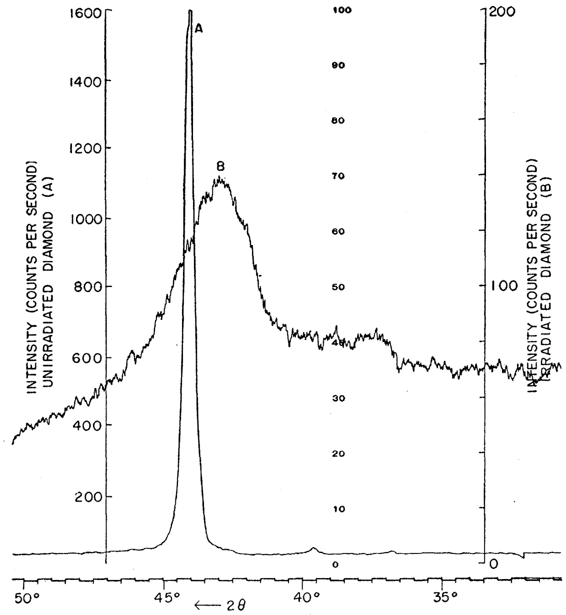

FIG 1. The (111) reflections of (A) normal and (B) severely damaged diamond.

damaged diamond, one may expect to find evidence for amorphous carbon, or perhaps, even graphite.

To search for these possibilities, 270-mesh diamond powder was first annealed at 500°C for two hours, to remove strain, and then irradiated in the Arco materials testing reactor. The total exposure was 2.4×10^{21} *nvt* "thermal" and about 3.8×10^{20} *nvt* "fast." It is estimated that the maximum temperature the sample reached was 65°C. Before irradiation the powder appeared perfectly white, and after irradiation it was shiny black, reminiscent of hardcoal dust. After irradiation, x-ray diffraction patterns of both irradiated and control material were run on a Norelco spectrometer using filtered $Cu-K_\alpha$ radiations. The pattern obtained from the unirradiated material was typical of normal diamond in every respect. In the irradiated sample, the normal reflections no longer appeared. Instead, we found the continuous almost structureless pattern of an amorphous material. Figure 1 shows the spectrometer tracings of the (111) reflection of both samples, and similarly, Fig. 2 is the tracings of the (220) reflections. Only these two reflections appear to be somewhat retained by the damaged material. From the data shown in Fig. 1, one can obtain a rough estimate of the lattice expansion, which is 2.4%. In addition, the damaged crystals contain a fairly definite but broad peak at $2\theta\approx18.5°$ and a much weaker broad peak at $2\theta=20.3°$. At the moment, we do not have a definite explanation for these reflections but they are probably due to hydrated aluminum oxide from the container in which the sample was irradiated. In summary, it can be said that this diamond sample has been damaged to the extent that it is now amorphous. A detailed x-ray study of this material is being made by D. T. Keating and will be published shortly.

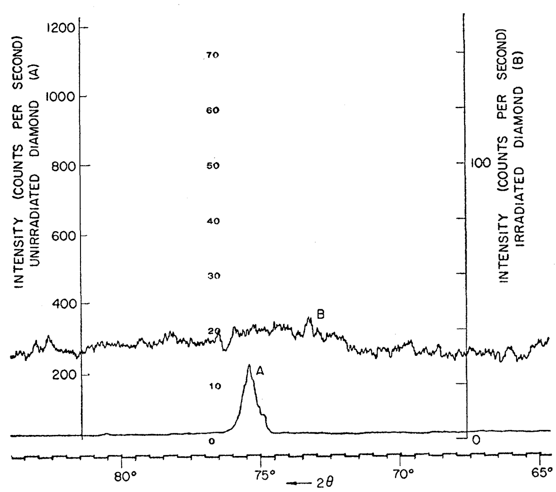

FIG. 2. The (220) reflection of (A) normal and (B) severely damaged diamond.

* Under the auspices of the U. S. Atomic Energy Commission.
[1] Primak, Fuchs, and Day, Phys. Rev. **92**, 1064 (1953).
[2] As described by J. H. Crawford and M. C. Wittels in paper No. 753, presented at the *International Conference for the Peaceful Uses of Atomic Energy* (1955).
[3] G. J. Dienes and D. F. Kleinman, Phys. Rev. **91**, 238 (1953).

Instability in the Motion of Ferromagnets at High Microwave Power Levels

P. W. ANDERSON AND H. SUHL
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received September 22, 1955)

DAMON, Bloembergen, and Wang[1,2] were the first to measure ferromagnetic resonance at high power. Among other phenomena they found a marked broadening and lowering of the resonance line at powers rather low compared to those thought to be necessary for saturation.

We have found that the equations of motion of ferromagnetism lead to a physical instability which probably accounts for this result. Because of the nonlinear effect of the demagnetizing field certain spatially inhomogeneous perturbations tend to grow rather than decay at high enough powers. The simplest case which shows the physical origin of the effect occurs in the disk-shaped sample perpendicular to the dc magnetic field. Suppose there is a small perturbation in the precession angle of a horizontal stratum in this sample. (Figure 1 illustrates the quantities involved in the following.) Then the average moment of the stratum in the z-direction changes by $-\delta M_z$, and because of the demagnetizing effect the effective dc field changes by

$4\pi\delta M_z$. This may bring the stratum closer to resonance than before, increasing thereby the rf permeability, and thus, by the relationship $M_x^2+M_y^2+M_z^2=M_s^2$,[3] causing δM_z to take on a new value $\delta M_z'$. If $\delta M_z'/\delta M_z>1$, the perturbation will grow indefinitely.

Using for convenience circular polarization and Landau-Lifshitz damping, the equation for M_z' is

$$(M_z')^2=M_s^2\left(1-\frac{H_{\mathrm{rf}}^2}{(H_z^{\mathrm{eff}}-\omega/\gamma)^2+(\Delta H)^2}\right).^4 \tag{1}$$

The instability condition $\delta M_z'/\delta M_z>1$ is equivalent to

$$4\pi MH_{\mathrm{rf}}^2\cdot\frac{H_z^{\mathrm{eff}}-\omega/\gamma}{[(H_z^{\mathrm{eff}}-\omega/\gamma)^2+(\Delta H)^2]^2}\leq -1. \tag{2}$$

This may finally be optimized with respect to $H_z^{\mathrm{eff}}-\omega/\gamma$, the deviation from resonance, and we get

$$H_{\mathrm{rf}}^2\geq 3.08(\Delta H)^3/4\pi M \tag{3}$$

at $H_z^{\mathrm{eff}}-\omega/\gamma=-\Delta H/\sqrt{3}$. Note that (3) predicts, for a typical 40-oersted half-breadth, that the power required for instability is only of the order 1/30 of saturation power ($H_{\mathrm{rf\ sat}}^2=\Delta H^2$). This justifies our use of small-signal theory in (1).

While it is conceptually simple, the horizontal stratum of the disk is unfortunately a poor example, since the disk moving as a whole is itself unstable under the same conditions. However, we have found similar striations to be unstable under similar conditions in all sample shapes we have considered (e.g., the sphere, which moving as a whole is perfectly stable at all times). The most unstable striations even in the disk are not of macroscopic size but so small that the exchange field must be included in their equations of motion. The appropriate wavelength depends on the demagnetizing fields of the sample. These short-wave striations are most unstable at resonance, where instead of (3) we have

$$H_{\mathrm{rf}}^2\geq 2(\Delta H)^3/4\pi M. \tag{3a}$$

Perturbations of various other geometries than striations perpendicular to H_{dc} (e.g., striations in spheres parallel to H_{dc}) are also unstable, but the above is the best case. We have also calculated the growth rate of these instabilities, which is

$$\lambda=\left[\left(\frac{2P}{P_{\mathrm{crit}}}-1\right)^{\frac{1}{2}}-1\right]\frac{1}{T_1}, \tag{4}$$

where P_{crit} is the critical rf power from (3a) and T_1 the relaxation time. Calculations on the new steady state which is established are under way and will be published later.

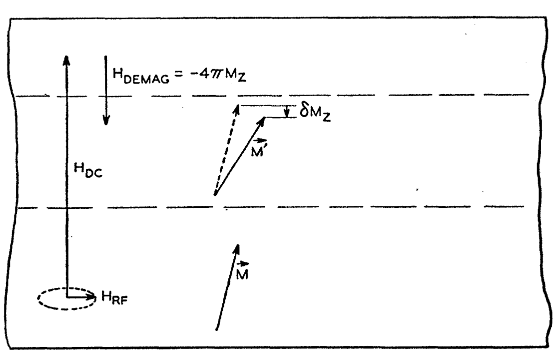

FIG. 1. Perturbed stratum in a disk-shaped sample.

TABLE I. Calculated and observed onset of instability.

T °K	$1/\gamma T_1$[a]	H_{rf} for onset: Theory [Eq. (3a)]	H_{rf} for onset: Experiment[b]
725	51 oe	8 oe	9
580	46	7	5.5
400	36	5	4
300	23	2.5	1
77	7	0.45	0.55

[a] Reference 2, Fig. 11.
[b] Reference 2, Fig. 8.

We have compared (3a) with experiment in the following way. The instability will almost certainly broaden the resonance. We thus compare the minimum rf field from (3a) with the point of onset of broadening from Bloembergen and Wang's figure 8,[2] for their sphere of $NiFe_2O_4$. For ΔH, we use $1/\gamma T_1$ as measured in reference 2 rather than the observed line breadth $1/\gamma T_2$, because $T_1\neq T_2$ cannot hold for fine-scale phenomena in ferromagnets, so that there must be contributions to $1/T_2$ from inhomogeneities of larger scale than those we consider here. We can only hope that the present phenomenon does not spoil the principle behind the T_1 measurement. Of course, above room temperature the line breadth and T_1 agree, giving us greater confidence in the comparison. The results are shown in Table I. The agreement in both trend and absolute value is gratifying in view of the possible experimental error. (we estimate one-figure accuracy in H_{rf}).[5] One obtains similar results for the Supermalloy data of reference 2; on the other hand, the polycrystalline ferrites seem to be more stable than (3a) predicts.

We have no explanation for the subsidiary low-field absorption peaks observed by Bloembergen *et al.*,[1,2] which may well be an entirely distinct phenomenon. We do feel we have probably explained the early onset of nonlinearity of the main peak.

We should like to acknowledge helpful discussions with A. M. Clogston, L. R. Walker, and H. W. Lewis.

[1] R. W. Damon, Revs. Modern Phys. **25**, 239 (1953).
[2] N. Bloembergen and S. Wang, Phys. Rev. **93**, 72 (1954).
[3] This relationship, while not always satisfied by the Bloch equations used by Bloembergen *et al.* to describe their data, nonetheless is required for the small-scale motions we shall discuss later; otherwise excessive amounts of exchange energy must be supplied.
[4] We have checked our use of small-signal theory to describe nonlinear behavior against the full nonlinear theory in the range of interest.
[5] Further errors of a factor of about $\sqrt{2}$ may enter because the experiments use linear polarization. The difference can hardly be important at this stage.