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Test of a Gravitational Detector in the FNAL Collider

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ABSTRACT

We have constructed a parametric converter operating at 10 GHz and have demonstrated that it is sensitive to harmonic displacements of the order of $\delta x = 10^{-13}$ cm. We expect to reach a sensitivity of $\delta x = 10^{-18}$ cm by June 1983. Conversely, the improved detector is sensitive to a harmonic gravitational potential $h \simeq 10^{-19}$; for an observation time of 10^{6} sec the limit $h \gtrsim 10^{-22}$ can be reached.

We propose to test for parametric conversion by placing the detector in close proximity to the bunched stored beam of the FNAL collider. The purpose of this test is to establish the lowest possible sensitivity and assess the practicality of constructing a mechanical gravitational detector. Furthermore, we will be able to search for any long-range interaction which couples to the em field with a strength $\sim 10^{15}$ times that of the em-gravitational coupling.

1. Gravitational Effects of a Stored Beam of Particles

The gravitational field of a beam of stored particles can be used, in principle, to test general relativity. As shown in references (1,2) a mechanical detector placed at a distance b from the beam is subject to a periodic tidal impulsive force F_t; this is equivalent to a harmonic acceleration at the beam circulation frequency with amplitude

$$\langle a \rangle = 2 \langle \frac{F_t}{M} \rangle = \ell 2 \langle \frac{\partial F}{\partial y} \rangle = 2 \frac{1}{\tau_o} \; \frac{2NmG}{\gamma\beta cb} \left(\frac{\ell}{b}\right) [2\gamma^2\beta^2 + 1] \qquad (1)$$

The detector is placed as shown in Fig. 1 and is of length ℓ at a distance b from the beam; γ,β,m,N refer to the energy, mass and number of circulating particles; G is the gravitational constant and τ_o the revolution period. We note that in the limit $\gamma >> 1$, Eq. (1) predicts an effect twice as large as would be calculated from a Newtonian interaction using (γm) for the gravitational mass of the particles. Furthermore, the energy dependence of Eq. (1) measures the spin of the quantum (graviton) carrying the interaction; for instance, for a vector field, as in electromagnetism, the impulsive force on a point charge is energy independent.

To detect the small acceleration indicated by Eq. (1) the detector is constructed so as to have a natural mode at the circulation frequency $\Omega = c\beta/R$; then the periodic impulses excite longitudinal oscillations that reach the equilibrium amplitude

$$\delta\ell_{max} = \langle a \rangle \; Q_m \frac{1}{\Omega^2} \qquad (2)$$

where Q_m is the mechanical Q-factor of the particular mode of excitation.

The amplitude of Eq. (2) is reached for times $t \gtrsim Q_m/\Omega$. For instance, if $Q_m = 10^9$ an amplitude of $\delta\ell = 10^{-22}$ cm can be obtained[1] for 10^{13} protons circulating at $E = 1000$ GeV and $b = 1$ cm.

An alternate approach is to consider the direct coupling of the gravitational and e.m. fields. This effect is known to exist and is manifested, for instance, in the bending of light; it can be described by a Lagrangian of the form

$$L = \sqrt{|g|}\ F^{\mu\nu} f_{\mu\nu} \tag{3}$$

where $|g|$ is the determinant of the metric tensor

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

The dimensionless gravitational potential $h^{\mu\nu}$ is a measure of the deviation from flat space generated by the passage of the beam. Thus $h^{\mu\nu}$ is a time-dependent perturbation and if the frequency coincides with the frequency difference between two modes of an e.m. field, $h^{\mu\nu}$ will induce energy transfer (transitions) from one mode to the other.

If the detector is placed next to the beam (as in Fig. 1), $h^{\mu\nu}$ has the form of a sharp pulse of width $\Delta t \sim b/\gamma c$ and peak amplitude $h \simeq 10^{-32}$, (for $N = 10^{13}$, $b = 1$ cm, $E = 1000$ GeV). The Fourier component at the fundamental frequency equals approximately twice the average value of the potential and has amplitude $h \simeq 10^{-40}$. We can also place the detector at the center of the ring in which case $h^{\mu\nu}$ is rotating at the circulation frequency with constant amplitude; the amplitude has the <u>same</u> magnitude as the fundamental Fourier component for a detector placed next to the ring. Locating the detector at the center of the ring has the advantage of eliminating particle and em backgrounds while the gravitational potential is not attenuated.

The best sensitivity that we can achieve is in the range of $h = 10^{-22}$ to $h = 10^{-25}$: this is not sufficient for detecting the gravitational potential through its direct coupling to the em field and one must therefore rely on a tuned mechanical resonator. The electromagnetic transducer can then be used to detect the displacement of the mechanical detector and has adequate sensitivity for that purpose. In addition, the em transducer will respond directly to any long range force that couples to the em field provided it has the correct frequency dependence.

2. The Detector

The parametric converter consists of two coupled superconducting cavities and its characteristics and performance have been described in ref. (3). The cavities operate at 10 GHz, the physical arrangement being as in Fig. 2; the frequency difference between the two modes can be adjusted and in the present model is $\Delta f \sim 700$ KHz. We operate the detector by loading one mode, f_1, and detecting power at f_2, the normally empty mode. Sensitivity of 10^{-14} Watts in a 100 Hz bandwidth has been achieved and will be further improved[3]. It can be shown[2] that in the presence of a harmonic perturbation h, the energy stored in mode-2 is given by

$$U_2 = U_1(Qh)^2 \tag{4}$$

where $U_{1,2}$ is the energy stored in modes-1,2 and Q the loaded e.m. quality factor. Thus the power radiated at f_2 is

$$P_2 = U_1 Q\omega_2 (h)^2 \tag{4'}$$

Equations (4,4') indicate the importance of achieving high Q-values and therefore the need for superconducting cavities. In Fig. 3 we show the unloaded Q that we obtained as a function of temperature. For $T < 3°K$ we fall below the BCS curve but expect to reach $Q = 10^{10}$ with our present configuration; the Stanford group has achieved a Q of 10^{11} at this frequency of 10 GHz. Note that for the same surface conditions one can achieve higher Q-values at lower frequencies, according to the approximate scaling law

$$Q_{BCS} \propto f^{-1.7} \tag{5}$$

To test the performance of the detector we induce transitions by moving the end-wall of the cavity at the appropriate frequency; this is achieved by using a piezoelectric crystal mounted on the outside of the end wall. In this case the dimensionless parameter h in Eqs. (4,4') is replaced by $\delta\ell/\ell$, the fractional change in the linear dimensions of the cavity. When the frequency of the mechanical motion coincides with the difference frequency of the electromagnetic modes, energy transfer takes place. This is indicated in Fig. 4, where the upper part gives the power at f_2 as a function of mechanical vibration frequency; the lower part indicates the position of the e.m. frequency difference which is measured by sweeping a frequency modulation sideband.

With this technique we have measured displacements of $\delta x = 10^{-13}$ cm and with straightforward improvements should obtain a sensitivity of $\delta x = 10^{-18}$ cm. Such a detector is a form of a "parametric converter"; more details on construction and testing are given in reference (3).

In principle the sensitivity can be improved beyond 10^{-18} cm by a factor of 10^{-3}-10^{-4}. However in this range quantum uncertainties become relevant.

3. Proposed Test

We would like to test the detector by placing it in close proximity to the circulating beam of the FNAL collider. The detector and its dewar will be located as close as possible to the beam pipe and in the inside of the ring. Under these conditions we expect that the e.m. fields of the particles in the bunch will penetrate into the region of the cavities, most probably through ground loops and hence down the coaxial lines. Such a coupling may give rise to parametric conversion and also produce spurious signals at the demodulation stage.

We believe that after eliminating r.f. pickup we will be able to isolate the direct coupling of the beam's e.m. field to the detector. In principle the direct coupling should be extremely small because the fields have to penetrate through a sizeable thickness of superconductor. It is also important to confirm that, as predicted, the converted signal does not depend on the beam energy. Phase locking with the machine frequency is an essential part of the detection scheme. In this way the sensitivity of the detector can be tested in close proximity to the circulating beam.

If the sensitivity tests indicate that the measurements of amplitude $\delta x = 10^{-21}$ cm can be performed in the tunnel and in close proximity to the beam one can plan the construction of a mechanical gravitational detector with $Q_m = 10^9$-10^{10}. Such a detector coupled to the parametric converter should have the sensitivity for detecting the gravitational effect of the stored beam, but poses technical problems which we do not address here.

An interesting possibility of the proposed test is to search for a long-range interaction of considerable weakness but still $\sim 10^{15}$ stronger than the gravitational force. The parametric converter has a high selectivity in frequency and a sensitivity to external couplings of $h \sim 10^{-20}$; if the known e.m. effects can be reduced to this level one will be probing for a long-range interaction in a completely new and unchartered domain. It will be easy to distinguish such an effect from the e.m. signal by its energy dependence and by interposing absorbers between the beam and the detector.

Technically we plan to remote control the detector; helium fills can be done once or twice a day. The microwave power source and receiver, however, must be accessible; therefore we need some experimental space not too far removed from the detector. The test is to be performed with the collider and we have assumed three bunches. Nevertheless one could begin these investigations during machine studies when bunched beam is run. No special demands are made on the laboratory or accelerator operation.

References and Notes

1. A. C. Melissinos, Il Nuovo Cimento 62B, 190 (1981). V. B. Braginsky, C. M. Caves and K. S. Thorne, Phys. Rev. D15, 2047 (1977).

2. "Working notes on gravitational effects of stored beams of high energy particles" compiled by A. C. Melissinos, University of Rochester internal report (unpublished).

3. C. E. Reece, P. J. Reiner and A. C. Melissinos, "A detector for high frequency gravitational effects based on parametric conversion at 10 GHz", to appear in the Proceedings of the 1982 Snowmass Meeting of the DPF. Also University of Rochester report UR-832.

Figure Captions

Fig. 1 Arrangement of a massive detector M with respect to a stored beam of high energy particles.

Fig. 2 (a) Sketch of the coupled cavity system; (b) the cavities with the ends removed.

Fig. 3 The unloaded Q of the cavities as a function of temperature. The solid curve is the BCS theory prediction.

Fig. 4 Evidence for parametric conversion. The upper trace is the response to 10V pzt excitation as a function of frequency. The lower curve is obtained by frequency modulating the source and locates the position and width of the second state; it is overlayed on the upper trace as a dashed curve. The integration time was 0.1 sec and the peak signal $\sim$ -88 dbm of IF; the data were taken at T = 2.25 °K and $Q_L \simeq 1.4 \times 10^7$.

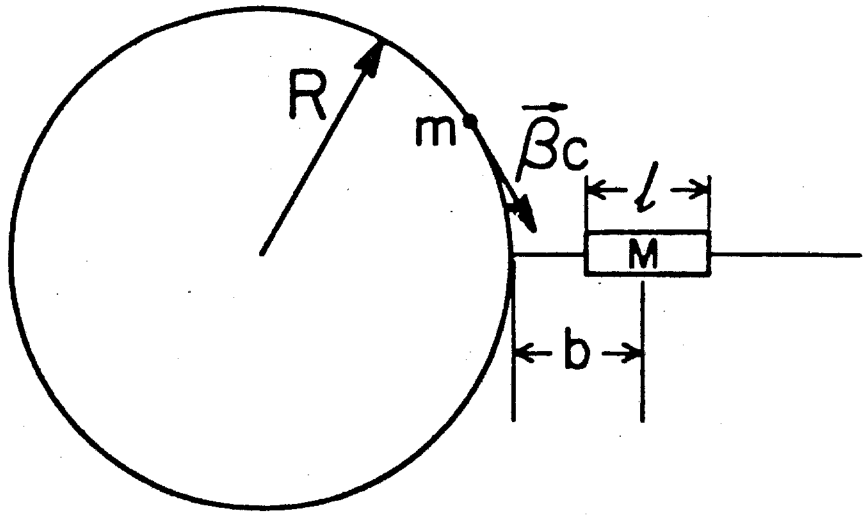
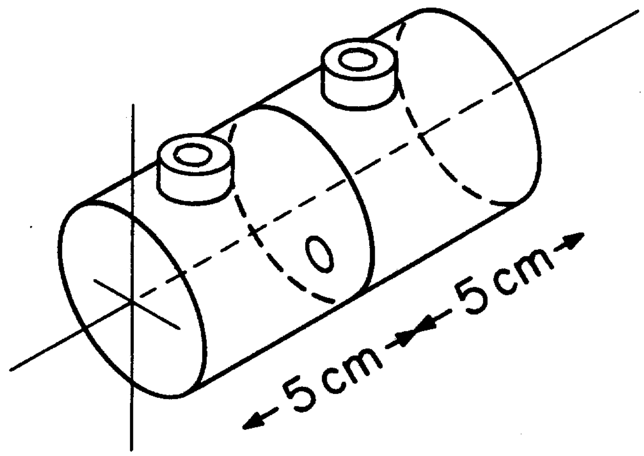


Figure 1



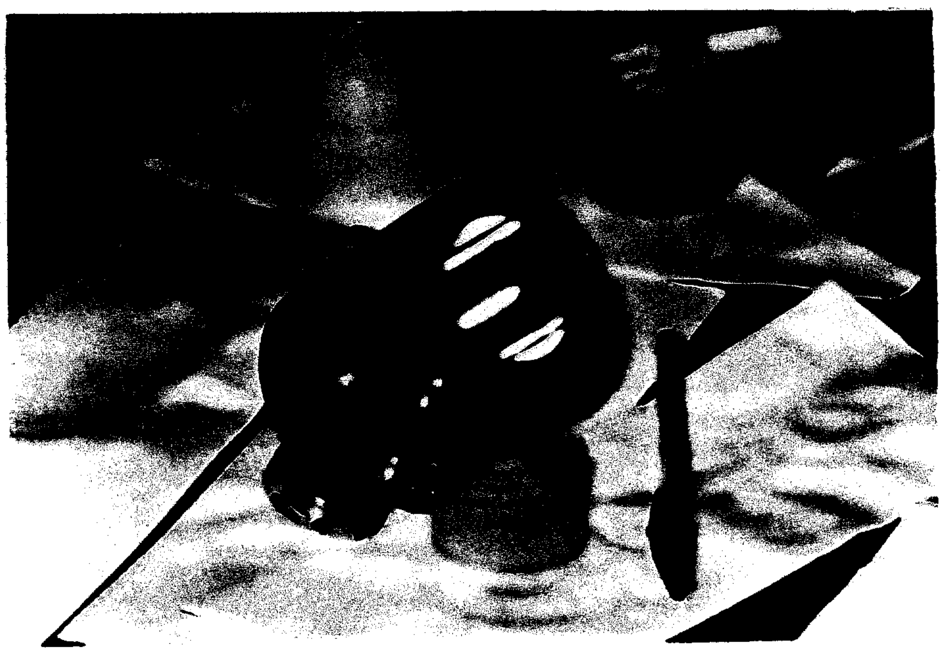


Fig. 2

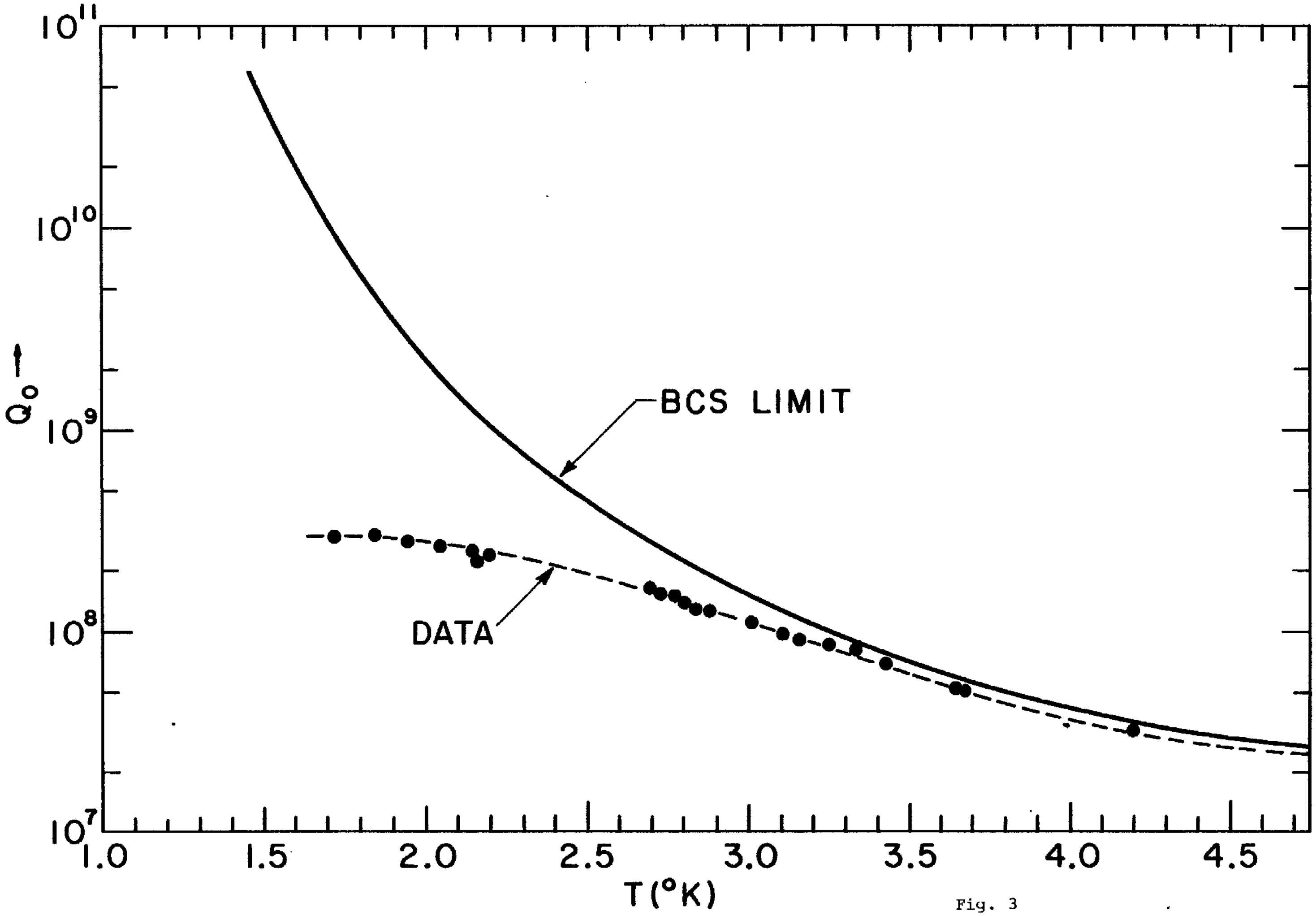


Fig. 3

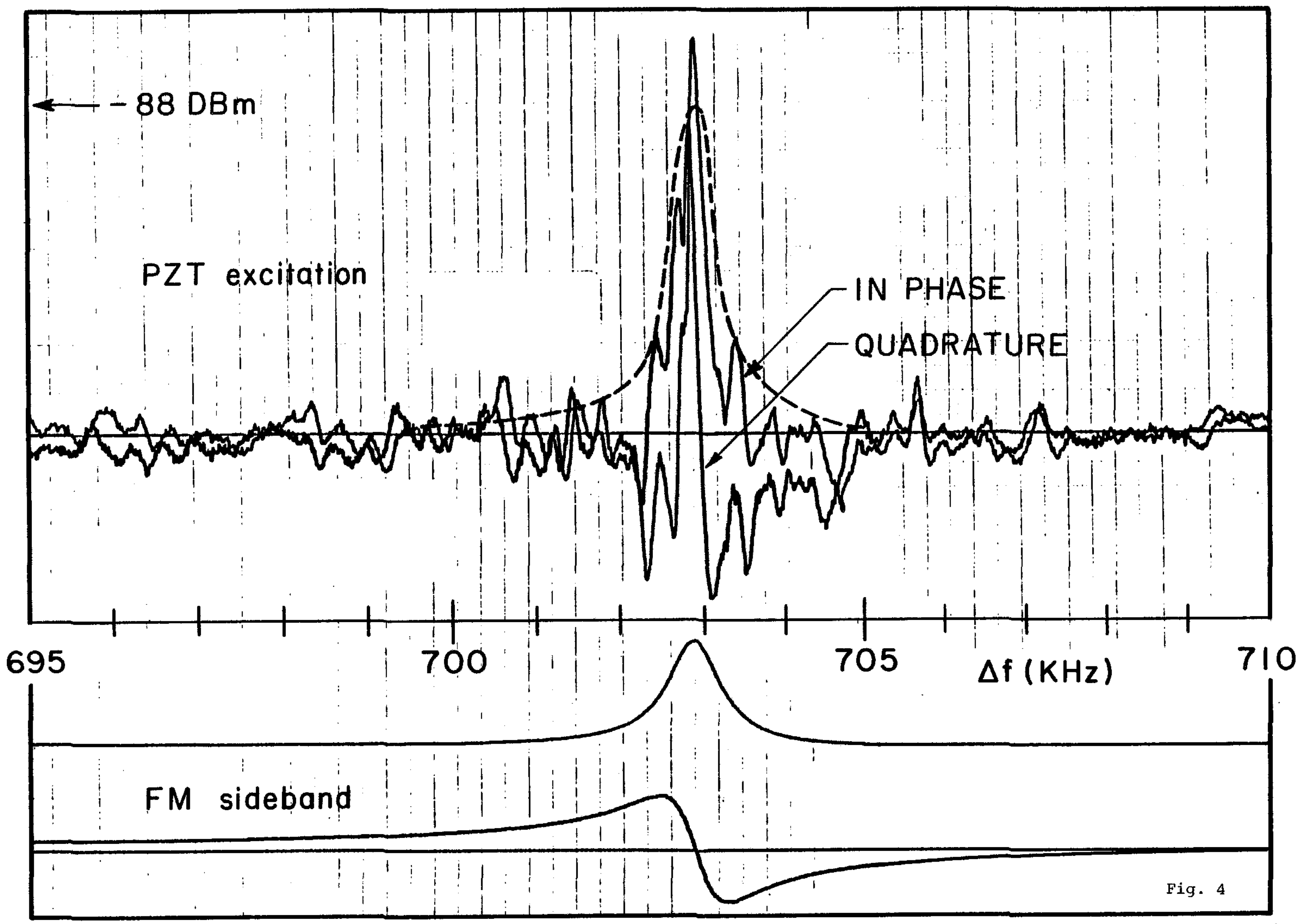

-88 DBm
PZT excitation
IN PHASE
QUADRATURE
695
700
705
Δf (KHz)
710
FM sideband

Fig. 4