Application of sub-cooled superfluid helium for cavity cooling at linac-based free electron lasers, energy recovery and proton linacs

S Putselyk

Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR),
Fraunhoferstr. 20, 53343 Wachtberg, Germany

E-Mail: sergiy.putselyk@fhr.fraunhofer.de

Abstract. In order to build a compact linear accelerator, high acceleration gradients of superconducting radio frequency (SRF) cavities have to be achieved. In many large accelerators, e.g. XFEL, CEBAF or SNS, operational limitations are caused either by a limit on available overall cooling power of refrigerators or on cooling capabilities of sc cavities. So, for the further improving of sc cavity cooling, it is possible to increase either a quality factor ($Q_0$) or to improve a heat transfer at the cavity surfaces. Application of a sub-cooled superfluid helium gives several advantages, e.g. higher heat flux densities, longer time for onset of a film boiling regime and shorter recovery time, reduced Kapitza resistances, etc. In the present paper, application of sub-cooled superfluid (sf) helium for linac-based Free Electron Lasers, Energy Recovery and Proton Linacs is considered. In order to limit the present discussion, its application to CEBAF/SNS-style cryomodules is discussed in detail. For operation at higher RF power levels, further cooling improvements of a fundamental power coupler are needed and design modifications also presented.

1. Introduction
Linear accelerators with superconducting radio frequency (SRF) cavities find many applications as “user” machines, for example, proton linacs (SNS, ESS), heavy ion linacs (FRIB, ISAC-II, Spiral-2, ISOLDE upgrade, ATLAS), linac-based Free Electron Lasers or Energy Recovery Linacs (FLASH, XFEL, Jlab-FEL/ERL, DIAMOND, SOLEIL, Taiwan Light Source, Beijing Light Source) and also several will be built in the future, e.g. Lighthouse accelerator in the Netherlands, Pohang Accelerator Laboratory in Korea, and Shanghai High Repetition Rate XFEL in China. In comparison to the linear accelerator designed for high-energy physics experiments (e.g. TESLA/ILC), which are operated at a short pulse mode, the “user” accelerators typically operate in a continuous mode with moderate acceleration power per unit length (typically calculated per unit length of accelerator), high beam currents, etc. Albeit these different operational conditions of all accelerators, the acceleration gradient has been permanently increased in order to accelerate beams to higher energies, for example by SRF cavity operation at the quench limit, or by making accelerator upgrade and installing more powerful cavities, or by new R&D activities devoted to production of new SRF cavities with higher gradients and fundamental couplers. Another example, by doubling accelerating fields for cryomodules, the
overall linac length could be significantly reduced and, therefore, substantial costs reduction could be also achieved, which significantly facilitates starting of new projects. In many cases, limitations are either available cryogenic power, i.e. total heat loads, or heat flux densities in cavity surfaces, which limit maximal RF power before a quench occurs. So, to overcome cryogenic limitations of sc cavities, it is possible to use other cooling schemes, e.g. a sub-cooled superfluid (sf) helium instead of boiling helium at saturated conditions. Also note that for operation at high accelerating gradients, modifications of other components, mainly fundamental and High Order Mode (HOM) couplers, must be done. Therefore, for the sub-cooled helium cooling scheme, the cryomodule parameters will be changed and significant modifications on cryomodule design must be applied [1, 2].

In the previous paper, modification of TESLA-style cryomodule in order to apply a sub-cooled cryogenic scheme and, therefore, to operate larger cryogenic heat loads was presented [2]. Detailed discussion of main advantages of sub-cooling scheme, e.g. reduction of Kapitza resistance, increasing heat transfer coefficient due to: i) no dependence on the height of LHe level, ii) larger heat flux densities before the transition to the film boiling occurs, iii) more robustness against short heat load peaks, iv) longer periods for the onset of burn-out (film boiling), v) shorter periods for the recovery from film boiling, are presented there [2]. In the present paper, an application of cooling scheme with sub-cooled sf helium (He) is considered for the electron/proton accelerators (similar to the CEBAF/SNS/ESS ones). More details will be given on the design of cryostats and some components, e.g. fundamental power coupler. For the simplicity reason, only one cavity version, namely, the 1.3 GHz 8-cell cavity (similar to “TESLA/ILC” design) with double-lever tuner (also known as “Sacley I” or “TTF” one), is considered.

In the first part, a short review of cryogenic process scheme is done, followed by a discussion of the most important components related to the RF power operation. Next chapter will deal with a design of the most critical components of the cryomodule, i.e. vacuum vessel, supporting frame, radiation shield, cryogenic valves and piping.

2. Cryogenic process scheme

For the practical realisation, it is possible to follow two main concepts, i.e. one is to install all (or nearly all) valves in separate boxes, which is connected to a single multiline transfer line, e.g. ESS accelerator, or to have separate coaxial transfer lines (“cold” flow is inside, and “warm” is outside) and part of the valves are directly installed on the transfer lines, part at the end cans of cryomodule, and it is possible (at least potentially) to install some valves on the vacuum vessel of cryomodule, e.g. CEBAF and SNS accelerators [3, 4]. The first concept could be expected to have smaller installation space inside a tunnel, while the second one – more flexibility for the location of the cryogenic valves. It is quite difficult to make estimations on the overall investments, because single multiline transfer line with valve box could have similar or higher cost as several single transfer lines and cryomodule end cans. For the present design, the second concept is arbitrarily chosen, which is mainly related to the flexibility of cryogenic valve locations, i.e. at transfer line, cryomodule feed and end cans, or cryomodule vacuum vessel. So, for that case, modifications of well-developed concepts of cryogenic system at CEBAF and SNS accelerators will be relatively limited, which is particularly important for the development of new generation of cryomodules.

Due to the unknown heat loads and operational temperatures of the fundamental and HOM couplers (or these parameters could vary in wide ranges), there are different design possibilities to connect the return lines from cryomodules to transfer line, i.e. either to supply He flows to the existing cryogenic transfer lines or to new lines. We have chosen an installation of an additional transfer line for a flexibility of overall cryogenic system operation.

Before one starts the discussion of process scheme, it is worth to make some comments on the operation of fundamental coupler.

Operation of Fundamental Power Coupler at very high RF powers (for example at Cornell injector) showed that there are two places, where large heat loads are generated.
- One place is a connection of coupler to cavity. First source is a large beam power particularly due to parasitic modes. Solution is to keep this place cooled by LHe [2]. Second source is a copper gasket at CF flanges. In order to have efficient cooling, the “step” and “continuous” heat exchangers are foreseen. Third one is a misalignment of coupler axis and axis of CF flange and tube, which is welded to the cavity (or by the other words, over a bellow at helium temperature). Due to this misalignment, significant fraction of RF power is reflected, which leads to an overheating. It is quite difficult to make an effective cooling, and the best solution is to make “alignment” with some mechanical tools (which is quite similar to the sliding supports for cavities at CORNELL/FLASH/XFEL/LCLS-II/ILC accelerators). This is done for Cornell injector coupler and will be also used for the present design.

- Another place is connection of “warm” to “cold” parts of coupler, i.e. at the place, where ceramic window is located. This place is overheated and it quite difficult to make an effective cooling there. Solution will be to have the “continuous” and “step” heat exchangers cooled by a separated cooling loop with helium flow at temperatures 40-300 K.

So, making one cooling loop with helium flow at temperature of 4-300K for cooling of two places with different requirements on heat loads and temperatures will be not an optimal solution. For the cold part of the coupler, one needs to hold the temperatures in tight range, in order to avoid coupler and cavity quench. For that reason, helium mass flow must be high. But then this mass flow is too high for the second place. Coupler at SNS accelerator could be chosen as an example, where one has only one cooling loop with inlet temperature of 5 K and outlet one around 210K. So, helium with temperatures of around 210K must be warmed up to room temperature with electrical heaters.

Figure 1. Simplified process scheme of a proposed cryomodule cryogenic distribution system. For the simplicity the safety valves are shown only for the 2K cooling system.
In ideal case, 5-8K for the first loop should be sufficient. However, during an operation the couplers are often overheated and so operated over extended periods, for example at XFEL accelerator. So, it could be the case that some coupler will be cooled with helium at 5-30K instead of 5-8K temperatures.

It is worth also noting that this cooling method, i.e. with two separate cooling loops and electrical heater at room temperature, is identical to the one used for cooling of superconducting current leads for I>25 kA.

Figure 1 shows a process scheme of a cryogenic system. For simplicity the safety valves for only 2K system are presented.

In order to have more flexibility in high RF power operation in comparison to SNS and CEBAF accelerators, several cryogenic loops are added, i.e. i) active cooling of fundamental power coupler with helium flow at 5-8K, ii) active cooling of HOM coupler with helium at 40-80K temperature, iii) active cooling of thermal intercept between HOM and sc cavity at 5-8K temperature range in order to reduce heat load on the sc cavity. Below, a short discussion of each cooling loop is presented and for more details one can refer to a previous paper [2]:

- 2K system: this cooling method is very similar to one applied at the SNS and CEBAF accelerators. Main modification is an addition of valve (V1 see Figure 1) connecting volumes of 2-phase boiling helium and pressurized one as well as cool down valve V3. Valve V1 has double function, namely – safety (release of pressurized LHe in two-phase one in case of accident), and open/close for the cool-down and warm-up operation.

- Cool-down line with valve V3 has two functions, i.e. cool-down/warm-up and filling with LHe. In addition, it could be used for the “fast-cooling” of cavity in the temperature range 120-4K.

- Cooling of the thermal radiation shield with flow regulation by V12 valve. This line is similar to one used at CEBAF and SNS accelerators.

- Cooling of fundamental power coupler with helium at temperatures 40-300K. This loop is similar to one used at SNS accelerator with a small difference – helium inlet temperature is around 40K instead of 5K at SNS.

- Cooling of the fundamental power coupler with the helium at temperatures 5-8K (eventually 5-30K). In order to have a flexibility of fundamental power coupler cooling, this line is also added.

- Cooling of thermal intercepts between HOM and cavities by flow controlling with V4 valve.

- HOM cooling with helium at 40-80K and flow controlling with V5 valve. Cooling of HOM and thermal intercepts between HOM and cavities was also applied at Cornell injector and main cryomodules [5].

It is also worth to mention that in order to have an operational flexibility, an additional cryogenic return line with main flow at 10-30K temperatures and shield flow at temperatures 40-120K is foreseen. Due to different heat loads on HOM and fundamental couplers, which depend on operation mode of accelerator, it is possible to obtain two flows inside this return line with different parameters, like temperature, pressure, flow rates. These flows will not disturb the refrigeration operation, if multiple connections will be foreseen in refrigerator JT- and turbine return lines. It is also possible (at least principally) to avoid this additional transfer line by rejection of 5-8K flow stream from thermal intercepts between HOM and cavities to 2K subatmospheric flow, and 5-8K from fundamental flow as well as 40-80K flow from HOM to shield flow of the return line. However, this will lead to several limitations particular to refrigerator operation. For example, 5-8K flow from thermal intercepts in the 2K return line could significantly vary inlet conditions, i.e. temperature, flow, pressure at cold compressors inlets; expansion of 5-8K flow from fundamental coupler in the shield return line will probably limit the lower pressure of around 2 bar or below of refrigerator medium pressure line (also known as “turbine flow”). So, installation of the additional coaxial transfer line will not impose the above mentioned limitations and will also allow operation of HOM and fundamental power couplers at different power levels.

3. Main components
In this section, the most important modifications of the main components are mentioned. As a baseline design, the 1.3 GHz 9-cells cavity with a double-lever tuner is considered. The next important component – HOM – has a similar design to the one applied at the Cornell injector and main cryomodules [5, 6].

3.1 Cavity

Figure 2 shows the 9-cell cavity with tuner, HOM and fundamental power couplers. The diameter of 2-phase tube with boiling LHe is around 100 mm, which is surrounded by another tube of 170 mm with pressurized LHe. It is expected that increase of the heat transfer from cavity to pressurized LHe is achieved by a reduction of Kapitza resistance [2] and increased effective heat conduction of the sub-cooled sf helium at 1bar(a) and around 1.7K. The connecting pipes of the fundamental power couplers to the beam tube are also cooled with LHe.

3.2 Fundamental power coupler

For cryomodule operation with high RF powers, the Cornell group has developed a fundamental power coupler for operation with a very high RF load [7]. This coupler was considered for the baseline design and the following modifications were applied in order to further improve cryogenic cooling: i) application of two separate flows, i.e. one at 5K and other at 40K inlet temperatures, ii) it is possible to vary the He flow in each coupler for temperature range 40-300K, iii) in addition to "point" cooling at flanges and tubes, the “continuous” cooling in heat exchangers is realized (“continuous” cooling is similar to one applied at the SNS coupler).

Figure 3 shows a simplified view of the fundamental power coupler.
Figure 3. Simplified view of fundamental power coupler.

It is also expected that after cooling of the “warm part” of coupler, the helium flow will be at temperatures 210-250K (depending on RF power level operation), so final warm up to the room temperature will be needed. For that a copper heat exchanger, which is clamped to tube with He flow and heated with an electrical heater, is foreseen. In some rare cases, it is noted that vacuum flange is also cold and water from air is condensed on it. In order to avoid the water condensation, the second heater for a flange heating is foreseen. In some very rare cases, the condensed water is also frozen. A countermeasure against that will be a placing of a cover around these two heat exchangers with a vacuum insulation and making a flange for vacuum pumping, which will significantly reduce the heat transfer from ambient air.

3.3 HOM coupler (beamline HOM dampers)
HOM coupler (also known as “beamline HOM dampers”) will have a similar design to ones applied at Cornell injector and main cryomodules [8].

4. Vacuum vessel and cryomodule design
In the present design, four cavities per cryomodule are considered. It is an important question, whether the supporting frame (similar to SNS and CEBAF upgrade cryostats) for cavities is also needed. Such supporting frame significantly facilitates a cavity installation inside the vacuum vessel, if number of cavities is more than two (for two cavities, it is possible to insert them by hand and to fix them on vacuum vessel with tie rods). However, an application of such frames leads to larger positioning uncertainties for cavities and beam tubes in comparison to rigid support posts, as well as in many cases to impossibility to adjust the cavity and beam tube positioning in cold state (“in-situ”). Though several possibilities to avoid such frame could be foreseen, e.g. cavity fixation on the tube of fundamental power coupler, or to design temporary frame, which after cavity fixation is removed from cryostat; for the present design such frame is considered. Further disadvantage is related to the fact, due to manufacturing and particular assembling uncertainties of this frame, it will be more difficult to align the axis of fundamental power coupler and flanges at cavities in order to reduce the reflected RF power. In case if additional cryogenic valve must be installed on the vacuum vessel, e.g. LCLS-II cryomodule design, this frame could lead to limitation of available free space for the piping.

The location of the cryogenic valves is summarized as follows:
- V1: at Feed or End Cans or at cryomodule vacuum vessel whenever free space is available. For the present design, the Feed can could be the most suitable place.
- V2: Feed Can (similar to CEBAF/SNS cryomodule).
- V3: Feed Can.
- V4: 10-30K return transfer line, “inside” flow.
V5: 10-30K return transfer line, “outside” flow.
V6: 10-30K return transfer line, “outside” flow.
V7: Feed Can (similar to the SNS cryomodule).
V8-V11: any suitable location (probably at the cool down and power coupler return line).
V12: supply transfer line (similar to the CEBAF/SNS transfer line)
V13: return transfer line (similar to the CEBAF/SNS transfer line)
V14: End Can (similar to CEBAF/SNS cryomodule)
V15: and position (this valve is “warm” and could be easily placed at any suitable location).

For the present valve location, the number of components, i.e. valves, Johnston couplings and sub-cooling heat exchanger (also known as “2K heat exchanger”) is similar to the SNS End Can. So, space inside the End Can and somehow around cryomodule should be reserved for the installation of large valves and heat exchanger in order to cope with the 2K heat load up to 200W (50 W per cavity).

In the Feed Can, four valves have to be located. V12 (thermal radiation shield) has practically the same size as one at the SNS cryomodule, while other have to be increased in size in order to accommodate high flow rates.

The sub-cooling heat exchanger will be larger, because the operating temperature of sub-cooled LHe is expected to be around 1.7K, while for the boiling one – 1.6K, and, therefore, larger volumetric flow rates are expected.

Figure 4 shows the cross-sectional view of the cryomodule and figure 5 presents detailed view of Feed and End Cans. For the simplicity of presentation, “cold” and “warm” magnetic shields are not shown.

The outside diameter of the vacuum vessel is ca. 1.05 m (at the ends – around 1.2 m). The total length between vacuum flanges is around 7 m.
Figure 5. Feed (left) and End Cans (right) of cryomodule

As it could be noted from figures 4 and 5, it is possible to locate all components within the cryomodule.

6. Conclusion

In the present paper, the design modifications of the CEBAF/SNS-style cryomodule to make it capable to operating up to 200W @ 2K temperature level are presented and discussed.

Main modifications are related to an application of sub-cooled LHe for cavity cooling, as well as to re-design and application of two fundamental power couplers per single cavity.

An application of the helium sub-cooling scheme for other types of cryomodules, i.e. for heavy-ion accelerators, will be presented during future conferences.

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