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

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Abstract

The radio frequency tuning of the multi-cell superconducting CH structure for low and medium beta values is investigated for a 19-cell niobium prototype cavity with beta = 0.1. By applying external mechanical forces the deformation of the structure is studied and the resulting change in frequency is analysed. A detailed mechanical analysis forms the basis of a conceptual study of a tuning system that consists of a slowly acting mechanical device and fast piezo elements. The whole sytem will be integrated into an existing horizontal cryostat for testing purposes.

Acknowledgements

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Introduction

The superconducting **C**rossbar-**H**-type **CH**-structure is a multi cell drift tube cavity operated at the H_21(0)-mode. It is designed for protons and ions in the low and medium energy range [1]. A 19-cell, β=0.1 prototype cavity with a length of 105 cm and a diameter of 28 cm has been developed at the IAP in Frankfurt. The corpus of the cavity is made of niobium sheets with a thickness of 2 mm and a RRR-value of 250. Figure 1 shows a schematic picture of the structure.

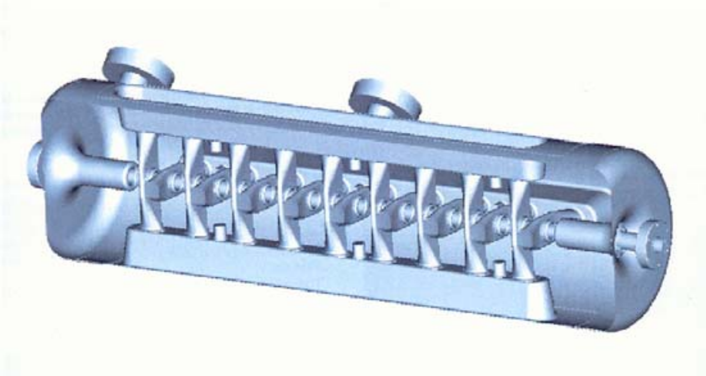

Figure 1: The 19-cell prototype CH-cavity

Several cryogenic tests in a vertical cryostat have already been performed and an effective accelerating voltage of 3.8 MV in cw operation has been achieved [2]. This report describes the main capabilities of the CH-cavity with respect to rf frequency control. It contains measurement results of the prototype cold tests as well as simulations. The design of a rf tuner and the status of the horizontal cryostat, the future testing facility are reported.

RF measurements in the superconducting state

To test the CH-cavity at 4K a new cryogenic RF laboratory has been established in Frankfurt.

It is equipped with:

- Class 10000 clean room
- Class 100 laminar flow box
- 3 m vertical bath cryostat
- Magnetic shielding
- 2 transport dewars for liquid helium
- 2 kW RF amplifier
- 50 W amplifier
- Helium recovery system
- RF control system
- Temperature measurement system

Figure 2 shows a view of the cryogenic laboratory with the RF system and figure 3 presents the CH-prototype with the position of 8 temperature sensors before mounting in the cryostat. The cavity has been pre cooled with liquid nitrogen and than cooled down with liquid helium

below the critical temperature. The cavity reached the superconducting state without problems.
At a field level of about 40 kV/m a first multipacting barrier occurred. But this barrier could be processed within one hour without problems. The experience with a large number of existing H-type structures showed that there is in general no problem with multipacting. As expected multipacting is not a severe problem for superconducting CH-structures too.
The control system which has been developed in Frankfurt worked very well. During the second day of the first cold test a maximum accelerating voltage (including the transit time factor) of about 3.54 MV has been reached in cw operation. The limitation in the test was given by the effect of field emission at electric surface peak fields of more than 20 MV/m. The maximum voltage corresponds to an electric surface peak field of 24 MV/m and a maximum magnetic peak field of 26 mT. The design gradient of the prototype cavity (3.2 MV/m) has been exceeded. The reached gradient with respect to the full cavity length was 3.4 MV/m and with respect to a length of $n*\beta\lambda/2=9.5\beta l$ was 4.45 MV/m. In pulsed operation these fields have been exceeded. Figure 4 shows typical RF signals of the CH-prototype cavity and figure 22 presents the measured Q versus E curves.

The Q-value decreases typically for superconducting structures due to non Ohmic losses like field emission. The Q-value at low field was 5e8 which corresponds to a total surface resistance of 110 nΩ. The BSC value at 4.2K and the design frequency is 41 nΩ. Together with an additional resistance due to trapped magnetic flux of 4 nΩ, the surface residual resistance is 65 nΩ. The dissipated power at the design gradient was approximately 15W.

Figure 2: The cryogenic RF laboratory in Frankfurt.

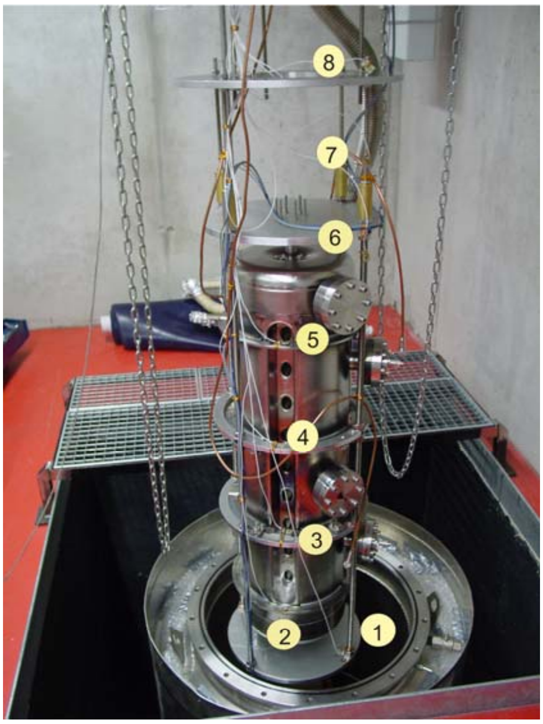

Figure 3: The superconducting CH-prototype with 8 temperature sensors ready for the first cold test.

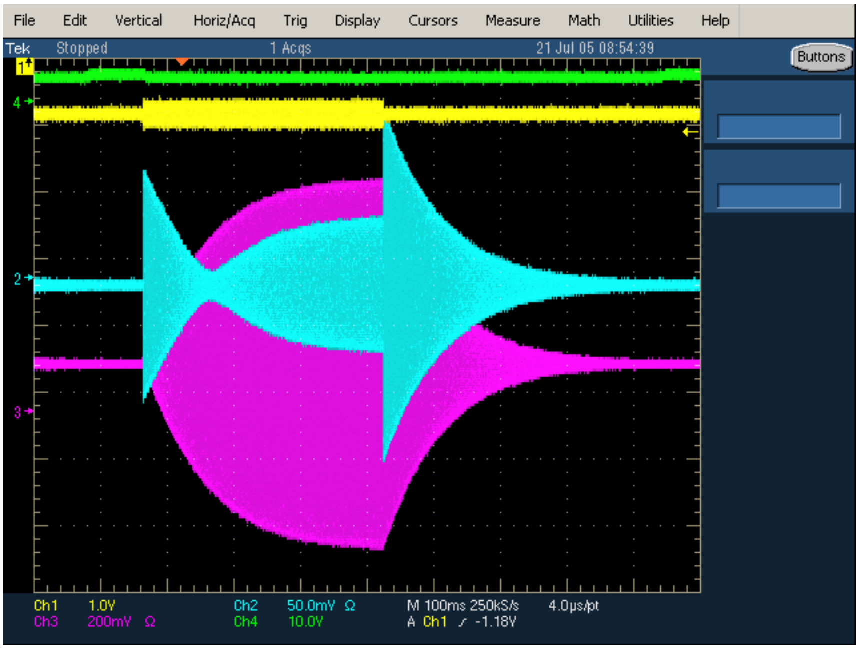

Figure 4: RF signals during the first cryo test of the superconducting CH-prototype. (Yellow=forwarded power, green=reflected power, purple=transmitted power.)

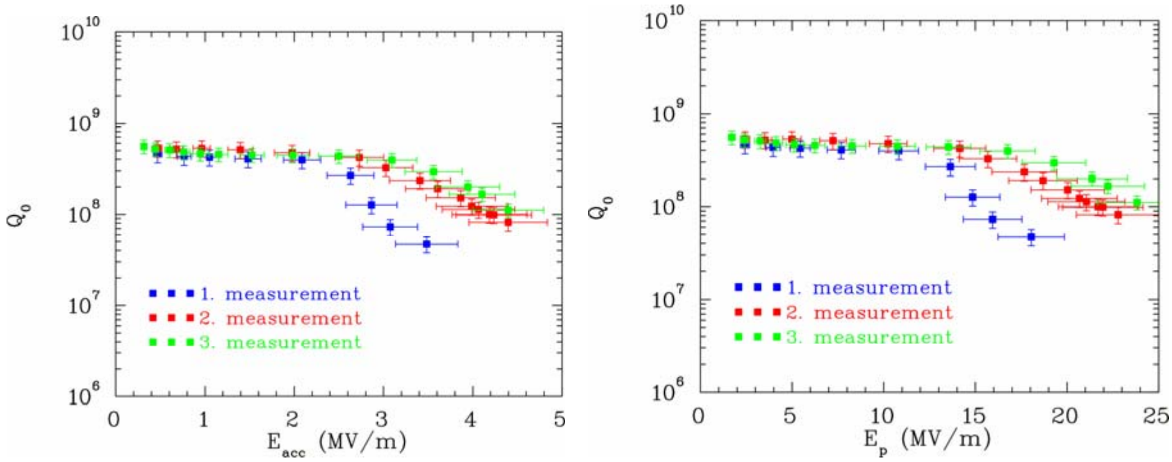

Figure 5: Left: Q-value as function of the accelerating gradient based on an accelerating length of l=9.5βλ. Right: Q-value as a function of the corresponding maximum electric surface field. The operation mode was cw.

Figure 6: The CH-cavity during a vacuum test before the chemical treatment

A detailed mechanical structure analysis of the cavity forms the basis for the design of a tuning device.

Mechanical Analysis:

Frequency shift during cooling down

The mechanical analysis of the CH-structure is focused on the description of the deformation under loads at liquid helium temperatures. Mechanical loads are either applied uniformly on the surface like the hydrostatic vacuum pressure inside the cavity or are applied locally by controlled external forces. Every deformation results in a change of the eigenfrequency and can be used to tune the cavity. All loads have to be limited by fracture criteria to avoid a mechanical damage of the structure. The first experimental evidence of a frequency shift is observed by the cooling of the structure which results in a homogeneous contraction. If the cavity is unconstrained no additional stresses occur in the material. The measured changes in frequency can be compared with calculated values, obtained by uniformly scaling the model for the CST Microwave Studio [3] analysis according to temperature dependent contraction data for niobium [4].

Figure 7 shows the comparison, where the data points with error bars are related to the experiments and the black data squares show the simulation results. Its has to be mentioned that relatively large temperature differences along the cavity occurred during the rather fast cooling procedure. The experimental temperatures are averaged values of all sensor outputs.

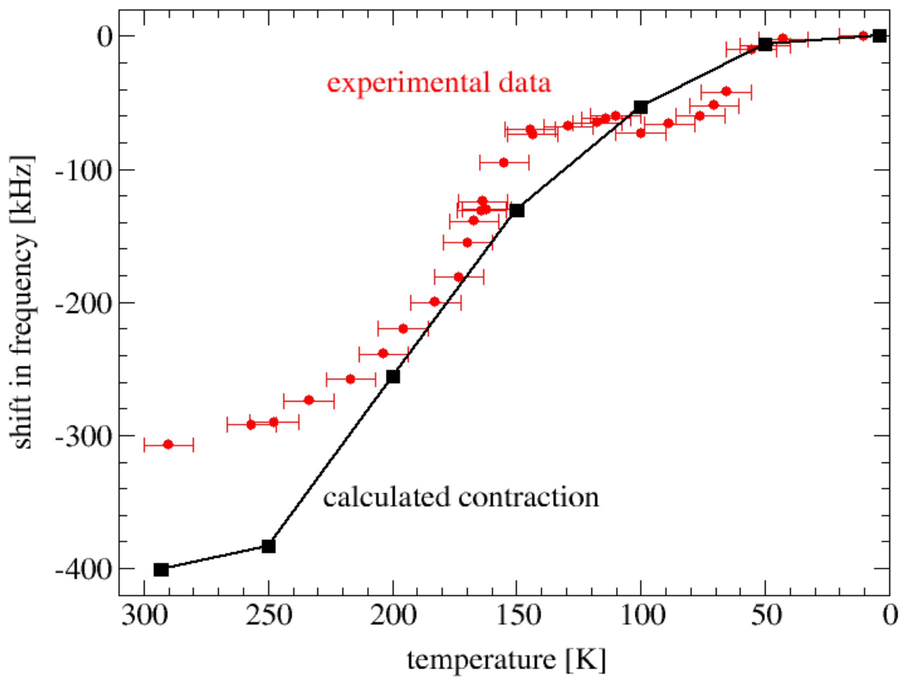

Figure 7: Shift in resonance frequency during cooling to liquid helium temperatures

Cavity rf tuning by a deformation of the end caps

For the tuning of the cavity the effect of an external force applied on the outer half drift tubes parallel to the beam axis is analysed. Since the body of the structure is quite rigid only the deformation of the end caps is considered. The FEM tool COMSOL Multiphysics [4] has been used to investigate the structure mechanical behaviour. The result of the simulation for a force of 4 kN pushing at the drift tubes of the cavity is represented by the distribution of the von Mises stress. Figure 8 and 9 show the deformed end caps from the outer and inner side of the cavity. The applied force leads to a maximum displacement of 0.59 mm.

The red shaded regions depict the maximum values of the von Mises stress that are plotted in figure 10.
A negative external force is obtained by pulling both ends of the structure. The minimum of the von Mises stress is not reached at zero external force, because it is assumed that the cavity is under vacuum and the atmospheric pressure applies on the outer surface.

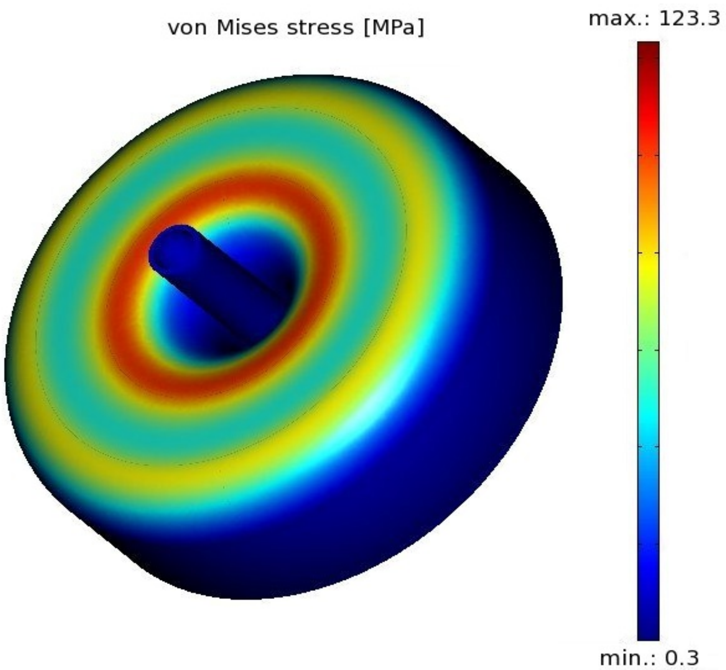

Figure 8: Deformed end cap at an external force of 4 kN from outer side of the cavity

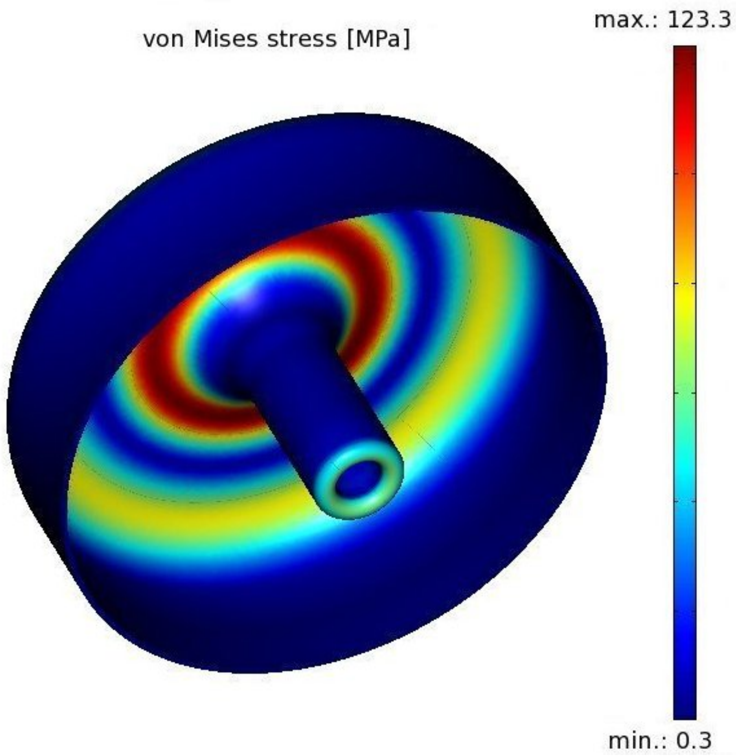

Figure 9: Deformed end cap at an external force of 4 kN from inner side of the cavity

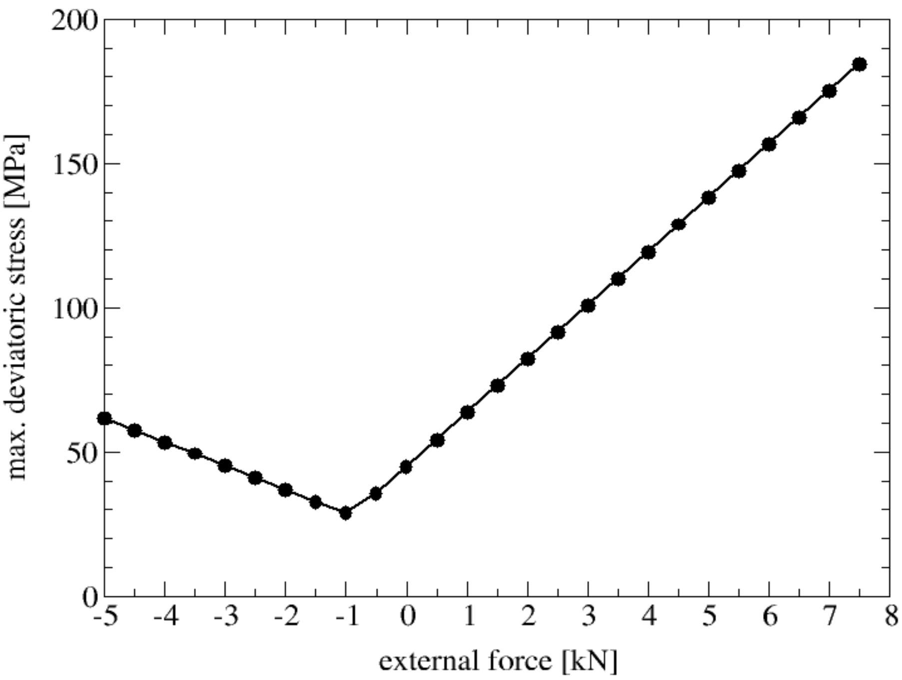

Figure 10: Maximum values for the von Mises stress

In order to calculate the shift in frequency we replace the undeformed end caps in the model for the CST Microwave Studio simulation by the deformed ones for several values of the external force and redo the eigenmode analysis with the same mesh parameters. The main effect that causes tuning is the change in capacity due to a variation of the end gaps. The result of this analysis is presented in figure 11.

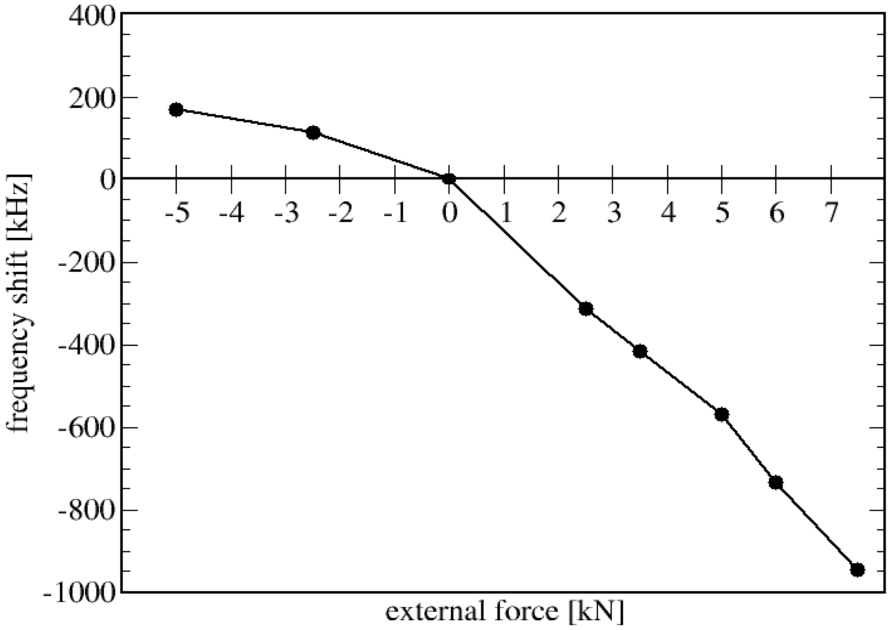

Figure 11: Shift in frequency due to external force

Figure 12 shows the change in the electric field distribution along the axis of the cavity mainly caused by a reduction of the end gaps. The black coloured line corresponds to the undefomed structure. The effect at the position of the first gap, where the displacement reaches its maximum value is depicted in figure 13 on a larger scale.

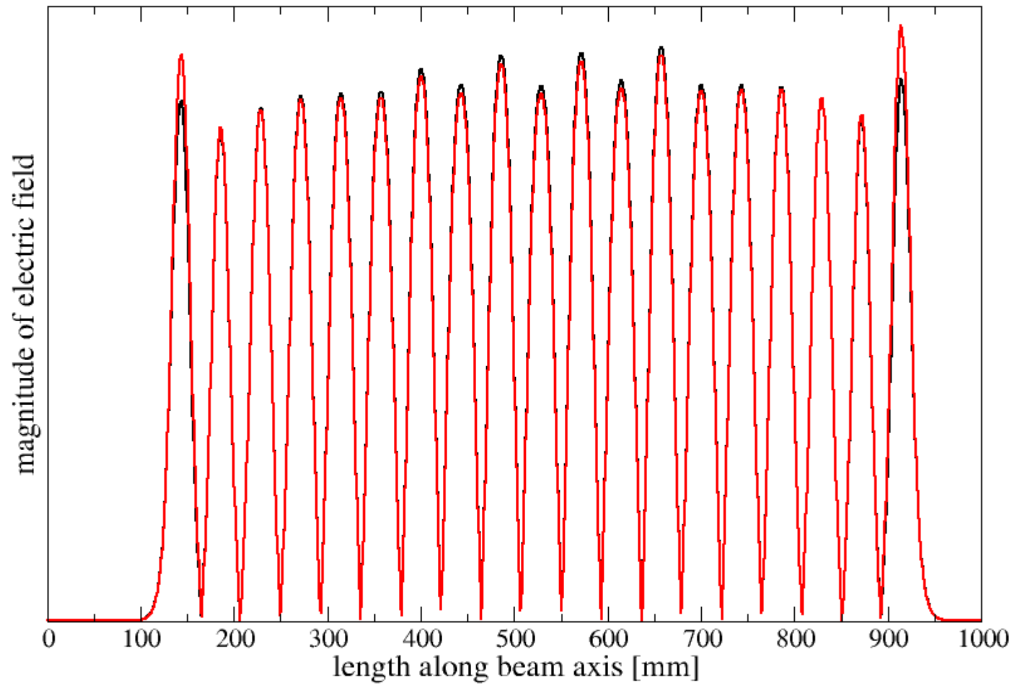

Figure 12: Simulated change in electric field distribution along the axis of the cavity. Each end gap length was reduced by 0.73 mm, the frequency was shifted by 600 kHz, corresponding to an external force of about 5 kN (fig. 11)

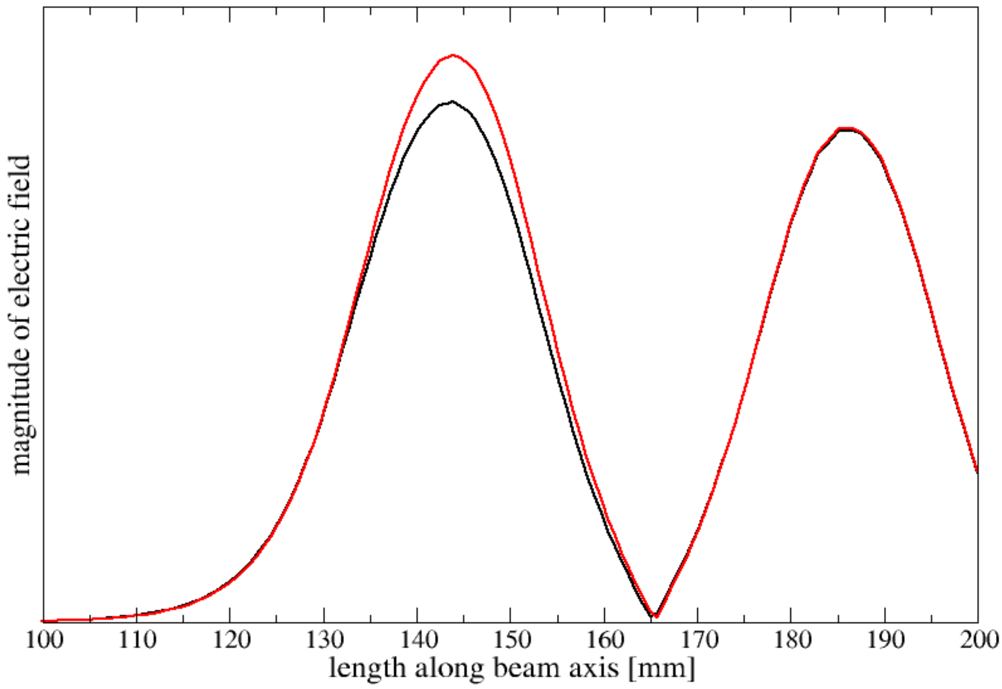

Figure 13: Change in electric field distribution across the first and second gap

Vacuum pressure and Lorentz detuning

There is further experimental evidence for a shift in frequency due to a change in external pressure (figure 14) and a variation of the squared electric field strength (figure 15).

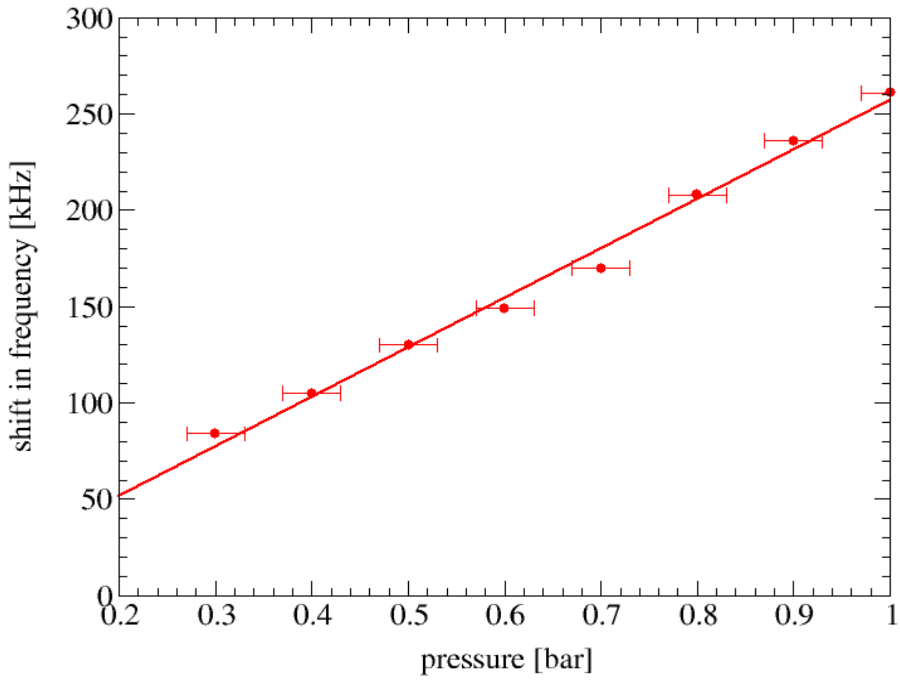

Figure 14: Shift in frequency due to change in external pressure

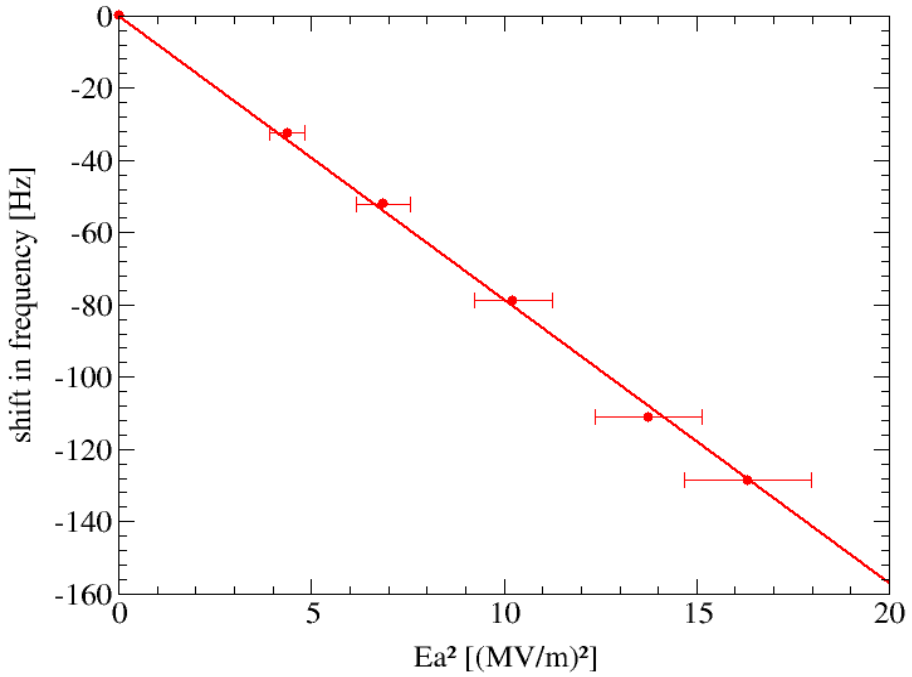

Figure 15: Shift in frequency due to a change in electric field strength (Lorentz detuning)

Mechanical Cavity Vibrations (Microphonics)

For the simulation of the vibrational eigenmodes of the system we take a connection between the outer drift tubes and the corpus of the cavity into account, which had not been implemented in the model from the very beginning. Figure 16 shows a picture of this detail, which has a strong influence on the characteristics of the vibrational modes at low frequencies. In addition new symmetry boundary conditions have been applied, which make it now possible to describe the whole length of the cavity. The advantage of this description is that a variation of the geometry of the inner structure of the cavity along the longitudinal axis can be taken into account in the future.

Figure 16: Connection between outer drift tube an corpus of the cavity

The ends of the drift tubes are fixed in space during the simulation, which explains why the minima of displacement are settled there as can be seen in figure 17. The vibrational modes in the area of frequencies < 100 Hz should be avoided (coupling to background noise and vibrations at the power supply frequency of 50 Hz).

Table 1 summarizes the first 3 eigenfrequencies of the CH-cavity.

1.	**2.**	**3.**	**Mode**
87	247	405	**Hz**

Table 1: Lowest 3 vibrational modes of the CH-prototype resonator

Figure 17 and 18 show a three dimensional representation of the first and second vibrational modes. The displacements are up scaled to get an impression of the motion. The first mode has no transverse displacement and shows a movement along the longitudinal axis only. The cavity is assumed to be fixed in a horizontal position under the impact of gravity. The second mode shows transverse displacement and is depicted in figure 18. In the new testing facility these mode will be damped by an accordingly designed mechanical support between cavity and cold mass of the horizontal cryostat.

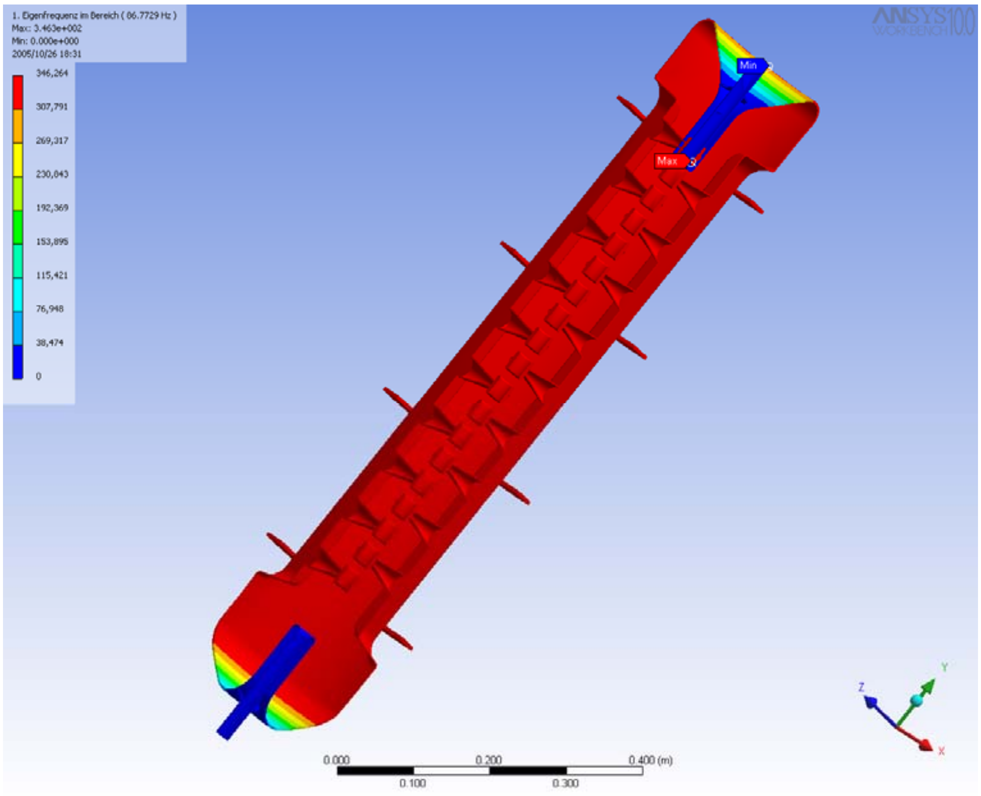

Fig. 17: First vibrational mode of the CH prototype at a frequency of 87 Hz.

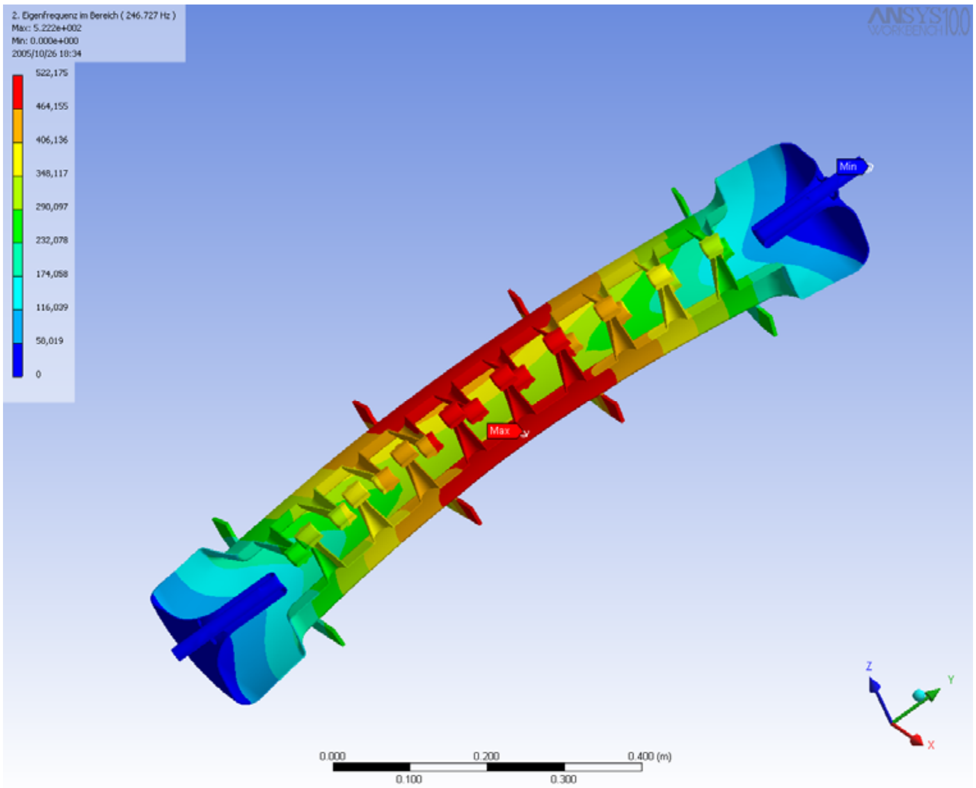

Fig. 18: Second vibrational mode of the CH prototype at a frequency of 247 Hz

Conceptual studies of a tuning system

The vacuum chamber and the thermal shield:

For testing purposes a cyromodule has been supplied, which offers the possibility to operate the cavity in horizontal position. Figure 19 shows the outside of the vacuum chamber as it has been delivered The copper thermal shield that can be seen in figure 20 is cooled by liquid nitrogen. So there are two supplies on the top tower of the cryostat, one for nitrogen and one for helium. In its original set-up also the vacuum for thermal isolation was applied from the top. The supply tower of the cryomodule has to be reconstructed, especially with respect to the helium supply in order to fit with the standards of the already existing equipment. Additionally a new vacuum pump has to ordered that can handle the large volume of the chamber for thermal isolation purposes. Many of the sealings have to be replaced. In the vacuum chamber mainly Viton sealings are used, while in the cold mass HelicoFlex sealings have been applied.

Figure 19: Cyromodule with tuning possibility for operation in horizontal position

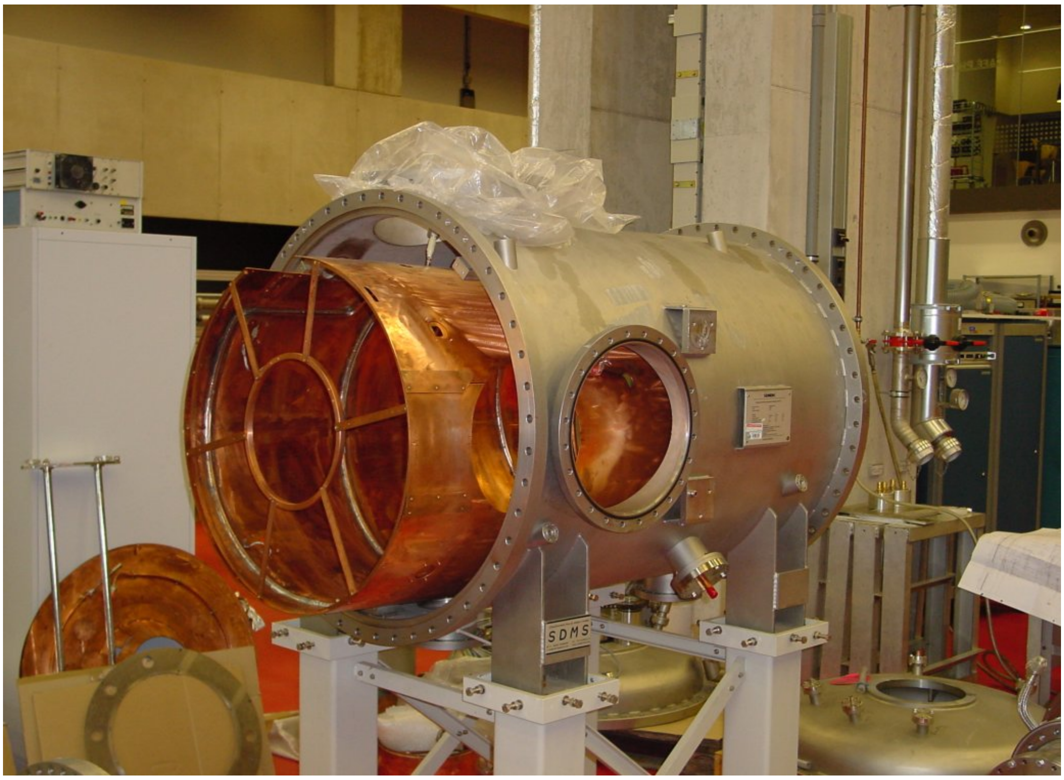

Figure 20: Center part of the vacuum chamber and the copper thermal shield inside

Coarse Mechanical Tuning:

On one end of the module the mechanical tuning unit is located, that is driven by a chain and a stepping motor. Figure 26 shows a more detailed picture. A new stepping motor has to be selected and there is a need for a controlling unit. The tuning range of this tuner is about 600 kHz for a displacement of the drift tube of the cavity of 0.73 mm. A force of 5 kN is necessary to achieve this.

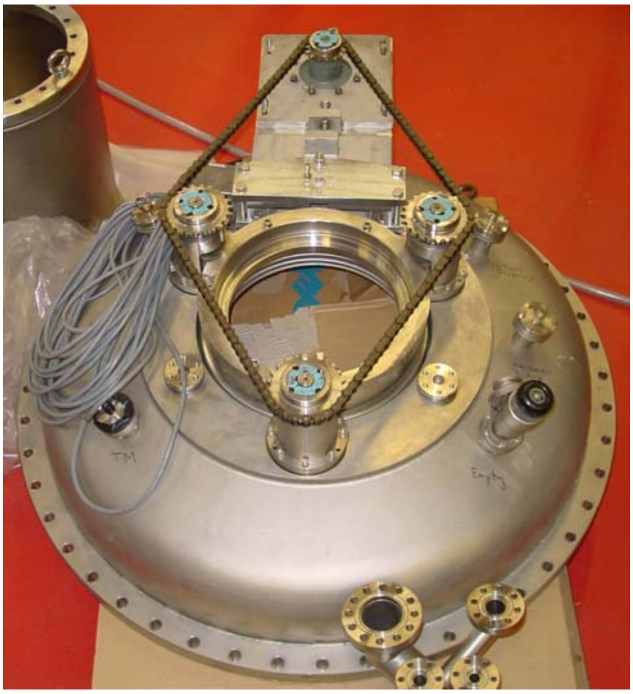

Figure 21: Mechanical tuning unit on one end of the cryostat

Incorporation of the cavity in the cold mass

Figure 22 shows a picture of the open cold mass that acts as a liquid helium tank and incorporates the cavity. The magnetic shielding is inside of this cylinder. In the schematic figure 23 the position of the cavity as well as the location of all the other surrounding components is shown.

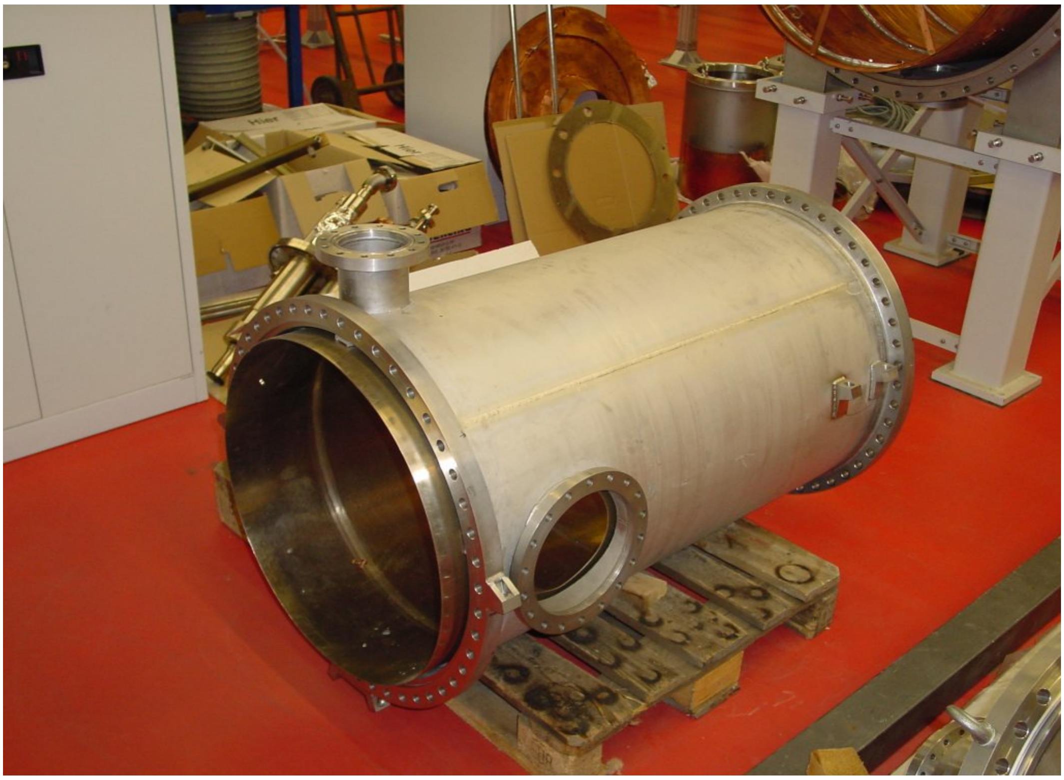

Figure 22: Main part of the cold mass with magnetic shielding inside

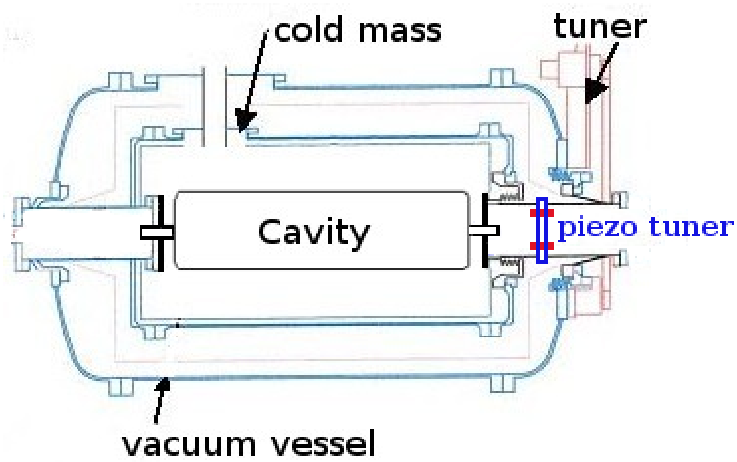

Figure 23: Cross sectional view of the cryostat showing the position of piezo tuner and mechanical tuner

Two flanges are designed to position the cavity in the cold mass. One flange constructed for a connection between the left side of the cavity and the end flange of the cold mass is shown in figure 24. This connection is stiff against axial motions, but it allows free choice of the angular position of the cavity.
The inner ring with 6 drill holes settles the position, where the ends flange of the cavity will be fixed.

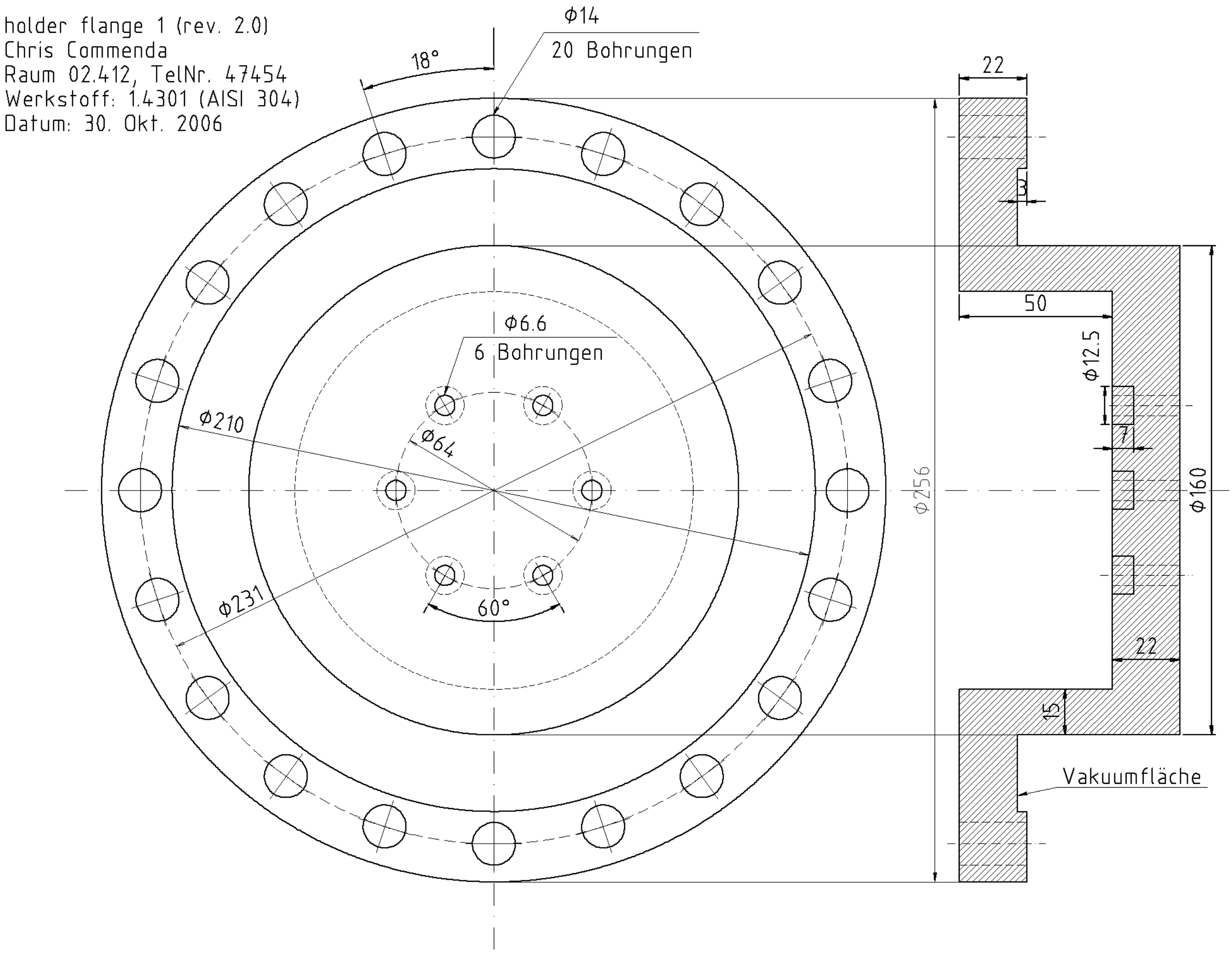

Figure 24: Fixed flange on one side connecting drift tubes of cold mass and cavity

The fast piezo tuner:

The axial drive of the cryomodule will incorporate the fast piezo tuner (Figure 23) with a tuning range of about 1 kHz corresponding to a total length cahnge of the cavity by 1.15 µm. The operation temperature of this fast tuner is at the liquid nitrogen level. Important is the mechanical coupling of the forces between piezo elements, chain drive of the cryostat and response of the cavity. For the analysis of this complicated situation we perform a FEM simulation. In order to get a more realistic picture of the situation of an operating cavity, three elements out of the beam line are used. Any misalignment leading to shear stresses above the allowed upper limit will break the brittle piezo crystals. For this design study the characteristics and measures of the piezo actuator P-242.20 from the company Physik Instrumente (PI) [6] is taken into account. A maximum elongation of 20 µm at room temperature is presumed. A cold test has to be performed in order to measure the true maximum elongation at liquid helium temperature. The low temperature version of this element is delivered without a jacket and preloading mechanism.

In principle it is possible to use a concept similar to a blade tuner to operate the superconducting CH cavity. Figure 25 shows a typical example of this type of tuner, the piezo-assisted tuner of a TTF- module at DESY. The testing of the CH prototype cavity in the new horizontal facility with fast piezo and slowly acting mechanical tuner will provide the necessary experience and data needed for the design of a dedicated CH-tuner. When all the necessary forces and the response of the cavity are known for the above mentioned tuner, the most important step to the stabilization of the frequency is done.

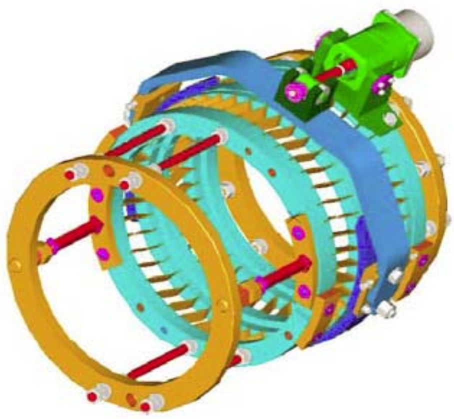

Fig. 25: Detailed 3D-drawing of a blade tuner frame with piezo-assisted tuner of a TTF-module at DESY (Courtesy of DESY TTF-facility).

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