EDDY-CURRENT-FREE SWITCHING OF PERMALLOY THIN FILMS

BY

J. K. WATSON

AND

H. C. BOURNE

REPORT # ORO-2572-11

AEC CONTRACT AT-(40-1)-2572

MARCH, 1967

COMPUTER PROJECT

DEPARTMENT OF ELECTRICAL ENGINEERING

RICE UNIVERSITY HOUSTON TEXAS

BLANK PAGE

ABSTRACT

"Eddy-Current-Free Switching of Permalloy Thin Films"

by J.K. Watson and H.C. Bourne

Results are presented from an experimental investigation of large-angle flux reversal of magnetic films. The reported measurements were made with an unconventional instrument with design features which are briefly outlined. Switching characteristics for a selected film are shown, and are compared with results of others in region II at 2° transverse bias. Our 6 oersteds-nanoseconds is an order of magnitude faster than others although the switching field rise time is an order of magnitude slower. On a two dimensional field plot, loci which define thresholds of incoherent rotation are found to have two prominent features: a disperse switching asteroid for $H_s \lessapprox H_k$, and an extension described by $H_s H_{\perp}/H_k = \Delta$ for $H_s > H_k$. The width of region II, the lower threshold for region II, and the independently-measured dispersion field are all approximately 0.1 oersted for the subject film. Thus $\Delta \approx 2H_k \sin \alpha_{90}$.

EDDY-CURRENT-FREE SWITCHING OF PERMALLOY THIN FILMS

by J. K. Watson and H. C. Bourne

1. INTRODUCTION

This paper describes the results of measuring large-angle flux reversal of a thin permalloy film in an instrument designed for minimum eddy-current retardation of the flux switching. Several studies of the switching of thin films have been carried out by various investigators over the past decade,[1-8] but several points of disagreement and confusion still remain. There is general agreement that at low amplitudes of pulsed fields the mechanism of flux reversal may be by the relatively slow process of domain wall motion. There is also agreement that at high amplitudes of pulsed fields, the reversal may be faster by a quasi-coherent rotation of the magnetization as a single domain. However, the reversal mechanism is obscure in the intervening region, called region II. Furthermore, the specification of the lower and upper thresholds for region II is uncertain, and in particular the upper threshold has been described as invariably too high.[6] In addition, the losses associated with the large-angle coherent rotational process have been found to be invariably greater by a factor of 4 or more than the losses inferred from free oscillation measurements and from ferromagnetic resonance line width measurements.[5,6,8]

It has recently been suggested that the latter two anomalies might be attributed to blocking torques arising from interactions between the crystallites of polycrystalline films.[6] However the experimental identification of the effects of such torques is obscure and incomplete at this time.

Manuscript received ______________________

The research reported here was supported partially by NASA Materials Grant NsG-6-59 to Rice University, partially under AEC Contract No. AT-(40-1)-2572 with the Rice Computer Project, and partially by a NSF Science Development Grant to the University of Florida.

J. K. Watson is with the Dept. of Electrical Engineering, University of Florida, Gainesville. He was formerly with the Computer Project at Rice University, Houston, Texas.
H. C. Bourne is with the Dept. of Electrical Engineering, Rice University, Houston, Texas.

In none of the above questions is it clear what effects may arise from the stray fields from the film, if eddy currents are induced in the instrumentation system by the rapid switching of all or a portion of the film flux. However, it is a well-known fact of the technology of thin film memories that eddy currents induced in nearby drive lines cause an increase in the effective field required to switch the films. Smay[9] has called this phenomenon "flux trapping". Eggenberger's description of the eddy-current-caused breakup of flux rotation is very similar to descriptions of the incoherent rotational process.[3] In his same paper, Eggenberger also gives an empirical relation for one eddy current effect as:

$$\Delta H_r \approx 2B_s T/d \qquad (1)$$

for the increase ΔH_r in the field required for flux rotation, where B_s is the saturation flux density of the film, T is film thickness, and d is the distance between the film and drive line. For a typical permalloy switching experiment of a 1000 Å film spaced by a .020 inch glass substrate from a stripline conductor, equation (1) suggests that the drive field with flux trapping would be about 4 oersteds more than the field required to switch the film alone. If this expression is indeed applicable to switching experiments, it is clear that the additional drive requirements for the eddy currents will substantially obscure the details of the flux reversal process.

Concern about measurement techniques, as well as concern about film switching mechanisms, form the basis of this investigation. This paper outlines the preliminary design of a pulsed-field flux reversal instrument designed for measurements into the low nanosecond range with minimum eddy current effects. Detailed results for a selected film are presented, primarily for region II of incoherent rotation. The switching coefficient reported here for region II is a factor of 5 to 10 times faster than reported by others, despite the slower rise time of the longitudinal switching field used here.

The flux reversal process in region II is interpreted as a dispersion-related transition from wall motion to coherent rotation. When the boundaries of region II are plotted on a plane whose coordinates are the hard and easy-axis fields, they suggest a dispersion of the boundary of the standard switching asteroid plus an extended region near the easy-axis coordinate. The lower threshold of the extended region is found to obey a constant product of the two H field coordinates, in agreement with others.[13,15] The value of the constant agrees with a measure of film dispersion and is interpreted as a blocking torque caused by crystallite interactions. The two standard plots of switching characteristics are related to H-plane traversals across switching loci for the film.

2. EQUIPMENT DESIGN AND FILM DATA

In attempting to minimize eddy current effects in the pulse system, we departed from previous experimental techniques in two major ways. Instead of using solid conductors such as in previous microwave bridge[2,4] or stripline[11] pulsers, we used an array of thin conductors. Furthermore, we were able to avoid electrostatic shielding of the pickup coil although with some sacrifice of field rise time to about 10 nanoseconds.

The coil for generating the drive field was flat and rectangular, made from a short length of 10-element, flat-conductor tape cable. For minimum inductance the individual elements of the coil were driven in parallel, with the current distribution tailored to provide a constant field through the 1/2 inch width of the coil. The length by height dimensions of 7/8 by 1/8 inch were chosen for constant field over a 1 cm diameter film, and for high value of H field per unit current. Drive current to the coil was from the discharge of a capacitor through a coaxial reed relay with mercury-wetted contacts.

The signal pickup coil was wound on a probe which slips inside the drive coil. Connections to the two single-turn pickup loops were made at their centers nearest ground potential, for minimum sensitivity to the transient E field which accompanies the rise of H field. Since the output signal was taken differentially, the E-field caused perturbation which was partly subtracted out at the sampling oscilloscope.

The repetition rate of the signal was slow enough to permit the sampled output from the oscilloscope to be recorded directly on an X-Y recorder. Two typical signal waveforms are shown in Figure 1. The top trace recorded with each waveform is the reference base line from which the signal amplitude is measured. The variation of the signal and trace together is the remaining sum-component interference which was tolerated for the exploratory measurements reported here.

Further developments of the instrumentation are intended to improve sum-component rejection, decrease the field rise time, improve the field uniformity over the film and provide for easier adjustment of the film position. For precise resolution of region II characteristics, the switching field should be uniform within one percent at all portions of the film. The angular orientation of the film should be readily adjustable within 0.1 degree of arc. These design specifications can be inferred from data which follow in Figure 4.

The data reported here are for permalloy film No. 9-20-5#2, a selected 1 cm diameter film of nominal 1000 Å thickness, vacuum deposited at 2×10^{-7} torr onto a Corning 7059 glass substrate at 180°C. The source material was MRC ultra high purity alloy of 82:18 Ni/Fe heated to evaporation by an electron gun and deposited in 10 seconds in a 35 oersted d-c field. The vacuum system had been lightly baked 2 days prior to deposition during which the substrate was at 300°C. Anneal after deposition was 10 minutes at 180°C, followed by slow cooling at about 1/2°C per minute. Anisotropy field H_k and coercive field H_c were 5 and 2.4 oersteds, respectively, from usual MH loop measurements of this film. The dispersion field of 0.1 oersted corresponds approximately to $\alpha_{90} = 0.6°$.

3. EXPERIMENTAL RESULTS

The results of measuring flux reversal time as a function of longitudinal switching field H_s are plotted in Figure 2 which is a conventional switching characteristic. The time of flux reversal is taken as the time between the points of 10 percent of peak amplitude of the output signal. The prominent break or knee in the switching characteristics in the vicinity of 50 nanoseconds is thought to correspond to the beginning of the transition from wall motion to coherent rotation. The completion of this transition at less than 10 nanoseconds was too fast to be resolved accurately.

Certain thresholds of the switching characteristics become more prominent if the perpendicular bias field is used as the independent variable, as first suggested by Telesnin and Kolotov.[13] Figure 3 is the result, which includes the points from the waveforms of Figure 1 labeled as (a), (b). Careful examination of the waveforms has shown that the knee of the curve corresponds to the onset of the initial prominent peak of the signal waveform.

The two orthogonal components of the H field, corresponding to Figures 2 and 3, are plotted in Figure 4. Since many of the data points of Figure 4 also appear in either Figure 2 or 3, it would be feasible to show loci of constant switching time in this representation. The approximate locations of the thresholds separating region II from I and III are shown. In the same figure there are plotted for comparison segments of two switching asteroids. A switching asteroid defines the homogeneous field requirement for flux reversal of mathematically ideal, single-domain films with zero dispersion and $H_c = H_k$. It is seen that a substantial portion of region II apparently corresponds to a dispersion of the boundary of the asteroid for $H_k = 5$ oersteds. However, for small values of transverse field $H_\perp$ and for longitudinal switching fields $H_s \gtrsim H_k$, region II departs from the asteroid region and extends along the H_s axis (hence along the easy axis of the film). To our knowledge, these details of region II have not been reported previously.

The two different representations of film switching shown in Figures 2 and 3 are seen to be sections taken horizontally and vertically, respectively across the region of Figure 4.

As implied earlier, the threshold loci of Figure 4 correspond to the onset of a change of character of the signal waveforms. The two loci drawn through the rectangular points are judged to be the two thresholds of region II for the subject film. That is, the lower threshold corresponds to the onset of the fast initial peak such as the prominent feature of waveform (b) of Figure 1. The upper threshold indicates the field condition where the area of the initial spike of the signal waveform comprises approximately .9 of the total area of the signal pulse.

The lower threshold is reasonably approximated by $H_\perp H_s$ = constant for a portion of its extent, and by a switching asteroid elsewhere. A similar form is used for the upper threshold, although the data were not adequate to define the curve precisely.

It is interesting that for $H_s \gtrsim H_k$, the 0.1 oersted transverse width of region II agrees with an independent measure of film dispersion field.

The dispersion was measured using a pulse technique similar to one used by Petschauer et al[14] for film memory evaluation. There is applied to the film a hard-axis pulse whose amplitude is greater than H_k. Just prior to the trailing edge of the first pulse, a second pulse is applied along the easy axis to control the fall-back of magnetization. The amplitude of the easy-axis pulse can be changed to control the remanent state of the film from single domain reset in one direction to single domain reset in the other. The change in easy-axis field corresponding to the transition between the two 90 percent reset states is taken as the dispersion field.

4. DISCUSSION OF RESULTS

In Figure 2 the upper part of the switching curves are uncommonly steep with a switching coefficient of approximately 6 oersted-nanoseconds for a bias field of 0.18 oersted. A precise comparison with results of other investigators is not feasible because of differences in the definitions of reversal time, but an order of magnitude comparison is interesting. Six Oe-ns compares with 70 and 50 Oe-ns for transverse bias of 0.14 and 0.22 oersted, respectively, taken from data by Telesnin and Kolotov;[13] their data probably are also in region II. The corresponding figures for 2 degrees bias reported by Humphrey[11] are 106 and 30 Oe-ns reversal in regions II and III, respectively. Our 6 Oe-ns compares to 8 Oe-ns estimated from the steepest data by Dietrich et al,[4] which is also in region III.

It is interesting that our switching coefficient is faster than reported by others, despite the fact that the 10 ns rise time of our pulsed magnetic field is an order of magnitude slower. We tentatively attribute the faster response to the relative absence of eddy-current effects in our apparatus.

In the context of relating the apparent width of region II to film dispersion, it is worth pointing out that the apparent width would also be increased by inhomogeneity of the pulsed field in the film vicinity. In other words, the apparent width of region II for a constant perpendicular bias field is that amplitude range of switching field which just corresponds to the change of reversal mechanism from wall motion to rotation. If the probability of rotation for an elemental film region is determined by whether the local drive field exceeds the local switching threshold, the apparent range of field amplitude is affected by any inhomogeneity of the applied field as well as by inhomogeneities of film properties over the surface of the film.

In Figure 5, normalized data from other investigators are compared with the loci from Figure 4. For any experiment for which equation (1) is valid, the threshold for coherent rotation will be displaced to the right of its expected location. Thus the highly variable flux trapping process would tend to confuse such comparisons as Figure 5. This concept is supported by that part of our data which is in close relation to the switching asteroid. That portion of our results which extends from the asteroid will now be discussed in justification of the hyperbolic description of the switching thresholds.

In the usual pulsed flux reversal experiment, the switching field is applied precisely antiparallel to the average easy axis. In the absence of a transverse field, there are components of torque due to H_s on only those local components of magnetization which are dispersed from the easy axis. The assumptions of dispersion symmetry and of interaction forces within the disperse magnetization system account for reversal by wall motion even for $H_s \gtrsim H_k$. However for a sufficiently large transverse bias field $H_\perp$ the average magnetization vector is no longer antiparallel to the applied switching field, such that a net unidirectional torque arises from the $\vec{M} \times \vec{H}$ interaction. It will be indicated below that a switching threshold described by a constant

$H_\perp H_s$ product implies the existence of a constant crystallite blocking torque.

It is well known from the analysis of the coherent rotational switching of an ideal single-domain film that the fast switching is a result of the precession of the magnetization around its own demagnetizing field.[8] This field arises from the precession of the magnetization vector out of the plane of the film, due to the applied field. The initial rate of precession is given by

$$\frac{d\theta}{dt} = -\gamma \frac{H_s H_\perp}{H_k} = -\gamma\Delta \qquad (2)$$

which is proportional to an initial torque.[12] The switching threshold description $H_s H_\perp$ = constant was first reported by Telesnin and Kolotov[13] who subsequently have found the film constant to depend on dispersion.[15] Harte has recently given a similar expression from his theoretical models of spin wave locking.[16] Our data suggest the approximate relationship

$$\Delta_2 - \Delta_1 \approx \Delta_1 \approx 2H_k \sin \alpha_{90} \qquad (3)$$

where Δ_2 and Δ_1 define the upper and lower boundaries of region II by the equation (2), and where Δ_1 is the dispersion field for the film.

5. CONCLUSIONS

One might conclude that eddy currents induced in nearby conductors by the stray fields from rapidly-switching films can be an important factor in switching experiments. Our concern about such effects has brought us to new and consistent experimental results for film switching, but we have not yet explicitly studied the film-drive-line interaction.

We find region II of incoherent rotation to be a dispersion-related region of transition from wall motion to coherent rotation. One effect of dispersion is that the switching asteroid has a blurred edge. Another effect is an extension from the switching asteroid of a blurred region along the average easy axis. Conventional switching characteristics are shown to be made by traversals of measurements across a two-dimensional field plot of the film characteristics.

For that portion of region II which extends from the switching asteroid we find the boundaries to be described by thresholds of constant torque and the width to agree with an independent measure of film dispersion.

REFERENCES

1. C. D. Olson and A. V. Pohm, "Flux Reversal in Thin Films of 82% Ni, 18% Fe", J. Appl. Phys., Vol. 29, pps. 274-282, March, 1958.

2. D. O. Smith and G. P. Weiss, "Steady-State and Pulse Measurement Techniques for Thin Magnetic Films in the VHF-UHF Range", J. Appl. Phys., Vol. 29, pps. 290-293, March, 1958.

3. F. B. Humphrey, "Transverse Flux Change in Soft Ferromagnetics", J. Appl. Phys., Vol. 29, pps. 284-285, March, 1958.

4. W. Dietrich, W. E. Proebster, and P. Wolf, "Nanosecond Switching in Thin Magnetic Films", I.B.M. J. Res. Develop., Vol. 4, pps. 189-196, April, 1960.

5. B. R. Hearn, "The Dynamic Behaviour of Magnetic Thin Films", J. of Electronics and Control, Vol. 16, No. 1, pps. 33-57, January 1964.

6. K. J. Harte, "Spin-Wave Effects in the Magnetization Reversal of a Thin Ferromagnetic Film", M.I.T. Lincoln Laboratory Tech. Report No. 364, August, 1964.

7. D. O. Smith and K. J. Harte, "Noncoherent Switching in Permalloy Films", J. Appl. Phys., Vol. 33, No. 4, pps. 1399-1413, April, 1962.

8. D. O. Smith, "Static and Dynamic Behavior of Thin Permalloy Films", J. Appl. Phys., Vol. 29, pps. 264-273, March, 1958,

9. T. A. Smay, "Energy Transfer Properties of Thin Magnetic Film Coupled-Pair Logical Elements", I.E.E.E. Trans. Communication and Electronics, Vol. 83, pps. 808-812, November, 1964.

10. J. S. Eggenberger, "Influence of Nearby Conductors on Thin Film Switching", J. Appl. Phys., Vol. 31, Nos. 1-6, pps. 287S-288S, May, 1960.

11. F. B. Humphrey, "Flux Reversal at Low Temperatures", J. Appl. Phys., Vol. 35, No. 3 (Part 2), pps. 911-912, March, 1964.

12. J. K. Watson, "Fabrication and Switching Characteristics of Ferromagnetic Thin Films", Ph.D. Thesis, Dept. of Electrical Engineering, Rice University, May, 1966. Available from University Microfilms, Ann Arbor, No. 66-10,395. Rice Computer Project Report #ORO-2572-2.

13. R. V. Telesnin and O. S. Kolotov, "Effect of a Transverse Magnetic Field Upon the Remagnetization Rate of Thin Permalloy Films", Fiz. Metal. Metalloved, Vol. 17, No. 6, pps. 834-838, 1964. Translation publ. May, 1965, pps. 37-41, (Pergamon Press).

14. R. J. Petschauer, W. V. Rausch, P. L. Morawetz, "Optimization of Magnetic Parameters in Thin Film DRO Storage Elements", J. Appl. Phys., Vol. 35 No. 3, pps. 766-769, March, 1964.

15. R. V. Telesnin, E. N. Ilicheva, O. S. Kolotov, T. N. Nikitina, V. A. Pogozhev, "Experimental Investigation of Some Features of Incoherent Rotation in Thin Permalloy Films", Phys. Stat. Sol., Vol. 14, No. 2, pps. 371-380, April 1, 1966.

REFERENCES CON'T.

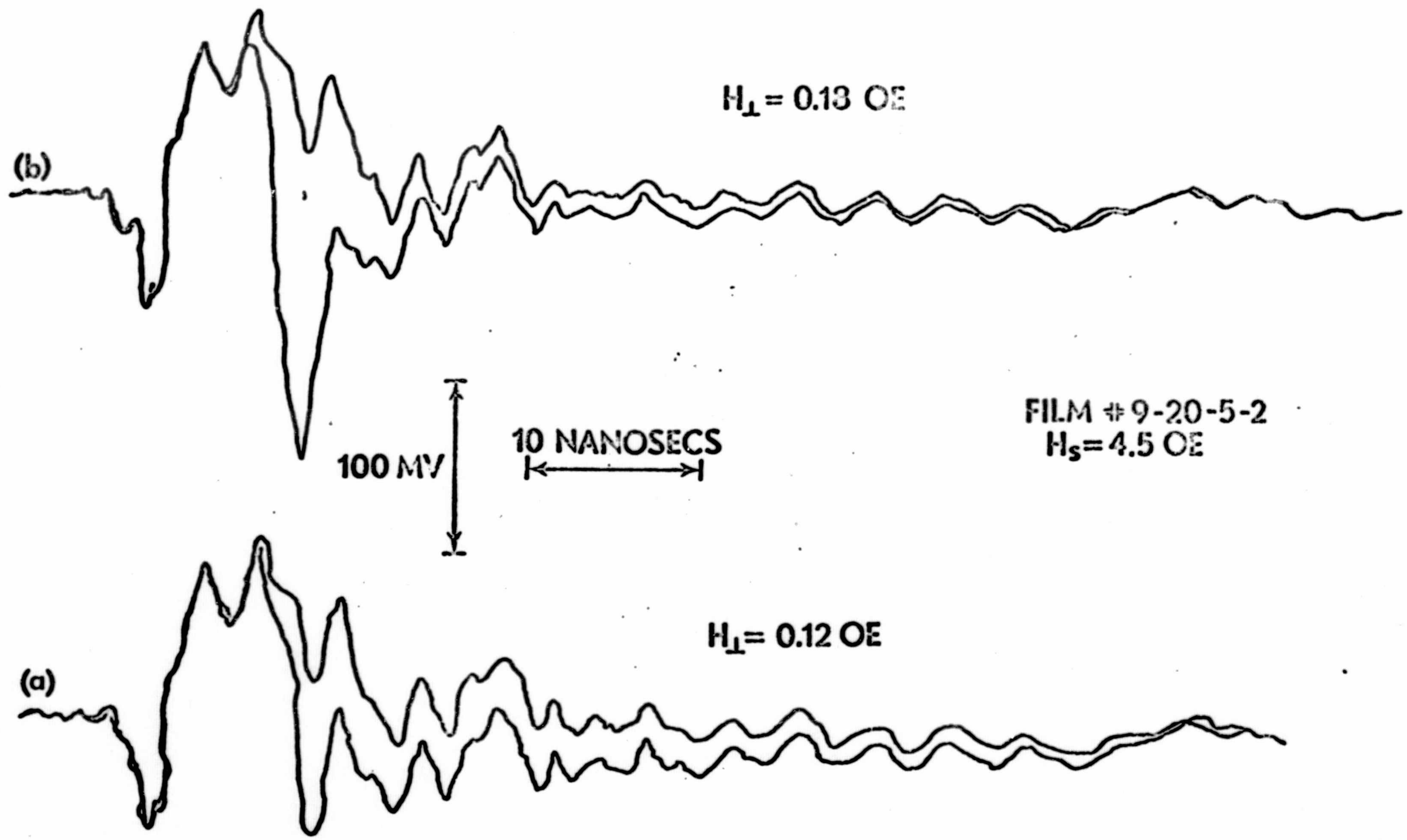
16. K. J. Harte, "Spin-Wave Locking of the Uniform-Rotational Switching Mode in Magnetic Thin Films", Presented at 12th annual Conference on Magnetism and Magnetic Materials, Washington, D. C., November 15-18, 1966. To be published in Magnetics Issue of J. Appl. Phys., Vol. 30, No. 3 (Part 2), March, 1967.

Titles for Figures for

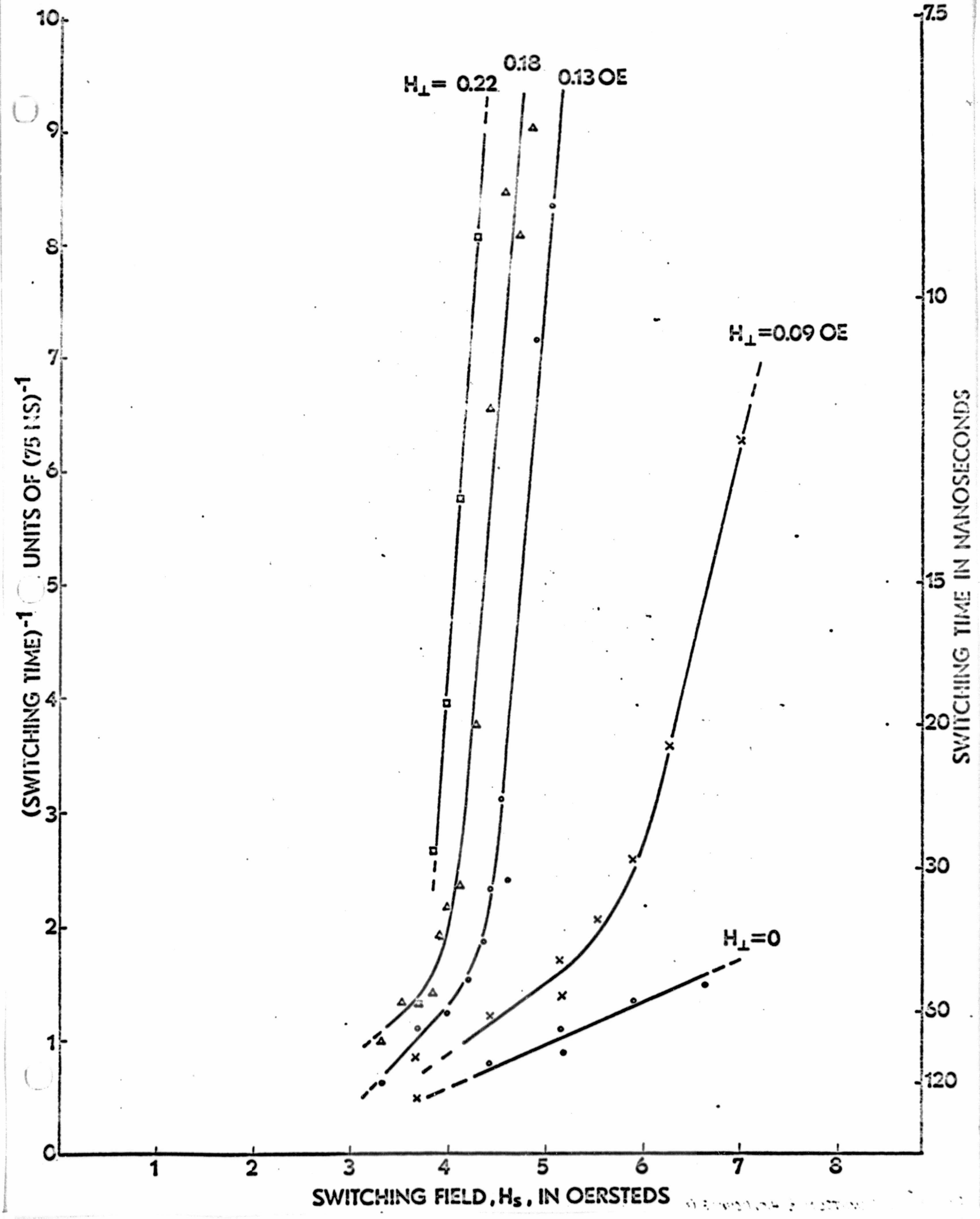
"Eddy-Current-Free Switching of Permalloy Thin Films"

by J.K. Watson and H.C. Bourne

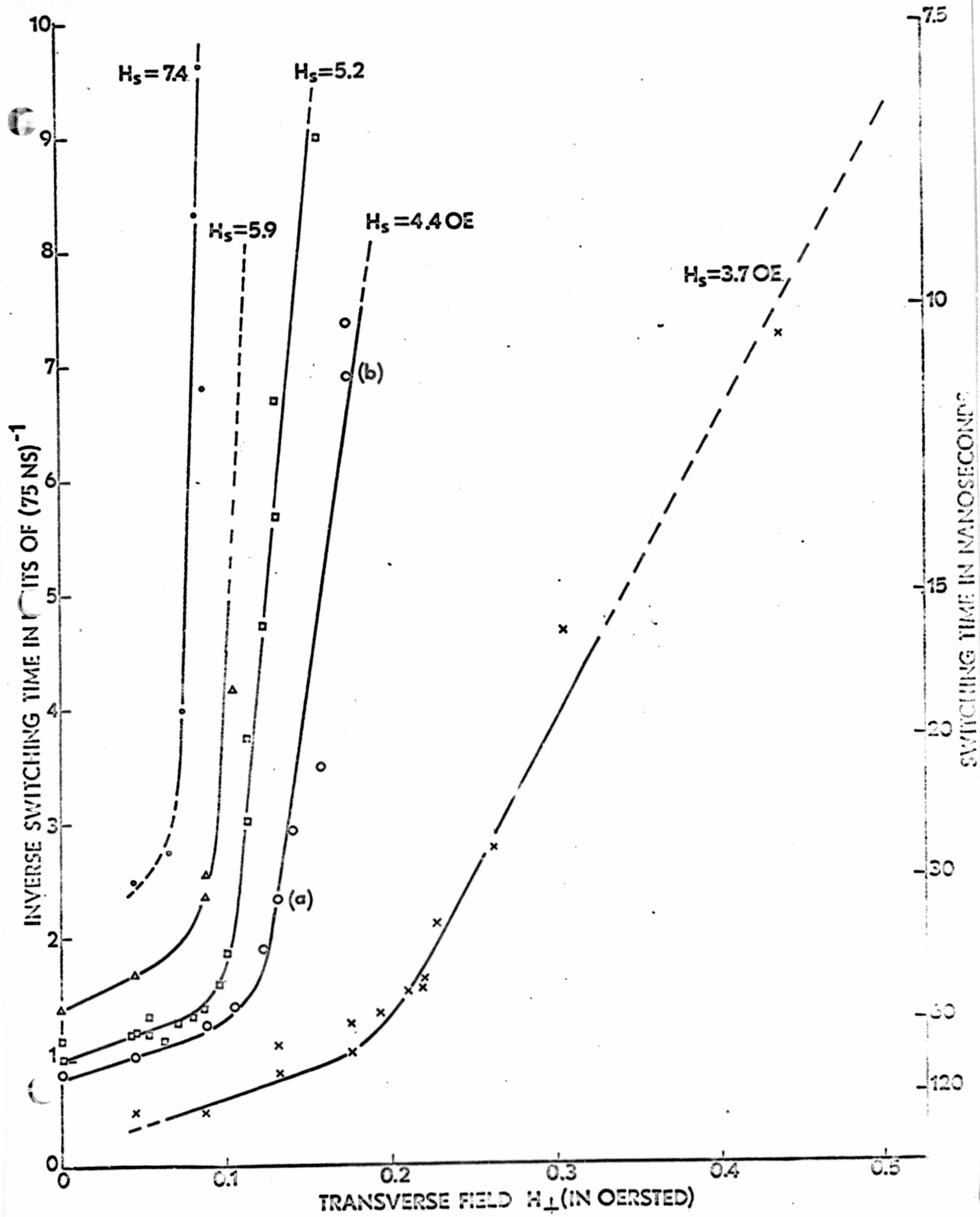
Figure 1	Two Typical Signal Waveforms
Figure 2	Switching Characteristics: Inverse of reversal time as function of longitudinal switching field with transverse field as parameter.
Figure 3	Switching Characteristics: Inverse of reversal time as function of transverse field with longitudinal switching field as parameter.
Figure 4	Threshold field conditions for incoherent rotational switching. Data points from switching characteristics are plotted on H-plane of transverse field vs longitudinal switching field.
Figure 5	Comparison of Switching Thresholds



H⊥ = 0.13 OE
(b)
100 MV
10 NANOSECS
FILM # 9-20-5-2
Hs = 4.5 OE
H⊥ = 0.12 OE
(a)

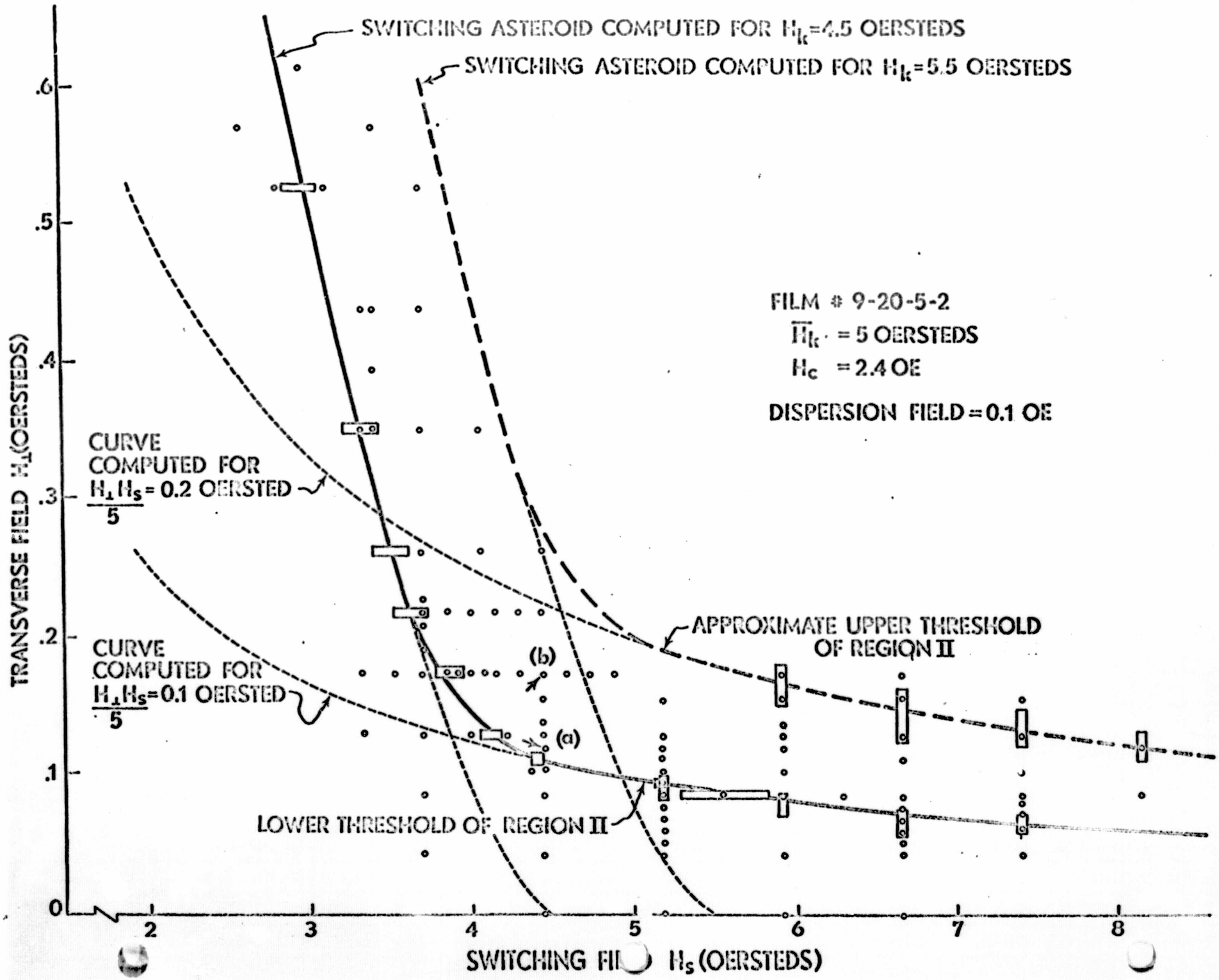


(SWITCHING TIME)$^{-1}$ UNITS OF (75 NS)$^{-1}$
SWITCHING TIME IN NANOSECONDS
SWITCHING FIELD, H_s, IN OERSTEDS
$H_\perp$ = 0.22
0.18
0.13 OE
$H_\perp$=0.09 OE
$H_\perp$=0
0
1
2
3
4
5
6
7
8
9
10
7.5
10
15
20
30
60
120



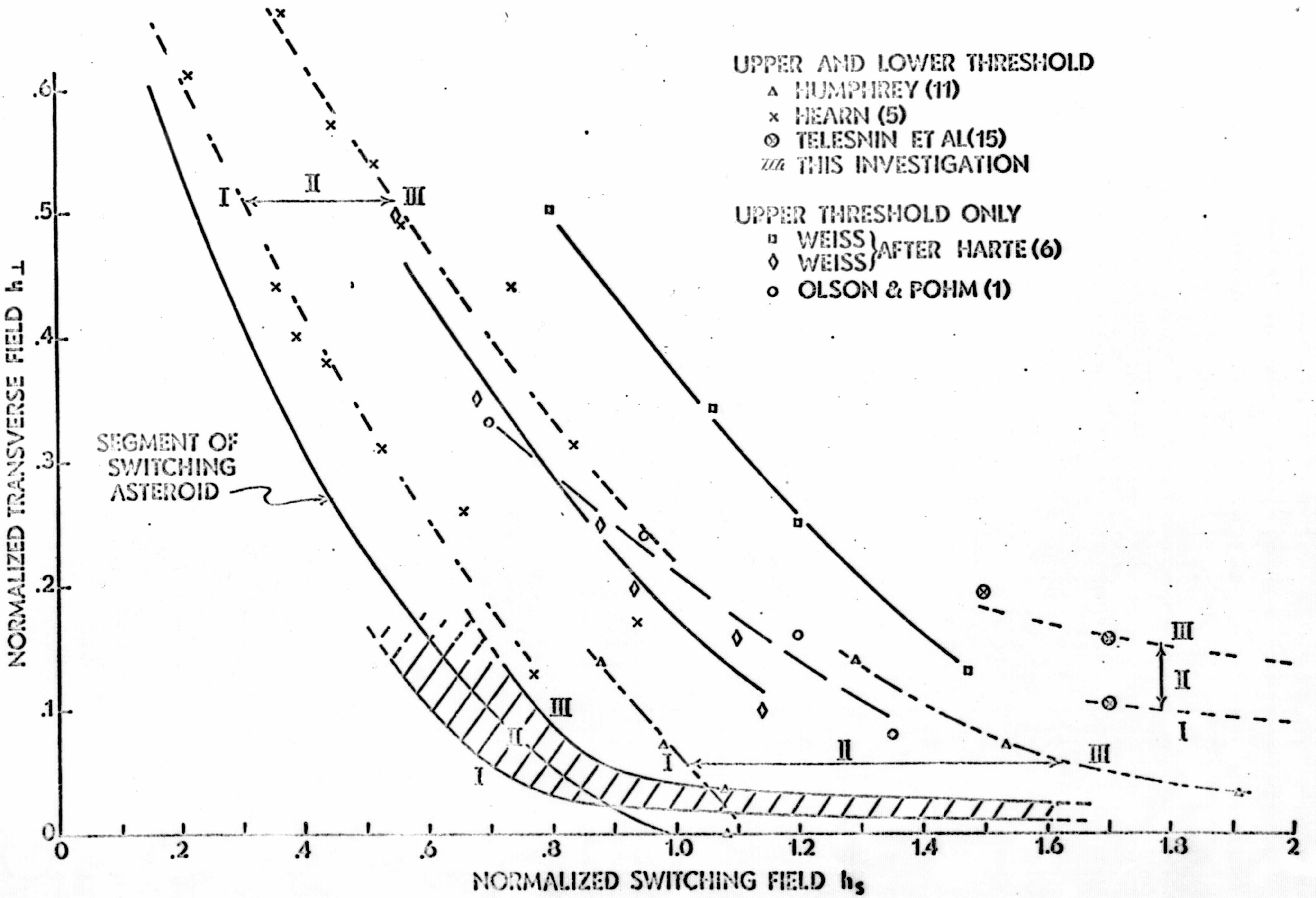
INVERSE SWITCHING TIME IN UNITS OF (75 NS)-1
SWITCHING TIME IN NANOSECONDS
TRANSVERSE FIELD H⊥(IN OERSTED)
Hs=7.4
Hs=5.9
Hs=5.2
Hs=4.4 OE
Hs=3.7 OE
(a)
(b)
0
1
2
3
4
5
6
7
8
9
10
0.1
0.2
0.3
0.4
0.5
7.5
10
15
20
30
60
120

BLANK PAGE

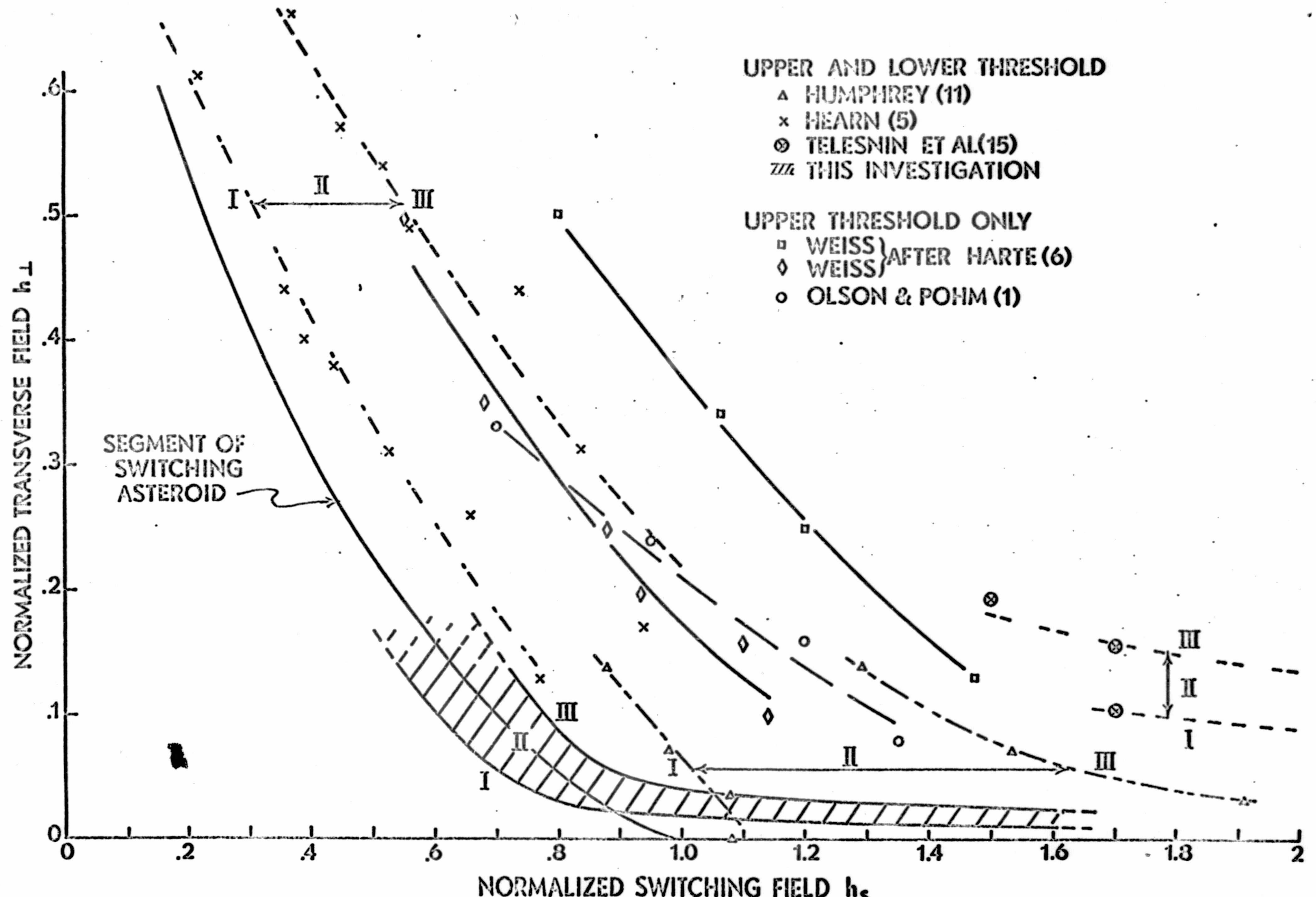


SWITCHING ASTEROID COMPUTED FOR H_k=4.5 OERSTEDS
SWITCHING ASTEROID COMPUTED FOR H_k=5.5 OERSTEDS
FILM # 9-20-5-2
$\overline{H_k}$ = 5 OERSTEDS
H_c = 2.4 OE
DISPERSION FIELD = 0.1 OE
CURVE COMPUTED FOR $\frac{H_\perp H_s}{5}$ = 0.2 OERSTED
CURVE COMPUTED FOR $\frac{H_\perp H_s}{5}$ = 0.1 OERSTED
(b)
(a)
APPROXIMATE UPPER THRESHOLD OF REGION II
LOWER THRESHOLD OF REGION II
TRANSVERSE FIELD $H_\perp$ (OERSTEDS)
SWITCHING FI… H_s (OERSTEDS)
0
.1
.2
.3
.4
.5
.6
2
3
4
5
6
7
8

BLANK PAGE



UPPER AND LOWER THRESHOLD
HUMPHREY (11)
HEARN (5)
TELESNIN ET AL(15)
THIS INVESTIGATION
UPPER THRESHOLD ONLY
WEISS
WEISS
AFTER HARTE (6)
OLSON & POHM (1)
SEGMENT OF SWITCHING ASTEROID
I
II
III
NORMALIZED TRANSVERSE FIELD h⊥
NORMALIZED SWITCHING FIELD hs
0
.1
.2
.3
.4
.5
.6
.8
1.0
1.2
1.4
1.6
1.8
2


UPPER AND LOWER THRESHOLD
HUMPHREY (11)
HEARN (5)
TELESNIN ET AL(15)
THIS INVESTIGATION
UPPER THRESHOLD ONLY
WEISS
WEISS
AFTER HARTE (6)
OLSON & POHM (1)
SEGMENT OF SWITCHING ASTEROID
NORMALIZED TRANSVERSE FIELD h⊥
NORMALIZED SWITCHING FIELD h_s
0
.1
.2
.3
.4
.5
.6
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2
I
II
III