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TOPICS IN ATOMIC HYDROGEN
STANDARD RESEARCH
AND APPLICATIONS

HARRY E. PETERS

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Harry E. Peters
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ABSTRACT

Hydrogen maser based frequency and time standards developed at Goddard Space Flight Center (GSFC) have been in continuous use at NASA tracking stations since February 1970, while laboratory work at Goddard has continued in the further development and improvement of hydrogen masers. Concurrently, experimental work has been in progress with a new frequency standard based upon the hydrogen atom using the molecular beam magnetic resonance method. Much of the hydrogen maser technology is directly applicable to the new hydrogen beam standard, and calculations based upon realistic data indicate that the accuracy potential of the hydrogen atomic beam exceeds that of either the cesium beam tube or the hydrogen maser, possibly by several orders of magnitude. In addition, with successful development, the hydrogen beam standard will have several other performance advantages over other devices, particularly exceptional stability and long continuous operating life. Experimental work with a new laboratory hydrogen beam device has recently resulted in the first resonance transition curves, measurements of relative state populations, beam intensities, etc. This presentation will cover the most important aspects of both the hydrogen maser and the hydrogen beam work.

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RESEARCH AND APPLICATIONS

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INTRODUCTION

Following is the approximately verbatim oral presentation given
by the author at the "Seminar on Frequency Standards and
Metrology" which was held in Quebec, Canada, at the Chateau
Montmorency on August 30, 31, and Sept. 1, 1971. This seminar
was sponsored by the Canadian National Research Council and
Laval University.

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I   HYDROGEN MASER WORK

Most of you here are already familiar with the hydrogen maser program at. NASA's Goddard Space Flight Center that I have been involved with for the past few years. While hydrogen masers and their applications have been our main effort in the past, I am going to ask you to bear with me today while I rush through the part of my talk dealing with masers, because, I would like to take up most of the time presenting some ideas dealing with a different type of standard.

For those who use frequency standards, and particularly time standards, I think the most useful property a frequency source can have, other than stability and accuracy, is the capability for long, continuous, and reliable operation.

The evidence shows, I believe, that hydrogen masers have this inherent property of long life and reliability to an excellent degree.

Slide 1 shows the experimental hydrogen maser which is called NX as it appears in the laboratory at Goddard today. This picture may look familiar to many of you because it is almost identical to the picture shown 3 years ago at a frequency control symposium in Atlantic City.

This maser has been operating continuously for four years now, it has also been continuously automatically tuned for this time. Well, there actually was one brief gap in its operation in 1970 for a week or so during which a new experimental variable state selector and a new experimental source was installed. Please note the hexagonal shaped object just below the blue upper assembly. This is the electrically variable state selector.

This hexapole magnet was primarily designed to investigate the velocity distribution of hydrogen atoms from the source. However, it also provided the opportunity to make a direct measurement of the degree to which hydrogen atoms come to thermal equilibrium with the maser storage bulb temperature. This is of course particularly interesting because the results tell us how realistic the usual temperature assumptions are when evaluating the second order doppler shift. More on this later.

Slide 2 shows one of the four Goddard prototype hydrogen masers — this is NP-1.

These were developed and constructed at Goddard and have been used extensively at NASA tracking stations, as well as at other places, since they were first completed in 1968 and 1969.

NP-1 has been oscillating continuously, except during shipments, since December 1968. It is shown here without its traveling wheels.

Slide 3 shows NP-1 with its wheels attached, and it is operating on batteries here. This maser has traveled quite a bit in its few years of life so far. It has been to MIT in Massachusetts (that was at the Haystack radio astronomy facility in 1969 for VLBI experiments).

Then, after a brief return to Goddard, it was flown to an Apollo Manned Space Flight Network tracking station in Bermuda, where it operated for over a year.

After finishing there with Apollo 14, it was shipped in March of this year to a Deep Space Network tracking station in Johannesburg, South Africa, where it is now being used in several interesting experiments — most importantly the Mariner Mars 1971 mission.

Slide 4 shows the overall picture of Goddard's hydrogen maser applications. I don't want to go into detail here, but one of the main points this figure illustrates is that we can sum up the operational periods and conclude there is an integrated operational experience with these standards totalling well over a decade. They have really had no fundamental problems. In most NASA applications the stability and the reproducibility have been much better than the limits set by other tracking station components or by measuring errors. This is one of the points illustrated by Slide 5.

Here we have a plot giving a stability comparison of some equipment used in the NASA Apollo unified S-band receiver and transmitter local oscillator system. These stability comparisons were obtained from data taken on typical station equipment using NP-2 as the frequency reference. In these stations the prime frequency source atomic standard is followed by buffer amplifiers and frequency combiners, and then by a synthesizer. The resultant frequency stability can never be better than that of the worst offender.

For radio wave propagation times of a second or less, the station synthesizer is the least stable component. This is followed by the combiners and buffer amplifiers.

For Lunar distances, where the propagation delay time is two and a half seconds, the local atomic standard used clearly becomes critical. This was definitely

confirmed during Apollo 14 when the network interchanged hydrogen and cesium, as well as rubidium standards during tracking of signals transponded from the Lem, the Lunar Lander, when it was on the surface of the Moon.

For missions to Mars, such as the Mariner that is now approaching the planet, it is clearly evident here that the standard used at the stations makes a great deal of difference in the tracking data residual noise and frequency biasses. The situation gets even worse, of course, for more distant planets. Similar conclusions may be reached with regard to Very Long Baseline Interferometry experiments in Radio Astronomy and in Geodetic positioning experiments.

Perhaps more to the point for this symposium — when laser frequencies and microwave frequencies are coherently related by direct synthesis to produce a unified frequency, time, and length standard system, the component device stabilities, both short and long term, are going to be a crucial factor in the success of the operation.

I'd next like to just mention a couple of experiments with hydrogen masers which have a bearing on accuracy capability and a bearing on efficiency in the attainment of intense hydrogen atomic beams. These involved the use of the variable field state selector as a velocity selector.

First the velocity distribution of atoms from the source was examined by observing the experimental maser oscillation power level as a function of focussed velocity. This gave a range of velocities over which the maser would oscillate strongly of about four to one. The velocity distribution looked normally Maxwellian for velocities below room temperature velocities, at least within the precision of the experiment. There is, however, a definite excess of atoms with higher than normal velocities. This tells the reason why long, strong field focussers are frequently much more efficient for hydrogen masers than designs based on theoretical distributions.

To measure the degree of thermal accommodation of the atoms on the bulb wall, the frequency of NX was compared with that of one of our field prototype masers, NP-2, while the focussed velocity was switched back and forth between two fixed values. These two values of velocity were chosen so that the maser had the same oscillation level at both points.

The velocity was changed here by a factor 2 to 1. The masers were both well tuned ahead of time, and preliminary experiments were performed which determined there were negligible magnetic field charges, that is in the main z field, as the focusser excitation was charged.

The result was that, with a resolution of one portion 10^{14} there was no difference in frequency with the different input atom velocities. This showed that temperature equilibrium exists within .1° Celsius, and that second order doppler corrections which use bulb temperature for atom temperature are quite accurate.

II HYDROGEN BEAM DEVELOPMENT

Now I'd like to stop talking about hydrogen masers for awhile.

I think just about everyone recognises the obvious advantages of the very simple atomic hydrogen hyperfine structure for standards applications. And also that the hydrogen transition frequencies have a very close and analytical relation to other atomic and nuclear parameters, as well as the fact that nearly every facet of its internal and external energetic interactions are beautifully described by modern versions of quantum mechanics.

And of course, all good physicists recall with warm affection that greatest of teaching aids, the hydrogen atom, which was sufficiently simple to be the first atom to succumb to the early quantum theories, and to give good agreement for the wavelengths of its observed and its predicted spectral lines. And so on.

But there has been one unfortunate stumbling block that has prevented this atom's hyperfine transition from being accepted as a basis for the standard of frequency or time. Of course, that is the wall shift. I know many of you will believe me when I say that I don't like the wall shift. I don't like the uncertainties involved in changing maser bulbs in the traditional wall shift experiments. Nor do I relish the idea of operating at some particular high temperature where the wall shift effect would be minimized. The only really generally acceptable solution to the wall shift problem is, I think, to use the hydrogen atom in such a way that it does not bounce off walls.

So with these thoughts in mind, let's look at the hydrogen standard problem from a different point of view. Let's look, first of all, at the hydrogen hyperfine energy levels.

In Slide 6, <u>hydrogen is on the left.</u>

As you know, we have energy, or frequency, on the vertical axis, and increasing magnetic field from left to right horizontally. Consider first of all, that very intense sources of hydrogen atoms are available — up to 10^{18} or 10^{19} atoms per second if we wish — and that from these sources we can select atoms which have a very narrow velocity range and which may be relatively slow atoms. This may be done with rather ideal state selector magnets which produce nearly

parallel beams consisting of atoms in only two of the hydrogen levels — the upper two shown on this slide. We can also cause transitions between the levels (F = 1, m = 1) and (F = 1, m = -1) so that only one energy level remains which can be refocussed and detected, and that's the ideal (F = 1, m = 0) state.

Since this is the origin of the single sigma transition in hydrogen, and since there are no neighboring transitions to broaden or distort the resonance line, we can go to as low a magnetic field as can be uniformly produced and cause transitions in free hydrogen atoms under what are, for all practical purposes, entirely field free conditions.

The conditions apparently exist for an ideal hydrogen beam magnetic resonance frequency standard to exist. Of course, the 64 Dollar question is — why hasn't this type of standard been seriously considered or proposed by anyone heretofore?

There are only two serious problems that seem to be in the way. The first is that hydrogen atoms are traditionally hard to detect with great sensitivity — unfortunately surface ionization detectors do not work with hydrogen. The second reason is that hydrogen atoms at room temperature have a high average velocity, about 11 1/2 times greater than cesium at the same temperature — and so the time spent by these fast atoms in the interaction region is correspondingly short, and a broad resonance line and low line Q result.

I think the first reason is not good on two counts; 1. I think the hydrogen atom has sufficiently unique properties that it should be detectable with a theoretical noise limit approaching beam shot noise; and 2. with such intense beams very great detector sensitivity is not actually required to get adequate signal to noise ratio.

I also think the second reason is invalid on two counts; 1. we can select a very good intensity of atoms from the broad distribution available which have much lower than the average velocity; and 2. with such a pure unperturbed state as we have here, a very symmetrical, undistorted, resonance curve may be obtained, and under these conditions a low line Q may be compensated for with a sufficiently high signal to noise ratio.

These statements may be debated. But assume for a moment that they are true. Then let's look at an overall schematic diagram of a free atom atomic hydrogen beam frequency standard.

Slide 7 shows one conceivable design configuration. The RF source dissociator is essentially the same as the latest design used on Goddard hydrogen masers. The A and B state selectors may be electromagnetically variable focussers of either the usual hexapole shape or of a quadrupole configuration — depending

upon which state we wish to maximize and upon the design atom velocity. Use of variable state selectors has several advantages, for example, modulated beam techniques may be used to determine velocity distributions. Also, several details relating to accuracy may be examined precisely by observing the transition frequency as a function of atom velocity.

From the A selector the beam passes through a hole into a magnetically shielded region between the two sets of magnetic shields. Here the A polarizing coil is located. After passing through the A polarizing coil the beam passes thru a null region at the entrance hole to the inner magnetically shielded region. The field of the polarizing coil defines a quantization direction for the atomic angular momentum. This field goes to zero smoothly and without direction change as the atom approaches the inner shield hole. Since at very low fields the Zeeman precession frequency is very low, the angular momentum vector will not change direction significantly, and the atom therefore emerges into the inner magnetically shielded region where the field direction may be selected to be different. Thus the states are charged — in the scheme shown here the (F = 1, m = 1) state becomes an (F = 1, m = -1) state.

Within the inner shields is the microwave cavity. This is a TE_{011} single mode cylindrical-coaxial mode cavity which has breaks at two places in the inner cylindrical conductor which allow RF energy to interact with the beam. As the beam passes the two interaction regions, transitions are induced from the single (F = 1, m = 0) state to the ground state. Atoms which do not make transitions are focussed to the detector. This is a simple separated oscillatory field magnetic resonance device.

The scheme at the bottom shows the progression of state selection and transition events. This is the normal operating mode illustrating what happens with a single velocity beam and an optimum transition power level, with the frequency set at line center. In beam tube jargon this is a "flop out" system, as illustrated by the resonance curve on the right.

There are several other possible operating modes and some of these are very useful. For example, use of transversely oriented polarizing coil fields does some very interesting things to the atomic states which are very useful in analyzing magnetic field radial inhomogeneities in the cavity region.

If what I've said so far is approximately true, it appears that the success of the hydrogen beam standard will be proportional to the square root of the success of the detector search, since signal to shot noise is proportional to the square root of the detected beam intensity. So let's look at the detector problem a minute.

6

Slide 8 is a list of some conceivable solutions. Some of these may be new, several are traditional and well known. But keep in mind that the atoms we wish to detect are highly localized, that is, they all appear at a focal point on the order of a millimeter in diameter.

Now the hydrogen atom has some rather unique properties, as have many free atoms or isolated radicals. Of course, it has a particular ionization potential. But being a free radical, it can also combine chemically with other atoms or molecules, with the release of considerable free energy. It can also trigger chemical chain reactions, and many such reactions are documented in the literature. Some of these reactions are also chemiluminescent — they give off optical, ultraviolet, or infrared radiations.

Hydrogen atoms, combining with other hydrogen atoms, produce 4×10^5 watt seconds of thermal energy per mole of H_2 formed. For a detected beam of say 10^{10} atoms per second, this amounts to 3.2×10^{-9} watts; this should be easy to detect at a point source.

But for intense point sources, conventional pressure gauges can be very effective also, since use of restrictions or collimators can now reduce background pressure to the extreme ultra high vacuum range.

For example, if the beam is passed to a gauge having a restricted entrance size with a vacuum pumping speed of 1/10 liter per second, there will be a pressure rise of 10^{-9} Torr when a hydrogen beam of only 10^{10} atoms per second is turned on.

Slide 9 shows one particularly attractive pressure gauge principle with which most people are familiar. This is the common penning discharge which is so useful in conventional sputter-ion pumps. I wonder if everyone realizes, as most people who work with hydrogen masers must, that when used at very low pressures to pump hydrogen, we get two electrons, approximately, for every molecule of hydrogen pumped. This is true if sufficiently low hydrogen flux is pumped that cathode cracking does not occur.

If we replace the traditional titanium cathode with a metal which does not getter or absorb hydrogen very much, and there are many of these, additional multiplication of the current can also take place, and the gauge time constant required will be the controlling limitation.

Besides signal to noise, the other primarily important parameter that determines how precisely the center of the resonance line can be located is the resonance width, or line Q. So what detected intensity can be expected as a function of atom velocity or temperature?

Slide 10 shows the relative number of atoms available at a detector when the geometry is held constant, and the state selector magnetic field is varied so as to bring to a focus a particular velocity (or temperature) with a relatively narrow velocity range. This theoretical curve is not accurate for high temperatures, we know, and it is not likely to be very accurate at the lowest temperatures either. In many experiments with velocity distributions people have found a lack of low temperature atoms. But in most cases that I have read about, it was not at all clear that this was not an apparatus, or particular experimental design, limitation, and my conclusion has been that the low temperature part of this distribution has not been adequately investigated.

However, for hydrogen sources operating near 300°K, the experimental maser velocity distribution experiment showed sufficient intensity of atoms between 300°K and 30°K to motivate me to design an apparatus to investigate as fully as possible the entire lower range of temperatures illustrated here. The point labelled HBX-1 is one experimental point as measured with this new apparatus. This shows, as a good starting point, 2×10^{10} detected atoms per second with a nominal temperature of 30°K.

Now 30°K represents a velocity of about 10^5 cm/sec, which for a 50 cm drift length with separated oscillatory fields, gives a line Q of about 1.2×10^6.

There are well known relationships for the stability of a beam tube as a function of line Q and signal to noise ratio. If we assume that we have a perfect detector, and so are shot noise limited, it is very simple to derive a relationship between relative stability and temperature (velocity) of the beam. This relationship is shown on Slide 11.

The relative instability normalized to unity for focussed atoms representative of the peak of the temperature distribution curve is given on the left. The horizontal axis is the normalized temperature. For a 300°K source temperature and a total hydrogen flow of 10^{17} atoms per second, the best theoretical stability is given by the scale on the right.

Now let's assume that our detector is only .1% efficient — this might be the case if the traditional electron bombardment ionizer were used. This would still give 3×10^{-12} stability for one second averaging and 30° Kelvin atoms. So it is clear that perfect detectors are not needed for intense hydrogen beams. This curve, incidentally, also defines the precision with which the resonance line center may be found.

It is worth noting that the high temperature, fast atom beam, could allow the use of a very fast servo loop, and therefore the fast atom hydrogen beam may conceivably be more stable than the hydrogen maser, or the crystal oscillator, for

very short measuring times. For best accuracy, however, it seems probable that such an apparatus should be optimized for highest line Q, and so lowest temperature of the beam.

Now it's time I think, to stop theorizing and to consider the actual device construction, and possibly do some experiments to test the theory.

Slide 12 shows what I believe is the first free atom atomic beam device designed to operate as an experimental standard using the hydrogen atom hyperfine transition. I call this one HBX-1.

This apparatus was particularly designed to examine velocity distributions and to evaluate several different source and detector schemes. It is also designed to provide many system controls and variables to fully examine all the physics and mechanics of the operation.

The A end, with the source, is at the right. The vacuum pumps shown are 400 liter per second bakeable, magnetically shielded, ion pumps. These can be valved off for rapid changes of parts without suffering long pump down times.

The magnetic shields, which are within the blue cylinder and surround the cavity and interaction region are identical to those used on our NP hydrogen masers. The interaction length, that is the distance between the separated transition field regions in the cavity, is 50 centimeters here. This can be much longer, in later designs, and so provide a proportionately better line Q than this design.

The detector, which is on the left here, is a penning discharge gauge. This one is a commercial gauge manufactured by General Electric under the trade name "Trigger Gage". The A and B ends of the vacuum systems are symmetrical, and may be interchanged. One feature, which is not obvious here, is that HBX-1 is mounted on wheels, and also operates automatically either on AC or batteries, so it can be moved around for remote use such as in frequency comparisons with other standards.

Let me pause here for a confession. I was very uncertain 6 weeks ago whether to discuss this new standard work right now. I am sure, on the basis of what has been given, there are many questions, as well as valid misgivings or doubts about its practicality. So I felt that this first presentation should, if at all possible, give some positive experimental results to back up the theory.

Actually, I had not been able to detect a beam with several initial trials using a very slow atom state selector and also using a new, untried, detector scheme. So at that time I quickly refitted HBX-1 with fixed hexapole focussing magnets which would focus 30° Kelvin atoms, and also put on the penning gauge detector.

After pump down, and a few adjustments, the first state flipping, and the first RF stimulated transitions were detected. And then I managed to get the first transition resonance curves. One of these is shown on Slide 13.

This is, of course, relatively noisy. But having detected atoms gives some very firm ground to stand on. Now it is possible to test detectors, for example, knowing there are atoms to detect, or to test sources and velocity distributions, knowing that if atoms are present, there will be some indication. And so optimization can begin.

This curve tells a lot, of course, to people who are familiar with beam tube resonances. This is, of course, relatively noisy — the signal to noise ratio in a one Hertz bandwidth is about 50 or 100 to one. The half width is exactly what was expected from focussed velocity calculations and length of cavity. Here we have a 50 centimeter interaction length and atoms of 10^5 cm/sec velocity. And the line width is 1.2 kilohertz which gives a line Q of about 1.2×10^6.

The horizontal jumps in this curve are all due to the use of a noisy electro-mechanical digital horizontal sweep. The slight asymmetry you see is not really a resonance distortion, as will be shown later, it is due to a secondary transient characteristic of the detector.

The height of the secondary peaks says the velocity range of the atoms making transitions is fairly small, and the broad base width tells us the effective length of the two individual transition regions in the cavity.

One of the first things that was found upon aligning the beam, was that the holes in the first source collimator were pointed off the geometrical axis of the collimator so badly, that the beam must have been directed off axis by about one inch during the earlier, unsuccessful tests, so the lack of results then was now more understandable.

So one of the first things done was to change the source. This immediately reduced the noise by a factor of about 10. Then the other curves I will show today were obtained.

Slide 14 shows the (F = 1, m = 0) state only being detected, and the curves were obtained at successively smaller values of the magnetic field.

The signal to noise ratio is about 1,000 to one here, but this is not obvious here because of the slow and noisy sweep rate. The resonance width is again about 1.2 kilohertz, and the detector initial time constant is about 1/3 second. These curves were taken one right after the other on the same x-y plot, and the vertical calibrations are identical on each curve. Several important facts are illustrated here.

First, there are no degenerate or coincident transitions which come into the picture as the field reduces to zero to destroy the resonance or pull the resonance peak. This is according to expectations, of course.

But second, and most interesting, the curves all have the same amplitude. The atoms are maintaining their polarization direction through the cavity region at the lowest magnetic field. We can, of course, operate at any higher magnetic field we wish, but at the minimum field obtainable here, the total magnetic correction is only 2×10^{-15}, and conceivably we can, in future use, just degauss the shields, and leave off the main magnetic field, and not worry about measuring the correction — at least until our accuracy requirements are less than the 10^{-14} region.

I think the magnetic field conditions existing in HBX-1 are quite unique, and since this may be crucial to later discussions, I will quickly show two slides giving measured field calibrations.

Slide 15 shows the main field calibration. This is a reproducible curve with very little hysteresis, and shows that excellent control down to the microgauss region is possible. Actual measurements show that the axial variation along the path of atoms through the cavity region is very small, in the range of ±10 microgauss immediately after degaussing. Purposely bringing small permanent magnets near the shields create changes of the order of only 20 microgauss, and the stability of the field is possibly best illustrated by the continued operation, without degaussing for periods of a year or more, which is being obtained in field use with NP hydrogen masers having identical shields. These masers have bulbs 41 to 43 centimeters long, and operate at a standard setting of one milligauss.

Slide 16 shows the polarization coil calibration. The main purpose in showing this is to illustrate that variations in polarizing coil fields have negligible effect on the main magnetic field.

At this time I would like to show that the slight asymmetry you observed in the previous transition curves is not due to resonance distortions.

Slide 17 shows two transition curves taken with a slow continuous sweep, first from right to left, then from left to right. This shows that there is a slow, probably thermal, long time constant drift which follows the initial rapid time constant of the detector. This is of course harmless in practice, since almost constant beam amplitude conditions prevail in the usual lock-on servo loop techniques.

Slide 18 shows several things. Here the (1, 1) state is being manually switched in and out of the detected beam at some places by changing the polarity of the polarizing coils. At other places, the (1, 0) state is being manually switched in and out effectively by manually turning on and off the optimum RF transition power. Of course the detector drift and double transient mentioned earlier are visible.

But the main interest here is that we can see the relative intensity of the (1, 1) states and the (1, 0) states. There are approximately 30% fewer (1, 0) atoms detected than (1, 1) state atoms. This is due, first of all, to slightly less efficient focussing of the (1, 0) states due to lack of a permanent dipole moment, and secondly, due to the fact that the atoms do not all have the same velocity, and of course the optimum power for unity transition probability is not the same for different velocities.

Gage calibration and pumping speed measurements also show there is a beam intensity of approximately 2×10^{10} atoms per second in each of these states.

Also shown here is the fact that the same amplitudes of detected states occur whether operating at the high field of 8.8 milligauss, or near zero field.

Slide 19 shows the resonance curve with only the (1, 0) state detected in the upper curve, and with both the (1, 0) and (1, 1) state detected in the lower curve. There is no difference in these two curves, other than a constant amplitude offset, and from this and the previous slide we can be pretty sure that (1, 1) state atoms are not making any significant contribution to the resonance line shape.

This is as far as the experimental work has gone at this time. I would like to mention again however, that the present data is not representative of the best beam intensities or detector noise levels theoretically obtainable — there are five orders of magnitude reduction in vacuum chamber background pressure which is physically possible, to reduce detector noise, and there is over an order of magnitude greater beam intensity available from the source, if desired. Of course longer cavities and more optimized shield and focusser spacings can contribute factors of two or more reduction in line width, while selection of slower atoms will also give improved line Q.

Now the last questions which I will take up at this time are — first, what is the accuracy capability, and second, what stability may be expected from a practical, operational, hydrogen beam standard?

There can't be a detailed discussion at this time — these questions are better settled after a few years of operational experience and many tests. But I will venture some statements.

I will group the accuracy uncertainties into several categories. 1. Cavity and RF exciting spectra and servo effects, 2. Magnetic effects, 3. First and second order doppler effects, and last, 4. Spin exchange effects.

1. Cavity Effects. With this hydrogen beam machine we have a single mode cavity, 10" diameter by 23" long with complete electrical symmetry about the beam axis. The beam also has axial and radial symmetry. This must be compared with a typical cesium cavity with up to 200 modes along the axis, with both cavity and beam cross sections not symmetrical.

   These facts coupled with the factor of 6.5 lower frequency for hydrogen will reduce all of the cavity and spectral or servo related effects by several orders of magnitude. When this is coupled with the experimental ability to focus a continuous range of velocities, so that accurate analysis may be made, and with the fact of negligible magnetic or neighboring level distortions, so that more accurate evaluations of cavity effects may again be made, I think all of this category will be negligible contributors to fundamental inaccuracy — possibly a few parts in 10^{15}-negligible on the present scale of things.

2. Magnetic Effects. The hydrogen beam machine has the capability, using various state selection modes of operation, of experimentally determining both the axial and radial magnetic field conditions. With an uncertainty of 20 microgauss at low or near zero operating fields, the magnetic uncertainties will be in the range of a part in 10^{15} or less.

3. First and Second Order Doppler Effects. Due to the relatively perfect geometry the first order doppler should be zero with negligible uncertainty. For 2nd order doppler, the conditions of operation allow excellent determination of velocity distributions, so that this effect should be small even in hydrogen beams operating with relatively fast atoms. For 10^5 cm per second atoms and a velocity inaccuracy of .1%, the uncertainty is 5×10^{-15}. This is at the present operating velocity, and should be much smaller with slower beams.

4. Spin Exchange. To evaluate spin exchange it is convenient to relate to measurements made on the experimental hydrogen maser for a moment. A very adequate measure of the NX total spin exchange pulling under operating conditions was obtained by measuring the tuned cavity frequency. As is well known, a tuned maser has an offset cavity frequency which just compensates for spin exchange pulling. From a knowledge of line Q and cavity Q the net spin exchange pulling may be calculated. The result of this measurement was that NX, with an atomic density

in the storage bulb calculated as approximately 3×10^8 atoms per cubic centimeter had a compensated spin exchange effect of 1.2×10^{-11}. The present beam device at 4×10^{10} atoms/sec detected, has a net density of atoms in the beam calculated to be about $1/10$ of the density in the maser bulb.

Now the spin exchange pulling depends on the relative atomic velocity also, and in the maser this is of the order of 3×10^5 centimeters per second. The relative velocities of atoms in the beam, however, are very low. From relatively accurate calculations based on the atomic trajectories and focussing parameters, this is calculated to be about 150 cm/sec. From this, for a high intensity beam, the net spin exchange effect is calculated as 5×10^{-16}.

With the above numbers staring us in the face, it is difficult to give what would be considered a conservative estimate for the total inaccuracy budget. We have:

1. Cavity 2×10^{-15}

2. Magnetic 1×10^{-15}

3. Doppler 5×10^{-15}

4. Spin Exchange 5×10^{-16}

I think the word conservative might be applied to the number 1×10^{-14} if I have not made any big errors. It is on this basis that Slide 20 is presented.

This gives an accuracy and stability comparison between operational H masers, commercial and laboratory cesium beam standards, and the potential stability and accuracy of the free atom hydrogen beam.

I think it is clear from this potential accuracy and stability improvement that the hydrogen beam standard deserves to be very seriously considered.

It is interesting that the hydrogen beam combines, in a rather nice way, the technologies of hydrogen masers and of cesium beams. I can assure everyone it is a rewarding experience to experiment with the trajectories and the transitions of an unadulterated quantum state, and I think there is also some very unusual and interesting physics involved in looking at these isolated quantum states under conditions where they are primarily restrained in space only by their own angular and linear momentum. Thank you.
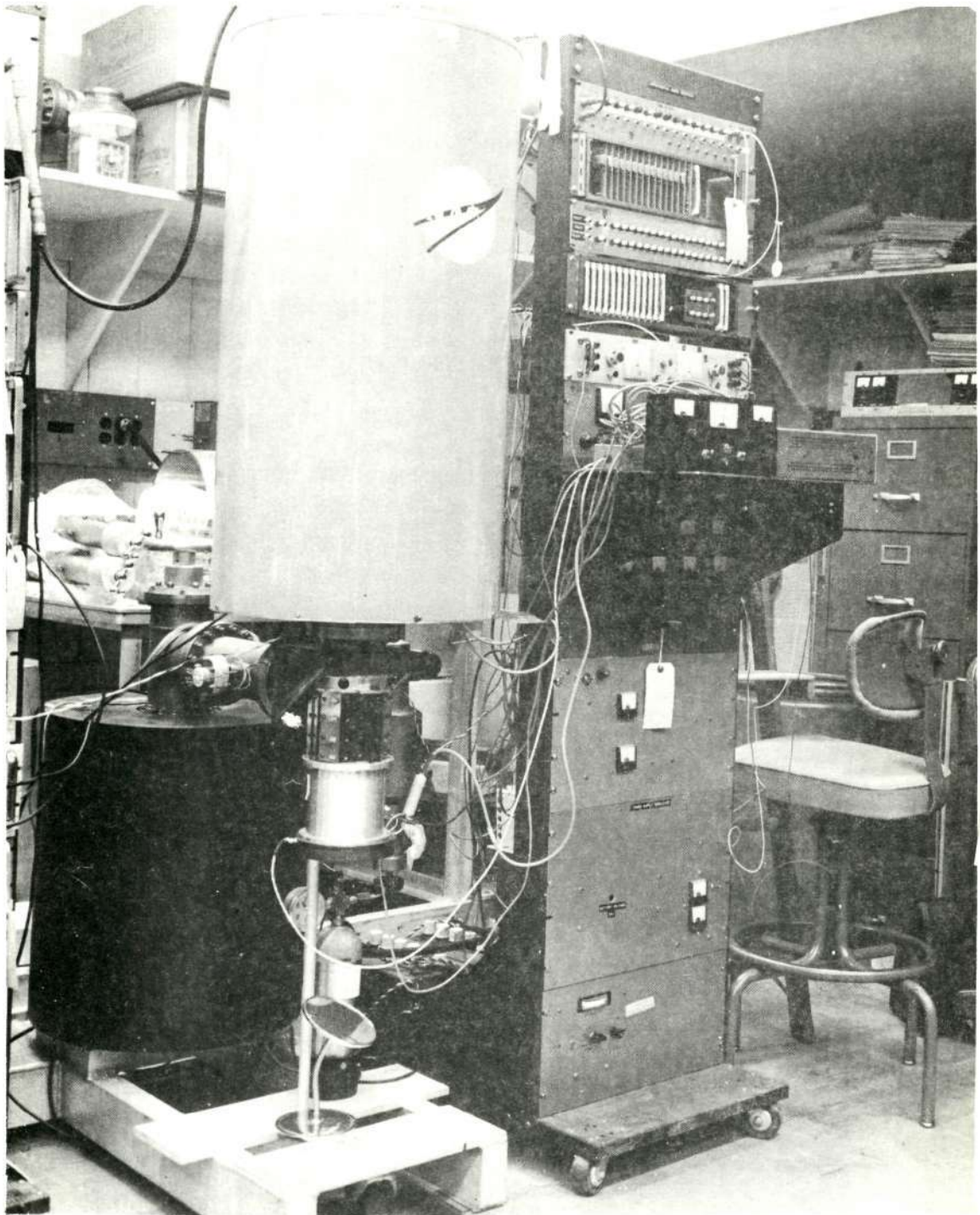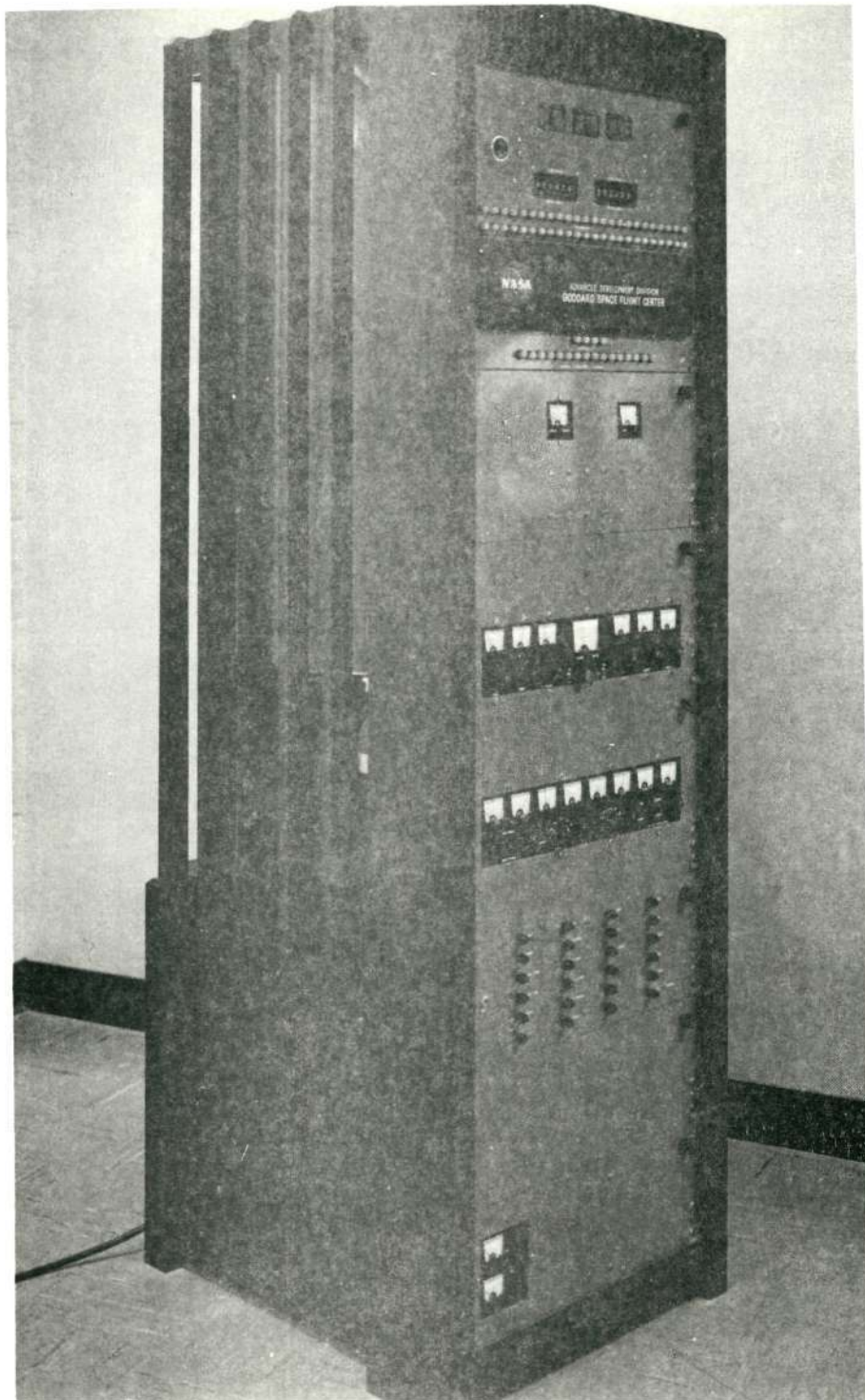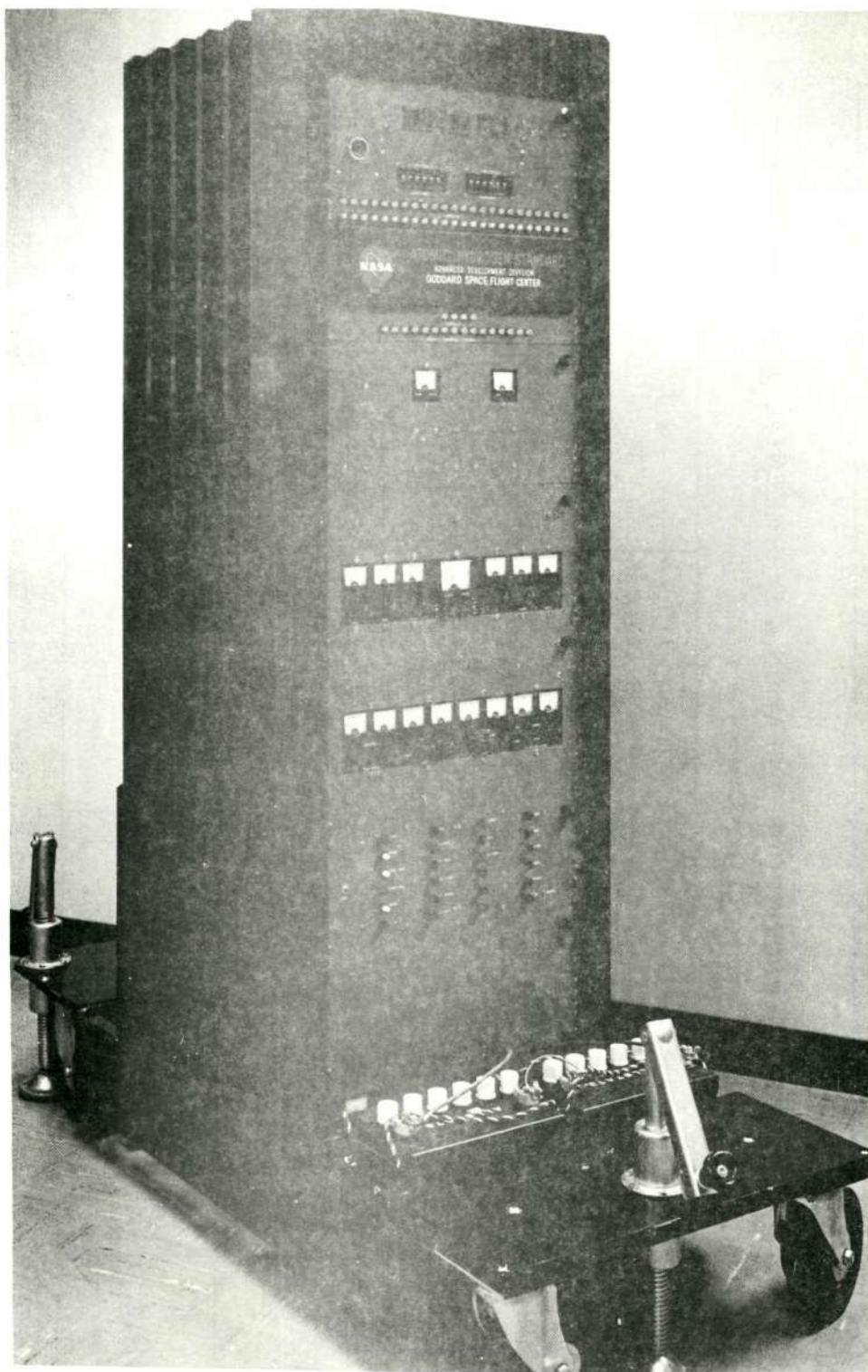
Slide 1

Slide 2

Slide 3
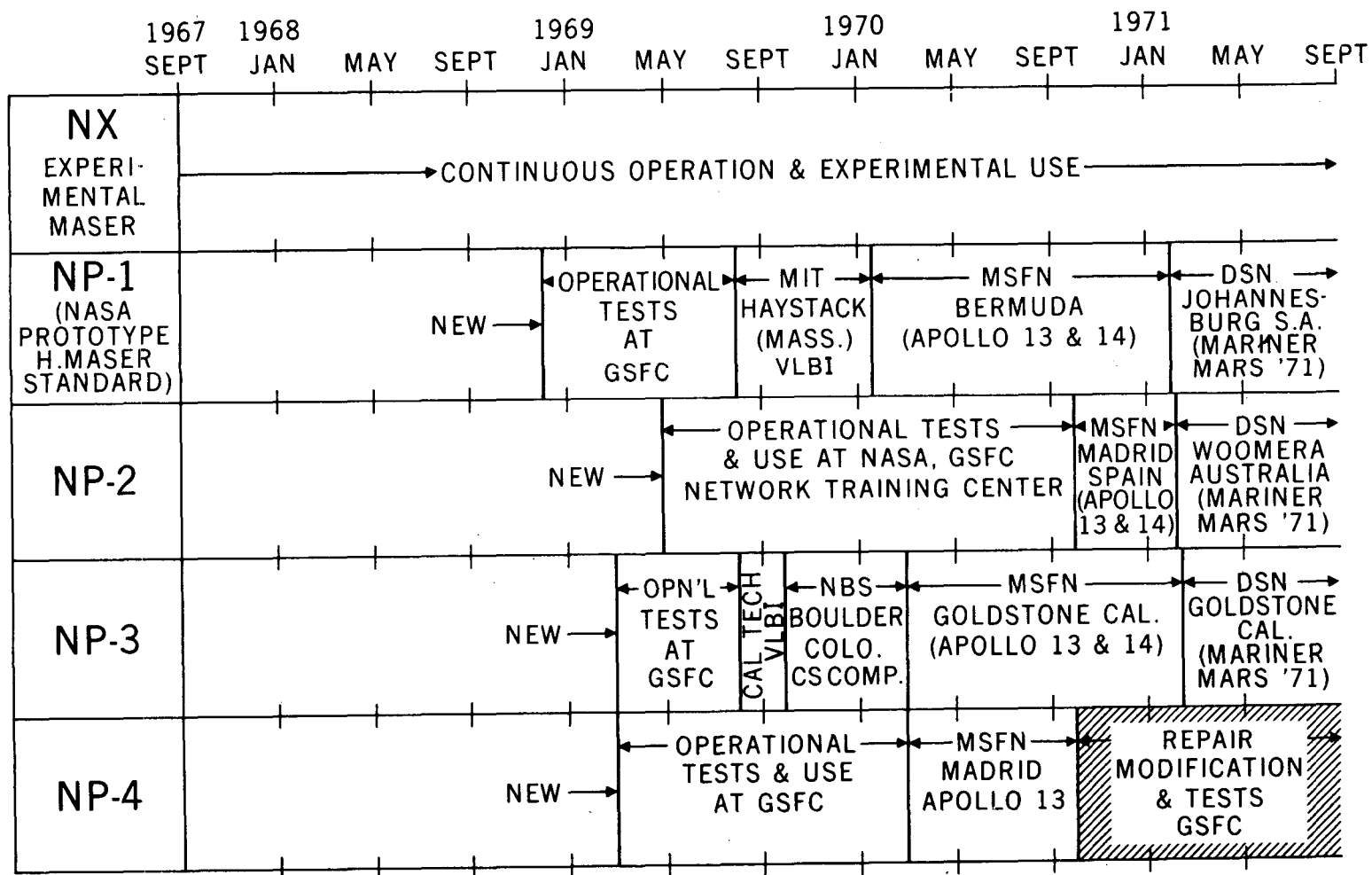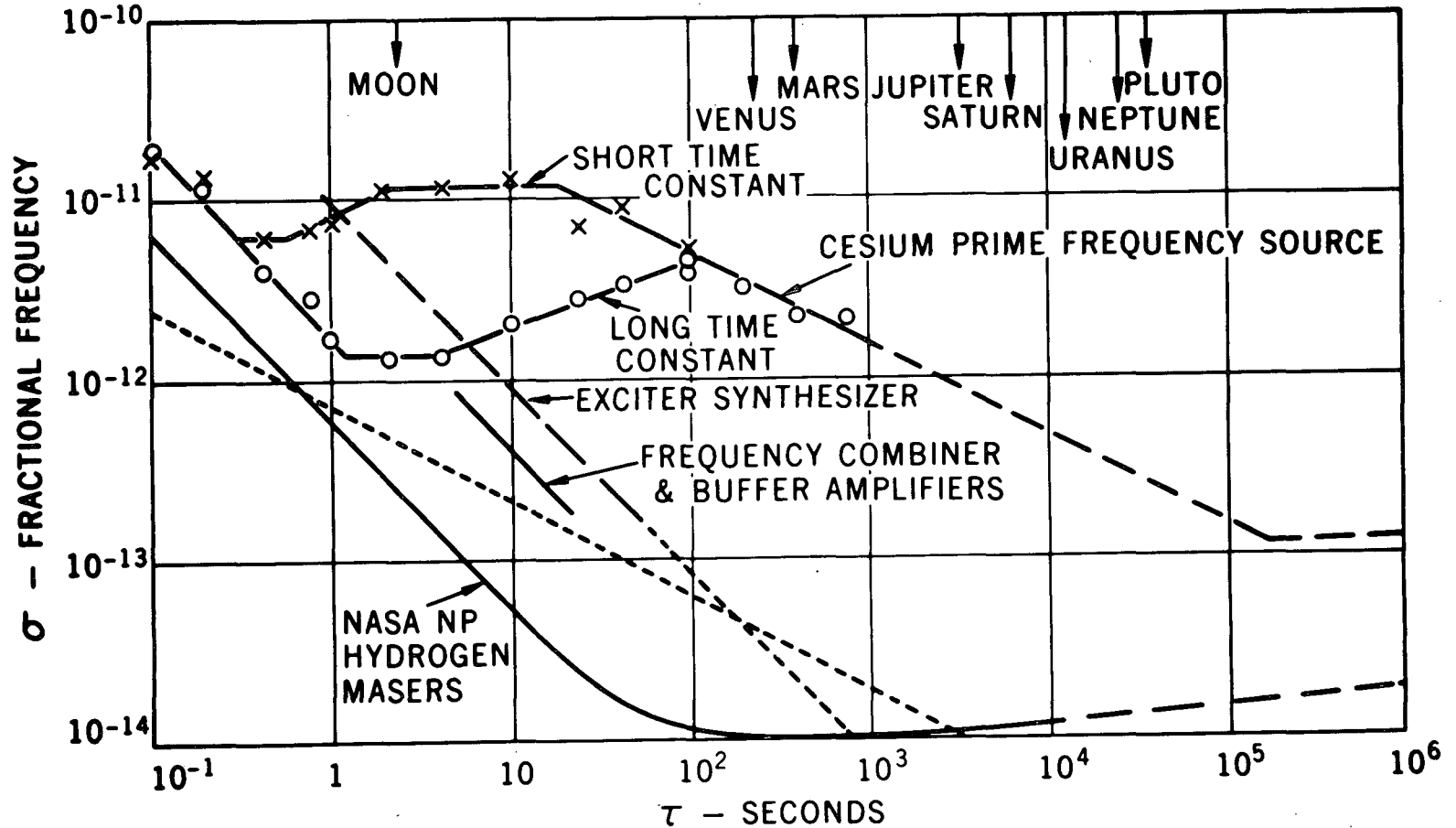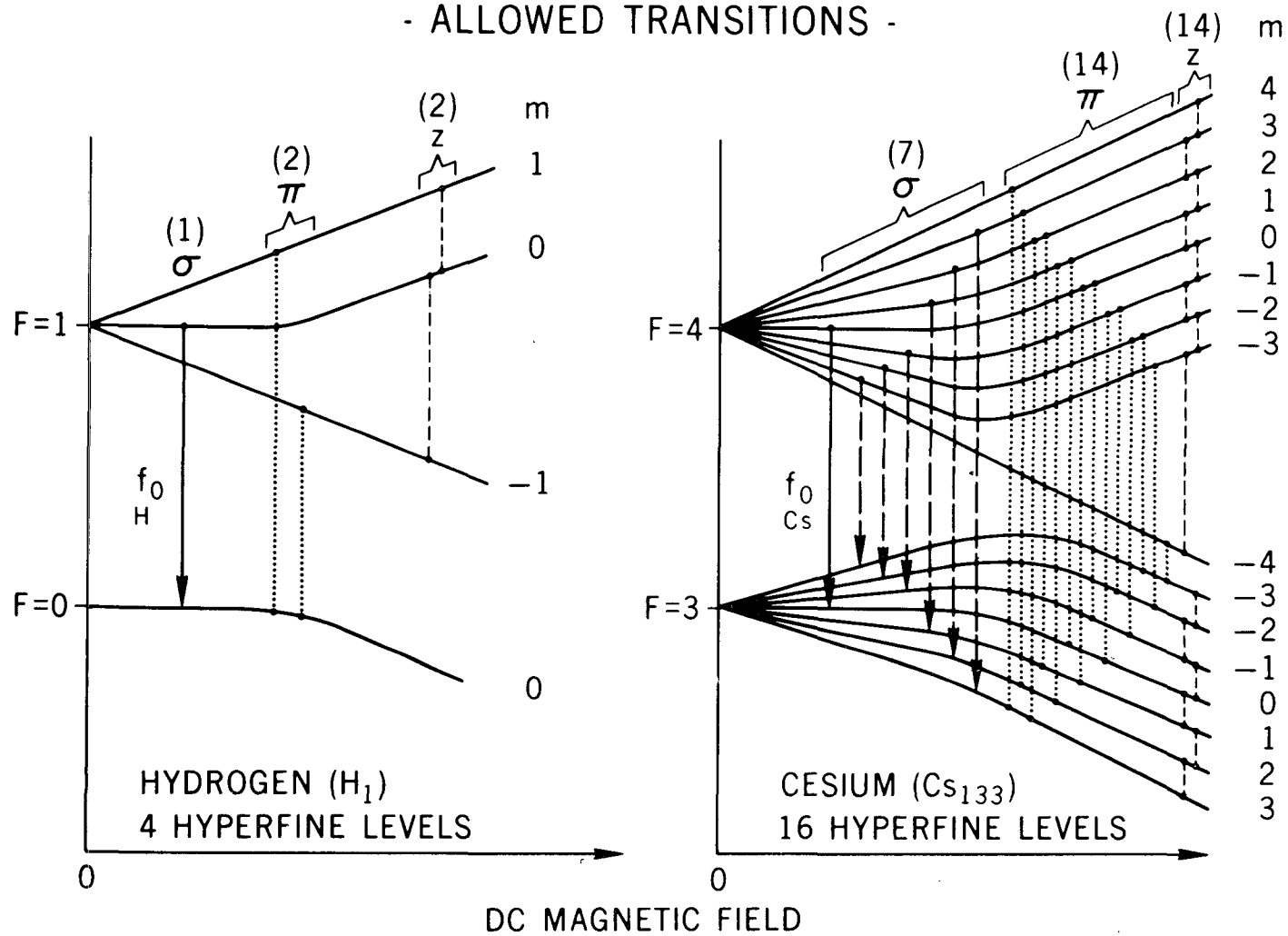
GSFC HYDROGEN MASER OPERATION

Slide 4

NASA USB SYSTEM INSTABILITY CONTRIBUTIONS
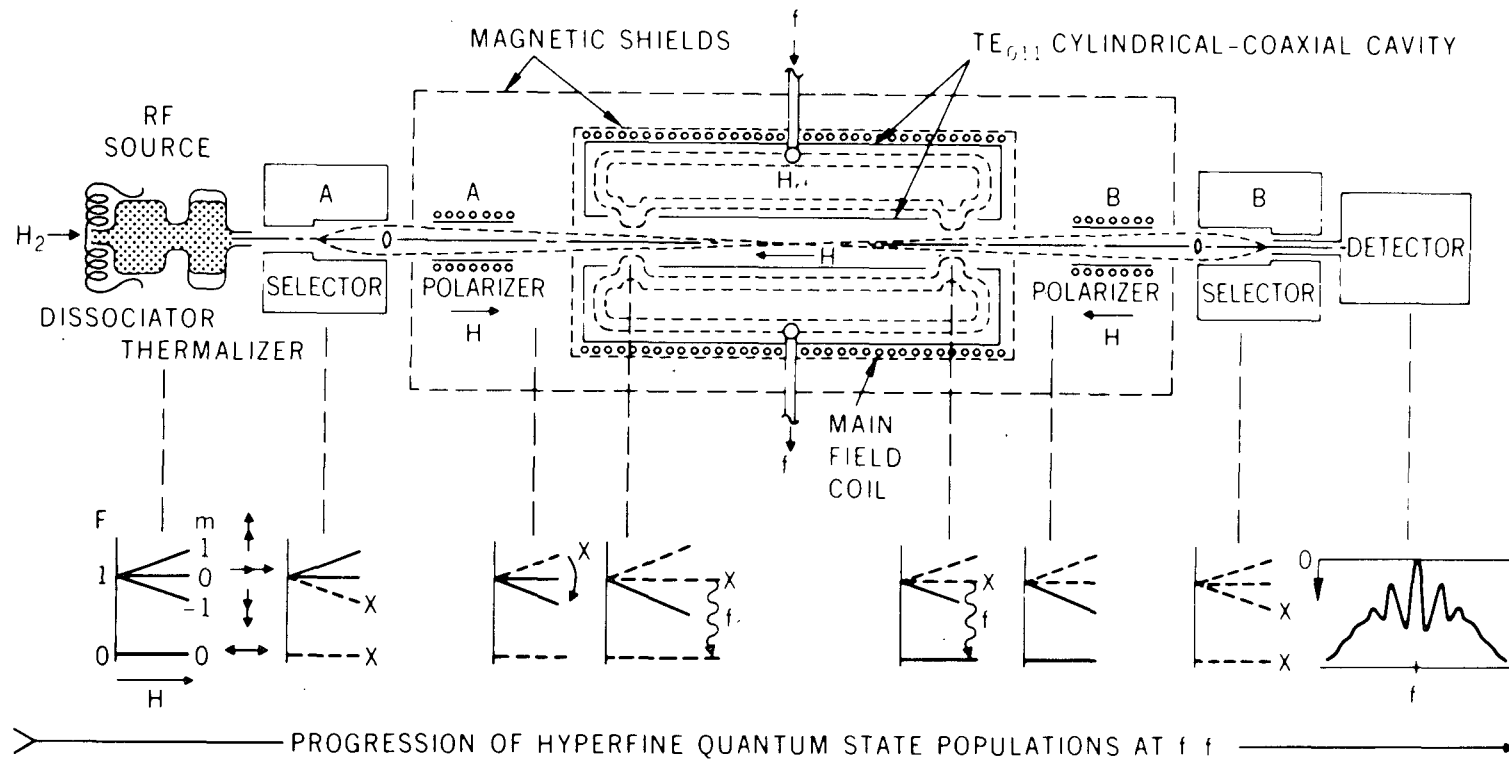
MINIMUM ROUND TRIP LIGHT TRANSMISSION TIMES

Slide 5

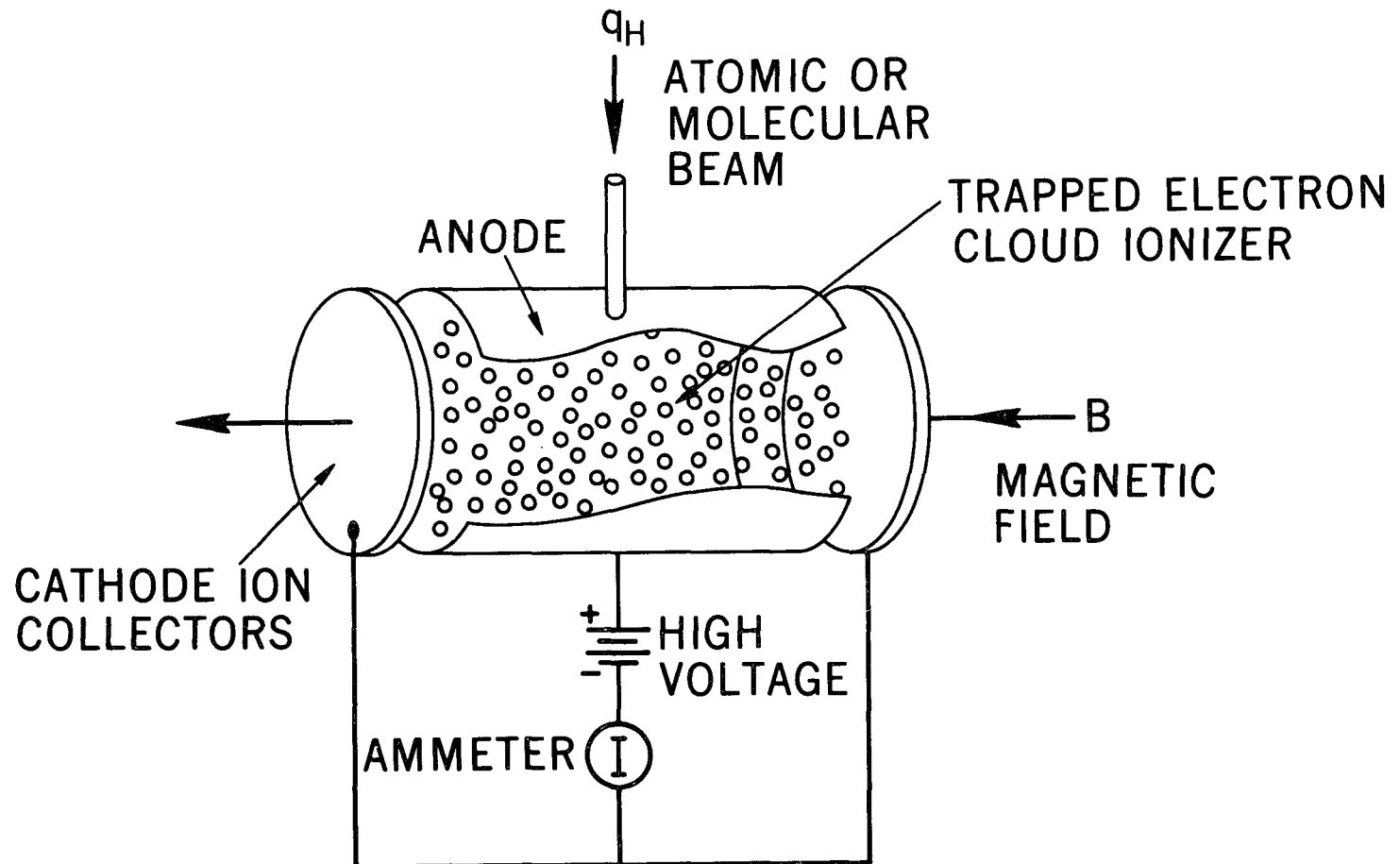HYDROGEN & CESIUM HYPERFINE ENERGY LEVELS
- ALLOWED TRANSITIONS -

Slide 6

HYDROGEN ATOMIC BEAM STANDARD SCHEMATIC
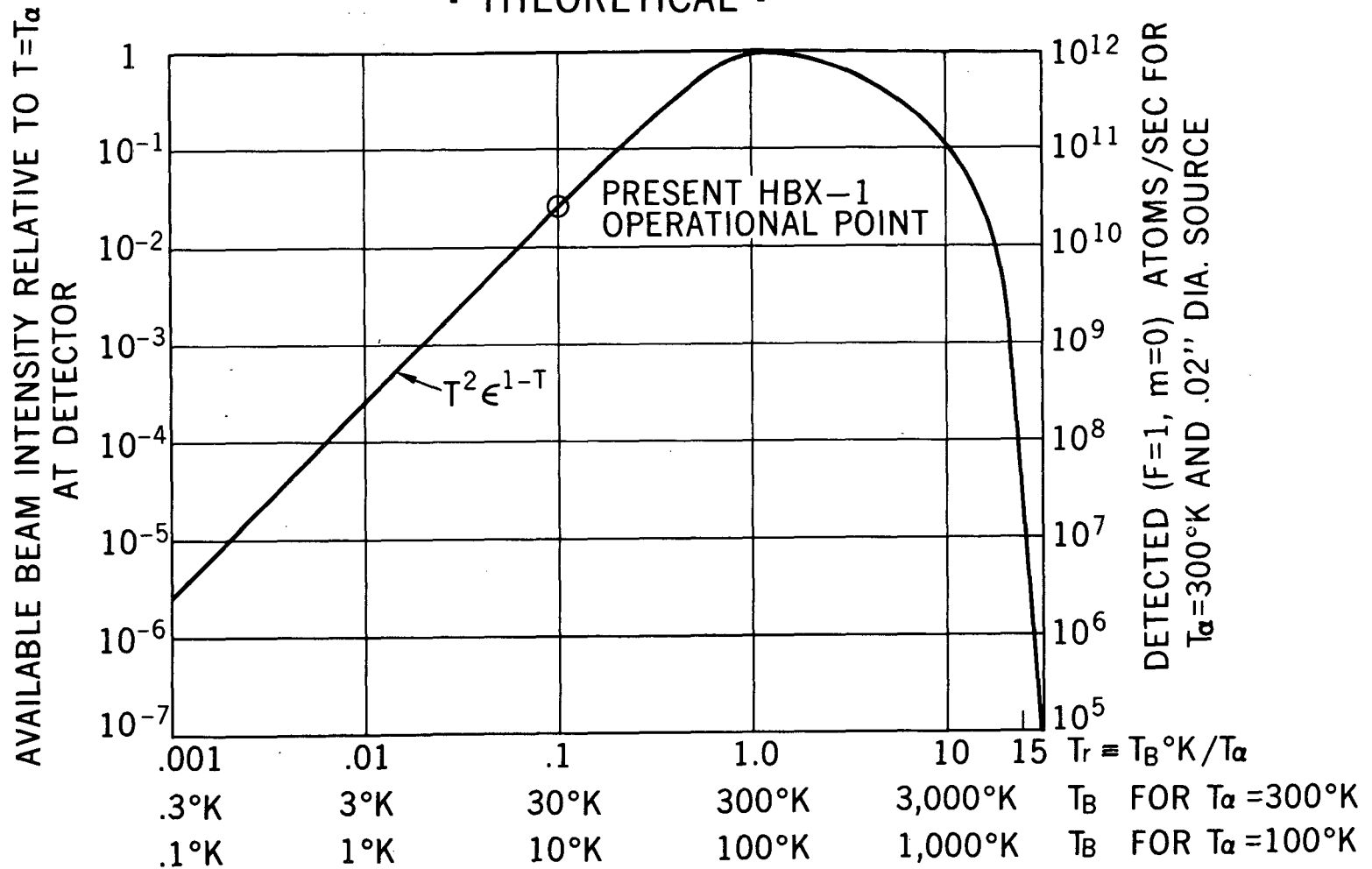

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CANDIDATE HYDROGEN ATOMIC BEAM DETECTORS

	DETECTOR	EFFICIENCY	NOISE	
1	ELECTRON BOMBARDMENT IONIZER WITH MASS SPECTROMETER	.001?	?	
2	METALLIC ELEMENT PIRANI GAUGE	?	HIGH	
3	SEMICONDUCTOR PIRANI GAUGE - ROOM TEMP - CRYOGENIC	HIGH ? HIGH	HIGH LOW ?	◄— 4
4	BOLOMETER - ROOM TEMP - CRYOGENIC	HIGH HIGH	HIGH LOW ?	
5	SEMICONDUCTOR BOLOMETER - ROOM TEMP - CRYOGENIC - SUPER CONDUCTING	HIGH HIGH HIGH	HIGH LOW ? LOWEST ?	◄— 3
6	ION GAUGE - TRADITIONAL	LOW	HIGH	
7	SEMICONDUCTOR TRANSISTOR - PN - FIELD EFFECT	? ?	? ?	
8	THERMOLUMINESCENT DETECTOR	?	LOW ?	
9	CHEMILUMINESCENT DETECTOR	?	LOW ?	
10	CHEMILUMINESCENT DETECTOR USING H-ATOM TRIGGERED CHEMICAL CHAIN REACTIONS	HIGH ?	LOW ?	◄— 2
11	ELECTRON BOMBARDMENT - SPECTRAL EMISSIVE	LOW	LOW ?	
12	PENNING DISCHARGE DETECTOR	HIGH	LOW	◄— 1
13	FREE RADICAL OR MAGNETIC MOMENT DETECTOR - CRYOGENIC	?		
14	CAVITY MAGNETIC MOMENT DETECTOR - CRYOGENIC	?		
15	HYDROGEN MASER DETECTOR	LOW	LOW	
16	OPTICAL STIMULATION, RE-EMISSIVE	LOW	?	

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Slide 9

HYDROGEN ATOM TEMPERATURE DISTRIBUTION
- THEORETICAL -

AVAILABLE BEAM INTENSITY RELATIVE TO T=Tα AT DETECTOR

DETECTED (F=1, m=0) ATOMS/SEC FOR Tα=300°K AND .02" DIA. SOURCE

$T^2 \epsilon^{1-T}$

PRESENT HBX−1 OPERATIONAL POINT

.001	.01	.1	1.0	10 15	$T_r \equiv T_B°K/T\alpha$
.3°K	3°K	30°K	300°K	3,000°K	T_B FOR $T\alpha$ =300°K
.1°K	1°K	10°K	100°K	1,000°K	T_B FOR $T\alpha$ =100°K

Left axis: 1, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}

Right axis: 10^{12}, 10^{11}, 10^{10}, 10^{9}, 10^{8}, 10^{7}, 10^{6}, 10^{5}

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HYDROGEN ATOMIC BEAM

BEST POTENTIAL STABILITY ESTIMATE AS FUNCTION OF RELATIVE TEMPERATURE OF BEAM
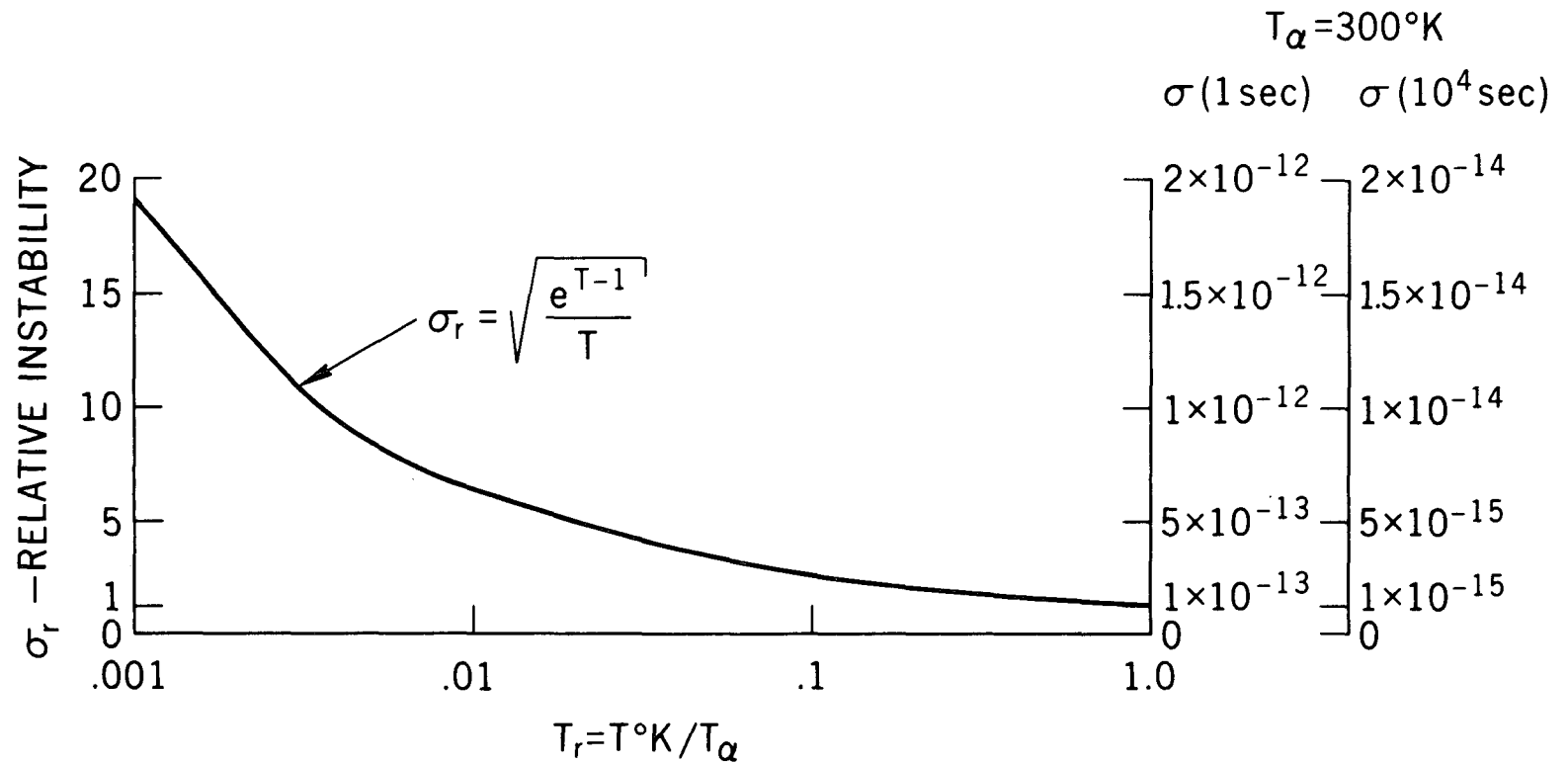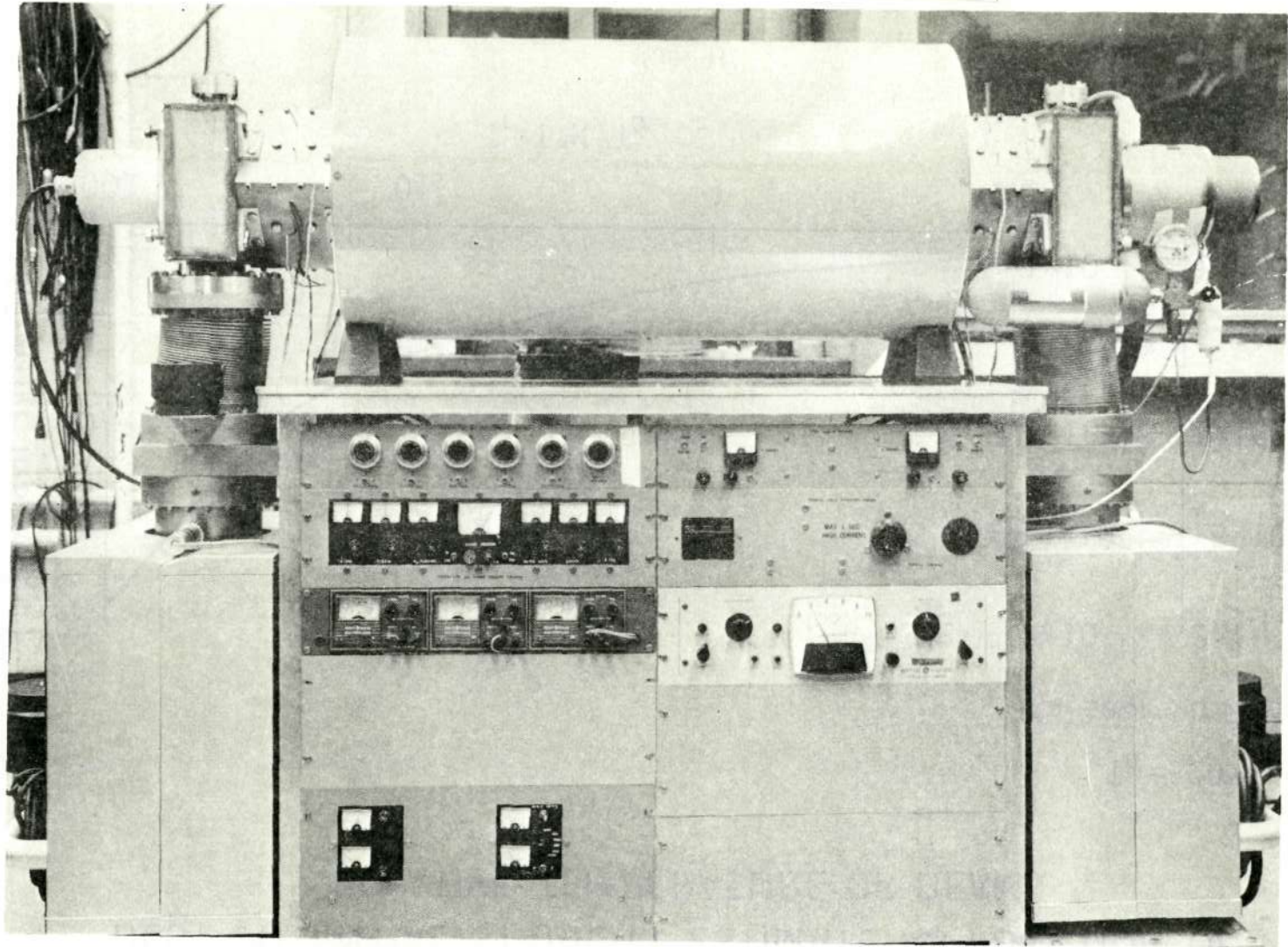
Slide 12

Slide 13
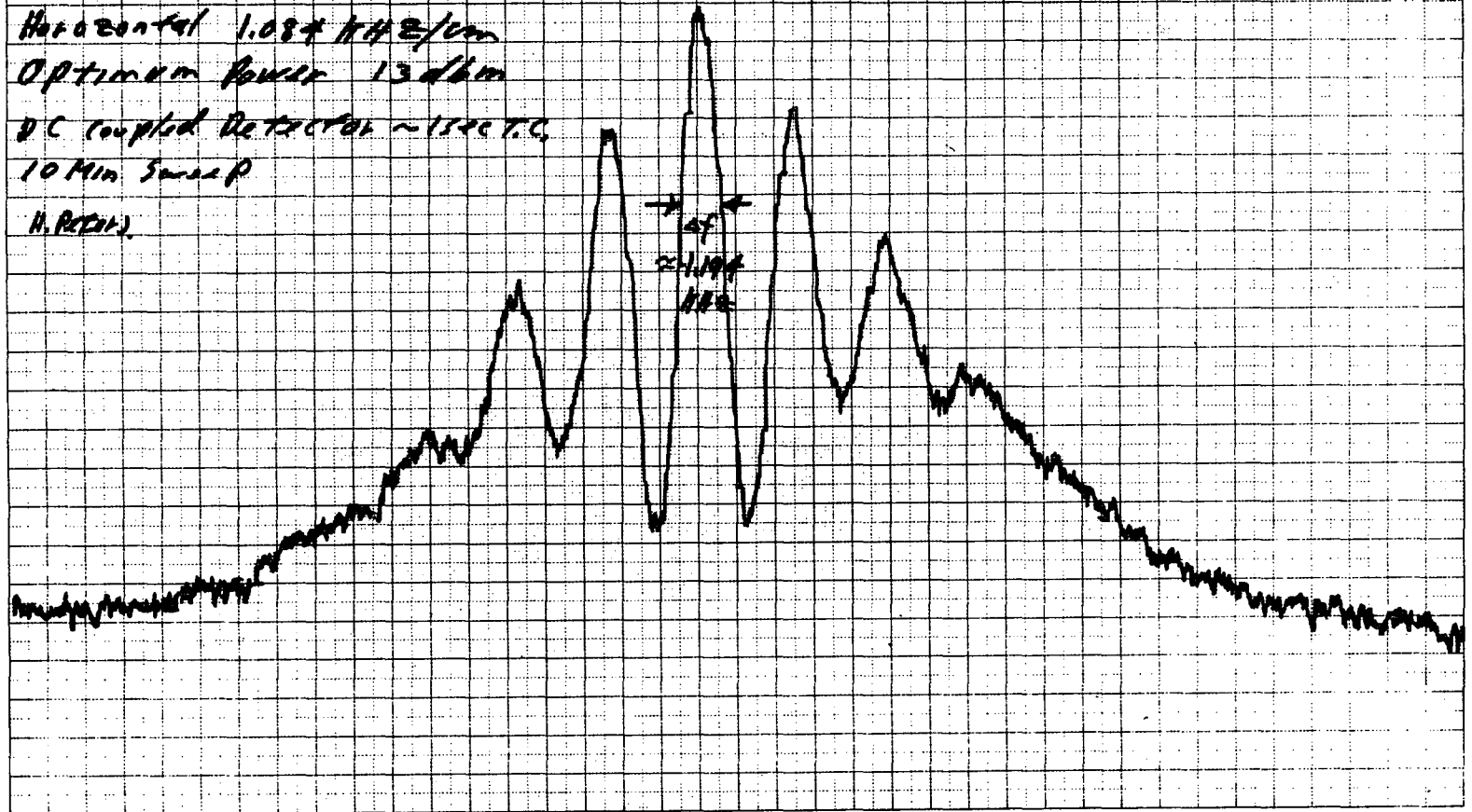
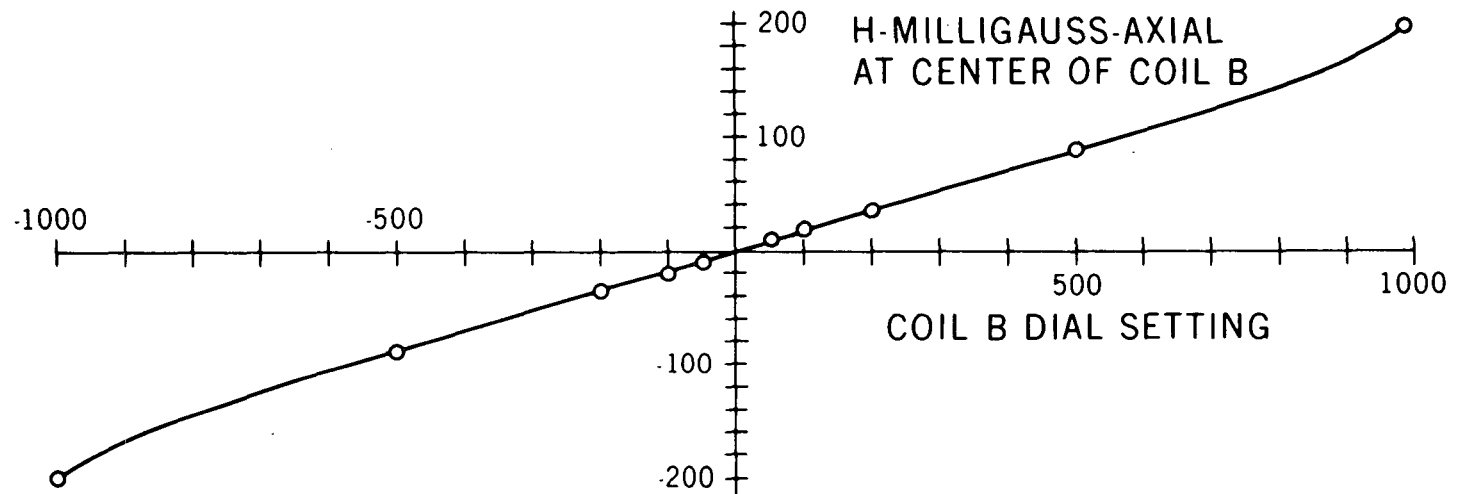# HYDROGEN TRANSITION (F=1, m=0)→(F=0, m=0) AT VARIOUS MAGNETIC FIELDS
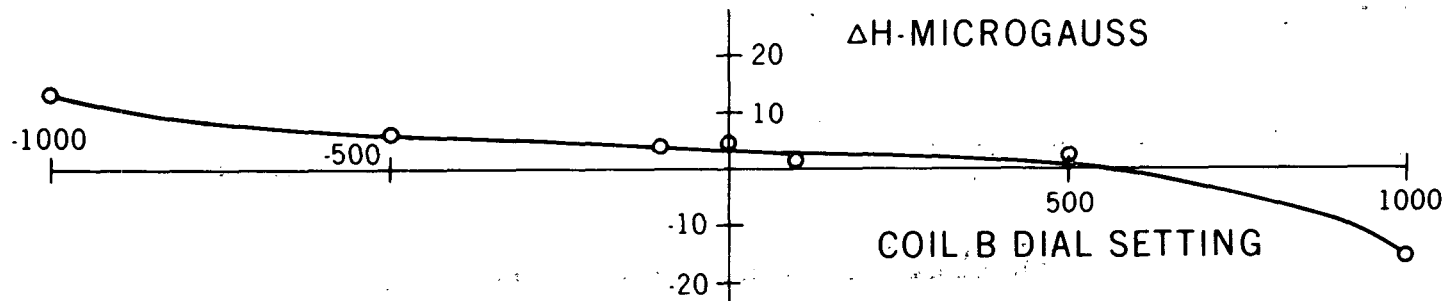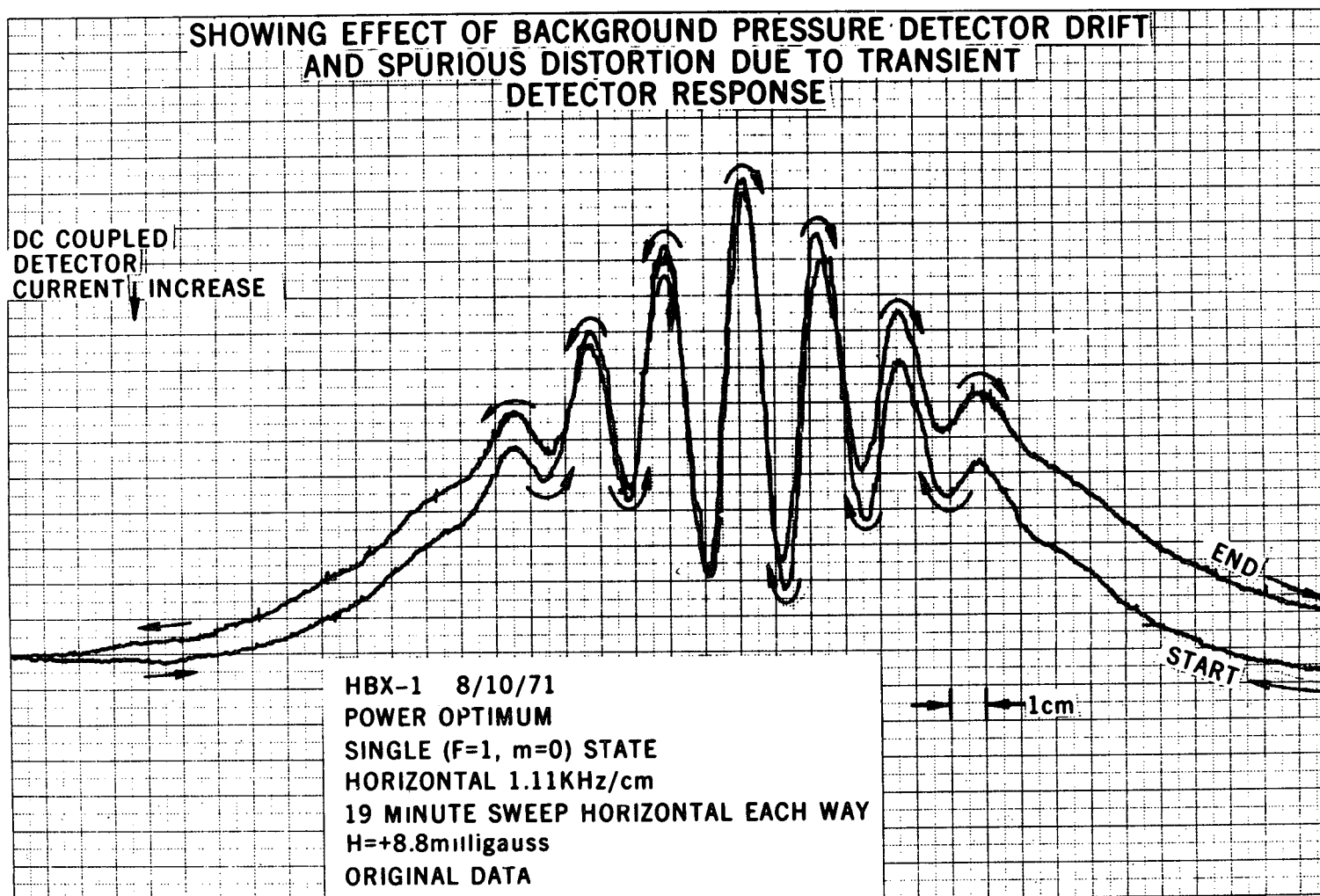

Slide 14
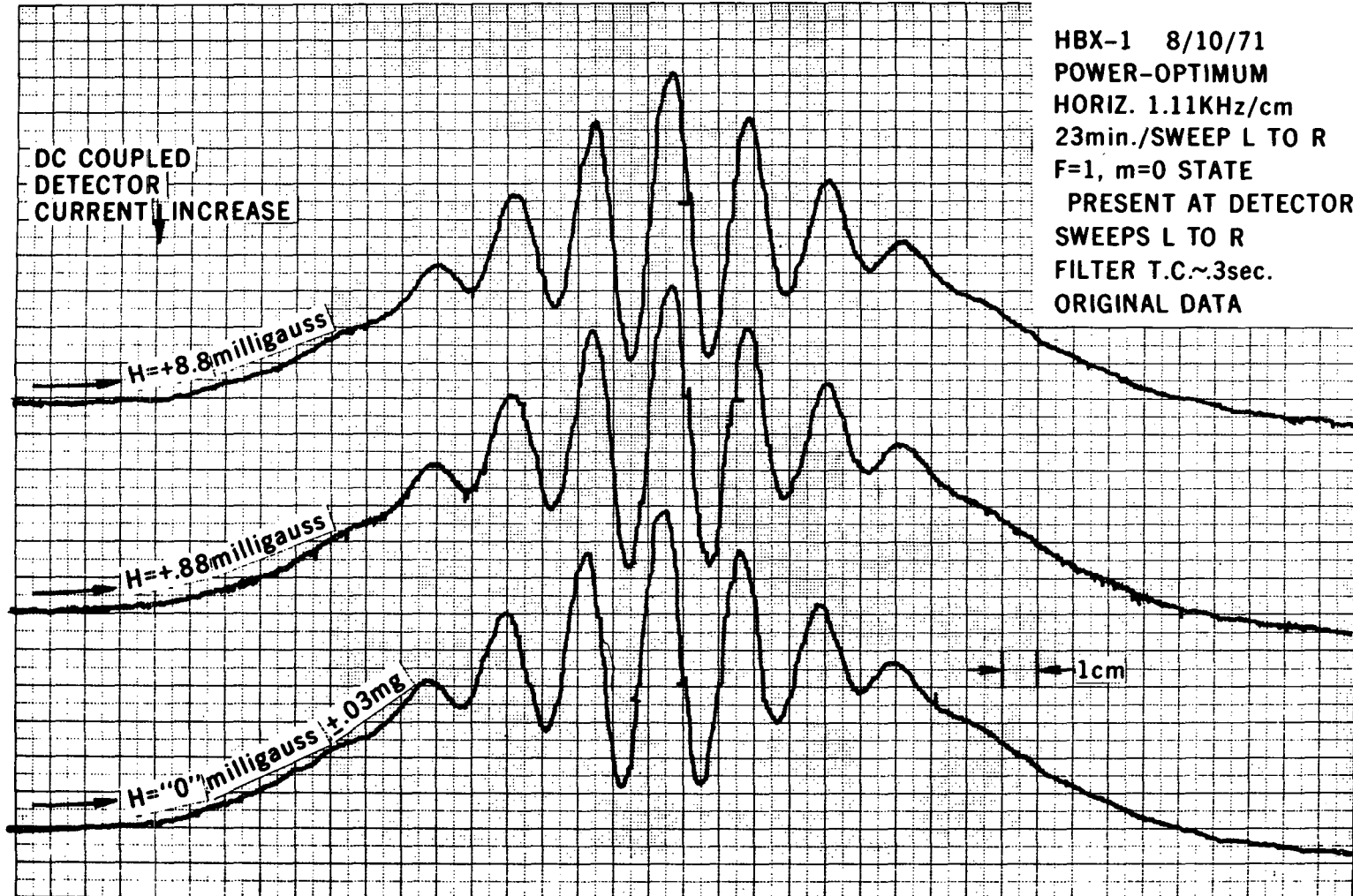
HBX-I MAIN FIELD CALIBRATION

Slide 15
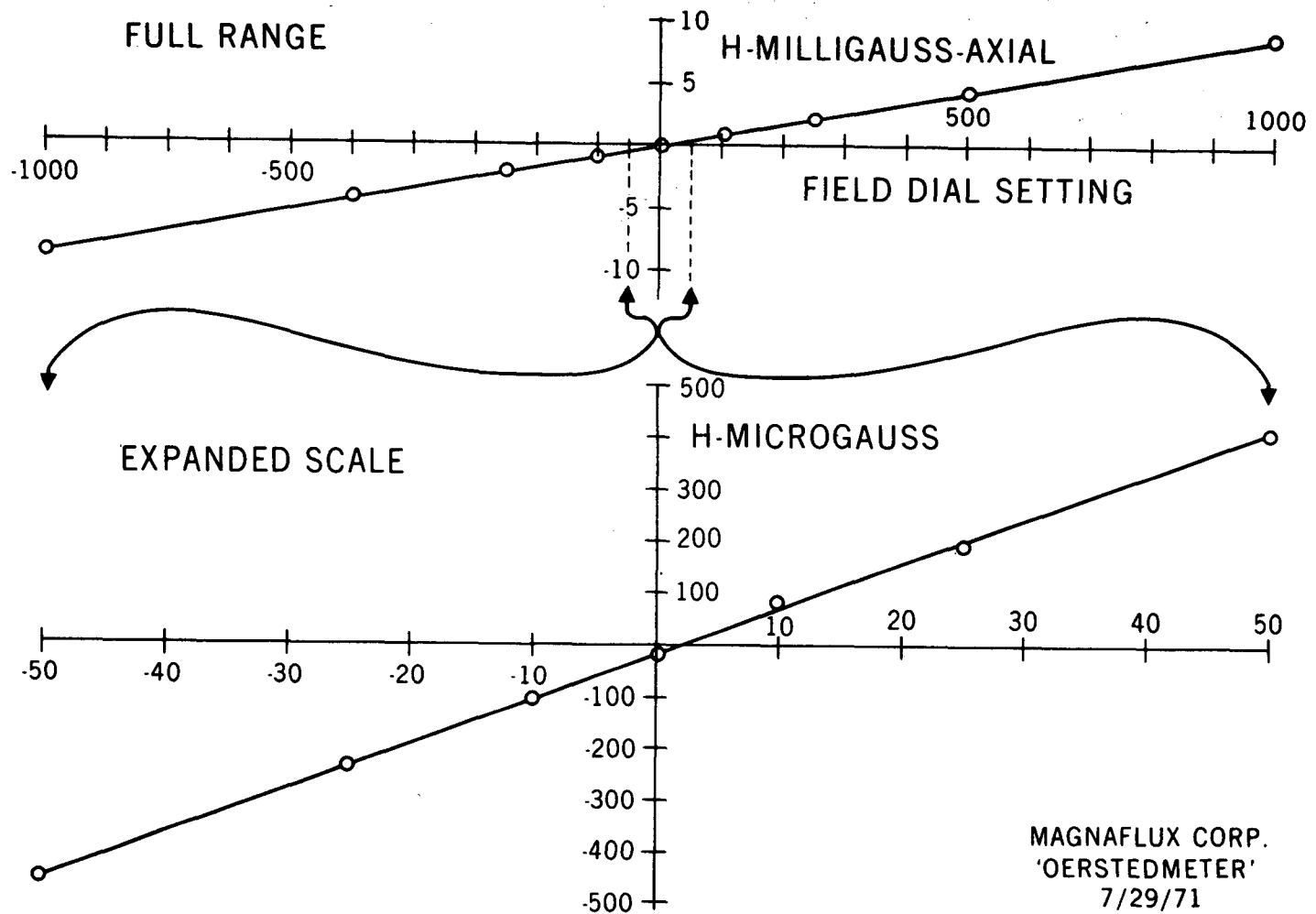
HBX-I POLARIZING COIL FIELD CALIBRATION

VARIATION OF MAIN FIELD ADJACENT TO INNER SHIELD
CAP HOLE AS POLARIZING FIELD IS VARIED

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HYDROGEN TRANSITION (F=1, m=0)→(F=0, m=0) WITH REVERSE RETRACE

SHOWING EFFECT OF BACKGROUND PRESSURE DETECTOR DRIFT
AND SPURIOUS DISTORTION DUE TO TRANSIENT
DETECTOR RESPONSE

DC COUPLED
DETECTOR
CURRENT INCREASE

HBX–1   8/10/71
POWER OPTIMUM
SINGLE (F=1, m=0) STATE
HORIZONTAL 1.11KHz/cm
19 MINUTE SWEEP HORIZONTAL EACH WAY
H=+8.8milligauss
ORIGINAL DATA

1cm

END
START

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HYPERFINE STATE SELECTION AND TRANSITIONS
SHOWING DETECTOR TRANSIENT RESPONSE AND
RELATIVE POPULATIONS OF DETECTED ATOM STATES

CODE (+ – 1)

B COIL A COIL TO OPTIMUM RF
POLARITY TRANSITION FIELD ON
OF POLARIZING COILS

SAME COIL SIGN MEANS
(1,1) STATE DETECTED,
OPPOSITE: FLOPPED OUT.

(+–1)

(+–1)

(+–1)

(+–1)

(+–1)

(+–0)

(+–0)

(+–0)

(+–0)

(+–0)

(+–0)

(+–0)

(+–0)

(++1)

(++1)

(++1)

(++1)

(++1)

(++1)

(++0)

(++0)

(++0)

(++0)

(++0)

(++0)

(––0)

(++0)

(––0)

8.8mg ⟵   ⟶ "0"mg

HBX–1   8/10/71
HORIZONTAL RATE~15sec/cm
FIELDS & RF SWITCHED
   MANUALLY
50mg ON POLARITY COILS (WHEN ON
VERTICAL SCALE: DETECTOR
CURRENT INCREASE ↓
T.C.~.3sec. ON OUTPUT

⟶ PROGRESSION

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Slide 19

STABILITY & ACCURACY

HYDROGEN BEAM STANDARD
VS
HYDROGEN MASER & CESIUM BEAM

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