Recording on Bit-Patterned Media at Densities of 1Tb/in^2 and Beyond

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Seagate Technology

Seagate
We turn on ideas

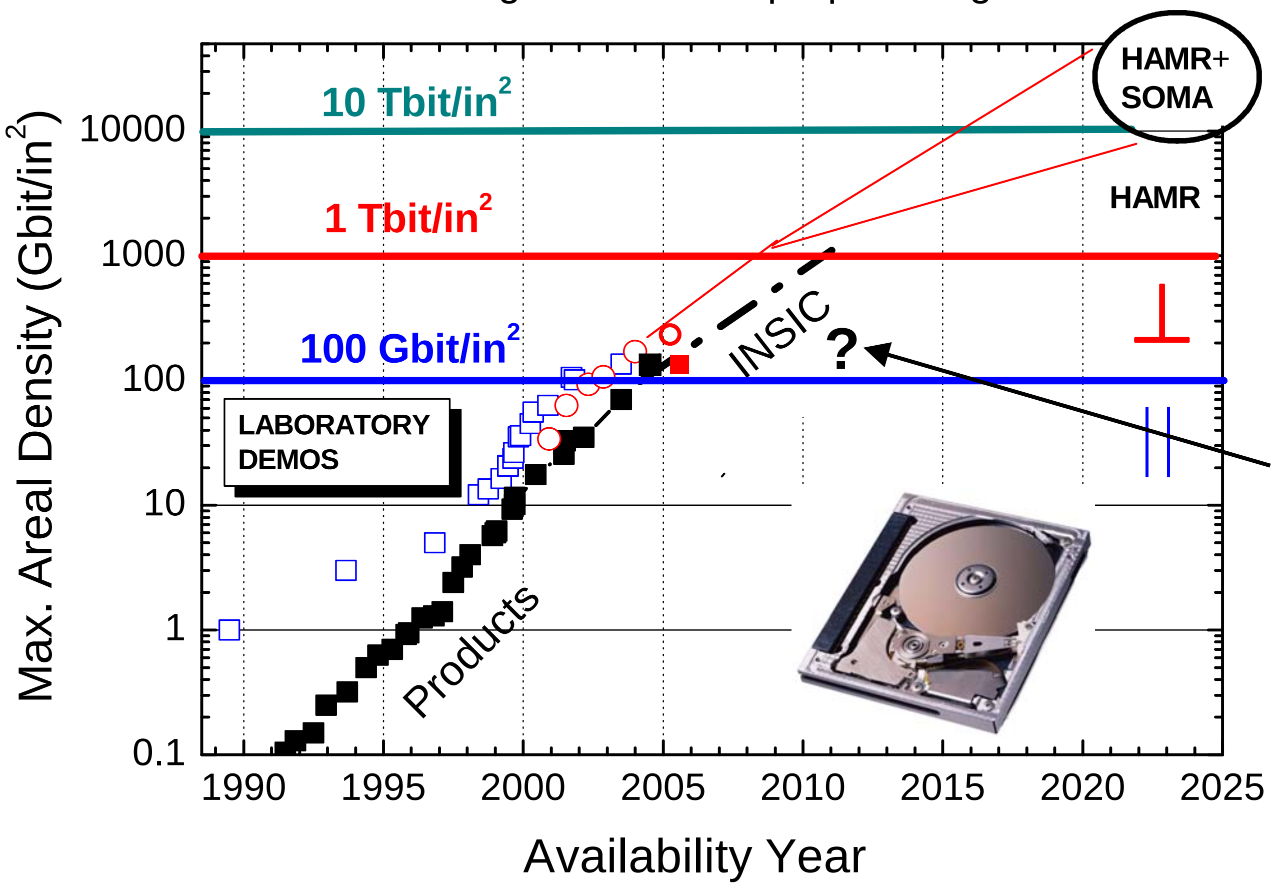
Areal Density Progress

Commercial products:
≤130 Gbits/in², 80-130 GB/3.5" Platter

Demonstrations:
up to 240 Gbit/in²

Research frontier:
≥500 Gbits/in²

40-50 Tbit/in² Single Particle Superparamagnetic Limit



Longitudinal
Perpendicular (incl. tilted, composite etc.)
Discrete Track
Heat Assist
Discrete Bit (Litho, NIL, etc.)

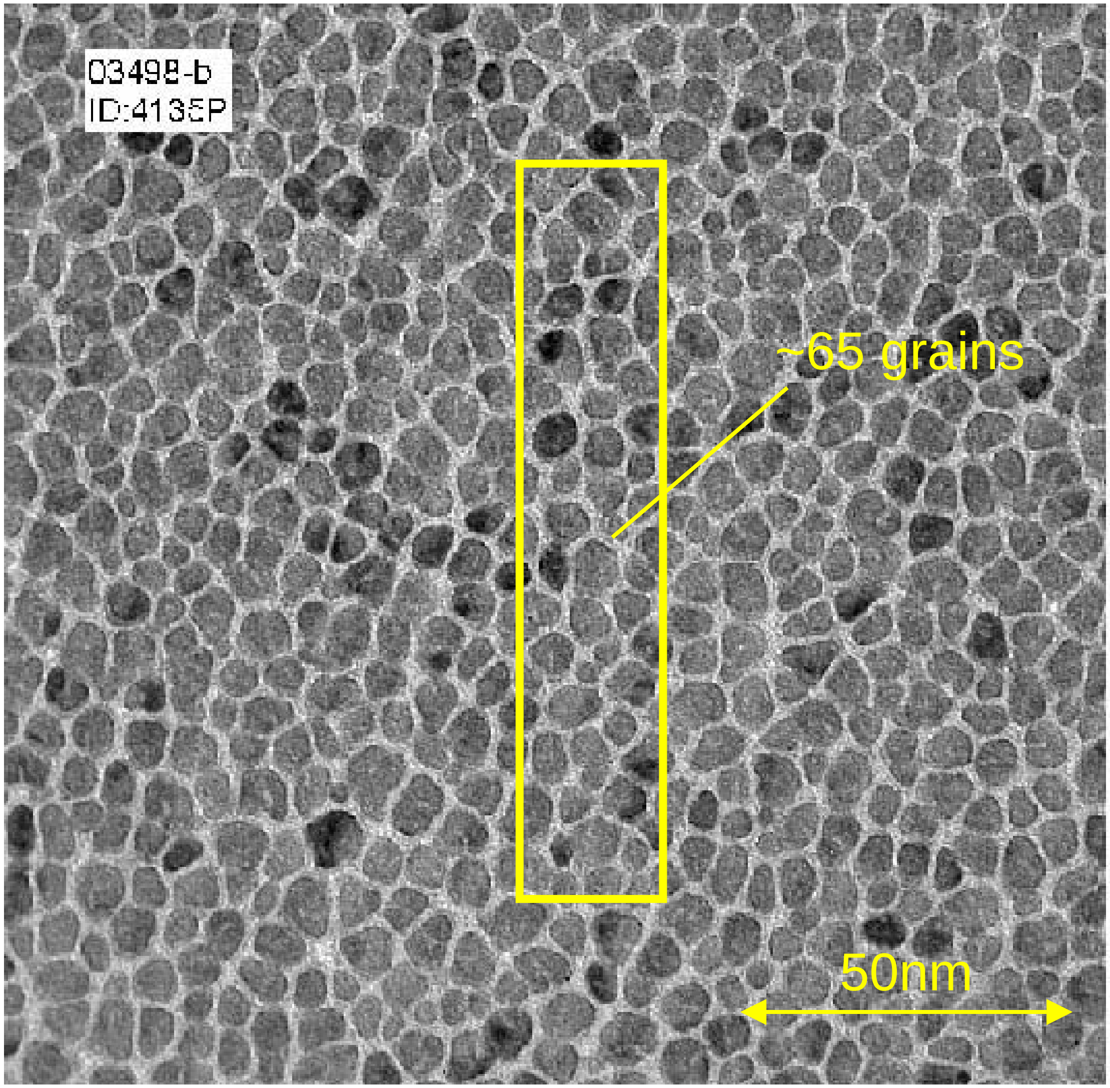
Self organized Media (higher AD)

Overview

- Why bit patterned media (BPM)?
  - Manufacturing aspects [1)]
- Writing on BPM
  - A new requirement: synchronized writing [2)]
  - Analysis of written-in errors
    - Timing
    - Writing margins
- SNR considerations at read-back
- Potential of BPM
- Conclusion

1) B.D. Terris, T. Thomson, J. Appl. Phys. D, vol. 38, p. R199, 2005
2) R.L. White et al. IEEE Trans. Magn. vol. 33, pp. 990, 1997, G. Hughes, "Patterned Media", Springer, 2001.

A Bit in Today's Media



Why BPM?

Dimensions correspond to Seagate's recent 240 Gb/in^2 demonstration

Too small grains become thermally unstable

So why not make one grain per bit?

The density can therefore increase by a factor of 65!

The Main Result of This Talk

BPM recording is limited by:

Written-in errors
(timing, write-miss)

(At Recording)

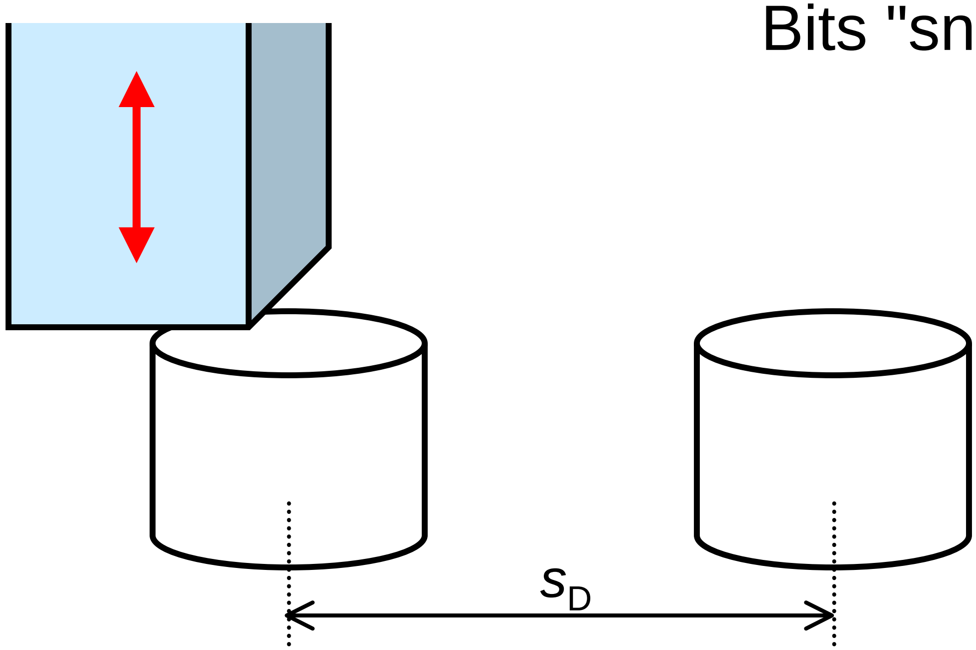
SMNR due to dot
position fluctuations

(At Read-back)

Written-in errors dominate

What is Different on BPM: Timing

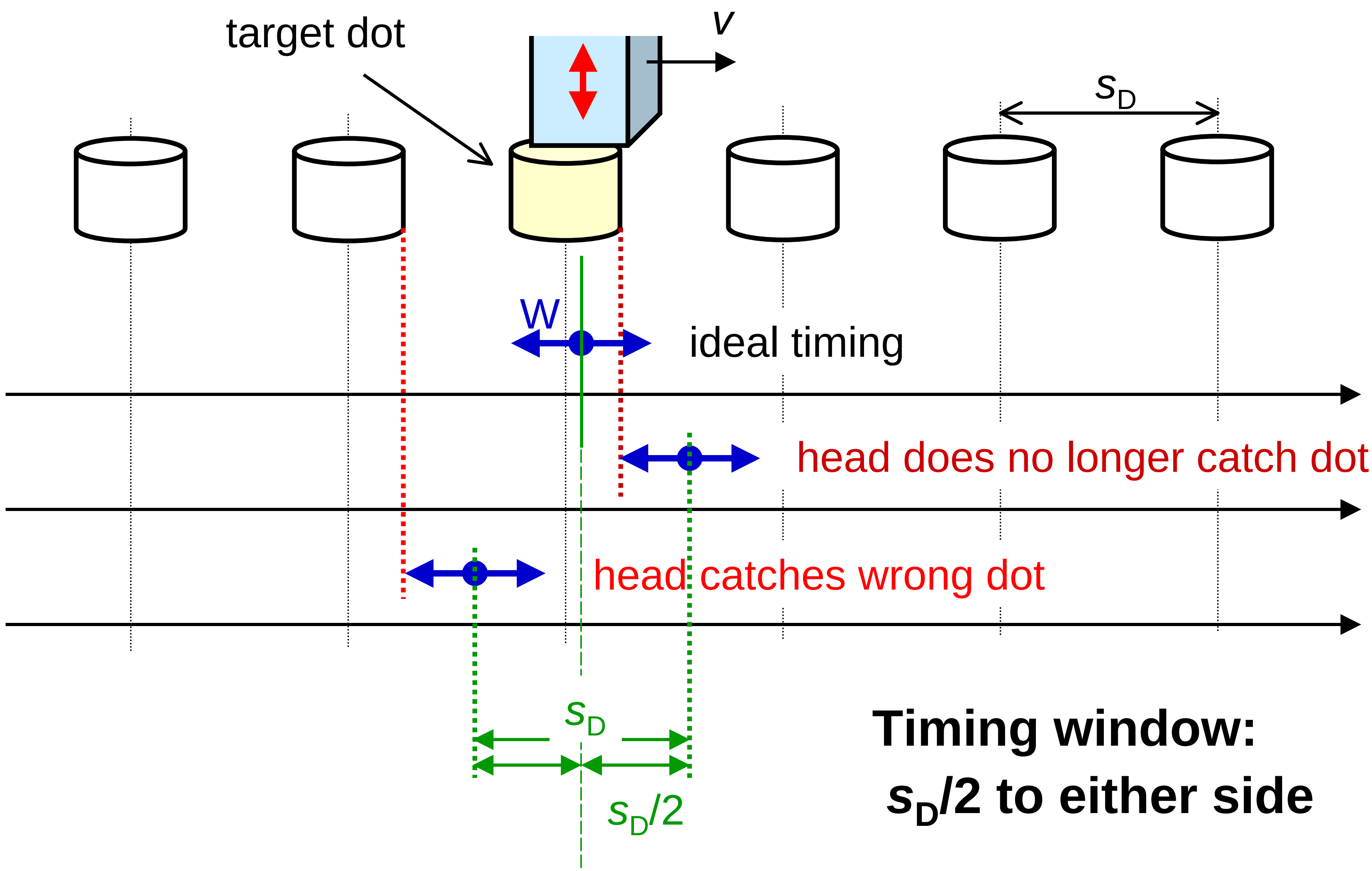
Bits "snap in" on the disk



Bits will always be recorded on fixed locations.

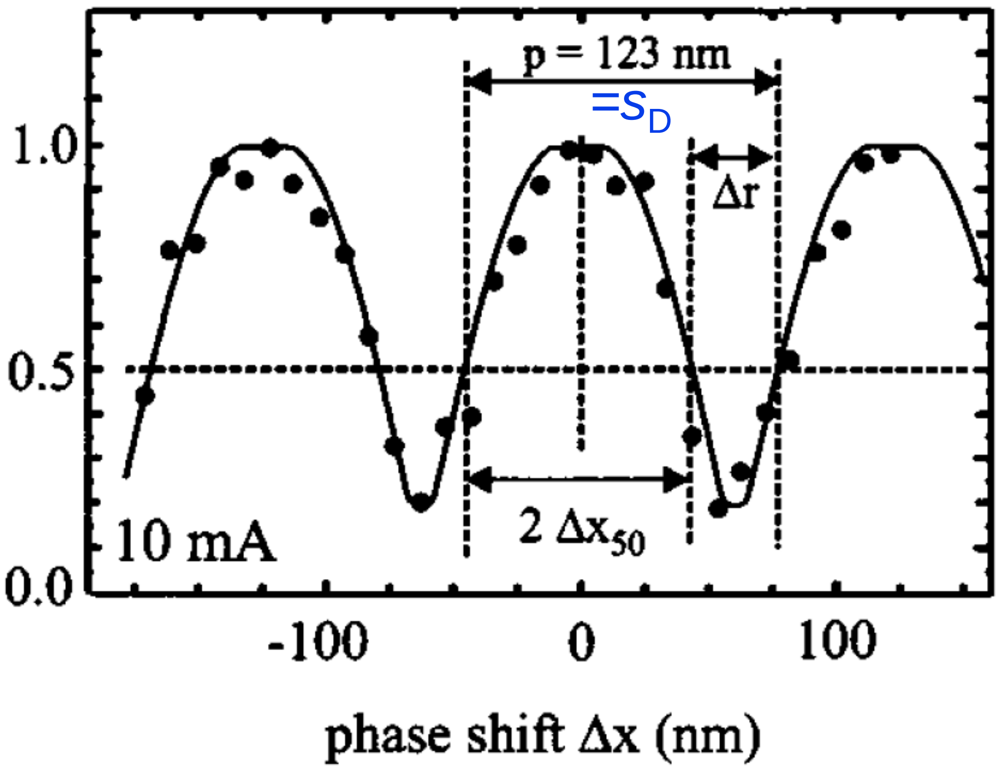
However: bits can only "snap in" if timing is sufficiently accurate

A new Aspect: Timing



Timing window:
$s_D/2$ to either side

Timing Requirements, Experimental

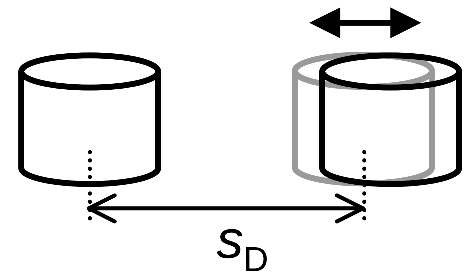


Ideal: Window is s_D but is experimentally found to be smaller - non-ideal materials

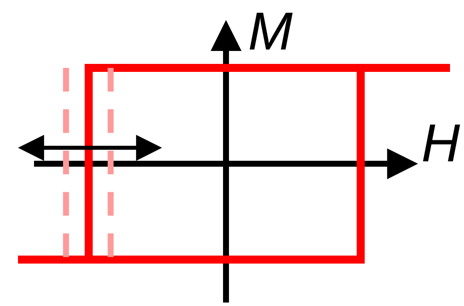
M. Albrecht et al, *Appl. Phys. Lett.*, vol. 80, pp 3409-3411, 2002

What Enters into the Timing Budget

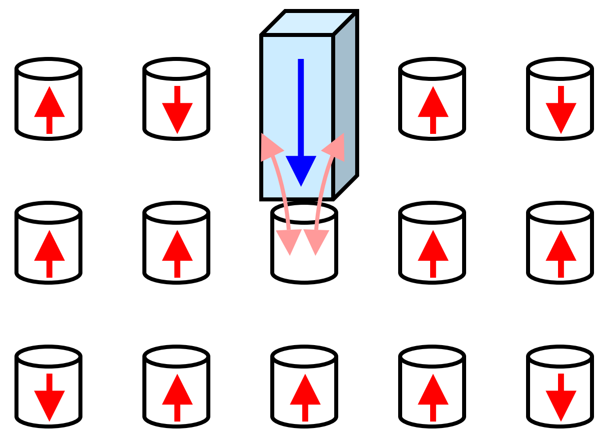
Dot positions fluctuations (primary down-track) $\sigma_x^{pos,x}$



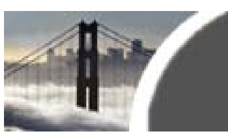
Switching field distribution



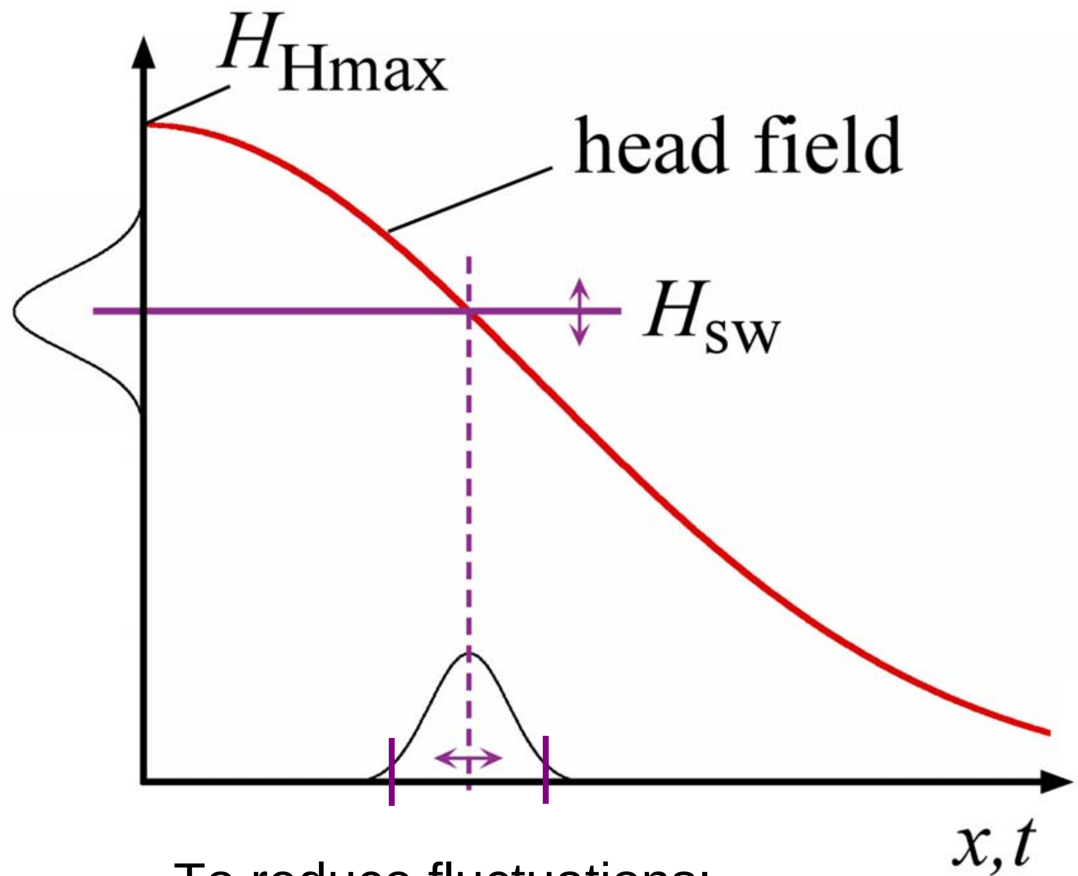
Interaction fields



...(+ electronics)

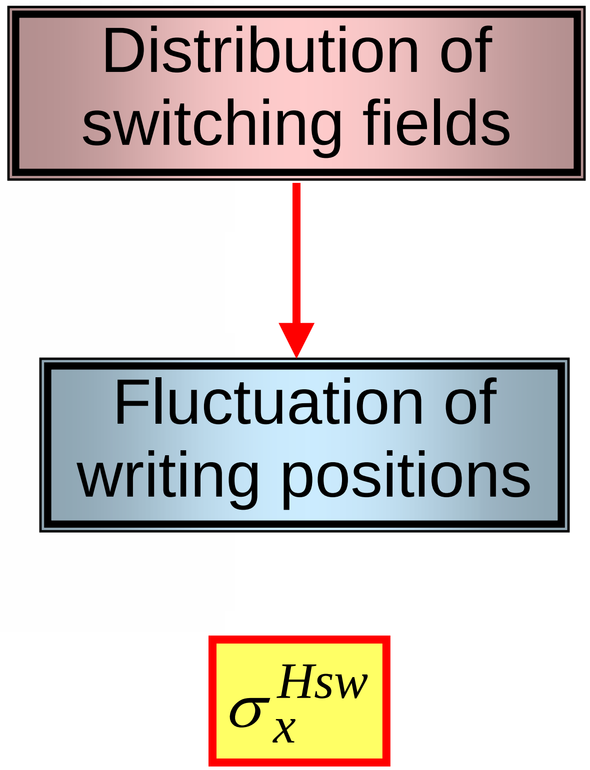


Timing Analysis: Switching Fields

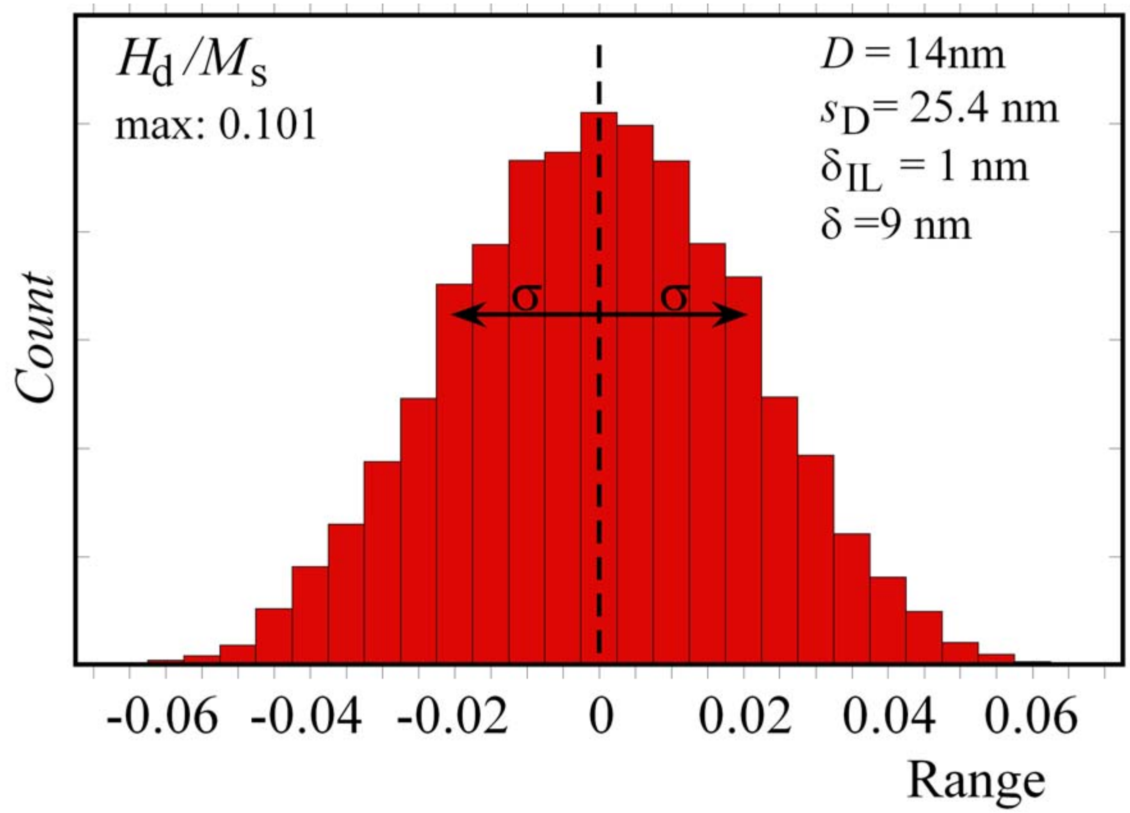


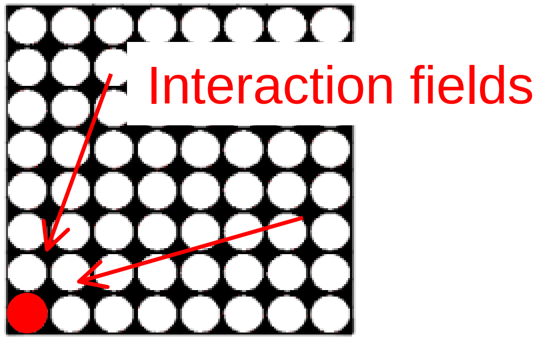
To reduce fluctuations:

Want to record at point
with sharpest gradient



Timing Analysis: Interaction Fields





Interaction fields add to head field

$$\sigma_x^{Hd}$$

H_{dmax}: All dots magnetized in same direction

σ_{Hd}: Calculation of H_d for random patterns, typically 1000

Variance Analysis: Timing

Probability of a timing error (all Gaussians)

$$P_t = 1 - \mathrm{erf}\left(\frac{B/2}{\sqrt{2}\sigma_x}\right)$$

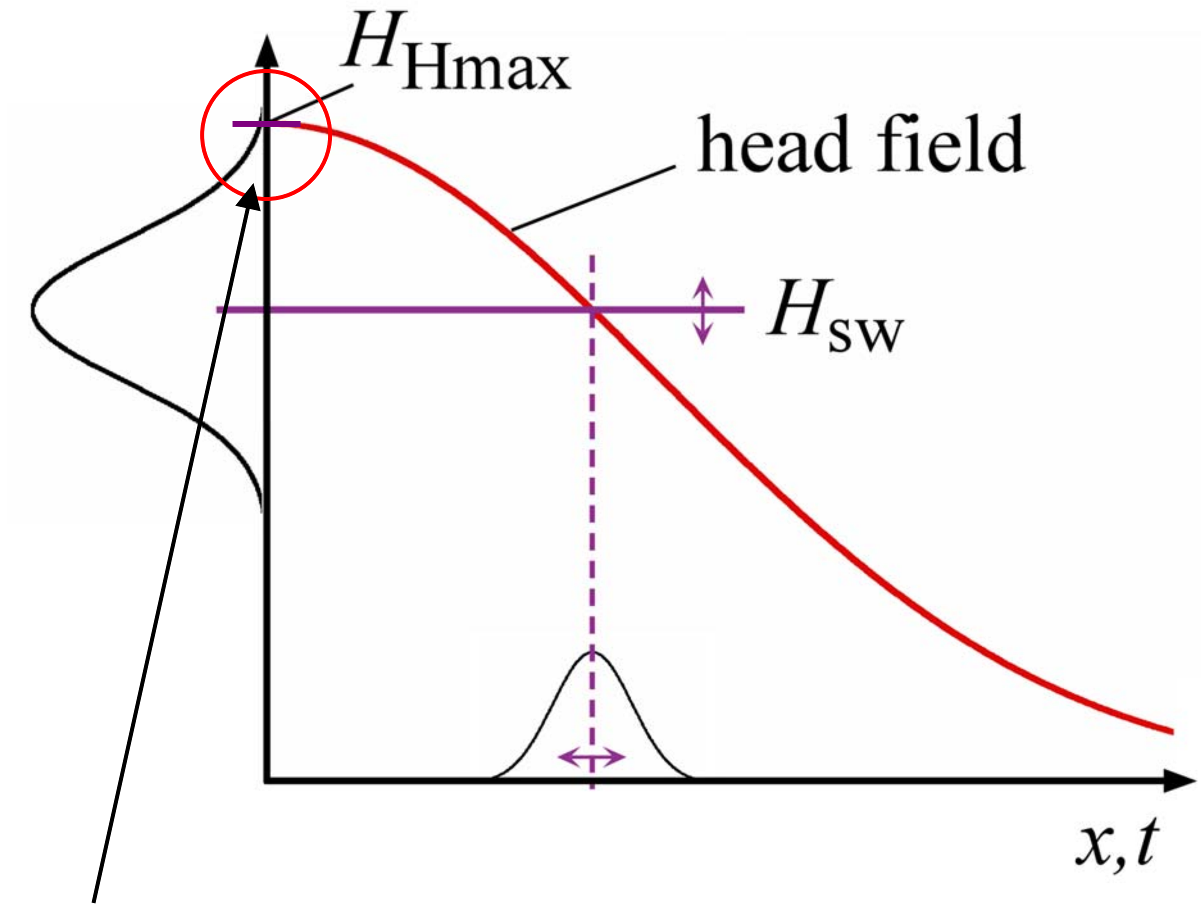
$$\sigma_x = \sqrt{\left(\sigma_x^{Hsw}\right)^2 + \left(\sigma_x^{Hd}\right)^2 + \left(\sigma_x^{pos,x}\right)^2}$$

Switching field distribution (anisotropy field distribution)

Interaction field distribution (surrounding dots)

Distribution due to dot spacing fluctuations

A Second Source of Error: Write-Miss



Finite probability some dots are not switched at all

Variance Analysis: Write Margin

Probability of a "write-miss":

$$P_w = \frac{1}{2}\left(1 - \operatorname{erf}\left(\frac{H_{H\max} - H_{sw0}}{\sigma_H \sqrt{2}}\right)\right)$$

$$\sigma_H = \sqrt{(\sigma_{Hsw})^2 + (\sigma_{Hd})^2}$$

H_{Hmax}: max eff. head field

H_{sw0}: mean switching field

Switching field distribution (anisotropy field distribution)

Interaction field distribution (surrounding dots)

Combined Effect

BER = *P*/2

(because there is a 50% chance that the dot is magnetized correctly)

For simplicity, we assume that timing errors and write-miss errors simply add:

$$BER \cong \frac{P_t + P_w}{2}$$

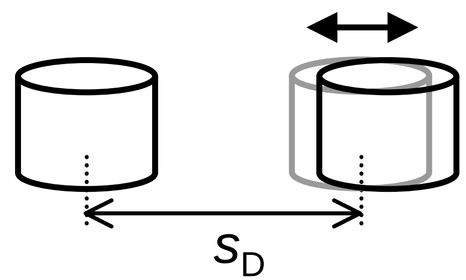
Read-Back

- Assume that all dots have been written as intended

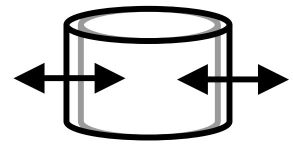
  (BER due to SNR adds to BER due to written-in errors)

- **Noise sources:**

→ Dot spacing fluctuations



→ Dot size fluctuation



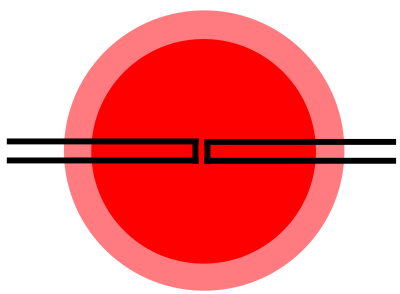
Others: M_s, thickness fluctuations

Noise Mechanisms at Read-Back

- Dot spacing fluctuations = jitter
- Effect of dot size fluctuations is reader dependent

Big dots in a small reader

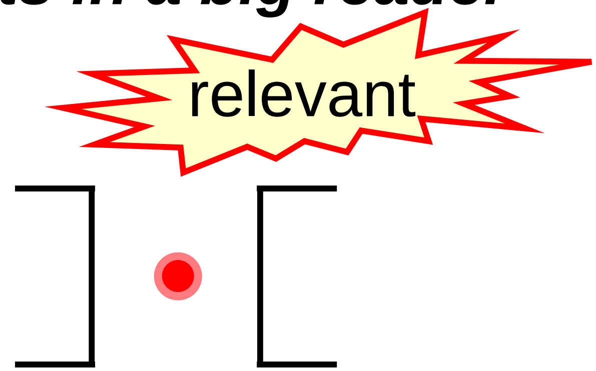
PW << D
R_W *<< D*



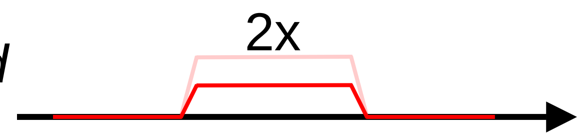
PW mod

Small dots in a big reader

PW >> D
R_W *>> D*



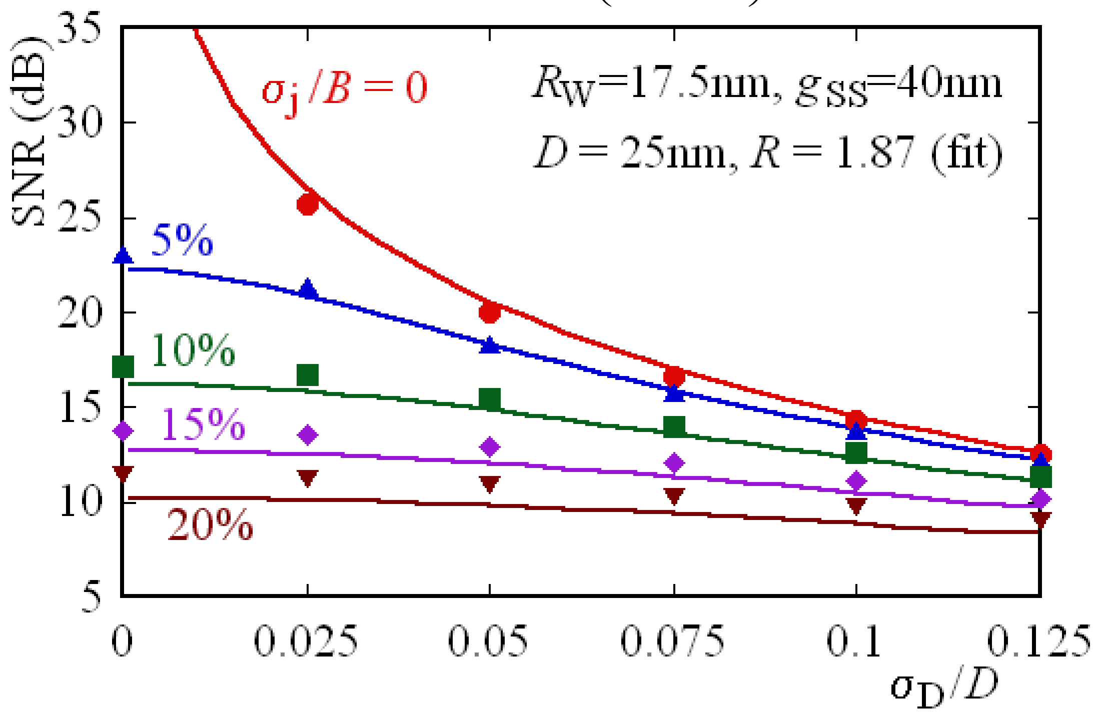
Amp mod



Flux fluctuation $\propto 2\frac{\sigma_D}{D}$

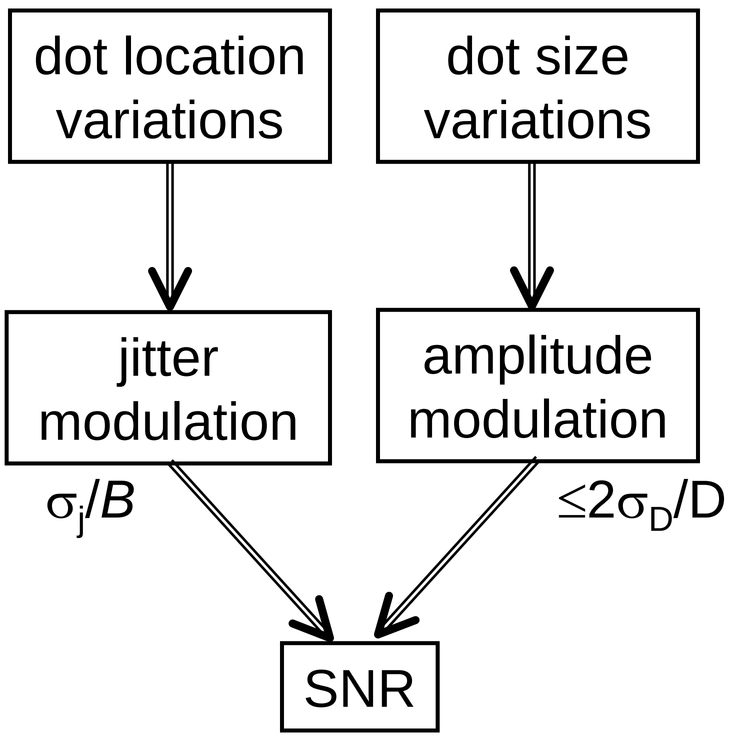
Read-Back Medium SNR

Simulation *versus* $SNR = \dfrac{1}{\left(1.54\dfrac{\sigma_j}{B}\right)^2 + \left(R\dfrac{\sigma_D}{D}\right)^2}$



Dots: simulation with reciprocity read-back, jitter is 1D.

Simplified picture



Areal Density Potential of BPM

- Assume elliptical dots (aspect ratio 4)
- Neglect all distributions: $\sigma_D/D = \sigma_{HA}/H_A = \sigma_{sD}/s_D = 0.05\%$
- Two configurations:

  pole head, SUL + storage layer

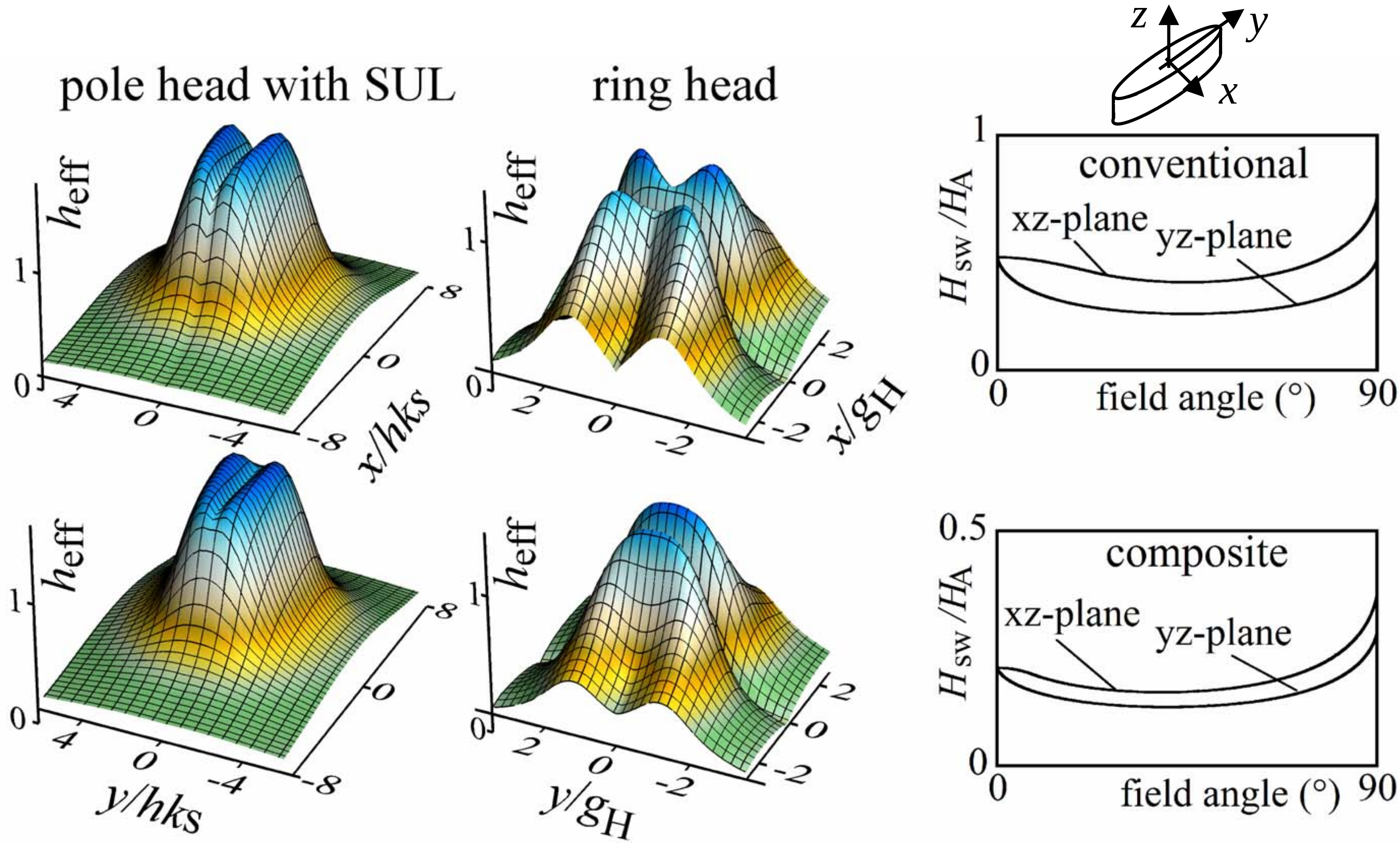
  ring head + storage layer
- Two hard layers:

  conventional

  composite with optimized coupling
- Limiting condition:

  20 *kT* minimum energy barrier at adjacent track

Effective Fields for all Combinations



g_H: half-gap, *hks*: head-keeper spacing

Results (Elliptical Dots)

AD (Tb/in^2)	W (nm)	g (nm)	d (nm)	s_D (nm)	D (nm)	$AR{\cdot}D$ (nm)	H_A (kA/m)	M_{s1} (kA/m)	δ_1 (nm)	δ_{IL} (nm)	M_{s2} (kA/m)	δ_2 (nm)	BER_w (dec)	BER_t (dec)	BER (dec)
1	42	na	7.5	12.7	8.5	34	1716	1300	2	1	na	na	<-13.4	<-15	<-13.4
2	30	na	3.97	8.98	7.5	30	1572	1300	3	1	na	na	-2.1	-3.2	-2.0
3	29	na	3.24	7.33	6.5	26	3184	400	3	0.5	1200	1	-12.7	-9.5	-9.5
3	26	na	3.24	7.33	6.3	25	3137	600	1.75	0.5	600	4	-7.4	-8.2	-7.3
4	23	na	2.24	6.35	6	24	3279	400	2.75	0.5	1200	1	-5.5	-6.5	-5.5
5	20	na	1.75	5.66	5.5	22	3431	400	2.75	0.5	1200	0.75	-2.4	-5.2	-2.4
1	55	25	7.5	12.7	8	32	1388	700	2.5	na	na	na	<-15	<-15	<-15
2	32	17	3.97	8.98	7.5	30	1622	1300	2	na	na	na	-7.5	-9.5	-7.5
3	33	18	3.24	7.33	6.3	25	2583	400	2.75	na	1200	1	-5.6	-5.7	-5.4
1	21	na	7.5	25.4	16	16	1032	1300	6	1	na	na	-1.0	-11.3	-1.0
1	24	21	7.5	25.4	16	16	1037	1300	5	na	na	na	-4.3	<-15	-4.3

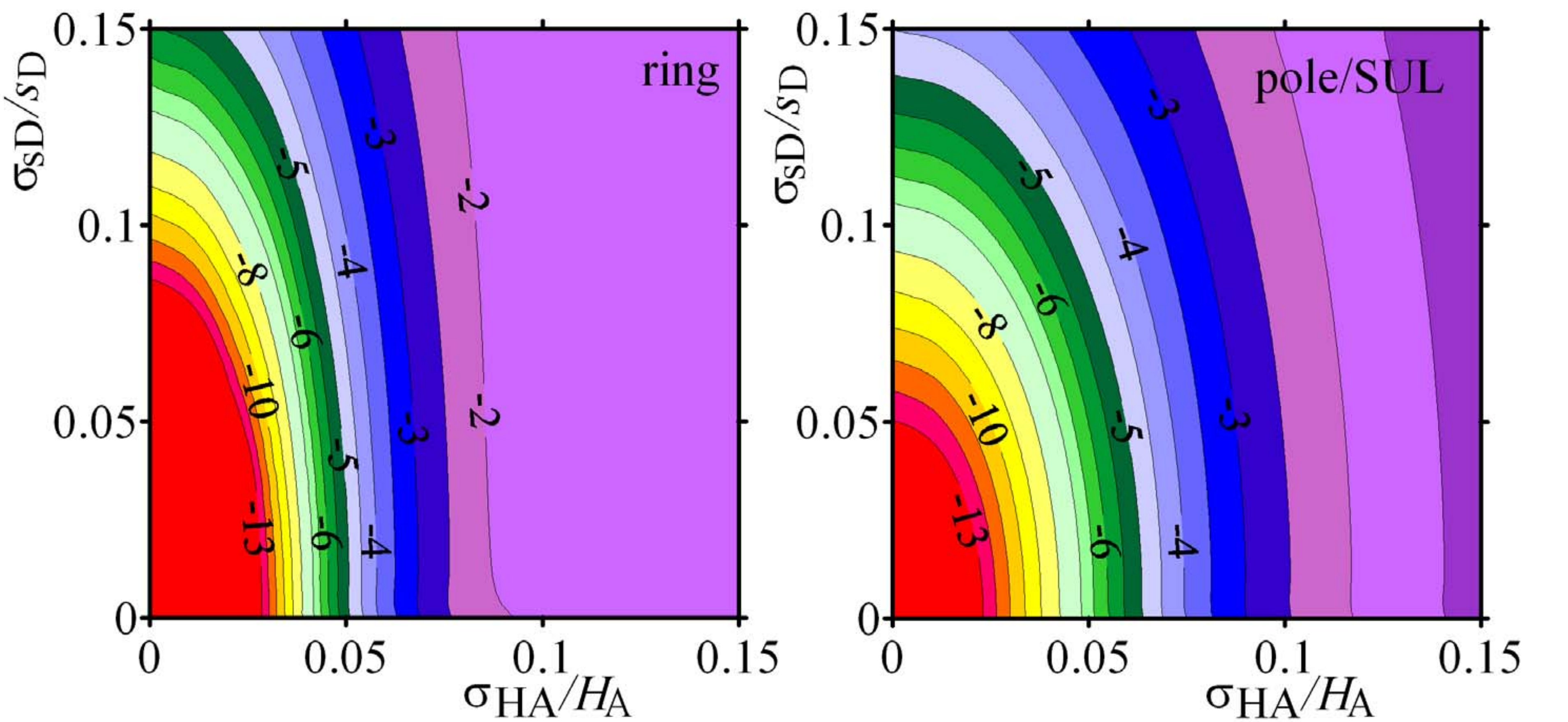
Pole head/SUL about equivalent to ring head

Pole head/SUL + composite is best

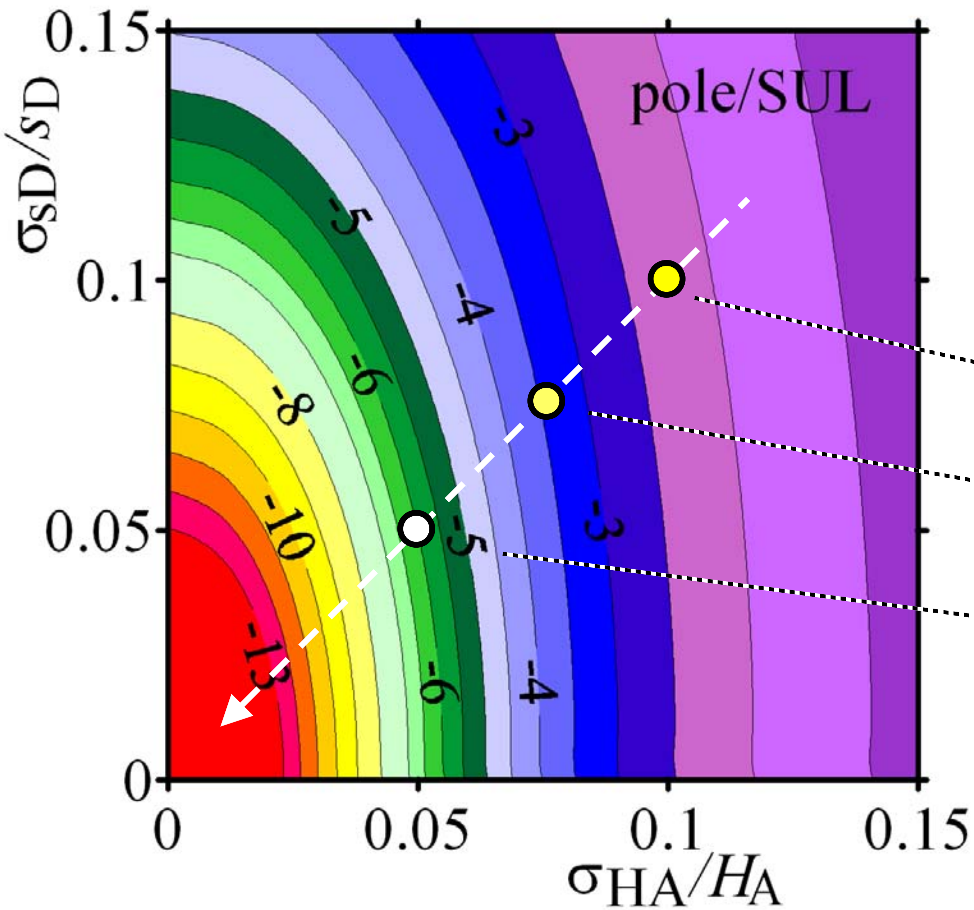
BAR = 1 is not good

Distribution Effects (1Tb/in^2)

Contours of written-in error rates due to timing errors



Distribution Effects and Read-back



$$\sigma_D/D = \sigma_{HA}/H_A = \sigma_{sD}/s_D = \sigma$$

σ	$\frac{P_t}{2}$	BER_{med} @ read
10%	$10^{-2.5}$	$10^{-3.9}$
7.5%	$10^{-3.8}$	$10^{-6.3}$
5%	$10^{-6.3}$	$10^{-12.9}$

Written-in Errors Dominate

Further loss in BER due to read amplitude, but: $\frac{P_t + P_w}{2} \ll BER_{med} \ll BER_{head}$

Conclusions

- BPM recording requires synchronized writing
- $BER_{written-in} >> BER_{mediumSNR}$ ($>> BER_{headSNR}$)
- Error rates are controlled by distributions
  - Anisotropy, dot spacing, dot size, etc.
- Ultimate performance is limited by:
  - Writing, adjacent track erasure/thermal stability
  - "distribution" caused by interaction fields
- Best combination: pole head + SUL + composite medium
- BPM recording beyond 1 Tb/in^2 should be possible