Design of injectors and stay-alone cryostats with superconducting cavities for high RF powers applications

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Abstract: Injectors and stay-alone cryostats with superconducting (sc) cavities are sometimes applied at modern particle accelerators. Typically, very stringent requirements on beam quality are foreseen at injectors, and application of sc cavities is advantageous, particularly if operation at high current densities and high accelerating gradients is foreseen. Stay-alone cryostats with one or few sc cavities also find applications, e.g. at ELBE, DIAMOND, S-DALINAC accelerators, and accelerate particle beams in High Frequency fields. In the future, very high RF fields will be needed, and improvement of the cooling of cavity surfaces will improve cavity performance. 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 [2]. In the present paper, an application of sub-cooled superfluid helium for injector and stay alone cryostats is considered. Design of the cryogenic system is presented in some details and possibility of adapting of such injector for future applications is also discussed.

1. Introduction
In the last two decades, superconducting (sc) cavities find wide applications at accelerators, 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 accelerators will be planned for the future or are under constructions, e.g. Lighthouse accelerator, Netherlands, Pohang Accelerator Laboratory, Korea, Shanghai High Repetition Rate XFEL, China. The acceleration gradient has been permanently increased in order to accelerate beams to higher energies, which often leads to surface overheating and cavity quenches. Therefore, 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. Due to increased RF power at cavities, mainly fundamental and High Order Mode (HOM) couplers must be also modified [1-3].

In the previous papers, modifications of TESLA-style as well as CEBAF/SNS cryomodules in order to apply a sub-cooled cooling scheme and, therefore, to operate cavities at larger cryogenic heat loads was presented [2, 3]. 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 till 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, is presented in [2].

In the present paper, an application of cooling scheme with sub-cooled sf helium (He) is considered for the injector or stay-alone cryomodules. Such cryomodules find applications, particular if stringent requirements on beam quality, high current levels as well as large accelerating gradients, are foreseen.

In the first part, a short review of cryogenic process schemes is done, followed by a discussion of the several typical designs of injector cryomodules. Next chapter will deal with stay-alone ones.

Due to free space limitation of the present paper, an application of the helium sub-cooling scheme for heavy-ion accelerators are not discussed but will be presented in a separate paper.

Figure 1. Simplified Pipe & Instrumentation Diagram (PID) of injector or stay-alone cryostat. In some cases, the HOM is located within vessel with cavity and no separate cooling loops are needed.

2. Cryogenic process scheme
Before one starts discussion of an application of the sub-cooled superfluid He for injectors, it is worth to consider alternative cooling schemes. Besides the boiling superfluid He scheme, which is extensively investigated for bath cooling, it is also possible to consider the supercritical helium forced flow at high pressures. Main advantages are avoidance of phase transition, i.e. it stays in single phase, and higher temperatures, particular if high-Tc superconductors are going to be applied. Main disadvantages are high pressures, which could lead to deformation or detuning of sc cavities, required large flow rates in order to keep helium warming temperatures to minimum, non-homogeneous cooling particular in “dead-volumes”, and high mass flow densities in the range of 30-50 g/s·cm² at 2-3 bar(a) pressure [4]. The heat flux densities are expected to be in the range 0.2-1 W/cm² for
temperature differences around 1K, which is still below ones typically occurred with sub-cooled superfluid He. Though this cooling scheme is not competitive with superfluid He, particular for applications with low-Tc superconductors; nevertheless, due to extensive experience on applications at superconducting magnets for fusion facilities, it is possible to use it for high-Tc cavities in the future.

In the present paper, it is foreseen that the cryomodule is designed for maximal cryogenic operational power. The actual cryogenic heat load will depend on whether accelerator is operated in short Pulse Mode (PM) or Continuous Mode (CM) one, i.e. on cryogenic heat transfers (either steady-state or transient modes must be considered). Additionally, the heat load will depend on accelerating beams, e.g. electron, proton, heavy ions, accelerating gradients as well as energy adsorption in High Order Modes (HOM) couplers. So, many types of injectors or stay-alone cryomodules are applied, and it is quite difficult to make some general assumptions on the best cryomodule designs. For that reason, several types of typically applied cryomodules are further considered.

The process scheme of subcooled superfluid He is similar in all cases, see figure 1: subcooled superfluid helium is closed in volume within the cavities or other components, like HOMs, and is also sub-cooled by heat exchanger with boiling superfluid helium. The heat exchanger is typically realized as horizontal tube in order to increase the contact surface area and to facilitate the phase separation of boiling superfluid helium. There are several other important components, like supply and return valves, 2-4K heat exchangers, though due to free space limitations at or around injectors or stay-alone cryomodules, these components are placed in separate valve boxes, and will not be discussed here. For that reason, only general designs of injector or stay-alone cryomodules are considered in the following chapters.

It is worth particularly to underline that the improvement of cavity operation is not possible without advantages in the operation of fundamental and HOM couplers. For high power operation, these components need to be actively cooled [2-10] as well as thermal intercept between cavities and these components has to be often applied. This significantly complicates the overall cryogenic process scheme; see reference [3] for more details.

3. General designs

In this section, several examples of injectors (also sometimes called “guns”) or stay-alone cryomodules are mentioned.

3.1 Injectors

Figure 2 shows several injector cryomodules with sub-cooled He cooling. Typically the tube with boiling superfluid He is located at the top, either within the LHe vessel with subcooled LHe and cavity, or above this vessel. In the second case, the separate tube with subcooled LHe must be installed around one with boiling LHe, see figure 3, and figure 4. These geometrical positioning of pipe with boiling LHe are very similar to the ones applied at LHC, CERN, namely for regular dipole and quadrupole magnets, as well as ones at “end groups”. For the simplicity of presentation, very short and straight connecting tubes are shown in figures.

Figure 2, left, presents CESR II module, originally developed at Cornell University and more than 10 cryomodules have been built by Research Instrument in Bergisch Gladbach, Germany. Figure 2, right, shows the high-power cryomodule, which is developed at Jefferson Laboratory. Figure 3 presents the cryomodule with 9-cell cavity, which is very similar to the TESLA-style one.

The injector cryomodules have three main styles, see figures 2 and 3:

− Single-cell cavity with fundamental power coupler of rectangular shape. In this case, it is possible to extract parasitic high order modes (HOM) and high power RF signal is applied. Due to available free space it is possible to integrate the tube with boiling superfluid He at the top, and it could be possible that some other components like valves could be integrated as well.

− Multi-cell (up to five) cavity, with fundamental and HOM couplers connected to the cavity through rectangular waveguides. In this case, high RF power and excellent cooling of components is achieved.
Multi-cell (typically 6 to 9) cavity, and fundamental as well as HOM couplers are not in direct contact with superfluid He. In this case, a relative high overall acceleration gradient is achieved. Typically, very compact design due to limitation of available space is foreseen. The fundamental coupler could be located beneath the cavity or horizontally at sides, see figure 4.

Typically, the cryomodules have many components and sensors and it is a challenging task to find additional free space for further components. In many cases, only at the top, some free space is available, and it is possible to integrate a tube with boiling helium. Depending on the heat load, such subcooler could be a tube or a small vessel. The supply and return lines are usually connected at the top to the transfer lines and boxes, though it is also possible to apply other scheme and to located the boxes with sub-cooling heat exchanger at the beginning and end of cryomodule, similar to CEBAF/SNS ones. Depending on the tuner design, the bellows must be located either at the middle or at the end of LHe vessel.

Figure 2. Several very simplified examples of injectors: left – CESR II, Cornell University; right – high power module, JLab.

Figure 3. Very simplified example of stay-alone cryostats based on “TESLA-style” design. This design is similar to Standford Cavity/Cryomodule as well as HZDI/RI Version for the ALICE and ELBE accelerators.
3.2 Stay-alone cryomodules

Stay-alone cryomodules are typically applied at the storage rings or “small” linacs, see for example ELBE, Jlab-FEL/ERL, S-DALINAC accelerators. Typically, one or two cryomodules with few cavities are foreseen and also could be used as injectors. Figure 4 shows an example of 9-cell TESLA-style cavity with two fundamental couplers (similar to TTF/Sacley 1 ones) and one HOM coupler [3]. In this case, number of cooling loops for HOM and fundamental couplers is maximized, see figure 1, for example of process flow diagram. The pipe with boiling He is located above the cavity in the separate tube. It is possible to install two (similar to ones applied at ELBE accelerator) or up to 8 cavities per cryomodule. In order to apply maximal RF power to fundamental couplers and to the particle beam, good cooling of HOM and fundamental couplers has to be foreseen. For that four separate cooling loops at two temperature levels for HOM and fundamental couples are considered, see figure 1. Other similar design but with other couplers is shown in figure 3. In this case, only one fundamental coupler and two HOM ones located radial and axial to cavities are installed and depending on RF operation power, the fundamental coupler could have one or two cooling loops.

![Figure 4. Cavity with LHe vessel, double-lever tuner, HOM and fundamental power coupler [3].](image)

3.3 Other applications

It is possible to apply sub-cooled scheme also for other cryostats, for example one with sc undulator. Due to compactness, it is possible to integrate undulator magnets within the vessel with subcooled liquid He.

4. Discussion

Due to application of sub-cooled superfluid helium scheme, it is possible to operate injector or stay-alone cryomodules at high accelerating gradients and cryogenic powers, e.g. up to 200 W for 9-cells TESLA-style cavity [2]. In comparison to multi-cell cavities, for single cell cavities, even larger gradients are achievable due to higher quality factors (Q0).

Though the process scheme for the sub-cooled superfluid He is relative simple, the overall cryogenic system could significantly be complicated, if several additional cooling loops for the fundamental and HOM couplers are foreseen. Due to very versatile requirements on injectors or stay-alone cryomodules, it is quite difficult to find a universal cryogenic process scheme and each case must be thoroughly considered. As an example of elaborate cryogenic system, the cooling of 9-cell
cavities with several fundamental and HOM couples inside the CEBAF/SNS style cryomodule could be considered [3].

It is also important to pay attention to cavity acceleration gradients and corresponding cryogenic heat load. The present formulas for the heat transfer are derived for very simplified geometries, e.g. one dimensional with constant cross-sectional area, cylindrical. In case of constant cross-sectional area along pipe or tube, it is possible to extend one-dimensional geometry to two dimensional one. For more complex geometries, like cavities, the basic physical equations describing heat transfer in sf helium must be derived. Though in the last decade, several attempts were devoted to the development of computer programs or simulation codes describing sf fluid, no experiments have described the theoretical results. The geometries of single cell as well as 9-cell TESLA cavities are surely more complicated than simple linear geometry, and only experiments could give reasonable estimation of heat loads.

The technological production of elliptical cavities reached a maturity. In many cases, cavity operation is limited by the cooling of manufacturing irregularities on cavity surfaces, which emit parasitic high frequency modes inside cavities. For that reason, the efficient cooling of such “emitters” is essential for the improvement of cavity performance, and, therefore, it is possible to say that application of sub-cooled sf helium will give immediate advantages, but it is difficult to estimate some values. Even for well-developed elliptical cavities, these estimations could be in the range 2 to 5 and also depends on several other operational parameters, like CW, quasi-CW or pulsed operation modes, see reference [2] for more discussion on Tesla-style cavities.

5. Conclusion
In the present paper, the design modifications of cryogenic systems of injector or stay-alone cryomodules are considered. Due to application of sub-cooled superfluid helium it is possible to significantly increase cryogenic cooling capacities of cavities, e.g. up to 200 W at 2K for TESLA-style cavities.

It could be possible that due to development of cavities made from high-Tc superconducting materials, the very low temperature levels will not be required and forced-cooling schemes could be also applied.

Some cryomodule modifications, which are related to an application of sub-cooled LHe for cavity cooling, as well as to re-design and application of HOM and fundamental power couplers are proposed and discussed.

6. References
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