Magnetic Sensor Review

Roger Koch - IBM Research

Review of sensitivities of vector magnetic field sensors

SQUIDs — Optical Pumping — Ferromagnetic

Types of ferromagnetic sensors

Driven

H = dc

- fluxgate
- induction coil

} magnetic readout

- MR sensor
- "driven MR sensor"

} resistive readout

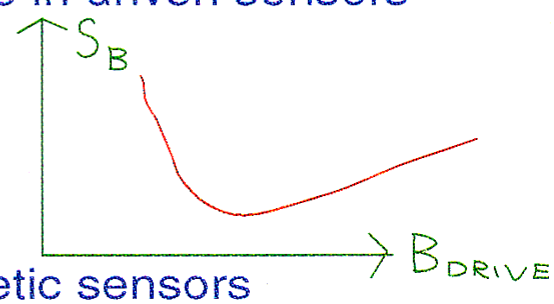
Equilibrium magnetic Johnson noise in MR sensors

$$S_m = \frac{4 k_B T \chi''}{\Omega \omega \mu_0} \rightarrow \chi'(0) = \frac{\Omega \mu_0}{k_B T} \langle \Delta M^2 \rangle$$

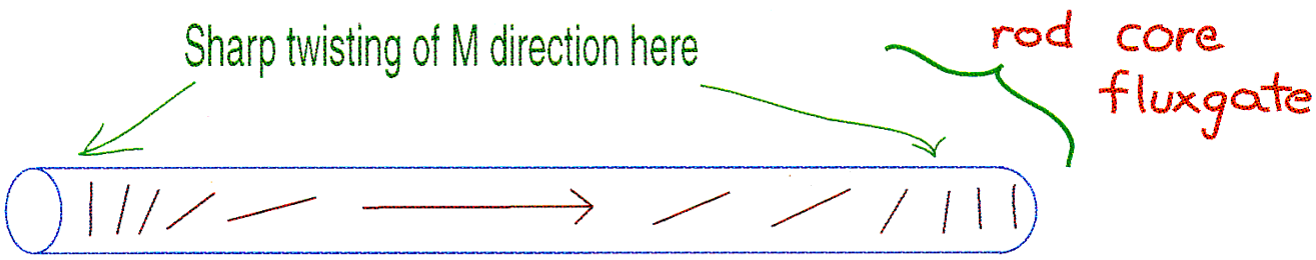
Equilibrium magnetic Johnson noise in driven sensors

$$S_m = \frac{4 k_B T \chi''}{\Omega \omega \mu_0}$$

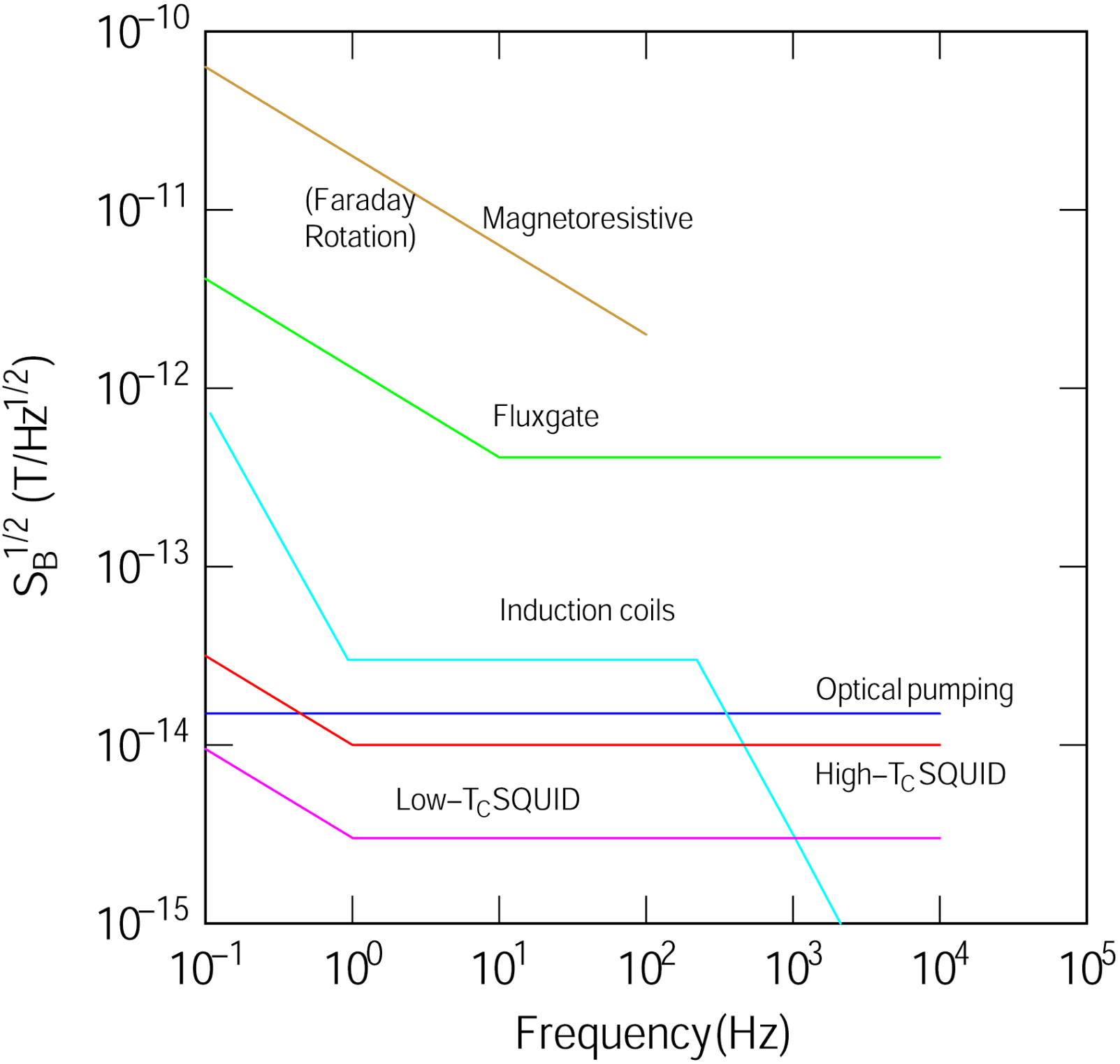
computer



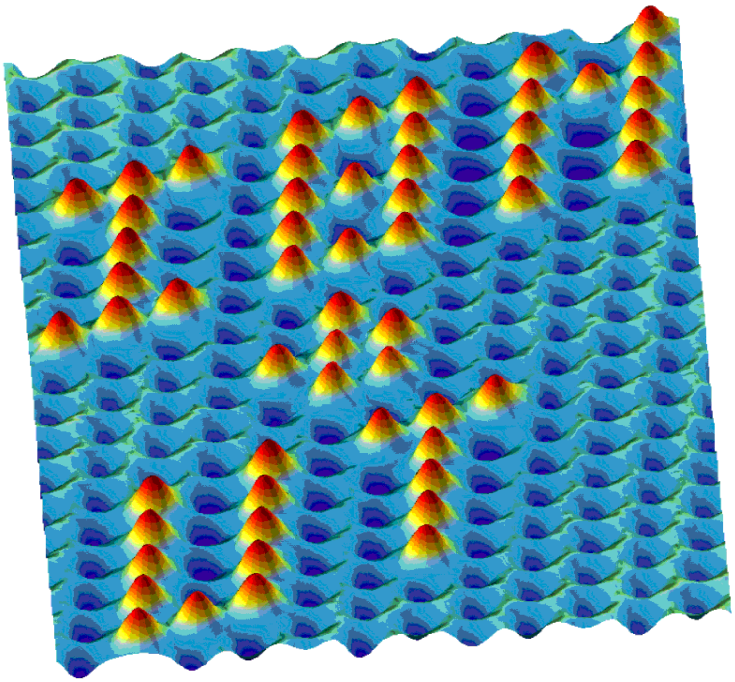
Non-equilibrium noise in ferromangetic sensors



Field noise of vector magnetometers



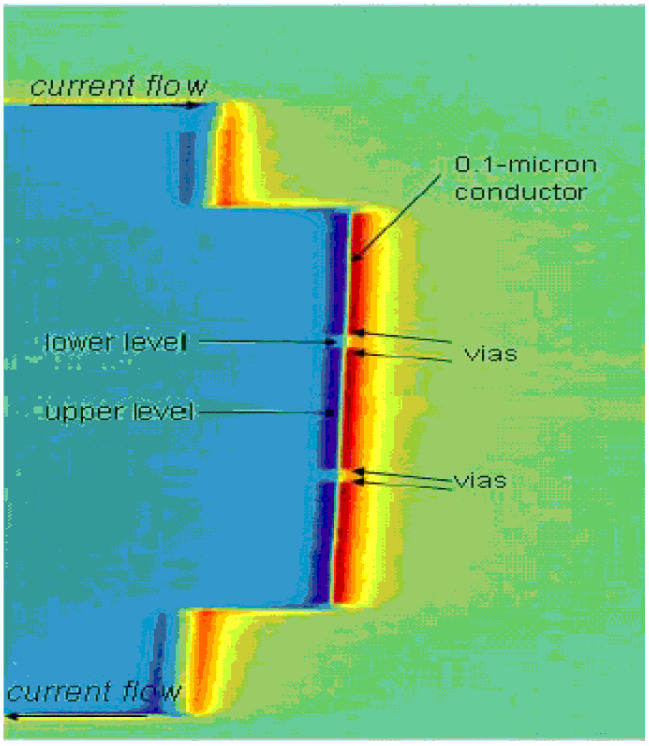
Scanning SQUID microscope



250 by 375 um^2
Kirtley, et al
IBM Research

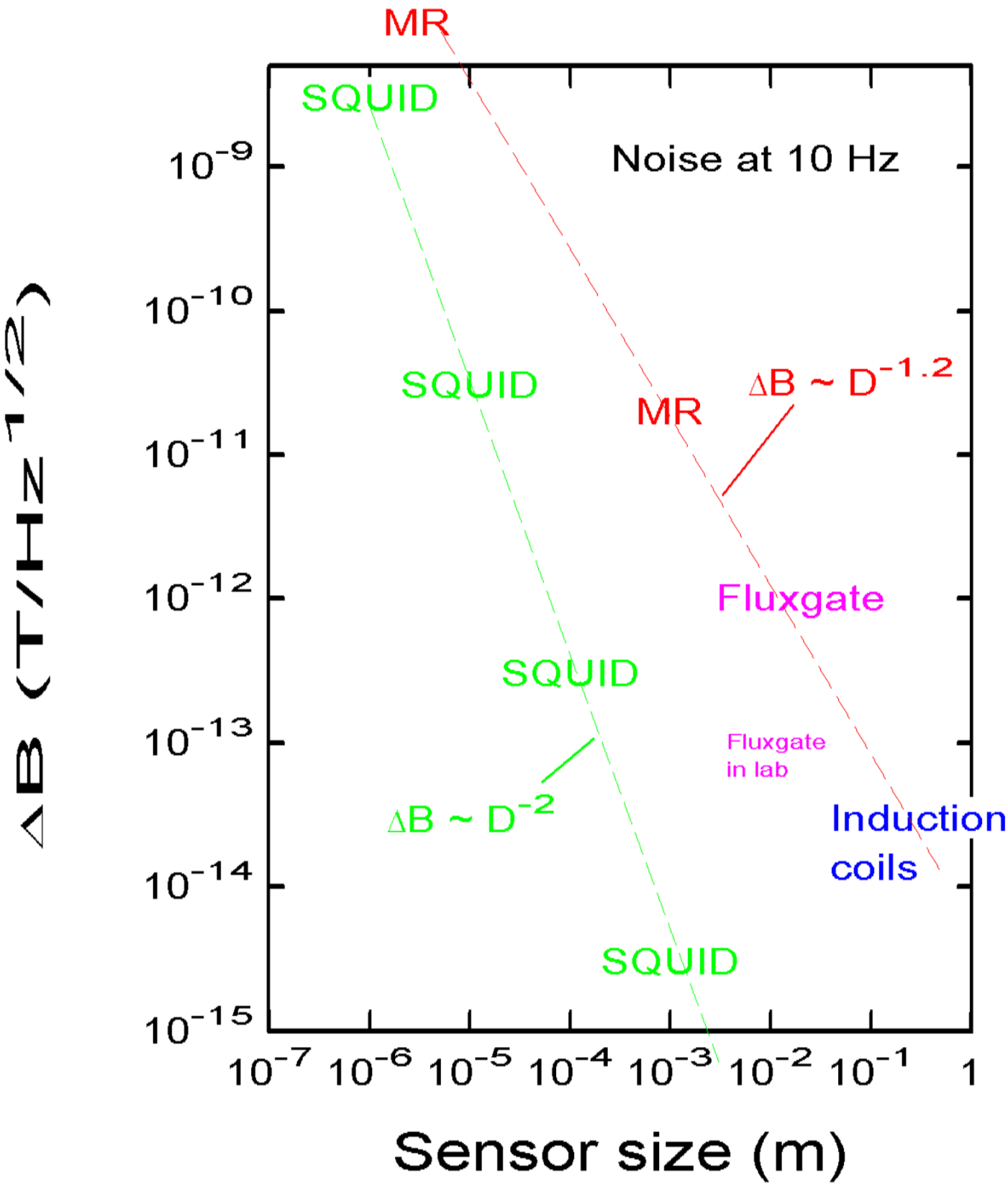
A triangular lattice of YBCO-Nb pi-rings, with 25 micron spacings between rings

Scanning TMR microscope



0.1 um line
Micromagnetics, Inc.

Magnetic field image of a
0.1 um Cu conductor carrying
an AC current of 200 uA


MR
SQUID
Noise at 10 Hz
SQUID
MR
ΔB ~ D^-1.2
Fluxgate
SQUID
Fluxgate
in lab
ΔB ~ D^-2
Induction
coils
SQUID
ΔB (T/Hz^1/2)
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1
Sensor size (m)

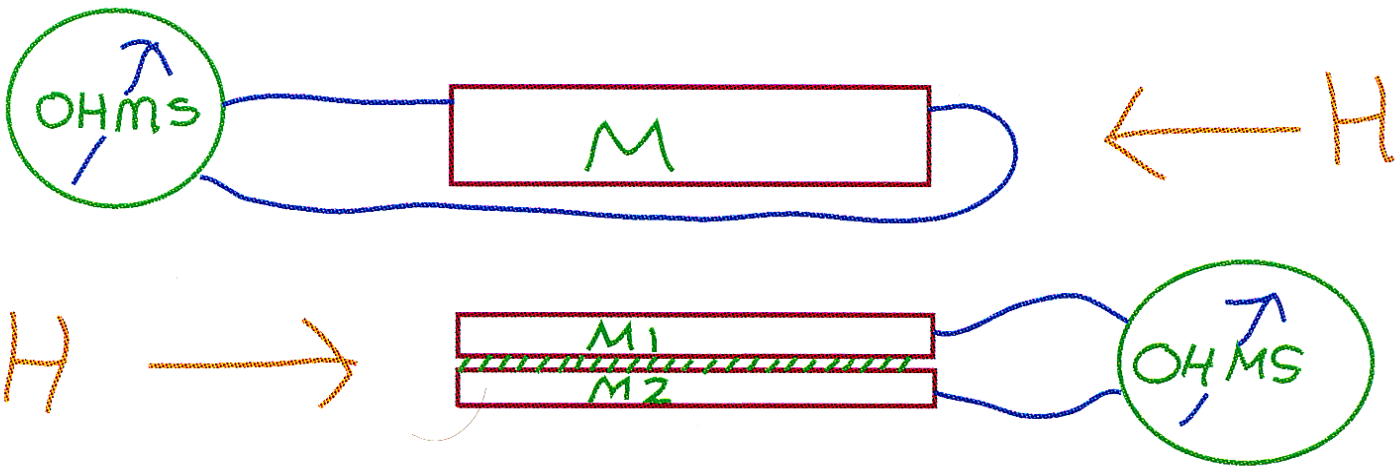
Types of ferromagnetic field sensors

	Equilibrium system magnetic Johnson noise	Driven non-equilibrium system domain wall motion noise
Magnetic readout large - bulk preamp noise is an issue	Induction coil $S_m = \frac{4 k_B T \chi''}{\Omega \omega \mu_0}$ $\Delta B \sim 0.03$ pT	Fluxgate $S_B^{PRED} \approx 0.1$ pT $\Delta B \sim 1$ pT
Resistive readout small - thin film thin film quality is an issue	MR sensor $S_m = \frac{4 k_B T \chi''}{\Omega \omega \mu_0}$ $\Delta B \sim 10 - 30$ pT	Driven MR Sensor can reduce preamp noise

Noise numbers at per root Hz at 1Hz

Flux concentrators not included

Can we predict the noise in an MR sensor?

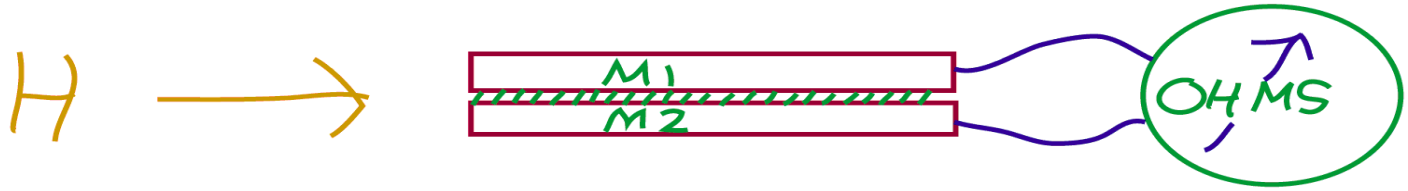


$$S_m = \frac{2 k_B T \chi''(f)}{\pi \Omega \mu_0 f}$$

magnetic Johnson noise

$$S_H = \frac{S_m(f)}{(\chi'(f))^2} = \frac{2 k_B T}{\pi \Omega \mu_0 f} \cdot \frac{\chi''(f)}{(\chi')^2}$$

MR sensor noise prediction



$$S_m = \frac{2 k_B T \chi''(f)}{\pi \Omega \mu_0 f}$$

$$S_m = A/f$$

$$\chi'(0) = \frac{\Omega \mu_0}{k_B T} A \log\left(\frac{\tau_L}{\tau_S}\right)$$

$$S_H = \frac{S_m(f)}{(\chi'(f))^2} = \frac{2 k_B T}{\pi \Omega \mu_0 f} \cdot \frac{\chi''(f)}{(\chi')^2}$$

$$S_H = \frac{k_B T}{\Omega \mu_0} \cdot \frac{1}{f \log(\tau_L/\tau_S)} \cdot \frac{1}{\chi'(0)}$$

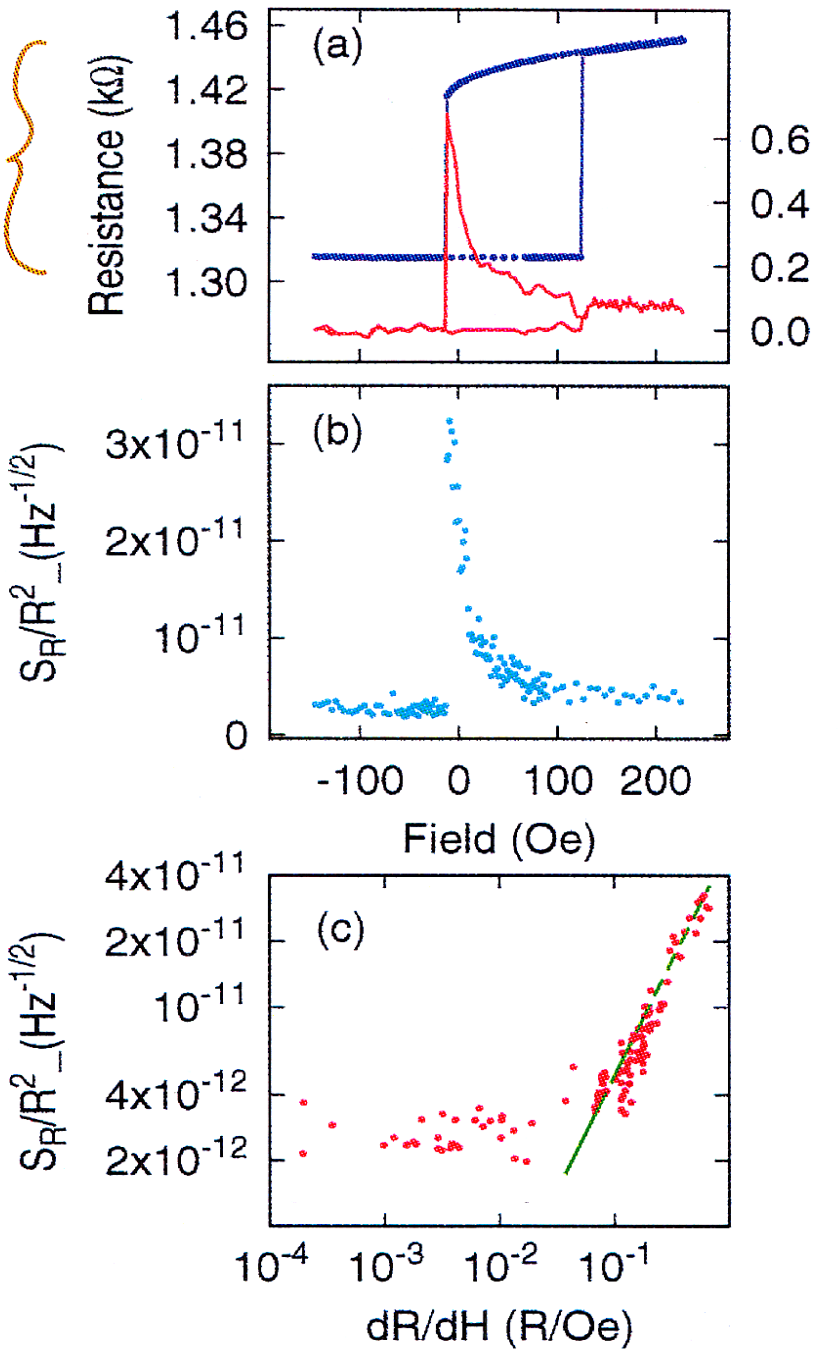
volume

better materials

shape

Compare slope of M-H vs 1/f noise

R-H curve

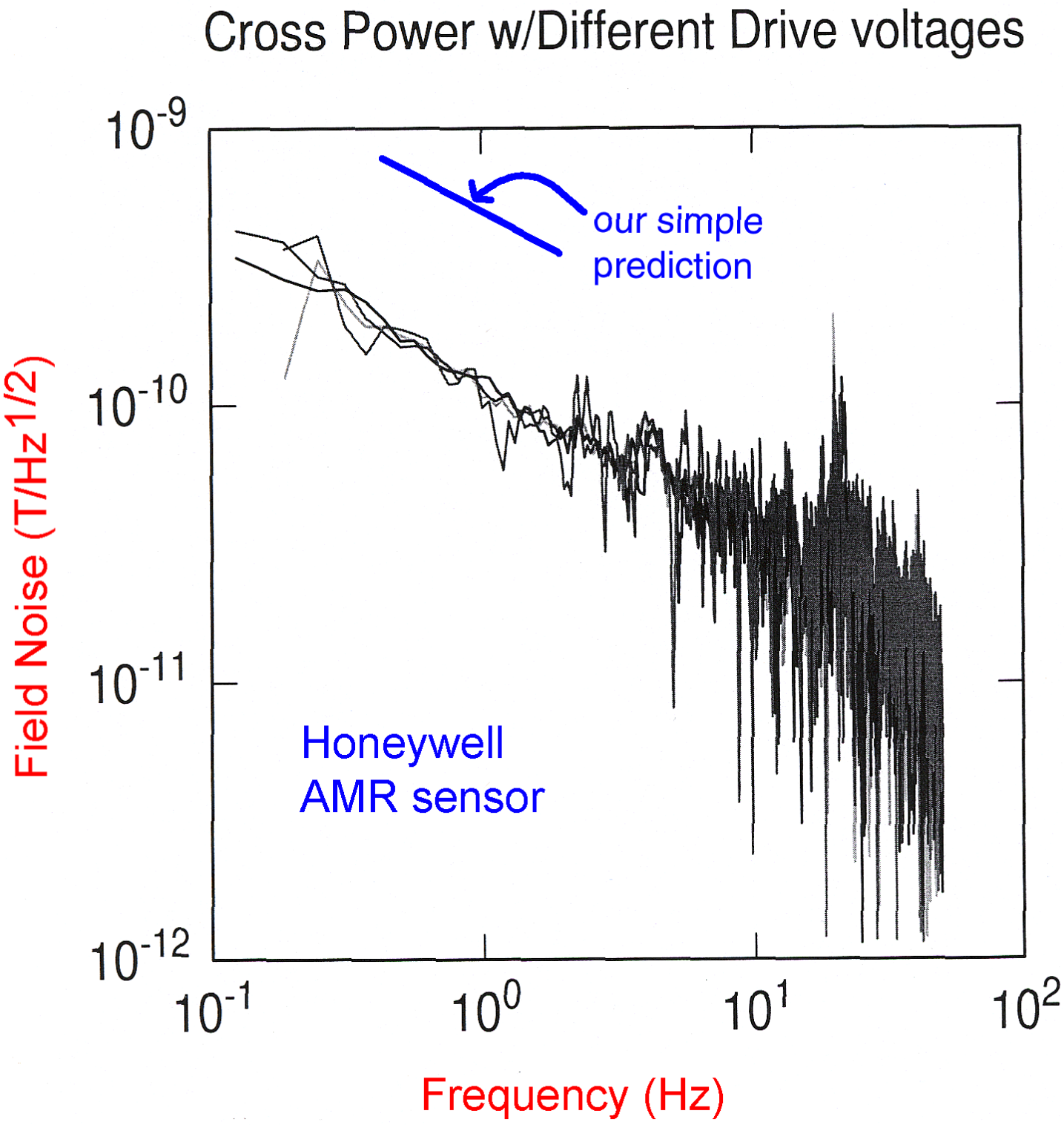


slope of M-H χ'

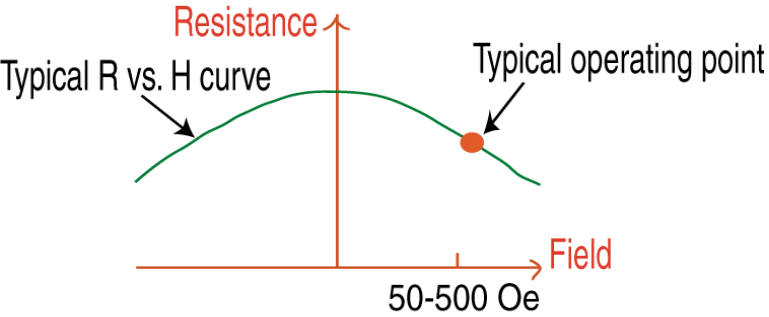
noise is 1/f noise

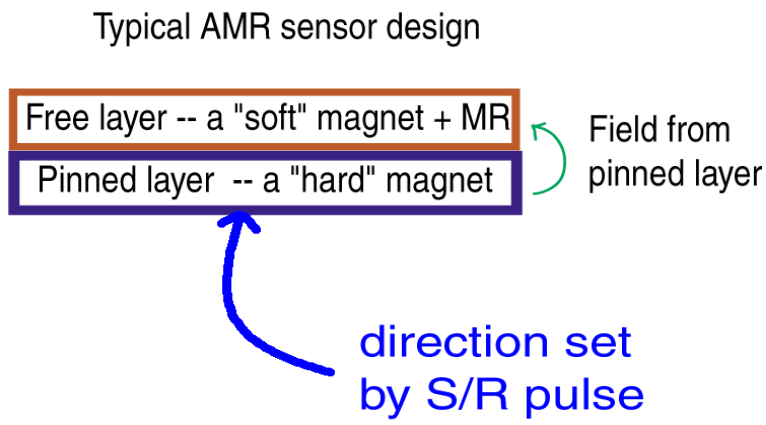
perfect fit!

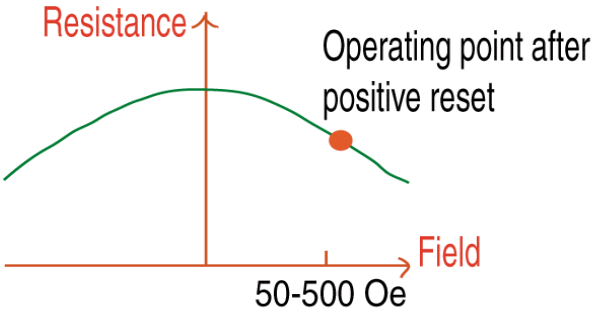
$$\log\left(\frac{\gamma_L}{\gamma_s}\right) \approx 10-15$$

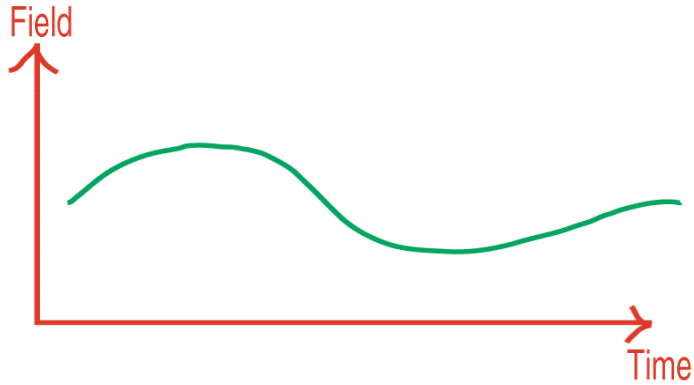

Cross Power w/Different Drive voltages
our simple prediction
Honeywell AMR sensor
Field Noise (T/Hz1/2)
Frequency (Hz)
10-9
10-10
10-11
10-12
10-1
100
101
102

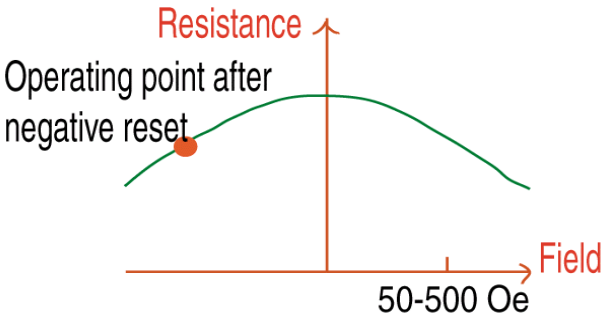
Chopping MR sensor operation

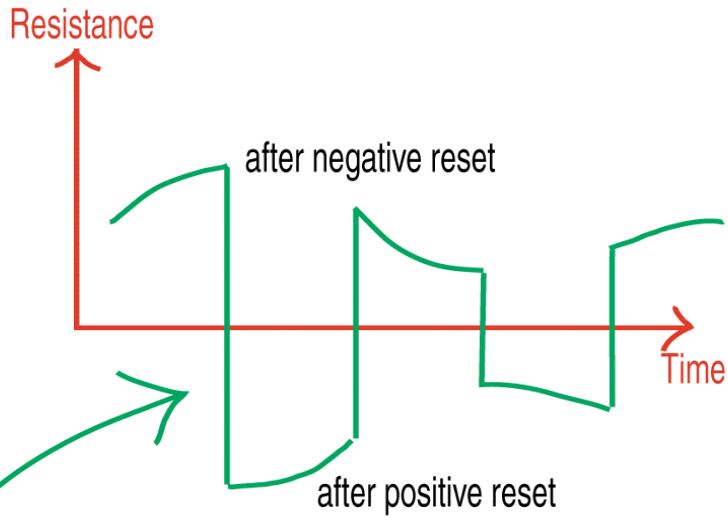




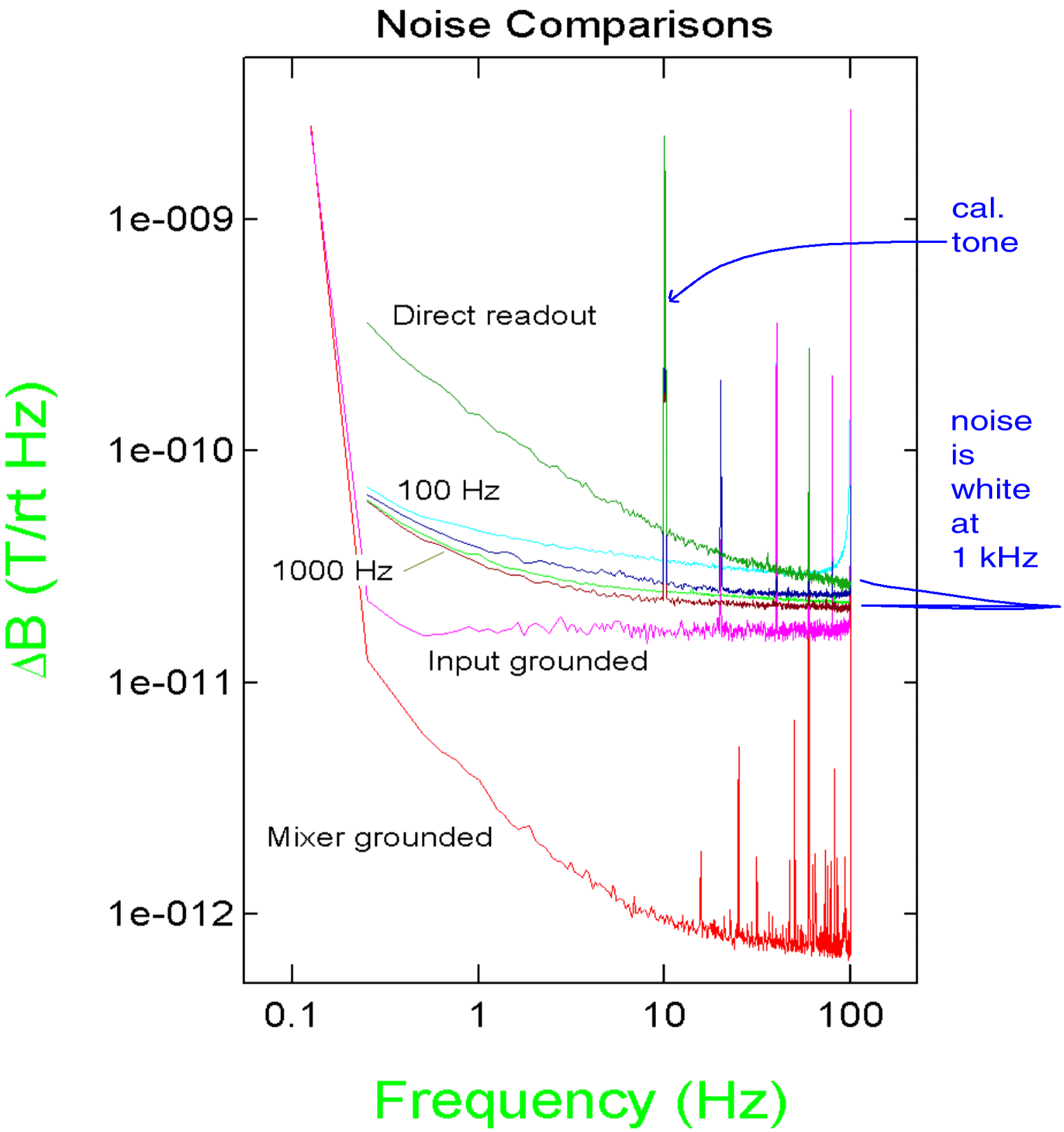


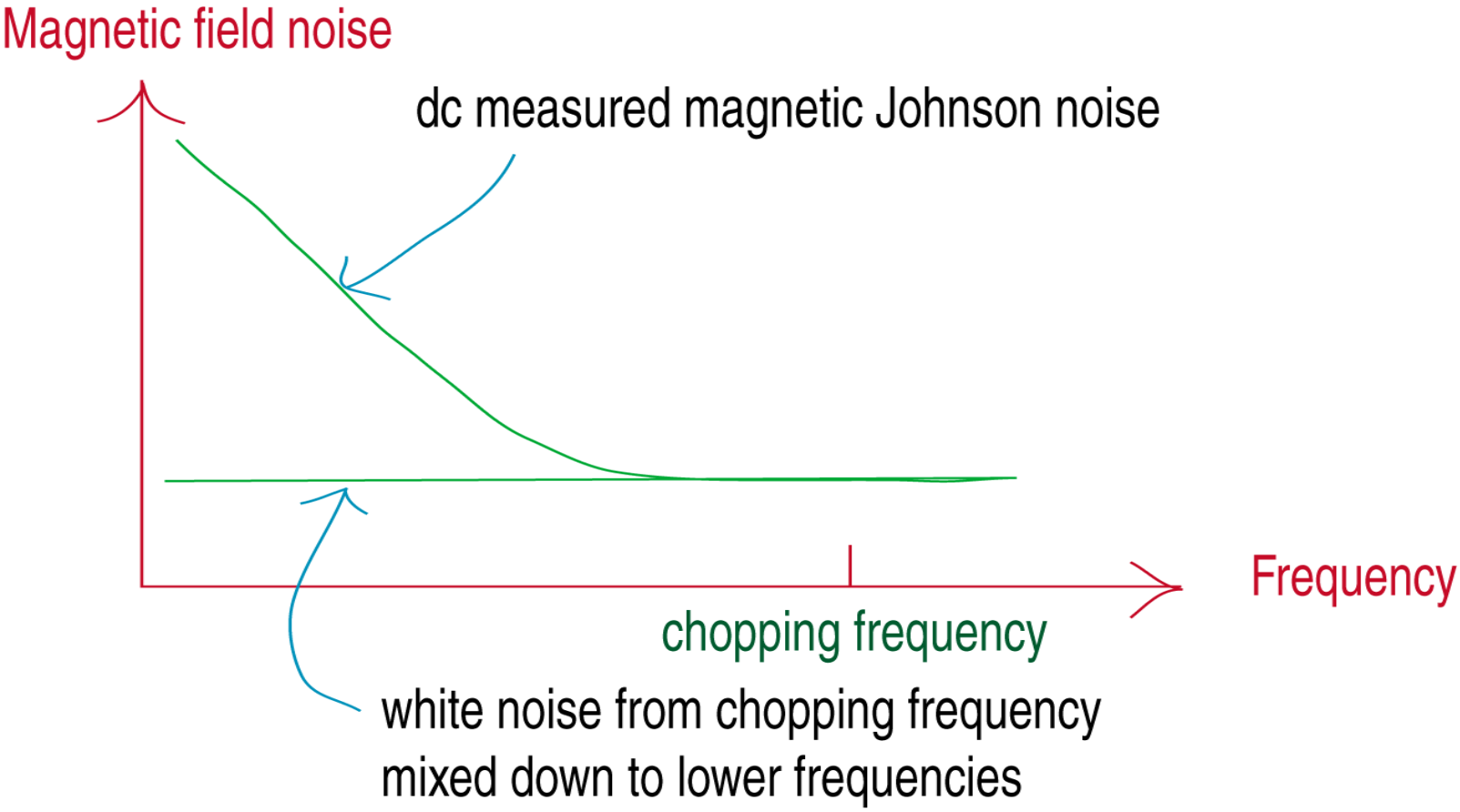


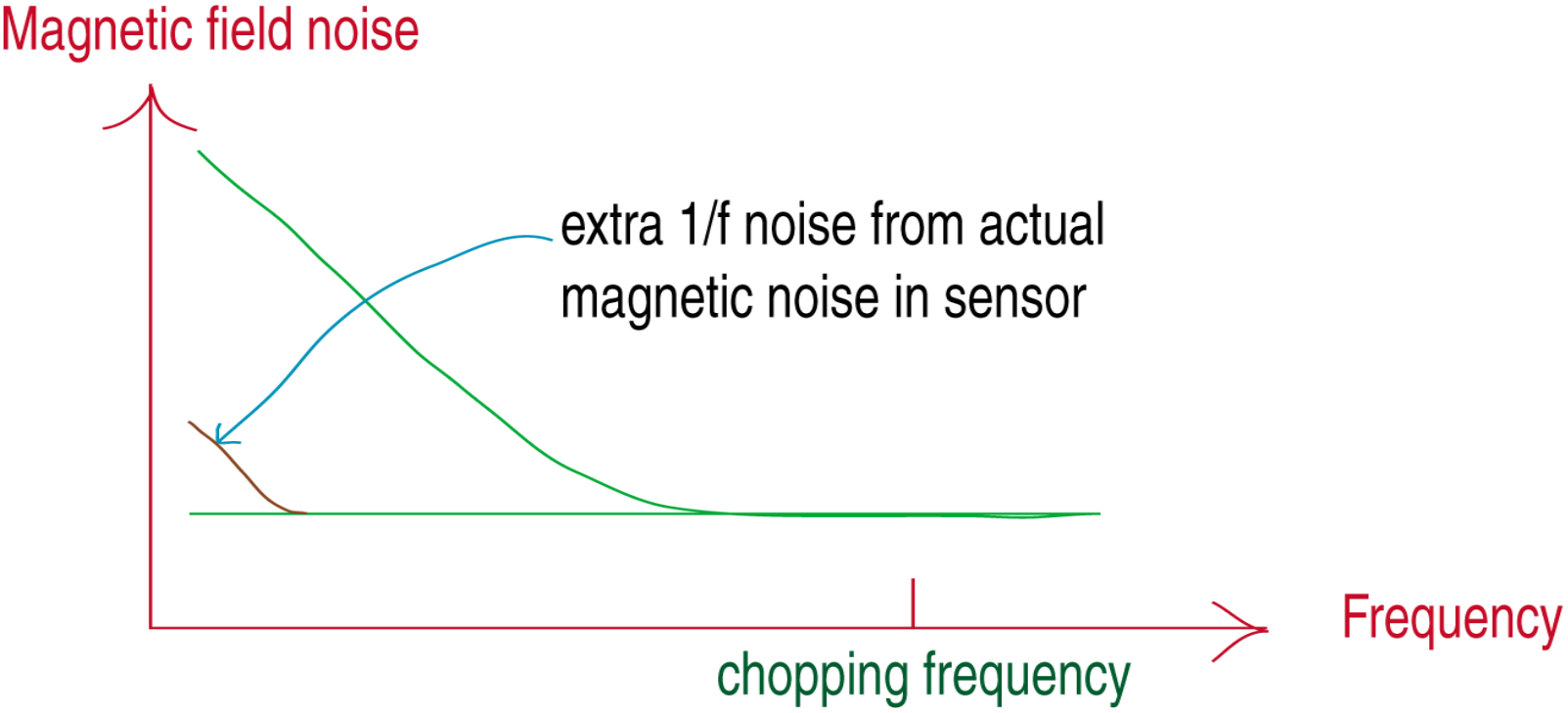


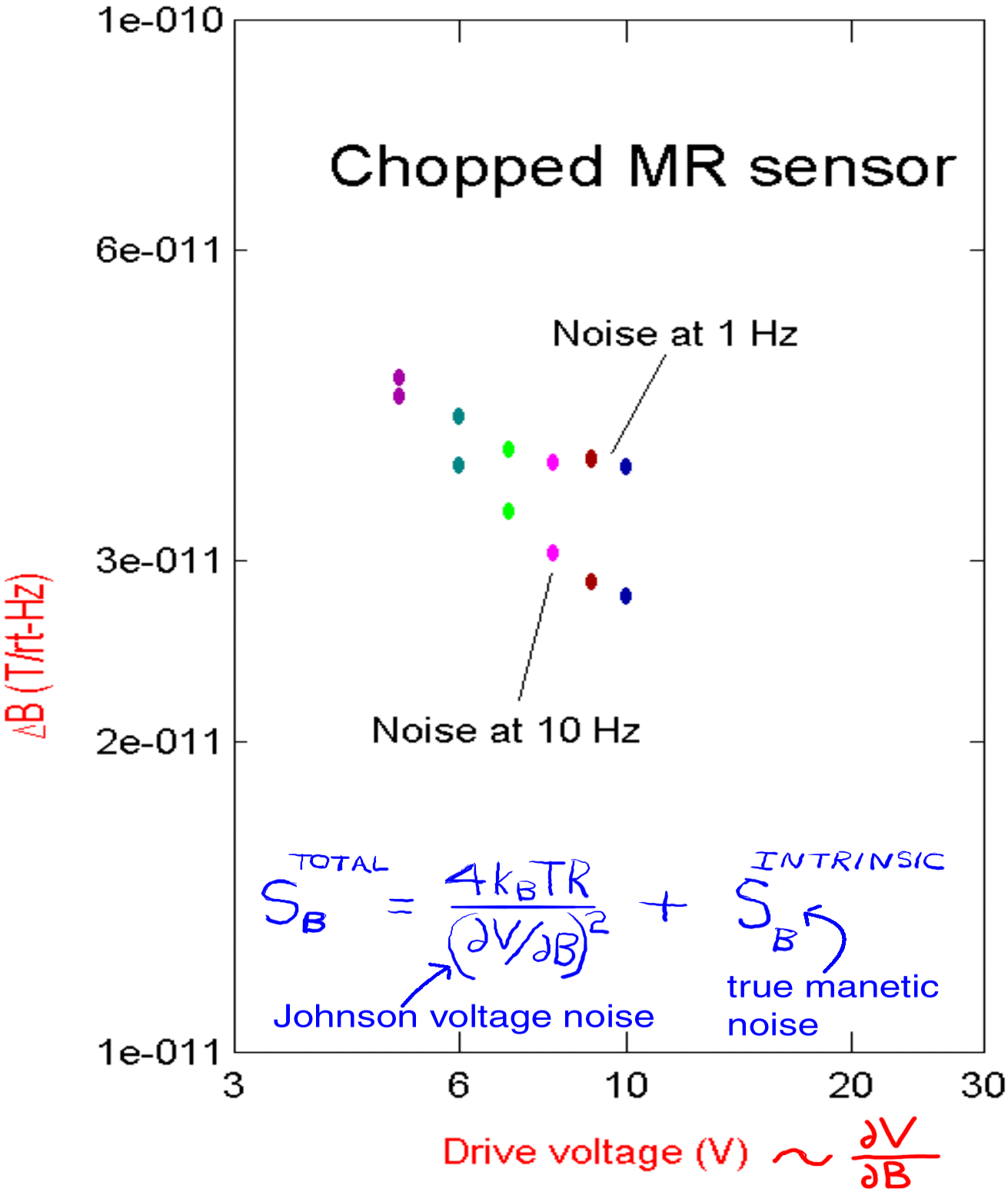


Amplitude of envelope proportional to the field


Noise Comparisons
1e-009
1e-010
1e-011
1e-012
ΔB (T/rt Hz)
0.1
1
10
100
Frequency (Hz)
Direct readout
100 Hz
1000 Hz
Input grounded
Mixer grounded
cal.
tone
noise
is
white
at
1 kHz


Magnetic field noise
dc measured magnetic Johnson noise
Frequency
chopping frequency
white noise from chopping frequency
mixed down to lower frequencies


Magnetic field noise
extra 1/f noise from actual
magnetic noise in sensor
Frequency
chopping frequency

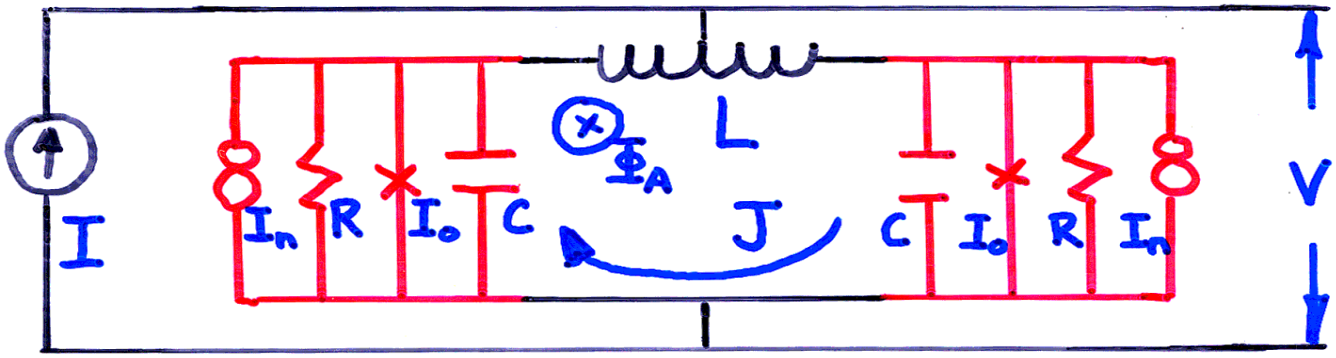

Chopped MR sensor
1e-010
6e-011
3e-011
2e-011
1e-011
ΔB (T/rt-Hz)
Noise at 1 Hz
Noise at 10 Hz
3
6
10
20
30
Drive voltage (V) ~ ∂V/∂B
$S_B^{TOTAL} = \frac{4k_BTR}{(\partial V/\partial B)^2} + S_B^{INTRINSIC}$
Johnson voltage noise
true manetic noise

CAN WE PREDICT THE NOISE IN A FLUXGATE?

(A DRIVEN NON-LINEAR MAGNETIC SYSTEM ...)

WHITE NOISE FIRST

DC SQUID EQUATIONS



INPUTS: I, Φ_A

OUTPUTS: V, J, S_V, S_J, S_{VJ}

$$\beta \equiv \frac{2 I_o L}{\Phi_o} \sim 1 \qquad \beta_c \equiv \frac{2\pi I_o R^2 C}{\Phi_o} \lesssim 1$$

$$S_I(\nu) = (2h\nu/R)\coth(h\nu/2k_BT)$$

USE DIGITAL COMPUTER FOR SOLUTION

LANDAU - LIFSHITZ - GILBERT EQ:

INPUTS

$H_{APPLIED}$

SHAPE

MATERIALS

$\rightarrow \Delta M$ OUTPUT

DAMPING

$$\frac{dM}{dt} = -\mu_0 \gamma \, \vec{M} \times \vec{H} - \frac{\mu_0 \alpha \gamma}{|M|} \vec{M} \times \vec{M} \times \vec{H} + \gamma \mu_0 \vec{M} \times \vec{F}(t)$$

$$S_F = \frac{4 k_B T \alpha}{\gamma \mu_0^2 M \Omega}$$

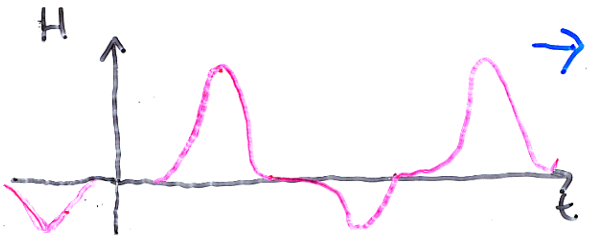
$$S_M = \frac{4 k_B T \chi''(\omega)}{\Omega \omega \mu_0}$$

RANDOM NOISE TERM

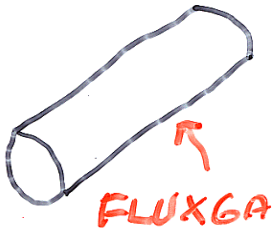
$H_{APPLIED}$ = "DC" $\rightarrow$

SIMPLE TO SOLVE

$H_{APPLIED}$ =

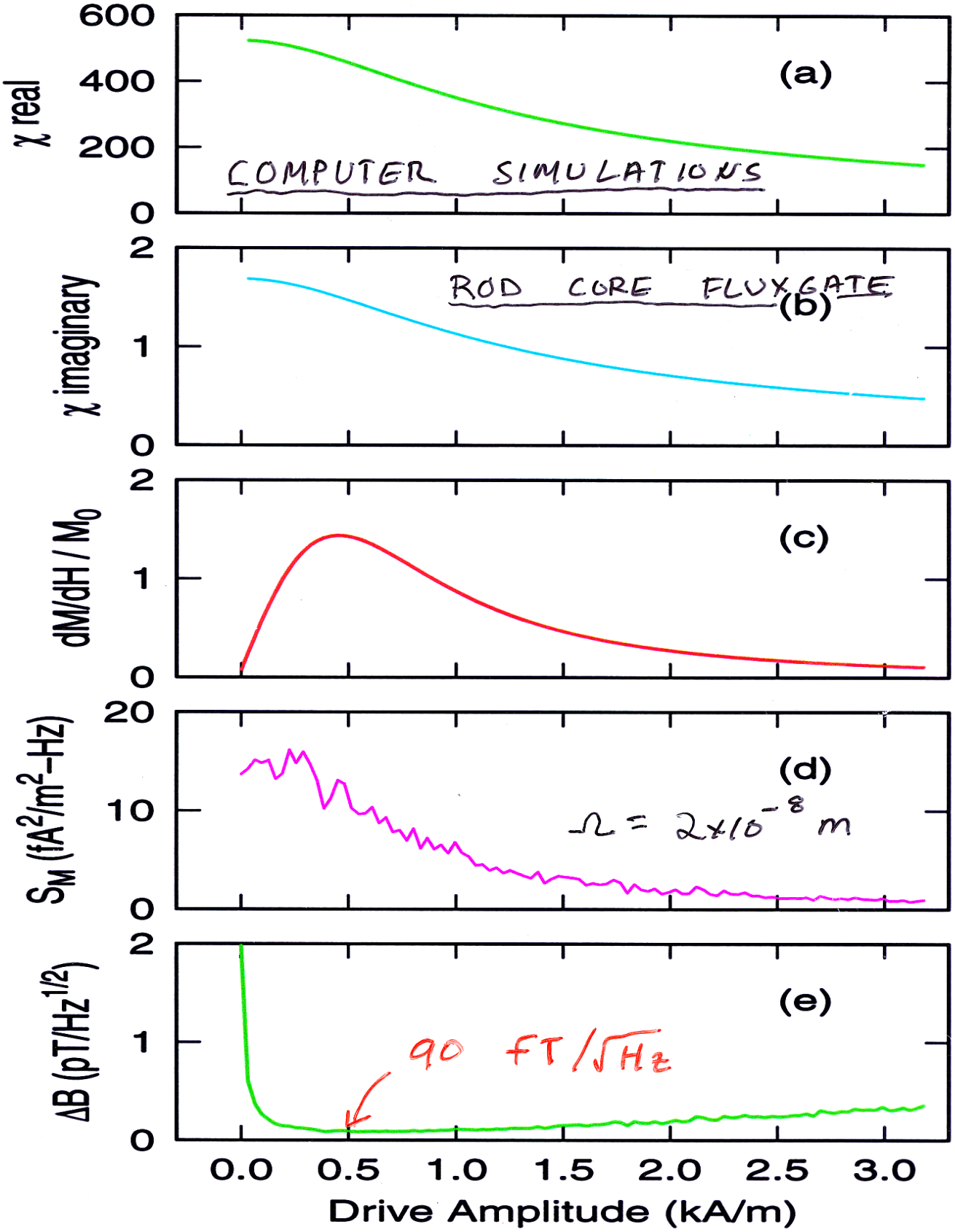


$\rightarrow$

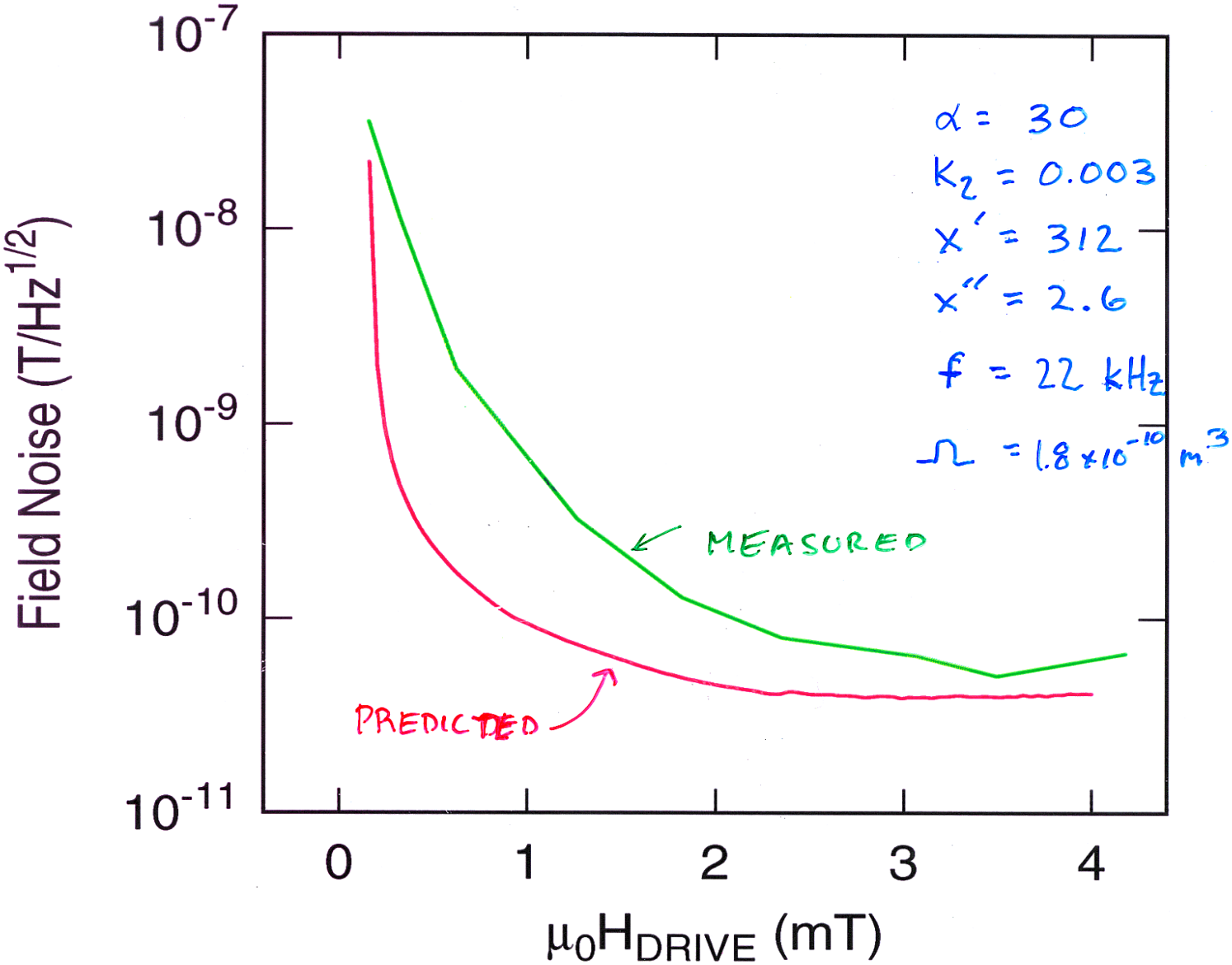


FLUXGATE

REQUIRES COMPUTER

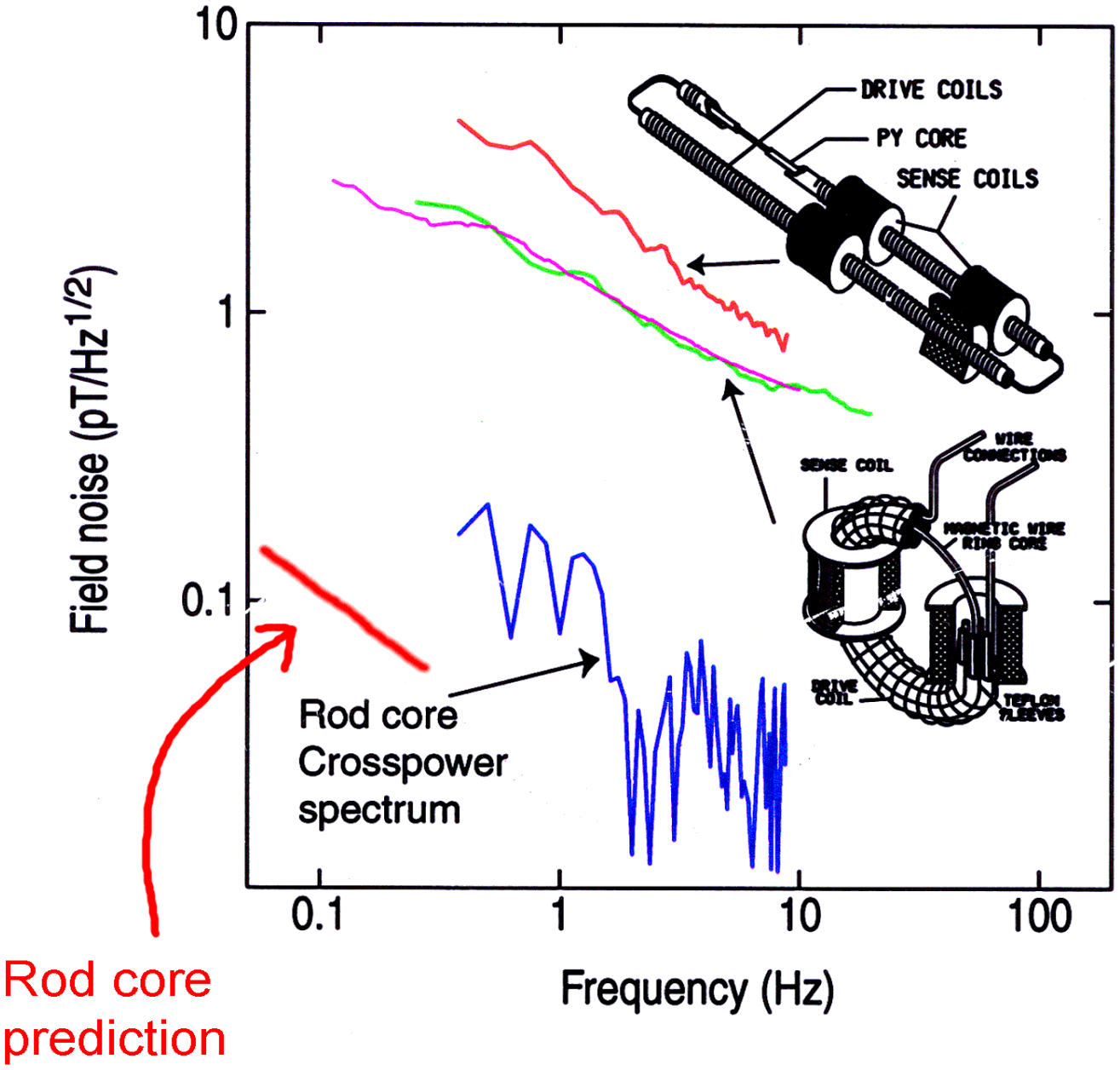

600
400
200
0
χ real
(a)
COMPUTER SIMULATIONS
2
1
0
χ imaginary
ROD CORE FLUXGATE
(b)
2
1
0
dM/dH / M0
(c)
20
10
0
SM (fA2/m2–Hz)
(d)
Ω = 2x10-8 m
2
1
0
ΔB (pT/Hz1/2)
(e)
90 fT/√Hz
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Drive Amplitude (kA/m)

THIN FILM FLUXGATE



$S_M = 6.0 \times 10^{-11}$ $A^2/m^2 Hz$

$\sqrt{S_B} = 6 \times 10^{-11}$ $T/\sqrt{Hz}$


10
1
0.1
Field noise (pT/Hz^1/2)
0.1
1
10
100
Frequency (Hz)
DRIVE COILS
PY CORE
SENSE COILS
SENSE COIL
WIRE CONNECTIONS
MAGNETIC WIRE RING CORE
DRIVE COIL
TEFLON SLEEVES
Rod core
Crosspower
spectrum
Rod core
prediction

CAN WE PREDICT THE

1/f NOISE IN A FLUXGATE?

≈ NO

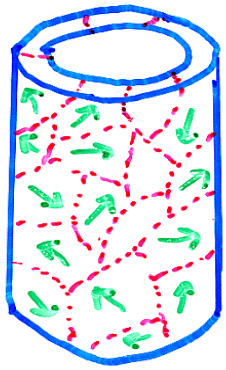
CAN WE UNDERSTAND THE

1/f NOISE IN A FLUXGATE?

≈ YES

K_u ≡ UNIAXIAL ANISOTROPY

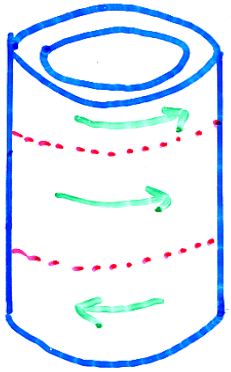
$K_u = 0$



APPLIED FIELD PRODUCES DISCONTINUOUS DOMAIN WALL JUMPS

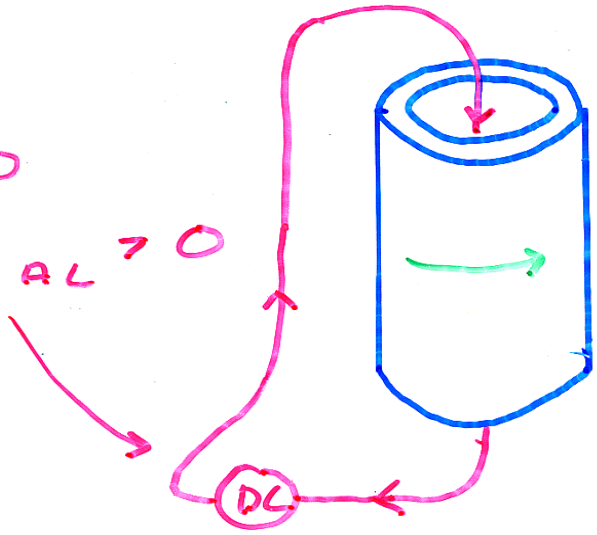
BARKHAUSEN NOISE

$K_u > 0$
$H_{AXIAL} = 0$



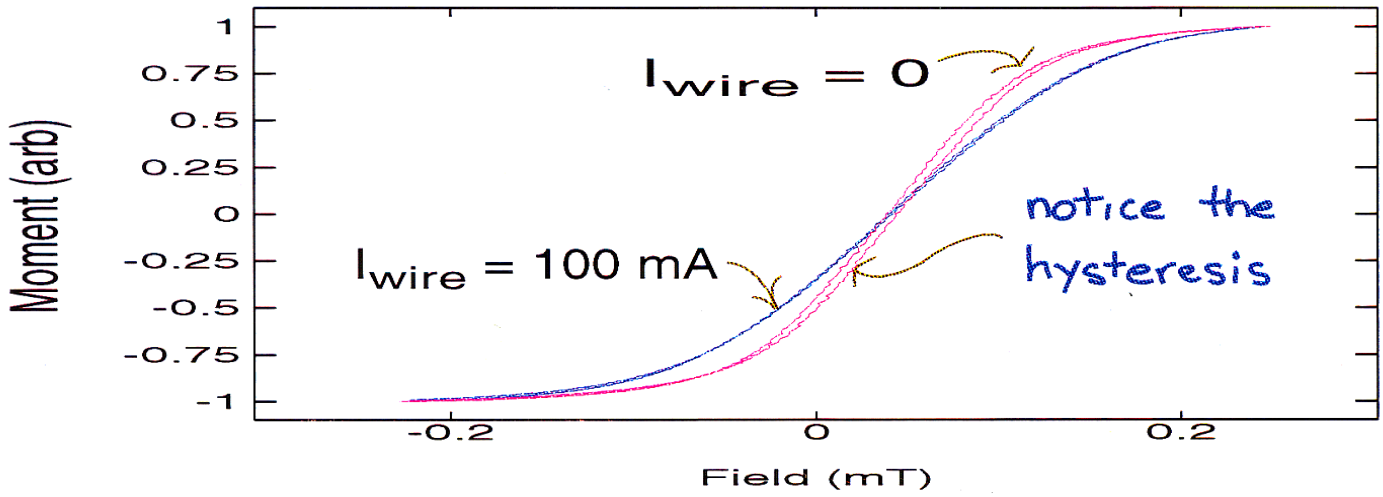
K_u INDUCED USING A MAGNETIC ANNEAL

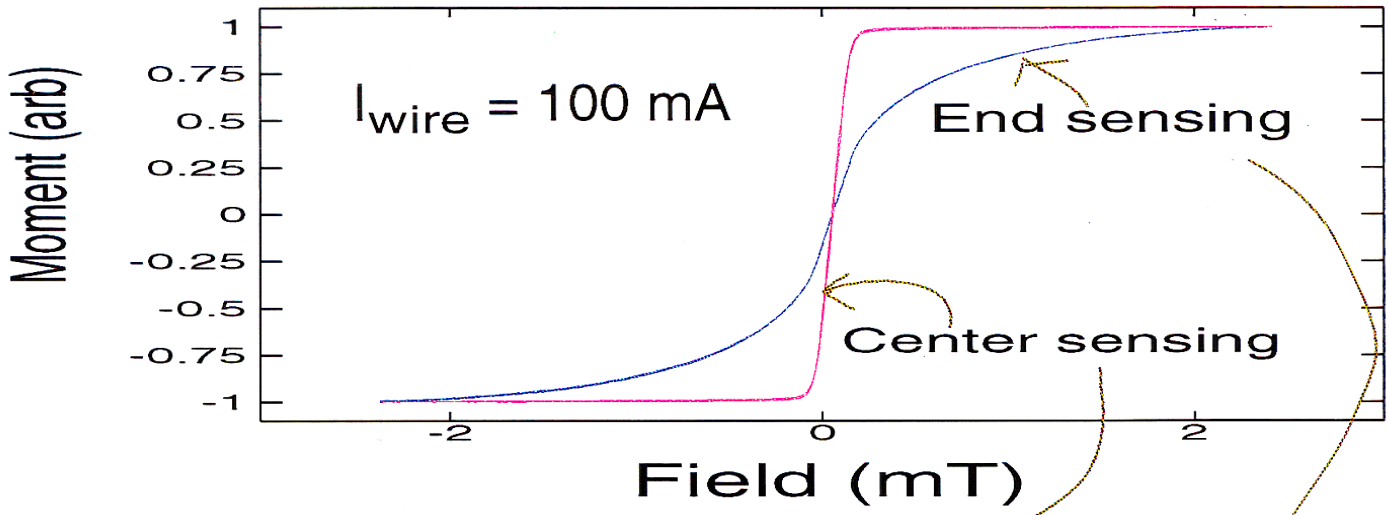
$K_u > 0$
$H_{AXIAL} > 0$

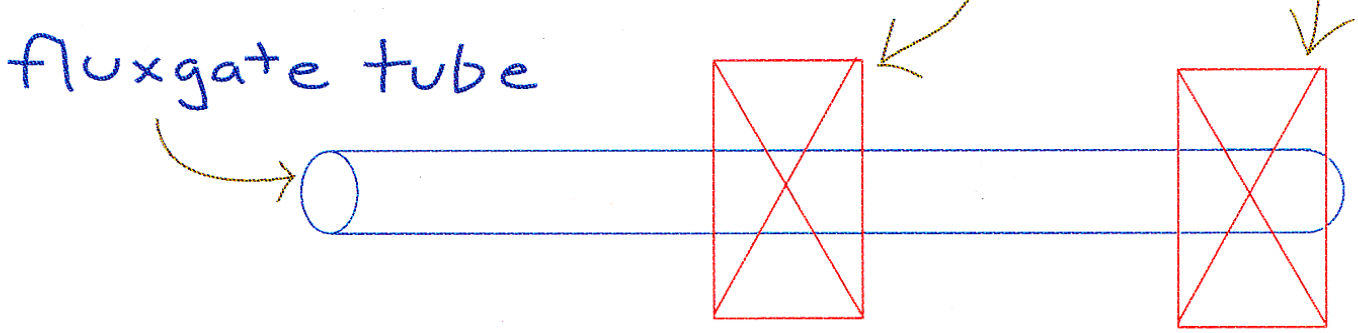


H_{AXIAL} PRODUCES A LARGE SINGLE DOMAIN THAT CHANGES BY ROTATION

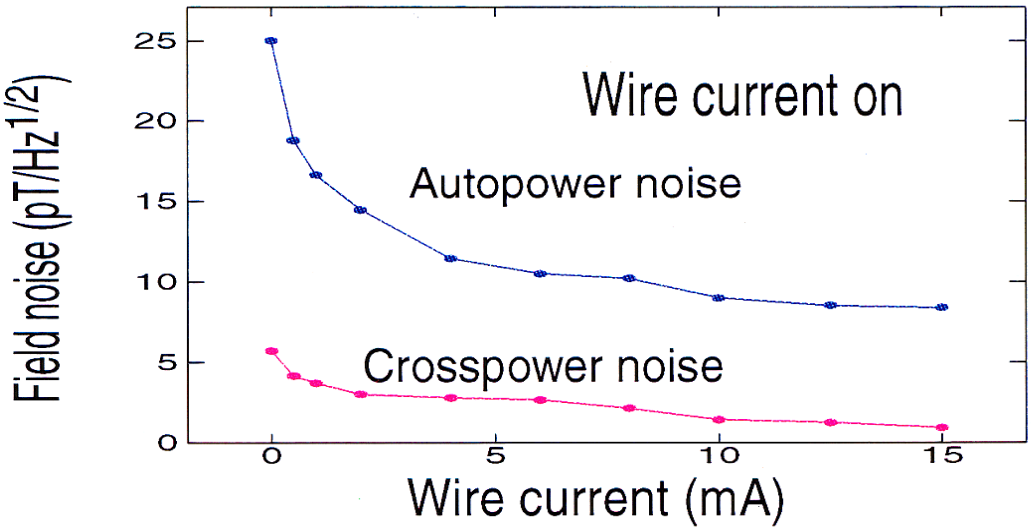
M-H loops in the rod core fluxgate

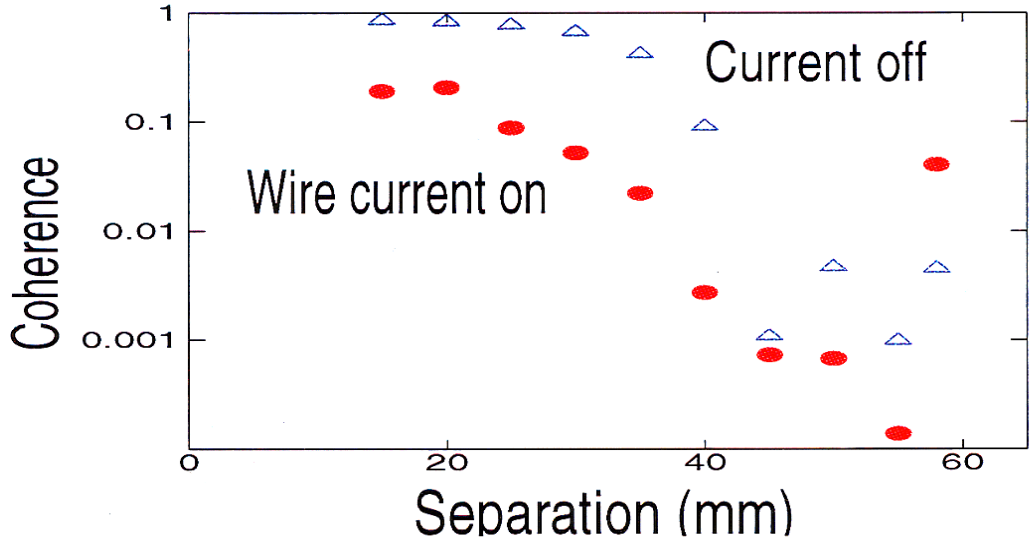


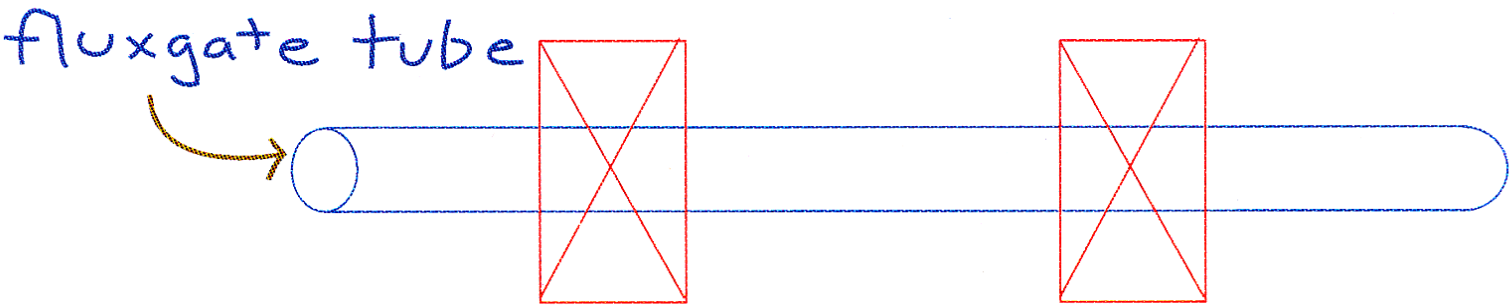




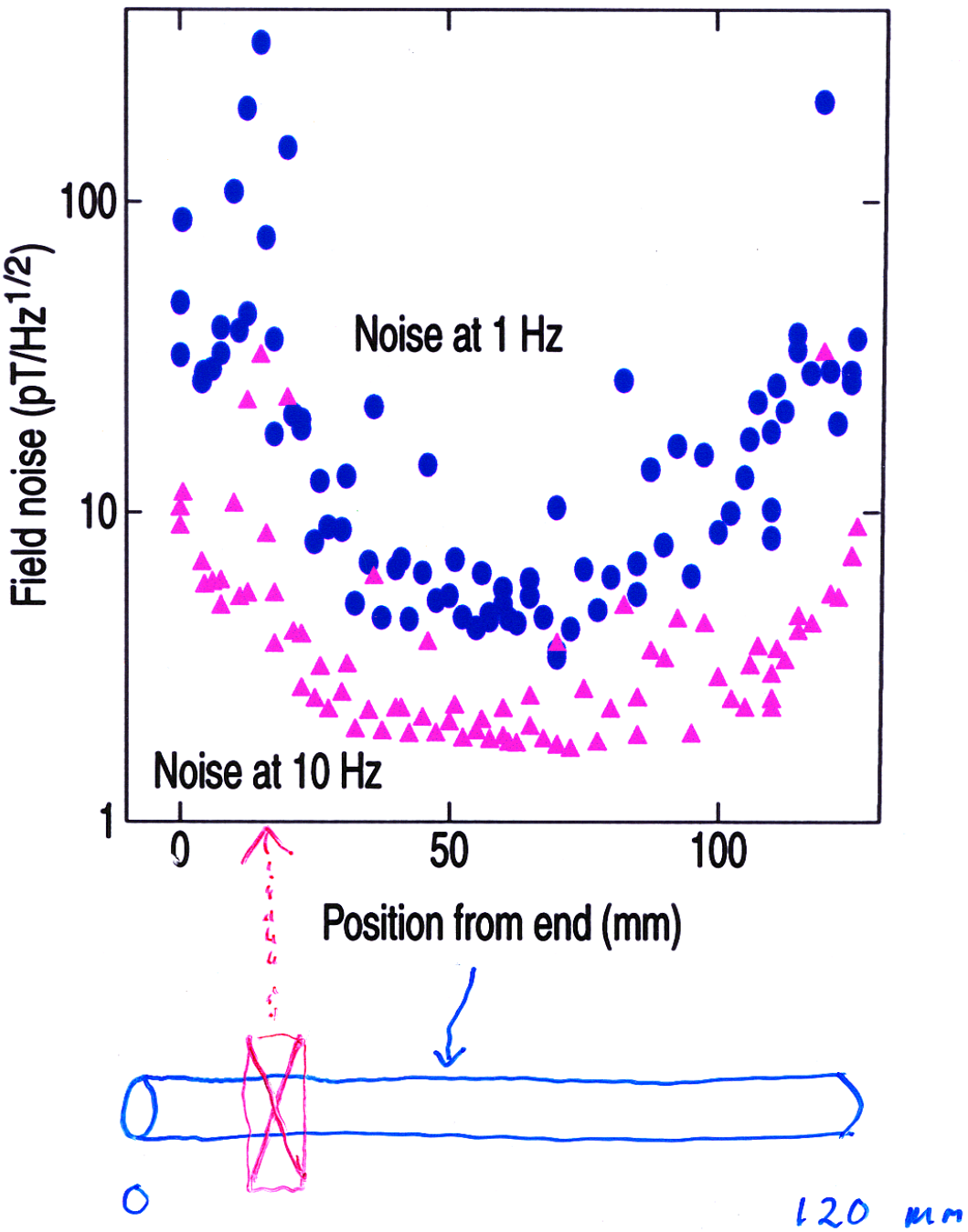
Cross correlation noise measurements



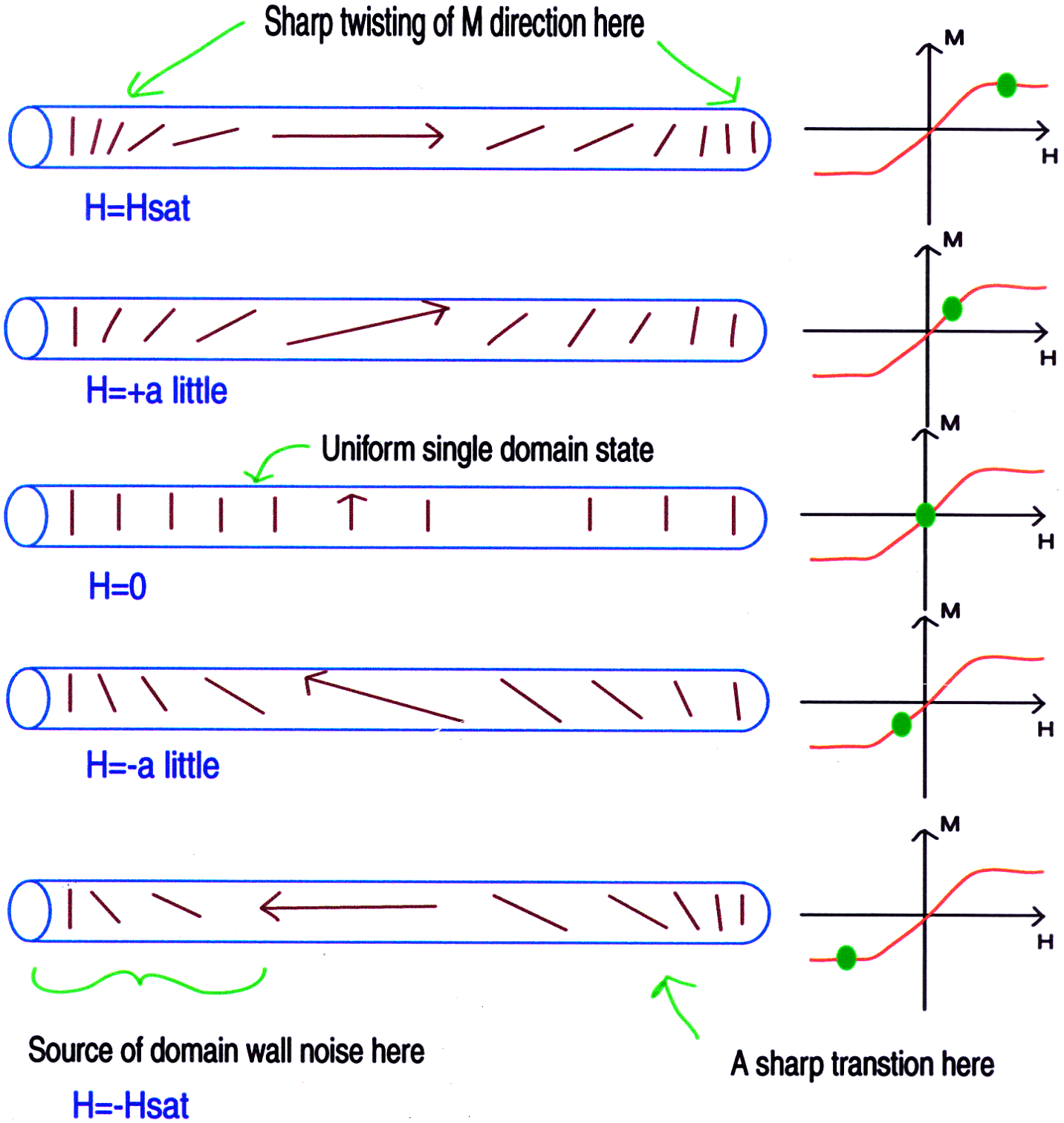




NOISE MEASURED ALONG TUBE:



Stochastic Reversal Noise



Summary

MR sensors

Increasing values of MR will reduce readout noise.

Fundamental noise limit depends on materials parameter χ''.

Chopping direction of pinned layer can reduce low frequency noise.

More work needed to make "single domain" MR sensor.

Fluxgate sensors

Electronic readout noise is a major problem.

Fundamental noise limits depends on materials parameter χ''.

Applied currents can improve magnetization uniformity and reduce noise.

More work needed to make "single domain" fluxgate sensor.