Hydrogen Masers

The first Hydrogen Maser was the brainchild of the American Physicist Professor Ramsey, who at Harvard University in 1960, succeeded in making the first operational model.

It had followed years of research into increasing the precision of the atomic beam magnetic resonance method by means of a narrowing of the resonance pattern. Kleppner (Kleppner et al 1962) soon made the realisation that the Hydrogen Maser was able to deliver an extremely stable frequency reference signal. This led to the consideration of using the Hydrogen Maser as a primary frequency standard. Sustained research was therefore carried out into studying the frequency shifts arising during the collision of the hydrogen atoms with the walls of the storage bulb. This is called the wall shift. The frequency of the hyperfine transition of the hydrogen atom has been measured with accuracy of the order of 1E-12

A major difference between Hydrogen Masers, Caesium Beam, and Rubidium Cell Frequency Standards, is that there is no direct access to the change of population difference in Hydrogen Masers. This is because there is, at present, no efficient means of detecting hydrogen atoms. The basic principle of operation is that the strong coupling between the atomic medium and the microwave field in the resonant cavity makes it very easy to see the necessary hyperfine transition via the amplification of the microwave field by stimulated emission of radiation. If the amplification is made large enough then the required oscillation may be sustained. There are then two ways in which the Hydrogen Maser may be operated. i) Actively as an oscillator and ii) Passively as an amplifier.

The principle of operation of the *Active Hydrogen Maser* is based upon the 5 MHz quartz crystal oscillator, phase locked to the hyperfine transition of the hydrogen atom. The atomic hydrogen signal generated within the physics package is then picked up by an antenna in the cavity and coupled to the synchronisation unit. The synchronisation unit amplifies this signal with the help of a super-heterodyne receiver. This in turn synchronises the 5 MHz crystal oscillator signal phase to the hydrogen signal phase producing the 5 MHz and 100 MHz spectral-pure sine-wave signal output.

The *Active Hydrogen Maser* provides the best-known Frequency Stability for a frequency generator. It excels itself in the domain of 1 sec to 1 day. At a 1 hour
averaging time, the Active Hydrogen Maser exceeds the stability of the best known Caesium Oscillators by up to a factor of 100, with an Allan deviation of ~2E-15.

Both the Active and the Passive Hydrogen Masers consist of five main sub-systems described below

a) *The physics package*. This consists of the Hydrogen maser (which generates a precise signal at approximately 1420.4 MHz) together with a number of self contained auxiliary electronic units necessary to maintain various physical states essential to the operation of the maser.

b) *The synchronisation unit.* This amplifies the low-level (one of the inherent disadvantages of the H-Maser) 1420.4 MHz maser signal from the physics package so that it may be used to synchronise the 5 MHz crystal oscillator. The output of the oscillator is in turn used to generate precise frequency outputs at 5 MHz and 100 MHz. The synchronisation process employs a synthesiser to accommodate the exact frequency generated by the maser source and to adjust the frequencies generated by the unit over a range of +/- 0.5 parts in 10^{10}

and in steps of 1 part in 10^{14}

c) *The power supply.* This supplies seven different voltages for the internal functions of the unit. All are in the low voltage range, except for the 3 kV low current supply required by the ion vacuum pumps. Continuous operation is essential to the precision of the unit and the power supply therefore includes a facility for automatic changeover from normal operation from the 115V or 220V AC. Mains powers to an external standby battery supply of 27V dc

d) *The remote control interface.* The interface permits the unit to be integrated into computer-based monitoring and control systems, as an implementation of a subset of the IEC 625-interface standard. This offer functionality identical to the IEE-488 standard. The interface allows remote control of the operating state of the unit and selection of output frequencies, also access to the diagnostic and status data gathered in the control and display subsystem.

e) The control and display subsystem. This subsystem provides the operator interface to the CH1-75 unit as it includes the front panel controls and indicators and the dividers and indicators, which provide time indication on the front panel. It also acts as a collection point for status signals from various parts of the system and thus provides operating mode and status information via the front panel displays and over the IEC bus.

The maser cavity auto tuning function also forms part of this subsystem. A frequency comparator within this unit generates a 1 Hz control signal, which is converted into a tuning control signal. This is routed to the physics package and changes the natural resonant frequency of the maser cavity until it matches the frequency of the spectral frequency emitted by the hydrogen atoms.

The *Active Hydrogen Maser (AHM)* owes it's high stability to the following:
i) The resonant line is narrow due to the long storage time spent in the storage volume (1s)
ii) If the amplifying elements are isolated atoms the noise level of the maser is very low.
iii) The storage of atoms at low pressure leading to free and un-perturbed movement during radiation.
iv) The exposure of atoms to a standing wave, leads to removal of the first order doppler shift. Also the average velocity for stored atoms is very low.

The *Passive Hydrogen Maser (PHM)* is based upon the 5 MHz quartz crystal oscillator, frequency locked to the hyperfine transition of the hydrogen atom. One the main reasons for the inception of the PHM was to provide an alternative technology to the high performance caesium oscillators currently being used. At present, the PHMs stability outperforms the best available caesium by a factor of 10. One of the big advantages possessed by the PHM is that, unlike caesium, it does not have an expensive wear-out physics package. The lifetime of the PHM is hence not constrained by the 3-7 year life cycle imposed upon caesium oscillators. The PHM would therefore be your number one choice over high performance caesium oscillators if better stability and competitive accuracy were needed at a comparable price

Long Term frequency stability of H-masers depends on whether or not the Cavity Pulling effect is eliminated by the cavity auto-tuning system (CAT). In CAT systems long term frequency stability similar to laboratory primary caesium beam frequency standards has been observed i.e. a few parts in 10^{14} over several years. The accuracy of an atomic frequency standard is the degree with which its output frequency agrees with the value of the unperturbed transition frequency. The accuracy of the H-Masers, whilst slightly below that of $1M laboratory Primary Caesium, is on par with the best commercially available caesium. The reproducibility is the degree to which the frequency standard reproduces its normal output frequency without the need for calibration against another frequency standard, while the environmental conditions are set to any value in the specified ranges. Normally one would expect the reproducibility to be slightly be than the accuracy. The H-Maser has a reproducibility of 10^{-14} , an order of magnitude better than caesium.

There are many present and future applications for Hydrogen Masers, such as:
i) In widely separated radio telescopes for very long baseline interferometry (VLBI) to control local oscillators and provide timing for data recording
ii) Laboratory standard / in-house reference. The UK time scale is formed by two active hydrogen masers coupled together by auto cavity tuning .
iii) The ultimate Stratum 1 primary reference clock standard for telephone networks.
iv) Satellite ground station clock/frequency standard.
v) Test equipment reference for measuring the quality of GPS disciplined oscillators
vi) Deep space missions clocks

Unlike the research into other types of frequency standard, relatively little research has been carried out in the west into the development of the H-Maser. Only recently has any concerted effort been made into producing smaller, user friendly H-masers. In contrast to this, work carried out into the H-maser in the Soviet Union has been far more advanced, with many hundreds of devices having been manufactured and sold to this day. A far greater reliance seems to be placed in the Soviet union upon the H-maser as a primary reference standard. The Market until now has been rather limited for H-masers, but with the increased emphasis on high Frequency Stability rather than high accuracy, the demand for H-Masers is growing rapidly. The is primarily due to the increased use of Two-way time transfer with GPS, GLONASS and communications satellites. One example of how this technology is being applied in the west is through a teaming relationship between Quartzlock (UK) Ltd and KVARZ Institute of Electronic Measurements of Nizhny Nogorod, Russia. These units have been built in substantial quantities for the last 30 years and form the major time-scales in Germany, Brazil, Spain, Japan, Russia, China, Belgium, Taiwan, S.Korea and the UK. The instruments are produced in Russia and are shipped to Quartzlock, where they are prepared for delivery to both domestic and European customers. It is also possible for these instruments to be tested by NIST in USA, PTB in Germany or at NPL in the UK

H-Masers will continue to find use in applications where very high stability is required for intervals between 1 second and 10^5 seconds. However, the medium term frequency stability is limited by the cavity thermal noise and goes as $\tau^{-1/2}$. Similarly, the short term frequency stability depends on the cavity thermal noise and on the electronic noise in the first stage of amplification. A reduction in the operating temperature of both the cavity and system electronics should lead to an improvement in the frequency stability. In addition the spin-exchange-broadening effect decreases at low temperature. Therefore, one aim of present work being carried out is to improve the frequency stability of the H-Maser by lowering it’s temperature. The development of a cryogenic H-maser has stimulated a lot of research interest. Early results show that it possesses the possibility to be a field operable atomic frequency standard with fractional frequency stability in the 10^{-18} range