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ARIEL E-linac Cryogenic System: Commissioning and First Operational Experience

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Abstract. The Advanced Rare IsotopE Laboratory (ARIEL) is a major expansion of the Isotope Separator and Accelerator (ISAC) facility at TRIUMF. A key part of the ARIEL project is a 10 mA 50 MeV continuous-wave superconducting radiofrequency (SRF) electron linear accelerator (e-linac). The 1.3 GHz SRF cavities are operated at 2 K. HELIAL LL helium liquefier by Air Liquide Advanced Technologies (ALAT) with a tuneable liquid helium (LHe) production was installed and commissioned in Q4'2013 [1]. It provides 4 K liquid helium to one injector and one accelerator cryomodules that were installed and tested in 2014. The 4 K to 2 K liquid helium transition is achieved on-board of each cryomodule. The cryoplant, LHe and LN2 distributions, sub-atmospheric (S/A) system and cryomodules were successfully commissioned and integrated into the e-linac cryogenic system. Required pressure regulation for both 4 K cryoplant in the Dewar and 2 K with the S/A system was achieved under simulated load. Final integration tests confirmed overall stable performance of the cryogenic system with two cryomodules installed. The paper presents details of the cryogenic system commissioning tests as well as highlights of the initial operational experience.

Introduction

The TRIUMF ten year plan (2010-2020) seeks to triple the laboratory nuclear physics scientific output by the addition of two new rare isotope beam (RIB) sources. These sources will supply the three existing experimental areas at the ISAC research facility which presently shares a single "driver" proton beam line (BL2A) for RIB production - resulting in under-utilization of experimental potential. The plan foresees a 50 MeV and 10 mA e-linac. Its major components are a 300 keV electron gun, 10 MeV injector cryomodule (ICM) with one 9-cell niobium elliptical cavity, and two 20 MeV accelerator cryomodules (ACM) each containing two 9-cell niobium elliptical cavities. The cavity frequency (1.3 GHz), type (9-cell elliptical), and operating temperature (2 K) have been chosen to benefit from the two decades of development, at the TESLA Test Facility.

1. Cryogenic System Architecture

For both budgetary and resource allocation reasons the e-linac project is planned in two phases. The first project stage, ARIEL phase-I, includes two cryomodules (Injector Cryomodule and Accelerator Cryomodule #1). A third cryomodule will be added in ARIEL phase-II. Due to the phased project schedule, installation and commissioning of some of the cryogenic system components is also split to two stages. Overall structure of the ARIEL cryogenic system is shown on figure 1.

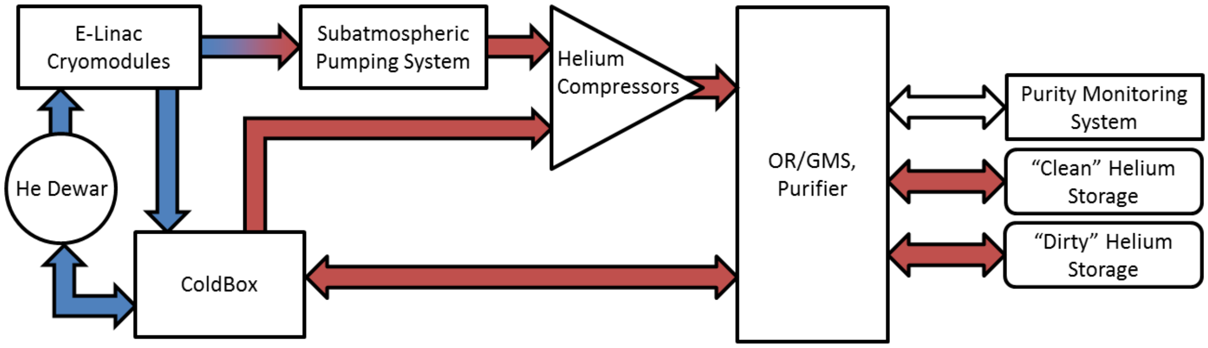

Figure 1. Architecture of the e-linac cryogenic system

1.1. Compressors and Gas Management System

The compression station contains two Kaeser screw-type compressors (figure 2). The main compression unit (Kaeser FSD571) has 112 g/s capacity. The nominal helium gas discharge pressure is 14.5 bar(a). In addition, a smaller air-cooled recovery/purification compressor is installed. This unit (Kaeser CSD85) provides 15 g/s flow rate and is used for a dual purpose. In the event of a power failure the compressor uses power from an emergency power generator to recover all helium boil-off. During regular operation, this same compressor handles the entire throughput of the S/A pumps when cryomodules are at full RF load. This helium flow can then be cleaned of impurities by passing through the freeze-out purifier. Recovery/purification compressor is equipped with dedicated oil-removal and gas management system (OR/GMS).

Oil removal system removes both oil vapors and oil aerosol particles from the process gas. The size of the coalescers and charcoal adsorber was increased compared to the standard 'HELIAL LL' liquefier to optimize the operation of helium cryoplant. Both main and recovery compressors oil removal systems (figure 2) are equipped with the third additional coalescer to decrease the risk of oil migration. Custom design of the charcoal adsorber includes high-temperature resistant materials (~150°C) to increase the temperature of charcoal bake-out and improve water removal. A larger volume carbon bed allows increasing the period of maintenance free operation without charcoal replacements from one to three years.

The stand-alone helium freeze-out purifier (figure 3) was manufactured with assistance from Fermi National Accelerator Laboratory (FNAL). The purifier meets the requirements of the ARIEL cryogenic system. When handling 15 g/s helium flow at maximum pressure 13 bar with 10 ppm nitrogen contamination, the interval between purifier regeneration is projected to 100 days [2]. The commissioning of the purifier is scheduled to Q3 of 2015.

Figure 2. Compressors and Oil-Removal / Gas Management System

Since the timing for the project was very tight, most of the warm piping for the gas management system was built before the cryogenic system documentation was finalized. Therefore, the majority of the compressor building equipment was not included on the project drawings. In order to capture the overall layout of the system components including piping in the compressor building and to produce 'as built' documentation, the 3D laser scanning technology (by Kickstart Technologies Ltd.) was utilized. Figure 2 shows an excerpt from the generated three-dimensional array of metadata.

The Phase II of the ARIEL project will also include the addition of the 'dirty' helium storage tank. Depending on the purity of helium gas coming from S/A part of the system, the flow could be directed to the pure storage tank, freeze-out purifier or to the dirty tank, if the single pass purification is not sufficient to remove all contaminants. After the installation of the 2nd tank, the recovery compressor would be used as a purification compressor, moving helium inventory from the 'dirty' storage through the purifier to the 'clean' storage tank. Helium purity is monitored by Linde multicomponent detector.

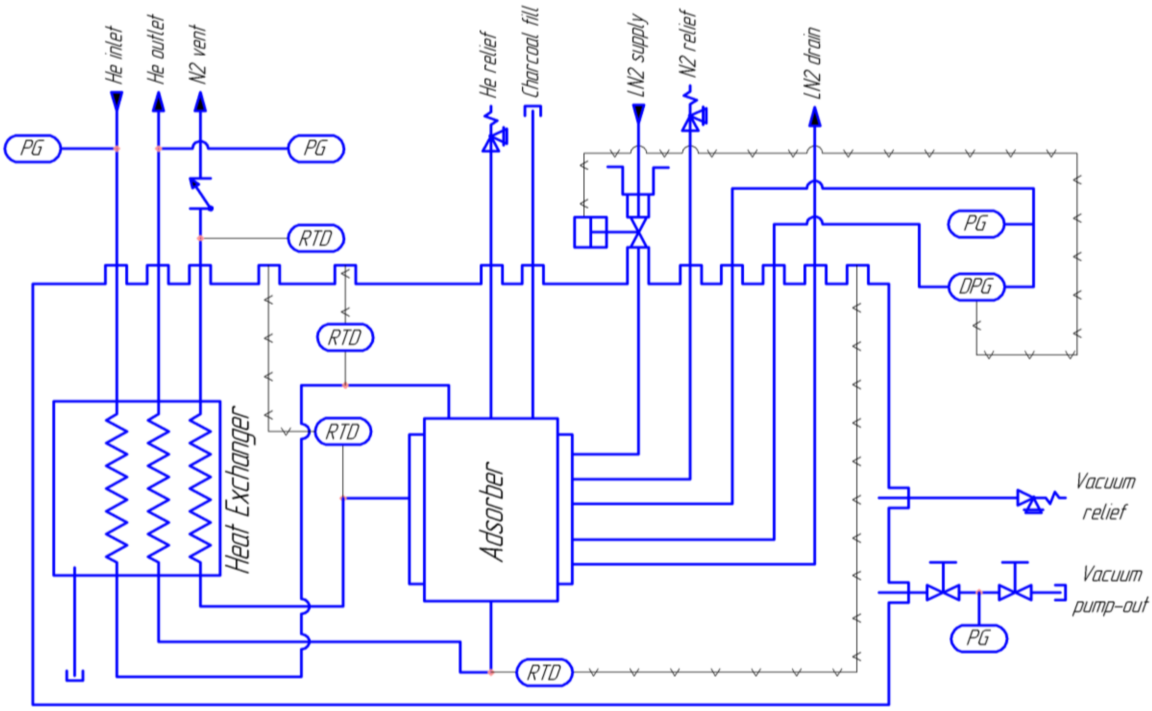

Figure 3. Process diagram of helium purifier

1.2. Liquid Helium Cryoplant

The supplied 'HELIAL LL' coldbox is an automatic helium liquefier-refrigerator provided by Air Liquide Advanced Technologies (figure 4a). The commissioning of the cryoplant is reported elsewhere [1]. The results of acceptance tests are shown in Table 1.

Table 1. Results of Air Liquide HELIAL LL cryoplant acceptance tests

Measured performance parameter	Measured (expected) values
Pure liquefaction capacity with LN2 precooling	367 (288) L/h
Pure refrigeration capacity with LN2 precooling	837 (600) W

Figure 4. Helium cryoplant during commissioning phase (a); S/A pumping system (b)

1.3. 4 K and 2 K Liquid Helium Distribution Systems

To minimize engineering effort, the concept and design of the major subsystems are based on the previous experience with the ISAC-II heavy ion superconductive linac, which is operational at TRIUMF since 2005 [3]. Helium coldbox and 1000 L liquid helium storage Dewar are positioned in the immediate vicinity of the e-linac cryomodules in order to minimize losses associated with LHe transfer. The LN2 precooled vacuum-jacketed 4 K helium distribution system is designed as a modular structure (figure 5). It uses a standard compression flange technology and allows a non-welded execution of the field joints. Due to positive gauge pressure of both liquid helium supply and gaseous helium return lines risk of helium contamination from cryomodule interfaces is eliminated.

The first cooldown of the LHe distribution was performed with only injector cryomodule (ICM) and one section installed. Recuperation of the cold helium return gas from LHe distribution was controlled by the coldbox control loop, actuating the process line valve and by-pass valve. The following cooldown of LHe distribution line and both ICM and accelerator cryomodule (ACM) was performed with active return helium recuperation control loop. Typical cooldown time of LHe distribution is close to one hour (figure 6).

The 2 K liquid is produced in each cryomodule by passing the 4 K liquid through a counterflow heat exchanger, cooled by returning exhaust gas from the 2 K phase separator, and expanding the forward-flowing gas to 31 mbar through a JT-valve. The 2 K phase separator above the cavity 2 K liquid helium bath delivers cold gas back through the 4 K – 2 K heat exchanger, then ambient heat exchanger and S/A pumps, to the recovery/purification compressor as a liquefaction load.

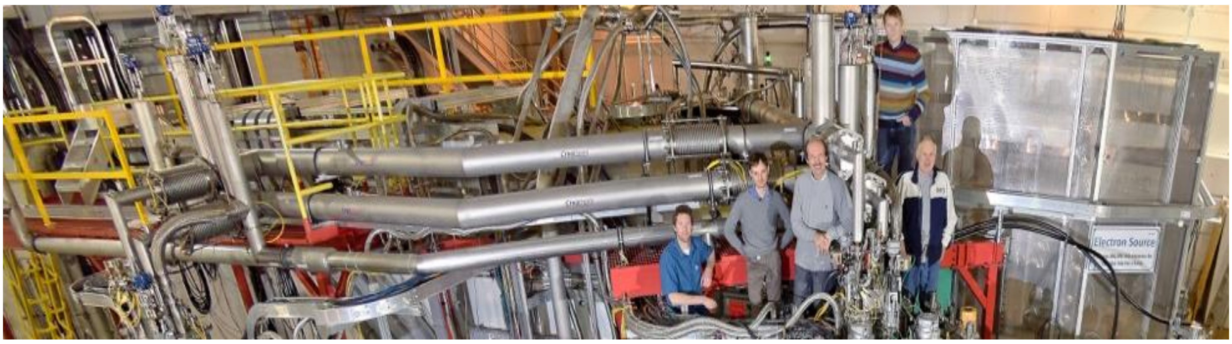

Figure 5. Liquid helium distribution system

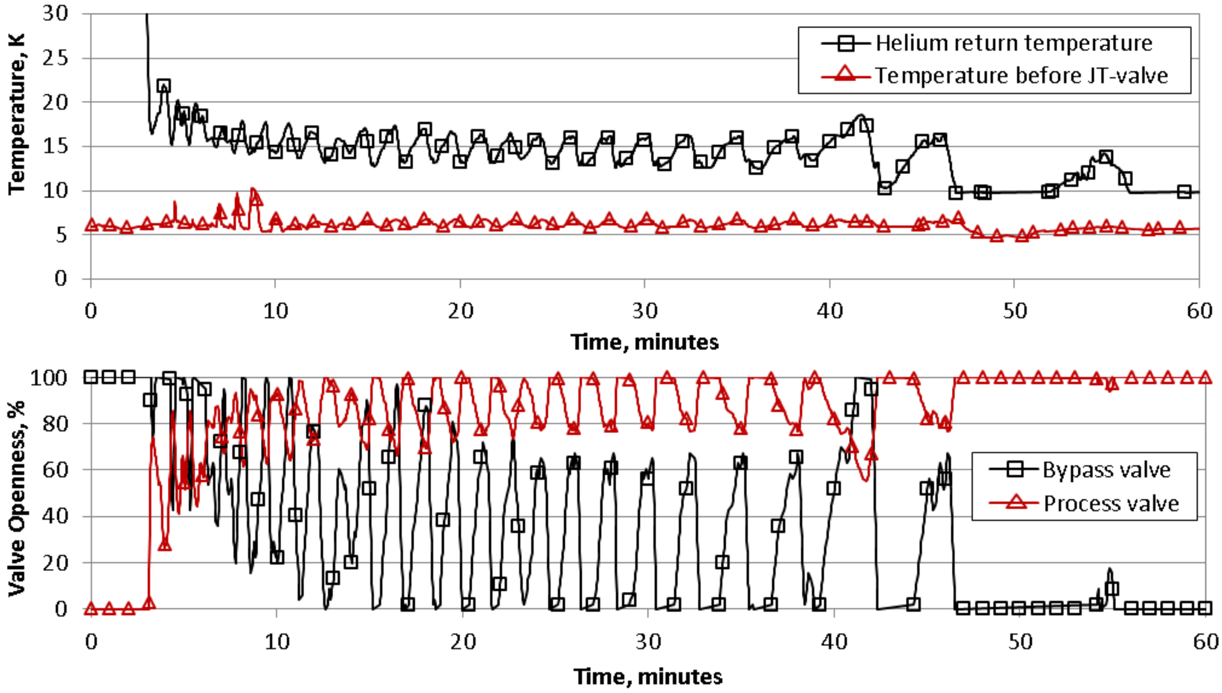

Figure 6. Coldbox return flow switch-over during LHe distribution line cooldown

The S/A vacuum-jacketed line is welded to the counter-flow helium heat exchanger which brings the temperature of S/A stream close to ambient. Recuperation of cold low-pressure helium flow is performed by ~300 K high pressure helium, thus, without significant increase of the cryoplant thermodynamic performance. Nevertheless, the passive design of the heat exchanger eliminates electrical power consumption and decreases the liquid nitrogen consumption for helium precooling [4].

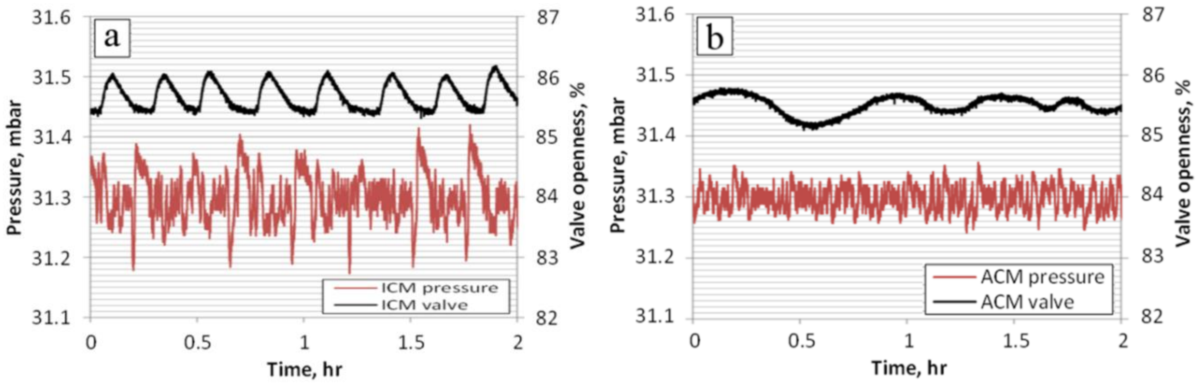

Figure 7. Pressure regulation in the SRF cavities bath

Warm helium S/A pumps remove helium vapor from the cryomodules 2 K dual phase reservoirs. The current installation of S/A pumping system includes four Busch Combi DS 3010B pumps (figure 4b). Standard PID control algorithm is utilized to actuate remotely controlled cryogenic valves on the S/A return side, keeping the pressure in the SRF cavities bath at 31.3 mbar independent of the variable RF load. Fine controllers tuning allowed us to achieve pressure stability within ±0.1 mbar range for ICM and ±0.05 mbar for ACM (figure 7).

2. Cryomodules design and commissioning

The ARIEL project requires three cryomodules with one, two and two nine cell 1.3 GHz cavities in each module respectively all operating at 2 K. The cryomodule is a continuation of the design philosophy initiated with the ISAC-II superconducting Linac [5]. The cold mass is suspended from the lid and includes a stainless steel strongback, a 2 K phase separator pipe, cavity support posts and the cavity hermetic unit. The hermetic unit consists of the niobium cavities, the end assemblies, an intercavity transition (ICT) with a stainless steel HOM damper, the power couplers (FPC) and an RF pick-up. The end assemblies include the warm-cold transition (WCT), CESIC® HOM damping tubes and beam-line isolation valves. Other features include a scissor jack tuner and warm motor, liquid nitrogen (LN2) cooled thermal isolation box, two layers of mu metal and alignment monitoring via a wire position monitor (WPM) diagnostic system. The assembly of the hermetic unit takes place in a class-10 clean room. The hermetic unit is filled with filtered dry nitrogen gas with a slight over pressure before installation in the module.

Each module has a cryogenic insert on board (figure 8, figure 9) that receives the 4 K liquid helium and produces 2 K liquid helium into a cavity phase separator [6]. The insert consists of a 4 K phase separator, a 2.5 g/s heat exchanger and a JT expansion valve, a 4 K cooldown valve and a 4 K thermal intercept siphon supply and return. During cooldown the 4 K valve is used to direct liquid helium to the bottom of the cold mass until 4 K level is reached. The level in the 4 K reservoir is regulated by the liquid helium supply valve, the level in the 2 K phase separator is regulated by the JT-valve and the 2 K pressure is regulated by the S/A line valve. Piping within the module delivers the siphon supply to a number of 4 K thermal intercept points (WCT, ICT and FPC) and then returns the two phase helium back to the top of the 4 K phase separator.

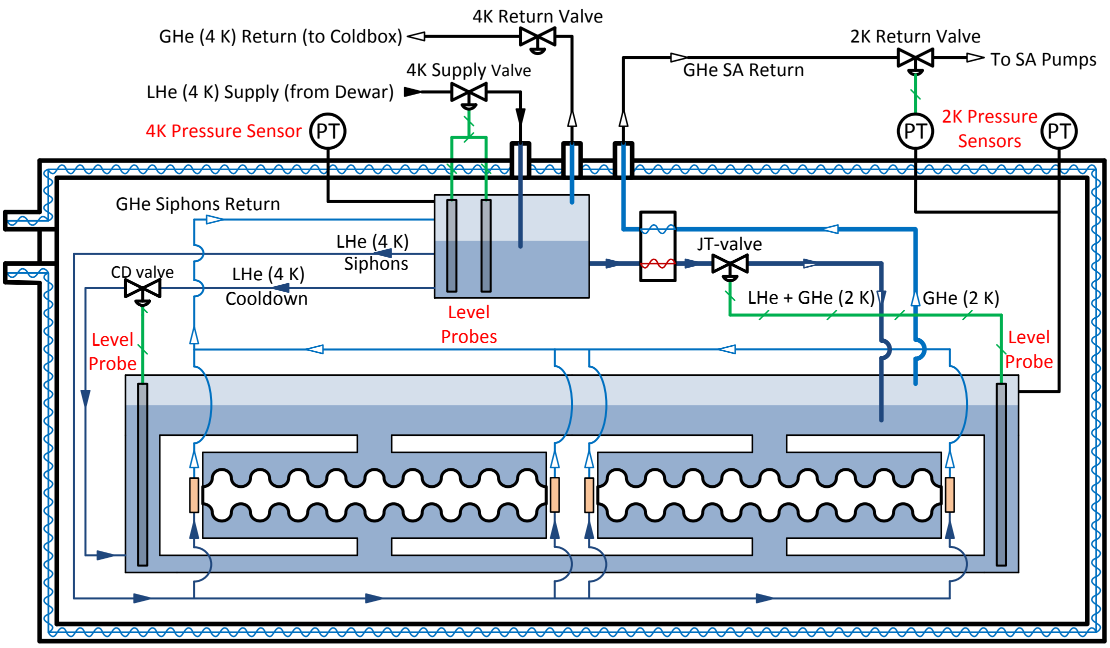

Figure 8. Flow diagram of ACM

In 2014 two cryomodules have been installed and tested: the injector cryomodule (ICM) with one nine cell cavity (ARIEL1) and an accelerating cryomodule (ACM) with one nine cell cavity (ARIEL2) complete with FPCs and tuner and one "dummy" cavity [7] to replicate a second cryogenic load. The "dummy" cavity includes all cryogenic interfaces, Helium jacket, WCT and connection to the ARIEL2 cavity through the ICT. The couplers are not installed on the "dummy" cavity with the 4 K siphon loop loaded with a heater near the point where the connection to the FPC would be. The "dummy" cavity allows a full cryogenics engineering test of a two cavity module.

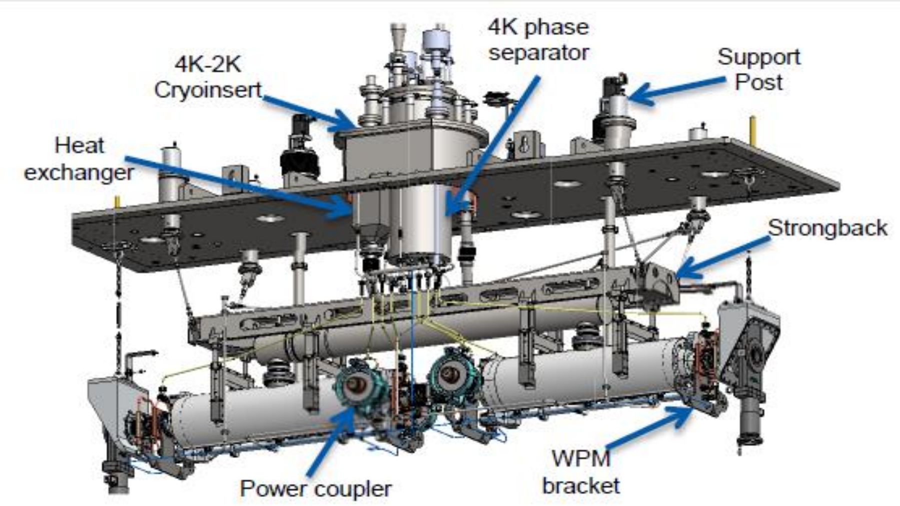

Figure 9. Model (ACM) for the ARIEL cryomodules

The static loads are measured through falling level tests with calibration coming from the known separator volumes augmented by repeating tests with additional loads from DC heaters. The tests are completed with the 4 K and 2 K spaces separated by closing the JT valve, the cool down valve and the 4 K supply valve. A temperature sensor is installed on the top of Siphon loop return branch outside of the 4 K reservoir to indicate mass flow in the Siphon loop. The 4 K static load in the ICM is 3 W for no siphon loop flow and 6.5W with siphon loop mass flow. The 4 K static load for the ACM is 6.5 W. The 2 K static loads are 5.5 W and 6.7 W for the ICM and ACM respectively.

The efficiency of 2 K production is measured by closing the 4 K supply valve while regulating the JT-valve to keep the level constant in the 2 K space. In this case the falling level in the 4 K space is a combination of the static loads of the 4 K and 2 K space load plus the vapour lost due to expansion from atmosphere to 31.5 mbar. In order to simulate the dynamic load caused by the RF losses, a series of different heater power levels were applied to the 2 K space. The 2 K production efficiency improves as a function of mass flow as the temperature of the heat exchanger and JT-valve decreases (figure 10). For both cryomodules 86% 2 K production efficiency can be achieved for the operating regime. A dynamic load in excess of 20 W can be regulated.

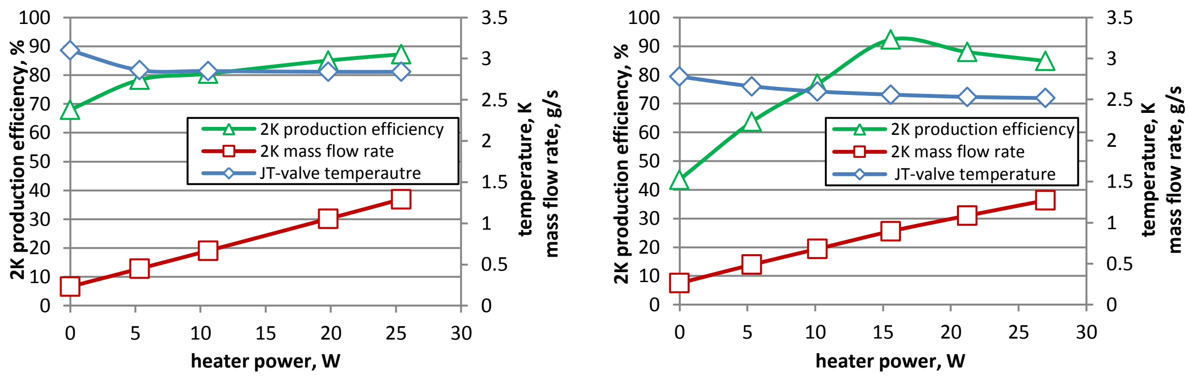

Figure 10. ICM and ACM 2 K production efficiency plots

In order to measure the characteristics of RF performance of the installed cavities a series of 2 K helium falling level rates were measured at different accelerating field settings. During these tests the RF field was established and then thermal stabilization was achieved as indicated by the stability of the 2 K Helium level, the J-T valve, the 2 K pressure and the 4 K Helium level. The JT-valve is then closed and the 2 K falling level rate measured. The RF loss in the cavity P_{cav} can be derived from the falling level rate with and without RF. During the measurements the 4 K level was kept constant in order to keep the Siphon loop status unchanged. Both cavities meet specifications with a gradient of more than 10 MV/m and an active load of 10 W per cavity. During the beam commissioning the ICM and ACM cryomodules produced a final energy of 23 MeV [8] with the cryomodule cryogenic parameters fully regulated.

Conclusion

In 2013-2014 the e-linac project team has accomplished the complex task of e-linac cryogenic system components commissioning and overall system integration limited to ARIEL Phase-I components. The installation, integration, device and sub-system testing proceeded as planned. The acceptance test of the cryoplant confirmed that the manufacturer fully satisfied the design requirements for the liquefier-refrigerator. Cooldown and operation of all the cryogenic system elements confirmed the successful integration of the subsystems.

All custom-designed elements were successfully integrated to e-linac cryogenic system during the commissioning phase. Custom-designed SA heat exchanger provides adequate heat transfer to SA helium gas flow to prevent overcooling of its outer shell. SA trunk pressure regulation control loops meet the requirements of pressure stability in the cryomodules. SA pumping system with two SA units active successfully passed the performance test.

Both injector and accelerator cryomodule #1 were successfully integrated into the e-linac cryosystem. Both cavities meet specifications with a gradient of more than 10 MV/m and an active load of 10 W per cavity.

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The 3D laser scanned image of compressor building is courtesy of Kickstart Technologies Ltd.

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