Cryogenic Considerations for CW Operation of TESLA-type Superconducting Cavity Modules for the BESSY FEL*

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Abstract

The proposed BESSY FEL uses a CW superconducting driver linac to provide acceleration up to 2.3 GeV. Its design is based on TESLA cavity modules, originally intended for pulsed operation and heat loads of order 1 W/m at 2 K. CW operation increases this load to about 21 W/m for a total heat load of 3 kW. Presented here is an analysis of the cryogenic layout, including two-phase-flow simulations of the superfluid helium which help identify the changes needed for reliable CW operation. A modified "CW" module and helium distribution scheme is proposed.

INTRODUCTION

TESLA superconducting radio-frequency (RF) cavities were originally designed for pulsed operation in the TESLA linear collider and X-FEL[1]. In part due to the success of the TESLA Test Facility at demonstrating their reliable operation, a number of proposals for CW linacs are now based on this technology. They include the BESSY FEL[2], the Cornell ERL[3], and the 4GLS[4].

Although much of the pulsed TESLA technology can be directly transferred to CW applications, an important aspect that must be examined is the significantly larger heat load dissipated in the liquid helium. About 21 W/cavity are planned for the BESSY FEL for a total load of 3 kW at 1.8 K, whereas the original pulsed TESLA proposal was limited to values of order 1 W/cavity. It must be demonstrated that the individual cavity units and modules are able to handle the larger CW loads and that an effective cryogen-distribution system can be designed.

Following is a brief description of the existing TESLA technology and the proposed (cryogenic) changes for CW operation. Then presented is a theoretical analysis of this system to demonstrate the feasibility of CW operation.

TESLA/XFEL MODULES

TESLA technology is based on 1.3-GHz superconducting Nb cavities[5]. They are individually welded in a titanium helium tank and are each equipped with a high-power input coupler and a tuner. For TTF, eight cavity units are integrated in one cryostat, whereas 12 cavities per module are planned for TESLA.

The cavities are cooled by 2.0-K He-II. A 1.2-bar, 2.2-K supply line expands liquid through a Joule-Thompson (JT) valve into a 2-phase line spanning several modules. It supplies each helium-vessel via a "chimney" with 2.0-K liquid. Boil-off gas in the two-phase line is returned to the refrigeration plant via a 300-mm gas-return pipe (GRP). This GRP forms the "backbone" of the module, serving as the reference and support for all components.

10 modules are connected in series with no warm transitions to form a cryogenic "string"[6], several of which are then grouped in one cryogenic "unit." The 2.2-K supply line and the GRP span the entire cryogenic unit, whereas the two-phase line is terminated at the end of each string.

At the beginning of each string the JT valve supplies the two-phase line. At the end of the string, the two-phase line ends in a reservoir containing a level meter for level control and a heater to balance dynamic-load changes. In each module a connection between the two-phase line and the GRP allows the evaporated helium to enter the return stream to the refrigeration plant.

2.0-K losses for a 12-cavity module are of order 15 W for TESLA operation for a total load of nearly 150 W per string. A complete cryounit comprising up to 16 strings must then be able to handle heat loads of order 2800 W.

Further details on the cryomodule design are available in the TESLA TDR[1] and numerous papers (e.g., [7, 8])

CW MODULES

Among the cryogenic issues that have to be examined for CW operation are:

1. The capacity of the JT valve; its throughput must be sufficient to cool at least one module.
2. Capacity of both the He tank and chimney to conduct heat to the two-phase line without inducing boiling.
3. Stable helium flow in the two-phase supply line.
4. Mass flow and pressure drop in the GRP.

Note that a single cryostring in the TESLA design, which is supplied by one JT valve, dissipates 150 W. If each 8-cavity CW module is equipped with its own JT valve then this is nearly equivalent to one TESLA cryostring, except that there are fewer connections between the two-phase line and the GRP. Item 1 above will then not be an issue. Also, in the TESLA design the helium boil off from one cryounit (approximately 2.8 kW) is handled by the GRP. Similar values apply to the entire BESSY FEL. These general considerations suggest that TESLA modules can indeed be used for BESSY-FEL CW operation with only minor modifications. This has been confirmed by calculations and simulations, as discussed in the next sections.

Layout of BESSY-FEL modules

Fig. 1 depicts the proposed layout of the modules for CW operation. Eight cavities (as in TTF) are included for a total

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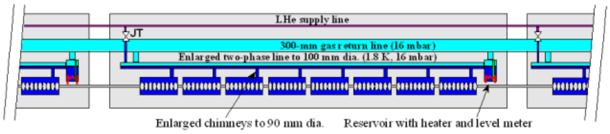


Figure 1: Schematic of the CW BESSY-FEL module.

load of 165 W per module. Since dynamic losses dominate the refrigeration budget and these decrease rapidly as the temperature is reduced, a lower bath temperature than the 2 K for TESLA will likely reduce the cost of the refrigeration system (both capital and operating). The optimum temperature depends on the achievable cavity quality factor but is likely to be around 1.8 K, so that the module is designed for this temperature.

Each module will be equipped with its own JT valve. The connection of the two-phase lines between neighboring modules has been removed to minimize “cross talk” which otherwise would complicate the liquid-level control.

The diameter of the two-phase line has been increased from 76 mm to 100 mm to improve the mass-flow. Similarly, the chimney diameter was also increased from 54 mm to 90 mm for better conduction.

An additional connection between the two-phase line and the GRP was incorporated in each module. One connection near the JT valve removes flash gas. The other is located near the reservoir to exhaust the gas that is produced by the compensation heater.[1] The diameter of these connections was scaled from 76 mm to 90 mm.

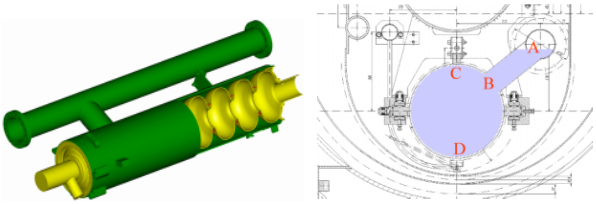
As discussed later, the pressure drop in the GRP is small so its size (300 mm) need not be changed. This fact is useful because any changes to the critical GRP would impact the overall design of the cryomodule.

ANALYSIS

Heat transfer in helium II

Even though the heat-transport capacity of He II is larger by orders of magnitude than that of other materials[9] boiling within the bulk is possible. The potential for increased microphonic detuning of the cavities then exists and the stable cryogenic operation may be adversely affected.

In a column of He II, a heat source at the bottom will establish a temperature gradient and boiling occurs when the local temperature exceeds the saturation temperature. But the hydrostatic pressure (and hence the saturation temperature) increases with the depth as well. These two effects roughly cancel, so that the critical flux ($\dot{Q}_{\text{crit}}$) at which boiling occurs is nearly independent of the tube height.[10] A conservative value for $\dot{Q}_{\text{crit}}$ is 1 W/cm^2 and the helium tank must be dimensioned such that this value is not exceeded.



Pos.	P_{loc}	T_{sat}	T_{loc}
A	1638 Pa	1.800 K	1.800 K
B	1780.6 Pa	1.824 K	1.802 K
C	1716.5 Pa	1.813 K	1.803 K
D	2044.5 Pa	1.864 K	1.805 K

Figure 2: Helium tank with cavity and cross section (right).

Fig. 2 depicts the cavity in the helium tank and the transverse cross section. Within the tank itself, the largest heat flux is expected in the narrow annular regions between the cavity equator and the tank wall (area = 66 cm^2). For BESSY-FEL operation the maximum flux will therefore be 0.5 W/cm^2 or less.[2] This produces a temperature gradient of at most 0.11 mK/cm at 1.8 K.[9]

The chimney must be able to conduct the full cavity losses. Its cross section in the TESLA design is 23 cm^2, which only is marginally sufficient for CW operation. For the BESSY-FEL modules, the cross section has been enlarged to 64 cm^2 (dia. 90 mm) to ensure that the heat flux in this region is also less than 0.5 W/cm^2.

In Fig. 2(b) the three critical points where boiling is most likely to occur are marked B, C, and D. Also listed are local hydrostatic pressures (P_{loc}) and saturation temperatures (T_{sat}) if the pressure at A is maintained at 1638 Pa.

Given a 16 cm long chimney, the expected temperature at point B is 1.802 K for a heat flux of 0.5 W/cm^2. The heat-transfer analysis for positions C and D is more complicated because of the three-dimensional configuration. As a rough but safe estimation we assume the heat flux along these two annular sections also equals the full 0.5 W/cm^2. Hence the temperature difference between position C and B (arc length = 10 cm) and between position D and B (arc length = 26 cm) is 1.1 mK and 2.9 mK, respectively. Given that the liquid surface at A is maintained at 1.8 K, worst-case temperatures at the other points are listed under T_{loc}. Clearly, they are all significantly lower than the local saturation temperature so that boiling is unlikely to occur.

Mass flow in the two-phase line and GRP

Special attention has to be paid to the large mass-flow in the two-phase line and the GRP to maintain stratified two-phase flow. Excessive waves or even plugs may cause microphonics and unstable cryogenic operation. The pressure drop in the GRP should also be small so that all cavities operate at the same temperature.

The 18-module BESSY-FEL linac is divided into four cold sections to accommodate (warm) bunch compressors and beam extraction points. Fig. 3(a) depicts a possible scheme for the cryogenic distribution. The linac is split roughly in half at the first beam-extraction point, creating two parallel paths of 8 and 10 modules, respectively. This layout minimizes the total pressure drop in the linac and permits the cryogenic operation or commissioning of one

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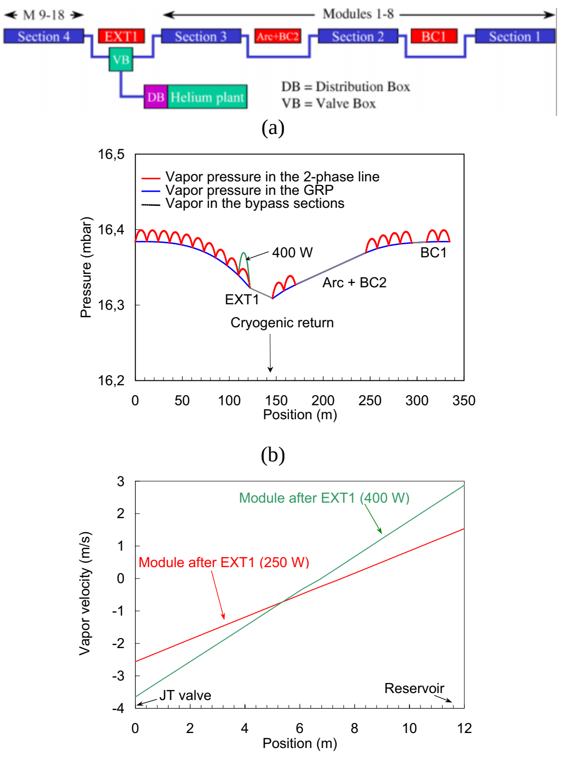
[1] It is not yet clear whether a single heater in the reservoir can be used or if a distributed heating system must be employed.

[2] The chimney is between the 2nd and 3rd cell and so that the heat flow through a given annulus is alway less than the total load.



(a)

(b)

(c)

Figure 3: (a) Cryogenic distribution in the BESSY FEL. (b) Simulated helium pressure in the linac. (c) Vapor velocity in the two-phase line of the most critical module.

half of the linac while the other is at room temperature.

Given the complexity of the system, we simulated the heat and mass flow in the two-phase line and GRP for the entire linac. References [11] and [12] describe in detail the program used for these studies. As discussed below, they have demonstrated that stable operating conditions exist for the BESSY FEL with an ample safety margin.

Cryogenic bypasses for the warm sections were included in the calculations, as well as flash gas after the JT valve (13%). The liquid level at the reservoirs was fixed at 1/3 of the pipe diameter. To provide for a substantial safety margin, a heat load of 250 W per module was assumed even though the BESSY-FEL modules will dissipate only 2/3 of this value. To investigate the operation of a hypothetical, under-performing module, an extreme heat load of 400 W in a single module was also included.

Fig. 3(a) depicts the gas pressure in the GRP and the two-phase lines of the individual modules. The pressure drop over the linac is only 0.1 mbar, so that the temperature difference between the ends will be a negligible 2 mK.

The vapor velocity in the most critical module (after the extraction point EXT1) is shown in Fig. 3(b). The flow is bidirectional because of the two connections between the two-phase line and the GRP at the ends of the modules.

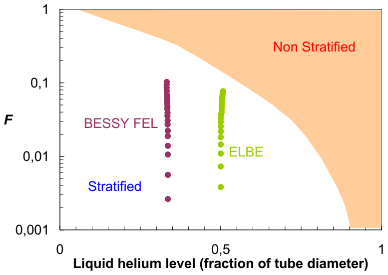


Figure 4: Flow pattern at several points in the two-phase line of the most critical BESSY-FEL module and in an ELBE module[15].

Importantly, though, the flow speed remains below 4 m/s in all modules. Measurements with He II have identified this value as being the threshold to unstable (non-stratified) two-phase flow.[13] Thus, even for a total cryogenic load of 18×250 W $= 4.5$ kW, the linac could still be operated stably, providing an ample safety margin for the planned 3-kW BESSY-FEL operation. Even in the module dissipating 400 W, the flow remains in the stratified regime.

A more rigorous analysis of the flow pattern is provided by the dimensionless parameters F as defined in Reference [14]. It is used to distinguish between stratified and non-stratified flow. Fig. 4 depicts the results for the most critical module. Clearly the flow pattern is expected to be stratified. For comparison, simulations of the two-cavity CW ELBE module[15] were also performed. The cryogenic and operational aspects of this module are very similar to the BESSY-FEL modules (1.8-K CW operation with a heat load of $\approx$ 50 W per cavity) and the results illustrate that the flow pattern is also similar, although somewhat closer to the non-stratified regime. Still, the ELBE module has been operated stably for some time so that we expect stable conditions for the BESSY-FEL modules as well.

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