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EVOLUTION OF PERPENDICULAR MAGNETIC RECORDING MEDIA AND UPCOMING CHALLENGES

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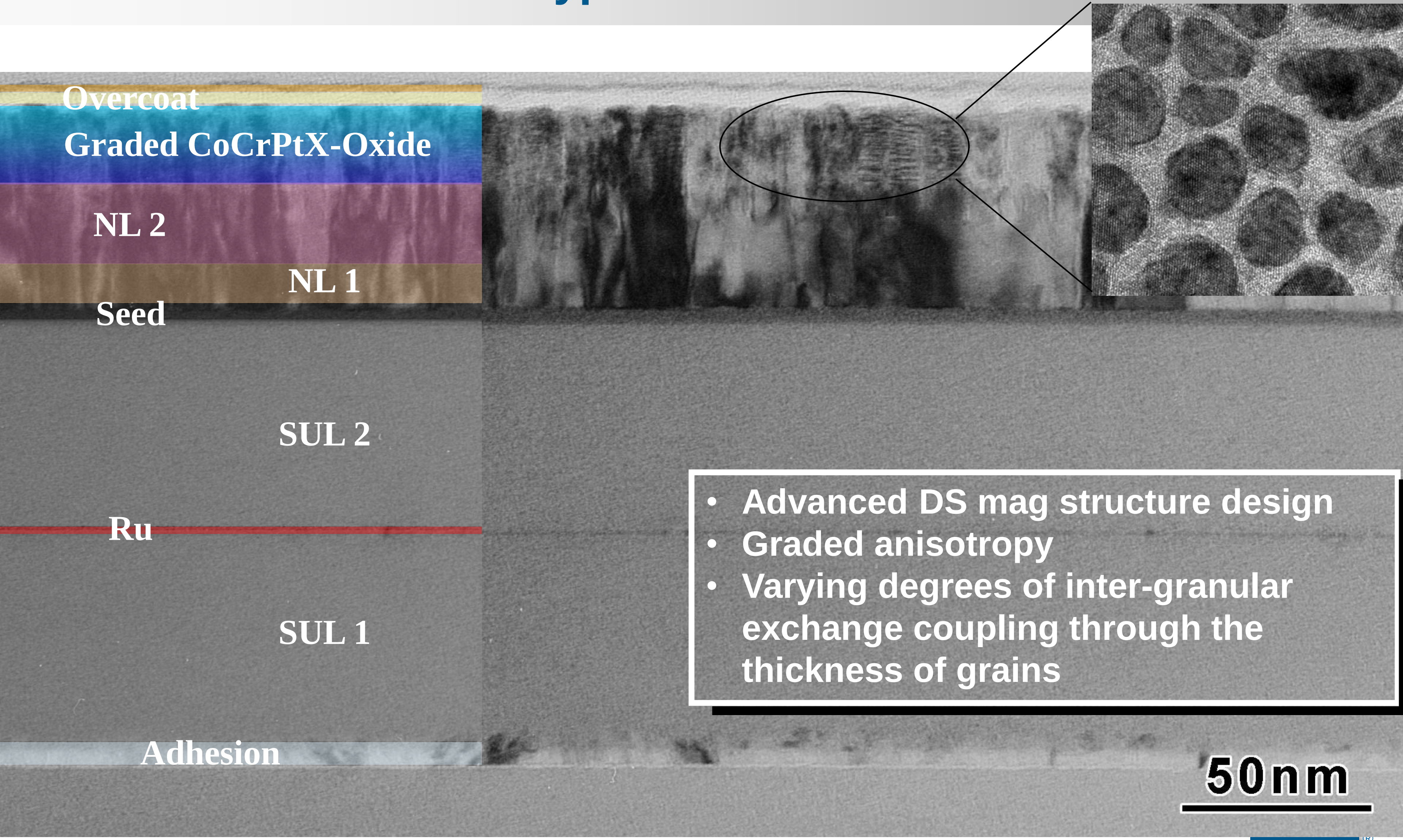
Outline

- ❑ **Introduction**
- ❑ **PMR Media**
  - ❑ Evolution by Product Generation
  - ❑ Limitations Going Forward
- ❑ **Recording Technology Options**
  - ❑ Microwave Assisted Magnetic Recording
  - ❑ Heat Assisted Magnetic Recording
  - ❑ HAMR Media Challenges
  - ❑ Bit Pattern Media (not covered here)
- ❑ **ASTC Industry Consortium**
- ❑ **Summary and Discussions**

Introduction

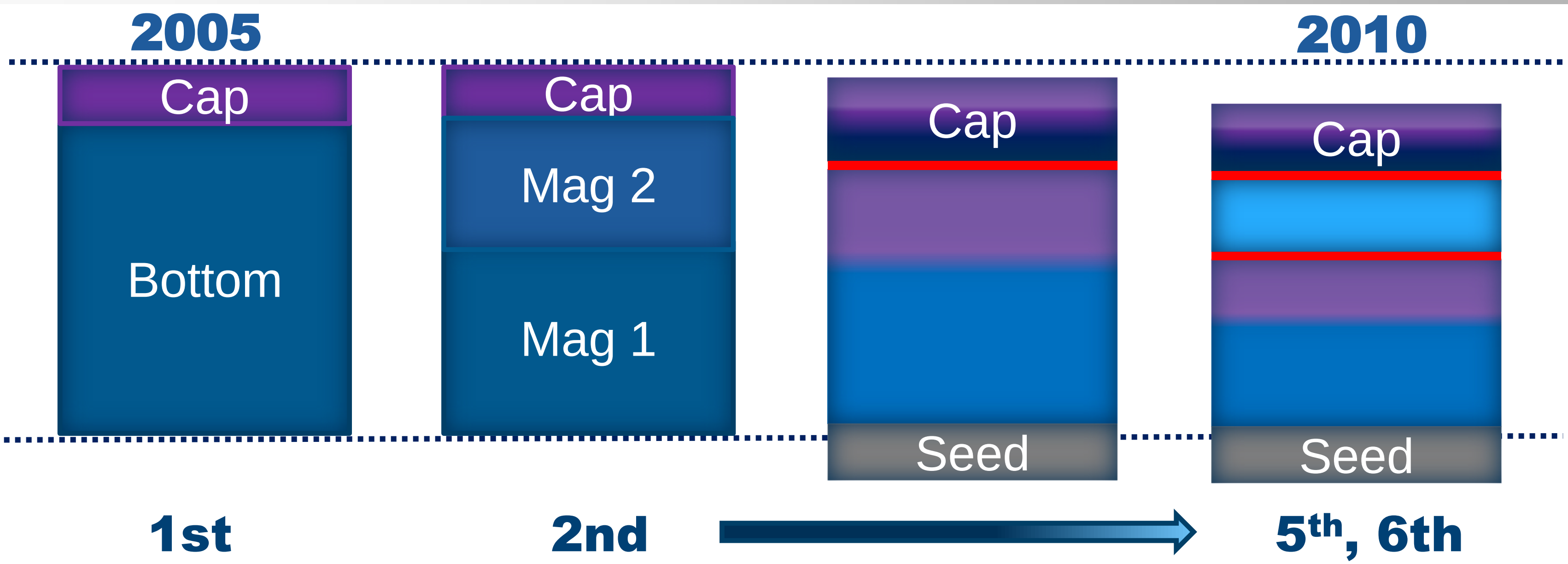
- Introduced commercially in 2005, conventional perpendicular recording can now be considered a mature technology in its 6^{th} (or 7^{th}) product generation.
- Alternative technologies such as Energy Assisted Recording and Bit Patterned Media Recording are not yet ready for productization.
- Here we will address the key technical challenges regarding media extendibility for CMR and will also discuss the main issues in the development of media for the next likely technologies.

Cross-Section TEM of Typical PMR Media Structure



- Advanced DS mag structure design
- Graded anisotropy
- Varying degrees of inter-granular exchange coupling through the thickness of grains

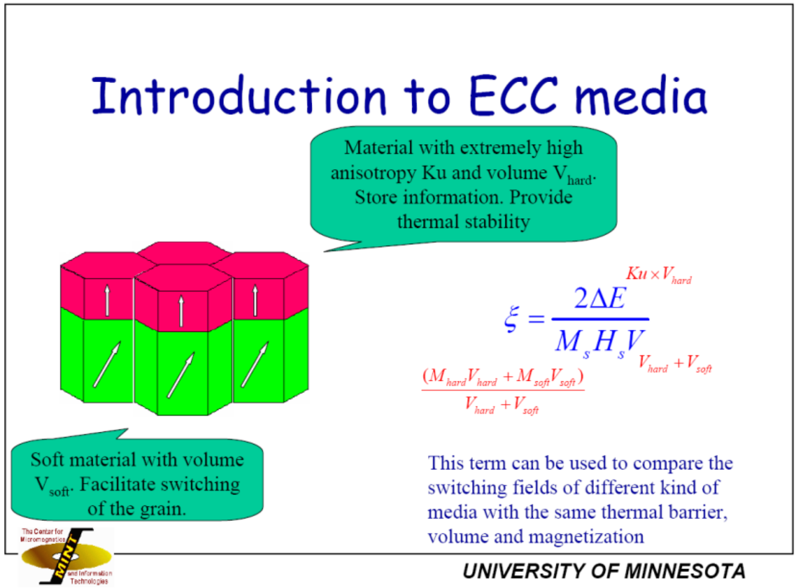
PMR Media Design By Generation

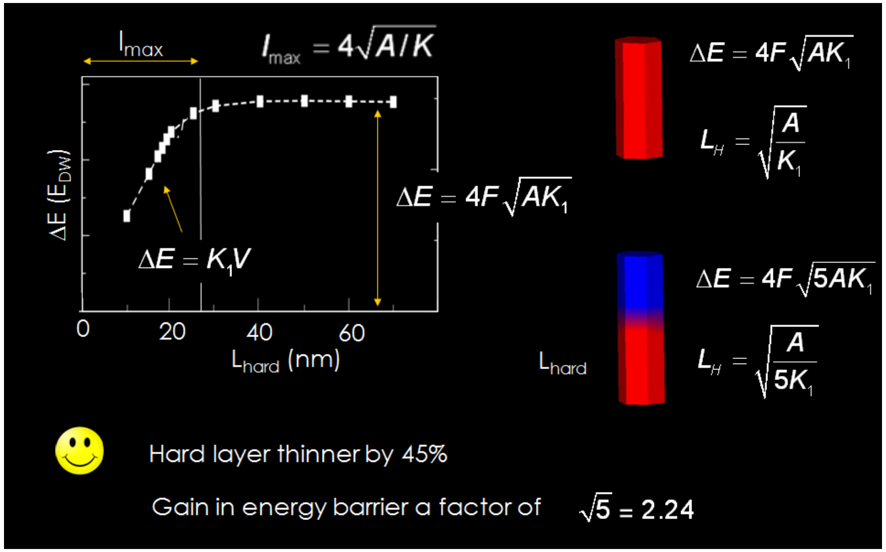


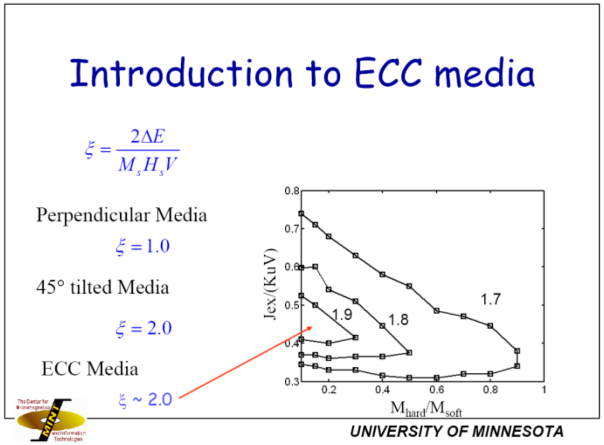
Hard Magnetic Layers Only

From the simple 2-layer capping layer media to the latest 7-8 layer magnetic structures, PMR media has increased significantly in complexity since it was first adopted.

ECC and Exchange-Spring Media



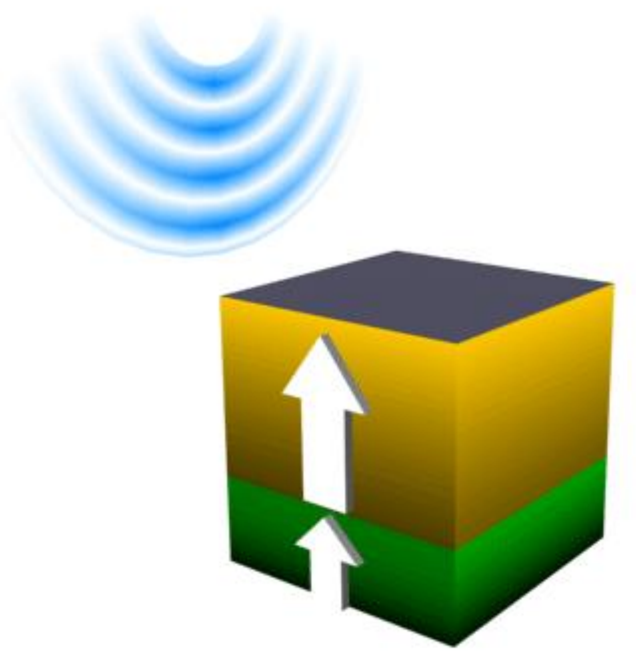




- ❑ Inspired by the “tilted media” concept
- ❑ Incoherent switching through column of grain
- ❑ Compared to “Stoner-Wahlfarth” media, in its simplest rendition it provides twice the energy barrier with same switching field.

R.H. Victora and X. Shen, *IEEE Transactions on Magnetics*, **41**, NO. 2, 537-542, (2005).
D. Suess *et al.*, *J. Magn. Magn. Mat*, **551**, 290-291, (2005).

Dynamic-Spring Media (Media Write Field Boost)



Assist layer
high Ms/low Ku

Storage layer
low Ms/high Ku

Effective field to reverse storage layer is a combination of:

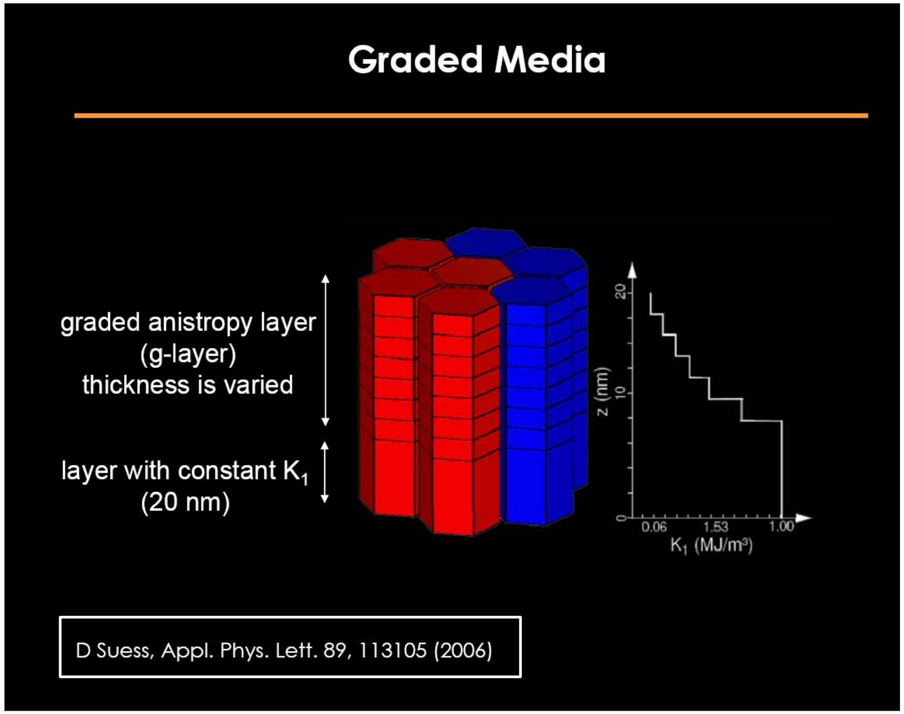
1) Head Field

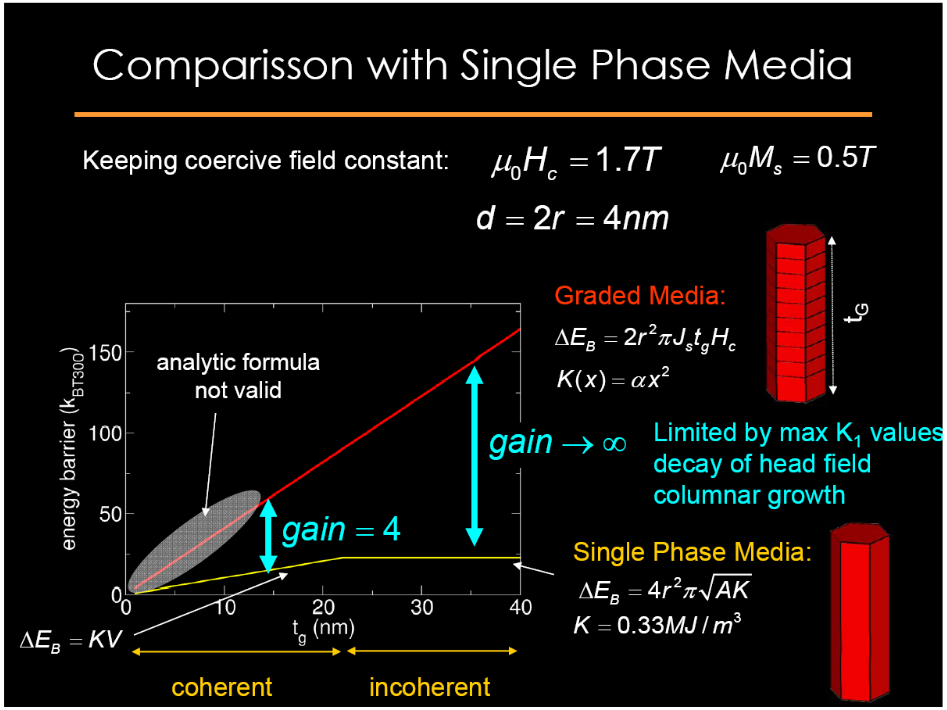
2) Assist Layer Ms*t

3) Interface Exchange

- **Dynamic-spring media is an intrinsic magnetic self-assisted switching stack**
  - The high Ku portion of the media provides for the required thermal stability
  - The softer portion of the media is used to adjust (lower) the switching field
  - This technology is currently being introduced into high volume manufacturing

Graded Anisotropy Media





- Micro-magnetic simulations predict further gains in performance by extending the single ECC or Exchange-Spring concept to a system where the anisotropy is graded.
- Caveat is that switching has to take place by incoherent rotation for advantage to be realized.

Advanced ECC Media

Concept:

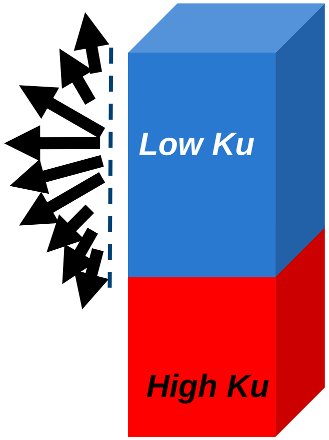
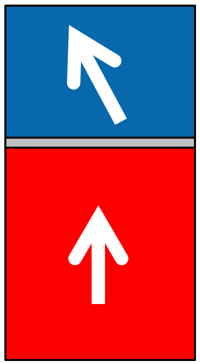


Figure of merit = 2

Practice:



Two-Spin Model

$$H_c = \frac{1}{4} \times \frac{2K_H}{J_{hard}}$$

Single EBL

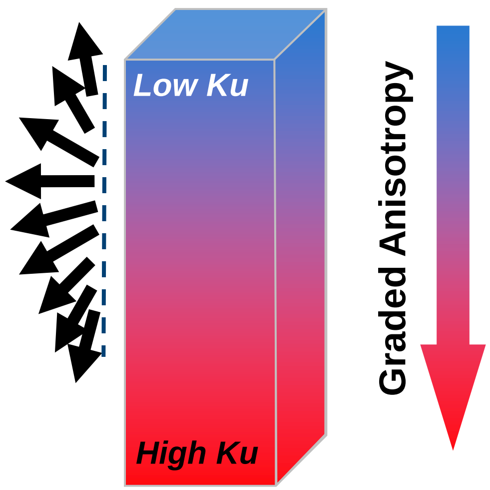
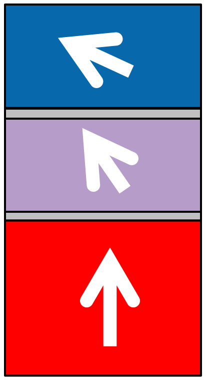


Figure of merit > 4



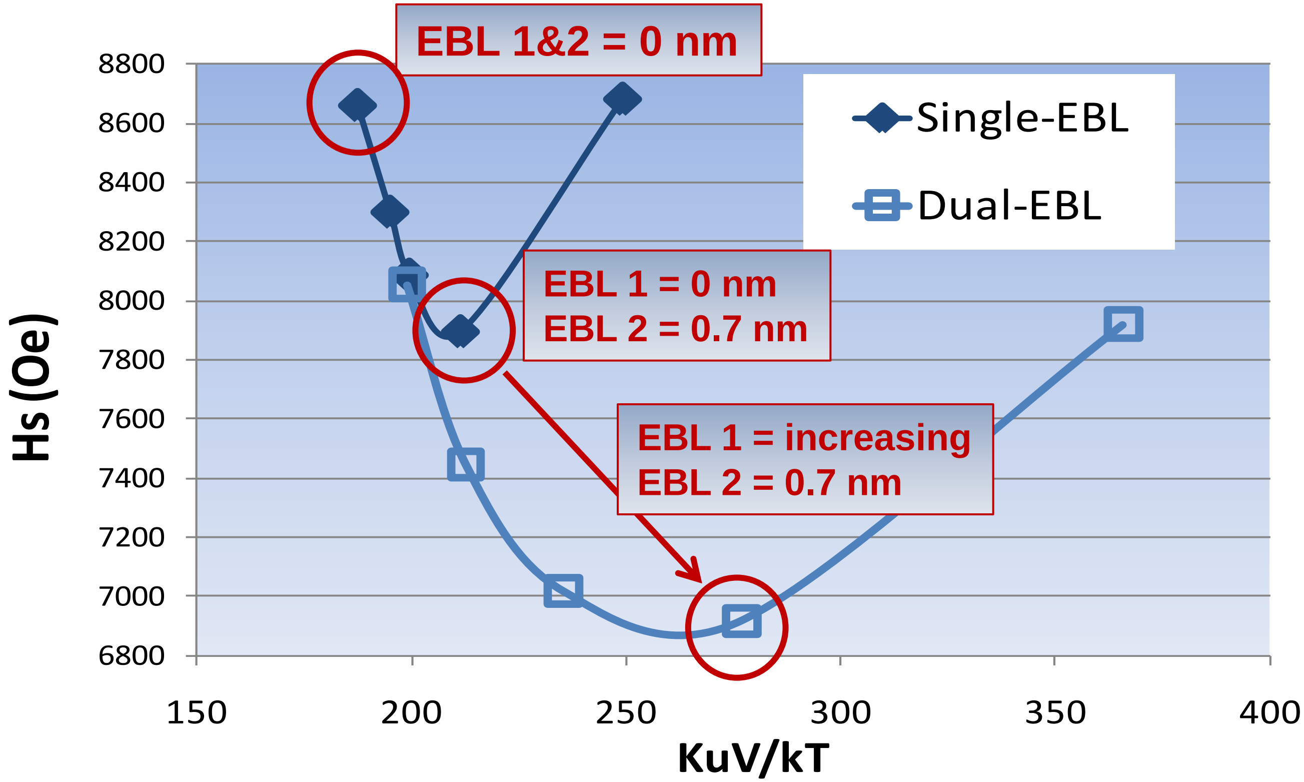
Three-Spin Model

$$H_c = \frac{1}{C} \times \frac{2K_H}{J_{hard}}$$

C>4

Double EBL

Hs and KuV/kT as function of EBL 1/2

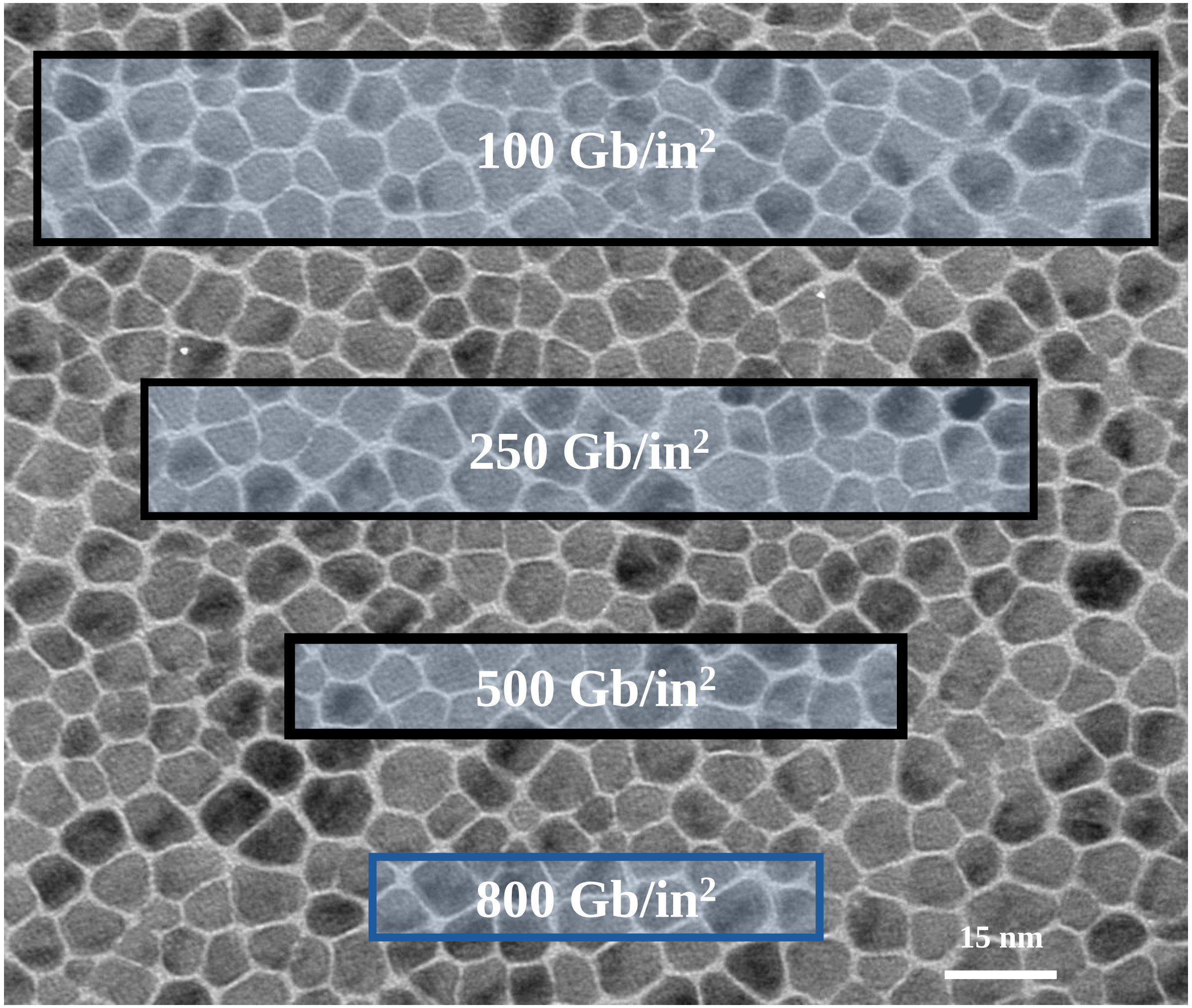


Double ECC structures allow for higher degree of freedom when optimizing Hs and KuV/kT (i.e., writability and thermal stability)

ECC PMR Media

- Double exchange-break layer media is latest generation media structure
- It allows higher degree of incoherent switching through the grain column.
- Provides higher design and performance optimization flexibility
- Allows higher anisotropy (Ku) media to be used yet maintaining good writability
- Can result in thinner overall media stacks
- It should be a key enabler for smaller media grains which is required for extending conventional PMR recording past the 1 Tb/in^2 mark.

Magnetic Grains and Bit Size



~90 Grains/Bit

~40 Grains/Bit

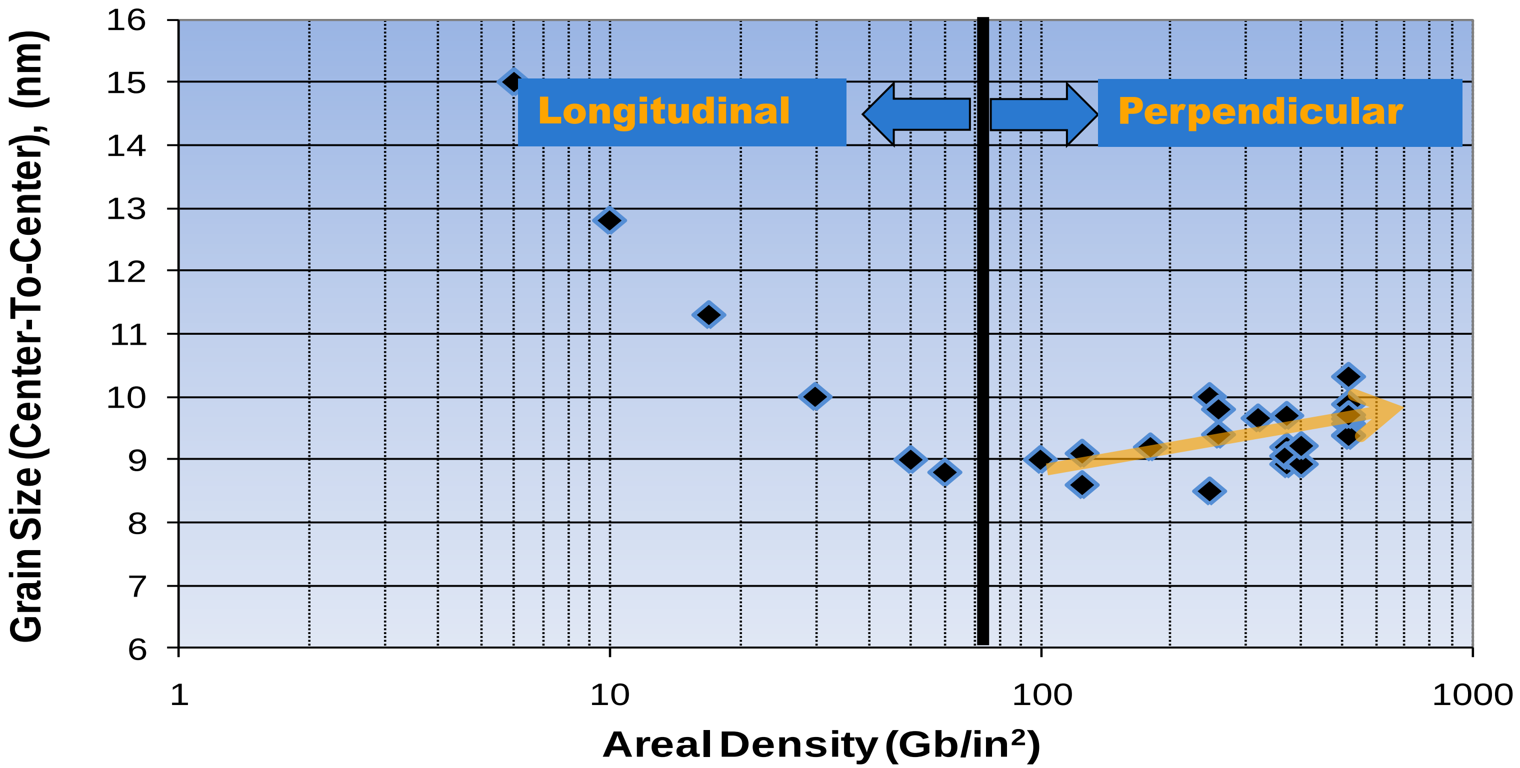
~20 Grains/Bit

~11 Grains/Bit

To maintain SNR, number of grains per bit should *ideally* be kept constant

Magnetic Grains and Bit Size

Presented at TMRC 2010



To maintain SNR, number of grains per bit should *ideally* be kept constant

Simple Picture of Grain Size Scaling in Media

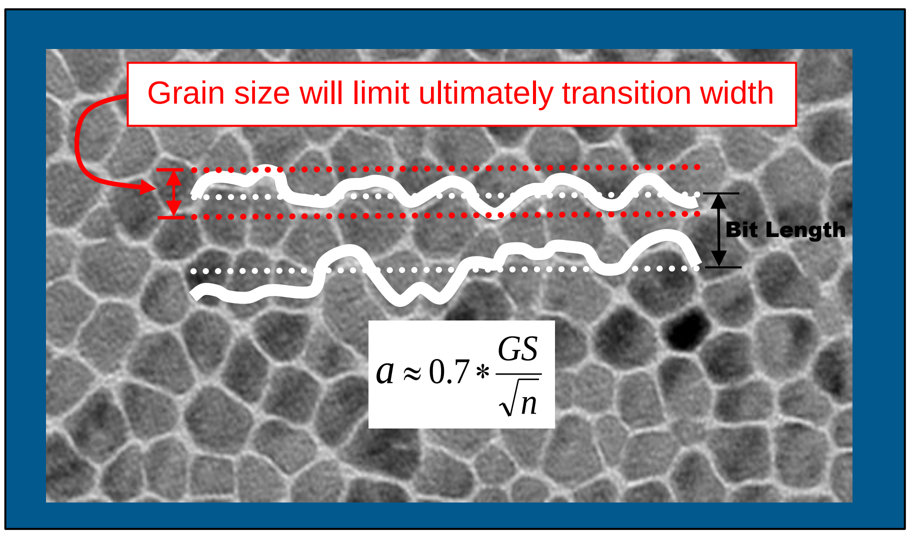
$$SNR \approx \frac{0.31 * PW_{50} * B * W}{a^2 * S}$$

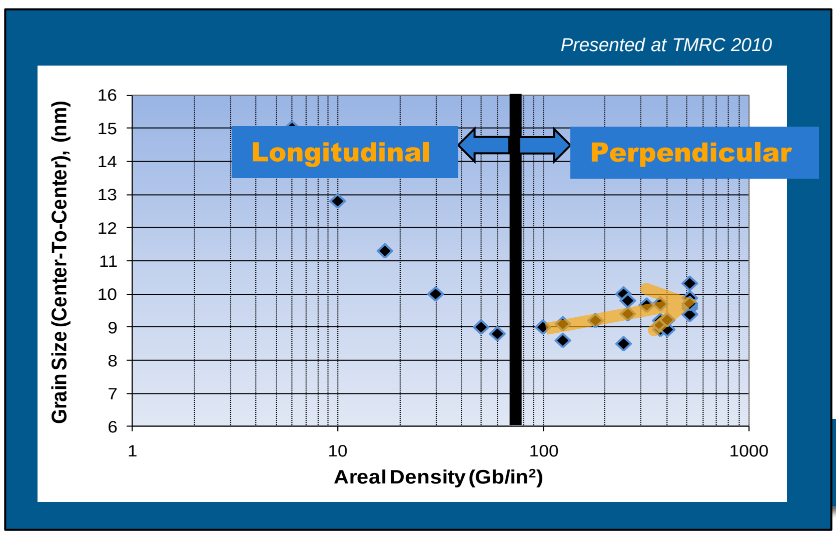
W: Read Width (MRW)
B: Bit Length
S: Cross-Track Corr. Length ~ Grain Size
a: Transition Parameter

$$SNR \approx 0.31 \frac{PW_{50}}{B} \times \frac{B^2}{a^2} \times \frac{W}{S}$$

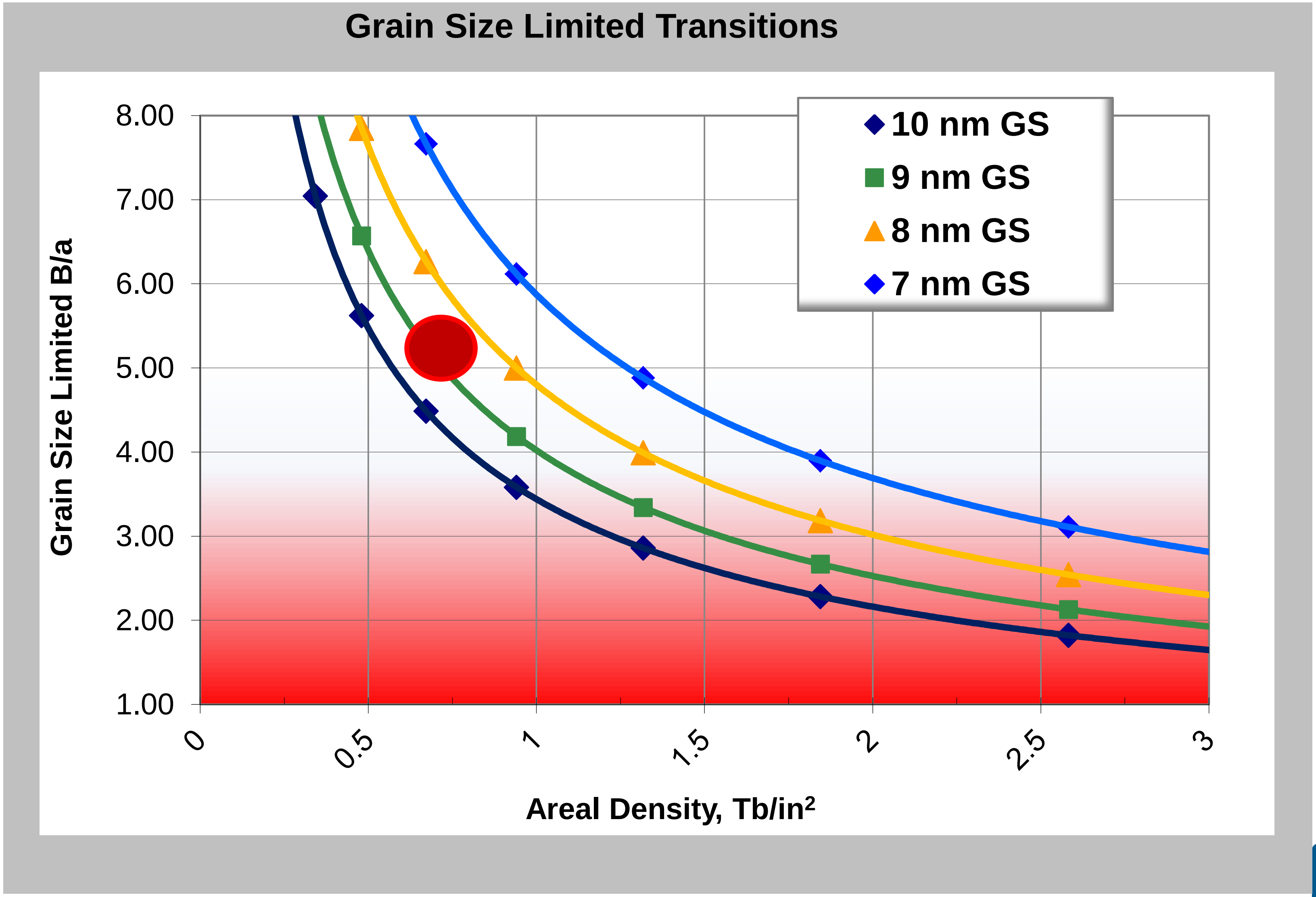
~ constant over generations of products

Decreasing with product generation

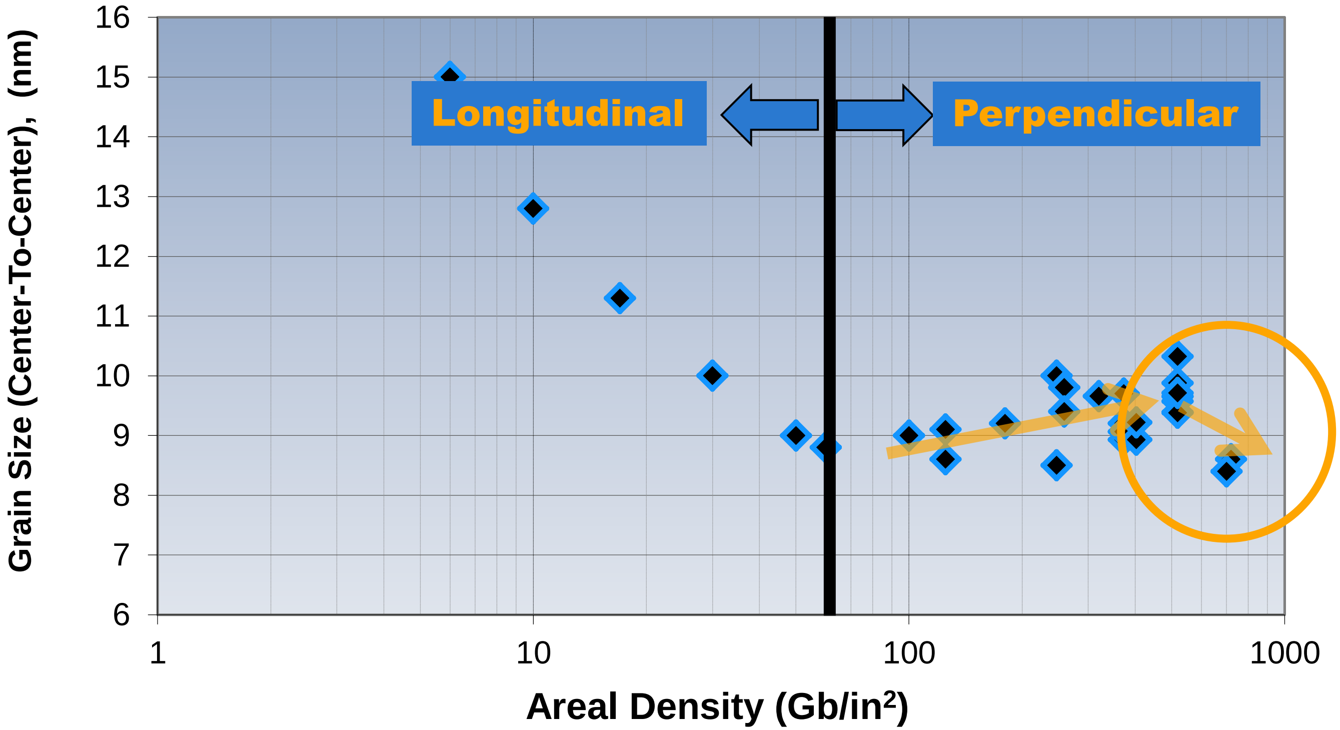




Simple Picture of Grain Size Scaling in Media

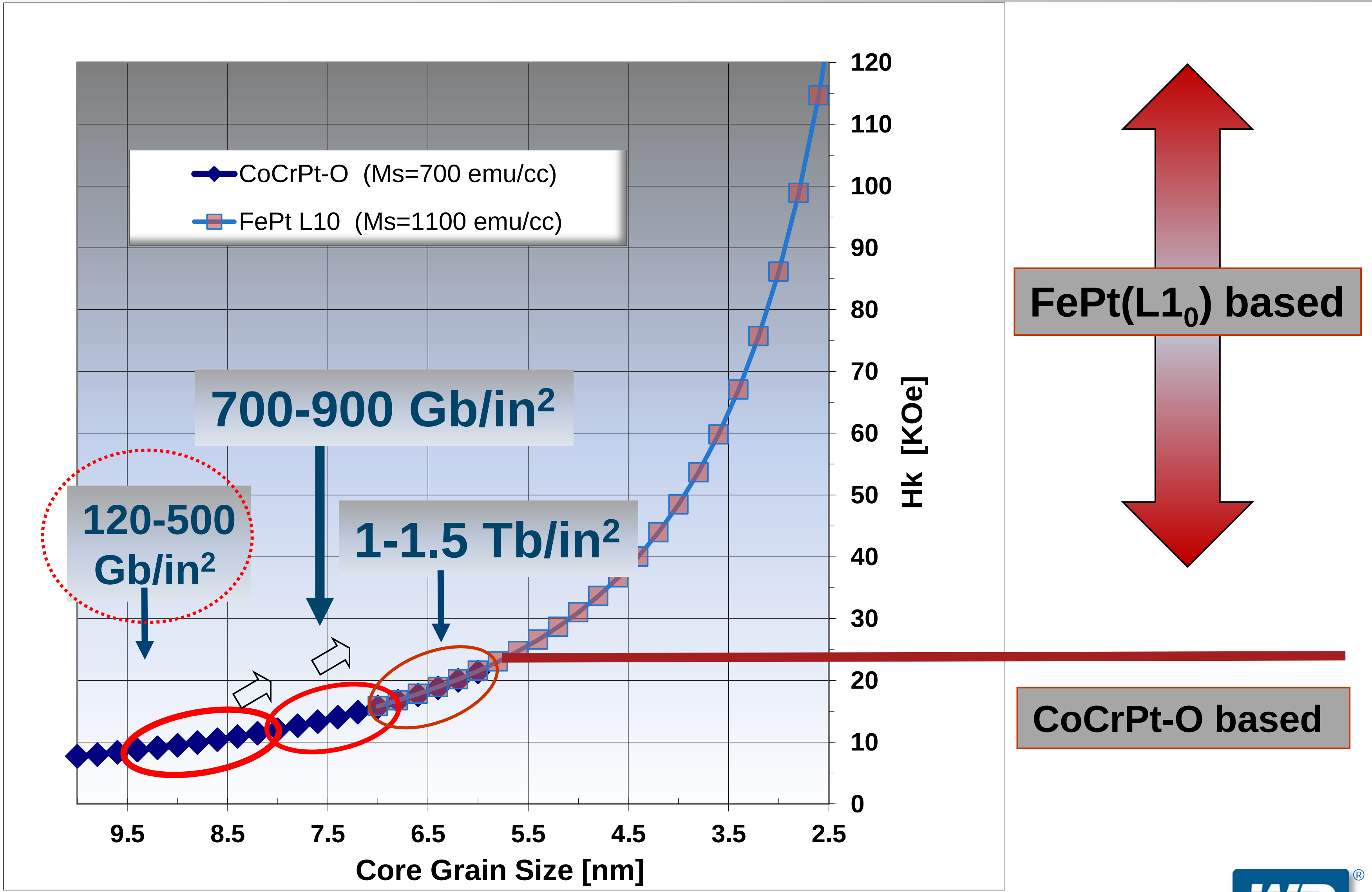


Grain Size Progression vs. Areal Density

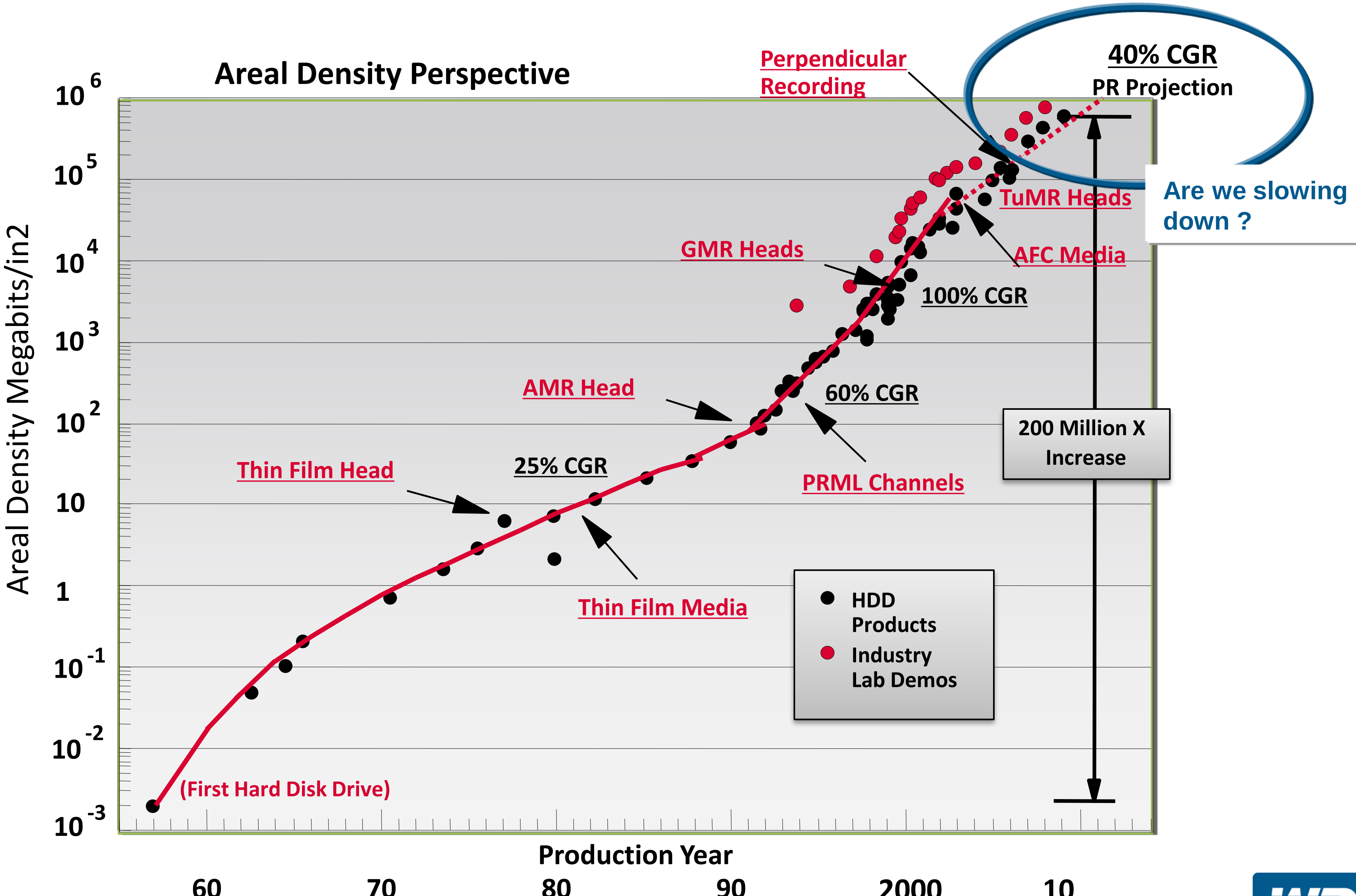


- ECC media structure was expected to yield higher areal density capability by enabling smaller grain size in media.
- In practice, grain size has remained practically unchanged since PMR introduction.
- Instead, the trade-off of choice was to use ECC media to improve writability, maintain acceptable adjacent track erasure, and optimize transition parameter with utilization of higher Ku alloys and optimization of lateral exchange coupling through the various layers.

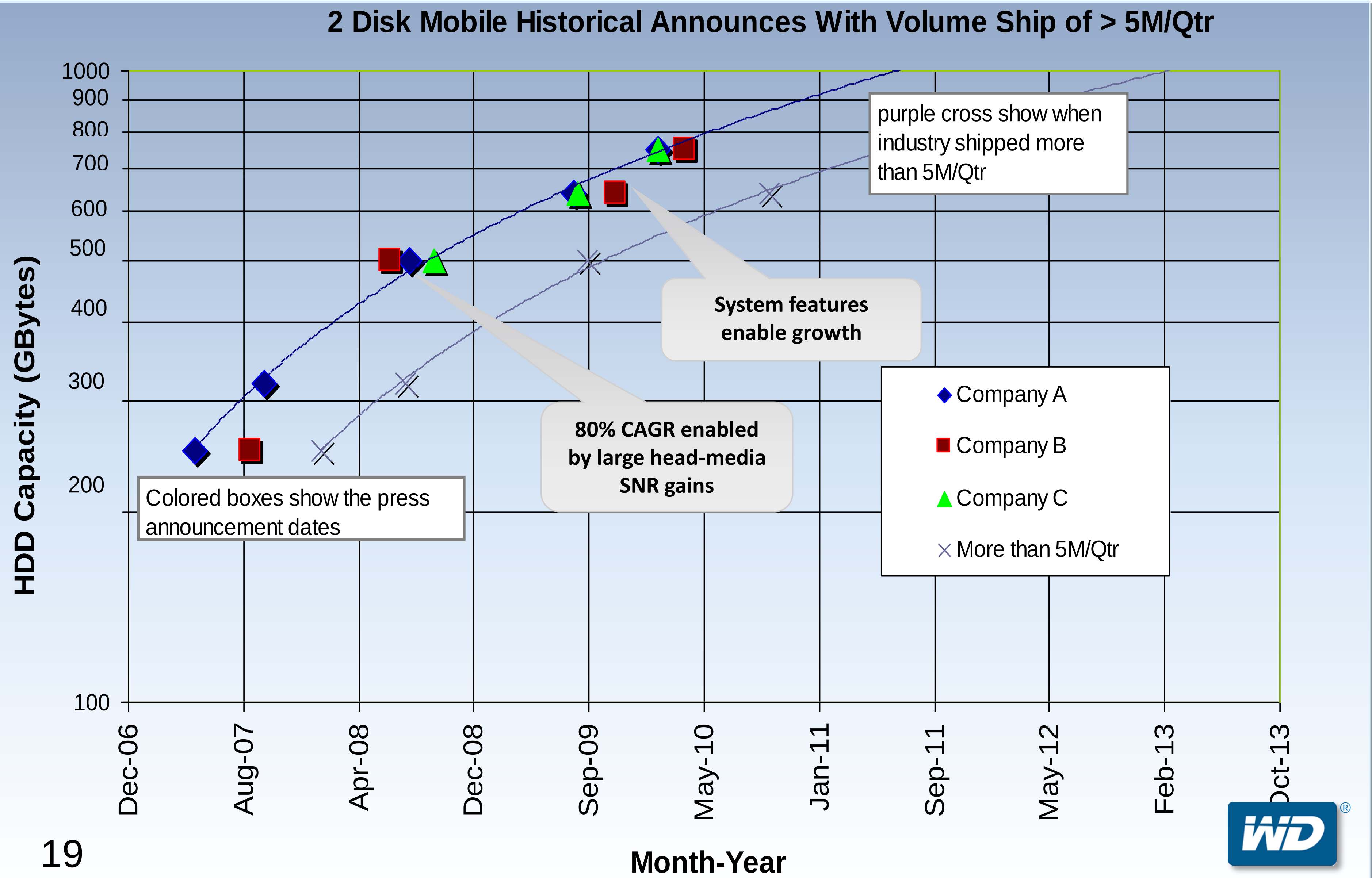
Grain Size and K_u Scaling



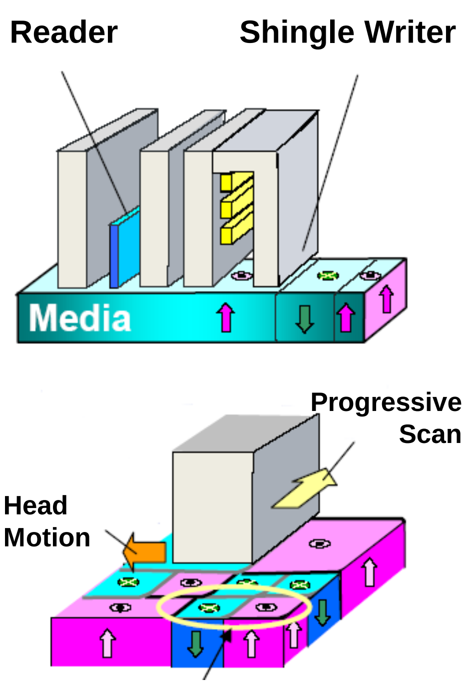
HDD Industry Historical Areal Density Trend

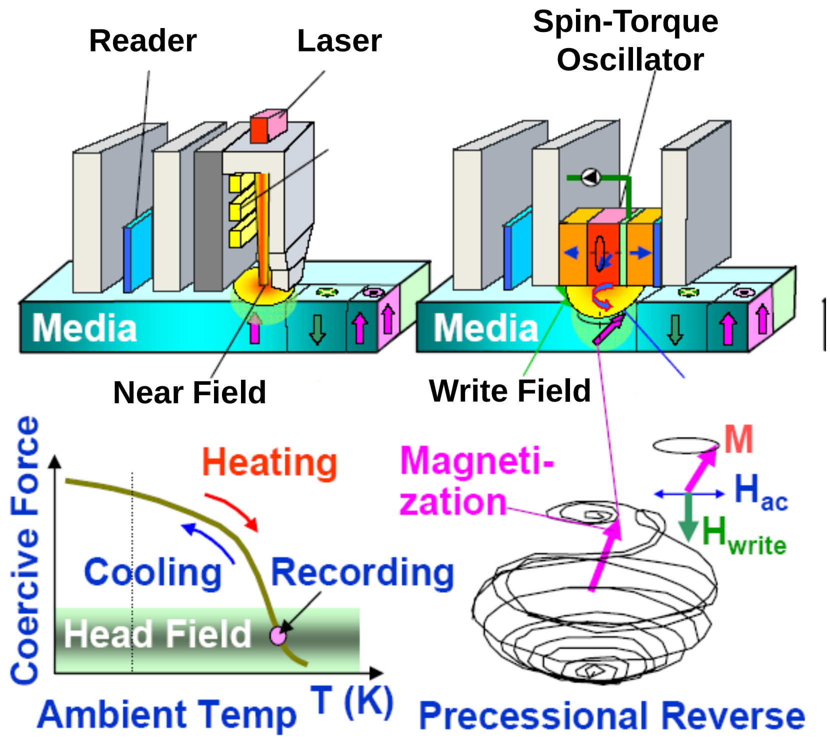


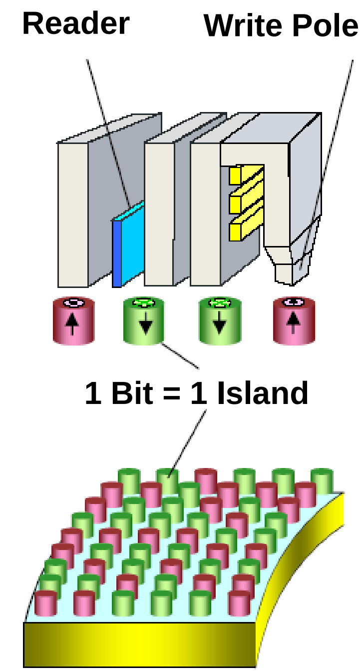
Current Technology Is Reaching Maturity



Technology Options





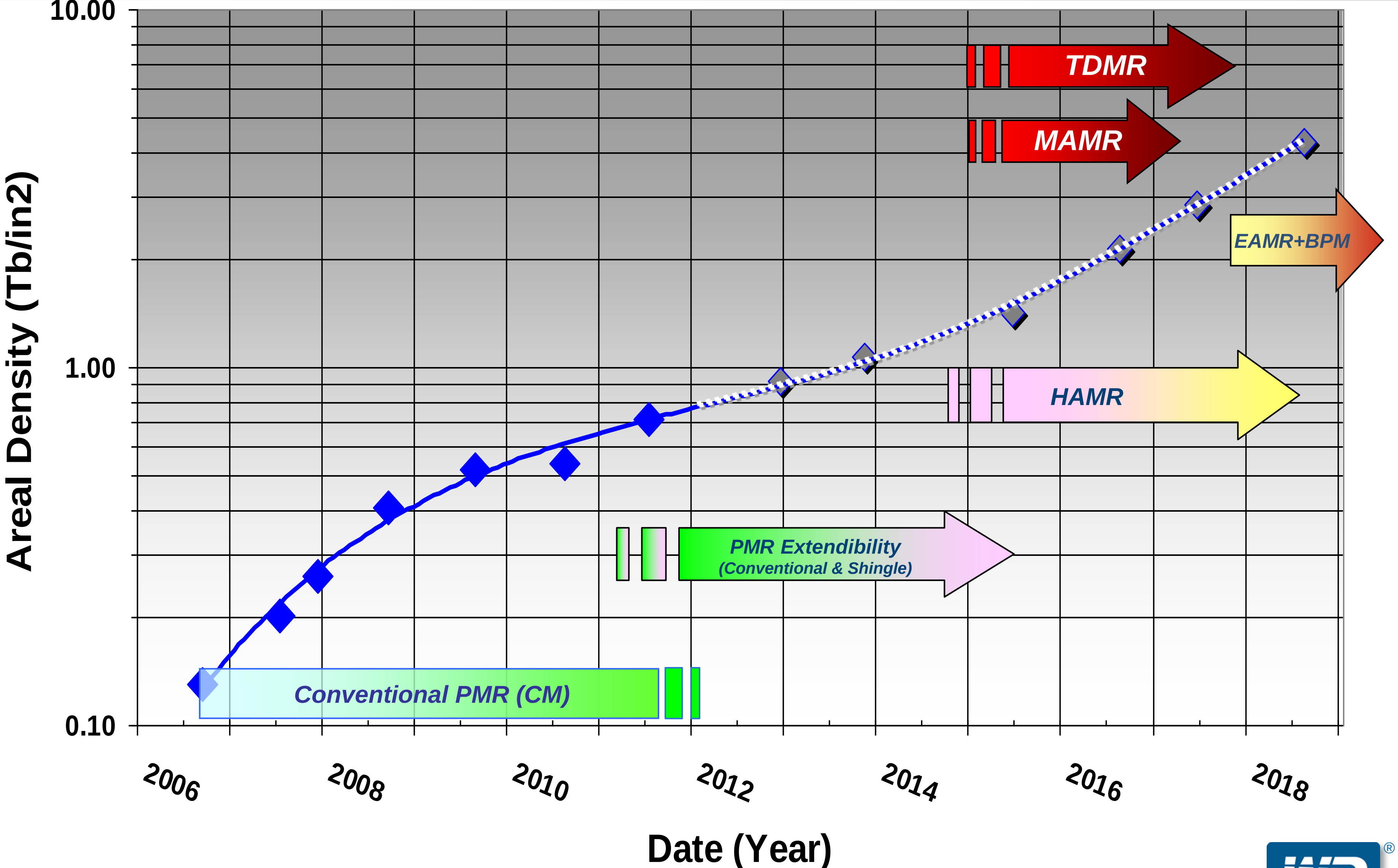


SMR/TDMR | **Energy Assisted Recording** | **Bit Patterned**

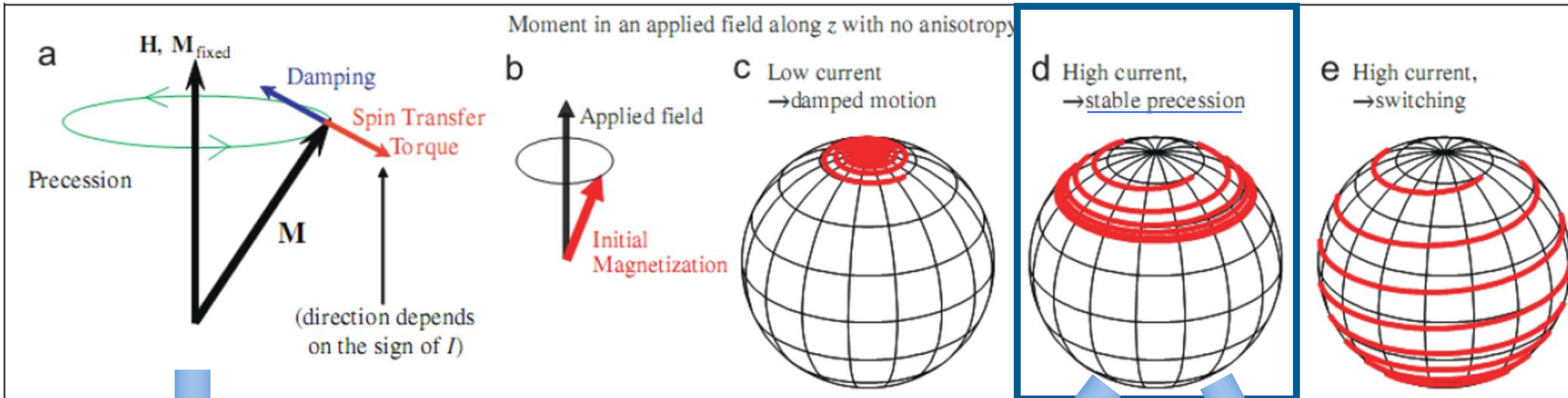
- Continued scaling requires innovations in systems technologies, materials science and process engineering to advance areal density

(Illustrations courtesy of Y. Shiroishi, Intermag 2009)

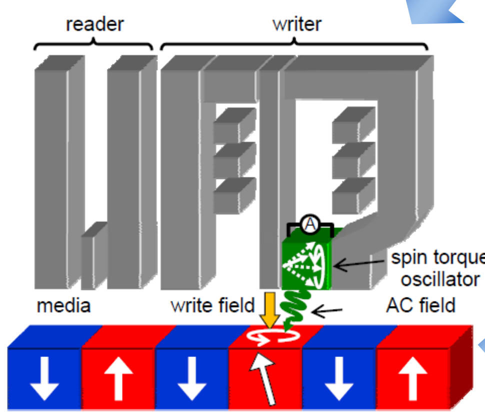
Technology Options for > 1.5 Tb/in²

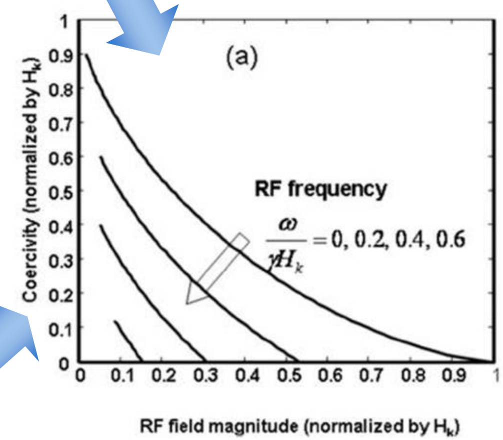


MAMR: Spin-Torque Oscillator Physics



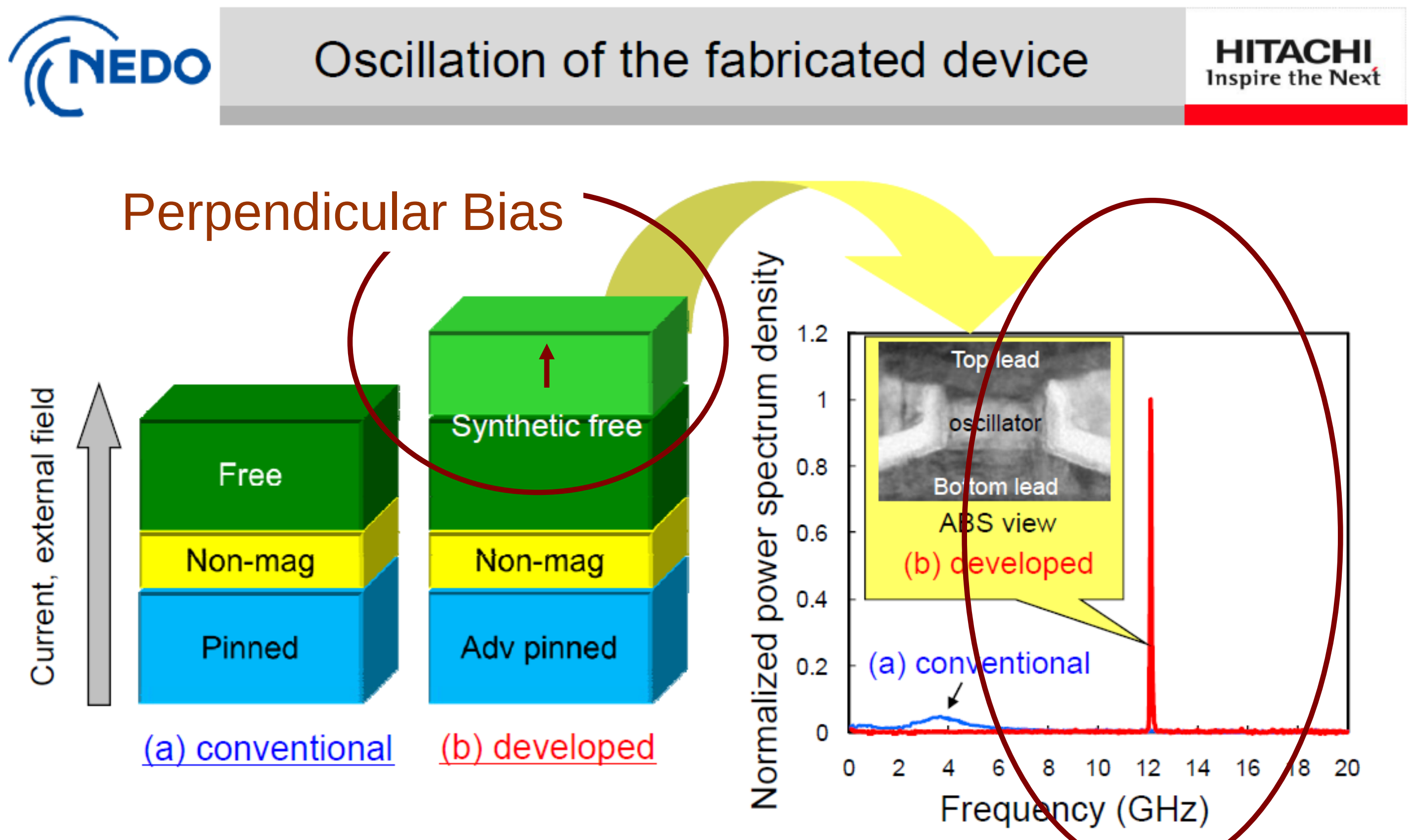
- **The spin-transfer torque opposes the damping torque**
  - When both are equal, precession becomes stable (condition "d" above)
- **Damping is energy loss per cycle (into lattice waves, spin waves, electron excitations, etc.)**





- **Reduction of 30- 40% of media switching field**
- **Effective gradients of 1500-3000 Oe/nm**

Hitachi/NEDO STO Demonstration



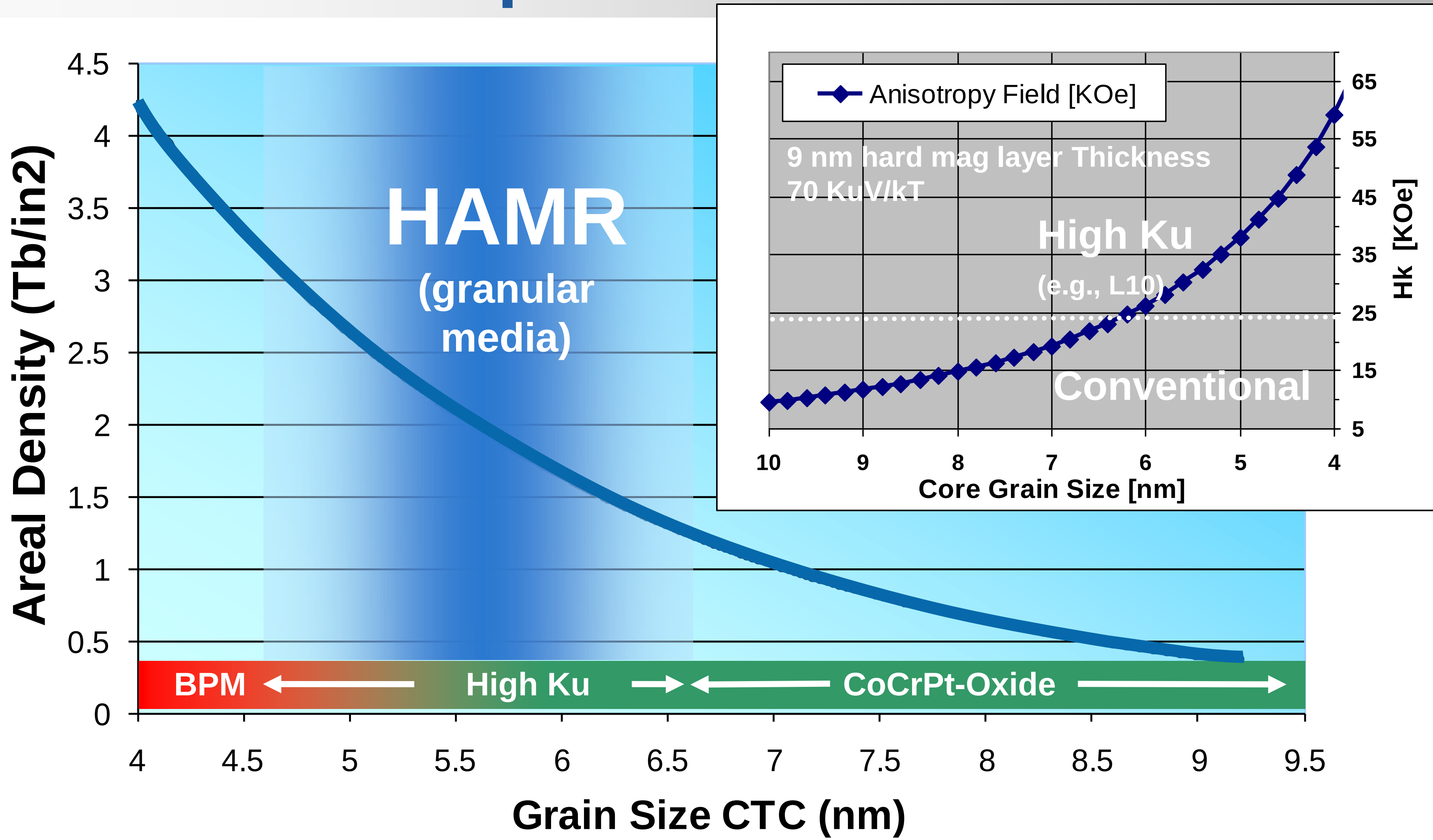
Stable & high frequency (10 GHz class) oscillation confirmed from newly developed device.

2

MAMR Technology and Media

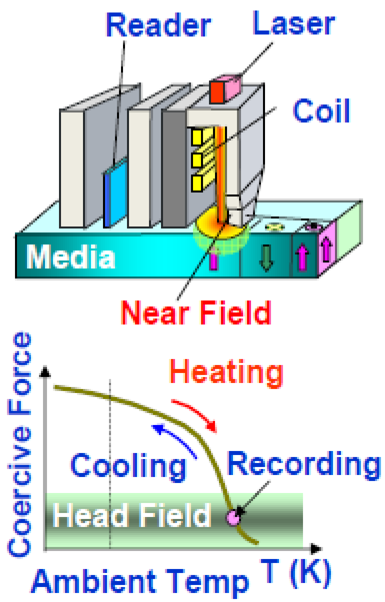
- **MAMR can extend the use of conventional PMR media. Higher Ku in CoPtX-Oxide alloys must be realized.**
- **With the higher Ku materials, media grain size must be decreased aggressively for this technology to show its promise.**
- **If MAMR is extendible to >2Tb/in^2, new high Ku material systems will be required**
  - …but could be simpler than HAMR media as Curie temperature is not part of the design criteria.
- **Companies now assessing MAMR's potential. Not much energy has been devoted to it across industry.**

Grain Size Expectations



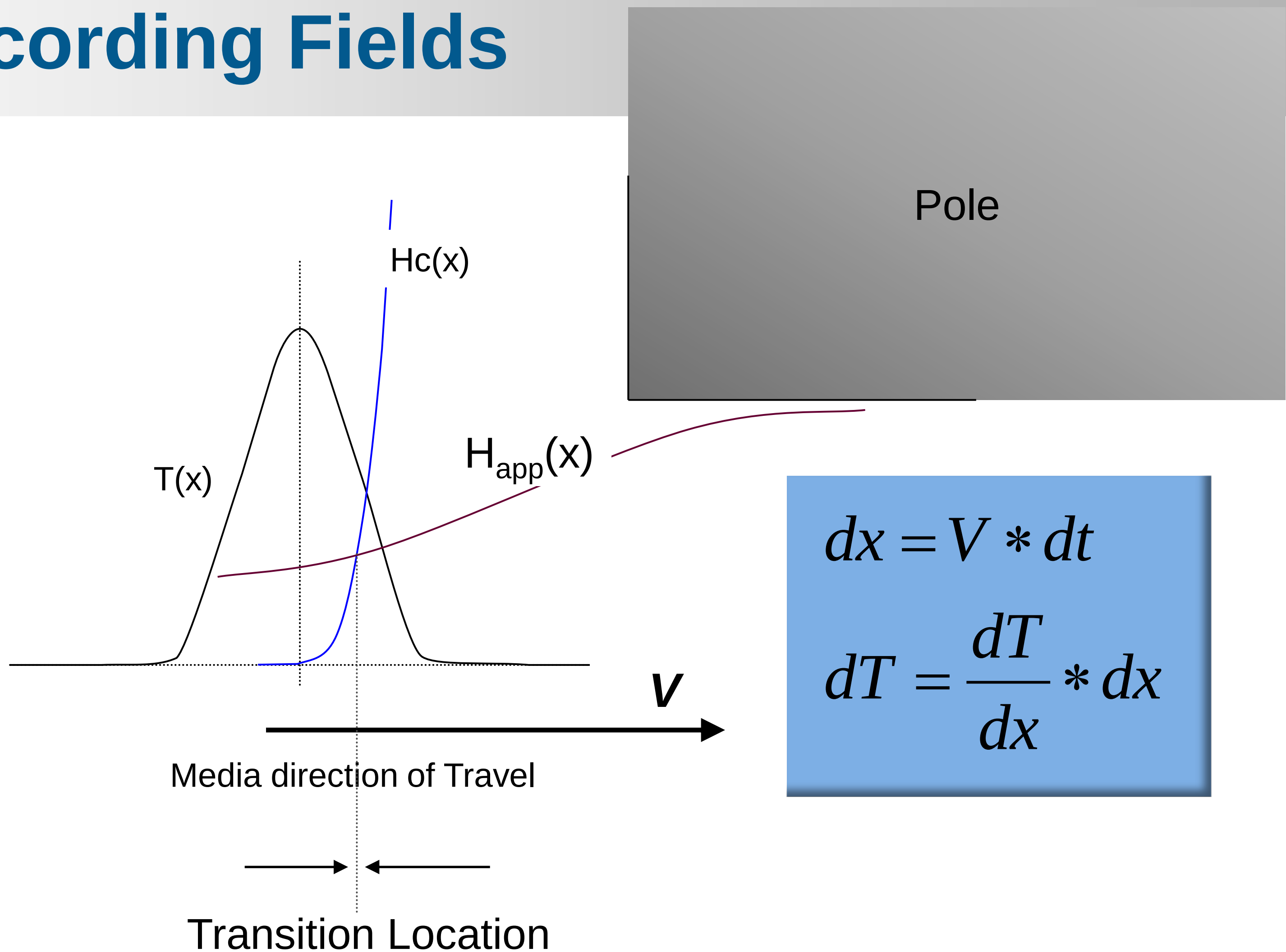
Grain size must come down to enable higher areal densities. HAMR has potential to switch extremely high Ku materials.

HAMR Recording Fields



(b) Heat Assisted

Y. Shiroishi, Intermag 2009)

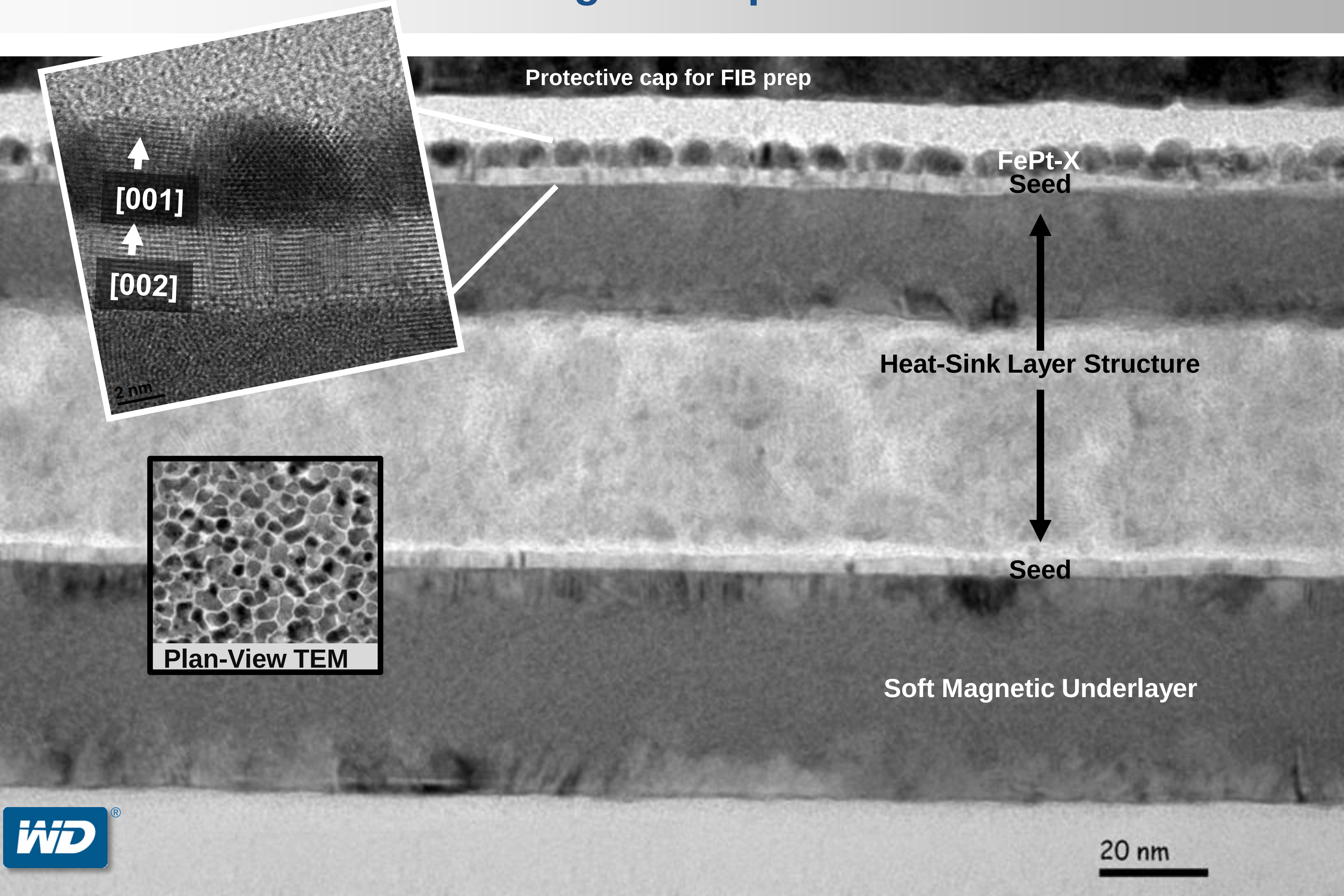


$$dx = V * dt$$

$$dT = \frac{dT}{dx} * dx$$

By knowing T(x), M(x), Ku(x), Hk(x) and Happ (x) we can make simple observations of the recording process for grains of different size.

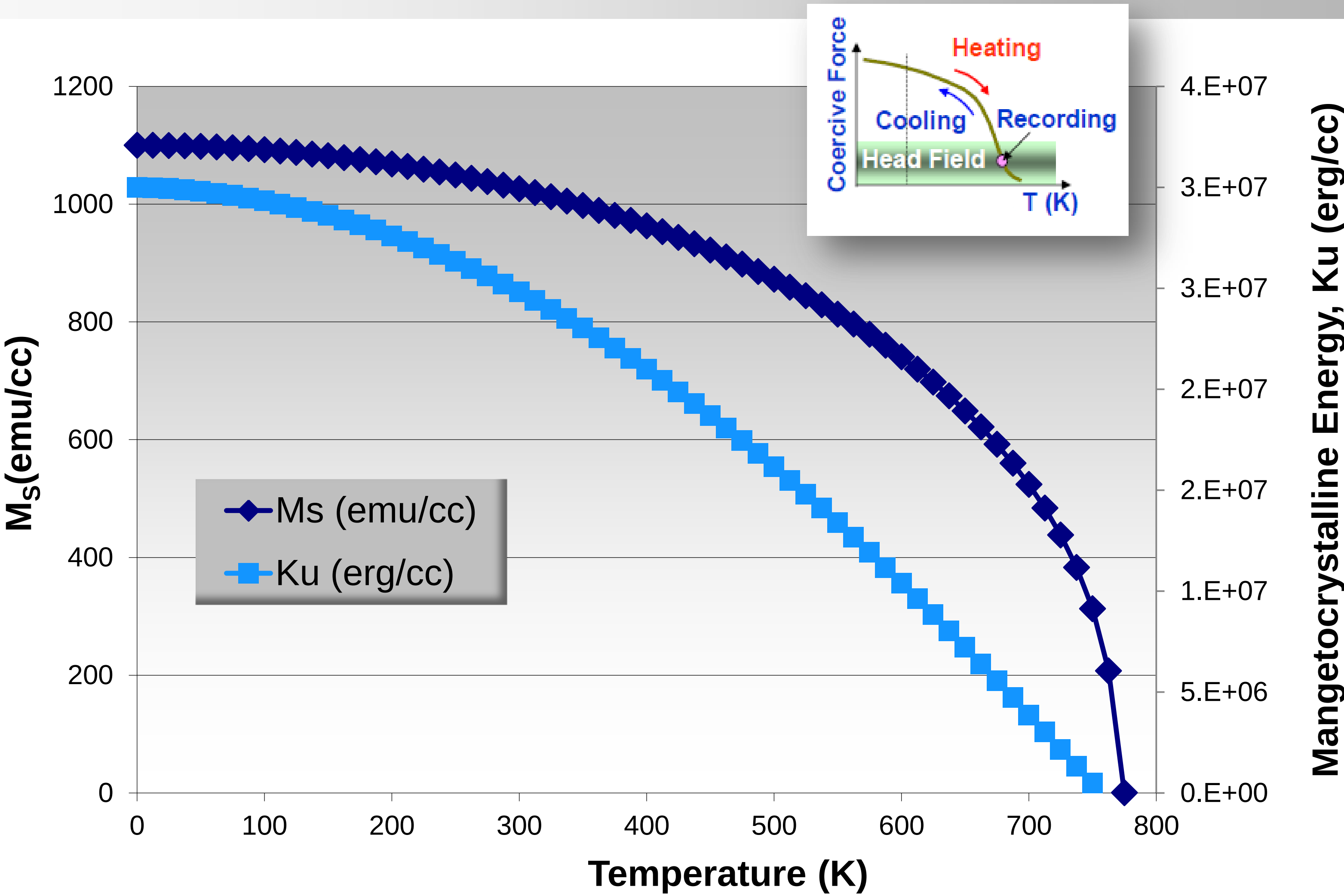
Cross-sectional TEM Image of Experimental EAMR Media



Heat Assisted Media Challenges

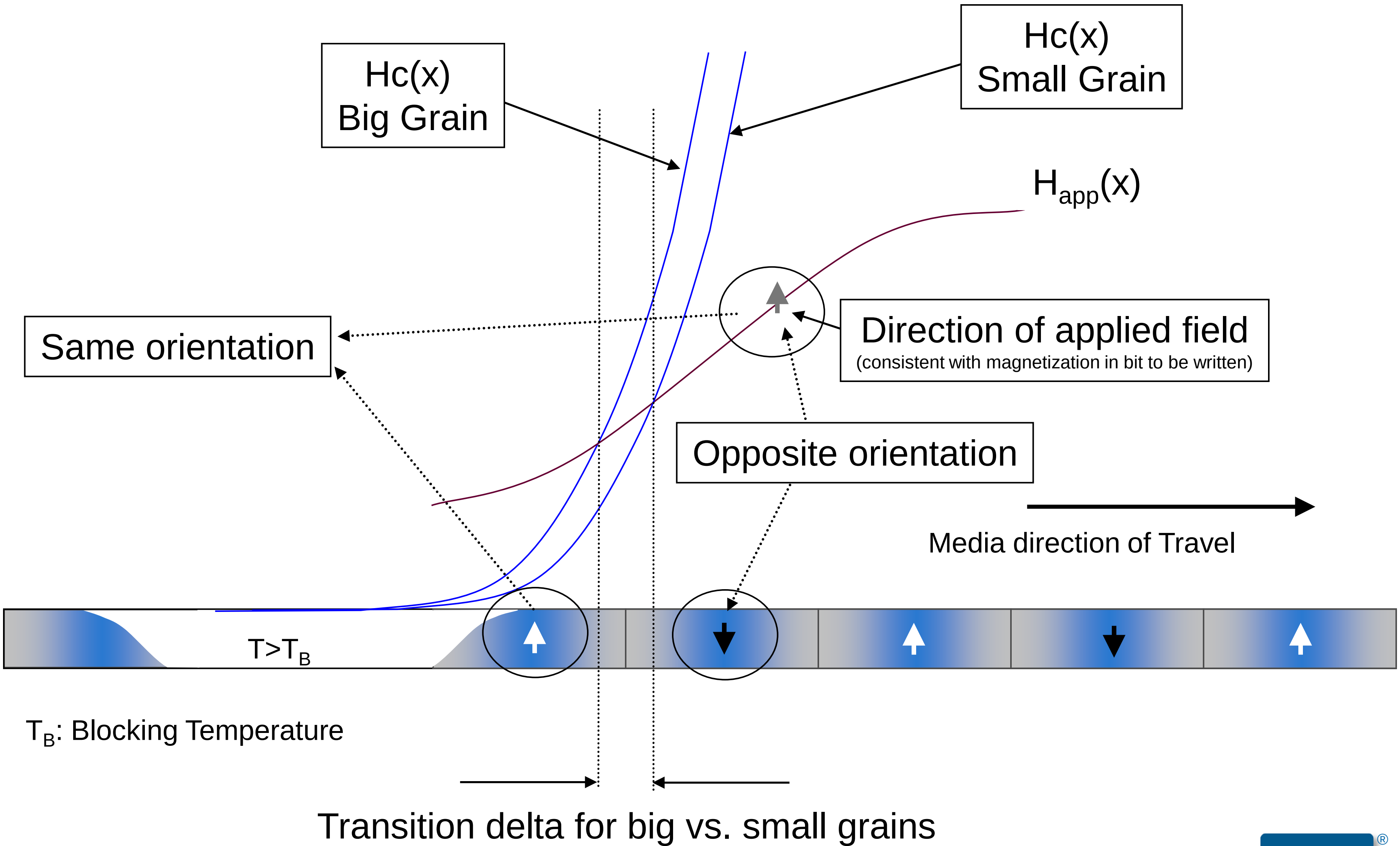
- **Grain Size and Morphology**
  - **Grain Size Uniformity**
  - H_K Uniformity
    - Grain-to-grain $L1_0$ atomic ordering uniformity
    - Grain-to-grain compositional uniformity
  - Intergranular Magnetic Exchange Uniformity
    - E.g., grain boundary width uniformity
- **Roughness**
- **Thermal Design**
  - Heat-sink and thermal barriers
  - Tc tailoring
- **Overcoat/Lubricant**

Magnetization and Anisotropy as Function of Temperature



Knowing Ms(T) and Ku(T) allow us to estimate many aspects of the writing process

EAMR Recording: Grain Size Effect on Transition Location



Energy Balance for Grains at Either Side of Transition

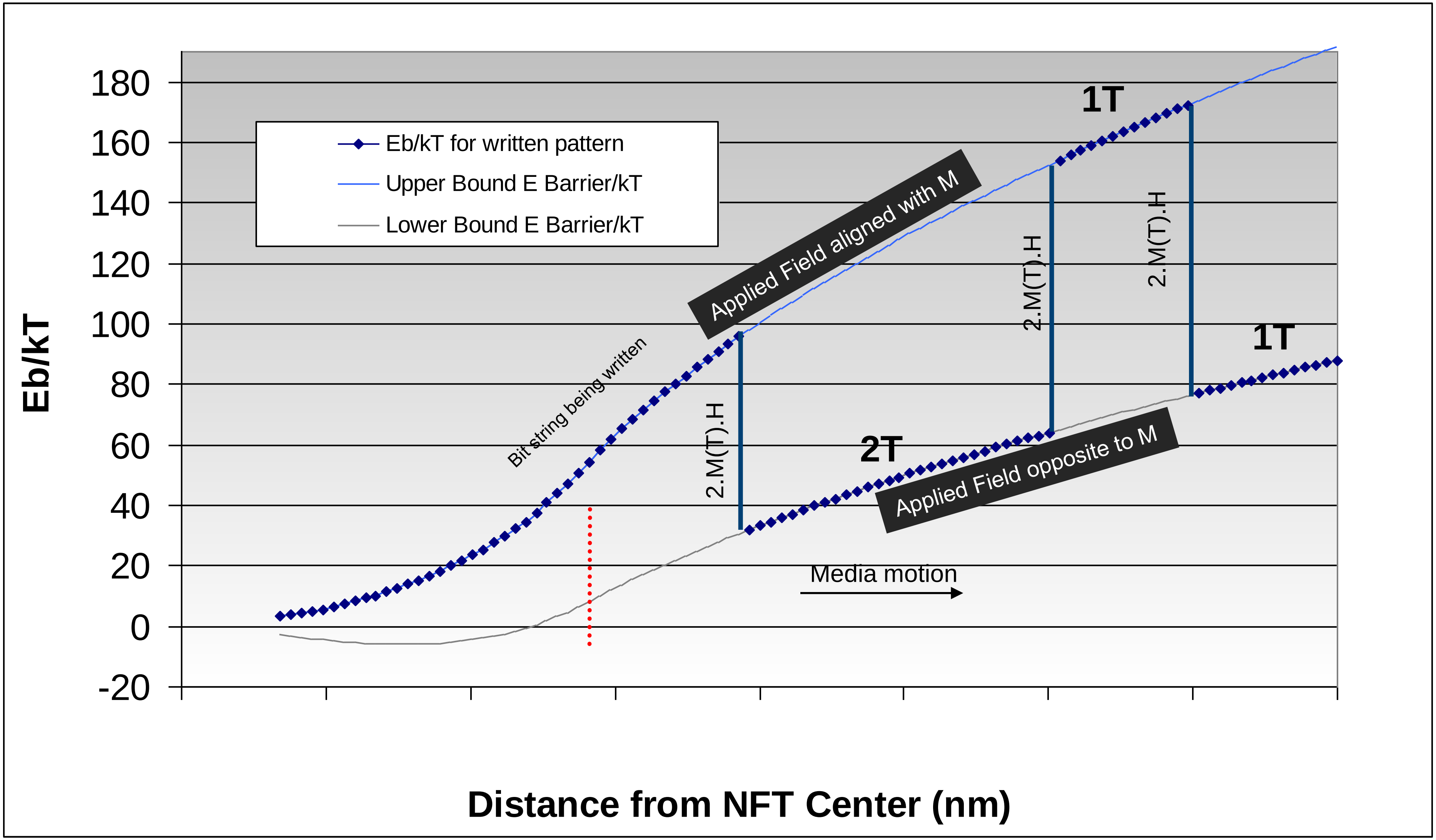
Magnetocrystalline:	$K_u \times \mathrm{Sin}^2(\theta) \times \mathrm{Vol}$
Zeeman :	$\mathbf{M}.\mathbf{H} = M \times H \times (\mathrm{Cos}\ \psi) \times \mathrm{Vol}$
Demagnetizing:	$2 \times \pi \times N \times M^2 \times \mathrm{Vol}$

Magnetocrystalline + Zeeman - Demag

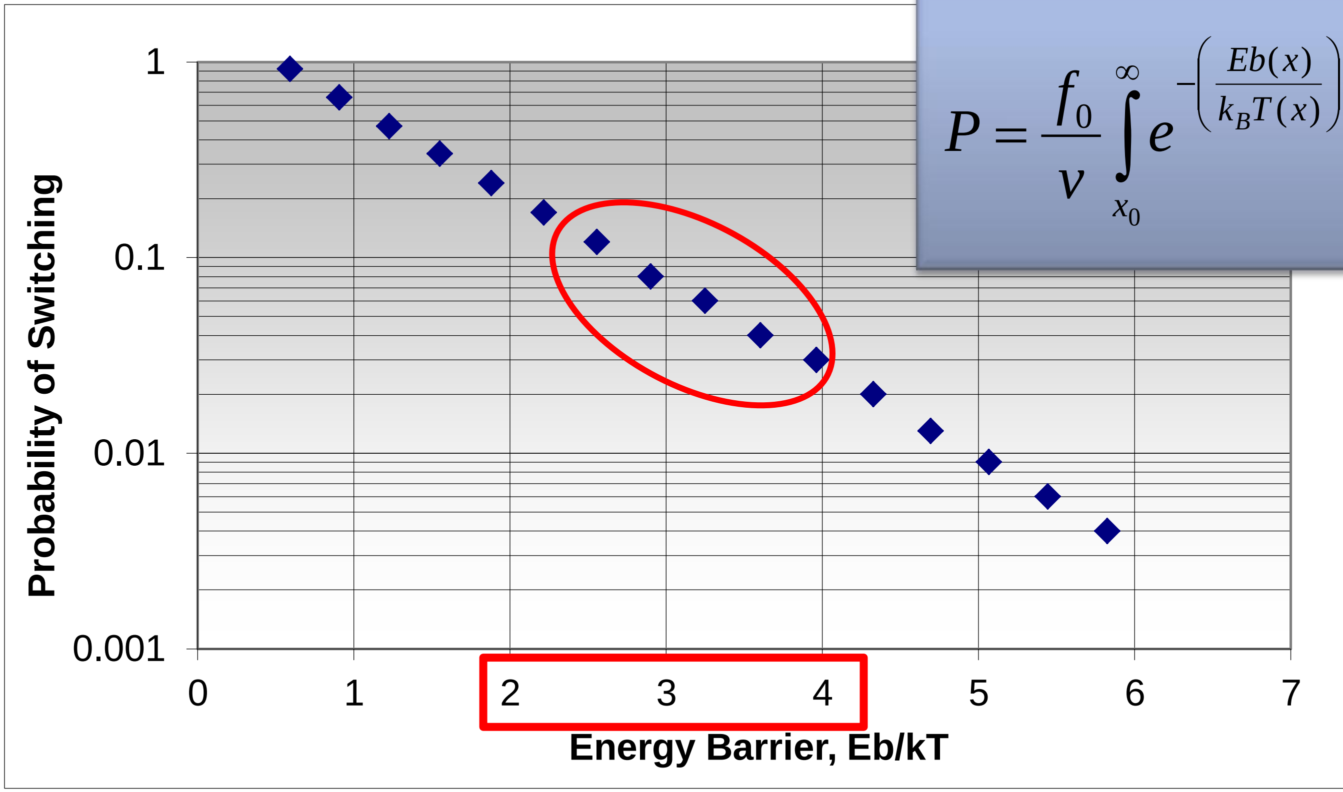
Magnetocrystalline - Zeeman - Demag

For a particle (grain) to freeze magnetically its Energy Barrier/K_bT must be larger than a certain value.

Energy Barriers During Writing



What Energy Barrier to Freeze Grains in Their State?

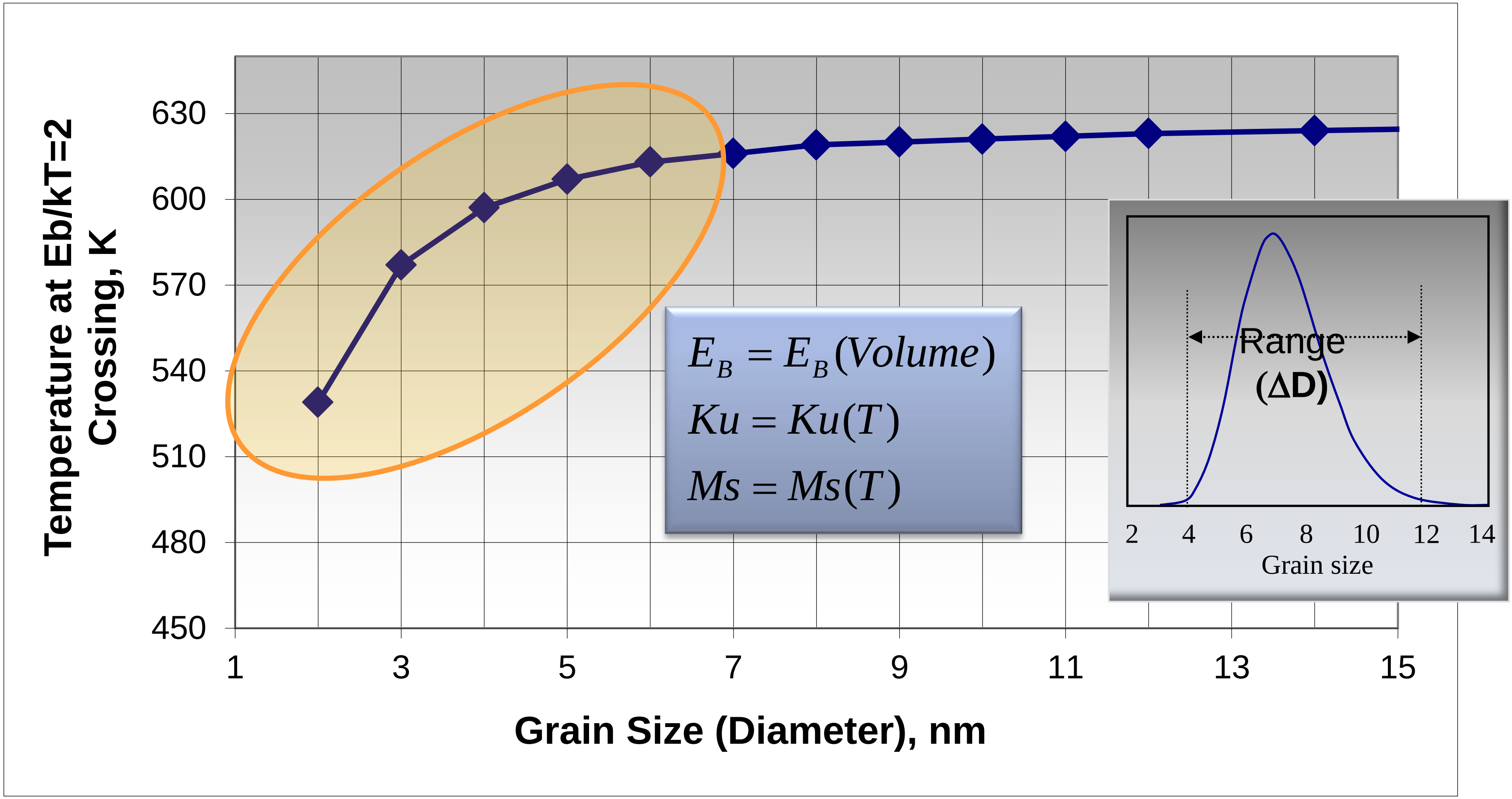


$$P = \frac{f_0}{v} \int_{x_0}^{\infty} e^{-\left(\frac{Eb(x)}{k_B T(x)}\right)} dx$$

$$f_0 = 10^{11} \frac{1}{s}$$

Contrary to conventional recording in HAMR, grains freeze magnetically once their energy barrier is as low as 1.5-4 times k_BT. Media grain volume difference effects are magnified by this fact. Thermal gradients must be steep enough to guarantee the freezing of all grains within a short distance from the intended transition location.

Grain Size Sensitivity to Magnetization Freezing



As grain mean size is reduced, grain size distribution sigma must be reduced significantly for linear density capability. ***Smaller grain size does not automatically result in better performance.***

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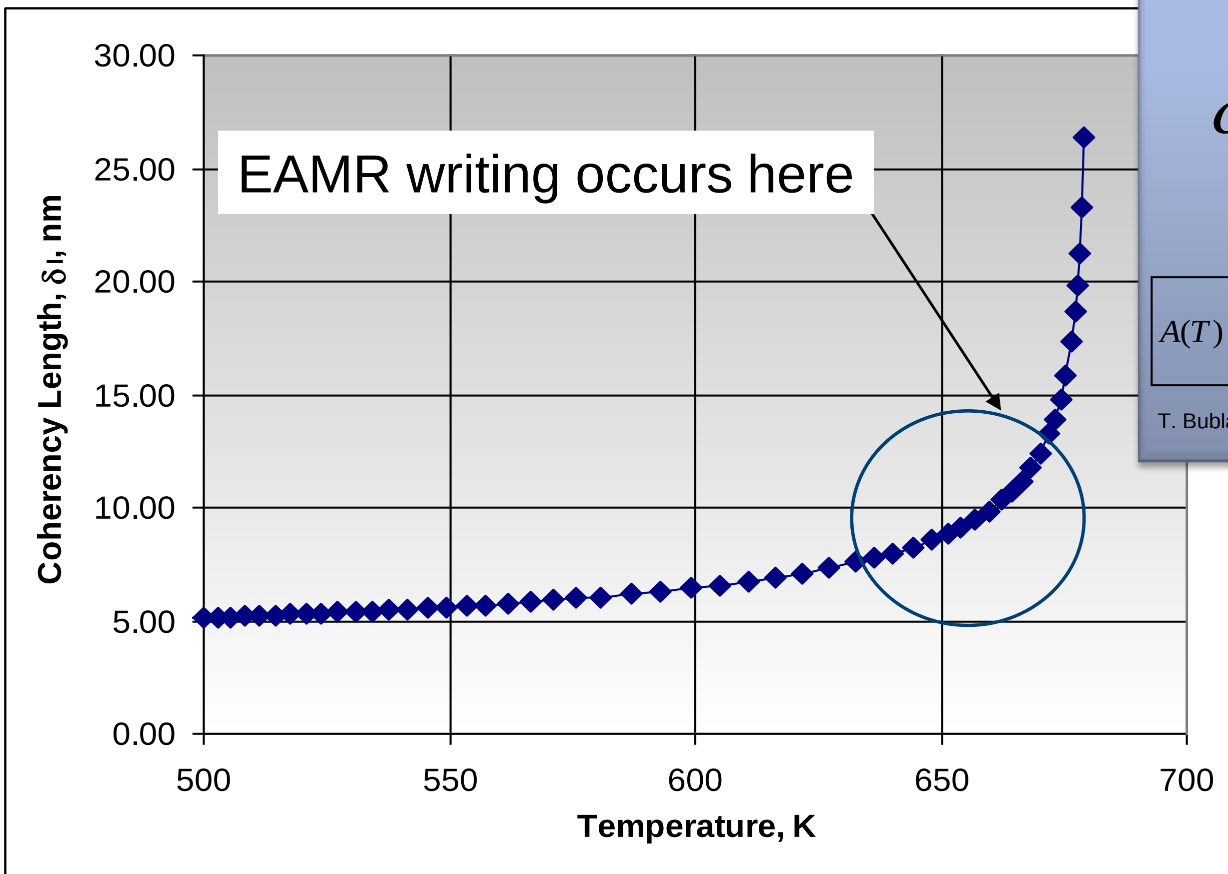
FePt-L1_0 Coherency Length as Function of Temperature

At high temperature the domain wall width is significantly larger than at RT.

Increasing thickness beyond 10 nm may not necessarily increase energy barrier based on this estimate of coherency length for FePt.



$$\delta_l(T) = 4\sqrt{\frac{\mathrm{A}(T)}{\mathrm{K_u}(T)}}$$

$$A(T) = \frac{M_S(T)k_bT_0}{2g\mu_0\mu_B}\left(\frac{0.117\,\mu_0\mu_B}{M_s(0)}\right)^{2/3} = Cont.M_s(T)$$

T. Bublat and D. Goll, *J. Appl. Phys*. 108, 113910 (2010)

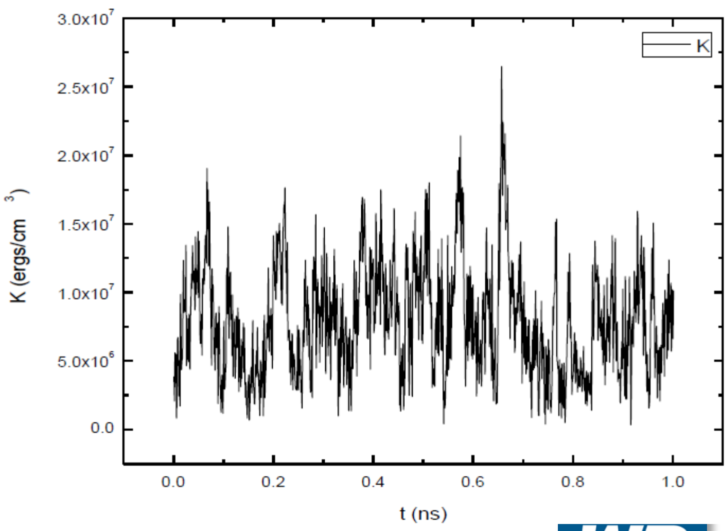
HAMR Media Grain Size Observations

- Grains of smaller size require lower temperatures to magnetically freeze.
- Under typical HAMR recording conditions freezing takes place near E_B/k_BT~1-3.
- Grain size effects are magnified under EAMR (high T) conditions.
- For grains in a given distribution to freeze within a distance corresponding to a fraction of the bit length, they must meet very tight size sigma requirements.
- Sigma requirements for grain sizes in the 2-4 Tb/in^2 are very stringent if $Eb/k_BT>>2$. What is the correct energy barrier to use ? (strongly dependent on media design).
- Physics of high speed switching near Tc have not been sufficiently studied.

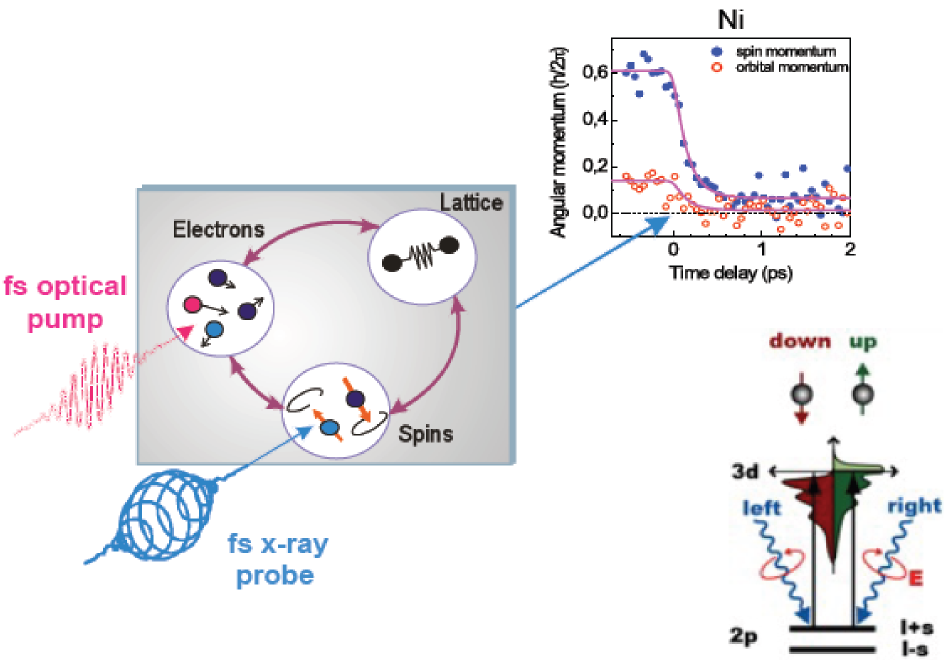
Hk Fluctuations near Tc

- **The promise of heat assisted recording is rooted on the premise of extremely high thermal gradients to write transitions much sharper than possible by just magnetic means.**
- **In order to capitalize on the high switching effective gradients and achieve high recording linear density,**
  - The magnetic anisotropy of the media must be as high as possible
  - The Curie point of the media must be as low as possible (but safely higher than RT for archivability)
  - → FePt is an nearly ideal system for satisfying both conditions above.
- **However, we assume <u>time averaged</u> properties for anisotropy vs. temperature of the media.**

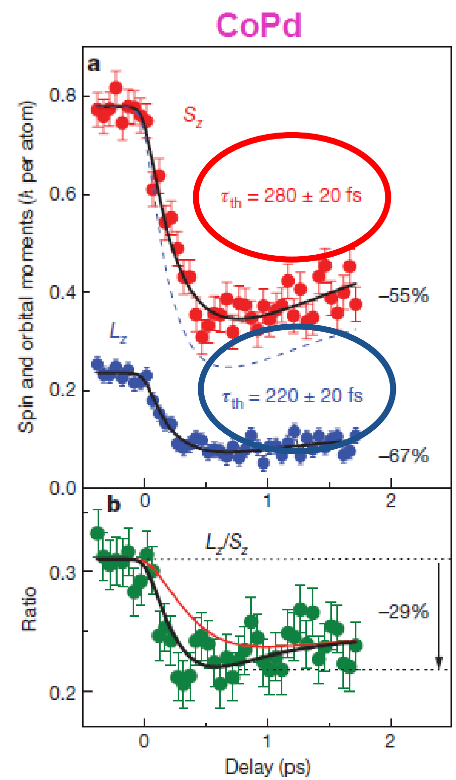
- There are some suspicions that temporal fluctuations in Hk near Tc can be large and relevant during the writing process.
- Modeling by R.Victora, UMN, support this conjecture, with particle size being a big factor.
- If experiments confirm this behavior, ways to minimize the negative effects through novel layer structure designs will be needed.



Ultrafast Measurements at LCLS



Stamm, Dürr, et al., Nature Materials **6**, 740 (2007);
Stamm, Dürr, et al., PRB **81**, 104425 (2010)



Experimentally, these fluctuations could be time resolved by new tools such as the LCLS facility at Stanford with femto-second resolution.

New Industry Consortium

"Advanced Storage Technology Consortium"

ASTC
ADVANCED STORAGE TECHNOLOGY CONSORTIUM

IDEMA®

- **New consortium created to expand and enhance the power of R&D funding**
  - Acceleration of technology development by targeted collaborations between storage industry participants, suppliers, universities, laboratories, and institutes
- **Mission: member-directed, scalable R&D organization to address fundamental technology challenges**
- **Supply chain involvement**
- **HDD technology roadmap**

WD®

Why Do We Need Something Different ?

- Pace of technology transitions and scope of change required means business as usual approach won't work
- Need to collimate and focus entire industry R&D to be successful
- Need coordinated transitions in supply base - components, equipment, and materials

Expected Outputs from ASTC

- **Focused, collaborative research projects that will enable better understanding of key scientific challenges**

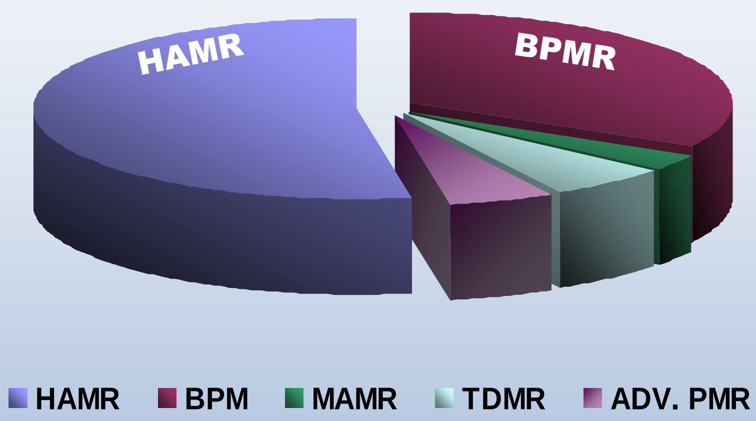
- **Shared, realistic roadmap for the Industry**

- **Solutions – <u>science</u> to <u>engineering</u> to <u>manufacturing</u> options – *that will shorten time from invention to productization***

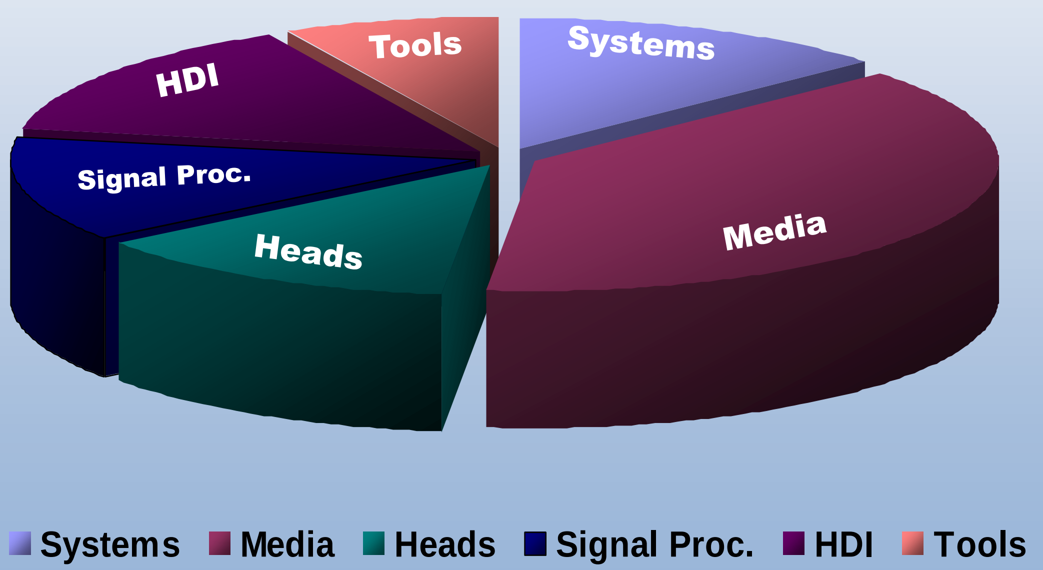
ASTC Funding Allocations

29 projects preselected for 1st year of funding

By System



By Area



Summary And Conclusions

- **Conventional perpendicular media will continue to evolve to higher Ku and smaller grain size as we extend CPR technology.**
- **Magnetic head fields and Ku limits of CoPtX-Oxide media will limit densities to 1-1.5 Tb/in^2 range. Shingling may help extend that range.**
- **Media for heat assisted recording based on FePt has improved significantly but big challenges remain.**
  - Reducing grain size and size distributions while preserving columnar morphology remain challenging given the high processing temperatures required for $L1_0$ ordering.
  - Optimum heat-sink design of media to enhance thermal gradients is limited somewhat by other functional requirements such as low surface roughness.
- **Pace of development needs to increase in order to productize these new technologies as per roadmaps.**
- **New ASTC consortium provides a forum for more open collaboration in addressing the most challenging industry problems.**