Using Resonating Superconducting Cavities towards making a Quantum Computing Processor

Vincent Austin Hall

working with the Experimental Quantum Information Group

for the final year project of my Integrated MPhys & BSc Degree

School of Physics and Astronomy

University of Leeds

Submitted 27 April 2009

Summary

A micromaser is a one atom version of a maser, which is a microwave laser. The micromaser can form the core of a quantum computing processor. In a micromaser a beam of atoms interacts with microwaves sent through a superconducting device called a cavity to produce quantum bits or qubits. These qubits are later detected and determined to be either binary ones or zeros. The microwave frequency is the frequency needed to excite the atoms to a higher energy level from the ground state to the excited state, here either 21.4560 or 21.5065GHz. The main aim of this project is to find the resonant frequency and the quality or Q factor of each superconducting cavity. The quality of a cavity determines how long an emitted photon is stored – a high Q is needed so there is enough time for it to interact with the atom in the cavity. Closed and open cavities are to be tested; the closed cavity is a small, superconducting cylinder with a small hole at each end, the open cavity is made of two facing, concave, superconducting mirrors that reflect the microwaves between them. Once a suitable method for finding a cavity's resonance – and thus Q – is found, a niobium cavity can be cooled to low temperature (about 30mK) and used as part of a quantum computing processor. This field is called cavity quantum electrodynamics.

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Acknowledgements

I would like to thank the Experimental Quantum Information group at the University of Leeds, in particular Professor Ben Varcoe, Dr Martin Jones, Mr Mark Everitt, Mr Hawri Majeed and Mr Peter Shadbolt for their hours/days of help in testing the cavities and helping me understand the physics of the micromaser system and other setup processes. Thank you to the whole group for always being friendly and helpful. Thank you to the mechanical workshop for their work with making and improving certain apparatus.

1.0 Introduction

The group is working towards making a quantum computing processor using a superconducting microwave cavity as part of a micromaser system, using the Jaynes-Cummings Model (JCM) for a two-level atom (absorber) interacting with a mode of a cavity. In this case a stream of Rubidium atoms in Rydberg states interact consecutively with a single mode of an electromagnetic field inside a superconducting microwave cavity, thus producing a steady state quantum field [4]. The effect is that the atom is entangled with the vacuum field in the cavity, and detecting the states of the atoms once they have been through the cavity enables one to gain information about the field inside. In this manner information can be processed and the mechanism is quantum mechanical in nature, so the system functions as a quantum computing processor. In the JCM the atom and the field are *both* quantised and the model describes the vacuum field Rabi oscillations. In the Rabi model, the field is treated classically. This will be explored more later in the text. The experimental setup used is called a one atom maser, and what follows is a description of the maser and how it functions.

The (macro) maser was first built in 1954 by J. P. Gordon *et al* [2], this system fired many ammonia molecules into the cavity at once. Transitions were induced inside their cavity producing a change in the power level when the beam of molecules was present. If the power was high enough the power from one beam of molecules could excite the next beam, maintaining oscillations between the excited state and the ground state. While sustained this would stay at a precise frequency, and could be used as an atomic clock. If the oscillations are not maintained, the system could act like an amplifier of microwave power near a molecular resonance.
The first complete micromaser experiment was published by Meschede *et al.* in 1985 using ^{85}Rb atoms [12]. The micromaser uses only one atom at a time. The micromaser produces photons with very low energy, which are very hard to detect.
To increase/decrease the spontaneous emission of radiation at/off the resonant frequency a superconducting cavity is used [8]. A laser excites the rubidium (^{85}Rb) atoms into Rydberg states. When atoms are excited by lasers into configurations with high principal quantum numbers, such states are more stable and have much longer life times: around 0.2-0.4 seconds rather than tens of nanoseconds exhibited by much lower excited states. The Rydberg atoms are also extremely large: atoms with a diameter of 10^{-2}mm are known, which is 10^{5} times the diameters of atoms in the ground state. They can easily be polarised, even ionised by weak electric fields. When the electron is excited into very high energy levels it enters an extended orbit far out from the rest of the atom. At this point the excited electron experiences the rest of the atom as having a charge of e+, like that of the nucleus of a hydrogen atom. The excited electron will behave as though it belonged to a hydrogen atom, provided it stays far from the atomic core. The orbital radius of an electron in an atom is proportional to n^{2}, and the spacing between levels is proportional to n^{-3}. The large effects for large n caused by these powers of n give the Rydberg atoms their properties. These atoms can be used to study the links between classical and quantum physics.

Rydberg atoms are atom-field interaction experiments for three reasons: they couple very strongly to the radiation field, the transitions are at microwave lengths, so the cavity can be made large enough for long interaction times, and finally Rydberg atoms have long life times with respect to spontaneous decay [9, 12]. Rydberg atoms were first discovered in interstellar space in 1965 by measuring the light an atom emits when the excited electron emits a photon in the far infrared to microwave as it falls to a lower energy level [5, 7]. The Rydberg state atoms form a two level system: a ground state and an excited state – the lower and upper maser levels, these energy levels are very close to each other compared with much lower levels [5]. Transitions used in the micromaser are $61D_{5/2} \leftrightarrow 63P_{3/2}$ and $61D_{3/2} \leftrightarrow 63P_{3/2}$. The 63P state is the excited, e state and the 61D states are ground, g states. Which lower level used depends on the cavity frequency: 21.5065GHz corresponds to $61D_{3/2} \leftrightarrow 63P_{3/2}$, and 21.4560 GHz corresponds to the $61D_{5/2} \leftrightarrow 63P_{3/2}$ transition. The cavity is fabricated and tuned so that it resonates at the microwave frequency that equals the transition frequency of the atoms. When the atoms enter the cavity they are almost all in the excited state, this is achieved by collimating the beam of atoms to select for excited or upper level atoms. The field inside the cavity consists of one or a few photons. There is a peak in signal when the microwave light frequency goes through the transition frequency of the atoms, and an atom beam is inside the cavity [2,3]. The states of the atoms are detected by a field ionisation detector as they leave the cavity, in this way the interactions of the atoms with the electromagnetic field inside the cavity can be determined [4]. This detector is being prepared by Hawri Majeed and Peter Shadbolt.

Rabi oscillations keep the system in a steady state. Rabi oscillations occur when an atom absorbs a photon and is excited, then subsequently emits a photon of the same frequency as the light that excited it, this can excite another atom, so the cycle is repeated. The frequency with which it oscillates is called the Rabi frequency. The accumulated Rabi phase determines the emission probability of the atom when it leaves the cavity. When the cavity field is in a steady state, the photon probability distribution is Poissonian, which results in dephasing of the Rabi oscillations which causes their collapse. A revival of the Rabi oscillations occurs after the collapse, due to the evolution of the atom and quantized cavity field. These revivals occur periodically. This phenomenon is known as 'collapse-and-revival' and is an entirely quantum mechanical feature which has no classical counterpart. [9]

Closed Cavity

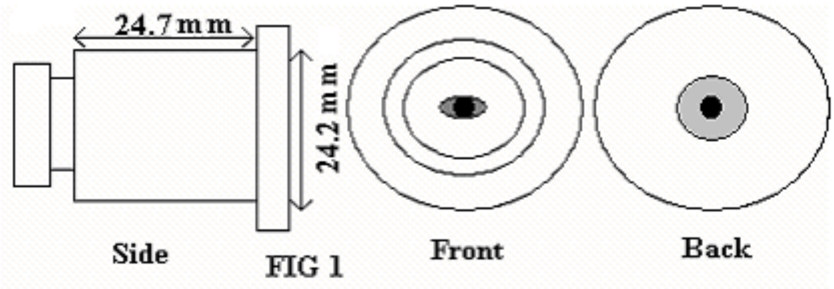

FIG1a

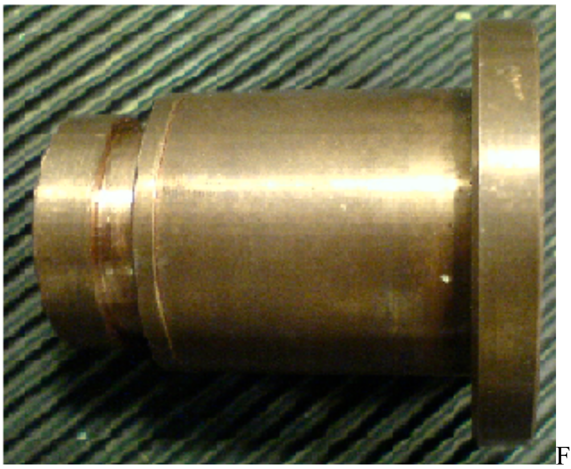

FIG1b

The cavity is a short metal cylinder with a small hole at each end, see figure 1a, b above. A cavity has a length of about 24.7mm and a diameter of about 24.2mm. Figure 1b shows the closed Cu cavity at about actual size. The microwaves enter through the hole in the top, or the left side of the cavity in figure 1b. Materials used include Al, Nb, Cu. Al and Nb superconduct, but Cu does not. Cu and Al cavities are not used inside the cryostat: they are just used to test the methods of finding the resonances of cavities. This is because the resonance of an Nb cavity is very hard to find (Cu and Al are much easier as lower Q cavities produce larger peaks above the noise), and if it is exposed to microwaves of far off resonant frequencies it may be damaged and Nb cavities are more expensive than Cu cavities. The plan is to find resonances of the three Cu cavities, one has a lower Q factor than the other two, and then that of the Al cavity with each of three different lids, each with different Q factors, finally the resonance of one of two identical Nb cavities is found. This cavity remains outside the cryostat: it shows where the resonance peak for the Nb cavity in the cryostat should be. The cavity inside the cryostat would be used for a quantum computing processor. Each cavity has two resonance modes, manifesting themselves as peaks on a plot of power against frequency; one peak is at a higher frequency than the other. If the resonance is not exactly on the transition frequency then the cavity can be tuned, for example by squeezing it as in [1]. This is needed, as the resonance must be within ±10kHz of the resonant frequency to be in the strong coupling regime. Microwaves are sent into the cavity by means of a cable called corrugated rigid coax or by wave guide. The microwaves interact with Rubidium atoms that are fired into the cavity by an oven. The atoms are fired in a beam at a speed such that less than one atom is in the cavity at any one time, with a narrow velocity distribution. For this reason the system is called a micromaser [1]. A cavity has something called a quality factor, Q: this number must be high enough that an emitted photon is stored for a period longer than the time it takes for the atom to interact with the field, and the average atom-atom separation. The interaction time can the varied by varying the speed of the atoms fired through the cavity [4].

The Q is also the measure of the sharpness of the resonant frequency peak, and is given by:

$Q=F/\Delta F$

F is the resonant frequency, and ΔF is the FWHM of the peak. The quality of the cavity is dependent on several factors, including the finish of the internal surface, the size and depth of the entrance hole and the size of the exit hole. If the entrance hole is wider, the microwaves will couple to the inside of the cavity more strongly, but this will reduce the quality factor. If the exit hole is larger, again it will have a lower Q factor. If the hole of the cavity is longer it will have a higher Q factor. The size and shape of the cavities' holes are designed so that the photons inside will be more likely to decay through the walls of the cavity than through the holes.

Open Cavity

As mentioned in the abstract, the open cavity is made from two circular, concave mirrors held a distance apart, rather than an actual enclosed space. This setup is called a Fabry-Perot interferometer rather than a Fabry-Perot étalon, as the distance between the mirrors can be varied by moving one mirror up or down. The microwave light is sent into the cavity either from the side or through a hole in the centre. The Q of the open cavity can be varied by varying the separation between the mirrors. Theoretically increasing the distance between the mirrors would increase the Q, but this would reduce the intensity of the resonance, making it harder to extract the signal from the noise. It would also move the resonance away from the desired frequency to excite the Rydberg atoms as increasing the separation between mirrors reduces the resonant frequency. The open cavity is housed in a copper cylinder, just to hold the mirrors and keep them apart – securing the upper mirror with a retort stand may result in the mirror falling onto the lower one, and destroying both. See figure 2 below for an image of the shield for the open cavity.

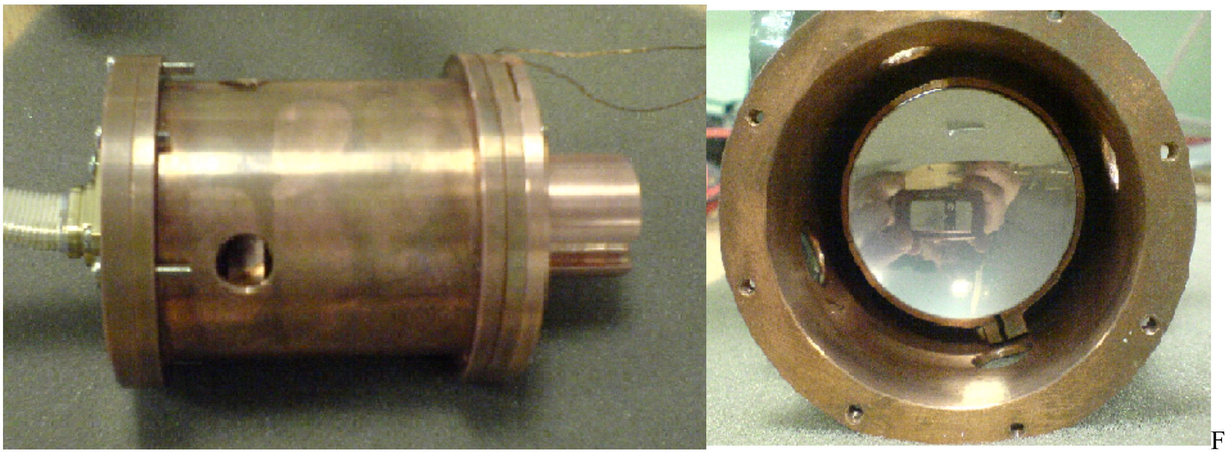

FIG 2 a, left the open cavity shield can be seen, the mirrors are inside. Two of four holes can be seen, the centre of the open cavity is located where the holes are, these are used to pass the microwaves into the cavity, and to insert the power meter probe. At this point – during the test stage the microwaves were sent in via the wave guide that can be seen attached to the left of the image, this should be the top of the shield – it is usually held vertically. The wires for controlling and reading out the position of the mirror can be seen exiting to the top right of the image. Figure 2 b, above right shows the bottom mirror inside the cavity shield, with the 4 holes visible.

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The Cryostat

The cavities are housed in a cooling device known as a cryostat, a large metal cylinder with chambers cooled by vapour and liquid ^{3}He/^{4}He mixture, i.e. a dilution refrigerator. The cryostat cools the cavity down to below its T_c, this is the critical temperature below which a superconducting material will superconduct. The critical temperature of Nb is 9K. The cryostat will cool the cavities down to the milli Kelvin range, about 30mK. The system must be cooled down to remove thermal photons in the cavity that would interfere with the microwave photons fired into the cavity. The cryostat has three cooling chambers: a room temperature to 77 K chamber, a 77 K to 4K chamber, and a 4 K to 30mK chamber, which the Nb cavity is housed in. See a picture of the cryostat in figures 3a, b below. The cryostat was made by Vericold Technologies [13].

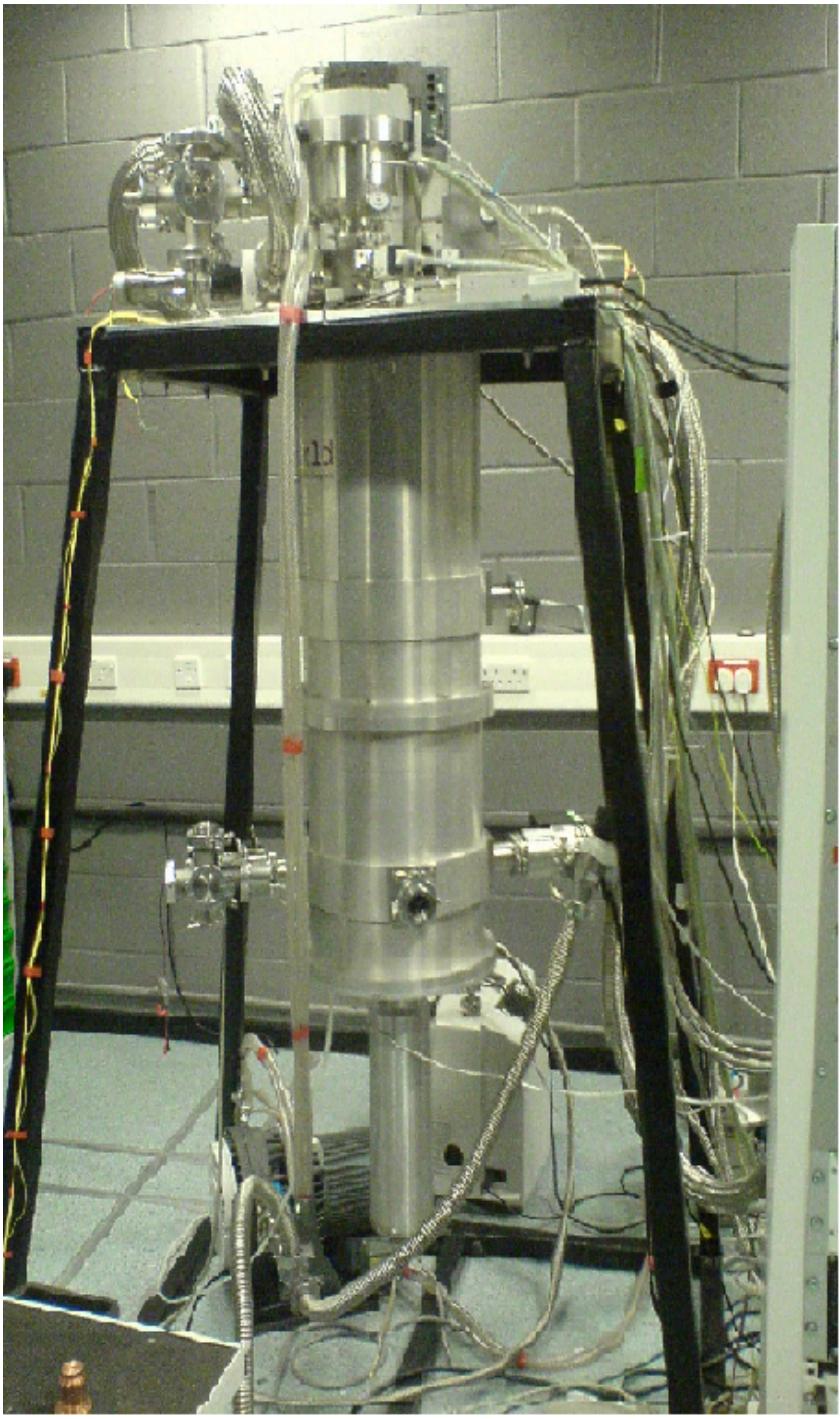

FIG 3 a, the closed cryostat

FIG 3 b, the inside of the cryostat. Here the cavity shield can be seen attached to the cold finger.

The Electronics Model

The apparatus in this experiment can be modelled as an AC LRC circuit: an inductor, a resistor and a capacitor in series. The voltage of the inductor, V_L leads the current by 90 degrees, the voltage of the resistor, V_R is in phase with the current and the voltage of the capacitor, V_C lags the current by 90 degrees. The resistance of a perfect cavity would be zero. Using Kirchhoff's rules, the differential equation for the inductance, resistance and capacitance of the circuit can be found. The junction rule: the sum of currents into a junction must equal the sum of the currents coming out of the junction. The loop rule: When any closed circuit loop is traversed, the algebraic sum of the changes in potential must be zero.

$$\Sigma v = 0 = V_L + V_R + V_C = - L(di/dt) - Ri + V_o - (1/C)\,{}_0\!\int^t i\,dt$$

This is true if there is an initial voltage in the capacitor. Differentiates and rearrange:

$$L(d^2i/dt^2) + R(di/dt) + (1/C)i = 0$$

$$\text{Let } i = A\exp(st)$$

where A is the amplitude, and s is the frequency. The equation becomes:

$$s^2LA\exp(st) + sRA\exp(st) + (1/C)A\exp(st) = 0$$

the solution to this is:

$$s^2L + sR + (1/C) = 0$$

the roots are: $s_1 = - R/2L + \sqrt{[(R/2L)^2 - 1/LC]}$

and $s_2 = - R/2L - \sqrt{[(R/2L)^2 - 1/LC]}$

alternatively $i = \sqrt{2}I\cos\omega t$

Then the equation at resonance would be:

$$- L\sqrt{2}I\omega_o^2\cos\omega_o t - R\sqrt{2}I\omega_o\sin\omega_o t + (1/C)\sqrt{2}I\cos\omega_o t$$

The resonant frequency of the circuit needs to be found, it is given approximately by the reciprocal of the square root of the product of the inductance and the capacitance, or $\omega_O=1/\sqrt{(LC)}$ rad s^{-1}, ω is the angular frequency, f is the frequency and $\omega=2\pi f$., so $f_o =(2\pi\sqrt{(LC)})^{-1}$ Hz. For a given current, I the impedance is directly proportional to the voltage. When the driving frequency is less than the natural frequency, V_C is greater than V_L, so a larger applied voltage is required than when in resonance, and the admittance is lower. The inverse is true when the driving frequency is greater than the natural frequency: $V_L > V_C$. When driven at the natural frequency, the impedance of the circuit is at a minimum, because the sum of V_L and V_C comes to zero, so the impedance comes solely from the resistance. The impedance is given by:

$$z = R + j\omega L + 1/(j\omega C) = R + j(\omega L - 1/\omega C)$$

$z = \sqrt{[R^2 + (X_L - X_C)^2]}$ this equals R at resonance, as X_L and X_C are equal, so the second part cancels out.

The individual impedances are:

$$z_R = v/i = R$$

$$z_L = v/i = sL$$

$$z_C = v/i = 1/sC$$

The reactances, X_L and X_C cancel as they are equal in magnitude and 180 degrees out of phase from each other, ie: the inductive reactance is 180 degrees ahead of the capacitive reactance.

$$X_L = \omega L \text{ and } X_C = 1/(\omega C)$$

The quality of the circuit is given by $Q = \omega_{O}/\Delta\omega$, where $\Delta\omega = R/L$.

2.0 Method

To find the resonant frequency of a copper cavity, the method used was to pass microwaves into the cavity at a well controlled frequency, and plot the power as a function of frequency. When the frequency matches the natural frequency, there is a peak in power – a resonance. So far several different techniques have been used, including various reflection and transmission techniques. Reflection technique: the microwave light is reflected through the cavity and back into the wave guide that sent the light. Transmission technique: transmit the microwave light through the cavity and into the wave guide at the other end of the cavity, this produces a much lower power signal, as most of the light is reflected off the outside of the cavity without ever reaching the inside. Three Cu cavities were used, a low Q cavity and two identical, higher Q cavities. An Al cavity was used with three different lids, each of different Q factors, lid 1, lid 3 and lid 5. Lid 1 having the shallowest/shortest hole –therefore the lowest quality, and lid 5 the deepest/longest hole – ie: the highest quality. The lids of the Al cavity were fastened on with foil tape: they have yet to be welded on. An Nb cavity was also used: it was fabricated with exactly the same specifications as a second Nb cavity that had been used inside the cryostat. The Nb cavities were manufactured with the highest Q factor of all the cavities used, but the cavities need to be kept safe from contaminants so as not to degrade [Q reduces dramatically]. For this reason the best cavities are wrapped in foil and stored in a sealed (air tight) vacuum tube. The microwaves from the synthesiser were given a frequency modulation by the synthesiser.

2.1 Beam Reflection Technique with 'Synth Sweeps'

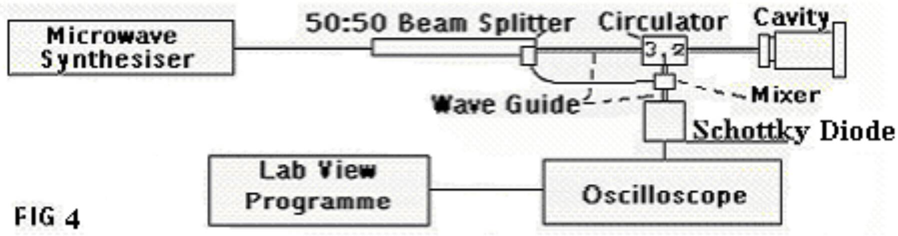

FIG 4

The microwave light from the synthesiser used is half the frequency needed, so this frequency is doubled before it gets to the cavity. The microwave light passes from the synthesiser into a 50:50 beam splitter, through a circulator then into the cavity. The light is reflected out of the cavity and back into the circulator, then the mixer [1]. One cable leads from the mixer back to the beam splitter, another cable leads to the Schottky diode, the oscilloscope and the high pass and low pass filters: see figure 4 above. The Schottky diode produces little noise and switches quickly between non-conducting and conducting. The function generator frequency must be above the frequency of the high pass filter, and below that of the low pass filter, these settings were varied with respect to each other to help produce a higher resonance peak. The synthesiser, also called the 'Systron Donner' is controlled by a Lab View programme written by Mark Everitt, which sweeps through a pre-set frequency range at a pre-set power and plots signal intensity against frequency. See figure 5 below for synthesiser sweeps on the Lab View programme.

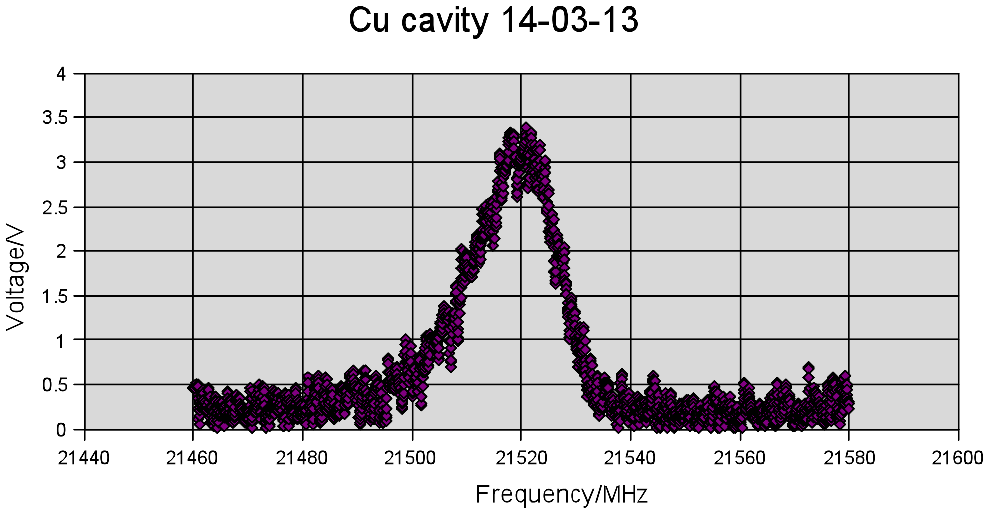

FIG 5.a

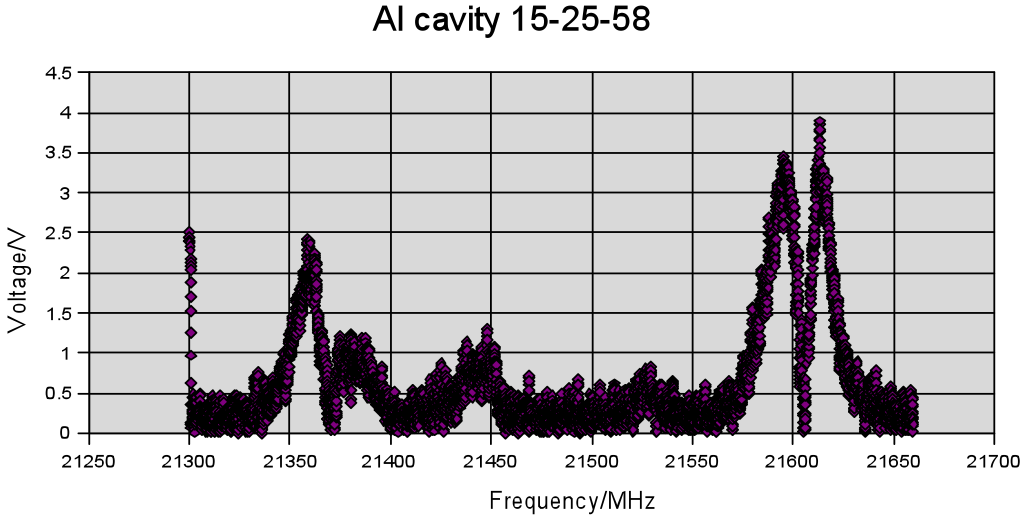

FIG 5.b

Figure 5.a shows the 21.522 GHz peak of the old Cu cavity, and 5.b shows the two apparent line resonances that appeared for different cavities, using the reflected beam setup (the centres of the peaks are troughs).

2.2 Beam Transmission Technique

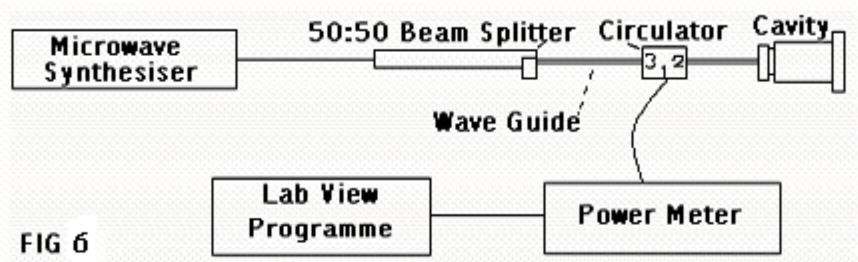

FIG 6

2.2.1 Transmission Synth. Sweeps

Another method used is to pass the microwave beam through the cavity: This method is similar to the reflected beam method, except that the beam goes right through the cavity, and on to the rest of the apparatus, without passing through the circulator again. If there is a resonance in the wave guide before or after the cavity, it should not interfere with the cavity in this transmission setup. The circulator is used to control the direction the microwave light travels in the waveguide.

2.2.2 Transmission Power Meter

For the last method attempted with the closed cavities: the mixer is taken out and a power meter is attached instead of a Schottky diode. There is no signal sent back for reference. The power meter can be linked to the Lab View programme to plot the voltage against the frequency, but this has not been done at this time with the closed cavity, but was used for the open cavity. The power meter registers the power of light coming from the end of the cavity, and a peak is observed at the resonant frequency. The transmitted beam produces a lower intensity peak than the reflected beam, but it may be easier to find the peak this way nonetheless. In this test the power meter registered a negative peak when the resonance was reached; regions where there were no peaks had higher power output. See figure 6, above for a diagram of the transmitted beam setup with a power meter.

2.3.1 Open cavity testing

The open cavity – two concave mirrors – is housed in a copper cylinder, just to keep the mirrors apart and to hold them both in position. Unfortunately it was found that the shield can also act as a resonator, just like the waveguide – producing false resonances at frequencies other than the resonant frequency of the cavity (see section 3.1 Results & Analysis: Closed Cavities). To counter this problem a rubber material that absorbs microwaves (stealth material called Eccosorb GDS by Emerson & Cuming Microwave Products [10], which absorbs frequencies in the range: 6 - 35 GHz) was used to line the inside of the shield with. This removed the excess resonant frequencies, leaving only that of the open cavity. A gap was left in the stealth material so that the coax (coaxial) or cobra flex cable, of the power meter, could be passed into the cavity. Coax is a wire coated in plastic insulation and a ribbed metal shell that breaks when bent back and forth enough. The purpose of the coax is to waveguide the light and prevent it from spreading, this is done by totally internally reflecting the light by using optical fibre that has a higher refractive index in the core surrounded by cladding with a lower refractive index, or by focussing the light with a gradual decrease in refractive index from core to edge. A piece of coax was attached to the input cable of a rather sensitive (sensitive enough to detect about -99 dB) power meter to read the output power from the cavity. The coax had a wire loop on the end: the end of the coax had been stripped of insulation and the wire inside bent round and soldered to the outside of the coax so as to sense the microwave light inside the cavity. The power meter was needed as no useful measurement of the power output to find the resonance could be made with the oscilloscope previously used for the reflection and transmission techniques for the closed cavities. It was found, as expected, that the resonant frequency of the open cavity increased when the mirrors were moved closer together. For the testing, a niobium mirror and a copper mirror were used.

2.3.2 Placing Open Cavity on Cold Finger of Cryostat

Once the resonances were found, the open cavity could be placed inside the cryostat, attached to the cold finger. The cold finger is the section of the apparatus that cools down to temperatures that the niobium material can superconduct at, and is low enough to reduce noise satisfactorily – about 30mK. To pass microwaves into the cavity while inside the cryostat more cobra flex had to be used. Two lines of cobra flex were threaded from the top of the cryostat and wound down around the apparatus inside, taped with foil tape, usually to the copper elements so as to cool the coax down as much as possible before it reached the cavity. One cobra flex line sent in the microwave light, the other passed the power output to the power meter outside so the resonance of the cavity could be found without dismantling the cryostat again. To move the bottom mirror of the cavity, two wires from the piezoelectric motor, made by Attocube of Munich Germany [11], underneath the mirror will have to be attached to superconducting wires, and these to the "ANC 150" position that is used to control the position of the mirror by changing the shape of the piezoelectric cube motor. The Attocube piezoelectric motor should be held upright so the cube is beneath the mirror (or more generally the mass) while moving the mirror. There are two movement modes for the attocube: step and continuous, here the steps cannot be trusted to move the mirror the same amount each time, so the continuous mode was used - which is also much quicker. This is because the step sizes are not always the same size, as the motor works like a ratchet. The mirrors inside the cavity were both replaced by two Nb mirrors, as these are the best superconducting mirrors, they are also more highly reflecting – cleaner.

3.0 Results & Analysis

3.1 Closed Cavities

Using the reflection technique two very large peaks were observed: about 21.375 GHz and just above 21.6 GHz for various Cu and Al cavities and the Nb cavity, showing that both peaks must be features of the apparatus, not the cavity. Each peak looked like a double peak, or a very large peak that had the centre removed/reflected to zero. This was the shape of peak expected, but the peaks appeared in cavities of more than one material, so must be line resonances. A line resonance occurs when an element of the apparatus, for example a stretch of wave guide, acts like a resonating cavity, this produces large peaks at the resonant frequencies of the wave guide. These peaks can be removed by adjusting the length of wave-guide used: a shorter section of wave guide should produce peaks that are further apart, while a longer section of wave guide should move the line resonance peaks closer together. So the line resonances must be moved away from where the cavity resonance is thought to be, around 21.5 GHz for our cavities (see introduction). The circulator was removed to determine if it was a source of line resonance, but the line resonance remained. However, the reflected beam technique did produce a resonance at about 21.522 GHz for the old Cu cavity.

Using the transmission method, there appears to be a resonance at (21522.3±0.5) MHz for the oldest and lowest quality of the Cu cavities, the Q was found to be $10^4 \pm 4\text{x}10^3$. This frequency agrees with that found for the same cavity using the Synthesiser Sweep method. However, there were peaks at similar positions when the one of the two higher Q Cu cavities and the Al cavity with 'lid 1' were scanned. The cavities were made to resonate at or near this frequency, so it is not clear whether these are real cavity resonances. No less than three peaks were found for the Al cavity with lid 3, but these peaks were also found for one of the twin, newer, higher quality Cu cavities, so they cannot be cavity resonances, but must be resonances of the apparatus.

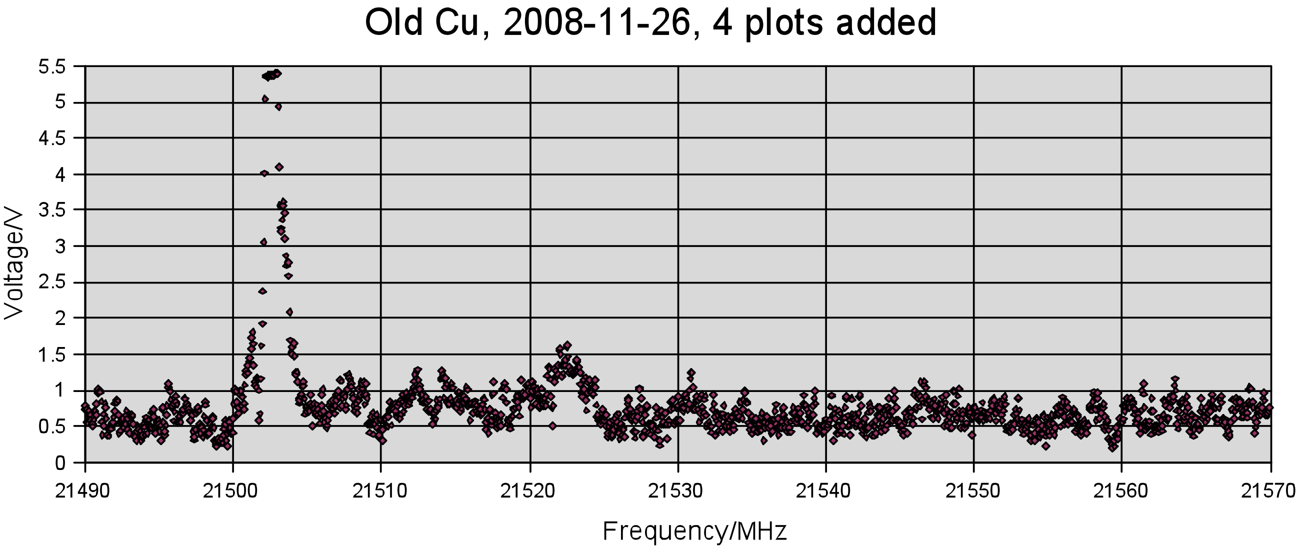

FIG 7

In figure 7, four resonance scans were added together to attempt to highlight the peak at 21.5223 GHz – it is a much smaller peak than the line resonance at 21.503 GHz from only two of the four scans. This is likely to be the peak, as it showed up on four scans with varying waveguide length.

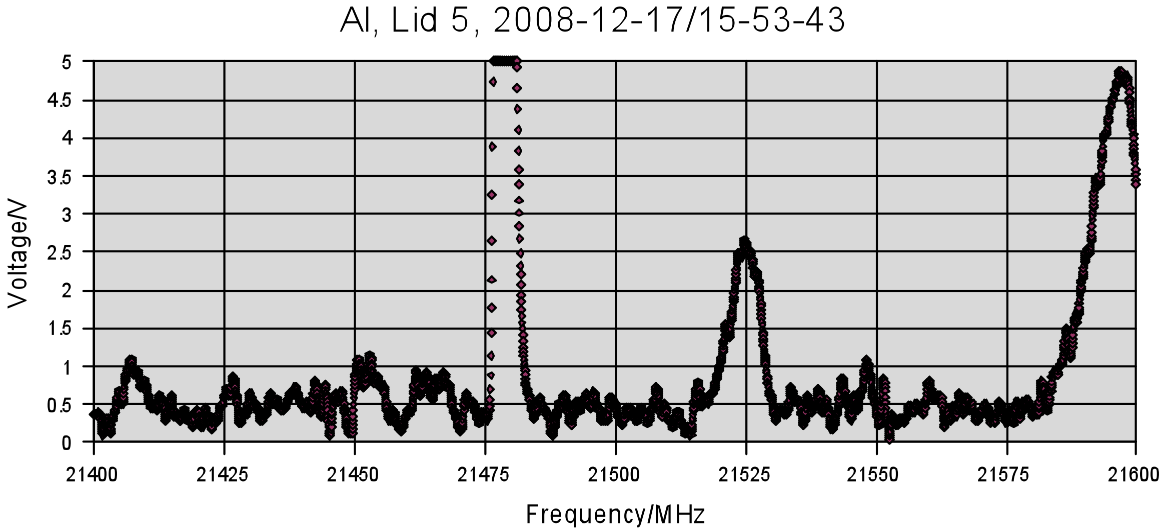

FIG 8 a

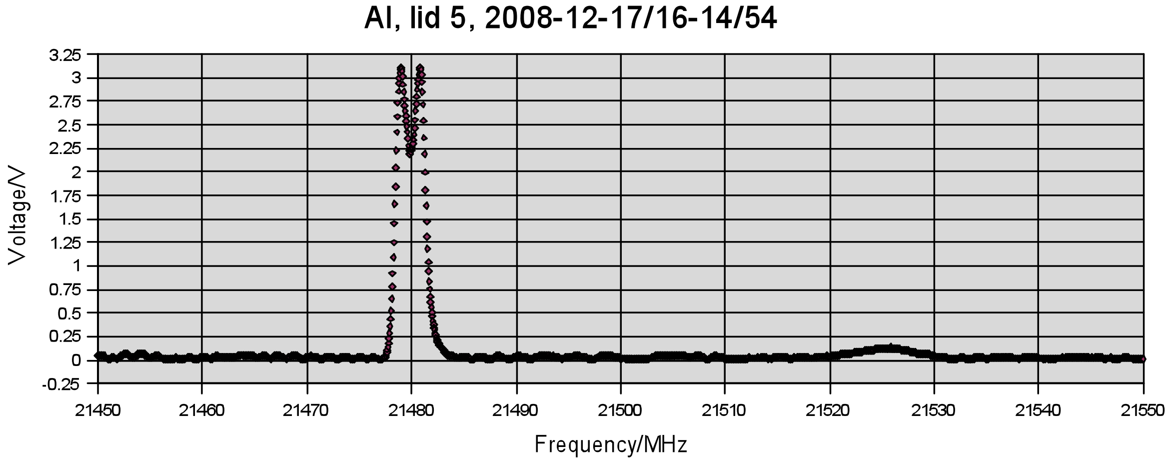

FIG 8 b

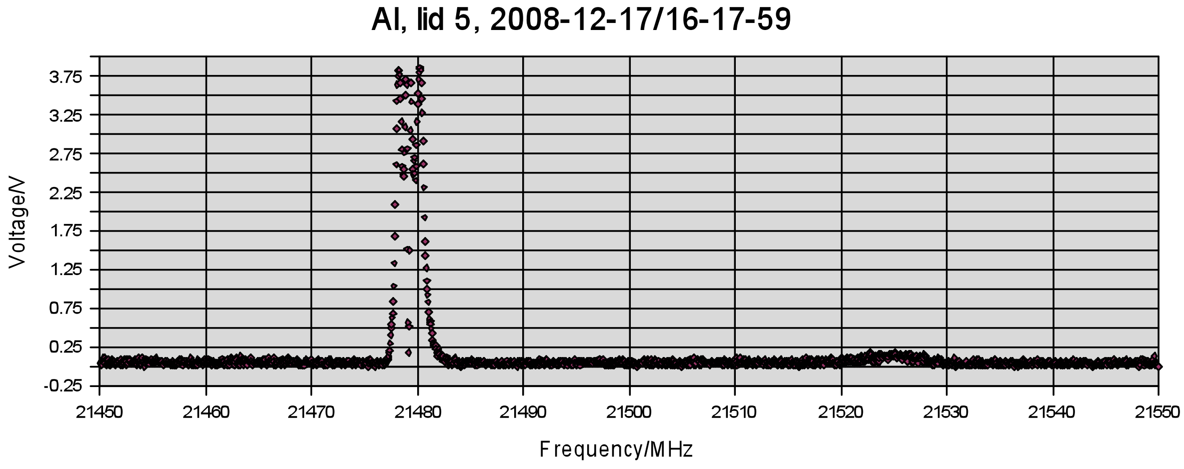

FIG 8c

Figure 8a-c above show three scans of the Al cavity a with a low quality lid ('lid 5'), these were the plots used for the cavity's resonance and quality.

The resonance of the Al cavity with the number 5 lid taped on with foil tape was found from the average of three scans to be (21 479.63 ± 0.5) MHz. The desired value would be 21 456 or 21 506.5 MHz. The Q factor or quality was found to be 6000 ± 7000, so a very low quality compared with what would be required for a cavity to hold the photons long enough for them to interact with the atoms fired through it, but this is not the cavity that would be used inside the cryostat. Clearly the error is very large compared with the value of the Q – the values ranged from about 4000 to 15300. This resonance was found by removing the line resonance at about 21.455 GHz using a diode to stop reflection.

3.2 Open Cavity

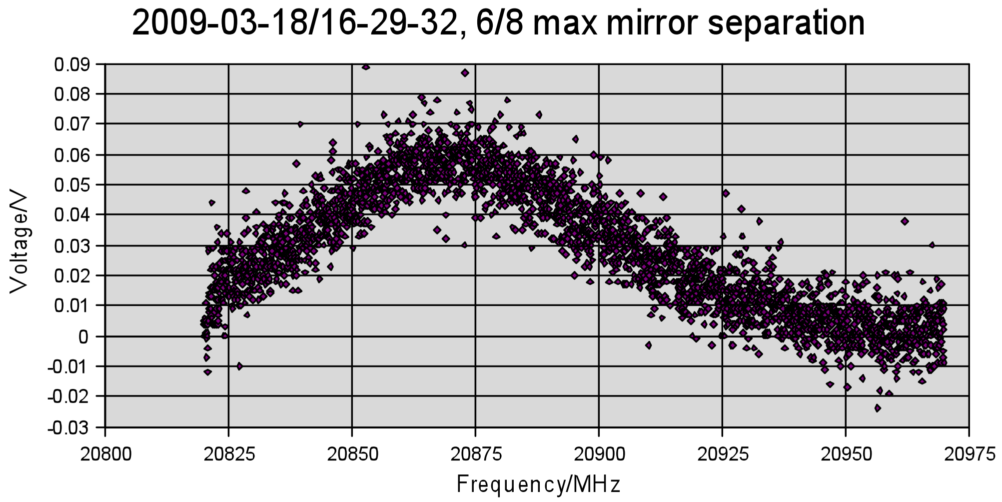
2009-03-18/16-29-32, 6/8 max mirror separation

fig 9 a

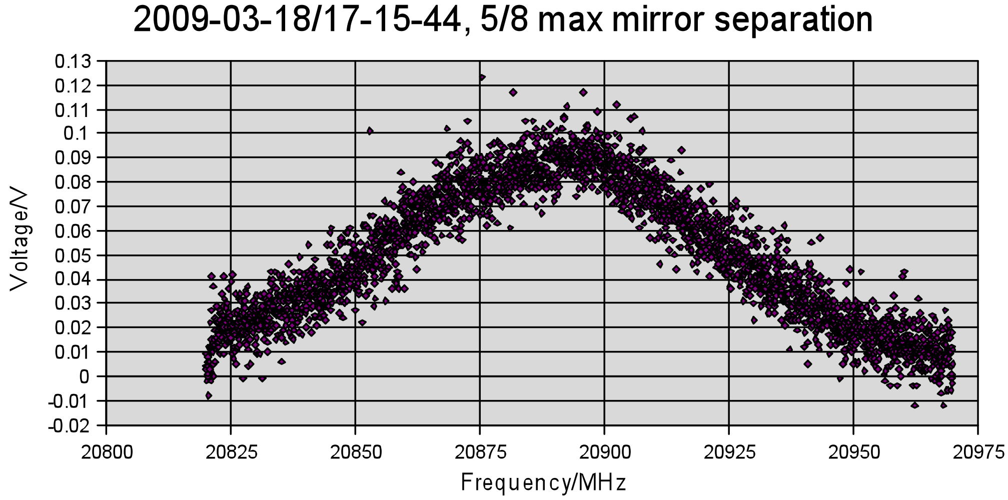
2009-03-18/17-15-44, 5/8 max mirror separation

fig 9 b

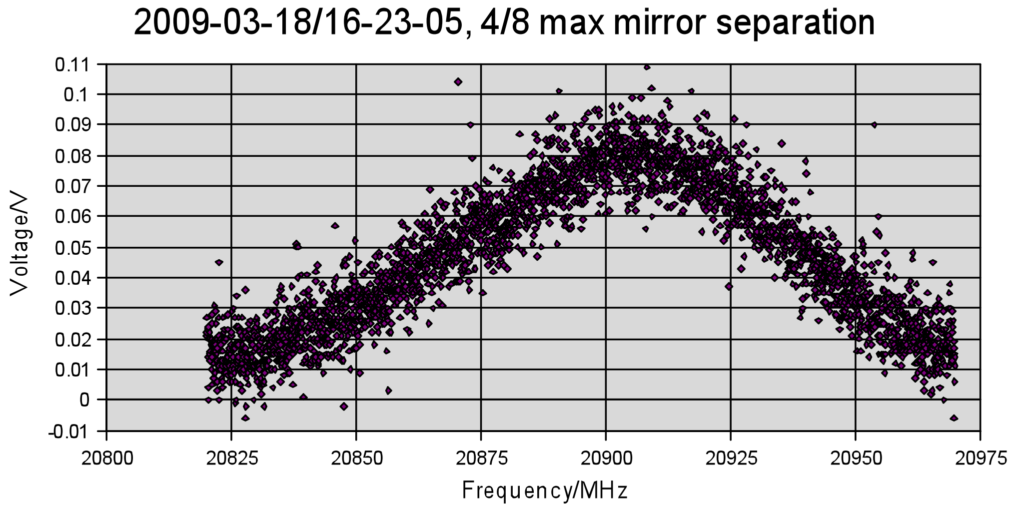
2009-03-18/16-23-05, 4/8 max mirror separation

fig 9 c

Here, in figures 9 a-c, the shifting of the resonant frequency as the separation between mirrors is reduced can be seen. The resonant frequency increases as the mirrors get closer.

Once attached to the cold finger a sweep through a large frequency range was done, this produced many peaks on a plot of amplitude verses frequency. There appeared to be microwaves from another source (or multiple) interfering with the scans. The coax was removed from the cavity and the scan was done again, this highlighted some of the problem, but this was negligible compared with the false peaks seen while inside the cavity. Using wire loops can cause problems depending on how deeply they are inserted into the cavity, as a higher frequency can be measured, because perturbation of the tip causes deformation of the microwave field. This introduces an error of ±30MHz for the cavity resonance [1]. The resonance was found from the above three plots to be (21880±80) MHz – but as mentioned above – the resonant frequency depends on the separation of the mirrors. The Q factor of the open cavity was found to be 360±30.

4.0 Conclusions

4.1 Summary of work done

Various methods to find the resonant frequencies of the superconducting cavities; open and closed, were used. Using the beam reflection technique the resonance frequency of a copper cavity was found, this frequency was confirmed by the transmission technique to be (21522.3±0.5) MHz, the Q was found to be $10^4 \pm 4\times10^3$. The resonant frequencies of the Al cavity with "lid 5" with the lowest quality lid was found to be (21 479.63 ± 0.5) MHz, and the Q was 6000 ± 7000 a rather low Q. The Q of the open cavity with one Cu mirror and one Nb mirror is 360±30, also a very low Q, but this was at room temperature. The resonant frequency of the open cavity being tunable.

4.2 Future Work

The open cavity has to be enclosed inside the cryostat, and once the cryostat is cooled to about 30mK, the next stage of the experiment can begin. When looking for the resonant frequency of the open cavity in the cryostat, care must be taken, as the cryostat can act as a resonator as well, as highlighted in [1]. If the cryostat resonance becomes a problem, then the stealth material can be placed inside, initially on top of the base plate to see if that is all that is needed. The importance of the open cavities is that the cavities can be coupled together to build up a multi-qubit processor or a 'cluster state', which cannot be done with closed cavities, due to geometry. Here four atom beams would fire through four open cavities arranged in a square formation – each cavity shield having 4 holes in the curved, vertical wall, at the height of the gap between the mirrors.

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