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# Integration and commissioning of the ARIEL e-linac cryogenic system at TRIUMF

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## Abstract

The Advanced Rare IsotopE Laboratory (ARIEL) is a major expansion of the Isotope Separation and Acceleration (ISAC) facility at TRIUMF. The key part of the ARIEL project is a superconducting radiofrequency (SRF) linear electron accelerator (e-linac). The e-linac helium cryogenic system was designed to meet the ARIEL specifications. The HELIAL LL helium liquefier by Air Liquide Advanced Technologies supplies 4 K liquid helium (LHe) to cryomodules via a LHe distribution system. The cryomodules have a top-loaded-cold mass design. The 4 K - 2 K temperature conversion is achieved by a counter flow heat exchanger and a JT-valve installed onboard each cryomodule [1]. The temperature in the 2 K volume of the cryomodules is controlled by pressure control in the sub-atmospheric line. Sub-atmospheric helium is warmed up in a custom-designed heat exchanger and after passing sub-atmospheric pumps goes to the helium compressor suction line. The LN<sub>2</sub> system supplies liquid nitrogen to the liquefier, 80 K shielding of the cryomodules and LHe distribution system, as well as to the freeze-out helium purifier. The installation of the e-linac cryogenic system components started in February 2013 while the corresponding subsystems tests started in November 2013.

This paper describes the e-linac cryogenic system components integration and presents the results of the acceptance tests and commissioning activities performed at TRIUMF since November 2013.

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\* Corresponding author. Tel.: +1-604-222-1047 ext. 7381; fax: +1-604-222-1074. *E-mail address:* akovesh@triumf.ca The Advanced Rare IsotopE Laboratory (ARIEL) is TRIUMF's facility that will expand Canada's capabilities to produce and study isotopes for physics, materials science and medicine. Utilizing SRF technology, it will showcase a high-power electron accelerator to produce exotic isotopes for research and development. [2]. A key part of the ARIEL project is a 10 mA-50 MeV continuous-wave superconducting radiofrequency (SRF) electron linear accelerator (e-linac). The 1.3GHz SRF cavities are cooled by 2 K liquid helium [3]. Liquid helium at 4 K is produced by the Helial LL cryoplant supplied by Air Liquide Advanced Technologies. 2 K liquid helium is generated inside each cryomodule [4]. After successful commissioning of the 4 K cryoplant, a 2 K sub-atmospheric (SA) system was installed. Ultimate integration test aims to operate two cryomodules containing a total of three 9-cell SRF cavities. Particularities of this cryogenic system include the top loading design of the cryomodules, the 2 K liquid helium production on-board of each cryomodule, the conservative design of the oil removal system, the original passive heater in the SA pumping system, the hermetic dry SA pumps, the inline full S/A flow helium purifier, the multipurpose recovery/purification compressor, the sectioned cold helium distribution system, and the overall system radiation resistant design.

#### 2. ARIEL e-linac cryogenic system structure

The ARIEL e-linac project is developed in two main stages. 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. The cryogenic system follows the ARIEL project requirements. The overall structure of the ARIEL cryogenic system is shown on Fig 1.



Fig. 1. The diagram of e-linac helium cryogenic system.

The compression station contains two Kaeser screw-type compressors (Fig. 2a). The main compression unit (Kaeser FSD571SFC) has 112 g/s capacity. The nominal helium gas discharge pressure is 14.5 bar(a). The recovery and purification compression unit (Kaeser CSD85) provides 15 g/s flow rate.

The customized main and recovery compressors oil removal systems are equipped with a 3rd additional coalescer and larger capacity carbon bed (Fig. 2b). Helium purity is monitored by a Linde multicomponent detector for purity control (Fig. 2c).

The warm helium piping connects the new compressor building to the electron-hall (acceleration facility). The total length of warm helium lines between the compressor and cold box is about 90 m. All helium piping was additionally degreased, washed and dried at TRIUMF before the installation in order to avoid turbines malfunction during startup or operation similar to mentioned in [5].



Fig. 2. (a) Main and recovery compressors; (b) main compressor oil removal system; (c) multicomponent purity analyzer.

The turbine-based Helial LL cold box is supplied by Air Liquide Advanced Technologies (France). The cold box unit is based on a modified Claude cycle, equipped with seven heat exchangers, two turbine expanders, 80 K nitrogen absorber and a 20 K neon absorber (Fig. 3a).



Fig. 3. (a) E-linac cryoplant; (b) installation of liquid helium distribution lines.

The liquid helium distribution system was designed for a sectional structure. To minimize engineering effort, the concept and design of the major subsystems is based on our previous experience with the ISAC II heavy ion SC linac, which is operational at TRIUMF since 2005 [6]. The quality of cryogenic helium valves and joints helps to optimize the supply of LHe. The field joints contribution to the heat load is approximately 2 W per joint. The heat load of the cryogenic valves varies from 0.7 W on the CM supply branch (DN14) to 2.9 W on the cold return line (DN45) [6].

The 2 K liquid is produced in each cryomodule by passing the 4 K liquid through a counter flow 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 and sub-atmospheric pump, to the main compressor as a liquefaction load [4]. The vacuum-jacketed line was welded to the counter-flow helium heat exchanger (Fig. 4b) which brings the temperature of sub-atmospheric stream close to ambient. The opposite end of the heat exchanger is connected by a non-insulated pipe to the bank of sub-atmospheric pumping units.

Warm helium sub-atmospheric pumps remove helium vapor from the cryomodules 2 K dual phase reservoirs and keep the pressure at  $31 \pm 0.5$  mbar independent of the variable RF load [7]. The current installation of sub-atmospheric pumping system includes four Busch DS 3010B pumps (Fig. 4c).



Fig. 4. (a) Vacuum-jacketed sub-atmospheric gaseous return section; (b) counter-flow sub-atmospheric helium heat exchanger; (c) Busch pumps with sub-atmospheric manifold.

For both budgetary and resource allocation reasons the e-linac project is planned in three stages. The complete implementation of the e-linac cryogenic system is also broken into two phases. Phase I, subject of this paper, covers most of the cryoplant infrastructure, LHe and  $LN_2$  distribution systems for injector and  $1^{st}$  accelerator cryomodule [6].

### 3. Helium cryoplant acceptance test

The performance requirements of the cryogenic system for the ARIEL project were established based on the cryogenic heat loads expectations [8]. According to the requirements of SRF cavities and heat leaks to the distribution systems, estimated cryogenic loads were calculated (Table 1). This in turn defined the performance requirements of the helium cryoplant. During the acceptance tests of the helium liquefier-refrigerator, the performance of the pure liquefaction and pure refrigeration regimes was confirmed.

Heat load	at 2 K	at 4 K	at 77 K
Static load, W	21	91	790
Including contingency, W	25	109	948
Dynamic load, W	51	3.0	180
Including contingency, W	76	4.5	216
Total, W	101	113	1,164

Table 1. Estimated cryogenic loads of the ARIEL cryoplant.

During the cold box acceptance tests, the performance of the three working regimes was confirmed [9]. The results of the cryoplant tests are shown in Table 2.

Table 2. Results of the helium liquefaction-refrigeration cryoplant acceptance tests.

Parameter	Expected value	Measured value
Pure liquefaction capacity with LN2 precooling	288 L/hr	367 L/hr
Pure refrigeration capacity with LN2 precooling	600 W	837 W

The liquefaction rate is determined by the liquid level rise in the dewar. The refrigeration capacity is determined by the heat load applied to the heater submerged in liquid helium inside of the dewar at a constant level (Fig. 5b).



Fig. 5. (a) Rate of liquefaction test (b) refrigeration capacity test.

The stability of the dewar pressure during all the tests was confirmed within  $\pm 2$  mbar limits during a 2 second period and within  $\pm 10$  mbar limits in slow excursions.

#### 4. System integration and commissioning

After the completion of the acceptance test, the e-linac project team has accomplished a complex task of system integration, which includes e-linac cryogenic system components limited to the injector cryomodule. The liquid helium supply and return lines were connected to the injector cryomodule. LN<sub>2</sub> supply and distribution system was significantly upgraded. The vacuum-jacketed sub-atmospheric line was delivered and installed on site by Demaco (the Netherlands). The final step was to bring the injector cryomodule (CM) and to connect its interfaces to the rest of the e-linac cryo-system. With all sub-systems installed and readiness of the services such as cooling water, power, compressed air and controls, the system was prepared to go through the rigorous routine of checks and commissioning tests. The operation of the e-linac cryogenic system was resumed in May 2014 to match the overall schedule.



Fig. 6. (a) Lambda-point transition (b) liquid helium bath temperature evolution during the first 4 K - 2 K cool down.

Finally after the end of the services installation and prerequisite checklists procedures, the 4K - 2K cool down test was performed (Fig. 6a and Fig. 6b). The pumping capacity of one sub-atmospheric pumping unit is sufficient to achieve stable 2 K operation of the injector cryomodule with no RF load. There were no pressure oscillations in the dewar during the 2 K test.

The functional tests of the sub-atmospheric subsystem components (pressure and liquid level regulation control loops) were repeated during several 4 K - 2 K tests. Control elements were tuned to achieve stable system automation response to heat loads present when the RF power is applied. Pulse RF mode and CW RF mode tests areunder way. Several low-power quench events were successfully recovered by the cryo-system during RF conditioning. Injector CM SRF tests will be completed by the end of July 2014.

### 5. Conclusion

All major components of cryogenic system were specified, designed, procured and delivered to TRIUMF in time to meet the e-linac delivery schedule.

The installation, integration, device and sub-system testing is proceeding according to plan. The acceptance test of the cryoplant shows that the manufacturer fully satisfied the design requirements for the e-linac liquefier-refrigerator. Helial LL is the first Air Liquide helium liquefaction-refrigeration system installed in North America.

The injector cryomodule was successfully integrated into the e-linac cryo-system. It went through all stages of cool down and thermalization, final alignment procedure and finally was brought to 2 K.

The e-linac integration team is performing functional checks and commissioning of various subsystems. At the moment the sub-atmospheric and SRF systems are subject of undergoing tests.

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