A TUNER FOR A SUPERCONDUCTING CH-PROTOTYPE CAVITY

A. Bechtold, M. Busch, H. Liebermann, H. Podlech, U. Ratzinger,
IAP, J. W. Goethe-Universitaet, Frankfurt, Germany.

Abstract

The superconducting CH multi-cell prototype cavity will be equipped with a frequency tuning system. The rf-tuning during operation bases on the principle of a slight elastic deformation at both ends of the tank. This is causing a change in the gap width of the first and last accelerating cell and the accompanying variation of capacity finally results in a frequency shift. The effects on rf-frequency and field distribution have been measured and were compared with previous calculations. The tuning system implies two stages, a slow mechanical device and a fast piezo system, all parts were manufactured already. Additionally, the mechanical resonances of the cavity have been investigated experimentally in the environment of an acoustical laboratory at room temperature and recently within the vertical cryostat at 4 K. Moreover, an active periodic cavity detuning provided by the piezo tuners was implied, while stable superconducting cavity operation was kept by a frequency control loop acting on the rf-frequency oscillator.

INTRODUCTION

Multi-cell CH-structures could improve the efficiency of DTL-structures for protons and light ions in the low and medium energy range [1,2]. A superconducting CH-prototype (fig. 1) has been developed at IAP in Frankfurt to investigate the potential of that structure experimentally. It has 19 accelerating gaps, the resonance frequency is 360 MHz and the achievable accelerating gradient was expected to be E_{acc} = 6 MV/m. First cryogenic tests performed in July and September 2005 and in January 2006 ended up with only E_{acc} = 4.7 MV/m and an increasingly intensive X-radiation towards higher gradients [3]. Detailed investigations with thermo luminescence detectors (TLDs) allowed a precise localization of field emitter [4]. It was then decided to repeat the chemical surface treatment (Buffered Chemical Polishing, BCP) removing 50 µm material from the inner surface followed by High Pressure water Racing (HPR). A recent cryogenic test ended up very successfully with E_{acc} = 7 MV/m.

The rf-oscillator just followed the frequency changes of the resonator in earlier tests. Recently, active periodic tuning by piezo actors was successfully included in the cold test. Within the frame of the HIPPI project, an appropriate tuning system for the multi gap CH-structure, then operated at a horizontal cryostat, is under development.

Figure 1: CH-prototype and investigated piezo actuator.

Operating frequency	360 MHz
Relativistic β	0.1
Total length of tank	1048 mm
Active length ($\beta\lambda$-definition)	810 mm
Tank diameter	280 mm
# accelerating gaps	19
Accelerating field gradient $E_{acc.}$ (meas.)	7 MV/m
Surface peak field gradient E_{peak}	36 MV/m
Maximum magnetic flux B_{peak}	40 mT
Accelerating voltage $U_{acc.}$	5.6 MV

Table 1: CH-cavity parameters and measurements.

RF RESPONSE ON APPLIED EXTERNAL TUNING FORCES

An elastic deformation of the cavity by applying an pushing or pulling force at the end flanges of the tank changes the width of the outer most accelerating gaps and thus gives an efficient possibility to tune the rf-frequency during operation [4]. The rf-response of the cavity was simulated with MWS [5] and by multi-physics program COMSOL [6] (fig. 2). These calculations can now be compared with a measurement which had been executed at room temperature. The force was applied by the outer corset that allows a variation of the cavity length. From simulation results a force of $F_{def.}$ = 6.5 kN must be applied to have a deformation of Δx = 1 mm at both ends of the tank; $\Delta f/\Delta x = 850$ kHz/mm were calculated. However the measured frequency tune shift is only $\Delta f/\Delta x = 400$ kHz/mm (fig.2), which is indeed considered to be sufficient enough for our needs. The change of field distribution according to the deformation of the tank has been measured by using the bead pull method. The experimental results are in good agreement with MWS simulations. The effect is mainly concentrated on the end cells of the structure, where a maintainable maximum field variation of 10% within the tuning range (fig. 3) was observed.

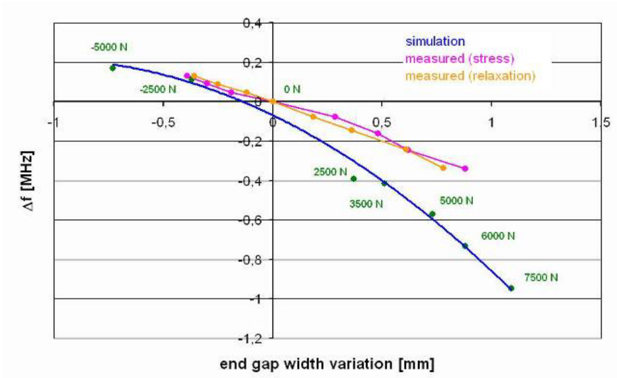

Figure 2: Simulated and measured rf-response.

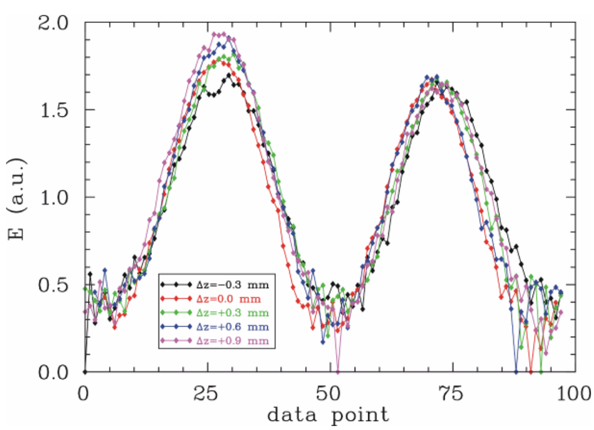

Figure 3: Measured change of field distribution according to an end gap deformation Δx.

TUNER DESIGN

The frequency tuning device comprises two stages: A slow mechanical tuner with a tuning range of $\Delta f_{mech.} = \pm 1$ MHz and a fast piezo tuner operating in an expected range of $\Delta f_{piezo} = \pm 1$ kHz. The piezos will be inserted into the beam pipe, between the inner cold mass containing the helium and the outer room temperature vacuum vessel, so that they will operate at a temperature somewhere between 4 K and 80 K, which determines their maximum stroke (see below). The mechanical requirements of the piezos had been carefully taken into consideration during the design of the tuning system (fig. 4, 5). Since they are sensitive to canting and shearing forces, their action should be very well controlled. We introduced guiding bolts and a tight over all fitting of the parts. Additionally, the piezos are pre-stressed ether by 3 M6 screws with well defined moment of torque or by 6 spring shims for M8 screws alternatively. To avoid canting the force will be transmitted to a supporting plate over a spherical surface at one end of the piezo; a rigid fixation is given only at one end.

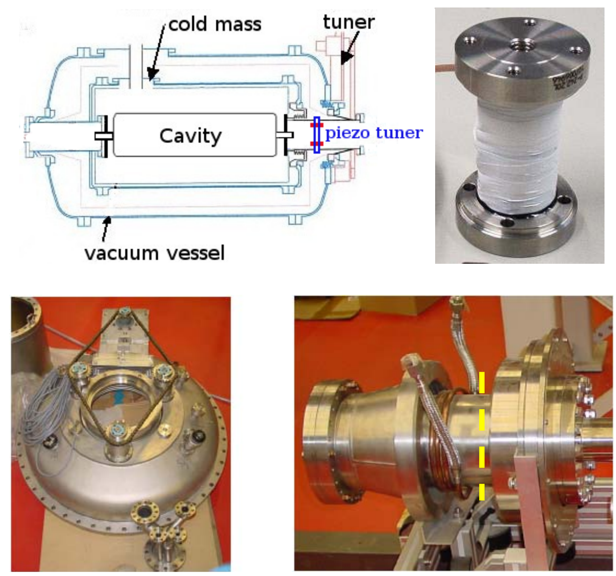

Figure 4: Scheme of the cryostat with tuner positioning on top right, a piezo from Physical Instruments (PI) top left, the mechanical tuner bottom left and beam pipe were piezo tuner shown in fig. 5 will be included close to the cooling loop in the middle (dotted line).

Figure 5: Scheme of the piezo tuner on top and one part of the tuner carrying the three piezo actuators below.

PIEZO TEST

For a preliminary performance check, the piezos have been tested at room temperature and at 77 K within a specially designed test set up. The stroke of the piezos was measured by means of an altimeter with a nominal resolution of 1 µm on a measuring bench. All available 5 piezos have the same stroke within the accuracy of the measuring system (fig. 6). At 77 K the stroke is reduced by a factor of 2, which corresponds very well to other comparable piezo types of which measurements can be found in literature [7]. Up to 1750 N compressive load no evident change in performance was observed. Going down to 4 K typically reduces the stroke again about a factor of 5.

Since the piezos will operate somewhere between the inner cold mass at 4 K and a liquid nitrogen cooling loop around the pipe (fig. 4) we expect a maximum stroke of at least 5 µm corresponding to the above mentioned $\Delta f_{piezo} = \pm 1$ kHz.

Manufacturer	PI
Type	P-242.20L
Nominal max. stroke at 300 K	20 µm ±20%
Voltage	0…1500 V
Max. tensile load	2 kN
Max. compressive load	12.5 kN
Measured max. stroke at 300 K	35 µm
Measured max. stroke at 77 K	16 µm
Expected max. stroke at 4 K	3.5 µm

Table 2: Basic piezo data.

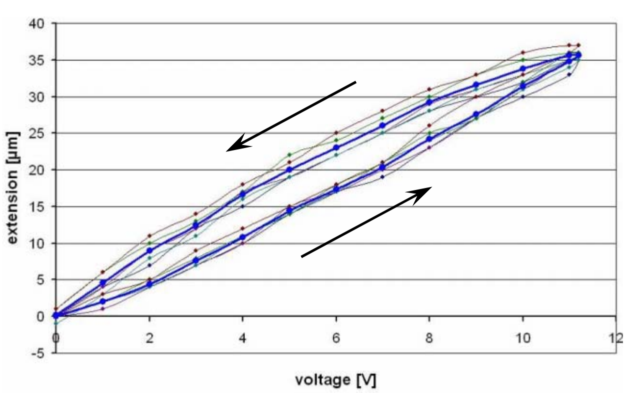

Figure 6: Measured piezo stroke hysteresis curve vs. control voltage at room temperature; slim lines for 5 individual piezos, averaging in fat blue.

MICROPHONICS AT ROOM TEMPERATURE

Due to the radiation pressure of the electromagnetic field a force F_{LF} acts on the inner tank walls of a superconducting cavity. This changes the geometry slightly and thus causes a frequency shift Δf_{LF} called Lorentz-force detuning (LFD). The effect is proportional to the square of the accelerating field $E_{acc.}$ and was measured to $k = -8$ Hz/(MV/m)^2 in the case of the superconducting CH-structure.

LFD was measured by observing the Voltage Controlled Oscillator (VCO) signal $U_{VCO} = 0\ldots1$ V of the rf-system (fig. 7). This signal determines the oscillator frequency within a preset frequency range (deviation). Since the actual test system is not operating at fixed frequency, but follows the rf-variations of the cavity, the rf-detuning can directly be observed by means of the VCO signal. LFD is very precisely reproduced from pulse to pulse, but is modulated by microphonics [8]. Mechanical resonances, which can especially be excited at pulsed operation, can reinforce the sonic effects, causing large variations of the rf-resonance [9]. Up to a certain degree, this can be compensated by increasing the output power of the rf-amplifier, but this becomes increasingly unfeasible at higher gradients since $\Delta f_{LF} \propto E_{acc}^2$. A fast piezo tuner is an alternative to compensate the mechanical detuning.

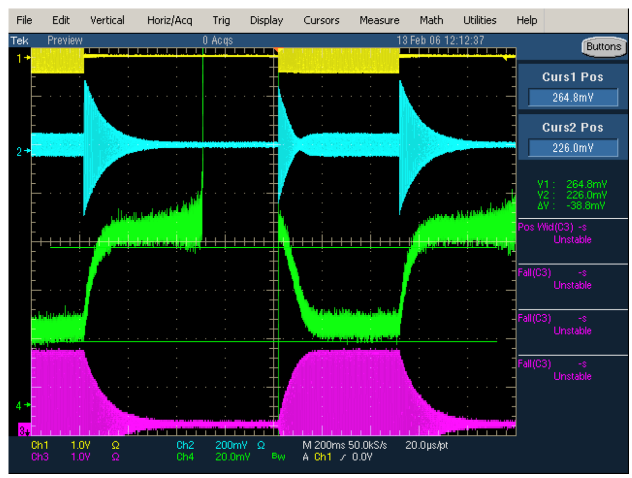

Figure 7: The VCO signal (green) as a direct indication of Lorentz-force detuning. Rf-pulse (yellow), Reflected power (blue), transmitted power (pink).

To avoid instabilities in the control system it is important to care about mechanical resonances of the cavity and their impact on the resonance frequency. Very low resonances can then be damped or pushed to higher frequencies if necessary. We have measured the resonances by using one of the piezos as an actuator stimulating the cavity with either a sinusoidal signal from an acoustic wave generator or with white noise comprising all frequencies between 0 and 100 kHz, alternatively. The response of the cavity was then detected by a microphone or by a second piezo used as a detector and was digitally recorded (fig. 8). These wave data were Fourier analyzed subsequently.

The first measurement was taken in the environment of our cryo-lab, showing clearly a resonance around 250 Hz which also was predicted by ANSYS [10] simulations and a second one at 450 Hz (fig. 9). These measurements have been taken by sweeping over a frequency range between 0 and 500 Hz. It was found that sweeping time has an effect on the spectra we obtained. Sweeping too fast gives not enough time to stimulate high quality mechanical resonances. Sweeping too slow evokes interferences between decaying resonances and altered stimulating frequency. Good results were obtained in general by using 30 seconds sweeping time for the above mentioned frequency range.

Because of the dependency on sweeping time it was desired to have a second method to confirm the results, which we found by using a white noise signal (fig. 10). Meanwhile the setup had moved into an anechoic chamber of an acoustic laboratory to avoid perturbing background noise. Here we found a good agreement between sweep and noise measurements, although the resonance spectrum was not exactly the same as before in the cryo-lab; since the cavity had moved the mechanical conditions had changed a little affecting the resonances. Exploring deep resonances below 100 Hz by using larger exciting amplitudes for sweeping, which could be applied at such low frequencies without having distortions, we found another predicted resonance at 83 Hz (fig. 11), but with quite low amplitude, which is considered to be harmless.

Last measurements within the anechoic chamber have been done by using a second piezo as an impact sound microphone at the opposite side of the tank. These spectra differed in some detail from the ones that had been taken with the microphone since the piezo is only sensitive to vibrations at the area of contact, but they are generally in good agreement (fig. 12). It could quite impressively be shown that especially resonances between 200 and 300 Hz can be attenuated by introducing additional fix points at the longitudinal corset rods shown in fig. 8. - An estimation of the Q-values for the main resonances was done following the 3 dB method (tab. 2).

Figure 8: Setup for microphonics measurements at room temperature. The actuating piezo is installed between an endplate of the outer corset and the cavity near the beam pipe.

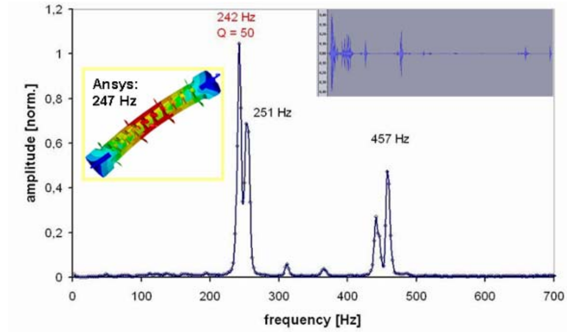

Figure 9: Measured resonances between 200 and 500 Hz. A graphic data output of an ANSYS simulation shows the displacements encoded in colours of the basic transverse mode between fixed ends measured at 242 Hz. The simulated value is 247 Hz. The recoded wave data during sweeping are displayed on top right of the graph.

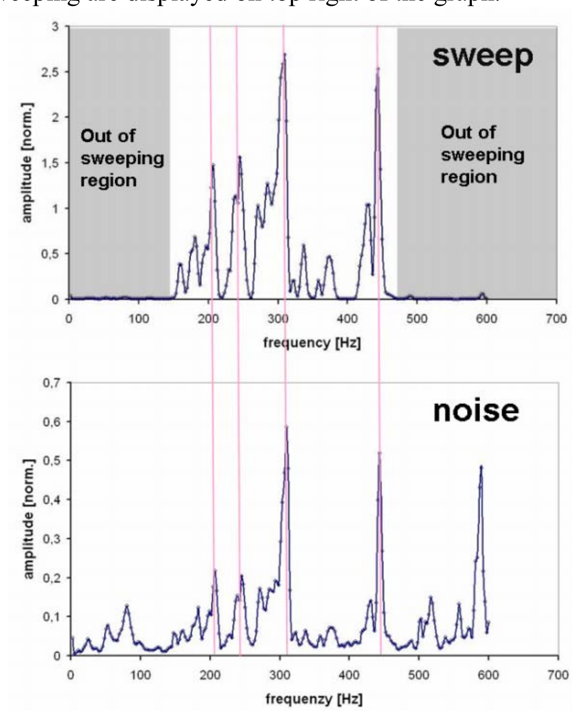

Figure 10: Same frequency range as in fig. 9 but now measured after moving into an anechoic chamber. A good agreement between sweeping technique and white noise method is seen for modes occurring in both cases.

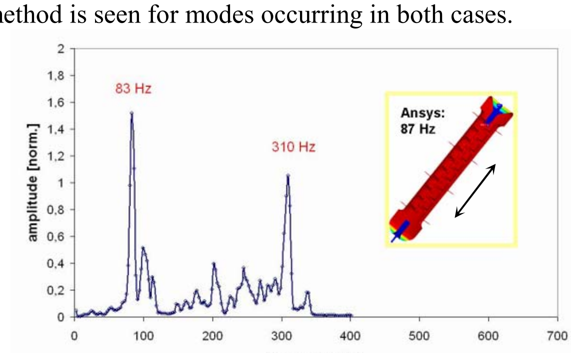

Figure 11: Focus on deep resonances (sweeping method) and corresponding ANSYS simulation, showing the basic longitudinal mode between fixed ends.

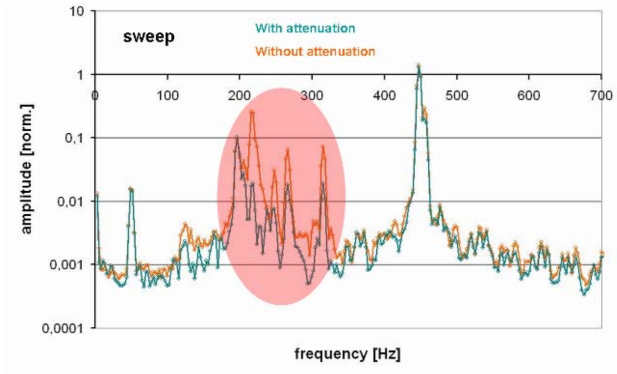

Figure 12: Damping of resonances between 200 and 300 Hz (plotted in logarithmic scale). Extra fix points at the corset rods were added (highlighted region in fig. 7).

Frequency	Quality
85 Hz	12
250 Hz	50
310 Hz	40
450 Hz	100

Table 2: *Q*-values of the most distinct mechanical resonances.

FIRST PIEZO TUNING

Resonances were again observed and analyzed at cryogenic temperatures with a second piezo used as an impact microphone. In addition, the rf-detuning by the acting piezo was observed for the first time via the VCO-signal of the control system (fig. 13). A perfect deviation control was provided even at highest mechanical amplitudes. It is obvious that some mechanical resonances affected the VCO-signal considerably (279 Hz) while others do not (450 Hz). It is an interesting fact that especially resonances between 200 and 300 Hz can effectively be damped (fig. 12), which is not the case for the 450 Hz resonance; but that one can be neglected because it does not have an impact on the rf-resonance.

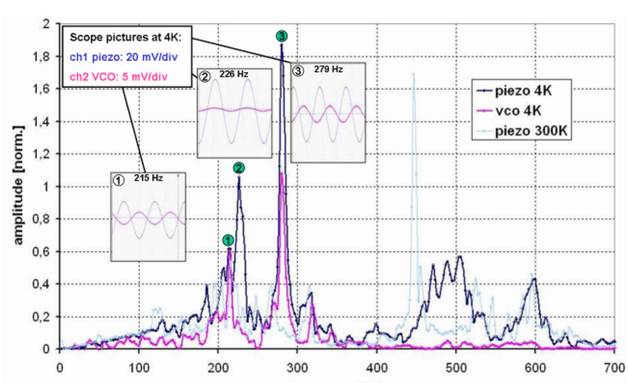

Figure 13: Microphonics at cryogenic temperatures and the impact on the rf-resonance. Three resonances are pointed out, corresponding oscilloscope pictures are shown. Case 2 at 226 Hz can clearly be detected by the piezo sensor, but has no impact on the VCO signal.

CONCLUSIONS

A piezo tuner has been designed and manufactured for the superconducting CH-prototype structure. The piezos have already been tested at cryogenic temperatures and have proven their reliability and tuning capabilities. Mechanical resonances were investigated in detail and an effective damping technique for low resonances has been elaborated. The control system has proven a perfect rf-deviation control during mechanical resonance testing. Next step will be the preparation of a horizontal cryostat and subsequent tests of the complete tuning system.

ACKNOWLEDGEMENT

This work has been supported by GSI, BMBF contr. No. 06F134I and EU contr. No. 516520-FI6W. We acknowledge also the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contr. No. RII3-CT-2003-506395) and EU contr. No. EFDA/99-507ERB5005CT990061 between EURATOM/FZ Karlsruhe IAP-FU. The work was carried out within the European Fusion Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Special thanks to Dr. K. Schnell for friendly support with data analysis and acoustic requirements. We also would like to thank the company ACCEL for excellent work, and our technical staff at the IAP Frankfurt, especially D. Bänsch, I. Müller, G. Hausen, S. Reploeg and H. Kronenberger; thanks also to K. Dermati (GSI) for mechanical ANSYS simulations.

REFERENCES

[1] U. Ratzinger, Habilitationschrift, Uni. Frankfurt, 1998.
[2] H. Podlech, A. Bechtold, M. Busch, H. Klein, U. Ratzinger, "Developement of the Superconducting CH-Cavity and Applications to Proton and Ion Acceleration", these proceedings.
[3] H. Podlech, C. Commenda, H. Klein, H. Liebermann, U. Ratzinger, A. Sauer, "First Cryogenic Test of the Superconducting CH-Structure", proc. EPAC2006.
[4] H. Podlech, A. Bechtold, H. Liebermann, U. Ratz-inger, "Status of the Superconducting CH-Structure", proc. PAC2007.
[5] http://www.cst.com.
[6] http://www.comsol.com.
[7] M. Fouaidy, et al., "Full Characteriza-tion at Low Temperature of Piezoelectric Actuators used for SRF Cavities Active Tuning", proc. PAC2005.
[8] M. Liepe, et al., "Dynamic Lorentz Force Compensation with a fast Piezoelectric Tuner", proc. PAC2001.
[9] G. K. Davis, J. R. Delayen, "Piezoelectric Tuner Compensation of Lorentz Detuning in Superconducting Cavities", proc. PAC2003.
[10] http://www.ansys.com.