Introduction to Magnetic Recording

From Medium Grains and Head Poles to System Error Rate and High Density Limits

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Outline

- Part I: System Overview
  - Basic recording configuration, Product density growth, Parameter definitions
  - Digital recording, Medium microstructure, Writing a digtial "1", Definitions of transition parameter and cross track correlation width.
  - Basic medium jitter noise, Overview chart of design – course direction.

- Part II: Magnetic Fields
  - Fields from currents and magnetized materials, Concept of poles
  - Fields from heads and media, Probe-SUL effect on medium fields
  - Imaging, Units

Outline (cont.)

- Part III: Magnetic Materials
  - Hard Materials: M-H loop characteristics, Curie temperature, Atomic exchange, Grain boundaries structure, Anisotropy, and coercivity, Reversal versus grain orientation, Effect of exchange and anisotropy distributions, Loop shearing.
  - Soft Materials: M-H loop characteristics, Permeability, Domain walls, Hysteresis, Walls in thin films, Unstable GMR response
  - Thermal Reversal Effects in Hard Materials: Coercivity versus time, temperature, Magnetization versus time, temperature, Effect of intergranular exchange and magnetization.

- Part IV: Read Back Process
  - GMR structure and basic design, Bias fields, Transfer function, Sensitivity in microvolts per micron of track width.
  - Isolated pulse shapes, Analytic expressions for Pulse Shape, Roll-off curve, T_{50}, PW_{50}, $D_{50,}$ Track edge effect, Instabilities.

Outline (cont.)

- Part V: Write process
  - Basic write head structure, flux patterns, head efficiency and dependence on current rise time and head saturation magnetization.
  - Basic write process, Slope models, Effect of intergranular exchange and head-medium geometry on transition parameter.
  - NLTS, Overwrite and Track edge effects.

- Part VI: Medium noise
  - Medium microstructure and noise, basic transition noise, Separation of DC (uniform) and transition noise power, Noise voltage analysis, Correlation function, Effect of intergranular exchange.
  - DC noise analysis, DC noise for longitudinal and perpendicular media, Comparison with transition noise.

Outline (cont.)

- Part VII: SNR and BER
  - SNR definitions, simple expressions using only jitter noise, SNR versus areal density, SNR dependence on grain size and anisotropy field, Comparison chart of media and head noise versus density.
  - BER analysis: Viterbi channel, PR equalization, Why BER does not scale exactly with SNR,
  - Off track effects: Bathtub curve and OTC, Squeeze and “747” curves, Multipass thermal erasure, Setting of Track pitch relative to write width (TP/W_w).
  - Pseudo Random Sequences

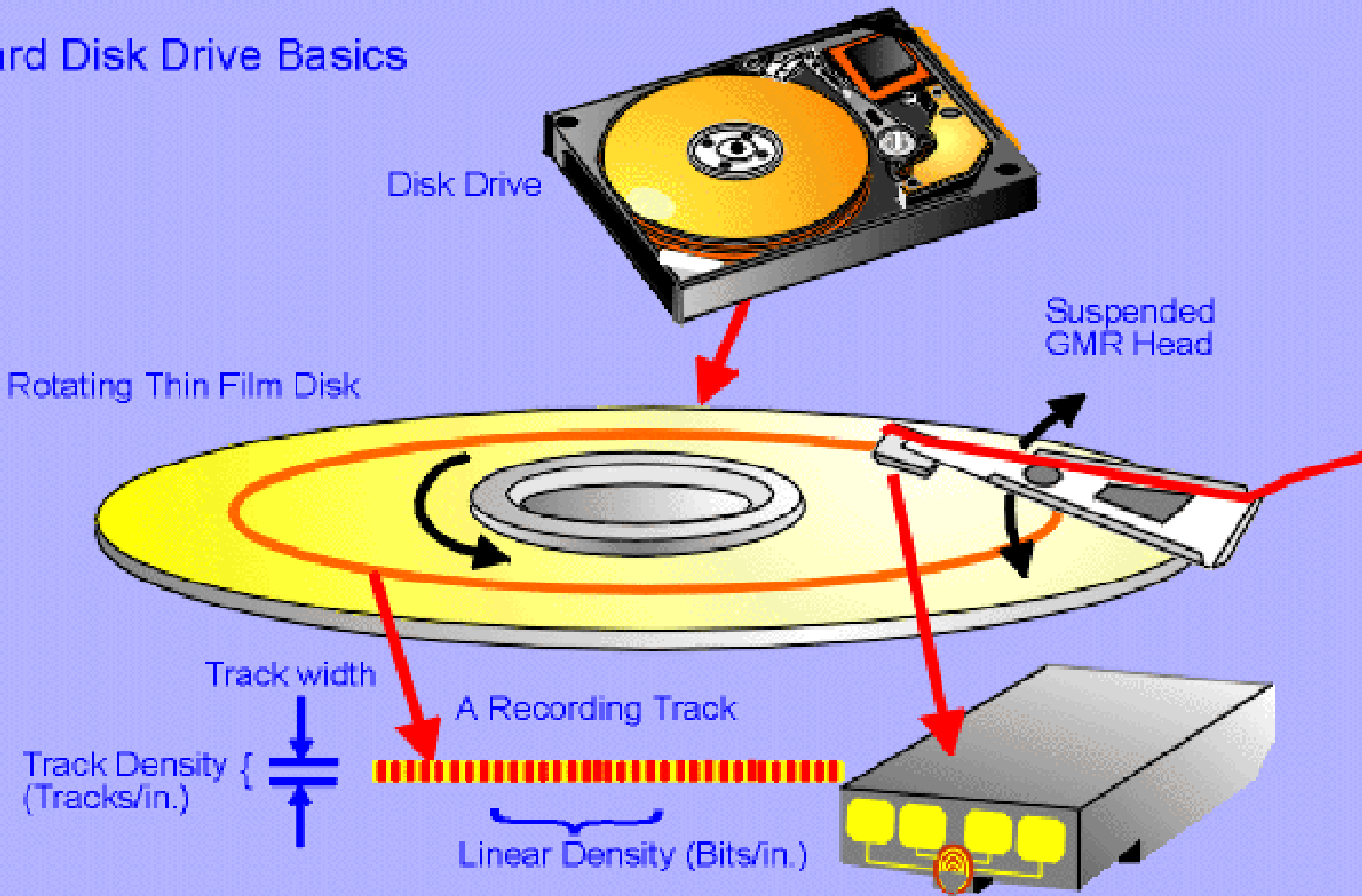
- Part VIII: System Density Limit Considerations
  - Basic trade off of SNR and thermal decay, Example of design for 200 Gbit/in^2, Longitudinal versus Perpendicular recording.
  - Advanced perpendicular media; tilted, composite and patterned media.

Outline (cont.)

- Problems/Solutions
- Extra Foils
- Text references

I. System Overview

Hard Disk Drive Basics

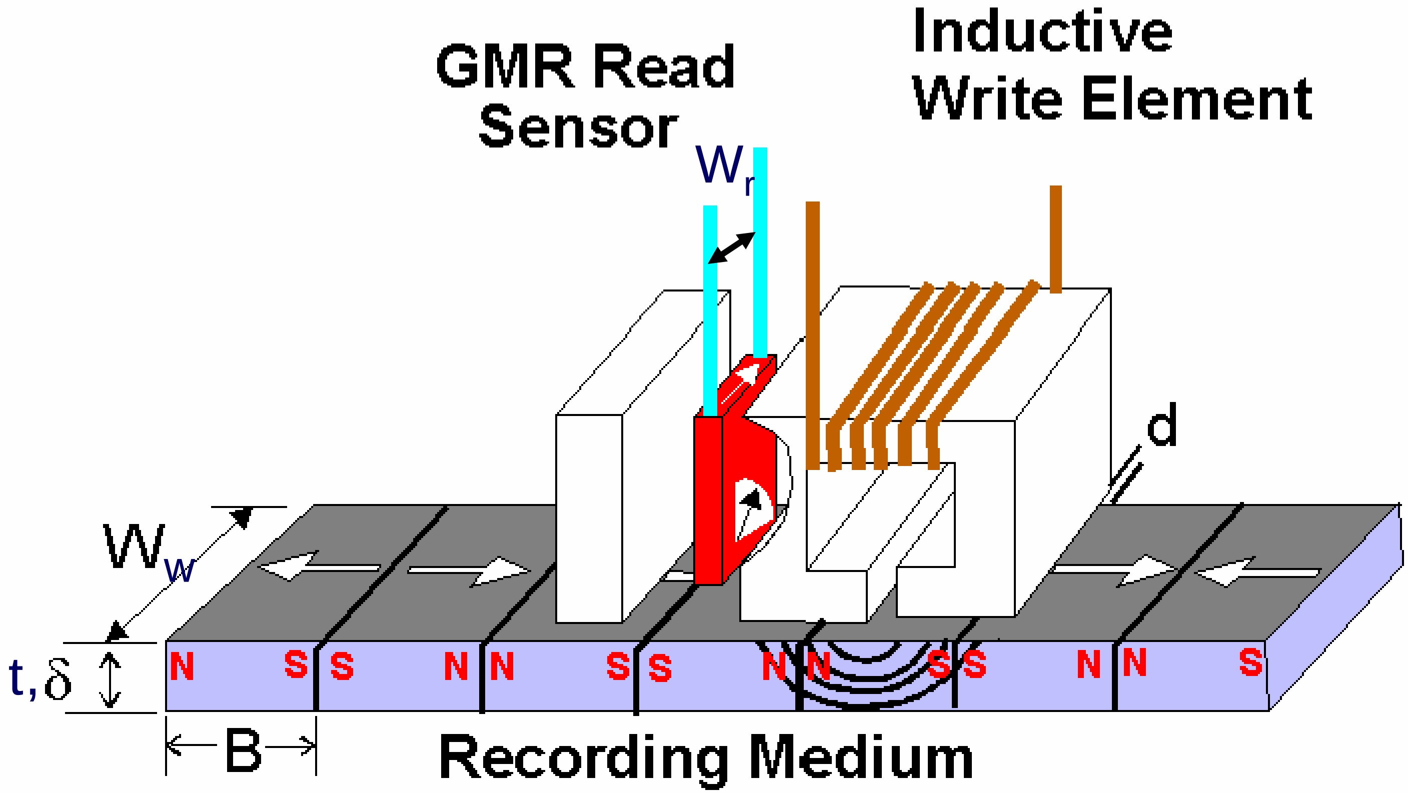


Areal Density = Linear Density x Track Density

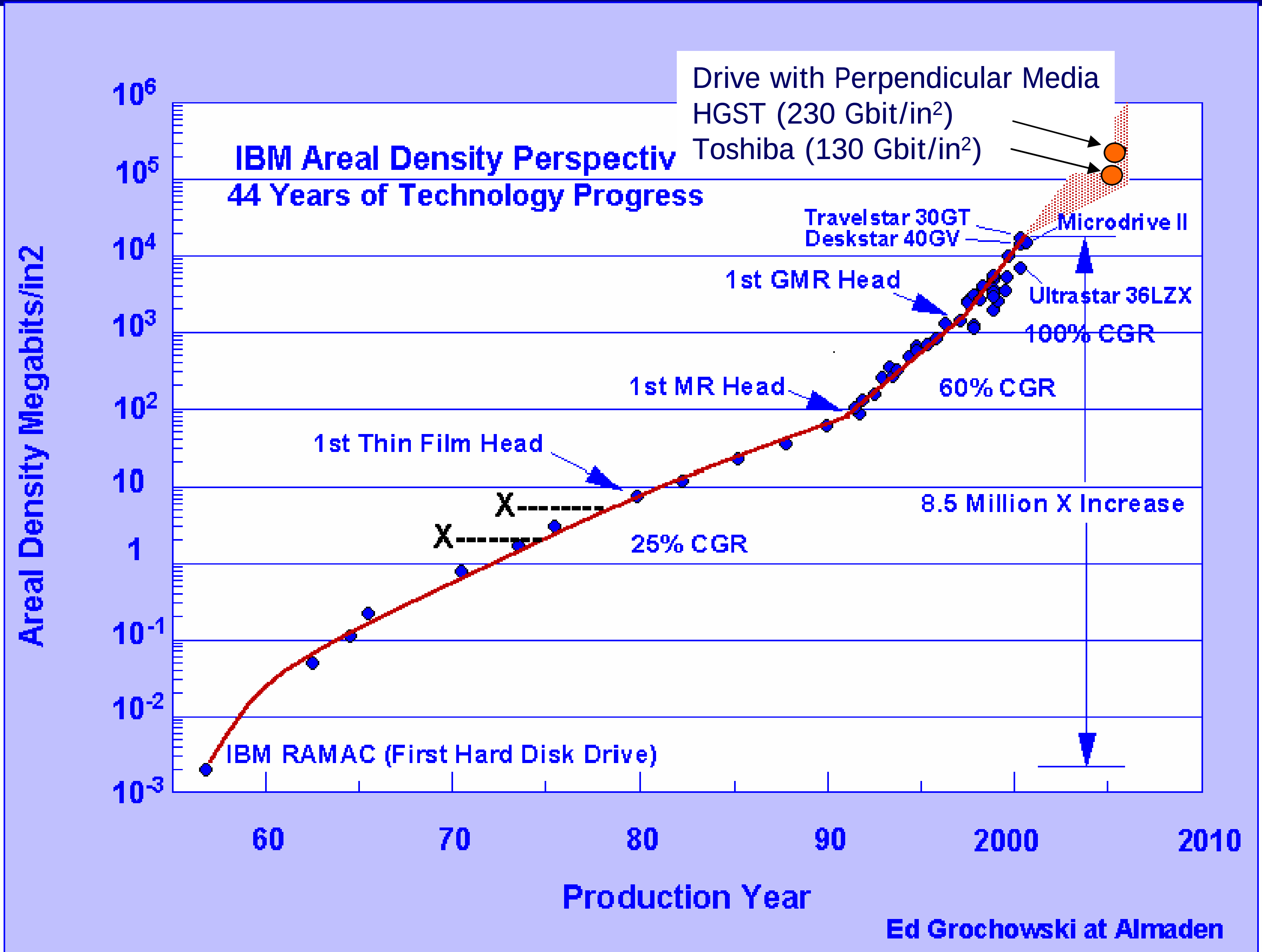
(bits/in^2) (bits/in) (Tracks/in)

IBM Advanced Technology

MAGNETIC RECORDING PROCESS



AREAL DENSITY HISTORY



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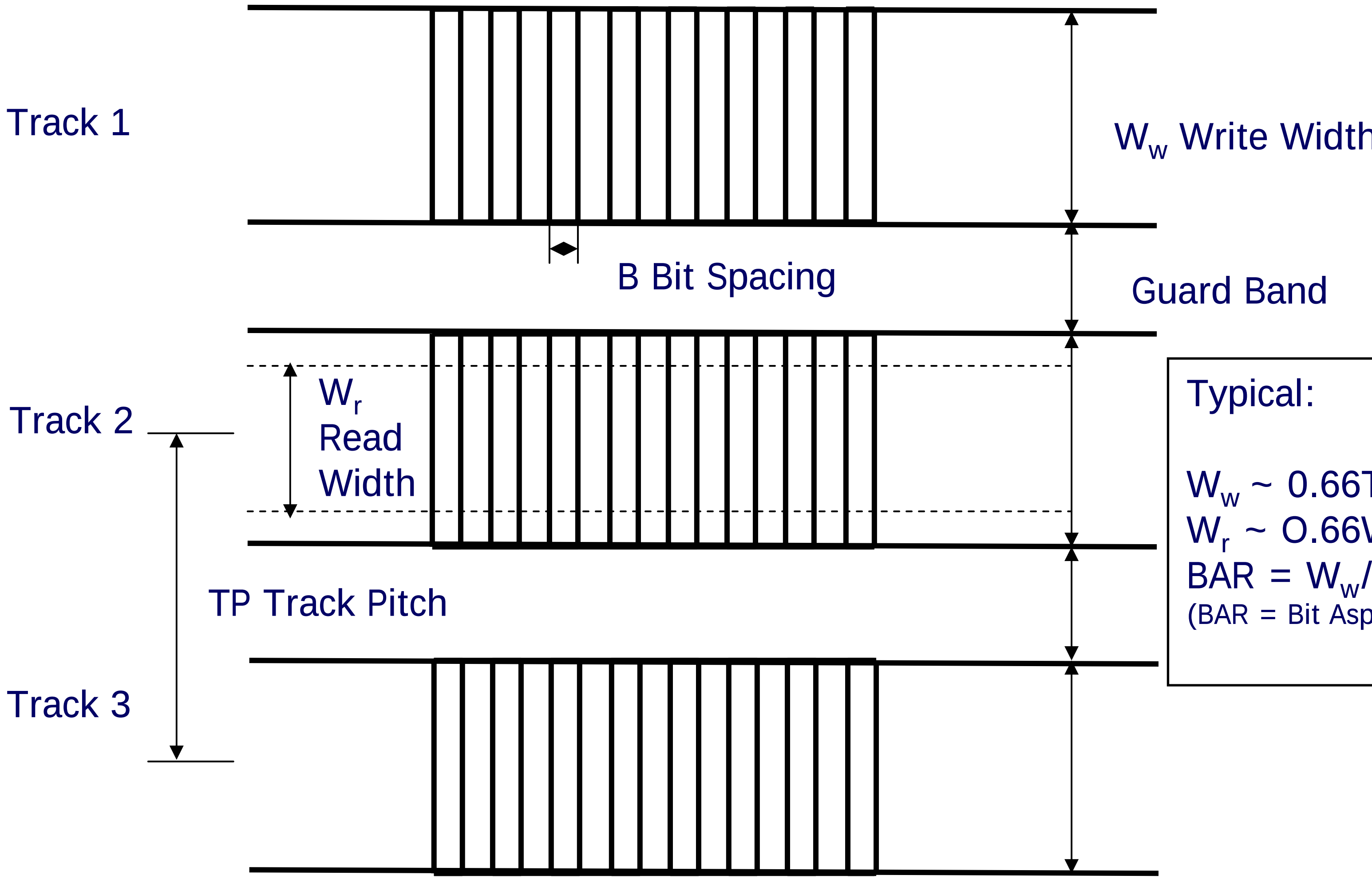
Record Geometry Details



Typical:

$W_w \sim 0.66T_{sp}$
$W_r \sim 0.66W_w$
$BAR = W_w/B \sim 8$
(BAR = Bit Aspect Ratio)

Record Density Example

- Suppose we are given a head with a 200 nm write width and media that will support 500 kfci.

  What is the BAR and the areal density in Gbit/in^2?

B = (1/500000 Bits/in) x 2.54cm/in x 10^7nm/cm = 51nm (~ 2 μ")
Track Pitch (TP) = (200/.66)nm = 303nm (~ 12μ")

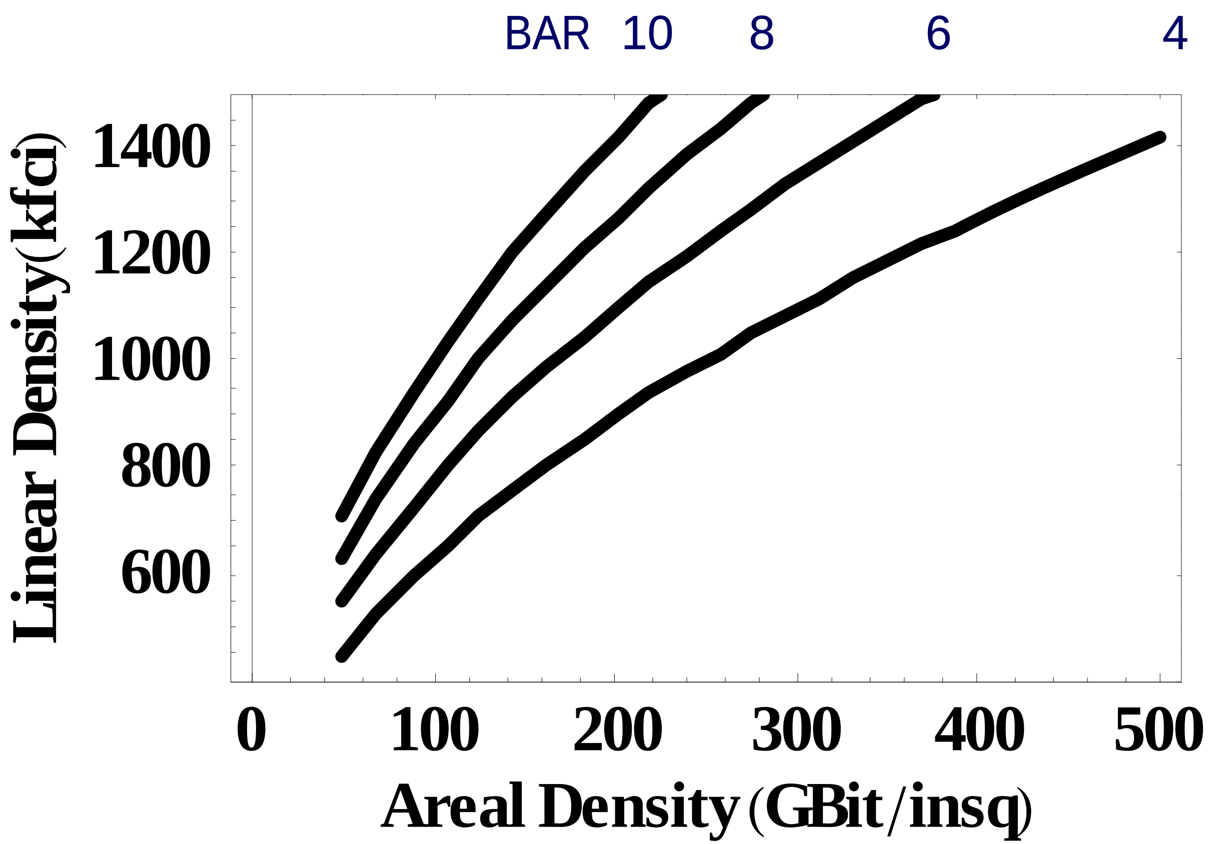
=> BAR = TP/B = 6

Linear Density = 1/B = 500 kfci
Track Density = 1/TP = 84 ktpi

Areal Density = 500 x 84/1000 Gbit/in^2 = <u>42 Gbit/in^2</u>

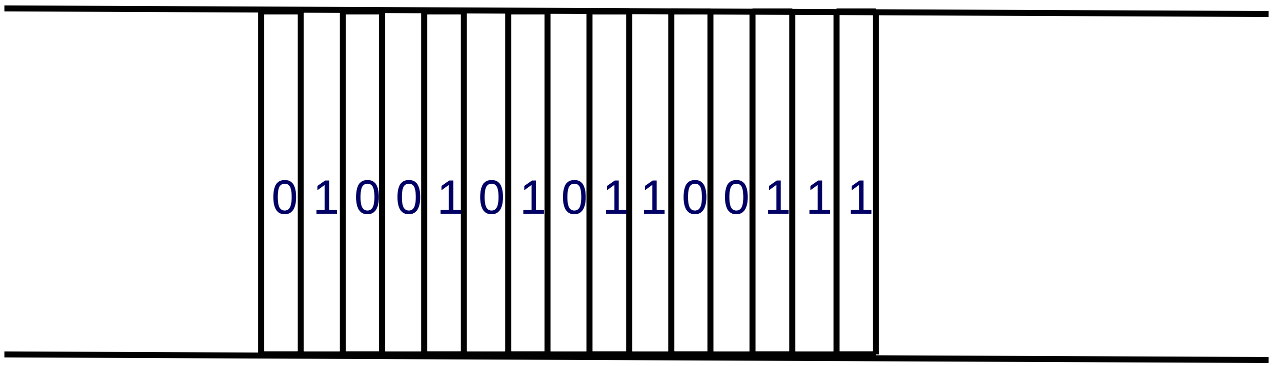
Record Density Examples cont.

$$\text{Linear Density}\,(kfci) = \sqrt{1000 \times ArealDensity(GBit/in^2) \times BAR}$$



Digital Recording

- At each cell we record "1" or a "0" of information (e.g)



- Word of information:

(010010101100111) (e.g 15 million in your bank account)

- Suppose read with an error:

(010010100100111) (e.g 15 cents in your bank account)

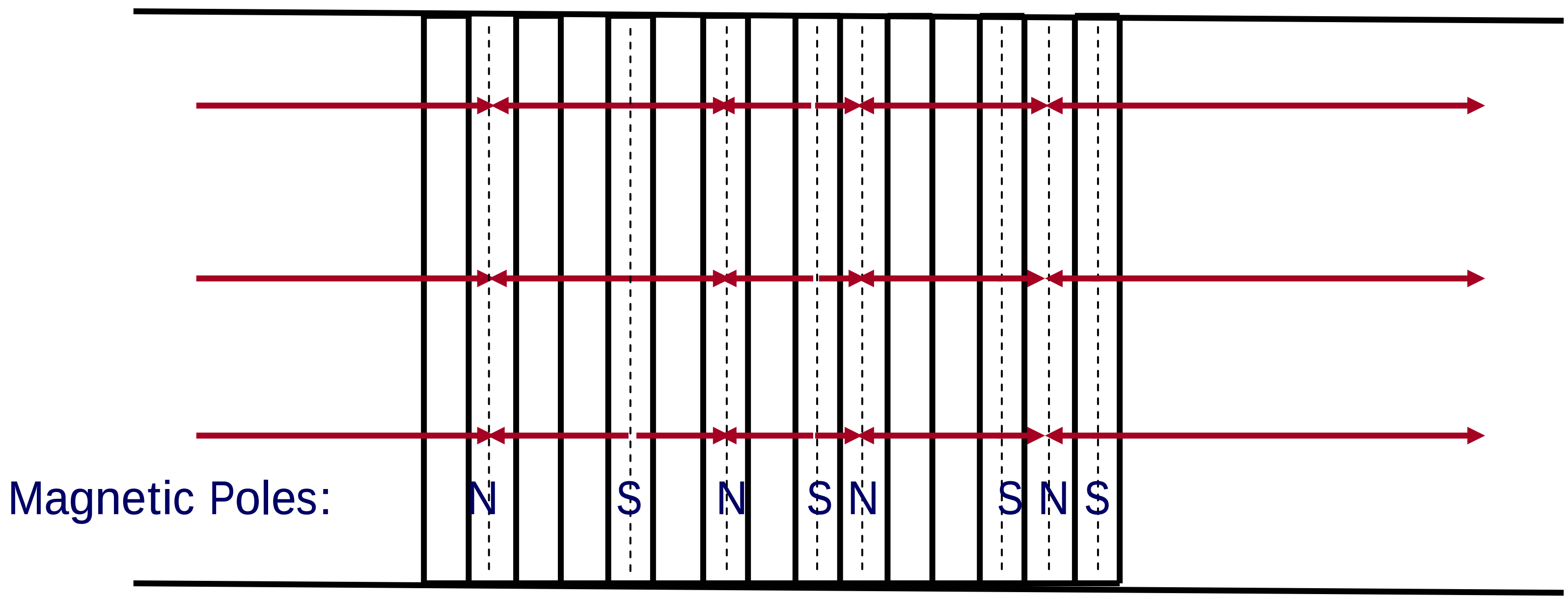
- We want a probability of raw error BER: 10^{-6} -10^{-5}
  Corrected to system BER of 10^{-12}

Writing "1"s and "0"s

- In our magnetic medium "1" corresponds to changing the direction of the magnetization in the cell. "0" corresponds to no change.

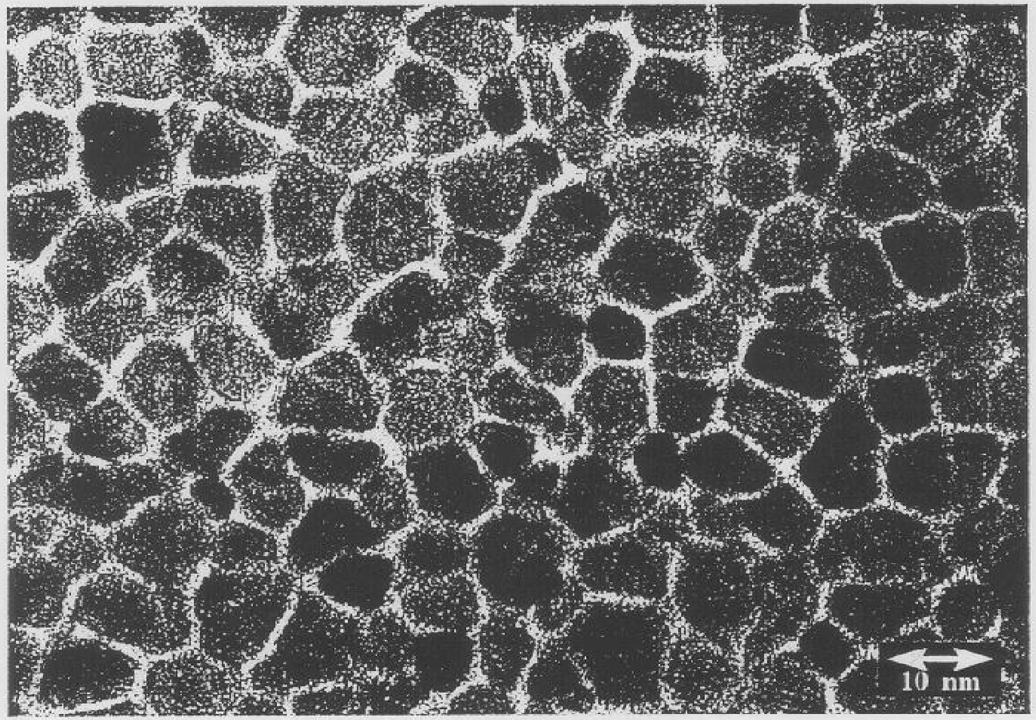
- Our example pattern is:

(0 1 0 0 1 0 1 0 1 1 0 0 1 1 1)



Medium Microstructure

• Medium consists of a tightly packed array of columnar grains with distributions in both size and location



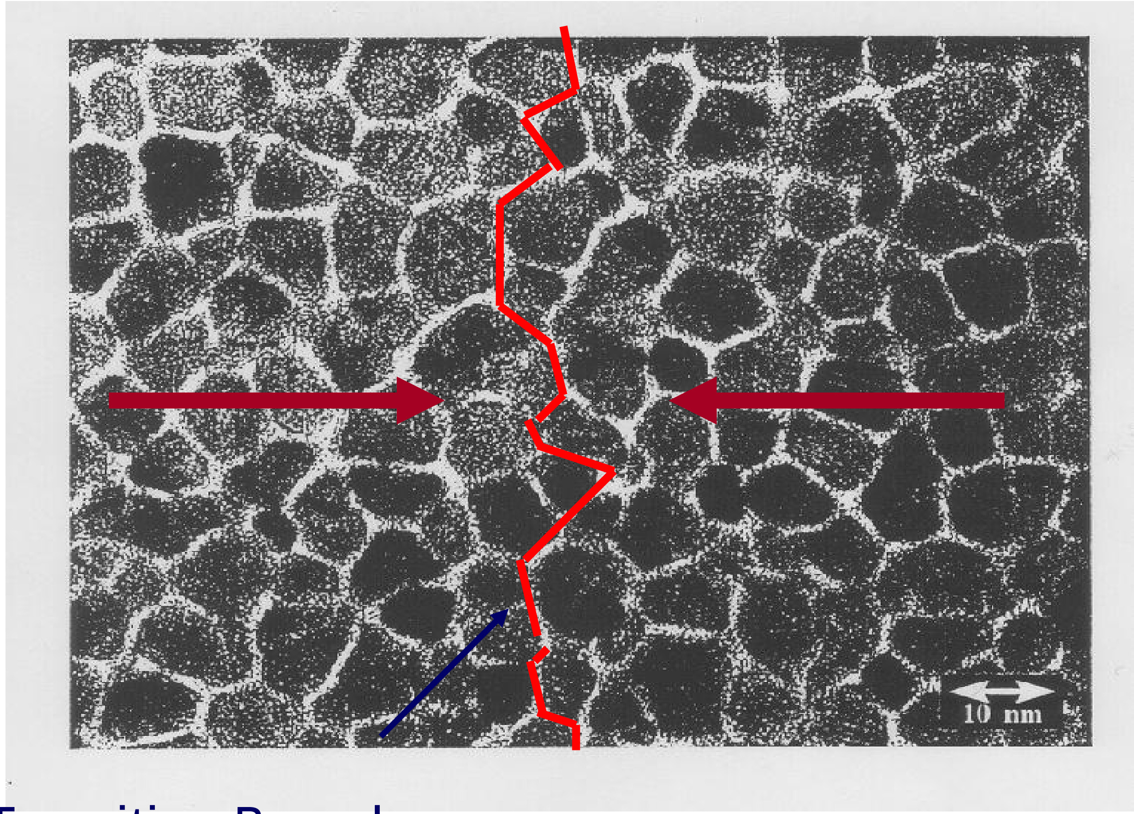
TEM – Top View

Average grain Diameter: <D> ~ 10nm

Illustration of a Recorded Magnetization Transition "1"

Down track direction ->

Cross track direction ->



Cross Track Correlation Width s_c

Transition parameter "a" is limited to <D>/3

Crosstrack correlation width $s_c \sim$ <D>

Transition Boundary

Transition Width πa

Issues

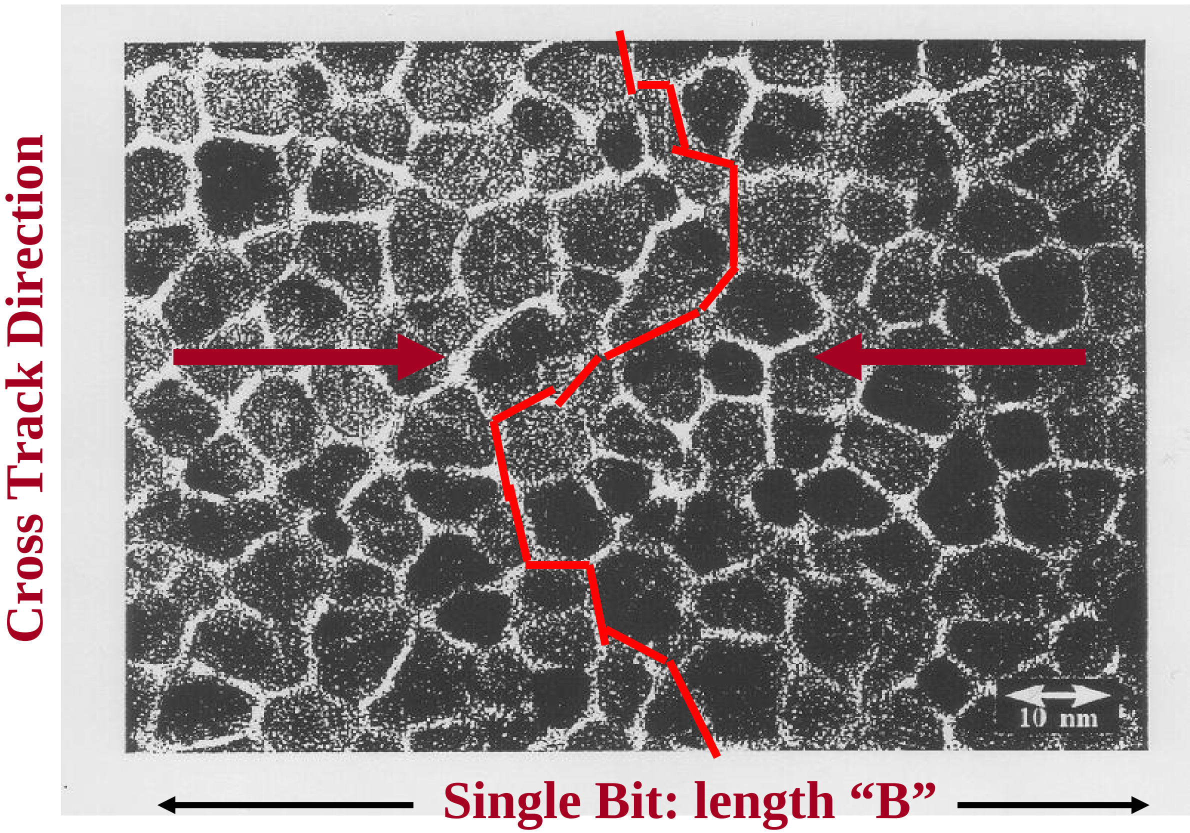
- We want a perfectly straight vertical transition boundary.

- Grain location and size randomness gives noise:
  - A “zig-zag” boundary occurs which varies from a “1” bit cell to another.

- Reducing the average grain size may reduce the noise.
  - Too small a grain size gives thermal induced decay of the signal over time

- Thermal effects cause a high density limit

Illustration of a Typical Transition (even more problems!!)



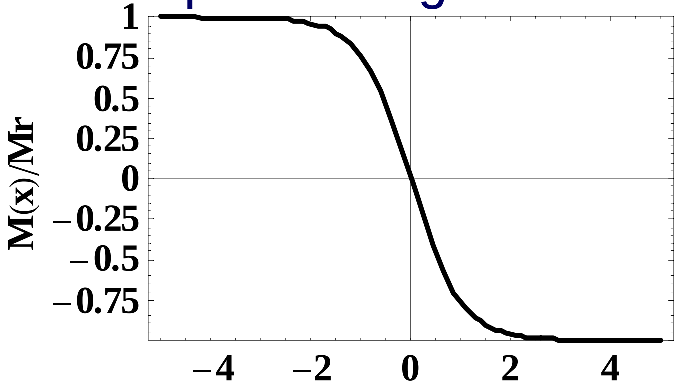
A "poor" transition!!
Low SNR, High BER

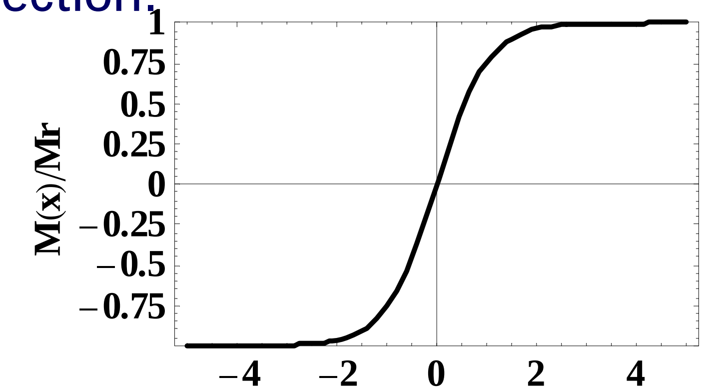
Caused by poor head field spatial variation "gradient" and large "demagnetizing" fields

Transition parameter "a" and Crosstrack correlation width "s_c" are large and somewhat independent of the grain diameter

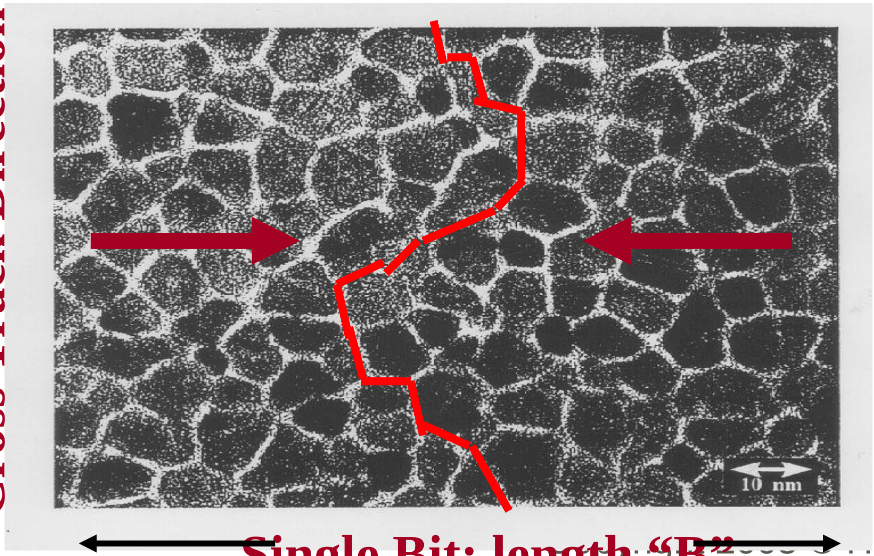
Track Averaged Magnetization

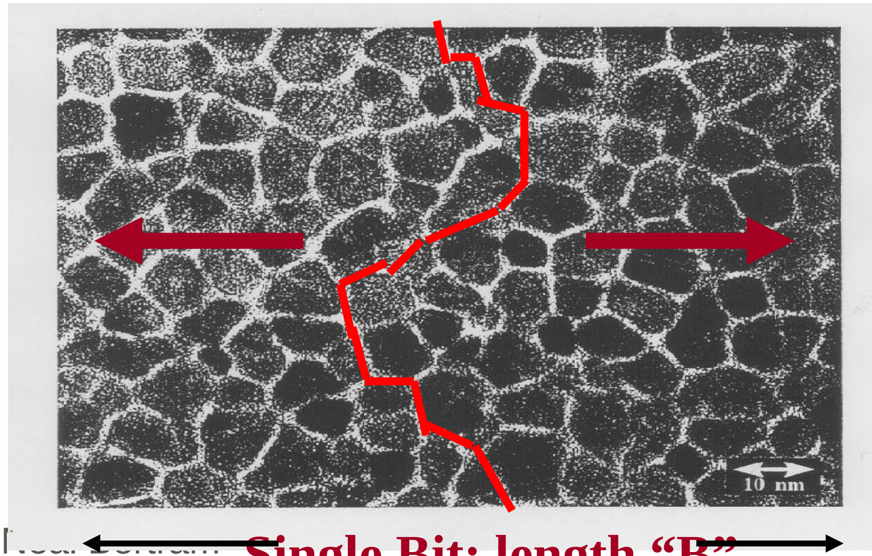
Magnetization is the net vector dipole direction per unit volume. Here we average across the read width to find the average magnetization at each point along the recording direction.





Cross Track Direction

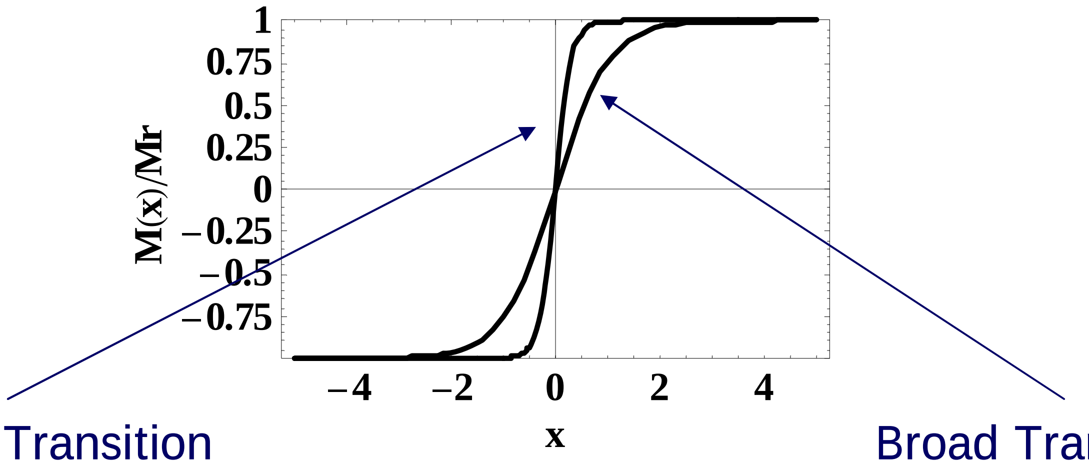




Single Bit: length "B"

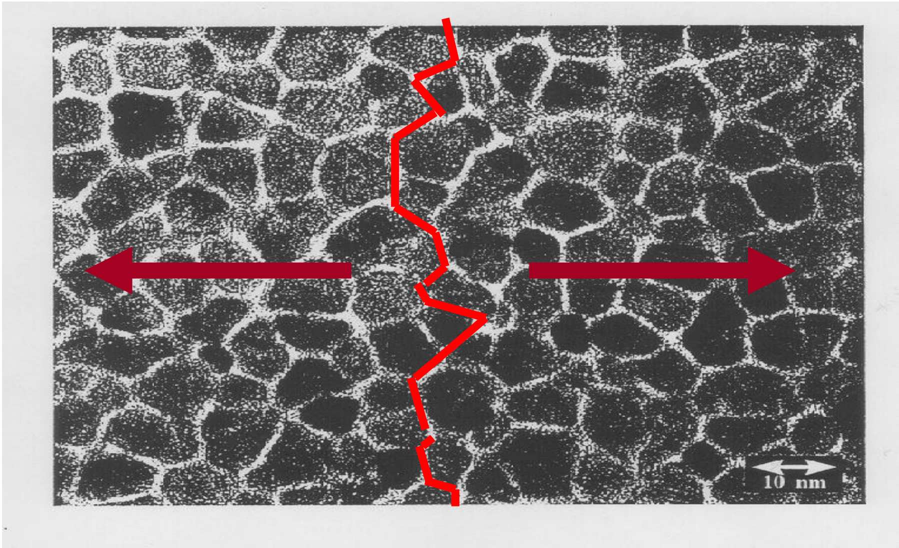
Single Bit: length "B"

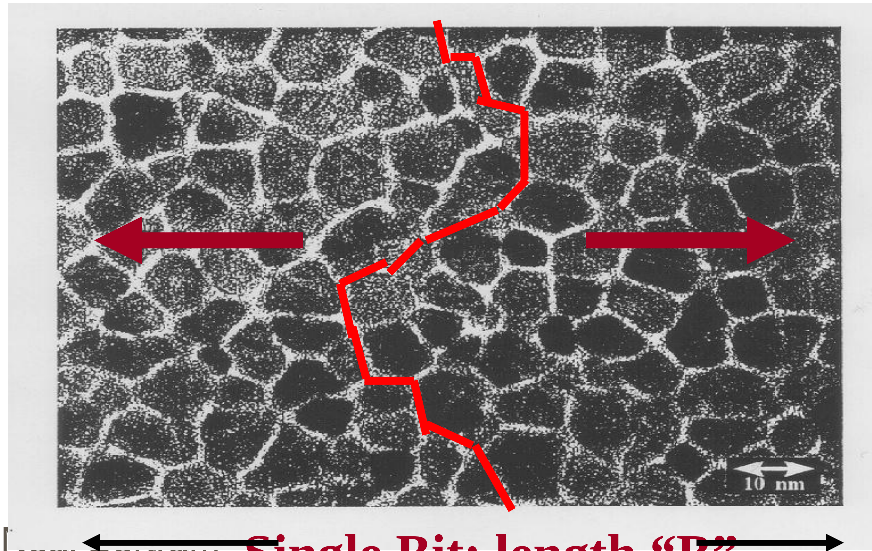
Effect of Transition Parameter



Narrow Transition

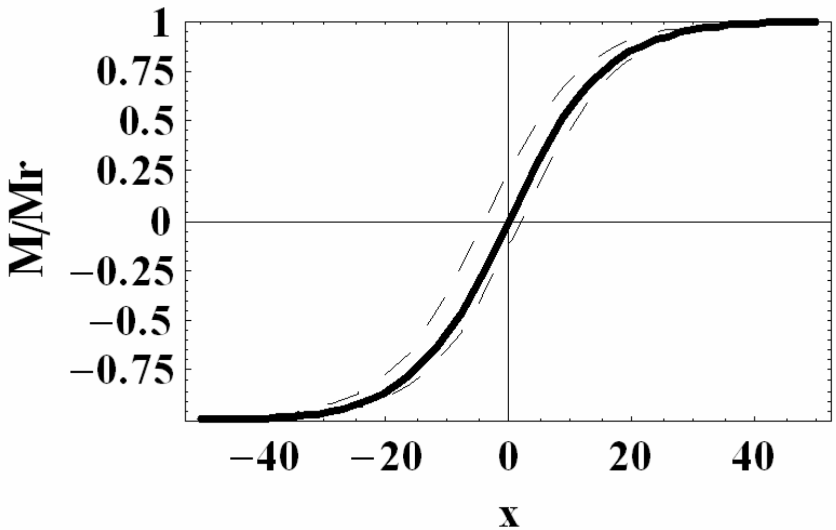
Broad Transition





Single Bit: length "B"

Essential System Noise



Cross track average magnetization profile:

$$M(x) = M_r \tanh\left(\frac{2x}{\pi a}\right)$$

Due to random grain growth, at each bit cell the average transition center position is shifted a little (dashed above). This yields dominant jitter noise.

Jitter noise variance:

$$\sigma_J^2 = \frac{\pi^4 s_c a^2}{48 W_r}$$

What It's All About!!!

What we will cover in detail in this course

- For a system with 10% jitter (SNR ~ 18dB BER ~ 10^{-6} , BAR=6, W_r=3B)

$$\frac{\sigma_J}{B} = 0.10 \approx \sqrt{\frac{2a^2 s_c}{B^2 W_r}} \qquad \text{or} \qquad a^2 s_c \approx \frac{B^2 W_r}{200}$$

Density	B	$a^2 s_c$ (W_r/B =3)	<D> (thermal stability)	s_c (1.2<D>)	a	a/<D>
200 Gbit /in^2	22.4	170nm^3	7.5nm	9nm	4.34nm	0.6 Difficult
1 Tbit /in^2	10nm	15 nm^3	5nm	6nm	1.6nm	0.32 Very very Difficult!

Can We Improve Media, Heads and Signal Processing to Achieve Higher Densities??

- Signal processing:
  - Work with lower SNR and higher BER
  - Advanced products utilize raw BER ~ 10^{-5} - 10^{-4}

- Media:
  - Transfer from longitudinal to perpendicular grain magnetic orientation.
  - Optimize intergranular grain interactions
  - Tilted or composite perpendicular grains to reduce thermal grain size limit.
  - Patterned media

- Heads:
  - Optimize field patterns (down track and cross track)
  - Down track shielded heads are being introduced

II. Magnetic Fields

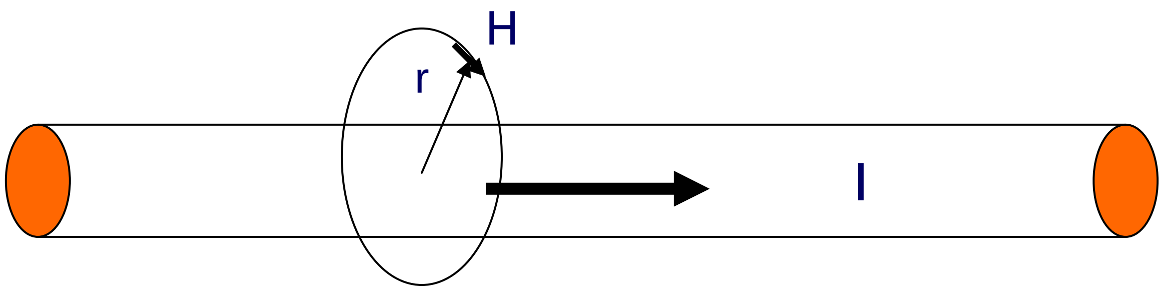
Magnetic Fields H

- Magnetic fields arise from the motion of charged particles.

- In magnetic recording we care about:
  - Currents in wires (write head) , current sheets (GMR reader)
  - Electrons revolving about atomic axis (Magnetostatic fields)

Magnetic Fields H cont.

- Examples of field H from currents:



- Field direction circles around wire (Right hand rule). Away from the ends and outside the wire the field magnitude is given by:

$$H = \frac{I}{2\pi r}$$

Magnetic Fields H (cont.)

- Assume I = 10mA and r = 25μm (thermal limit for a wire):

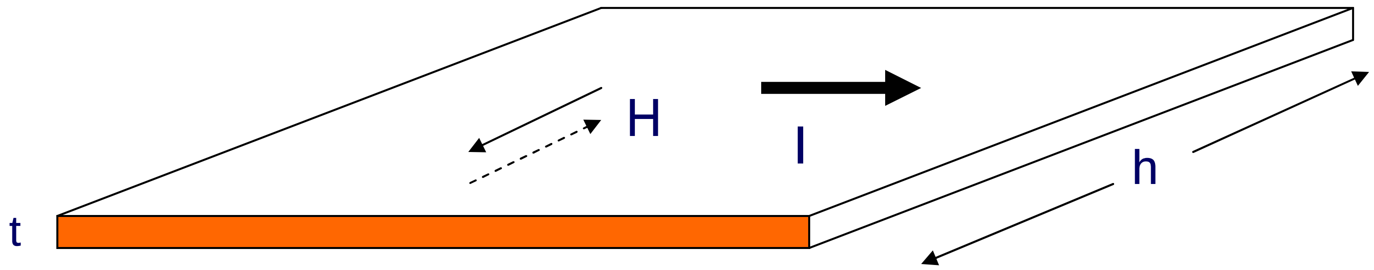
$$H = \frac{10mA}{2\pi 25\mu m} = 64A/m \approx 0.8Oe$$

- The conversion factor is 80A/m ~ 1Oe. It takes a lot of Amps to yield Oe!!

- If the distance is reduced to r = 25nm(like a record gap) the field is now 800 Oe. We achieve large fields (15,000 Oe) by using many turns (7-8) and a magnetic structure (head) to focus the flux.

Magnetic Fields H (cont.)

- Another example is a very thin current sheet:



$$H = \frac{I}{2h}$$

- Again with the RHR, H circles around the sheet as indicated. Away from the edges the field is fairly uniform and not very dependent on distance from the film

Magnetic Fields H (cont.)

- RHR – "Right Hand Rule": If you point your thumb along the current direction, then your fingers give the direction of the field as it circulates around the current.

- Current Density – "J": Current per unit cross section area. For the wire with radius "a" and the thin film with thickness t and width h:

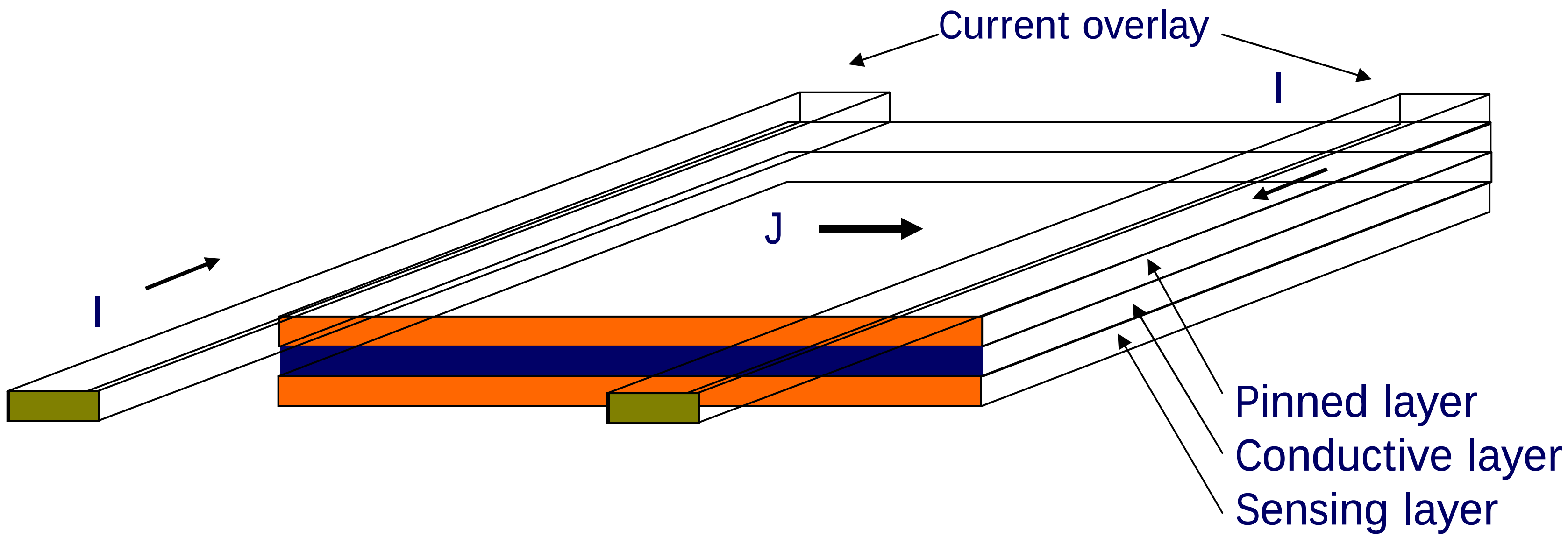
$$J_{wire} = \frac{I}{\pi a^2} \qquad J_{film} = \frac{I}{ht}$$

- In terms of J the fields are;

$$H_{wire} = \frac{I}{2\pi r} = \frac{Ja^2}{2r} \qquad H_{film} = \frac{I}{2h} = \frac{Jt}{2}$$

Magnetic Fields H (cont.)

- Example of the field from the pinned element in a GMR structure acting on the sensing layer (schematic):



- The current through the films follows closely a uniform current density J divided equally between the three layers.

Field H due to Current in the GMR Pinned Layer

- The current divides into the three films:

$$I = I_s + I_c + I_p \approx J_s h t_s + J_c h t_c + J_p h t_p$$

- If the current densities are equal in all three films:

$$I = I_s + I_c + I_p \approx J_p h\left(t_s + t_c + t_p\right)$$

- For sensing current I ~ 2mA, a film height h ~ 70nm, film thicknesses 4,1,4 nm for the pinned, sensing and conducting layers, respectively:

$$J_p = \frac{I}{h\left(t_s + t_c + t_p\right)} \approx 3.17\times 10^{12}\, A/M^2 \approx 3.17\times 10^{8}\, A/cm^2$$

Field H due to Current in the GMR Pinned Layer

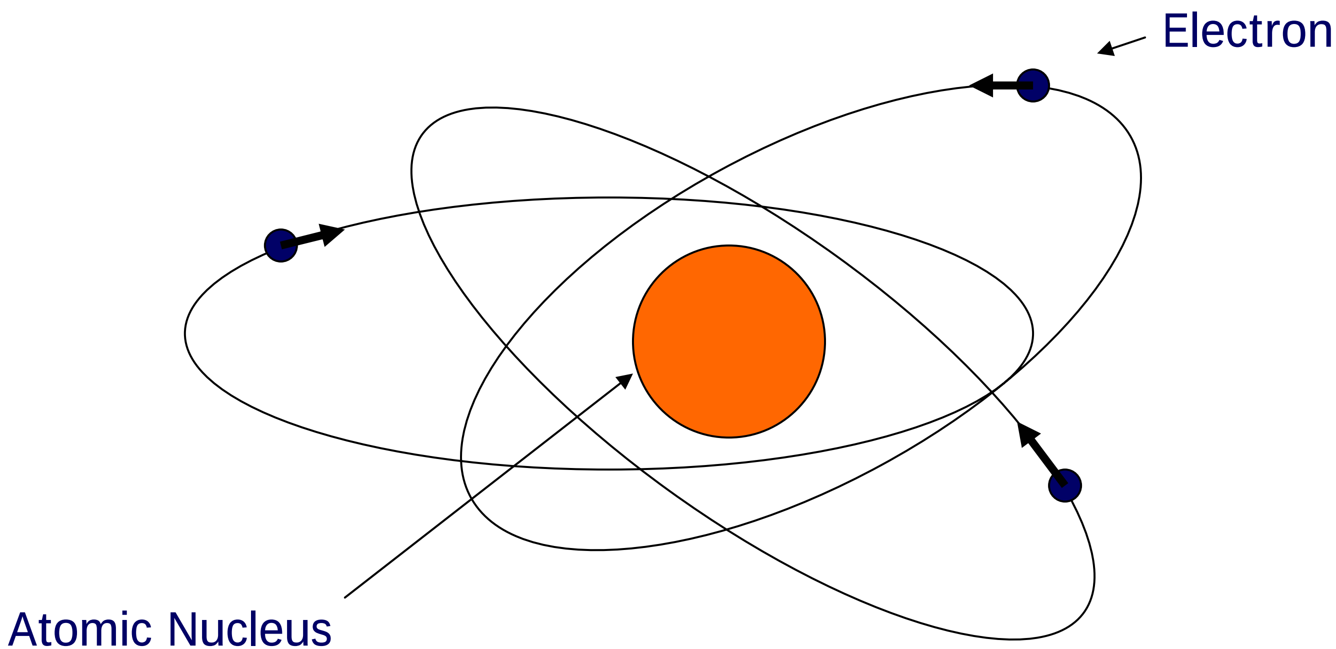
- Near the center of the film, the film width and film height are both large (~50-100nm) compared to the distance between the pinned and sensing film(~5nm):

$$H \approx \frac{t_p}{2} J_p \approx 6.34 \times 10^3 A/M = 80 Oe$$

- Note that this field is quite large. As we will discuss it makes it difficult to “bias” the sensing layer magnetization optimally in the cross track direction before signals fields are applied. A solution in use is to make multilayer film structure that includes a pinned layer on the opposite side of sensing layer.

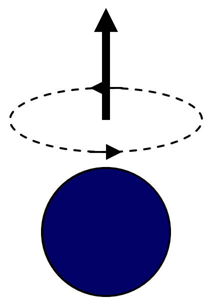
Magnetization

- The term "Magnetization" characterizes the net "orbital" and "spin" currents of the electrons abut the atomic core.



Magnetization

- Electrons are finite size and spin on their axes



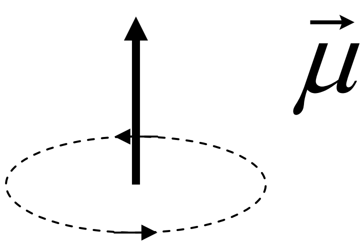
- Spin is like the earth rotating on its axis and orbital motion is like the earth rotating around the sun.

- Both motions represent currents and thus produce magnetic fields!

Dipole Moment

- In most elements the net rotation of spins in one direction is just canceled by rotations in the opposite direction—except in Transition elements (e.g. Fe, Ni, Cr, Co) and Rare Earth elements (e.g. Tb, Sm, Pr, Eu)

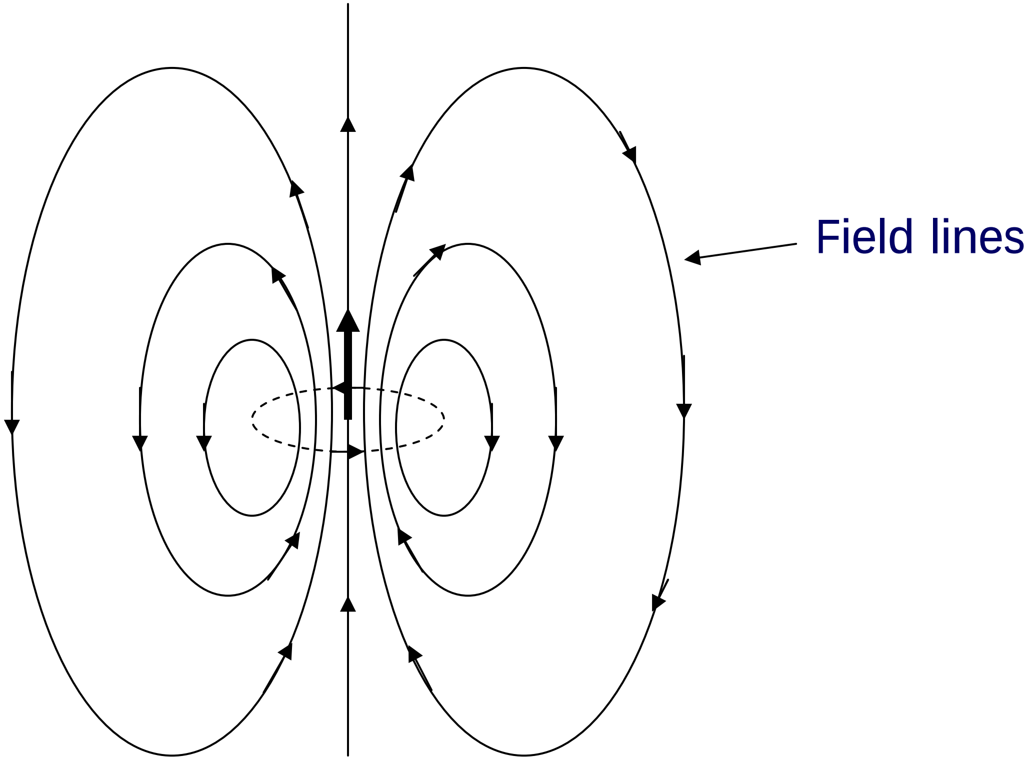
- In magnetic ions we can characterize the net rotational charge as a "dipole moment" μ. The net moment has magnitude and direction.



- The units are AM^2 or emu (charge angular momentum)

Schematic of field produced by Dipole Moment:

- RHR shows that field produced by dipole moment is along axis in direction of moment.

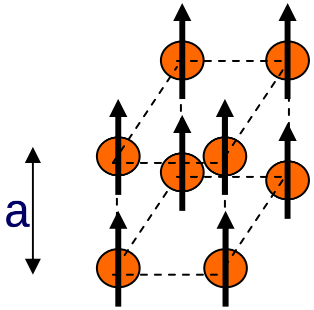


Magnetization

- Magnetization is the number of dipole moments per unit volume – with respect to magnitude and direction.

- Magnetization is a "specific" quantity – independent of the size of the object.

- For atoms on a cubic lattice with dipoles or net spins all oriented in the same direction:



$$M_s = \frac{\mu}{a^3}$$

Units: A/M, emu/cc
(1kA/M=1 emu/cc)

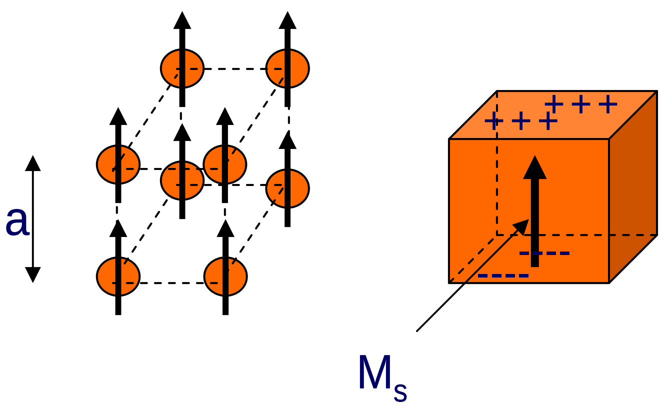
Materials Overview

	M_s (emu/cc)	B_s (Tesla)	$H_K(2K/M_s)$ (Oe)	K (10^6ergs/cc)	
Co	1200	1.5	5000	4	Hard
Fe	1711	2.2	500	0.44	Soft
Ni	500	0.63	200	0.05	Soft
CoCrX	400-800	0.5-1.0	10-20,000	2-8	Hard
NiFe	795	1	1-50	0.0004 -0.02	Soft
FeCoX	2000	2.4	1-50	0.001-0.05	Soft

Fields from Magnetized Materials

- We can simply add up the dipole field from each atom (slide 37). Not only is this a vector addition, but with billions of atoms it is very complicated.

- A simpler way is to use the idea of magnetic “poles”. They are a fiction, but make life simple:

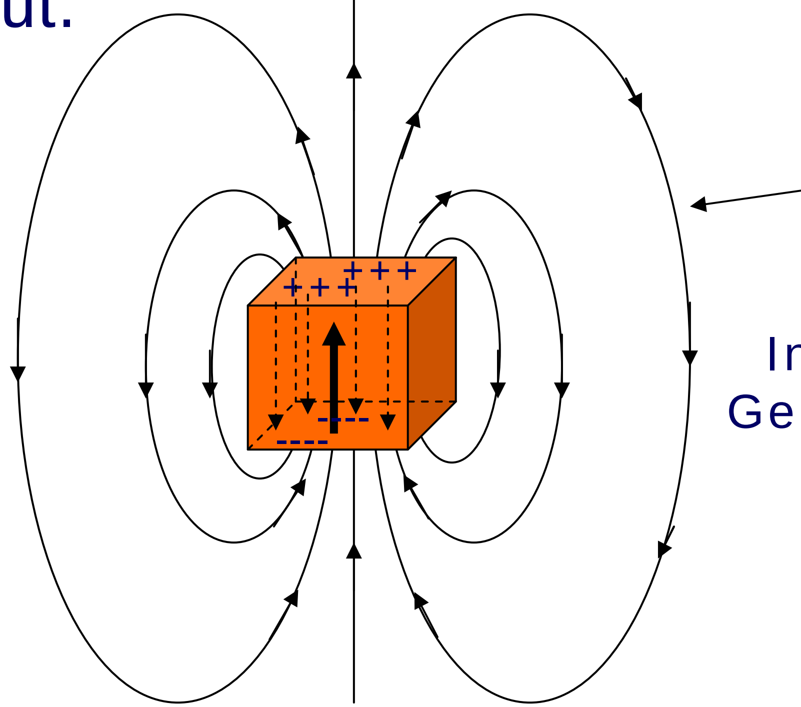


+ poles on the top

– poles on the bottom

Fields from Magnetized Materials (cont.)

- We use the idea of "electric charges" where the fields go from plus charges to minus charges - both inside and out.



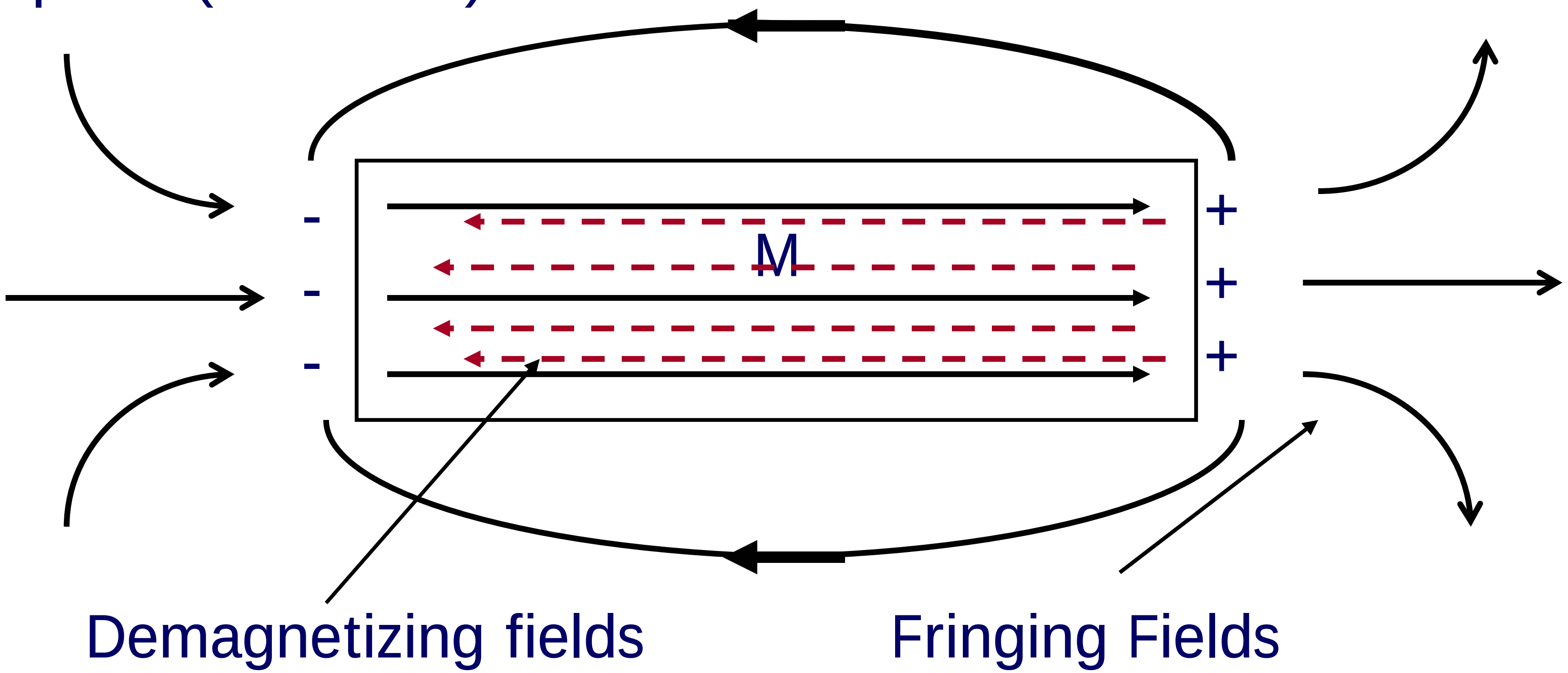
Field lines:

Outside called "Fringing field"
Inside called "Demagnetizing field"
General term is "Magnetostatic field"

- With this simplification the fields "<u>outside</u>" the material look very much like the fields of a large dipole.

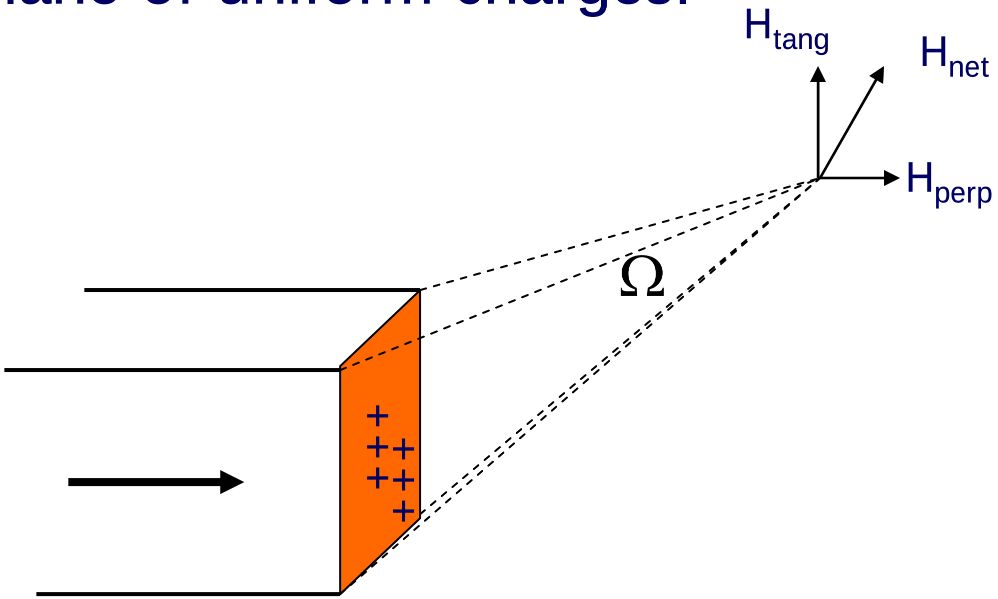
Another Illustration of Magnetostatic Fields

- Magnetostatic fields can be thought to arise from “poles” and generally are directed from North” poles to “South” poles (side view):



Field Examples: Magnetized Materials

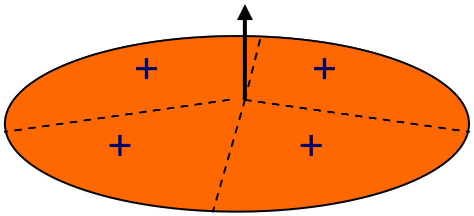
- In general fields must be evaluated numerically.
- A somewhat simple case is the field perpendicular to a plane of uniform charges.



$$H_{perp} = 2\Omega M$$

Field Examples: Magnetized Materials

- Fields point "away" from plus charges and towards "minus" charges.
- Far from charges field is small since solid angle Ω is small.
- At the center of the plane (for any shape) very close to the surface Ω -> π:



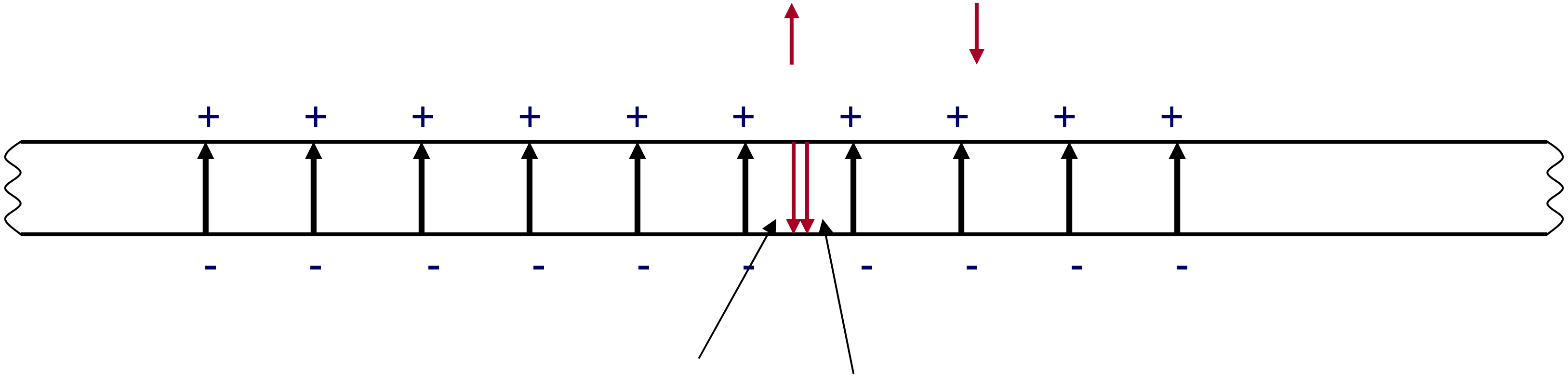
$$H_{perp} = 2\pi M \qquad \text{(M in emu)}$$

e.g. Co: H_{perp} = 7540 Oe

Field Examples: Thin Film

- Consider a very thin film uniformly magnetized perpendicular to the surface (only side view is shown).

Outside: $$H_{perp} = H^{+}_{perp} + H^{-}_{perp} = 2\pi M - 2\pi M = 0$$

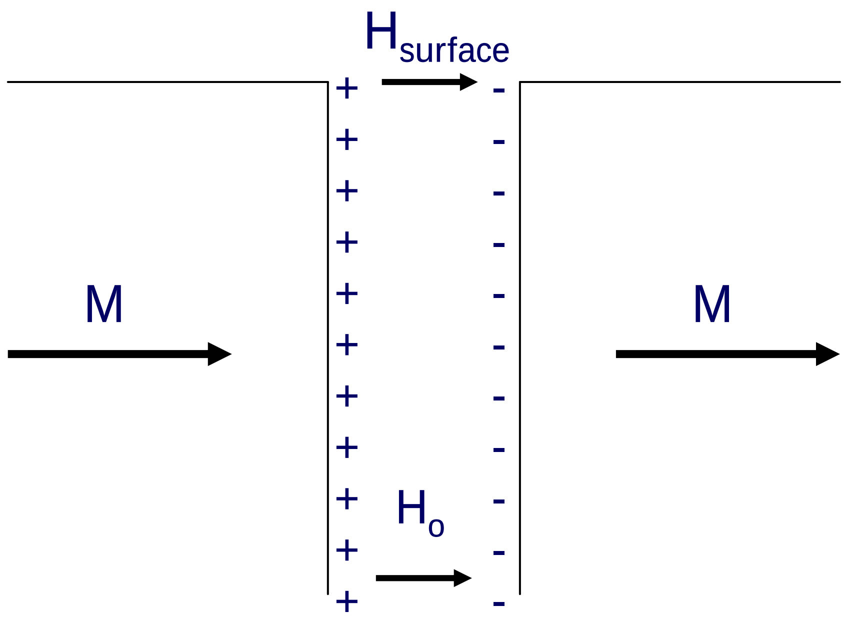


Inside: $$H_{perp} = H^{+}_{perp} + H^{-}_{perp} = -2\pi M - 2\pi M = -4\pi M$$

- E.g. in a Co film the internal demagnetizing field is H_{perp} = -15080 Oe

Field Examples: Inductive Write Head

- Side view with idealized uniform magnetization
- Deep gap $H_o = 4\pi M$ Surface field $H_{surface} = 2\pi M$ (Why? Estimate solid angle Ω!)



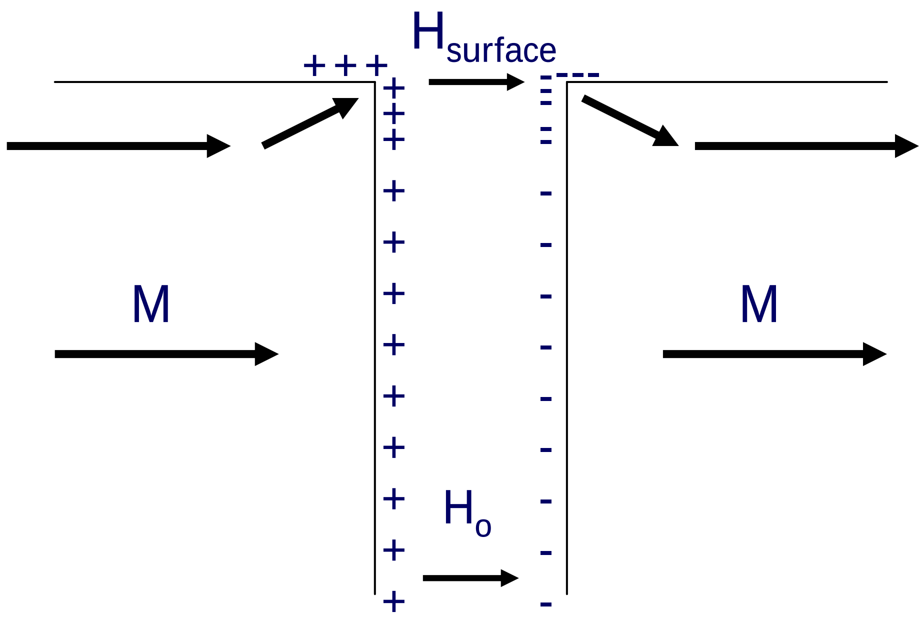
E.G. FeAlN $M_s = 2000$ emu

$H_o = 24000$ Oe $= 2.4$Tesla

$H_{surface} = 12000$ Oe $= 1.2$T

Realistic Inductive Write Head

- Tangential field at edge of a plane of poles is very large. Magnetization , in general, gets rotated towards corners.
  - Lots of poles occur at the corners, in creasing $H_{surface}$:
  - Deep gap $H_o = 4\pi M$ Surface field $H_{surface} \sim (.82)4\pi M$



E.G. FeAlN $M_s = 1900$ emu/cc

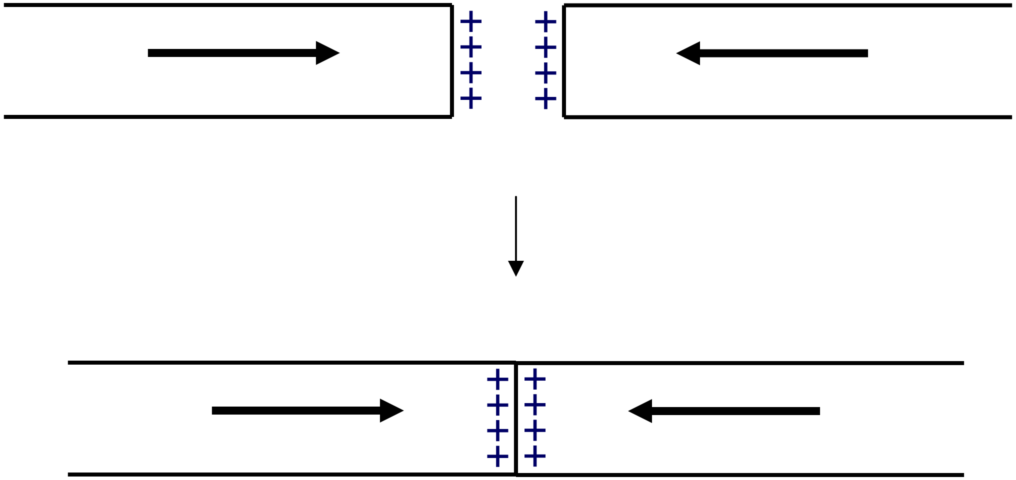
$H_o = 24000$ Oe = 2.4T

$H_{surface} = 19680$ Oe ~ 2T!!

Fields from Recorded Media

- Longitudinal Media, perfect transition.

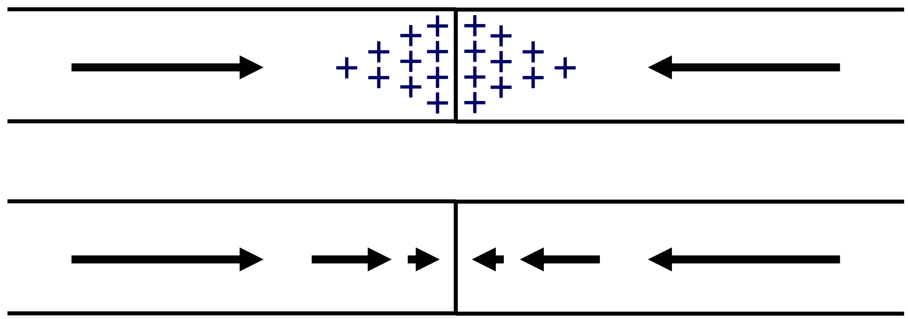
- A transition is like bringing two bar magnets together:



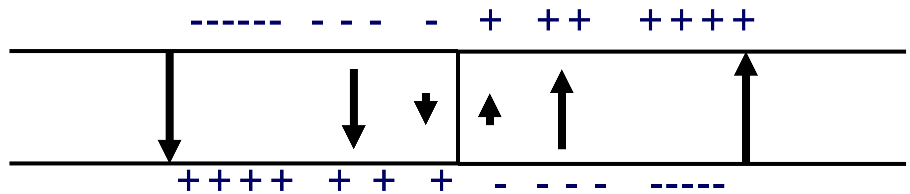
Fields from Recorded Media (cont.)

- In reality as shown in slides 17,19 the transition is spread out. A side view illustrating the track averaged magnetization would be:

- Longitudinal:

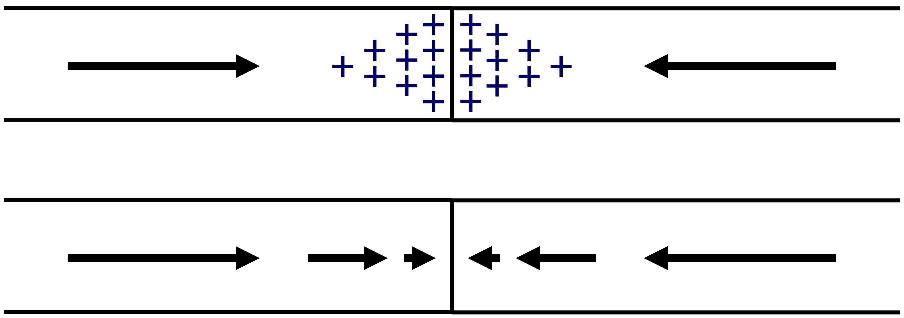


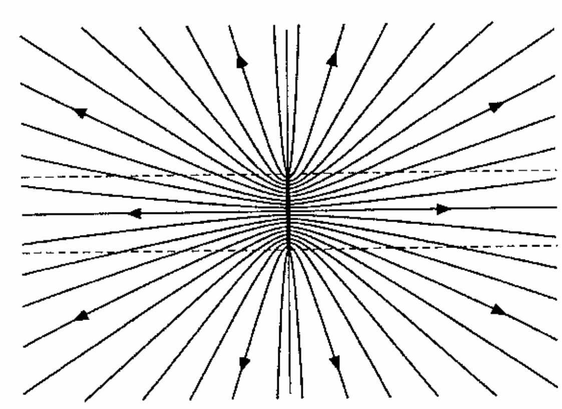
- Perpendicular:



Fields Patterns from Recorded Media (cont.)

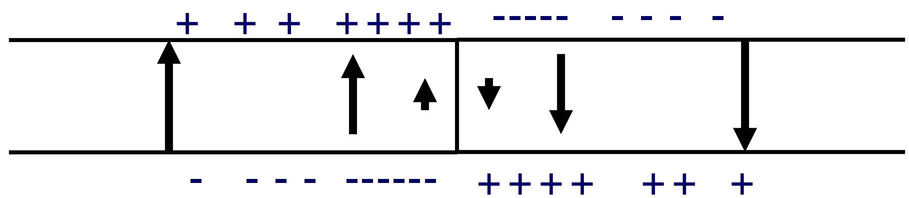
- Longitudinal:

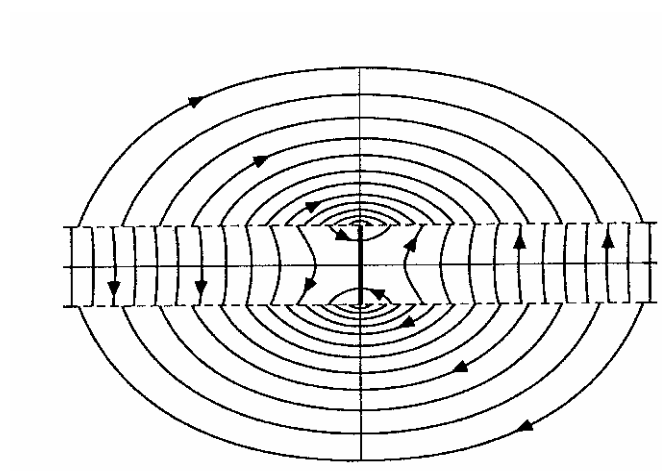




Fields Patterns from Recorded Media (cont.)

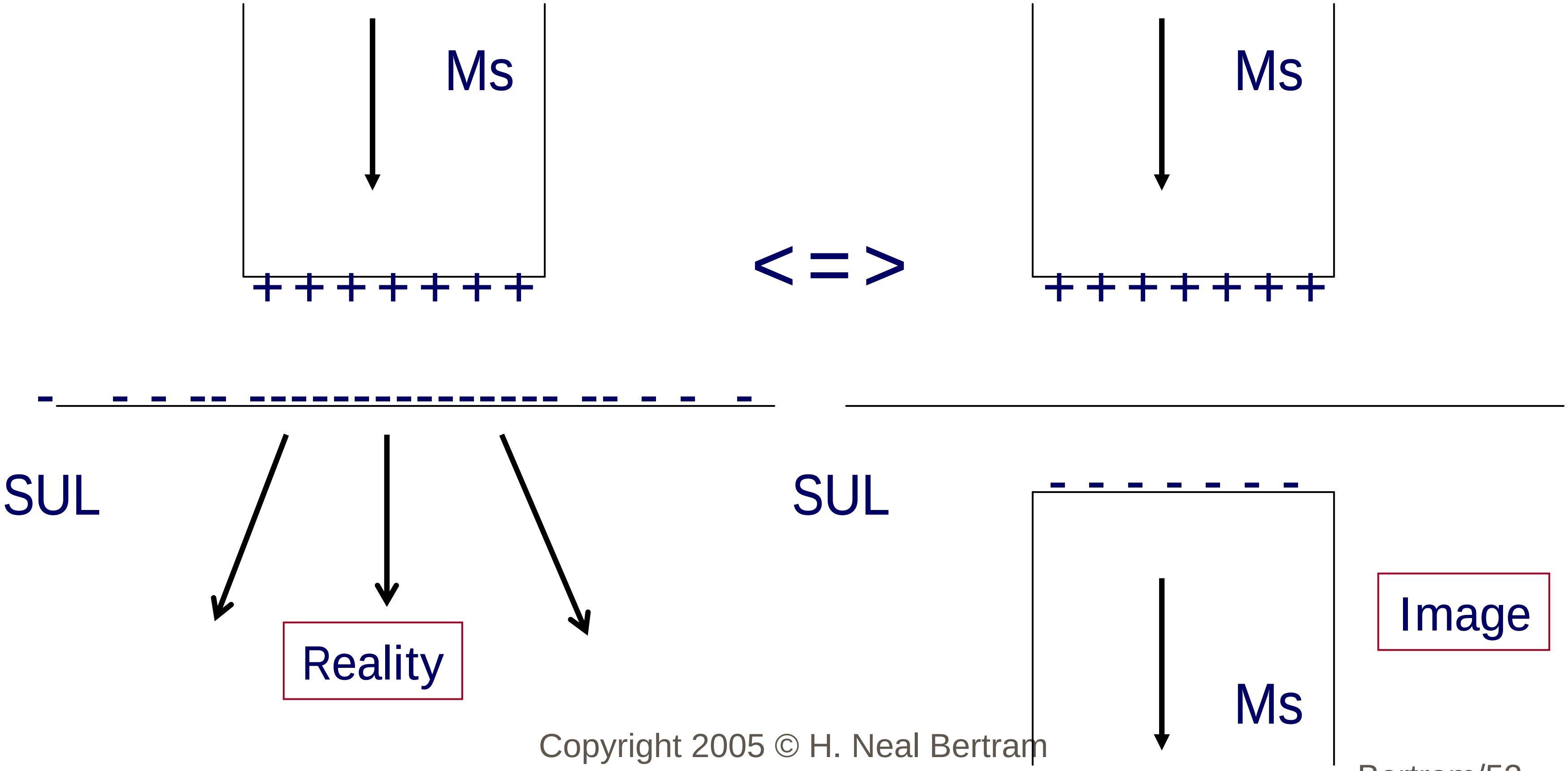
- Perpendicular:



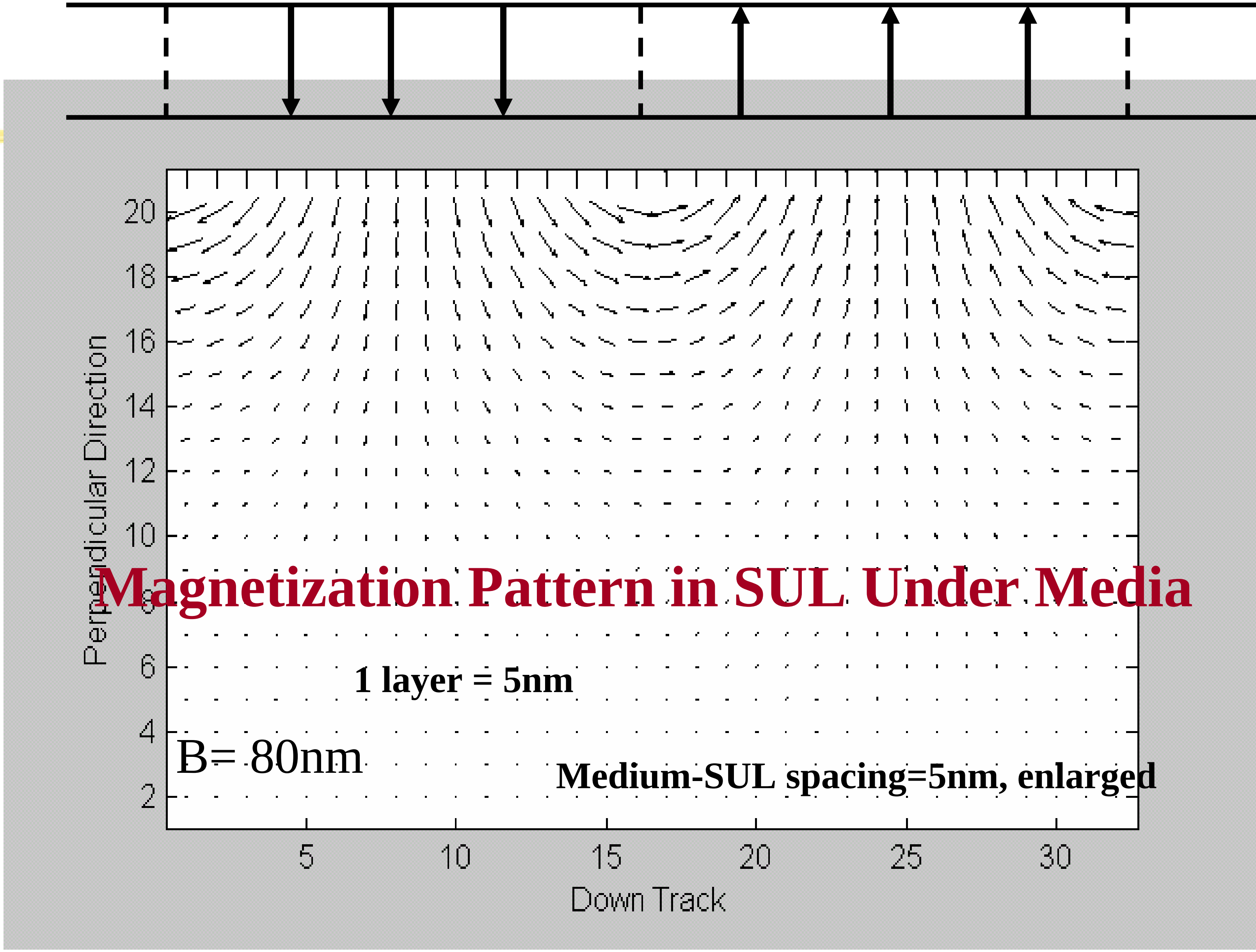


Imaging

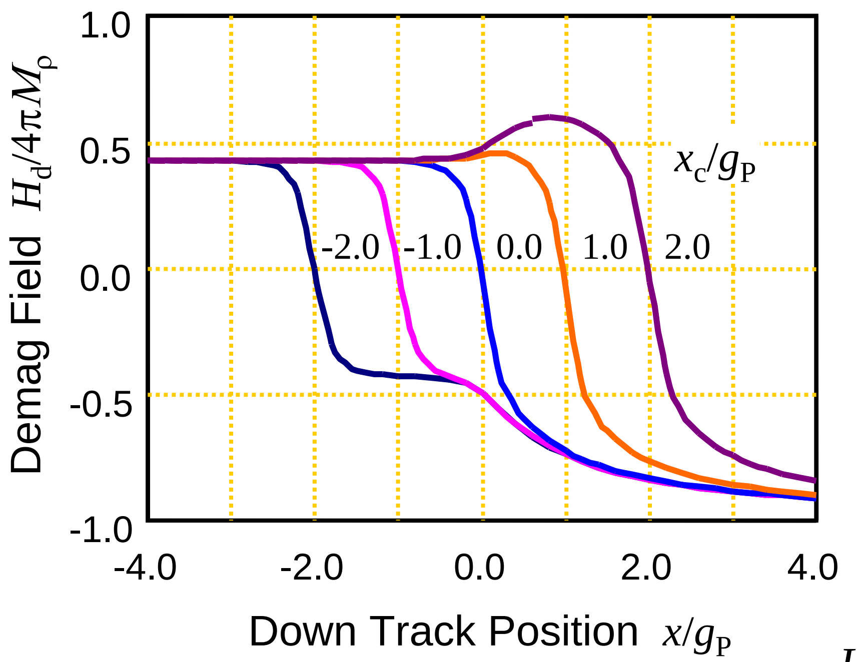
- Magnetostatic fields from (outside of) a flat semi-infinite region of high permeability (e.g. the SUL) can be treated by imaging. There are only surface poles:

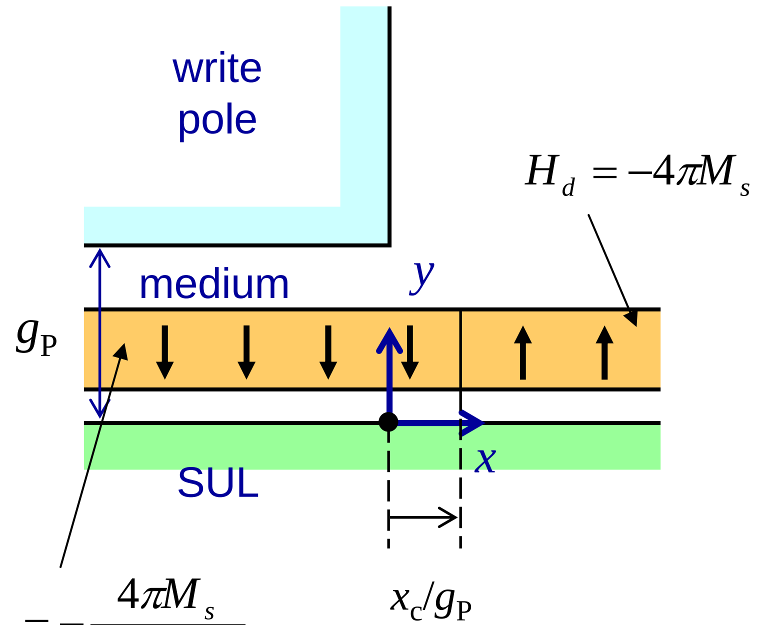


Magnetization Pattern in SUL Under Media



Demag Field *vs.* Transition Position





$$H_d = -\frac{4\pi M_s}{1 + \frac{t}{d+s}}$$

UNITS

- MKS
  - M(Amps/meter), H(Amps/meter), B(Tesla)
  - $B = \mu_o(H+M)$ $\mu_o = 4\pi x10^{-7}$Henries/meter

- CGS
  - M (emu/cc), H (Oe), B(Gauss)
  - $B = H + 4\pi M$

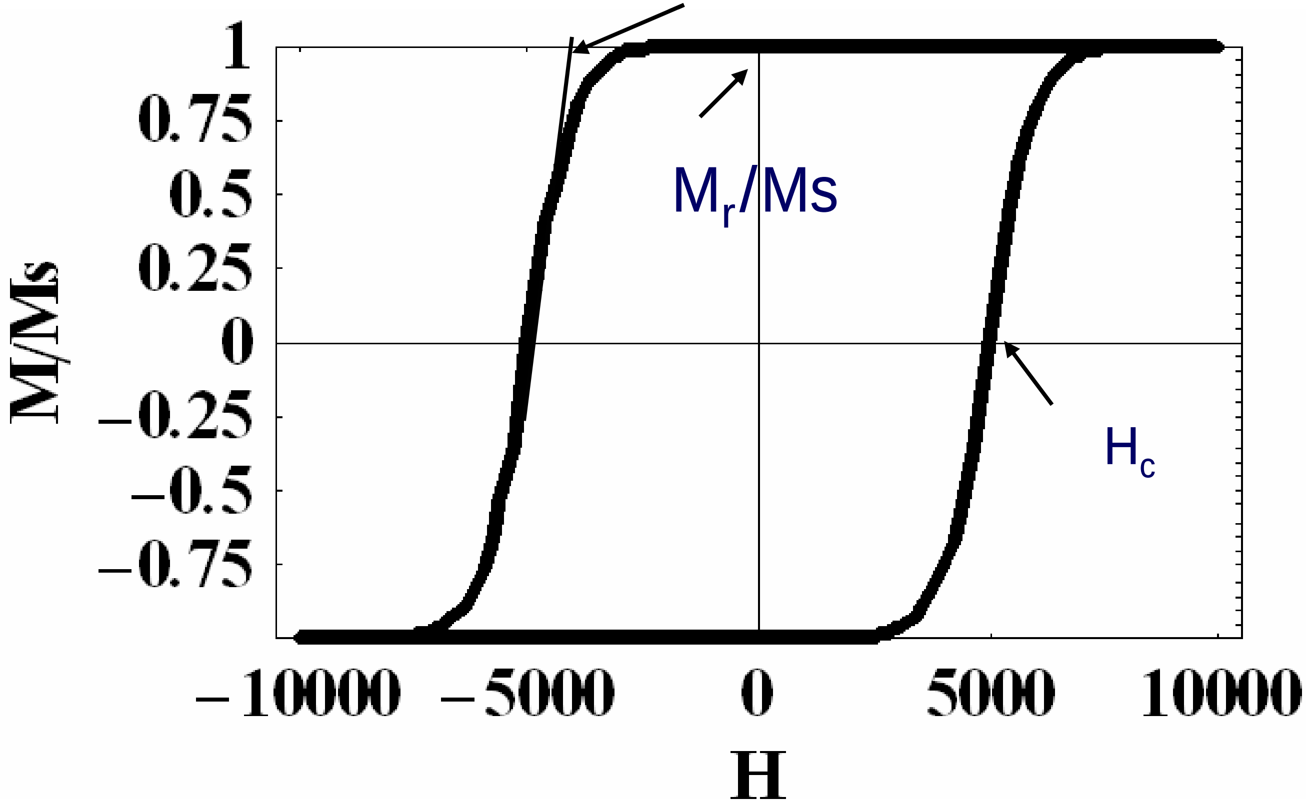
- Conversion:
  - M (1kA/m = 1 emu/cc), H(1 Oe = $(10^3/4\pi)$ A/m ~ 80 A/m)
  - B (1Tesla = 10000Gauss)

III. Magnetic Materials

Properties, Hysteresis, Temperature effects

Hard Materials Characteristics

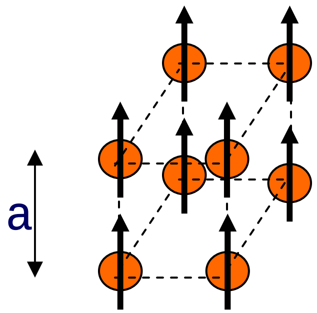
- Hard M-H Loop: Large Coercivity H_c (10-20 kOe), Large Good Remanent Squareness $S = M_r/M_s \sim 1$, Good Loop Squareness $S^* \sim 0.8$ to 1 ($dM/dH = Mr/Hc(1-S^*)$ at $H = H_c$)



Ferromagnetism

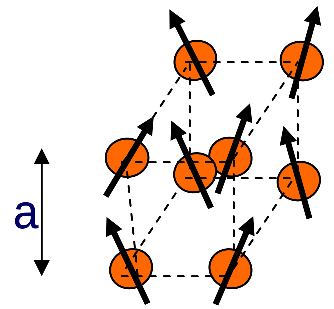
- Atoms may have spins, but there is no intrinsic reason why they should all be parallel so that the material would exhibit a net magnetic moment

- But in “Ferromagnetic” materials there is an “exchange interaction between adjacent atoms that tends to keep parallel (or antiparallel for antiferromagnetics, or ferrimagnetic for spins of unequal size in AF.).



Curie Temperature

- Thermal energy (a finite temperature) makes the spins randomly rotate (at a high frequency rate) away from equilibrium.

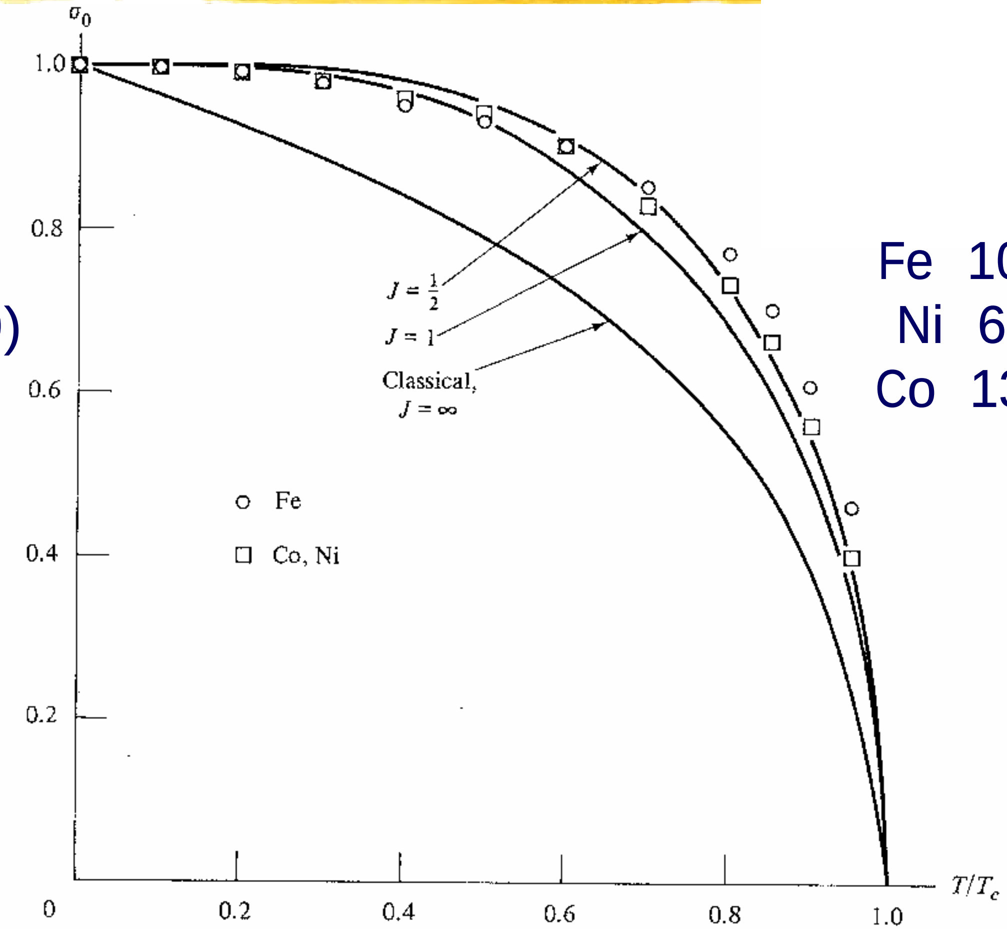


- This effect lowers the net average magnetization

- At a sufficiently high temperature (T_c) the average atomic scale magnetization vanishes

Magnetization versus Temperature

$M_s(T)/M_s(T=0)$



T/T_C

T_C

Fe 1043 (°K)
Ni 627 (°K)
Co 1388 (°K)

Exchange (Cont.)

- Exchange is a microscopic "Quantum" effect and acts between adjacent atoms. We are interested primarily in Ferromagnetic exchange that keeps the spins parallel and a specimen "magnetized".

- Interaction may be characterized by macroscopic "A" which for recording materials is typically: $A \sim 10^{-6}$ ergs/cm

- An approximate relation between the exchange constant and A and the Curie temperature T_c for Fe is:

$$k_B T_c = Aa$$

$$\text{e.g. Fe} : \mathrm{T_c} \approx 1000^0 K, a \approx 3Ang \quad A \approx 4 \times 10^{-6} ergs / cm$$

Exchange Field

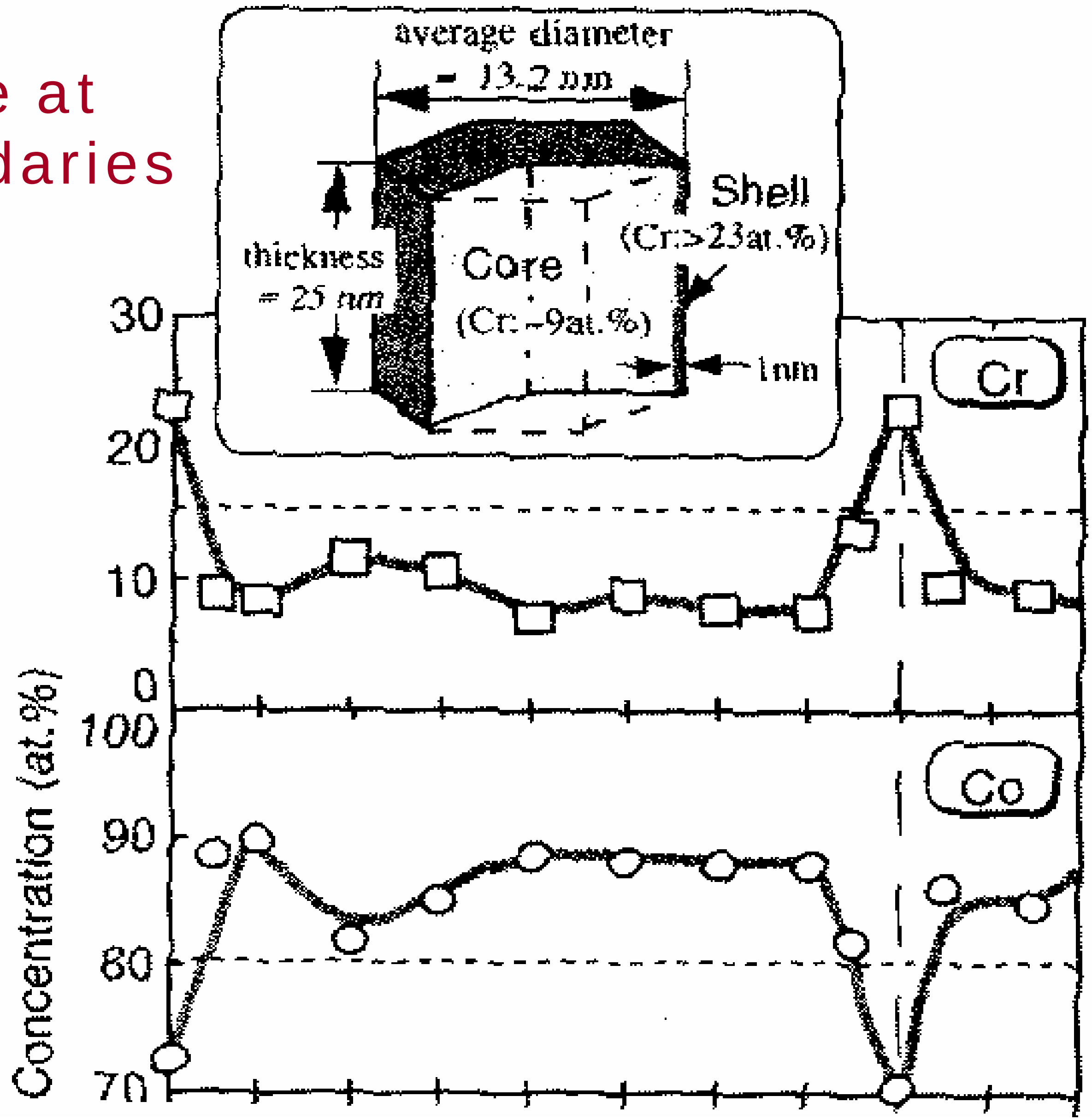
- The effective "exchange" field is:

$$H_{ex} = 2M_s\left(l_{ex} / D_{ex}\right)^2 \qquad l_{ex} \equiv \sqrt{A} / M_s$$

- Example CoCr Media:
  - M_s=400, D_{ex}=a= 3Ang.: l_{ex} =25nm Hex~4000kOe!!!
  - A grain is uniformly magnetized to a size of about 25nm. Thus in perpendicular media grain film thickness should not exceed about 25nm.
  - Exchange between adjacent grains is very small due to non-magnetic ions (e.g. B, Cr, T) at interface H_{ex}~400Oe. Thus grains can reverse (hopefully) individually.

- Example NiFe SUL
  - M_s=800 l_{ex} =12.5nm
  - SUL will demagnetize into domains of size not less than about 12nm and not remain uniformly magnetized through thickness of about 50-100nm.

Exchange at grain boundaries



Anisotropy/Coercivity

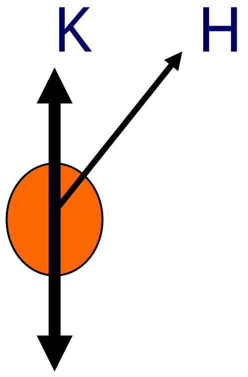
- Magnetic materials have an intrinsic preferred orientation or anisotropy due the crystalline structure.
- Anisotropy has the character of “easy” or low energy axes: e.g uniaxial, cubic, hexagonal.
- Most of the hard materials that are useful for magnetic recording are uniaxial: Cubic anisotropy exhibits a very strong decrease with temperature, which can be catastrophic in a modern drive.

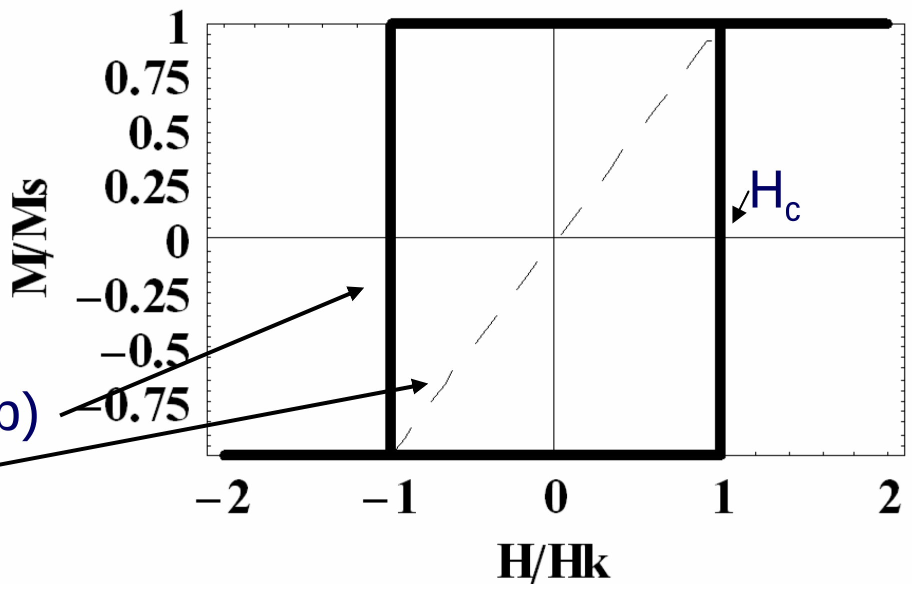
Anisotropy Field/Coercivity

- Anisotropy may be characterized by an effective field:

$$H_K = \frac{2K}{M_s}$$

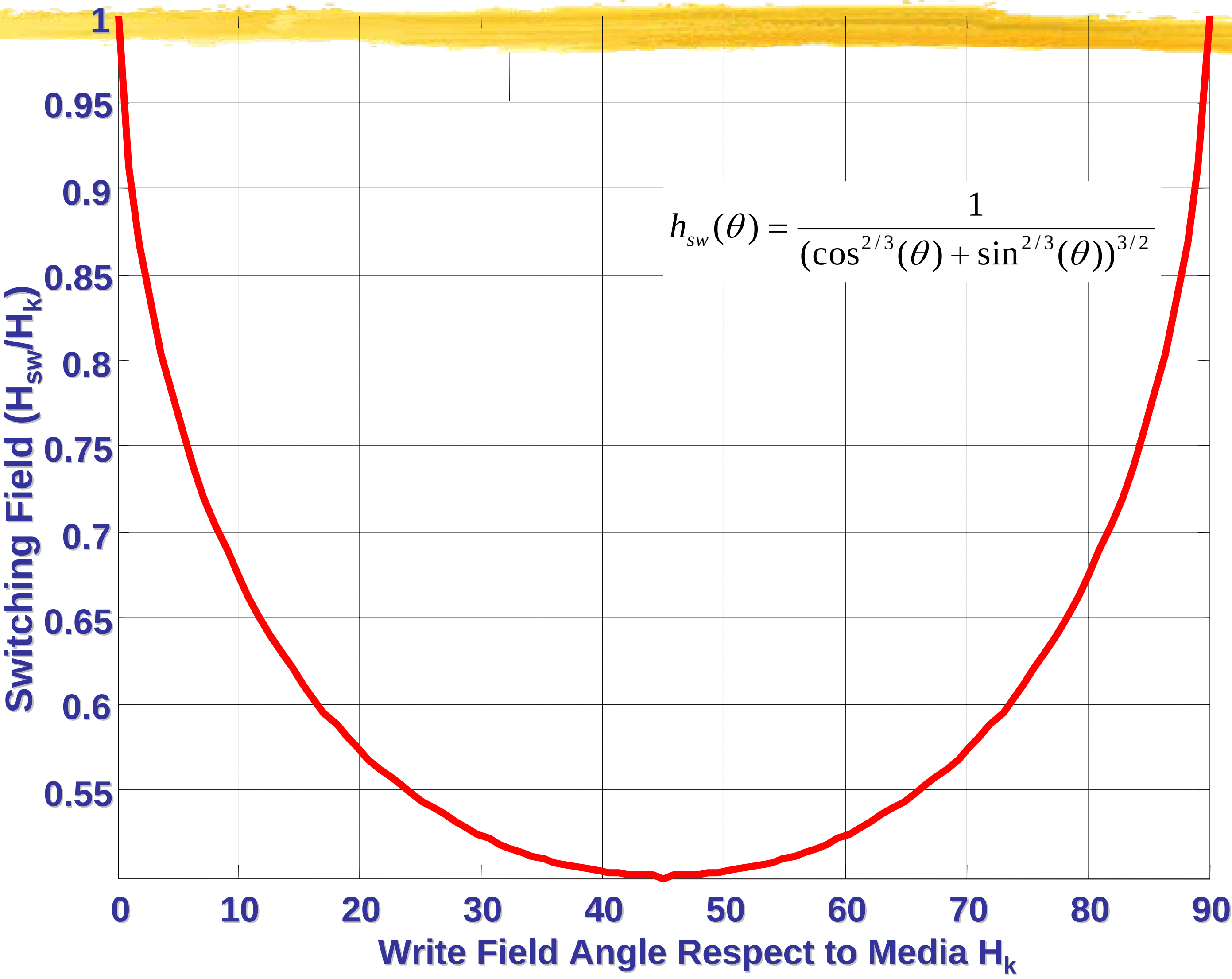
- M-H loops for a single domain grain are:



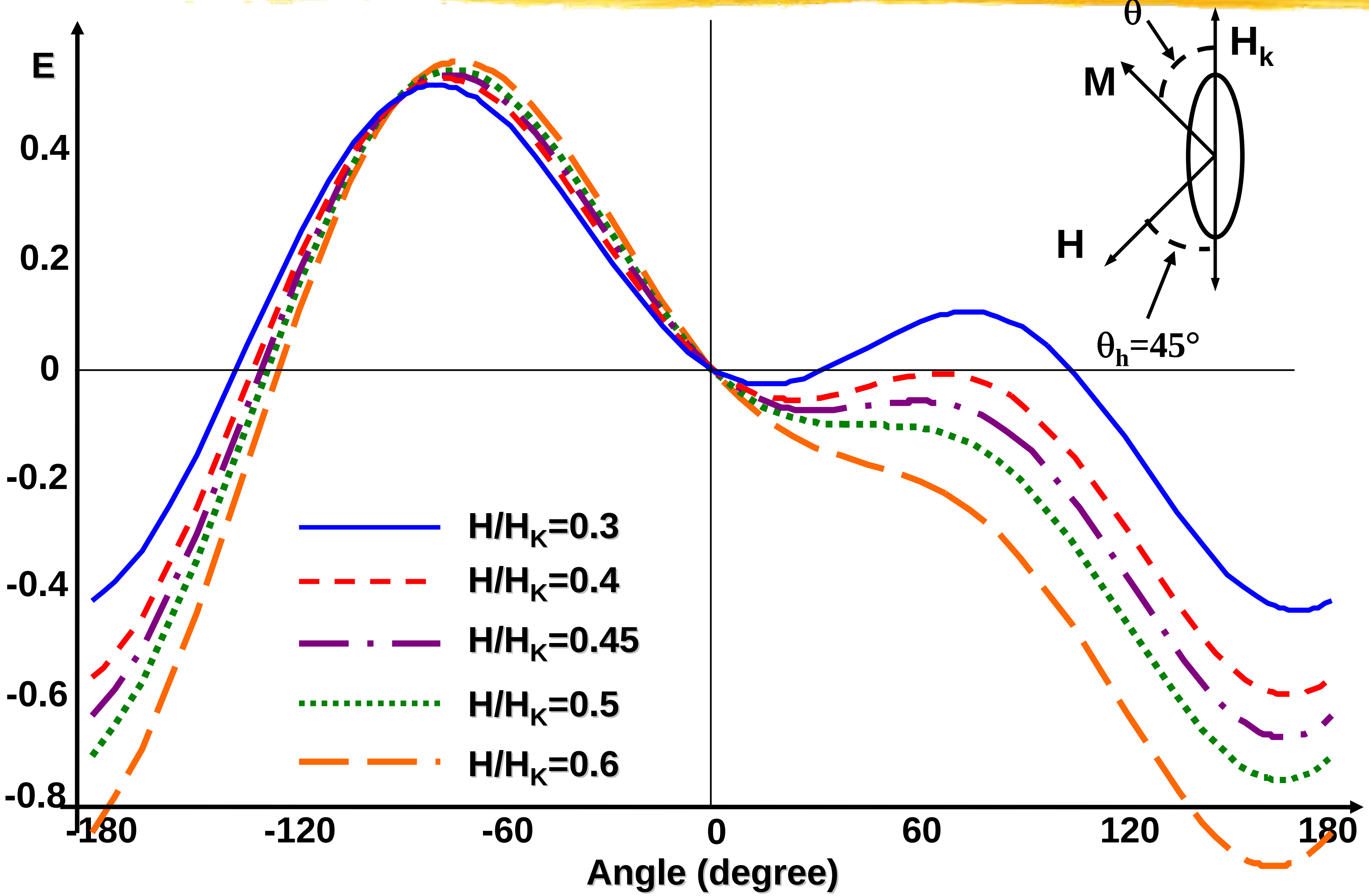


H parallel to K (Hard Axis Loop)
H perpendicular to K
(Easy Axis Loop)

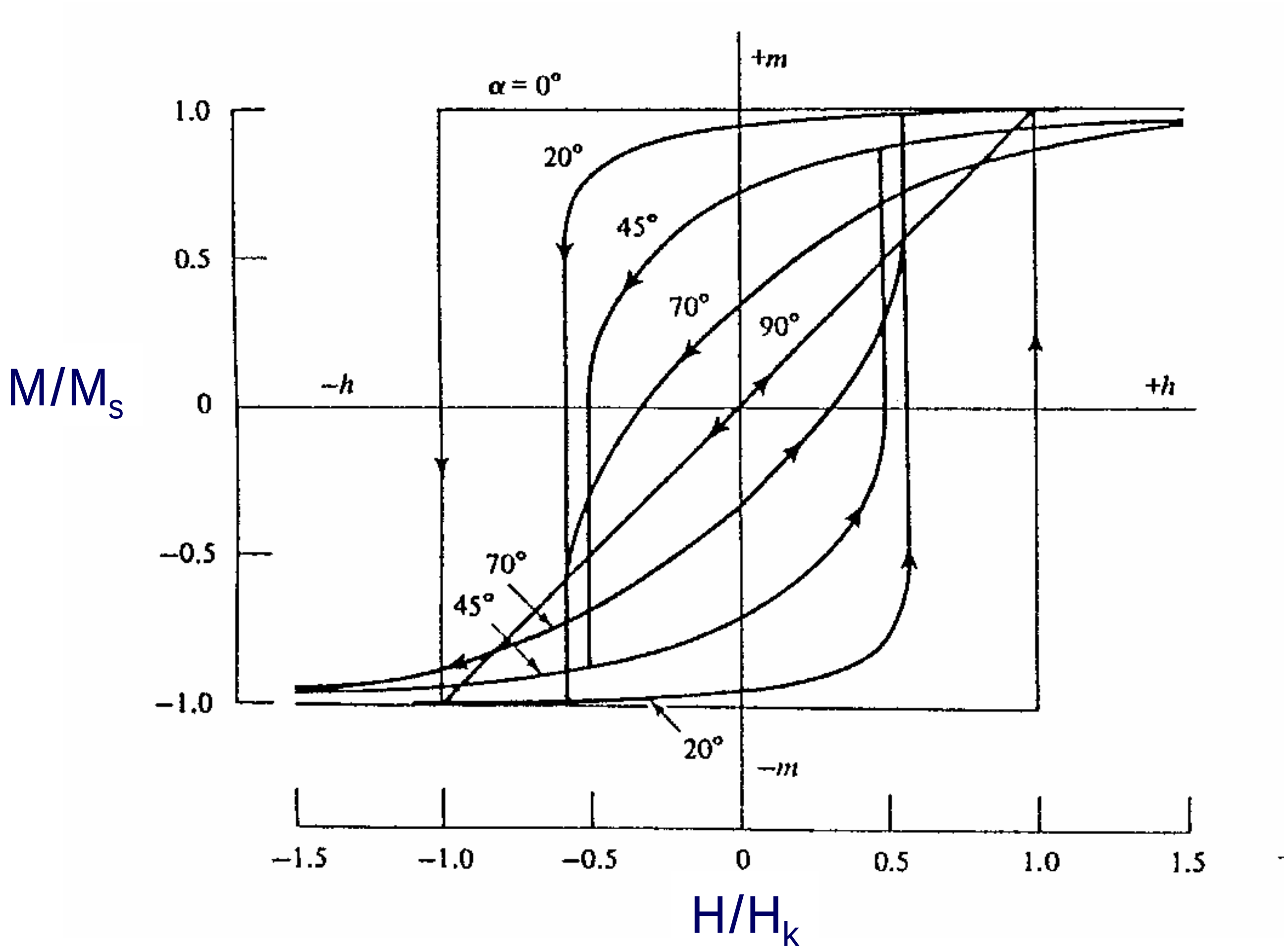
Switching Field vs. Field Angle



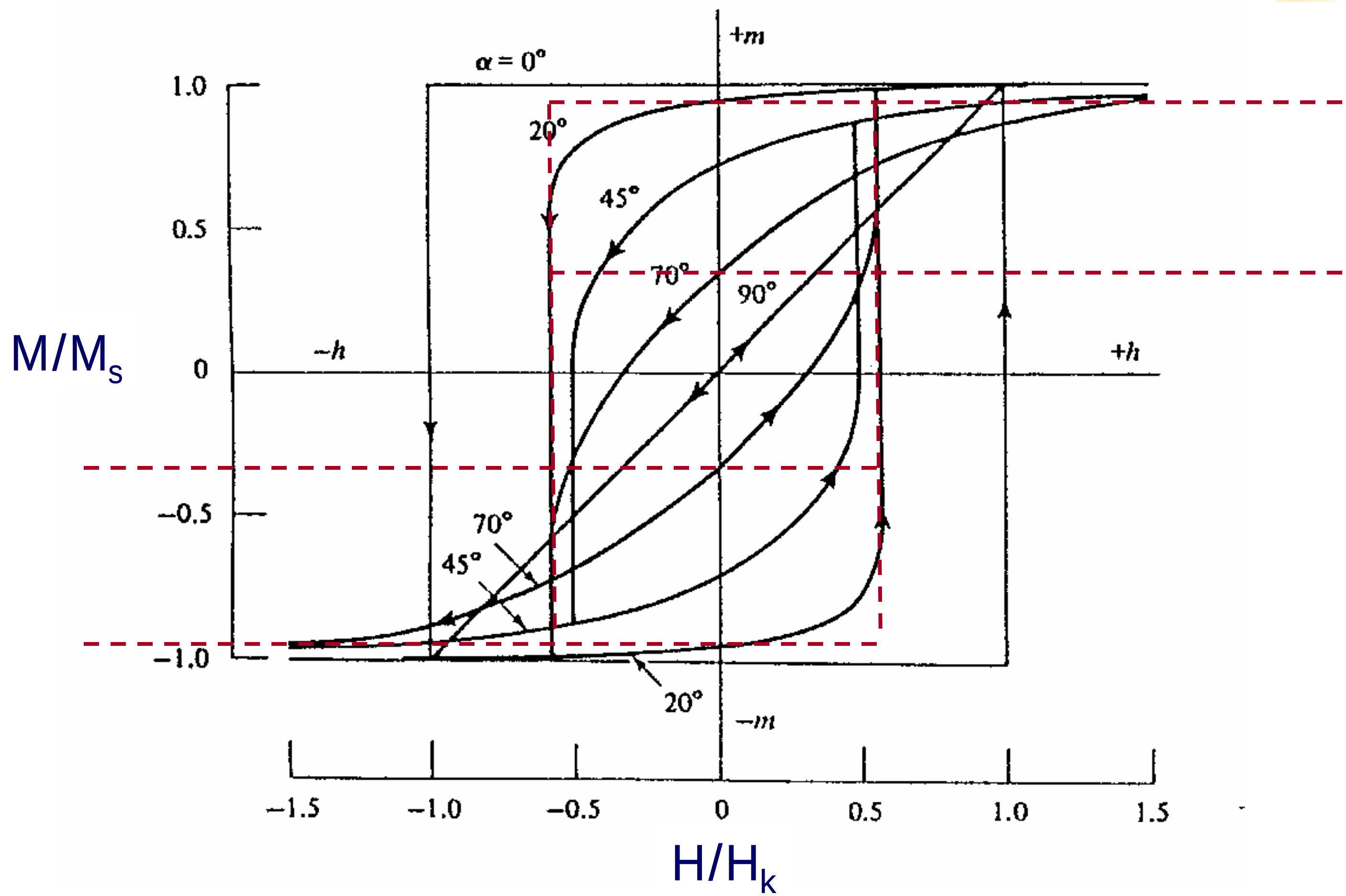
Energy Barrier View



Single Particle M-H Loops
versus field angle



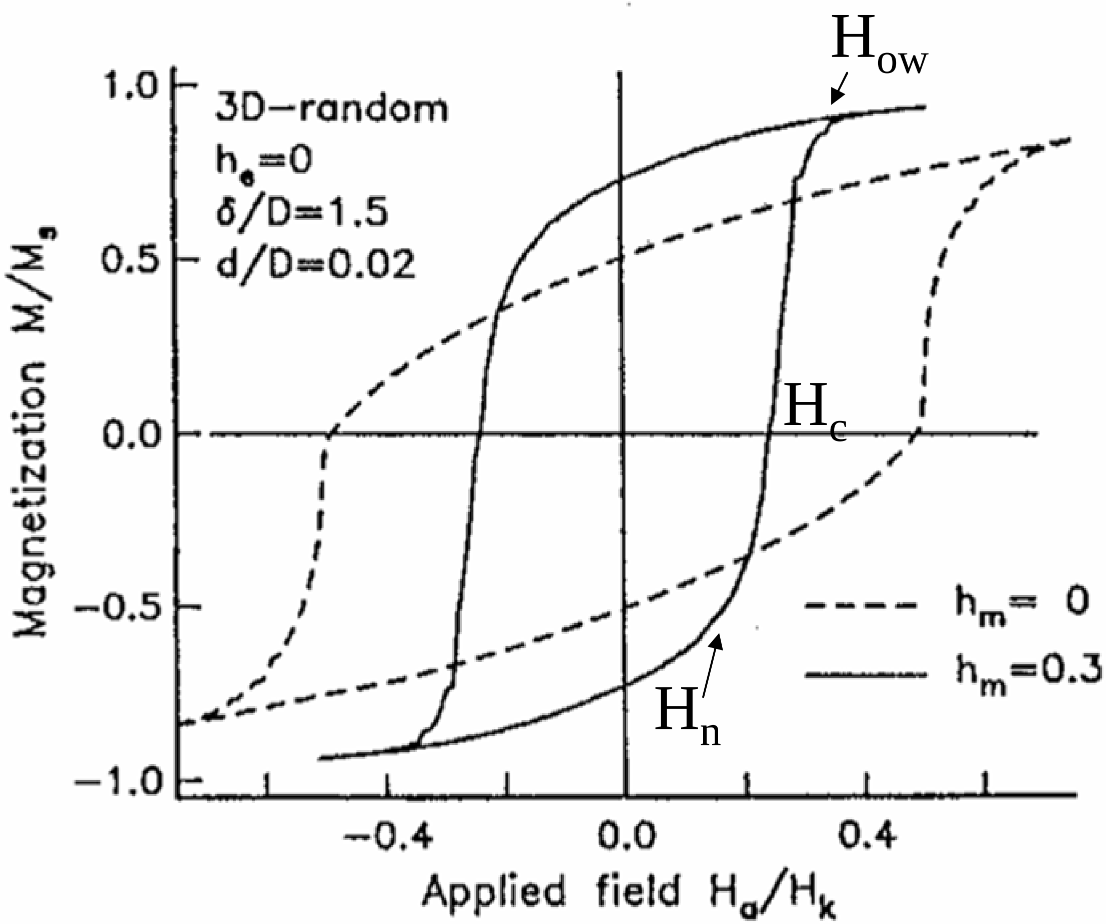
Remanence Loops (----) e.g.s for 20°, 70°



Apply field and then remove field and measure M

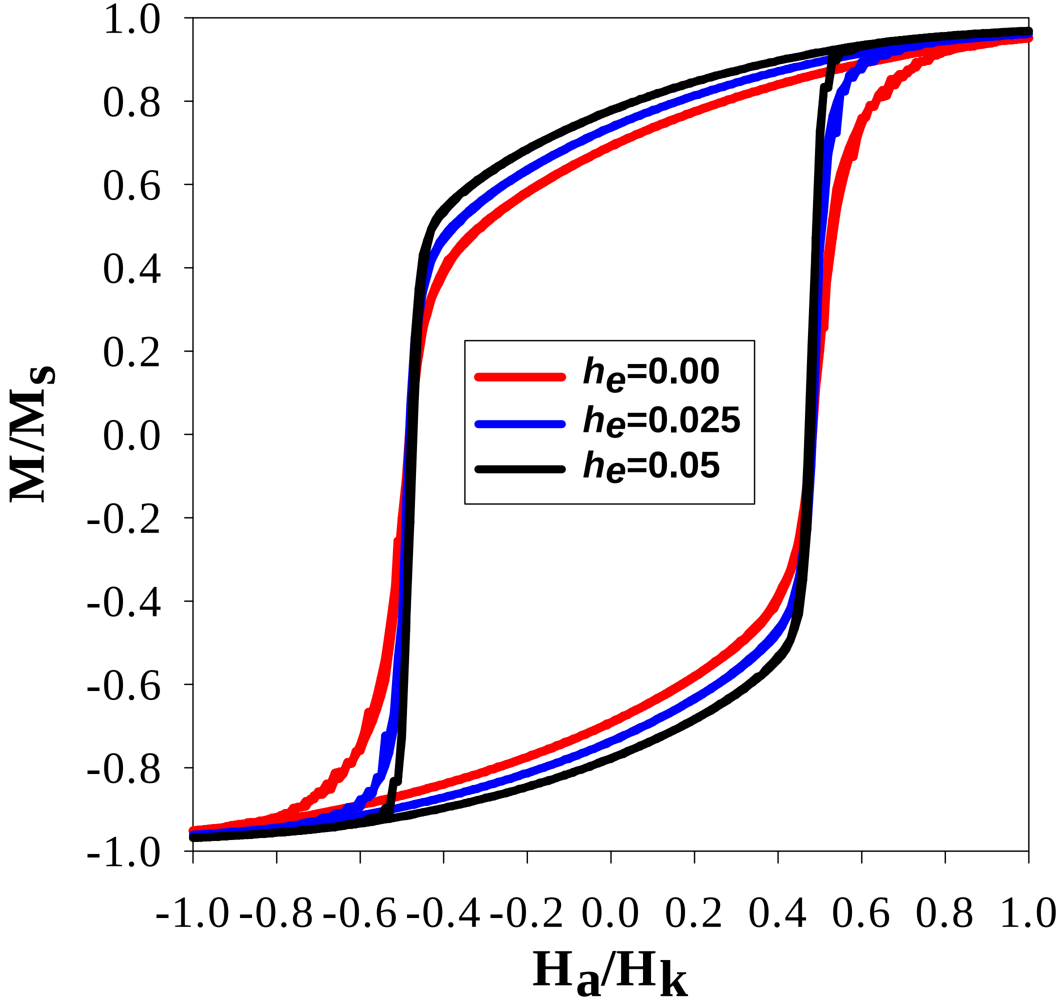
Note that for 70° $H_c < H_{cr}$

M-H Loop for Longitudinal Media (effect of exchange)



Very exaggerated example, but reduces H_c, increases coercive slope, reduces overwrite field H_{ow} relative to Hc, raises nucleation field H_n

Exchange effect on M-H loop (2D random anisotropy, $M_s/H_k=0.05$)



Note that a little exchange reduces the overwrite field and increases the loop squareness (S*)

Effect of Anisotropy Distributions on M-H loop shape

- The magnetization of a single grain

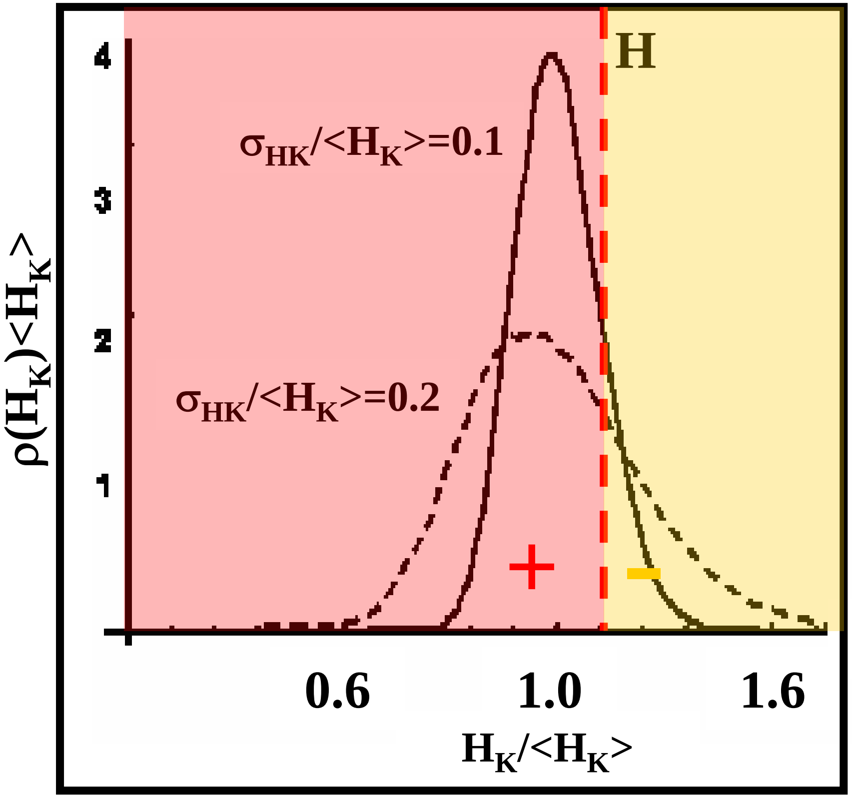
$$M_{grain}(H,H_K) = -M_s, H_K > H$$
$$= +M_s, H_K < H$$

- The M-H loop of an ensemble of grains is determined by the distribution in anisotropy fields.

$$\frac{M(H)}{M_r} = -1 + 2\int_0^H \rho(H_K)dH_K$$

- The magnetization vanishes at the coercive field:

$$H_c \cong \langle H_K \rangle$$



Effect of Anisotropy Distributions on M-H loop shape

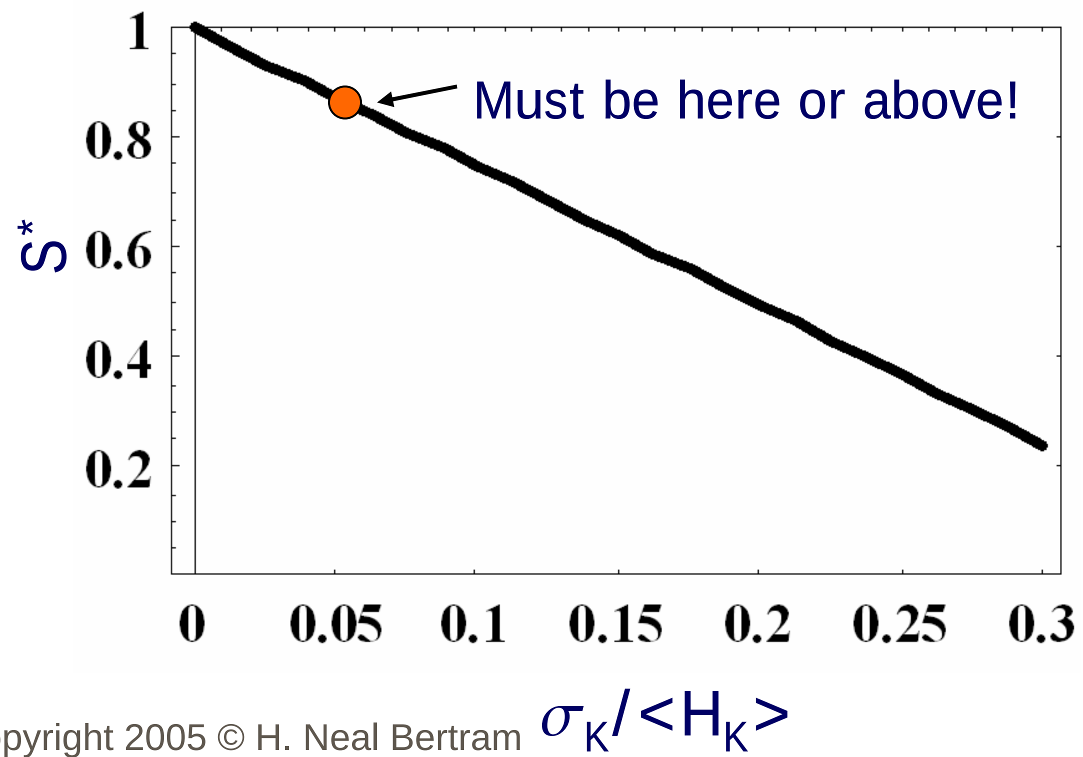
- Hard M-H Loops are not perfectly square due primarily to axis orientation and grain anisotropy dispersions.

- For anisotropy magnitude distributions only:

$$S^* \approx 1 - \sqrt{\pi}\,\beta e^{3\beta^2/16}$$

$$\beta = \sqrt{2\ln\left(1 + \sigma_K^2 / \overline{H}_K^2\right)}$$

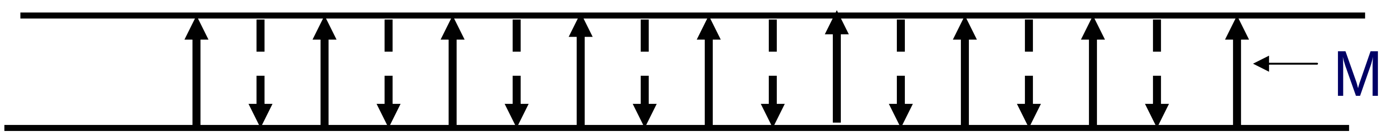
S* here is for intrinsic not sheared loop



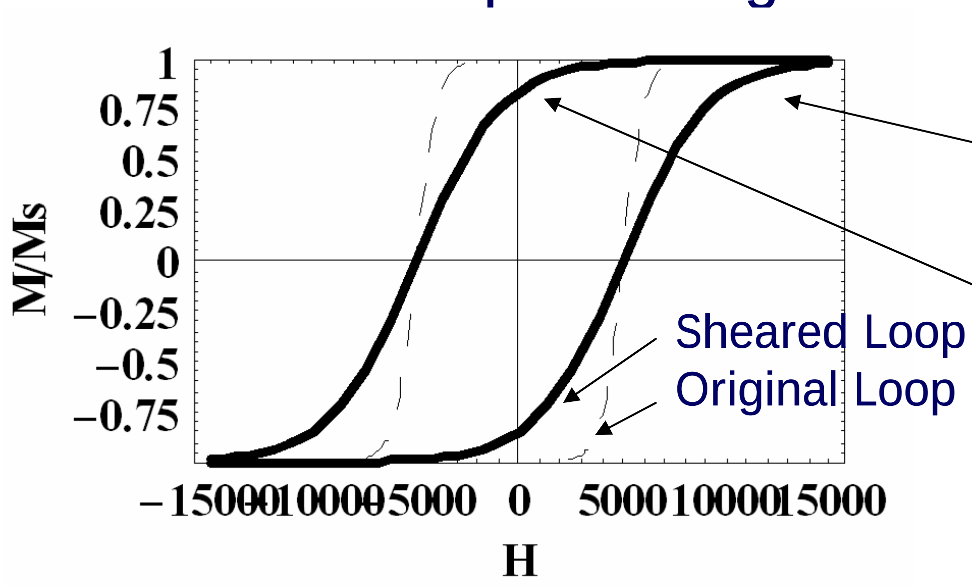
Loop Shearing
Perpendicular media

- Medium with uniform magnetization has $4\pi M$ demagnetization field.

$H_d = -\,4\pi M$



- This causes “loop shearing in measured M-H curves.



Potential Problems:
(1) Increased saturation Field for Overwrite.

(2) Reduced remanence S <1: yields DC noise

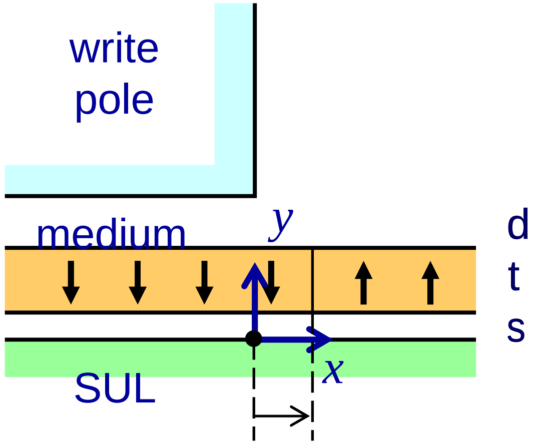
Solution: keep $4\pi M_s < H_c$

Loop Shearing with SUL and Head

- Medium with SUL does not change the low density saturated demagnetization fields.

- However the presence of the write head-SUL "sandwich" does reduce the demagnetization field during saturation or overwrite:

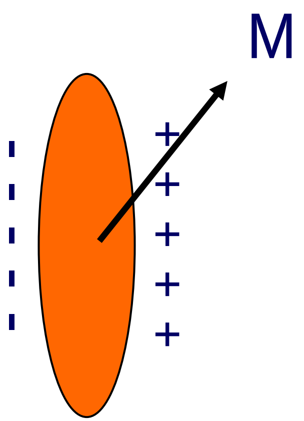
$$H_{demag} \approx -\frac{4\pi M_s}{1+\dfrac{t}{d+s}}$$



t = medium thickness
d= head-medium spacing
s= medium-SUL spacing

Shape Anisotropy

- For elongated particles a “shape anisotropy” occurs due to increased magnetostatic fields as grain magnetization rotates away from elongated direction.

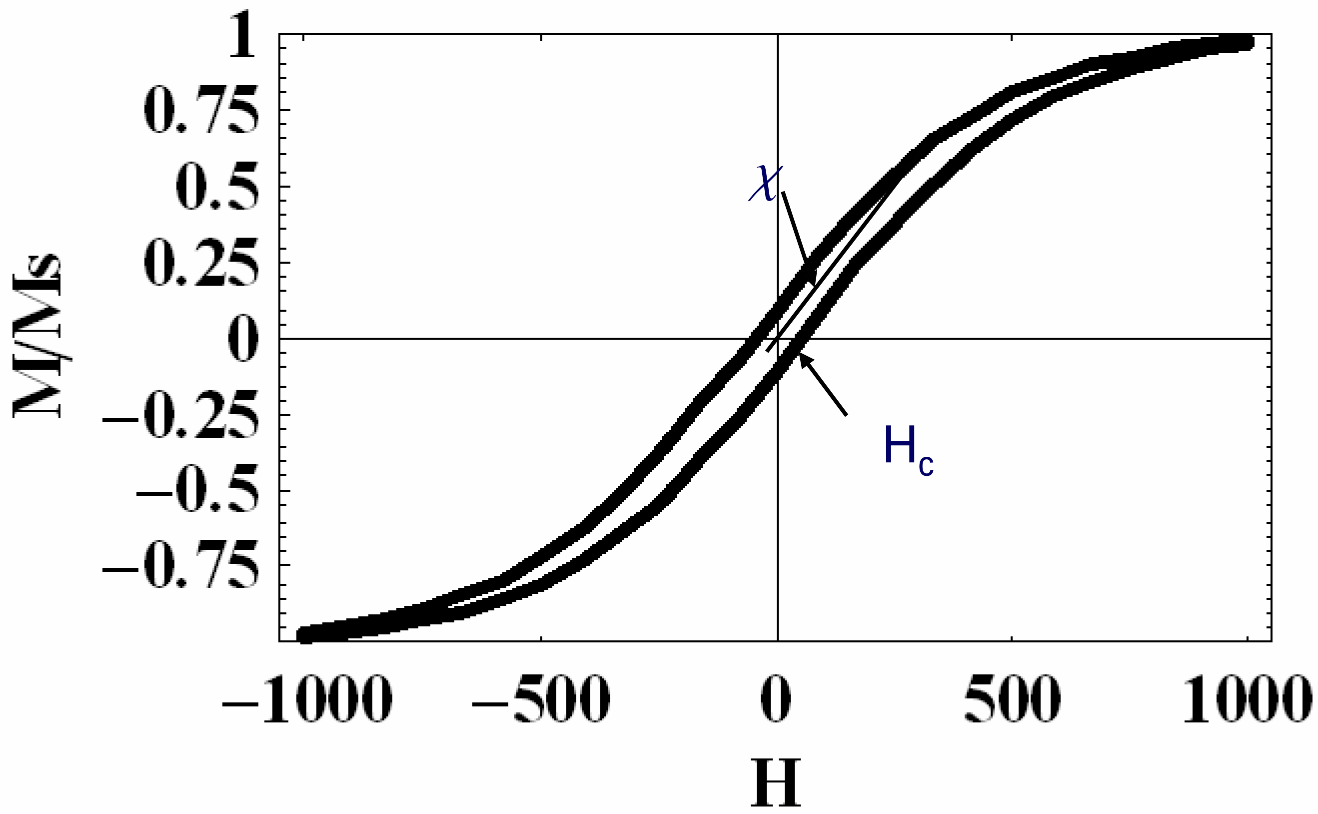


K_s can be as great as πM_s^2
with $H_{Kshape}=2\pi M_s$
For CoCr: $H_{Kcrystal}$ ~ 15,000 Oe

For perpendicular CoCr with t = 20nm, <D>= 7nm:
H_{Kshape} ~ πMs ~ 1,200Oe
Much less than $H_{Kcrystal}$!!

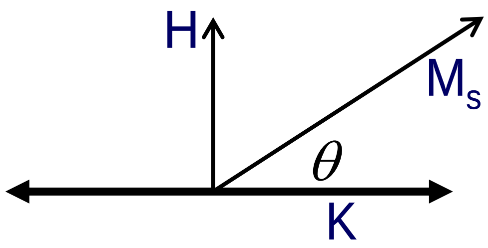
Hard and Soft Materials Characteristics

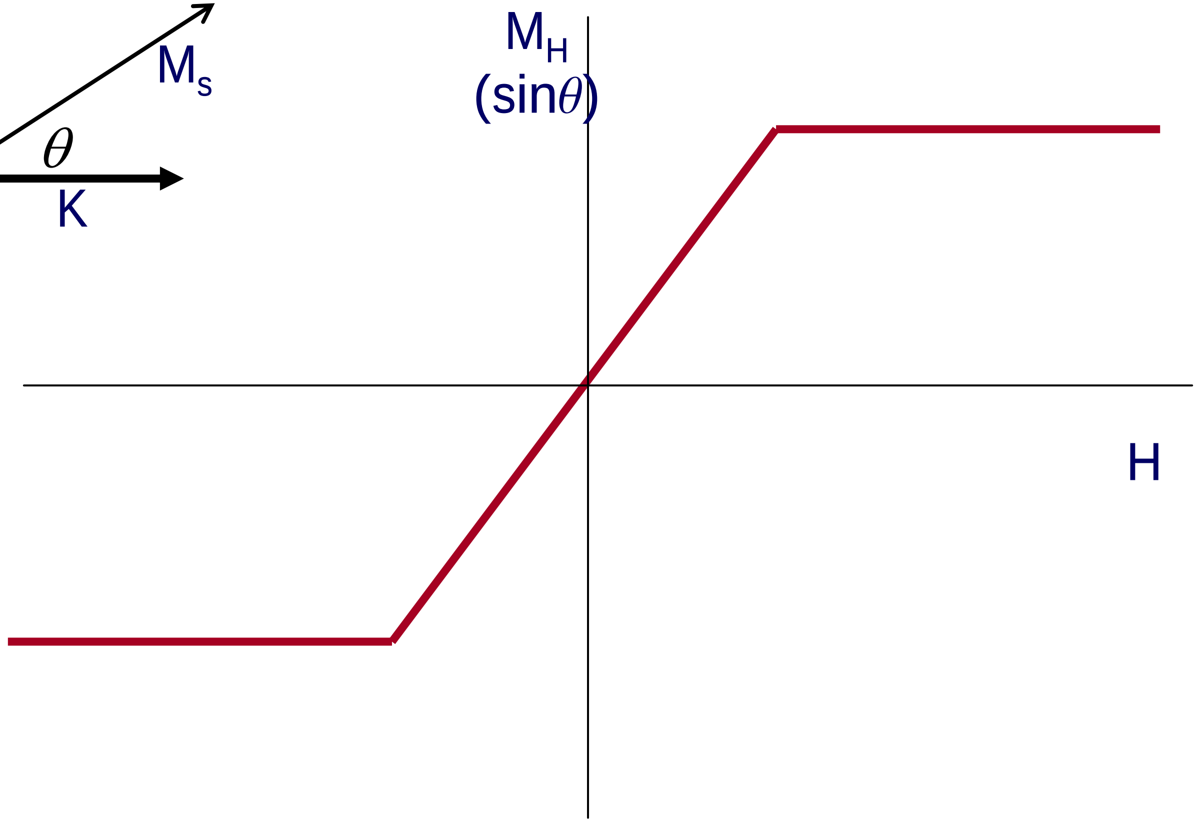
- Soft M-H Loop: Small Coercivity H_c (2-50Oe), Large Susceptibility χ=dM/dH (100-1000)



Permeability Sources in Soft Materials

1. Rotation against easy axis in Single Domain Material





Permeability: $$\chi = \frac{dM}{dH} = \frac{4\pi M_s}{H_K}$$

For Permalloy with H_K = 25 Oe

χ = 400 Oe

Permeability Sources in Soft Materials

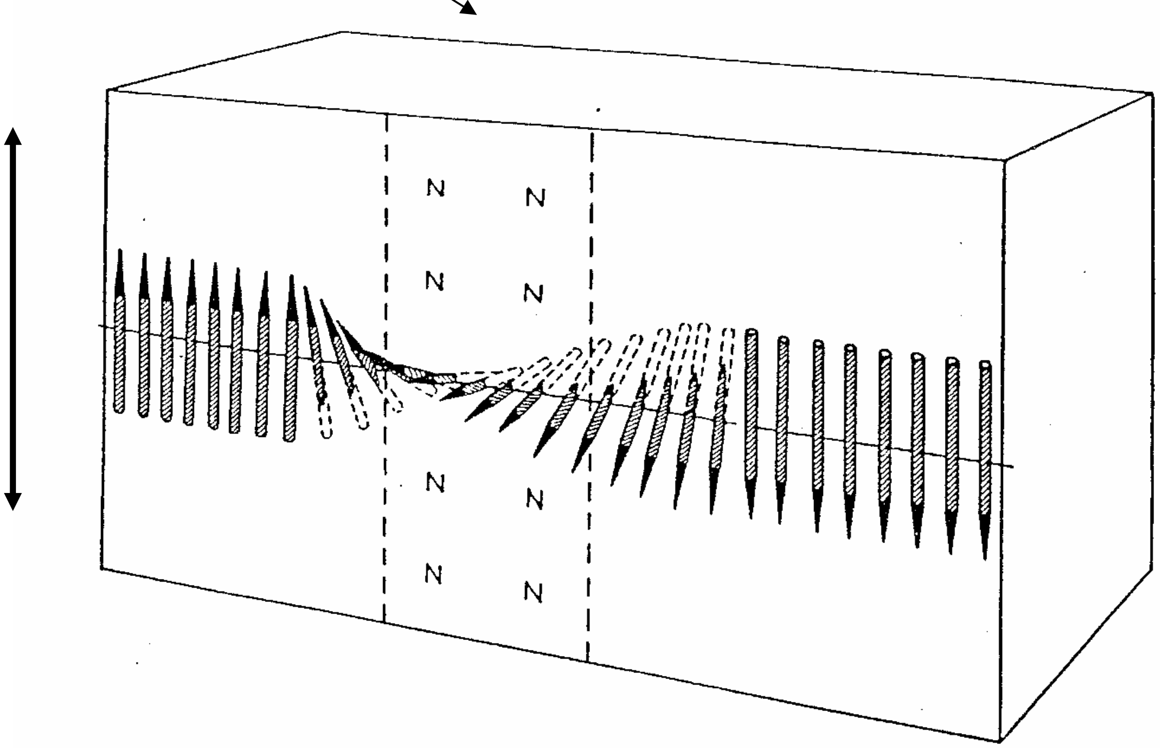
2. Domain Wall Motion

Domain wall thickness: $\delta = \pi\sqrt{A/K}$

Domain wall energy: $\sigma = 2\sqrt{AK}$

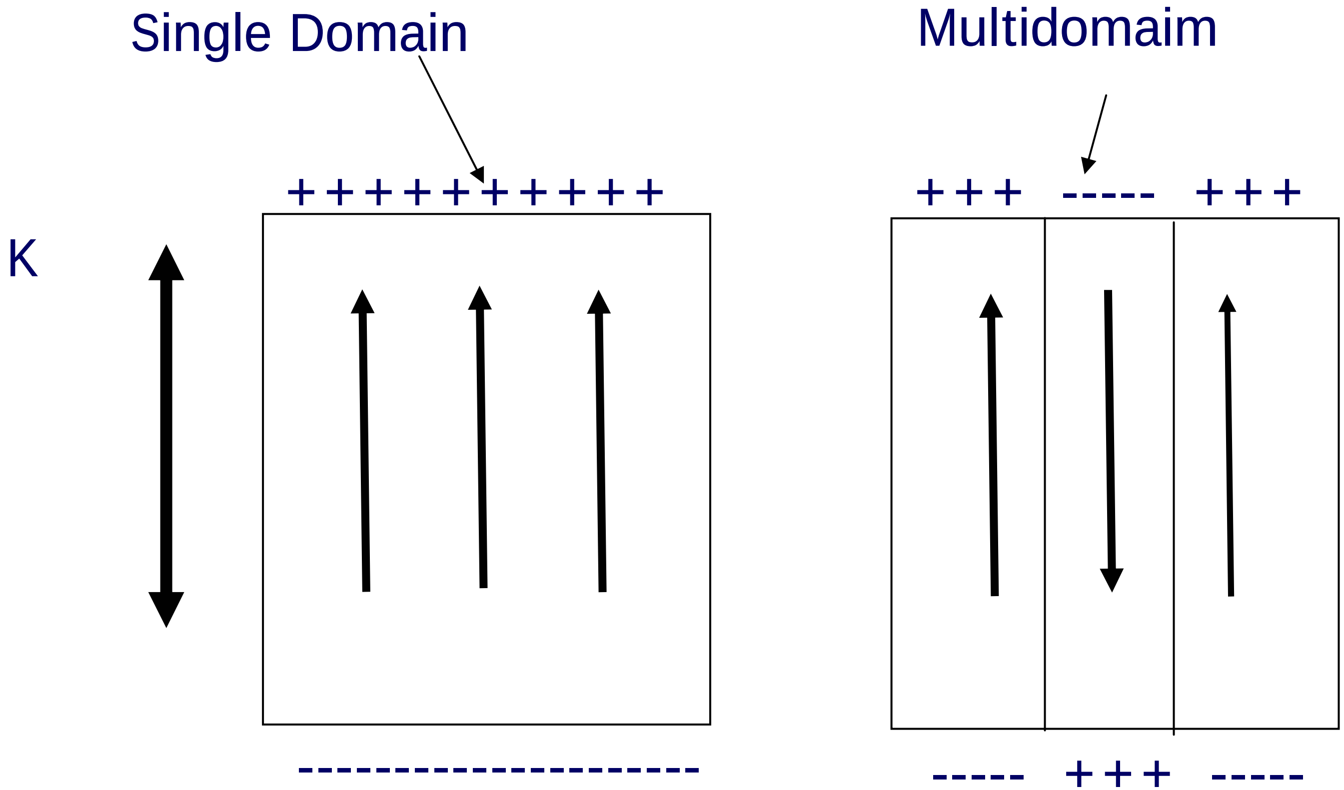
Domain wall

K



Permeability Sources in Soft Materials

2. Domain Wall Motion (cont.)



Domains form to reduce large surface magnetostatic energy
Cost is an increase in domain wall energy

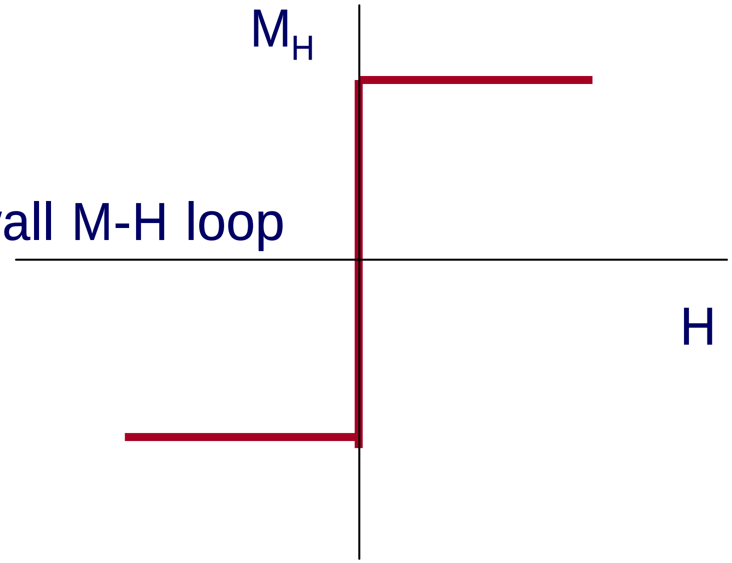
Permeability Sources in Soft Materials

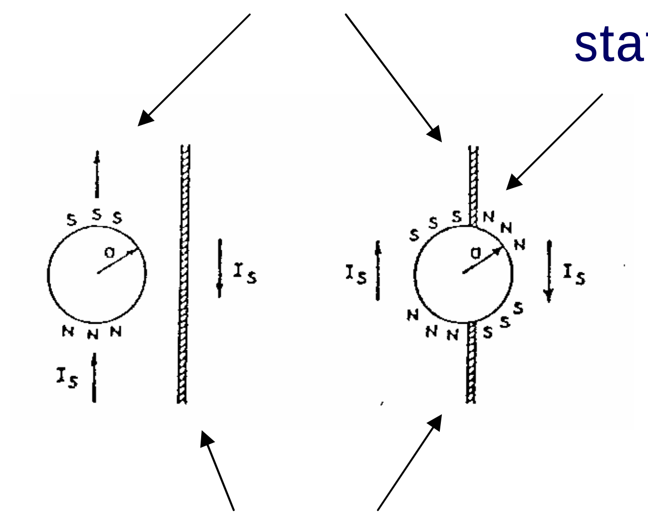
2. Domain Wall Motion (cont.)

- In an ideal case, applying a field causes the domain wall to move immediately through the material yielding an infinite permeability

- In reality there are imperfections (inclusions) in the material that hang up the walls and cause a coercivity (and “popping” noise)

Ideal wall M-H loop

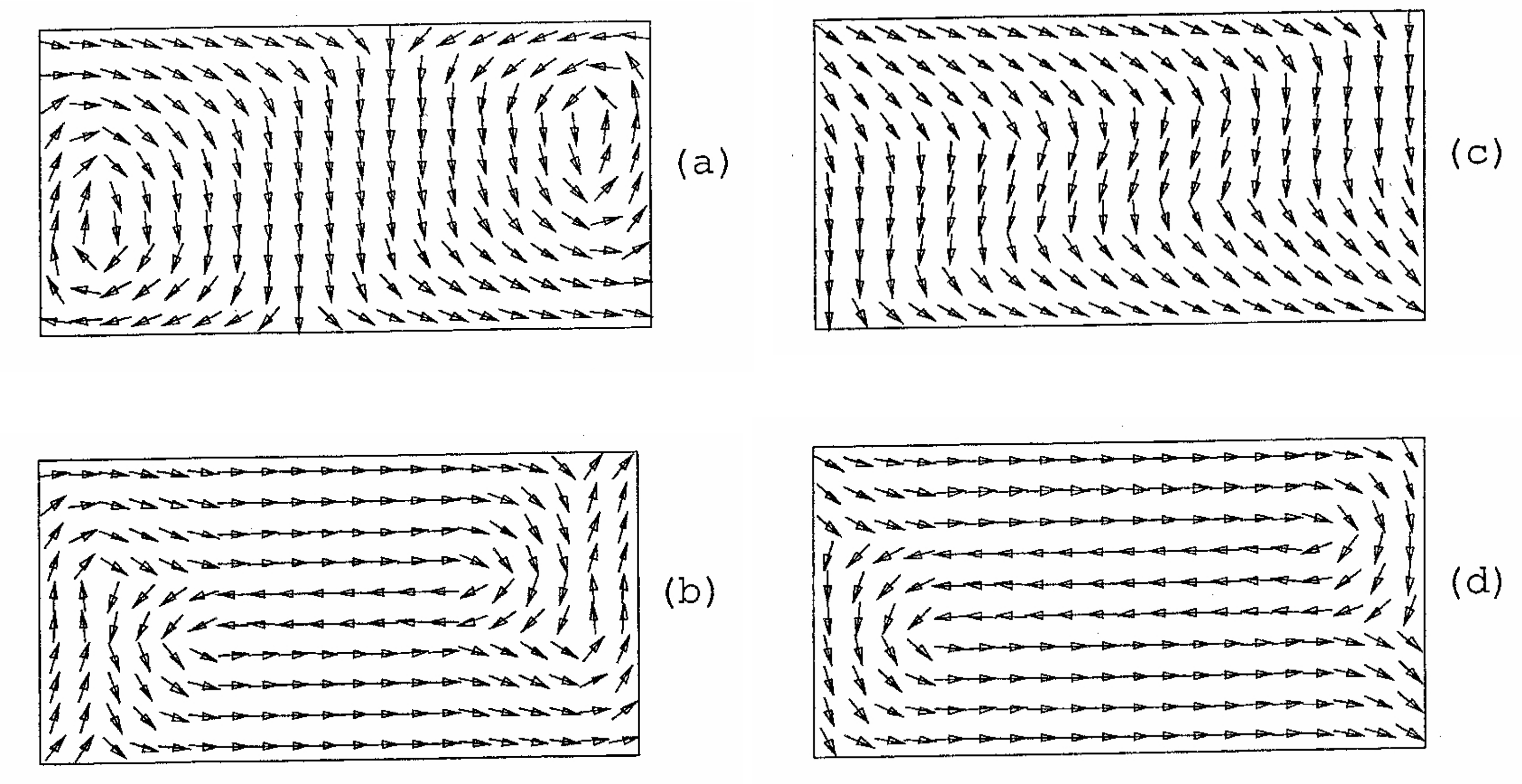




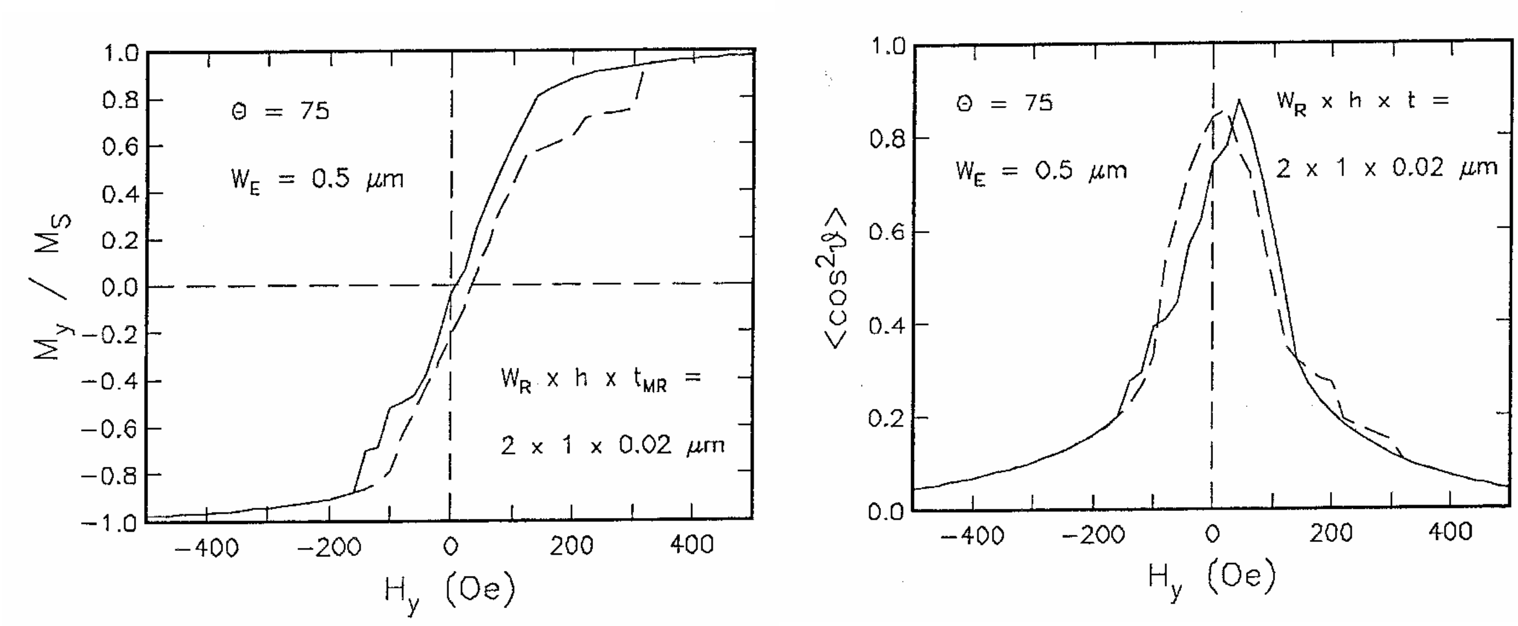
Wall Motion in an Ideal Thin Film

Single Element MR Domains/ Instability

Initial positive vertical saturation and decreasing the field to (a) H_y = 0, (b) H_y = -100 Oe and then negative saturation. Then increasing field from negative saturation to (c) H_y = -100 Oe and then to (d) H_y = 0.



Single Element MR Response



Hysteretic and Noisy!!!

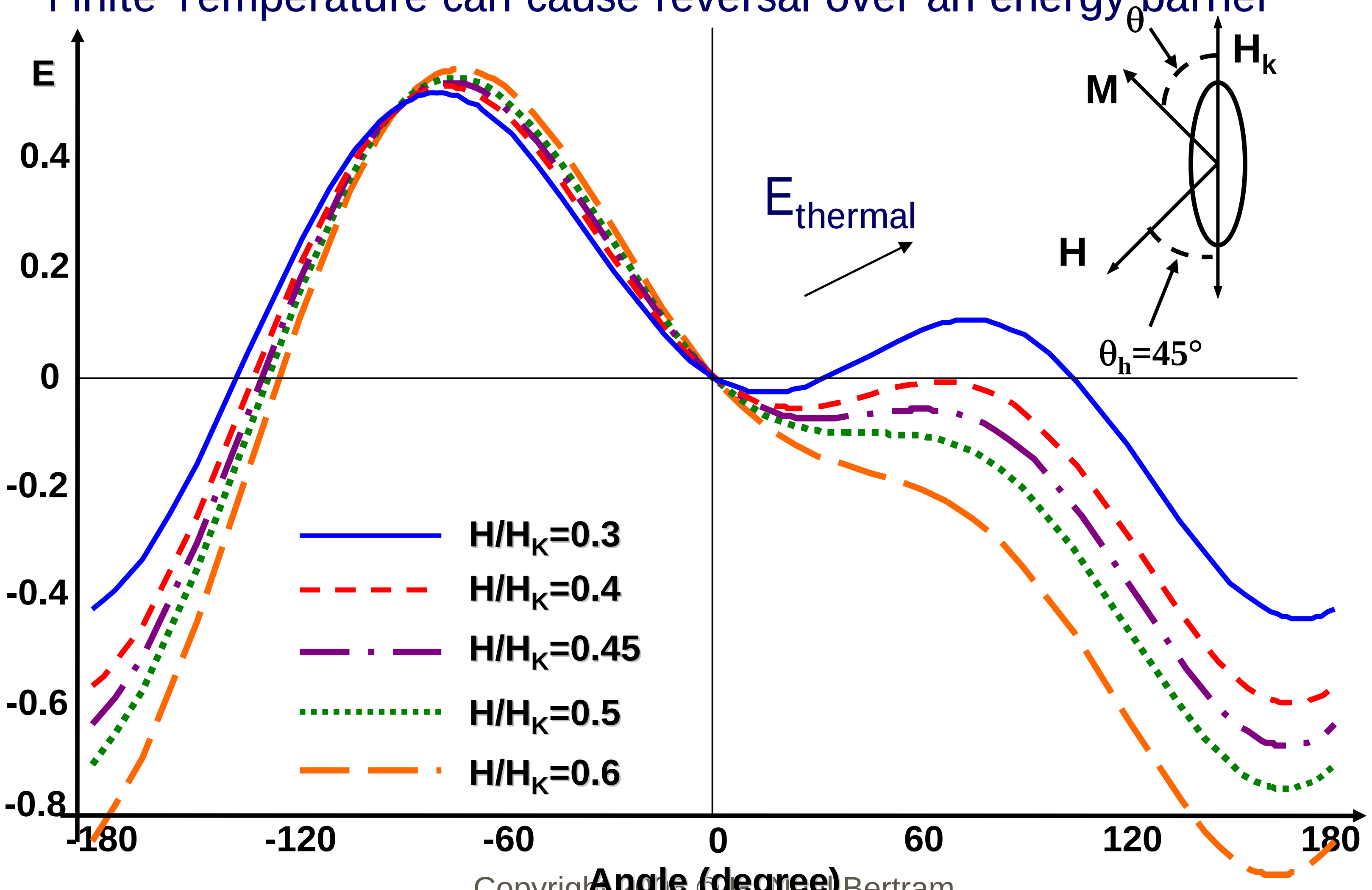
Comments about Soft Materials

- We do not want domain walls in order to obtain high permeability:
  - Walls are unstable (noise)
  - Generally get hysteresis
  - Thermal effects
  - Slow processes (MegaHertz)

- We do want high permeability by rotation against an easy axis:
  - Completely reversible
  - Ideally no noise or hysteresis
  - Very fast response (GigaHertz)
  - E.g. Multilayer SUL with cross track anisotropy

Thermal Effects

Finite Temperature can cause reversal over an energy barrier



Thermal Effects Continued

- Basic idea is a probability rate that the magnetization will reverse over an energy barrier E_b at a temperature T:

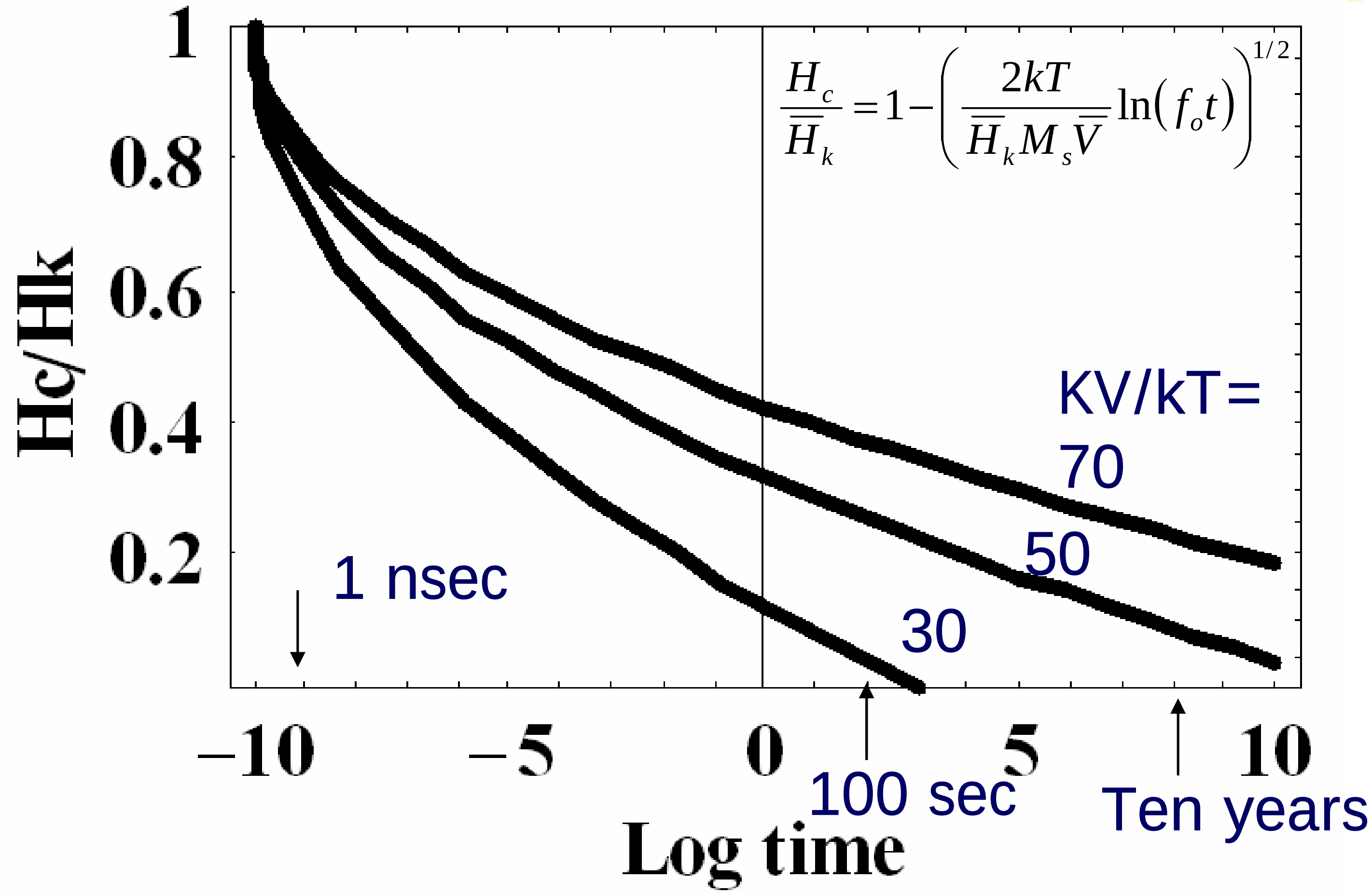
$$P = f_o e^{-E_b / k_B T}$$

- Typically: reversal rate $f_o \sim 10^{10}$/sec.
- $E_b = H_K M_s V/2 = KV$ for a single domain grain of volume V.

- Lower grain volume and higher temperature increases decay!!

Coercivity versus Time/Temperature

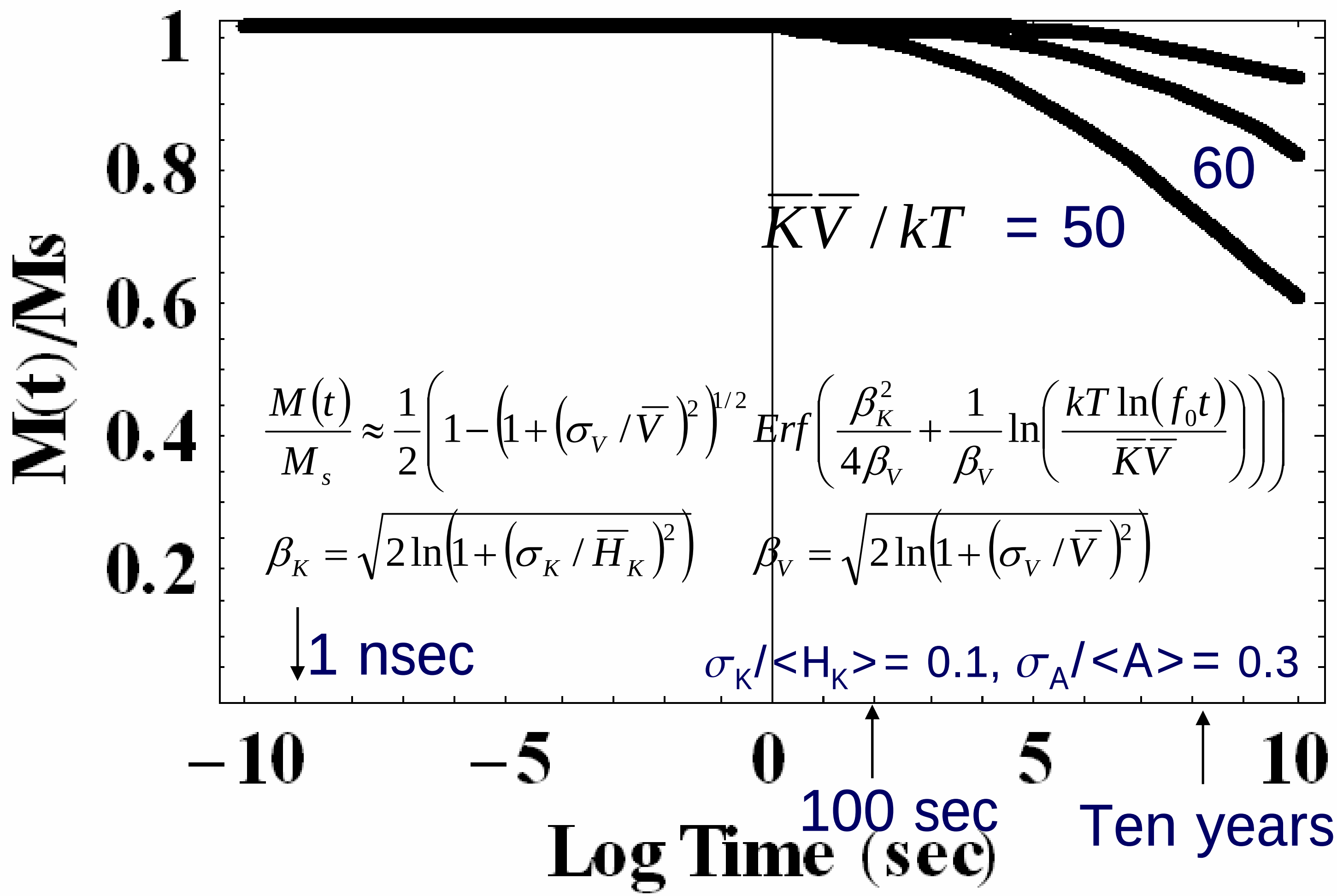
(no distributions)



For T = 375^{o}K, Ms= 600 emu/cc, H_k=15kOe, t = 15nm:
KV/kT = 30, 50, 70 => <D>=4.8nm, 6.2nm, 7.3nm

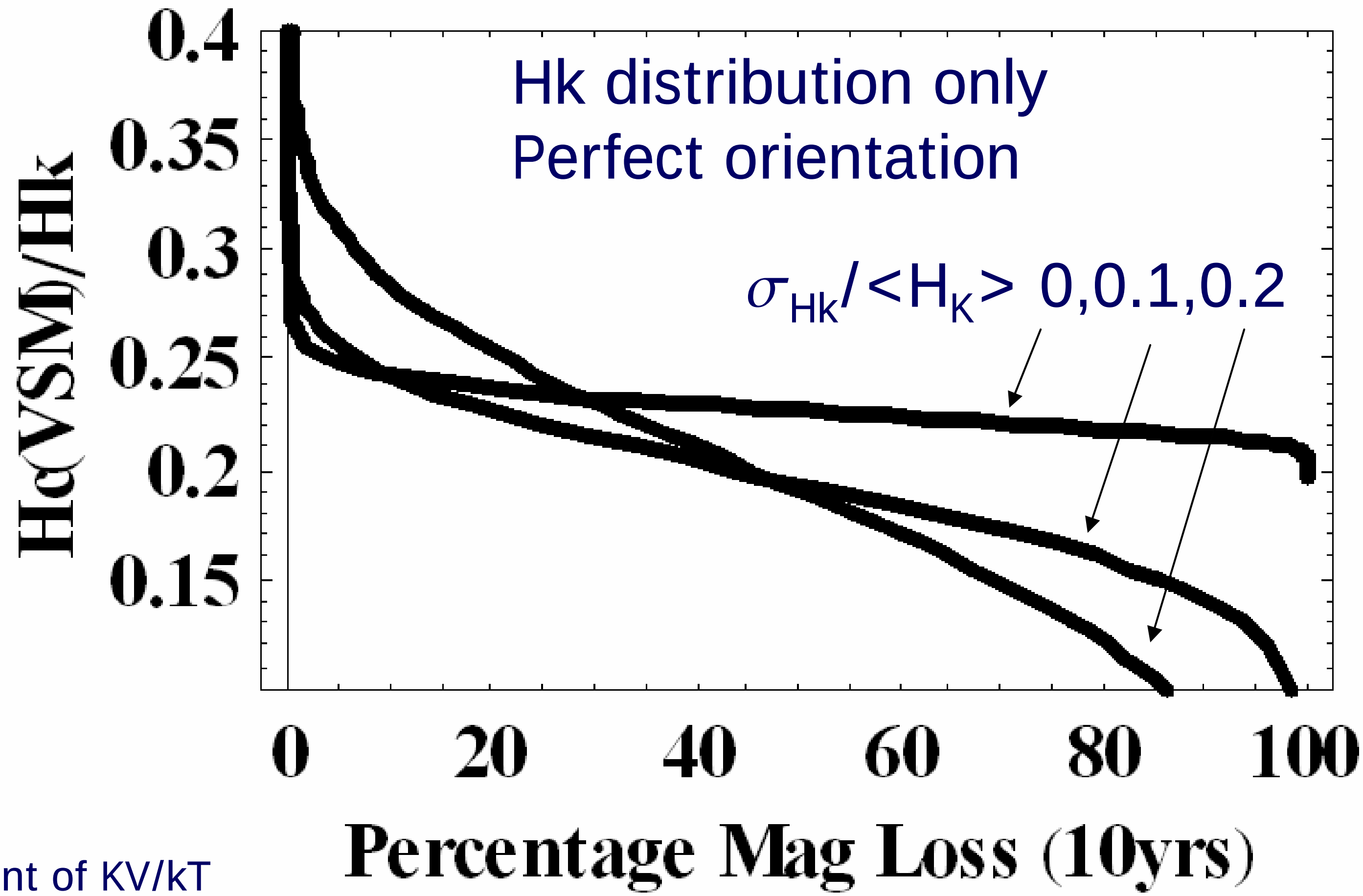
Magnetization Decay versus Time

(anisotropy and volume distribution, zero field)



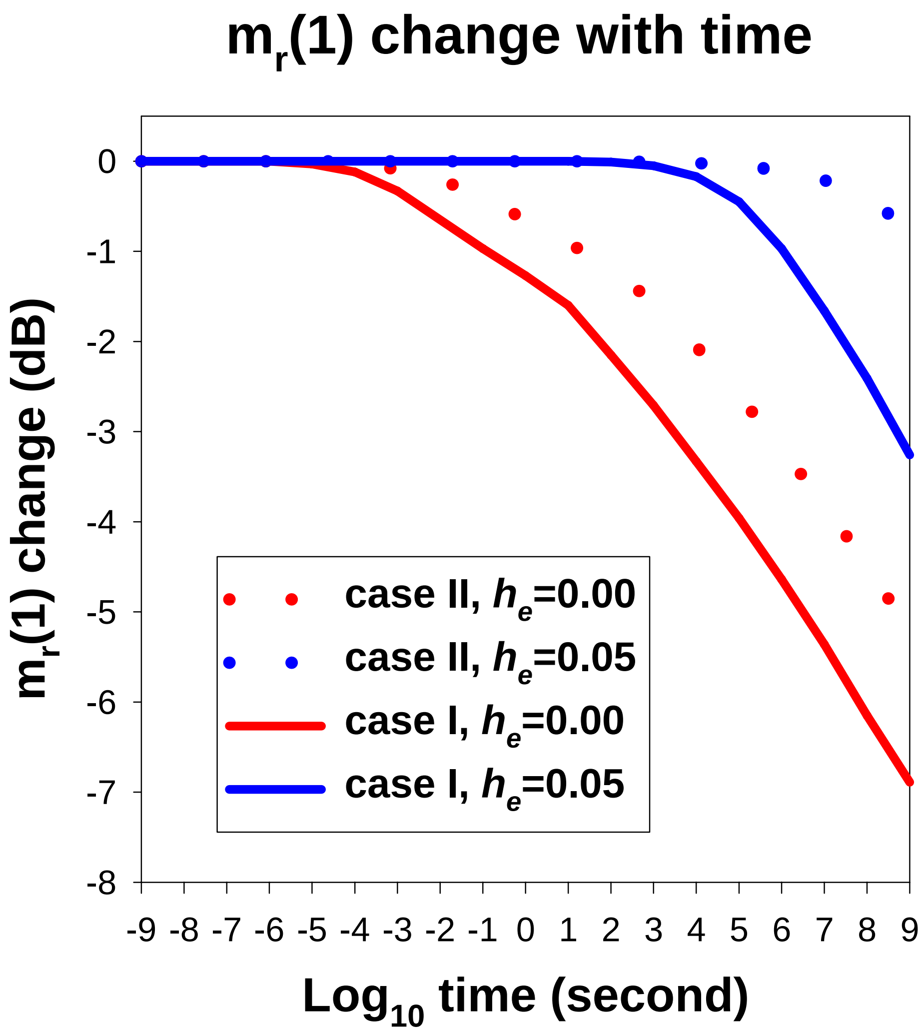
σ_D/<D>= 0.5σ_A/<A>

VSM Coercivity (100sec) versus Long time Magnetization Decay (10 years)



Independent of KV/kT

Thermal decay and Exchange



Case I: M_s=350 emu/cm^3,

H_K=14.6 KOe

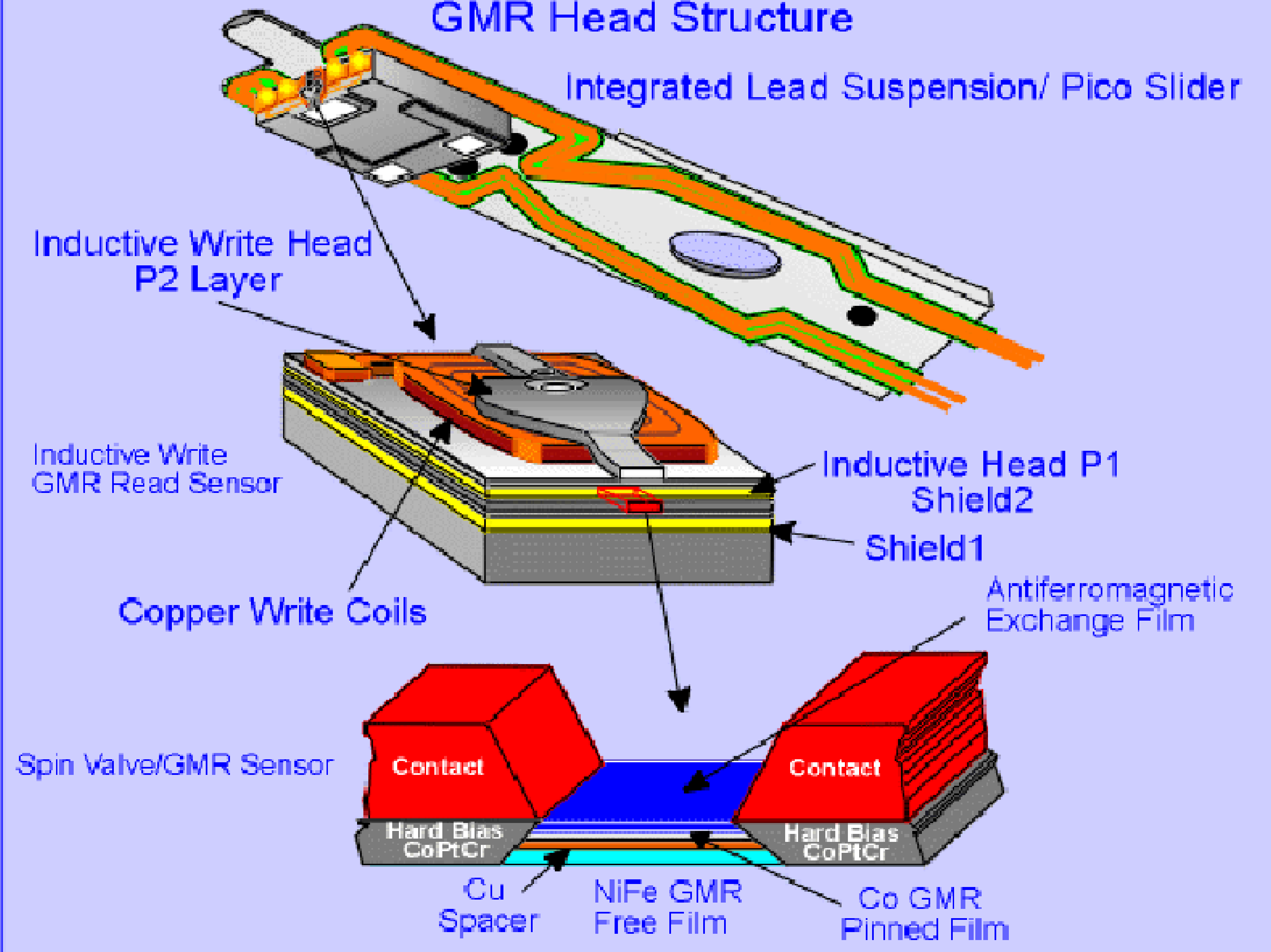
Case II: M_s=290 emu/cm^3,

H_K=17.6 KOe

From Hong Zhou

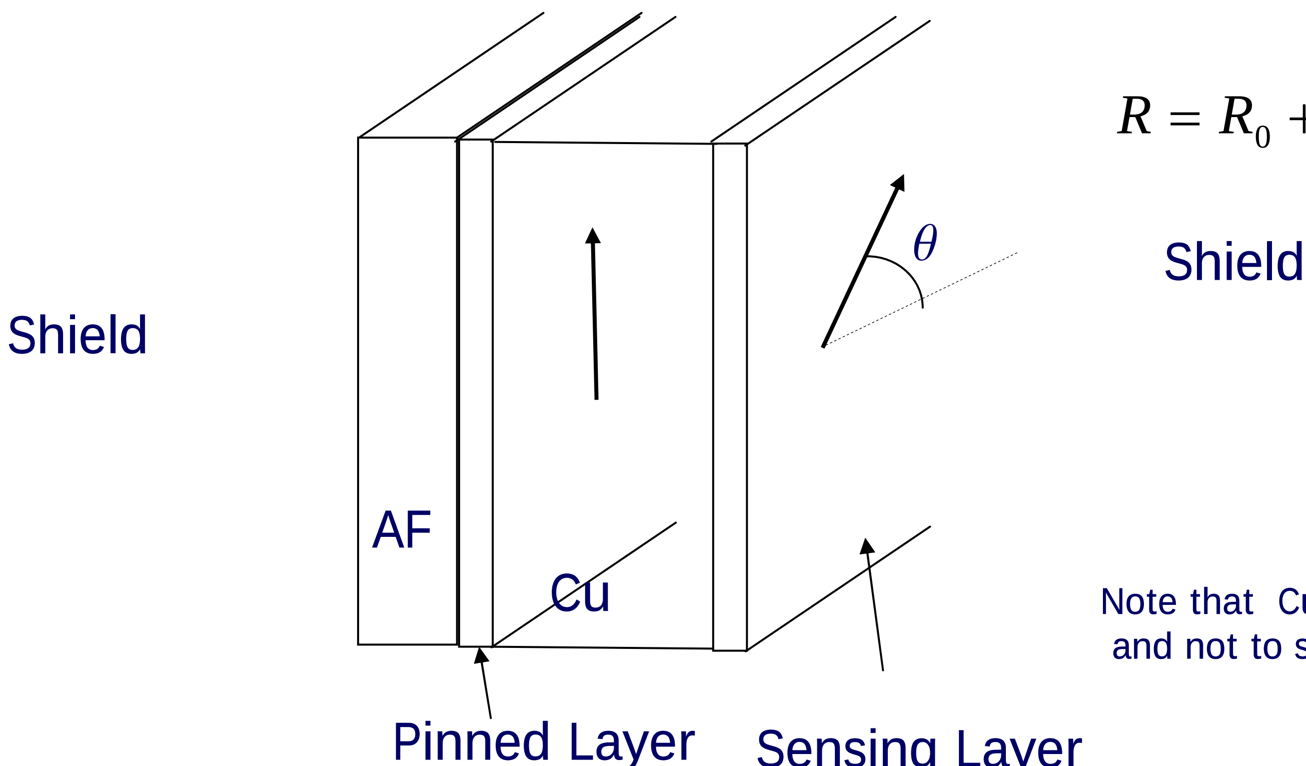
IV. Replay Process

GMR Head Structure



Basic GMR Process

- We have two magnetic films separated by a conductive spacer. The resistance varies as the angle of the magnetization between the films.

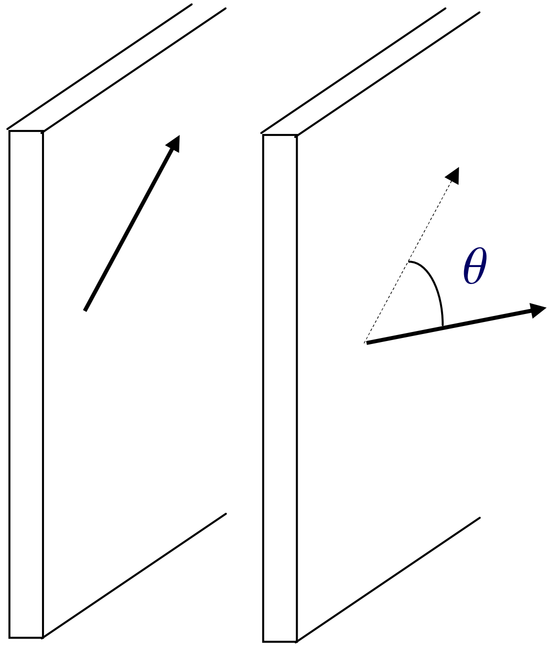


$$R = R_0 + \Delta R\left(\frac{1-\cos(\theta)}{2}\right)$$

Note that Cu layer is thin and not to scale here

Basic GMR Device

- An antiferromagnetic (AF) film is exchange coupled to the pinning layer to keep it in the perpendicular direction.

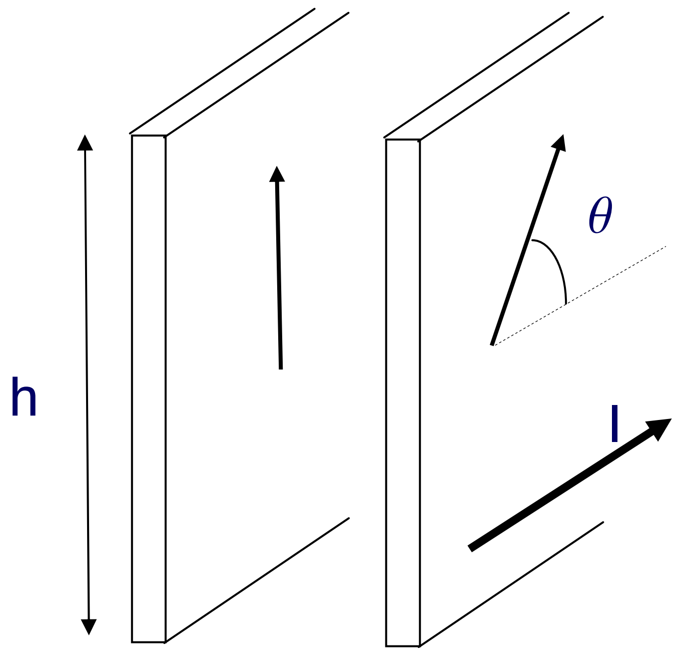


$$R = R_0 + \Delta R\left(\frac{1-\cos(\theta)}{2}\right)$$

Current is applied in both films in any direction

Basic GMR Device (cont.)

- If the pinned layer magnetization is perpendicular and the equilibrium (with no applied signal field) direction of the sensing layer is in the cross track direction, the replay voltage is:



$$V_{GMR} = IR_{sq} \frac{W_r}{2h} \frac{\Delta R}{R} < \sin\theta\left(H_{sig}\right) >$$

A current density J is applied to the three films and is approximately divided equally amongst them.

h is the film height, sinθ is called the “transfer function”.

Basic GMR Device (cont.)

- The maximum voltage that a GMR sensor can deliver is:

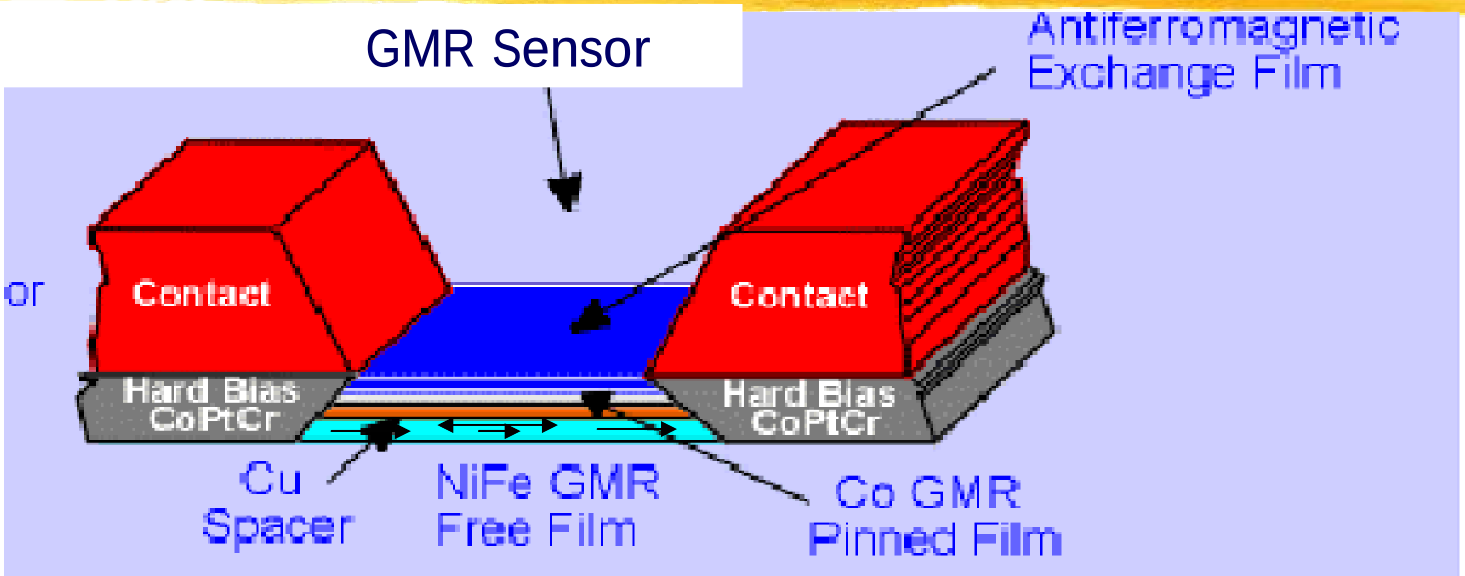
$$V_{GMR} = IR_{sq} \frac{W_r}{2h} \frac{\Delta R}{R}$$

- In terms of nVolts/nanometers of track width and assuming I = 7mA (heating limit), h = 70nm, R_{sq} = 15Ω, ΔR/R = 10%:

$$V^{0-pk} / W_r = 10mV / \mu m$$

- Useable voltage is less due to element saturation and asymmetry.

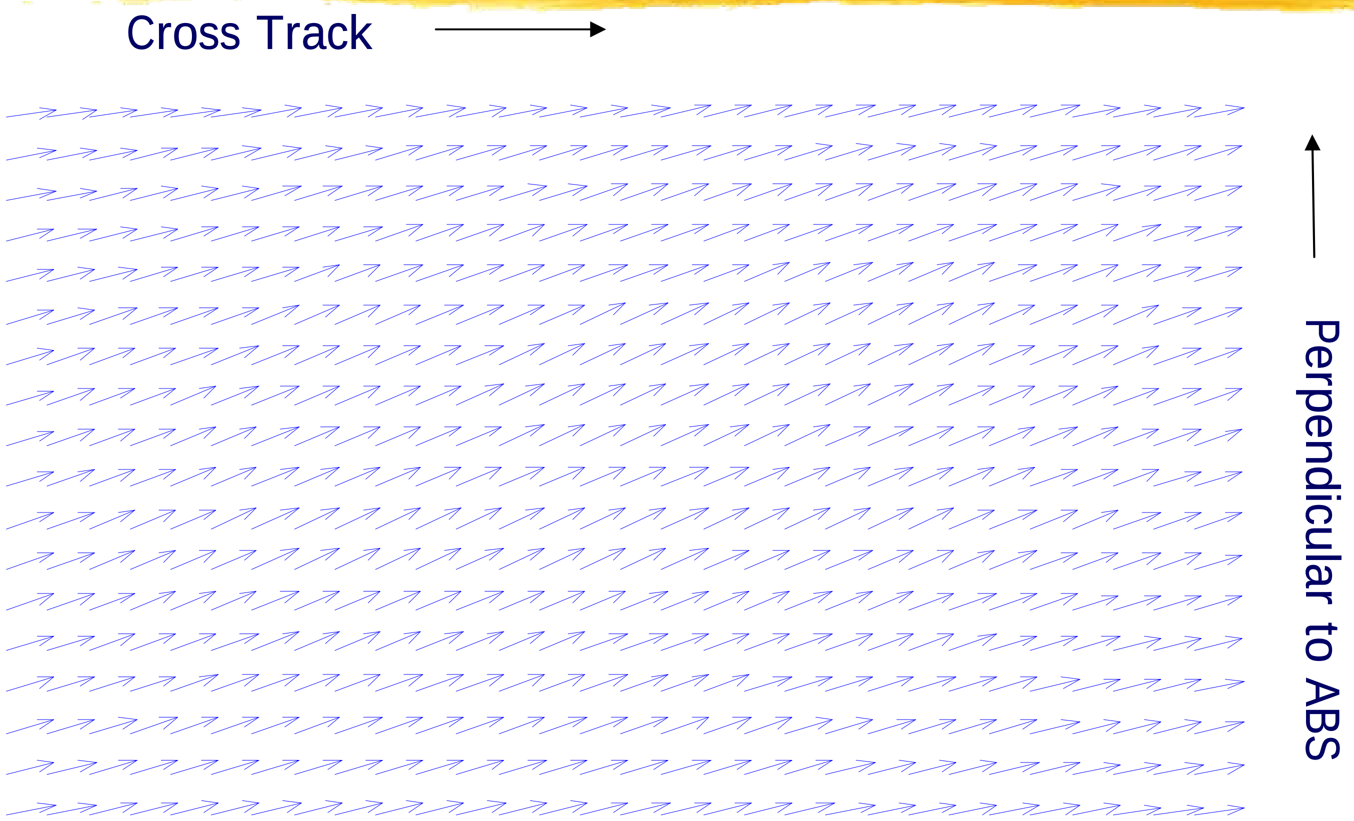
GMR Bias Fields



- Cross track anisotropy (K) is induced in free layer (⟷).

- Hard bias films are magnetized (saturated) in cross track direction to produce cross track field (⟶). Due to shields and simple geometry the fields are very large at track edge and much smaller at track center. Bias fields main purpose is to keep Sensors free of domain effects.

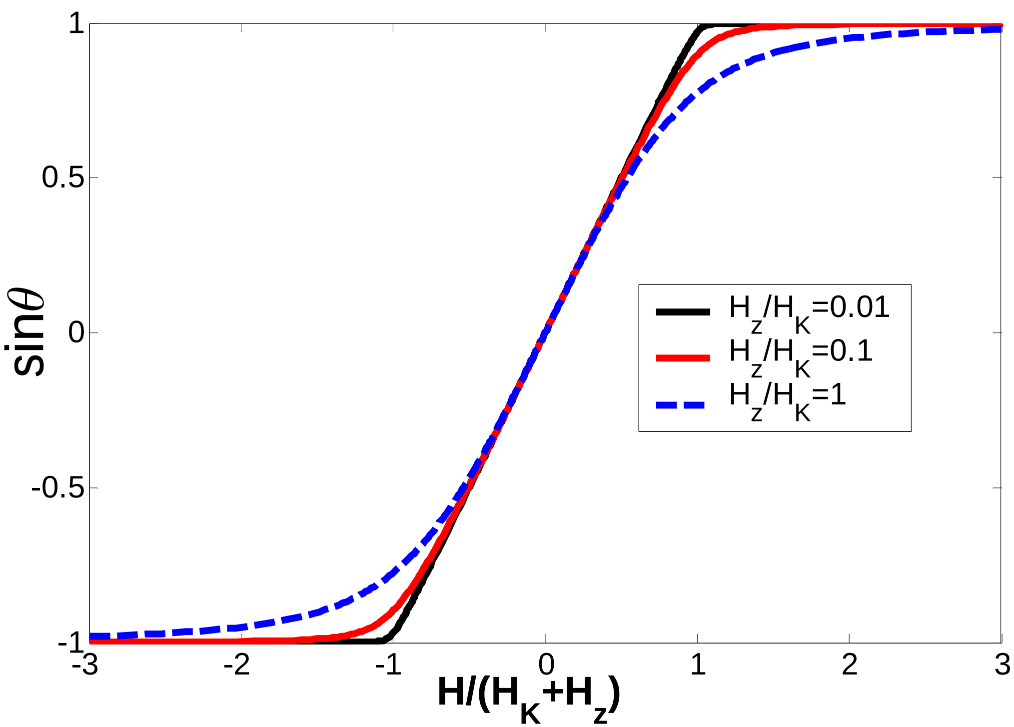
Actual Sensor Magnetization Pattern

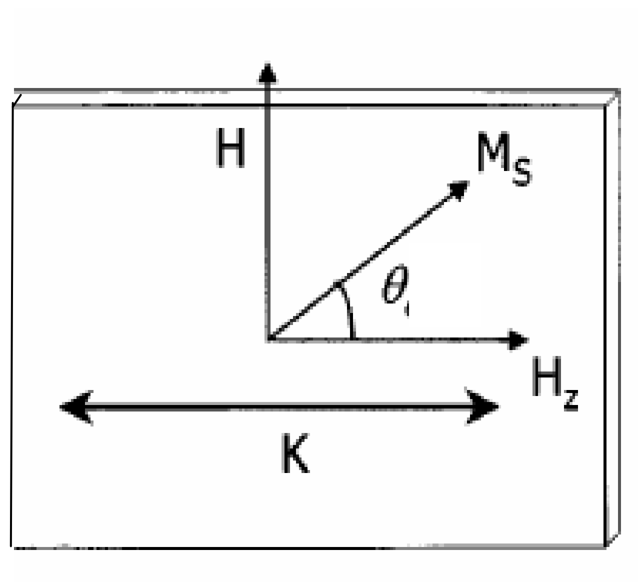


- When sensor layer is activated, only the center region rotates: the edges are pinned by the large bias field, the top and bottom are pinned by the demagnetizing fields

GMR Transfer Function

- The cross track equilibrium magnetization of the free layer is set by a growth induced anisotropy field and a cross track field from the permanent magnetization stabilization.





GMR Transfer Function (cont.)

- Operating at 5-10% saturation, asymmetry yields, for the previous parameters:

$$V^{0-pk}/W_r \approx 2.5\mu V/\mu m$$

- For perpendicular recording in terms of head-medium parameters (and neglecting saturation - can't exceed above limit):

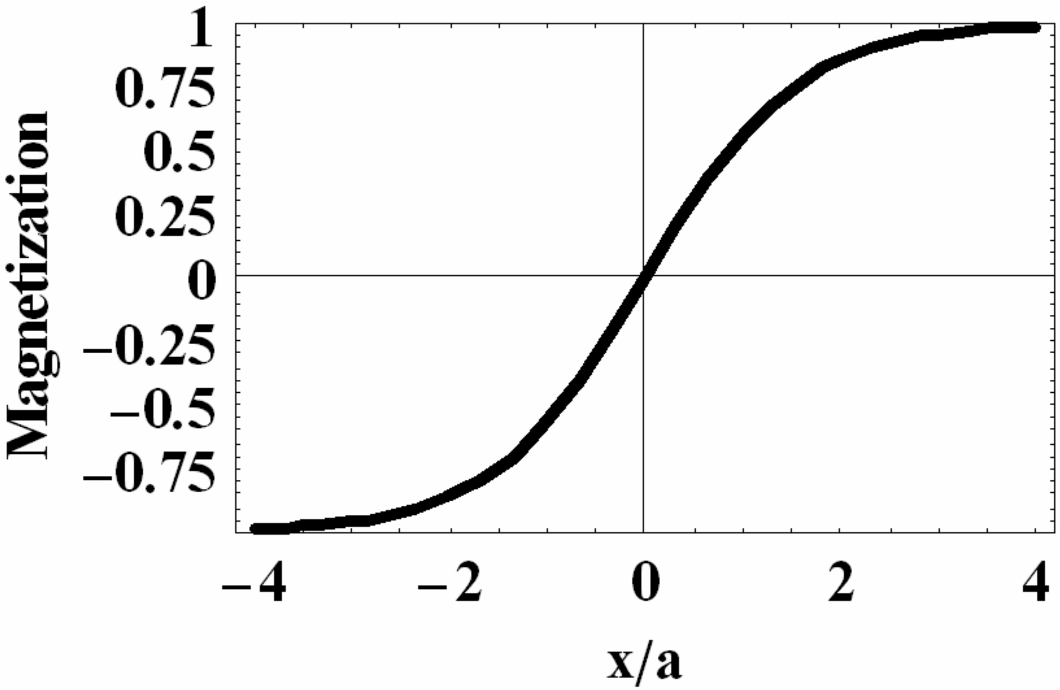
$$V^{o-peak} = \frac{IR_{sq}W_r E}{4h}\frac{\Delta R}{R}\frac{M_r t}{M_s t_{el}}\frac{\left(G_{eff}+t_{el}\right)}{\left(d+t+s\right)}$$

- t_{el} is the sensing element thickness, t is the medium thickness, d is the head- medium spacing, s is the SUL-medium spacing, G_{eff} is the effective shield to shield spacing (depends on the SUL distance a bit), E is the efficiency < 1 due to flux leakage to the shields (typically E = 0.5).

- <u>Note</u>: If optimum medium design has a rather large M_r that drives the GMR non-linear, one solution (as used in tape heads) is to compensate by increasing the element thickness t_{el}.

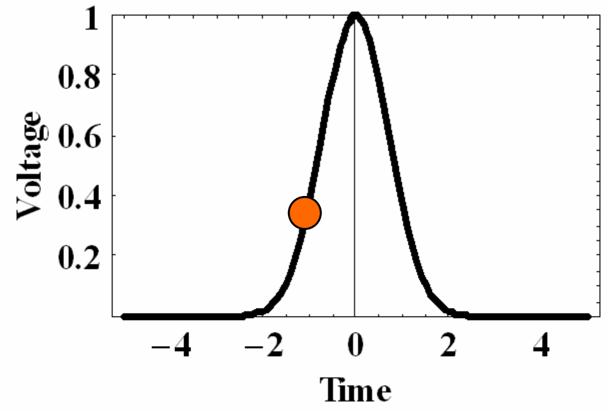
Cross Track Average Transition Shape

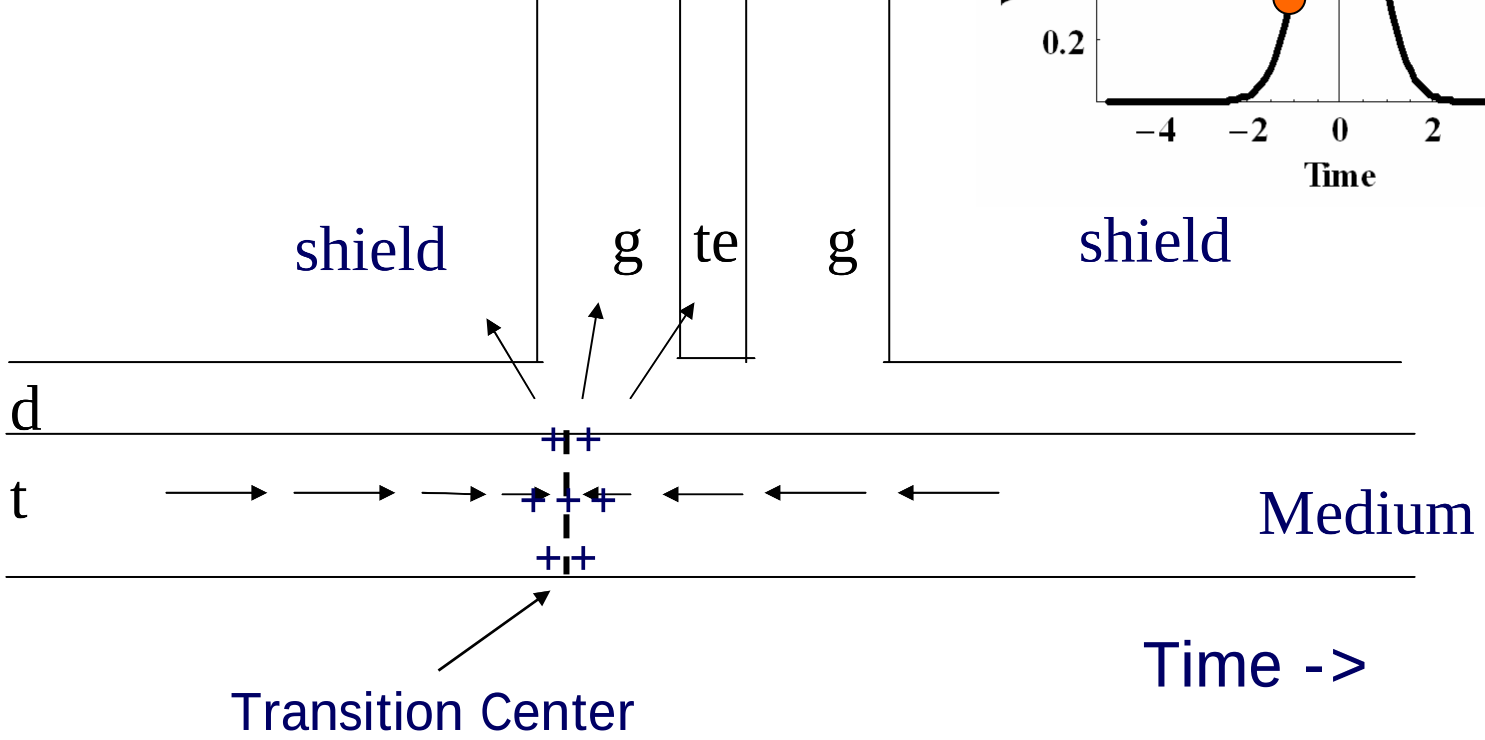
$$M(x) = M_r \tanh\left(\frac{2x}{\pi a}\right)$$



Replay Pulse with GMR Head

Longitudinal

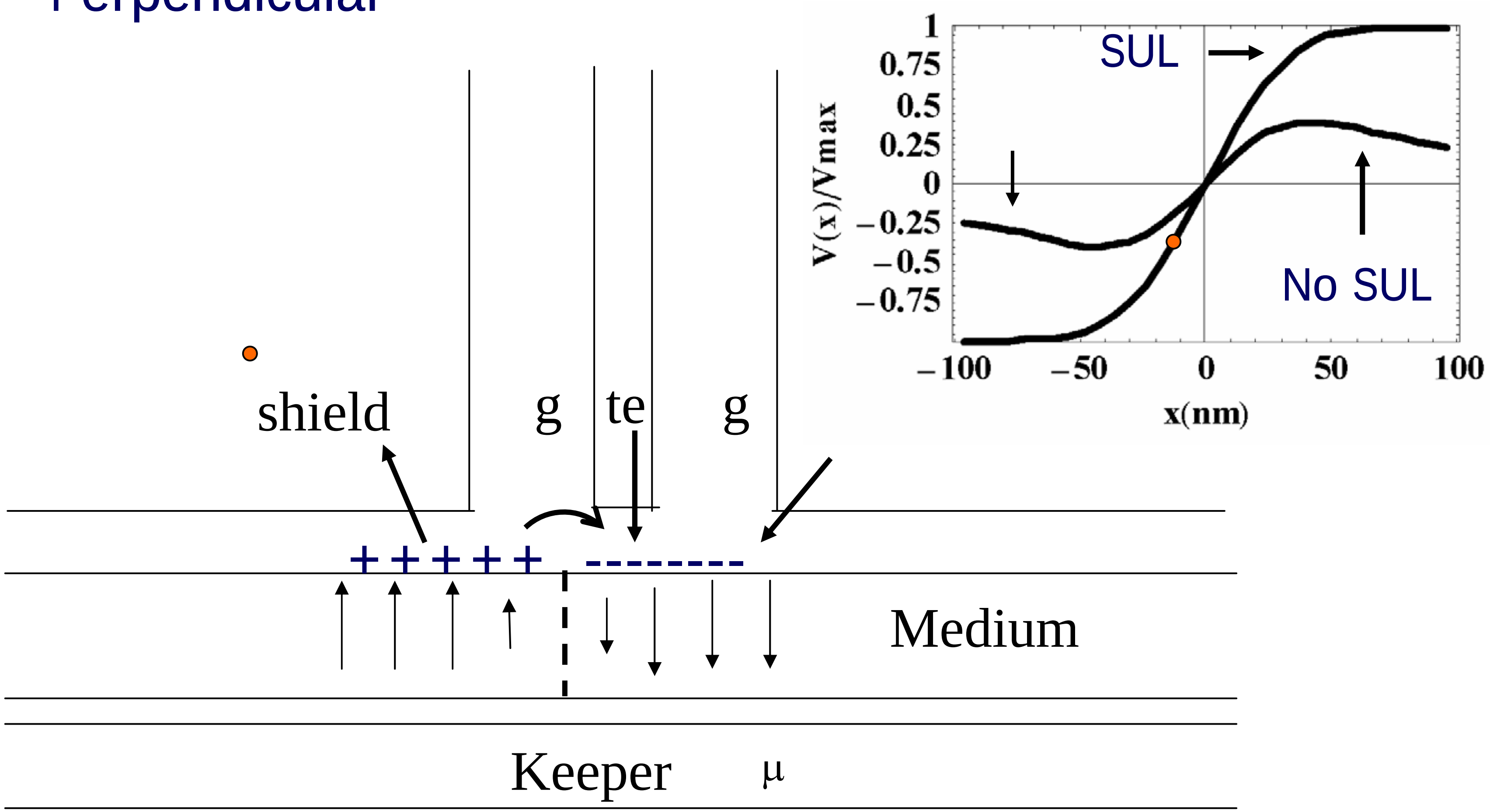




Time ->

Replay Pulse with GMR Head

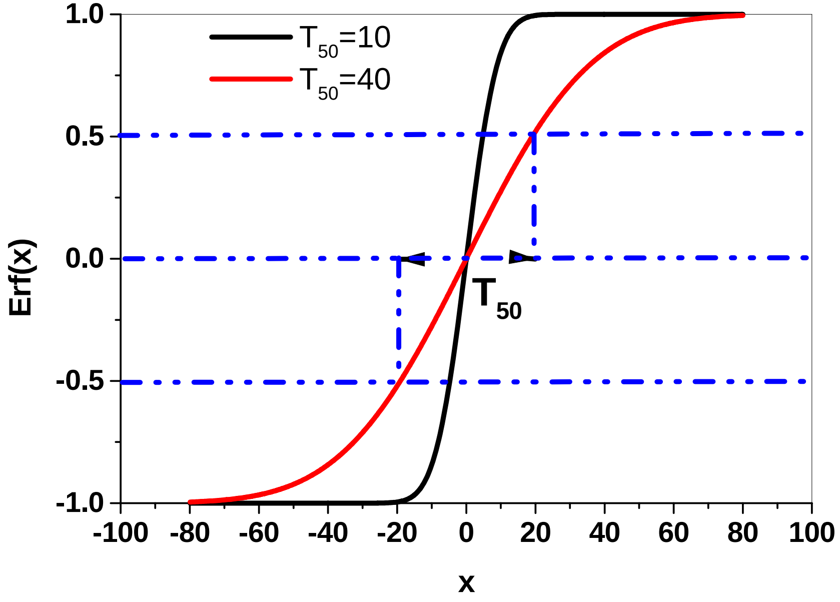
Perpendicular



Perpendicular Isolated Pulse Approximation

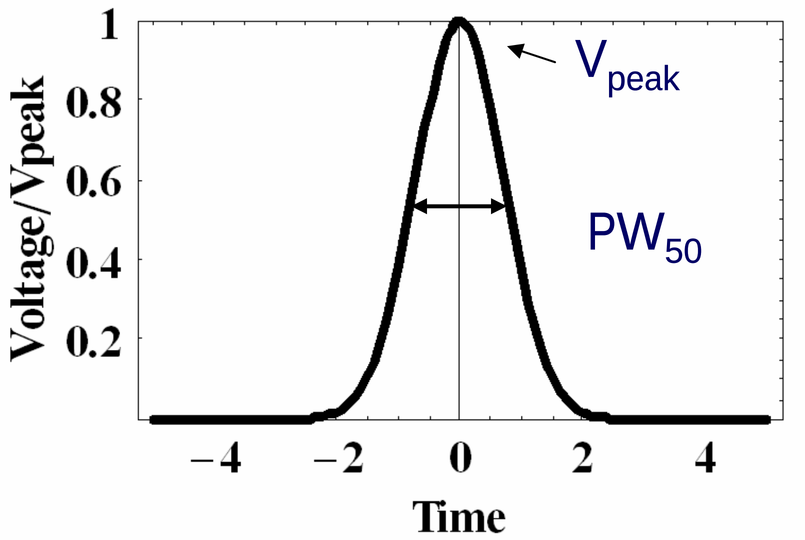
(Infinite μ_{sul})

$$V(x) \approx V_{max} \mathrm{Erf}[\frac{0.95x}{T_{50}}]$$



$$T_{50} \approx 0.77\sqrt{d^2 + 2d(s+t) - s(2s+t) + \frac{g^2}{4} + \frac{(g+t_e)^2}{4} + \frac{\pi^4 a^2}{16}}$$

Longitudinal Isolated Pulse Approximation



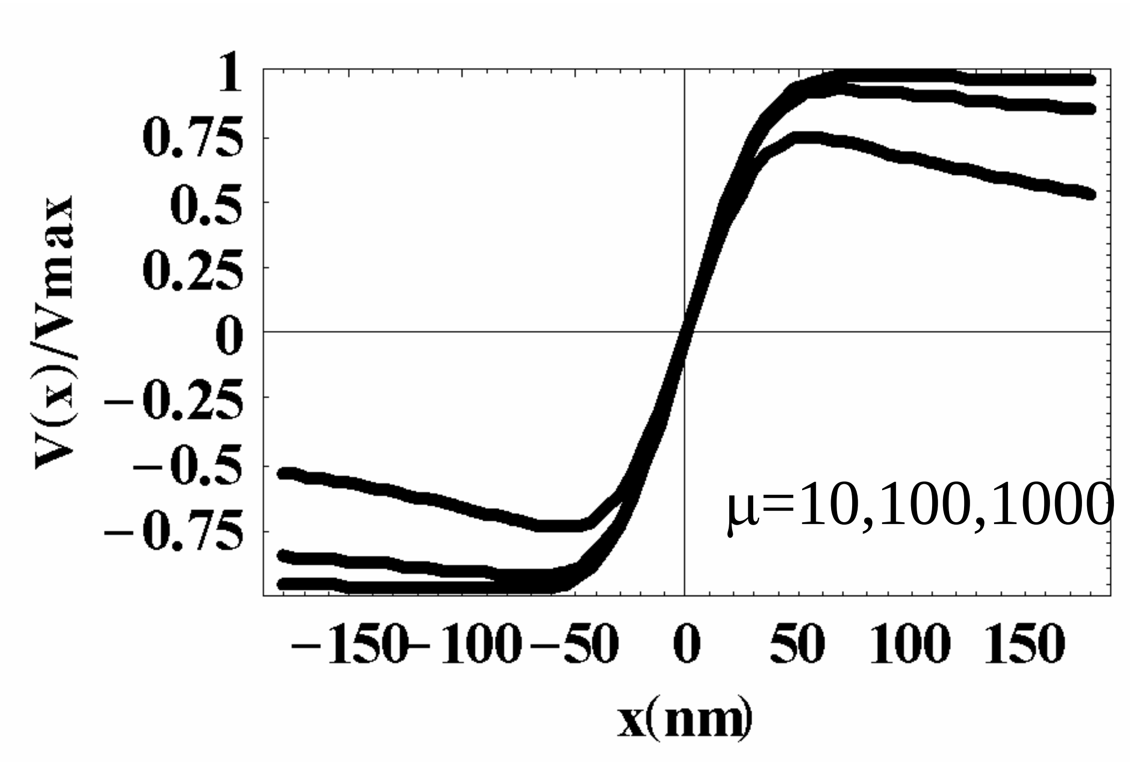
$$V_{peak} \propto \left(\frac{g+t}{2\sqrt{\pi\alpha}}\right) e^{\left((d+t/2)/2\alpha\right)^2}\left(1-\operatorname{erf}\left(\left(d+t/2\right)/2\alpha\right)\right)$$

$$PW_{50} \approx \sqrt{g^2+gt_e+t_e^2/2+12.2a^2}+1.1(d+t/2)$$

$$\alpha \approx 0.29\sqrt{g^2+gt_e+t_e^2/2+12.2a^2}$$

Pulse Shape: Effect of Finite Keeper Permeability

- Keeper permeability pulse shape normalized to infinite permeability keeper pulse maximum:



a=5nm
d=10nm
t=25nm
g=50nm
te=2nm
P=500nm

Ratio of Perpendicular Pulse Maximum to that of Longitudinal

- Longitudinal Maximum Voltage is:

$$V_{long}^{0-peak} \approx IR_{sq} \frac{W_r}{2h} \frac{\Delta R}{R} E \frac{2(G+t_{el})}{\pi PW_{50}^{long}} \frac{M_r t_{long}}{M_s t_{el}}$$

- Ratio of peak perpendicular to peak longitudinal is:

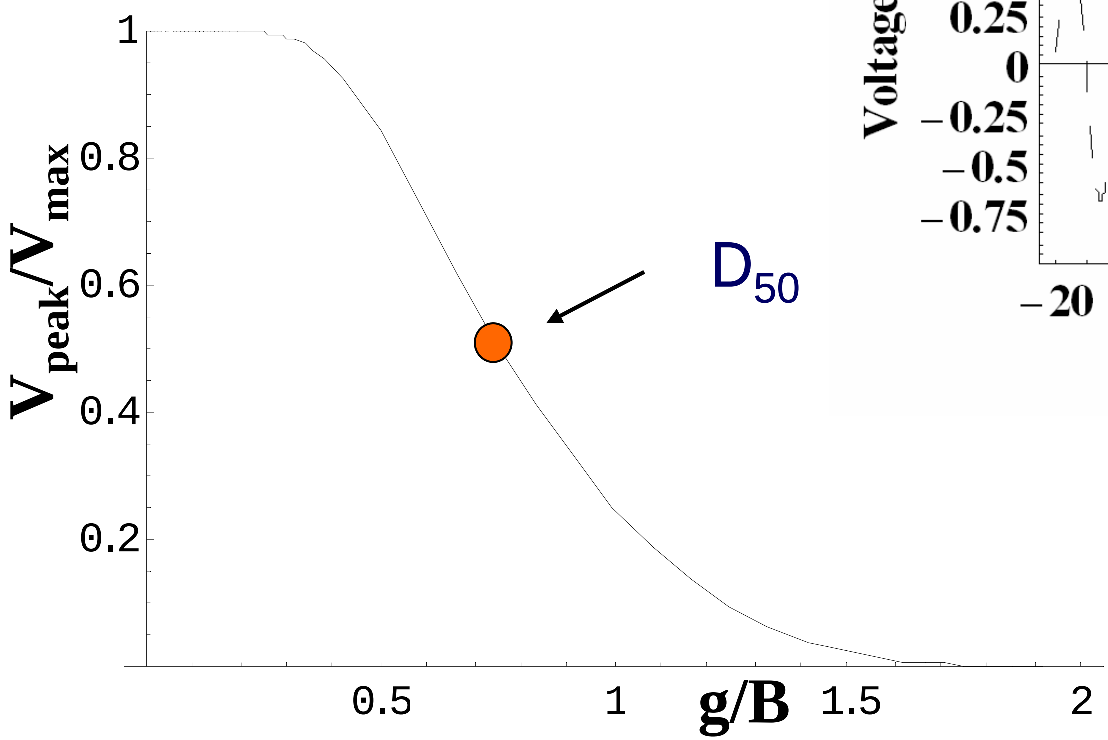
$$\frac{V_{perp}^{0-peak}}{V_{long}^{0-peak}} \approx \frac{\pi PW_{50}^{long}}{4(d+t_{perp}+s)} \frac{M_r t_{perp}}{M_r t_{long}} \frac{G_{eff}+t_{el}}{G+t_{el}}$$

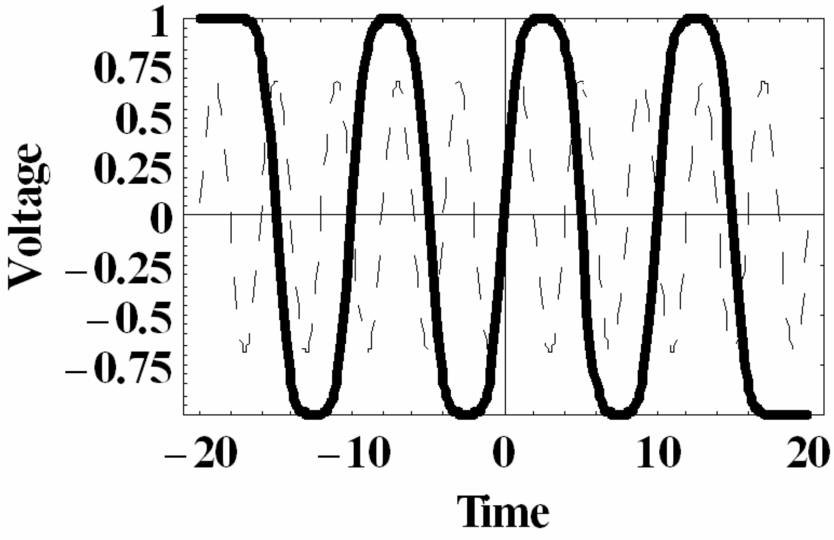
- For PW_{50} ~ 50 nm:

$$V_{perp}^{0-peak} \approx 2V_{long}^{0-peak}$$

Roll-Off Curve

Peak Voltage versus Density





$T_{50}D_{50}$, $PW_{50}D_{50}$ Product

- For longitudinal recording, the general rule is:

$$\boxed{PW_{50}D_{50} \approx 1.45}$$

- For perpendicular recording we can initially examine the pulse and the rolloff curve. For this one example D_{50} occurs at

$$D_{50} \approx 0.75/g$$

- From the pulse shape, the distance from -.5V_{max} to +.5V_{max} is about:

$$T_{50}^{perp} \approx 0.8g$$

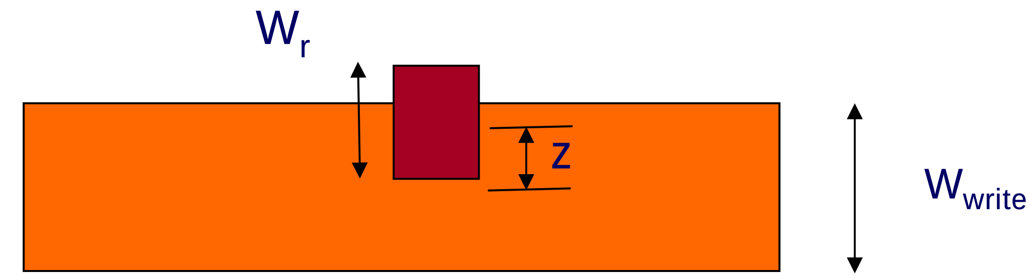
- THUS:

$$\boxed{T_{50}^{perp}D_{50} \approx 0.6}$$

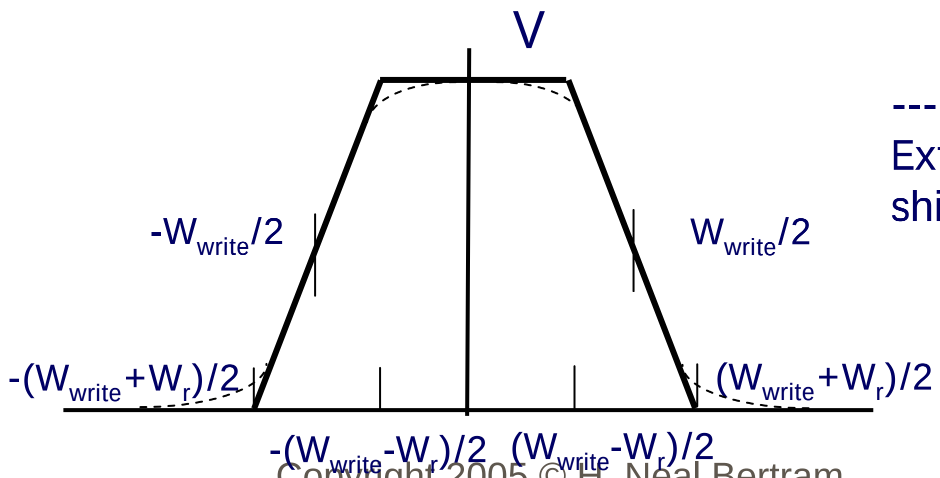
- All published data confirms this result- But beware of GMR head saturation!!!

Track Edge Effects

- For read head off center only a portion of the written track may be written:



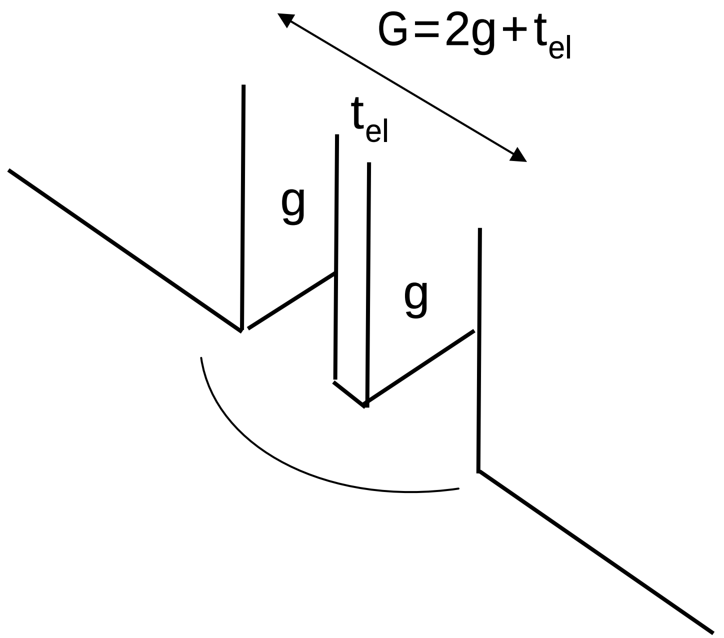
- The voltage is reduced as read head is off track, illustrated by simple geometric effect:



--- Dashed is more realistic, Extent is set by shield to shield spacing.

Effective Read Width

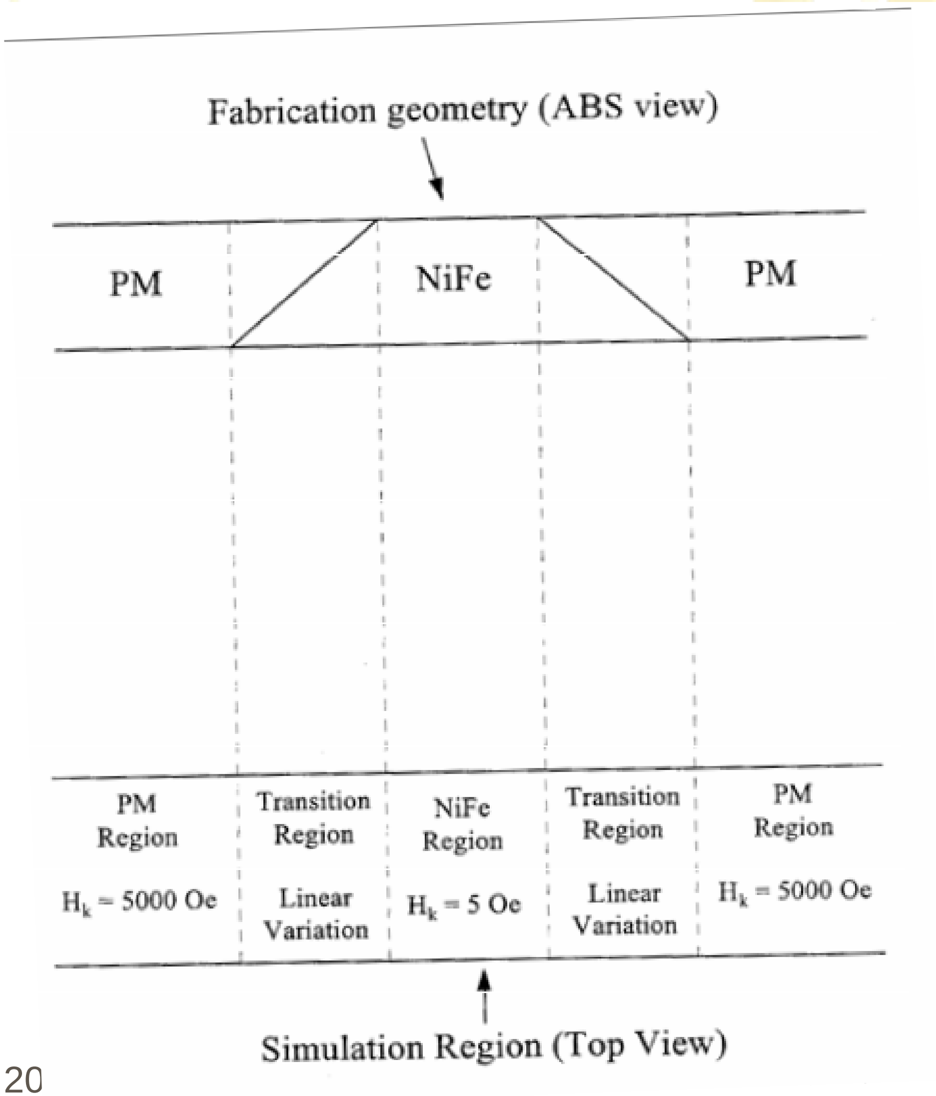
- The GMR head senses signals off to either side a distance of about g.



- The effective read width including both sides is about: W_r+G. This is complicated due to GMR structure at track edges.

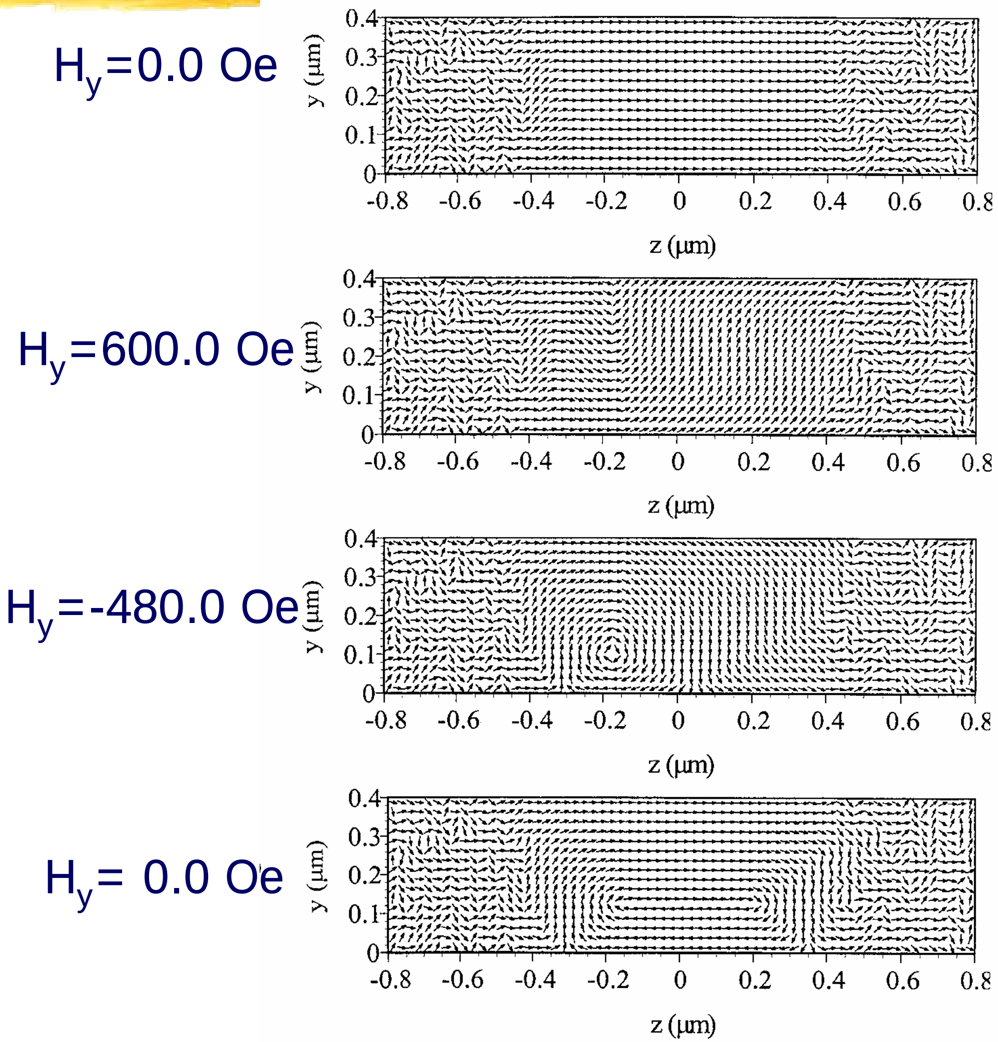
GMR Instability Effects

- Deposition process can give a graded region between the hard PM bias layer and the soft sensor layer.
- Domain wall pinning and noise can occur.
- Micromagnetic simulation follows.



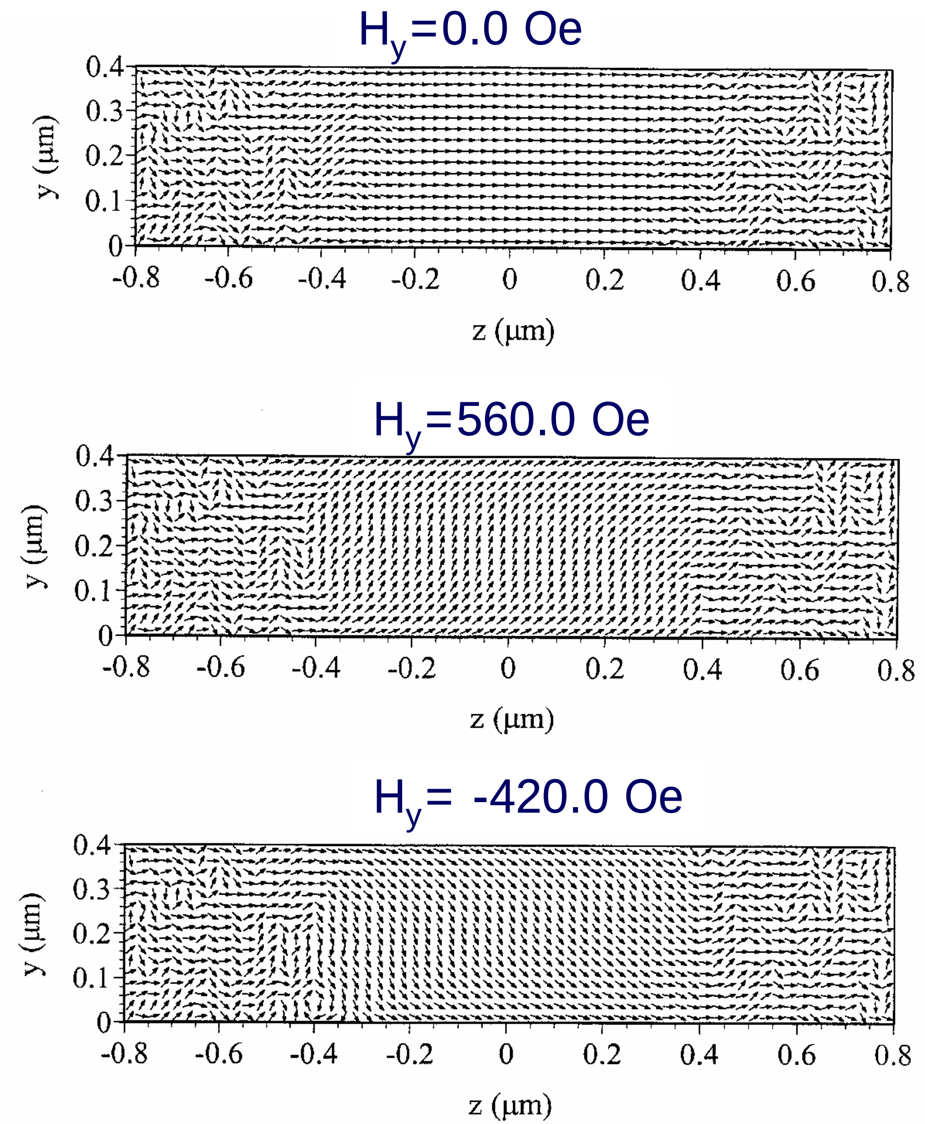
GMR Instability Effects (cont.)

- Can get hysteretic and noise effects due to wide transition region between hard PM and soft sensor.
- Similar to unshielded MR element example
- Can cause thermal noise effects!!



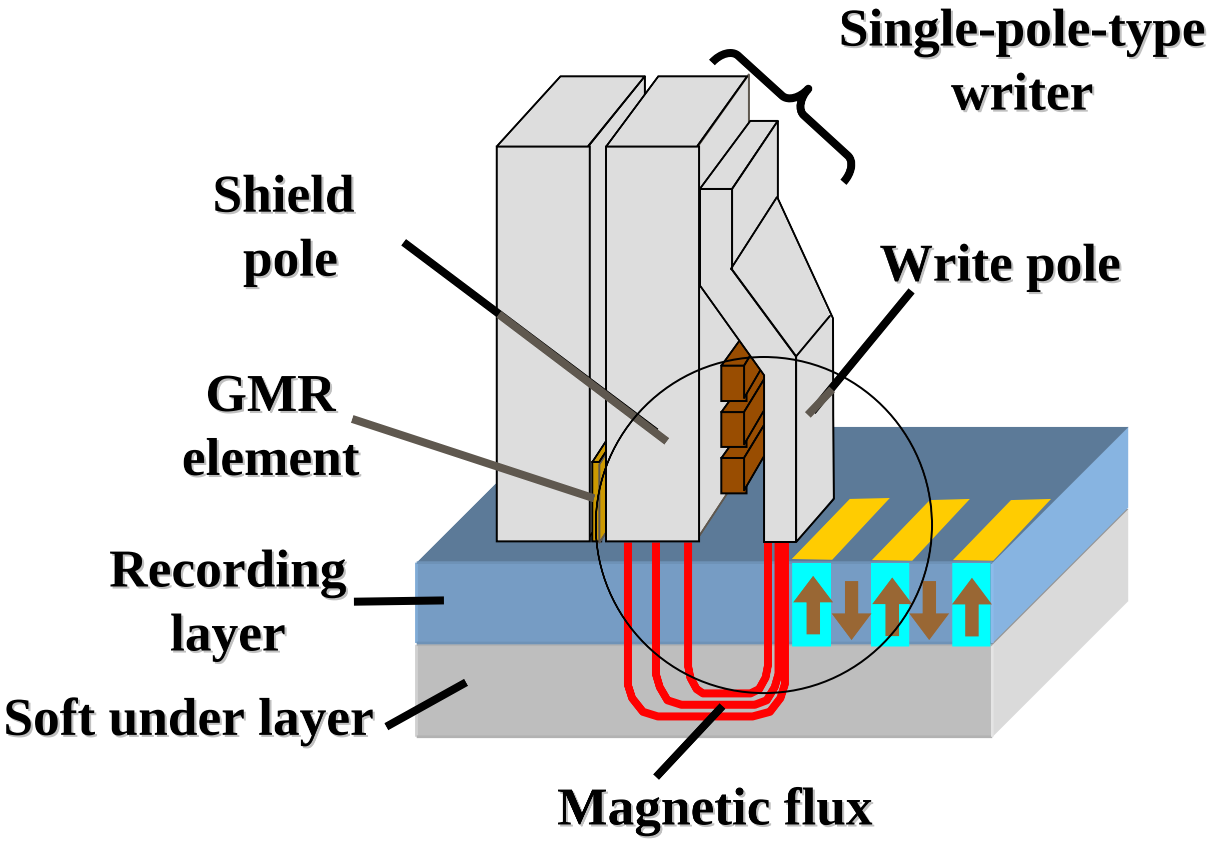
GMR Instability Effects (cont.)

- Hysteretic and noise effects can be reduced by narrow transition region
- Note that magnetization rotation in film center does not reach top or bottom. This is due to large surface demagnetizing fields. Direction of pinned magnetization can yield asymmetry in transfer curve.
- Current leads should only overlap non-hysteretic region



V. The Write Process

The Single Pole Head



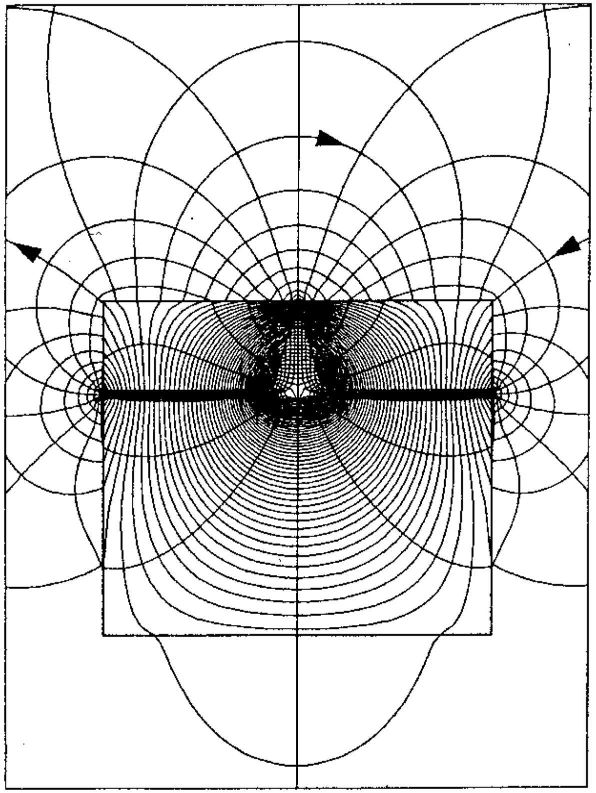
Record Head Flux Pattern

• Basic pattern is illustrated here for an inductive (tape) head. The flux flows as magnetization in the core and field outside. The field outside is produced by poles on the surfaces of the core.

• Flux is concentrated near the core center. Although most of the external field is just above the gap, fringing does occur generally around the core.

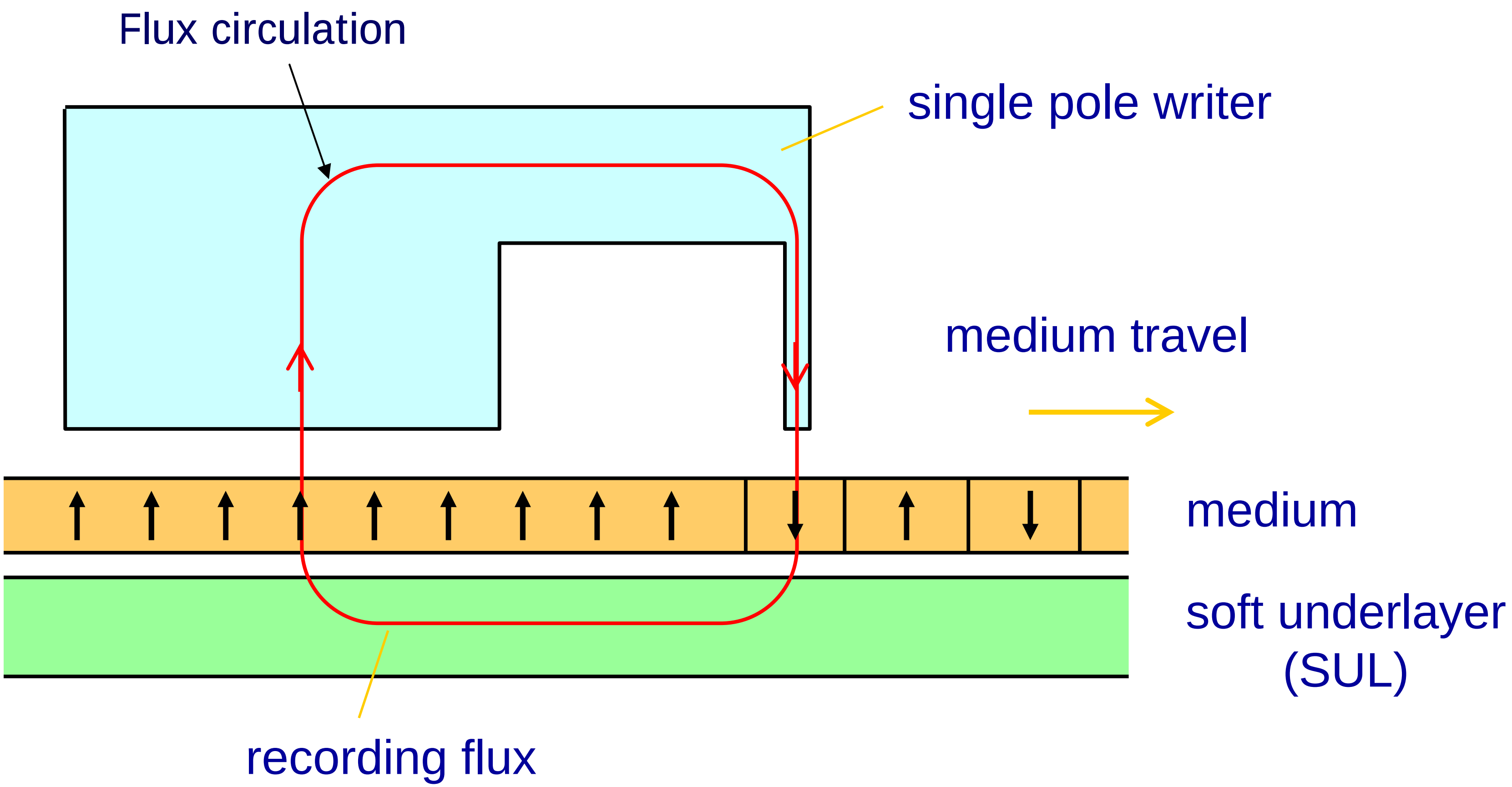
• Core permeability and fringing affects head efficiency (H_{gap} =NIE/g).

• Inductance is affected by fringing and geometry.



Flux Patterns

Perpendicular single poll head - pole length not to scale!!



Write Head Efficiency

- Flux flow is primarily around core with a small region across the gap.

- Simple expressions for efficiency in an inductive write head (neglecting fringing):

$$E \approx \frac{1}{1+\dfrac{A_g l_c}{\mu_c g A_c}}$$

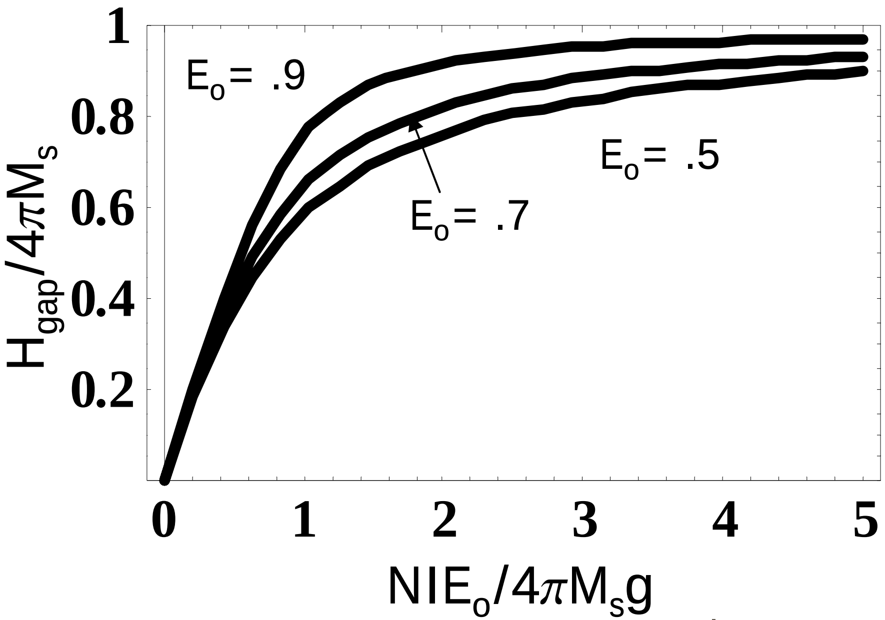
  - Permeability μ_c of the core should be as high as possible.
  - Gap g should be relatively large (d+t+s in a Probe-SUL head).
  - Length of flux path in core l_c should be as small as possible (parameter to reduce is l_c/g).
  - Gap cross section area A_g should be as small as possible.
  - Core cross section area A_c should be as large as possible (varies around core – tapering helps- sets A_c/A_g).

Head Efficiency - Saturation

- Permeability will decease as head saturates:

$$\mu_{core} \approx \mu^{o}_{core} \left(1 - M / M_s\right)$$

- But (near the gap face) the field is: $H_{gap} = 4\pi M$



Note: This is a simple approximation to get the flavor.

$$E(M) = \frac{1}{1 + \left(\frac{1}{E_o} - 1\right) / \mu_{rel}(M)}$$

Head Efficiency – Saturation (cont.)

- Application to perpendicular recording:
  - g= t+d+s =10nm +15nm+10nm =35nm
  - N = 7
  - $4\pi M_s$ = 2.4Tesla
  - Assume E_o = 0.9 (gap is not small compared to pole surface area, but there is tapering)
  - Assume apply current to reach H = 0.85 x $4\pi M_s$ =20.4 kOe
  - What is the peak current??

- From previous plot:

$$\frac{NIE_o}{4\pi M_s g} \approx 1.25 \quad \Rightarrow \quad I = 1.25 \times 4\pi M_s g / NE = 27mA$$

Head Efficiency - Rise time

- Want fastest rise time of head field (τ_{rise} < 1nsec). However voltage is applied to head wires.

$$H = \frac{NI}{g} E(t) \approx \frac{V\tau_{rise}}{2\pi L} \frac{N}{g} E(\tau_{rise})$$

  - Decreasing the inductance L is important. Since L varies as N^2, number of turns should not be too large.
  - Permeability μ_c should be high at short times or high frequency (1 GigaHz) => Eddy currents can be a problem => reduce conductivity.
  - Assess efficiency at frequency of interest, low frequency or DC tests can be misleading.

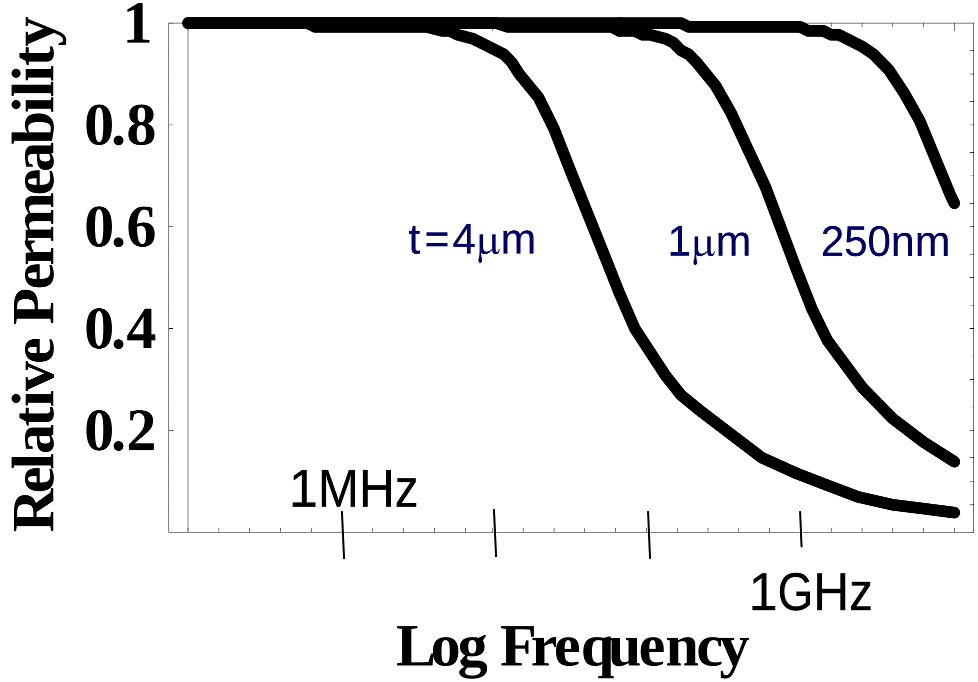
Head Permeability versus Frequency

- Permeability depends of frequency (or time) due to conductivity:

$$\mu(f) \approx \mu_{DC} \frac{\tanh(t/2\delta)}{(t/2\delta)}$$

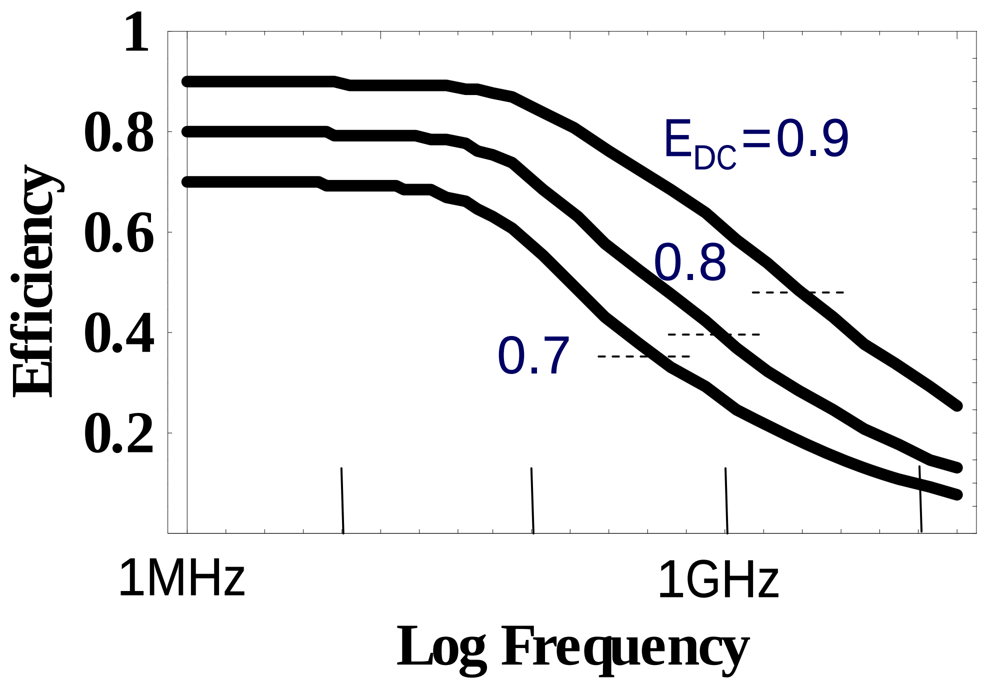
- t is the film thickness and the "skin depth" $\delta = \sqrt{\rho/(\pi f \mu_{dc})}$

- For μ_{DC} =500, resistivity ρ=20 $\mu\Omega$-cm (δ at 1MHz =10μm)



Head Efficiency versus Frequency

- Efficiency can be written as: $$E = \frac{1}{1 + \left(\frac{1}{E_{DC}} - 1\right) / \mu_{rel}(f)}$$



Parameters as before, but with t = 4μm

---- is where $E(f)=E_{DC}/2$ is a frequency or rise time limit estimate

Head Efficiency Comments

- Note that small changes in DC efficiency make a large difference in high frequency response (or rise time).

- Frequency cut off-of the permeability is much lower than that of the efficiency and thus does not give a good estimate of head dynamic response. For example shown (t = 4m) permeability limits at less than 100MHz, but if E_{DC} > 80%, head will operate at 1GHz.

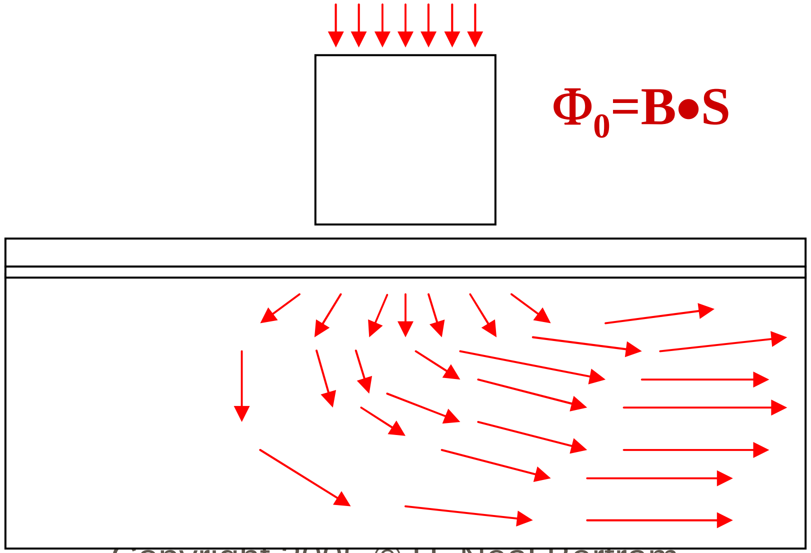
- Want head material with highest M_s and highest resistivity ρ, but watch ut for magnetostriction (e.g. $Ni_{45}Fe_{55}$)!

The Role of SUL Thickness

The Return Path

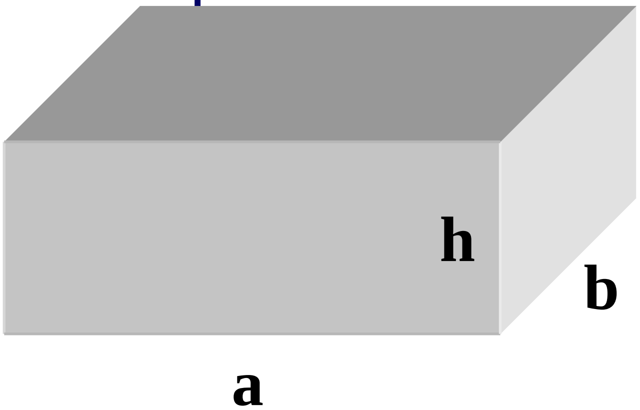
- Due to flux leakage and fringing, both the **H** and **B** field decrease as the flux penetrates the SUL.

- Just below the write pole, the return field not only points in the down track direction, but also extends through the cross track and the perpendicular directions.



Effect of SUL Thickness

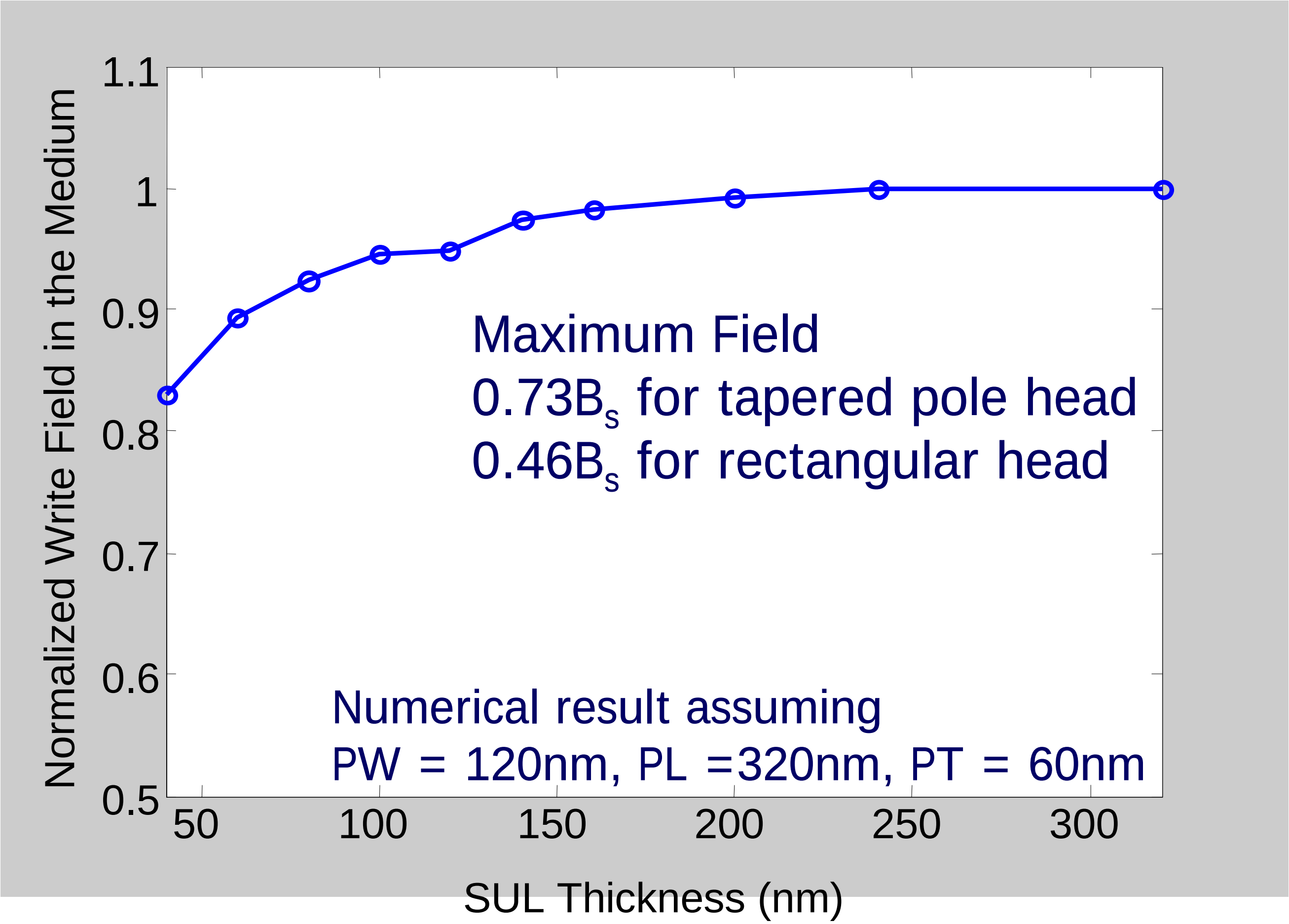
- We consider an SUL section directly below the write pole with the same Ms as the write tip:



h = SUL thickness
a = down track pole length
b = cross track pole width

- The total (ABS) area with (nearly) saturated flux is: “ab”.
- The total SUL total (side) area that permits a return path for the flux is: “2(a+b)h”.
- For flux continuity: “ab= 2(a+b)h”
- For a real tip, a>>b => $h_{min} \approx W/2$

Normalized Write Field versus SUL Thickness

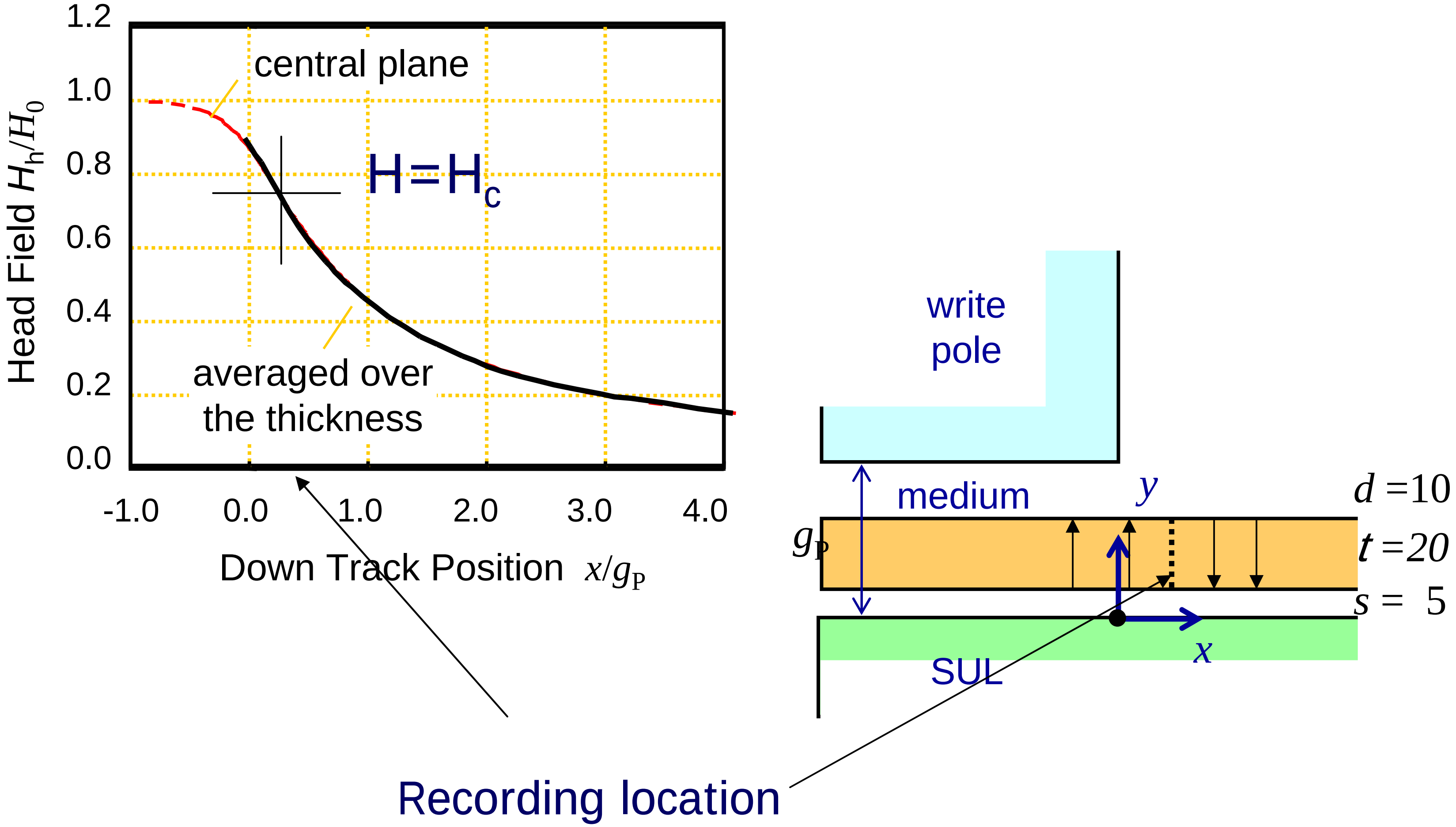


Write Process Issues

- The write process is complicated due to a combination of:
  - Head field gradients
  - Demagnetization fields.
  - Intergranular exchange
  - Finite grain size
  - Field angle effects

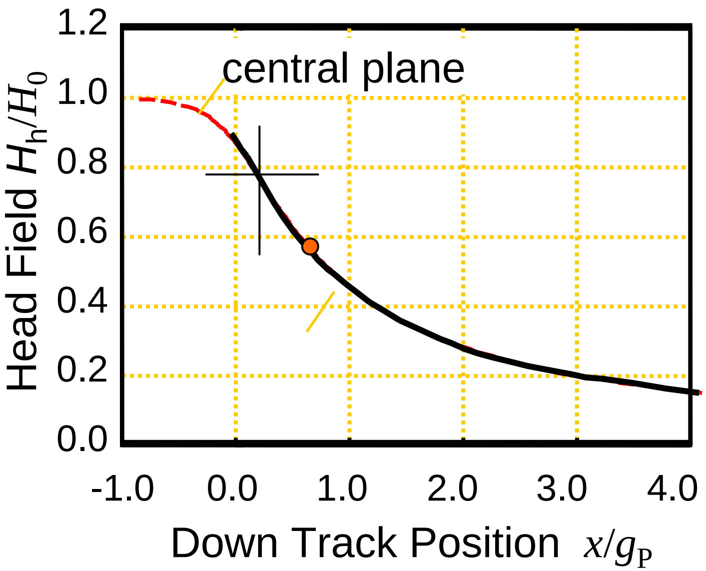
- We will examine these effects methodically:
  - Simple Williams Comstock model
  - Inclusion of field angles
  - Effects of finite grain size and exchange

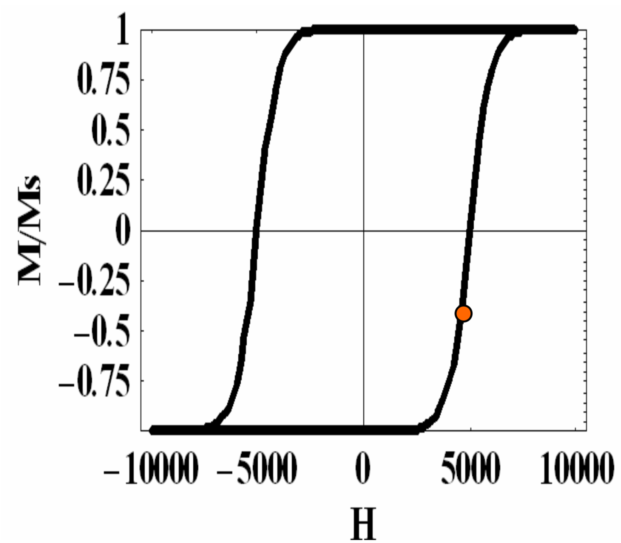
Basic Reversal Process

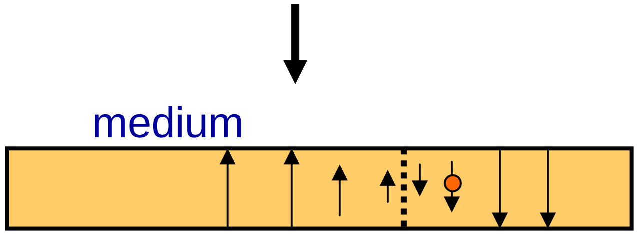


Head Field Dominated Transition Parameter

- For a continuum viewpoint medium responds to fields via the M-H loop







A gradual magnetization variation occurs!!!

Essence of the Williams–Comstock Model

- A transition shape is assumed e.g tanh

$$M(x) = M_r \tanh\left(\frac{2x}{\pi a}\right)$$

- With one unknown to find “a” one condition is used.

- This criterion involves the magnetization change at the center of the transition: a location where the poles are and therefore dominates the output voltage:

$$\frac{dM(x=0)}{dx} = \frac{2M_r}{\pi a}$$

Evaluation of W-C with only Head Fields

- Lets us "walk" along the medium just where the transition center is located.

- If we walk a distance "dx" the magnetization will change by dM.

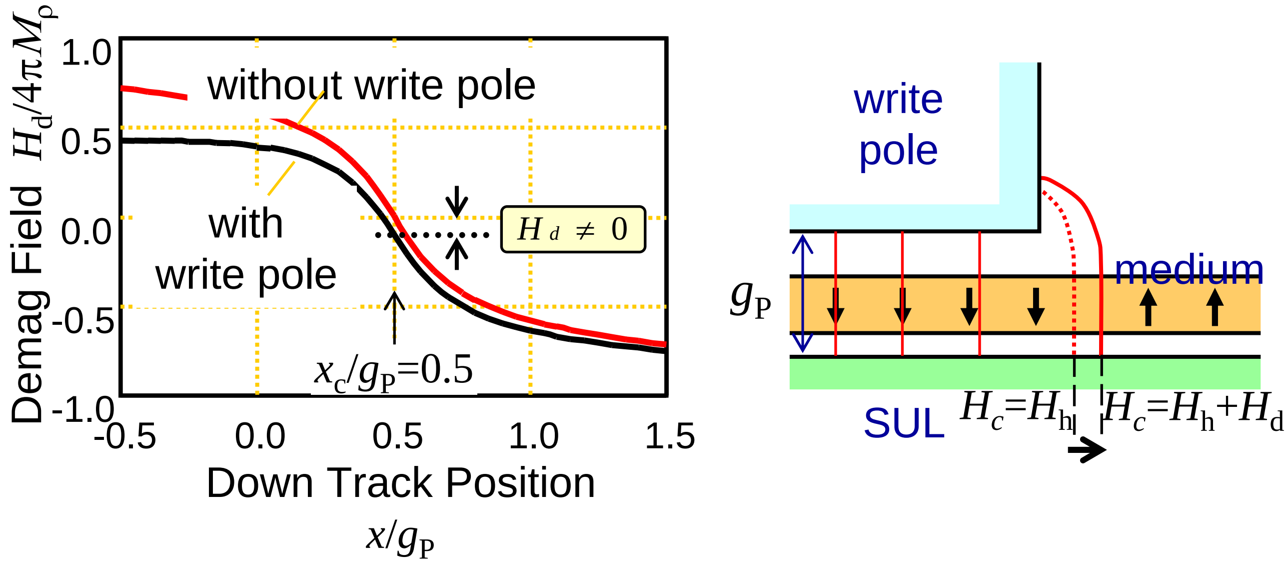
- But the magnetization "sees" the field via the M-H loop:

$$dM = \frac{dM}{dH_{loop}} dH_{head}$$

- Or

$$\boxed{\frac{dM}{dx} = \frac{dM}{dH_{loop}} \frac{dH_{head}}{dx}}$$

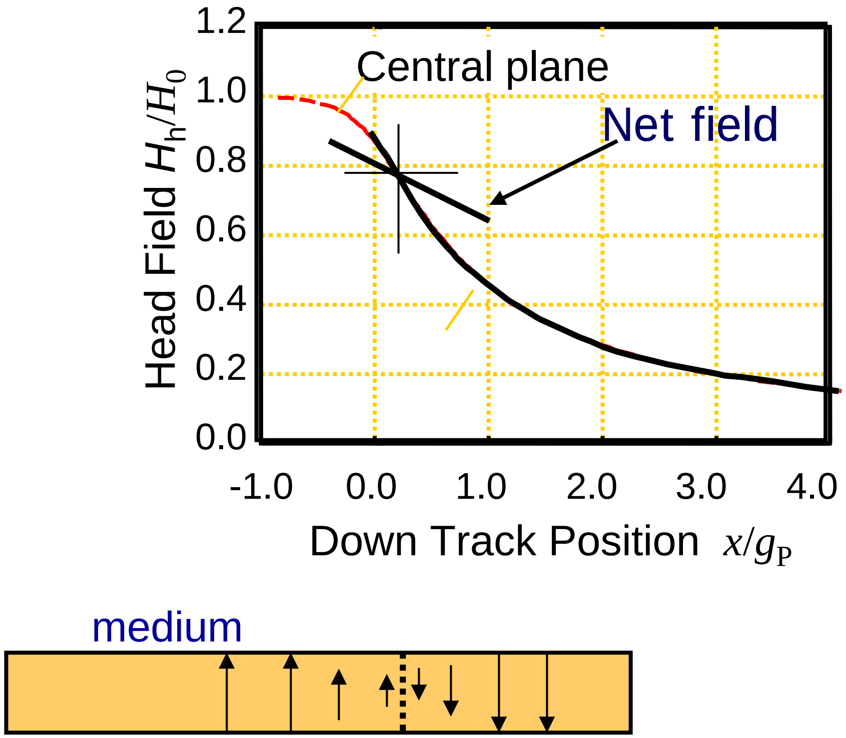
Demagnetizing field



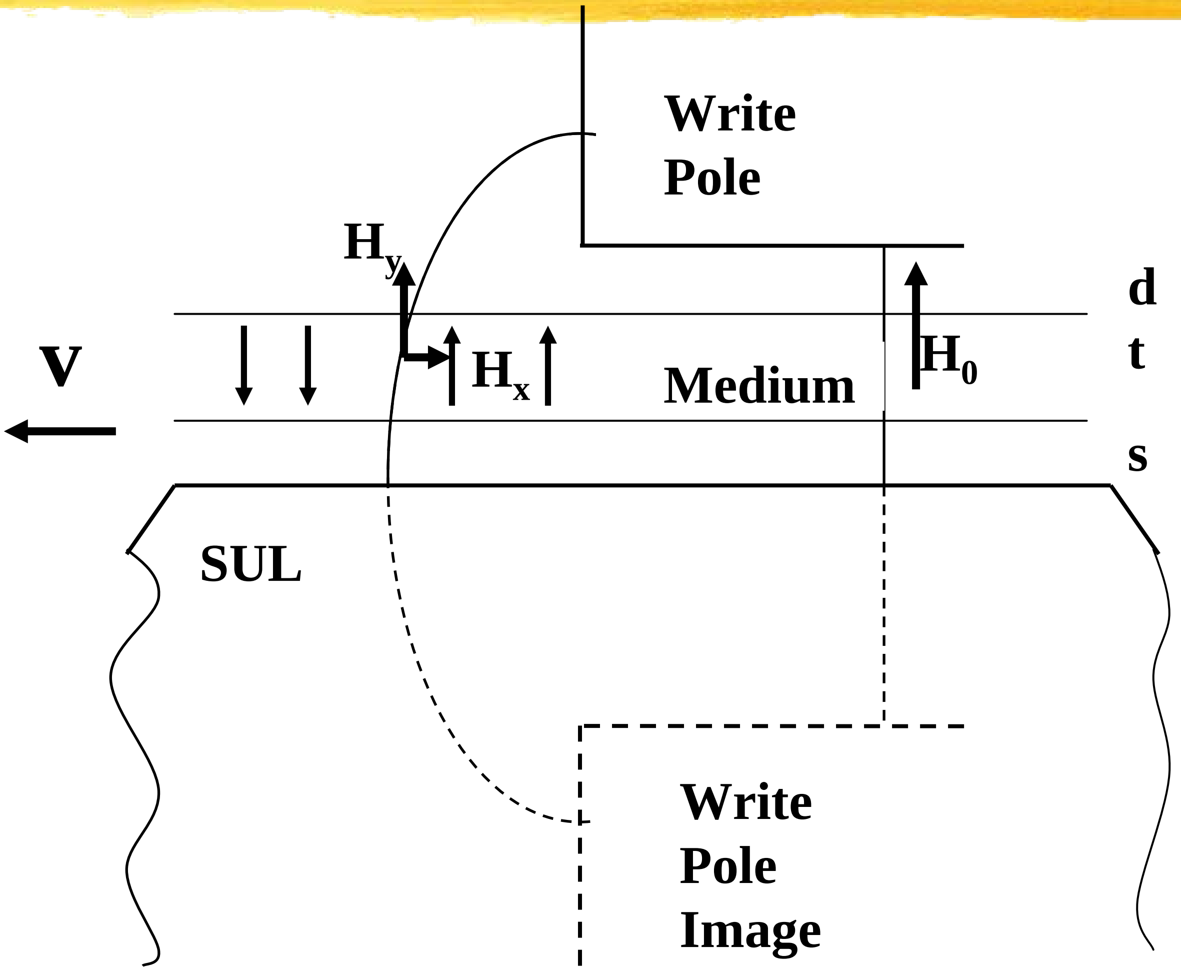
- This picture has a reversed magnetization transition from the previous. However, comparing with the previous foil it is seen that the demagnetizing field reduces the head field where it is large (>H_c) and increases the field where it is small (<H_c).

Demagnetizing Field (cont.)

- The effect is to reduce the net field gradient, increasing the transition parameter.



Inclusion of Field Angle Effects



Micromagnetic Simulation

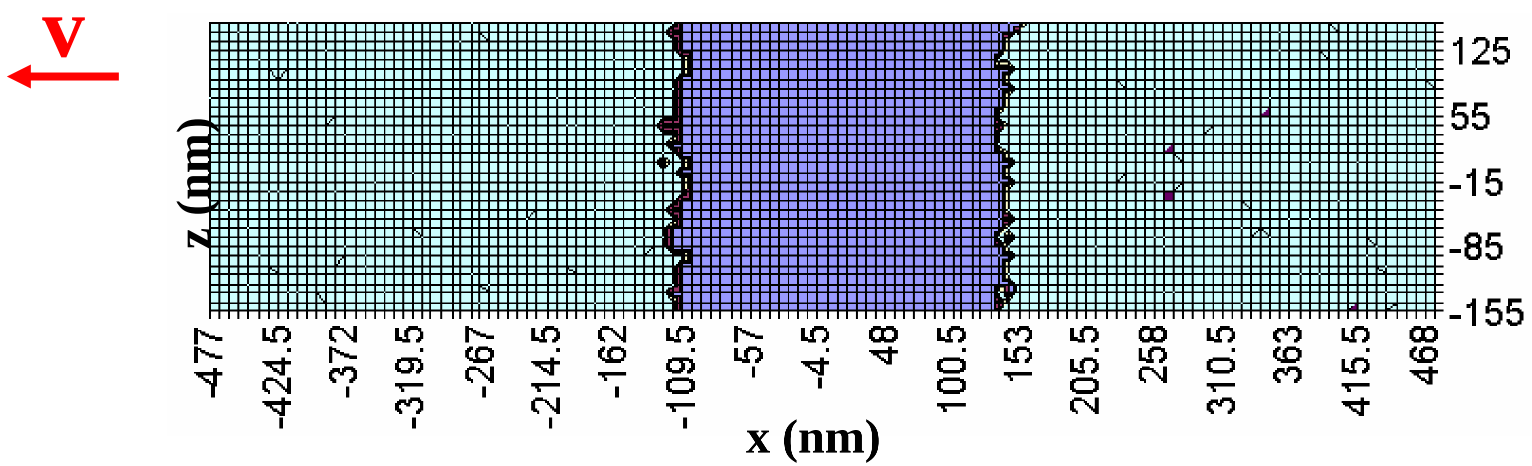
- **Parameters:**

H_0=25 kOe
d=10 nm
t=15 nm
s=10 nm

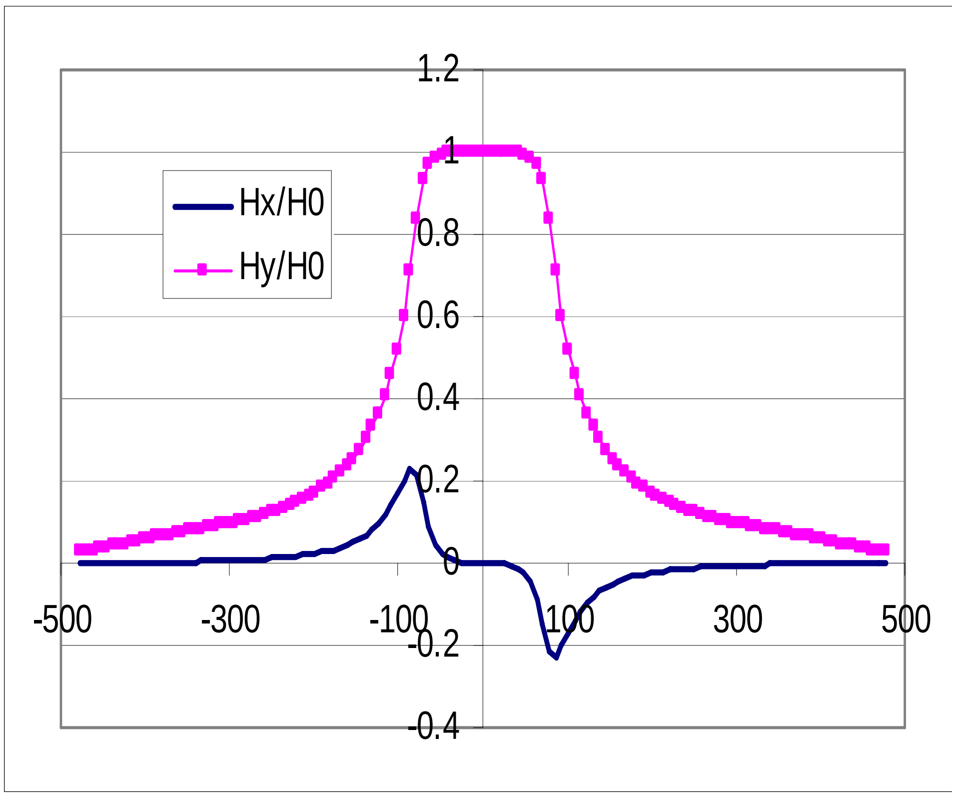
$<D>$=7.5 nm
M_r=600 emu/cc
$<H_K>$=15 kOe
σ_{HK} / $< H_K >$=5%
$h_{exchange}$=0.0

$a_{micromag} \approx 12$ nm
$a_{W\text{-}C} \approx 42$ nm

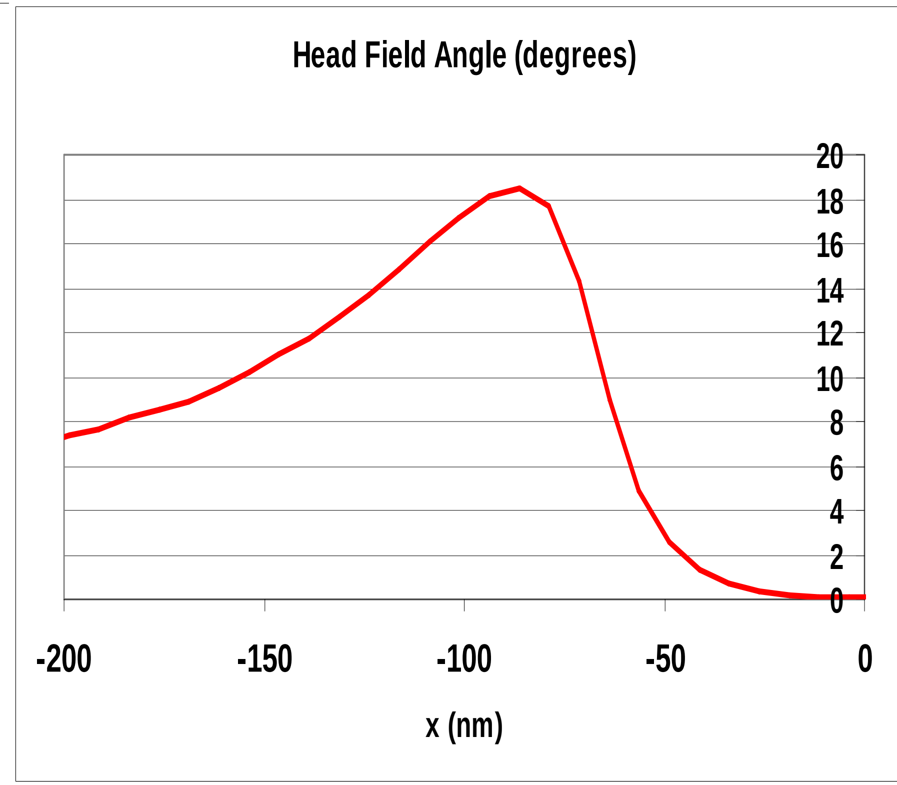
- **Top view of the transition**



Field Plots



Hx/H0
Hy/H0
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-500
-300
-100
100
300
500



Head Field Angle (degrees)
20
18
16
14
12
10
8
6
4
2
0
-200
-150
-100
-50
0
x (nm)

Magnetization Transition (cont.)

Angular Varying Fields

- The modified slope model is:

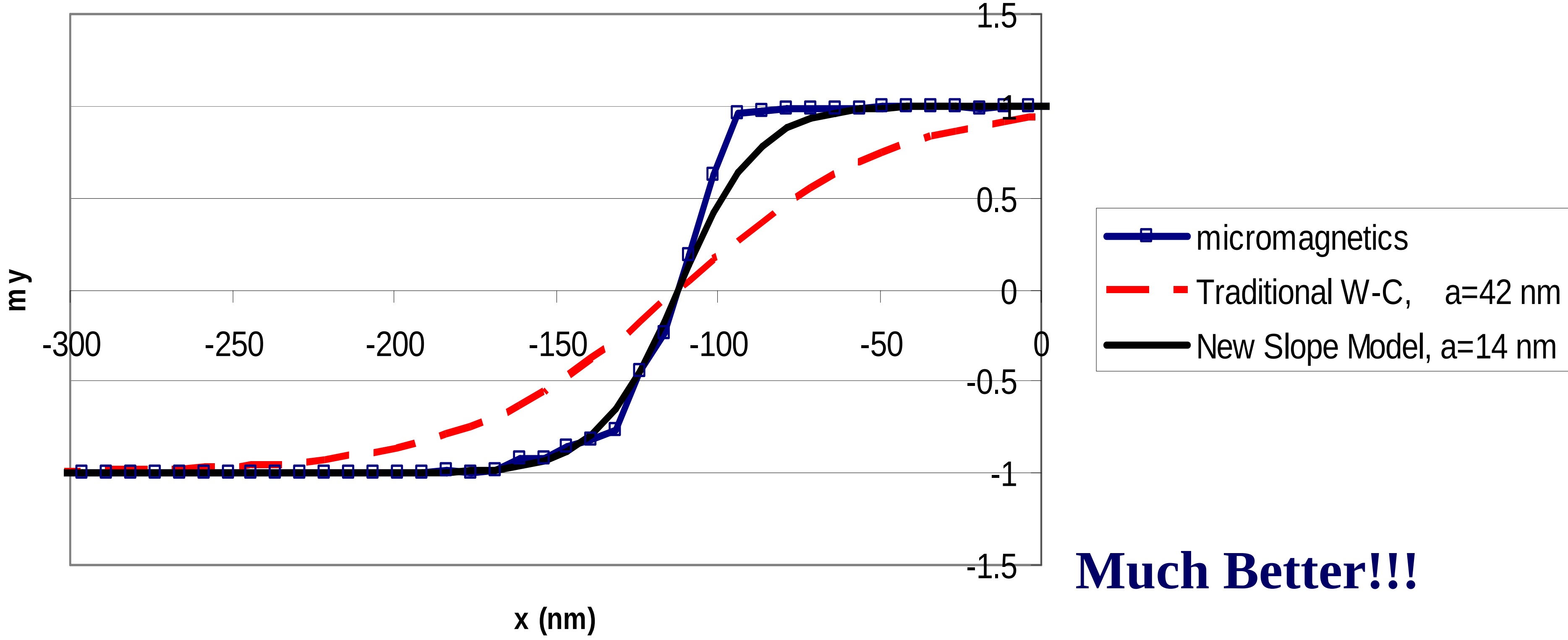
$$\left.\frac{dM}{dx}\right|_{H=H_c} = \frac{M_r}{H_c}\frac{1}{1-S^*}\times$$

$$\left.\left(\frac{d|H_h|}{dx} - \left(\frac{H_{hy}}{|H_h|} - \left|\frac{dH_c}{d\theta}\right|\frac{\sin\theta_c}{H_c}\right)\left|\frac{dH_{demag}}{dx}\right| + \left|\frac{dH_c}{d\theta}\right|\frac{d\theta}{dx}\right)\right|_{\substack{x=x_c \\ H=H_c \\ \theta=\theta_c}}$$

- Note that the effect of a rotating field is to reduce the demagnetizing field gradient and increase the net field gradient (for this field design) due to the rotating angle.

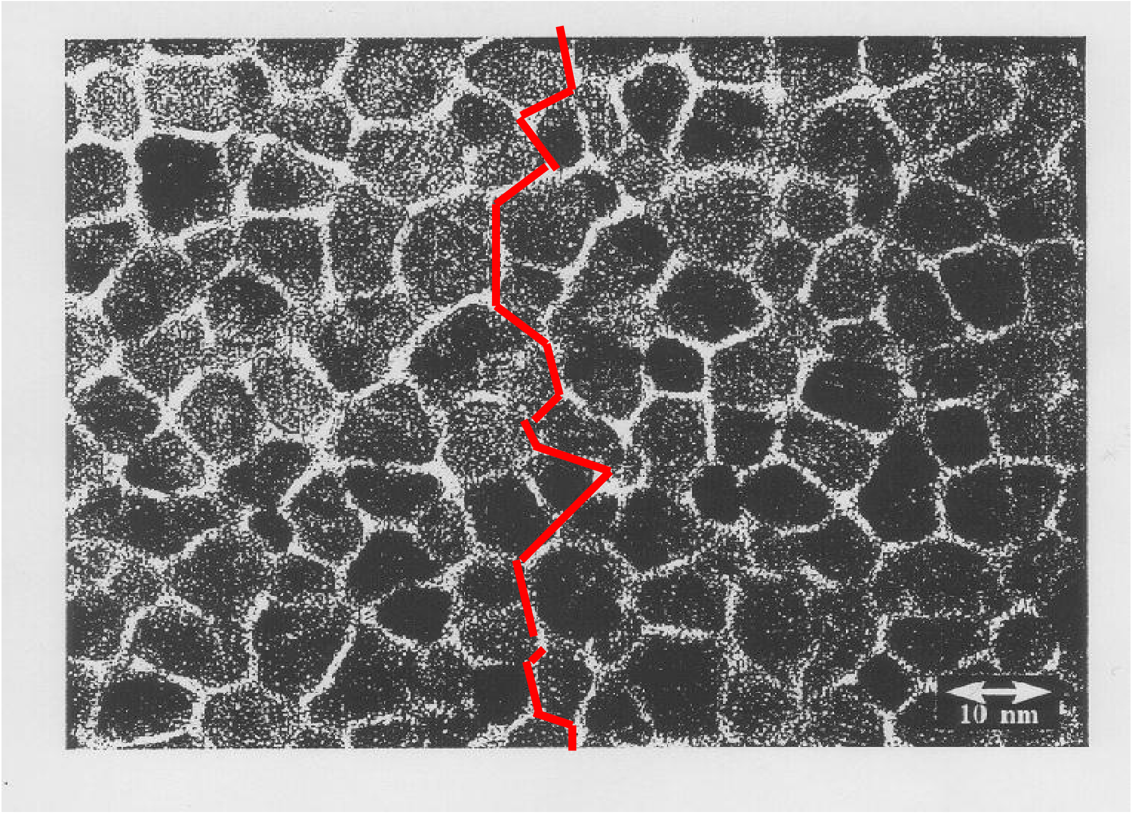
- The net effect is to reduce the transition parameter.

Comparison with Micromagnetics



Much Better!!!

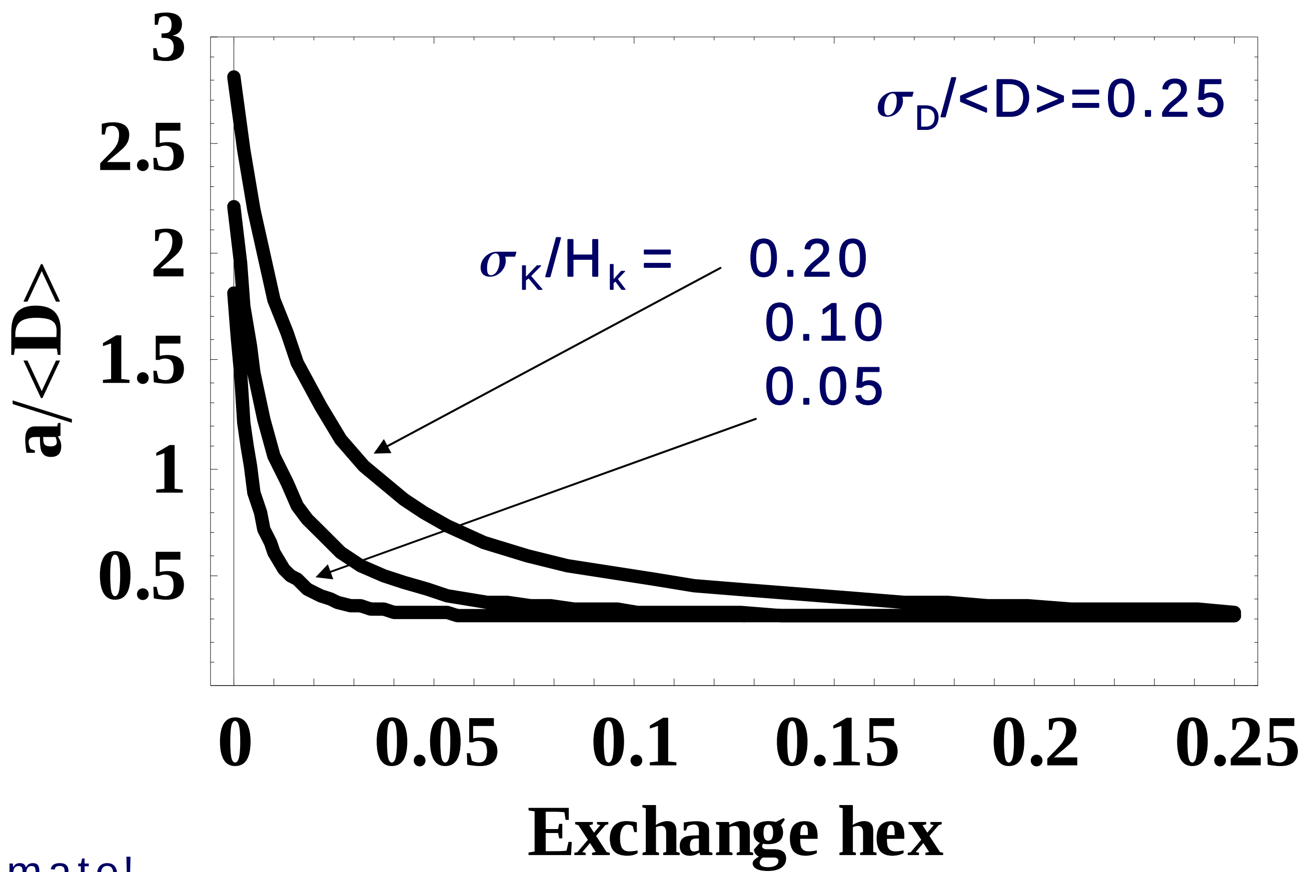
Effect of Finite Grain Size, Intergranular Exchange and Grain Clustering



Cross Track Correlation Width s_c

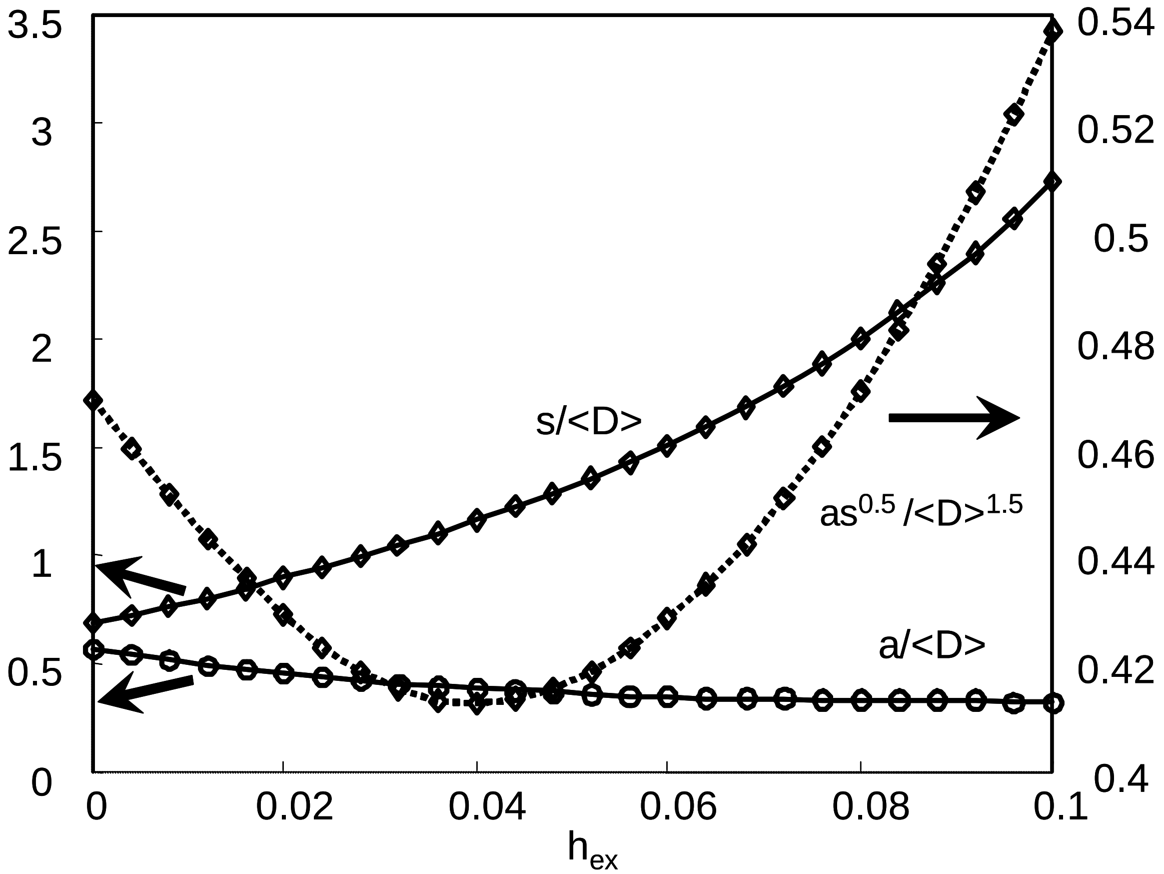
Transition Width πa

Effect of Grain Size and Exchange on the Transition Parameter



Approximate!

Transition Jitter For Perpendicular Media
Where are we now?



Corresponding to:
M_s=350emu/cc
H_K=12K
H_c/H_K=0.8
D=10nm
S^*=0.85
Medium thickness: 15nm
SUL thickness: 20nm

Transition Jitter For Perpendicular Media. Where are we now?

- Current measurements with <D> ~ 7.5nm gives:

  $a \sim 9\text{-}11\text{nm},\ s_c \sim 18\text{-}21\text{nm}$?

- This seems large?
  - Large exchange and grain clustering?
  - Large H_k distribution?
  - Poor write field gradient?
  - Head-medium spacing probably not a factor.
  - Possibly a medium effect yet to be determined!!
  - But not bad for recent product at 130Gbits/in^2

Evaluation Parameters

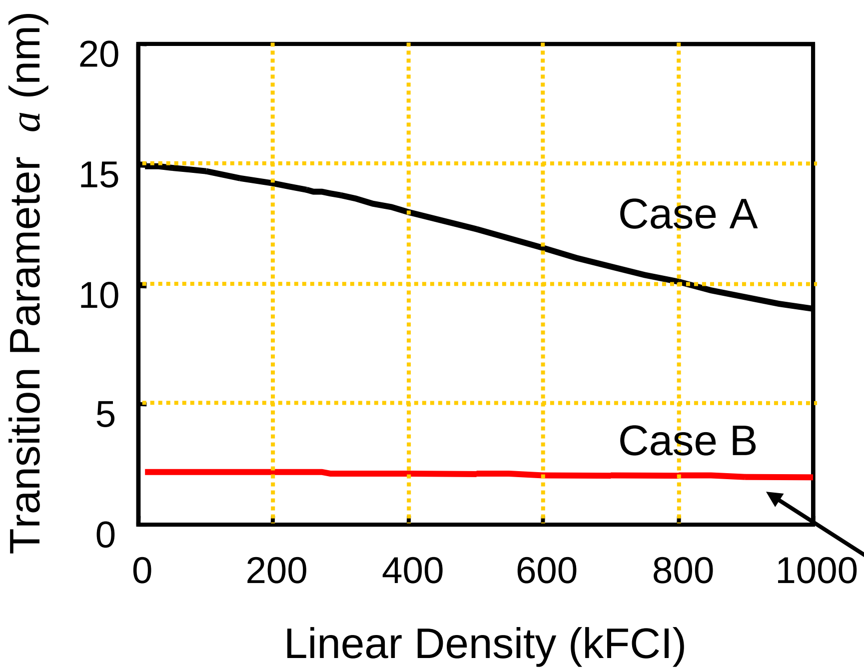
For some numerical analysis

	H_c^{write} (kOe)	M_r (emu/cc)	S^*	H_0 (kOe)	d (nm)	t (nm)	s (nm)
Case A	7.0*	210	0.98	12.0	20	20	20
Case B	16.0	230	0.98	22.0	10	20	5

* Fitted from SNR=20 dB @ 600 kFCI

Transition Parameter

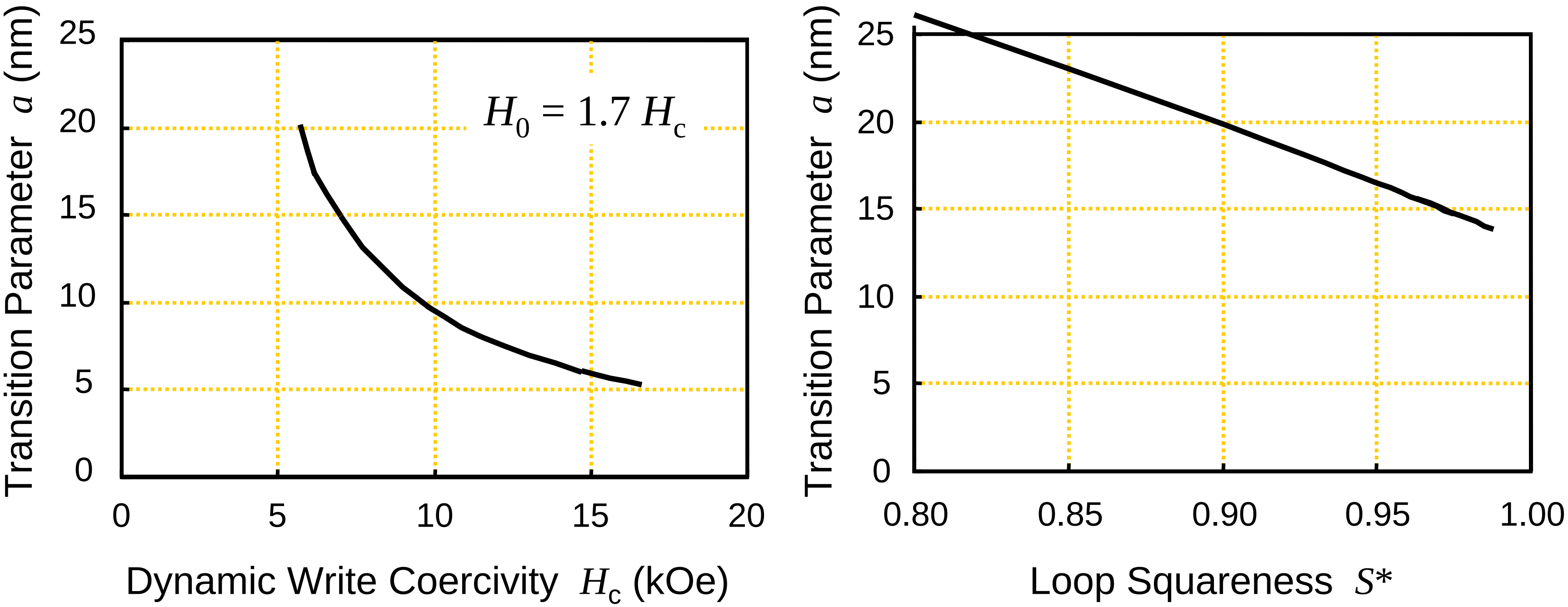
Case A & B, square wave recording



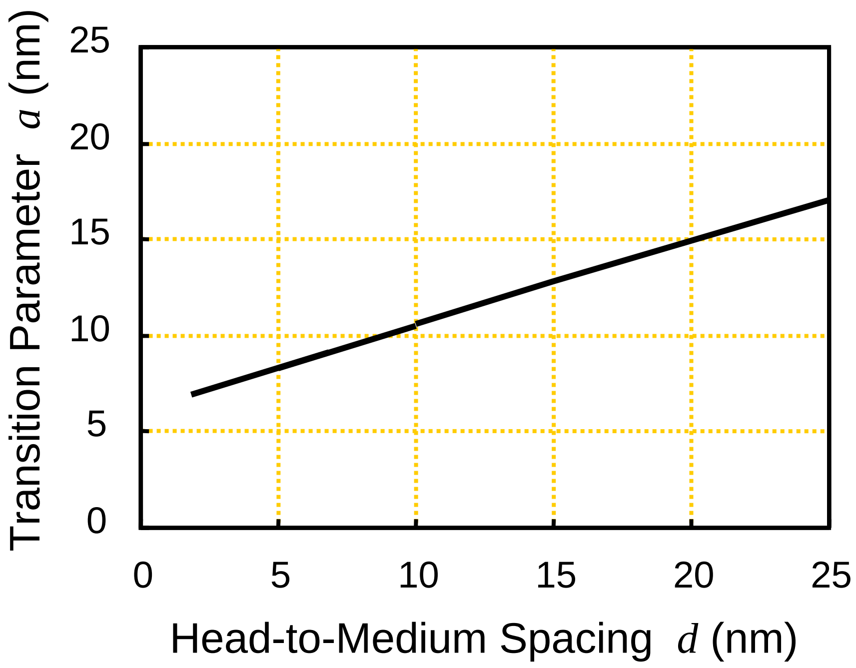
	H_c^{write} (kOe)	d (nm)	s (nm)
Case A	7.0	20	20
Case B	16.0	10	5

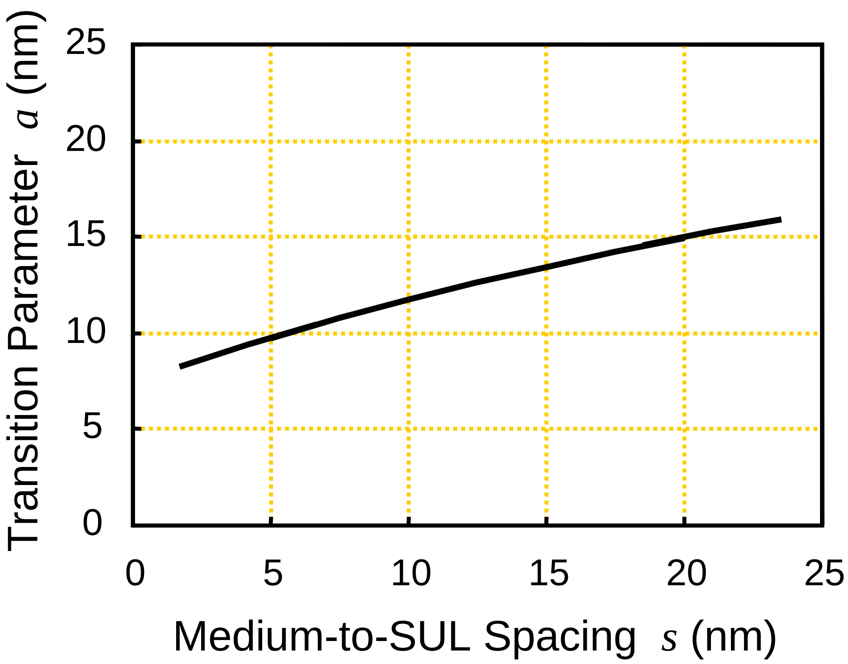
Will be limited by grain diameter

Transition Parameter *vs.* *H*c, *S**



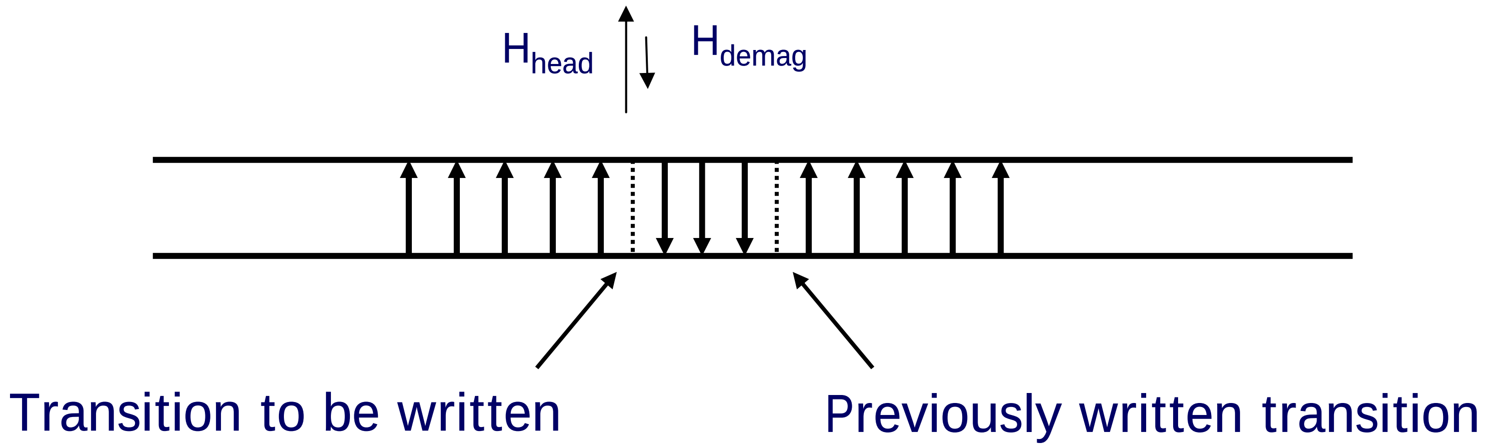
Transition Parameter *vs.* *d*, *s*





NLTS

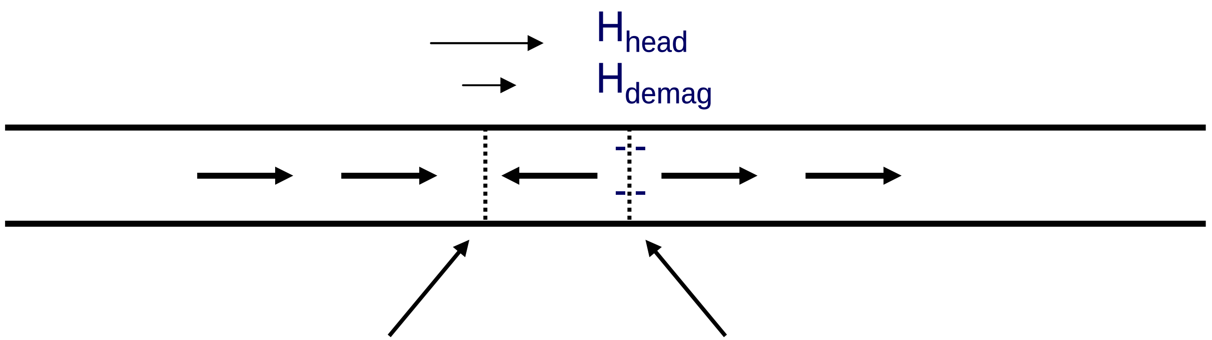
- Fields from previous written transitions move the recording location:



- For perpendicular recording the field acts to move the transitions apart

NLTS

- For longitudinal recording:



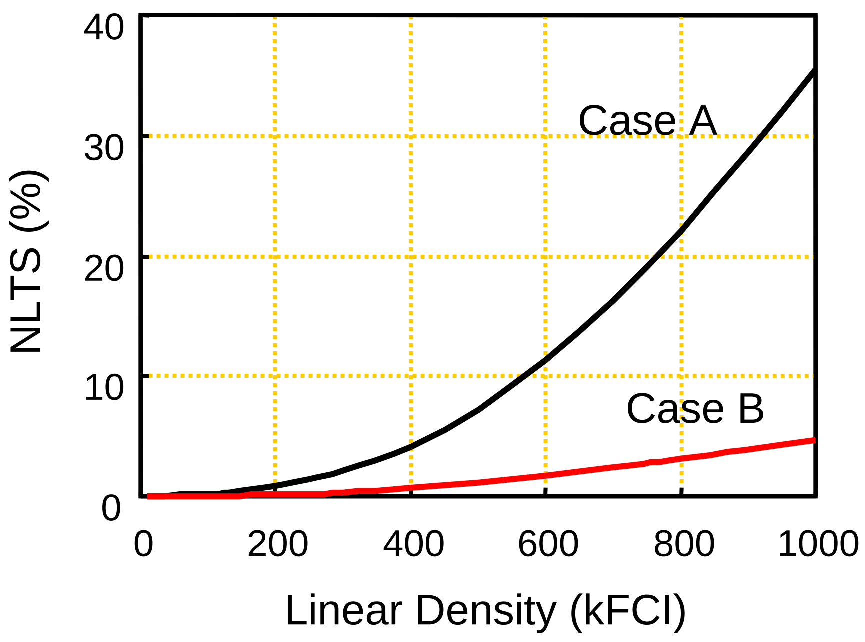
Transition to be written

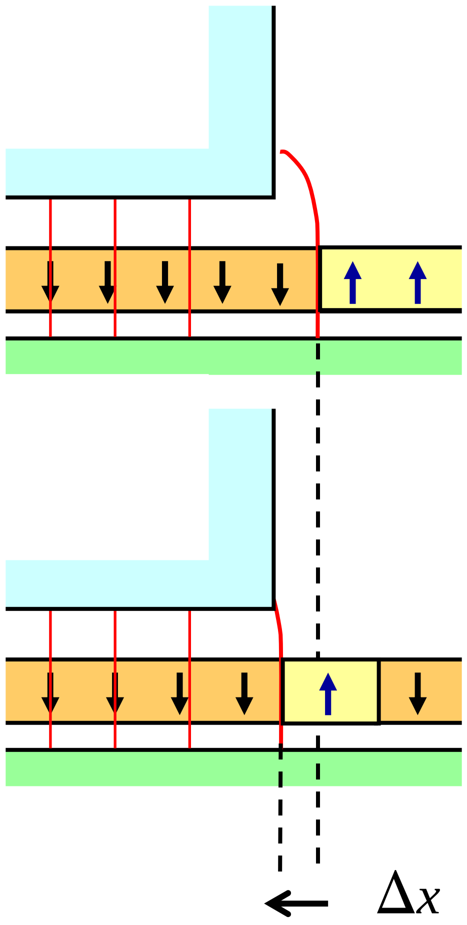
Previously written transition

- For longitudinal recording the field acts to record the transitions closer together!

Perpendicular NLTS *vs.* Density (dibit)

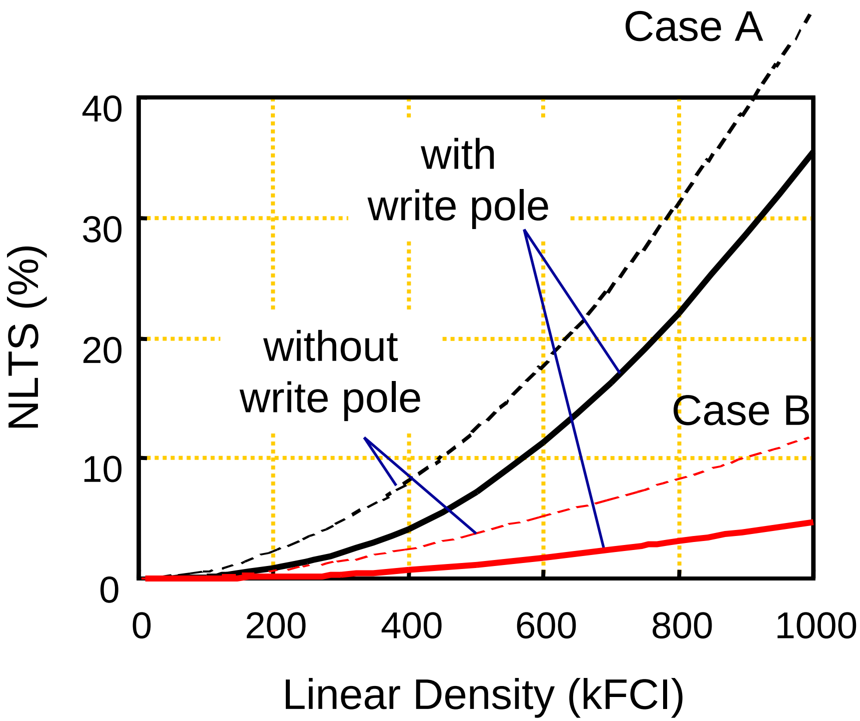
NLTS = Δx / bit length

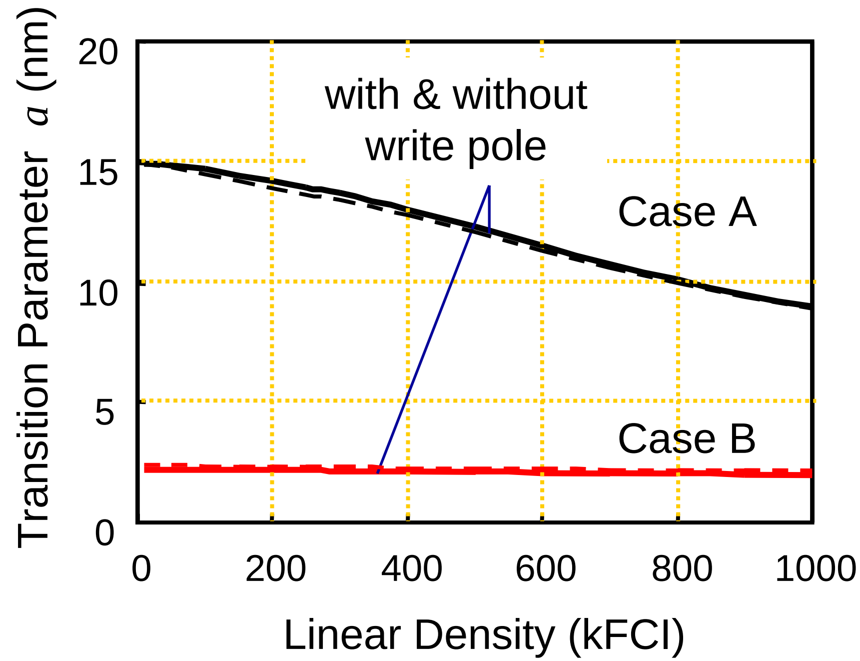




Spacing is critical!!!

Comparison with Simple Model





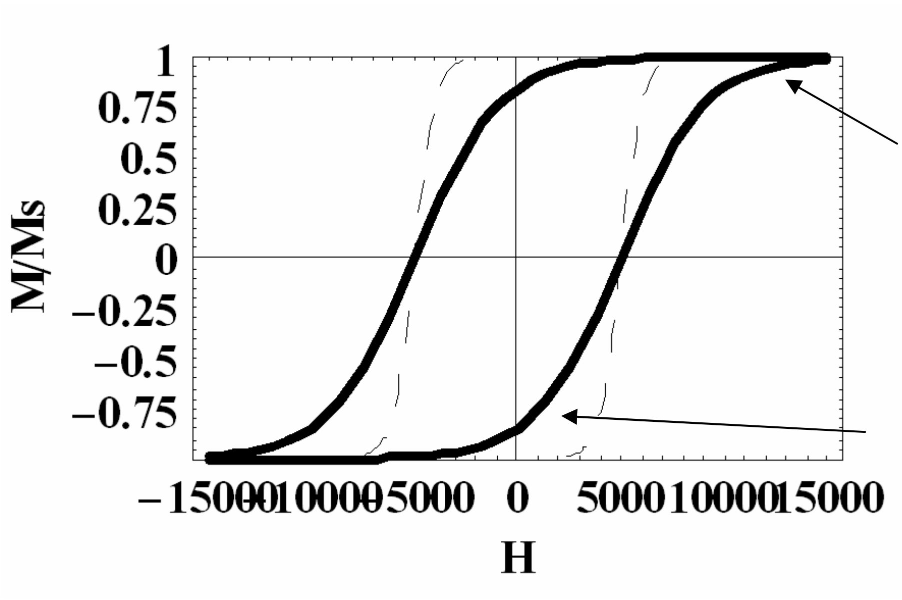
- Simple approximate scaling expression:

$$NLTS \propto \frac{M_r t(d+t/2)^3}{H_c B^4} F_{SUL}(t,s,B)$$

Overwrite

- Need to saturate previously recorded medium to noise level (-30 to -40dB).

- Head fields to overcome intrinsic reversal field distribution “tail” (σ_{HK}) , demagetization fields, and exchange:



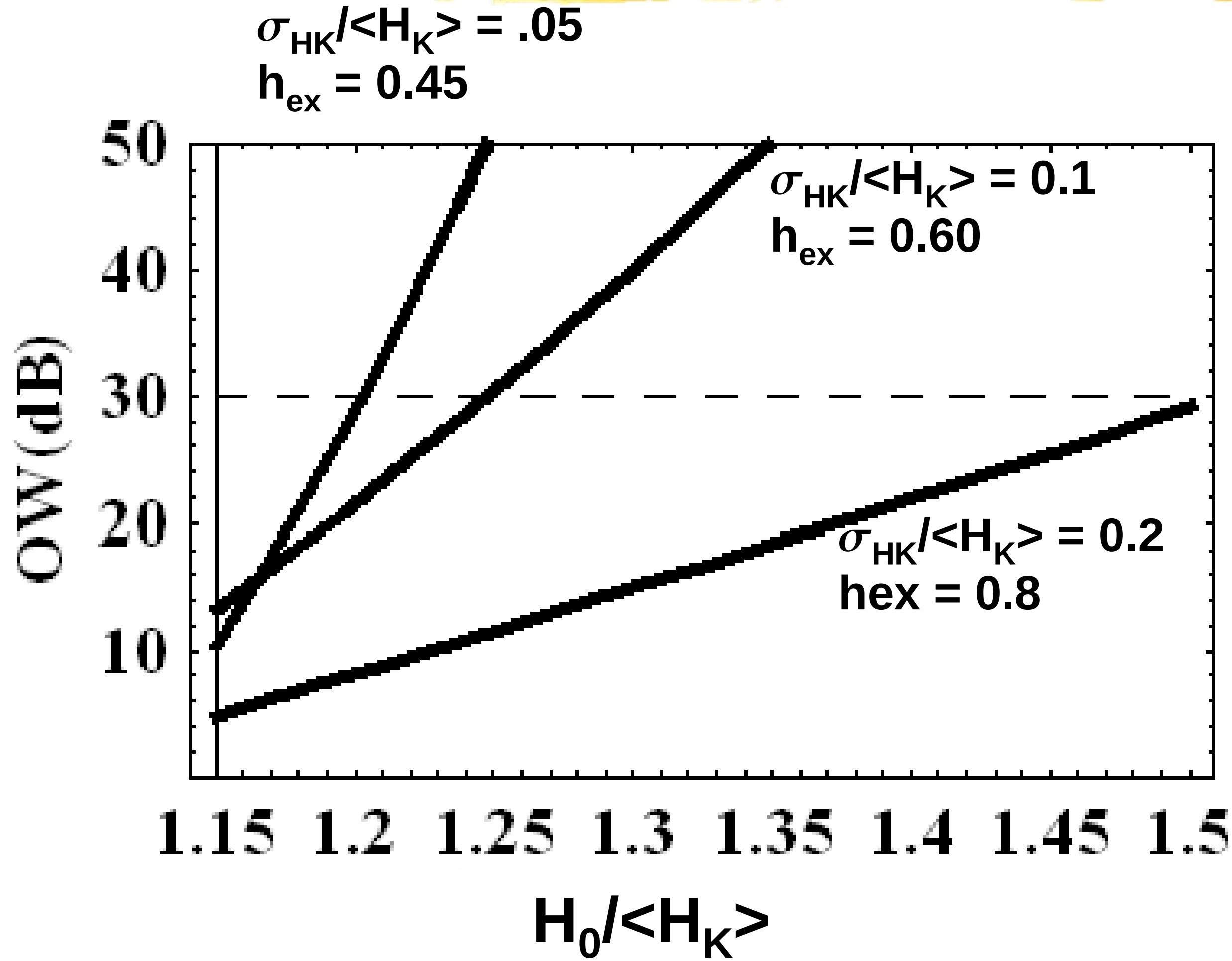
Overwrite closure field

$$\propto H_c + \sigma_{Hk} + 4\pi M_r - H_{ex}$$

Thermal reversal field barrier levels

Basic Overwrite

vs Deep Gap Field

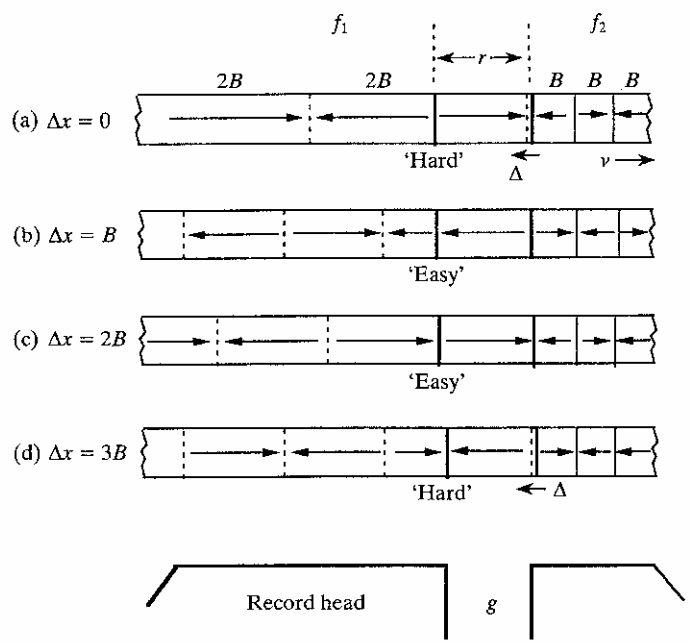


Optimizations needed !!!

Pattern Dependent Overwrite

- Even if head field saturates medium, fields from previously written data (entering the gap region) will yield Overwrite.

Example of longitudinal recorc
from Bertram “Theory of
Magnetic Recording pg. 254



shift

no shift

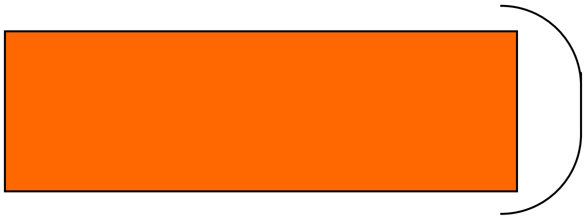
no shift

shift

Fig. 9.6. Schematic of magnetization pattern during the overwrite of an all-one's pattern at frequency f_1 by an all-one's pattern at f_2 at ($f_1 = f_2/2$). Configurations at four time shifts are shown where the medium has moved in distances equal to the f_2 bit cell length $B(B = 2v/f_2)$. Fig. 9.6(a): initial position, (b) shift by B, (c) shift by $2B$, (d) shift by $3B$.

Track Edge Effects
Recording Contour

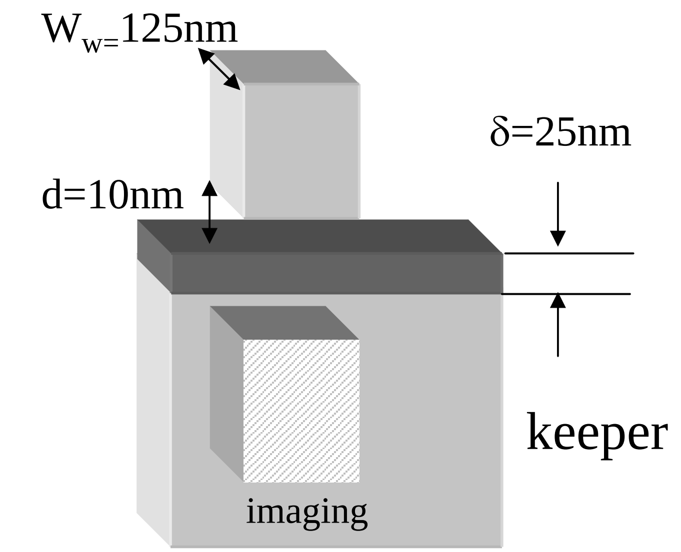
- Finite track width yields curved recording contour:



- Effect is to broaden track averaged transition parameter: alters both signal and noise.

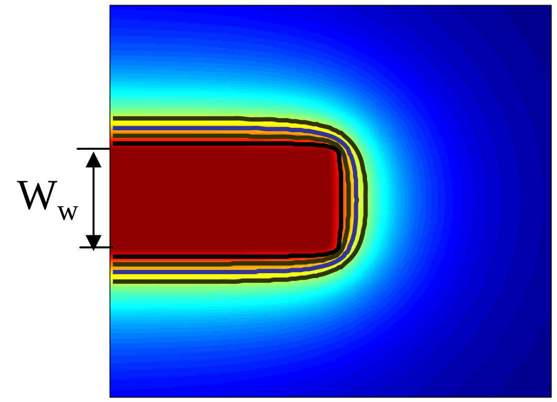
- For Hitachi (80Gbit/in^2) demo: “a” averaged is about 25 nm, twice that from WC model. Gives $T_{50} \sim 48$nm (instead of 42 nm in agreement with T_{50} expression.

SPT Head

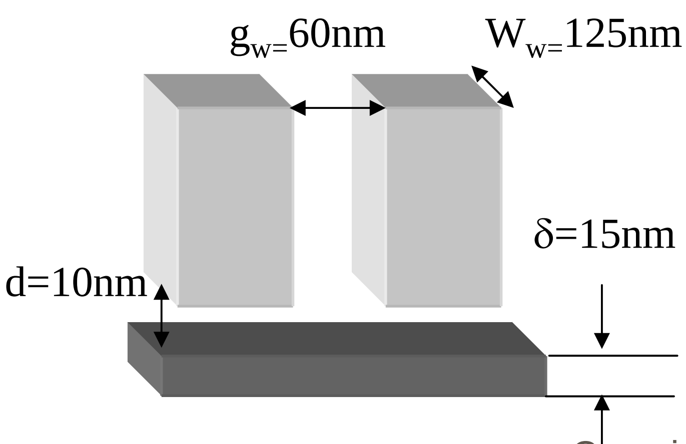


Contour Plot of the Field Strength at the Center of the Media (Top view , Plot size: 500nmx500nm)

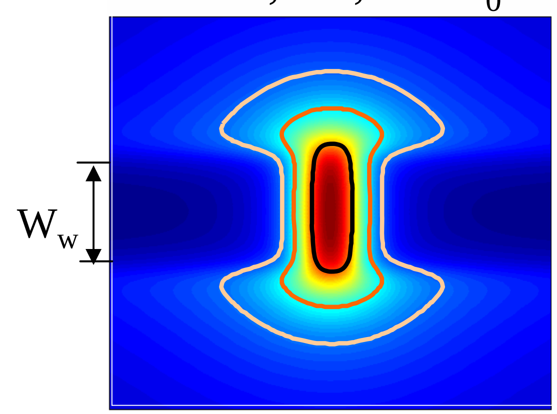
$H=0.6, 0.7, 0.8, 0.9\ H_0$



Longitudinal Head



$H=1/5, 1/3, 2/3\ H_0$



Reasons for Some Intergranular Exchange

- Reduces overwrite field relative to write coercivity.
  - Allows for higher anisotropy K for a given maximum write field.
  - Thus smaller grain size can be used resulting in enhanced SNR.

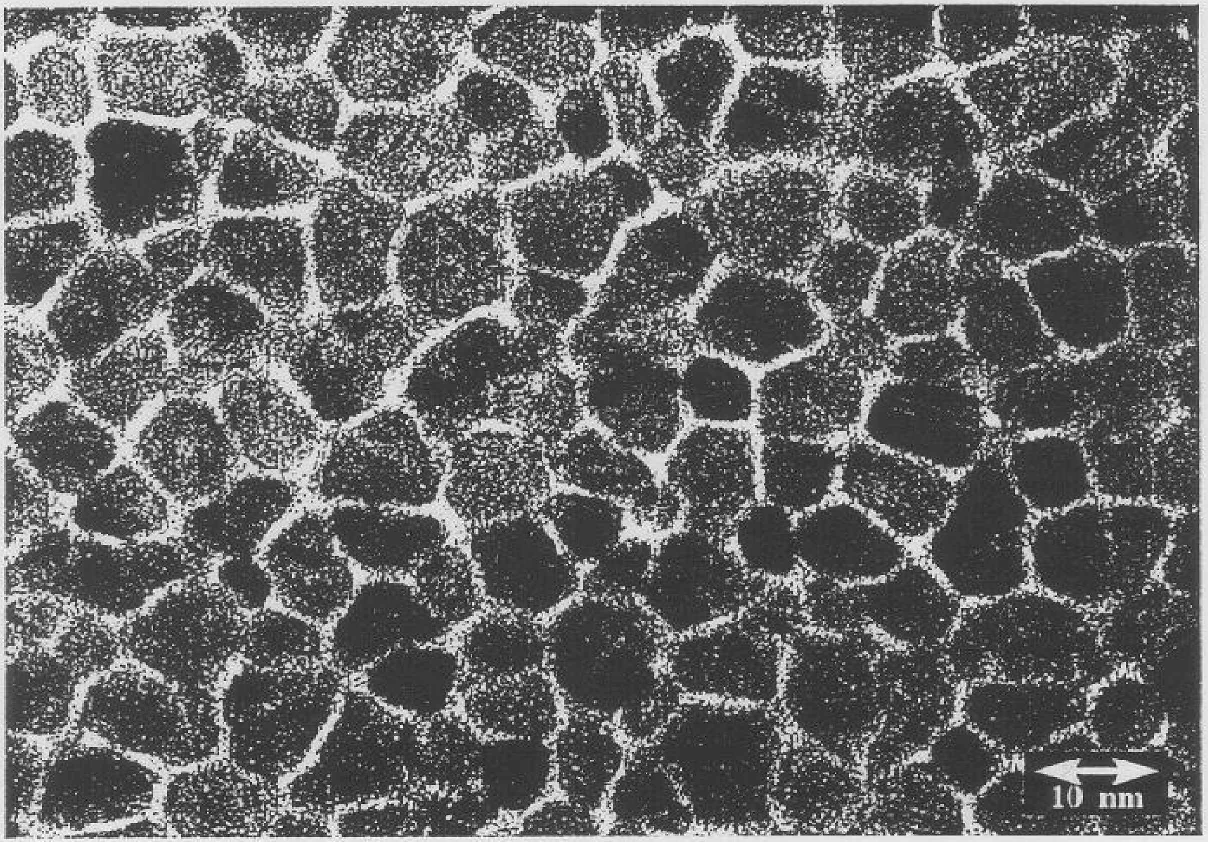
- Reduces recorded magnetization thermal decay
  - Allows for a further decrease in grain size and enhanced SNR.

- Reduces transition parameter
  - Cross track correlation width increases with exchange, thus an optimum occurs where jitter is minimized and SNR is maximized.
  - Maximum occurs for about he = 0.05 or He = $0.05H_k$=750Oe (for H_k = 15000)

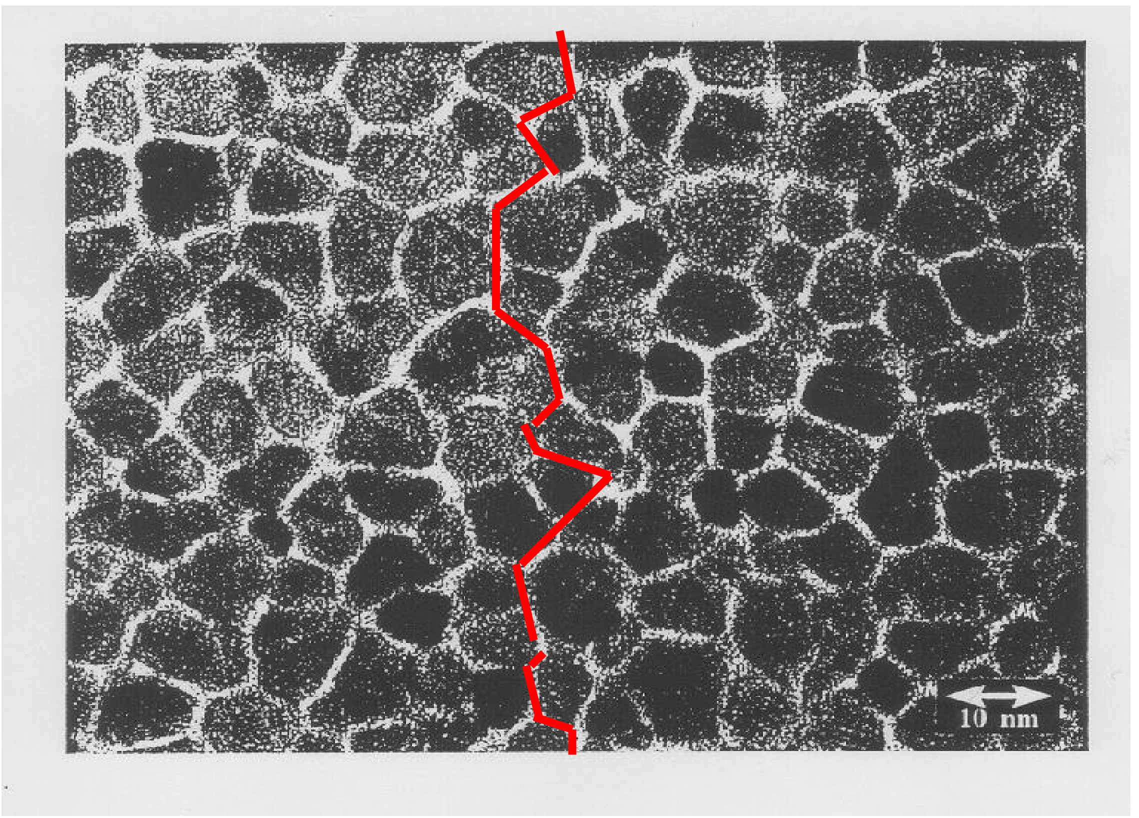
- Careful!!! Too much exchange can cause clustering into larger effective grains, increasing the transition parameter and the cross track correlation width.

VI. Noise Mechanisms

Film Grain Structure



Transition Boundaries



Cross Track Correlation Width s_c

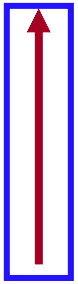
Transition Width πa

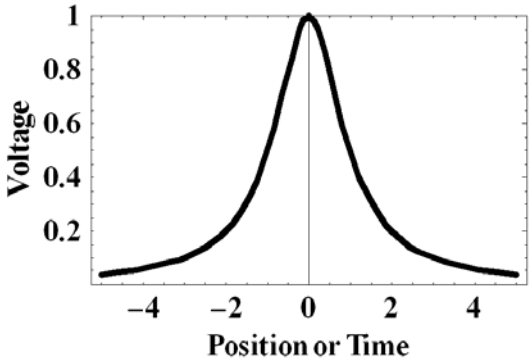
Basic Noise Mechanism

- Each magnetized grain gives a small replay pulse.
- Spatially averaged grain pulses over read track width gives dominant signal plus noise.
- Noise results from random centers locations and sized, anisotropy orientation variations, intergranular interactions, and spatially random polarity reversal at a recorded transition center.
- Characterize by correlation functions, eigenmodes, spectral power, etc.

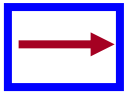
Illustration of Grain Pulse

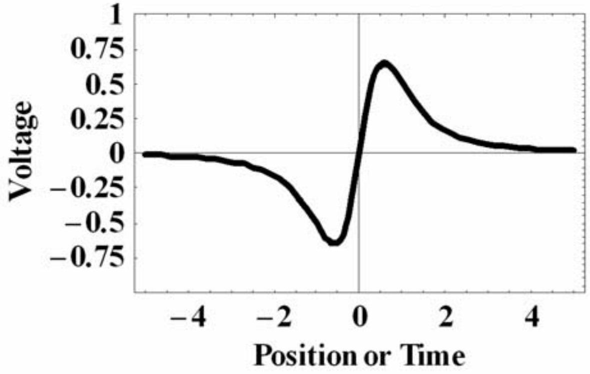
- Perpendicular:





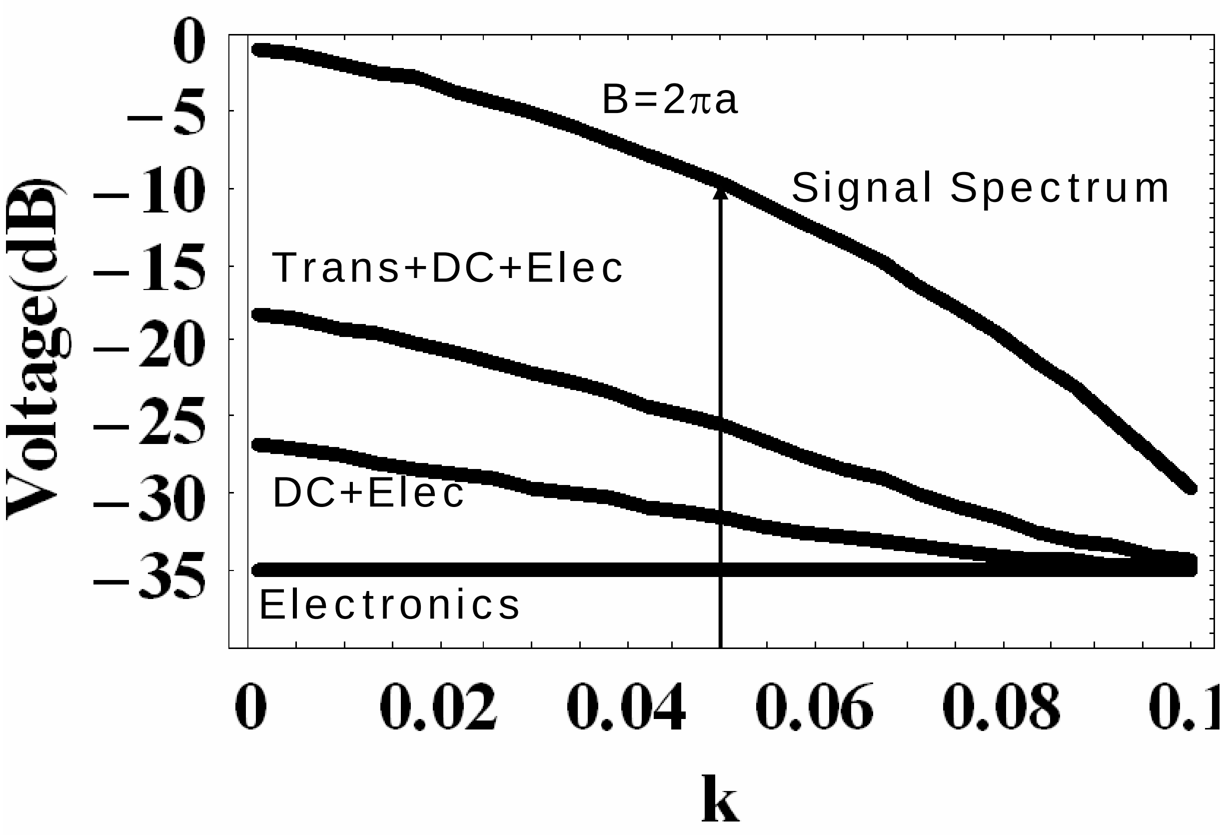
- Longitudinal:





Illustrative Spectral Plots: rms Signal, DC Noise, Total Noise

Perpendicular recording



Comments on Transition Noise

- Transition parameter “a” sets length of fluctuations along recording direction.
- Increased “a” gives longer fluctuations and hence more noise!!!
- Cross track correlation width “s_c” sets fluctuation distance in the cross track direction.
- Larger “s_c” due to larger grain size or intergranular ferromagnetic magnetization interaction coupling gives less averaging across track width and hence more noise!!!

Packing Fraction/ Squareness

- Packing fraction "p" is the fraction of magnetic material:

$$p \equiv \frac{V_M}{V_{Total}} \approx \left(\frac{\overline{D}}{\overline{D} + \delta} \right)^2$$

δ= inter grain separation; e.g. D_{ave}=5nm, δ=1nm => p =0.7

- Squareness:

$$S \equiv \frac{M_r}{M_s} = < \cos\theta >$$

- Squareness Variance:

$$\sigma_S^2 \equiv < \cos^2\theta > - < \cos\theta >^2$$

Magnetization Noise Power Variance

- Noise Power variance versus distance along the record track is given by:

$$\sigma^2(x) = < M^2(x) > - < M(x) >^2$$

- We consider grains in the remanent state at a packing fraction p:

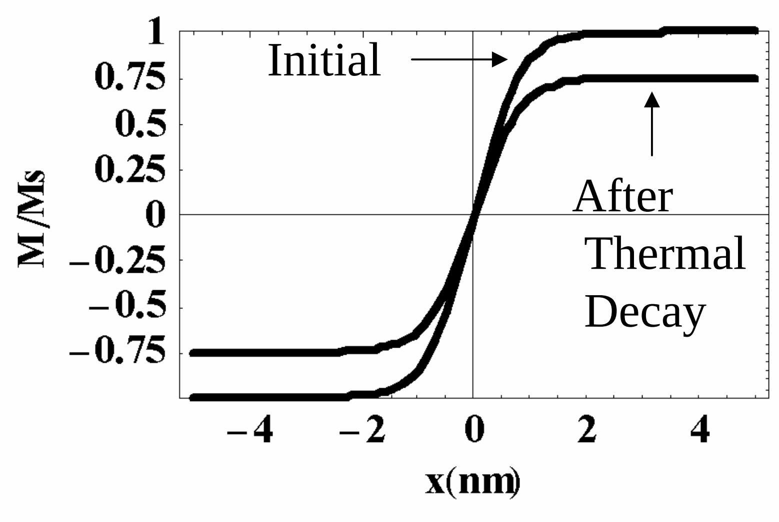
$$\sigma^2(x) / M_{gs}^2 = p < \cos^2(\theta) > - p^2 m^2(x) < \cos(\theta) >^2$$

- M_{gs} is the saturation grain magnetization ($M_s = pM_{gs}$) and m(x) is the average normalized transition shape ($m(x) = M(x)/M_r$).

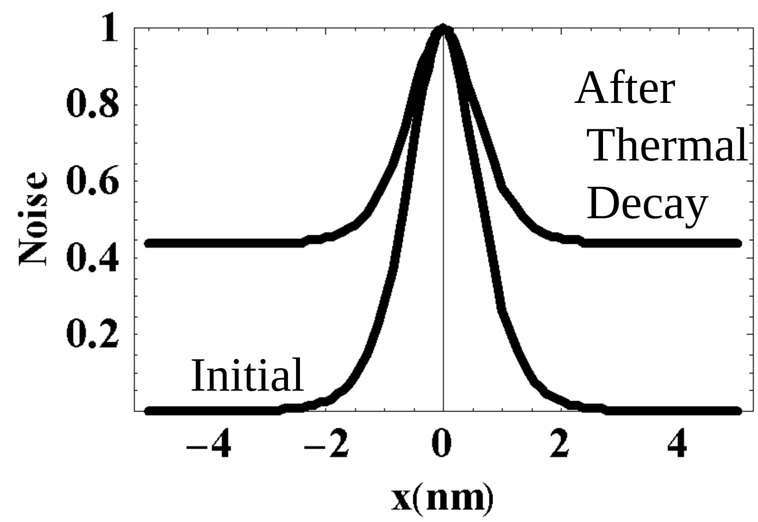
Medium Noise versus Distance

- For properly designed perpendicular medium, noise is similar to longitudinal noise.

Transition



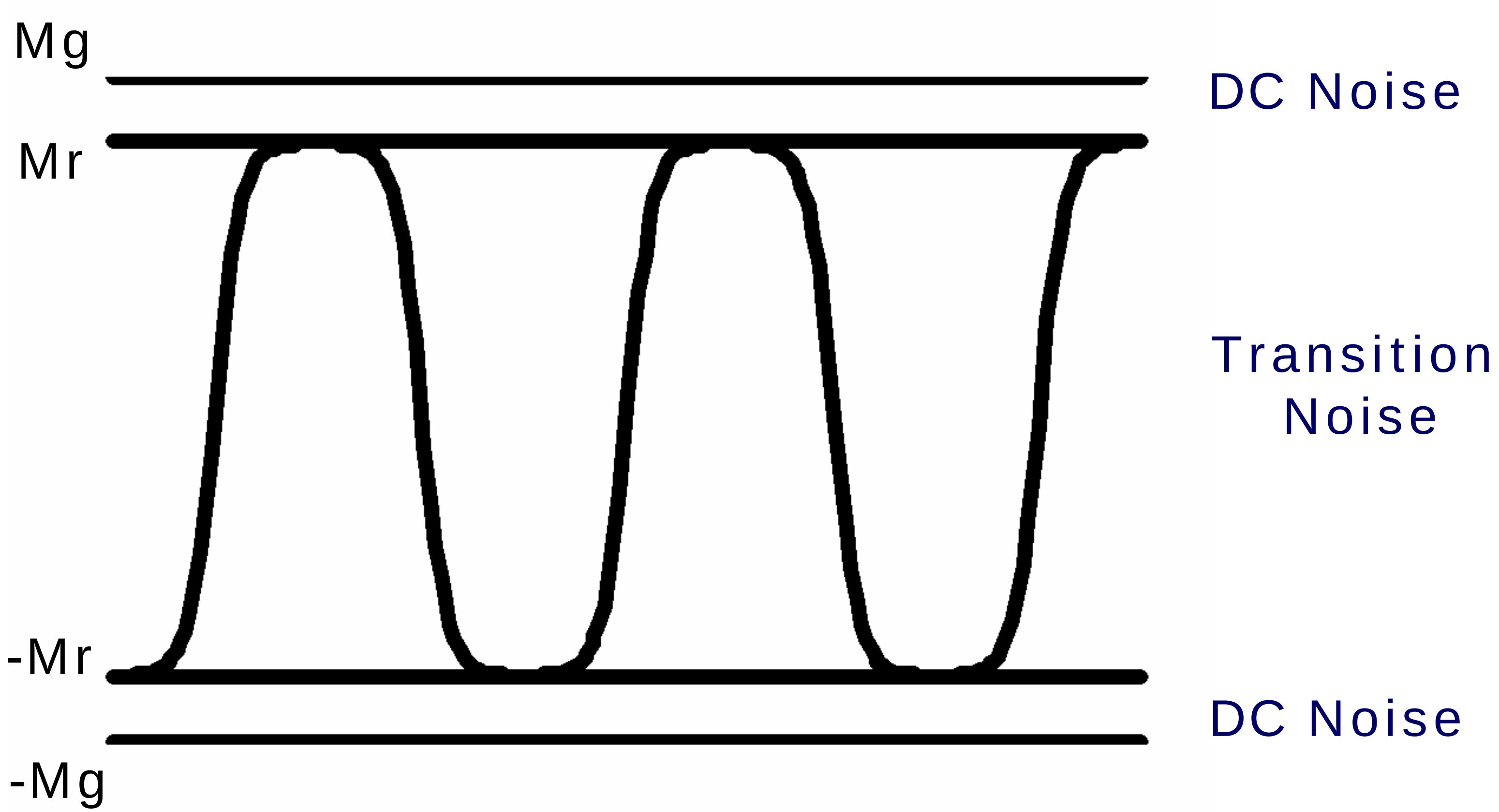
Noise



Basic Noise Forms

- Random growth pattern of grains results in medium noise:
  - DC noise (uniform independent of recording pattern-stationary correlation function)
  - Transition noise (localized at transition centers-non-stationary correlation function)

Separation of DC and Transition Noise Powers



Note: M_g > M_s due to p!!!!

Separation of DC and Transition Noise Powers (cont.)

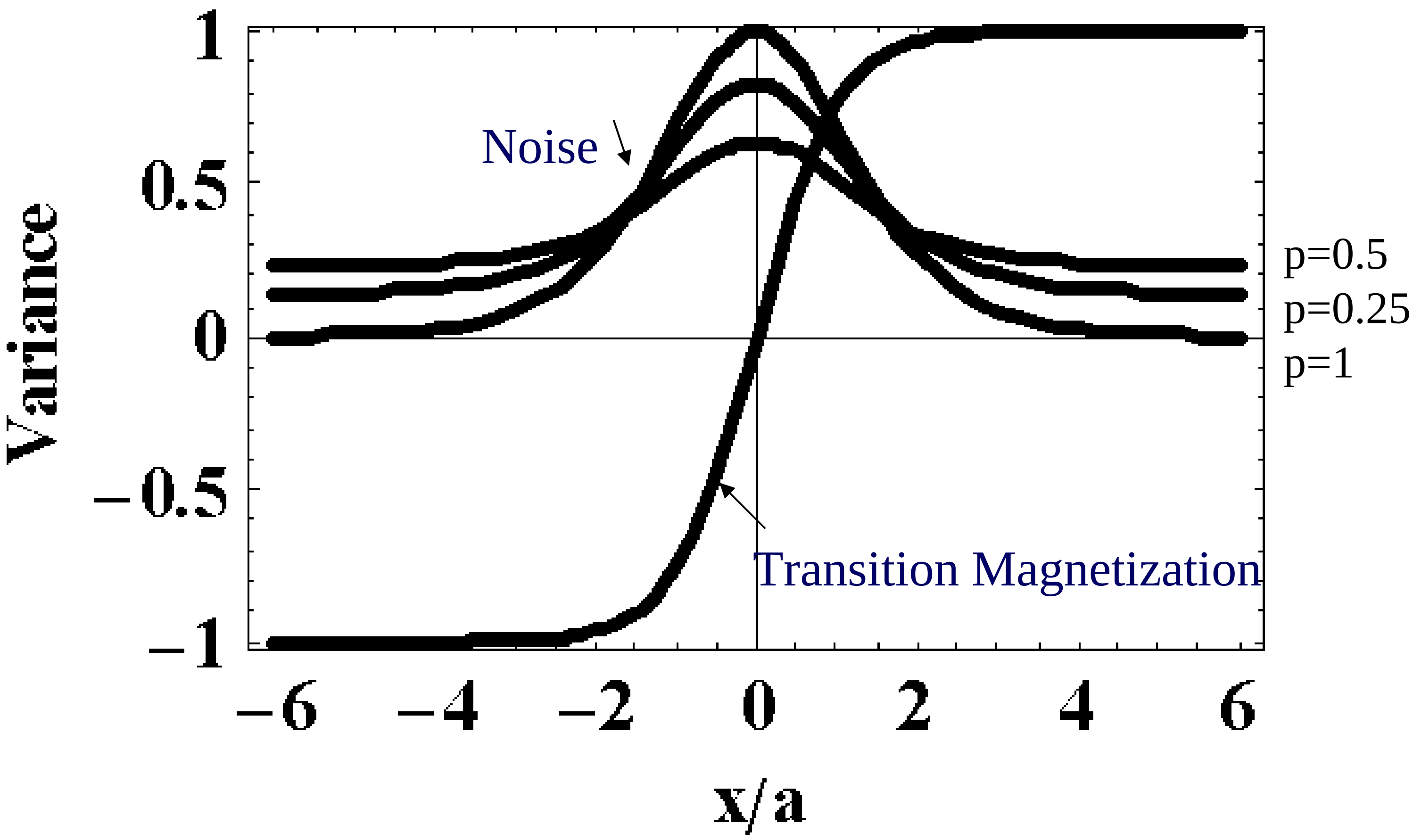
- We add and subtract to the normalized variance the constant term $p^2<\cos\theta>^2$:

$$\sigma^2(x)/M_{gs}^2 = p < \cos^2(\theta) > -p^2 < \cos(\theta) >^2 m^2(x)$$

$$= p < \cos^2(\theta) > -p^2 < \cos(\theta) >^2 \longleftarrow$$ DC Noise (Stationary)

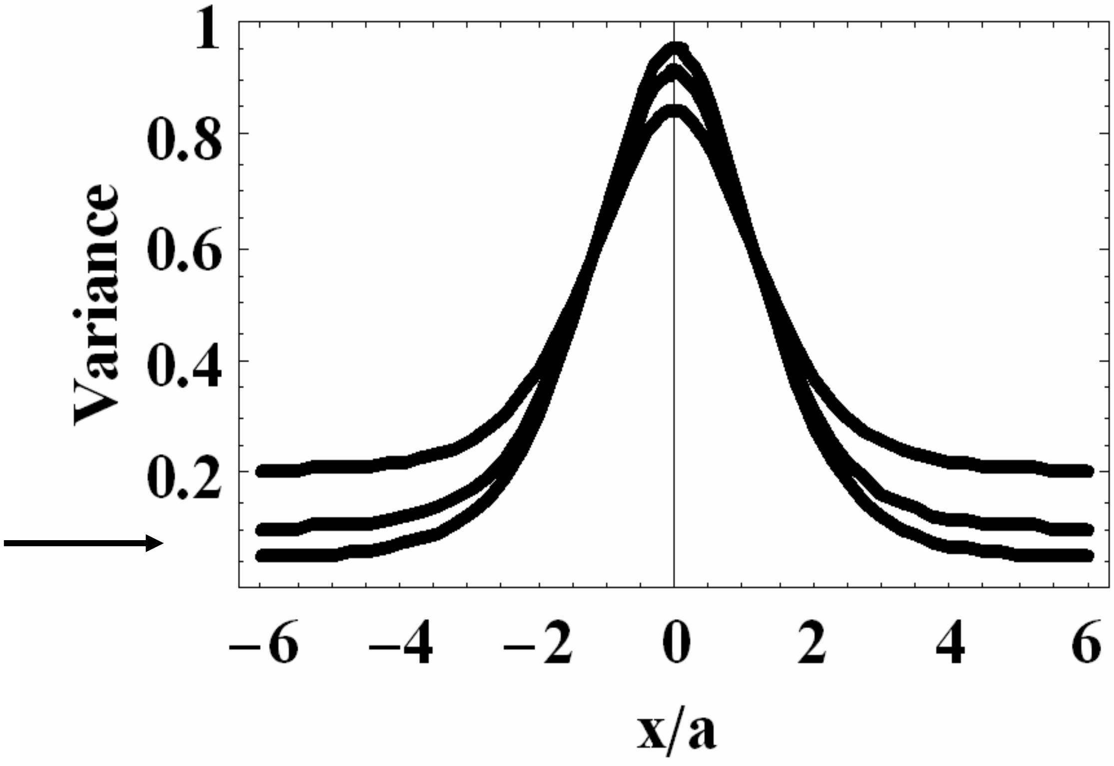
$$+ p^2 < \cos(\theta) >^2 \left(1 - m^2(x)\right) \longleftarrow$$ Transition Noise (Non-stationary)

Magnetization Noise Variance versus Position (p=1,.5,.25) and $M_r=M_s$



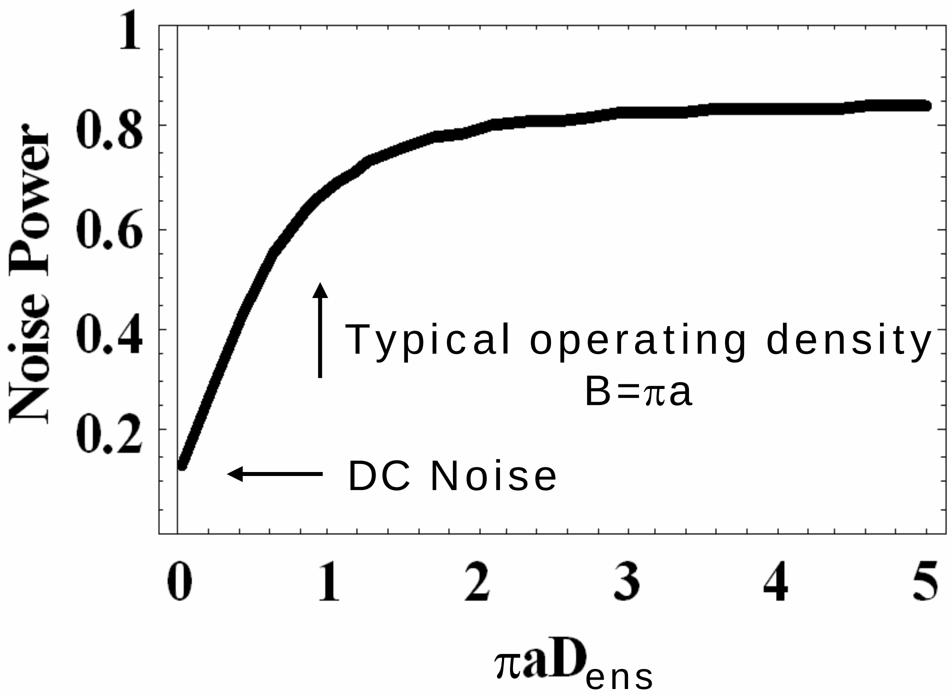
Transition Noise Variance versus Position ($S=M_r/M_s$=0.95,0.9,0.8; p=1)

S=0.8
0.9
0.95



Magnetization Noise Power Versus Linear Density (D_{ens}=1/B)

- Neglect orientation effects ($\theta \sim 0$), assume p =0.85 and include non-linearity due to transition overlap at high densities:



$$NP \approx p - p^2 + p^2 D_{ens} \int_{-B/2}^{B/2} dx \left(1 - m^2(x)\right)$$

Voltage Transition Noise Mode Approximations

- In general for the voltage:

$$V(x) = \overline{V}(x) + V_n(x) \approx \overline{V}(x) + \Delta x \left(\frac{\partial \overline{V}}{\partial x} \right) + \Delta a \left(\frac{\partial \overline{V}}{\partial a} \right)$$

"Jitter" "Breathing"

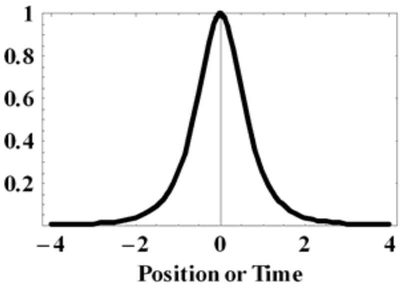
- The variance is

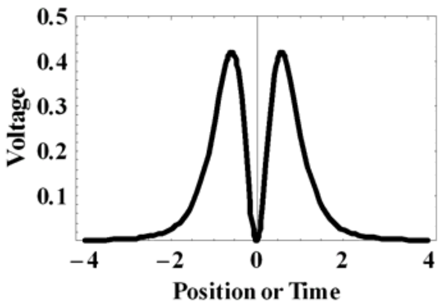
$$\sigma_{tn}^2(x) = \sigma_J^2 \left(\frac{\partial \overline{V}}{\partial x} \right)^2 + \sigma_a^2 \left(\frac{\partial \overline{V}}{\partial a} \right)^2$$

Voltage Mode Pictures

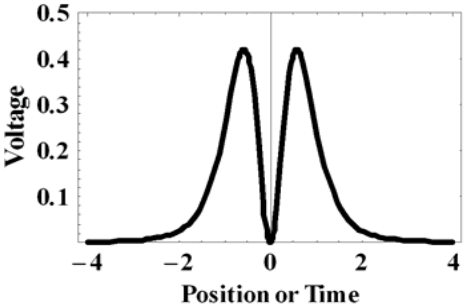
Perpendicular | Longitudinal

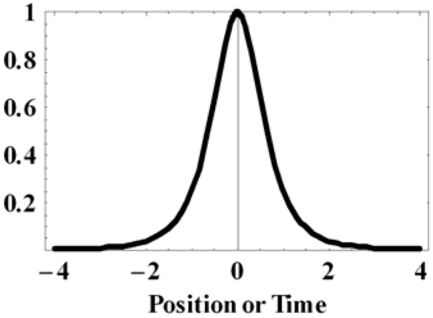
- Jitter:





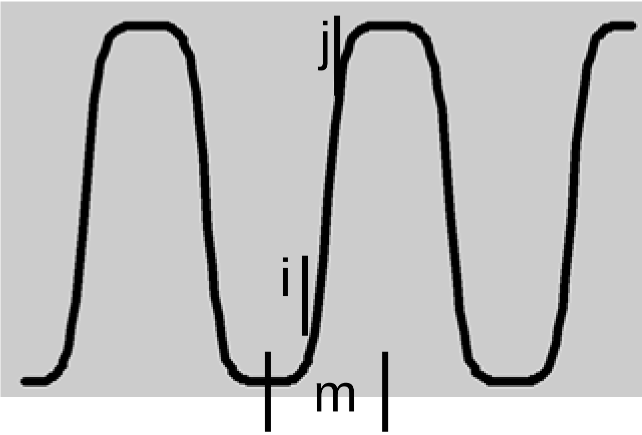
- Breathing:





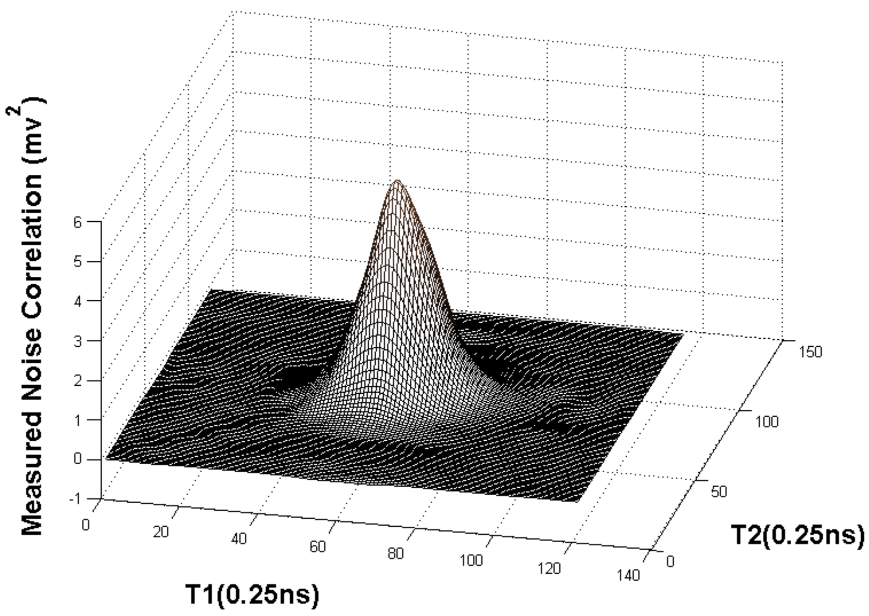
AutoCorrelation Measurements

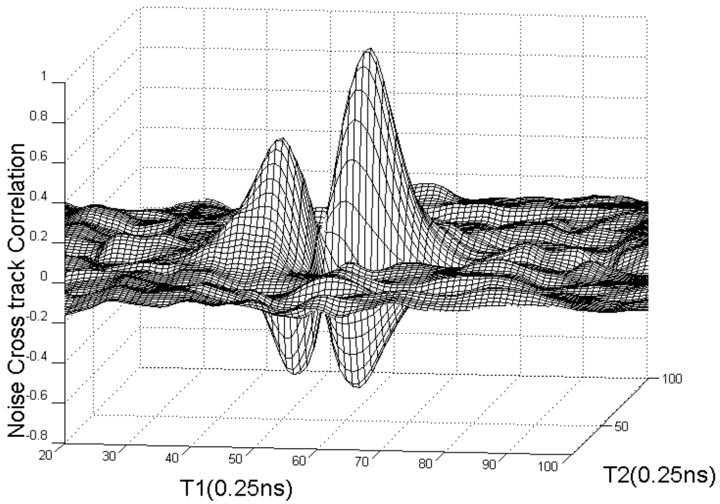
- Need statistical information over many bit cells for proper medium averaging.
  - Record all "1's" pattern at low density (M cells).
  - With timing information get well averaged transition.
  - Divide bit cell into N samples (i) and find V_{im} for each cell (m).
  - Determine the matrix: $R(i,j) = \frac{1}{M}\sum_{M}\left(V_{im} - \bar{V}\right)\left(V_{jm} - \bar{V}\right)$



Measured Autocorrelation Matrices

Perpendicular Noise Autocorrelation



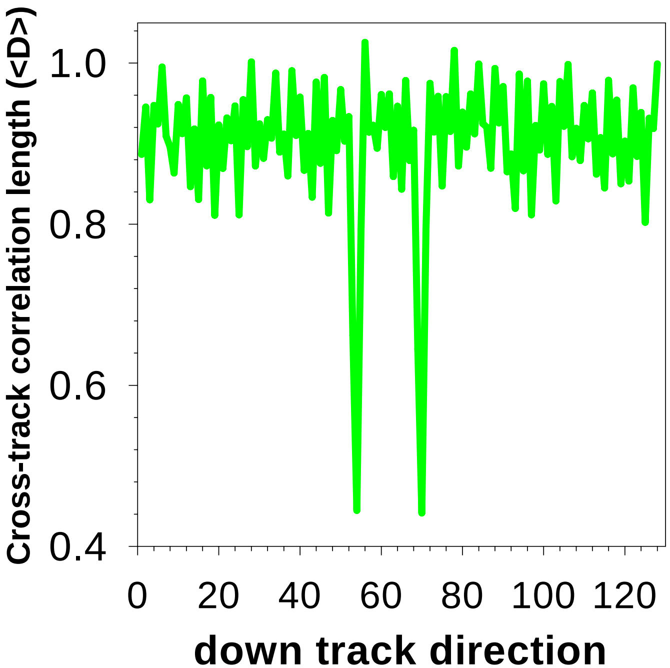


Longitudinal Noise Autocorrelation

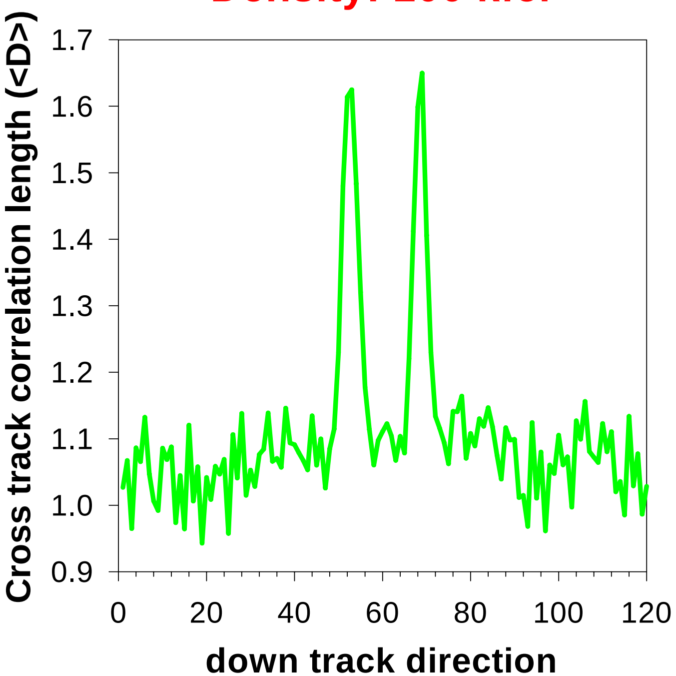
Cross Track Correlation Length versus Exchange-Longitudinal

Hong Zhou

Cross-track correlation length of uniform grain size at *h_e*=0.00
Density: 100 kfci

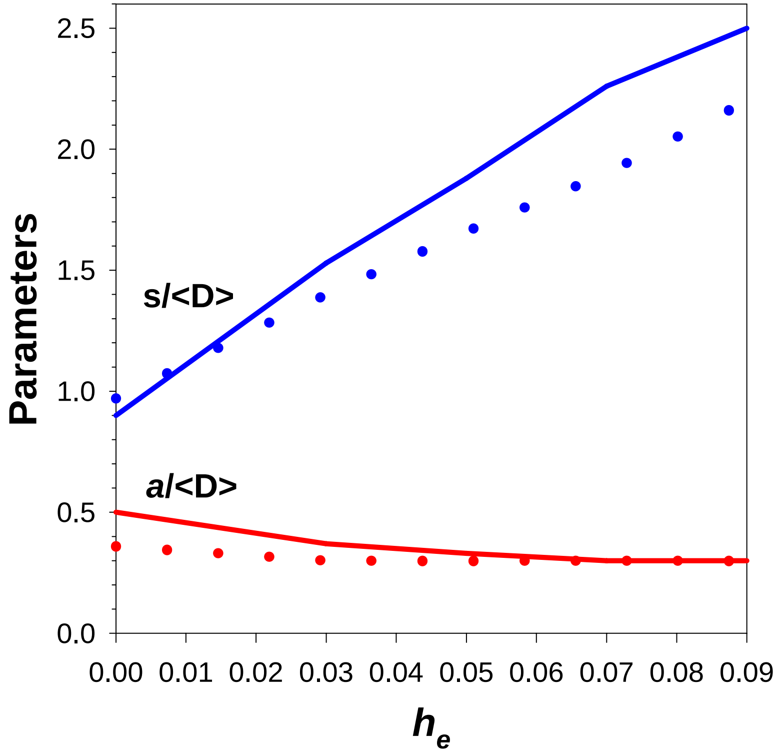


Cross track correlation length of uniform grain size at *h_e*=0.05
Density: 100 kfci



Cross Track Correlation Length versus Exchange-Perpendicular

Noise parameters change with exchange (no thermal effect) (solid: case I; dotted: case II)



Case I: M_s=350 emu/cm^3, H_K=14.6 KOe

Case II: M_s=290 emu/cm^3, H_K=17.6 KOe

Hong Zhou

Noise Mode Variances

- Equating the general expansion of the transition noise power spectrum with the approximate noise mode spectra:

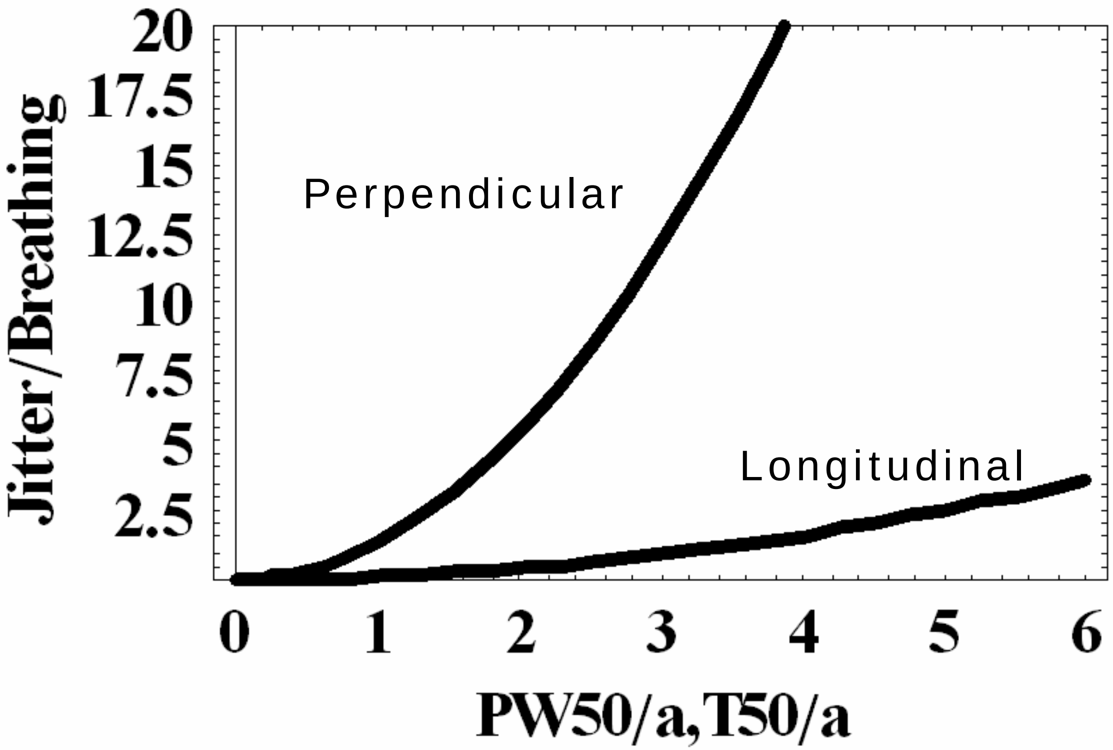
$$\sigma_J^2 = \frac{\pi^4 s_c a^2}{48 W_r} \approx \frac{2 s_c a^2}{W_r} \qquad \sigma_a^2 \approx \frac{\pi^8 s_c a^4}{2880 W_r} \approx \frac{3.3 s_c a^4}{W_r}$$

- Recall that the Jitter variance was determined directly from the microtrack statistics.

- Jitter is usually measured from slope of Noise Power versus density:

$$\frac{d\left(TNP / V_{isopeak}^2\right)}{dDens} \approx 01.74 \frac{\sigma_J^2}{T_{50}}$$

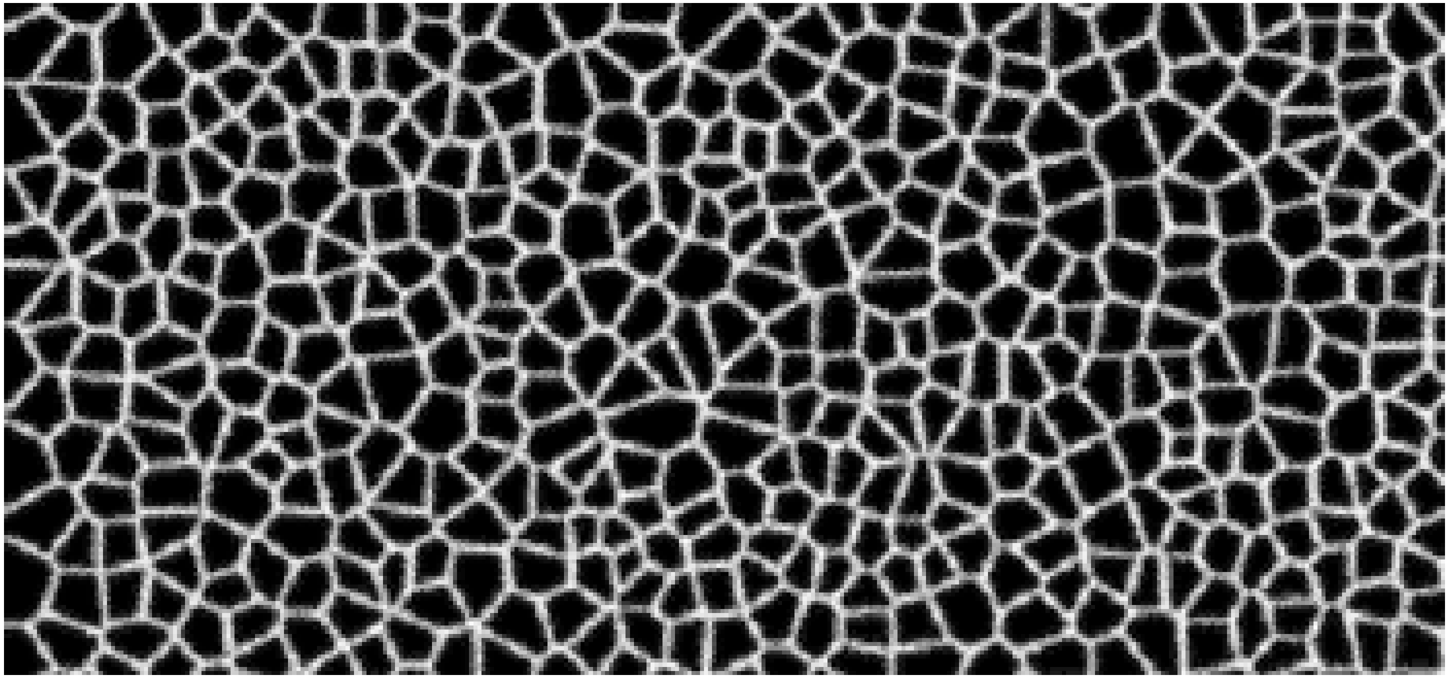
Noise Power Ratio of Jitter to Transition Width



For a PR channel Typically: PW50=2B,T_{50}=B. With B=πa =>PW_{50}/a =6, T_{50}/a = 3 => $Ratio_p$~ 10, $Ratio_L$~ 5

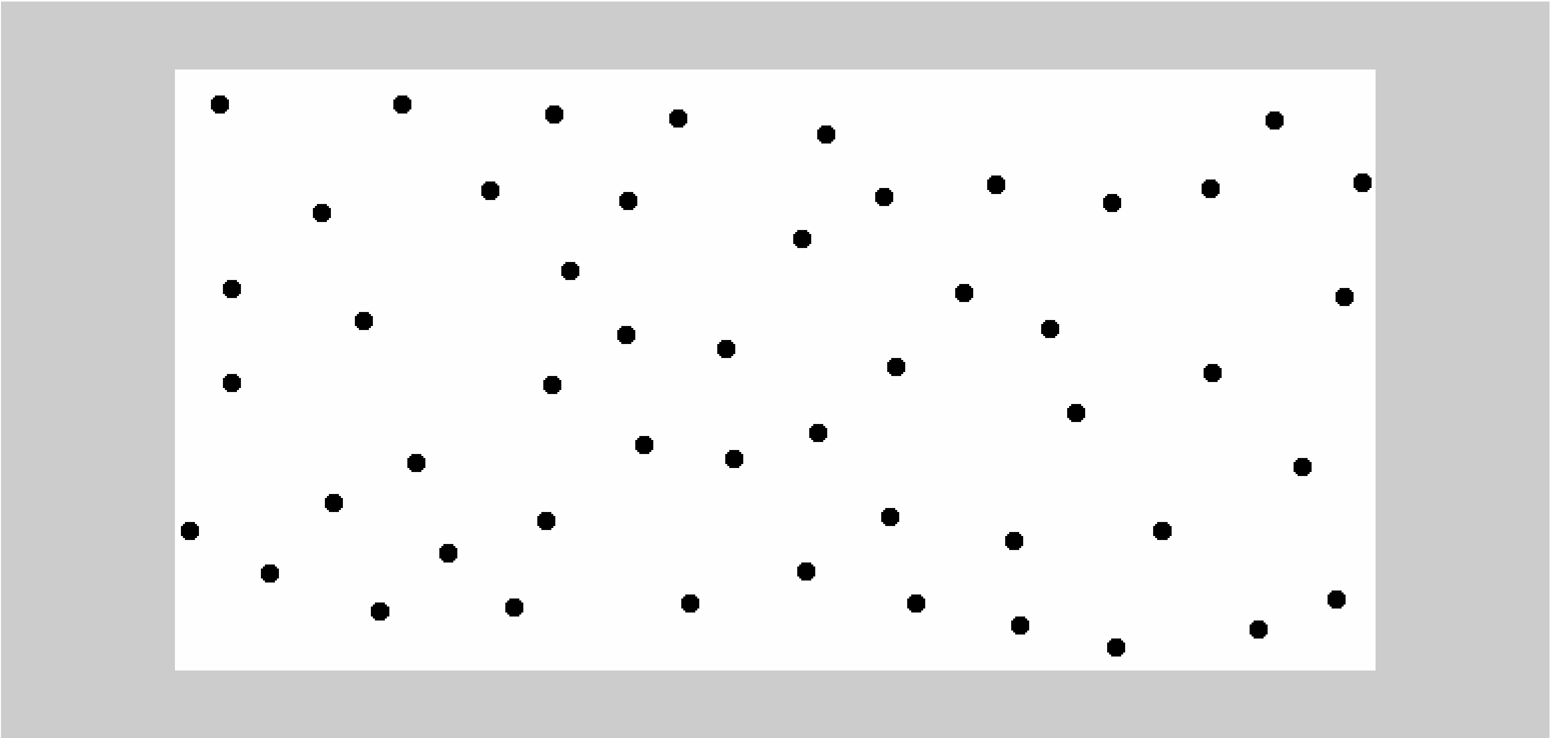
A Comparison of Transition and Uniform (DC) Noise

Model of Simulated Media



- “Grown” by random seeds with fixed boundary separation.

Grain Growth Simulation Movie



Total DC Noise Power

- The total DC power is:

$$TP_{DC} = R(0) = W_r M_g^2 p A_{corr} \left(< \cos^2 \theta > - p < \cos \theta >^2 \right) \int_{-\infty}^{\infty} dx' H^2(x')$$

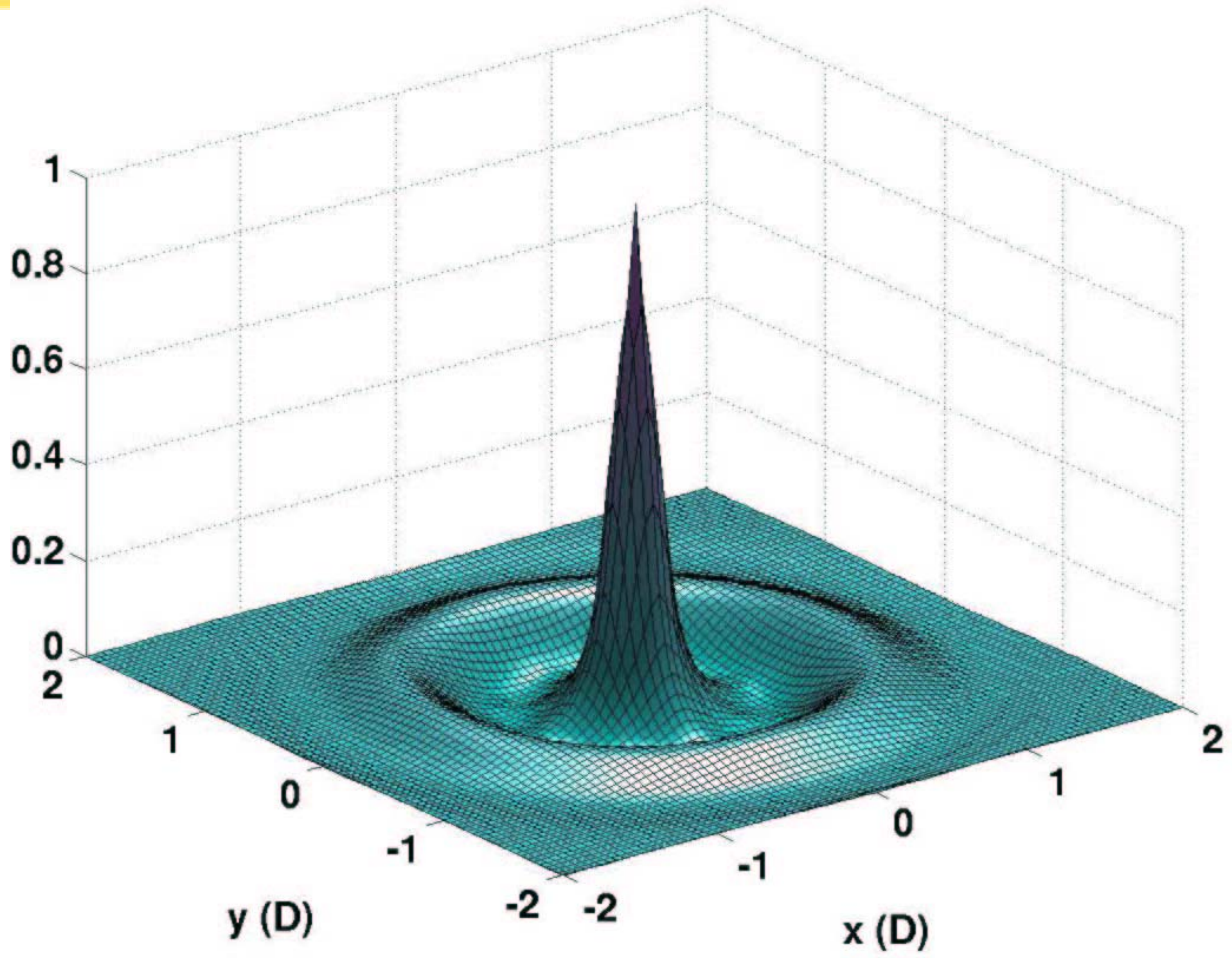
$$A_{corr} = \iint dx' dz' \rho(x', z')$$

- The key factor is the noise correlation area A_{corr}. Is it bigger, smaller, or equal to the grain size??

- Neglects
  - Track edge effects
  - Assumes read width (~PW_{50}) much greater than A_{corr}

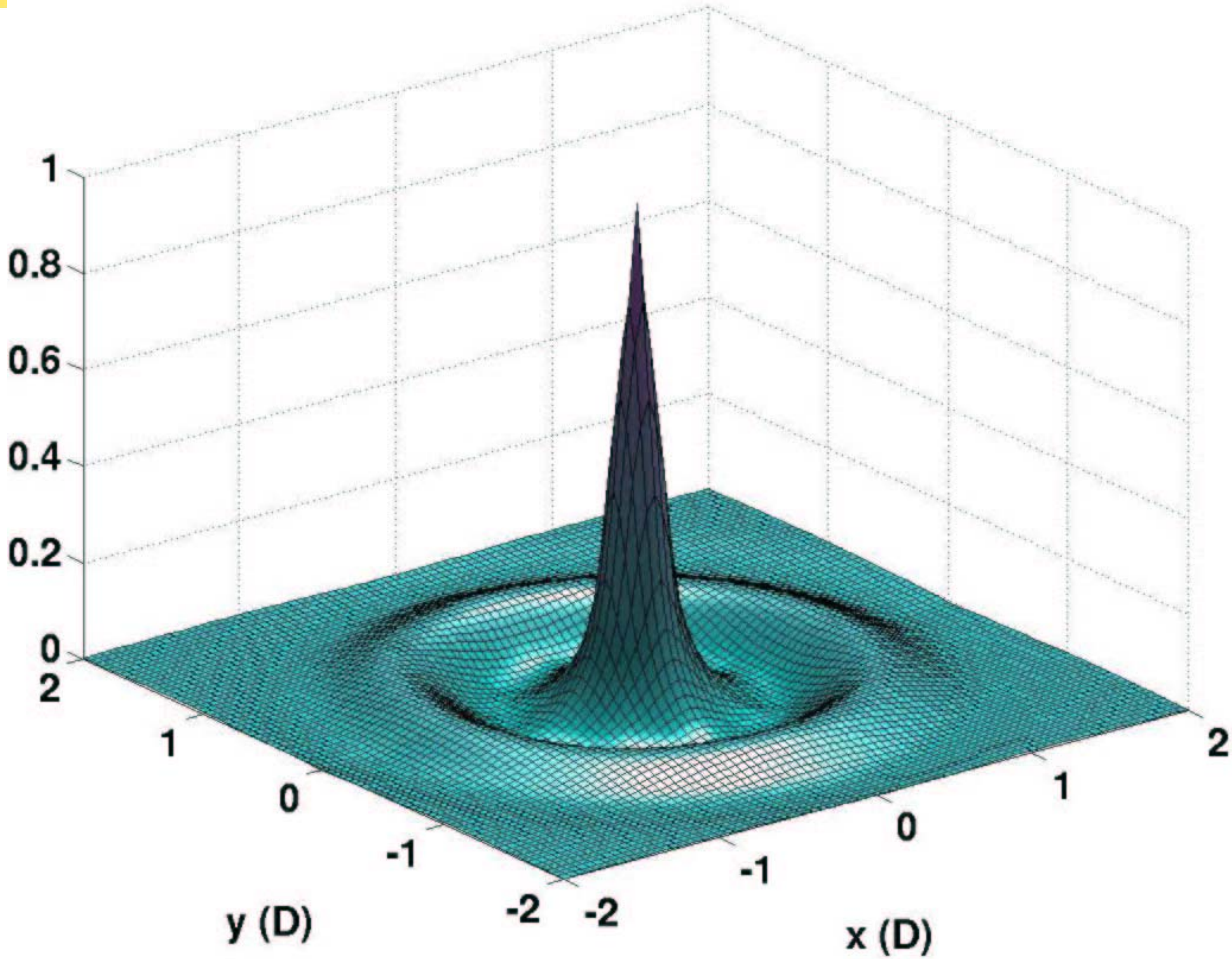
DC Noise- 2D Correlation Function

$\theta_{max} = 0^o$



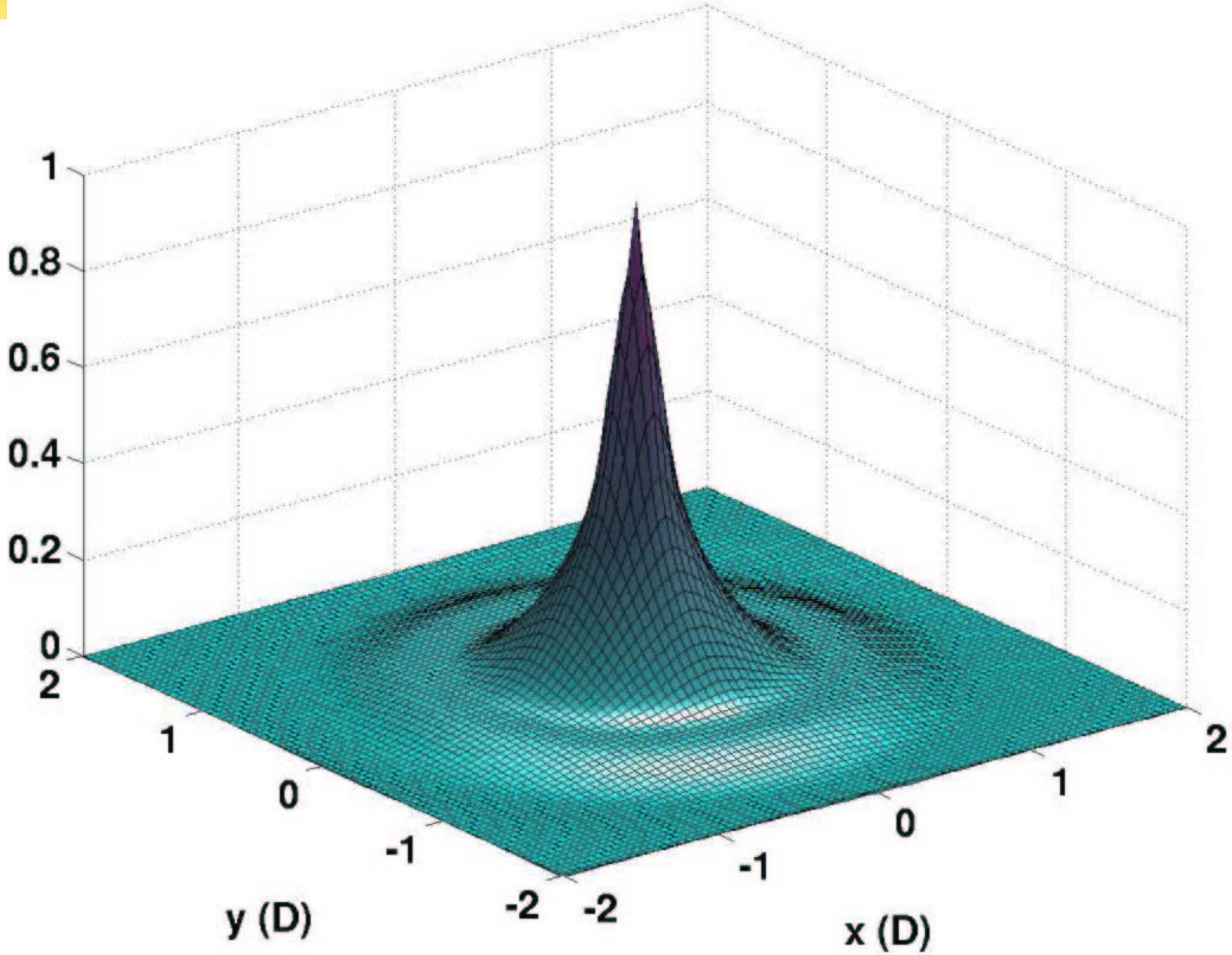
DC Noise- 2D Correlation Function

$\theta_{max} = 52^o$



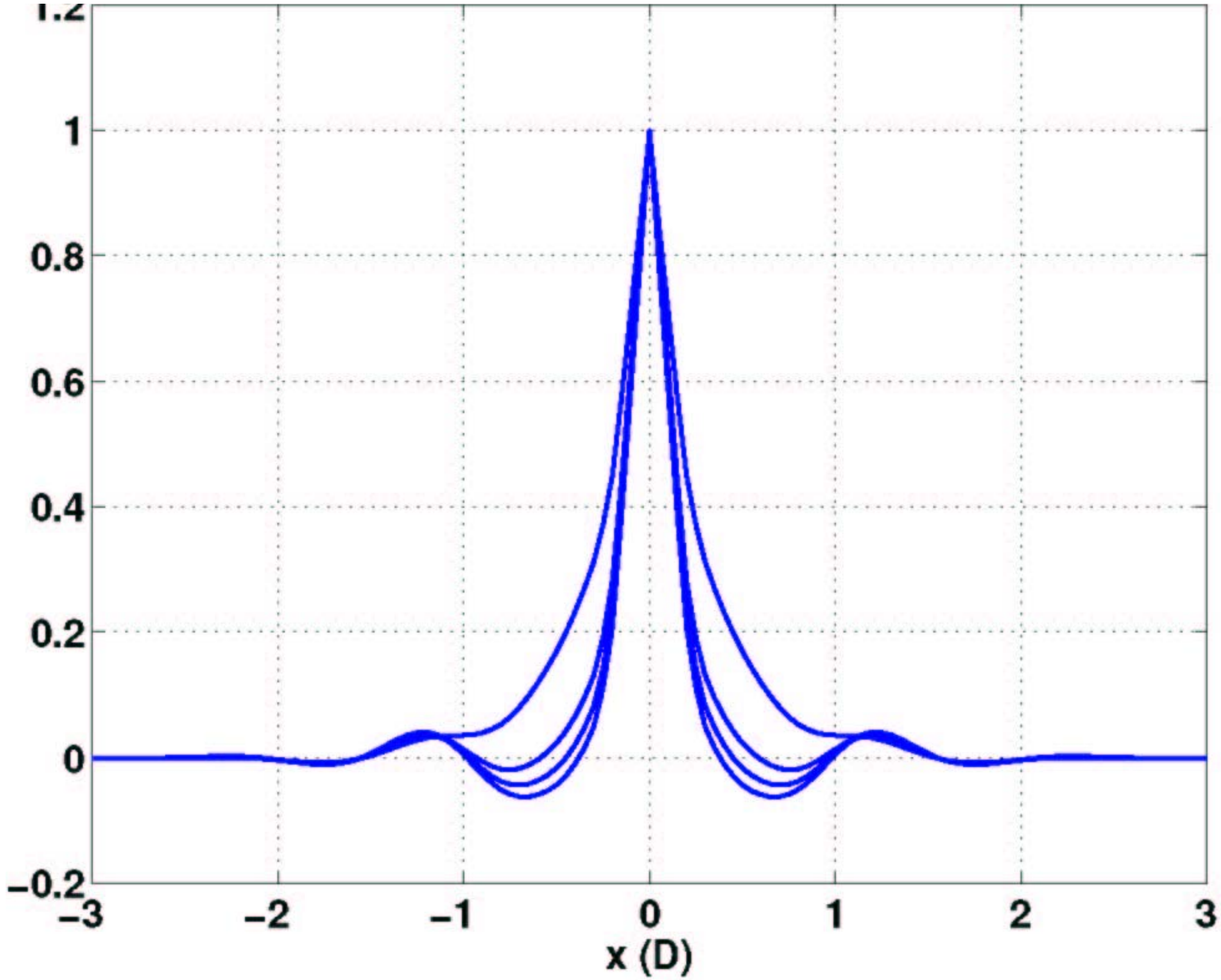
DC Noise- 2D Correlation Function

$\theta_{max} = 90^o$

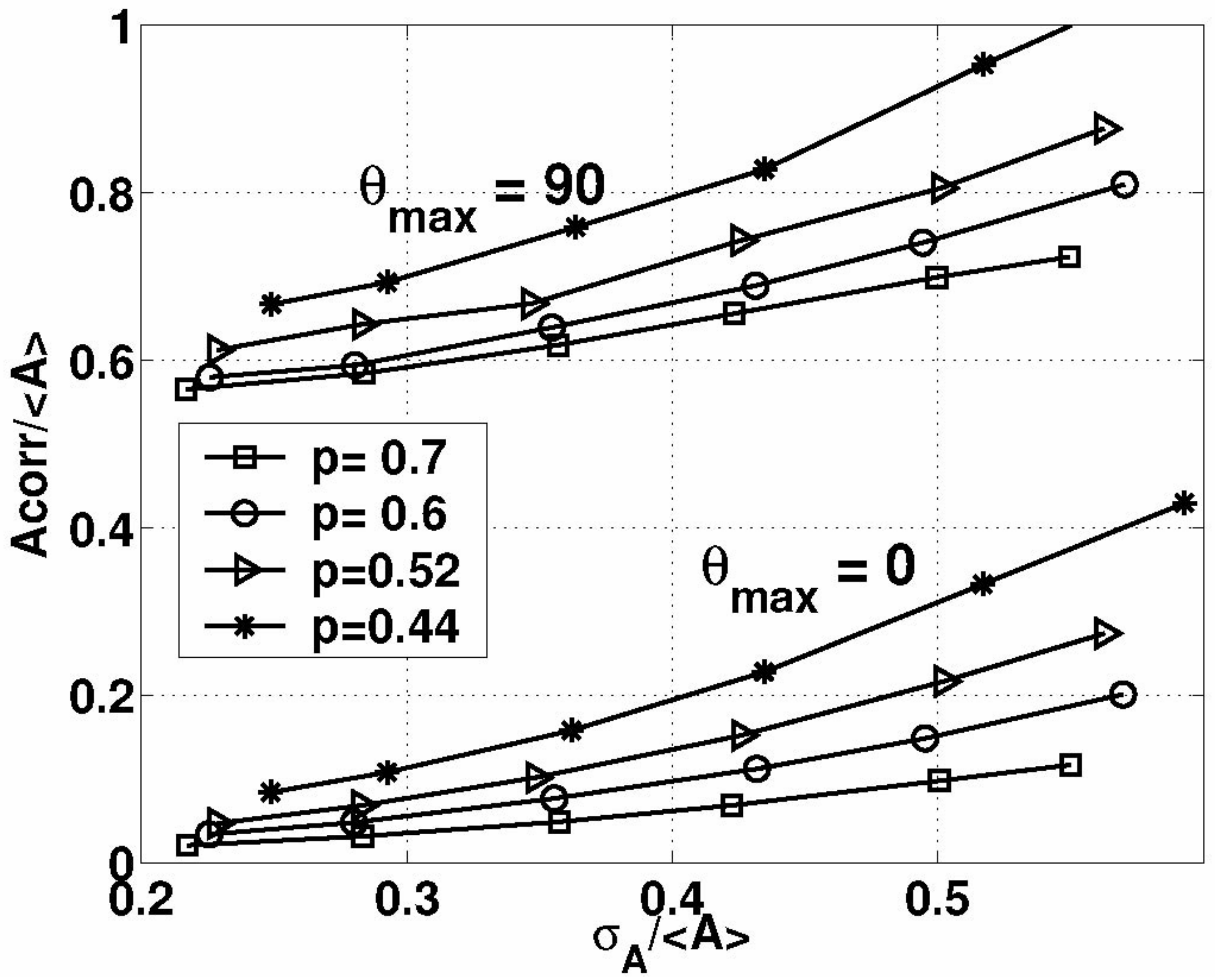


Correlation Function Comparison

θ_{max} = 0, 52, 65, 90^o



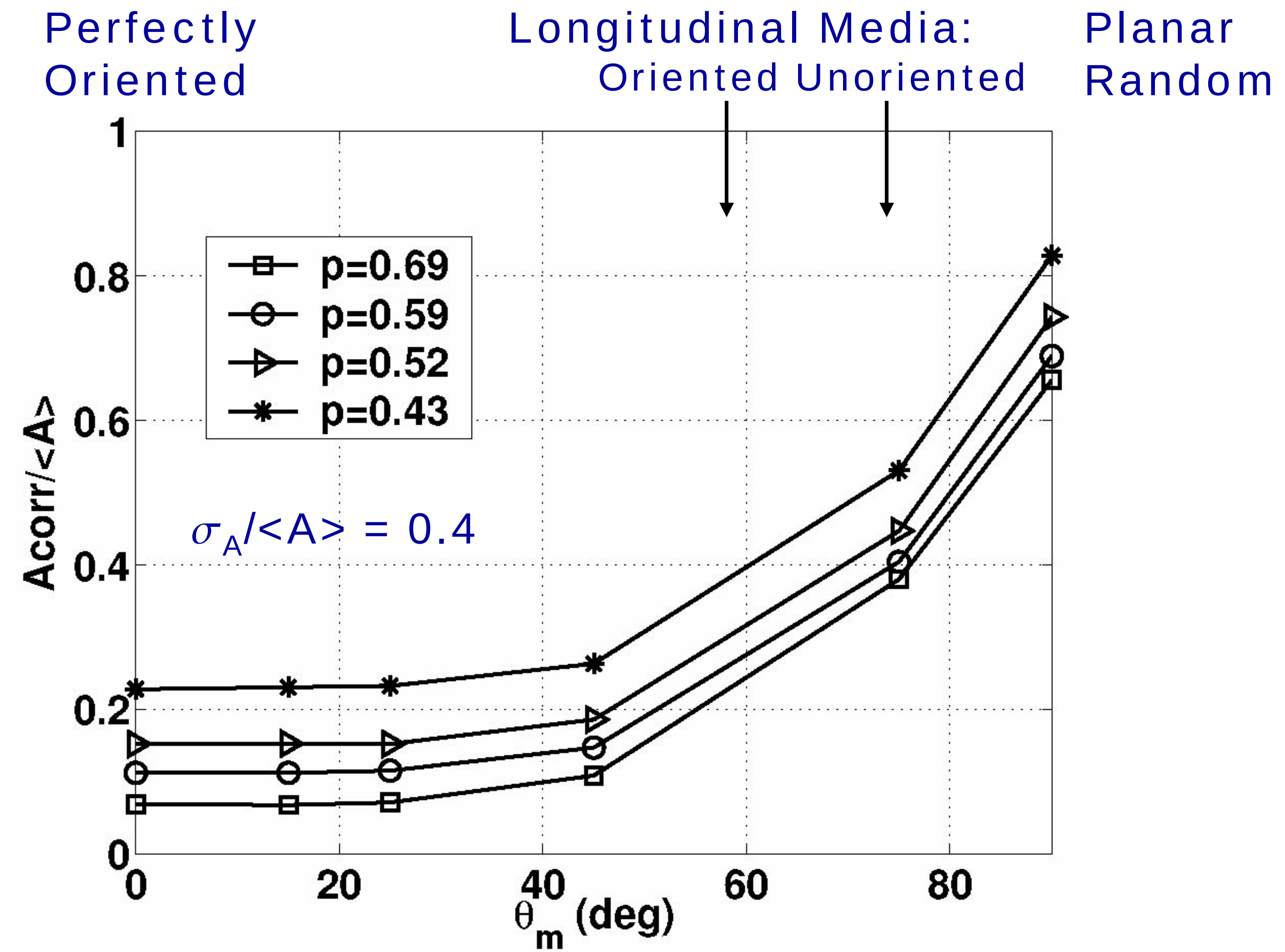
Spatial Correlation Area



Planar Random

Perfectly Oriented

Spatial Correlation Area



Ratio of DC to Transition Noise Power

- The total transition noise power is:

$$TP_{TR} = <R(0)> = \frac{\pi^4 W_r M_g^2 <\cos\theta>^2 \ p^2 a^2 s_c}{12B} \int_{-\infty}^{\infty} dx' H^2(x')$$

- Neglects
  - Track edge effects
  - Assumes read width (~PW_{50}) much greater than πa.

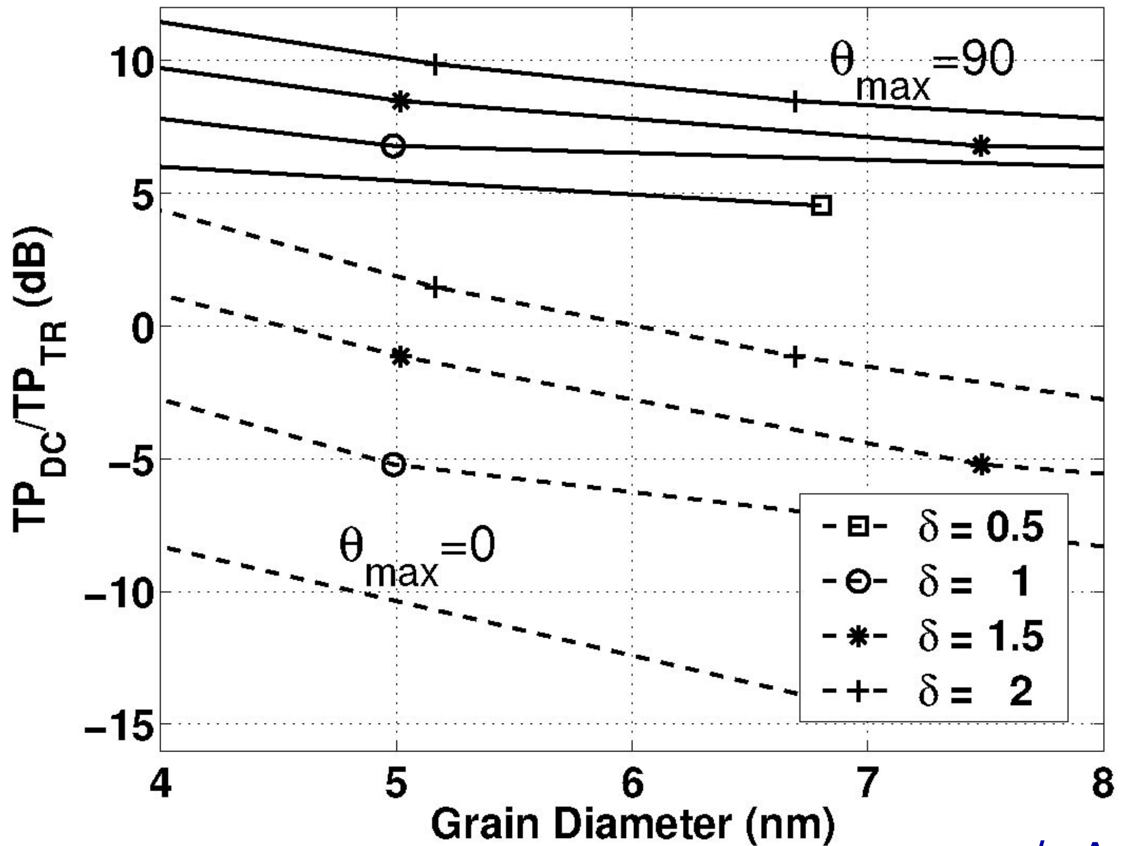
- Ratio of DC to Transition Noise Power

$$\boxed{\frac{TP_{DC}}{TP_{TR}} \approx \frac{A_{corr} B}{8a^2 s_c}\left(\frac{\left(<\cos^2\theta> / <\cos\theta>^2\right) - p}{p}\right)}$$

Scaling of $B/a^2 s_c$

Density	100 Gbits/in^2	1T Gbits/in^2
B (BAR=6)	100nm	10nm
a/<D>	1.3	0.45
s_c/<D>	1.2	1
$B/a^2 s_c$	$\sim 50/\langle D\rangle^2$	$\sim 50/\langle D\rangle^2$
$B_{ps}/a^2 s_c$ (used for T_{DC}/T_{TR})	$\sim 100/\langle D\rangle^2$	$\sim 100/\langle D\rangle^2$

Ratio of DC to Transition Noise Power

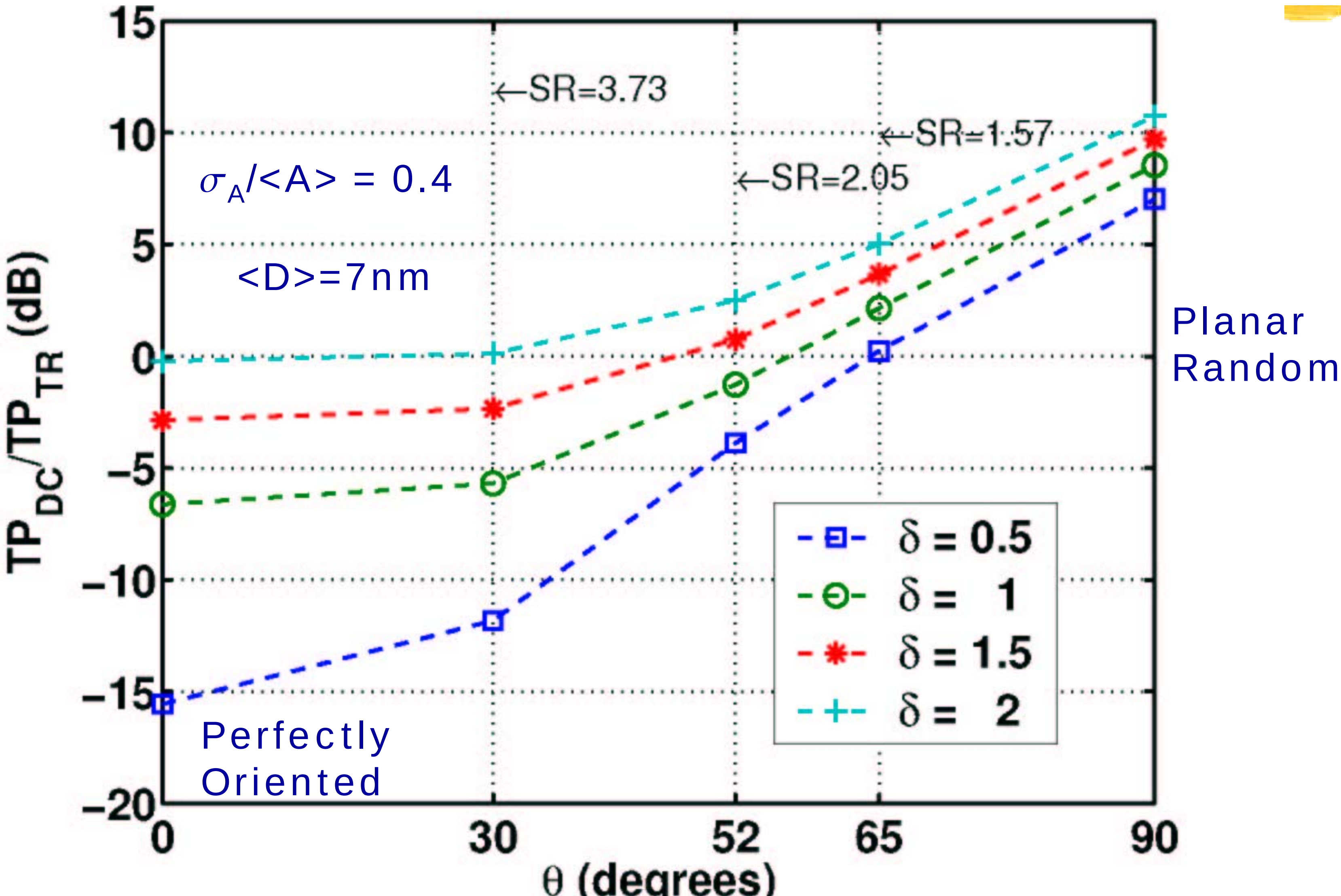


Planar Random

Perfectly Oriented

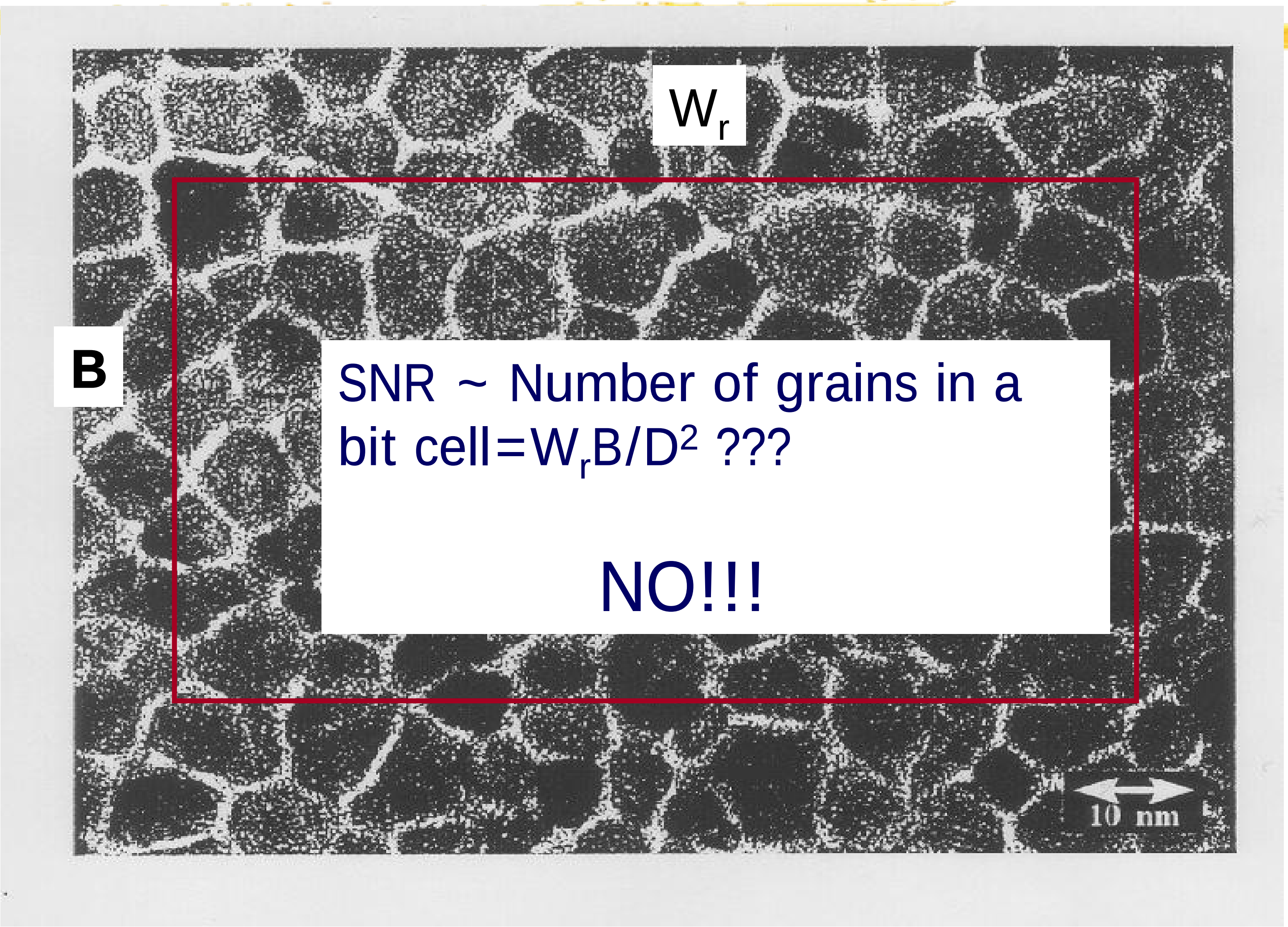
$\sigma_A/\langle A \rangle = 0.4$

Ratio of DC to Transition Noise Power



VII. SNR and BER

Simplest SNR



SNR Definitions

- SNR_1: Square of isolated pulse peak/total noise power at given “all ones” density.
  - Easily Related to BER
- SNR_2: RMS Signal Power at “2T” peak/total noise power at “T” density.
  - Can include edge track noise
- SNR_3: RMS Signal Power/Noise spectral power at a given density.
  - Lowest SNR, but channel generally has a null at band edge

SNR_1 : Square of isolated pulse peak/total noise power at given "all ones" density.

- For both longitudinal or perpendicular recording:

$$SNR_1 \equiv \frac{V^2_{\max isopulse}}{Total\ Noise(B)}$$

- Thus, for square wave recording at bit spacing B and including only the jitter noise jitter:

$$SNR \equiv \frac{BV^2_{\max}}{\sigma_J^2 \int_{-B/2}^{B/2} dx \left(\frac{\partial V(x)}{\partial x} \right)^2}$$

SNR_1 Relations (cont.)

- The transition noise variance is given generally by:

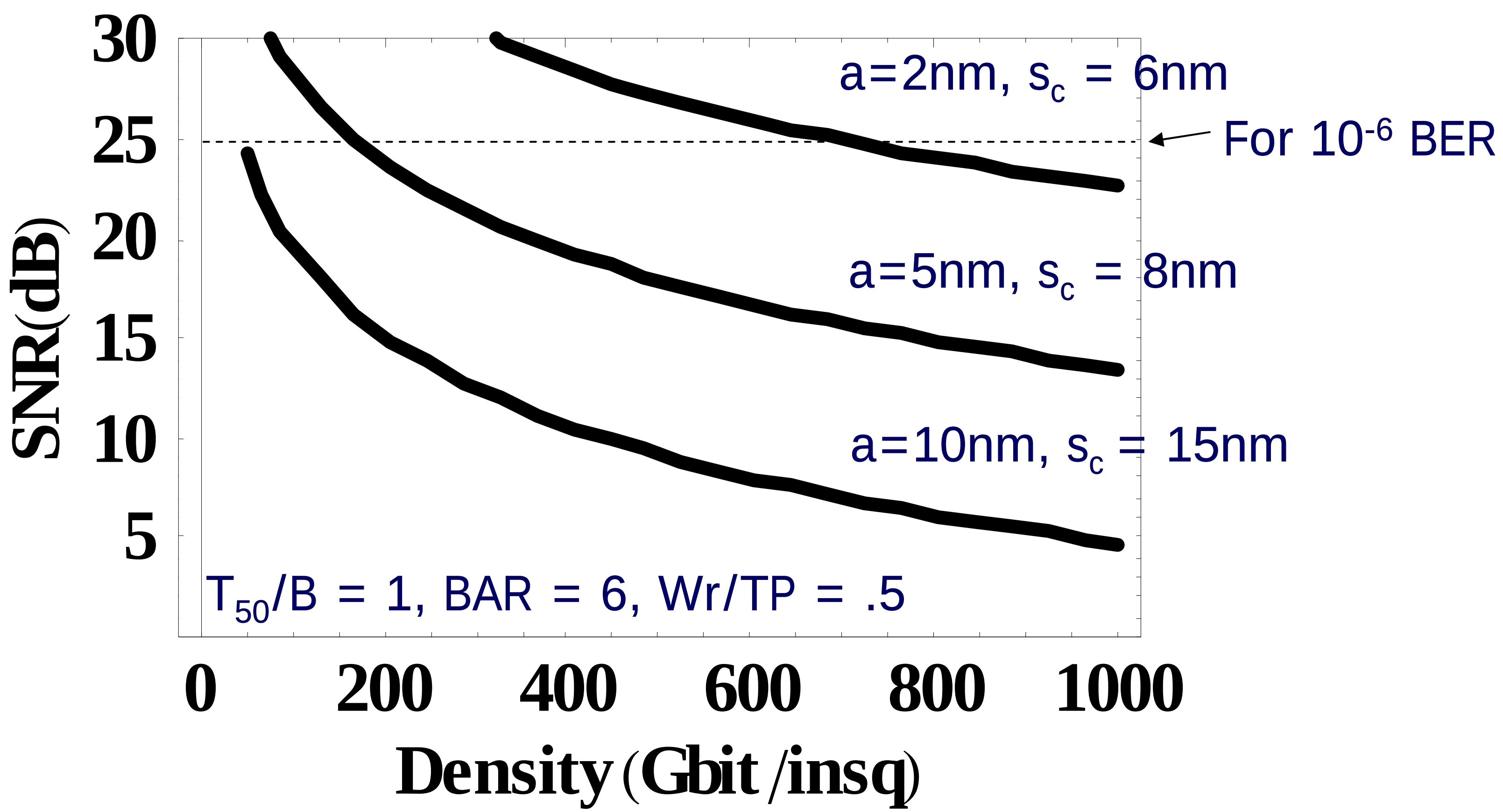
$$\sigma_J^2 = \frac{2a^2 s_c}{W_r}$$

- Lets assume that the pulse is well approximated by an Erf (Perp) or Gaussian (Long. or Diff. Perp.):

$$\boxed{SNR_1^{Perp} \approx \frac{0.33 T_{50} W_r B}{a^2 s_c} \qquad SNR_1^{\substack{Longor \\ Diffperp}} \approx \frac{0.42 P W_{50} W_r B}{a^2 s_c}}$$

SNR_1 versus Density

Perpendicular Recording



SNR Scaling Relations

- We use the (long.) form of SNR_1 and realize that the BAR (TP/B) and the normalized code density ($PW_{50}/B=\gamma$) may be fixed. We assume $TP/W_r=2$:

$$\boxed{SNR_1^{\substack{Longor\\Diffperp}} \approx \frac{0.42 PW_{50} W_r B}{a^2 s_c} = \frac{0.21 B^3 \gamma BAR}{a^2 s_c}}$$

- Note: the SNR varies inversely as the linear density cubed.

SNR Scaling Relations
Grain Diameter Effects

- If head field gradients or medium distributions <u>are not</u> sufficient (assume s_c=1.5<D>, a $\geq$<D>):

$$SNR_1^{\substack{Longor\\Diffperp}} \approx \frac{0.14B^3\gamma BAR}{a^2\bar{D}} \propto \frac{B^3}{a^2\bar{D}}$$

- If head field gradients or medium distributions <u>are</u> sufficient (assume s_c=1.5<D>, a =0.5<D>):

$$SNR_1^{\substack{Longor\\Diffperp}} \approx \frac{0.56B^3\gamma BAR}{\bar{D}^3} \propto \frac{B^3}{\bar{D}^3}$$

- Although scaling may vary it is always beneficial to reduce the grain diameter!!

SNR Scaling Relations
Anisotropy Effects

- We assume KV = Constant , M_s/H_k = Constant, fixed medium thickness:

$$H_k \propto 1/\overline{D}$$

- For a $\geq$<D>:

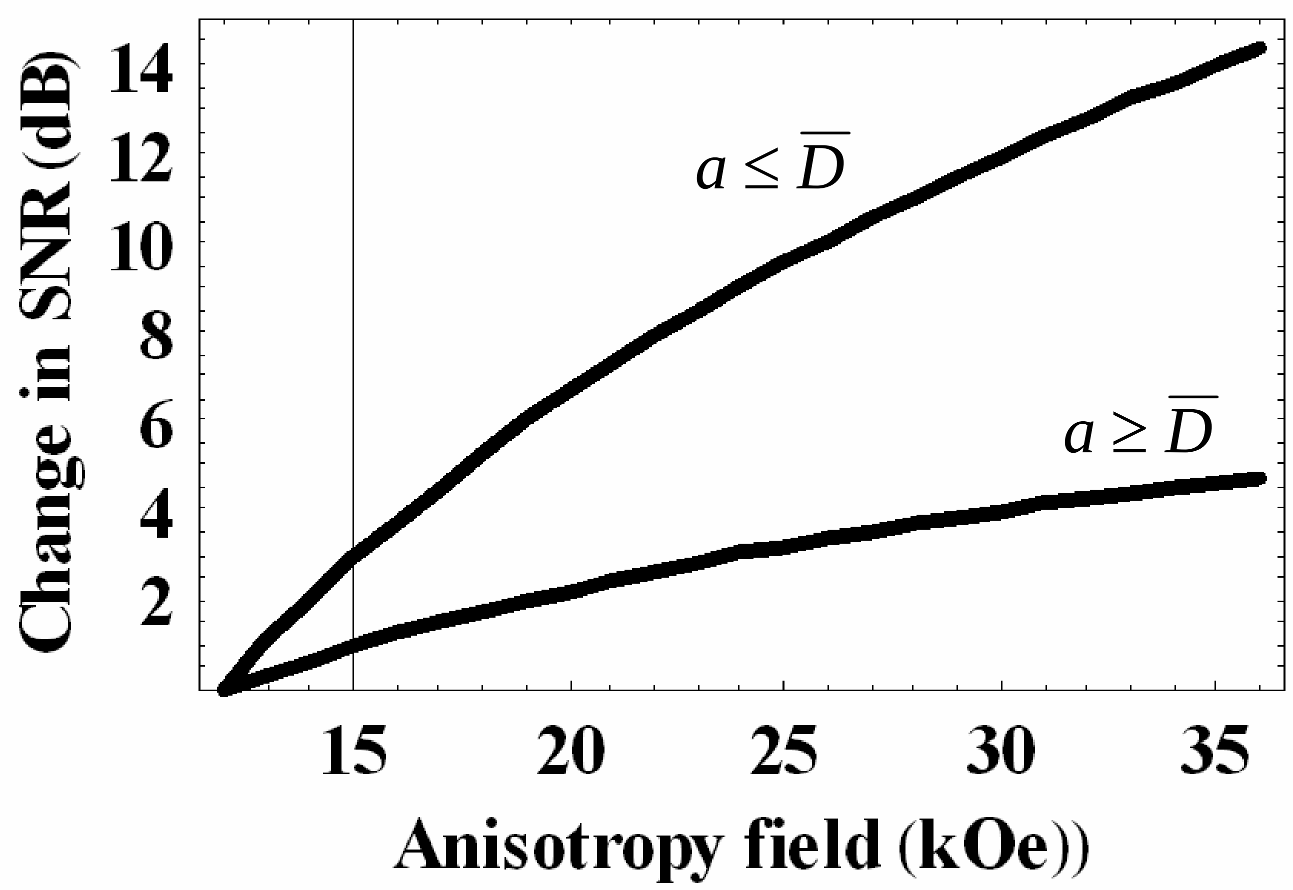
$$SNR_1^{\substack{Longor \\ Diffperp}} \approx\propto H_K$$

- For a < <D>:

$$SNR_1^{\substack{Longor \\ Diffperp}} \propto H_K{}^3$$

Effect of Anisotropy Increase

- SNR increase with H_k relative to H_k = 12kOe.



SNR Definitions SNR_2, SNR_3

- To a good approximation, jitter limited SNR is:

$$SNR_{peak\ sig} \approx \frac{0.33 T_{50} W B}{a^2 s_c}$$

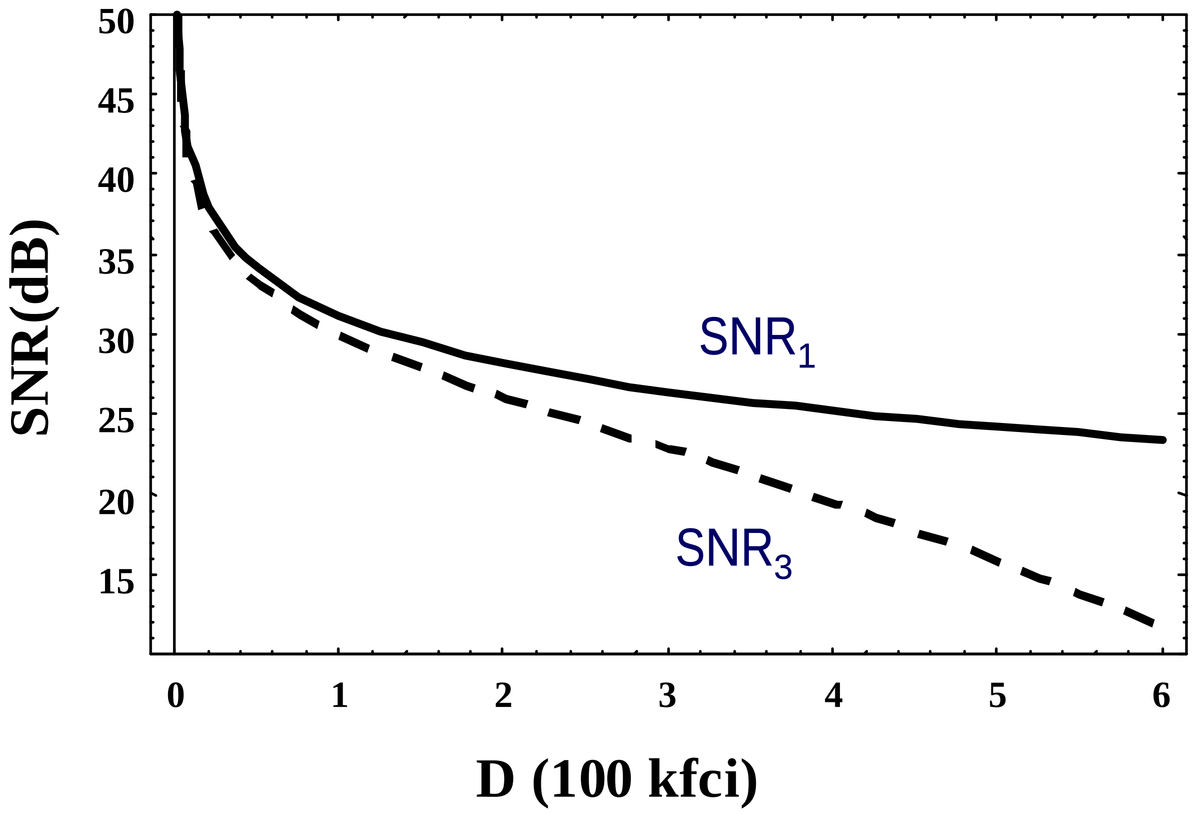
- SNR defined as rms squared at density (1/B) divided by total square wave noise:

$$SNR_{rms} \approx \frac{8}{\pi^2} \frac{0.33 T_{50} W B}{a^2 s_c} Exp\left[-5.5 \left(\frac{T_{50}}{B} \right)^2 \right]$$

- For SNR_2 use 2B in Exp, For SNR_3 use as is.

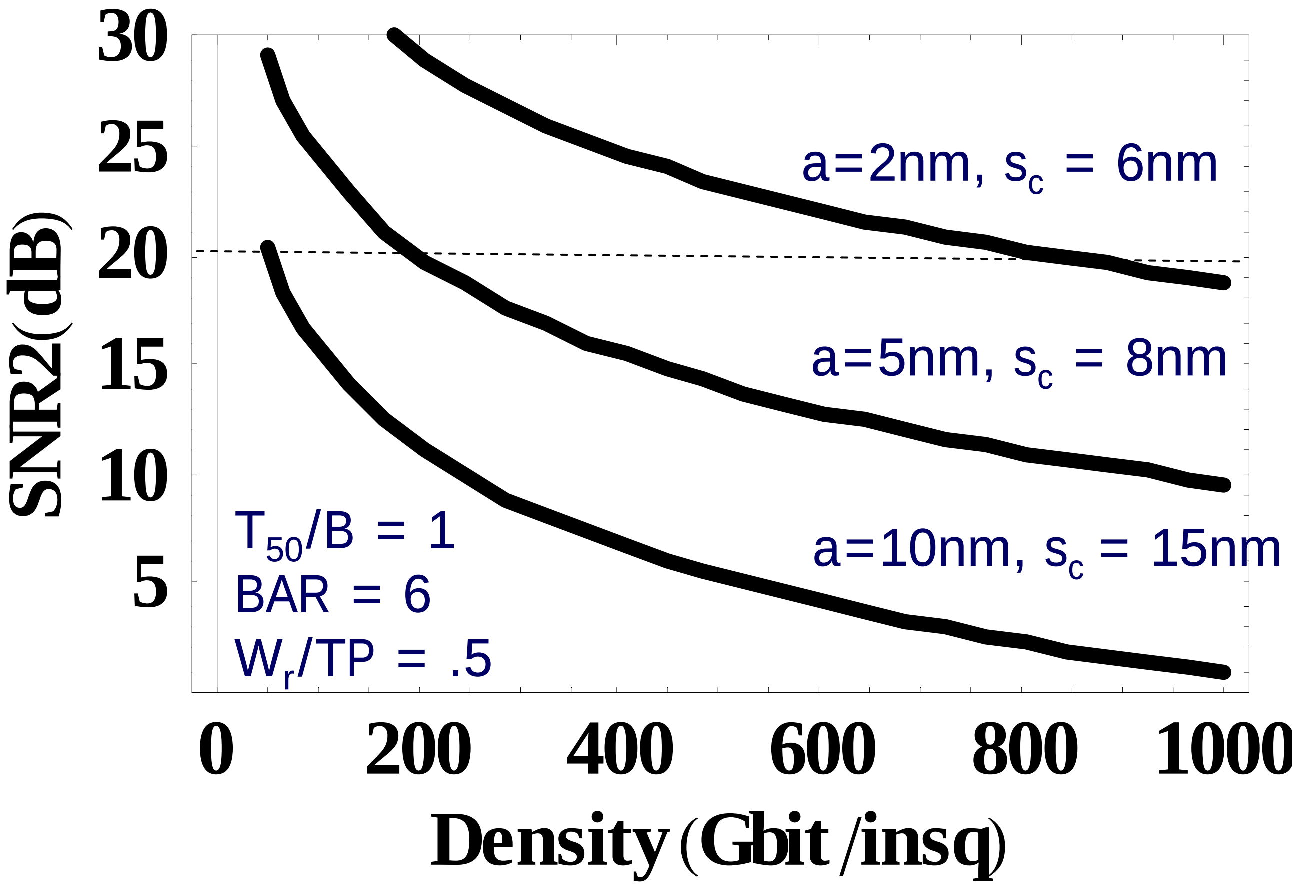
Comparison of SNR Definitions

W_r = 200nm, a = 7nm, s_c = 7nm, t = 20nm, d = 10nm, s = 5nm, T_{50} = 28nm



SNR$_2$ versus Density
Perpendicular Recording

$$SNR_2 \approx \frac{16}{\pi^2}\frac{0.33 T_{50} W_r B}{a^2 s_c} Exp\left[-5.5\left(\frac{T_{50}}{2B}\right)^2\right]$$

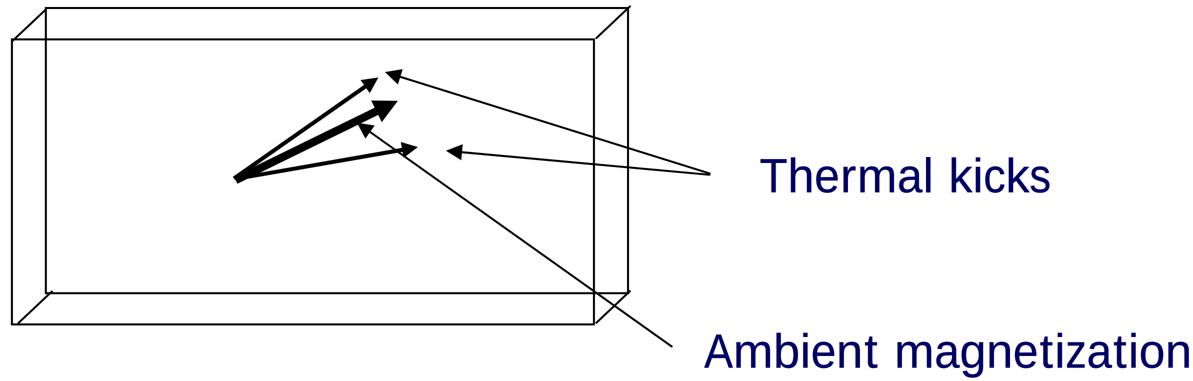


Probably most useful since measurement can include track edge effects.

20 dB is perhaps reasonable limit since edge effects will lower SNR.

GMR Thermal Noise

- The sensor magnetization will fluctuate due to thermal energy.



- This yields a noise voltage:

$$TNP_{GMR} \propto \left(IR_{sq} \frac{W_r}{2h} \frac{\Delta R}{R} \right)^2 f_{\max} \frac{\eta k_B T}{\gamma^2 M_s V_{sensor}}$$

- The problem is that as we go to higher densities the sensor volume V_{sensor} will decrease leading to a larger GMR thermal noise!!

Noise Comparison versus Density

Including GMR Saturation

(mV)	NV_{jitter}	NV_{ele}	NV_{res}	NV_{GMR}
20 Gb/in^2	0.40	0.026 (0.9nV/RtHz)	0.017	0.027
100 Gb/in^2	0.39	0.025 (0.7nV/RtHz)	0.025	0.105
500 Gb/in^2	0.40	0.019 (0.5nV/RtHz)	0.038	0.367
1Tb/in^2	0.52	0.022 (0.5nV/RtHz)	0.044	0.590

BER Motivation

- Consider a data sequence, e.g:

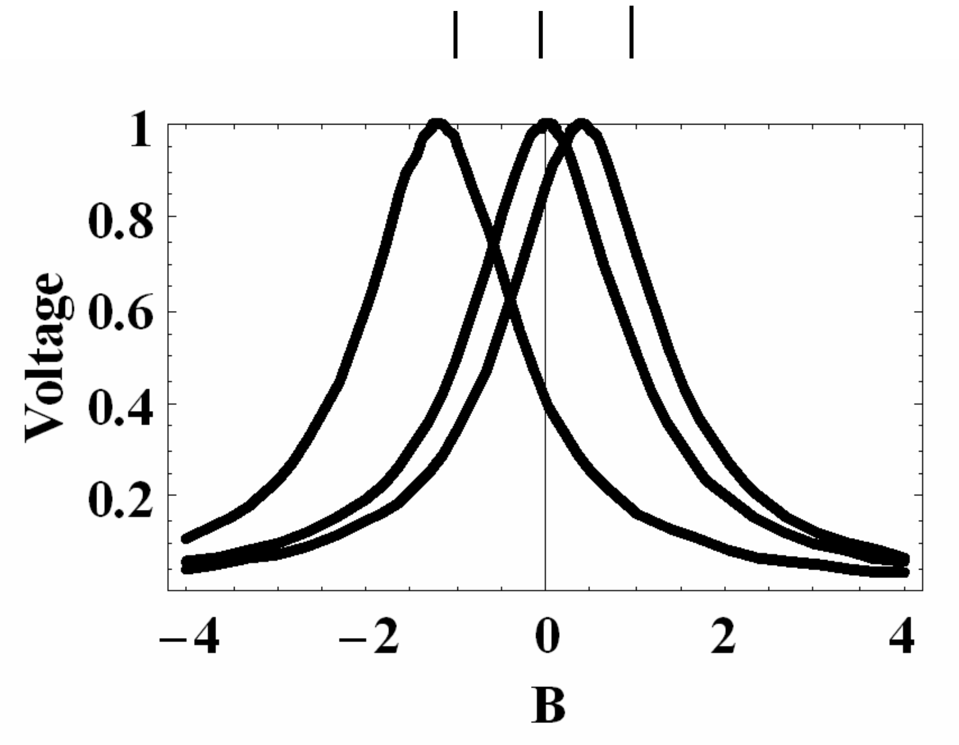
1 1 0 1 0 1 1 0 1 0 1 0 1

- We want the Probability of Error that the written sequence will be confused with another pattern, e.g:

1 1 0 0 1 1 1 0 1 0 1 0 1

Position Jitter Noise

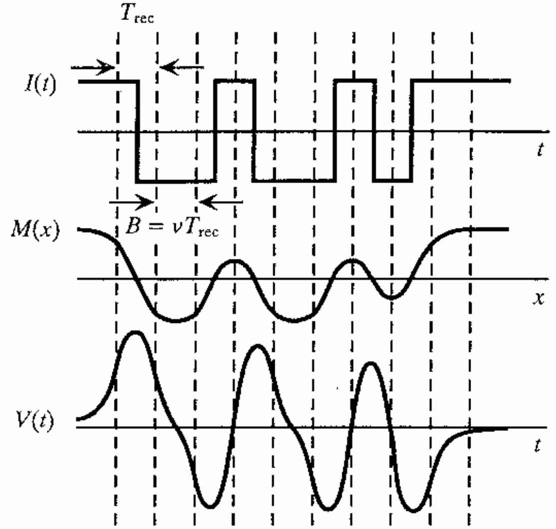
- Simplest Error analysis comes from peak detection with medium position jitter noise:



$PW_{50}=2B$

Channel Equalization and Detection

- General problem of high density recording is intersymbol interference (ISI): 1 0 1 1 0 1 1 1 0

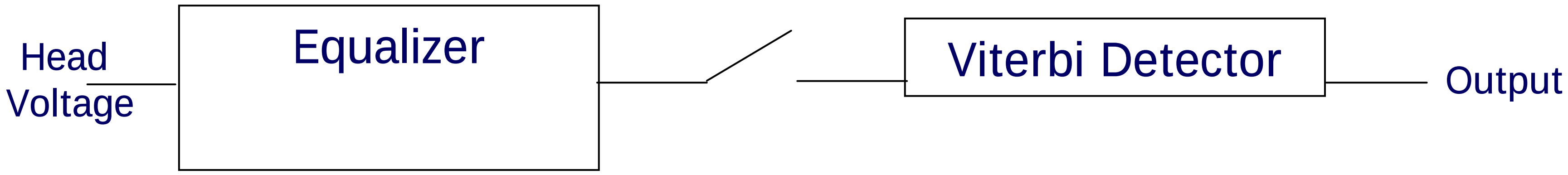


- If sample voltages (ala Nyquist), a sample in one cell will be affected by voltage tails of neighboring transitions.

- How should we effectively equalize? Lots of ISI is hard to implement. Simple pulse slimming raises noise.

Viterbi Detection

- PR channel with Viterbi detector is a good approximation.



- Equalize to minimize ISI.

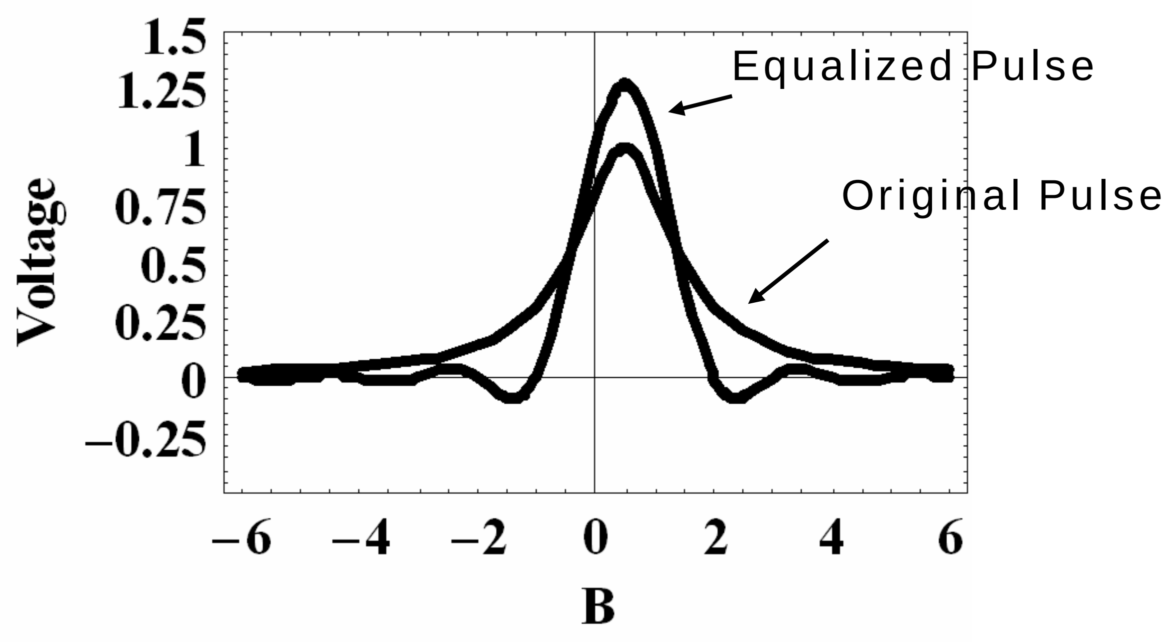
- Sample voltage every bit cell (T) of cells, (only a few in A PR channel).

- Virturbi detector takes sampled voltages and reconstructs the original data. Optimal of white Gaussian noise, but used for non-stationary colored noise in a magnetic recording channel.

PR Channels

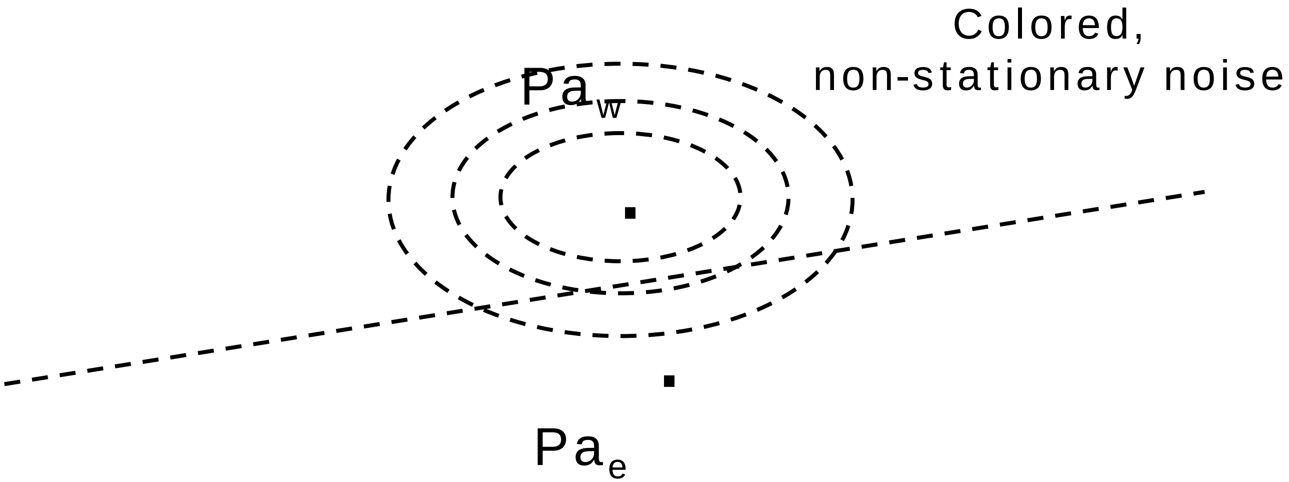
- Modern channels use PR or EPR encoding.
- The pulse shape is equalized so that Viterbi detection is only over a few sample points:

PR4
PW_{50}=2B



PR Channel Error Rate

- We look at sample space of sequences:

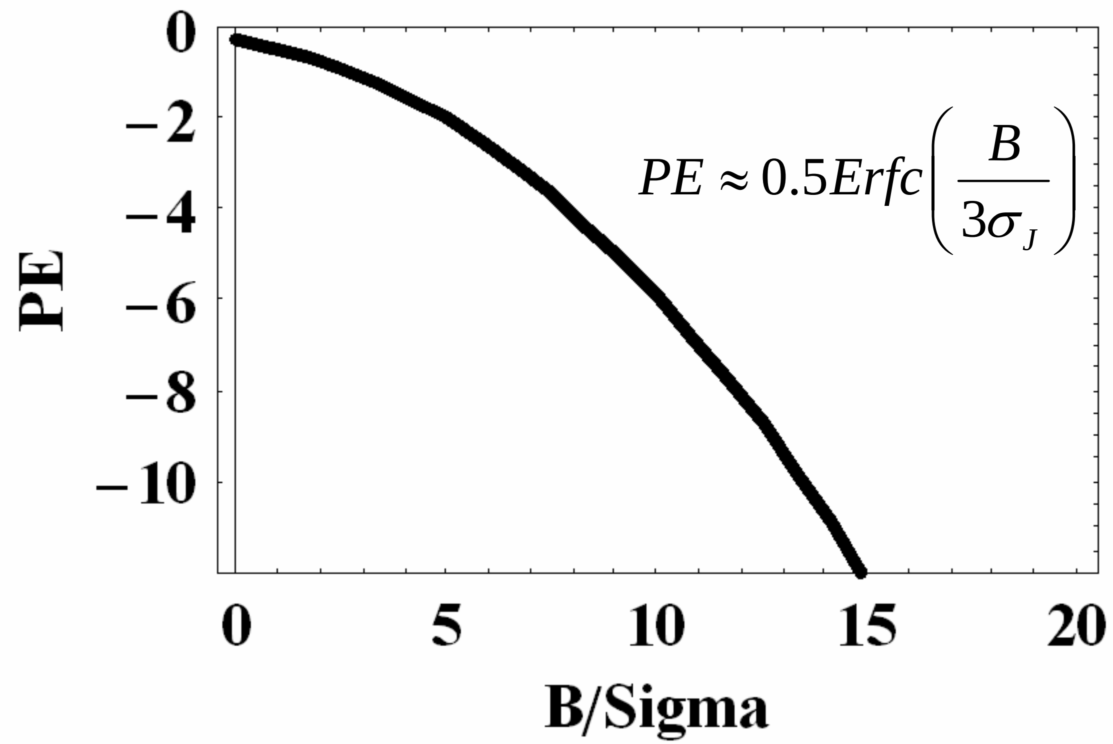


- <u>We need to find noise correlation function R!!</u>

$$BER \approx Q\left(\frac{(Pe, Pe)}{2\sqrt{(Pe, RPe)}}\right) \qquad Pe = Pa_e - Pa_w$$

Jitter Error Rate

- If we assume Gaussian jitter noise with variance σ_J :

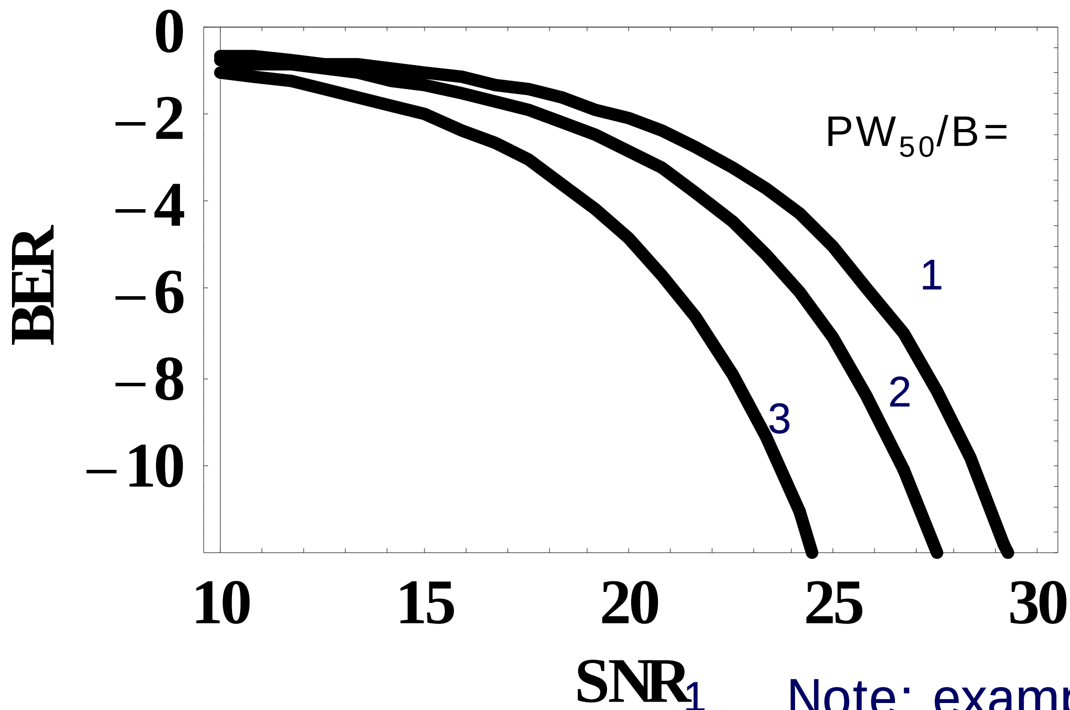


- 10% jitter yields about 10^{-6} BER!!

Simple BER for a PR4 channel

- Simple relation (Long. or Diff. Perp.)

$$BER_1^{Long} \approx Q\left(\sqrt{\frac{\pi}{36} SNR_1^{Long}}\,\frac{B}{PW_{50}}\right) \qquad \left(\approx \frac{1}{2}\mathrm{erfc}\left(\frac{B}{3\sigma_J}\right)\right)$$



Note: example where BER is <u>not</u> directly related to SNR!

BER Example Including Electronic and Surface Roughness Noises

$$BER \approx Q\left(\frac{1}{\sqrt{\dfrac{36\gamma}{\pi SNR_{jitter}} + \dfrac{17.5}{SNR_{elec}} + 2F\left(B\right)\dfrac{\sigma_d^2}{B^2}}} \right)$$

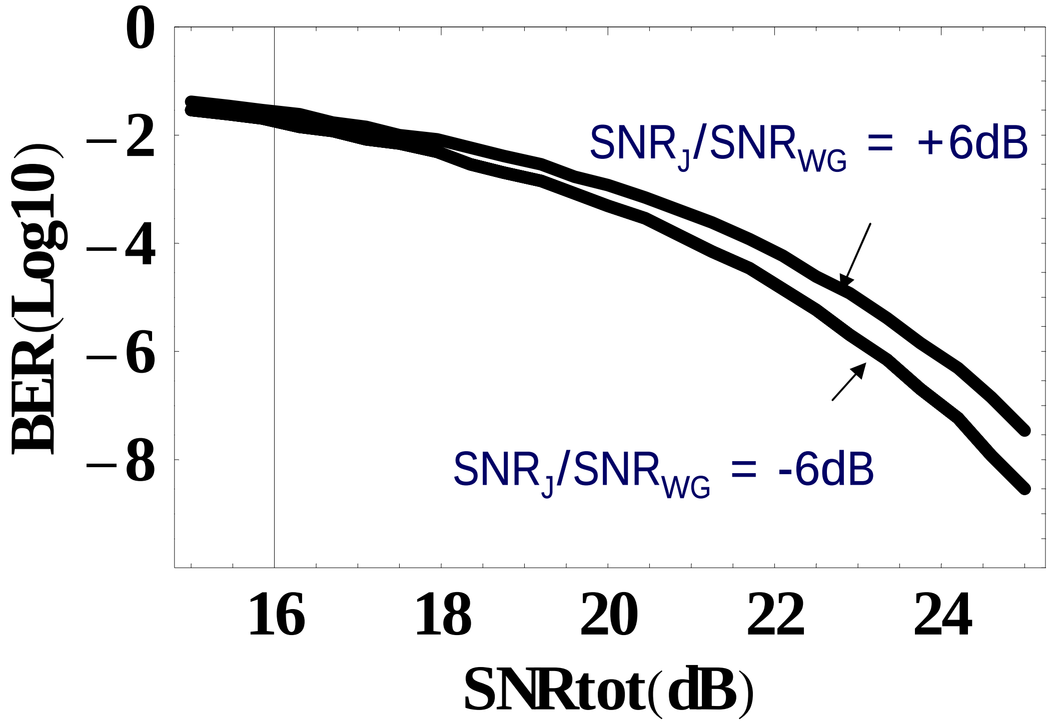
F(B) depends on rms surface roughness and texture correlation distance. γ = PW_{50}/B

"Error rate analysis of partial response channels in the presence of texture noise."

X. Xing and H. N. Bertram. IEEE Trans. Magn. 35 (3), p. 2070-2079, May 1999.

BER versus Total SNR

- Assume SNR is comprised of only Transition Jitter and Background (electronic) Noise.

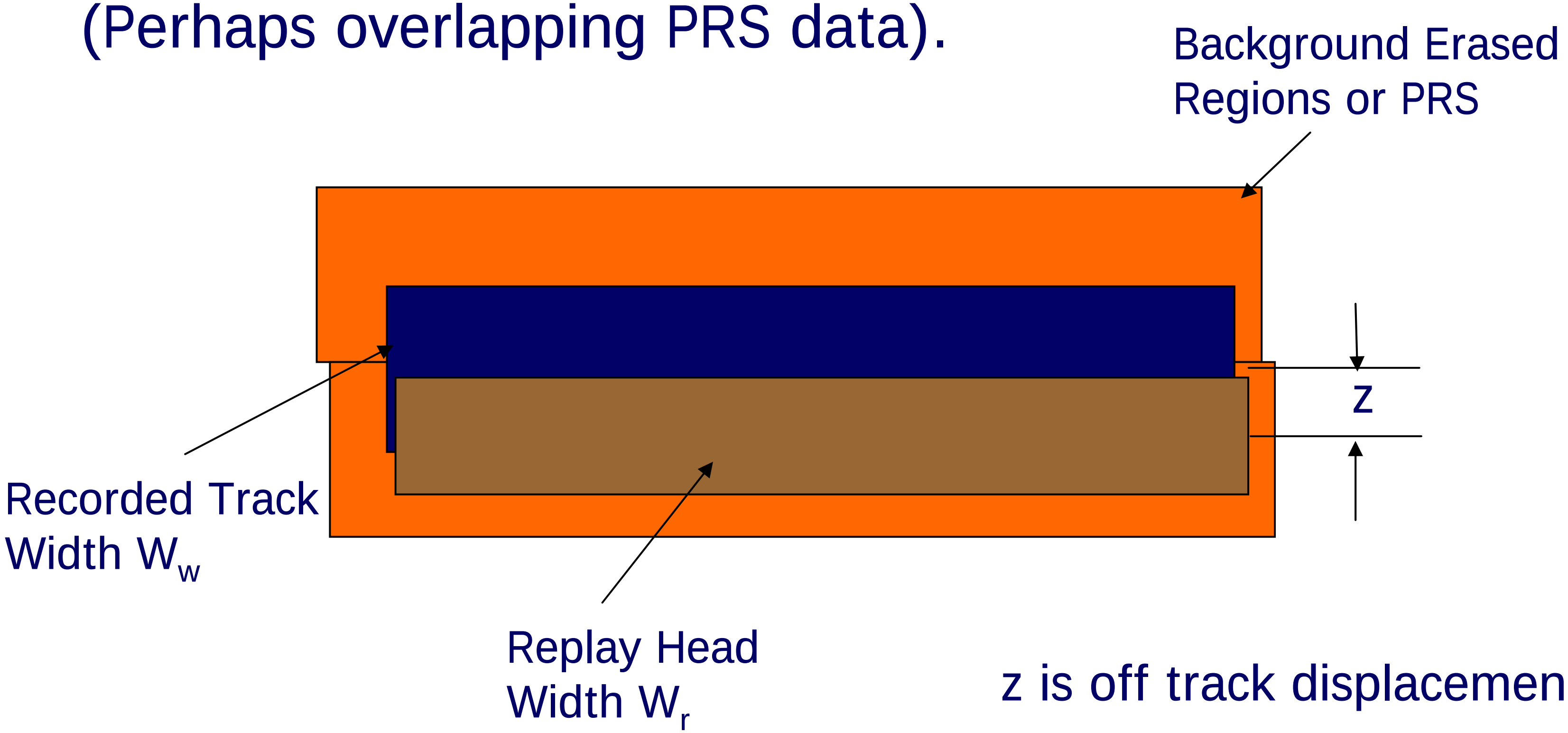


Note: (1) Again BER does not depend solely on total SNR.
(2) For a given SNR total, better to be dominated by AWGN than Transition Noise!

Off Track Effects

Bathtub Curve

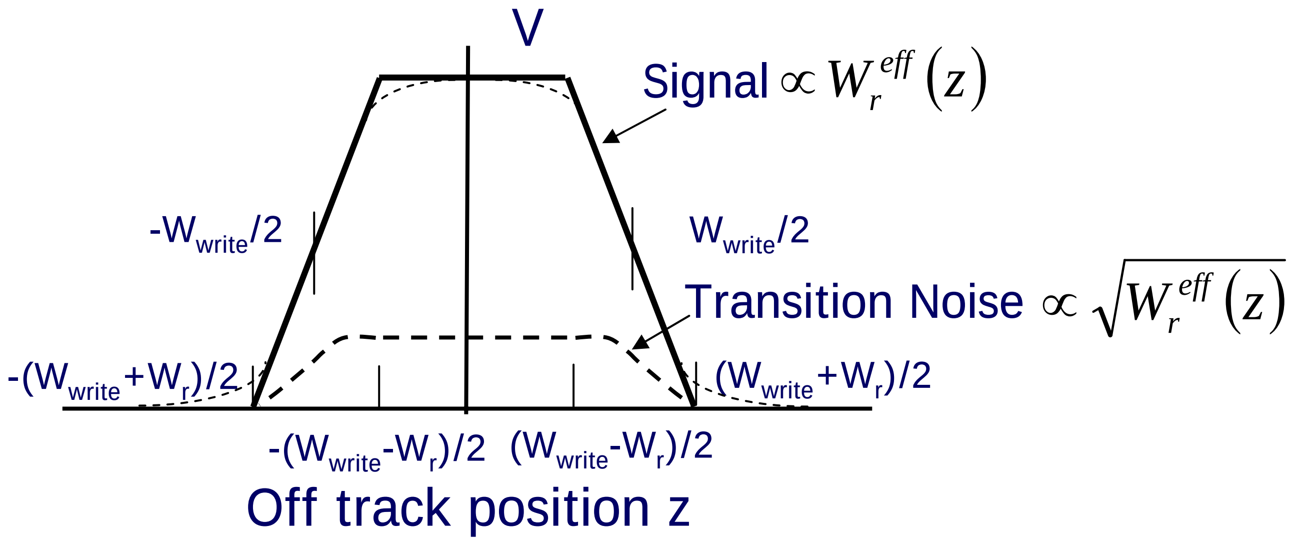
- Record a single track over a uniform background (Perhaps overlapping PRS data).



z is off track displacement

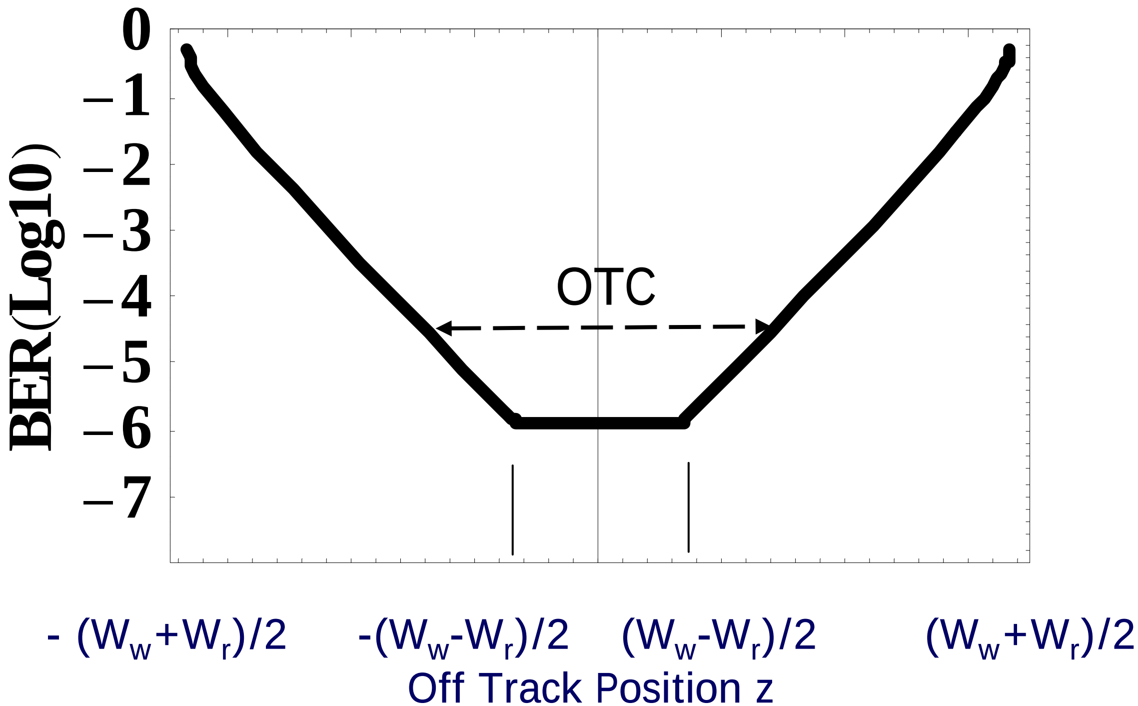
Off Track Effects (cont.)
Bathtub Curve

- Signal and Transition Noise Voltages versus off track position:



Off Track Effects (cont.)
Bathtub Curve

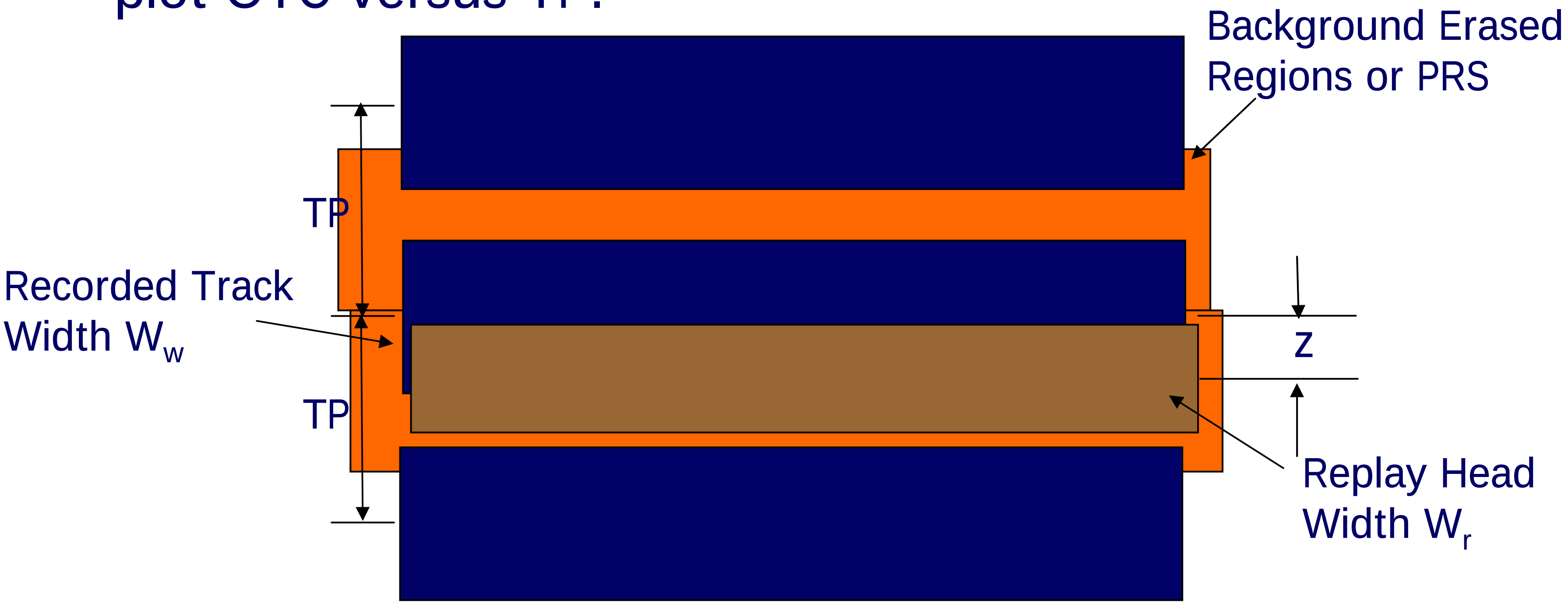
- BER versus off track position:



Off Track Capability (OTC) is the distance off track that the read head may go before the BER exceeds a certain amount (e.g. $10^{-4.5}$).

"747" or Squeeze Curve

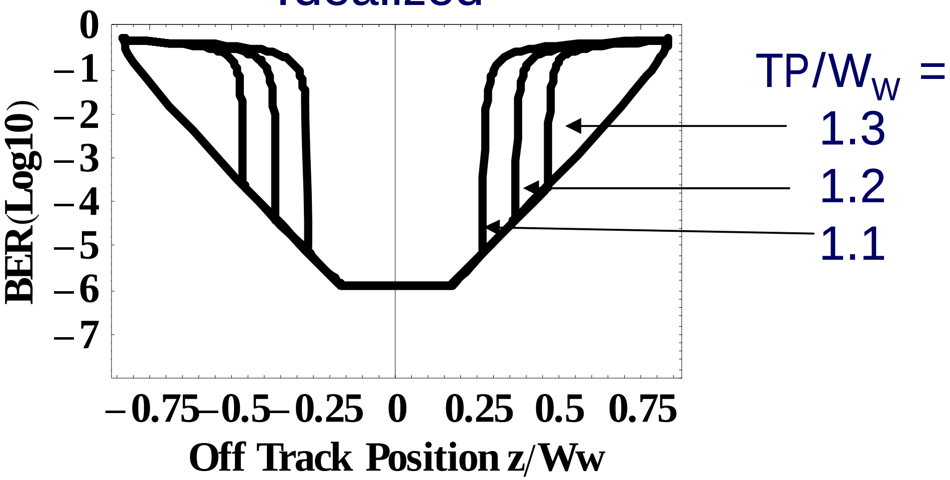
- We record adjacent tracks at a given track pitch TP and plot OTC versus TP.



z is off track displacement, TP is cross track center to center distance between adjacent tracks.

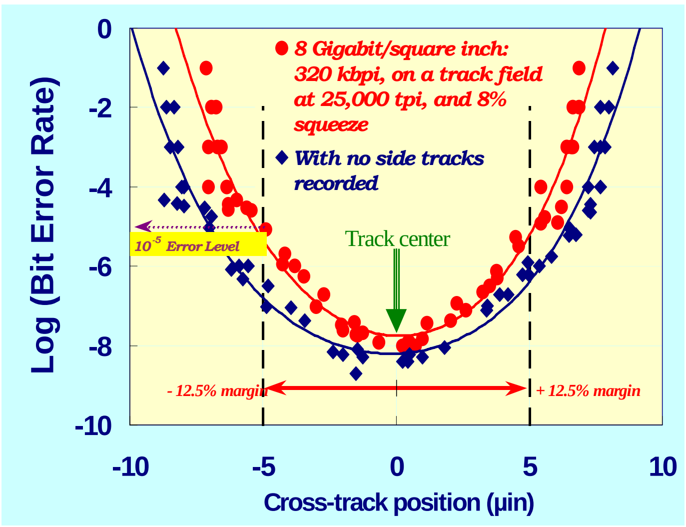
Bathtub Curves (cont.)

Idealized

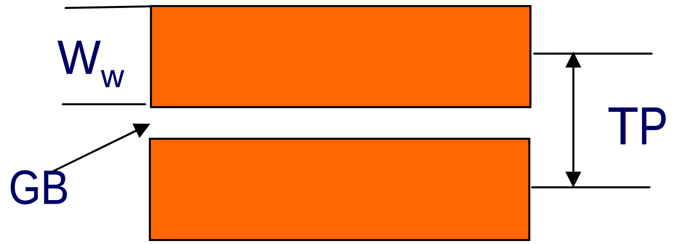


Assumes $W_r = 2/3 W_w$

Some old data

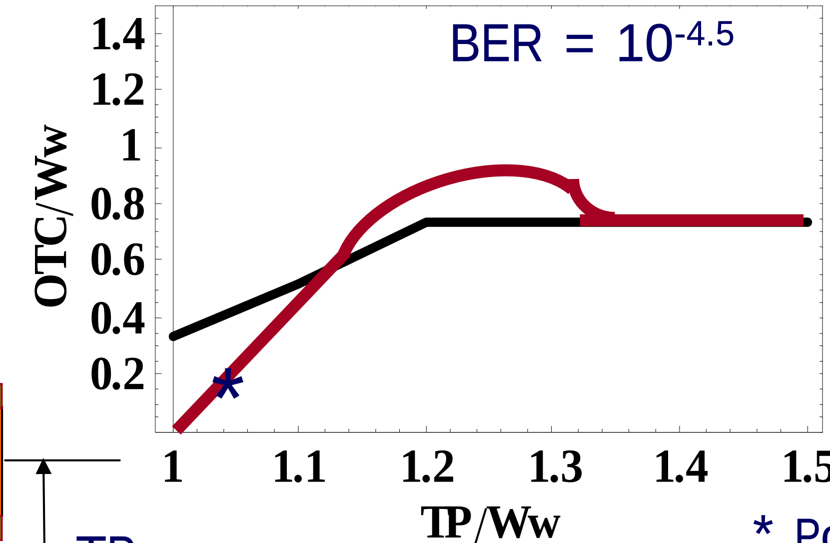


E.G For TP 136nm, W_w = 90nm,
Guard Band GB = 46nm:
TP/W_w = 1.5 => $10^{-4.5}$ BER Limited by
Off track OTC for isolated track!



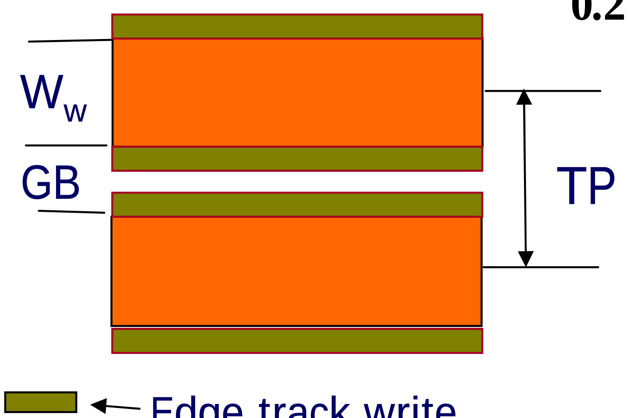
Squeeze of "747" curve (cont.)
(idealized)

Squeeze or "746" Curve is OTC versus TP at Fixed BER



Assumes $W_r = 2/3 W_w$

* Possible operating point



Edge track write
~ head-SUL spacing
for Perp.

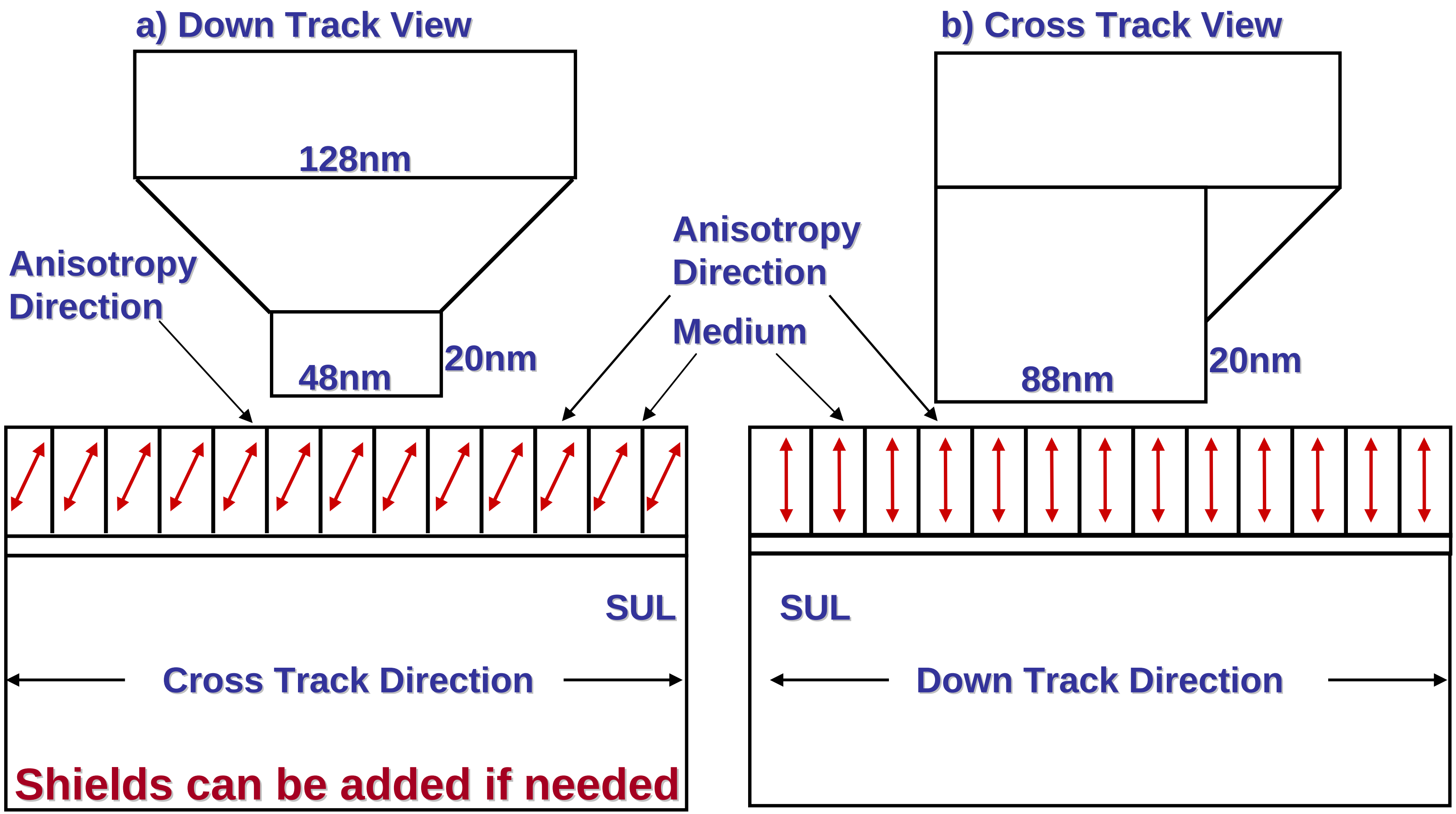
"747" is "Red Curve" with a little increase in OTC due to write head side writing/erasure (increase not always seen).

But multipass adjacent track erasure may Dominate at high densities!

Multipass Edge Track Erasure (TP Limit)

Tilted Perpendicular Recording

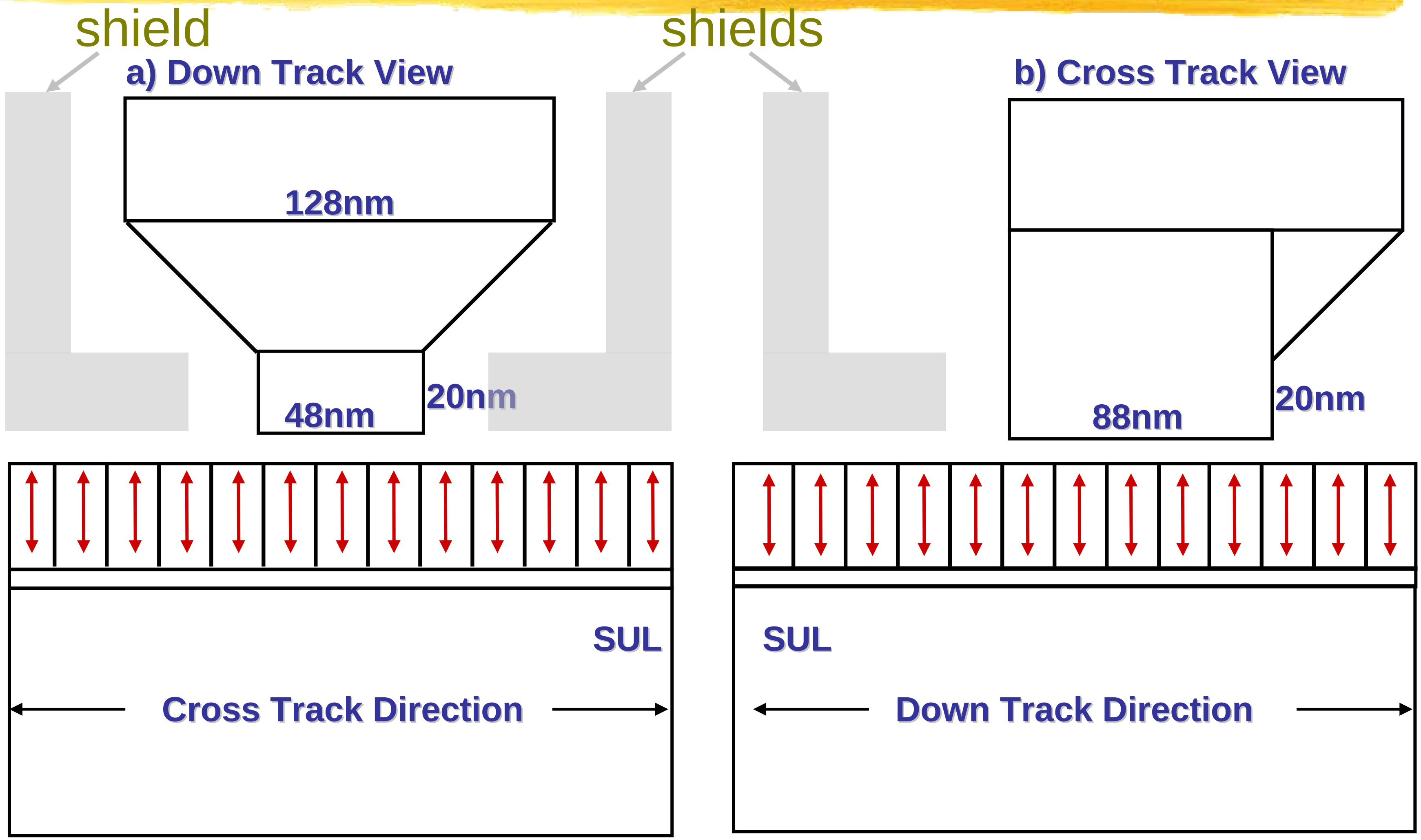
3 side tapered pole with small throat height (TH<TW<PT)



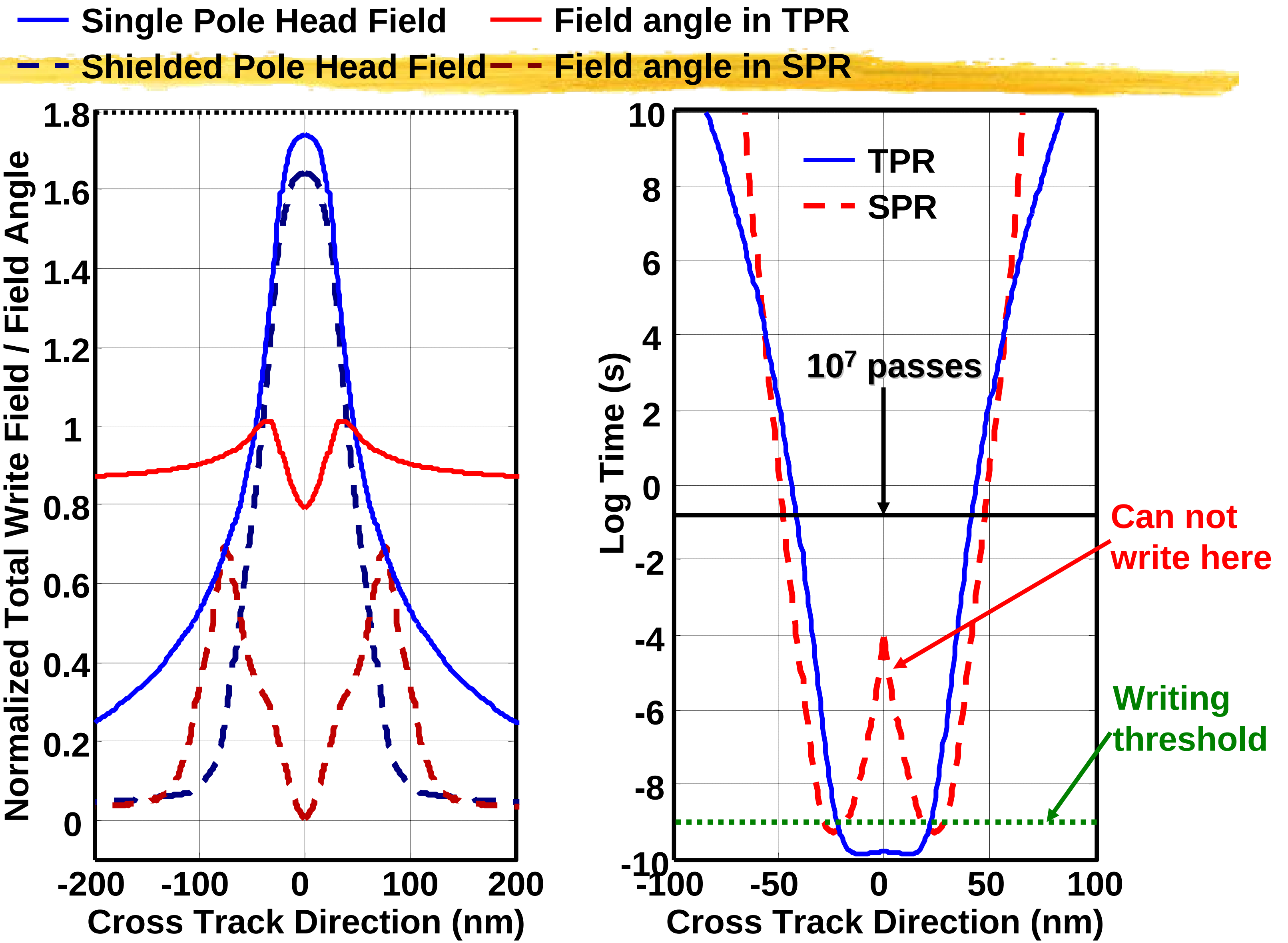
Multipass Edge Track Erasure (TP Limit)

(Shielded) Perpendicular Recording

By Mike Mallary

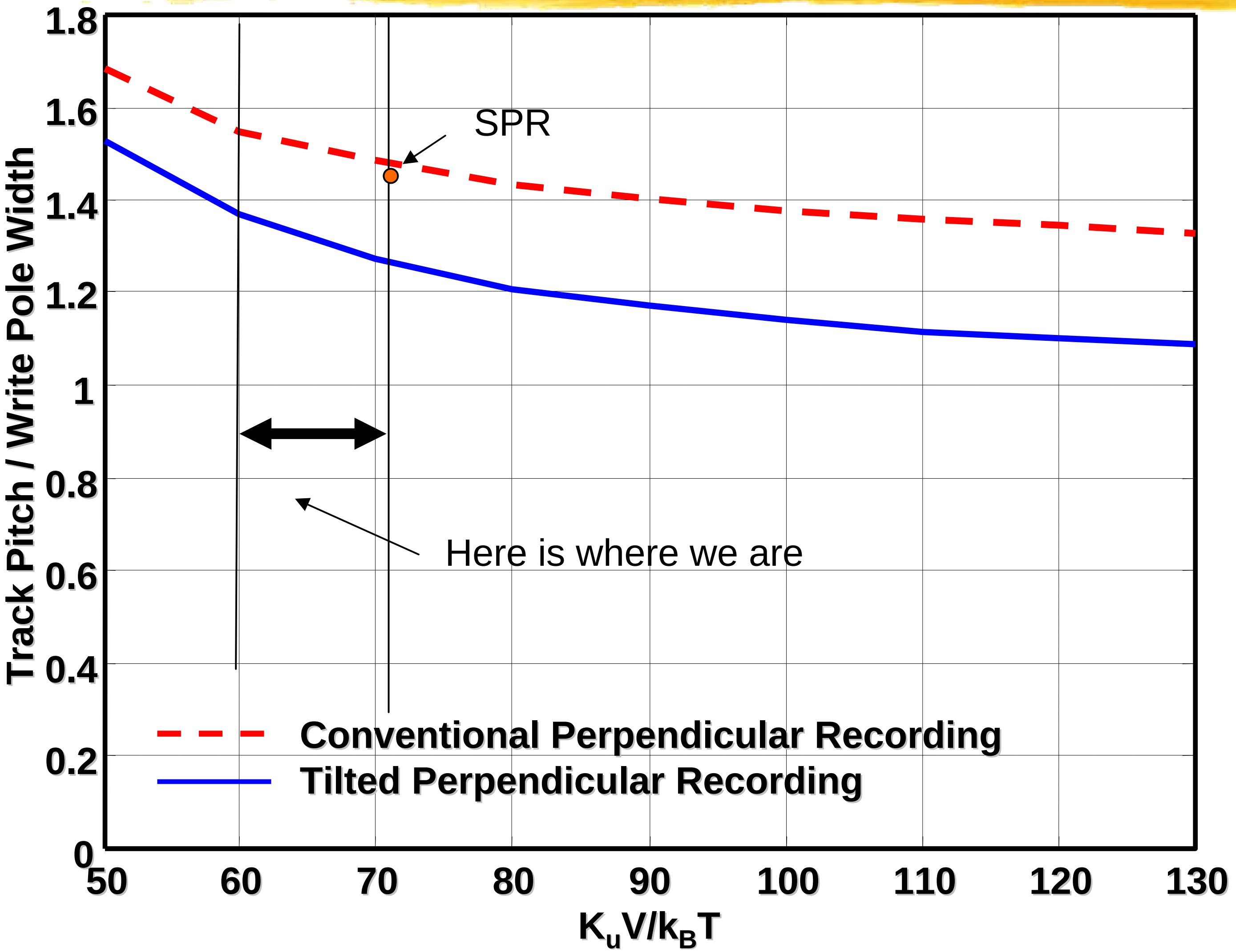


Track Edge Effect in TPR & SPR



Guard Band vs. Medium K_UV/k_BT

Probably dominant criterion for TP/W_w at very high densties



Pseudo Random Sequences

- Record random sequence of digital information (e.g. 01101110010100...) with basic minimum time window ("Pseudo" since sequence is finite). Plot the spectrum:

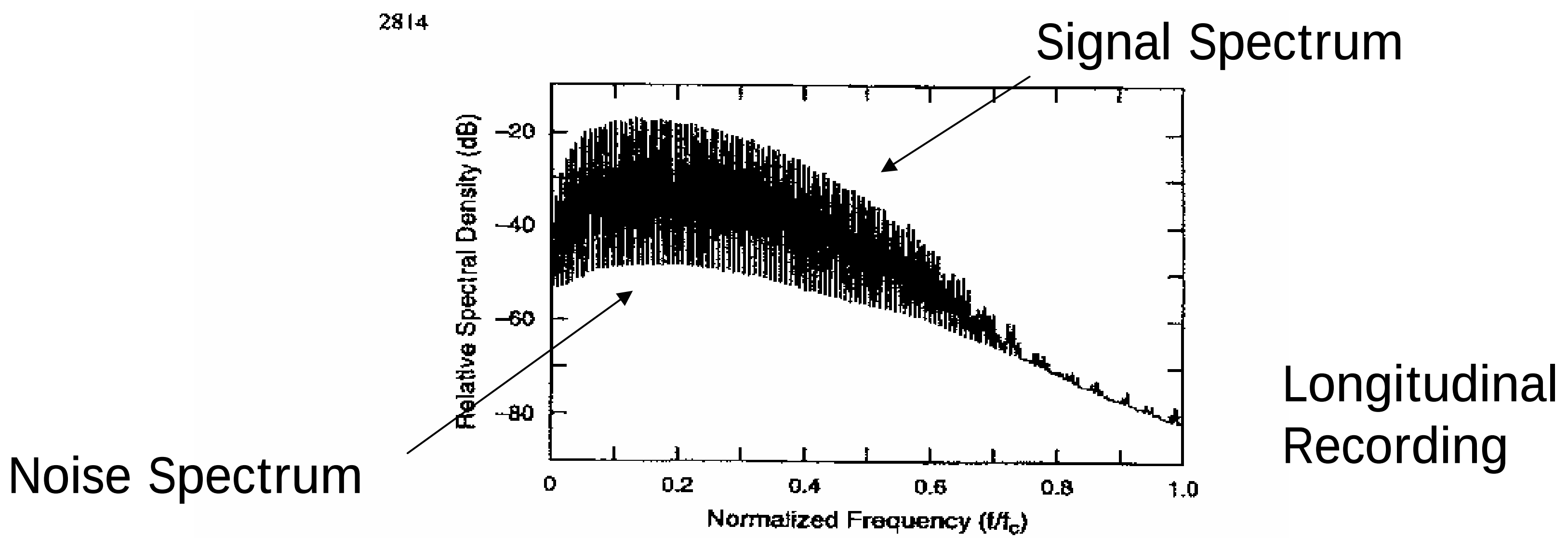


Fig. 9. Spectrum of readback signal from 127-bit pseudo-random sequence after low pass filtering. Clock frequency is f_c = 31.5 MHz. Taken from [9]. Courtesy of T. D. Howell, © 1990 IEEE.

Pseudo Random Sequences

Advantages and Uses

- Get full channel response:
  - NLTS
  - Edge track effects
- Channel equalization is clear
- “Bottom” envelope is noise spectrum
- Can give total BER since all patterns are recorded
- Mathematical manipulation is easy: (get series of voltages):
  - “Transition Noise Analysis of Thin Film Magnetic Recording Media,” B. Slutsky and H. N. Bertram. IEEE Trans. Magn., 30 (5), p. 2808-2817, September 1994.

Part VIII. System Density Limit Considerations

Essential Argument to Determine a Density limit

- We desire the highest possible density for an acceptable system Error Rate.
- Since the BER is dominated by transition noise, with all else constant the BER increases with increasing density.
- This can be countered by simultaneously decreasing the transition parameter “a” and the cross track correlation width “s_c”.
- Sometimes SNR is used as a criterion, but the final BER is preferable.

Density Limit Argument (cont.)

- Reducing the grain diameter causes thermal instability.
- Increasing the grain coercivity or anisotropy counters this effect, but increases are limited by record head saturation.
- This thermal limit gives a density limit for a given SNR. Higher densities can only be achieved by sacrificing SNR and thus BER.

Essential Argument to Determine a Density limit (cont.)

- Here we will use a simple expression for the BER in a channel that has both transition noise and white Gaussian background noise. The background noise will include uniform magnetization (DC) noise, electronics noise and GMR thermal noise.
- First we shown how varying the transition noise jitter for various levels of background SNR affects the BER.
- Second we will fix the BER and plot achievable density versus transition noise for various background noise levels.

Essential Argument to Determine a Density limit (cont.)

- Plots of achievable areal density versus noise gives us a "Design Curve".
- With the Design Curve we can specify medium and head parameters in order to achieve the desired Density.
- We will also use the Design Curve to compare Longitudinal, Perpendicular and Advanced Perpendicular recording.
- To achieve pour design goal we must design media and heads so that the transition parameter "a" and the cross track correlation width "s_c" are sufficiently reduced.

Error Rate Estimate

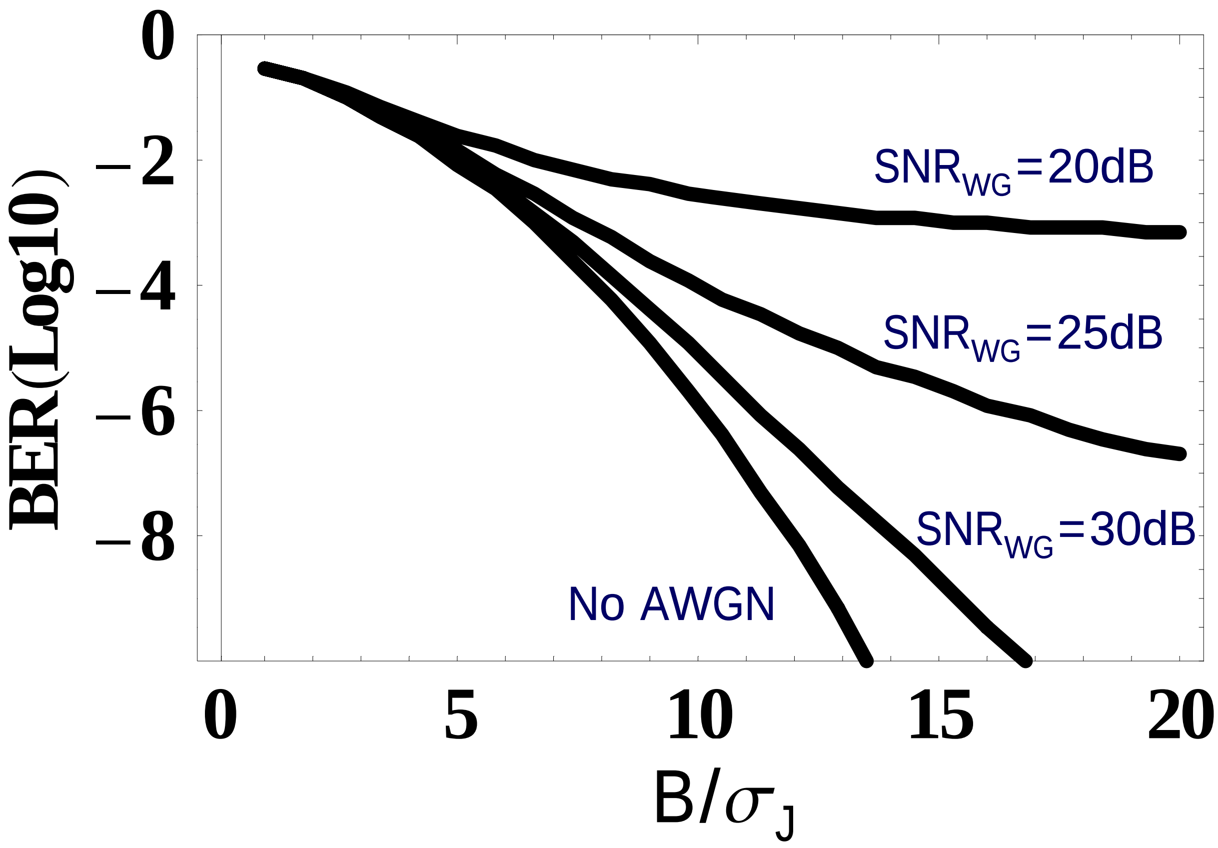
- From before, for a PR4 channel (and longitudinal recording):

$$BER \approx Q\left(\frac{1}{\sqrt{\frac{36\gamma}{\pi SNR_{jitter}} + \frac{17.5}{SNR_{elec}} + 2F(B)\frac{\sigma_d^2}{B^2}}}\right)$$

- We will use this in general, neglect surface roughness, use SNR_{WG} instead of SNR_{elec} and write Jitter SNR in terms of variance:

$$BER \approx 0.5erfc\left(\frac{1}{\sqrt{\frac{9\sigma_J^2}{B^2} + \frac{17.5}{SNR_{WB}}}}\right)$$

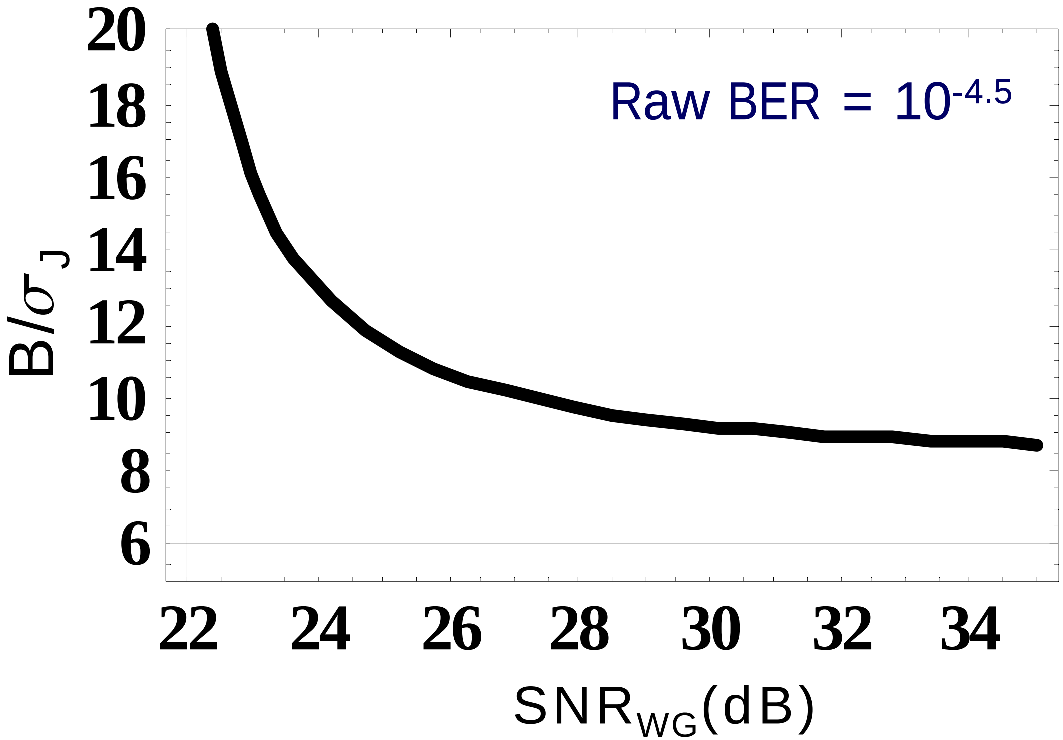
BER versus Transition Jitter



<-Increasing Density   Increasing Transition SNR ->

Transition Jitter versus SNR_{WG}

"Design Curve"



Head – Medium Design

- Let us assume BER = $10^{-4.5}$:
  - Longitudinal: SNR_{WG} = 26dB => B/σ_J=11
  - Perpendicular: SNR_{WG} = 29dB => B/σ_J=9

- Suppose we want at 200 Gbit/in^2 product.
  - Assume OTC curves give BAR = 6
  - Thus we have B ~ 23nm, TP ~ 136nm and (assume) W_r ~ 68nm.

- The jitter variance requirement is:
  - Longitudinal: σ_J=2.09nm
  - Perpendicular: σ_J=2.56nm

Medium Design (200Gbit/in^2)

- For a given σ_J with W_r = 68nm, using $\sigma_J = \sqrt{2a^2 s_c / W_r}$:
  - Longitudinal (σ_J = 2.09nm) $a^2 s_c$ = 149 nm^3
  - Perpendicular: (σ_J = 2.56nm) $a^2 s_c$ = 223 nm^3

- To achieve a workable medium we need a and s_c to be small and controlled by the grain diameter. The grain diameter is set by thermal decay. Let us assume that a sufficient thermal barrier is:

$$KV \approx 60 k_B T$$

- We want the grain in plane diameter as small as possible. Thus we want K as large as possible.

Medium Design (cont.)

Minimum Grain Diameter

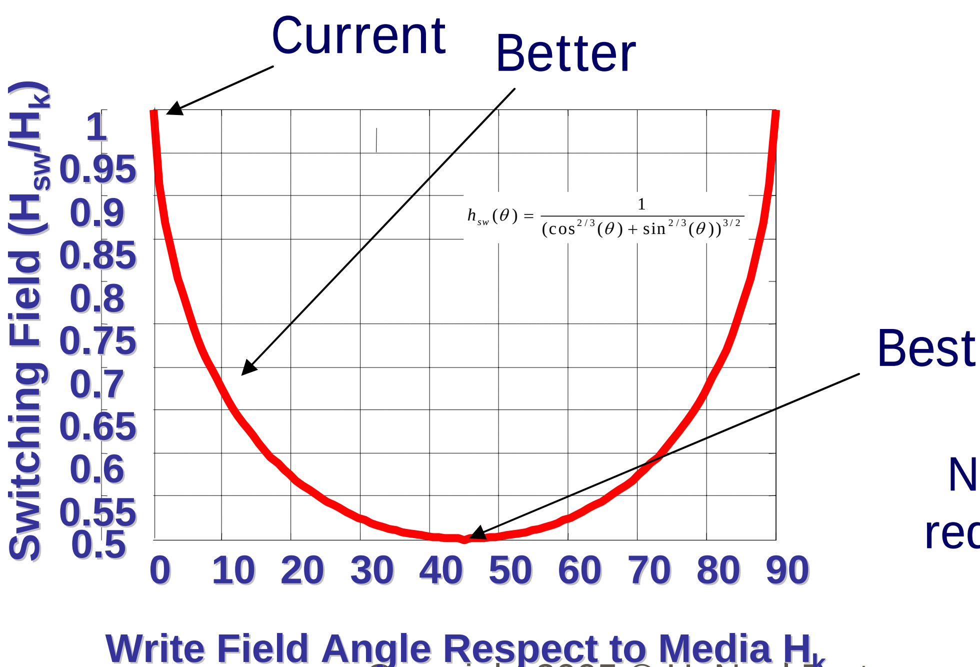
- The anisotropy field is $H_K = 2K/M_s$. Let us assume that we require a maximum field from the head $H_{headmax}$ for overwrite In that case:

$$K = \frac{H_K M_s}{2} = \frac{M_s}{2}\frac{H_K}{H_{OW}} H_{head\,\mathrm{max}}$$

- The value of H_K/H_{OW} will depend on the mode of recording (Longitudinal, Perpendicular, Advanced Perpendicular.

Head-Medium Design for Increasing K

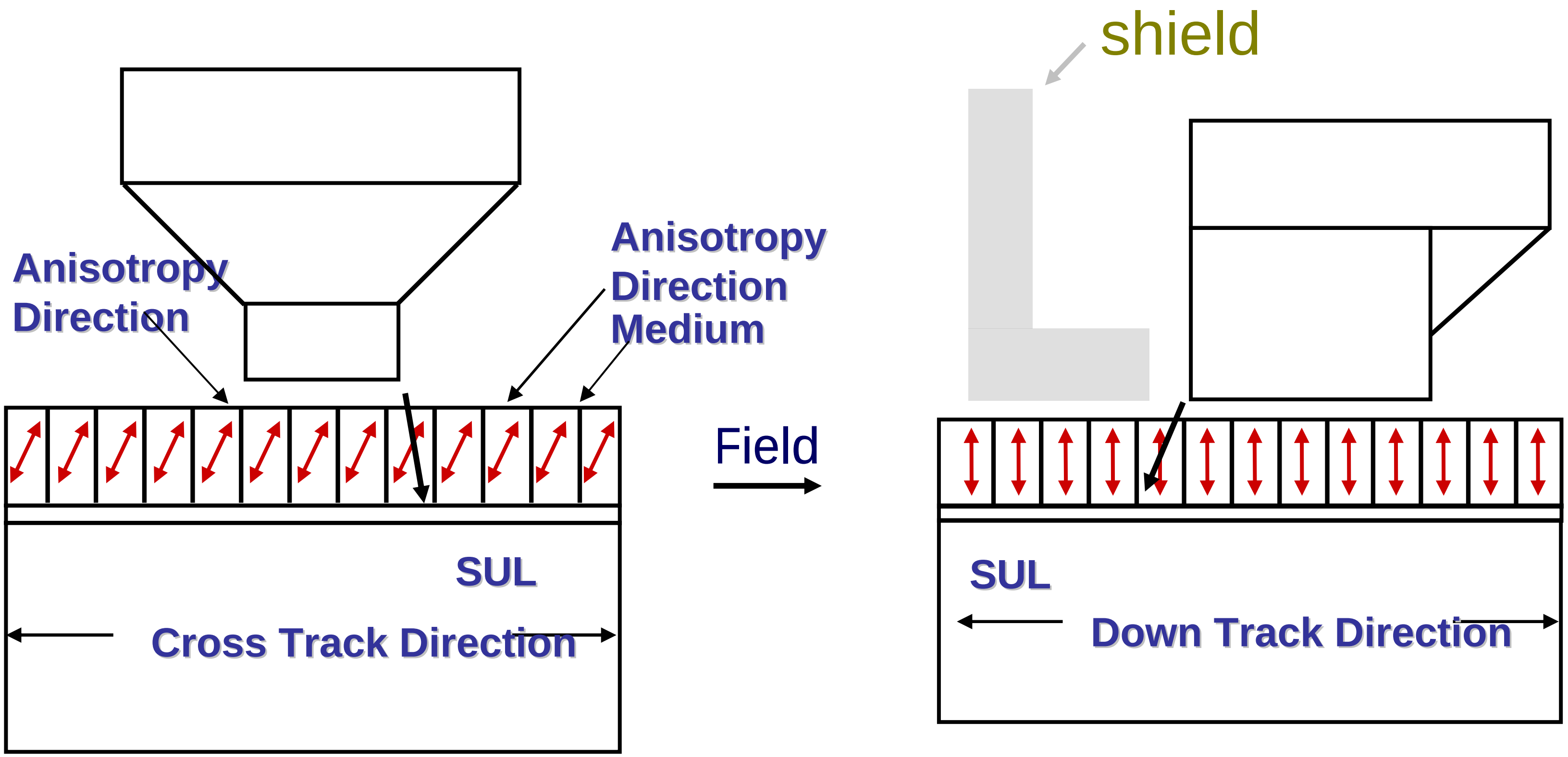
- We have a fixed maximum write (or over write field), but we want K (or $H_K = 2K/M_s$ as large as possible).
- If particle K axis is parallel to field then $H_{write} \sim H_{K.}$



Note: Overwrite conditions reduce this effect somewhat.

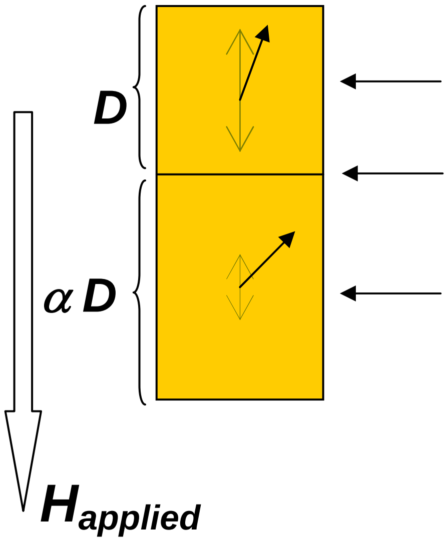
Head-Medium Designs for Increasing K (cont.)

- Tilted Perpendicular Recording: Grow media with grain anisotropy axes at 45° to field: $H_K \sim 2H_c$.
- Use conventional perpendicular media and angle the head field (Down Track Shield Pole Head): $H_K \sim 1.5H_c$



Medium Design for Increasing K

- Composite Medium



Very Hard Material: H_K ~ 100kOe, M_s ~ 200 emu/cc

Exchange coupling layer

Very Soft Material: H_K ~ 0kOe, M_s ~ 1000 emu/cc, $\alpha \sim 2$

- Medium reverses non-uniformly: $H_{keff} \sim 2H_c$

- A very promising candidate for ultra high density recording. (Good track edge performance).

Medium Design (cont.)

Minimum Grain Diameter

- Let us assume that the maximum recording fields are (Head B_s = 2.4T):
  - Longitudinal: $H_{headmax}$ = 15kOe (Ring Head)
  - Perpendicular: $H_{headmax}$ = 18kOe (SUL-Probe)

- Estimates for the values of H_K/H_{OW} are:
  - Longitudinal: $H_K/H_{OW} \sim 0.85$
  - Perpendicular: $H_K/H_{OW} \sim 0.85$
  - Perpendicular (with down track shield): $H_K/H_{OW} \sim 1.5$
  - Composite or Tilted Perpendicular: $H_K/H_{OW} \sim 1.85$

- Use all this combining:

$$K = \frac{M_s}{2} \frac{H_K}{H_{OW}} H_{head\,\max} \qquad KV = 60 k_B T$$

Medium Design (cont.)

Minimum Grain Diameter

- Lets determine the minimum grain diameter.
  - Longitudinal ($V = D^3$):

$$D_L = \left(\frac{120 k_B T}{M_s H_{head\,\max}} \frac{H_{OW}}{H_K} \right)^{1/3}$$

  - Perpendicular ($V = tD^2$):

$$D_P = \left(\frac{60 k_B T}{M_s H_{head\,\max}} \frac{H_{OW}}{H_K} \right)^{1/3} \quad (t/D = 2)$$

- Assuming Ms = 500 emu/cc, T = 375K:
  - Longitudinal: $D_L \sim 9.9$nm
  - Perpendicular: $D_P \sim 7.4$nm
  - Perpendicular (with down track shield): $D_P \sim 6.1$nm
  - Composite or Tilted Perpendicular: $D_P \sim 5.7$nm

Medium Design (cont.)

Relation of Grain Diameter to Transition Parameters

- Lets us assume that the cross track correlation width is close to the grain diameter (exchange and magnetostatics and distributions affect the relation):
  - In all cases $s_c \sim 1.0D$
  - Probably optimistic!
- The transition parameter must be (from slide 221):
  - Longitudinal: a ~ 3.9nm
  - Perpendicular: a ~ 5.5nm
  - Perpendicular (with down track shield): a ~ 6nm
  - Composite or Tilted Perpendicular: a ~ 6.3nm
- Can we do this??? Very difficult for Long. a ~ D/3

Head - Medium Design (cont.)

Can we reduce "a" relative to grain size?

- Write head optimization:
  - Maximum field: Bs ~ 2.4 probably maximum, Taper poles?
  - Maximize field gradient: Reduce d, t, s.

- Medium optimization:
  - Reduce all distributions (D, H_k)
  - Increase M_s (but hurts overwrite)
  - Increase (a bit) intergranular exchange (good for OW too)
  - Improve medium microstructure: Composite media
    - "a" may be controlled now by microstructure rather than head geometry!

- Critical to measure "a" and "s_c" to evaluate candidate media.

Medium Parameter Summary

200 Gbit/in^2

	BAR	B (nm)	W_r (nm)	SNR WG (dB) (PRS)	a^2s (nm)^3	H_{head} max (kOe)	H_K/H_{OW}	D (nm)	s_c (nm)	a (nm)	a/D
Long	6	23	68	26	149	15	0.85	9.9	13	3.9	0.39
Perp	6	23	68	29	223	18	0.85	7.4	9.6	5.5	0.74
Perp-SPH	6	23	68	29	223	18	1.5	6.1	7.9	6	0.98
Perp Tilted /Composite	6	23	68	29	223	18	1.85	5.7	7.4	6.3	1.1

Head Design

- Assume optimum channel equalization of:
  - Longitudinal: PW_{50} ~ 2.5B = 57.5nm
  - Perpendicular: T_{50} ~ 1.25B = 29nm

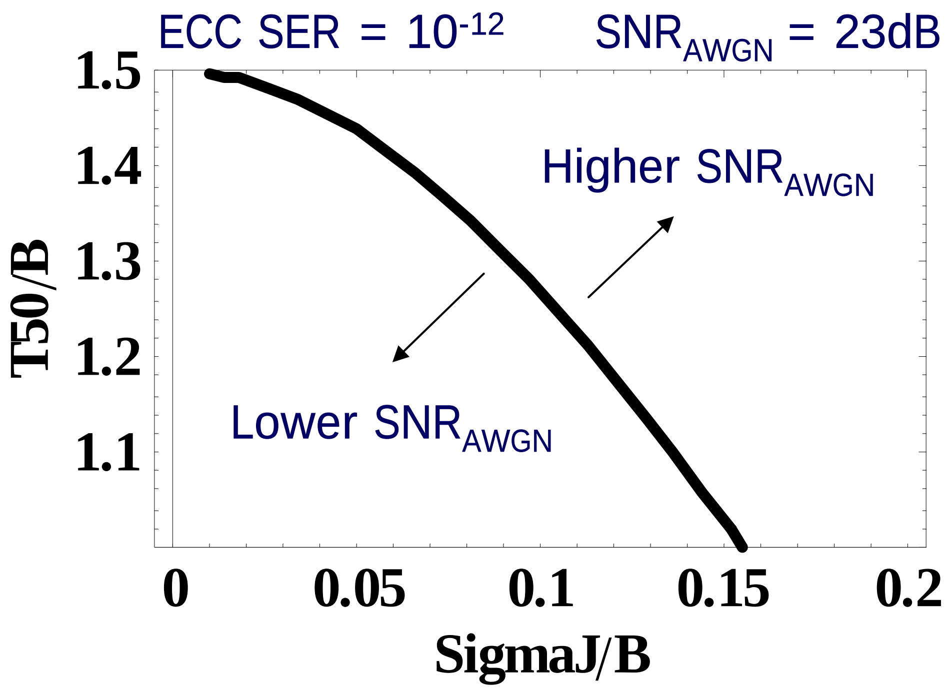
- Assume head-medium (net) spacing d = 15nm, transition parameter a = 5nm, GMR sensing element thickness t_e = 2nm.

- Using simple T_{50} approximation expression gives g = 25 (for d = 20nm), g = 40nm (for d = 15) or Shield to Shield spacing of about 50, 80 nm, respectively. (Perhaps need CPP head?

- Of course need B_s ~ 2.4T and suitably low conductivity.

More Sophisticated Design Curves

- The next step in design is to choose SER and use ECC.
  - Choose areal density and estimate BAR to find B
  - Measure SNR_{AWGN} (as an estimate to all other noises)
  - Find T50 and σ_J from design curve



  - Work in progress at CMRR-UCSD and INSIC

Patterned Media

- Thermal effects give a limit to conventional recording.
- Patterned media records a ”bit” of information a single larger “grain”.

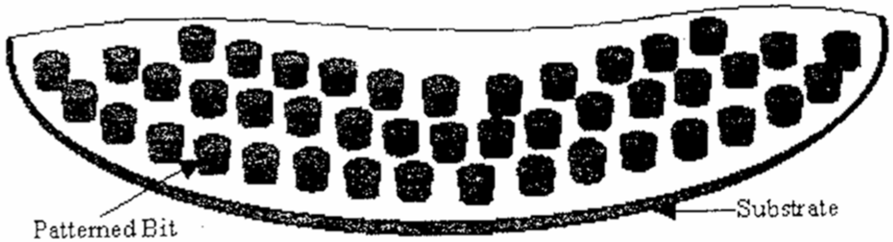


Fig. 7.1. Patterned hard disk

- For a review see: G. Hughes, “Patterned Media”, in *The Physics of Ultra-High-Density Magnetic Recording*, edited by PLumer, van Ek, Weller, pgs 205-229. Springer (2001)
- Figures here are from this reference.

Patterned Media (cont.)

- Research is under way to develop media.

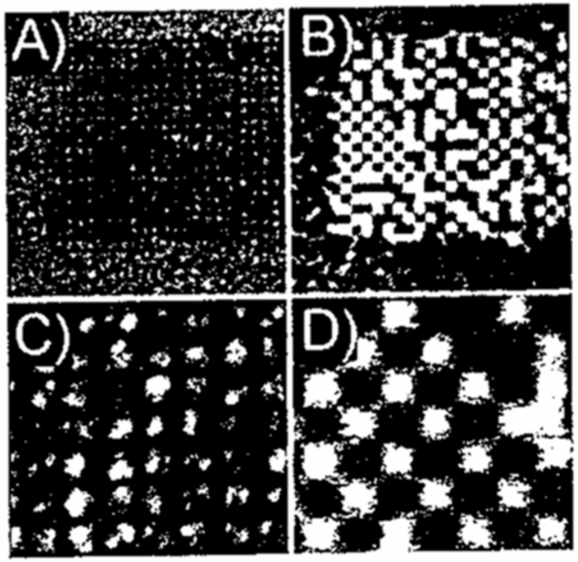
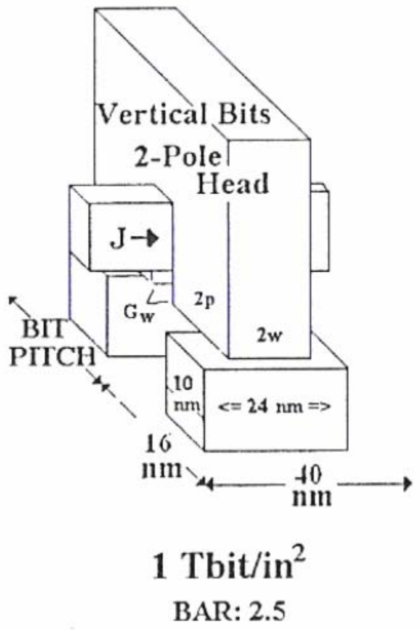


Fig. 7.2. 2 × 2 mm patterned region; AFM (A) and MFM images (B); higher magnification images (C) and (D), respectively. Pattern period is about 100 nm, made with a 60 s exposure to a 1 pA 30 keV beam (courtesy IBM Almaden Research Center) [9]

Patterned Media (cont.)

- Write process configuration



- Can inexpensive media with circular tracks be made?
- Can adjacent track erasure be controlled?
- Can write head heads be manufactured?

System Advancement

Density	Medium	Write Head	Read
< 125 Gbit/in^2	Longitudinal	Ring	GMR
125 to 500 Gbit/in^2	Perpendicular	Shielded Pole	GMR/CIP/CPP/ Spin Tunnel Junctions
500 to 800 Gbit/in^2	Composite/ Tilted	Shielded Pole/Simple Pole	CPP/ Spin Tunnel Junctions
> 800 Gbit/in^2	Patterned	Narrow Tip?	Spin Tunnel Junctions/ MFM ?

Exercises

by Section

Problems "System Overview" Section I.

- Design a write pole width and read GMR active element width (nm) for an areal density of 200 Gbit/in^2. Examine possible BAR's = 4,6,8. What are the linear densities (kfci)? What are the track densities (ktpi)? (Assume $W_r = 0.66W_w$, $W_w = 0.66TP$).

- Suppose that the system will allow a 15%, 20% percentage jitter. Work out the new ratios a/<D> for the last column in the Table in slide 23

Problems: “Magnetic Fields” Section II.

- Show by RHR that two identical pinned layers on either side of the sensing layer with equal currents in the same direction will cancel the fields from the pinned layers.

- Using the values from slide 32 what is the net field if there is a 10% difference in pinned layers thickness?

- Show from slide 48 that the demagnetizing field on either side of a sharp longitudinal transition at the very center is $-4\pi M$. Illustrate directions.

- Argue that the presence of an SUL near the pole face (Slide 52) doubles the field magnitude.

Problems: "Magnetic Materials" Section III.

- Calculate the domain wall thickness $\delta = \pi\sqrt{A/K}$ for bulk Permalloy with M_s = 800emu/cc, A = 2 x 10^6 ergs/cm. Assume a growth induced anisotropy of $H_k = 2K/M_s$ = 50 Oe.

- For a thin film the wall magnetization rotation must lie in the film plane due to the high out of plane demagnetizing fields. What is the domain wall thickness is this case using: $\delta = \pi\sqrt{A/(2\pi M_s)^2}$

- Find the critical size(diameter) that a cubic particle will form domains by balancing the single domain magnetostatic energy with the wall energy in a single wall confuguration: $2\pi M_s^2 D^3 = \sigma D^2$ Assume for CoCrX: Ms = 500emu/cc, A = 2 x 10^6 ergs/cm, H_K= 15000 Oe.

Problems: “Replay Process” Section IV.

- Calculate the peak GMR voltage for perpendicular recording using parameters on slide 96 and W_r = 140nm, E = 0.5, t_{el} = 2nm, G_{eff} = $2g_{eff} + t_{el}$ = 180nm, d = 20nm, t = 12nm, M_r = 600 emu/cc, Ms = 800emu/cc, s = 5nm:

$$V^{o-peak} = \frac{IR_{sq}W_rE}{4h}\frac{\Delta R}{R}\frac{M_rt}{M_st_{el}}\frac{\left(G_{eff}+t_{el}\right)}{\left(d+t+s\right)}$$

  - If your result exceeds the 5-10% limit on slide 100, how much should the element thickness t_{el} be increases to compensate for the high medium M_r

- Consider a longitudinal product with PW_{50} = 80nm. Using the expression on slide 105 find the shield to element spacing g of the GMR head assuming d = 20nm, a = 15nm, t_e = 4nm. Using the expression on slide 109 find the resolution D_{50}.

Problems: "Write Process" Section V. (cont.)

- We start a series of exercises to determine the effect of head write width (process) variations on the system. We assume the current applied to the head is fixed. A write with variation gives a change in the record field applied to the head as seen in the slide 119.

- Suppose the write width varies by $\pm 10\%$. From slide 119 we can deduce that the percentage change in efficiency is:

$$\% change E = -E_o (1 - E_o) \% change W_W$$

- Use slide 120 to "estimate" (guess) the percentage change in the head field H_{gap}. Assume operating a little into saturation with (fixed) $NIE_o/4\pi M_s g = 1$. Do this for $E_o = 0.5, 0.7, 0.9$.

Problems: "Medium Noise" Section VI

- From slide 174 find the transition parameter "a" required for an areal density of 100Gbit/insq, assuming BAR = 8 and $\pi aD_{ens} = \pi a/B = 1$.

- Slide 195 is very important for understanding why longitudinal recording with give way to perpendicular recording. Suppose one can make a longitudinal medium that has been better oriented with SR (OR) = 3.73 compared to typical with SR ~ 2. At the same time assume that the intergrain boundary has been reduced from 1.5nm to 1 nm. For a grain diameter of 7nm as plotted in slide 195, what is the decrease in DC noise (in dB) compared to transition noise for this new media.

Problems: “SNR and BER” Section VII

- What is SNR_1 (foils 200-201) for perpendicular recording at 200 Gbit/in^2. Assume s_c = a =6nm, W_r/TP = 0.5 and examine:
  - BAR = 4,6,8 with $T_{50}/B = 1$
  - T_{50}/B = 1, 1.25,1.5 with BAR = 6

- Consider longitudinal recording (foils 199-200) at 200 Gbit/in^2. Assume PW_{50}/B =2.5, W_r/TP = 0.5, BAR = 6, s_c = a and plot SNR_1 versus a(nm).

Problems: "SNR and BER" Section VII (cont.)

- Lets follow slides 203-204 and explicitly plot SNR_1 versus H_k for longitudinal recording at $100Gbit/in^2$
  - Assume thermal limit of $KV = 60k_BT$, $V = D^3$, $H_K = 2K/M_s$, $M_s = 500emu/cc$ to find D versus H_k
  - Assume $a = D$, $s_c = 1.5D$, BAR = 8, $TP/W_r = 2$

- Repeat above, but plot BER versus H_k
  - Use expression on slide 217 (199 for σ_J)

- Use technique above for BER to find the effect on the BER for a $\pm 10\%$ change in W_r (Only for H_k = 18kOe).

Problems: "System Design" Section VIII. (Cont.)

- Let us look at the effect of replay voltage variations on the raw BER.

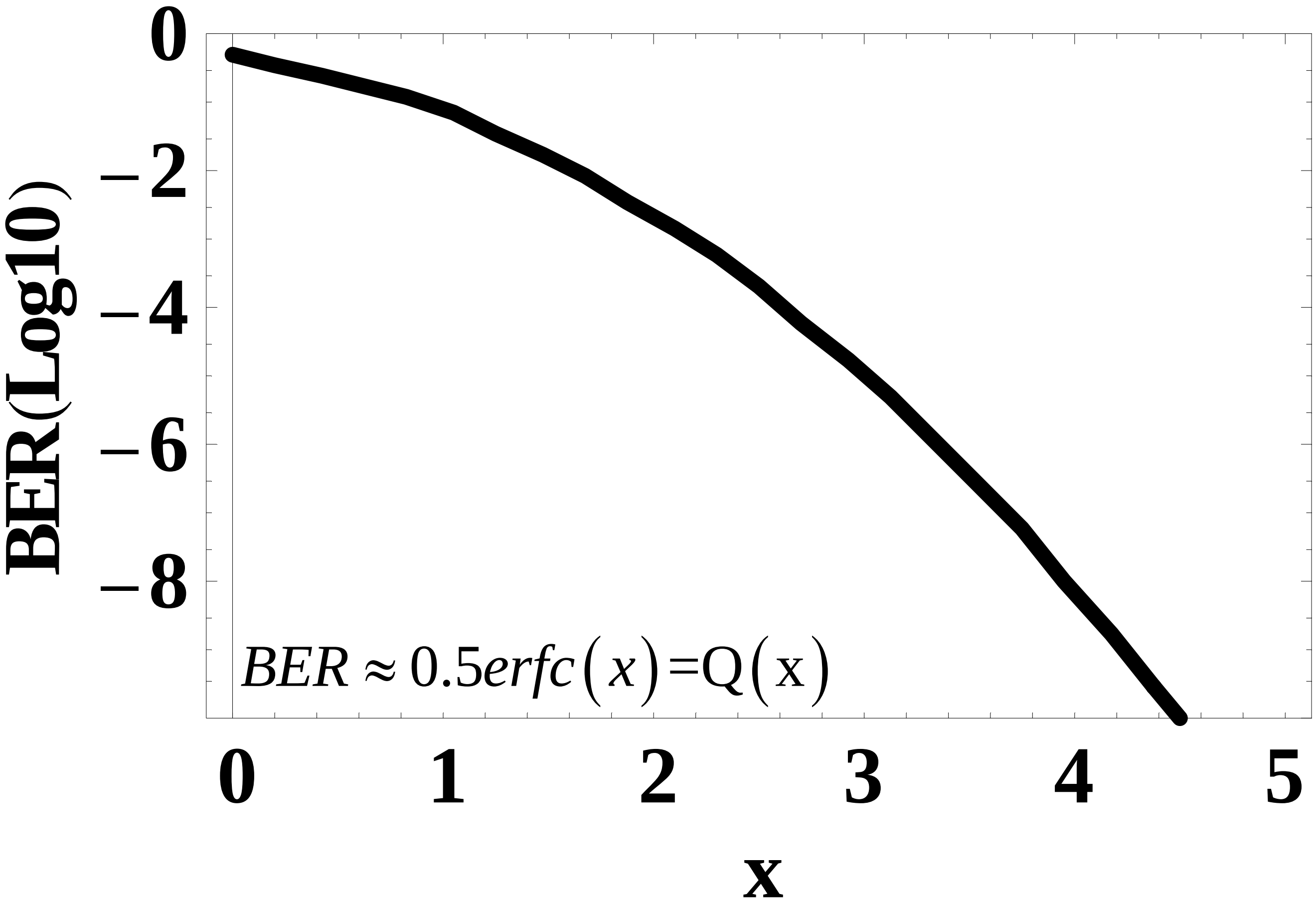
- Lets us assume that the relative jitter is fixed at $B/\sigma_J = 10$. On slide 239 you can see the raw BER for SNR = 20, 25 and 30 dB.

- If the voltage fluctuates by ±5% how much does the SNR change??
  - Use SNR(dB) = $10\mathrm{Log}_{10}(V_{sig}/V_{noise})$.
  - This gives: change SNR (dB) = Percentage change $V_{sig}/5$
  - Do this for SNR = 20, 25 and 30 dB using slide 239

- Find the BER changes. What happens if the signal voltage fluctuates by ±10%?

Problems: "System Design" Section VIII. (Cont.)

- For the problem on the previous pages you can use slide 238. However a general curve is:



Problems: "System Design" Section VIII. (Cont.)

- We will use the expressions on slide 238 (neglecting surface roughness) to compare longitudinal recording with different degrees of orientation. Use slide 194 assuming the intergranular spacing is 1 nm. Use each of the 5 points on the curve (circles). Assume that the DC noise can be treated as an electronic or background noise. From slide 238 find the medium SNR for γ = PW_{50}/B = 2.5 and B/σ_J = 10. Then find the BER assuming the $SNR_{DC}/SNR_1 = TP_{trans}/TP_{DC}$ for each of the five cases.

Solutions to Problems

Section I Problem I

BAR	4	6	8
kfci (slide 13)	890	1080	1250
ktpi	225	185	160
TP(nm)	113	137	159
W_W (nm)	75	90	105
W_r(nm)	50	61	71

Solutions to Problems

Section I Problem II

- For a system with 15% jitter, BAR=6, W_r=3B)

$$\frac{\sigma_J}{B} = 0.15 \approx \sqrt{\frac{2a^2 s_c}{B^2 W_r}} \qquad \text{or} \qquad a^2 s_c \approx \frac{B^2 W_r}{89}$$

Density	B	$a^2 s_c$ (W_r/B =3)	<D> (thermal stability)	s_c (1.2<D>)	a	a/<D>
200 Gbit /in^2	22.4	382nm^3	7.5nm	9nm	6.5nm	0.87
1 Tbit /in^2	10nm	34 nm^3	5nm	6nm	2.4nm	0.48

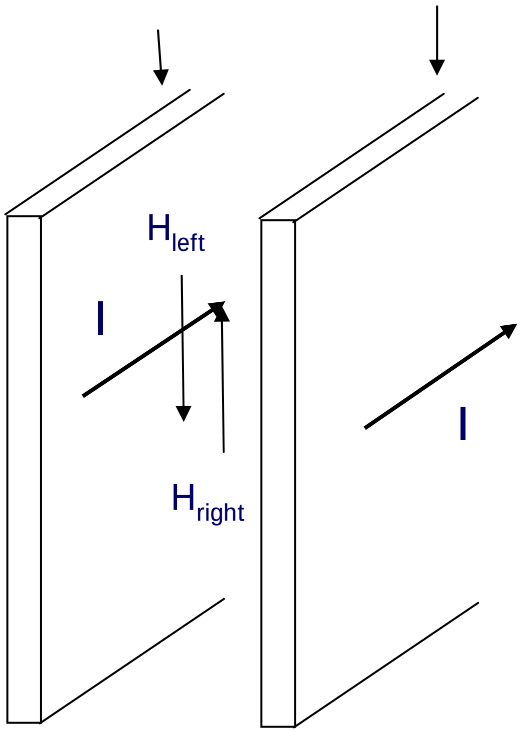
Lets discuss if we can do this in a drive!!!

Solutions to Problems

Section II

Problem II

Pinned layers sandwiching sense layer (not shown)



Problem III

We had three layers of 4,1,4 and now have 4,1,4,1,3.6 (where the last pinning layer is 10% thinner). With the assumptions of Slide 32 In each film $J = (9/13.6)x\ 3.17 \times 10^8\ A/cm^2$ $= 2.1 \times 10^{12}\ A/cm^2$

The net field is:

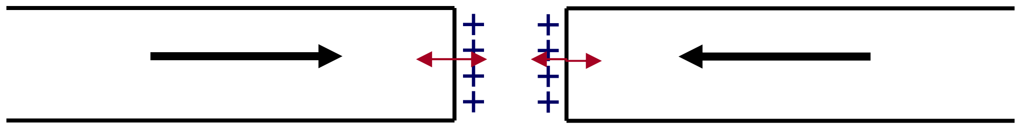
$H = 2.1 \times 10^8\ A/cm^2 x(4nm-3.6nm)/2$
$= 420A/M \sim 5.25Oe$

Solutions to Problems

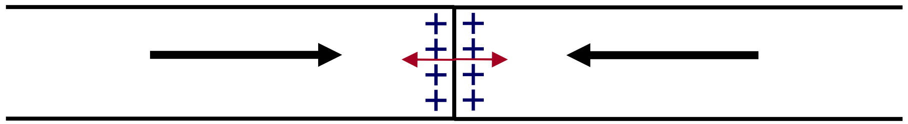
Section II

Problem III

Close to the surface (center region) of an area of constant poles the field is $H = 2\pi M$ pointing away from positive poles The red arrows in the picture below indicate each field contribution.



Summing all the contributions gives fields of $H = 4\pi M$ indicated by the red arrows below:



Solutions to Problems

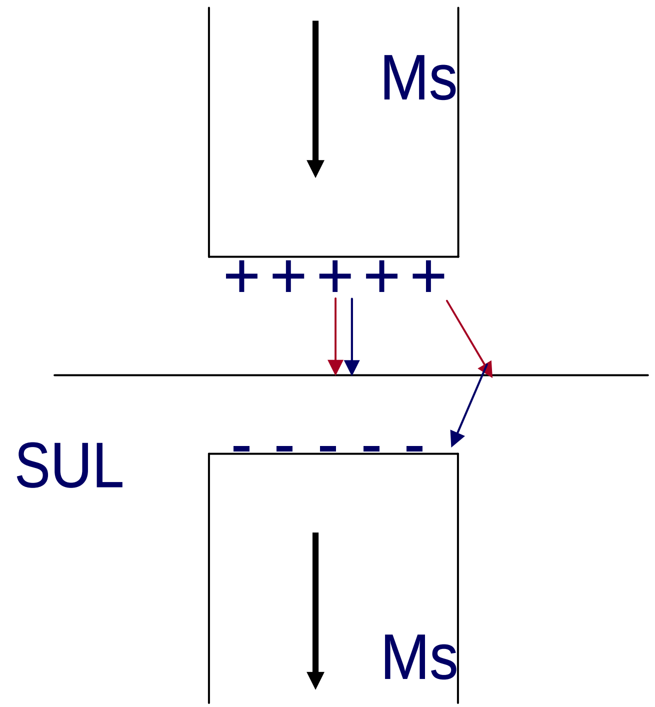
Section II

Problem IV

At SUL surface the field from the plus pole of the magnetized “real” head pole points downward as shown in red.

The SUL “image” with opposite poles also gives a downward field as shown in blue.

Because the image poles are equally spaced from the SUL as are the poles of the actual pole head, the field contributions are equal and the net field doubles, but only at the center point. As indicated the rule is that the field component perpendicular to the SUL surface doubles at any point on the SUL surface.

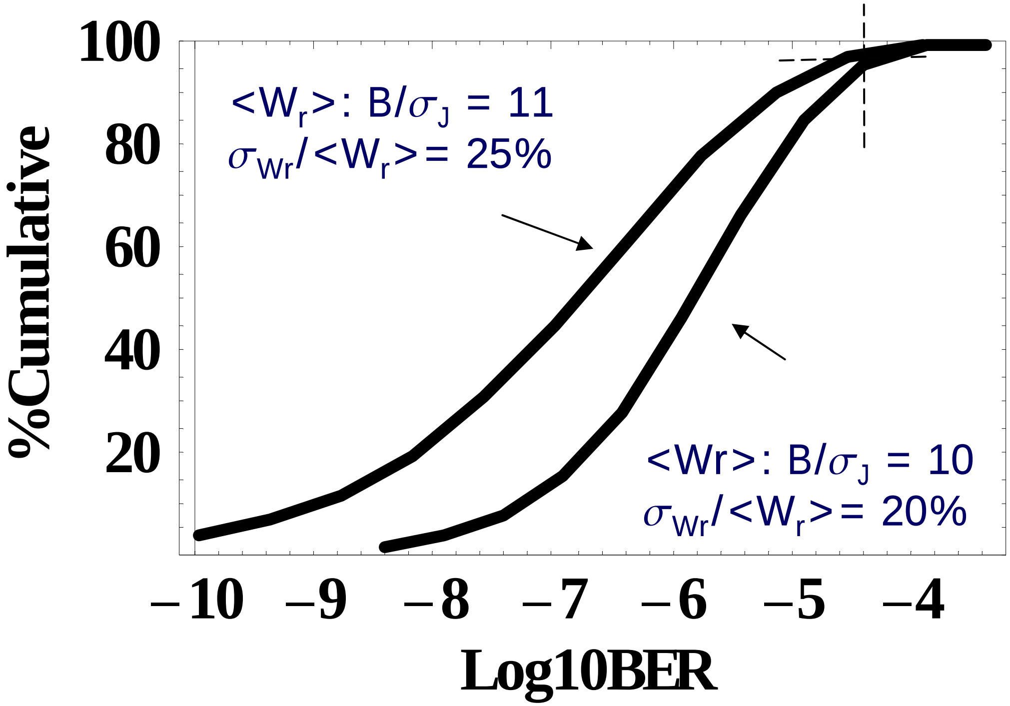


The field away from the SUL surface is complicated, but the “method of images” can simplify the calculation.

EXTRA FOILS

Cumulative Distribution

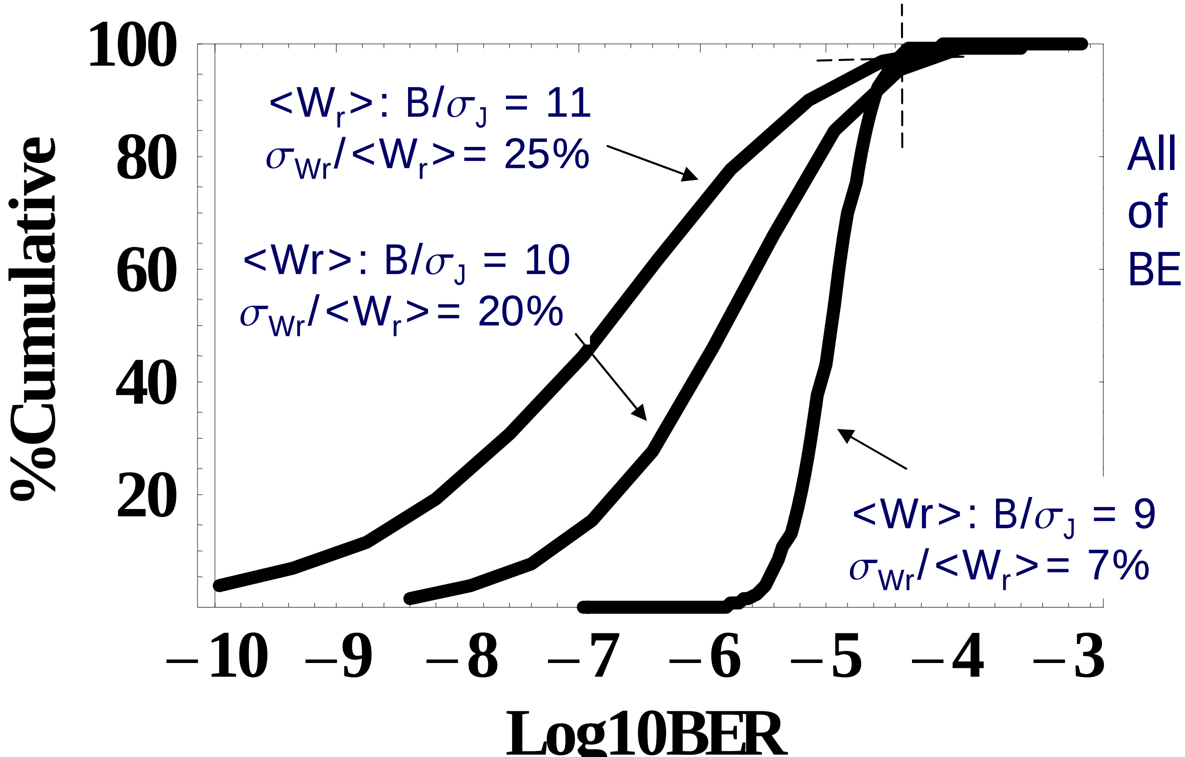
- Suppose have a distribution of read widths in a batch of heads. As an example, we require 95% of the heads to give a system raw BER of $10^{-4.5}$ or better.



Both give 95% of heads with BER < $10^{-4.5}$

Cumulative Distribution (cont.)

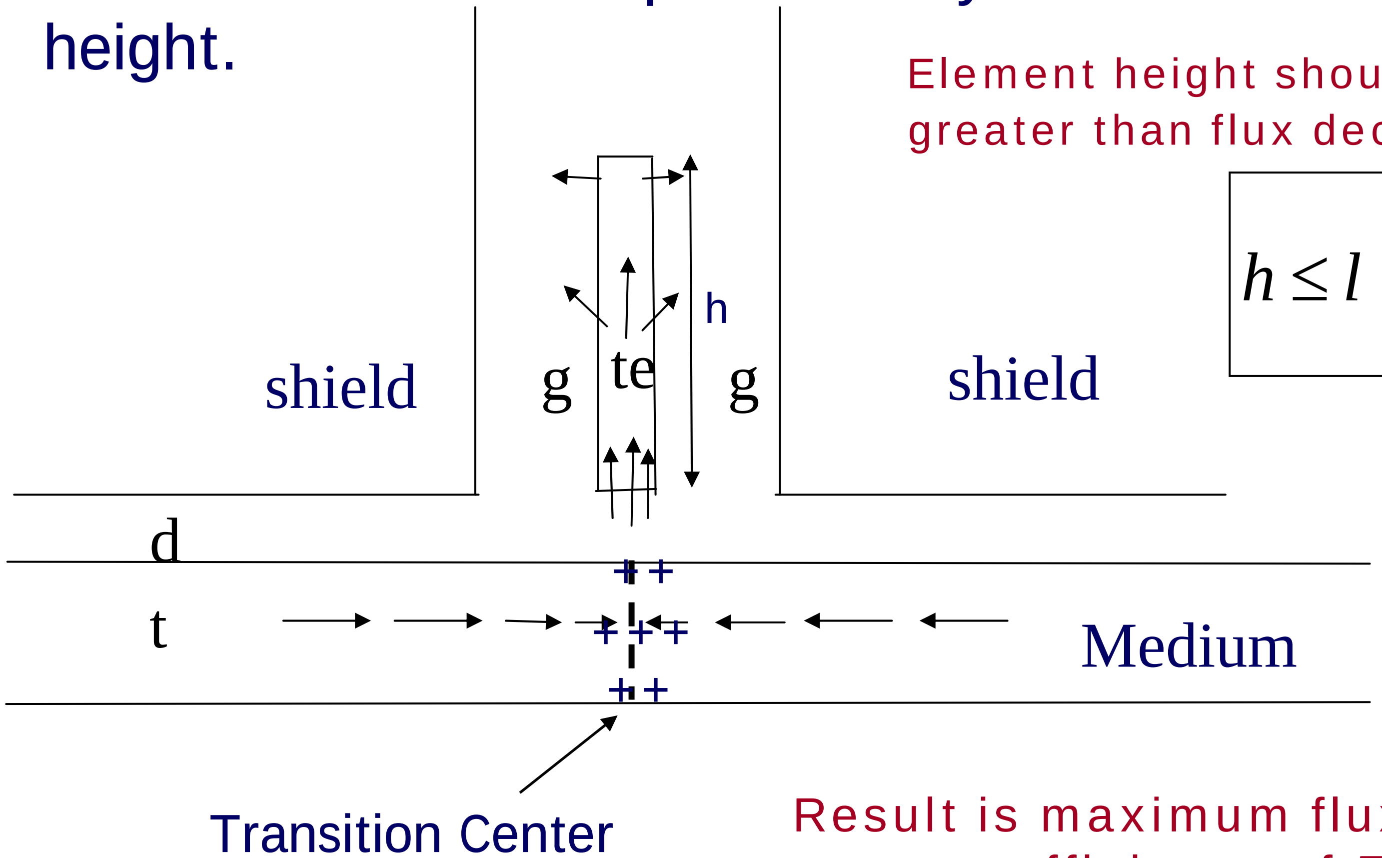
- Suppose have a distribution of read widths in a batch of heads. As an example, we require 95% of the heads to give a system raw BER of $10^{-4.5}$ or better.



All give 95% of heads with BER < $10^{-4.5}$

GMR Head Efficiency

- Finite sense element permeability will limit element height.



Element height should not be greater than flux decay length:

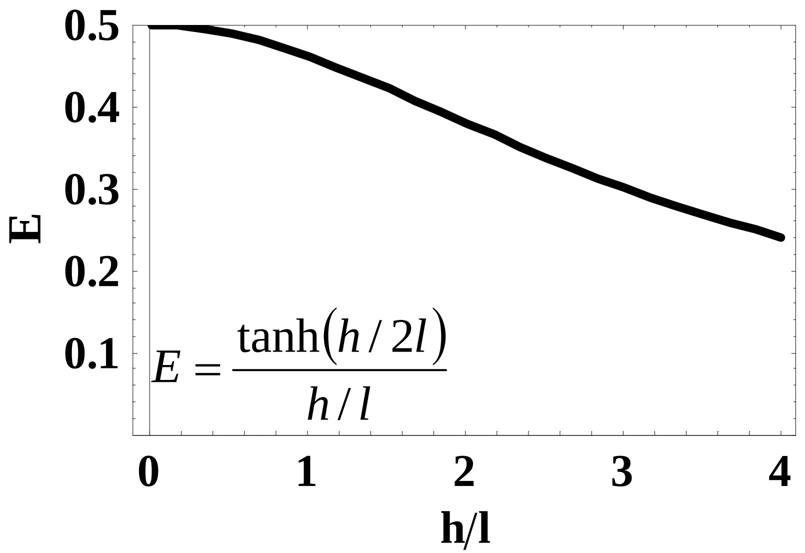
$$h \le l = \sqrt{\frac{\mu g t_{el}}{2}}$$

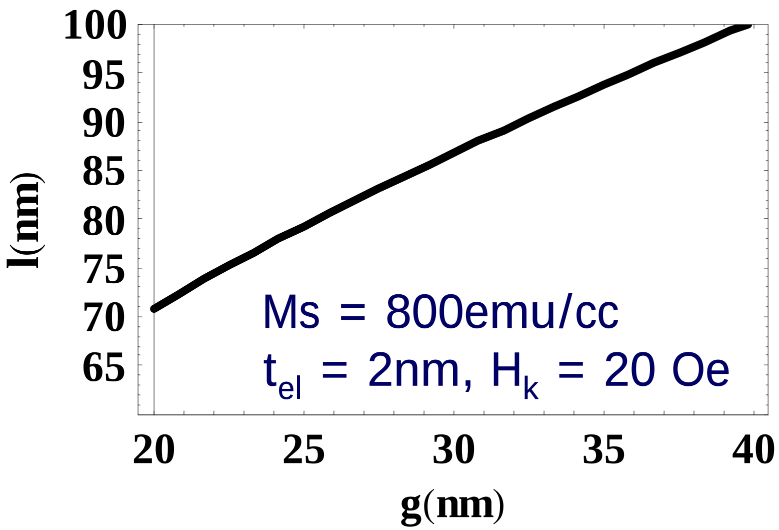
Result is maximum flux capture efficiency of $E = 0.5$

GMR Head Efficiency (cont.)

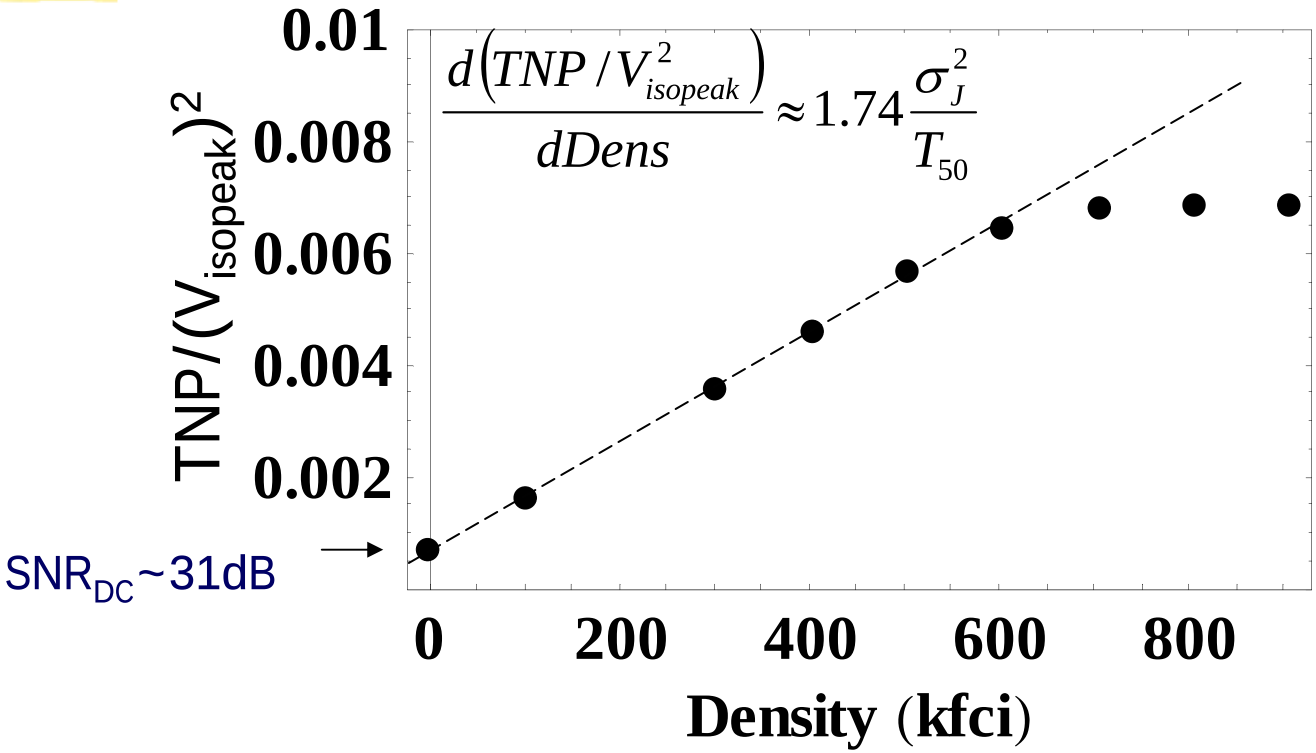
Flux decay length:

$$l = \sqrt{\frac{\mu g t_{el}}{2}} \approx \sqrt{\frac{\pi M_s g t_{el}}{H_k}}$$





Example of Jitter Evaluation on Perpendicular Media



$$Slope = \frac{.0065 - 0.00075}{600\times 10^3 / in \times \left(1in/2.54cm\right)\times\left(1cm/10^7 nm\right)} = 0.24nm$$

$$T_{50} \approx 32nm \Rightarrow \sigma_J \approx 2.2nm$$

Helpful Texts

- K. G. Ashar, Magnetic Disk Drive Technology-Heads, Media, Channel, Interfaces and Integration", IEEE Press, 1997
- H. N. Bertram, "Theory of Magnetic Recording", Cambridge University Press, 1994
- R. L. Comstock, "Introduction to Magnetism and Magnetic Recording", John Wiley and Sons, 1999
- A. S. Hoagland and J. E. Monson, "Digital Magnetic Recording", Reprint Edition, Krieger, 1998
- R.C. O'Handley, "Modern Magnetic Materials, Principles and Applications", John Wiley and Sons, 2000
- E. M. Williams, "Design and Analysis of Magnetoresistive Recording Heads", John Wiley and Sons, 2001
- S. X. Wong and A. Taratorin, "Magnetic Information Storage Technology", Academic Press, 1999