CW OPERATION OF SUPERCONDUCTING TESLA CAVITIES*

W. Anders †, J. Knobloch, O. Kugeler, A. Neumann, BESSY, Berlin, Germany

Abstract

Several recently proposed superconducting linacs are designed to operate in CW mode. The TELSA 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 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 TESLA technology can be applied directly to CW machines, new issues uniquely related to CW operation (and not necessarily addressed at FLASH) now need to be investigated. The HoBiCaT test facility was installed at BESSY to investigate all relevant CW issues.

CW RELATED ASPECTS

There are two different categories of CW related effects that have to be taken into account:

1. Effects resulting from the duty factor of 100% instead of 1% in the pulsed mode on the higher average power in each cavity.
2. Effects resulting of the lower beam loading due to the fact, that there will be a unique beam distribution with lower maximum currents in CW operated machine instead a high current bunch train in pulsed linacs.

Effects of the first category will result in up to a factor of 40 higher thermal heating in each cavity. 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, the layout of the gas return pipe as well as to the power capability of the RF input coupler and HOM damping devices. Also, investigations have to be made to evaluate the proper bath temperature to find a cost minimum for the cryogenic infrastructure.

The second category stands for a coupling of the main RF input coupler, that has to be adjusted for much lower maximum currents. The optimum loaded Q-value in CW operated SC linacs is higher by a factor of 10-100 as compared to pulsed machines. This results in typical bandwidths of CW operated cavities of 1-30 Hz instead of a few hundred Hertz in pulsed mode. As a consequence, the cavities get more sensitive to the pressure stability of the helium bath and microphonics. Microphonics has to be quantified and compensation schemes have to be evaluated.

THE HOBICAT FACILITY AT BESSY

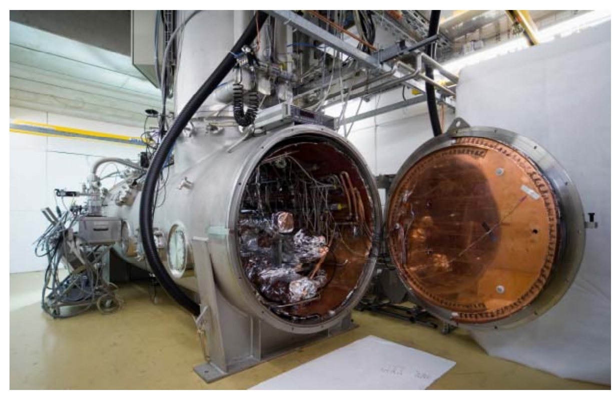


Figure 1: The cryostat of the HoBiCaT facility for CW operated SC TESLA cavities

The HoBiCaT test facility includes a cryostat, feedbox, helium refrigerator plant and 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.1) provides room for two 1.3 GHz 9-cell cavities with their helium tanks, tuners and input couplers. The cryostat has a LN_2 thermal and a 2mm μ-metal magnetic shield.

A 180 l/h TCF50 helium refrigeration plant at BESSYII supplies 4.5 K Helium via a 150-m long LN_2 shielded Nexans transfer line (type FGL 21/110). A vertical

* Work partially supported by the EU Commission in the sixth framework program, contract no 011935 EURO-FEL-DS5, the BMBF and Land Berlin
† anders@bessy.de

feedbox at the cryostat distributes the helium via a heat exchanger to the Joule Thompson valve of the cavities as well as to the 4K cold support table for the cavities. Warm vacuum pumps with a pumping speed of 6400 m³/hr provide a cooling capacity of 80W at 1.8 K. Even lower temperatures down to 1.5 K at reduced power are possible. By optimizing the loops a pressure stability of 30µbar (σ) at 16 mbar (limited by the resolution of the pressure sensors) are typical values of operation.

The RF power sources of HoBiCaT are solid state amplifiers, klystron and IOT transmitters at 1.3 GHz with low amplitude and phase noise in a power range of 200 W to 30 kW CW.

LAYOUT OF THE CRYOMODULE

Limits of the Cryogenic Load of the Helium Vessel of the Cavity

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. 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 causing a quench of the superconductivity.

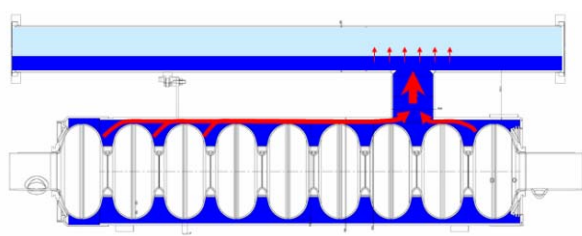


Figure 2: Layout of the helium vessel.

The helium vessel of the cavity was designed for the pulsed operation of 1% duty factor and 23-35 MV/m gradient for the TESLA project corresponding to a cryogenic load of 0.75 W/cavity [2]. The CW linacs have 100% duty factor at reduced gradients of 15-20 MV/m corresponding to a cryogenic load of up to 30 W/cavity.

At HoBiCaT the limitations of the maximum heat load of the helium vessel were tested. The cross-section area of the helium path at the place of the iris of the cavity is 62 cm². At the TESLA design of the helium vessel the area of the chimney connecting the helium vessel with the two phase supply line is only 23 cm² being the limiting part for the heat conduction.

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. At all three field settings, there was a quench at a total load of 35 W (fig.3) corresponding to a value of 1.53 W/cm²@1.8K heat conductivity. This is close to the theoretical value.

The same experiment was performed with a cavity in a BESSY design vessel having an increased diameter of the chimney with a 63 cm² cross section. The same limit was measured corresponding to a power limit of 96 W. This design has enough overhead to be used in CW operated cavities.

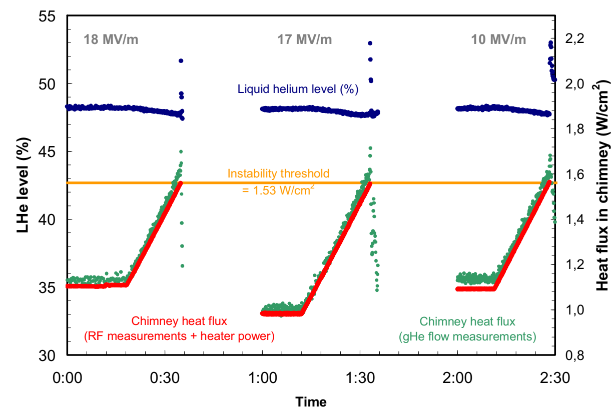


Figure 3: By using a electrical heater the total losses (red) of the heater and the dissipated cavity wall losses for different field settings (blue) were increased. The quenching occurred at total power of 35 W or 1.53 W/cm² in the chimney.

Layout of the Gas Return Pipe (GRP)

The gas return pipe of the cryo modules is a sensitive device because it is the mechanical reference of the cavities in the module. Calculations for the pressure drop in the GRP have been made for the BESSY FEL using 18 modules. The assumption of 250 W/cavity is a worst case scenario. To avoid high pressure drop along single modules, the LHe supply should be in the middle of the linac as is shown in figure 4.

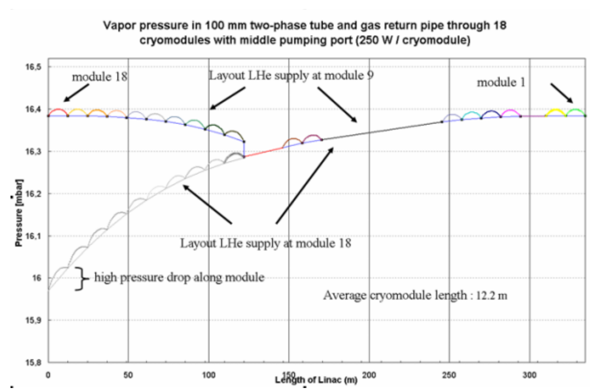


Figure 4: Pressure drop along the gas return pipe calculated for the BESSY FEL. Feeding the helium at the end of the linac will cause high pressure drop along the modules at the end. Supplying the helium in the middle of the linac gives better results.

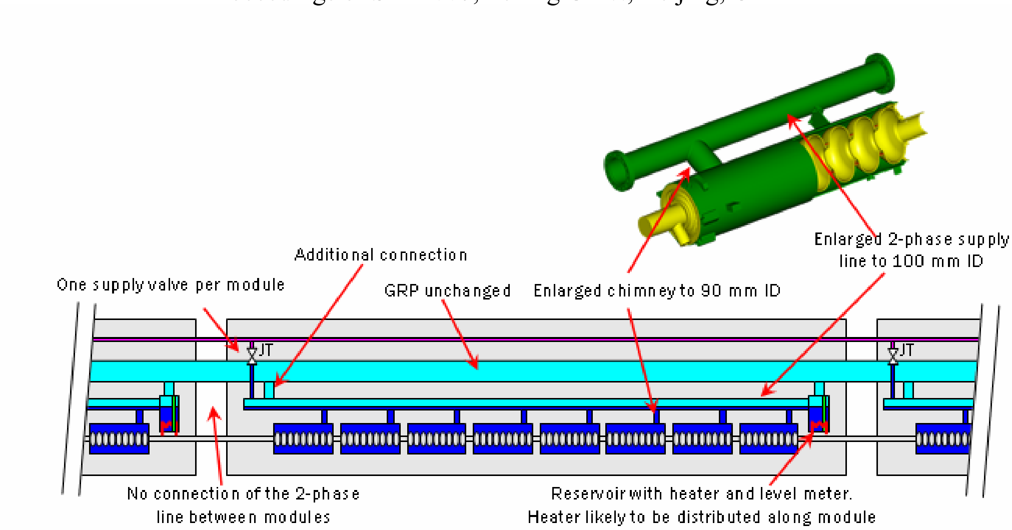


Figure 5: Design of a CW cryo module

Layout of 2-phase Line

Special attention has to be taken to the two phase line. The amount of gas in a CW driven module is much higher than in the pulsed version. The speed of gas should be kept slower than 4 m/s in order to avoid wavy conditions on the surface of the liquid phase [7]. Calculations show, that stable conditions can be reached by increasing the diameter of the 2-phase line to about 100 mm, setting the filling level of the liquid to 33% and introducing a second connection of the 2-phase line to the gas return pipe on every module.

CW Modul Layout

Summarizing the discussed aspects a CW cryo moduled can be designed (fig.5) as follows:

The gas return pipe will be unchanged. There will be a supply Joule Thompson valve, resistive heater and level meter on every module. Therefore there is no longer a connection of the two phase line between the modules. The 2-phase line will be increased in diameter to about 100 mm same as the chimney of the helium vessel to about 90 mm. This module will be operable reliable at a total cryogenic heat load of 250 W.

Pressure stability

As seen in the following chapter, the pressure stability is a dominant factor causing detuning of the cavity. At HoBiCaT a value of σ = 30 µbar @16mbar has been achieved by optimizing the loops in the cryo plant. This value is limited by the accuracy of the pressure sensor. Due to the fact, that large scale cryo plants will run with cold compressors, a value can not be predicted.

RF ASPECTS

Choice of Temperature

The thermal losses in the walls are related to the unloaded quality factor Q_0 of the cavity as described by BCS theory. This value shows a strong temperature dependence as can be seen in Figure 6. Note that no saturation of Q_0 was observed down to 1.5K, which hints at a sufficient shielding of the cavity of better than 5 mG. This value was realized by two magnetic shields. One shield of 2 mm µ-metal is at the diameter of the vacuum vessel of HoBiCaT cryostat, the otherone is acold TESLA-style cryo-perm shield on the helium vessel of the cavity. Tests have to be repeated at the TESLA cryomodule because of the different magnetic shielding. Due to these measured results lowering the temperature will be the best choice. As large scale cryo plants running at 1.8 K are commercially available, it is planned for the BESSY FEL to run the cavities at a temperature of 1.8 K with the option to still lower it.

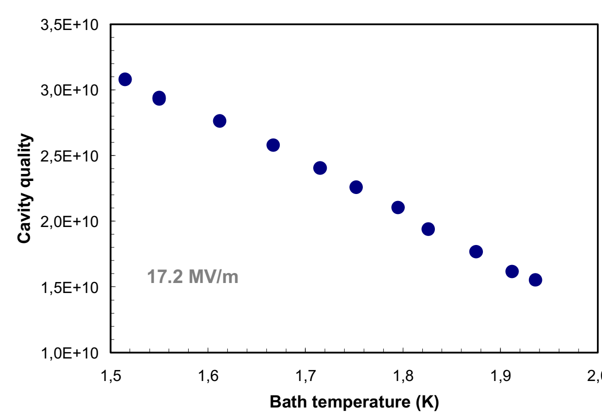
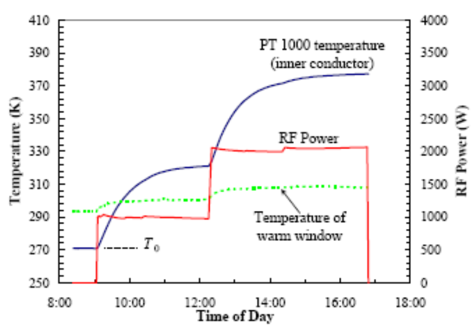


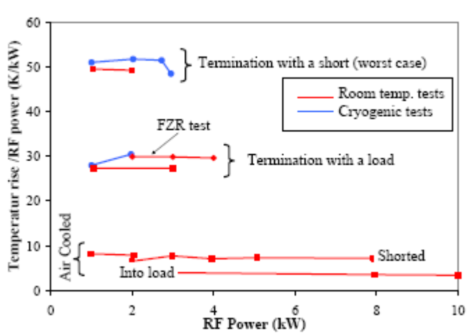
Figure 6: Unloaded quality factor of the TESLA cavity versus bath temperature. At low temperatures the quality factor increases. There is no saturation by other loss mechanisms seen at these measurements at HoBiCaT.

CW Coupler Test

The main RF coupler will be operated in the pulsed operation not more than an average-power traveling wave of 1.5 kW. For CW operation the average power will be about 5kW. To check the power handling capability a TTF-III type coupler [8] was tested at HoBiCaT under CW conditions at room temperature as well as under cryogenic conditions [9]. Measurements were performed into a waveguide load (traveling wave) as well as into a shorted waveguide with different lengths (standing wave). Only the worst case of length of the waveguide is discussed. It was demonstrated, that the most critical component is a bellow on the warm part of the inner conductor. Data of a PT1000 thermosensor close to the critical bellow are shown in Figure 7. Part (a) shows the heating versus time yielding a time constant of about 50 minutes. Part (b) depicts the temperature rise measured per kW of RF power as a function of power under various operating conditions. No significant difference in ($\Delta T/\Delta P$) was observed between warm and cold tests. Because the heating of the bellow was too high for 5 kW operation measurements with an additional air cooling of the inner conductor was added. By using air cooling, the resulting temperature rise was acceptable up to the power limit of the transmitter of 10 kW. Extrapolating the data suggests that power levels of up to 25 kW should be possible. A modified version of the warm part of the coupler including nitrogen gas cooling is under fabrication. Tests will follow soon.



(a)



(b)

Figure 7: CW measurements at the TTF-III type coupler. (a) Example of PT1000´s temperature versus time. Measurements were made with HoBiCaT cold and the waveguide shortened. (b) Summary of all tests.

Heating of HOM Feed Through

When operating TESLA cavities in CW mode Q-switch was detected at *field levels about 10 MV/m* in HoBiCaT and at the ELBE FEL in Rossendorf followed by a decreasing Q-value and causing high cryogenic losses. This effect was correlated with heating of the HOM feedthroughs (Fig. 8). Cavities without mounted HOM feedthroughs have not shown this effect. Good thermal anchoring of the HOM pot and feedtrough to 4 K was not sufficient.

The HOM pickup is exposed to a small part of the accelerating field. Tip heats up by a very small amount (<<1W), but the heat can only be conducted through the ceramic of the feedthrough. The ceramic has a poor heat conductivity. A solution is replacing the ceramic by an isolating material with high thermal conductivity. At CEBAF feedthrough using sapphire instead of ceramics was developed. DESY mounted this feedthrough on the TESLA cavity S33 and CW tests were performed at HoBiCaT

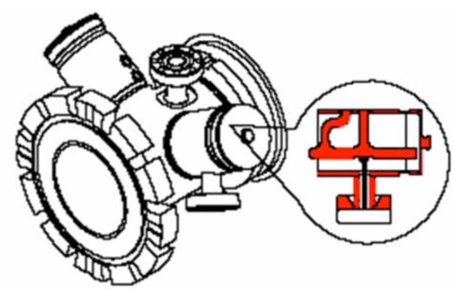


Figure 8: HOM feedthrough of of the TESLA cavity. There is a SMA connector with a tip coupling capacitive to the F-part of the HOM antenna of the cavity.

As a result 20 MV/m were reached limited by quench caused by the small diameter of the chimney of the helium vessel. We see still a small rise of temperature at the HOM coupler but effect is low (fig. 9). Thermal anchoring of the HOM feedthroughs is not necessary. The pickup cables (RG223) are a significant source of heat. They need a thermal anchor for inner and outer conductor or have to be replaced by low thermal conductivity cables.

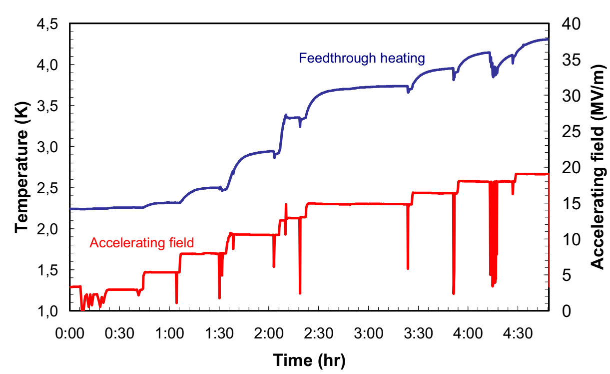
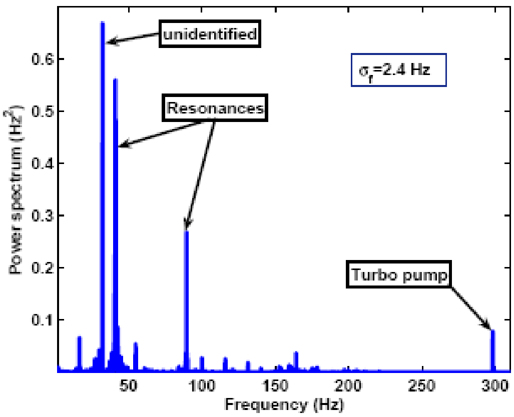


Figure 9: Temperature rise of the sapphire HOM feedthroughs and accelerating field versus time of the S33 cavity in CW operation. The HOM heating is at a moderate level.

Microphonics and Compensation

Microphonics is the dominant error source for field stability in CW operated superconducting linacs. Due to this fact, there is much activity at HoBiCaT to characterize and suppress microphonic detuning [10], optimize the tuner systems [11] and find compensation schemes to counteract the detuning of the cavities [12].



Fig

Figure 10: Power spectrum of microphonics

In figure 10 the power spectrum of the RF-feedback signal is depicted. Typical signals are the 300 Hz signal of the turbo pump of the isolation vacuum, resonances of the cavity-tank-tuner system at 41Hz, 90 Hz and 170 Hz and an unidnetified source at 30 Hz. Pressure fluctuations of the helium bath are the source of broadband microphonics below 1 Hz. This amount is about 40-50% but not documented in figure 10 due to the short measuring time.

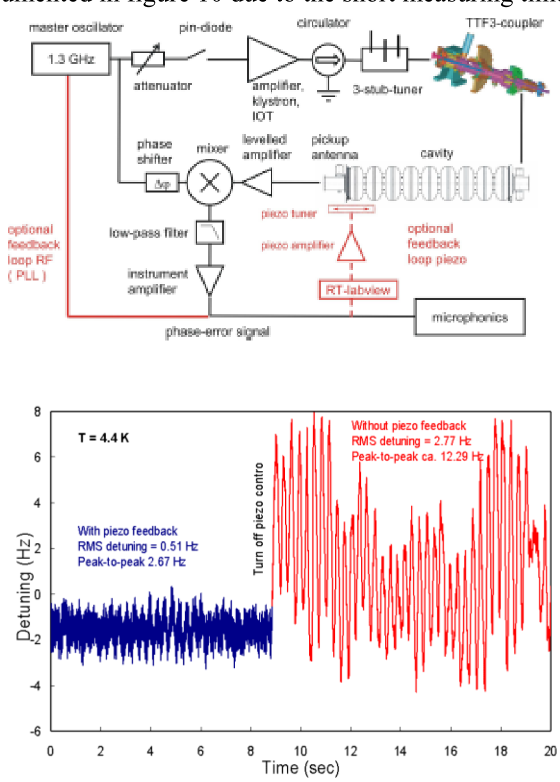


Figure 11: Electrical setup (upper figure) of the microphonics measurement and feedback loop. Lower figure shows the Microphonic detuning (red) versus time and the reduction (blue) by closing the feedback loop.

Feedback and feed forward schemes have been tested to fight microphonics using a fast piezo tuner. The low frequency fluctuations caused by the helium bath have been compensated by a feedback loop using a Real Time LabView system (fig. 11). The higher frequency components of the microphonics had been successfully suppressed by using adaptive feed forward.

CW ACKNOWLEDGMENT

We would like to acknowledge the significant help from discussion with B. Petersen, K. Jentsch, R. Lange, D. Kostin, A. Matheisen, W.D. Möller, C. Albrecht and D.Proch from DESY, Xian Yu from GSI, M. Luong, G. Devanz, E. Jacques and P.Bosland from CEA Saclay. Thanks for the support and operation of HoBiCaT to A. Frahm, M. Schuster, S. Klauke, P. Lauinger, D. Pflückhahn, S. Rotterdam, Th. Westphal, H.G. Hoberg and K. Ludwig.

REFERENCES

[1] J.Knobloch, W.Anders, D.Pflückhahn, M.Schuster, *HoBiCaT – a Test Facility for Superconducting RF Systems,* Proc. 11th Workshop on RF Superconductivity, Travemünde, Germany (2003)

[2] R.Brinkmann *et al.,* editors, TESLA *Technical Design Report,* Part II – The Accelerator, DESY Report 2001-011.

[3] DESY XFEL Project Group, *The European X-Ray Free-Electron Laser Technical Design Report*, DESY 2006-097, ISBN 3-935702-17-5, 2006

[4] D.Krämer *et al.,* editors, *The BESSY Soft X-ray Free Electron Laser, TDR,* ISBN 3-9809534-0-8, BESSY Berlin (2004).

[5] I.Bazarov *et al.,* CHESS Report No. 01-003, 2001, Cornell University.

[6] M.Poole *et al., 4GLS: A new type of fourth generation light source facility,* in Proc. 2003 PAC, pp.189-191, 2003.

[7] B.Rousset, L.Grimaud, A.Gauthier, *Stratified two-phase superfluid helium flow,* Cryogenics 37 733-737; (1997).

[8] B. Dwersteg et al., *TESLA RF Power Couplers Development at DESY,* Proc. 10th Workshop on RF Superconductivity, Tsukuba, Japan (2001)

[9] J. Knobloch et al., *CW Operation of the TTF-III Input Coupler,* Proc. 2005 PAC, Knoxville (2005)

[10] Oliver Kugeler , Wolfgang Anders, Jens Knobloch, Axel Neumann, *Microphonics measurements in a CW driven TESLA type cavity,* EPAC 2006, Edinburgh (2006)

[11] Axel Neumann , Wolfgang Anders, Sascha Klauke, Jens Knobloch, Oliver Kugeler, Michael Schuster, *Characterization of a piezo based microphonics compensation system at HoBiCaT,* EPAC 2006, Edinburgh (2006)

[12] Oliver Kugeler, Axel Neumann, Wolfgang Anders, Jens Knobloch, *Measurement and Compensation of Microphonics in CW-operated TESLA-type Cavities,* ERL 2007, Daresbury (2007)