ILC CRAB CAVITY VERTICAL TEST RESULTS

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Abstract

A superconducting RF vertical test facility (VTF) has been constructed at Daresbury Laboratory to enable the commissioning of an ILC Crab Cavity LLRF Control System. Two single cell 3.9 GHz dipole mode cavities were tested simulataneously to enable the evaluation of the control system. Careful tuning of the cavities for frequency and external Q factors enabled a low noise reference oscillator to be utilised. Several tests have been performed throughout the past 12 months, each test enabling a much improved system performance. The system is described, and the latest performance of the system is presented.

EXPERIMENTAL SET-UP

The experimental set-up was described in previous reports [1,2]. Briefly, it consists of a magnetically shielded vertical helium vessel containing both cavities at 4.2K. A Labview interface allows us to monitor and log temperature, helium level and gas flows. A pump allows us to cool the system down to 2K when required.

Cavities

The cavities used are single-cell 3.9GHz niobium dipole mode cavities, manufactured by Niowave Inc. Coupling into the cavities is done by antennae penetrating off-axis through the beam-pipes. Two cavities were used, designated C1 and C3.

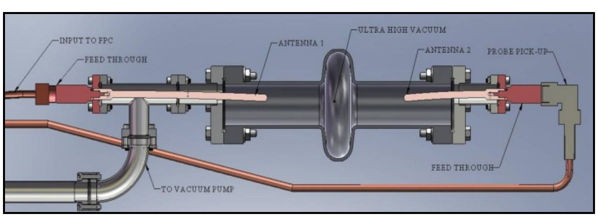

Figure 1: Cavity and coupler configuration.

The coupler lengths were determined by simulation and improved after taking transmission parameter measurements. The coupling factors were fine-tuned by careful adjustment of the flanges in the cleanroom in order to achieve the desired external Q values. This operation was quite time-consuming due to the sensitivity of the relationship between the antenna position and the coupling.

Frequency Tuning

The cavity frequencies were pre-tuned by stretching them in a purpose built rig. The target warm frequency was 3.8941GHz, which was chosen to account for the frequency shift that occurs due to vacuum and operation at 4K. The desired cold frequency was 3.9003GHz, which gives some margin for the cold tuners to operate.

Early measurements emphasised the need to carefully control the frequencies of the cavities during measurements. As such, the design was improved upon subsequently to the initial tests. The tuners can only compress the cavity (thereby shifting the dipole mode frequency downwards), and care must be taken during the experiment not to exceed the elastic limit of the cavities to avoid any plastic deformation beyond the operating frequency of 3.9GHz. The tuners were designed to apply up to 2000N of force on the load-cells, which allow a frequency shift of up to 10MHz and theoretically a fine-tuning accuracy down to 10Hz by the addition of grams of weight on the lever arms.

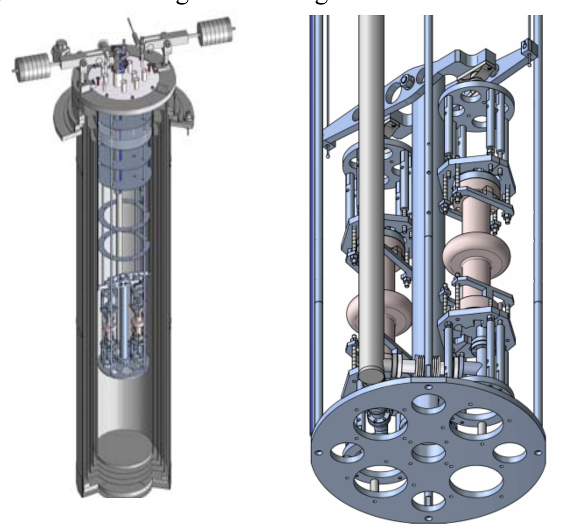

Figure 2: View of the cells in the cryostat and detail of the cavities, tuner arms and load-cells.

In order to phase lock two cavities it is necessary for their natural frequencies to be relatively close with respect to their bandwidth. An accurate prediction of the cavity frequency to within a few tens of Hertz at 4.2 K is not possible while the cavities are at room temperature, where the cavity bandwidths are about 2 MHz. As described above, the resonant frequency also shifts as the cavity cools. In order to tune the cavities for phase locking a tuner range of several MHz is required. The longitudinal tuning sensitivity of our cavity is 17.4 MHz mm^{-1}. This means that 17 kHz corresponds to a movement of 1 μm. Ideally the tuner must give tuning stability at the level of 10% of the cavity bandwidth. For bandwidths near to 1 kHz the tuning mechanism must be smooth with steps not exceeding 6 nm. The tuning mechanism as implemented showed some friction and limited smoothness to steps exceeding 60 nm, hence throughout the tests we had considerable difficulty tuning the cavities to within 1 kHz frequency.

Consideration of tuning drift from cable expansion is also of interest. The linear expansion of the steel cable at 4.2 K is extremely small ($\ll 1 \times 10^{-6}\,K^{-1}$). There were however about 0.5 metres of cable in a transition region between 100 K and 300 K. The average thermal expansion of steel in this range is about $8 \times 10^{-6}\,K^{-1}$ hence when the average temperature of this part of the cable fluctuates by 0.5 K then the length change is about 2μm. The leverage ratio between cable movement and cavity movement was 1:3 hence for this 0.5 K fluctuation we get a movement of 600 nm. Using the tuning sensitivity of 17.4 MHz mm^{-1} a 0.5 K fluctuation equates to a tune shift of 10 kHz. Cavity frequency shifts of this magnitude were observed and added to the difficulty running the experiment.

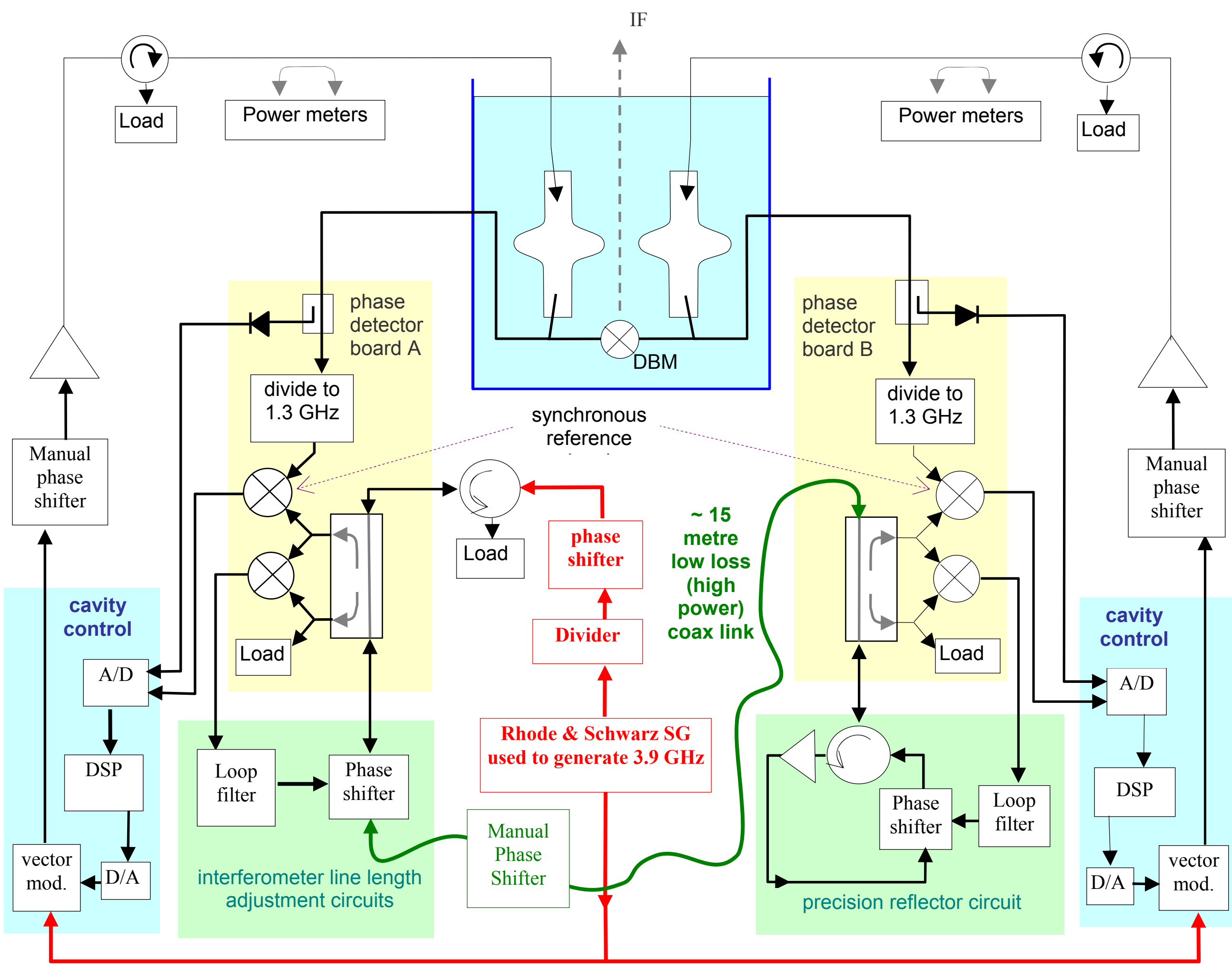

Figure 3: LLRF system used for November 2008 tests

PHASE CONTROL RESULTS

Phase Noise Floor

The required phasing accuracy for the ILC crab cavities with respect to each other is 0.125 degrees r.m.s. at 3.9 GHz which corresponds to a timing accuracy of 90 fs. One distinctive feature of the control system used for the tests is the use of Hittite HMC439QS16G digital phase detectors on the phase detector boards shown in Figure 3. These detectors were investigated as their linearity offer advantages with respect to system calibration. Their phase jitter performance however is significantly worse than double balanced mixers. The phase noise at 1280 MHz is about -135 dBc/Hz and is relatively flat with offset. Noise in 1 MHz bandwidth is about -80 dBc. corresponding to an r.m.s. phase jitter of 1.41×10^{-4} radians = 8 milli-degrees and a timing jitter of 17 fs. This is quite large but still significantly less than the

ILC crab cavity to cavity timing requirement. Frequencies greater than 1 MHz have virtually no effect on the cavity phase jitter performance where a superconducting cavity with a bandwidth near to or less than 1 kHz is used.

Digital phase detectors only operate up to a frequency of 1.3 GHz hence they must be used either after down conversion or with frequency dividers. Down conversion adds the complexity of generating multiple phase locked frequencies. For simplicity we chose to divide the frequency using HMC437MS dividers; these generate an additional 2 milli-degrees r.m.s. phase jitter at 1.3 GHz. The big drawback of frequency dividers is that the phase gets divided hence 8 milli-degrees of phase jitter at 1.3 GHz implies 24 milli-degrees of phase jitter at 3.9 GHz. The LLRF system in figure 3 with its interferometer uses four digital phase detectors. Assuming that their noise is uncorrelated they will contribute 48 milli-degrees of phase jitter at 3.9 GHz. The dividers will add a further 2.82 milli-degrees hence the system will performance is not expected to exceed 51 milli-degrees of phase jitter. Another source of jitter is the digitization error. The sixteen bit ADCs used have just 13 significant bits on a sample to sample basis. Without averaging, we nominally resolve the angular range into 8192 levels. For convenience of obtaining the lock we mapped 100^{o} at 3.9 GHz to the 8192 levels hence the digitization error for two uncorrelated channels is approximately 9 milli-degrees.

When the experiment was conceived we anticipated that both cavities would have identical Q factors and hence the time delay of signals through the cavities would be identical. In this situation source noise would be unimportant with respect to cavity to cavity jitter. Unfortunately the probe couplers did not permit accurate enough adjustment and cavity Qs were never identical. 1/f source noise combined with differing cavity transit times gave an additional contribution to the noise.

November 08 Tests

The November 08 tests gave relatively poor results as a result of a failure of the double balanced mixer in the cryostat shown in Figure 3 and a poor choice of external Q factors. The consequence was very low output signals from both cavities and a cross coupling of -10dB. In spite of this it was still possible to lock both cavities and make cavity to cavity phase measurements [3].

The cryostat assembly was quite sensitive to vibrations. Normal speech 2 meters from the cryostat produced microphonics at a level of 1 degree pk-pk. A small loudspeaker was attached to the cryostat to generate controllable microphonics. Control system performance for a single cavity was recorded against controlled microphonics up to several kHz and is shown is Figure 4.

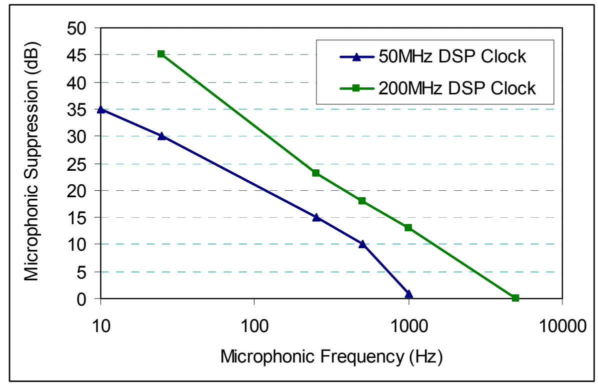

Figure 4: Control system performance for microphonics at different frequencies.

Cavity Parameters, April 2009

Our final tests were conducted in April 2009. For these tests the double balanced mixer was placed outside the cryostat to avoid a repeat of the previous difficulties. Cavity bandwidths were reduced and output signals increased. Data for the cavities is given in Table 1.

Table 1: Experimental parameters

	Cavity 1	Cavity 2
Cavity bandwidth	2710 Hz	2270 Hz
Q loaded	1.439e6	1.718e6
Q external (input)	2.215e6	2.546e6
Q external (output)	1.264e8	1.277e8
Q_o	4.245e6	5.511e6
R/Q	53 W	53 W
Amplifier power	7 W	7 W
Cable losses (each way)	-5 dB	-5 dB
Forward power into cavity	2.21 W	2.21 W
Peak cavity voltage	36639 V	32900 V
Power dissipated in cavity	1.86 W	1.95 W
Energy stored in cavity	0.42 mJ	0.34 mJ
Output to probe at cavity	80.4 mW	65.5 mW
Output from probe after cable	14.05 dBm	13.16 dBm

At the start of the tests it was found that the Rhode and Schwarz Signal Generator SMA100A had developed a software fault after exposure to X-rays in a separate experiment. The April test commenced with a Vectron 10 MHz oscillator stabilizing a MITEQ DRO narrow band oscillator BCO-10-03900-4-1-12P. Figure 5 gives the relative phase noise performance of the two oscillators.

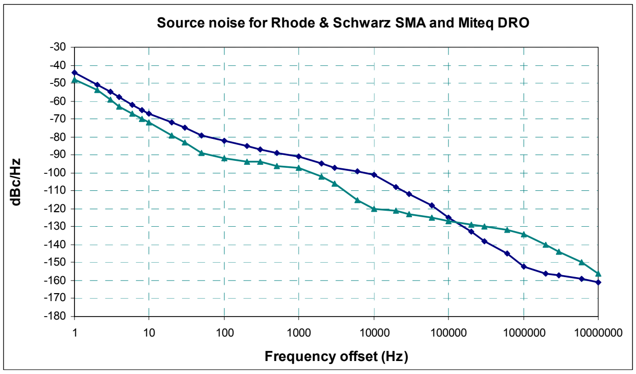

Figure 5: Source noise comparison, Rhode and Schwarz SMA-100 (purple) and MITEQ DRO (blue).

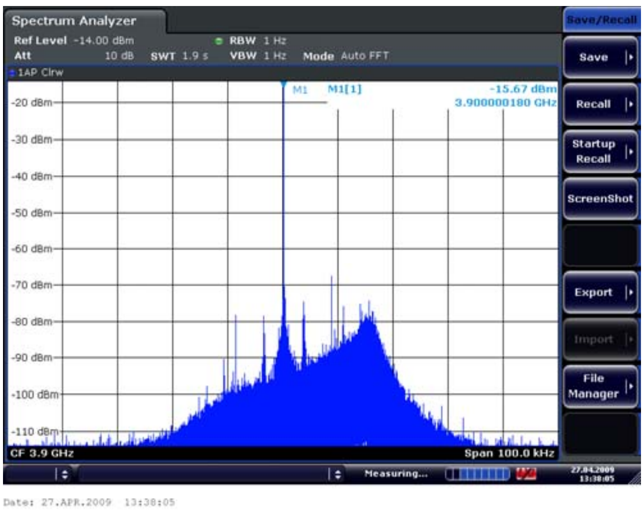

Figure 6: Cavity output spectrum with noisy source and off tune cavity.

The additional 20 dB of noise at 10 kHz was immediately visible when the output spectrum of the cavity was observed as shown in Figure 6 and whilst unwelcome, the second peak made cavity tuning very easy.

Cavity to Cavity Phase Jitter Measurements

Cavity to cavity phase jitter measurements were made with a double balance mixer for both sources, cavity to cavity jitter measurements were made without the interferometer and cavity to source jitter measurements were made on cavity 1. The bandwidth for the measurements was about 1 MHz, results are given in Table 2.

In the table note that the third row gives the cavity to cavity jitter when the controllers are off. In this instance the cavities are driven from the same source and no additional microphonics are induced over the background level. With the addition of induced microphonics this value increases dramatically whilst for the other entries where the controllers are on, phase jitter barely increases at all. The additional cavity to cavity phase jitter for measurements with the MITEQ source as compared with the Rhode and Schwarz source is about 20 milli-degrees. This value is consistent with the difference in cavity bandwidths and the phase noise plots of figure 5. We have estimated that the MITEQ source should add 35 milli-degrees of jitter whilst the Rhode and Schwarz source will only add 10 milli-degrees of jitter.

For the Rhode and Schwarz source the best cavity to cavity phase jitter performance that we might anticipate (with our Q factor imbalance) is about 70 milli-degrees and for the MITEQ source about 95 milli-degrees.

Rows 6 and 7 of Table 2 give values when the interferometer is disconnected and the source feeds directly to the two controllers. In this situation two of the digital phase detectors are not in use hence the phase control performance might be expected to improve, surprisingly it did not, however we had made no attempt to shield RF cables from vibration.

The last two rows gives cavity to source jitter using the Rhode and Schwarz source. Figure 5 suggests that a contribution of 25 milli-degrees will come from comparing the source with itself after passage through a cavity with bandwidth 2.7 kHz. This means that about 33 milli-degrees comes from phase detector noise, divider noise and digitization error. This compares well with our estimate of 24 milli-degrees from the phase detector, 2 milli-degrees from the

Table 2: Jitter measurements made with a double balanced mixer

		Source	Period	Jitter (degrees)
1	Cavity to cavity control on	Vectron & Miteq	300 secs	0.123
2	Cavity to cavity control on	Vectron & Miteq	10 secs	0.108
3	Cavity to cavity control *off*	R&S SMA100A	10 secs	*0.7942*
4	Cavity to cavity control on	R&S SMA100A	10 secs	0.0852
5	Cavity to cavity control on	R&S SMA100A	0.05 secs	0.07428
6	Cavity to cavity no interferometer	R&S SMA100A	10 secs	0.0888
7	Cavity to cavity no interferometer	R&S SMA100A	0.05 secs	0.0763
8	Cavity1 to source	R&S SMA100A	0.05 secs	0.0576
9	Cavity1 to source	R&S SMA100A	10 secs	0.0600

divider and 6 milli-degrees from digitization (one channel).

Conclusion

Using a very simple control system we have been able to meet the phase control tolerance for the ILC crab cavity system for a pair of cavities in a vertical test facility. Further improvement might easily be achieved by use of digital down conversion and better matching of bandwidths. Reduction of the digitization error can be achieved either by averaging, or using ADCs with lower clock speeds, or using fast 24 bit ADCs or switching ranges once the cavity has locked.

FUTURE PLANS FOR SRF INFRASTRUCTURE

The current infrastructure used for superconducting RF tests suffers from several limitations. The current location of the cleanroom is not ideal, as there is no space for expansion, vertically or laterally. More space would enable us to add such facilities as BCP stands, a dedicated High Pressure Rinsing stand, and more space for cavity strings. The vertical test dewar's location is not ideal either, as it is impractical to shield it completely and a 2 metre maximum length of structures that can be inserted is limited by the maximum crane height.

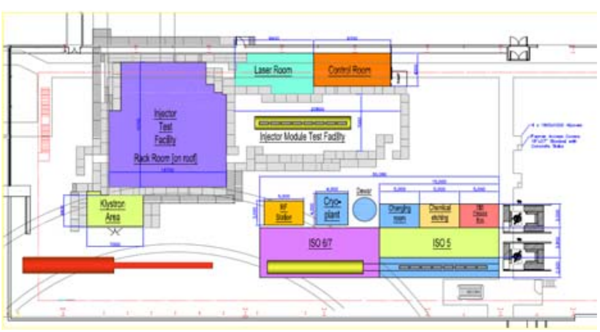

Figure 7: Schematic of proposed Outer Hall layout.

The former SRS Outer Hall is the location chosen for the new superconducting RF facility. The Outer Hall is a large area with 20t crane support. The new facilities will include an expanded cleanroom with space for a self-contained buffered chemical polishing cubicle and a high pressure rinse stand. The layout of the cleanroom will also be optimised, and allow for the assembly of cavity strings.

The vertical test facility will also be moved into pits dug into pre-existing service tunnels in the floor. It is planned that the vertical test stand will be covered by a rail mounted lead-lined concrete radiation shield. Cryogenic support will be provided to the testing area, which would give more flexibility in terms of testing.

The area will also have the space, shielding and power sources to perform high power tests of cryomodules. As such, it is planned that we will be able to take cavities as received from the manufacturer and integrate them into a cryomodule assembly, performing all the steps required in-house.

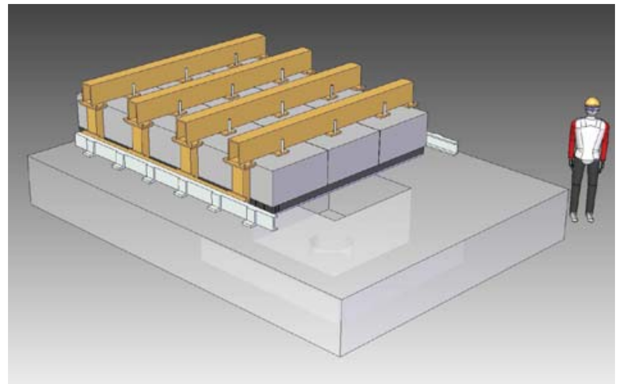

Figure 8: Shielding design for the vertical test pits.

CONCLUSION

The vertical cryostat facility allowed us to carry out low power tests on two superconducting cavities. Continual improvements to the tuning system and noise environment allowed us to achieve good conditions for the low level RF tests.

The tests allowed us to verify the performance of the phase control system on real cavities set with realistic values of the input and output external Q factors. The performance of the control system was shown to be able to meet the desired specifications.

The experience from this series of tests also enabled us to design the future test facility in the best possible conditions.

REFERENCES

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[2] P. Goudket et al., Phase Control Testing of Two Superconducting Cavities in a Vertical Cryostat, Proc. PAC 2009, Vancouver, May 2009.

[3] A. Dexter et al, ILC Crab Cavity Phase Control System Development and Synchronisation Testing in a Vertical Cryostat Facility, EuroTeV-Report-2008-073, Dec 2008.