TMO Progress Report 42-134 August 15, 1998

Design of a Cryocooled Sapphire Oscillator for the Cassini Ka-Band Experiment

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We present design aspects of a cryogenic sapphire oscillator that is being developed for ultra-high short-term stability and low phase noise in support of the Cassini Ka-band (32-GHz) radio science experiment. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} *(1 second* $\leq \tau \leq$ *100 seconds) and a phase noise of* -73 *dBc/Hz at 1 Hz measured at 34 GHz. Test results are reported for several subsystems, including the cryocooler, vibration isolation system, and ruby compensating element.*

I. Background

Cryogenic oscillators make possible the highest stability available today for short measuring times ($\tau \leq 100$ seconds) [1–3]. However, they have so far proven impractical in applications outside the research environment due to their limited operating periods. Interruption of normal operation typically is required while a cryogen is replaced, the system then returning to nominal operation as temperatures settle down again to a stable operating condition. It is ironic that standards that are optimized for very short measuring times must operate for periods of a year or more without interruption to be considered for many applications. This is because a short-term frequency standard typically is utilized to "clean up" the short-term variations of an atomic standard, the combined output then being distributed to various users in a facility to be used by each for their own purposes—e.g., radio science on one hand and event scheduling on another. Frequent interruption of the operation of such a timekeeping facility would be unacceptable.

Cryogenic standards also represent the best promise for improved local oscillator (LO) performance as required by a new generation of passive atomic standards. These include both the cesium fountain and the trapped ion standards that are under development at many laboratories around the world and whose potential presently cannot be met using available local oscillator technologies. Because these *are* long-term frequency standards, continuous operation of the LO is crucial to its applicability.

For some time, cryocoolers have been available that can operate continuously for long periods of time, achieving operating temperatures as low as 7 to 8 K for two-stage Giffard–McMahon (G-M) coolers and 4.2 K or lower with an additional Joule–Thompson (J-T) expansion stage. However, they generate vibrations that, if coupled to the high quality factor (Q) electromagnetic resonator, would degrade the frequency stability. Furthermore, the J-T expansion units are relatively large and expensive, and the

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[1] Tracking Systems and Applications Section.

two-stage G-M units show large temperature swings at a cycle frequency of a few Hertz, together with a cooling capability that, while marginal at best, may degrade by as much as 1 K in the course of a year's operation.

Sapphire resonators have been tested that show quality factors of $Q \approx 10^9$ at temperatures up to 10 K [2]. However, stable operation can be achieved only near a preferred "turnover temperature" that typically is too low (1.5 to 6 K) to reach with a cryocooler, and that varies from resonator to resonator depending on the concentration of incidental ($\sim$1 part per million (PPM) paramagnetic impurities. If the impurity levels could be accurately controlled in each resonator, it might be possible to construct resonators that would be compensated in the relatively narrow temperature band between that which can be achieved with available cryocooler cooling and the point at which the Q is degraded.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at much higher temperatures. A resonator with a mechanical compensation scheme has achieved stability of better than 1×10^{-13} at a temperature above 77 K [1], and combined sapphire–rutile resonators presently are under study [4]. However, the Q values of a million or so that so far are achievable with these schemes are far below those desired here.

The Q requirements for any stability value can be thought of in terms of how many times the line can be split, a value based on the degree of residual phase noise in the supporting electronic equipment. This number is typically about one million, with the highest value reported to date being six million [1]. Thus, depending on the capability of the supporting electronics, a stability of 1×10^{-15} requires a resonator Q between 2 and 10×10^8.

II. Introduction

We are developing a cryogenic frequency standard to meet requirements of the Cassini Ka-band Experiment. This cooperative mission between NASA and the Italian Space Agency makes use of a 34-GHz link to the spacecraft to greatly reduce instabilities due to the solar plasma. During periods of the mission when the spacecraft is away from the Sun, the solar plasma contribution is at a minimum, and a search for gravitational waves will be undertaken. Later, during the orbital phase of Saturn, the rings will be examined by radio-frequency occultation.

Substantial efforts are being made to increase stability and reduce phase noise for ground-based systems of NASA's Deep Space Network (DSN) and to dramatically reduce uncertainties in (wet) tropospheric delay for the purposes of this experiment. For the two-way ranging experiments associated with the gravitational wave search, the premium is on medium-term frequency stability. The cryogenic oscillator requirement for this part of the experiment is a frequency stability of 3×10^{-15} (1 second $\leq \tau \leq$ 100 seconds), and the requirement for the occultation phase is a phase noise of -73 dBc/Hz at 1 Hz measured at 34 GHz.

It would have been possible to install and maintain helium-cooled frequency standards for the relatively few months of operation for these experiments; however, such an approach would have done little towards improving DSN capabilities for future missions. The possibility of helium gas release and the physical logistics of cryogen replacement would result in a greater impact on and risk to operation of the other frequency standards during the course of this mission, while providing an uncertain long-term benefit.

III. General Design Aspects

The vibrations associated with cryocooler operation present a considerable challenge to our design. However, the requirements associated with Mossbauer experiments are at least as stringent as ours, and the experimental Mossbauer community has successfully adopted a methodology that transfers heat from the experiment to the cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas [5]. A small dewar is constructed to closely fit around the cryocooler, and the space between them is filled with helium gas at atmospheric pressure. This methodology, which has not previously been applied to frequency standards, allows the cryocooler and cryostat to be mounted independently from the floor. Conventional vibration reduction techniques then are applied to the cryocooler and cryostat supports.

A new two-stage cryocooler design recently has come onto the market with capability that previously was possible only by means of an additional Joule–Thompson (J-T) expansion stage. While J-T coolers have been in use in the DSN for many years to provide cooling for the low-noise ruby maser amplifiers, they are relatively large and expensive. With an ultimate temperature below 5 K, the new two-stage coolers allow a small cryogenics package, and this proven technology should provide excellent reliability.[2]

However, thermal losses in the vibration isolation system, severe requirements on allowed temperature fluctuations, and an expected degradation of cooling capacity over the lifetime of the cryocooler all work to limit achievable temperatures. Thus, even with an initial 4- to 5-K cooling capability, a design that calls for a resonator temperature below about 8 K seems risky.

This situation calls for operation of the sapphire resonator at a higher temperature than previously has been practiced in a 1×10^{-15} frequency standard. Although operation at temperatures up to 10 K seems possible without undue degradation of the quality factor, Q, the turnover temperatures for whispering gallery sapphire resonators typically are 5 to 7 K, with the temperature determined in each case by incidental concentrations of paramagnetic impurities in the sapphire.

A relatively small window of opportunity is thus defined by cryocooler capability and resonator Q that requires a resonator turnover temperature of 8 to 10 K, a fairly stringent requirement. We present a methodology to adjust the value of the sapphire turnover temperature by means of a proximate and thermally attached ruby element. The high chromium concentration in the ruby gives a large compensation effect that can be reduced by adjusting its position. Individual sapphire and ruby elements thus can be mated in such a way as to achieve a turnover temperature of 8 to 10 K. A disadvantage of this method is that spin-dependent losses or other losses in the ruby might prevent a high Q from being achieved. This issue is discussed in the following section.

Higher-temperature operation also precludes the use of simple low-temperature superconductors such as lead ($T_c = 7.2$ K) and niobium ($T_c = 9.2$ K) to reduce losses in the shielding container [2]. However, finite element calculations show that a (nonsuperconducting) copper container with a slightly larger diameter may be used with no degradation of the sapphire quality factor, even for Q's as high as 10^{10}. The accompanying reduced RF magnetic fields at the container's surface are well suited to achieving near critical coupling with a simple waveguide coupling port.

IV. Design Details and Experimental Aspects

Figure 1 shows a schematic diagram of the cryogenic system. Design calculations showed that the cooling capability of the helium-gas thermal transfer system was only weakly dependent on the size of the gap between the cryocooler and cryostat [6], and so a gap value of 4 mm was chosen because it is large enough to prevent mechanical interference while small enough to prevent a large radiative heat influx. The area of the thermal transfer regions is found to be more important, and for this reason, the low-temperature station of the cryocooler was "bulked up" somewhat with attached copper conducting elements.

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[2] Balzers KelCool$^{\text{TM}}$ 4.2 GM Cryocooler, Leybold Vacuum Inc., Cryogenics Division, Hudson, New Hampshire.

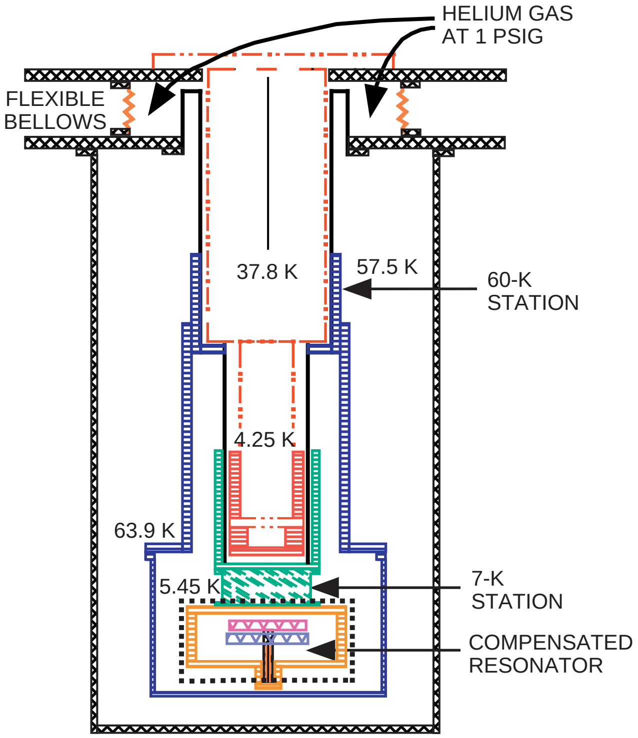

Fig. 1. The cryogenic system, where the cryocooler (shown in dashed lines) is independently supported from the floor, contacting the rest of the system only through a flexible bellows at room temperature.

Overall cryogenic performance is found to be excellent. As shown in the figure, the 60-K station associated with radiation shields achieves a temperature of 57.5 K, and the crucial 7-K station is cooled to 5.45 K with a design heat input of 0.5 W into that station.

Figure 2 shows a plot of the cooling capacity measured at the 7-K station. The thermal impedance of 1.69 K/W for the heat transfer system is not a bad match to the 1.27 K/W measured for the cryocooler itself. This capacity is somewhat more than needed by our design, and we might have opted for a lower capacity cooler if one had been available with the temperature performance of this one. In order to prevent helium condensation and associated helium gas management problems, a power of 0.5 W was applied to the cryocooler. The temperature step in the graph at 0.5 W of applied power is due to turning off this added power.

Thermal stability of the system is excellent. We had been prepared for relatively large fluctuations at the 2.5-Hz cycle frequency and had included a margin for several stages of thermal regulation. This was based partly on verbal indications from the manufacturer that the thermal variation at the cold head could be expected to be approximately 1-K peak to peak. Our expectation was that the variations would be reduced to about 0.1 K by the large thermal mass of the helium gas, and we had planned fairly extensive thermal regulation to further reduce the variations. We find instead that the thermal variations are only about 2-mK peak to peak with 0.5 W or less of input. For reference purposes we also include as Fig. 3 the results of a measurement of cold-head cooling capacity for input powers up to 4 W.

Compensation of temperature-induced variation has been accomplished in sapphire resonators by paramagnetic spin [2,3] and mechanical [1] tuning effects. Such a technology is necessary to relax temperature regulation requirements. For example, compensation of sapphire's first-order temperature dependence of $\approx 1 \times 10^{-8}$/K at 10 K leaves a quadratic coefficient of $\approx 1 \times 10^{-9}/(\mathrm{K}^2)$. Thus, for a 10^{-15} frequency

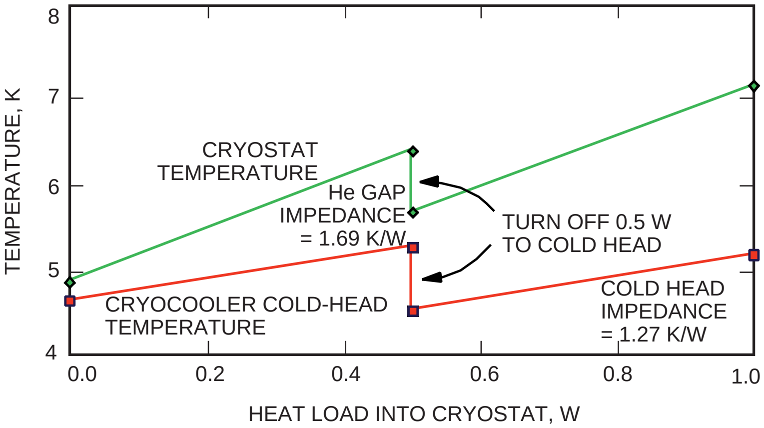

Fig. 2. Response of the cryogenic system to applied heat at the 7-K station.

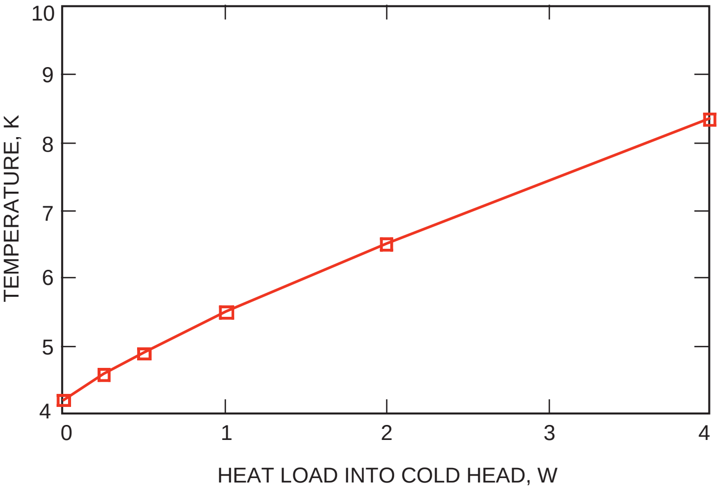

Fig. 3. Measured cold-head cooling capacity.

stability, temperature regulation would need to be 0.1 μK for an uncompensated sapphire resonator as compared with 1 mK for a compensated one.

While a 1-mK regulation requirement might seem to indicate an easy thermal design task, previous experience with externally compensated resonators has shown that it also is crucial to properly deal with temperature differential effects between resonator and compensator. For example, sensitivity of a sapphire resonator's frequency to temperature without external compensation typically is parts in 10^9/K at 8 K. Even with a short (0.1-second) time constant for the thermal contact between ruby and sapphire, a 1-mK temperature variation at the 2.5-Hz cryocooler cycle frequency would be largely uncompensated. This would give an unacceptable frequency variation of parts in 10^{12} at the 2.5-Hz rate. This effect can be greatly reduced by the use of a thermal ballast. Figure 4 shows a block diagram for thermal aspects of an externally compensated resonator.

Even if the shielding-can temperature varies, the sapphire temperature will follow only slowly, and so the ruby temperature error will be small. Adding a ballast with a 1000-second time constant provides a relieved thermal stability requirement by reducing (for times less than 1000 seconds) the differential temperature variation by 10,000 times as compared with the can-temperature variation. Thus, at the turnover temperature, a 1-mK variation in the temperature of the shielding can will give a frequency

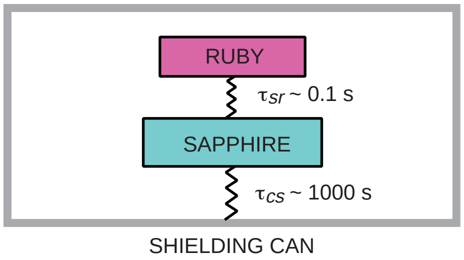

Fig. 4. Thermal aspects of the compensated resonator.

variation of only parts in 10^{16}. The ballast and compensator have somewhat complementary functions—without the compensator, the ballast does a fine job alone for times of 1 second or less, and without the ballast the compensator does just as well for times of 100 seconds or more.

Several resonators previously tested with recently available high-quality sapphire material[3] show the inherent 1×10^{-8}/K variation at 8 to 10 K to be partially compensated by incidental paramagnetic spins, leaving a variation of $\pm 3 \times 10^{-9}$/K [2]. Figure 5 shows a resonator design that compensates the remaining variation by coupling a small fraction of the electromagnetic resonant energy into an ancillary ruby element containing a (relatively large) paramagnetic chromium spin concentration of 0.01 to 0.05 percent. By operating either 1-GHz above or below the zero field splitting of 11.4 GHz, either sign of variation can be accommodated. Because of the difficulty and expense of obtaining a high-quality factor, Q, in sapphire resonator samples, each sample can be characterized individually and the coupling to its ruby element adjusted to achieve compensation in the 8 to 10 K range, irrespective of variations in their own paramagnetic impurity content.

While experimental measurements of reactive and resistive components for chromium in sapphire are both consistent with the Lorenzian line shape shown in Fig. 6, we are not aware of any simultaneous

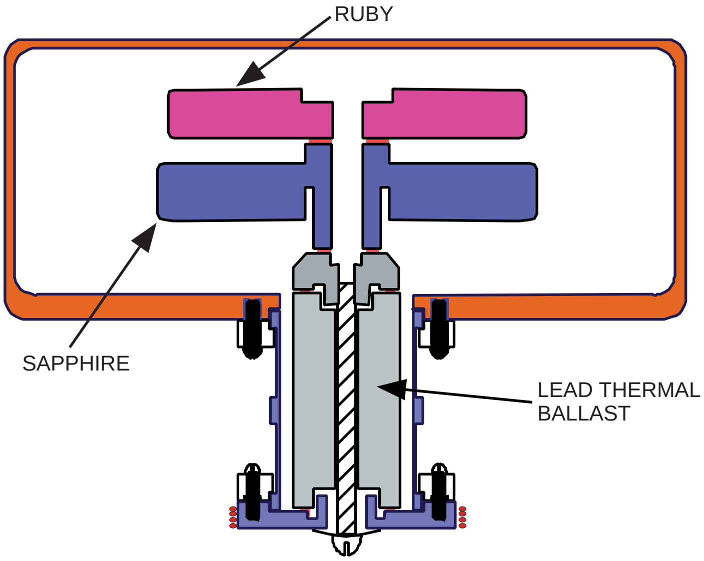

Fig. 5. The compensated sapphire resonator. Thermally induced variations in the frequency of the sapphire resonator are canceled by paramagnetic spins in a weakly coupled ruby element.

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[3] HEMEX Sapphire, Crystal Systems, Salem, Massachusetts.

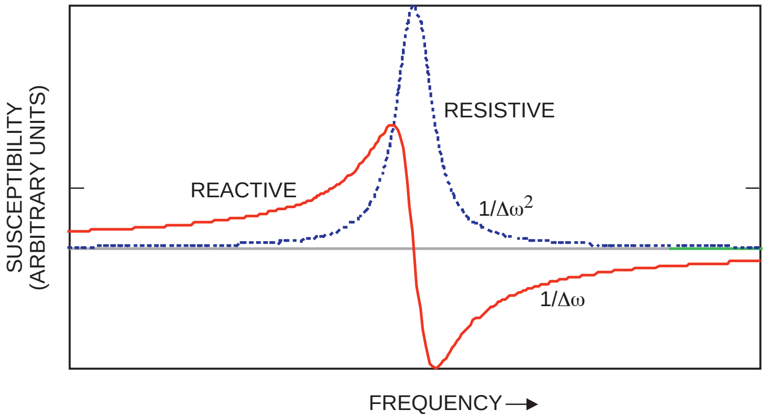

Fig. 6. Resistive and reactive components for a Lorenzian absorption line.

measurements of the two components for the same sample. A knowledge of the ratio of these two effects in our ruby is crucial to our design in order to know the spin limitation to the resonator quality factor, Q, given the required tuning rate.

The $1/\Delta\omega$ tuning dependence for incidental chromium spins in sapphire resonators has been well documented. However, the associated losses are not easy to determine at these very low concentrations, and a concern is that the line width may be different in ruby with its much higher chromium levels. A study done some years ago measured the spin-dependent losses in various ruby samples, finding a $1/\Delta\omega^2$ component for the losses, in agreement with the expectations of a Lorenzian line width, but the reactive effects were not measured [7]. Combining the results of various measurements at widely varying and somewhat uncertain chromium-concentration values allowed us to extrapolate a ratio between tuning and losses that was encouraging enough to proceed with our study. The ratio of tuning to loss, of course, improves for increasing values of $\Delta\omega$. We have chosen a value corresponding to $\Delta f = 1$ GHz as a compromise between low losses on one hand and the requirement of a single design that will work for both signs of tuning, depending on the characteristics of any given sapphire sample.

We measured the frequency and quality factor, Q, for three resonant modes of our ruby-tuning element at temperatures of 6 to 15 K. From these measurements, we can calculate the $1/T$ dependent part of the frequency variation that is due to paramagnetic spin tuning and directly infer the spin-dependent losses.

Following Mann et al., we characterize the spin-dependent part of the frequency dependence on temperature in terms of a constant $C(K)$, where $\Delta f/f = C/T$ [8]. With aligned crystal and cylindrical axes, we find, in agreement with their results, that the transverse magnetic whispering gallery (WGH) mode family shows the strongest spin tuning. The three modes characterized in Figs. 7 and 8 are $\mathrm{WGH}_{11,1,1}$, $\mathrm{WGH}_{12,1,1}$, and $\mathrm{WGH}_{14,1,1}$. As shown in Fig. 7, the frequency dependencies for C and Q are in very good agreement with linear and quadratic predictions, respectively, of a Lorenzian line shape. Figure 8 shows a comparison of temperature tuning with previously reported results on samples with small levels of incidental impurities. Properly scaled, our results are in good agreement with theirs for WGH modes in the 5-cm resonator identified in [8]. The figure also shows that a distinctly smaller tuning effect can be expected for transverse electric whispering gallery (WGE) modes.

Although tuning effects are expected to be simply proportional to impurity concentration, the losses might not be. The line width of the ruby absorption may vary with chromium concentration. This could have meant, for example, that the losses were worse at the higher ruby concentration, and so might have prevented use of ruby as a compensating element. Our results show that, at least for the 0.03 percent ruby, this apparently is not the case.

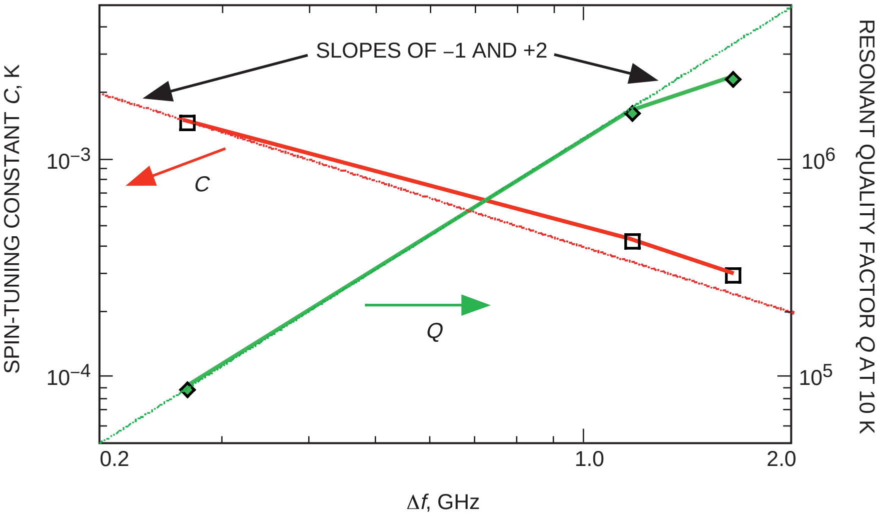

Fig. 7. The measured reactive and resistive components for the permittivity of the 0.03 percent ruby sample. The Δf is the frequency deviation from 11.44-GHz ruby zero-field splitting.

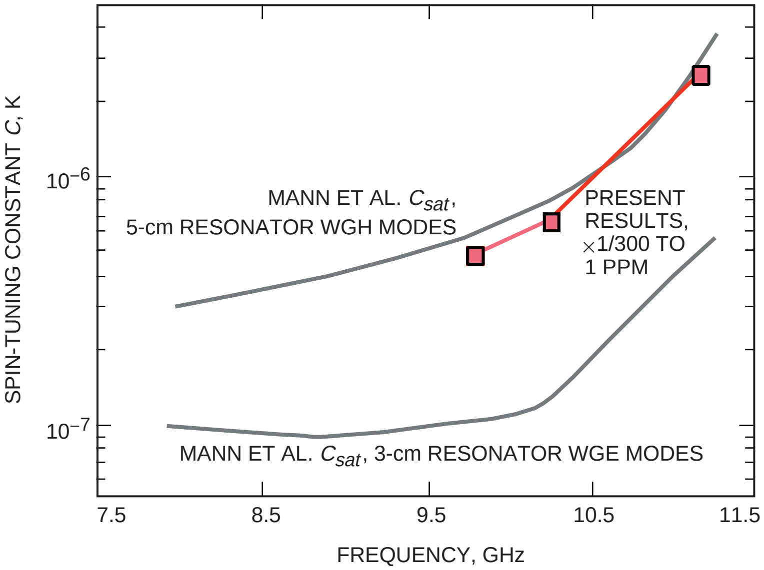

Fig. 8. The frequency dependence of spin tuning for the 0.03 percent ruby sample extrapolated to 1-PPM concentration to allow comparison with previously published results.

From the data in Fig. 7, we can calculate the spin-limited Q for a resonator compensated by the 0.03 percent ruby element and operating at $\Delta f = 1$ GHz. These results are provided in Fig. 9. The values are calculated using the Q and C values for each of the ruby modes independently. One might expect that the $14, 1, 1$ mode, with much larger spin losses and spin tuning, would give the most accurate determination of these parameters. However, all measurements are consistent with spin-limited Q's of from 2 to 3×10^9 and energy coupling to the ruby element of from 0.4 to 0.5×10^{-3}. Previous experience in splitting the high-Q line in a sapphire resonator by a factor of 6×10^6 was demonstrated by an optimized Pound frequency-lock system in the 77-K compensated sapphire oscillator (CSO) [1]. Applied here, this capability would allow a stability of 1×10^{-15} with a Q of only 1.7×10^8.

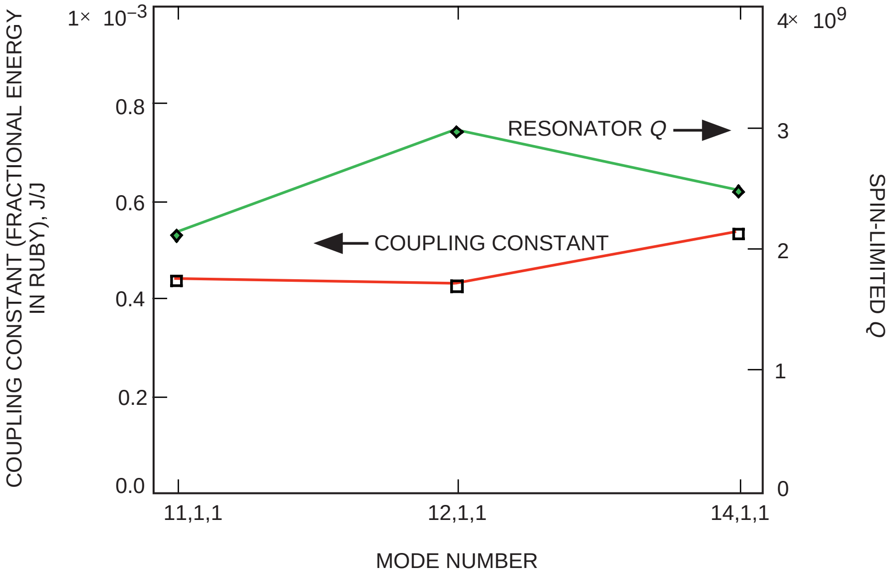

Fig. 9. The required ruby coupling constants and the achievable *Q* values for a sapphire resonator operating at 10.44 GHz and compensated at 10 K.

V. Conclusions

Principal design issues have been addressed for a cryocooled frequency standard to provide parts in 10^{15} short-term frequency stability for the Cassini Ka-band Experiment. New cryogenic and electromagnetic design aspects have been developed to mate sapphire resonator technology to the characteristics of available cryocoolers. Technical aspects have been verified, including cooling capability, temperature stability, and spin-dependent losses in a ruby temperature-compensating element. Two units currently are under construction, and more units are scheduled to be installed in three Deep Space Network stations starting in the year 2000.

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