CRYOGENIC REFRIGERATION EQUIPMENT FOR THE NEW LIGHT SOURCE (NLS) SUPERCONDUCTING LINAC

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Abstract

The proposed New Light Source (NLS) based on a CW superconducting linear accelerator requires large scale cryogenic refrigeration equipment comparable to some of largest installations around the world (for example CEBAF/SNS and LHC). The maximum refrigeration power requirement is estimated to be 3.4 kW at 1.8 K. The ratio of the dynamic to the static heat load is in excess of 20 and handling such large variations in the refrigeration power is the key issue in the development of the cryogenic system for NLS. In this paper we present our approach to address the issues relating to efficient and reliable operability, operational functionality and capital costs, in order to develop an effective and economic solution for NLS.

INTRODUCTION

The NLS LINAC consists of 144, 1.3 GHz, 9 cell SRF cavities, operating at a temperature of 1.8 K. [1] [2] These cavities will be contained within 18 cryomodules, each of approx 12.2 m in length. The heat load (or the refrigeration power required to maintain the temperature) of SRF cavities at 1.8 K is the key parameter and the main cost driver for the design of the cryogenic system for NLS.

CRYOGENIC HEAT LOADS

The heat loads as stated in Table 1 dictate the basic specification of the helium refrigerator.

Table 1: Primary design parameters of NLS refrigerator

Parameter	Value
Operating temperature	1.8 K
Overall dynamic heat load (including safety factor of 1.5)	3.4 kW
Length of a cryomodule	12 m
Overall length of the linac	~325 m
Cooling power at 40 K to 80 K	4 kW
Cooling Power for 5 K to 8 K	0.6 kW
Distance between the linac and Cryo-hall	~50 m

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For safe and reliable operation the calculated heat load values have been multiplied by the normal "safety factor" of 1.5. The NLS refrigerator will have a capacity of 3.4 kW @ 1.8 K. Large refrigerators with a capacity of 2.4 kW at 1.9 K have been supplied by industry and are successfully operated by CERN for the LHC [3]. The XFEL refrigerator will also be of similar capacity as the LHC systems. The CEBAF [4] refrigerator, 4.8 KW @ 2.1 K is currently the world's highest capacity cryogenic system.

REQUIRED MODES OF OPERATION

There are three required operating modes, in which the helium liquefaction requirements differ greatly, due to the high ratio of dynamic (RF ON) to static heat loads (radiation losses) as shown in Table 2 and described further below.

Table 2: Helium Mass Flow Rates

Mode	Helium Mass Flow (g/s)
Full Load at 1.8 K	~164
Stand-by at 1.8 K	> 8.7
Stand-by at 4.5 K	> 7.0

- Full load at 1.8 K: normal operating condition with full dynamic & static heat loads being applied.
- Stand-by at 1.8 K: SRF modules remain at normal operating temperature ready for use. Only the static heat loads are being applied. The system may remain in this mode for several days, during non cryogenic fault periods and normal accelerator operational requirements.
- Stand-by at 4.5 K: SRF modules are warmed up to 4.5K, only the static heat loads and no cold compression is required as the module pressure is above atmospheric. This is an accelerator shut-down mode, where it has been elected to keep the modules cold.
- Transient Modes: Changing from Stand-by at 4.5 K to Stand-by at 1.8 K needs to be achieved within a 4 hour period, a further 2 hours is allowable to achieve stability at full load.
- Cooldown: From ambient temperature cooldown to operation (1.8 K, Full Load) must be achievable within one week; the cooldown capacity of the refrigerator is shown in Fig. 1.

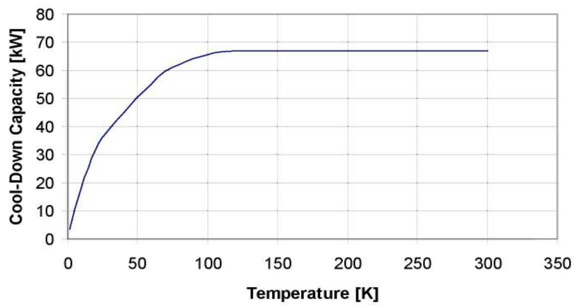

Figure 1: Cooldown capacity of refrigerator.

SOLUTION

In our approach to finding a solution for NLS, the functionality of the plants at CEBAF/SNS and LHC were considered as well as XFEL proposals and some work previously done by STFC and Monroe Brothers [5] for the then proposed 4GLS accelerator. We concluded that a full industrial design study should be undertaken to properly address the specific cryogenic requirements of the NLS project and that this study would contribute to the Conceptual Design Report (CDR) [6] and costings study.

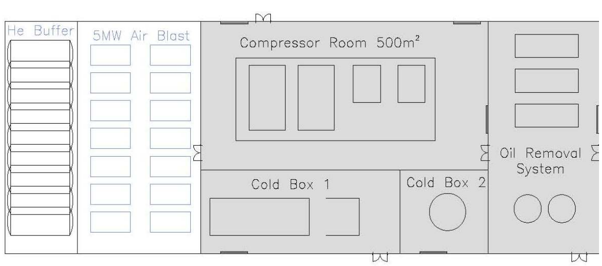

Figure 2: Ancillary Building – Layout show sizes!

In addition to the information about heat loads and modes of operation, there is a pressure stability requirement of ± 1 mb. The following information formed the outline of the industrial study remit:

- The complete Linac is to be cooled and or warmed together, as the proposed cryogenic distribution system [2] did not require or allow modules to be operated individually.
- The estimated operational load is ~2.3 kW, with the system design load 3.4 kW (2.3 x Safety factor of 1.5). For optimal efficiency the control system must utilise floating pressure control technology, similar to that used at CEBAF/SNS (Ganni Cycle).
- The operational heat load should be less than the maximum capacity of the refrigerator, some redundancy would exist within the compression system and if necessary further capacity could be added as and when required. However in other parts of the system, redundant capacity issues may be more difficult. For example, if the proposed solution has only one coldbox, any major failure would result in an enforced accelerator shut-down. If this were the case, a mitigation strategy would need to be developed.
- The plant and equipment required, should be efficient in its use of space and should be compatible with the outline building design as seen in Fig. 2 & 3.

Figure 3: Ancillary Building – Architect's vision.

INDUSTRIAL DESIGN STUDY

Completed in March 2010 and suggested that in terms of both capital and operational costs, the optimal solution for NLS would be a single large refrigerator.. The proposed system consists of the following major components:

- Compressor systems (4 off)
- Gas management system
- Oil removal system
- Gas drying system
- Regeneration system for 80K & 30K absorbers
- Refrigerator coldbox
- Cold compression coldbox
- Warm gas storage @ 20bar
- Liquid storage
- Control system

During the refrigeration process (Fig. 4), the high pressure gas (HP) delivered from the warm compressor system is purified, firstly by three coalescing filters and one charcoal absorber that removes excess compressor oil; then a molecular sieve dryer bed removes moisture, before it enters coldbox 1. Within the coldbox 1, the gas stream is cooled in counter flow aluminium fin heat exchangers to the warming up low pressure return streams LP1, LP2 and LP3. The heat exchangers are tagged HX1 to HX4, all of them have sub-sections which are indicated by a letter A,B or C.

Refrigeration is performed by seven gas bearing turbines which are operating at different temperatures. These turbines are tagged Tu1 to Tu7. Six of the seven turbines work together as pairs serially connected. Tu7 is a single turbine.

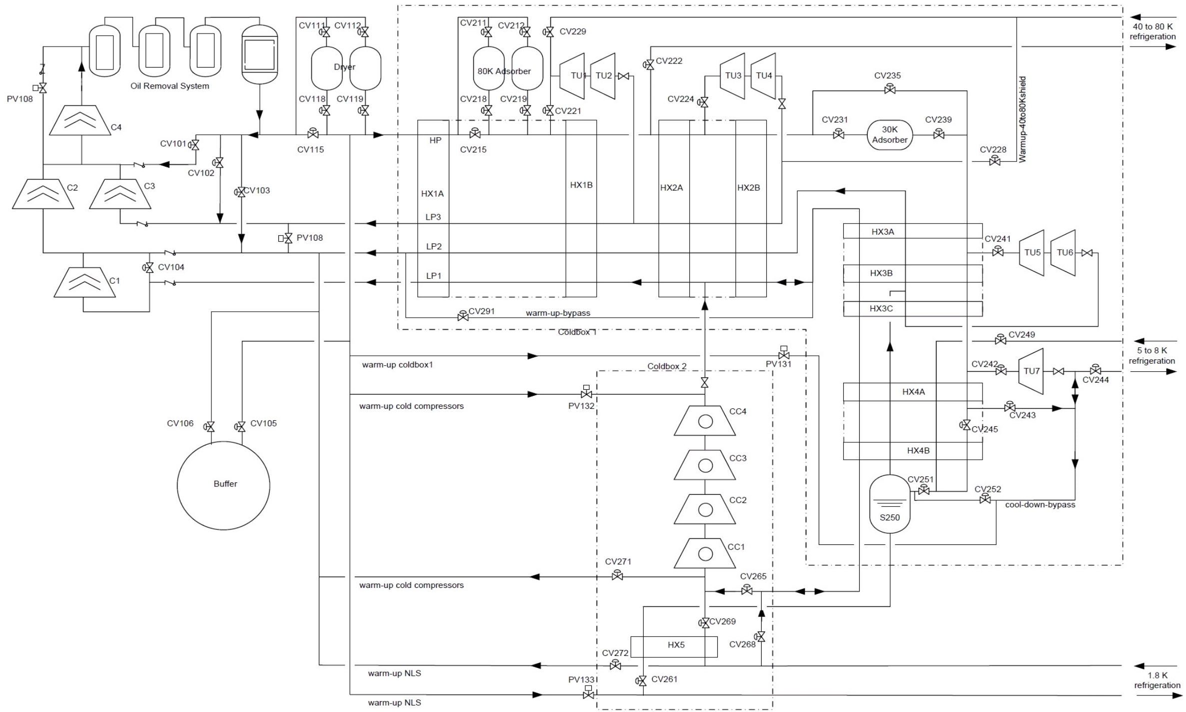

Figure 4: Refrigeration Process Diagram.

The turbine string TU1/TU2 is fed by a gas flow which is split from the HP line between the heat exchangers sections HX1A and HX1B. The gas flow is mixed with the return flow from the 40-to-80K shield before entering the turbine1. The return flow from these turbines joins to pressure level LP3 between the heat exchangers HX1B and HX2A. The supply flow helium to the 40-to-80 K radiation shields is also taken from the HP line between the heat-exchangers HX1B and HX2A.

The turbine strings TU3/TU4 and TU5/TU6 receive gas flows which are taken from the HP line at lower temperatures. The string TU3/TU4 return flow also rejoins to pressure level LP3. The string TU5/TU6 return flow rejoins to pressure level LP2, this increases the pressure ratio and delivers a lower outlet temperature. The turbine TU7 is operating at the lowest temperature. Unlike the flows of the other turbine strings the discharge flow of Tu7is further cooled down by throttling. This flow is used, first for the 5-8 K radiation shield refrigeration and then for the 1.8 K refrigeration. The discharge pressure of Tu7 is 4.0 bar, the discharge temperature roughly 5.7 K at full load.

Vapour and liquid are separated in the vessel S250. The vapour returns through the LP2-line. The liquid is transferred to coldbox 2, where it becomes sub-cooled in the heat exchanger HX5 before it is supplied to the 1.8 K cryostat.The gas returning from the 1.8 K evaporation is first warmed up in heat exchanger HX5 to approximately 3.8 K before being supplied to a 4 stage cold turbo compressor system. The discharge flow LP1 of this system is still sub-atmospheric. It becomes further compressed to LP2 pressure level at warm end by the compressor C1.

To protect against surge conditions, the cold turbo compressors have to be supplied with a fixed mass flow. To achieve this gas is by-passed in a closed loop from the discharge of the cold compressors to the suction side by re-cooling in the heat exchangers HX3 and HX4 to 4.5 K.

SUMMARY

The results of the industrial study, lead us to conclude that the most optimal solution for NLS is a single large refrigerator, in terms of both capital and operational costs. The mitigation strategy to prevent long periods of enforced accelerator shut-down in the event of coldbox failure, is to hold sufficient moving part spares (valves & cold compressors), which hopefully should minimise fault durations to an acceptable level. The utility consumption estimate for full load running (3.4 kW) is 3.04 MW, operating with floating pressure control should reduce this to 2 – 2.5 MW at full operational load.

REFERENCES

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