Cryomodule development for high RF power operation

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Compactness of linear accelerator is significant factor in achieving short construction times, low infrastructure and operation costs, and is considered as one of a key parameters for next accelerator generation particularly for high-energy physics. Operation of XFEL and design of LCLS-II accelerators as well as tests of Cornell injector and main cryomodule show the possible limitations on present technologies related to the RF power operation inside the modules. The next development steps could be either further increase of $Q_0$ factor of the cavities or other cooling schemes. In the present paper, modification of the helium bath cooling scheme is proposed. This will allow increasing the RF power by factor two or more. Its application for TESLA-style cryomodule is considered.

1. Introduction

Future large linear accelerators with superconducting (sc) cavities will need cryomodules capable to accelerate beams to higher energies. E.g. by doubling accelerating fields for cryomodules, the overall linac length could be substantially reduced. So costs reduction could be also achieved, which significantly facilitates starting of large projects like International Linear Collider (ILC). In many cases, one of limitations is available cryogenic power, i.e. either total heat loads, which limits the power capacity of refrigerators or heat flux densities in cavity surfaces, which limit maximal RF power till a quench occurs. To overcome cryogenic limitations, it is possible either to increase of cavity quality factors $Q_0$ or by using other cooling schemes, e.g. with sub-cooled superfluid helium. In the last case, cryomodule parameters will be changed and significant modifications on cryomodules must be applied.

In the present paper, modification of TESLA-style cryomodule in order to apply larger cryogenic heat loads is considered. Improvement of heat transfer is mainly related to reducing the Kapitza resistance at the surface of sc cavities as well as to applying subcooled superfluid (SF) helium. As a reference for the present discussion, the LCLS-II cryomodule with heat loads in the range of 80-160 W at 2 K is taken.

It is worth to note that TESLA-style cryomodules have been adapted for two application fields, i.e. high energy physics, which requires high energy accelerator working in pulsed mode (PM) operation, and ”user” (XFEL, ERL, etc.) accelerators, which typically need continuous wave (CW) operation. In the present design, the cryomodule is designed for maximal cryogenic operational power, though the actual cryogenic heat load will depend on whether accelerator is operated in short PM or CM one, i.e. on cryogenic heat transfers in these modes (either steady-state or transient modes must be considered).
In the first part, a short review of requirements on cryomodule is summarized, followed by discussion of cryogenic heat transfer. Next chapter will deal with design of most critical components, i.e. cavity and fundamental couplers. Overall cryomodule design is presented in chapter 5.

Due to free space limitation, similar improvements to other types of cryomodules, e.g. for heavy-ion accelerator or electron/proton ones (similar to CEBAF/SNS/ESS ones), are not discussed but will be presented during future conferences.

2. Requirements
Main requirement on next generation of TESLA-style cryomodule could be summarized as following:

- Cryogenic heat load is in the range of 160-400 W. Due to last developments on high $Q_0$ cavities, it is assumed that $Q_0$ value will be in the range 2.7·10^10.
- Fundamental power coupler power is in the range of 100-200 kW for CW.
- Similar cryomodule design for long (extra-long) pulse or CW operation modes. If it is possible an operation at very short pulses, i.e. at low duty factor, should be also possible. Assuming constant $Q_0$ value and quadratic scaling of acceleration field ($E_{acc}$) with cryogenic heat load, doubling of cryogenic heat load capacity, will increase acceleration field of around 41%.

CW operation test of TESLA-style cavity with the chimney cross-sectional area 23 cm$^2$ showed limitation on heat load of ca. 35W, which could be increased up to 96 W, if chimney is increased to 63 cm$^2$ ($d_0=90$ mm) [1]. This value is still high in comparison for the accelerator module under construction, e.g. LCLS-II with dynamic heat load of 80 W (or possible up to 150 W) for 8 cavities. Though it is worth to note one important detail, i.e. 96 W were measured by combined operation of RF and heater powers. It could be the case, that during operation with full RF power, i.e. without heater; because of local overheating of cavity, quench could occur earlier. For that reason, it could be helpful to have test of TESLA cavities with full RF power in the range of 96 W. In many practical cases, cavity operation is typically limited to three cases, i) limitation on available RF power from klystron or solid state amplifiers, ii) limitation on X-Ray emission, which could disturb the beam, and iii) cavity quench. Nowadays first two reasons are relative seldom, and cavity quench (or degradation of $Q_0$, which leads to high values of heat load) is main reason. So, further advances are mainly related to the improvement of cavity surface cooling, which could allow operation at higher cryogenic heat loads. Presently, maximal cavity heat load of 24 W at $E_{acc}=18$ MV/m for CW was measured [1] and this value will be taken as reference for the further discussion. Our goal is to increase the value of heat load by factor 2 till 4, which will roughly correspond increase of $E_{acc}$ by factor $2^{0.5}=1.41$ (or 2) for a fixed value of $Q_0$.

3. Heat transfer
Main improvement of heat transfer will be done by reduction of Kapitza resistance between cavity and superfluid Helium (He), as well as by applying subcooled SF He (similar cooling method is applied at LHC for main dipoles and quadrupoles).

3.1 Kapitza resistance
Though Kapitza resistance is often a limiting factor for effective heat transfer, e.g. also for sc cavities [3-5, 7, 8], thorough investigation for the $\Delta T_{Kapitza}$ is still missing. Several effects could contribute to its reduction, e.g.:

- Polishing and heat treatment of Nb surface. It is noted that this effect can increase by factor 2 the thermal conductance. In most of the cases of cavity treatments, this effect is already used.
- Application of thin (0.1 μm till 1 mm) layers of different material. At the present, copper is mostly investigated or in some cases titanium [2, 6]. It is noted that bringing of thick layer of Cu or Ti brings insignificant advantages due to additional interface or oxide layer. It could be possible that application of thin layer, e.g. around 0.1 μm, in combination with polished/rough surface could give reduction of Kapitza resistance.
- Application of impurities inside the surface layers, e.g. titanium [2, 4]. It is noted that the
resistance reduction could be by factor 2, e.g. reaching value of $0.157 \cdot T^3$ (W/cm$^2$K). Investigation with other materials could be very helpful.

- Application of thin sinters, e.g. from silver. Silver sinters could be connected to the bulk surface and due to large surface area; effective temperature difference could be decreased.
- In some measurements it is noted that resistance of super- and normal conducting materials could be different by factor 2 to 3 [9]. This is related to the fact that for the heat transfer, only phonon contribution is considered. In normal conducting state, also electrons could participate in heat transfer. So it would be also helpful to have this effect investigated.
- It was noted that for some materials, the Kapitza resistance could be decreased, if subcooled helium is used. It seems that for pure Nb, this effect is negligible, but for other materials, it would be helpful to have this information.

At the time being, it is quite difficult to estimate possible improvement factor related to the reduction of Kapitza resistance, though it is very conservatively assumed that factor 2 will be reached.

3.2 Subcooled superfluid helium

Subcooled SF helium is intensively applied for the cooling of sc magnets, e.g. at LHC accelerator (cryomodules with main dipole and quadrupole magnets) or in Roubeau-Claudet cryostats. Though present idea to use subcooled SF helium is not new, present technological development of cryomodule reached mature and further development steps are a challenge, but surely they are feasible. Main advantages of pressurized SF helium in comparison to the saturated one are: i) no dependence on the height of LHe level (in the present TESLA-style design LHe height is around 60 mm), ii) larger heat flux densities till transition to the film boiling occurs, iii) more robustness against short heat load peaks [10], iv) longer periods are needed for the onset of burn-out (film boiling), v) shorter periods for the recovery from film boiling.

Before one starts discussion of the advantages of pressurized LHe, it is worth to note that many formulas for the heat transfer for SF He were derived for simple geometry, e.g. one-dimensional, two-dimensional with constant cross-sectional area, cylindrical. The geometry of 9-cell TESLA cavity is surely more complicated and other correlation formulas or calculations from the first principles must be applied. So for the further discussion, we consider “ideal cases” of heat transfer.

Steady-state critical heat flux

In saturated LHe, the heat transfer depends strongly on the level of LHe above the heating elements (for TESLA cavities it is around 60 mm). In addition, heat transfer depends on materials and surface areas, e.g. heat flux is larger for small wires in comparison to the plates. For that reason, it is better to compare experimental data of heat transfer for saturated and subcooled SF He for "plates" and assuming 10 cm LHe height above the surface of LHe. Unfortunately it is difficult to find data with all possible operational parameters in opened literature sources, and comparison on other geometries is also mentioned below.

Measurements on heating wires showed that increase of heat flux could be in the range 2 till 5. For the pressurized LHe, heat flux increased by factor about 3 for temperature decrease from 2.1 to 1.85 K [12]. The time averaged integrated values of excess critical heat fluxes are also 30 to 70% higher for the case of pressurized LHe.

Similar effect of increase of heat flux up to 50% for temperature range below 1.8 K in comparison to the saturated LHe was noted for long one-dimensional channels [10]. Temperature reduction from 2.1 to 1.8 also increased the heat fluxes by factor 3-4 for one-dimensional channels with opened or closed ends [10, 13].

Recovery from burnout

Pressurized LHe also allows short time for the recoveries after excess heating power is applied [11]. It was also noted that recovery after excess heating is also possible for the case if post heating is present (in this case post heating must be below steady-state value). We note, that post heating is quite similar
to the operation of sc cavities at the limit of quench, i.e. also called as "soft quench" operation, where quench detection system slightly reduces power supplied to sc cavities just to avoid cavity quenching. This is related to the fact that pressurized LHe has large enthalpy between operating temperature and T_c. Also direct comparison of pressurized and saturated LHe at 1.8 K showed that recovery time could be up to 3.5 times better for pressurized LHe, which is most probably related to efficient heat transfer of LHe a 1.3 bar(a) [10].

**Time delay (Lifetime) for onset of film boiling**

Time delay depends on several parameters, e.g. heating material, maximum admissible energy and post heating heat current density, temperature [11]. Lifetime (time to onset of film boiling) could be significantly increased for pressurized LHe, e.g. 40 % or more [12].

Investigations performed on heated plates with scalable heating surface and placed inside LHe volume could be most relevant measurements in order to simulate real behaviour of sc cavities [14-19]. TESLA-style 9 cells cavity could be roughly approximated as several volumes connected in series and finally connected over duct to 2-phase tube. Real operation of sc cavities also implies that not whole surface is heated by the same RF power, but there are several points/small surfaces, where heating is maximal and cavity could quench. Measurements showed that up to 7 W/cm² heating power at steady-state (or "quasy" steady state) could be transferred to pressurised LHe at 1.8 K.

Though it is quite difficult to estimate the increase of cooling power due to application of pressurized LHe, we conservatively assume that factor 2 could be gained in comparison to present applications. It could be possible that this factor could be a bit lower for the operation at CW mode, and could be larger (maybe significantly) for the operation in pulsed mode. Further investigations will be very helpful.

So, for the design of cryomodule, it is assumed that the cryogenic cooling power is increased by factor 4, i.e. factor 2 due to improvement of Kapitza resistance and factor 2 due to application of pressurized LHe.

It is also worth to stress that in-situ measurements dedicated to distinguishing the quenches inside cavity itself and ones of Ti-tube connected to end groups, e.g. fundamental or HOM couplers, are often a challenge. In the following design, the direct contact of Ti-tube of fundamental coupler with pressurized LHe is foreseen. In case if HOM coupler has no direct contact to LHe or is not cooled with supercritical helium, it will be avoided.

4. **Design of cavities and fundamental couplers**

*Cavity*: in the present design with 100 mm tube connecting to 2-phase line, TESLA-style cavities are capable to sustain up to 100 W heating power [1]. Nevertheless, in order to further improve performance, it could be necessary to improve performance of end groups, i.e. mechanical and thermal connections of fundamental power and HOM couplers.

In order to have flexibility in power operation, two symmetrical DN63 flanges at cavities are foreseen for connections to two fundamental couplers. RF operation with two couplers and with increased connection flange (62 mm instead of 40 mm) will lead to flexibility in RF power variation as well as to easiness of Q_{ext} adjustment for pulsed or CW operation. Design of two fundamental couplers with 62 mm flanges is very similar to ones applied at Cornell injector [22]. One important detail – in order to have sufficient cooling at the connection place of CF63 flange to cavity DN80 tube, the direct contact with LHe must be present, which could be achieved by shifting of welded flange (or making an additional one) of LHe vessel toward connecting flange between cavities, see Figure 1. Design with several penetrations tubes through LHe volume is a challenge but it is within present technological development, see e.g. design of spoke, quarter- and half-wave cavities for FRIB accelerator.

Present operation of HOM coupler shows operational limitations [23], and for RF power increase at least by one order of magnitude, a new design is needed. Good solution will be to adapt design developed for Cornell injector and main linac cryomodules [22]. HOM (also called “beamline HOM
dampers”) is placed between cavities and is actively cooled, e.g. by 5 K and 40 K GHe flows. Installation of HOM coupler will make modifications on the RF coupling between cavities and could lead to somehow increase of cryomodule length by approximately 2 meters. Though these two modifications are considered to be of minor importance in comparison to the possibility to have more powerful HOM coupler with flexible operation range due to active cooling with GHe flow. In case if Cornell HOM coupler design has to be used, it could be possible to make small grooves (channels) for GHe flow cooling in cylindrical body as well as in CF flange.

Figure 1: cross-sectional view of coupler flange connections to cavity
Figure 2: Coupler modifications (as based design, coupler from Cornell injector cryomodule is taken)
Figure 3: Simplified cross-sectional view of cryomodule

2-phase tube: Design of 2-phase tube is one of the challenges. At the present, the most experience was gained at LHC accelerator at the dipoles and quadrupoles magnets at interaction regions (also called “end groups”) [20, 21]. For the corrugated copper tube diameter of around 100 mm diameter (corrugations increase effective surface by factor 2 to 3) and outer tube diameter for pressurized LHe of around 170 mm, the maximal heat transfer was measured of 10 W/m. In our case, this value has to be increased by factor 5 (400 W for cryomodule or 50 W per cavity). Assuming LHC parameters for the “dirty” copper surface and neglecting temperature difference over copper tube, and increase of surface area by factor 3 due to corrugations (or fins), the temperature difference due to Kapitza resistance is $\Delta T_{\text{Kapitza}} = q \left( \frac{1}{h_{Kap1}} + \frac{1}{h_{Kap2}} \right) = 40 \text{ mK}$ [20], where $h_{Kap1}$ and $h_{Kap2}$ are Kapitza conductance on both sides of heat exchanger at 1.8K and taken to be identical, $q$ is heat flux density assuming 50 W heat load per cavity, i.e. $q=50\text{W}(\pi \cdot 0.1\text{m} \cdot 1\text{m} \cdot 3) = 53 \text{ W/m}^2$, where 0.1 m is pipe diameter, 1 m is cavity length and 3 is surface increase due to corrugation or fins. The value of Kapitza resistance will be somehow increased if one assumes that only part of the surface is effectively participating in the heat transfer. 40 mK temperature difference due to Kapitza resistance is acceptable for most of engineering case, though it is possible to reduce if one assumes clean surfaces or surface coatings.

It is also important to estimate minimal cross-sectional areas of 2-phase tube in order to limit GHe flow velocity to 5 m/s. For the LHe supply in the middle of the cryomodule, where quadrupole is located (similar to ILC design) and assuming that flash gas will be immediately supplied to 300mm tube and GHe is also released to 300mm tube also at the ends (similar to LCLS-II design), the effective length of 2-phase tube for GHe flow is reduced to 2 cavities, i.e. around 2 m. In this case, the minimal cross-sectional area is $A_{\text{min}} = \frac{Q \cdot L}{(\Delta h_{1.6K} \rho_{v1.6K} V_{\text{max}})} = 50\text{W} \cdot 2\text{m} / (22.5 \cdot 10^3 \text{ J/kg} \cdot 0.230 \text{ kg/m}^3 \cdot 5\text{m/s}) = 3.87 \cdot 10^{-3} \text{ m}^2$ or 70 mm assuming circular cross-section. In the present design, 100 mm tube with free cross-sectional area of $7.85 \cdot 10^{-3} \text{ m}^2$ is assumed, so it would be sufficient to fill it up to 50% LHe level. It is also important to note that it is possible to operate module at higher power by making connection of 2-phase tube to the 300mm one at the ends of each cavity. Assuming only half of 100mm tube is filled with LHe, the effective length for gaseous helium flow is reduced to half cavity, i.e. around 0.5m, and so maximal cryogenic power per cavity is around 200 W (or 1.6 kW per cryomodule with 8 cavities). Therefore there is a significant potential for the further developments.
**Fundamental coupler**: in order to have flexibility in RF power operation, two couplers are considered. At the present time, the most powerful coupler was developed for Cornell injector cryomodule, capable of transferring of 60-100 kW for CW operation mode, which could be taken as baseline for a new development. New R&D activities could be summarized as follows:

- **Materials**: it is worth to try some other materials, e.g. W-Cu alloy. By variation of W-content, it is possible to increase the mechanical properties and Cu-content ensures high thermal conduction.
- **Active cooling with N\textsubscript{2} or Air gas of inner rod used for \( Q_{\text{ext}} \) adjusting**: (though water cooling could be more efficient).
- **Active cooling of warm window with N\textsubscript{2} or Air gas**.
- **Active cooling with cold GHe flow at 5-30 K and 40-300 K.** It is proposed to have temperature variation of GHe flow in wide ranges. For effective cooling, it is important to have thermal contact as “local”, i.e. with pipes brazed to flanges or tubes (similar to Cornell Injector coupler) but also “continuous” with small groves in tube (similar to SNS coupler). With the continuous cooling it is possible to extract more heating power. Depending on extracted power, 5K GHe from supply line is warmed up to 20-40K, and if it is possible, it could be further used for cooling of HOM coupler. The 40 K GHe is used for cooling of “warm” part of coupler and after that is resupplied to warm gas recovery line (heater and small valve must be installed at coupler at room temperature in order to warm up GHe to 300K and to have possibility to vary the GHe flow in each coupler). So in this case, one cold valve will vary flow to “cold” part of fundamental coupler, while other cold valve will vary total flow to “warm” part and individual adjustment of GHe flow in “warm” coupler parts is possible with small warm valves.

So, taking the Cornell injector coupler as basic design, see Figure 2, it would be possible to modify it even to operation at higher RF power levels.

**Tuner**: end lever tuner or blade tuners could be applied. It should be noted that tuner has to support larger forces due to pressure difference of 1 bar, so blade tuner could be a better choice. It is worth to note that it would be possible to reduce pressure of pressurized LHe to 0.5 bar or below in order to adapt present tuner design.

5. **Cryomodule design**

As the reference design, the LCLS-II cryomodule, which is developed for high RF and cryogenic power operation, is chosen. Main modifications could be summarized as following:

- **Application of pressurized superfluid LHe with operation temperature of around 1.7 K and temperature of 2-phase LHe of around 1.6 K.** The volume with pressurized LHe and 300 mm tube must be connected through valve, which has two functions, i.e. opened/closed for operation during the cool-down and filling of cavities with LHe; and safety function, for the case if large heat load on cavities occurs and G-/LHe mixture must be released into 300mm tube. This double function is similar to one at valve applied at LHC for cryostats with main dipoles and quadrupoles (also named as “QV9XX”). DN65 valve will be sufficient in order to coupe with G/LHe flow during accidents as well as for large flow during cooling down and LHe filling of cavities.
- **The diameter of 2-phase tube is chosen as 100 mm, and one for pressurized LHe – 170 mm.** These dimensions are also very similar to ones applied at cryomodules at LHC end groups. The two-phase tube has no surrounding 170 mm one in the middle of the cryomodule and at the ends.
- **The conduction-cooled quadrupole and beam position monitors are placed in the middle of cryomodule.** Main reason is to have possibility to connect 2-phase tube to the 300 mm one, (i.e. it is in the middle and at the ends of cryomodule), as well as to connect valves, which will be placed in the middle of cryomodules.
- **Number of cold valves could be summarized as following**: i) opened/closed one with safety function for pressurized LHe, ii) cool-down valve for cavity cooling, iii) JT-valve, iv) one for cooling of fundamental couplers at 5-20 K temperatures, v) one for cooling of fundamental couplers at 40-300 K temperature. It is worth to mention that two additional valves for cooling in the range 5-8 K and 40-80 K of HOM couplers were also applied at Cornell injector and main
linac cryomodules. In present design, 5-8 K thermal intercepts for HOM are connected in series, i.e. no supply manifold is needed, while 40-80 K lines for HOMs, 5-20 K lines and 40-300 K ones for fundamental couplers will be supplied through DN32 manifold tubes.

- Similar to LCLS-II design, no 5-8K thermal radiation shield is applied. No supply line with temperature 5-8 K is installed, but return line with temperature range of 20-30 K is kept. Main reasons are: i) supercritical GHe at pressure 2.5-3 bar(a) for fundamental and HOM couplers is taken from the supply line, ii) this return line will be at pressure of around 1 bar(a), so sufficient pressure difference for the flow will be present. It is worth to mention that place for 5 K supply line is available, so this line could be installed, if it is necessary.
- It could be possible that due to installation of beamline HOM dampers between cavities, cryomodule will be a bit longer (according to estimations – around 2 m).
- Similar to LCLS-II design, electrical heaters for each cavities and two at cryomodule ends are installed. LHe level meters and heaters are located inside two LHe vessels at the ends of cryomodule
- Two fundamental couplers per cavities, located at the opposite sites (similar to Cornell injector) are installed. These couplers are actively cooled by 5 K and 40 K GHe flows.
- If challenges with thermo-acoustic or density-wave oscillations in the line with 5-20 K temperatures are presented, it is possible to install surge vessel with heaters, similar to ones applied at SNS cryomodules.

Figure 3 and 4 also shows some details on the design of internal components.

Figure 4: Cross-sectional view of cryomodule

For the easiness of future discussion, it is helpful to have a naming of new generation of cryomodule. In the past very few laboratory were involved in the development of TESLA-type cryomodules, so naming was easy to make, e.g. TTF-I, TTF-II, TTF-III. With increasing number of cryomodules developed, e.g. at KEK, SLAC, HZB (Germany), DESY (XFEL project), ILC, Cornell University, many new details were developed and added, and direct naming is a challenge. For that reason, author makes proposal to logically consider cryomodule according generation naming, i.e. XFEL cryomodule as TTF-III+, ILC – TTF-III++, LSLS-II as TTF-IV, Cornell ones as TTF-V, and presently proposed design as TTF-VI. So, in the further, this cryomodule generation will be sometimes named as sixths one.

It is worth also to consider design modifications of helium refrigerator. Though the total heat loads are not defined in the present paper, it is possible to define types of loads and corresponding temperatures. Operation at 1.6 K (saturation pressure is ca. 746 Pa) will most probably require one additional cold compressor (CC), so depending on final pressure, chain with 5 or 6 CC will be needed. There will be some liquefaction load in temperature range 40-300 K due to fundamental coupler cooling. Operation of fundamental and HOM couplers will also leads to non-isothermal heat load in the range 5-20 K (or maybe up to 30 K depending on actual design of couplers). The most challenging modification is the operation of chain of 5 or 6 CC, though long-term experience with 5 CC is gained at JLab refrigerators and operation experience with 6 CC could be gained at LCLS-II ones.
6. Conclusion
In the present paper, the design modifications of TESLA-style cryomodule capable to operation up to 400W @ 2K temperature level are presented.

Main modifications are related to application of sub-cooled LHe for cavity cooling, modification and application of two fundamental power couplers.

It is possible that in the future this high power cryomodules will be used either for ILC or other accelerators, e.g. for light sources or energy recovery linacs.

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