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CW OPERATION OF SUPERCONDUCTING TESLA CAVITIES — CRYOGENIC ASPECTS [*]

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Abstract

Several recently proposed superconducting linacs for future light sources are designed to operate in CW mode. The TESLA technology, which they are based upon, was originally developed for pulsed mode. In order to demonstrate the feasibility of CW mode with TESLA technology, BESSY has built the HoBiCaT test facility [1]. The main issues of CW operation were examined and solutions are shown on the following topics: Limits of heat conduction in the Helium vessel, gas dynamics in the two-phase line, layout of a CW cryo module, heating of HOM couplers, CW operation of the main RF coupler, choice of helium bath temperature, pressure stability of the helium bath and microphonics and their compensation.

INTRODUCTION

TESLA superconducting radio-frequency (RF) cavities were originally designed for pulsed operation in the TESLA linear collider and European X-FEL [2, 3]. These machines are planned for high-energy operation and require high acceleration gradients to limit their lengths. The refrigeration cost dictates that these machines be pulsed with 1% duty factor. Therefore, the peak beam loading is very high. In part due to the success of the FLASH accelerator demonstrating their reliable operation, a number of proposals for CW linacs are now based on this technology. They include the BESSY FEL [4], the Cornell ERL [5] and the 4GLS [6]. These machines are designed for moderate energies (2-5 GeV), so that CW operation can be realized.

Although much of the pulsed TESLA technology could be directly transferred to CW applications, an important aspect that had to be examined was the significantly larger heat load dissipated in the liquid helium. About 21 W/cavity are planned for the BESSY FEL for a total dynamic load of 3 kW at 1.8 K, whereas the original pulsed TESLA proposal was limited to values of order 1 W/cavity. It was 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 pre-existing TESLA technology and the cryogenic changes for CW operation. Then presented is a theoretical analysis of this system to demonstrate the feasibility of CW operation. Measurements in HoBiCaT have been used to confirm many of the theoretical predictions.

TESLA/XFEL MODULES

TESLA technology is based on 1.3-GHz superconducting niobium cavities [7]. Each cavity is welded into a titanium helium tank and is equipped with a high-power input coupler and a tuner. For TTF, eight cavity units are integrated in one cryostat.

The cavities are cooled by 2.0-K He-II. This temperature is achieved by Joule-Thompson expansion of single-phase liquid Helium supplied at 1.2-bar and 2.2-K into a 2-phase line spanning several modules. The latter supplies each helium-vessel through a “chimney”. Boil-off gas in the two-phase line is returned to the refrigeration plant through 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” [8], 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 [2] and numerous papers (e.g., [9, 10])

CW RELATED ASPECTS

As the cavities are operated at a duty factor of 100%, instead of 1% in the pulsed mode, the average power is significantly higher which results in up to 40 times higher thermal heating (up to 30 W). Attention has to be paid to the limits of heat conduction in the helium vessel, the gas dynamics in the two-phase helium supply line and the layout of the gas return pipe.

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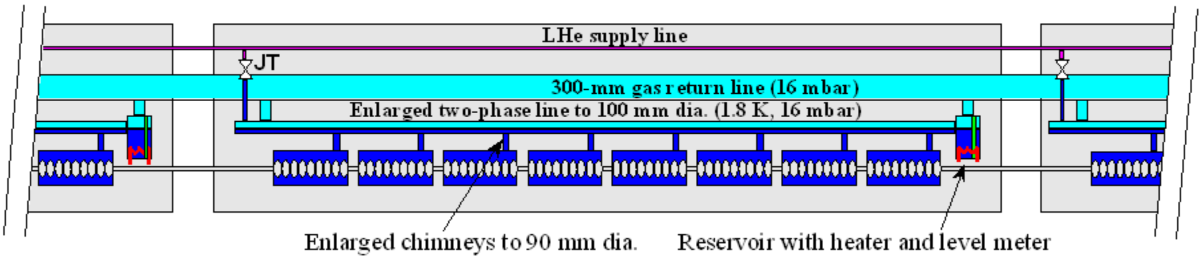

Figure 1: Schematic of the CW BESSY-FEL module.

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.

CW MODULES FOR THE BESSY FEL

Fig. 1 depicts the proposed layout of the modules for CW operation. Eight cavities (as in TTF) are included for a total load of 165 W per module.

Since dynamic losses dominate the refrigeration budget and they decrease rapidly as the temperature is reduced [11], a lower bath temperature than the 2 K used in 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, which is why 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.

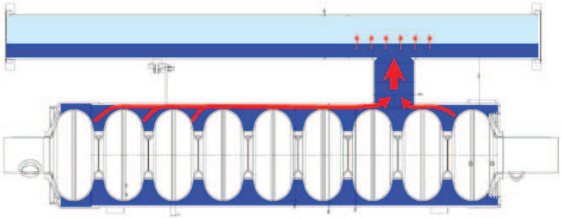

Figure 2: Layout of the helium vessel.

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.

The TESLA cavity is installed in a helium vessel (Fig. 2) and cooled below the lambda point (2.17 K) with superfluid helium. The advantage of superfluid helium is the much higher thermal conductivity compared to normal liquid helium which helps to avoid boiling. Also, the dissipated power in the cavity is smaller at lower temperatures. The heat of the cavity walls is disposed in the helium bath and conducted to the gas phase at the surface area in the two-phase supply line. It has to be ensured, that the limitation given by the heat conductivity is not reached. Otherwise there will be Helium boiling on the surface of the cavity possibly causing a quench of the superconductivity.

THEORETICAL CONSIDERATIONS

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 [14] 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 ($\dot{Q}_{\mathrm{crit}}$) at which boil-

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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.

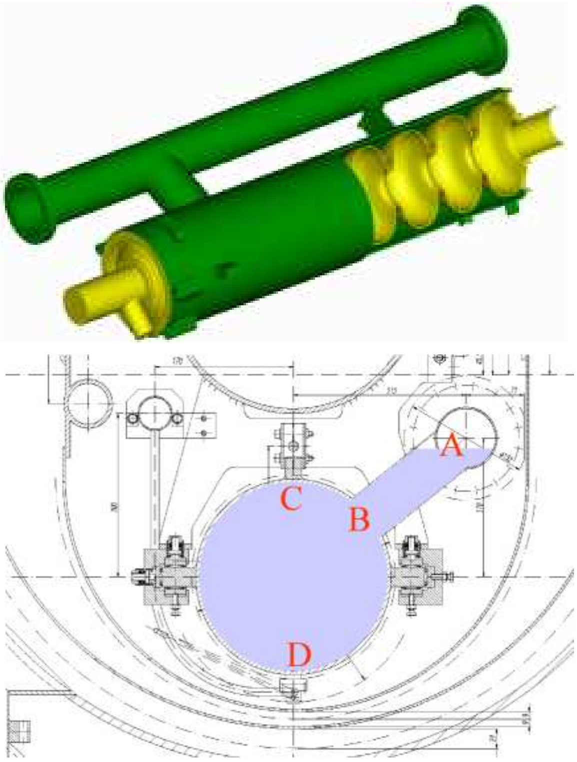


Figure 3: Helium tank with cavity and cross section (bottom).

ing occurs is nearly independent of the tube height [15]. 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.

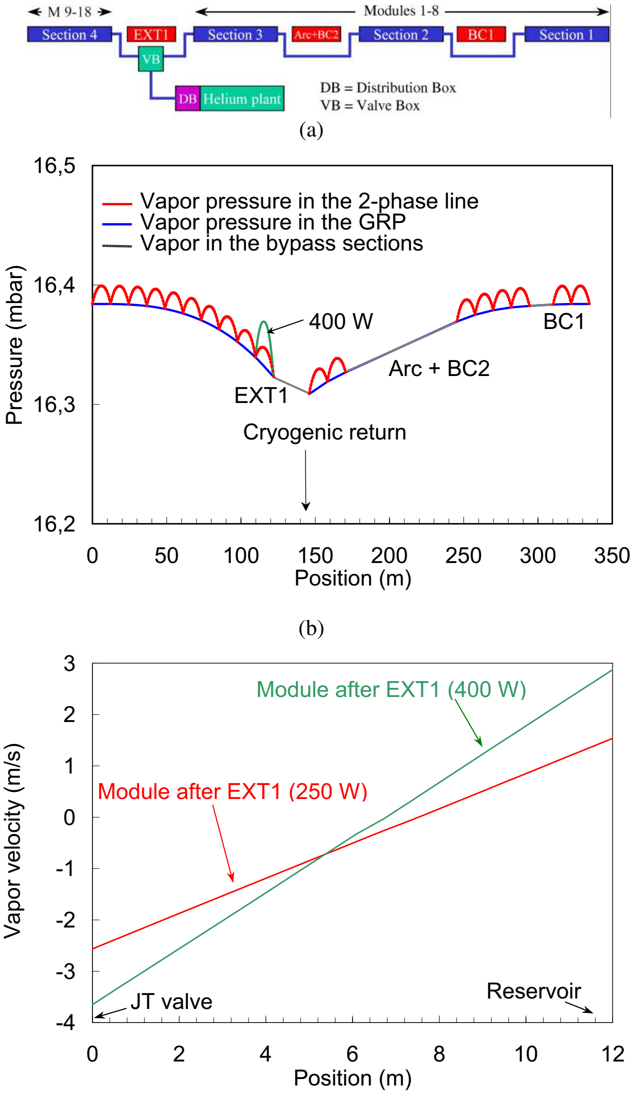
Fig. 3 depicts the cavity in the helium tank and the transverse cross section.

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 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 [14].

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. 3(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.



(a)

(b)

(c)

Figure 4: (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.

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. 4(a) depicts a possible scheme for the cryogenic distribution.

The linac is split roughly in half at the first beam-

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[2] The chimney is between the 2$^{\text{nd}}$ and 3$^{\text{rd}}$ cell and so that the heat flow through a given annulus is always less than the total load.

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 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 [16] and [17] 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. 4(b) 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. 4(c). The flow is bidirectional because of the two connections between the two-phase line and the GRP at the ends of the modules.

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 [18]. 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 [19]. It is used to distinguish between stratified and non-stratified flow. Fig. 5 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 [20] 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.

MEASUREMENTS

To underpin the theoretical analysis above, measurements were performed with TESLA units in the HoBiCaT test facility at BESSY under conditions similar to those expected for the BESSY FEL.

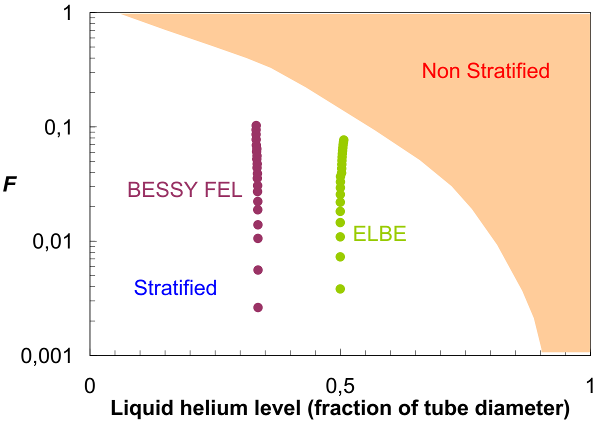

Figure 5: Flow pattern at several points in the two-phase line of the most critical BESSY-FEL module and in an ELBE module [20].

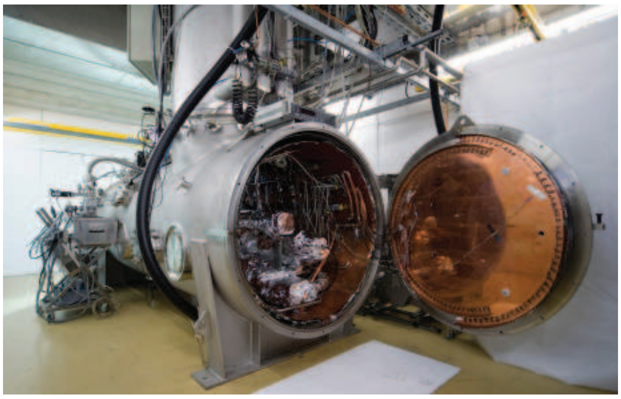

Figure 6: The cryostat of the HoBiCaT facility for CW operated SC TESLA cavities.

The HoBiCaT test facility [1] includes a cryostat, feedbox, helium refrigerator plant, vacuum pumps to produce superfluid helium, RF power transmitters, TESLA cavities in different helium vessels and associated ancillary equipment like couplers, tuners, HOM-pickups, etc. The 3.5 m long, 1.1 m diameter cryostat (Fig. 6) provides room for two 1.3 GHz 9-cell cavity units for tests from 1.5-2.2 K.

For several experiments two cavities were installed in HoBiCaT simultaneously, permitting the study of correlations between the cavities.

Critical flux in helium-II

First, the limitations of the maximum heat load of the helium vessel were tested. In the experiment a cavity was set to different field gradients of 18/17/10 MV/m corresponding to a heat load of 24/19/5 W. Using a resistive heating foil on the helium vessel additional heat load to the helium was applied, ramping the heater power slowly to maintain equilibrium conditions for the crogenic plant (see Fig. 7).

At all three field settings, the cavity lock was lost (possibly due to a quench) at a *total* load of 35 W (Fig. 7). This corresponds to a heat flux of 1.53 W/cm^2@1.8K heat flux.

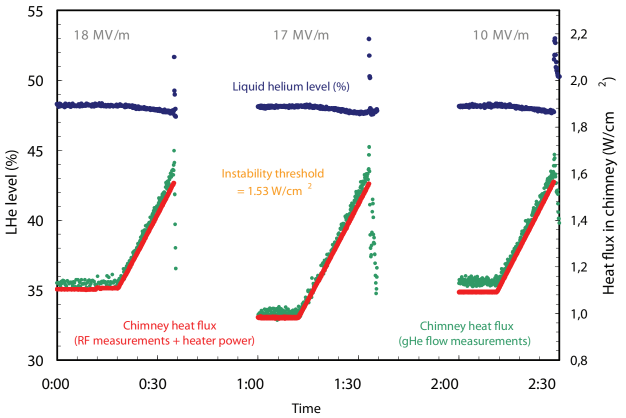

Figure 7: By using a electrical heater the total losses (red) of the heater and the total losses in the helium tank (blue) were increased. The quenching occurred at total power of 35 W or 1.53 W/cm^2 in the chimney.

This is close to the theoretical value at which boiling should occur [12] and confirms the theoretical considerations for the dimensioning of the helium tank.

The same experiment was performed with a cavity in a BESSY design vessel having an increased diameter of the chimney with a 63 cm^2 cross section. The same loss of lock was observed, albeit at a higher power level of 96 W. Given the larger chimney, this still corresponds to a critical flux of 1.5 W/cm^2 . Thus the modified helium tank provides for enough overhead to operate the cavities CW .

Cryo-related microphonics

It was investigated, to what extent an increased Helium flow contributes to the overall microphonics of the system. For that purpose, the heater foil was used to simulate increasing power loads on the cryo-system, while the actual accelerating field was kept small (<1 MV/m), just sufficient to get a signal from the pickup antenna. In order to maintain near-equilibrium conditions in the control-loops of the cryo-plant, a very slow ramp has been used, linearly raising the heater power on one of the cavities to 100 W in 2 hours, followed by a 10 minute sustain and a 2 hour release time.

In order to determine the (open-loop) microphonics, the cavity phase error signal has been recorded over time periodically during the entire heating cycle. In Fig. 8 the RMS value of each measurement is plotted against the corresponding Helium flow, which is offset by 1 g/s due to static losses and power consumption due to the cavity monitoring field. It can be clearly seen, that the equilibrium microphonics is elevated at higher gas flow rates. The red dots are the microphonics in the cavity WITH the heater in operation. Here, the effect is much stronger, which suggests that the source of the elevated microphonics level is to be searched in the tank - most likely the chimney connecting the Helium tank and the two-phase-flow pipe. Changing the heater operation to the second cavity reverses the effect.

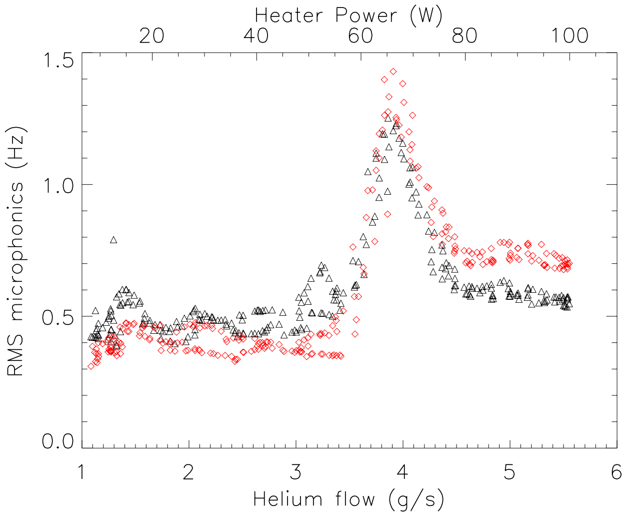

Figure 8: RMS microphonics recorded while ramping the cryo power from 10 to 100 W in 2 hours. The red dots correspond to the cavity with the attached heater. Measurements were performed at 30 mbar Helium pressure. Each measurement point represents an average over 5 subsequent microphonics measurements.

A second effect that can be observed is the strong peak of both microphonics signals at gas flow rates around 4 g/s. As it occurs for both, the cavity with and without heatload, the effect has to originate from the cryo-system. The control-loops exhibit oscillations at these flow rates leading to the increased microphonics signal.

Cross-correlation of microphonics

Two different mechanisms that lead to an undesired detuning of a cavity have been identified: On a slow scale (< 1Hz) the cavity resonance frequency follows the fluctuations of the Helium pressure in the 2-phase line. On a faster scale, the mechanical resonances of the cavity-tank-tuner systems are excited by any kind of external vibration. The lowest mode of the system has been measured to be at 30 Hz for a DESY type tank and 41 Hz for an BESSY type tank [13] which is beyond a detectable fluctuation in the Helium pressure.

A straightforward way to determine the origin of the detuning is to measure the phase-error signal in two cavities simultaneously and compare both time-series. This is depicted in Fig. 9. It is clearly visible that the lines follow a similar pattern.

In order to investigate the influence of the cryogenics system, these spectra have been correlated to the Helium pressure signal, that is measured at the end of the two-phase-flow line. From the cross-correlation analysis it becomes clear, that more than 60% of the detuning is governed by the cryogenics, see Fig. 10. Hence, we expect a significant correlation of the sub-Hertz microphonics throughout the entire machine.

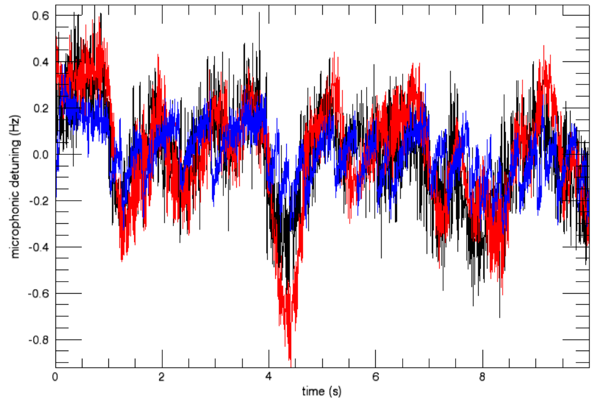

Figure 9: Time dependent cavity detuning (black and red lines) and Helium pressure in a.u. (blue line)

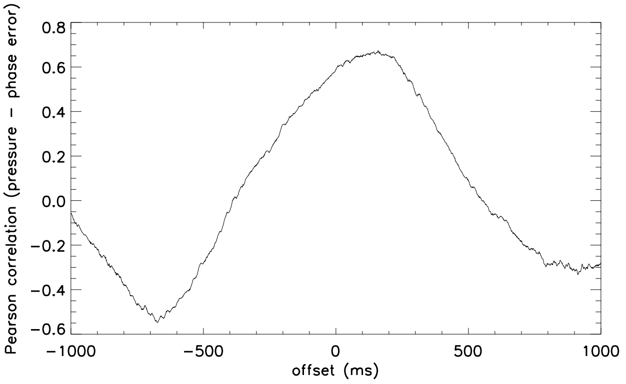

Figure 10: Correlation between phase error signal and Helium pressure (low-pass filtered). The x-axis represents the time difference between cavity signal and pressure signal. The pressure signal is occurring later due to the longer measurement of the pressure sensor.

Discussion

Both measurements and theoretical considerations have shown that CW operation of the modified TESLA modules is feasible. The enlargement of the chimney of the two-phase flow pipe has led to the desired effect of increased heat removal. It was also shown that the overall microphonics of the system depends strongly on the stability of the cryo-plant.

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