Final Report for the SLAC-INFN Summer Exchange Program

Nico Kleijne
September 27, 2019

I. Introduction

In this final report, I explain and summarize my experience and the obtained results during my SLAC-INFN Summer Exchange Program. At SLAC I worked as a part of the LZ (LUX-ZEPLIN) group for a total of 9 weeks. First, I introduce the LZ experiment by explaining what Dark Matter is and how this and other experiment are trying to detect it. Then, I proceed by explaining what the krypton removal group is trying to accomplish and with which technique. Finally, I expose what my actual work consisted of, in particular, I explain how I optimized the liquid nitrogen system used by the krypton removal group.

II. The Lux-Zeplin experiment (LZ)

A. Dark Matter

The standard cosmological model to describe the evolution of the universe (lambda cold dark matter) implies the existence of the so-called Dark Matter (DM). The first evidence for this are the gravitational effects observed on different scales, from dwarf satellites to galaxy clusters. Our galaxy and many others seem to be held together by the gravitational pull of invisible haloes which outweigh the visible matter and extend beyond the distribution of luminous objects. Besides, in N-body simulations of the evolution of the early universe, cold DM is an essential ingredient to explain the formation of galaxies from primordial perturbations. Recent measurements by the Planck telescope confirmed that the energy in the universe is approximately divided between 5% baryonic matter, 26% cold dark matter and 69% dark energy.

While the effects of DM are modeled and understood its nature remains uncertain. Astrophysical measurements show that the distribution of the total gravitational mass does not follow the distribution of baryonic matter. This implies that the effects cannot be explained by modified gravity and the existence of a new particle must be taken into account. Assuming this new particle was in thermal equilibrium with ordinary matter in the early stages of the universe, the relative abundance of DM can only be justified by a weak interaction with baryonic particles. The most valid candidates as DM are thus the so-called WIMPs (Weakly Interacting Massive Particles). Some theoretical models for WIMPs exist as well, such as supersymmetry (SUSY) which predicts the existence of the so-called *neutralino*.

DM can be searched through three different kinds of signals. First, it could be produced at colliders, such as LHC, and go undetected, resulting in missing energy and momentum. In the cosmos, DM particle could collect at the center of galaxies. Annihilation of two of them could produce secondary particles such as electrons, protons and gamma rays to be detected with telescopes. This second kind of search is known as Indirect Detection (ID). On the other hand, Direct Detection (DD) is possible through the interaction of DM particles with atomic nuclei resulting in Nuclear Recoils (NR). One of these DD experiments is Lux-Zeplin (LZ) which uses Liquid Xenon (LXe) as a target for NR.

B. Direct Detection Experiments

The basic principle for DM direct detection experiments is NR against atomic nuclei. There are a few relevant parameters to predict the results of the detection. First the local properties of the Milky Way's DM halo, such as the DM mass density and the velocities distribution of DM particles. Assuming that DM particles are WIMPs leads to the conclusion that the interaction with atomic nuclei is a non-relativistic two-body scattering. The kinematic of the scattering depends on the assumed WIMP mass, while the rate of seen scattering events depends on the exposure, the product between target mass and live time, the WIMP-nucleus cross section, and the energy threshold for detection of the NR.

Assuming the maximum velocity for a WIMP is the escape velocity from the galaxy ($v_{esc} = 544\,\text{km/s}$), straightforward kinematics gives the minimum detectable WIMP mass as $M_{\text{WIMP}}(\text{GeV}) \approx (1/4)\sqrt{E_{min}(\text{keV})A}$, where E_{min} is the threshold energy for the detection of the NR while A is the atomic mass of the target nucleus. This minimum M_{WIMP} is $1.6\,\text{GeV}$ for the recent CDMSlite Ge-target results, and $4\,\text{GeV}$ for the recent LUX results using LXe.

In figure 1 the sensitivities of the main experiments searching for DM are shown. The main features of a NR detection are visible in the LZ curve where the sensitivity starts to rapidly increase around $5\,\text{GeV}$, there the distribution of velocities kinematically allows the NR to be detected. The maximum sensitivity is reached around $40\,\text{GeV}$, the same order of magnitude of the target nucleus mass. This is also the region where the probability of finding the mass of a WIMP is higher since is the same order of magnitude of the weak gauge bosons (Z^0 and W) masses.

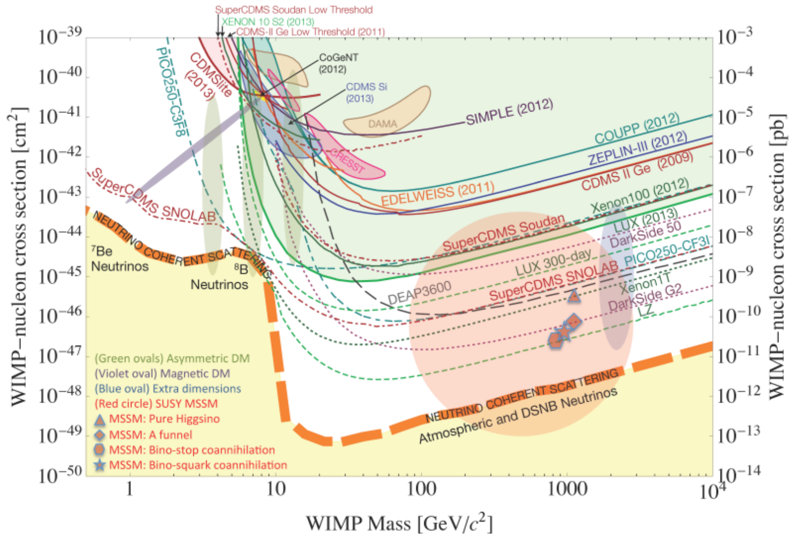

Figure 1. A compilation of WIMP-nucleon spin-independent cross-section sensitivity (solid curves), hints for WIMP signals (shaded closed contours), and projections (dot and dot-dash curves) for DD experiments of the past and projected into the future. This figure captures the experimental situation as of the end of 2013. Also shown is an approximate band where the coherent nuclear scattering of ^{8}B solar neutrinos, atmospheric neutrinos, and diffuse supernova neutrinos will limit the sensitivity of DD experiments to WIMPs. Finally, a suite of theoretical model predictions is indicated by the shaded regions.

C. LZ Experiment

The LZ detector will be located inside a large water tank at the 4,850 foot level of the Sanford Underground Research Facility (SURF). A model of the LZ detector is shown in figure 2. The main part of the LZ experiment consists of a two-phase

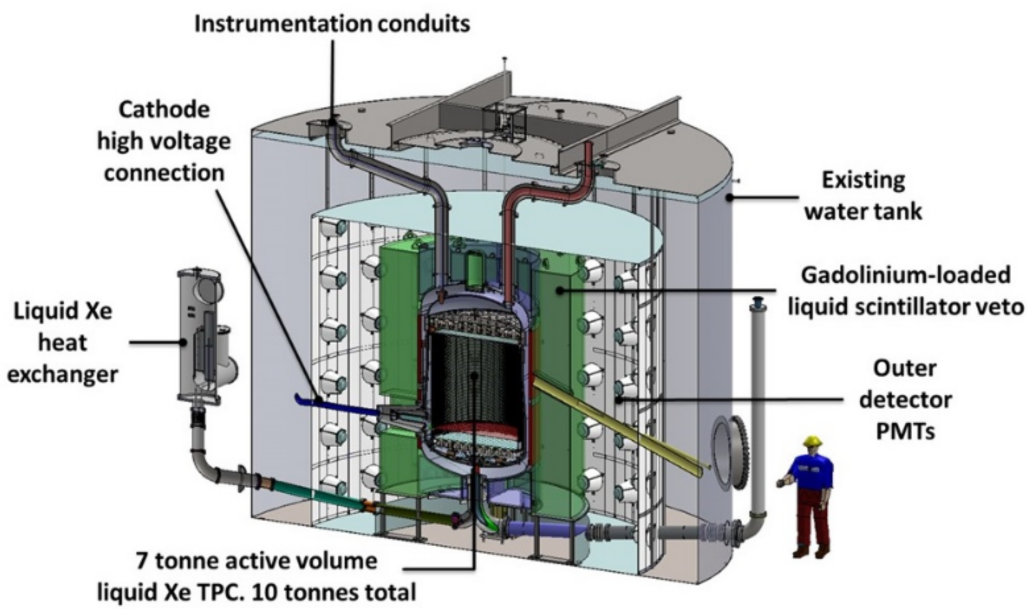

Figure 2. LZ 3D concept

Xenon TPC (Time Projection Chamber) containing 7 fully active tonnes of LXe. When a WIMP scatters off a Xenon nucleus it produces a prompt scintillation signal (S1) and free ionization electrons. The free electrons are drifted by an electric field to the liquid surface and then accelerated by the same field inside the gas phase, to create a second proportional scintillation signal (S2). The two signals are detected by arrays of photomultipliers tubes (PMT) located at the top and at the bottom of the TPC. The difference in time between S1 and S2 detection times gives the z position, while the pattern of S2 light in the top PMTs gives the x, y position. A graphical interpretation of an event is shown in figure 3.

Both the Xe "skin" layer and the outer detector which are shown in figure 2 are used to reduce the background from internally generated gammas and neutrons. If these particles were to scatter only once in the TPC they could mimic WIMPs. Using the

outer regions of the detector as vetoes, these backgrounds can thus be suppressed. In particular, the choice of the outer detector scintillation material is made to increase the interaction probability for neutrons. Both the outer detector and the Xe ”skin” are instrumented with PMTs.
In order to distinguish the interesting events of NR from the more common Electron Recoil (ER) a discrimination is necessary. Due to the different ratios of ionization electrons and scintillation photons in the two kind of events a good figure of merit is the ratio of the signals S2/S1. The plot in figure 4 shows the logarithm of S2/S1 as a function of S1. The NR and ER clearly form two distinct bands that allow for discrimination.
Most of the backgrounds signals coming from material radioactivity are located in the outer region of the central TPC. To reduce this kind of backgrounds a fiducial volume of 5.6 tonnes of Xe is thus defined as the active region in which to look for WIMPs signals. The high density of LXe allows having a thin self-shielding layer (few centimeters) after which the likelihood of penetrating gammas or neutrons is exponentially suppressed. In figure 5 the spatial distribution of backgrounds events, both with and without outer vetoes is shown. One of the few backgrounds which are not coming from the outer region but that could be dispersed uniformly in the volume of the TPC is given by ^{85}Kr, an isotope of Krypton with a relative abundance of $2{\times}10^{-11}$. This isotope can undergo a $\beta-$ decay which could create ER backgrounds. A purifying process is thus required to reduce the quantity of Kr to 0.015 ppt (g/g), which corresponds to a background of $< 10\%$ of the intrinsic pp solar neutrinos background.

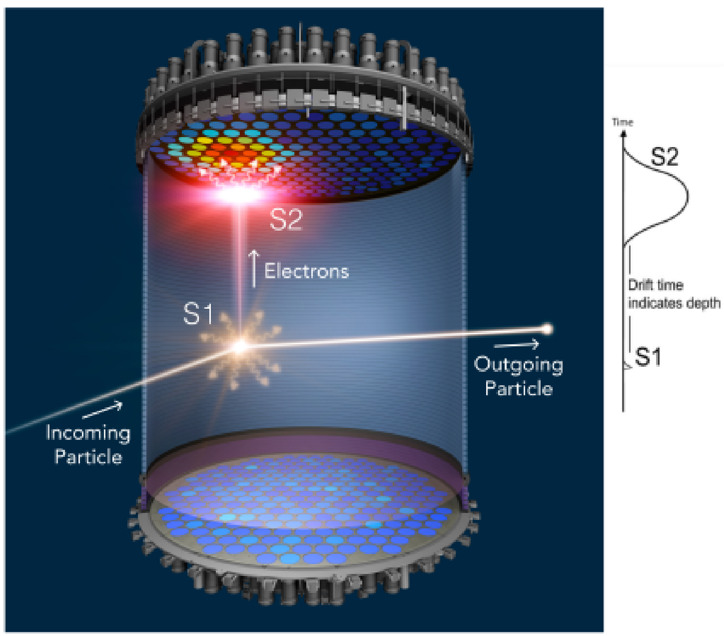

Figure 3. Operating principle of the double-phase Xe TPC. Each particle interaction in the LXe (the WIMP target) produces two signatures: one from prompt scintillation (S1) and a second, delayed one from ionization, via electroluminescence in the vapor phase (S2). This allows precise vertex location in three dimensions and discrimination between nuclear and electron recoils.

III. The Krypton Removal System At SLAC

The commercially available Xe contain traces of Kr at a concentration up to 100 ppb, which is $\sim 10^7$ times larger than requirements. To achieve the required levels of Xe purity for the LZ experiment the quantity of Kr present inside the gas must be reduced to 0.015 ppt. The required purification process is currently undertaken at SLAC by the LZ Kr removal group. The removal system is located at the IR2 building, inside the SLAC campus.
The main technique involved in the process is known as *gas charcoal chromatography*. This technique exploits the fact that the Van der Waals binding between activated charcoal and Kr is weaker than the binding between activated charcoal and Xe. If the Xe-Kr gas mixture is forced to flow through a charcoal column using He (Helium) as a continuously circulating carrier, the Kr will flow faster through the column due to its weaker interaction. Figure 6 shows the time profiles of the two flows coming out of a test column, the separation between the two elements is sharp.
The Kr removal process thus follows three main steps which are also schematically shown in figure 7. After forcing the Xe-Kr mixture inside the column with He, the Kr-He mixture flows out of the column and goes through a cold trap where the Kr is frozen while the He keeps going through to be reused. As soon as the Kr flow stops the cycle gets switched and the recovery

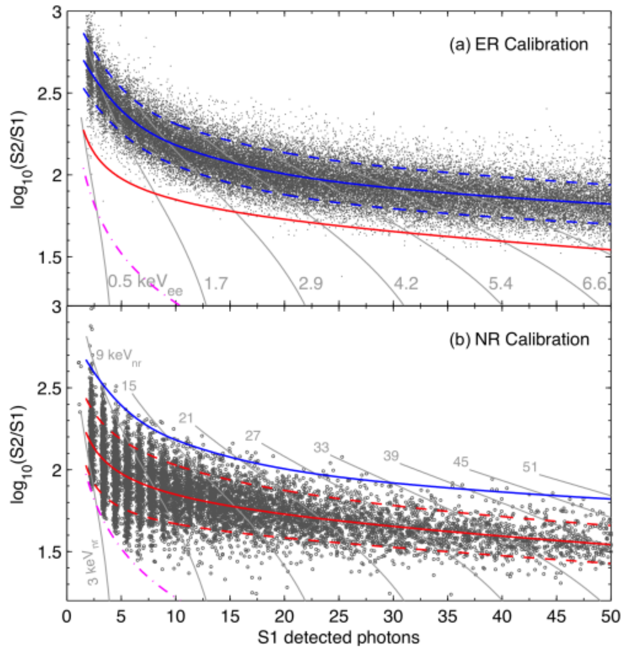

Figure 4. Discrimination parameter log_{10}(S2/S1) as a function of S1 signal

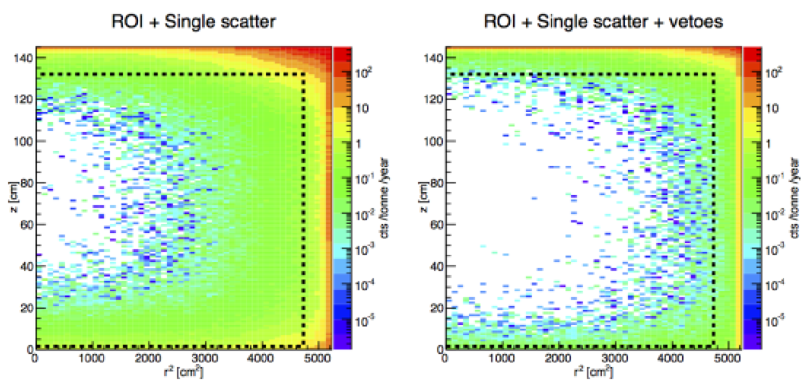

Figure 5. Left: Single scatters only, no vetoing by the anti-coincidence systems. Right: Adding the combination of both the skin veto and the outer detector. The dashed line shows the boundary of the 5.6 tonnes fiducial mass.

starts. The Xe-He mixture now flows to a freezer where the Xe freezes and gets stored, while the He keeps going. Finally, when the freezer is full the temperature is increased, the Xe returns to the gas phase and is compressed inside the storage bottles. Both before and after freezing the Xe, some small quantities of this gas are extracted to analyze them with a sampling system. A picture of the charcoal columns is shown in figure 8.
In total the system will purify 200 Kg of Xe a day and passing it twice it will take a total of 6 months of production. Extra carefulness is needed at each step of the purification. A 40 cm^3 leak of air at standard pressure and temperature in the 10 tonnes of Xe is sufficient to produce a level of Kr corresponding to 0.015 ppt. The most complete and updated project of the removal system is shown in figure 9.

The entire system is automatically controlled through the use of a PLC (Programmable Logic Controller), which is a standard industrial solution that allows a robust and reliable control of the processes. The PLC controls all the main valves of the system using some auxiliary pneumatic valves. It also reads and writes to pumps, mass flow controllers, heaters, thermometers, pressure transducers, etc. The PLC interfaces with a SCADA software package called Ignition that allows for a slower and more user-friendly control of the removal system. Through the GUI of Ignition, all the value of the sensors can be read and the state of the pumps and valves can be manually changed. Some processes can also be automated through the use of Python-like scripts run through Ignition.

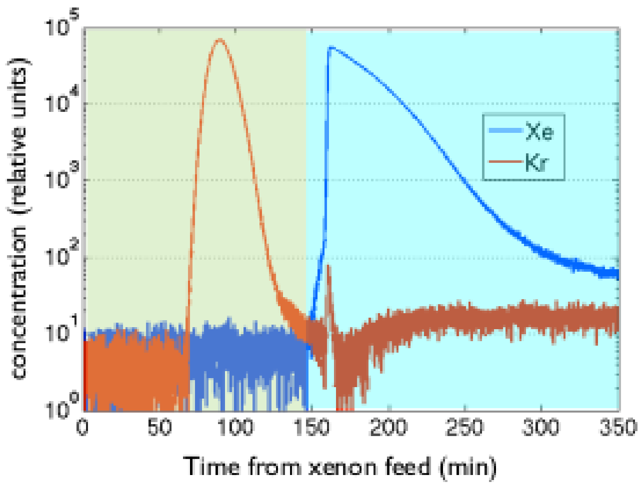

Figure 6. Test data illustrate the time profiles for Kr and Xe as they exit the column for a sample of Xe spiked with approximately 1% Kr.

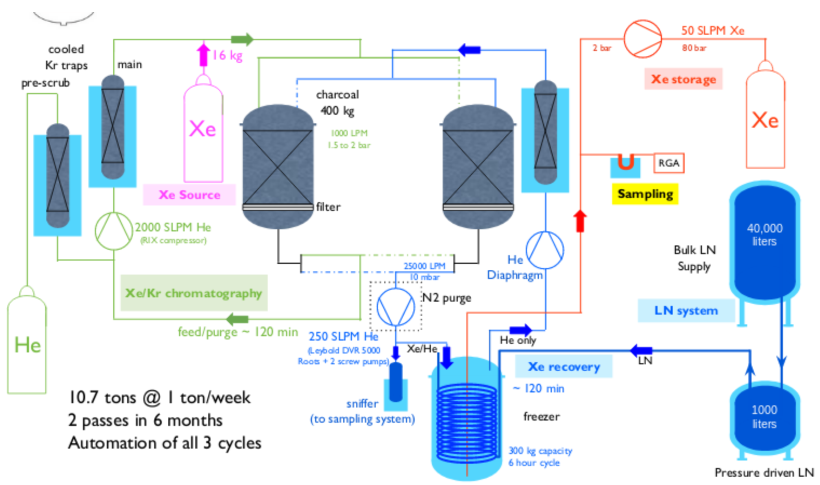

Figure 7. Main components of the LZ Kr removal system. In green the chomotography loop in which the Kr is purged and collected in a cold trap. In blue the recovery loop in which the Xe is collected from the column and freezed in a condenser. In red the Xe from the condenser is stored and analyzed.

IV. The Liquid Nitrogen System

Several components of the KR removal system need a cooling apparatus that keeps them at cryogenic temperature. These components include the freezer where the Xe is stored during the recovery cycle, 4 cold traps used to capture the Kr impurities, and some smaller storing bottles. The 4 cold traps and the freezer are shown in figure 10. The cooling is provided by Liquid Nitrogen (LN) whose extremely low temperature (77 K) allows to freeze both Xe and Kr.

To store the LN close to the rest of the apparatus, two dewars are located on the pad (the place where all the apparatus is located) as an active part of the system. The dewars are shown in figure 11. The first dewar[1] has a capacity of 1000 L and is used to cool down the freezer only. The second dewar[2] has a capacity of 450 L and is used to cool down everything else. Both dewars are then supplied by a 9000 gallons tank, called Tank 15, which is located on top of the hill behind the IR2 building. This last bigger tank is then filled approximately every 10 days by a truck belonging to the company which sells the LN to SLAC. Tank 15 is shown in figure 12.

The main task I was assigned during my Summer Exchange Program was to optimize the LN system by reducing the overall consumption and consequently the costs of operations. Minor works on the system that allowed a higher efficiency included the mitigation of the freezing effects on the lines going around the pad by covering the lines with insulation foam. Another necessary work was to improve the vacuum inside the jacket insulation of the hose running from Tank 15 to the dewars. In order to achieve a good level of thermal insulation, the heat-conductivity process inside the gas must be stopped. This happens at a pressure of the order of 10^{-7} Pa and a turbomolecular pump had to be used.

[1] I will refer to it as 1000L from now on
[2] I will refer to it as 450L from now on

Figure 8. Picture from the removal system, the two white charcoal columns (left and right) and one of the circulating pumps (middle) are visible.

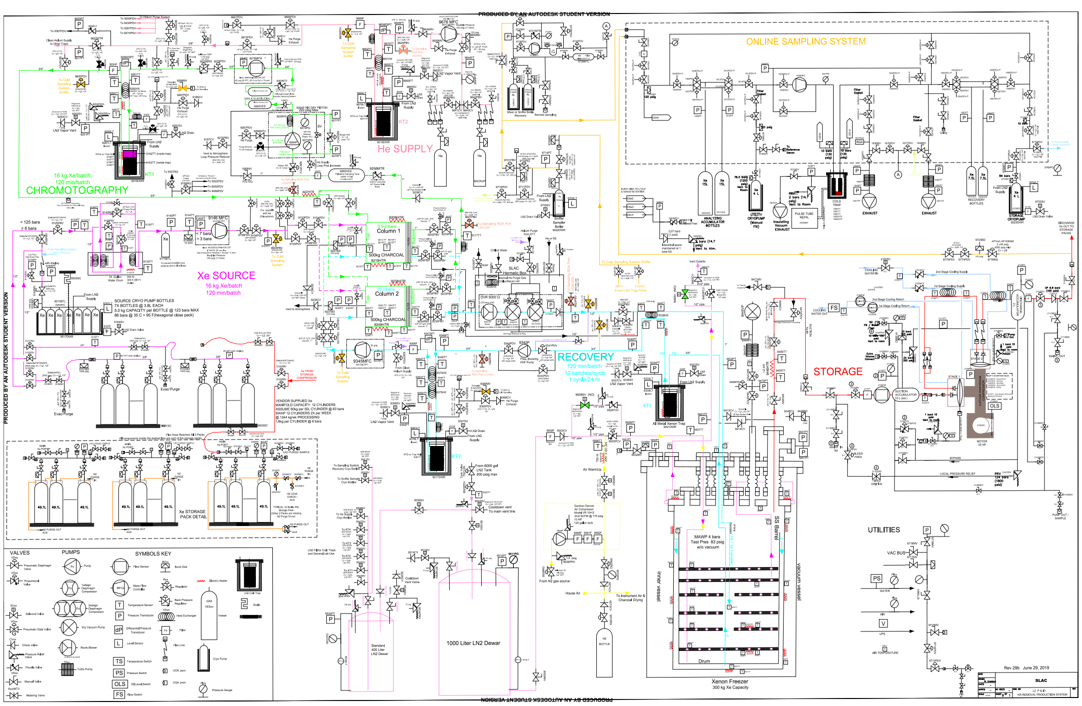

Figure 9. P&ID for the Kr removal system.

Figure 10. On the left the 4 metals cylinders are the cold Kr traps, on the right the larger cylinder inside the holding structure is the Xe freezer.

Figure 11. 450 L dewar (left) and 1000 L dewar (right).

A. The Liquid Nitrogen Transfer Process

Whenever the level of LN inside one of the two dewars gets too low (40%-50%), LN must be transferred from Tank 15 to the semi-empty dewar to fill it. This transfer process is controlled and monitored through an Ignition page as the one I designed, shown in figure 13. The standard way to execute the filling procedure involves opening the valves at the bottom of Tank 15 (TSCV25 and PV9523 in figure 13), waiting until all the gas contained in the hose is vented out through the vent valve (SV9524) and LN fills the entire transfer line. At this point the inlet valve of the dewar (either SV9516 or SV9536) can be opened and the dewar starts to fill.

All the filling mechanism is simply pressure-driven, without any auxiliary pump. In order for the fill to be possible is thus necessary that the pressure inside the dewar is consistently lower than the one at the bottom of Tank 15. The easiest way to achieve a lower pressure inside the dewar is to open its vent valve (either SV9513 or SV9538), letting nitrogen gas flow out and decreasing the pressure to the atmospheric one. The decrease of pressure inside the dewar involves the downside that the boiling temperature of LN is lowered. At this point, more LN starts to boil, turns to the gas phase and vents out. In the process of filling the dewar at atmospheric pressure, a large quantity of LN is therefore wasted through the vent valve. This kind of LN losses are known as *flash losses*.

B. Dewar Pressure Control

A possible way to reduce the LN flash losses is to maintain the pressure inside the dewar at a value lower than Tank 15 bottom pressure but higher than the atmospheric one. In this way, less LN boils and vents out. The possible way to maintain

Figure 12. Tank 15, 9000 gallons.

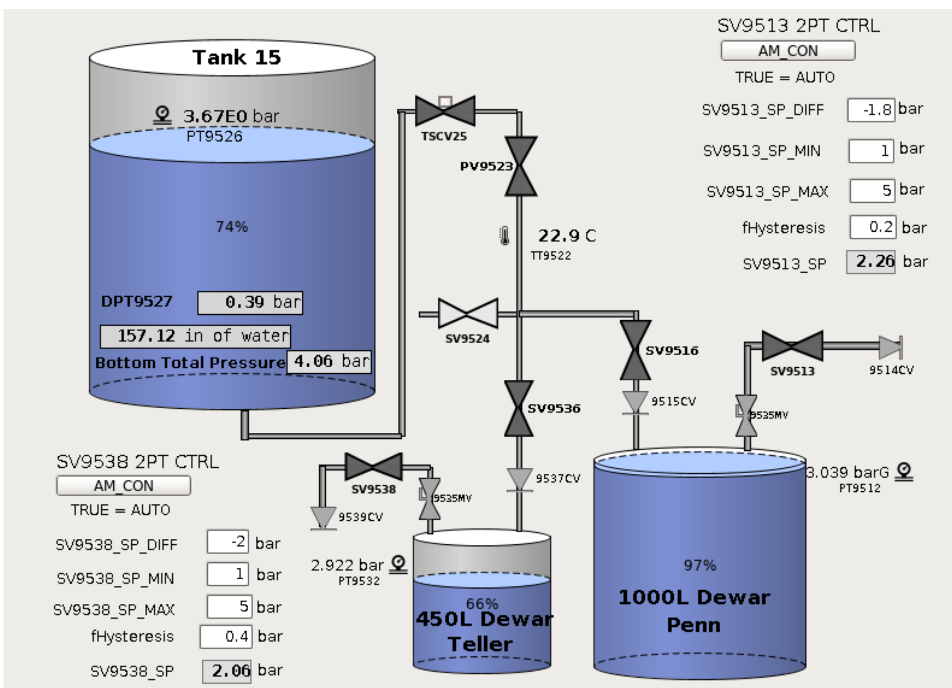

Figure 13. Ignition page to control the transfer of Liquid Nitrogen from Tank 15 to the two dewars. The controlled valves are TSCV25, PV9523, SV9524, SV9516, SV9513, SV9536, and SV9538. The pressure control settings are visible in the top right and the bottom left corners.

the pressure around a fixed average valued is to alternately open and close the dewar vent valve (either SV9513 or SV9538), making the actual pressure oscillate around the wanted setpoint.

As a part of my work, I wrote a code to be run on the PLC that allows the execution of this open-close cycle automatically. The code was written using the TwinCat 3 software that allows writing code in a block diagram visual programming language. A sample of my code is shown in figure 14. The main block of this code is the two-points-control (2PTCTRL). The boolean output of this block directly controls the state of SV9538 vent valve (0 is closed, 1 is open). The 2PTCTRL decides its output based on a hysteresis cycle. Once the setpoint pressure and the hysteresis amplitude are determined the output of the block will oscillate between 0 and 1 according to the diagram of figure 15. A similar code was written to control the state of SV9513 vent valve.

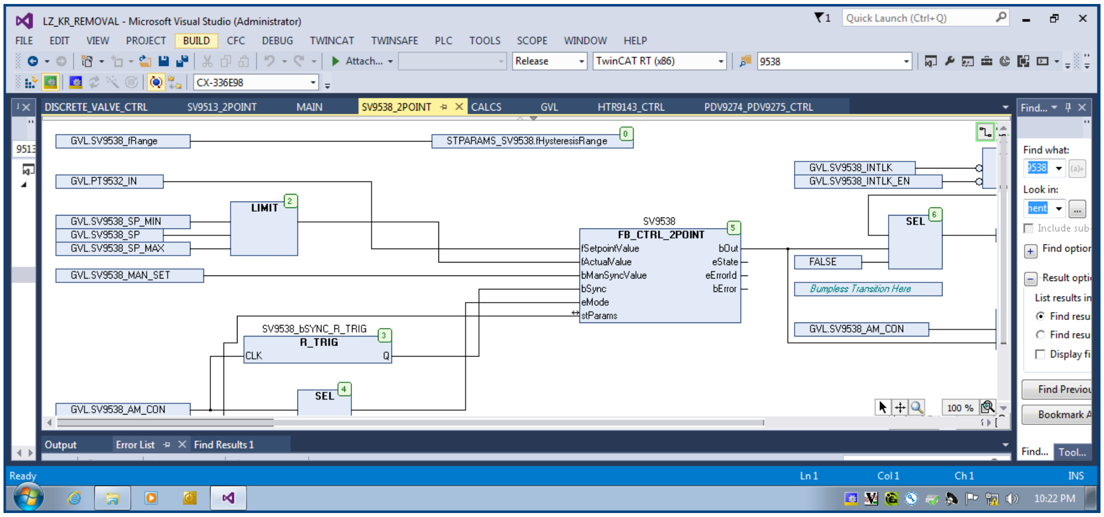

Figure 14. Sample of PLC code used to control pressure inside of 450L. FB_CTRL_2POINT, the main block of the program, is visible in the center.

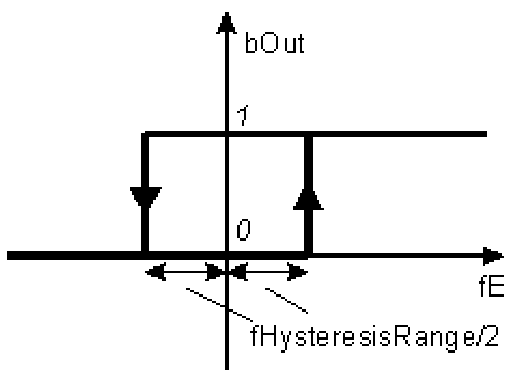

Figure 15. Hysteresis cycle for the two-points-control in the PLC code.

C. Pressure Transducers On Tank 15

Once it became possible to maintain the pressure inside the dewars around a fixed setpoint, the value of this setpoint had to be decided. Since the speed of the fill process depends on the difference between Tank 15 bottom pressure and the dewar pressure, the sensible variable that needs to be directly controlled is not the absolute pressure inside the dewar, but rather the differential pressure at the two ends of the transfer line.

When I started working on the LN system the only way to monitor the pressure inside Tank 15 was by manually reading two dial pressure gauges, located directly under the tank, up on the hill. One of the two dial pressure gauges measures the absolute top pressure inside Tank 15 while the other one reads the difference between top and bottom pressures. The differential pressure gauge was also used to monitor the level of LN inside Tank 15. A differential pressure read of 0.53 bar corresponds to a full tank, while a differential pressure read of 0.31 bar corresponds to 55% of the total volume. When the level is lower than 55% a new order of LN is placed.

For the aforesaid reason, I installed two new digital pressure transducers on Tank 15. The first one, called PT9526 in the system, reads the absolute top pressure of Tank 15. The second one, called DPT9527, reads the differential pressure inside the tank. A picture of the two old dial gauges and the two new pressure transducers is shown in figure 16. Once the pressure transducers were installed, I routed the cables down the hill to the PLC and added the variables related to the sensors into the control software. At this point, the bottom pressure inside Tank 15 can easily be read in Ignition by summing up the two values read by PT9526 and DPT9527. The level of LN inside the tank can be monitored via software by reading DPT9527 pressure value.

Figure 16. Pressure sensors of Tank 15. The small dial gauge measures the absolute top pressure; the big dial gauge measures the differential pressure; the left transducer reads the absolute pressure; the right transducer reads the differential pressure.

D. Setting Dewar Pressure During The Transfer

With all these setups ready it was finally possible to modify the filling procedure. Instead of simply opening one of the vent valves (either SV9513 or SV9538), at the beginning of the fill the 2PTCTRL of the PLC is set to active mode and the PLC starts controlling the value of the pressure inside the dewar by opening and closing the vent valve. The setpoint value for the 2PTCTRL is calculated by subtracting from the bottom pressure of Tank 15 (PT9526 + DPT9527) the wanted difference in pressure. This last difference in pressure can be set by changing the related variable inside the box on the Ignition page of figure 13.

The level and pressure values of a typical fill of 450L without controlling the pressure can be seen in figure 17. The level and pressure values of a typical fill of 450L with the pressure under control are instead in figure 18. In both figures it can be seen that while the level of LN inside 450L increases the differential pressure and absolute top pressure of Tank 15 start to decrease as expected. The main difference between the two figures is given by the second graph. In the first case the pressure inside 450L starts to drop exponentially to the atmospheric pressure, as soon as the vent valve SV9538 is opened. On the other hand with the implemented controls the pressure keeps oscillating between the two limits given by the hysteresis cycle of figure 15. Similar results were produced for LN fills of 1000L.

The last step to optimize the LN transfer was to find the differential pressure at which the efficiency was maximized. To do so, some points at different differential pressures had to be sampled. The sampling of these points had two major problems. First, data could only be taken once or twice a day, when the dewars actually needed to be refilled. This prevented the possibility of collecting a large number of data points, in particular for 1000L. Second, the conditions of the apparatus were not easily reproducible, since the dewars were actively used by other parts of the system that were consuming LN in the meantime. For that reason at some differential pressures more than one data point was taken.

In figure 19 the efficiency of 450L transfers is shown as a function of the differential pressure. In figure 20 the same graph is shown for 1000L. In the case of 450L only points taken with the pressure under control are shown. In the case of 1000L instead, in order to increase the statistical sample, all points, even those without pressure controls, are shown. Because of the large systematic uncertainties given by the reproducibility issues, no error bars are shown. To find the maximum of the efficiency, in the case of multiple points at the same differential pressure the highest value must be considered. From all these considerations I conclude that the optimal differential pressure value to be set as default inside the Ignition page is $\sim 2\,\text{bar}$.

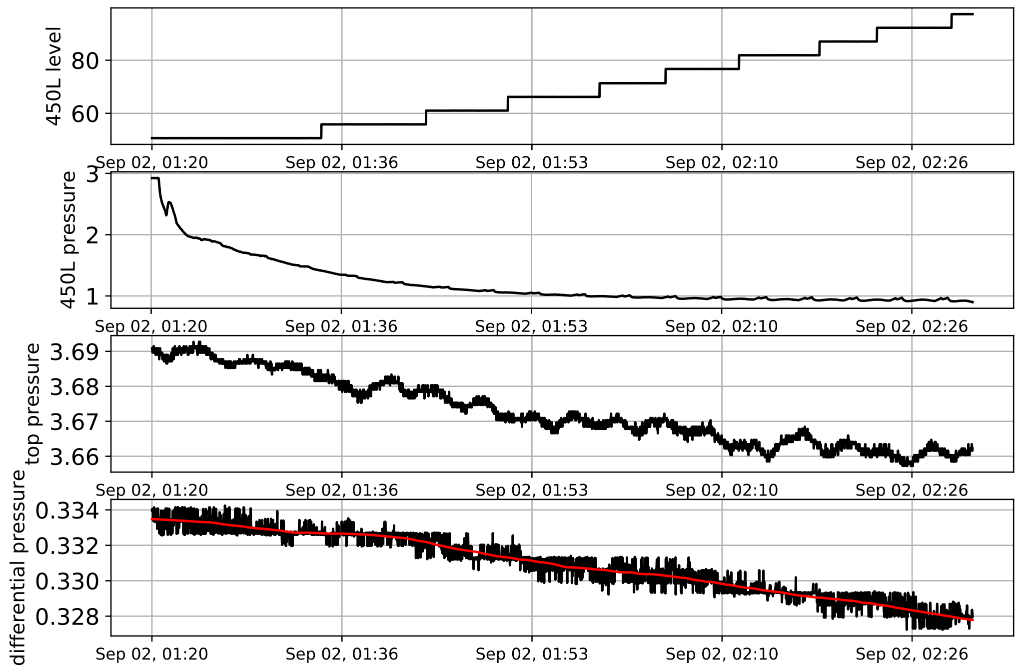

Figure 17. Level and pressure reads during a typical fill of the 450L without the pressure control active.

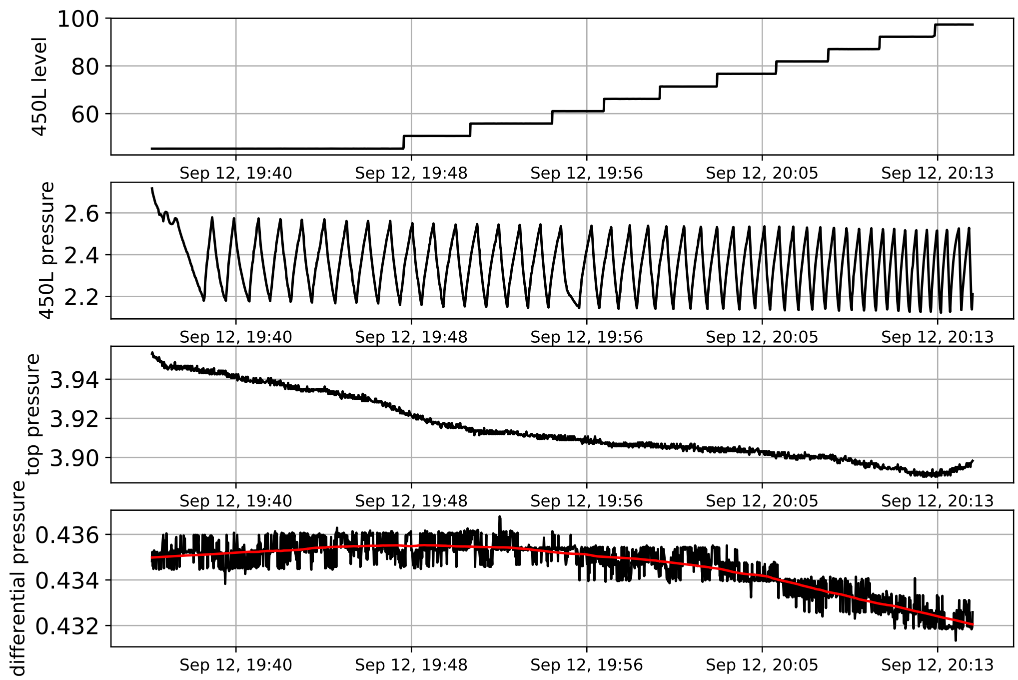

Figure 18. Level and pressure reads during a typical fill of the 450L with the pressure control active.

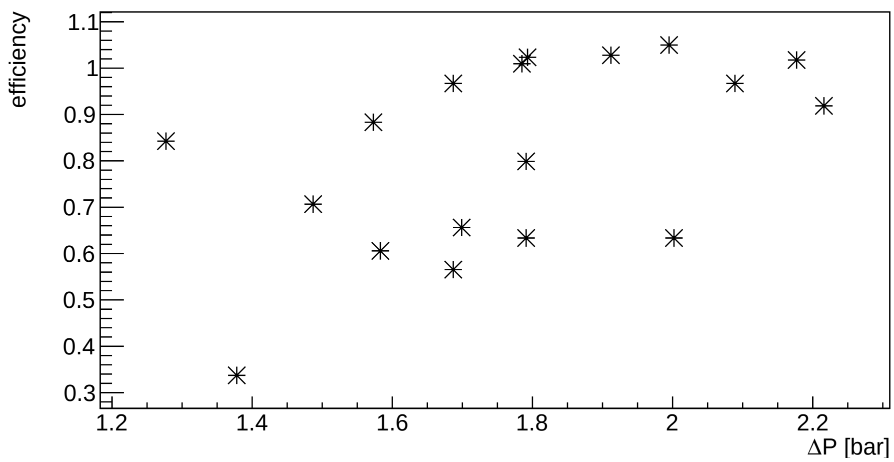

Figure 19. Efficiency of 450L LN transfers. The efficiency is calculated as the ratio between the level increase inside 450L converted in liters and the differential pressure drop inside Tank 15 converted in liters as well.

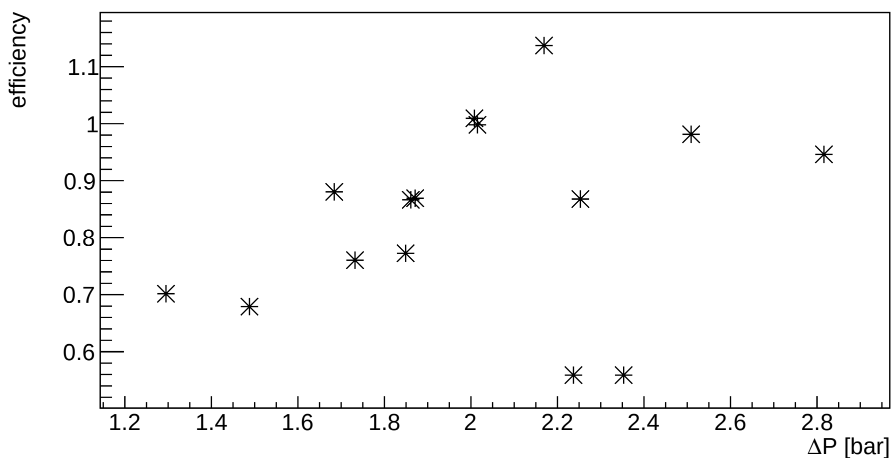

Figure 20. Efficiency of 1000L LN transfers. The efficiency is calculated as the ratio between the level increase inside the 1000L converted in liters and the differential pressure drop inside Tank 15 converted in liters as well.

V. Conclusions

The main task I was given during my Summer Exchange Program was to improve the efficiency of the LN system used by the Kr removal group at SLAC. This was achieved by improving the overall thermal insulation of the LN lines inside the apparatus and by controlling the pressure value inside the LN storage dewars. In particular thanks to the new setup, both hardware (pressure transducers) and software (PLC code and Ignition page), it was possible to find the optimal differential pressure between Tank 15 and the dewars to minimize flash losses and maximize the transfer efficiency. In the coming months, the Kr removal system will enter the production phase and I expect that using a differential pressure of 2 bar will decrease the LN consumption and, consequently, the operational costs.

VI. Acknowledgements

First of all, I would like to sincerely thank Seth Digel and Concetta (Tina) Cartaro for organizing this SLAC-INFN Summer Exchange Program and for helping me with everything during my period here. I would then like to thank Daniel Akerib, Christina Ignarra, Eric H Miller, and Maria Elena Monzani for their help, teaching, and suggestions in my daily work and for giving me the opportunity to work on this project. Many thanks to all the other members of the SLAC LZ group for sharing little moments and ideas during the entire summer. Finally, my best gratitude goes to Alessandra, Anna, Lorenzo, and Mattia for sharing all together a lot of funny moments.

VII. Bibliography

LUX-ZEPLIN (LZ) Technical Design Report arXiv:1703.09144 [physics.ins-det]