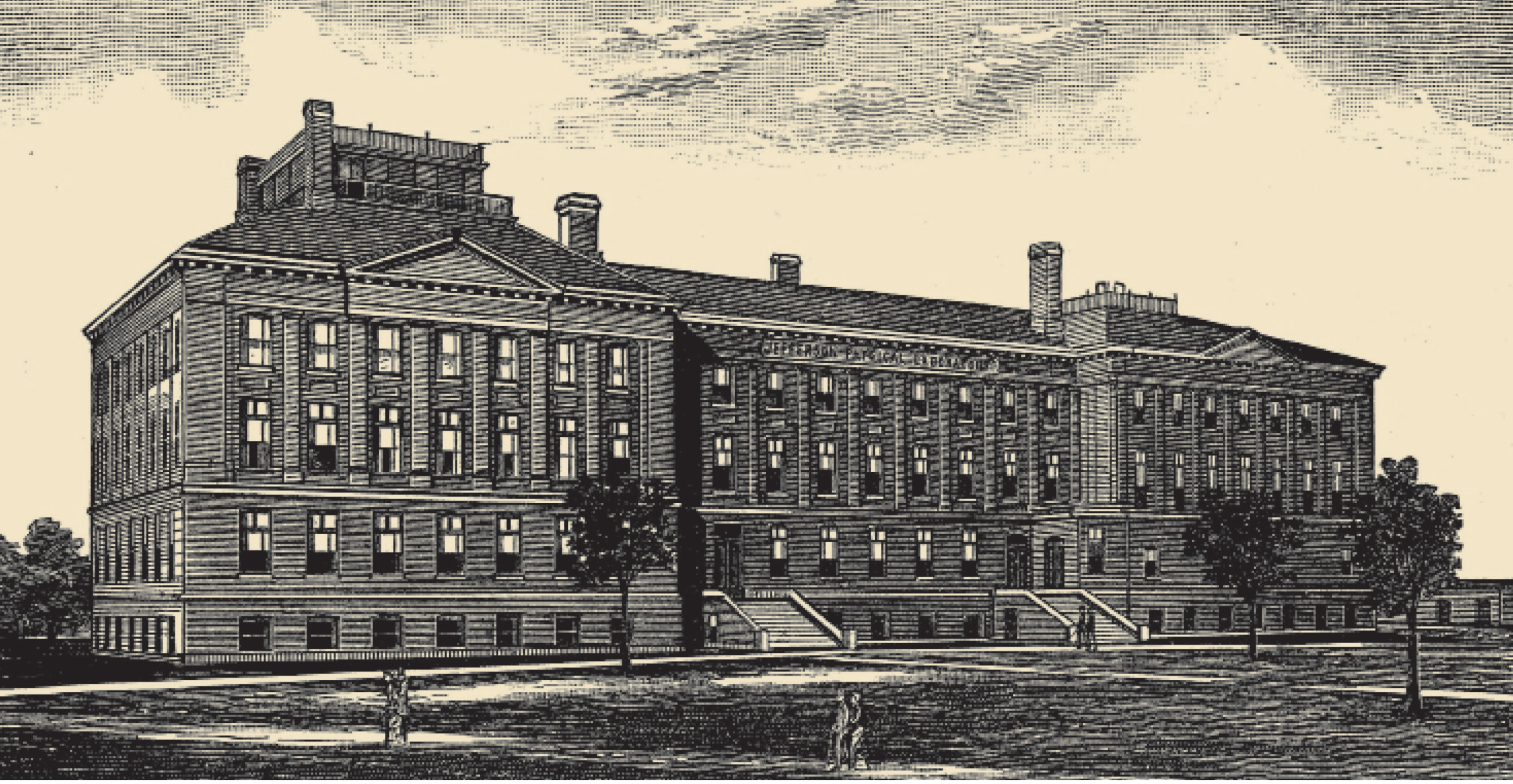

“UNPRECEDENTED SPECTRAL PURITY”:
The Invention of the Hydrogen Maser

by Paul Horowitz

“It’s oscillating!” wrote Dan Kleppner in his lab notebook in the predawn hours of September 8th, 1960.[1] What was oscillating, in the Ramsey group’s first-floor laboratory in Lyman, was the first maser comprising a gaseous atomic (versus molecular) species – in this case the hydrogen atom’s hyperfine transition (the same 1,420 Mc/sec responsible for the galactic 21cm signal first detected by Harold (“Doc”) Ewen and Edward Purcell[2] in 1951).

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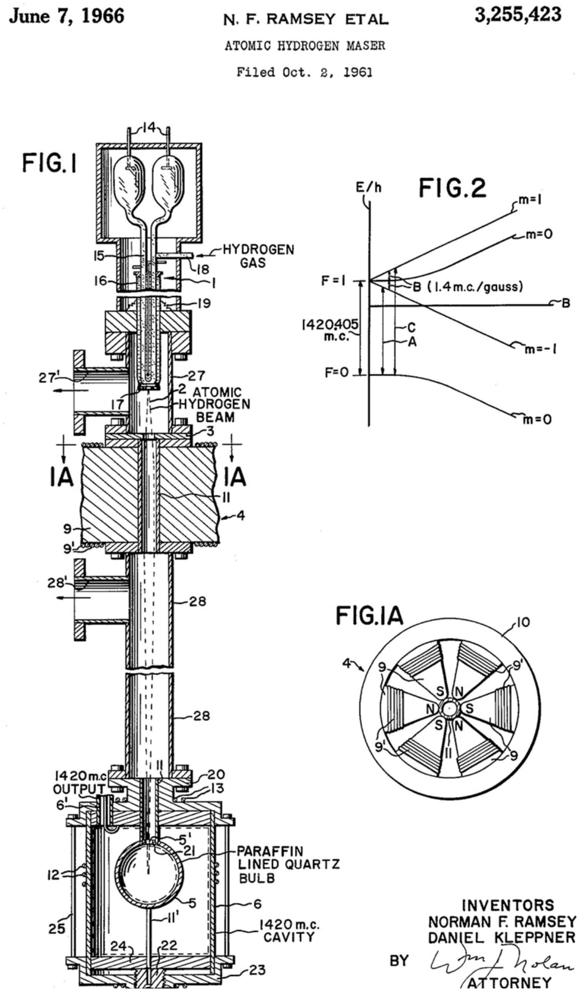
[1] The date may be in error by a day: the notebook has not been located, having been requisitioned by Varian to support an improvement patent; and, with characteristic physicists’ disregard of the historical record, the discovery date is not mentioned in any publications. More remarkable, perhaps, is the use of the exclamatory – Kleppner is parsimonious in its use, once advising this author that it should be used “at most seven times in one’s lifetime.”

[2] See P. Horowitz, "Radioastronomy’s First Spectral Line: A Glimpse of the Handiwork of Creation,” *Harvard Physics Newsletter* (2020).

In the opening words of the patent [3] by Norman Ramsey and his post-doc Kleppner, "The present invention relates to a device for generating microwave energy of unprecedented spectral purity, and thus of importance in such applications as frequency standardization and stabilization, magnetic field measurement and control, and radio frequency communication." The first page of the mercifully short (5 pages) patent is shown in Figure 1.


June 7, 1966 N. F. RAMSEY ETAL 3,255,423
ATOMIC HYDROGEN MASER
Filed Oct. 2, 1961

INVENTORS
NORMAN F. RAMSEY
DANIEL KLEPPNER
BY Wm J Nolan
ATTORNEY

Figure 1: First page of Kleppner and Ramsey's 1961 patent.

Indeed, the hydrogen maser has become a mainstay of timekeeping and frequency stability in contemporary applications such as navigation satellites (GPS, Galileo, Glonass, BeiDou) and aperture synthesis radioastronomy (VLBI: very long baseline interferometry, essential for observations like the Event Horizon Telescope that imaged the happenings near M87's black hole [4]). A rocket-borne hydrogen maser was used in a test of the gravitational redshift, confirming Einstein's prediction to better than a part in 10,000. [5]

Although it is not viewed as a *primary* frequency standard (owing to frequency-pulling effects such as those produced by collisions with the container wall), its superb stability over time scales from seconds to days makes it the preeminent "flywheel" oscillator for demanding applications – see Figure 2, which compares the stability versus time (the "Allan variance") for precision atomic frequency standards (and the best oven-stabilized piezo-mechanical quartz oscillators).

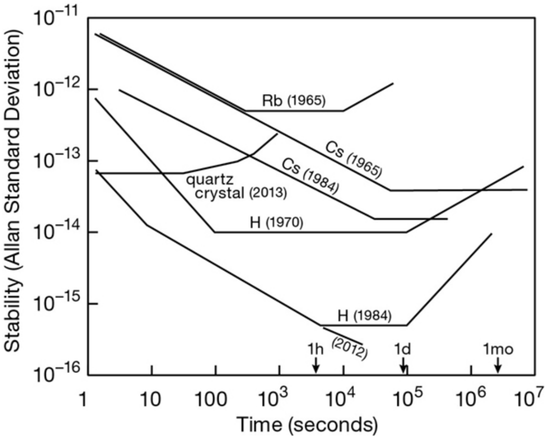


Figure 2: Stability of oscillator types, as measured by their "Allan deviation." More recent "cesium fountain" and "optical lattice clocks" are better still – they slide right off the bottom. (After Fig. 9.17 in Thompson, Moran, and Swenson, *Interferometry and Synthesis in Radio Astronomy*, 3rd ed., 2017).

A BIT OF HISTORY

I. Molecular Beam Resonance

To set this discovery in context, rewind thirty years to the birth of what's now called "molecular beams." In the early 1930's, in a series of novel experiments, Otto Stern's group in Hamburg [6] observed resonance phenomena in beams of alkali atoms subjected to magnetic fields with spatial alternation along the atoms' path. The moving atoms thus experienced time-varying magnetic fields; however, the broad thermal velocity distribution caused the atoms to see a range of frequency variations in the magnetic field, smearing out any resonance effects. By the end

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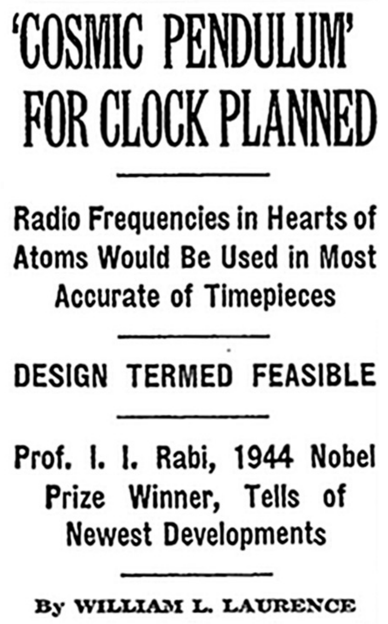
[3] U.S. Patent 3,255,423, *Atomic Hydrogen Maser*, filed Oct. 2, 1961, issued June 7, 1966.

[4] The Event Horizon Telescope Collaboration, "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole," *Ap.J. Lett.,* 875:L1, 1 (2019).

[5] R.F.C. Vessot, et al., "Test of relativistic Gravitation with a Space-Borne Hydrogen Maser," P*hys. Rev. Lett.*, 45, 26, 2081 (1980). See also P. Horowitz, "Testing Einstein's Prediction: the Pound-Rebka Experiment," *Harvard Physics Newsletter* (2021).

[6] R. Frisch, T.E. Phipps, E. Segrè, E., and O. Stern, "Process of Space Quantization," *Nature*, 130, 3293, 892 (1932).

of the decade, though, thanks to work by I.I. Rabi and colleagues at Columbia, the idea of using *time*-varying (rather than space-varying) fields led to the observation of sharp resonances in both atomic and molecular beams. In the last paragraph of their 1939 paper,[7] the Columbia group wrote "Our results show that it is possible to apply exact spectroscopic principles and procedures to spectral regions which correspond to ordinary radio waves." The new technique was called "molecular-beam magnetic resonance"; thus was born the field of atomic and molecular radiofrequency spectroscopy.



'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

DESIGN TERMED FEASIBLE

Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

By WILLIAM L. LAURENCE

Figure 3: The first modern publication proposing an atomic clock: a 1945 New York Times article reporting on Rabi's Richtmyer Award Lecture.

II. Intrinsic Atomic Resonances

The resonance frequencies in the early molecular-beam experiments depended on the strength of an applied magnetic field, thus were not candidates for a precise clock. The next step was to exploit the internal energy states of molecules or atoms, with the hope of achieving a stable and narrow resonance. In 1940 the Columbia group, in a paper[8] modestly titled "The Radiofrequency Spectra of Atoms," reported the first atomic beam resonances of the hyperfine separation in the ground state of an atom; this is the difference of energies caused by the quantized orientation of the nuclear spin relative to the magnetic field at the nucleus due to the atom's electrons. In their words "since the measurement of frequency alone [i.e., not dependent on external applied field] is involved, the results are of very high precision."

The first proposal for an "atomic clock" based on these ideas was made by Rabi in his 1945 Richtmyer Memorial Lecture ("Radio-Frequency Spectroscopy") to the American Association of Physics Teachers; reported two days later in *The New York Times* (Figure 3), this newspaper article[9] became the first modern publication on atomic clocks. Of note is Rabi's wish that he "would like to see someone build an atomic clock that would be capable of providing for the first time a terrestrial check on the Einstein postulate that the gravitational field produces a change in the frequency of radiation." [10]

Progress toward an atomic clock sputtered along during the next decade. In the early 1950's several atomic or molecular clocks were considered at NBS (the National Bureau of Standards, the predecessor of NIST). Among them was the first NBS clock, exploiting the so-called ammonia "inversion frequency" (a pair of states of the NH_3 molecule with the nitrogen atom occupying one side or the other from the plane of the three hydrogen atoms). In the several NBS ammonia clocks, the 24 GHz resonance was probed in a 25-foot length of waveguide, stabilizing a quartz crystal oscillator, obtaining stabilities of a few parts in 10^8. Figure 4 shows the public face of the NBS clock, and its elaborate internal electronic systems.

Around the same time NBS was exploring the possibility of an atomic-beam apparatus, which, though more complex,

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[7] J.M.B. Kellogg, I.I. Rabi, N.F. Ramsey, and J.R. Zacharias, "The Magnetic Moments of the Proton and the Deuteron – The Radiofrequency Spectrum of H_2 in Various Magnetic Fields," *Phys. Rev.*, 56, 728 (1939).

[8] P. Kusch, S. Millman, and I.I. Rabi, "The Radiofrequency Spectra of Atoms: Hyperfine Structure and Zeeman Effect in the Ground State of Li^6, Li^7, K^{39} and K^{41}, *Phys. Rev.*, 57, 765 (1940).

[9] "'Cosmic Pendulum' for Clock Planned, Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces" by William Laurence, on 21 Jan 1945, an issue replete with war news, and bearing the 32-point all-caps headline "ROOSEVELT SWORN IN FOR FOURTH TERM; EXTENDS GOOD NEIGHBOR POLICY TO WORLD; RUSSIANS GAIN 25 MILES; FRENCH OPEN DRIVE."

[10] And just such a test was performed by Vessot and colleagues in 1976, flying a hydrogen maser to 10,000 km (and back) on a rocket. See P. Horowitz, "Testing Einstein's Prediction: the Pound-Rebka Experiment," *Harvard Physics Newsletter* (2021); see also R.C. Vessot, et al., "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser," *Phys. Rev. Lett.*, 45, 2081 (1980).

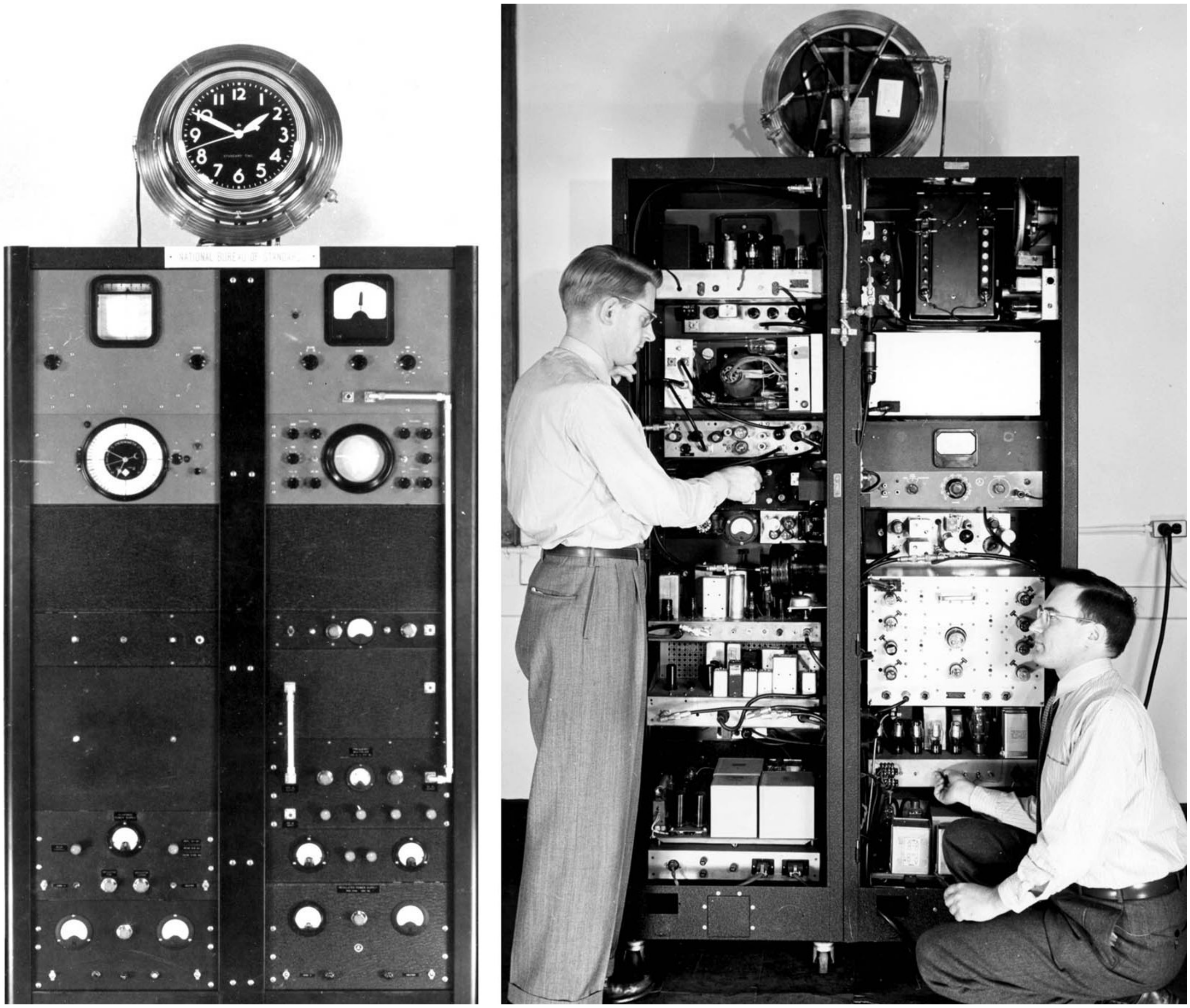

Figure 4: The NBS ammonia clock, circa 1949. But where's the ammonia? It's in the 25-foot waveguide coiled around the clock (which is plugged into the wall outlet – it's there for appearances only).

offered the potential of greater stability. Such a device was made possible by Ramsey's recently invented "separated oscillatory field" method, with a crystal oscillator "locked" onto the microwave absorption frequency of a beam of cesium atoms. The latter's ground-state hyperfine transition is a good choice, for a fundamental reason: apart from other effects, the precision of a frequency measurement is proportional to the product of the resonance frequency and the observation time, i.e., to the number of cycles.

Speaking in the language of the "quality factor" Q of a resonator, the precision is $Q \approx f\Delta t$; so, for a beam traversing an apparatus of length L, $Q \approx fL/v$. So it's good to have slow atoms, a high frequency, and a long beam path. Cesium is a relatively heavy atom (atomic number 55), so a beam of evaporated atoms moves slower than those of a lighter element; and its hyperfine frequency is high – around 9 GHz.[11]

III. Self-Sustaining Oscillator

These atomic and molecular resonance devices shared the common characteristic that their intrinsic "radio frequencies in the hearts of atoms," as eloquently phrased in *The New York*

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[11] 9.192,631,770 GHz, to be exact. And that *is* exact, because it is currently the international definition of the second.

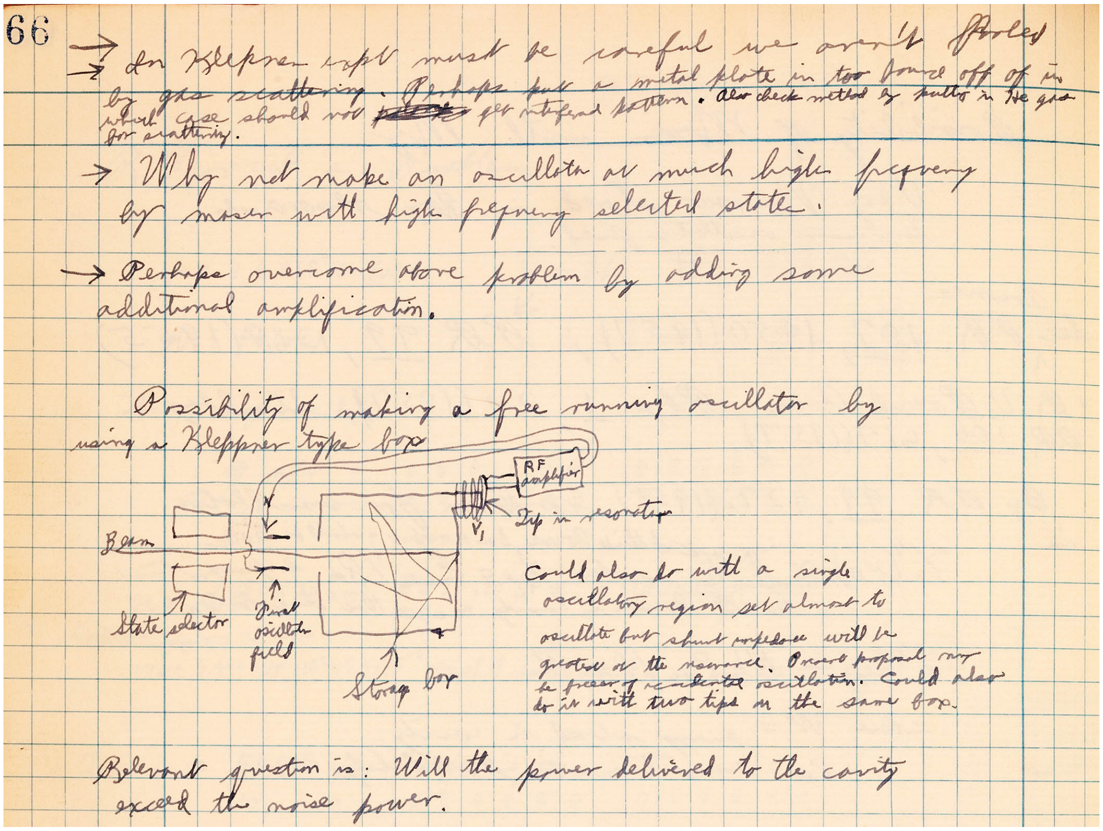
Times, did not sing aloud their tunes – they had to be probed with an externally generated radiofrequency signal to tease out the resonance frequency, which was then used to stabilize a conventional quartz-crystal oscillator of lesser stability. Soon things would change.

In 1953 the first maser amplifier was built at Columbia, by Charles Townes, James Gordon, and Herbert Zeiger. A beam of ammonia molecules, passed through a quadrupole state selector to discard those in the lower energy state, entered a microwave cavity tuned to the resonance at 23.87 GHz. The maser had enough gain to be used as an oscillator, suggesting the possibility of a self-oscillating frequency standard (rather than active probing of an atomic or molecular absorption, as in the ammonia or cesium standards). The ammonia maser, as an oscillator, was the first such system. But for numerous reasons its frequency precision and stability were mediocre – no better, in fact, than the high quality quartz oscillators of that era.

Around this time Ramsey wondered if it might be possible to make a self-sustaining atomic oscillator, in particular using the simplest atom, hydrogen. The major problem was the feeble signal expected from the (magnetic dipole) hyperfine transition, some four orders of magnitude weaker than that of the electric dipole transition of the ammonia maser. Perhaps the weak energy radiated by the atoms could be overcome by extending their storage time by accumulating a cloud of atoms stored within a resonant cavity. If so, such a configuration offered important advantages: (a) by storing the atoms for a much longer time than in a beam apparatus, a much narrower resonance would be possible – for example, atoms stored for one second, oscillating at 1.4 GHz (the hydrogen hyperfine transition frequency), represent a Q of 10^9; and (b) because stored atoms have approximately zero average velocity, first-order Doppler shifts are suppressed. On the other hand, there's a new problem: can an atom undergoing many collisions with the storage-bulb's wall retain radiative phase coherence (a necessary condition for a lifetime-limited resonance width, and self-sustained oscillation)?

MAKING THE MASER

This last question was a potential show-stopper. To get a handle on it, Ramsey's student Dan Kleppner undertook a series of experiments, bouncing atoms from surfaces.



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→ In Kleppner expt must be careful we aren't fooled
→ by gas scattering. Perhaps put a metal plate in to bounce off of in which case should not get interference pattern. Also check method by putting in He gas for scattering.

→ Why not make an oscillator at much higher frequency by maser with high frequency selected state.

→ Perhaps overcome above problem by adding some additional amplification.

Possibility of making a free running oscillator by using a Kleppner type box

Could also do with a single oscillatory region set almost to oscillate but shunt impedance will be greater at the resonance. Present proposal may be freer of accidental oscillation. Could also do it with two tips in the same box.

Relevant question is: Will the power delivered to the cavity exceed the noise power.

Figure 5: A page from Ramsey's notebook, toying with the idea of using external amplification to sustain oscillation.

Atoms of hydrogen are difficult to detect (the best method was a Pirani gauge, which sensed the tiny cooling effect on a heated filament), so Kleppner's experiment instead launched cesium atoms, which are easier to detect (surface impact-ionization on a hot tungsten wire), easy to generate, and whose 9 GHz hyperfine frequency was well known (though not to high precision). This frequency was also a convenient one for Ramsey, who had been head of the X-band (8-12 GHz) microwave group at MIT's wartime Radiation Lab. Happily, Kleppner and colleagues found that substantial phase coherence remained after a few bounces, and with some wall coatings (particularly paraffin) the resonance could still be observed with as many as a hundred wall collisions.

A self-oscillating stored-atom hydrogen maser would require many more bounces – but hydrogen has several factors in its favor: the surface interaction would be diminished by hydrogen's smaller polarizability (a factor of 75); and its far smaller mass would reduce the surface residence times during collisions. Based on these considerations, as well as the results of the "broken atomic beam resonance experiments" (the title of Kleppner's 1958 thesis), it seemed altogether practicable to construct a storage-bulb self-oscillating hydrogen maser. As they remarked in their 1961 paper,[12] "With long enough storage times, maser action can be used to detect the resonance, rather than a conventional beam detector, thereby eliminating the original objection to hydrogen." (Although the Ramsey group hoped that self-oscillation could be achieved, there was always a plan-B: adding external gain to make up for losses in the resonator. Figure 5 is a page from Ramsey's notebook, sketching such a possibility.)

So, encouraged by the promising results of the bouncing-cesium experiments, Kleppner, Mark Goldenberg (a new graduate student), and Ramsey set to building a stored-atom hydrogen maser. In place of the cesium-oven source they used a Wood's gas-discharge source of hydrogen atoms; and for the storage bottle they fashioned a 6-inch quartz bulb, coated inside with paraffin. The bulb was placed inside a cylindrical metal resonator tuned to the hyperfine frequency of 1420 MHz. The major experimental challenge was to provide a strong enough beam of atomic hydrogen in the upper hyperfine state; this was done by passing the beam through a six-pole "state selector" electromagnet (it's the large white object, outfitted with heavy lugs for lifting, in Figure 6, also featured in the patent's Figure 1 and 1a); this focused or defocused the atoms according to whether they were in the upper or lower hyperfine state, respectively.

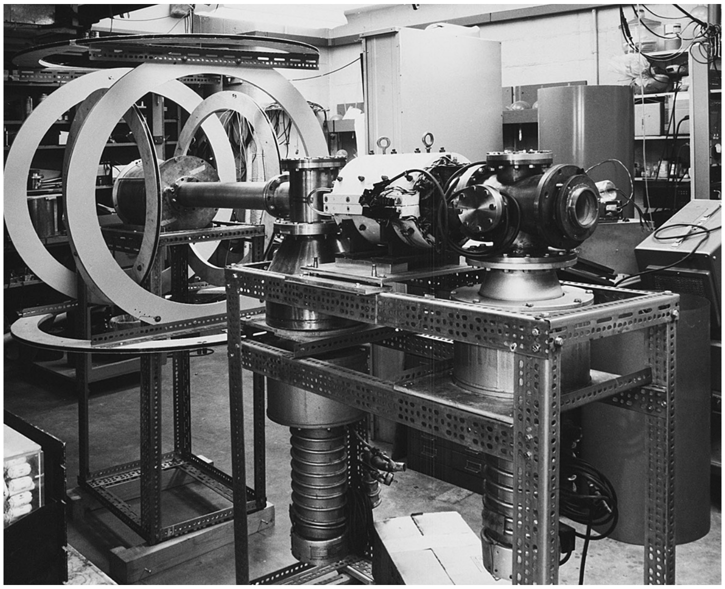

Figure 6: The original hydrogen maser, seen from the source end. The glass storage bulb is inside the cylindrical resonant cavity in the Helmholtz coils. The state-selecting hexapole electromagnet is the cylindrical object between the two vacuum pumps. See also Figures 7 and 8.

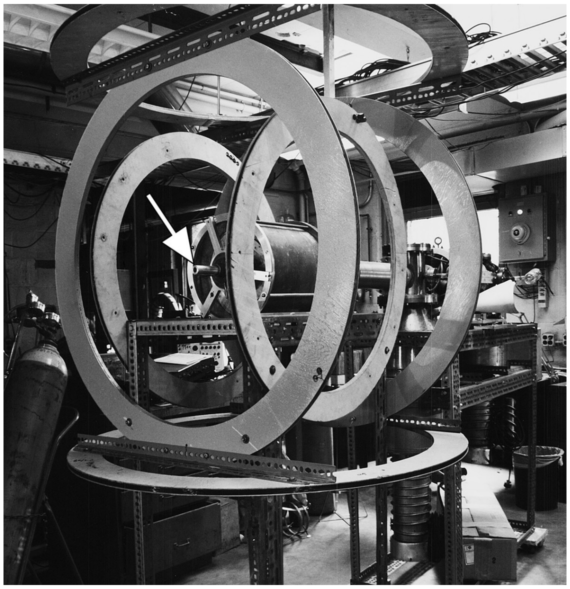

Figure 7: View from the cavity end. The prominent Helmholtz coils were designed to cancel Earth's magnetic field (later masers used compact magnetic shielding instead). The arrow points to the fine-tuning plunger, used to set the cavity's resonance precisely to the hyperfine frequency, maximizing oscillation strength and suppressing frequency "pulling."

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[12] H.M. Goldenberg, D. Kleppner, and N.F. Ramsey, "Atomic Beam Resonance Experiments with Stored Beams," *Phys. Rev.*, 123, 2, 530 (1961).

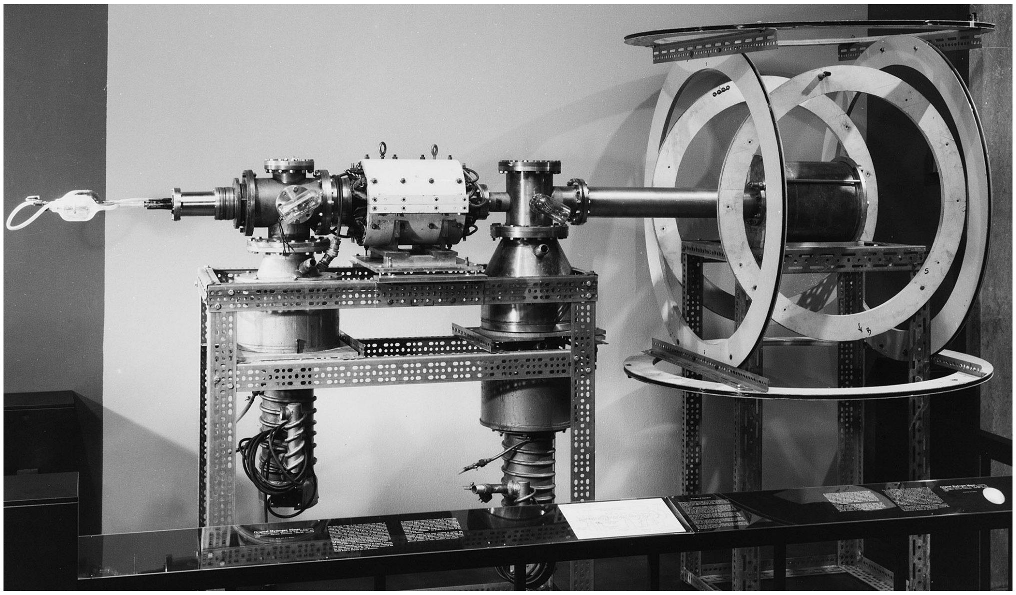
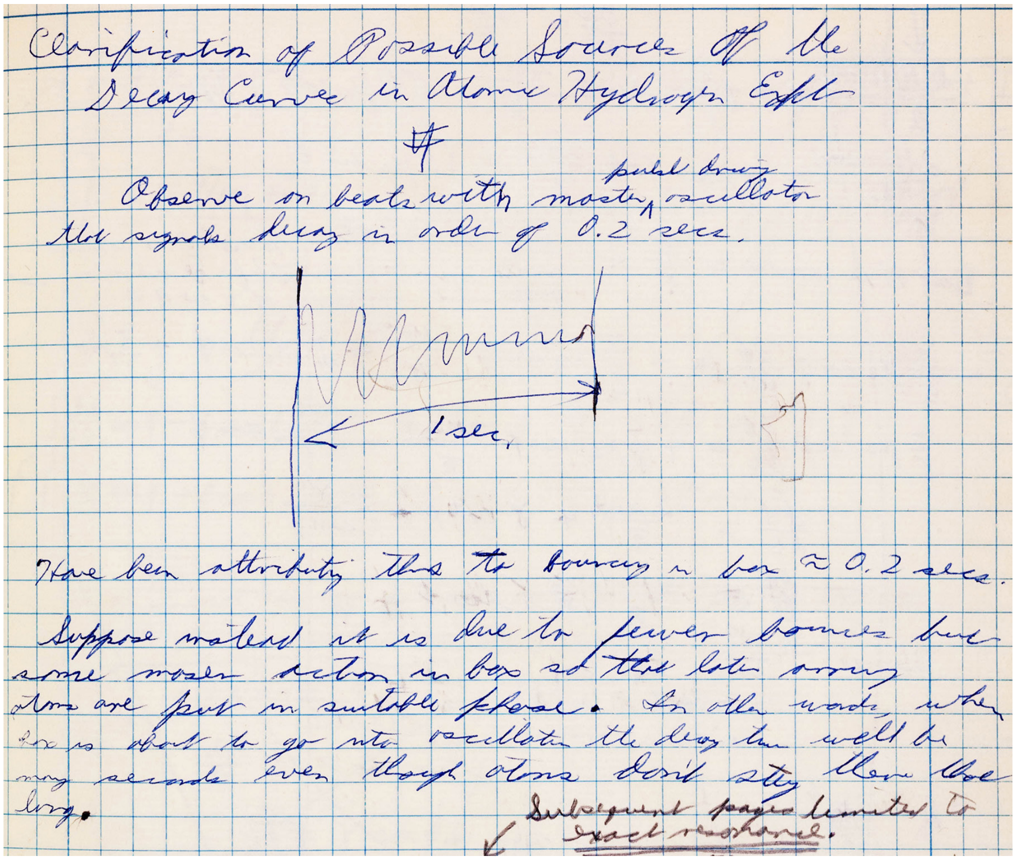


Figure 8: A nice view of the original hydrogen maser, freed from the clutter of a working laboratory, displayed in the *Atomic Clocks* exhibition at the Smithsonian National Museum of American History in 1980. Kleppner reports, "I stood waiting for somebody to ask me about it so that I could tell them that I made it, but nobody came."



Clarification of Possible Sources of the
Decay Curve in Atomic Hydrogen Expt
#
Observe on beats with master pulsed driving oscillator
that signals decay in order of 0.2 secs.

1 sec.

Have been attributing this to bouncing in box ≈ 0.2 secs.

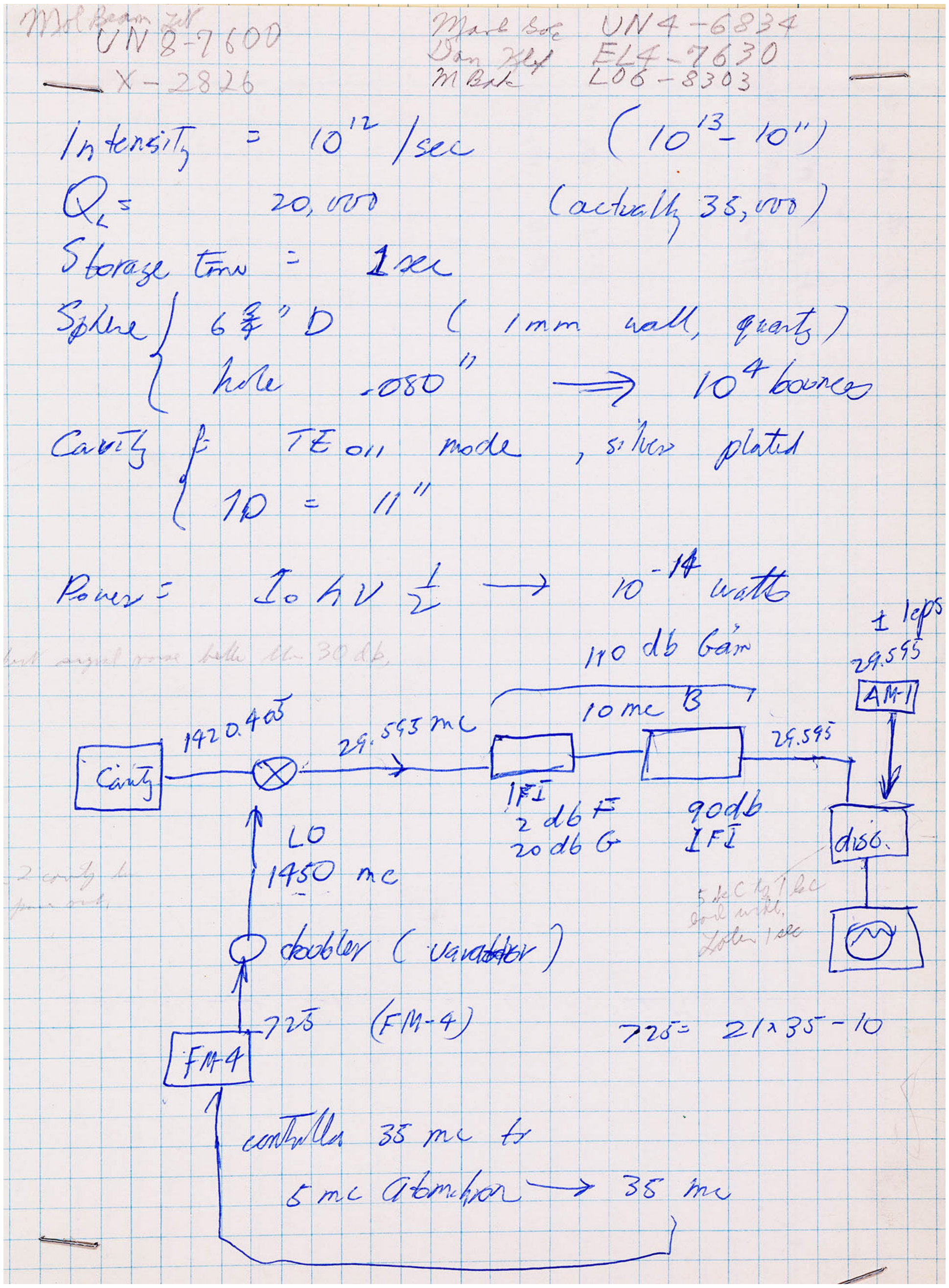
Suppose instead it is due to fewer bounces but
some maser action in box so that later arriving
atoms are put in suitable phase. In other words, when
box is about to go into oscillation the decay time will be
many seconds even though atoms don't stay there that
long.

Subsequent pages limited to
exact resonance.

Figure 9: Getting to oscillation – tuning it up by observing oscillatory decay after pulsing the cavity.

GETTING TO OSCILLATION

No one expected the newly born maser to pop out of the womb with a full-throated wail. And it didn't. What was needed was a way to gauge its progress toward oscillation, so various parameters (e.g., gas pressure, or cavity tuning) could be trimmed. With the maser just sitting passively, you'd not know what to change; or, as Jan Hall once pithily remarked, "you can't tweak up zero." The first idea was to excite the cavity with a small amount of externally applied sinewave, optimizing its properties as an amplifier. This was not successful; as Kleppner related, it was difficult to keep the applied signal from contaminating the feeble output. In desperation they put the oscillator in a metal box and buried it outside the lab's window!



Mol Beam Lab UN 8-7600
X-2826

UN4-6834
EL4-7630
LO6-8303

Intensity = 10^{12} /sec (10^{13} – 10^{11})

Q_L = 20,000 (actually 35,000)

Storage time = 1 sec

Sphere { 6 3/4" D (1 mm wall, quartz)
hole .080" ⟹ 10^4 bounces

Cavity { TE_{011} mode, silver plated
ID = 11"

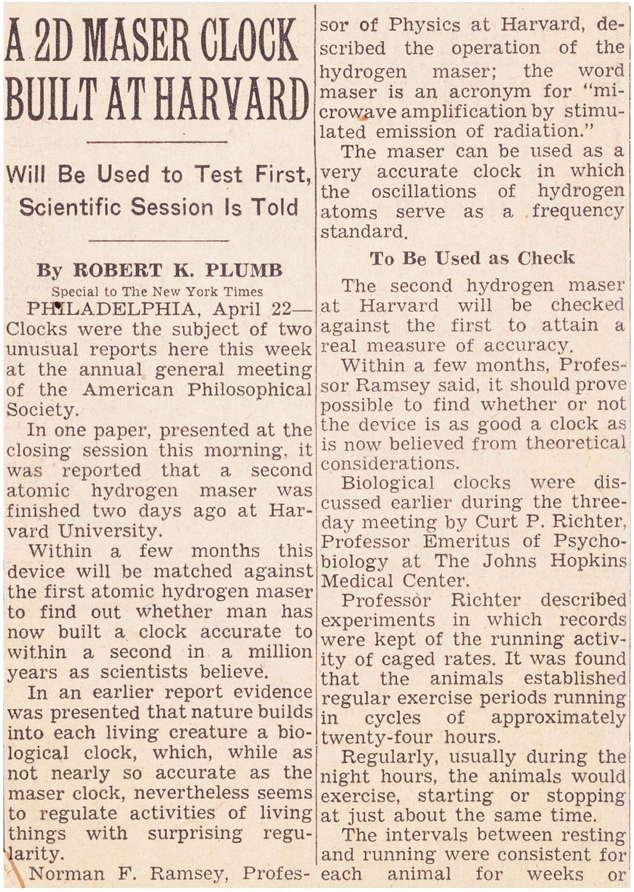
Power = $I_0 h\nu \frac{1}{2} \rightarrow 10^{-14}$ watts

Figure 10: Notebook page showing setup to compare maser stability with that of the National Radio Company's AM-1 "Atomichron" cesium-beam standard. The maser won.

The breakthrough came when Glen Rebka[13] suggested they simply *pulse* the cavity and observe its free decay, as sketched in Figure 9 from Ramsey's notebook; that eliminated any confounding signal, and provided a measure of the degree of damping (as we all learned in elementary mechanics, when studying the notorious harmonic oscillator). With this convenient metric in hand, it didn't take long to tease the maser into a satisfying oscillation, one of record-setting spectral purity.[14] A few days later the trio submitted a two-page discovery paper, titled simply "Atomic Hydrogen Maser," to *Physical Review Letters*; it was published just one month later.[15]

MEASURING ITS STABILITY

The discovery paper reported a resonance width (below the threshold of oscillation) of about 1 Hz, comparing it with the ammonia maser's "several kc/sec [kHz]." But making an accurate assessment of its spectral stability was not easy. The only useful comparison (Figure 10) would be with the best clock available, which at the time was the first practical atomic clock, the commercial "Atomichron" cesium-beam standard. And a careful comparison showed only that the maser was at least as good – and probably better, but not by how much. So, to gauge the ultimate stability it was necessary to build a second maser and see how much they wobbled against each other; this was evidently worth a note in *The New York Times* (Figure 11). The subsequent measurements demonstrated excellent *short-term* (seconds to days) stability of one part in 10^{14}, better than that of other contemporary oscillator types for durations less than a month (as seen in Figure 2). However, the absolute *precision* was affected by properties of the storage-bulb's wall material, and by slight errors in cavity tuning. The cesium-beam (passive) standard, by comparison, though afflicted with poorer short-term stability, maintained better long-term precision, and continued to serve as the national standard of time and frequency.



A 2D MASER CLOCK BUILT AT HARVARD

Will Be Used to Test First, Scientific Session Is Told

By **ROBERT K. PLUMB**

Special to The New York Times

PHILADELPHIA, April 22—Clocks were the subject of two unusual reports here this week at the annual general meeting of the American Philosophical Society.

In one paper, presented at the closing session this morning, it was reported that a second atomic hydrogen maser was finished two days ago at Harvard University.

Within a few months this device will be matched against the first atomic hydrogen maser to find out whether man has now built a clock accurate to within a second in a million years as scientists believe.

In an earlier report evidence was presented that nature builds into each living creature a biological clock, which, while as not nearly so accurate as the maser clock, nevertheless seems to regulate activities of living things with surprising regularity.

Norman F. Ramsey, Professor of Physics at Harvard, described the operation of the hydrogen maser; the word maser is an acronym for "microwave amplification by stimulated emission of radiation."

The maser can be used as a very accurate clock in which the oscillations of hydrogen atoms serve as a frequency standard.

To Be Used as Check

The second hydrogen maser at Harvard will be checked against the first to attain a real measure of accuracy.

Within a few months, Professor Ramsey said, it should prove possible to find whether or not the device is as good a clock as is now believed from theoretical considerations.

Biological clocks were discussed earlier during the three-day meeting by Curt P. Richter, Professor Emeritus of Psychobiology at The Johns Hopkins Medical Center.

Professor Richter described experiments in which records were kept of the running activity of caged rates. It was found that the animals established regular exercise periods running in cycles of approximately twenty-four hours.

Regularly, usually during the night hours, the animals would exercise, starting or stopping at just about the same time.

The intervals between resting and running were consistent for each animal for weeks or

Figure 11: The maser was more stable than any available frequency standard; so the Ramsey group built a second maser, earning themselves a note in *The New York Times*.

For applications that require its stability, the hydrogen maser remained unmatched. The poster-boy for this may be radio-astronomy, which depends on it for aperture-synthesis image recovery in very-long-baseline interferometry (VLBI).[16] In the words of radioastronomer Ken Kellermann, "Hydrogen masers provide the precise time and frequency alignment needed to operate radio arrays extending over thousands of miles, which produce celestial radio images and accurate coordinates with resolutions as fine as a few microarcseconds, or about a thousand times better than the Hubble Space Telescope." And radio-astronomer Jim Moran remarks "In 1963 Haystack had one of the few H-10 masers, a commercial version by Varian Associates of the laboratory device built by Kleppner and Ramsey; they used it

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[13] Of Pound-Rebka fame; see P. Horowitz, "Testing Einstein's Prediction: the Pound-Rebka Experiment," *Harvard Physics Newsletter* (2021).

[14] Though of rather low power: the incoming beam of atoms delivered about one picowatt to the cavity, with an order of magnitude less extracted by the output-coupling probe.

[15] H.M. Goldenberg, D. Kleppner, and N.F. Ramsey, *Phys. Rev. Lett.*, 5, 8, 361 (1960).

[16] Each of the internationally spread radio astronomy observatories uses a stable hydrogen-maser reference for the local oscillators and digitizers in its receivers. The resultant disk-drive recordings are brought together and their signals aligned (in a "fringe search," adjusting delay and rate) to produce the interferometric data from which the distant source's image (intensity and polarization) can be reconstructed. The result is effectively an Earth-size telescope aperture, albeit one that is sparsely filled.

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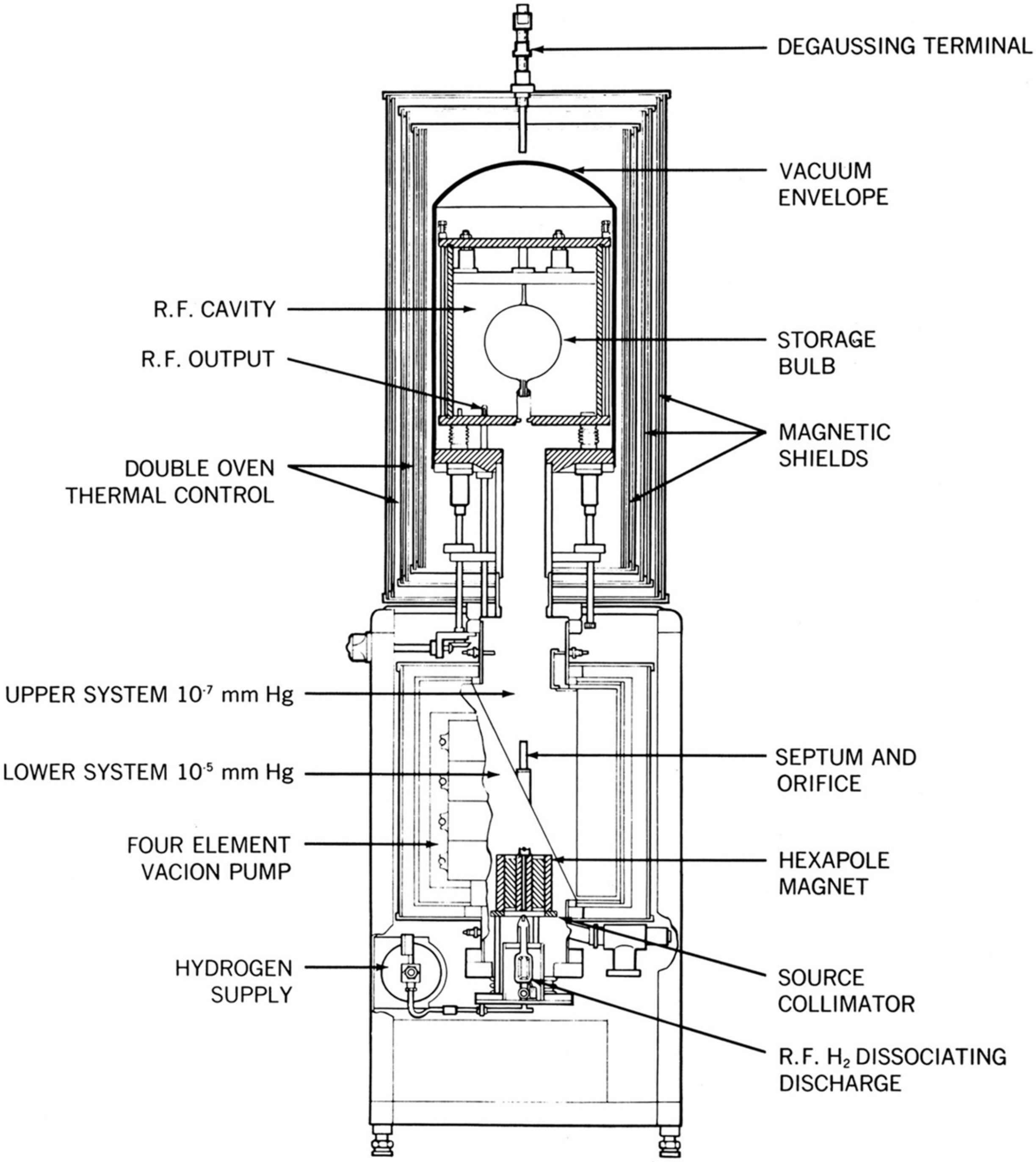

Figure 12: This diagram of a commercialized version of the hydrogen maser shows the components in nice detail. The state-selector hexapole is made from permanent magnets ("Alnico," an alloy of iron, nickel, copper, and aluminum), more compact than the electromagnets used in the first maser. Contemporary designs exploit the superior rare-earth alloys.

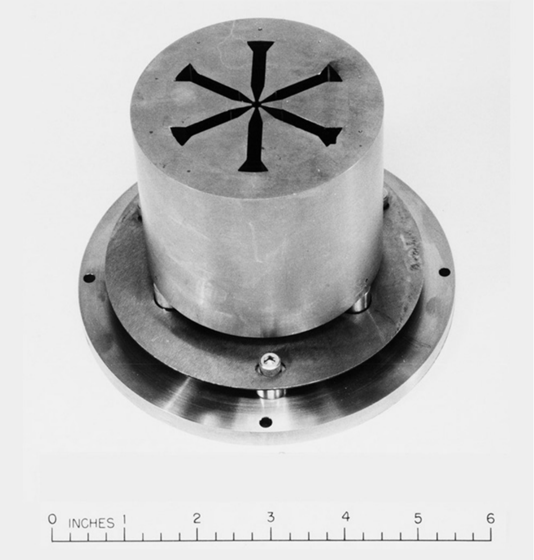

Figure 13: Permanent-magnet hexapole, built by Howard Berg for the second-generation maser at Harvard. To polarize it he stacked five automotive batteries and ran 500 amps through a serpentine winding of 5.5 turns around each pole; the central field strength was 9,900 gauss (0.99 T).

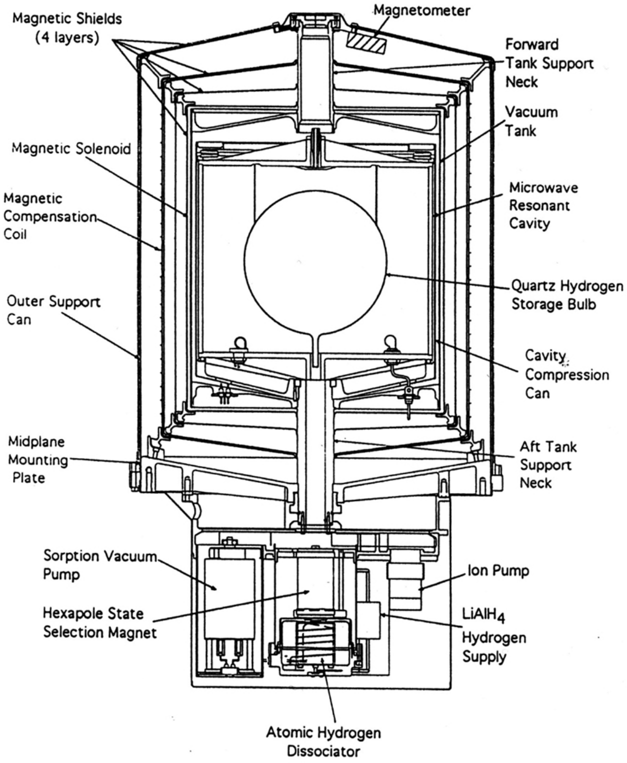

Figure 14: Hydrogen maser designed for space applications at Smithsonian Astrophysical Observatory (SAO), an evolution of the maser used in the NASA/SAO 1976 Gravity Probe-A test of general relativity (from Vessot, R.F.C., "The atomic hydrogen maser oscillator," *Metrologia*, 42, S80 (2005)).

as the frequency standard for the precision radar timing experiments on the inner planets, including the fourth test of general relativity [the Shapiro time-delay effect[17]] in 1966. The spectacular Event Horizon VLBI experiments at 230 GHz would not have been possible without maser frequency standards – a rubidium standard would not provide temporal coherence even at the shortest integration time. Even 50 years later all serious VLBI observations at dozens of radio observatories around the world use hydrogen masers. This is partly because the hydrogen maser provides phase stability that exceeds that of the atmosphere even at the best terrestrial stations."

SUBSEQUENT DEVELOPMENTS

Commercial hydrogen masers based on the Harvard design were soon developed (Figure 12). With compact permanent-magnet state selectors (Figure 13) and other space-saving improvements, such devices could launch the atomic beam vertically, conserving floor area. More recent masers became compact enough for use in spacecraft (Figure 14).

Meanwhile, contemporary feats of optical trapping have led to a new generation of superbly stable atomic standards. The technique of an "atomic fountain" (slowed atoms launched upward and allowed to fall back under gravity) has produced cesium standards of unprecedented stability, owing to greatly reduced Doppler broadening and greatly increased storage times.[18] Comparisons of several cesium fountains at NIST demonstrated stabilities of a few parts in 10^{17}; they were used to compare five of NIST's hydrogen masers, finding linear drifts of order 10^{-13} and short-term stabilities (with linear drift removed) of order a few parts in 10^{-15} over periods of a few hundred days.[19]

Another recent technique is laser-trapping of single ions, and, even better, the formation of stable "optical lattices" of atoms trapped in

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[17] See I. Shapiro, "Fourth Test of General Relativity," *Phys. Rev. Lett.*, 13, 789 (1964), and I. Shapiro, et al., "Fourth Test of General Relativity: Preliminary Results," *Phys. Rev. Lett.*, 20, 1265 (1968).

[18] Zacharias attempted this in 1954, but was unsuccessful because scattering effects at the source depleted the slow-moving tail of the Boltzmann distribution. Hearing of this, Ramsey said "we goofed," overlooking a really good idea. But that good idea had to wait for the later development of laser atom-slowing techniques.

[19] See T.E. Parker, S.R. Jefferts, and T.P., Heavner, "Medium-Term Frequency Stability of Hydrogen Masers as Measured by a Cesium fountain," *IEEE International Frequency Control Symposium*, paper 2010-06, 318 (2010). The authors were surprised by "a moderate level of correlation in the frequency fluctuations of the masers," suggesting that averaging the frequencies of N masers does not guarantee improvement of the stability by the expected (uncorrelated) factor of $\sqrt{N}$.

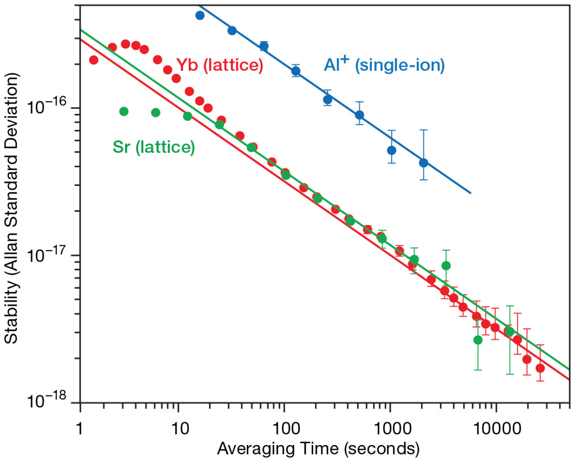

Figure 15: Trapped-ion and optical-lattice clock stability (adapted from the plot in Smart, A.G. (footnote 20)). Data is from Bloom, B.J. et al., "An optical lattice clock with accuracy and stability at the 10^{-18} level," *Nature*, 506, 71 (2014); Hinkley, N. et al., "An atomic clock with 10^{-18} instability," *Science*, 341, 6151, 1215 (2013); and Chou, C.W. et al., "Frequency comparison of two high-accuracy Al^+ optical clocks," *Phys. Rev. Lett.*, 104, 070802 (2010).

laser-generated standing waves.[20] A decade ago these techniques already resulted in laboratory-scale standards with stabilities of 10^{-16} and 10^{-17} (Allan variance at 1000 seconds), respectively (Figure 15). A pair of strontium optical-lattice clocks have been used to measure the gravitational redshift over a 450m vertical path[21] to a part in 10^5. These lattice clocks improve stunningly over the current U.S. civilian time standard (the NIST-F1 cesium fountain clock); the latter must be averaged for several days, whereas NIST-developed ytterbium lattice clocks achieve comparable results in one second of averaging. And, in a stunning *tour de force*, a group at JILA used a strontium lattice to demonstrate the gravitational redshift over a vertical path of *one millimeter*.[22] The creation of ultra-cold atoms, combined with techniques for handling optical signals as if they were in the familiar regime of microwaves and millimeter waves, has revolutionized atomic clocks. Their stabilities have risen by a factor of 1000 and promise continued improvement. Engineering these devices as practical clocks is underway, and progress appears certain.

One might think such a scenario would make the hydrogen maser obsolete, but it has actually given it a crucial new role. At NIST, hydrogen masers are used as a "flywheel," steered by the primary cesium fountain clocks (NIST-F1 and NIST-F2). The maser, kept tuned according to the fountain references over long timescales, acts as an oscillator of superior short-term stability: the maser signal has greater purity because its oscillation signal is generated directly by the atoms, rather than by a system of electronics that repeatedly interrogates the resonance absorption of bunches of upward-launched cesium atoms. In practice the signals from a cluster of a half-dozen hydrogen masers are averaged to create the time and frequency standards distributed to the community. Its long term stability is guided by comparing with the primary fountain clocks on a monthly time scale.

Today the hydrogen maser plays a crucial role in our timekeeping systems, not only because of its stability, but also because of its unprecedented spectral purity.

SOURCES AND REFERENCES

In addition to the references cited in the text and footnotes, the following were used in the preparation of this short history:

- Daniel Kleppner, *The Broken Atomic Beam Resonance Experiment*, Ph.D. thesis, Harvard University (1958);
- H. Mark Goldenberg, *The Atomic Hydrogen Maser*, Ph.D. thesis, Harvard University (1960);
- Howard C. Berg, *Spin Exchange and Surface Relaxation in the Atomic Hydrogen Maser*, Ph.D. thesis, Harvard University (1964);
- Norman Ramsey, *Oral Histories at the American Institute of Physics*, Niels Bohr Library and Archive;
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[20] See, for example, A.G. Smart, "Optical-lattice clock sets new standard for timekeeping," *Physics Today*, 67(3), 12 (2014).

[21] M. Takamoto, et al., "Test of general relativity by a pair of transportable optical lattice clocks," *Nature Photonics*, 14, 411 (2020). They report an astonishing stability for their lattice clock of 10^{-20}, averaged over a day.

[22] T. Bothwell, et al., "Resolving the gravitational redshift within a millimeter atomic sample," *Nature*, 602, 420 (2022).