

# CRYOGENIC CONSIDERATIONS ON SRF OPERATION AT 2K FOR A LIGHT SOURCE USING A STANDARD 4.5K CRYO-PLANT

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## Abstract

The feasibility of SRF operation at 2K using the remaining refrigeration capacity of an operating 4.5K cryogenic plant at NSRRC is examined. A refrigeration configuration with warm compression is proposed under an assumption that a reasonable amount of cryogenic heat load is required at 2K. The expectation of the efficacy of the cold and warm heat exchangers (HEX) is evaluated in terms of the corresponding equivalent cryogenic heat load on the 4.5K cold box. A factor approximately 9.5 or 6.0 is required to convert the cryogenic loss, 12 W at 2K, into our 4.5K cold box operated in a refrigeration mode without or with the cold heat exchanger (efficiency 85 %), respectively. An additional benefit is that the required volumetric pumping speed of the warm compressor can be greatly decreased. Moreover, a considerable cold capacity from the sub-atmospheric cold return helium gas can be ultimately converted by combining the cold HEX working together with a highly effective warm HEX, to a conversion factor 3.8 with an efficiency 95 %. Special attention must be devoted to minimize the risk of contamination or impurity for a turbine refrigerator.

## INTRODUCTION

Many recently upgraded or commissioned light sources such as BEP-II at IHEP, CLS, DLS, SOLEIL, SSRF and TLS at NSRRC use the SRF module to accelerate continuously the circulating electron beam to avoid coupled-bunch instabilities, because the SRF module is capable of heavy damping of higher-order mode impedances. To support the stationary operation of the SRF module, a standard 4.5K liquid helium (LHe) cryo-plant with a sufficient safety margin (commonly a safety factor 1.5) of refrigeration capability must be implemented. This condition opens the possibility for the specified light sources to operate an exotic SRF module such as a harmonic cavity or a crab cavity to fulfill specific requirements of machine operation using the already available cooling capacity from the existing cryo-plant. From considerations of the SRF performance, operating the SRF module at a lower temperature favors exponentially lowering the BCS surface resistance and increasing the achievable maximum reliable operating gradient, but condition involves the SRF module operating at sub-atmospheric pressure, i.e. at 16 mbar and 31 mbar for SRF operation at 1.8 and 2K, respectively. The existing 4.5K cryo-plant is typically not designed optimally for 2K SRF operation, and its overall cooling efficiency degrades greatly to support a SRF operation at sub-atmospheric pressure.

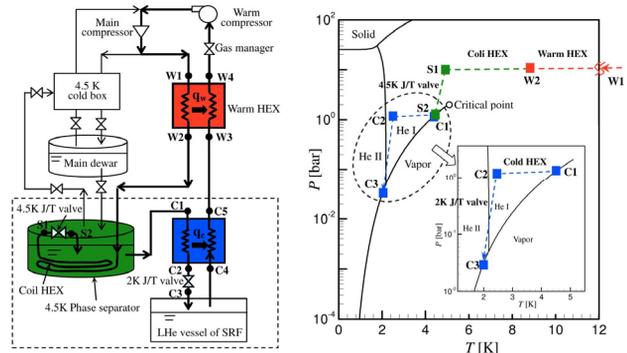


Figure 1: Cryogenic layout for 2K SRF system and corresponding operating points of HEXs on the phase diagram.

In this work, we report our operation in terms of its equivalent refrigeration load seen by the 4.5K cryo-plant. In addition, the connection between the efficiency of cold HEX on the volumetric pumping speed for SRF operation at sub-atmosphere is also discussed.

## 2K CRYOGENIC SCHEME

Several cryogenic schemes have been proposed and operated for supporting 2K SRF operating [1]. Multi-stage cold compressors are available for a large scale application at 2K but a warm compressor alone for operating the SRF module when a small amount of cryogenic heat load required, typically less than 100 W at 2K [2]. The later one fits to our need for the possible SRF operation at 2K using remaining cryo-cooling capacity at NSRRC.

A proposal for a 2K SRF operation using the standard 4.5K cryo-plant is given. The main components are shown in Fig. 1 (left). Note that the 2K cold return gas at sub-atmospheric pressure needs to continuously pump down by the warm compressor and regulate pressure by gas manager [3] but cannot be sent back to the 4.5K cold box. Its cold capacity cannot be recovered by the heat exchangers inside the 4.5K cold box but by the external cold and warm HEXs as much as possible which need to implement additionally dedicated for 2K SRF operation. By this way, the equivalent cryogenic load at the 4.5K cold box will be decreased considerably to achieve the aim of energy saving.

The small amount of pressurized helium gas at 14 bar ( $P_{W1}$ ) and 295 K ( $T_{W1}$ ) flows into the warm HEX and is cooled down to  $T_{W2}$  determined by the efficiency of warm HEX. It proceeds to be cooled down in a 4.5K phase separator to below a critical temperature ( $T_{S1}$ ) and expanded through a 4.5K J/T valve to produce the liquid-vapor coexistence helium at 4.5K ( $T_{S2}$ ) back into the

phase separator. A sufficient amount of 4.5K liquid helium (at  $T_{C1}$ ) continuously flows from the phase separator through the cold HEX and 2K J/T valve into the LHe vessel of the SRF module to maintain the stationary 2K SRF operation. The outlet temperature of supply LHe after the cold HEX,  $T_{C2}$ , is determined by the efficiency of cold HEX. The supply sub-cooled liquid helium at  $T_{C2}$  passing through the 2K J/T valve causes a significant pressure drop which is accompanied by a large temperature drop to produce the liquid-vapor coexistence helium at 2K ( $T_{C3}$ ) into the LHe vessel of the 2K SRF module. The corresponding phase diagram related to 2K operation is illustrated in Fig. 1 (right).

## MODELING

Our modeling is based on following assumptions: (1) The change of mass flow rate is independent on the gas pressure drop. A reasonable estimation on gas pressure drops,  $\Delta P_{W1-W2}$ ,  $\Delta P_{W2-S1}$ ,  $\Delta P_{W3-W4}$ , and  $\Delta P_{C4-C5}$  are set as 0.2 bar, 0.2 bar, 5 mbar, and 3 mbar, respectively. (2) The fluid properties of sub-cooled liquid helium at C2 are insensitive to the pressure drop of cold HEX's. Given  $\Delta P_{C1-C2}$  is 20 mbar. (3) The total cryogenic loss of the 2K SRF module is estimated to be 12 W (with a safety factor of 1.5) at 1.8K or 2K. (4) The cryogenic losses of cold and warm HEXs and 2K J/T are negligible. (5) The cryogenic losses in the piping lines and the 4.5K phase separator are not considered.

Neglecting kinetic and potential energy changes for each fluid and no work interaction, the heat transfer rate from the hot fluid to the cold fluid under stationary state can be expressed as

$$\dot{q} = \dot{m}_h (h_{h,inlet} - h_{h,outlet}) = \dot{m}_c (h_{c,outlet} - h_{c,inlet}) \quad (1)$$

where  $\dot{q}$  is the actual heat transfer rate,  $\dot{m}$  the mass flow rate, and  $h$  the enthalpy. The subscripts,  $h$  and  $c$ , designate the hot (supply) and cold (return) fluids. The thermal performance of a heat exchanger is measured by its efficiency written

$$\varepsilon = \dot{q} / \dot{q}_{\max} \quad (2)$$

where the maximum possible heat transfer rate  $\dot{q}_{\max}$  is defined as

$$\dot{q}_{\max} = \min \{ \dot{m}_h \Delta h_h^*, \dot{m}_c \Delta h_c^* \} \quad (3)$$

where  $\Delta h_h^*$  and  $\Delta h_c^*$  is the maximum possible fluid's enthalpy change at the hot (supply) and cold (return) fluids, respectively.

For the cold HEX,  $\dot{m}_h = \dot{m}_c$  and  $\dot{q}_{\max} = \dot{m}_h (h_{h,inlet}(T_{h,inlet}) - h_{h,outlet}(T_{c,inlet}))$ . Substituting Eqs. (1) and (3) into Eq. (2) obtains

$$h_{h,outlet} = h_{h,inlet} - \varepsilon_c (h_{h,inlet}(T_{h,inlet}) - h_{h,outlet}(T_{c,inlet})) \quad (4)$$

Given the efficiency  $\varepsilon_c$  of the cold HEX, the outlet of the hot and cold fluids,  $T_{h,outlet}$  and  $T_{c,outlet}$ , are obtained with

help of the commercial software HEPAC (Cryodata Inc.) for determining the cryogenic fluid properties. Applying law of energy conservation for an ideal 2K J/T valve shown in Fig. 1,

$$h_{h,outlet} = h_{2K} = x h_{g,2K} + (1 - x) h_{l,2K} \quad (5)$$

Herein  $h_{2K}$  is the enthalpy of the saturated fluid at 2K LHe vessel of the SRF module.  $x$  is the quality defined as the ratio of vapor mass flow rate  $\dot{m}_g$  to total mass flow rate,  $\dot{m}_t = \dot{m}_l + \dot{m}_g$ . The quality  $x$  is obtained by inserting Eq (4) into Eq (5).

Note that the required liquid mass flow rate  $\dot{m}_l$  into the 2K SRF module can be obtained from by dividing its cryogenic loss of 12W by the latent heat at 2K. Therefore, the total mass flow rate  $\dot{m}_t$  is determined by given the liquid mass flow rate  $\dot{m}_l$  and the quality  $x$ . Furthermore, the required pumping speed for the warm compressor is determined by the mass flow rate of the cold fluid return to the cold HEX  $\dot{m}_c$ , equal to the total mass flow rate,  $\dot{m}_t$  under the stationary operating condition.

For the warm HEX, its mass flow rate of hot fluid,  $\dot{m}_w$ , can be different from that of cold fluid,  $\dot{m}_c$ , in order to maximize the recovery of cold capacity from the cold fluid. Herein the subscript  $w$  designates the warm HEX. The  $\dot{m}_w$  is usually slightly smaller than the  $\dot{m}_c$ . Repeat the analysis procedure for the cold HEX to the warm HEX and under assumption of stationary operation, the required LHe mass flow rate from the cold box to the 4.5K phase separator is obtained. Recall that the 4.5K cryo-plant at NSRRC has either a refrigeration capacity of 460 W or a liquefaction capacity of 110 lit/h, the equivalent cryogenic loss of a 2K SRF module seen by a 4.5K cold box can be estimated by approximately a linear conversion from the liquefaction to refrigeration capacity of a given cold box.

## RESULTS AND DISCUSSION

As expected, considerable amount of cold capacity can be extracted from the cold return sub-atmospheric helium gas from the 2K LHe vessel of the SRF module via a cold HEX, as shown in Fig. 2 for the plots with solid curves of (a) the outlet temperature of sub-cooled liquid helium after the cold HEX or inlet temperature to the 2K J/T valve,  $T_{C2}$ , (b) quality of liquid-vapour coexistence helium fluid after the 2K J/T valve,  $x_{C3}$ , (c) total mass flow rate into the 2K LHe vessel,  $\dot{m}_t$ , and (d) equivalent cryogenic loss to 4.5K cold box,  $\dot{q}_{CB}$ , as function of efficiency of the cold HEX,  $\varepsilon_c$ , under a stationary operation with a total cryogenic loss of 12 W at 2K. The equivalent cryogenic loss is ranging from 113W (w/o cold HEX) to 68 W (with an idea cold HEX) in refrigeration mode of a 4.5 K cold box depending on the efficiency of the cold HEX. An up to about 45% of cold capacity, 113W-68W of 113W-12W, can be extracted from an idea cold HEX, strongly dependently on the efficiency of the

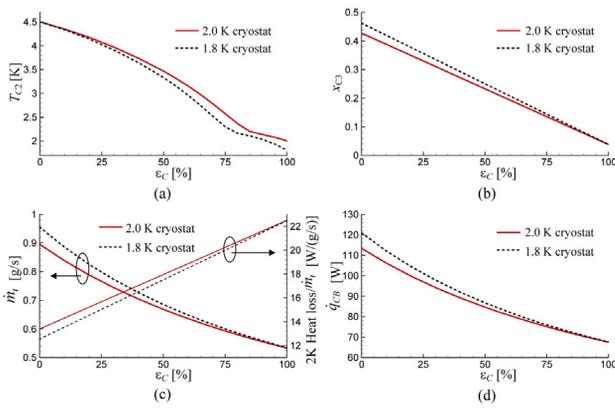


Figure 2: Effect of efficiency of cold HEX ( $\epsilon_c$ ) on outlet temperature at sub-cooled supply line of cold HEX ( $T_{C2}$ ), quality after 2K J/T valve ( $x$ ), total mass flow rate providing 12W heat loss at cryostat ( $\dot{m}_t$ ), and equivalent cryogenic loading at 4.5K cold box ( $\dot{q}_{CB}$ ).

cold HEX. Equivalently speaking, the ratio of heat loss at 2K to total mass flow rate is ranging from 13.4 to 22.5 W/(g/s) at 2K, in comparison with the corresponding latent heat of 23.4 W/(g/s). Whenever anonymous heat either into the cold return piping from the 2K LHe vessel to the cold HEX or the static heat loss of the cold HEX itself, the extraction of cold capacity from the cold return GHe may be heavily destroyed. Given are also the results at 1.8 K (in dash lines) in Fig. 2. No relevant deviation is found in performance of cold HEX within the operating temperature from 1.8K to 2.0K.

Fig. 3 shows the equivalent cryogenic loading at 4.5K cold box for a combination of cold and warm HEXs together in variation of efficiency. Calculated results indicate the efficiency of warm HEX,  $\epsilon_w$ , should be larger than 0.92 to effectively extract the cold capacity but not to create extra cryogenic loss in the 4.5K phase separator. The  $\epsilon_w$  in TTF cryogenic system at 1.8K is greater than 0.97 [4]. In our calculation, the need of  $\dot{q}_{CB}$  is about 44 W with  $\epsilon_w = 0.97$ , up to about 68% of cold capacity, 113W-44W of 113W-12W, can be extracted from a feasible warm HEX alone. Combination with high efficiency in cold and warm HEXs together, the decrease in cryogenic loading will be more relevant. Whether a LN2 pre-cooling to the warm HEX is effective or not depends on the production cost ratio of LN2 to LHe. For example, LN2 pre-cooling will not be necessary when the efficiency of the warm HEX  $\epsilon_w$  is greater than 0.95, 0.97, and 0.99 corresponding to a production cost ratio of LN2 to LHe of 1/2, 1/4, and 1/8, respectively. This explains why a high effective warm HEX may not need LN2 pre-cooling.

The required volumetric pumping speed (at 275K) on the warm compressor is roughly doubled for SRF operating temperatures at 1.8K in comparison with that at 2K, as shown in Fig. 4 under different budgets on pressure drop along the GHe return line from 2K LHe vessel of SRF module, cold and warm HEX, and gas manager of the warm compressor. Reference is the

pressure drop for the TTF's SRF operation at 1.8 K with a pressure drop up to 4 mbar at a mass flow rate of 10 g/s [5] (the pressure drop due to gas manager may not be included). A higher  $\epsilon_c$  implies a lower volumetric pumping speed required under a given pressure drop but the efficiency of warm HEX  $\epsilon_w$  is not related to the required pumping speed. Nevertheless, enhancing the efficiency of the HEXs usually results in an increase of the pressure drop unless by implementing an over-size design. Trade-off among the efficiency, size, and pressure drop (or the volumetric pumping speed) of the HEXs will be discussed elsewhere.

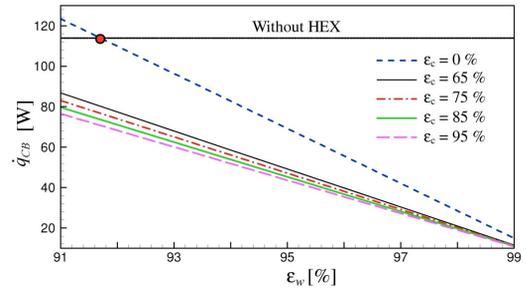


Figure 3: Equivalent cryogenic loading at 4.5 K cold box,  $\dot{q}_{CB}$ , for combination of cold and warm HEXs with efficiency of  $\epsilon_c$  and  $\epsilon_w$ , respectively.

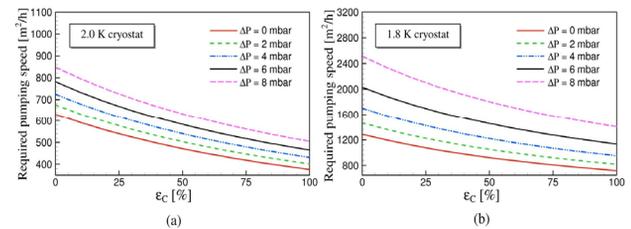


Figure 4: Effect of efficiency of cold HEX on pumping speed at different pressure drop in cold return line. The pressure drop is caused from cold HEX, warm HEX, and piping lines. (a) cryostat is 2.0K, and (b) cryostat is 1.8 K.

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