HIGH POWER PULSED TESTS OF A BETA=0.5 5-CELL 704 MHZ SUPERCONDUCTING CAVITY

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Abstract

A β = 0.5 5-cell 704 MHz cavity was developed in the framework of European R&D programs on high intensity pulsed proton injectors. Medium beta elliptical cavities are known to be sensitive to Lorentz detuning, which can become difficult to deal with in pulsed operation. The cavity was optimized to reduce the Lorentz detuning by means of two series of rings welded around the irises, and equipped with a piezo tuning system. In order to test the cavity in pulsed mode, a power coupler with 1 MW capability was connected to the cavity. We report here on the fully equipped cavity tests at 1.8 K carried out in the horizontal cryostat Cryholab at Saclay to study its RF and mechanical behavior in pulsed mode, mostly with 2 ms pulses at a 50 Hz repetition rate. The compensation of Lorentz force detuning has been achieved at an accelerating gradient of 13 MV/m (44 MV/m peak surface electric field).

THE EQUIPPED BETA=0.5 CAVITY

The 5-cell 704 MHz Resonator

The cavity was designed specifically for pulsed operation [1]. The main feature of the cavity is the double series of rings for Lorentz force detuning (LFD) minimization. The stainless steel helium vessel has also been optimized in order to provide stiff mechanical boundaries to the cavities when combined with the tuner. The cavity was previously prepared with standard BCP followed by high a pressure water rinse (HPWR). It was tested in vertical cryostat [2] without and with its helium tank reaching an accelerating field of 15.5 MV/m at 1.8K. Field emission was observed during this test. Then it was installed in the Cryholab horizontal test cryostat [3] in order to test the magnetic shielding designed specifically for this cavity [4]. The low field Qo was measured at 3 10^{10}, proving the effectiveness of the magnetic shielding. Field emission was observed above E_{acc} = 8 MV/m, but could be processed away and a maximum accelerating gradient of 16.5 MV/m was obtained. During a measurement on the 4pi/5 mode of the fundamental passband, field emission resumed and could not be processed in-situ. The field emission onset on the fundamental mode was even reduced to 5 MV/m. This led us to perform an additional chemical etching and HPWR before subsequent tests.

Saclay-V Type Tuning System

The cold tuning system is a based on the same principle as the Saclay II tuner [5] for the slow tuning part. When the main screw rotates, the arms (red parts on Figure 1) communicate a rotation movement to the vertical eccentric spindles. The latter provide a function similar to a cam, so that a longitudinal displacement is created between the two main horizontal beams and the "feet" (in green on Figure 1), leading to cavity elongation. The tuner is attached to the cavity at the beam tube flange. Three supports are used to connect it to the helium tank, one on the piezo side, two on the opposite side. The tuner can lengthen or shorten the cavity by 2.7 mm symmetrically with respect to its neutral point.

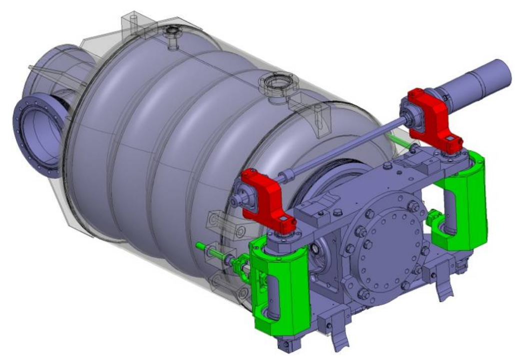

Figure 1: CAD model of the β = 0.5 cavity.

In the previous systems, the mandatory preload force on the piezo actuator was generated by the cavity spring-back force. A minimum elongation of the cavity was necessary in order to preload the piezo element with the correct force. The main improvement in the new tuner is the piezo support which is designed to provide this force independently of the actual cavity elongation needed to bring the cavity on tune.

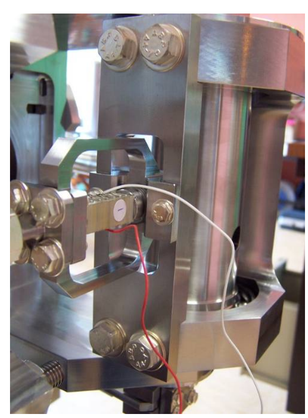

Figure 2: Close-up of the piezo support.

It consists in a stainless steel frame equipped with an adjustment screw acting as a support and a preload spring for the piezo (Figure 2).

In order to provide a force independently of the cavity elongation, the frame stiffness is ten times higher than the cavity stiffness. The piezo elements are 30 mm long stacks with a blocking force of 4 kN, and are able to produce a 3 μm stroke at temperature below 10 K for a maximum operating voltage of 200 V. This tuner prototype includes only one piezo actuator, but the design can accommodate a second piezo on the opposite side (motor side) if more stroke is required, or control of the transverse deformation of the cavity is needed. This was not required for the series of tests presented here.

In order to obtain a robust operation of the slow tuning mechanism, the gear box installed on the new tuner is a three-stage planetary system, with a reduction ratio of 1:100. Both the stepper motor and the gear box are working under vacuum and cryogenic temperatures.

Before assembly on the cavity, the tuner has been installed on a measurement bench to evaluate its stiffness at room temperature. The pneumatic jack of the bench is able to deliver a 7 kN force. At this maximum force, the displacement between the simulated cavity flange and helium vessel supports is 0.2 mm. The corresponding stiffness of the tuner is 35 kN/mm.

1MW Power Coupler

One pair of power couplers has been designed, built and tested in the framework of the CARE-HIPPI FP6 program (Figure 3).

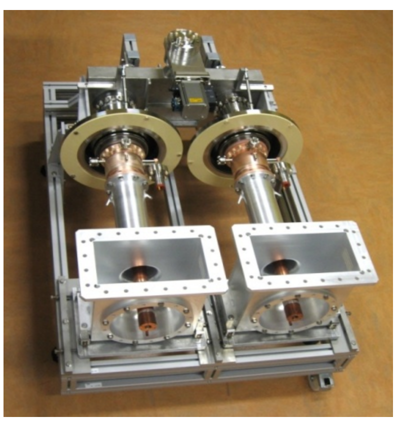

Figure 3: the coupler pair assembled on the connecting waveguide.

The RF window is based on the KEK-B design [6], consisting in an alumina disk matched by chokes. The main design characteristics are in Table 1:

Table 1: main coupler characteristics

Peak power (MW)	1
Average power (kW)	100
Inner conductor cooling fluid	Water
Cold external conductor	Double wall tube, 5K helium counterflow
Waveguide to coaxial transition	Doorknob type
Coaxial line impedance (Ω)	50
Coaxial line external diameter (mm)	100

The nominal power available on the 704 MHz power RF test stand at Saclay is 1 MW, with pulses up to 2 ms in duration at a repetition frequency of 50 Hz [7]. The conditioning of the coupler pair was done in travelling wave mode up to 1.2 MW then in standing wave mode up to 1 MW for several standing wave configurations in need of further processing [8].

PREPARATION OF THE HIGH POWER TEST

The assembly of the coupler on the cavity was performed in the class 100 laminar flow in the clean room of Orme des merisiers. The transfer of one of the power coupler from the test waveguide to the cavity was carried out in vertical position due to a lack of space available, but was assisted by a robotic arm to minimize the risk of cavity contamination. The tuning system multilayer insulation and the magnetic shield were installed on the cavity before its installation in Cryholab (Figure 4).

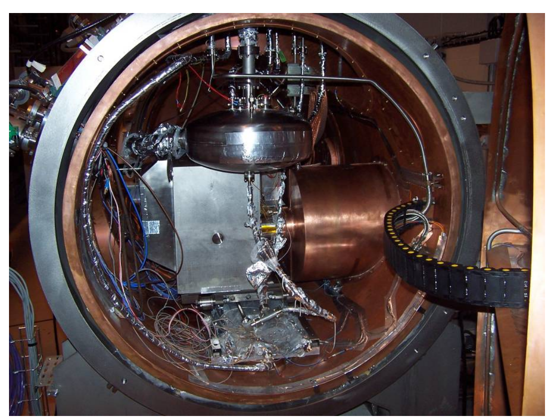

Figure 4: The complete system installed in Cryholab (the cavity and coupler are hidden by the magnetic and thermal shield respectively).

The coupler was conditioned on the cavity in the superconducting state (4.5 K), in full reflection while the cavity was detuned with respect to the RF generator. The maximum power of 1 MW was reached with 2 ms pulses at 50 Hz. The external Q was measured at 1.8 10^6. Details on the preparation, assembly and conditioning are in reference [9]. More recently, we have tested the possibility of cooling the inner conductor using air. The power was raised up to 300 kW forward power at 10% duty cycle, on the detuned cavity (full reflection).

TUNER MEASUREMENTS

After cooldown, the temperature of the tuner main beams stabilized between 20 and 25 K. The tuner was used in the direction corresponding to cavity lengthening at all times. Its linearity is very good over the whole range as shown on Figure 5. The maximal detuning obtained is 760 kHz corresponding to a cavity elongation of 2.5 mm, very close to the theoretical value of 2.7 mm. The spring-back force from the cavity at full extension is 5.6 kN. This force generates a deformation of 0.16 mm of the tuner itself due to its finite stiffness, which makes up for most of the difference between the theoretical and measured cavity elongation. The remainder is due to the helium tank deformation. The static detuning provided by the piezo actuator is measured at 1 kHz with our piezo amplifier at its maximum voltage of 150 V.

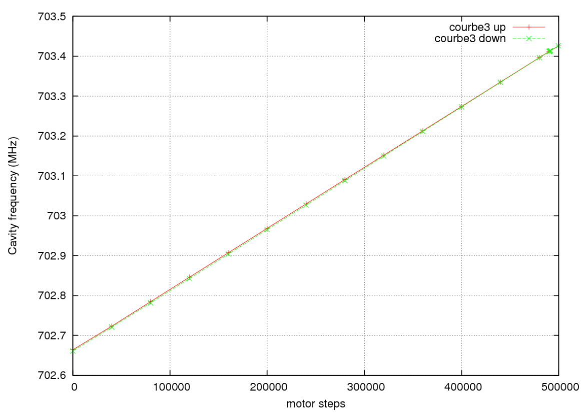

Figure 5: measurement of cavity frequency versus motor steps

The transfer function between piezo drive signal and detuning was measured at 1.8 K (Figure 6). It shows that the main mode contributing to the cavity detuning are in the 200 to 300 Hz range.

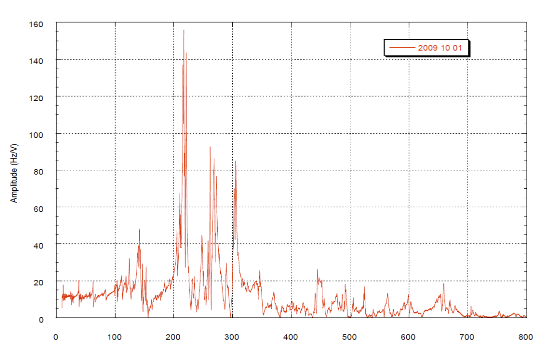

Figure 6: piezo voltage-to-cavity detuning transfer function (amplitude)

PULSED MEASUREMENTS AT 1.8 K

Dynamic LFD

In pulsed mode, the Lorentz force excites the mechanical modes of the cavity. Measurements of the amplitude and phase of the cavity voltage pickup signal for different values of the forward power are shown on Figure 7. The data was obtained with 2 ms pulses repeated at 50 Hz, the piezo actuator being idle. The data was acquired using a 4-channel IQ digital RF measurement crate developed at CERN based on a LHC LLRF system [10].The lower E_{acc} value shown here is 9.8 MV/m (red dashes) and the highest E_{acc} value is 14.3 MV/m (red line). The other curves represent intermediate values between these two extremes. The end of cavity filling is around 0.6 ms. For the lowest gradient, the phase variation is almost linear with time after cavity filling. This is not the case for the highest gradient setting, because the field in the cavity voltage drops so much during the RF pulse due to LFD that in turn the Lorentz force is reduced by a factor of approximately 4 during the pulse. One of the low frequency mechanical modes which have been excited by the RF pulse drives the cavity back in tune, which can be observed both on the amplitude and phase.

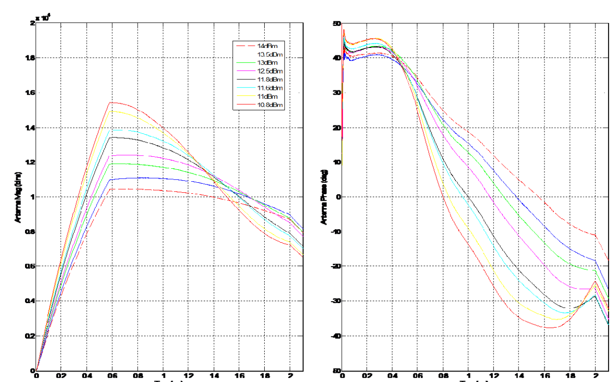

Figure 7: Cavity voltage amplitude (left) and phase (right) during 50 Hz measurements. Piezo compensation is off.

The consequence of this behaviour is can be summarized by plotting the peak-to-peak phase deviation during the 'flat top' with respect to E^2_{acc} (Figure 8). A saturation of the phase deviation at higher gradients can be observed. The green line represents the phase shift that would have been observed in CW operation due to static Lorentz detuning (static Lorentz coefficient for this cavity K_L = -3.8 Hz/(MV/m)^2 [2]). The dotted line is for visual aid only and illustrates the departure from the simpler behaviour of LFD starting at E_{acc} = 11 MV/m. We also observed that the accelerating field at the end of the filling time is almost unaffected by the LFD in this cavity.

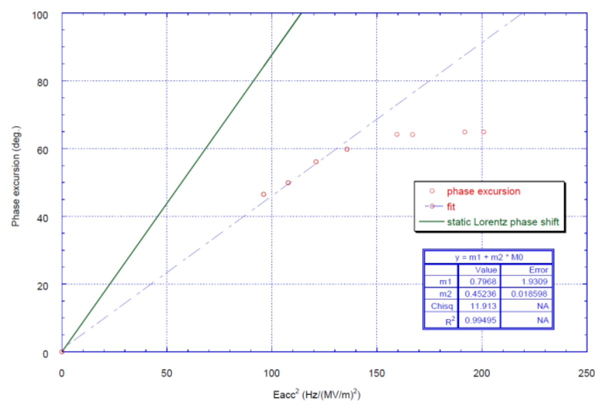

Figure 8: Peak-to-peak phase excursion during flat top for E_{acc} ranging from 9.8 to 14.3 MV/m.

Using the piezo element as a sensor, we could analyse how the pulses excite vibration modes in the cavity (Figure 9). The first part of the record (up to 0.6 ms) corresponds to the excitation of the cavity at 50 Hz by 2 ms RF pulses corresponding to Eacc=14.3 MV/m. At 0.6 s, the RF power is switched off, so the mechanical system is oscillating freely. The decay of mechanical modes coupled to the piezo sensor can be observed. After 3 s all the mechanical modes excited by the RF pulses have decayed, the mechanical vibrations due to the environment, the source of microphonics, is recorded by the piezo element.

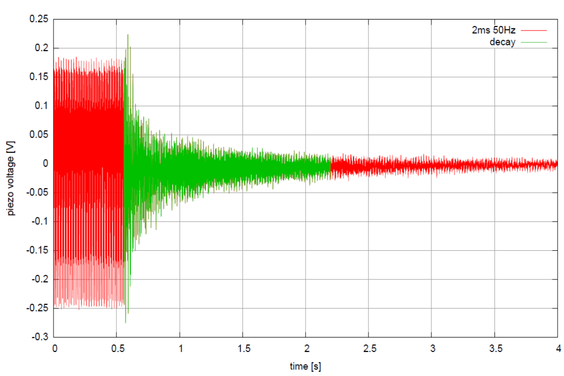

Figure 9: piezo signal decaying from strong LFD pulsed operation.

The data corresponding to the decay (green area of Figure 9) has been analysed. Most of this signal originates from two modes at 198 and 301 Hz. An estimate of their quality factor is 400 and 300 respectively. Observing the time domain data, it is obvious that these modes have no time to decay between two RF pulses, separated by only 18 ms in the present settings. The existence of numerous high Q mechanical modes in the range 200-300 Hz is underlined by the transfer function of Figure 6. The experimental evidence is that they are not excited by LFD in the present pulsed configuration, unless they are standing close to the harmonics of the repetition rate, as expected.

Feed-forward LFD Compensation

We used the piezo tuner to compensate the detuning during the flat top in different combinations of E_{acc} and repetition rates. The example showed here is for an accelerating gradient of 13 MV/m, 2 ms RF pulses at 50 Hz.

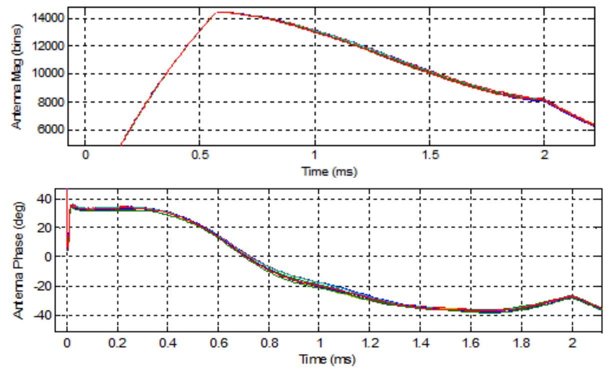

Figure 10: Cavity pickup voltage amplitude (top) and phase (bottom) signals without compensation.

Without compensation (Figure 10), Eacc drops by 45% and the phase is modulated within +/- 25 degrees during the 'flat top'. Eight pulses are displayed on Figure 10, illustrating the pulse-to-pulse stability of the detuning. Using simple signal generators, the piezo actuator was excited with a pulse starting 940 µs in advance with respect to the RF pulse, an amplitude of 60 V and a duration of 3 ms. Several settings of the piezo drive pulse were found to be adequate. In particular, lengthening the piezo pulse and simultaneously decreasing the driving voltage produced the same effect. The result of compensation is shown on Figure 11 for amplitude and phase of the cavity pickup voltage. The amplitude variations are reduced to 1.4% and the phase variation are restricted to +/-8 degrees during the flat top.

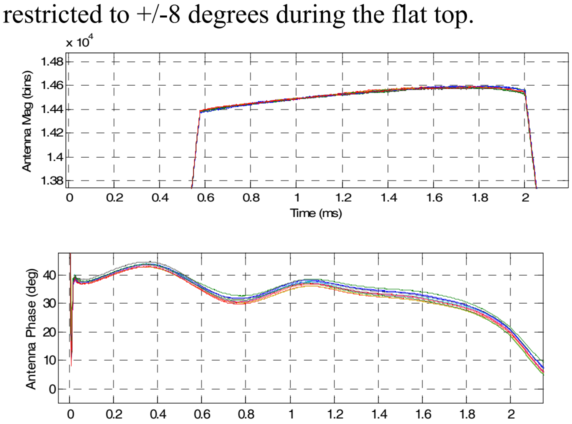

Figure 11: Cavity pickup voltage amplitude (top) and phase (bottom) signals with piezo compensation.

The obtained phase and amplitude stability is sufficiently small to be handled by a LLRF system in order to provide field stabilization at the level required for beam operation in a linac.

AKNOWLEDGMENTS

This work is part of the SLHC-PP CNI which is a project co-funded by the European Commission in its 7th framework Programme under the Grant Agreement n° 212114.

REFERENCES

[1] G. Devanz et al., "Stiffened medium beta 704 MHz elliptical cavity for a pulsed proton linac", Proc. of SRF07, Beijing (2007).
[2] G. Devanz et al. "Experimental characterization of a 700 MHz β=0.47 5-cell superconducting cavity prototype for pulsed proton linac", Proc. of EPAC08, Genoa (2008).
[3] H. Saugnac et al., "Cryogenic installation status of the CRYHOLAB test facility", Proc. of the 10th SRF workshop, Tsukuba (2001).
[4] J. Plouin, "Magnetic shield for the 5-cell HIPPI superconducting cavity", internal report (2010).
[5] G. Devanz et al, Active compensation of Lorentz force detuning of a 9-cell cavity in Cryholab, Proc of Linac06, Knoxville, TN (2006).
[6] S. Mitsunobu et al., "High Power Input Coupler for KEKB SC Cavity", Proc of the 9th Workshop on RF Superconductivity, Santa Fe, NM (1999).
[7] S. Chel et al. "New 1 MW 704 MHz test stand at CEA-Saclay", Proc. of EPAC08, Genoa (2008).
[8] G. Devanz et al., "Conditioning of the 1 MW 704 MHz Coaxial Power Coupler", Proc. of SRF09, Berlin (2009).
[9] G. Devanz et al., "Cryogenic test of a 704 MHz 1 MW power coupler", Proc. of IPAC10, Kyoto (2010).
[10] D. Valuch et. al, report on CERN LLRF crate : https://edms.cern.ch/file/994198/1/MeasurementSetupForCavityDetuning-Valuch-2009-02-01.pdf