Making our world more productive

Superfluid helium refrigeration system

Fermilab, Batavia, USA

In any project, it's the people that make it happen. You can have the most fantastic equipment, but if you don't get along and don't work very hard with the customer, the project will not be successful.

At Fermilab, we integrated the coldbox into an existing infrastructure. Projects like this require a lot more coordination and communication for everything to fit together. In the end, the project stands as an outstanding example of how well our teams work with the customer.

John Urbin,
Business Unit Manager, Linde Cryogenics USA

Teamwork doesn't stop with the plant's acceptance. As we go forward, the same people who work on the project's realization will also continue to contribute to the project's success and long lifetime.
Picture: © Fermilab

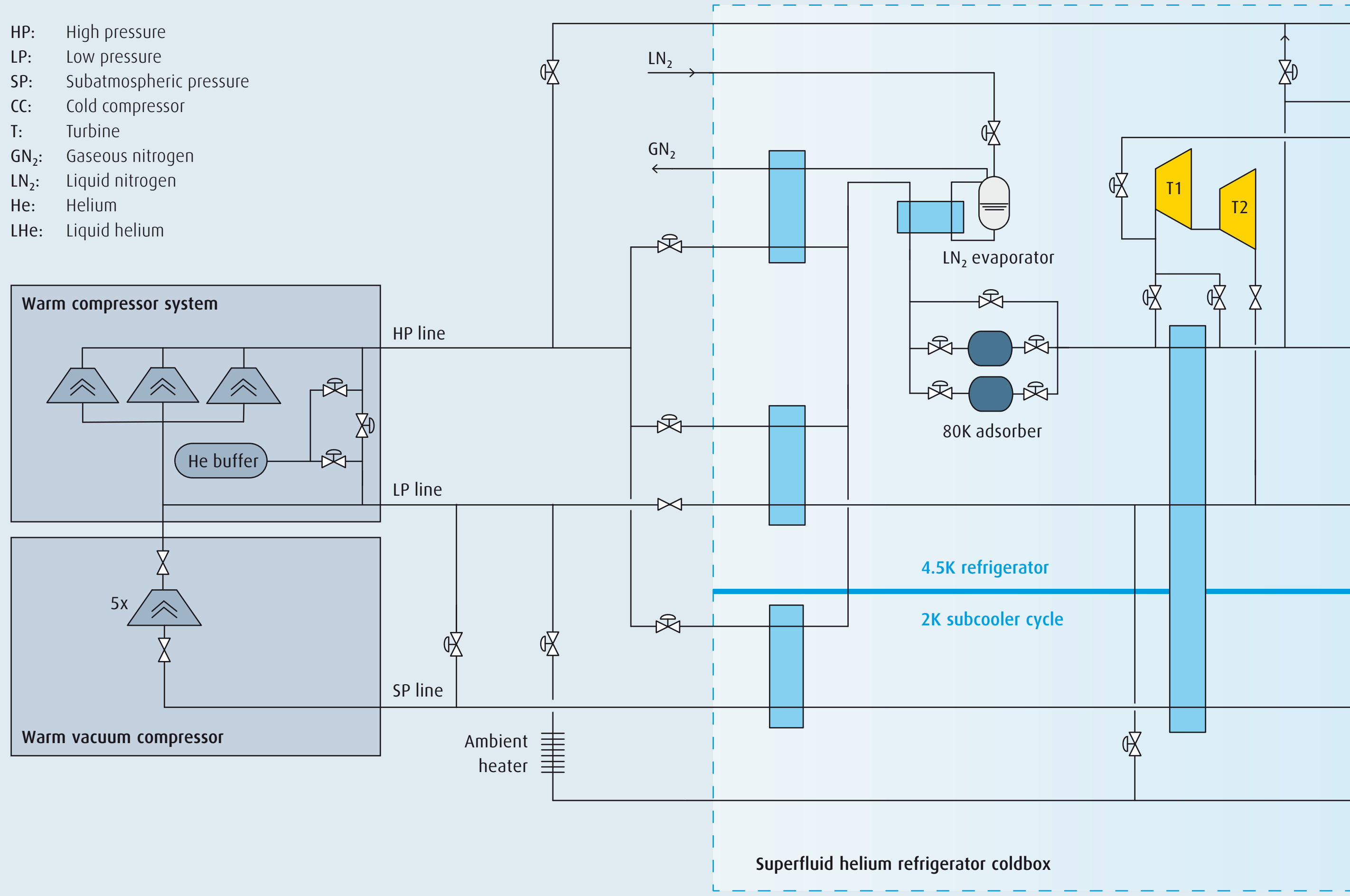
Future accelerators will require as many as 2000 cryomodules.

Our understanding of the subatomic world is inextricably linked with the evolution of particle accelerator technologies.

The Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, represents a hotspot in the endeavor to develop, build and operate the next generation of particle accelerators, such as the International Linear Collider (ILC). The facility enables beam-based experiments in prototypic beam conditions that cannot be reproduced anywhere else and will lead to a better understanding of linear accelerator beam intensity and stability.

Several of Fermilab's current projects are aimed at testing and further developing critical system components for future accelerator assemblies. Their successful completion validates concepts and thus minimizes the primary technical risk element common in prototype developments. For this, several stand-alone superconducting radio-frequency (SRF) cryomodule test stands are currently being completed inside a new building on Fermilab's campus. The Cryomodule Test Facility (CMTF) also features a new Linde Kryotechnik coldbox that has been integrated into the existing cryogenic infrastructure. The setup is designed to be capable of supporting simultaneous operations within CMTF. Due to the necessary power and the wide scope of tests in different conditions, Fermilab requested a very flexible refrigeration plant that is able to deliver adjustable temperatures between 1.8K and 4.5K.

Cryomodules are vessels that contain superconducting cavities in a linear accelerator. Inside, liquid helium cools the cavities to −271°C – only slightly warmer than the coldest possible temperature. The superconducting cavities operate at these supercool temperatures, and transfer energy into the particles that are moving at nearly the speed of light within the accelerator. Because future accelerators will require as many as 2000 cryomodules, the design teams must consider two very important factors: manufacturability and cost. Achieving this perfect balance will require many design iterations that can all be tested in Fermilab's new facilities.



Process flow diagram

The setup for Fermilab's new cryogenic plant was chosen in regard to specific requirements of a test facility.

This 2K refrigeration system sets a new standard: it is the first superfluid helium refrigerator plant realized within the last decade that provides a high standard of operator-friendliness, flexibility and compactness. It is able to service four different consumers: two shield cycles at different temperature levels, one adjustable 1.8–2K cycle servicing the superfluid helium bath cooling and the helium liquefaction to a dewar. This variety of services and the flexibility in operation are basic requirements for test facilities, where the focus lies on the establishment of various environments and conditions in order to evaluate the integrity, performance and quality of cryomodules.

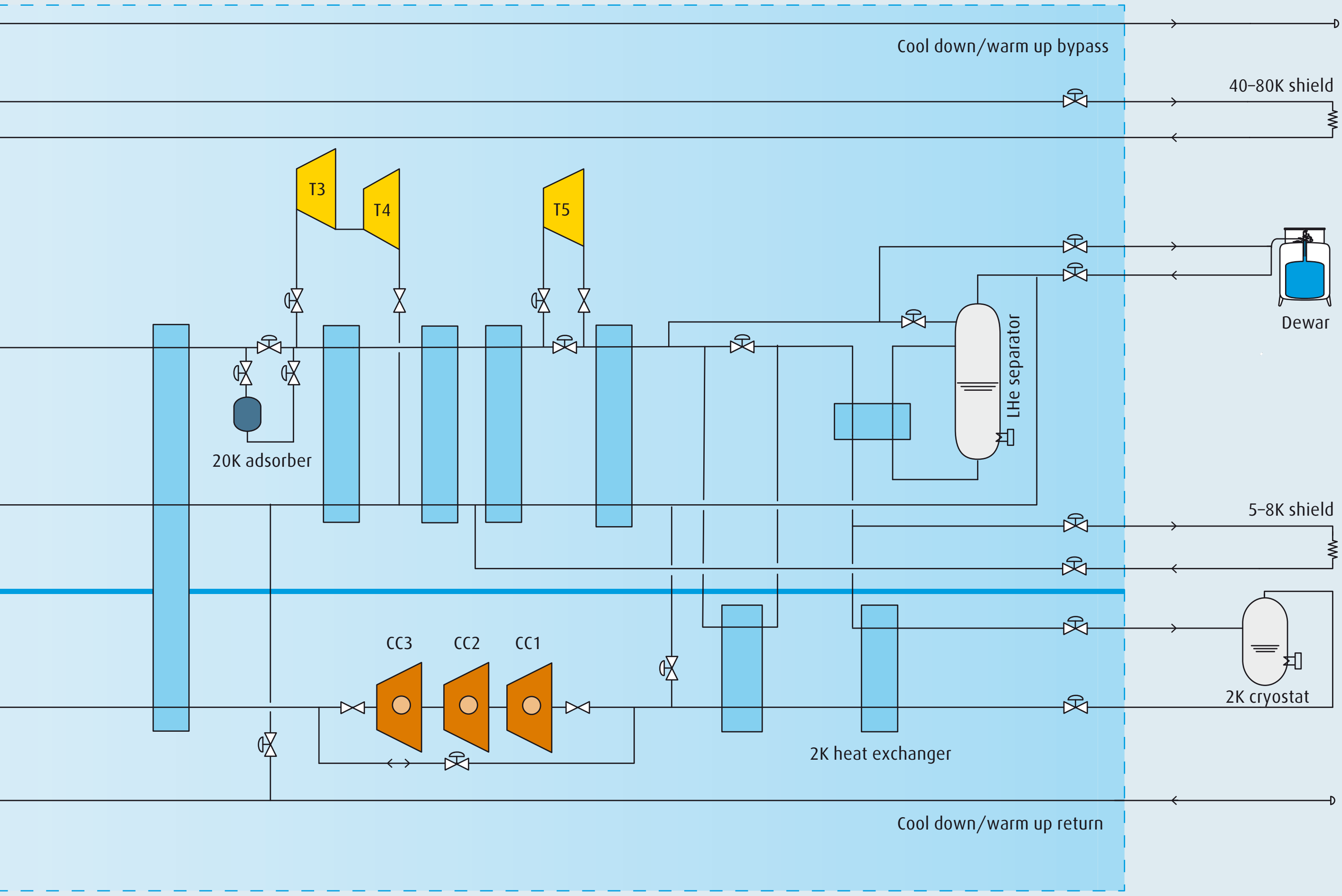
The total system sketched in the flow diagram above can be easily understood as team play between three subsystems: a (customer-supplied) warm compressor system, a warm vacuum compressor system and an "all-in-one" refrigerator coldbox, which combines a 4.5K refrigerator cycle with a 2K subcooler cycle. The arrangement of the individual items of equipment, i.e. compressors, turbines and heat exchangers, was chosen to ensure not only the highest process efficiency, but also to provide the best operability, stability and, in particular, robustness against disturbances.

The 4.5K cycle mainly works at two pressure levels: the high-pressure helium (HP line) is cooled down in counter-flow heat exchangers by warming up low-pressure helium (LP line) and nitrogen. Most of the cooling power is generated by expanding high-pressure helium in the three turbine strings and by evaporating liquid nitrogen. The main product of this process is a subcooled 4.5K helium flow which includes the refrigeration capacity provided to the 2K cycle. In addition to the aforementioned cycle, there are two additional refrigeration cycles used for shield cooling: the high-temperature shield is operated in the range of 50K to 80K, and the low-temperature shield is operated within 5K to 8K.

Even though the complete refrigeration cycle is a closed system, the helium process lines are exposed to the entrainment of air contaminants, which is particularly true for flows at subatmospheric pressure. The challenge facing cryogenic refrigerators lies in the fact that these contaminants freeze out while travelling from the warm to the cold end of the coldbox. This results in blockage and can even cause severe damage to the coldbox equipment.

Superfluid helium

Also known as Helium-II or LHe-II, superfluid helium is a state of matter attained at extremely low cryogenic temperatures and pressure where helium is capable of flowing without inner friction. This enables superfluid helium to creep up walls and escape, also known as Rollin film. Pure superfluid helium has no entropy, no viscosity and nearly ideal heat conductivity.



To prevent this, adsorbers set at critical locations act as cryogenic purifiers and trap the contaminants.

In order to generate temperatures below 4.2K, the vapor pressure of the helium bath has to be lowered to subatmospheric condition. This pressure range can only be achieved by using vacuum pumps. For even higher refrigeration capacities, what is known as a mixed cycle is applied. It consists of one or a series of warm vacuum compressors and one or a series of cold compressors. The latter machines are operated at very low temperatures, in the range of 4K to 25K. This unique setup, which is only found in large-scale superfluid helium refrigerator systems, requires technologies beyond the state of the art. The product of the 4.5K refrigerator, which is fed to the 2K cycle, i.e. the subcooled helium at 4.5K, is further cooled to nearly 2K before being throttled to subatmospheric pressure and supplied to the consumer – a heat load cooled in a superfluid helium bath at temperatures in the range of 1.8K to 2K. These extremely low temperatures are made possible by the cold and warm vacuum compressors that maintain the bath at subatmospheric pressure. The pumped helium flow also passes several heat exchanger units on its way from the cold end to the warm end. This improves the process efficiency by recovering cold to cool down a segment of the high-pressure flow.

The highest process efficiency is also realized during turn-down operation. The process design incorporates the various required operating modes as well as the possibility to adapt the plant to different heat load requirements or liquefaction rates. The controller is able to determine reduced heat loads in the system, resulting in reduced generation of refrigeration capacity. Simultaneously, power saving is performed by the adaptation of the recycle compressor capacity.

Plant performance

Refrigeration capacity	Unit	Mode I	Mode II
Bath cooling at 2K	W	500	–
Bath cooling at 1.8K	W	600	250
Shield cycle 5K–8K	W	–	600
Shield cycle 40K–80K	W	5000	5000

Specific features

- → **High flexibility**
  Several cooling cycles at various temperature levels are available and are individually adjustable.
- → **Highest process efficiency**
  High-performance equipment in conjunction with intelligent process design provides the highest process efficiency, also during part load operation.
- → **Compact design**
  All cold equipment is incorporated into one coldbox, which is not only space- but also cost-efficient.

To achieve high efficiency and flexibility in Fermilab's new coldbox (far right), Linde Kryotechnik implemented a serial configuration of three cold compressors (above).

Linde Kryotechnik cold compressors are characterized by the following:

- high thermodynamic (polytropic) efficiency
- significantly higher robustness than magnet bearings due to hybrid ceramic ball bearings
- standardized components for easy replacement
- extremely low maintenance
- high compression ratio

Cold compressors are an effective method to provide cooling below helium's normal boiling point (4.2K).

Cold compressors are turbo-machines that pump off helium vapor at subatmospheric pressures. The use of cold compressors in medium-sized refrigeration units is very cost-efficient; in large-sized units indispensable. Due to the compression of subatmospheric process gas, the essential advantage here lies in a drastic reduction in the size of downstream equipment such as vacuum pumps, compressors and heat exchangers. This effect is intensified through efficient machines, which provide higher compression ratios.

There are only a few facilities in the world running such turbo-machines. At each location the specifications are different, requiring a unique and tailored design for each facility. Linde Kryotechnik's cold compressors are based on standardized components, which are individually arranged to meet individual needs, while also enabling fast, easy and cost-efficient replacement.

The cold compressors implemented at Fermilab consist essentially of a single-stage radial compressor driven by an electric motor. Linde Kryotechnik makes use of hybrid ceramic roller bearings for this type of machine, providing much higher robustness than the commonly employed active magnet bearings. The consequence is an extremely low maintenance requirement. Additional cold compressor features are a helium guard system, which avoids air in-leak to the subatmospheric low-temperature cycle, and intercept cooling for improved process efficiency. Lastly, each cold compressor's assembly and disassembly can be carried out without the need to break the insulating vacuum of the coldbox. This makes any required maintenance very quick and easy.

The interior complexity of the superfluid helium refrigerator coldbox can be seen from the tight arrangement of components on the valve plate (above). Picture: © Fermilab

While accomplishing a subatmospheric pressure environment for the superfluid helium flow, highest process efficiency, stable and robust operation of the cold compressor system and operator-friendliness are of utmost importance.

As is the case with every highly efficient, high-tech machine, cold compressors are not only complex, but also sensitive to disturbances. It is in their nature that their operational tolerance is very narrow. Exceeding surge or maximum motor speed boundaries causes a system failure and results in a time-consuming start-up procedure of the complete cooling cycle and the entire particle accelerator. Consequently, operating three of these highly demanding devices in series at the highest efficiency in a long-term experiment requires a high performance control system. For this, Linde Kryotechnik developed the next generation of operator-friendly control systems that enable easy handling of the cryogenic setup's complexity. Operators can follow the current state of operation within the compressor map and are always up-to-date about its current state.

In addition, the integrated safety feature functions in the background and supports the operating system by automatically avoiding critical states. Moreover, the clever control concept also establishes the required suction pressure with the highest stability, thus maintaining process performance at peak efficiency.

Specific features

→ Operational safety due to the advanced control concept.
→ Precise speed control of the high-performance control system provides the highest possible process efficiency for the complete operation map by simultaneously maintaining process stability.
→ The sophisticated control concept broadens the operational range far beyond the limits of the ability of the cold compressors.

During start-up of the system, fast and smooth pump-down is achieved by fully exploiting the permitted operation map. This feature is also automatically performed by the Linde Kryotechnik control system.

3D illustration of the coldbox

■ cold compressors ■ turbines

Engineering excellence – every step of the way

Linde Kryotechnik AG and Linde Cryogenics are the world's LeadIng cryogenic technology and engineering companies, bundling low-temperature know-how and cutting-edge technologies with value-add services for scientific research and industrial organisations around the globe. Highly skilled Linde teams partner with customers to develop and deliver innovative cryogenic solutions for liquefaction and refrigeration systems at temperatures below 80 K (–193°C).

Linde Engineering is a leading player in the international plant engineering business, covering every step in the design, project management and construction of turnkey industrial plants. Drawing on its extensive, proven process know-how, this division sets the standards for innovation, flexibility and reliability with ground-breaking concepts and a dedication to engineering excellence.

Core competencies of Linde Kryotechnik AG and Linde Cryogenics:
→ Helium liquefiers
→ Helium refrigerators
→ Helium recovery systems
→ Hydrogen liquefiers
→ Storage and distribution systems
→ After sales services
→ Special cryogenic plant engineering services

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