Conceptual Study of a Tuning System for the Superconducting CH-Resonator

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Abstract

The superconducting CH multi-cell prototype cavity was equipped with a frequency tuning system. The rf-tuning during operation bases on the principle of a slight elastic deformation at both end walls 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. 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. The CH-Prototye is currently integrated into a horizontal cryostat. The mechanical preparation of the cryostat is already done, first vacuum and cold tests with liquit nitrogene have been accomplished successfully. In parallel first parts of the tuning control system are developed.

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 emission [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 cryogenic test campaign in 2007 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, was developed.

Figure 1: CH-prototype and investigated piezo actuator for application of tuning forces (red arrows).

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 a pushing or pulling force at the end 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 the 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 $F_{\mathrm{def.}} = 6.5$ kN must be applied to have a deformation of $\Delta x = 1$ 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 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.

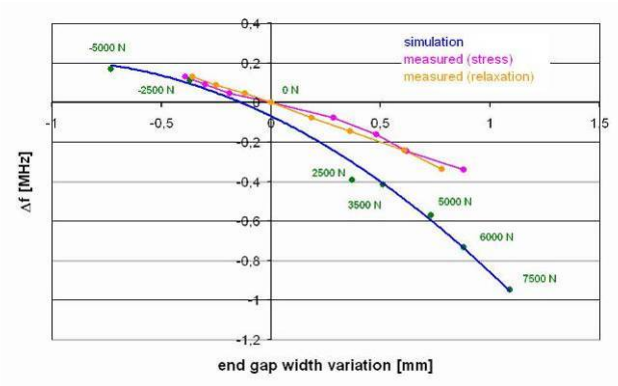

Figure 2: Simulated and measured rf-response.

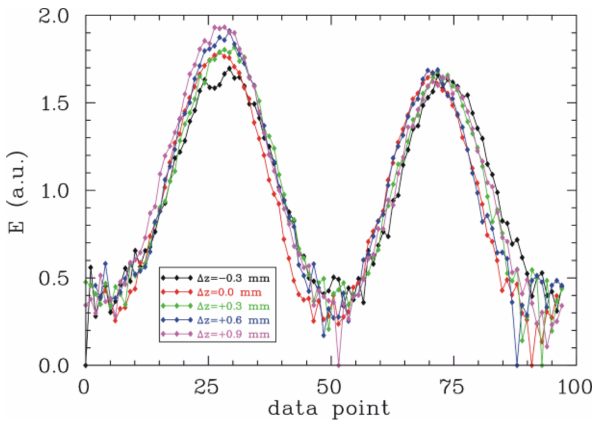

Figure 3: Measured change of field distribution according to an end gap deformation Δx.

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 an intermediate temperature between 4 K and 80 K, The operating temperature has strong impact on 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.

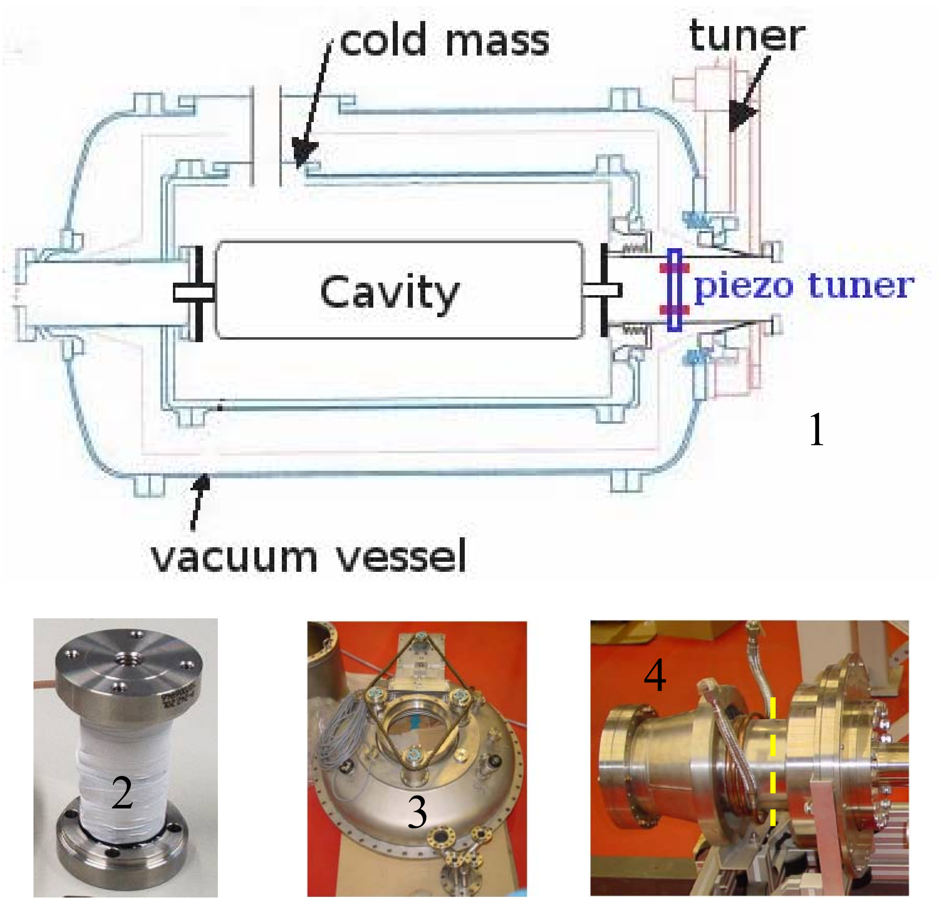

Figure 4: Scheme of the cryostat with tuner positioning (1), a piezo from Physical Instruments (PI) (2), the mechanical tuner (3) and beam pipe (4) were piezo tuner shown in fig. 1 will be included close to the cooling loop in the middle (dotted line).

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 at an intermediate temperature (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.

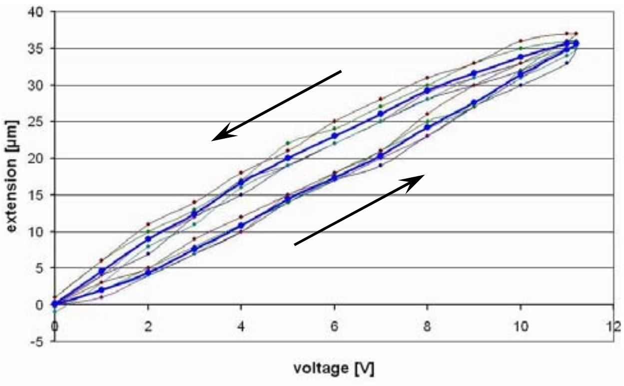

Figure 6: Measured piezo stroke hysteresis curve vs. control voltage at room temperature; slim lines for 5 individual piezos, averaging in fat blue.

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.

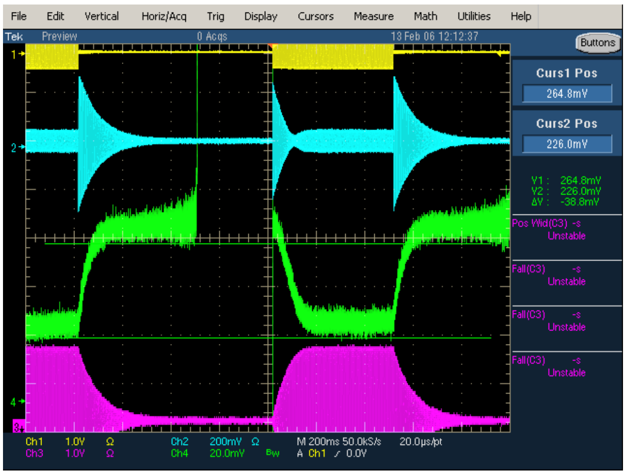

Figure 7: The VCO signal (green) as a direct indication of Lorentz-force detuning. Rf-pulse (yellow), Reflected power (blue), transmitted power (pink).

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 was 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 was 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 was detected (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.

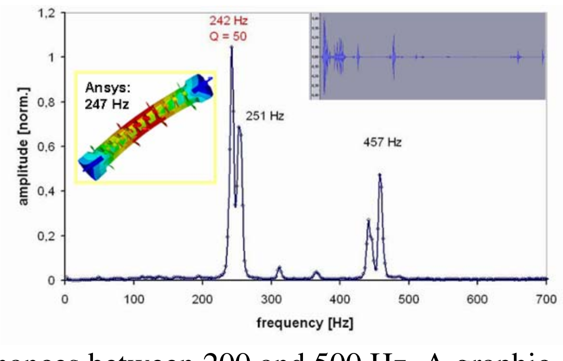

Figure 9: Measured resonances between 200 and 500 Hz. A graphic data output of an ANSYS simulation shows the displacements encoded in colours of the basic transverse mode between

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.

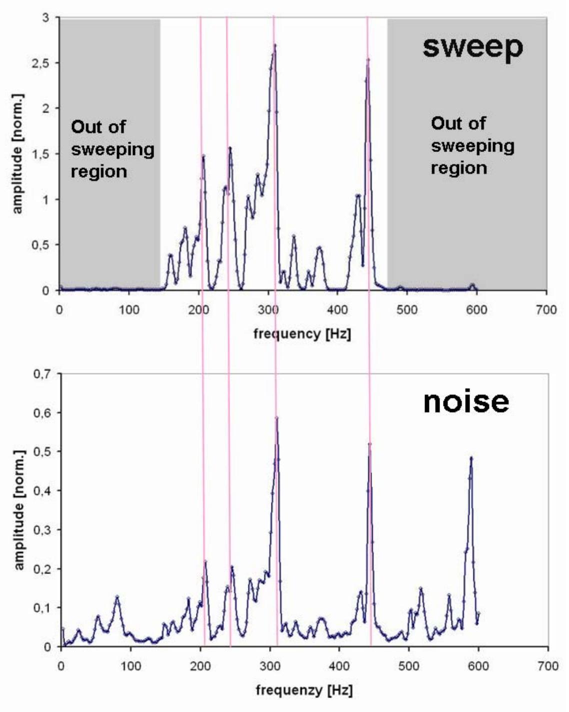

Figure 10: Same frequency range as in fig. 9 but now measured after moving into an anechoic chamber. A good agreement between sweeping technique and white noise method is seen for modes occurring in both cases.

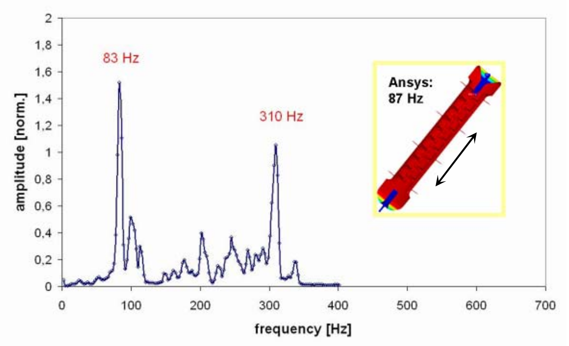

Figure 11: Focus on deep resonances (sweeping method) and corresponding ANSYS simulation, showing the basic longitudinal mode between fixed ends.

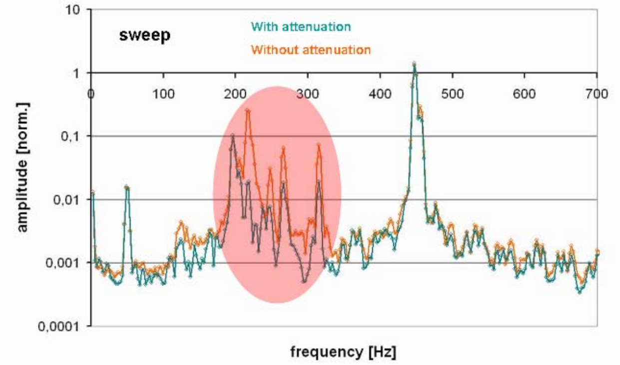

Figure 12: Damping of resonances between 200 and 300 Hz (plotted in logarithmic scale). Extra fix points at the corset rods were added (highlighted region in fig. 7).

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.

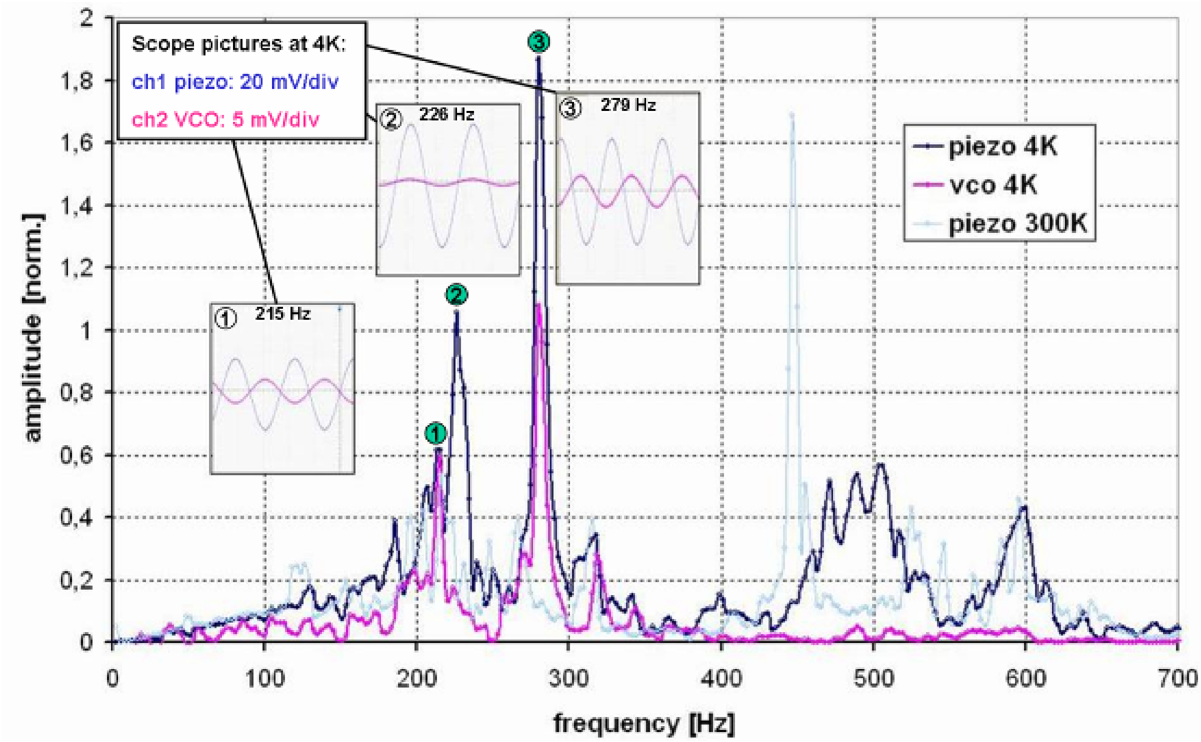

Figure 13: Microphonics at cryogenic temperatures and the impact on the rf-resonance. Three resonances are pointed out, corresponding oscilloscope pictures are shown. Case 2 at 226 Hz can clearly be detected by the piezo sensor, but has no impact on the VCO signal.

Installation of the CH-Prototype into a horizontal Cryostat

All parts of the horizontal cryostat are now assembled and aligned. A first vacuum test of the inner cold mass has been performed successfully. The liquid nitrogen cooling system is prepared and closed now; it has been extended by an additional cooling loop at the pump port of the cavity. A first cold test has been accomplished successfully. A driver for the slow mechanical tuner has now been designed and constructed and allows either a manual or a computerized operation. This device has passed a first test run. The driving speed of the stepping motor can easily be changed and will be adjusted during the first performance test with the cavity. The piezos are currently underlying a second performance test regarding the frequency dependence of their actuation. The basic idea is to transform the translation of piezo into an angle variation of a mirror, which can be observed by a reflected laser beam (fig. 14).

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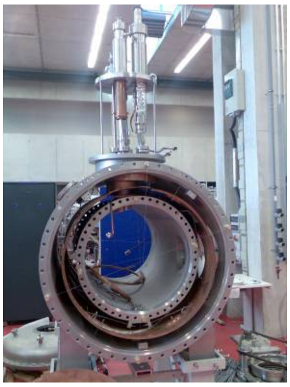
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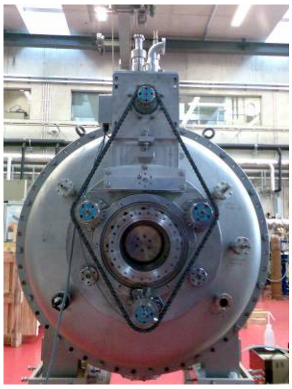
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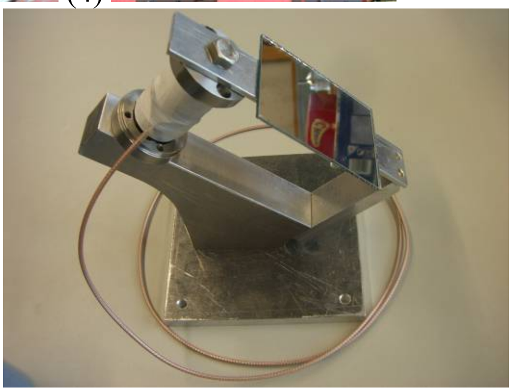

Figure 14: (1) The cryostat during alignment procedure (2) Beam lead-through including piezo retainer (3) Cooling loop at pump port (4) The slow mechanical tuner at performance

check (5) The control unit of the mechanical tuner (6) Set-up for piezo frequency response measurement.

The mechanical preparation of the cryostat is done; it is now ready to include the CH-structure. A first vacuum test and a cold test with liquid nitrogen have already been done successfully (fig.15, 16).

Figure 15: Cold test of the horizontal cryostat with liquid nitrogen.

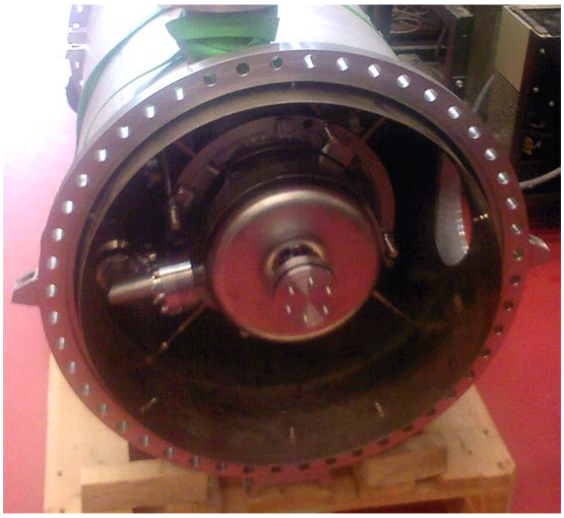

Figure 16: CH-prototype within the inner cold mass including μ-metal shielding.

An Advanced CH-Prototype Cavity with Membrane Tuner

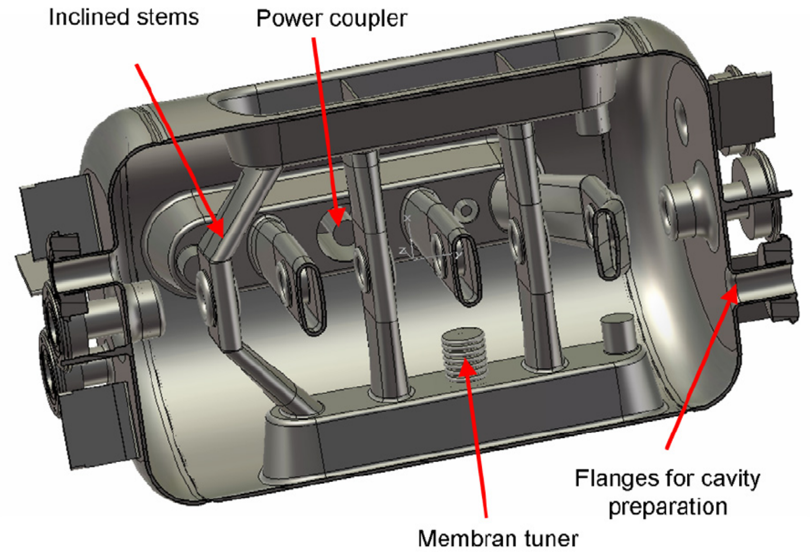

Figure 17: Layout of the superconducting 325 MHz, β=0.154 CH-cavity which will be tested at GSI for high power applications.

Recently the cavity geometry has been optimized based on the experience with the prototype cavity. The new de-sign has reduced drift sections in the end-cells which leads to very compact cavities with improved beam dynamics. Additionally, the new geometry is capable to handle more RF power and it has an innovative tuning concept using internal membrane tuners. A 325 MHz prototype cavity optimized for a particle β of 0.15 is under construction. This cavity will be fully equipped with cryo module, power coupler and tuner sys-tem. It is also planned to test this cavity with beam behind the Unilac at GSI. The above picture shows the new 7-cell CH-cavity.
The most obvious change compared to the first prototype is the inclining of the outermost stems to homogenize voltage distribution along beam axis. Field flattening was realized at the prototype by lengthening the drifttubes which are embedded in the tank wall, which is rather disadvantageous especially at high beam currents where elements should be connected to the cavities by minimized drift spaces.

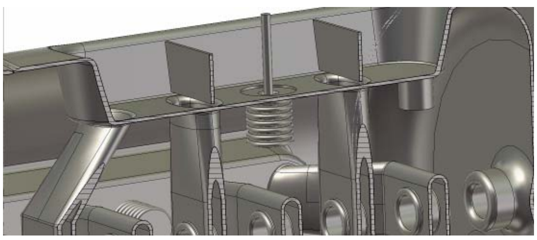

Figure 18: Fast Membrane tuner for the new CH-structure at 325 MHz, $\beta = 0.154$.

The design of the stems has been changed in a second way: The ratio between logitudinal and transversal stem diameter has been inverted, giving more space in between to locate the power coupler and the new membrane tuners. This change has been done by accepting a slightly higher magnetic peak field at the basis of each stem. The magnetic peak fields are a limiting factor regarding the maximum achievable accelerating field.

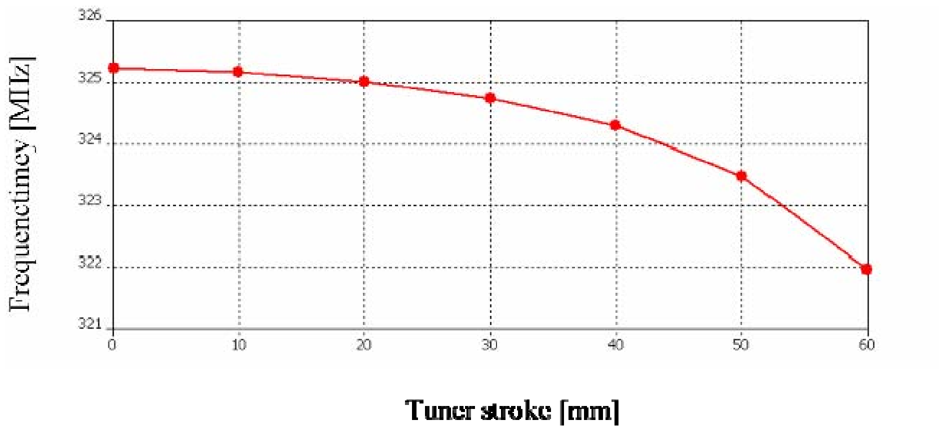

Figure 19: Performance of the membrane tuner.

Through the girders, the CH-cavity allows direct access to regions well suited for coactive frequency tuning (fig.17). At a height of 35 mm above the cavity wall, the tuning efficiency is about 50 kHz/mm (fig.18).

Figure 20: Membrane tuner, prototype for mechanical tests.

Conclusions

Important aspects of the rf-tuning of CH-cavities were especially investigated on the first prototype cavity. Tuning by deformation of the end walls is a possibility and will be demonstrated finally by a fixed frequency operation of the CH-cavity within the horizontal cryostat. The experiments will be performed in early 2009.
Disadvantages of this technique are the needed space for tuner installations at the end walls which causes some extra drift spaces. This results in linac performance limitations – especially in the case of high current beams. Moreover, deformations of the cavity surface imply high mechanical forces and a change in gap voltage distribution. This gave the motivation to test an advanced tuning system, namely the membrane tuner.
A prototype was welded and mechanically tested in close cooperation with ACCEL GmbH (fig. 20), Bergisch-Gladbach, Germany. It is expected that this concept will lead to a quite improved overall performance.

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