 72 l/h
- Cold box refrigeration performance resulting in the required 254 W plus a margin of 20.8 l/h
- Cold box mixed mode performance of 106 W + 83 l/h above the required 101 W + 52 l/h
- Dewar static thermal load of 19.8 l/h, equivalent to 0.498 W or 0.9%/day of the Dewar capacity

The graphics MCTL vacuum content of the Residual Gas Analyzer show that no trace of helium appears and more generally demonstrate the absence of any gas including residual air or water from analysis at ambient temperature compared to an analysis when process piping is at cryogenic temperature.

The MCTL demonstrated to be functional and operational with a measured temperature of 4.3 K in the valve box, but a precise heat load analysis was not possible from the stabilized thermo-hydraulic measurement configurations where helium return paths are open in parallel (cold return to Cold Box, cold return and thermal shield return to atmospheric heat exchanger), while mass flow rate is measured only at the atmospheric heat exchanger outlet. Collaboration engineers will take advantage of the next cooling down to obtain precise measurements of MCTL performance in various steady-state conditions.

7. Conclusion
The Cryoplant was designed for connection to a radiation-hard Cryomodule that would be subsequently installed. Commissioning resulted in the complete starting of the Cryoplant, with operational, performance and acceptance tests. Following the Cryoplant acceptance tests, all acceptance criteria were successfully reached. The Main Cryogenic Transfer Line and its valve box control loops will require additional measurements and analysis to finely tune regulation parameters according to the Cryomodule cryogenic behavior, after its connection that will complete the cryogenic loop final configuration.

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