

Development of a Cryogenic Hydrogen Maser at the NPL

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Abstract

We have been developing a prototype Cold Hydrogen Maser (CHM) for the past year. The novel features of this CHM, which is designed to operate initially at 4.2 K, are the use of low loss alumina, and later sapphire, in the fabrication of the microwave cavity; possible use of superconductors for shielding; use of a cryogenic amplifier; possible novel coating material; and a reliable rf discharge circuit for the dissociation of hydrogen. A numerical simulation has been performed to find the dimensions of the microwave cavity for the TE₀₁₁ mode and the model was confirmed experimentally. The system will be used to test various wall coatings adsorbed on top of a PTFE buffer underlayer.

The CHM is expected to be used as a flywheel frequency standard at the NPL with medium-term stability of one part in 10^{14} or better.

INTRODUCTION

Following its initial discovery in 1960 by Goldenberg, Kleppner and Ramsey [1] the hydrogen maser quickly established itself as the most stable of all atomic frequency standards for short and intermediate times, with stabilities of a part in 10^{15} for measuring times between 10^3 to 10^5 seconds. The high stability of the atomic hydrogen maser is due to the following:

- (i) the atoms remain in the storage volume for about 1 sec, which is much longer than the storage time in an atomic beam apparatus, so the resonant line is narrower;
- (ii) the atoms are stored at low pressure so they are relatively free and unperturbed while radiating;
- (iii) the first order Doppler shift is removed because the atoms are exposed to a standing wave and the average velocity is very low for atoms stored for 1 sec;
- (iv) the maser noise level is very low when the amplifying elements are isolated atoms.

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Cooling the hydrogen maser down to 4K can potentially lead to 3 orders of magnitude improvement in its frequency stability. This is obtained firstly, through an increase in the storage time of the atoms; secondly, by a substantial reduction in the spin exchange collision cross section, which limits the line Q and the power radiated in conventional masers; thirdly, by the use of more uniform and stable storage surfaces which give reproducible wall shifts; and finally; by the improved noise performance of cryogenic rf amplifiers. Thus far three research groups have set up and tested cold hydrogen masers.^{[2], [3], [4]}

The stability of a frequency standard is expressed in terms of the two-sample Allan deviation which is given by:

$$\sigma_y(\tau) = \frac{1}{Q} \sqrt{\frac{kT}{2P\tau}}$$

where Q is the maser line quality factor, k is the Boltzmann constant, T the absolute temperature, P the power delivered by the atoms, and τ the averaging interval. The quality factor of the transition depends on the total transverse relaxation time of the H atoms. This is determined by the storage bulb, the wall and the spin exchange relaxation rates, and is proportional to $T^{1/2}$. The Allan variance depends linearly on T and cooling from room temperature would give a significant improvement in frequency stability for intermediate measuring times.

The main drawbacks of the hydrogen maser are the change in the hyperfine frequency caused by the occasional collision of atoms with the walls which can give rise to wall shifts of the order of parts in 10^{11} , and the low level of the output signal, which at 10pW puts stringent requirements on the detection system.

Aside from its standards applications the maser has uses in fields as diverse as Very Long Baseline Interferometry, tests of general relativity, satellite navigation systems, telecommunications, and other fundamental research which should lead to a better understanding of spin-exchange, atom-surface interactions, and other relaxation phenomena.

THE COLD HYDROGEN MASER

The Cryogenic Hydrogen Maser (CHM) project was started in October 1991, after the completion of a feasibility study^[5], with the following longer term objectives: (i) to develop a flywheel time and frequency standard using recent advances in technology; (ii) investigate the physics and the absolute reproducibility of the standard. Our immediate objective is to acquire the necessary technology by constructing a prototype system before going on to a more sophisticated system.

The CHM assembly is displayed in Fig.1. Hydrogen molecules are dissociated in a discharge bulb energised by the rf circuit shown in Fig.2. They are then formed into a beam of atoms in their ground state having approximately equal populations in each of the four hyperfine sublevels (Fig.3). After flowing down the PTFE transport tube into the cryostat, they are state selected by a hexapole magnet. Atoms in the ($F=1$) states travel into the maser bulb where they decay into the ($F=0$) state and radiate power at 1420MHz. If the storage cell is located within a sufficiently high-Q microwave cavity, an oscillation at the resonant frequency will build up until an equilibrium value is reached. The oscillation is picked up by a probe positioned near one end of the cavity, preamplified and transmitted out of the cryostat through a low loss microwave transmission line.

Following a further stage of amplification, the signal is mixed down to audio frequencies and detected.

We will now give a detailed description of the system. The hydrogen discharge system consists of a bulb connected via copper tubing to the hydrogen gas supply and a Pirani gauge. The bulb is capacitively coupled to the rf circuit. We were able to obtain a discharge with 1 mbar pressure of hydrogen in the bulb and 5W rf power at 25MHz. The colour of the discharge changed from bluish red to purplish red with continuous operation.

The state-selector hexapole magnet is displayed in Fig.4. Its appearance was influenced by C. Audoin's original design^[6] and specially adapted for operation at low temperatures. The shape of the pole pieces ensures that a uniform positive field gradient is seen by the atoms as they move away from the centre of the magnet. The flux density maximises near the pole tips. We used a NdFeB magnet pieces inserted into soft magnet frame made out of Vanadium Permendur 49. The inter-pole field was measured to be approximately 1.1T using a moving coil galvanometer arrangement with an area of 9.4mm x 0.7mm.

A numerical simulation program was written to find the best configuration of an alumina cavity for use in the CHM. The frequency of the operating mode has to coincide with the hyperfine frequency of the hydrogen, which is 1420.405MHz in a field of 1 mG. The requirements of the hydrogen maser determine the ideal cavity mode to be the TE011. The variation in the cavity frequency of this mode with temperature is shown in Fig.5. This had to be included separately in our numerical model which is only valid at room temperature because of the unknown temperature dependence of the relative permittivity of alumina below 100K. The finished cavity is displayed in Fig.6. The outer surface of the cavity was then silvered to improve its Q factor. We intend to use sapphire in the longer term.

Wall coating of the masing volume is another important factor influencing the overall performance of the CHM. We have performed extensive PTFE coating trials using a solution of Teflon AF1600^[7] dissolved in Fluorinert FC77^[8]. It was found that 0.75% by weight of the AF1600 dissolved in Fluorinert yielded the best coverage on a thoroughly cleaned surface. Three applications of the solution was found to give the optimum coating. The solution has a transparent, non-viscous appearance when initially mixed. The preparation is comparatively easy; although care has to be taken in the mixing and pouring of the solution onto the surface to be coated. The uniformity of the coating was measured using a nanosurf surface profilometer and found to be smooth to 200nm over a distance of 0.5mm(see Fig.7). Tests of the Teflon film for pinholes using water at room temperature, and cool down as far as 4.2K, were successful; We are about to investigate its performance with atomic hydrogen; and are hoping to test frozen hydrogen and superfluid helium as wall surfaces on top of the Teflon buffer layer.

FUTURE PLANS

Following initial tests, the focusing of the hydrogen beam after the state selector will be observed using a sensitive thermometer made out of phosphorus doped silicon which is capable of measuring 0.5pW at 4.2K over an area of about 0.2 mm². The sensitivity of the microcalorimeter arises out of its low heat capacity at low temperatures. The detection threshold corresponds to a flux of 10⁶ hydrogen atoms per second impinging and recombining on the device. Since we expect a flux of

10^{12} to 10^{13} atoms per second entering the maser bulb, this gives us a very sensitive hydrogen atom sensor. Preliminary tests are encouraging but its longer term performance is yet to be evaluated.

In preparation for the design of the magnetic shields required for the maser, we have written a program based on Dubber's work^[9] which calculates the type and number of shields needed to keep out stray fields and the earth's field. This suggests that a three layer nested arrangement of mu-metal shields which will give a shielding factor of approximately 10^4 . Additional low temperature protection is will be provided by a Cryoperm^[10] shield.

The electronics for the detection of the free induction decay signal in the passive mode of the maser are assembled and we hope to observe the signal at 4.2K by the middle of next year. Our expectation is that changes to the cavity and in the detection electronics will then become necessary in order to observe the masing action.

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I would like to thank Brian Petley and John Gallop for their advice and support whenever it was asked for. Paul Hardman has been instrumental in much of the recent experimental progress and the NPL workshops have also played their part in realising some difficult designs such as the hexapole magnet.

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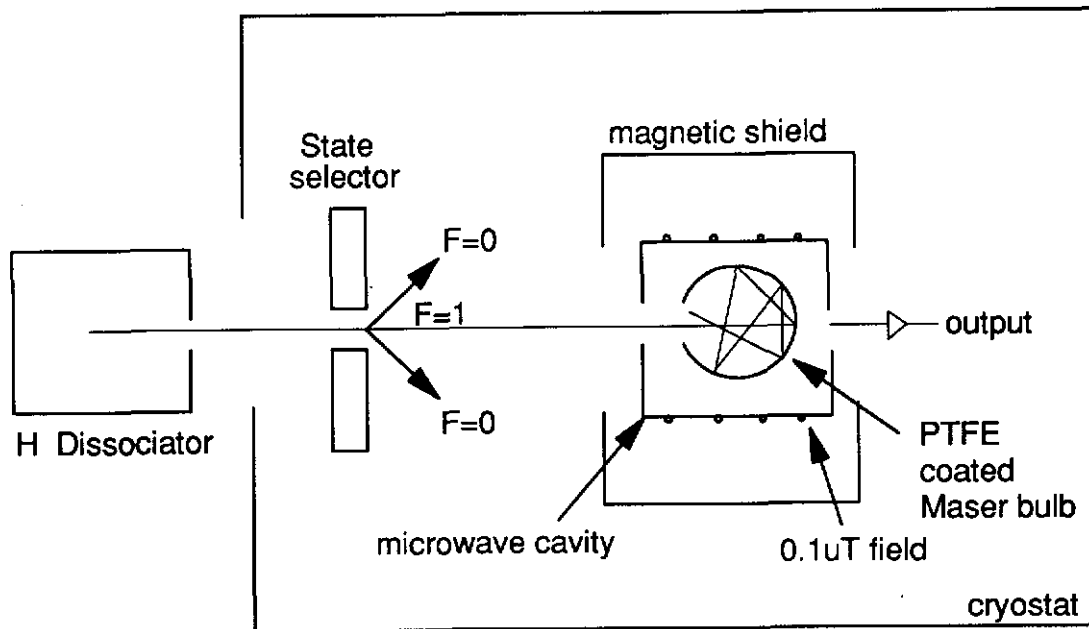


Fig.1 Schematic diagram of the CHM assembly

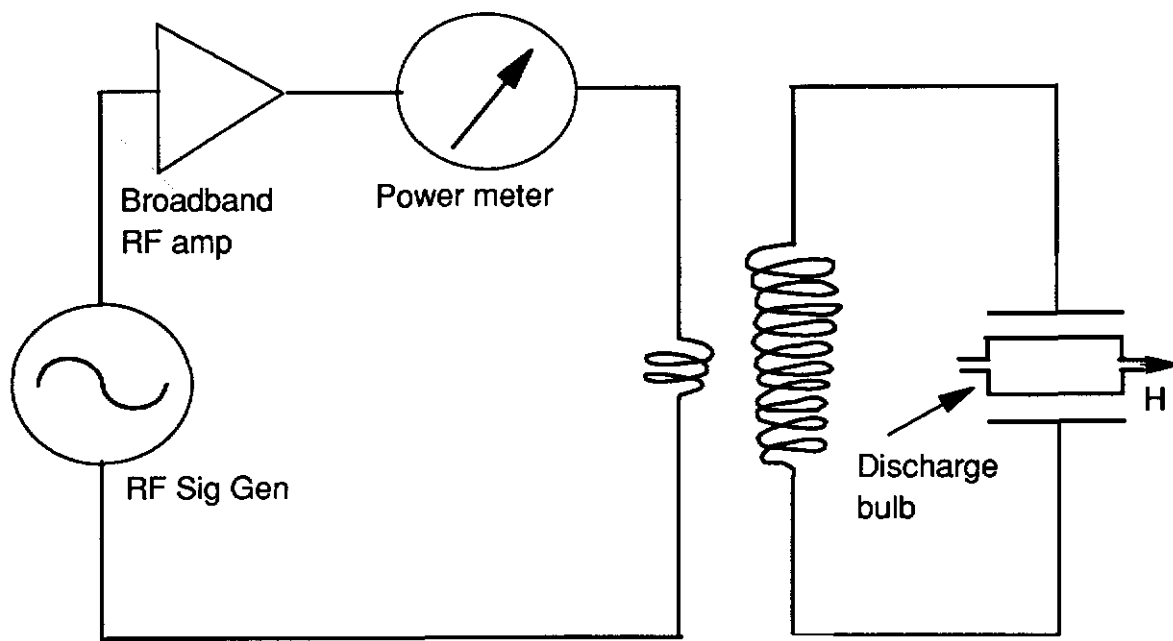


Fig.2 Hydrogen rf discharge circuit

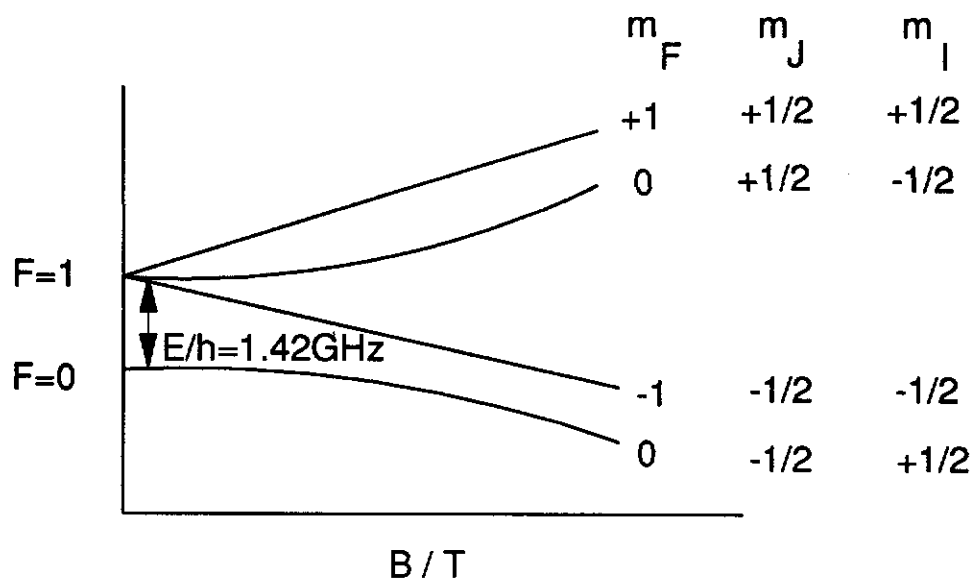


Fig.3 Hyperfine levels of the H atom

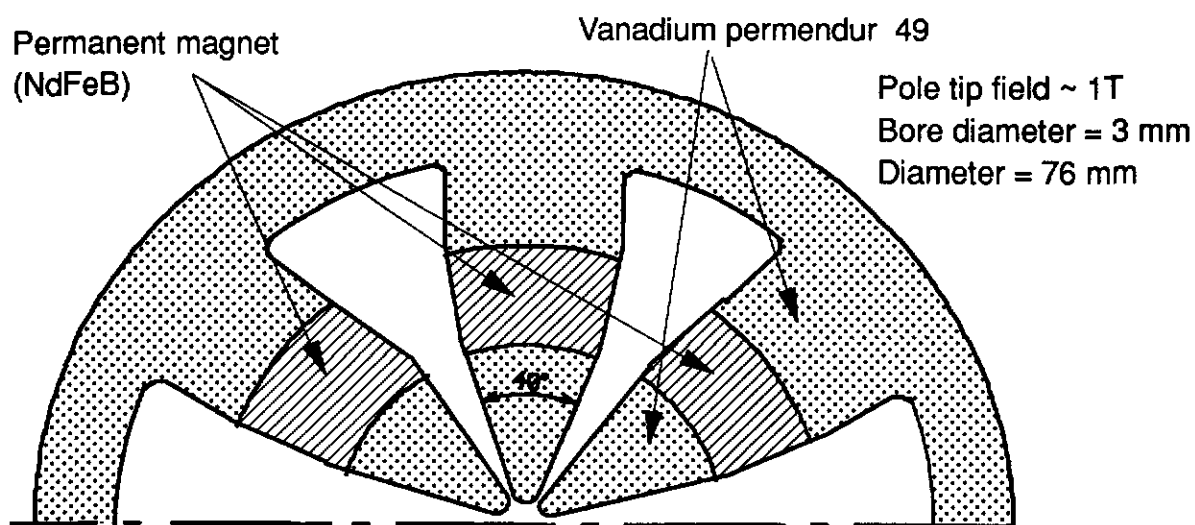


Fig.4 Half section view of hexapole magnet

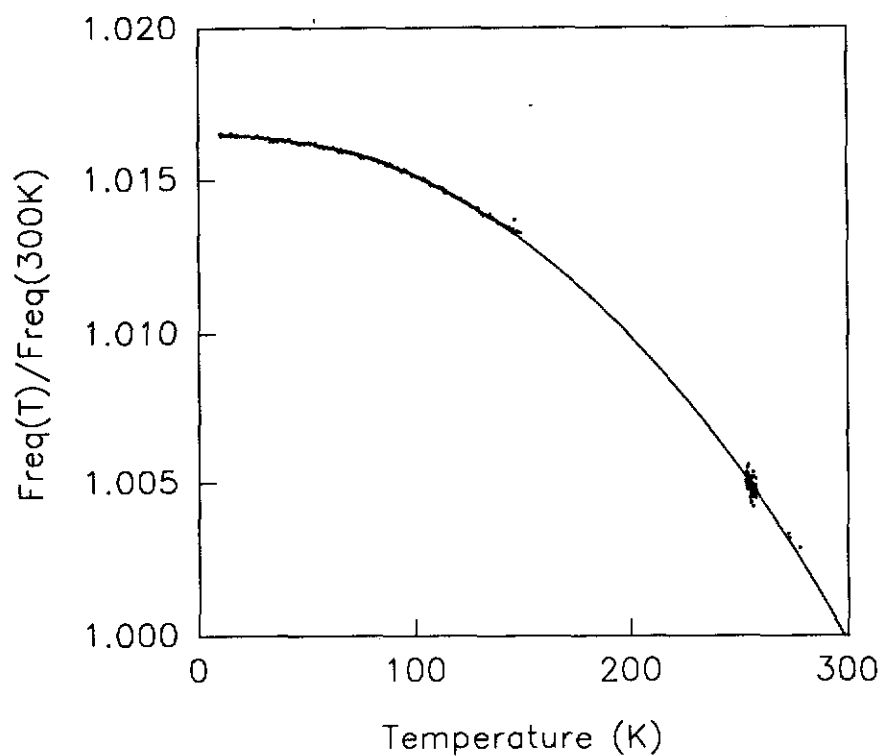


Fig.5 Temperature dependence of the TE011 mode of the alumina microwave cavity.

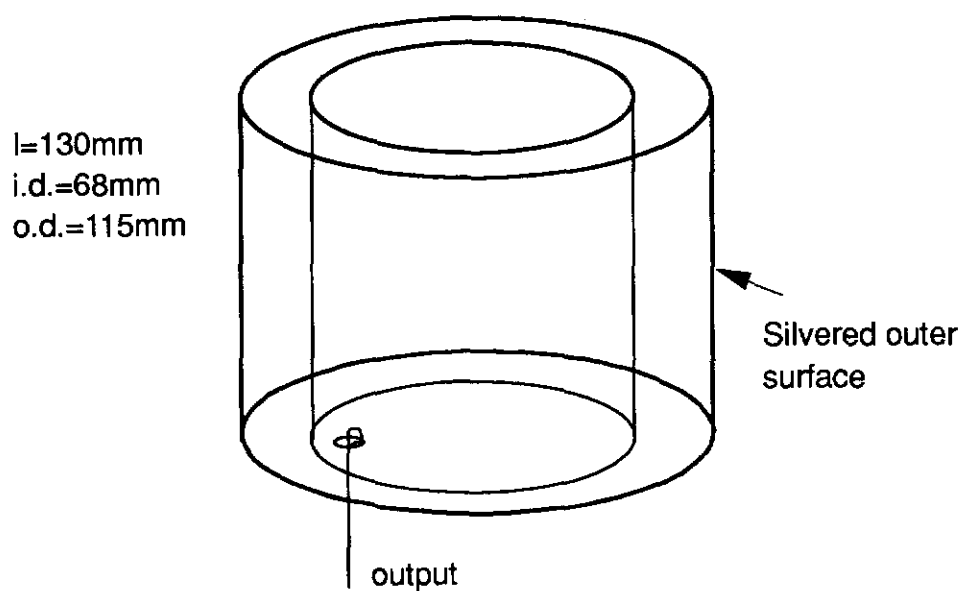


Fig.6 The alumina microwave cavity

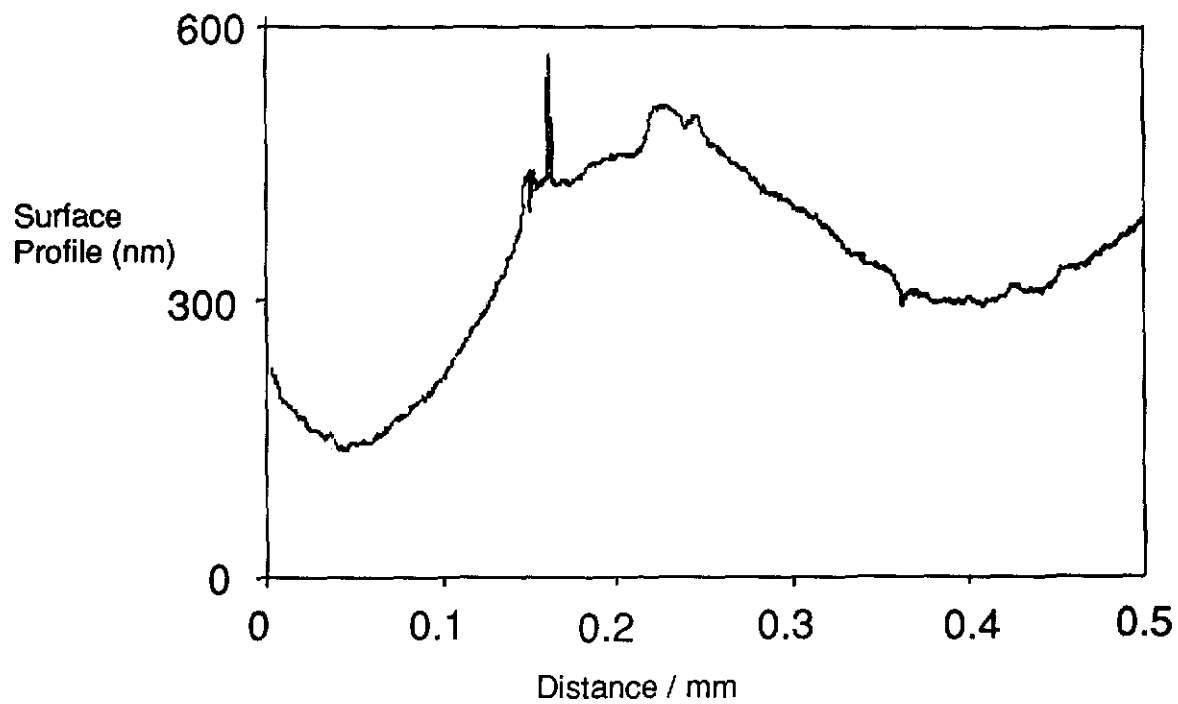


Fig. 7. Profile of the Teflon coating on microscope slide showing the smoothness of the surface.

QUESTIONS AND ANSWERS

E. Mattison, SAO: Do you plan to use liquid helium coating on your walls or just use the teflon?

R. Mossavati, National Physical Laboratory: That is one of the questions which I hope would be discussed at a meeting such as this and what the situation is we had hoped to work at 2.7 Kelvin which is very nice temperature in terms of temperature stability to work at with helium. As you probably know that the vapor pressure of helium goes up exponentially at about 0.6 or 0.7 Kelvin. Therefore we are praying for some new material to be discovered which will work at those set of temperatures. We have to consider so the moving on down in temperature to 0.6 to 0.7 Kelvin. That would be a shame because we would lose the lambda transition stability which we would have otherwise at 2.7 Kelvin. Frozen hydrogen is something that I have considered but I don not think getting masing action with frozen hydrogen is a very easy thing or at all possible.

A. Kirk, JPL: How many of these cold masers are you assembling and if the answer is one, how are you going to test it?

R. Mossavati: It is very much a research effort in terms of finding out the pitfalls with the cold hydrogen maser. We hope to, and as I said I have funding until the beginning of 1995. By that stage, I hope to have enough to show so that I can get additional funding to go on to develop a more sophisticated system. I would like to emphasize that this is a research and development effort and it is very much based in a scientific and research laboratory environment rather than an industrial application type of environment.