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CRYOGENIC SYSTEMS FOR LARGE SUPERCONDUCTING ACCELERATORS/STORAGE RINGS*

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Introduction

Particle accelerators and storage rings which utilize superconducting magnets have presented cryogenic system designers, as well as magnet designers, with many new challenges. When such accelerators were first proposed, little operational experience existed to guide the design.

Two superconducting accelerators, complete with cryogenic systems, have been designed and are now under construction. These are the Fermilab Doubler Project and the Brookhaven National Laboratory ISABELLE Project. The cryogenic systems which developed at these two laboratories share many common characteristics, especially as compared to earlier cryogenic systems. Because of this commonality, these characteristics can be reasonably taken as also being representative of future systems. There are other areas in which the two systems are dissimilar. In those areas, it is not possible to state which, if either, will be chosen by future designers. Table 1 lists some of the design parameters for the two systems.

Table 1
Cryogenic System Design Parameters

	ISABELLE	Doubler
Design Magnet Temperature	3.8K	4.6K
Capacity (below 5K)	24.8kW	23.9kW
Capacity (55K nom. heat shield)	55kW	0
Compressor Input Power	11.8MW	8.8MW
Liquid Nitrogen Input	0	2648 liter/hr
Number of Refrigerators	1	25
Number of Magnets in System	1084	990
Number of Parallel Cooling Loops	24	48

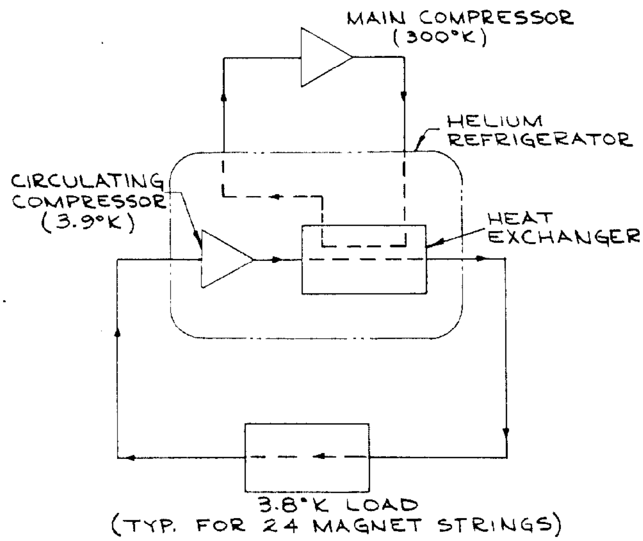

Fig. 1. ISABELLE Cryogenic System block diagram.

ISABELLE Cryogenic System

The ISABELLE cryogenic system has a single refrigerator as shown in Fig. 1. A cold (3.9K) centrifugal compressor will circulate compressed liquid helium in a loop through the magnets. This circulating stream is cooled to 2.6K by heat exchange within the refrigerator. There are 24 parallel flow paths through strings of magnets.

Doubler Cryogenic System

The Doubler cryogenic system[1] has 25 refrigeration stations arranged as shown in Fig. 2. A large liquefier (Central Helium Liquefier) is used as a source of liquid helium to supply 24 smaller (Satellite) refrigerators located around the ring. During operation in the design mode, these refrigerators amplify the refrigeration effect of the liquid supplied to them. Each refrigerator cools two strings of magnets for a total of 48 parallel flow paths.

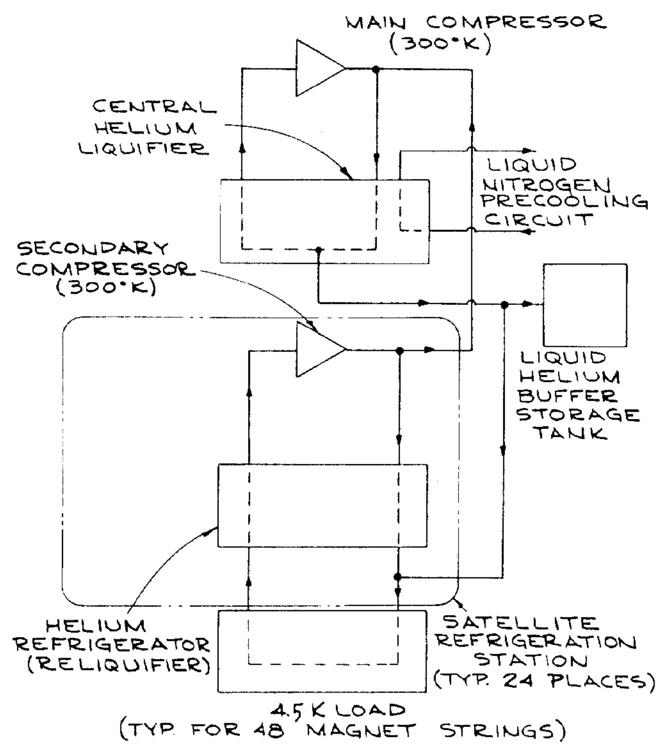

Fig. 2. Doubler Cryogenic System block diagram.

Common Characteristics

Large Capacity

The Doubler Central Liquefier has a larger capacity, by a factor of about three, than any other helium plant now operating anywhere in the world. When the ISABELLE refrigerator comes on line, it will be larger still by about another factor of two. The ISABELLE refrigerator has a nominal capacity of 24.8kW. The Doubler Liquefier can produce over 4000 liters/hr of liquid and, when it is coupled with the 24 Satellite refrigerators, the combined system has an equivalent capacity of 23.9kW.

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Single Phase Fluid

Both systems have been designed to utilize single phase helium, as opposed to boiling liquid, to cool the magnet coils. The operating points for the two systems are shown on a pressure-temperature plot in Fig. 3. The Doubler System will operate nearer to the liquid line at its system design pressure of 1.8 atm than will the ISABELLE system which is designed to operate at 5 atm pressure.

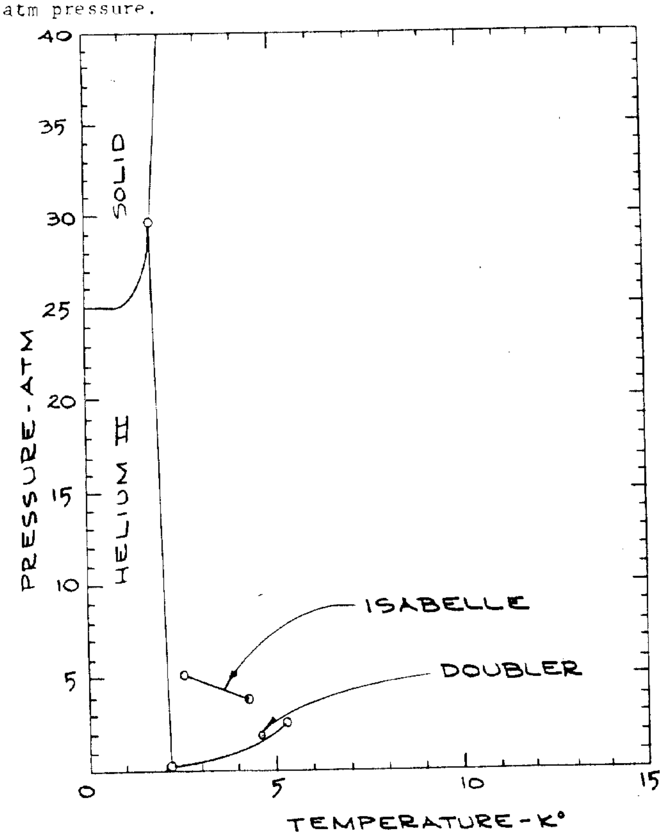

Fig. 3. System Operating Points

Complexity

Both of these systems contain many passive and active elements at cryogenic temperature. The Doubler, for instance, will have 51 expansion engines installed in its system. Most cryogenic plants have only two. When operated in the "satellite" mode, each of the satellite refrigerators will use only one of its two reciprocating expanders. The Central Liquefier has three oil-bearing turboexpanders. During Doubler operation, it will be necessary to operate 27 expanders to produce the design cooling capacity. Liquid helium from storage is used for back-up capacity in event of expander outages.

The ISABELLE system will utilize five oil-bearing turboexpanders in its refrigeration cycle. In addition, it will have four redundant expanders which are not normally in operation. This refrigerator also has three centrifugal compressors operating at temperatures below 10K. The coldest compressor has its suction at 2.5K. Eight turbomachines must be functional when ISABELLE is in operation.

The multiplicity of parallel cooling loops will make management of helium flow in each system a problem requiring careful attention. The problem will be compounded by the long time constants in these helium systems. The average time constant for the ISABELLE cooling loops will be about 45 minutes.

Computer control is planned for each installation. Work on the control algorithms has begun and will be an important element in determining the measure of success attained in operation.

Variations in Boundary Conditions

The Doubler Project and the ISABELLE Project have each presented a different set of boundary conditions to be satisfied by designers of their cryogenic systems. Some of these differences are discussed below.

Physical Plant

The Doubler magnets are to be installed beneath the existing normal magnets in the Fermilab tunnel. Services for the superconducting magnets must be installed without interruption of the on-going physics program. By contrast, a clean slate was presented to the ISABELLE designers which permitted a wider set of possible design variations.

Funding Patterns

This non-technical aspect of a project can and does have a large effect on some decisions. Because these cryogenic systems have components which require long delivery times, their procurement must be started early in the project's life. The funds available may limit the size and/or type of plant that can be purchased at a critical procurement time. The Fermilab design approach is more flexible with regard to funding pattern requirements than the ISABELLE approach.

Magnet Temperature

ISABELLE is designed to provide cooling as required to hold a maximum magnet temperature of 3.8K. The Doubler has a design temperature of 4.6K. While only 0.8K temperature difference, this is a 17% reduction in temperature. Carnot cycle analysis implies that 21% more input power per watt of refrigeration will be required in the ISABELLE system. The 3.8K design temperature of ISABELLE requires that some of the system be below atmospheric pressure. In order to minimize the chance of air leaking into the system, then freezing and plugging the flow passages, the extent of the sections at sub-atmospheric pressure have been sharply limited in the ISABELLE design. A system which is designed along the lines of the Doubler, if operated at 3.8K, would have very extensive parts of the magnets and the piping at sub-atmospheric pressure. This would give rise to serious reservations regarding the reliability of such a system and might lead to its rejection for use in applications designed to operate at sub-atmospheric pressure.

System Mass

The Doubler magnets use "warm iron", i.e., the iron magnetic return path is at room temperature. The ISABELLE magnets use a "cold iron" design which requires the iron to be at the same temperature as the coil. This means that each ISABELLE dipole magnet has a cooldown weight approximately 5000 kg greater than a Doubler dipole. For a given refrigeration input, the ISABELLE cooldown time will be longer because of this difference.

Load Characteristics

A large part (approximately 60%) of the cryogenic load of the Doubler is generated by the hysteretic losses of the magnets during ramping of the magnet current for the particle acceleration cycle. This is in sharp contrast to the ISABELLE system in which the particles are only accelerated once per day and the heat generated during acceleration is a small fraction of the total load.

Dissimilar Characteristics

Given the many variations in boundary conditions for the ISABELLE and Doubler cryogenic systems, it is not suprising that the designs are not identical. In fact, the only significant difference that exists between the two is the degree of centralization of the refrigeration plant.

The ISABELLE system with its single refrigerator represents one end of the spectrum, full centralization. The Doubler system is a hybrid which lies nearly midway between centralized and distributed. The Central Liquefier contributes about 52% of the refrigeration for the Doubler.

Once the system designs had branched on the centralization issue, some other differences followed naturally in the wake of that decision. For example, the use of liquid nitrogen as a precoolant is much more advantageous, from both the thermodynamic and the economic point of view, in a liquefier than in a refrigerator. When the use of liquid nitrogen precooling was studied for ISABELLE, it was determined that the costs were essentially the same with or without the nitrogen. On the basis of convenience, it was decided not to use it in ISABELLE. The Central Liquefier of the Doubler hybrid system uses liquid nitrogen precooling for logical reasons and the ISABELLE design, for equally logical reasons, does not.

Another example of a difference in hardware which is an outgrowth of the centralization difference is the use of reciprocating expanders in the Doubler (satellite) design, but not in ISABELLE. Reciprocating expanders are most appropriate for small refrigerators. Turboexpanders usually become more desirable than the reciprocating type when the plant capacity is in the one to two kilowatt range or greater. Therefore, it is not illogical to find this difference between the systems.

Observations

Designs of the ISABELLE and Doubler cryogenic systems plus some personal prejudices lead to the following observations pertaining to these two projects and to future superconducting accelerators.

Single phase fluids (compressed or subcooled liquid) will be used in systems of this type. Where the load which must be cooled is thinly distributed over a long distance, e.g., in an accelerator, the greater stability and predictability of flow and heat transfer characteristics make a single phase system desirable.

The cryogenic systems for this service will, of necessity, be complex. A corollary to this is that there will be problems during start-up. In particular, one can imagine that control problems will arise. These problems will be solved and, in the process, computer optimization of the system performance will be developed.

One can predict with reasonable confidence the refrigeration output of a helium plant. There is a much greater chance for error in the prediction of expected loads and in the execution, during fabrication, of design details relating to heat load. Therefore, "capacity problems" if any, are more likely to be due to the actual load exceeding the design load rather than plant output falling significantly below design capacity. Only very close attention to detail will prevent disaster in this area.

The "Real" Problem - Reliability

The success of a cryogenic system which is chosen for accelerator service will be judged, ultimately, on the basis of its reliability in service. The system may have many desirable characteristics such as low initial cost, high efficiency, innovative design and attractive packaging, but they will seem as nothing unless the system operates reliably.

The present generation of helium refrigerators, as a class, have not been notable for high reliability. They have suffered from premature failure of components due to poor design and have also suffered from operations related problems, primarily contamination. Some seem to believe that, like a case of adolescent acne, these problems will disappear with time. Unfortunately, the remedies for these two afflications are not the same.

Improvement in reliability will grow from attention to the basic principles of reliability theory and practice throughout all stages of cryogenic system design, fabrication, installation, operations and maintenance. All this, with a little good luck thrown in, will result in satisfactory performance. The reverse proportions - a lot of good luck with a little effort - probably would also work, but won't happen.

Acknowledgments

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