THE STATUS OF CESIUM BEAM FREQUENCY STANDARDS

Leonard S. Cutler
Hewlett-Packard Laboratories
Palo Alto, California

Abstract

There has been a lot of progress in cesium beam frequency standards in the last few years some of which will be reported here. Optical pumping is being pursued actively in a number of laboratories. Optically slowed and cooled beams have been demonstrated as well as traps for cold neutral atoms. The microwave cavity performance with regard to local phase shift at the beam holes has been improved by use of carefully designed and built ring structures for the cavity ends. Work is being done on improvements in electronics with some emphasis on use of digital circuitry and microprocessors. The frequency pulling due to microwave $\Delta M = \pm 1$ transitions (Ramsey pulling) has been analyzed and shown to be important. Status of cesium beam frequency standards in some of the laboratories as well as some of the commercial work will be discussed. Since much of the laboratory work going on involves optical pumping and detection, those items will get the most attention here.

INTRODUCTION

Cesium beam frequency standards occupy an important place in today's technology partially because the unit of time is presently defined by the hyperfine transition in the ground state of Cs_{133} and also because, even though they are highly developed, there is still the potential for considerable improvement in performance.

Factors important to performance include:

1. second order doppler shift
2. cavity phase shifts, end-to-end and local distributed
3. microwave power shift
4. C field homogeneity
5. microwave excitation spectrum symmetry
6. microwave leakage outside the cavity (running waves)
7. pulling by neighboring transitions (Rabi pulling)
8. pulling by $\Delta M = \pm 1$ transitions (Ramsey pulling)

9. pulling by even order modulation distortion

10. noise at even harmonics of modulation frequency on flywheel oscillator

11. defects in the electronic frequency lock servo

These cannot be covered in detail in this paper.

Most of the beam tubes up to the present have used magnetic state separation and a hot wire ionizer detector. The recent availability of diode lasers in the near IR and stabilization techniques have made optical pumping for state separation and detection practical.

Optical pumping has a number of advantages. Much better utilization of the beam can be achieved leading to higher signal to noise ratio for the same cesium flux from the oven. This is due to the velocity selectivity of the magnetic deflection systems. This same velocity selectivity makes correction of the second order Doppler shift (relativistic correction) more uncertain in the magnetic deflection tubes because the velocity distribution of the detected atoms is very dependent on the magnetic field strengths and the tube and magnetic field geometries. The second order Doppler shift is about -1×10^{-13} for the usual beam velocities involved (around 140 m/sec) and is the largest offset outside of that due to the C field and perhaps cavity phase shift in well designed tubes. Since the second order Doppler shift depends on velocity, the line shape will depend on the velocity distribution and will usually be asymmetric leading to a dependence on the microwave modulation waveform and amplitude as well as the microwave power hence good knowledge of the velocity distribution is essential. One other advantage of optical pumping is the absence of strong magnetic deflection fields close to the C field region. This can lead to more homogeneous C fields and consequently better accuracy.

The difference of magnetic moments of the sublevels of the ground state leads to asymmetric population distributions in the magnetic deflection case and consequently pulling from neighboring transitions (Rabi pulling). If $\Delta M = \pm 1$ transitions are present and the populations are asymmetric then Ramsey pulling will occur. With optical pumping and detection, the distribution asymmetries can be made much smaller with consequent reduction in both Rabi and Ramsey pulling.

Finally, if optical cooling is used to obtain slow beams the second order Doppler shift can be made negligibly small since the shift is proportional to temperature and temperatures as low as a few microdegrees Kelvin have already been achieved. In addition, slow beams reduce the Ramsey linewidth and thus improve the precision of the line center determination by the electronics. The reduced linewidth also offers potential improvement in short term frequency stability which can be achieved only if the flywheel oscillator has low enough noise at even harmonics of the modulation frequency.

Fig. 1 shows a fountain experiment with very cold sodium atoms. The atoms in a beam are slowed and then cooled in the "molasses" formed by three intersecting laser beams tuned in frequency below the resonance absorption of the sodium atoms. The cold atoms are then trapped in a magnetic quadrupole trap and finally given a push with a laser pulse to go through the RF cavity. Ramsey linewidth of 2 Hz has been achieved. A similar device would work with cesium. Fig. 2 shows a "funnel" formed from a two dimensional magnetic quadrupole generated by the wire structure. This can provide a continuous beam of cold atoms and thus be very useful for frequency standard work.

In the area of microwave cavity design, local distributed and end-to-end phase shifts are important. In principle, end-to-end phase shift can be measured by beam reversal and many laboratory tubes have this capability. For the measurement to be valid in the presence of local distributed phase shifts, the forward and reverse beams must follow identical trajectories and this requires very careful design and construction of the tube. Local distributed phase shifts are caused by the presence of running waves (a non-vanishing Poynting vector) due to power being fed to losses. Andrea DeMarchi suggested a ring cavity end shown in Fig. 3 that has vanishing Poynting vector by symmetry at the beam aperture. Here the phase shift should vary as the square of the departure from the symmetry plane and have no variation along it. This is in contrast to the linear variation with departure from the end short found in the usual structures . The symmetry of the ring is very important but it appears that frequency shifts versus position in the beam aperture due to the local distributed phase shift can be kept down to less than 5×10^{-14} for a 3 mm $\times$ 3 mm beam with reasonable care in the fabrication. Fairly valid ene-to-end phase shift measurement can then be obtained with this type of structure for the cavity ends. There are many other possible cavity designs based on this symmetry principle.

Pulling by $\Delta M = \pm 1$ transitions, Ramsey pulling, has been analyzed recently in detail (to be published in Journal of Applied Physics). The major part of the effect is fundamentally different from Rabi pulling in which the tails of the adjacent $\Delta M = 0$ transitions, which can be treated independently, just cause a background slope at the center of the desired line and thus lead to a shift. Rabi pulling can be greatly reduced either by detecting the third harmonic of the modulation signal instead of the fundamental or by using other modulation schemes that allow the background slope to be determined. The $\Delta M = \pm 1$ transitions adjacent to the desired 0,0 transition cannot be treated independently since they always have one level in common with the 0,0 transition. They add a component to the transition probability versus frequency of the 0,0 line that has the same periodicity as the normal Ramsey line but has a phase shift. This causes the line center to be offset and cannot be corrected for by any of the means that just detect background slope since the component has no average slope and cannot be distinguished from the Ramsey line itself. If all the level populations are symmetric the effects cancel just as in the Rabi pulling case mentioned above. Since $\Delta M = \pm 1$ transitions are caused by lack of parallelism between the microwave magnetic field and the C field they can be reduced to insignificant levels for reasonable size beams by careful design and construction of the cavity and C field structures.

Electronic defects such as modulation second harmonic distortion, synchronous detector and integrator offsets, modulation signal leakage around the beam tube, microwave spectrum asymmetry, etc. can be measured and corrected by proper design and construction. Low frequency square wave frequency modulation is highly desirable from the even order distortion standpoint. Digital techniques are of great value in reducing many of the defects.

Noise at even harmonics of the modulation frequency are heterodyned with the modulation signal and its harmonics by the beam tube to give a noise signal in the beam tube output at the modulation frequency. This cannot be distinguished from the real tube output and so represents a fundamental limitation to the short term stability. The effect is essentially the same as the pulling due to even order modulation distortion. Present high performance optically pumped laboratory standards are now close to being limited in their performance by the noise performance of available high quality quartz flywheel oscillators so this represents an area that will have to be addressed.

Frequency changes due to microwave power sensitivity can be reduced by power stabilization at the optimum power level. Some causes of power sensitivity are end-to-end cavity phase shift, Rabi and Ramsey pulling and, to a small extent, second order Doppler shift.

LABORATORY STANDARDS

Brief status reports are presented here for some of the laboratories around the world.

PTB at Braunschweig, Germany has done fairly complete evaluations of their tubes, Cs1 and Cs2. These both have longitudinal C fields and use hexapole deflecting magnets. They are flop-out systems and as a result suffer somewhat in short term stability. Both have excellent C field structures. Both have beam reversal capability. The biggest uncertainty reported is that due to end-to-end phase shift, the determination of which is not very good because of the local distributed phase shift in the cavity ends. The overall accuracy estimate is 2×10^{-14} and the difference in their frequencies is 2.5×10^{-14} which is presently unexplained. These standards have the lowest presently reported uncertainty and represent the state of the art for conventional cesium beam standards.

PTB has an experimental tube CSX in which DeMarchi Ring ends were installed on a cavity. The substantially reduced local distributed phase shift error expected was fairly well confirmed and the microwave spectrum was excellent with no visible evidence of $\Delta M = \pm 1$ transitions.

NIST in Boulder, Colorado is working on an optically pumped standard, NIST-7. This used D2 (852 nm) pumping and a cycling transition for detection in the initial experiments. Cavity length is 165 cm and DeMarchi ring ends are used with a longitudinal C field. Measured line width was 65 Hz in good agreement with predictions. The tube microwave spectrum looked very good. It had some slight asymmetry which is not unexpected with D2 pumping. The accuracy has not yet been determined but the goal is 1×10^{-14}. The tube is completely symmetric about the center of its length and thus should be ideal for beam reversal. It will have capability for a number of different pumping schemes. The laser used in the initial experiments has line narrowing produced by enhanced reflection at resonance from an off-axis optical cavity. This is similar to one they developed jointly with the National Research Laboratory of Metrology in Japan.

The Paris Observatory is also working on an optically pumped beam tube but it is not yet to a working stage. It is symmetric about the center of its length and will have capability for beam reversal. The C field will be transverse generated by current carrying rods. The cavity is conventional with a length of 102 cm. Initial experiments will be done with D2 pumping. The staff there has done excellent work on the theory of pumping and detection particularly on the Hanle effect and also experimental work on stabilized lasers.

The Laboratoire de l'Horloge Atomique at Orsay is also working on optical pumping. They have built a tube, Cs III, which has been tested on both D1 and D2 pumping. It has a longitudinal C field and a conventional cavity of length 21 cm with longitudinal microwave magnetic field at the ends. Because of the curvature of the microwave magnetic field due to the mode shape close to the entrance and exit holes in the cavity ends, there are very noticeable $\Delta M = \pm 1$ transitions in the tube microwave spectrum. These have the expected shape of a Ramsey pattern with 180 degrees phase shift between the excitations and linewidth corresponding to the length of the cavity ends. The linewidth of the 0,0 transition is about 500 Hz and demonstrated short term stability was $2 \times 10^{-14}\tau^{-1/2}$ with both D2 and D1 pumping. Considering the short length of the tube, this is an excellent result at this stage of development. The tube has provision for running the optical pumping and detection regions with a magnetic field of several hundred mG to reduce the state trapping associated with the Hanle effect. The microwave spectra with the exception of the $\Delta M = \pm 1$ transitions were excellent. The spectrum with D2 pumping showed slight asymmetry while the D1 spectrum looked very symmetric as expected. The group has also done excellent work on the theory of pumping and detection.

The Communications Research Laboratory (CRL) in Japan has built a conventional cesium standard. It uses hexapole deflection magnets with a transverse C field and a conventional cavity with length 55 cm. The linewidth is about 100 Hz. Accuracy is presently estimated to be 1.1×10^{-13}.

The National Research Laboratory of Metrology in Japan has built an optically pumped tube using D2 pumping. It has a conventional cavity 96 cm in length with a transverse C field. The accuracy is estimated to be 7×10^{-14} and short term stability about $1 \times 10^{-12}\tau^{-1/2}$. They have done very good work on lasers some of it in collaboration with the group from NIST as mentioned above.

Even though the Soviets have primarily pursued hydrogen masers they have had a significant effort in cesium beam standards. They presently have three standards, MTS1, MTS2, and MTS3. MTS3 is currently undergoing evaluation. MTS1 and 3 use dipole optics and MTS2 uses hexapoles. The cavity lengths in MTS1, 2, and 3 are 65, 100, and 194 cm respectively. Accuracy of all three standards is estimated at 1×10^{-13} and short term stability is about $5 \times 10^{-12}\tau^{-1/2}$. They have done a lot of work on C fields and power shifts. They are also working on optical pumping but not much information is available.

A lot of exciting work is going on in cooling and slowing of atoms, most of it being done at NIST in Gaithersburg, Stanford University, and the group at Ecole Normale Superieure in France. Spectacular results have been achieved in cooling cesium atoms to about 2.5 microdegrees Kelvin. Simple experiments with a sodium fountain at Stanford (see Fig. 1) demonstrated a linewidth of 2 Hz. Linewidth with cesium in a similar apparatus should be around 1 Hz. A very simple cesium cell apparatus with two diode lasers at JILA in Boulder, Colorado has already demonstrated a linewidth of 8 Hz. Short term stability could be very good and second order doppler shift extremely small as mentioned in the introduction. With such low temperatures and high densities, spin exchange collisions could be a problem but this remains to be seen.

COMMERCIAL WORK

Frequency and Time Systems (FTS) just announced (Dec. 1990) a new cesium standard, model 4065, that is microprocessor controlled and has servo control of the microwave power and zeeman frequency. It is capable of being remotely controlled. An earlier standard is model 4040, with microprocessor demodulation and integration of the frequency servo signals and control over loop time constant and monitoring of system parameters. It is designed for hands off operation. Another unit is model 4160, militarized and optionally radiation hardened. It too features microprocessor control over some functions. Typical specifications are: 7×10^{-12} accuracy at 25 degrees C and $5 \times 10^{-11}\tau^{-1/2}$ short term stability. An 8 year warranted tube is now available.

Frequency Electronics Inc. (FEI) has designed a new tube with a good microwave spectrum (see Fig. 4). The $\Delta M = \pm 1$ transitions are just visible. No other information is available at this time.

Kernco is developing a GPS block IIR satellite cesium standard that is very small, radiation hardened, and has a 7.5 year warranted life (18 year design) for the beam tube. Specifications include:

weight	19.5 lb
input power	<25 watts
size	4.75" x 5.25" x 16.5"
Short term stability	$3 \times 10^{-11}\tau^{-1/2} + 5 \times 10^{-14}$

NTT has an optically pumped cesium tube under development. It has a cavity length of 21 cm and uses D2 pumping. No details were given on cavity or C field design. The tube includes two ovens which can be operate simultaneously with a detection scheme that allows determination of cavity phase shift during operation. Short term stability is estimated to be $9 \times 10^{-13}\tau^{-1/2}$. No estimate of accuracy was given.

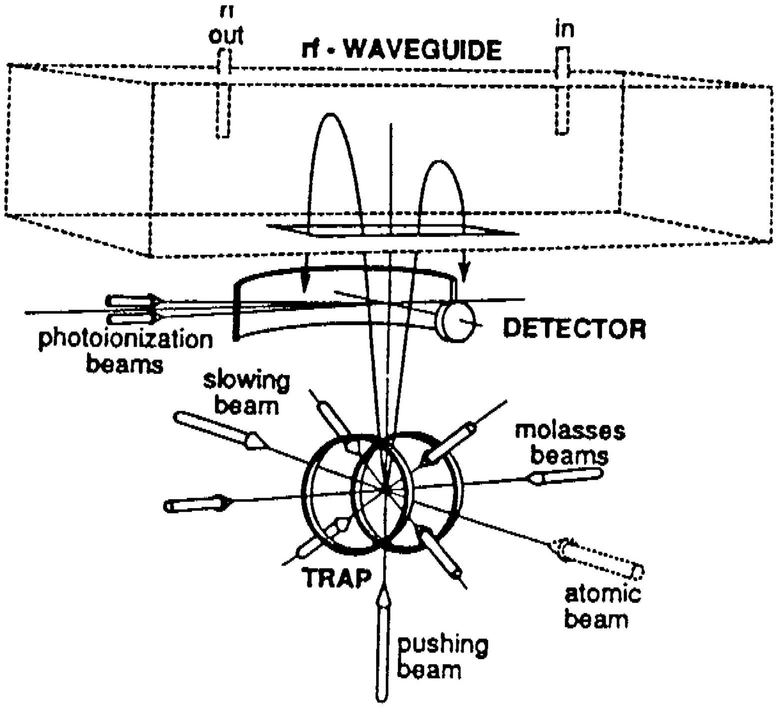
Hewlett-Packard has a new cesium tube in development. It has been optimized by using an accurate ray tracing program and particular attention was paid to reducing $\Delta M = \pm 1$ transitions. It has much better performance in this respect than the high performance tube presently supplied by Hewlett-Packard and equal or better performance in all other respects. The microwave spectrum is shown in Fig. 5.

SUMMARY AND OUTLOOK

Status at the present time for a number of laboratory and commercial standards as well as some of the work leading to the next generation has been presented. Good progress is being made and prospects for the future are bright. Several areas that need emphasis have been pointed out. The present status and future outlook in this writer's conservative view are given in Table 1.

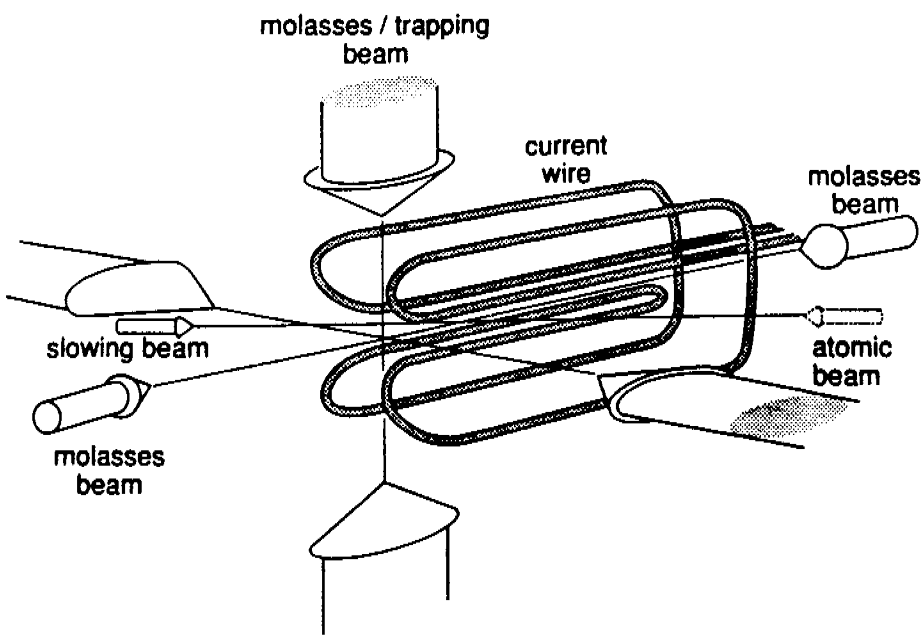
ACKNOWLEDGEMENTS

The author thanks people at the various laboratories and commercial organizations for supplying him the data presented here and apologizes for any omissions or errors.



Sodium atom Fountain. Cold sodium atoms pushed up into the cavity gave linewidth of 2Hz.

Fig. 1



Slow atom Funnel. Wire structure is a two dimensional magnetic quadrupole that provides continuous beam of slow, cold atoms.

Fig. 2

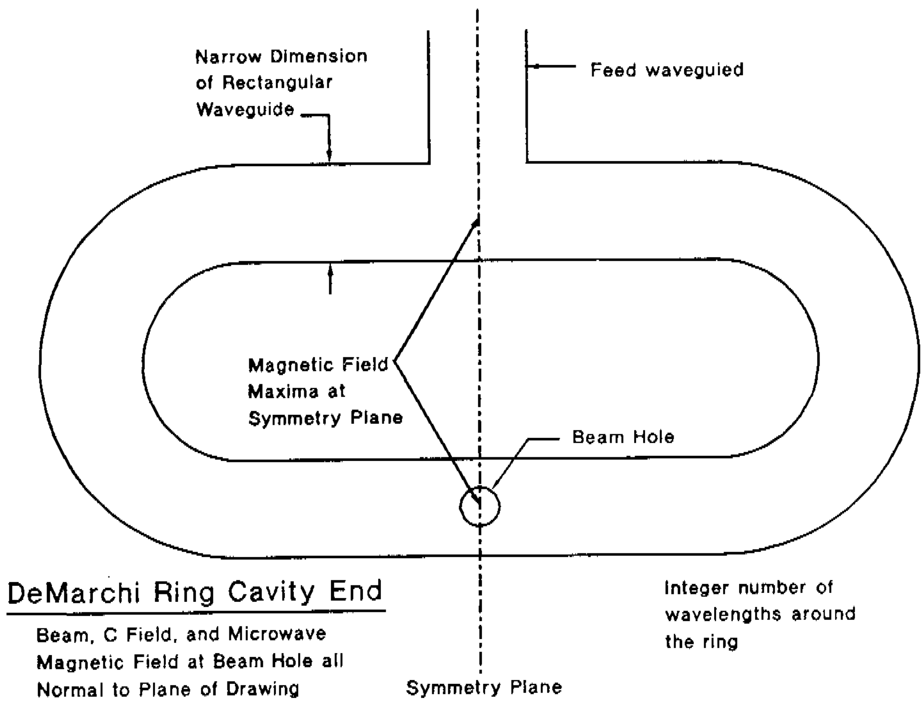
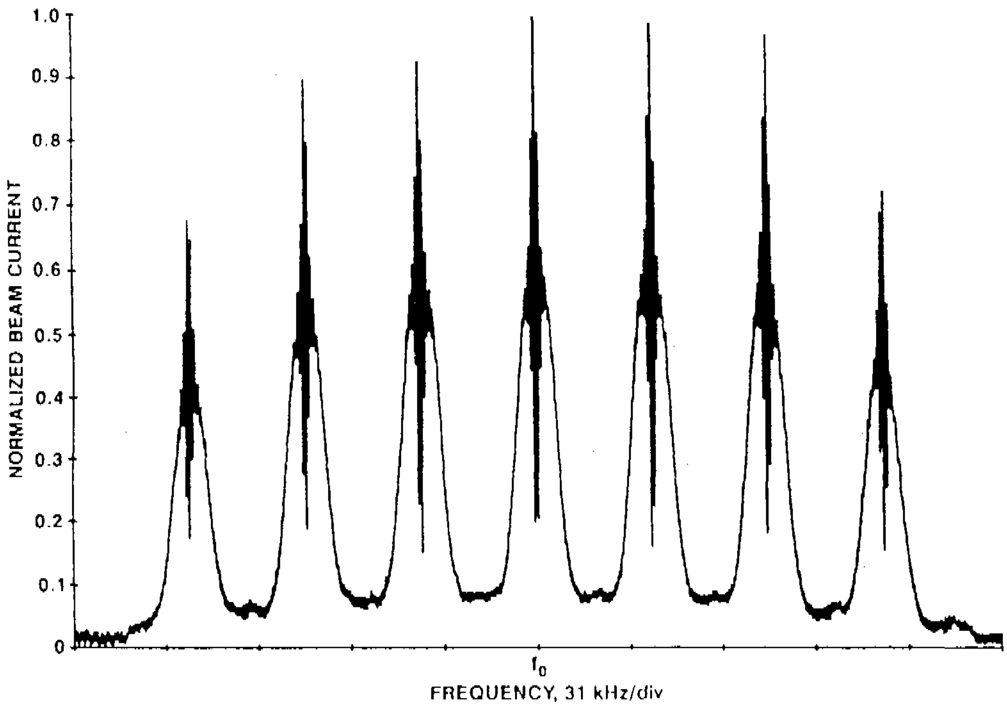
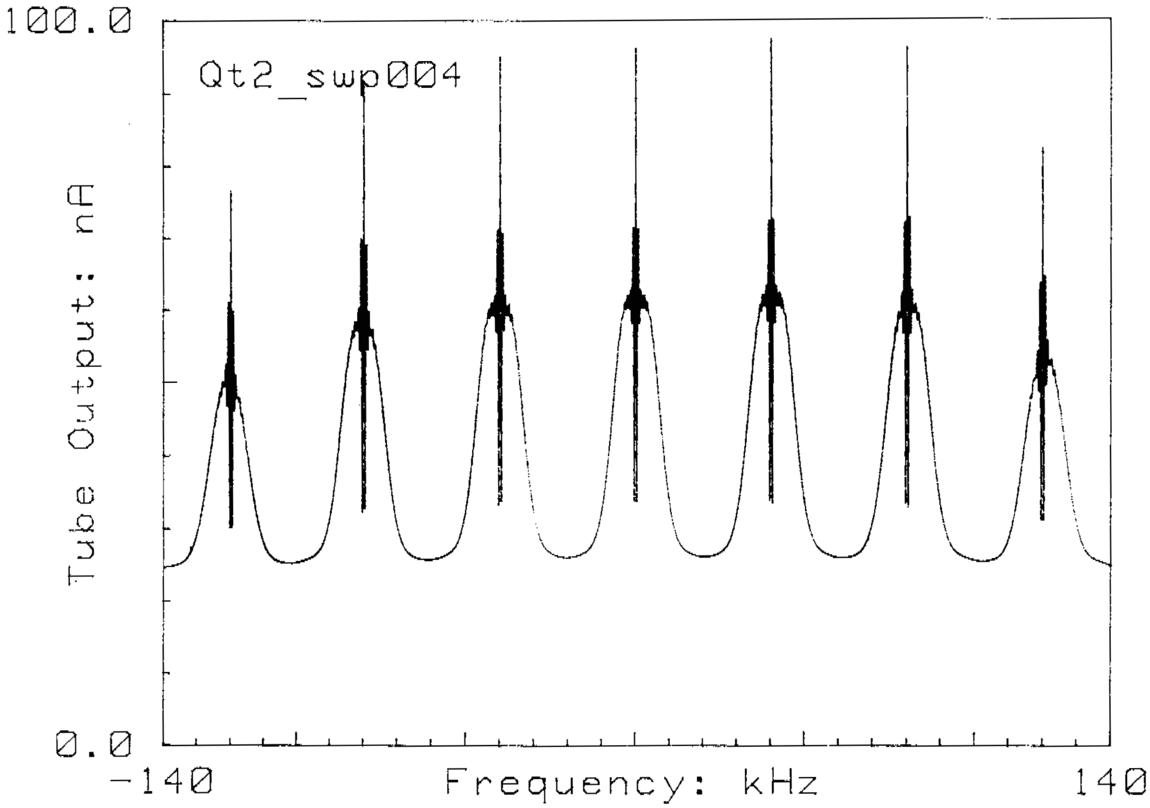


Fig. 3



Microwave spectrum of new Frequency Electronics Inc. cesium beam tube.

Fig. 4



Microwave spectrum of new Hewlett-Packard cesium beam tube.

Fig. 5