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Online helium inventory monitoring of JLab cryogenic systems

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Abstract. There are five cryogenic plants at Jefferson Lab which support the LINAC, experiment hall end-stations and test facility. The majority of JLab's helium inventory, which is around 15 tons, is allocated in the LINAC cryo-modules, with the majority of the balance of helium distributed at the cryogenic-plant level mainly as stored gas and liquid for stable operation. Due to the organic evolution of the five plants and independent actions within the experiment halls, the traditional inventory management strategy suffers from rapid identification of potential leaks. This can easily result in losses many times higher than the normally accepted (average) loss rate. A real-time program to quickly identify potential excessive leakage was developed and tested. This program was written in MATLAB© for portability, easy diagnostics and modification. It interfaces directly with EPICS to access the cryogenic system state, and with and NIST REFPROP© for real fluid properties. This program was validated against the actual helium offloaded into the system. The present paper outlines the details of the inventory monitoring program, its validation and a sample of the achieved results.

1. Introduction

Since 1988, Jefferson Lab (JLab) has maintained continuous operation of its cryogenic plants. These plants have included a wide variation of capacity from 200 W at 4.5 K to 4.6 kW at 2.1 K. At present, there are five different cryogenic plants at JLab supporting various loads. There are two Central Helium Liquefiers (CHL) that support the accelerator's cryo-modules at 2.0 K. Cryogenic loads and targets at three of Jefferson Lab's four experiment halls (Halls A, B and C) are supported by the End Station Refrigerator (ESR). The Hall D Refrigerator (HDR) supports the cryogenic load at the experimental Hall D – a new system developed for the 12 GeV era [1]. The cryo-plant at Cryogenic Test Facility (CTF), which supports cryo-module and super-conducting radio frequency (SRF) cavity testing and development. A schematic diagram of the cryogenic systems and helium storage is shown in figure 1. During a normal operating period, these cryogenic systems require an overall helium inventory of 15 tons. A significant portion (about 7.5%) of this available helium inventory has to be replenished every month to keep up with the leaks and losses. Hence, minimizing the helium losses while bringing the operational availability to a satisfactory level is of critical importance. However, due to the organic evolution of the cryogenic systems (and loads) over the years (pre-12 GeV and 12 GeV era), it can be very difficult to confine a specific cryo-plant's helium inventory and identify potential leaks.

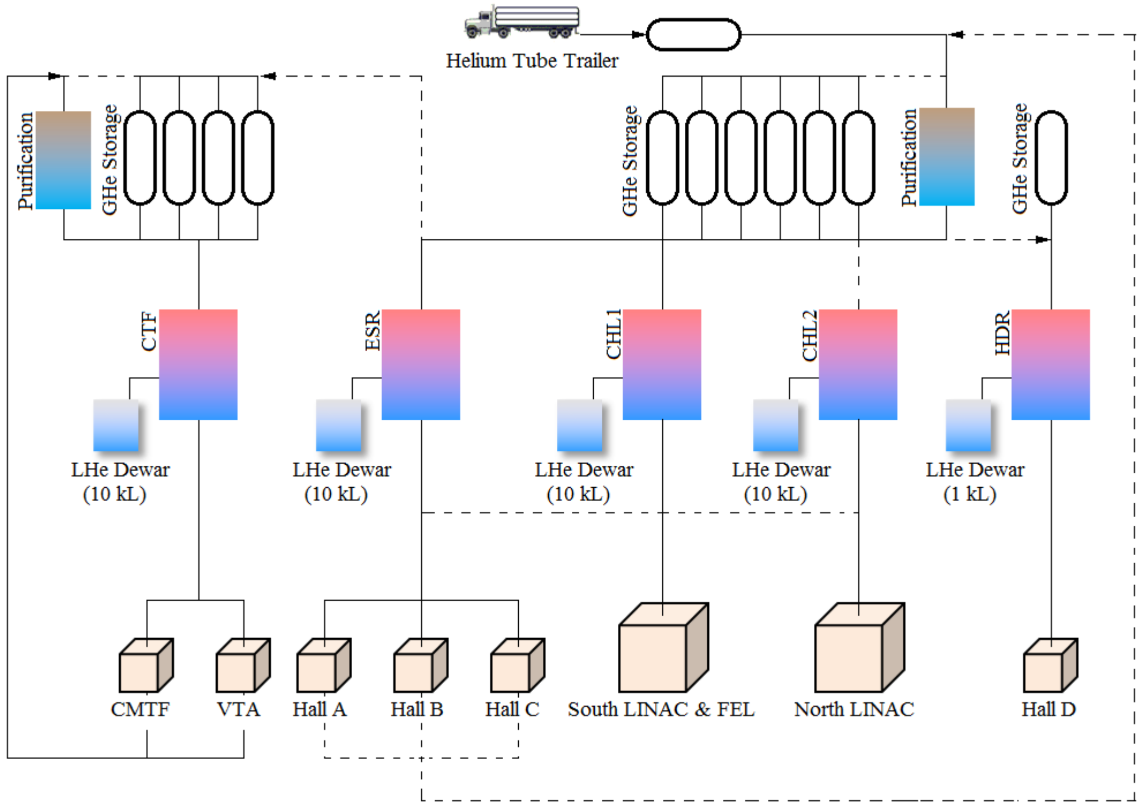

Figure 1. Schematic diagram of JLab's cryogenic systems and helium storage.

Inventory management strategy and tool development for large scale cryogenic systems is described in [2] and [3]. The present paper describes the development and deployment procedure of a real-time online helium inventory monitoring program for the JLab cryogenic systems and loads. The program was validated against the actual helium offloaded into the system. It also outlines the results (helium inventory tracking and identification of potential areas for major leaks) achieved so far with the developed program.

2. Background

The overall helium storage capacity at JLab is approximately 162,800 liquid liters, or 20.0 tons. The distribution of this storage capacity (cryo-plant and load, gaseous and liquid) are shown in figure 2. During normal operating periods, about a quarter of this storage remains empty. Gaseous helium (GHe) is delivered to JLab in high pressure tube trailers (approx. 200 barg or 3000 psig), and is then off loaded, purified and stored in the gas storage tanks at CHL. It is then distributed to different cryogenic plants around the site as required from this central location via inter-connecting warm piping. The standard gas storage tanks are approximately 114 m^3 (30,000 gal.) and are rated for 17.2 barg (250 psig). Each of the five cryo-plants is equipped with a liquid helium (LHe) dewar to provide operational flexibility. Due to the sub-atmospheric loads at CTF, it is more prone to contamination and as such is equipped with its own warm gas storage and purification system. HDR is also equipped with a gas storage tank (for shutdowns). ESR shares the CHL warm gas inventory via an inter-connecting warm helium transfer line. During regular operation, two of these five cryogenic plants (CHL2 and HDR) are operated as a fixed inventory, remaining isolated from their respective warm gas storage. As a result, any inventory loss is compensated from the LHe dewar, and rapidly identifiable. However, this is not the case for the other three cryogenic plants, and it is both time consuming and difficult to identify a leak location.

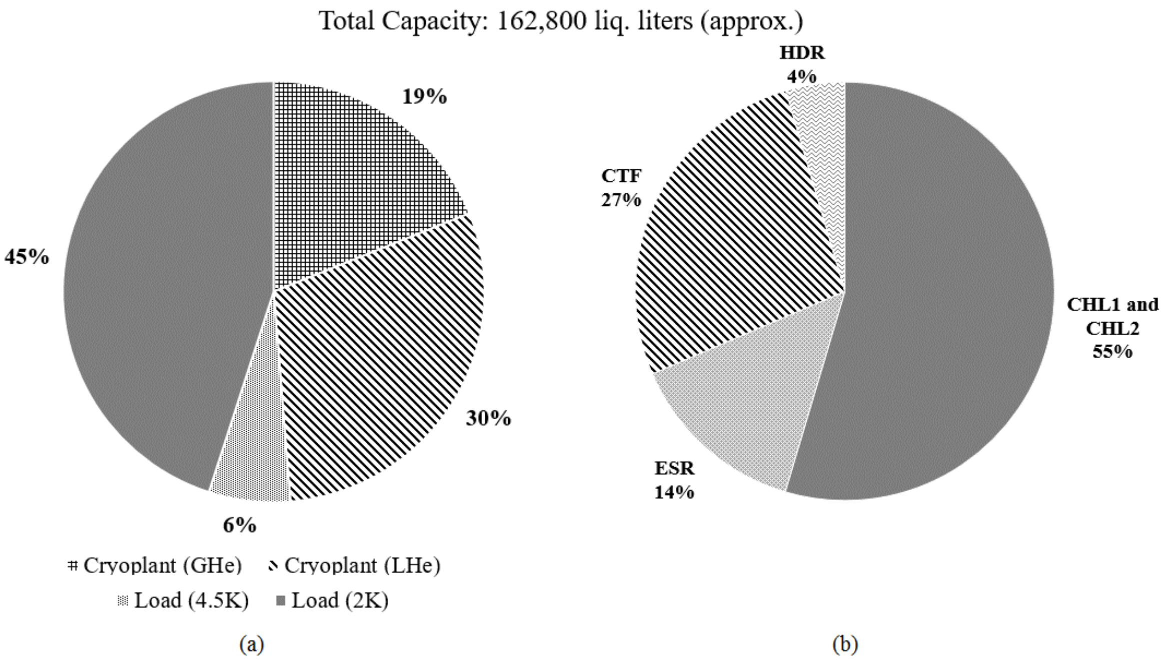

Figure 2. JLab Helium Storage – (a) overall capacity; (b) capacity distribution among cryoplants.

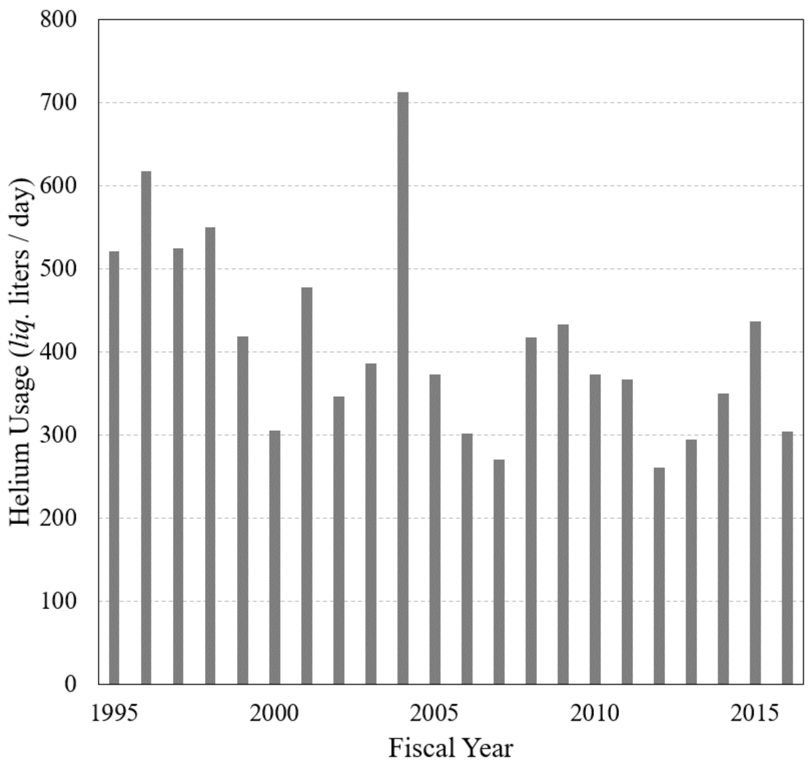

Figure 3. Overall helium usage at JLab over the last 21 years.

Primarily this is due to the end user's system. In the experiment halls there are three separate users (systems), plus a possible cryogenic target. Each of these systems is not well instrumented to allow inventory loss identification. This is also the case at the CTF, where there are two or three users (systems), and one of these (the vertical test area) is comprised of cryostats that are routinely opened and closed. Cryo-plants that share gas inventories and purification also present a difficulty.

Figure 3 shows the historical helium usage at JLab. It is observed that, the average loss rate remained at 350-400 liquid liters per day for the last two decades (with the minor exception in 2004 – when most of the on-site LHe inventory had to be vented during Hurricane Isabel). There was a steady rise in loss rate from 2011-15, mainly during commissioning of 12 GeV cryogenic system and loads. The average daily loss rate in 2016 was slightly over 300 liquid liters per day. This 'baseline' loss rate (~300 liquid liters per day) is attributable to the original design basis used for these systems, including the end users systems. New systems like CHL2 (for the 12 GeV upgrade) and HDR have low loss rates. The following sub-sections will describe the development of the monitoring program and discuss the break-down of this loss to an individual cryo-plant level and potential ways to minimize it.

3. Program development

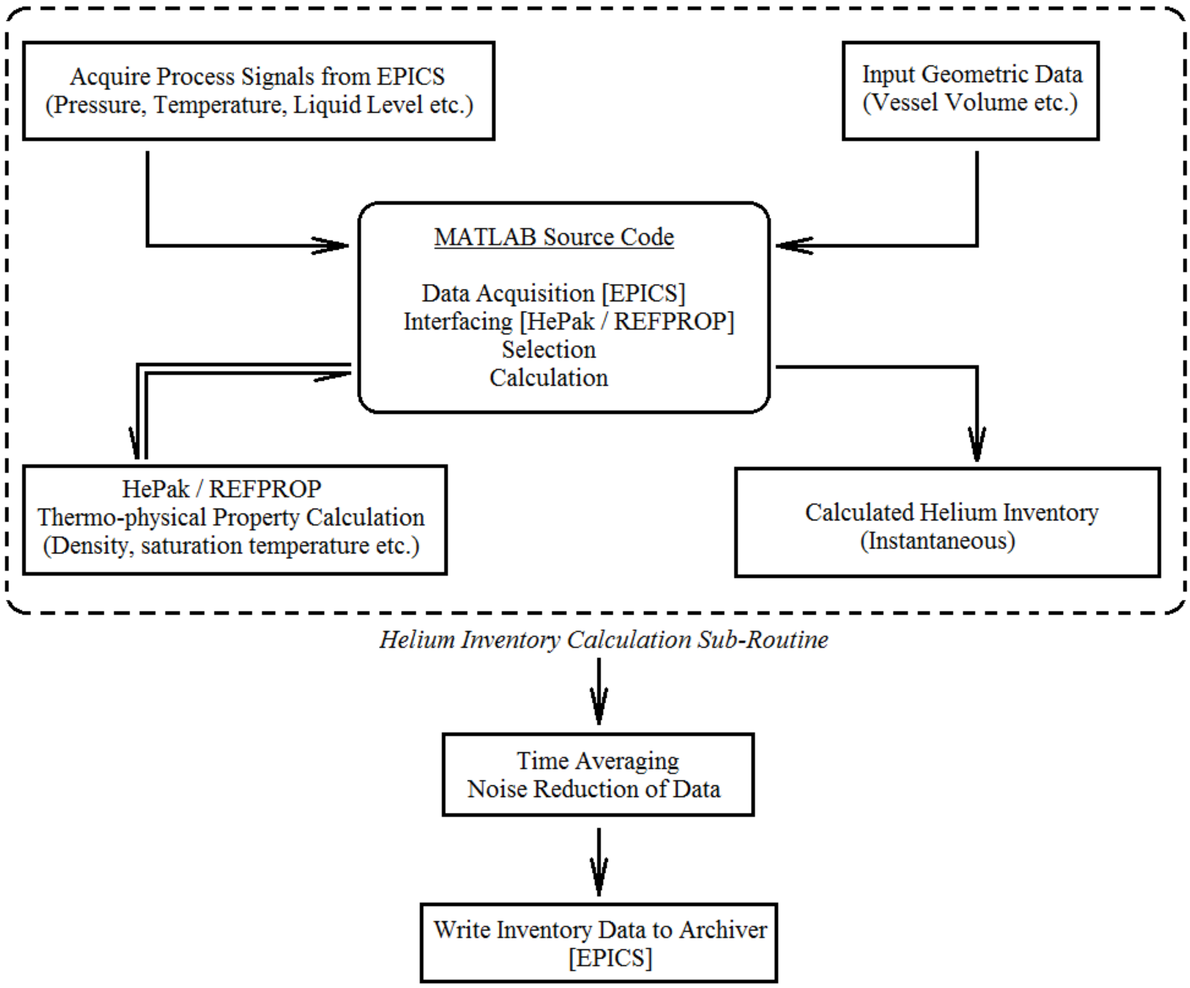

Figure 4. Block diagram for the helium inventory monitoring program.

Developing a computer program to calculate and archive real-time helium inventory for all of JLab's cryogenic systems requires interfacing between three different software applications; MATLAB©, which is used to calculate the inventory; REFPROP©, which is used to obtain thermo-physical properties of helium and EPICS (which is, Experimental Physics and Industrial Control System; a software environment used to develop and implement distributed control systems to operate devices), which is used to acquire process signals for the calculation. The geometric data for all helium storage vessels are provided as a user input. Initially, MATLAB is deployed within EPICS and the process signals are called by their specific EPICS channel name from the MATLAB script. Thermo-physical property routines are interfaced with MATLAB using the REFPROP dynamic link library (DLL), to obtain the fluid densities based on the process signals supplied by EPICS. To maintain accuracy in property calculation beyond REFRPOP's recommended range, HePak property routines are used instead. The mass in each of the different components of the cryogenic system is then calculated. This calculation is carried out twice every minute and provides an instantaneous snapshot of the helium inventory present in each of the components. However, due to noise levels present in the measured signal, it is not meaningful to store the data at this acquisition rate. Hence, the collected data is time averaged over a period of 15 minutes and is stored in JLab's central archiving system through EPICS. This makes it easier to monitor and plot the inventory information from EPICS. Until the implementation of this new software, the daily loss rate was estimated by 'manual' calculation (i.e., 'back-of-the-envelope' or simple spreadsheet) using selected process measurements, and more accurately, by the amount of helium delivered (and off-loaded). However, the latter is not able to provide an accurate real time usage needed to diagnose and address a possible helium loss (above the baseline) that is occurring.

4. Results and discussion

After the development and debugging of the code, the online helium inventory monitoring program was deployed in EPICS in mid-October 2015. The program has been operating and collecting helium inventory data since that time. Overall (site-wide) loss rate was calculated from a temporal plot for the helium inventory. Data was collected and analyzed in multiple 10 day time periods with a stable helium inventory (no equipment shutdowns, inventory transitions etc.) and site-wide loss rates for each of these periods were calculated. Then all the loss rates were time averaged to obtain an 'average daily loss rate' for the site during the fiscal year. This was validated against the amount offloaded to the system during the fiscal year.

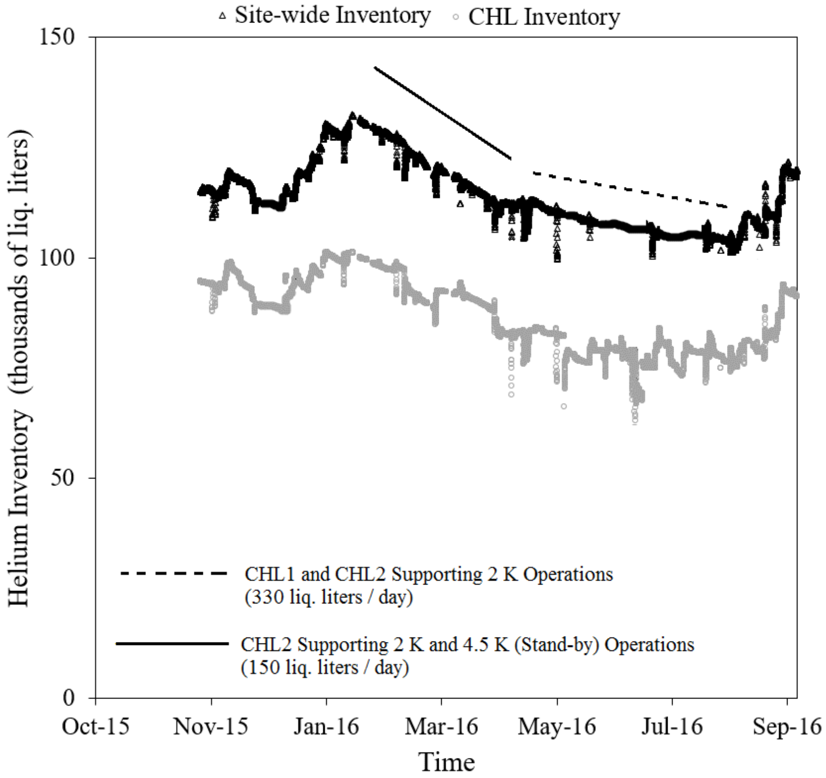

Figure 5. Calculated helium inventory at JLab for FY 2016.

The individual loss rates for each of the cryogenic plants were calculated separately. The individual loss rates for CHL2 and HDR were obtained from the LHe dewar liquid level depletion rate. The loss rate for CTF was obtained from the depletion rate of the overall inventory (GHe tanks and LHe dewar) during stable operation (i.e., when there are no loads on the plant except for the LHe dewar) and validated against the amount supplied to CTF from the CHL inventory. ESR loss rate was established by setting-up the plant for a fixed inventory operation and then monitoring the LHe dewar liquid level depletion rate. CHL1 loss rate was obtained by subtracting ESR loss rate from the inventory depletion rate of the CHL gas tanks.

Figure 5 shows the temporal evolution of the site-wide and CHL helium inventory up to the end of FY 2016. For comparison, CHL helium inventory data is presented without any time averaging and is characterized by significant noise in the temporal data. The initial rise in the inventory marks the addition of helium to the system at the end of the calendar year. Clearly, two different depletion rates in the helium inventory are visible from the plot. The first one (January – April, 2016) indicates the spring run of the accelerator when both CHL1 and CHL2 were operating (at 2 K). During this time, the overall loss rate was about 330 liq. liters per day. The second one starts at end of April 2016 and continues till end of August 2016. This is the scheduled accelerator down (SAD) period, when one of the two CHL's (CHL1 in this case) was shut down for maintenance and the LINACs were reconfigured to be supported by CHL2 only (at both 2 K and 4.5 K). The overall loss rate was reduced down to about 150 liq. liters per day. Two different factors contributed to this reduction – Shutdown of CHL1; which has a known loss rate of about 150 liq. liters per day and an elimination of a leak in ESR (~ 30 liq. liters per day).

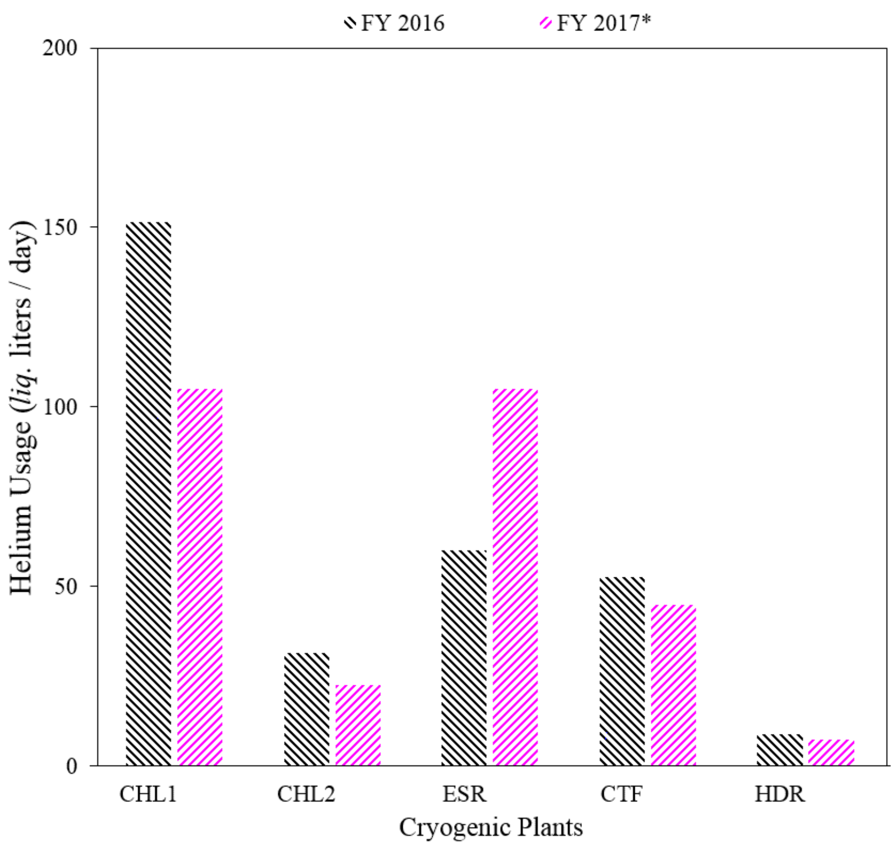

Figure 6. Average daily helium loss rates for FY 2016 and FY 2017 (up to June 2017) in different cryogenic plants at JLab.

Based on the calculated values of the helium inventory, baseline daily loss/leak rates at each of the five cryogenic plants at JLab were also calculated. Once these baseline (or reference) loss rates are established, a helium inventory monitoring plan for leak detection (above this baseline) was established. The long-term (accelerator down period) plan is to identify (and take necessary measures if possible) the components at each plant contributing to the major share of the daily leak rate. The short-term (daily) plan is to monitor the helium inventory and detect any sudden / massive losses that requires immediate action. Several inventory loss/leak detection events ensued after the execution of this plan, which resulted in the change in the baseline daily loss rates at the cryogenic plant. These are described below and the changes in the baseline loss rates between FY2016 and FY2017 (up to June 2017) are shown in figure 6.

- Increase in the leak rate was observed when two of the three CHL1 2nd stage warm compressors were restarted after the end of SAD 2016 period. The compressors were checked and leaks were detected in the shaft seals. Resolving this issue resulted in a reduction of about 40 liq. liters per day in helium losses from CHL1.
- Increase in the leak rate was observed in CHL2 during winter 2016-17. This leak was correlated with the decrease in ambient temperature (below 280 K). After thorough examination, leaks were found in several valve packings in oil coalescing vessels (due to different coefficient of thermal expansion between the materials). Detection and resolution of this leak resulted in a reduction of about 10 liq. liters per day in helium losses from CHL2.
- A reduction of about 10 liq. liters per day in helium losses from CTF was observed after the commissioning of a new 4.5 K cold box (and de-commissioning of the existing cold box). Significant changes in daily loss rate were also observed during operation of the vacuum skid for pumping 2.0 K process flow. Refurbishment of this skid is being planned.
- Calculating the helium inventory at CTF was found to be difficult due to the absence of accurate process signals (liquid levels, temperature etc.) at the load.
- The baseline loss rate at ESR was about 70 liq. liters per day during FY 2016. During several un-planned shutdowns and planned events (magnet testing, quenches etc.), a significant amount of helium inventory (approximately 5000 liq. liters) was lost from ESR in FY 2017. This caused a significant increase in the calculated average of the daily losses at ESR.
- Several maintenance actions on HDR warm compressors and utility valves resulted in a minor reduction in daily helium loss rate.

5. Conclusion

Recognizing the critical need to reduce the helium inventory losses at JLab cryogenic systems, an online helium inventory monitoring program was developed and deployed in the EPICS environment. The program is capable of real-time monitoring of the helium inventory at each of JLab’s five cryogenic plants (and their corresponding loads). Monitoring and analysis of the collected inventory data have already resulted in reduction of daily helium losses at different on-site locations. A need to improve some of the existing instrumentation for accurate monitoring of the helium inventory is also realized. It has led to the development of a long-term strategic plan for identification and further reduction of the losses. Efforts within the Cryogenics group and via coordination with other groups at JLab allowed reducing the helium losses during SAD periods. The algorithm for the inventory monitoring program presented here is site independent and could be applied to other large-scale cryogenic systems willing to consider helium management with a high degree of performance.

References

[1] Smith E 2009 The 12 GeV JLab Upgrade Project *ArXiv e-prints* **0901.3249.**

[2] Delikaris D, Brodzinski K, Claudet S, Ferlin G, Tavian L and Wagner U 2013 The LHC cryogenic operation availability results from the first physics run of three years *IPAC4 Shanghai, China* **CERN-ACC-2013-0098**

[3] Claudet S, Brodzinski K, Darras V, Delikaris D, Duret-Bourgoz E, Ferlin G and Tavian L 2015 Helium inventory management and losses for LHC cryogenics: strategy and results for run 1 *Physics Procedia* **67** 66-71

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