Microwave Assisted Magnetic Recording for 2Tb/Sqin

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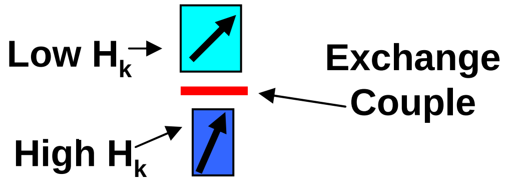
- **NIST Bolder:** Tom Silva, Justin Shaw
- **Colorado State U.,Ft Collins:** Prof. Mingzhong Wu, Lei Lu

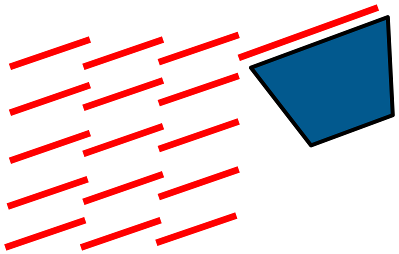
MAMR Topics

- Magnetic Recording Super Paramagnetic Limit
- MAMR with a Spin Torque Oscillator in the writer gap architecture
- Loop simulations
- Write/read simulations
- STO fabrication and test
- STO simulations
- Ferromagnetic Resonance media measurements (NIST Bolder & CSU)
- Microloop marks on media (Colorado State University , Ft Collins)
- Recent Jimmy Zhu MAMR talk

What can we do to extend recording?

- **Conventional PMR**
  - Exchange Coupled Composite media
  - Reduced switching field variability (+1dB/% σ_{Hk})
  - Reduced Inter Layer in media with granular Soft Under Layer
  - Shingled Magnetic Recording
    - Reduce track pitch ~35% ultimately
    - Increased write field from wide pole (higher H_k allows finer grains)
    - **System challenges to preserve performance** (fast access to data)

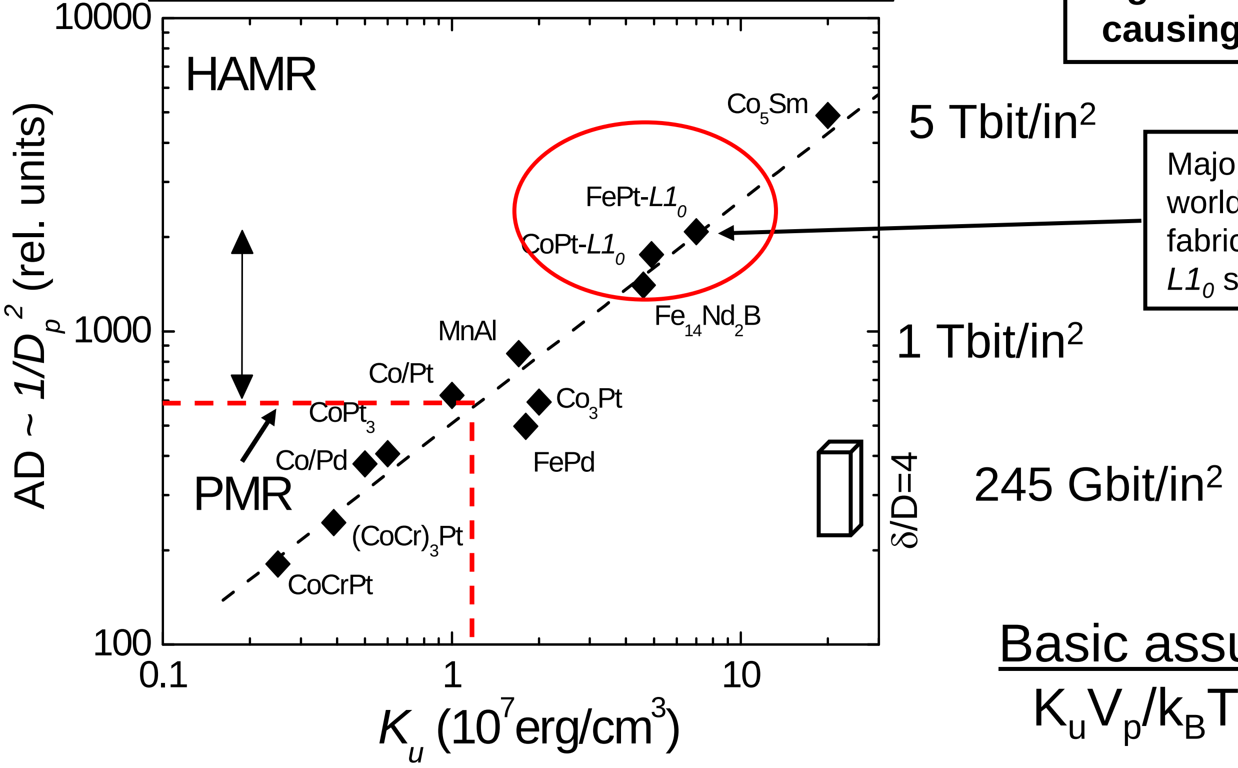




- **Bit Pattern Media allows 1 grain/bit vs ~15 but:**
  - 75% dead space between islands
  - Inadequate write field from very narrow pole (might require Shingling)
  - Requires good write timing to islands and perhaps read after write
  - **Expensive process to get flyable media**
- **Heat Assisted Magnetic Recording can write H_k > 90 kOe but:**
  - Many changes in heads and media need debug time
  - Perfecting L10 FePt media needs time
  - Could use an insurance policy
- **Microwave Assisted Magnetic Recording could**
  - **Gain x2** in data density or it may buy only a little (media properties?)
  - Only a small change to the head is required (media can be evolved to optimum)
  - **Will it work better than PMR?**

Heat Assisted Magnetic Recording for High K_u

$$AD_{\max} \propto K_u^{2/3} @ T_S = 350K$$



Plot is based on bulk materials properties (Ku, Ms); small grains have a lot of surface causing properties to change!

Major efforts worldwide to fabricate such $L1_0$ structures

Basic assumption:

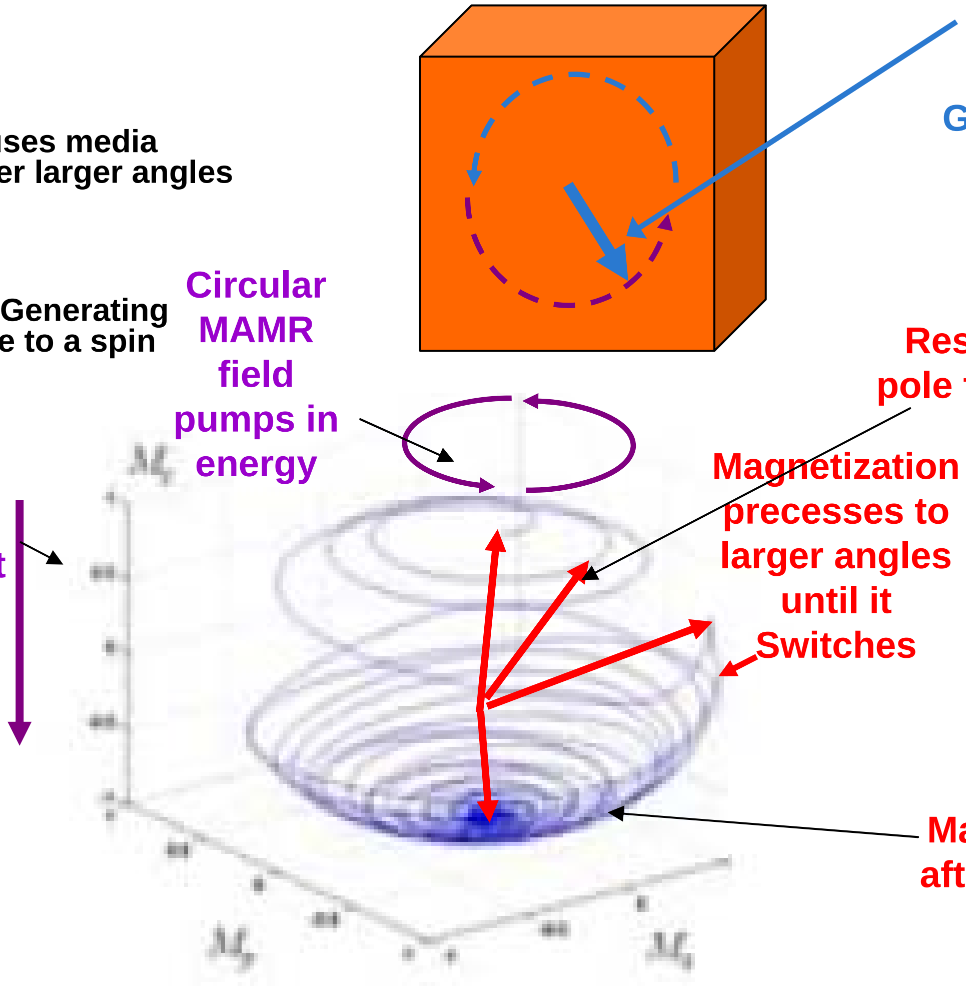
K_uV_p/k_BT~const

Scaling strategy: tall grains with small core size D_p!
Grain aspect ratio of δ/D=4 optimizes thermal stability!

D. Weller, et al., IEEE Trans. Magn. 36, 10(2000).

MAMR Switching Driven by a Spin Torque Oscillator Field

- Microwave field of the STO causes media magnetization to precess at ever larger angles until it switches
- The magnetization of the Field Generating Layer in the STO precesses due to a spin polarized current flowing int



Magnetization of the Field Generating Layer of the Spin Torque Oscillator precesses

Circular MAMR field pumps in energy

Pole Tip field is insufficient to switch by itself

Rest position due to pole field before MAMR field starts

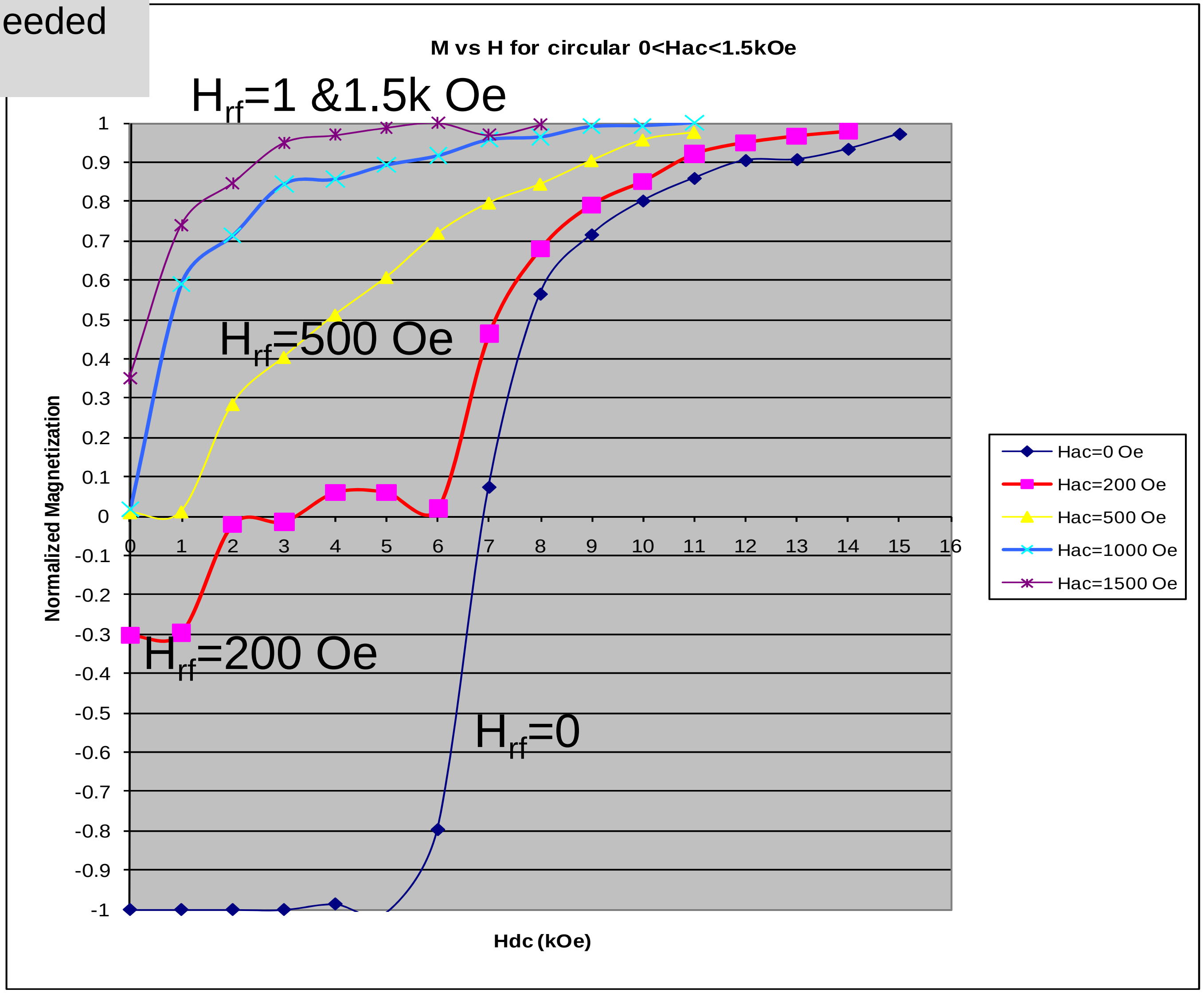
Magnetization precesses to larger angles until it Switches

Magnetization after switching

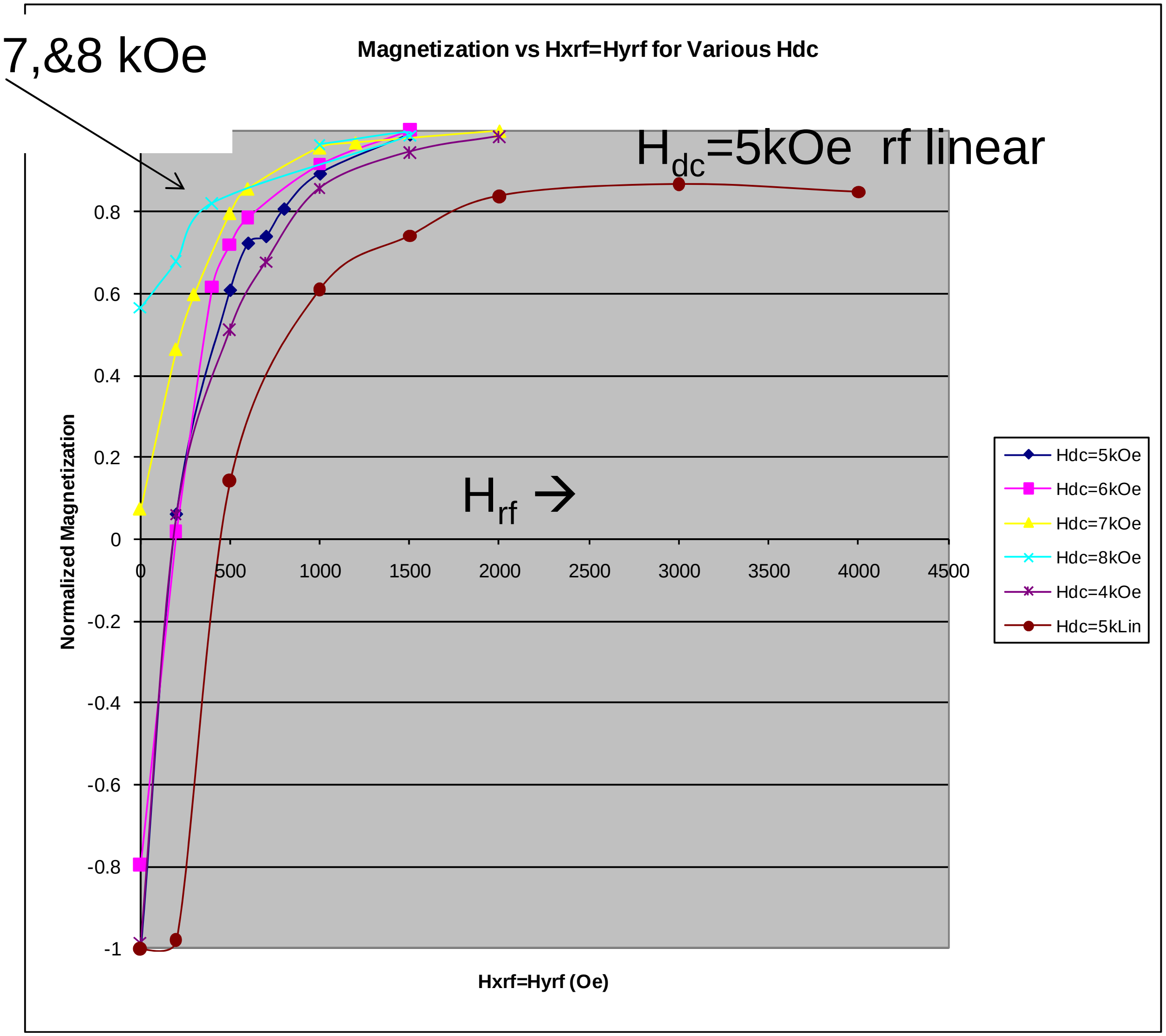
Circular AC Field

WD Simulated Loops with circular H_{rf} to understand Bf-09 MMM2012 , Bruce Terris, HGST (sees significant H_n reduction; little H_c effect with ~500 Oe rf with linear polarization)

H_{rf} => 1 kOe needed to get $M = M_s$



WD Simulation gives H_{dc} => 8 kOe to get $M=M_s$ with Hrf = 1 kOe (note that Hsat = 14 kOe for no RF)



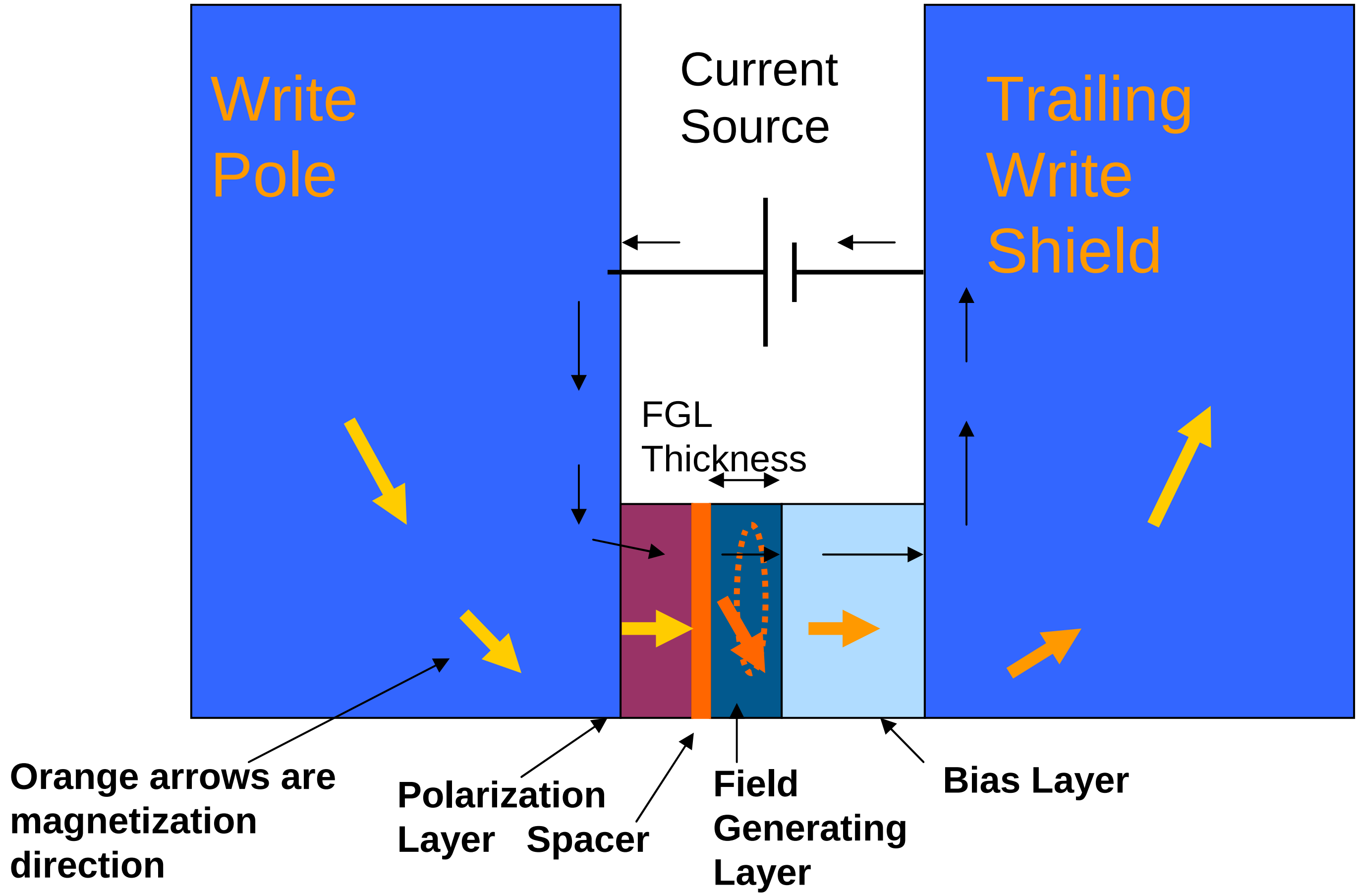
H_{dc}=4,5,6,7,&8 kOe
circular rf

H_{dc}=5kOe rf linear

H_{rf} →

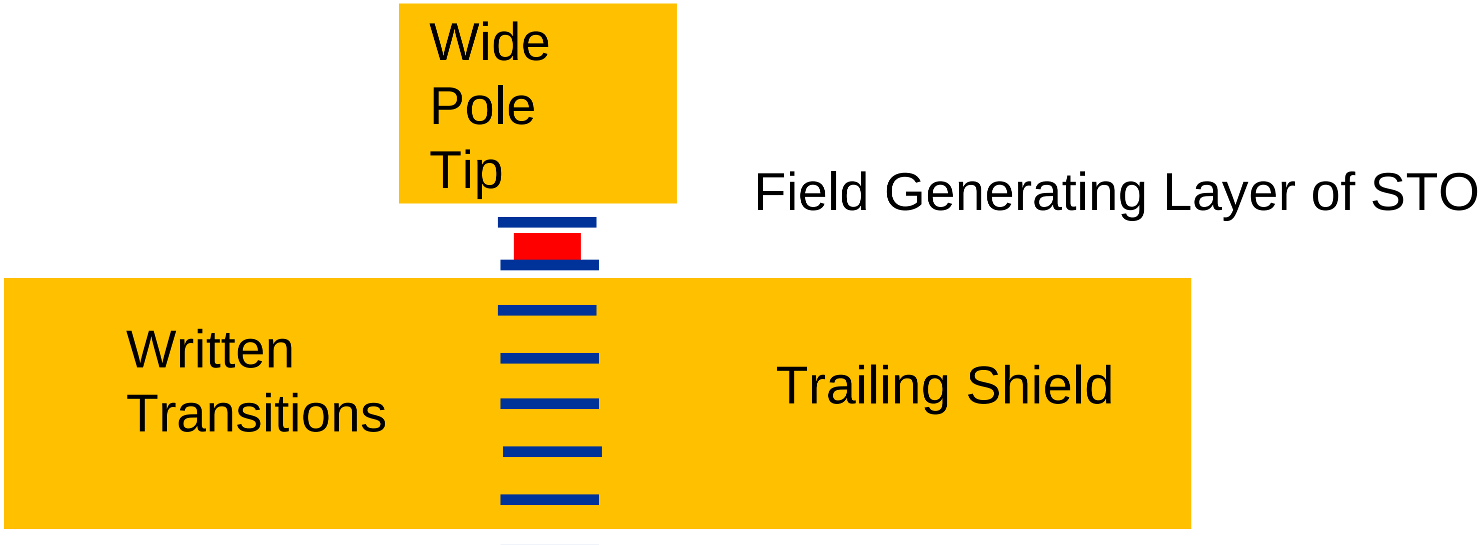
Spin Torque Oscillator in the Writer Gap

- **Field Generating Layer precesses due to the spin polarized current from the polarization layer**
- **The direction of precession reverses when the pole tip field reverses and flips the polarization layer and the bias layer.**

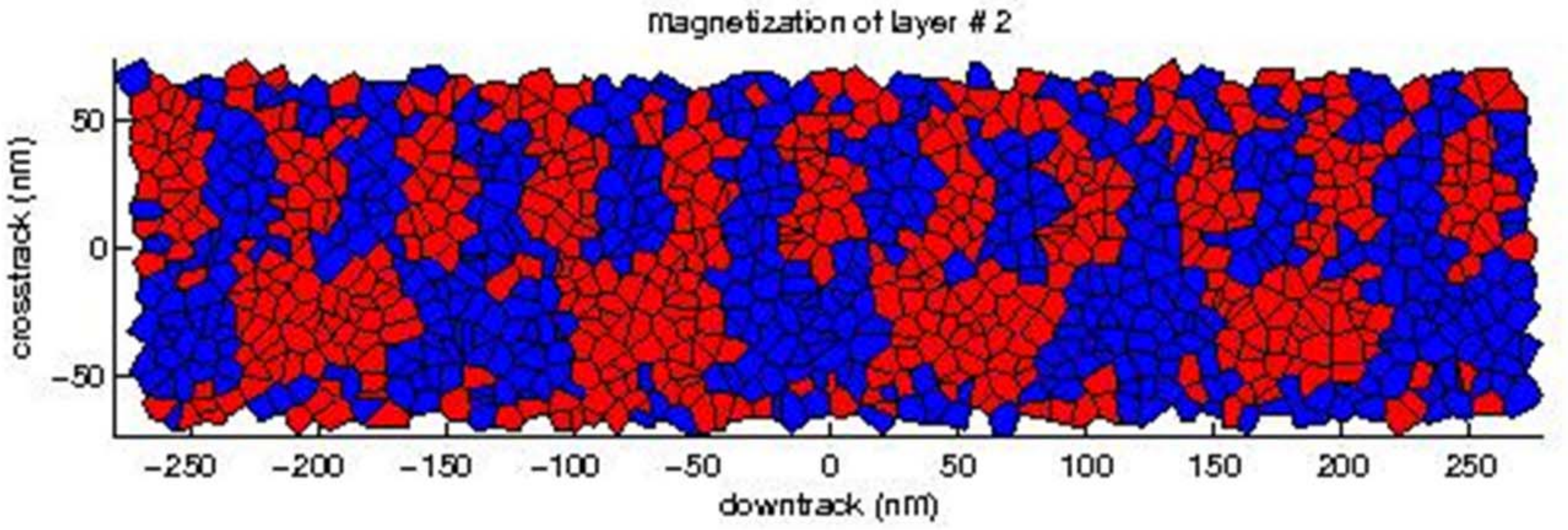


STO width sets Magnetic Write Width (ABS View)

- **Wide write pole with no Side Shields gives ~30% more field**
- **MAMR field lowers required (pole field)/Hk by ~40%**
- **Net (pole field)/Hk increases ~x2 for ~x2 AD gain**
- **Just right pole field, media properties, and FGL Mr*T give FGL defined track width**



400 kfci written 36 nm (700 ktpi) off 1000 kfi (jitter 6.5%→7%)

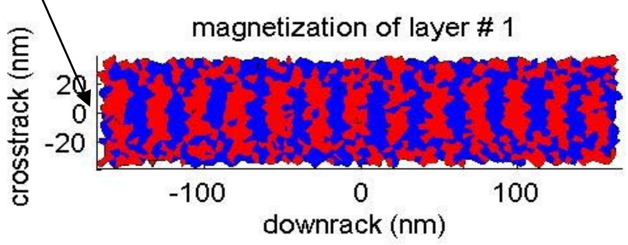


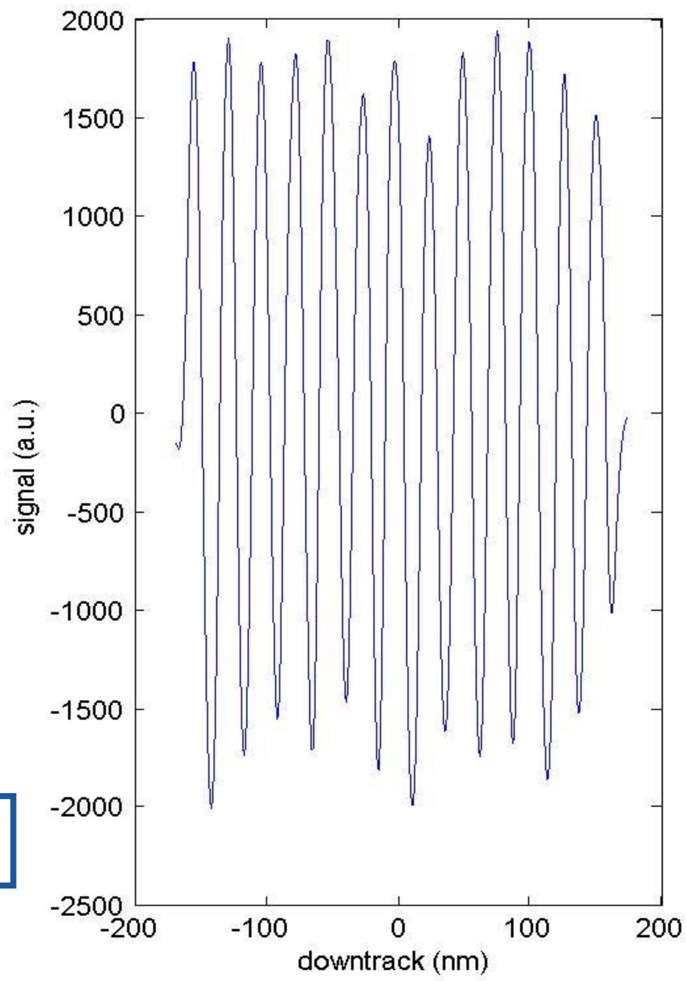
Hk=16 & 8 kOe bop/top

Simulated Single Layer Media Sigma Hk Sensitivity – 3%

- **MWW ~ 32 nm (635 kTPI for MWW=80% of pitch)**
- **3.33 MFCI for 10% jitter on ~2T pattern**

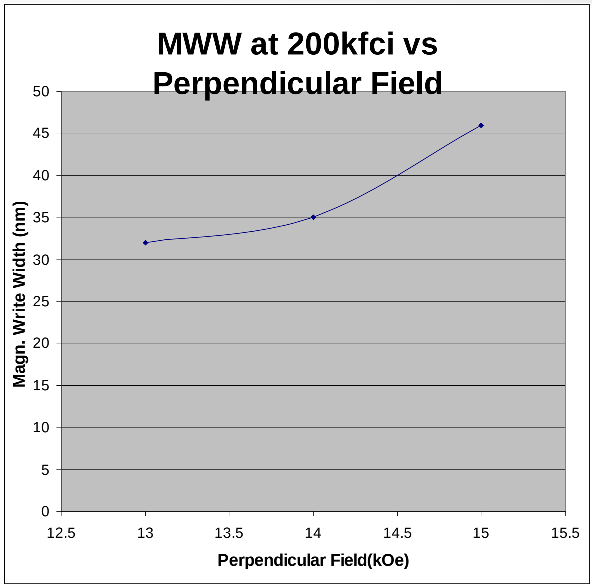
6% jitter at 2MFCI



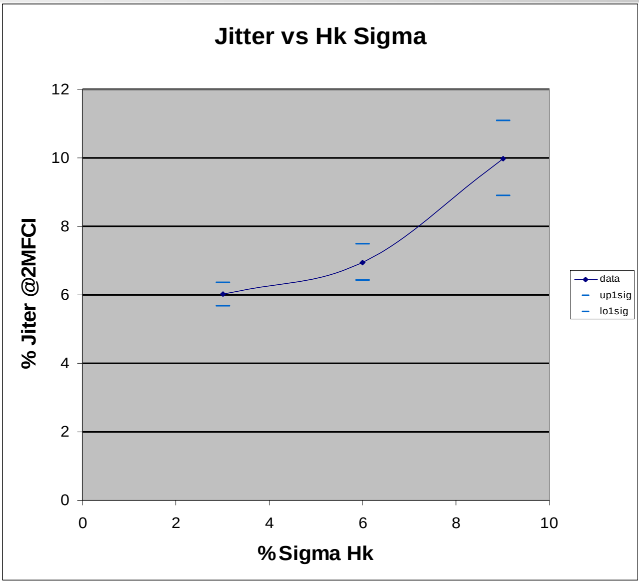


Sigma Hk=3% gives very good recording

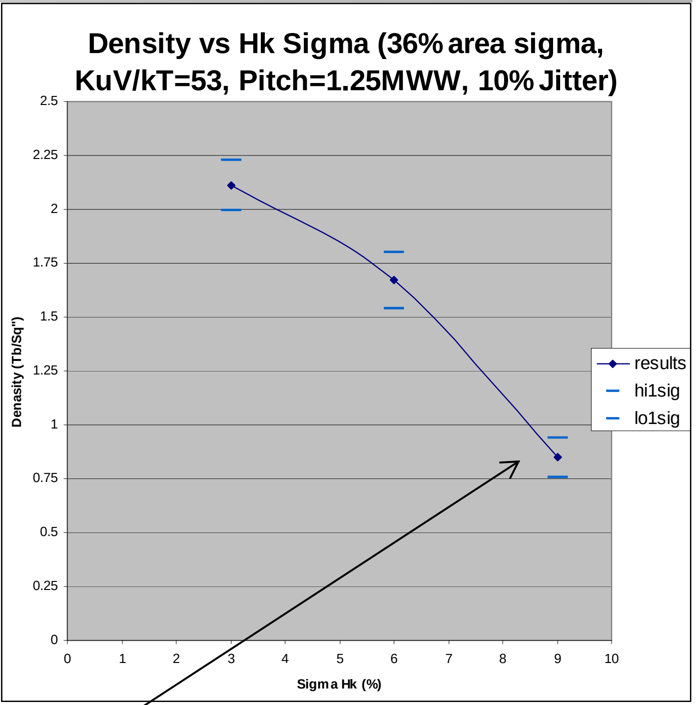
Simulated Single Layer Sigma Hk Sensitivity



MWW at 200kfci vs Perpendicular Field



Jitter vs Hk Sigma



Density vs Hk Sigma (36% area sigma, KuV/kT=53, Pitch=1.25MWW, 10% Jitter)

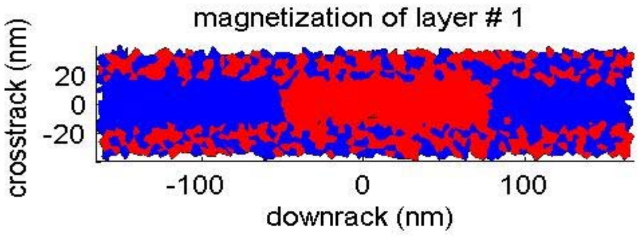
- **2Mfci all ones, 23 transitions/run**
- **36% grain area sigma (pseudo-Voronoi)**
- **Hperp (13, 15, 15kOe for 3, 6, 9% Hk sigma, respectively)**
- **Hk=27 kOe and Ms=500 emu/cc**
- **KuV/kT=53 (5 nm dia, 15 nm thk)**
- **No grain boundaries yet**
- **3 nm pole-media surface**
- **15x25x25 Field Generating Layer**
- **41 GHz rf (1.2x10^{8}A/cm^2 oscillator current density**
- **1 sigma error bars on figure**
- **Pitch = 1.25*MWW**

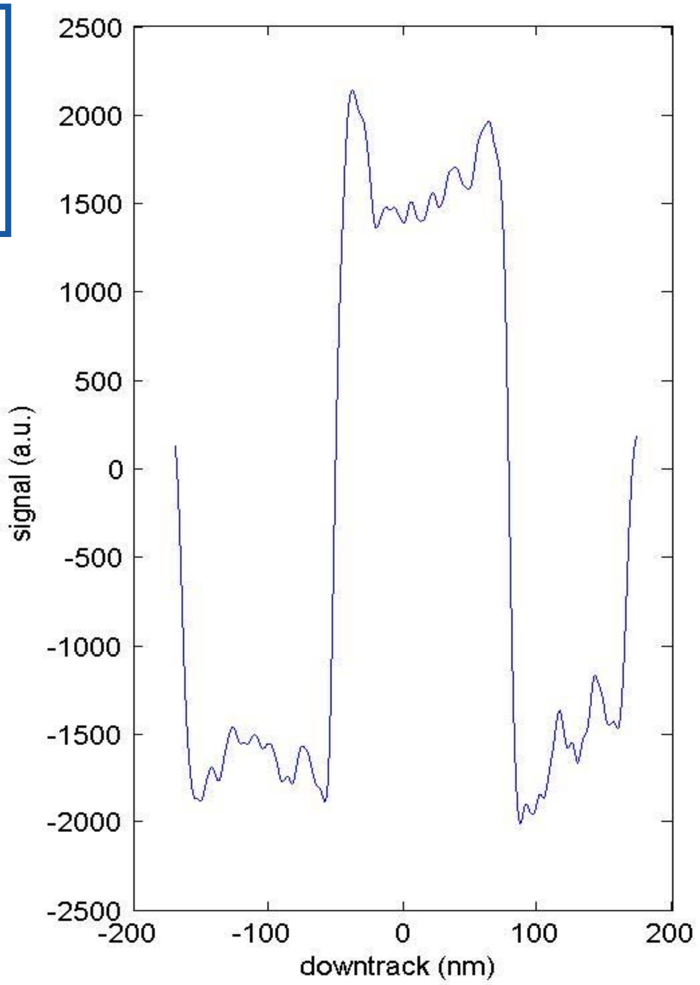
Sigma Hk = 9% is N.G. (Note that there is a -2/3 dB loss per 1% increase in sigma Hk for PMR so MAMR is similar to PMR for this)

Simulated Single Layer Media Sigma Hk Sensitivity – 3%

Sigma Hk = 3% gives low DC noise and narrow tracks

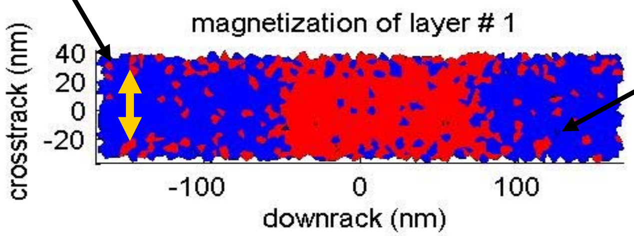
(MWW~ 32 nm for H_{perp}=13 kOe)



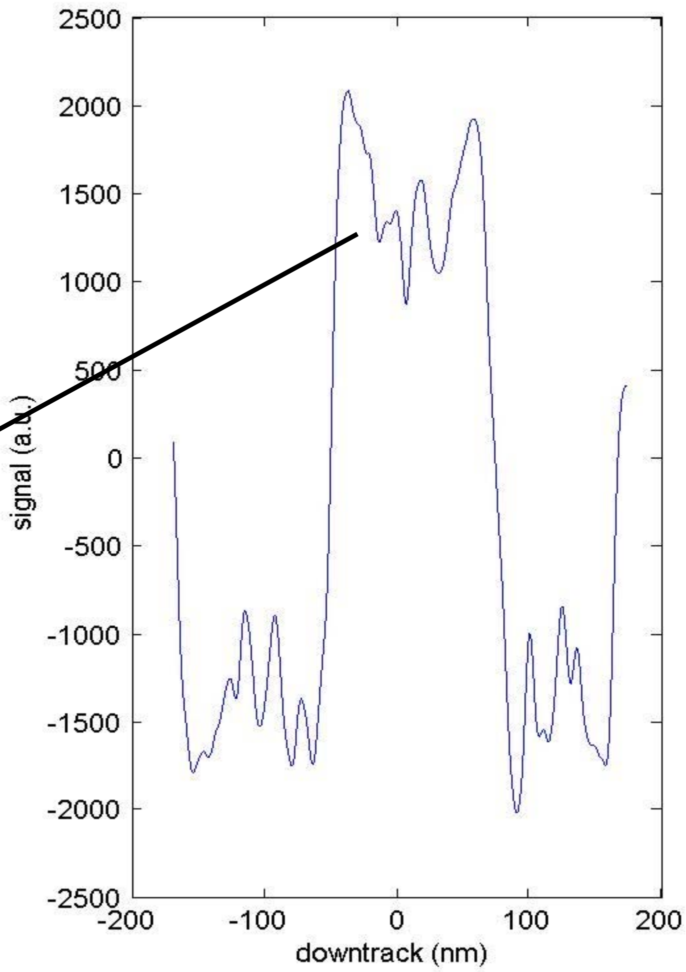


Simulated Single Layer Media Sigma Hk Sensitivity – 9%

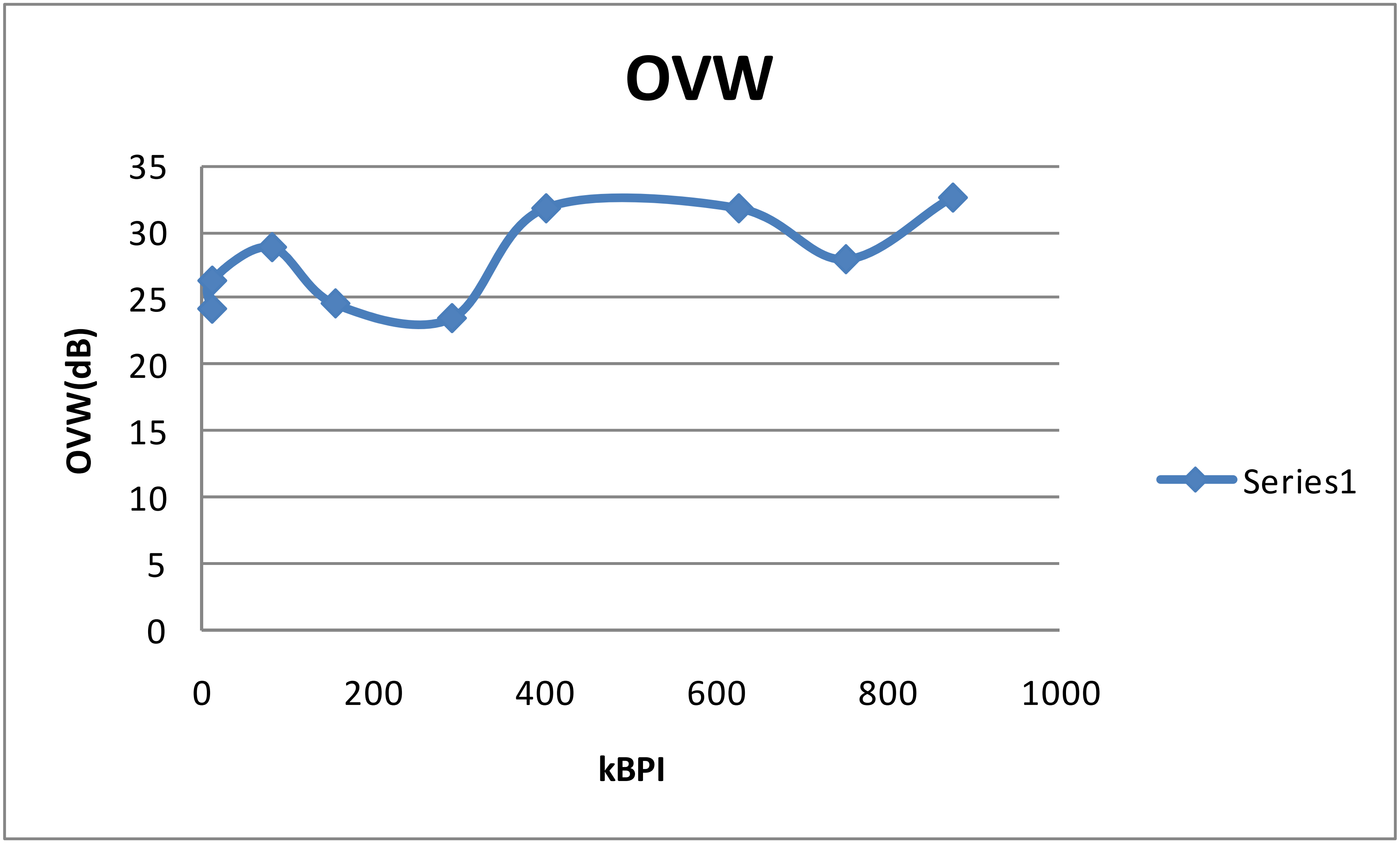
Sigma Hk=9% needs H_{perp} =15 kOe to reduce DC noise resulting in wide (MWW~ 45 nm) tracks



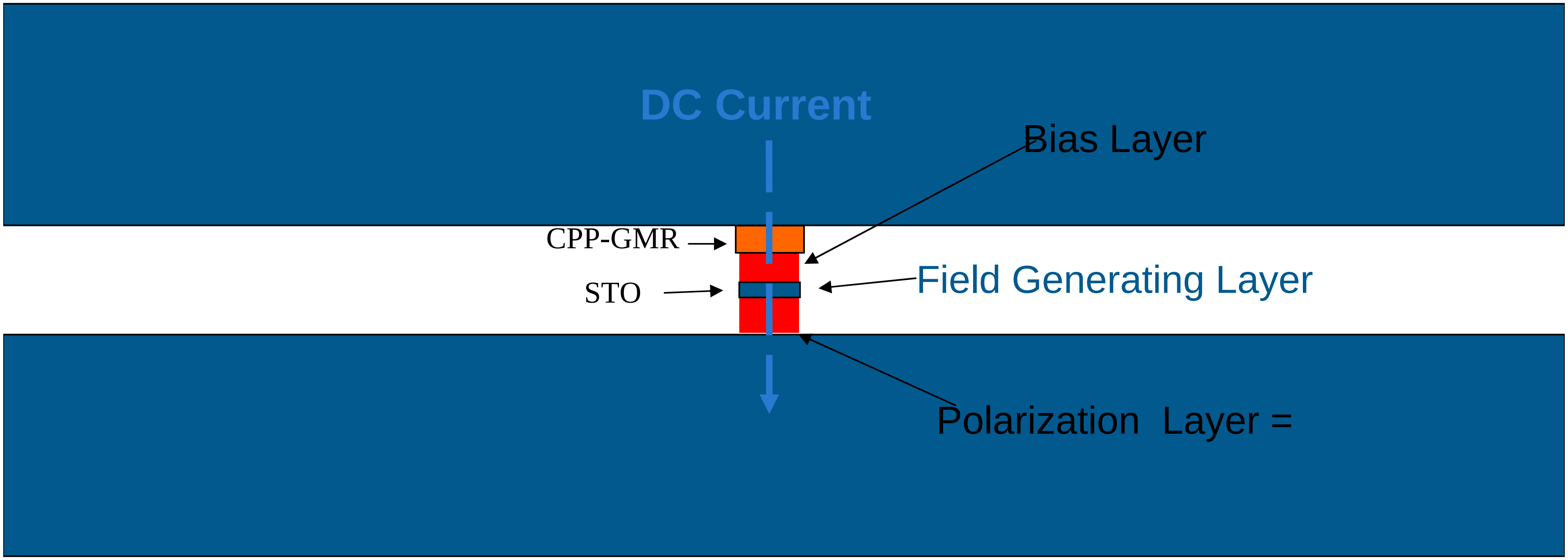
~ 45 nm MWW



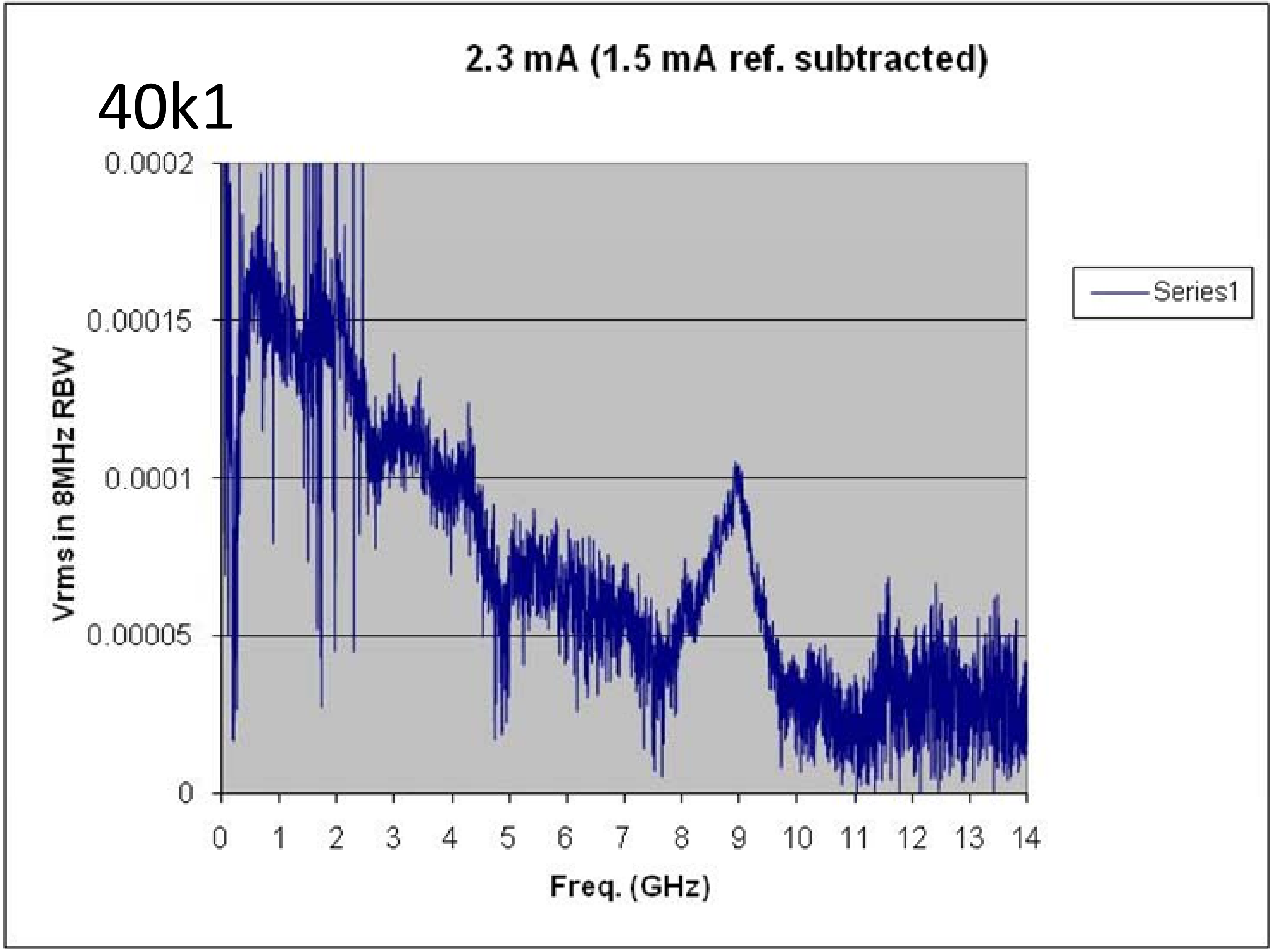
Overwrite Simulations (pessimistic .. short sequences)



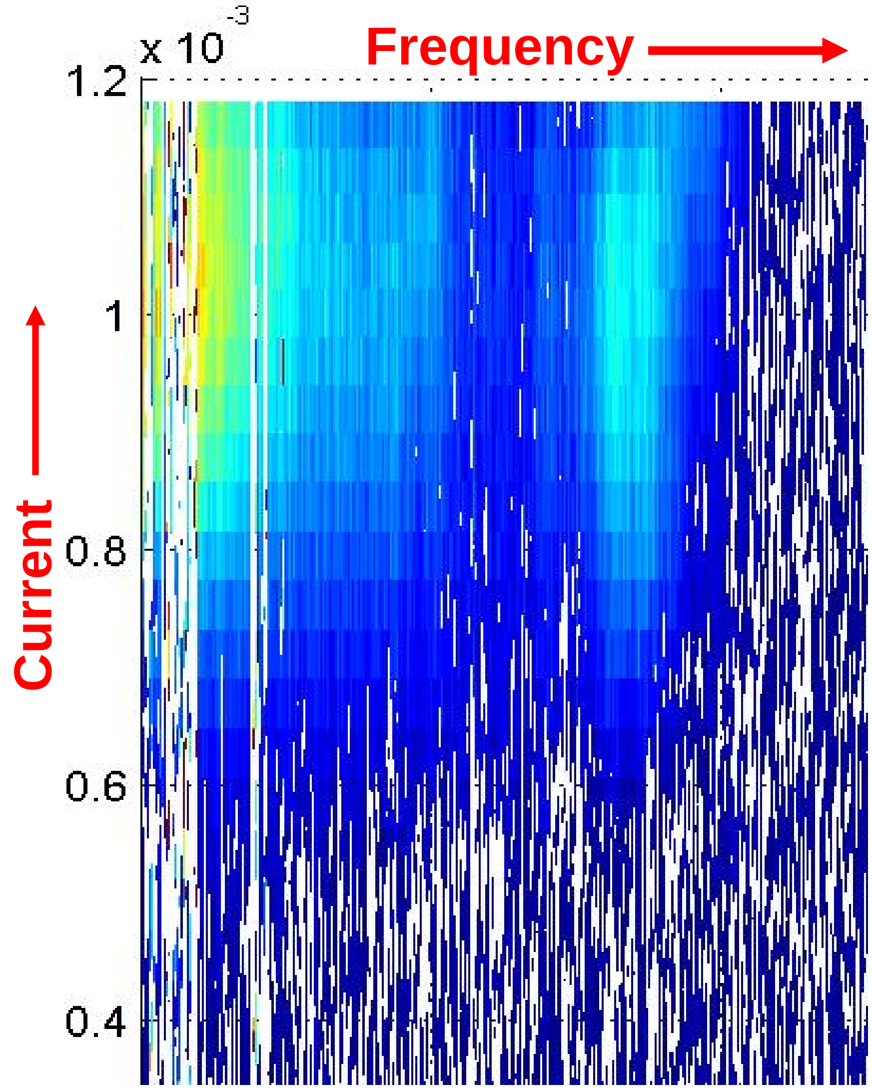
STO & CPP-GMR in the Reader Gap



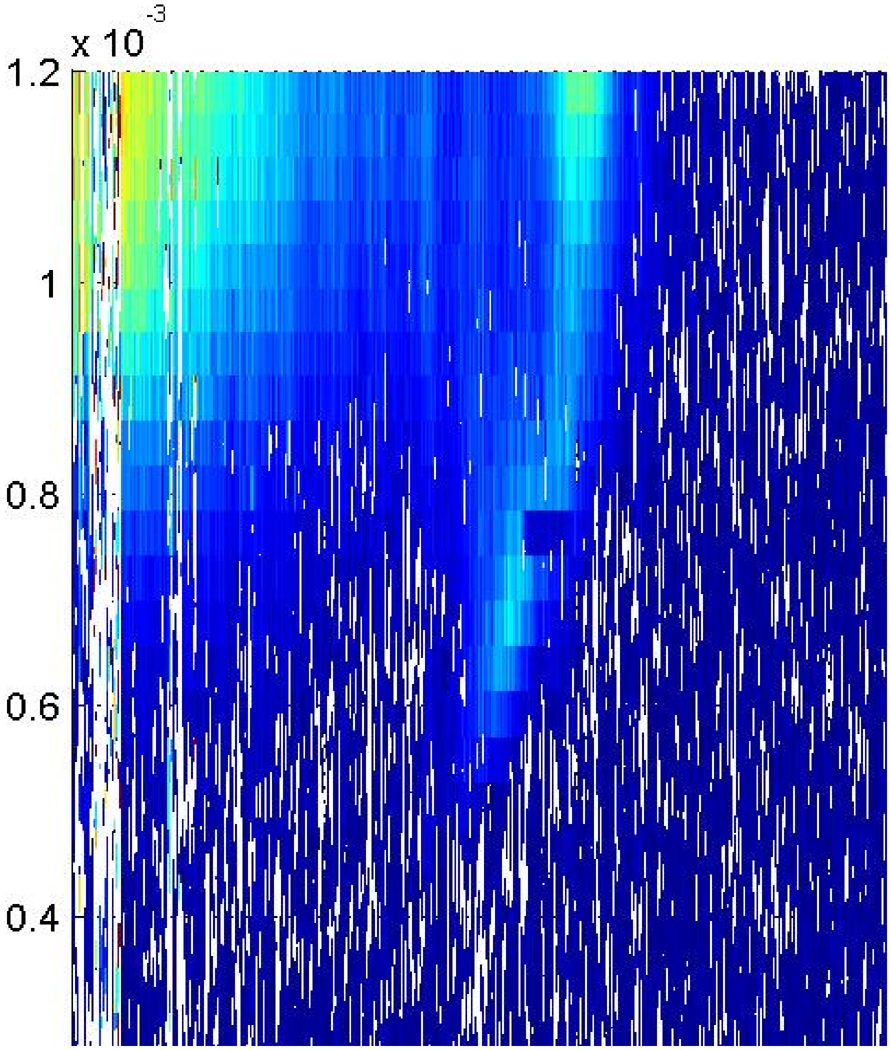
WD on Wafer Spin Torque Oscillator 9 GHz line



High resistance lapped bars with 8→10GHz lines

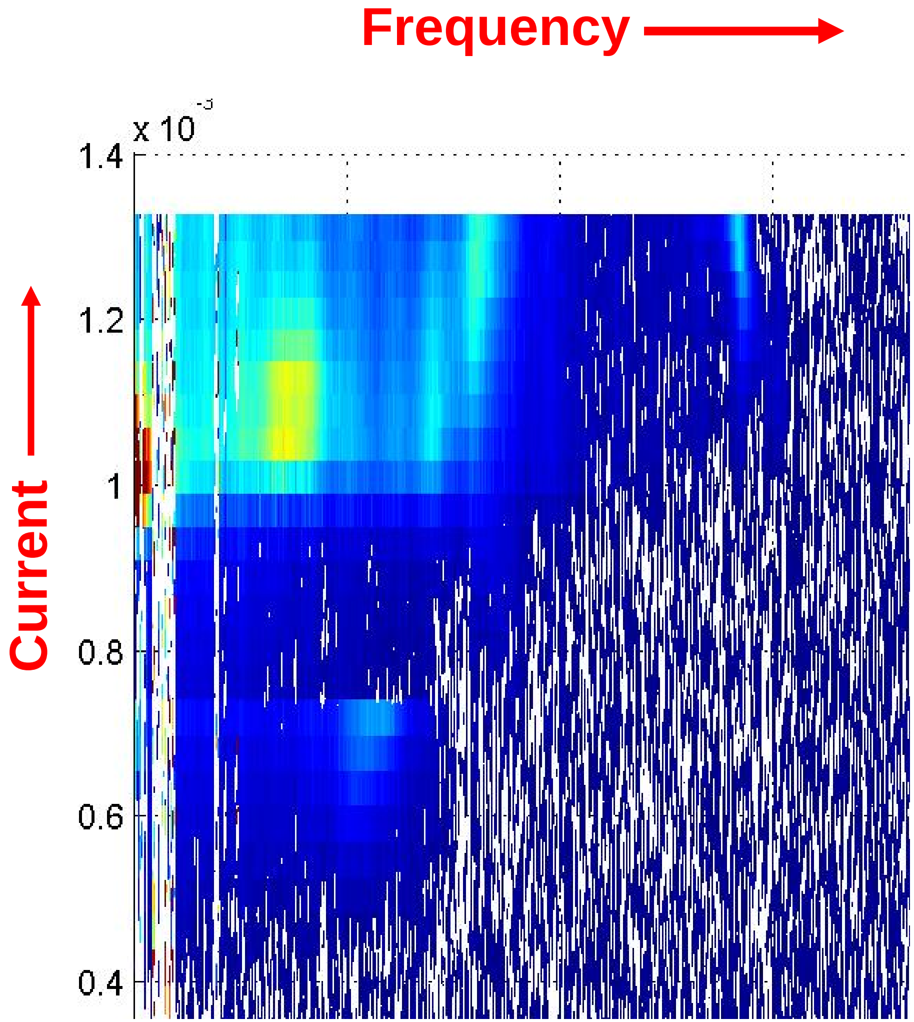


_0kG_spect_subt_zb

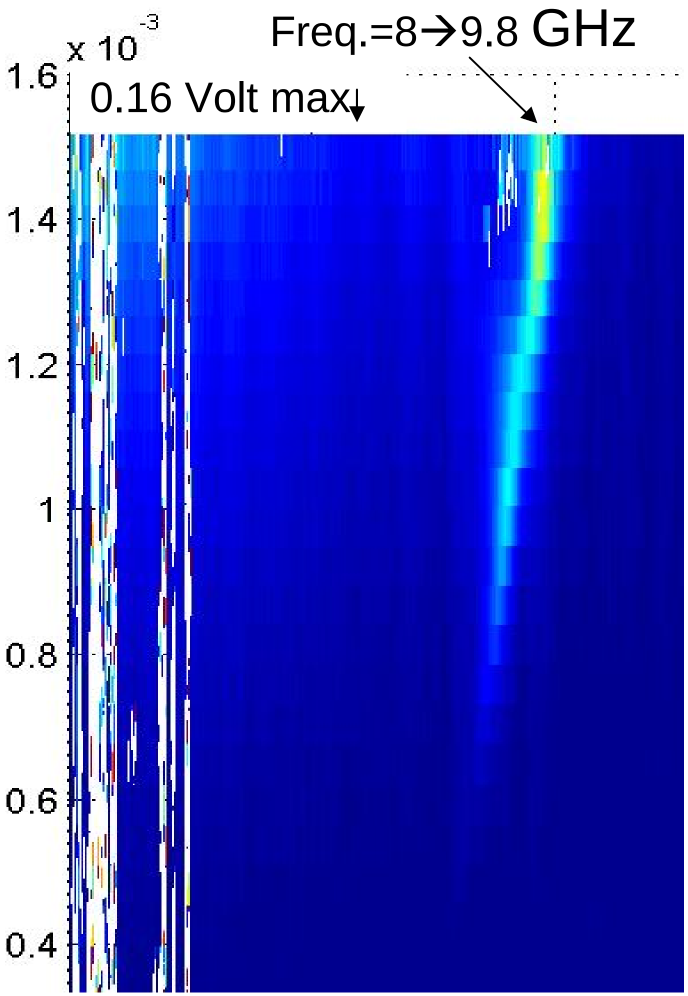


5k_0kG_spect_subt_zb

Progressively ion milled bar level STO tests

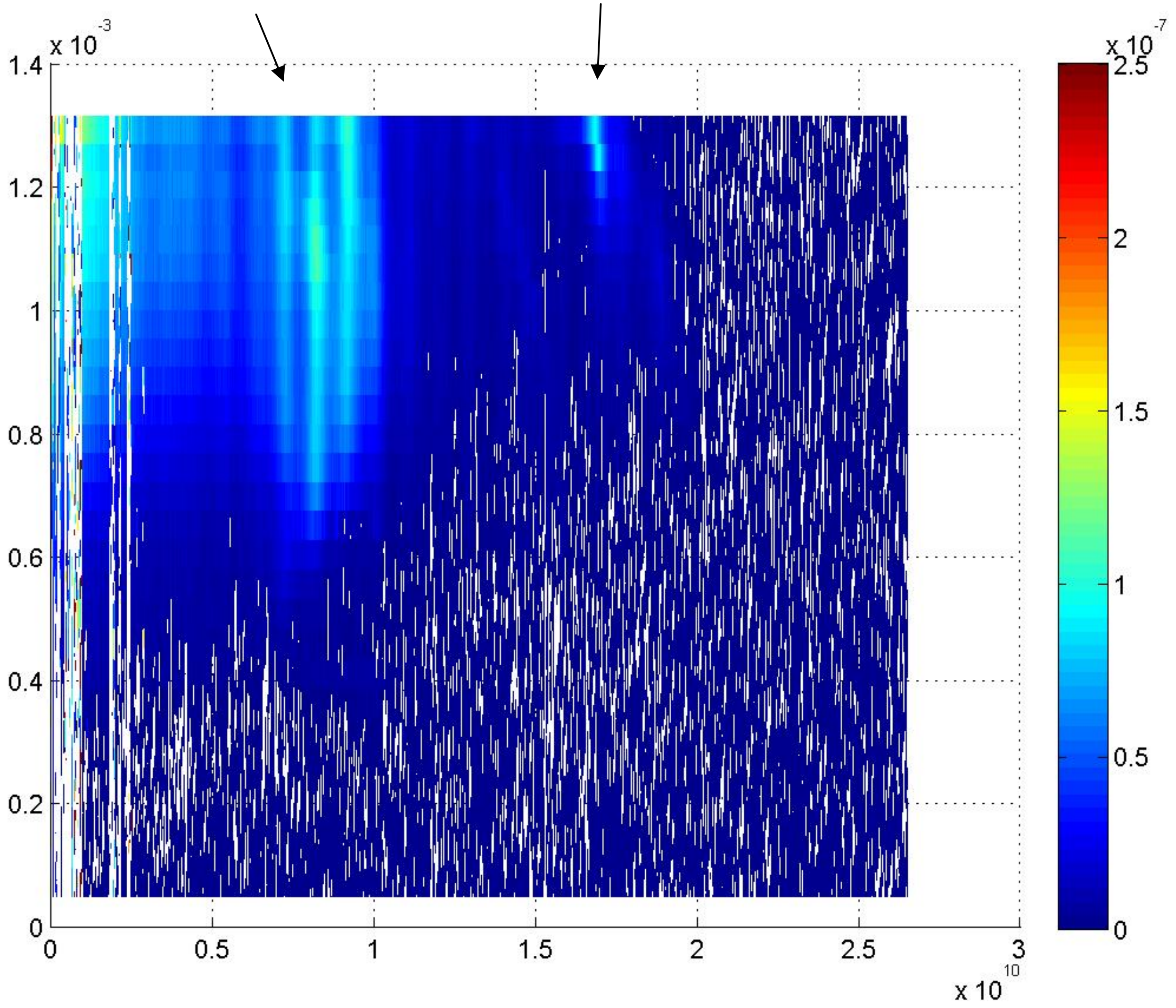


onMilled14nm-RB8MVB1k-T0_5_spect_subt_zb



_0kG-14nm_spect_subt_zb

Latest lapped bars with high resistance from ABS ion milling



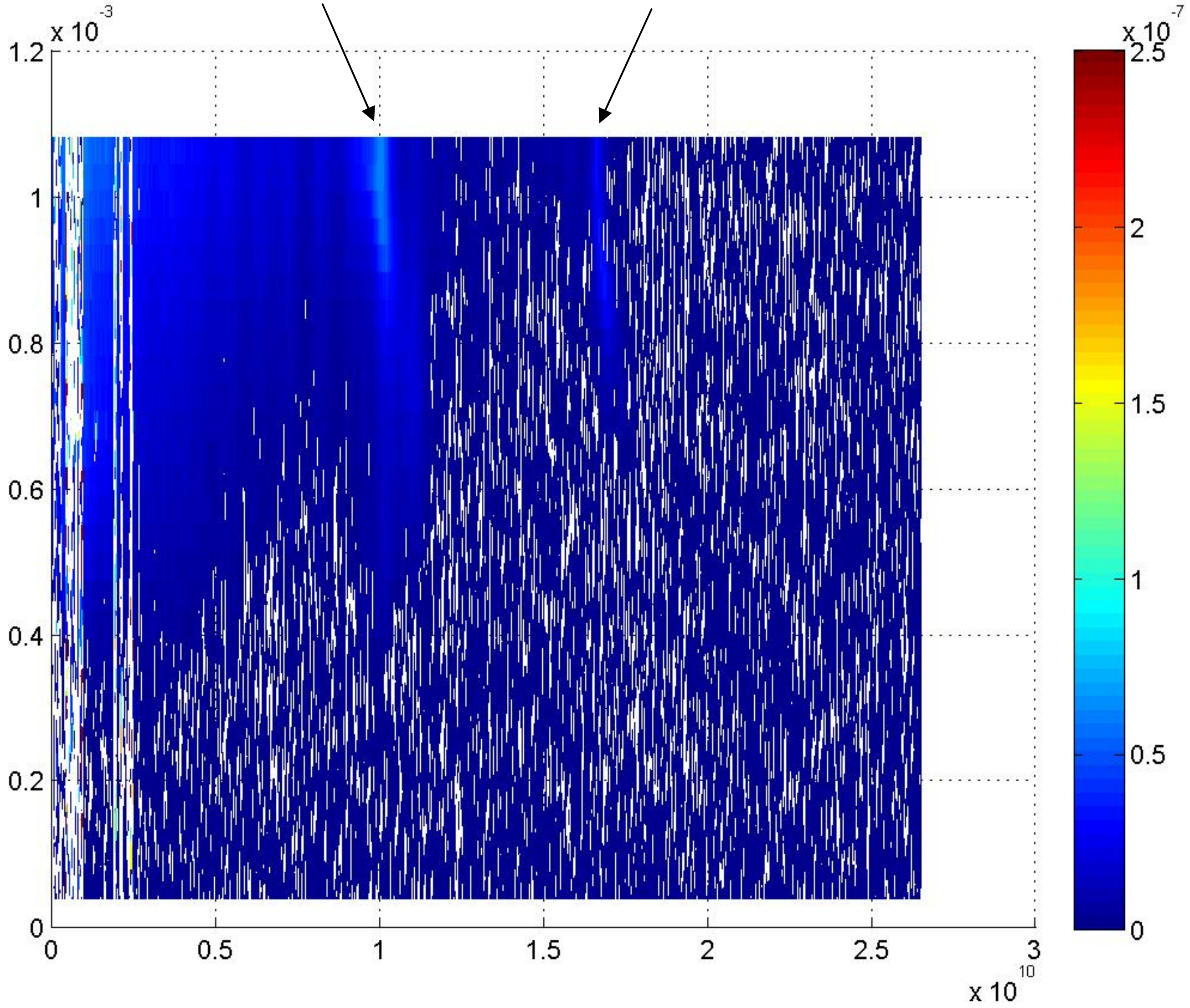
Frequency →

8→10GHz 17.5→17 GHz

Current →

Latest lapped bars (R~110 Ohms)

K271 R=125Ω 10GHz 17.5→17 GHz



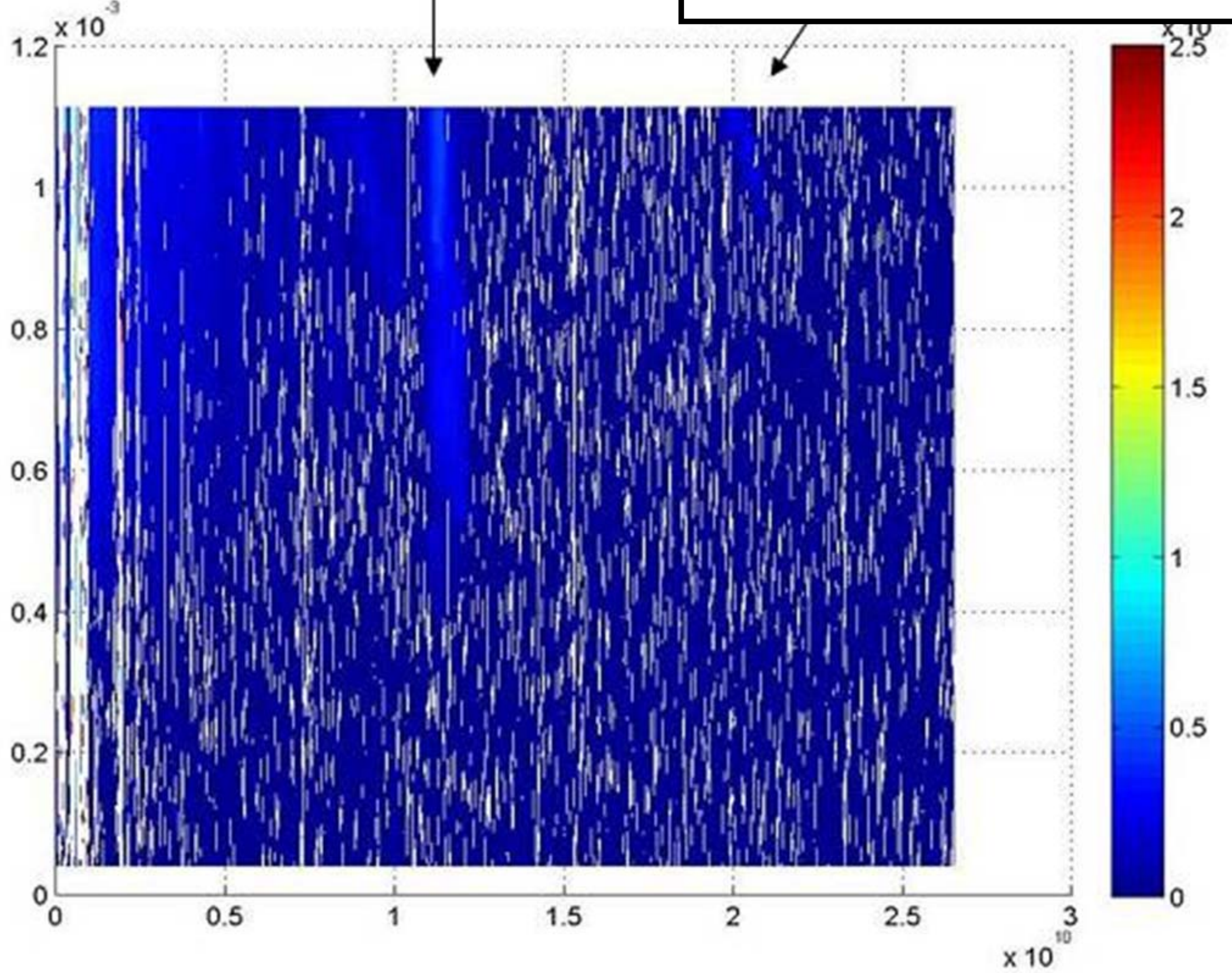
Latest lapped bars (ABS ion milled)

11 GHz

21.5→20 GHz for V> 130 mV

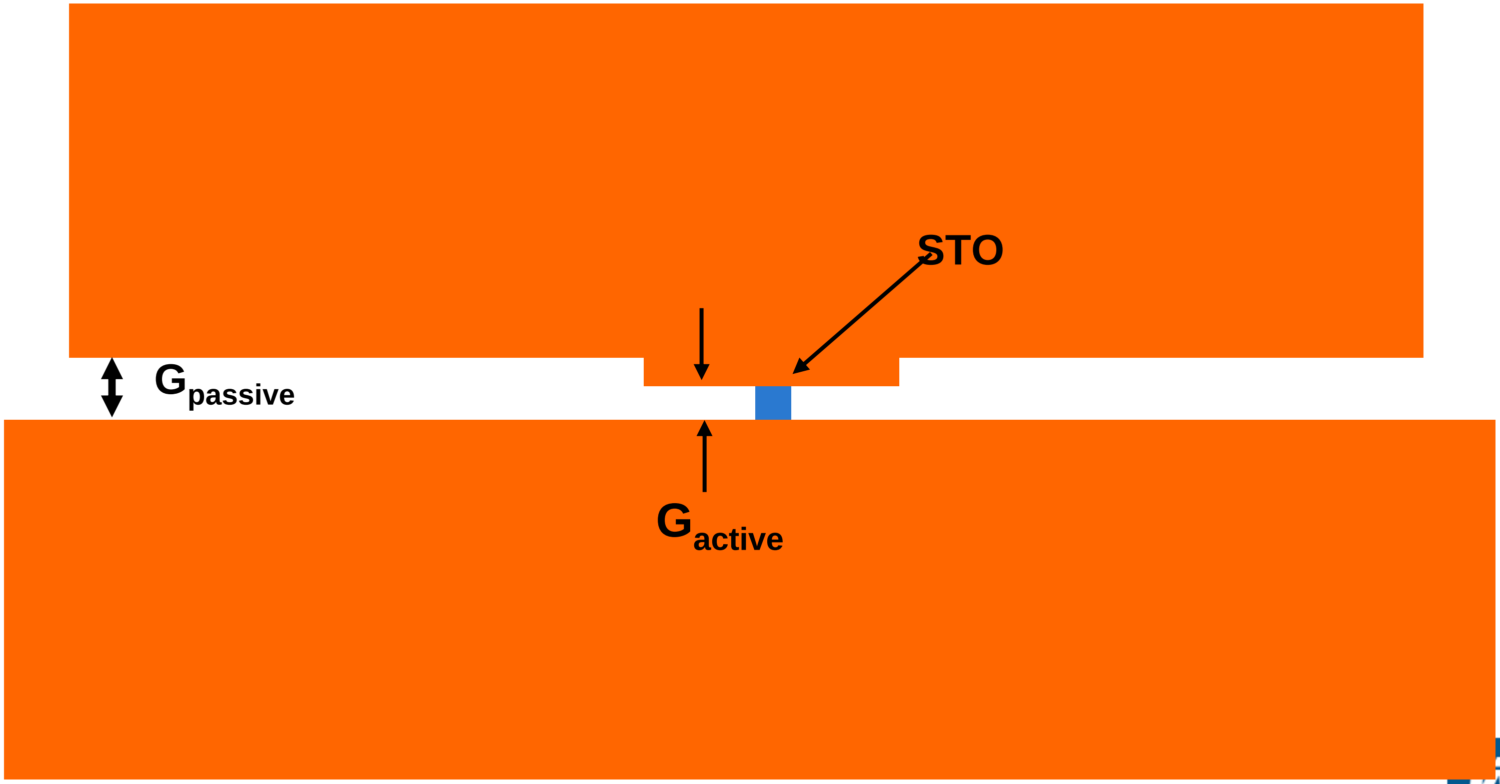
0 < volts < 140 mV

(ignore scale)



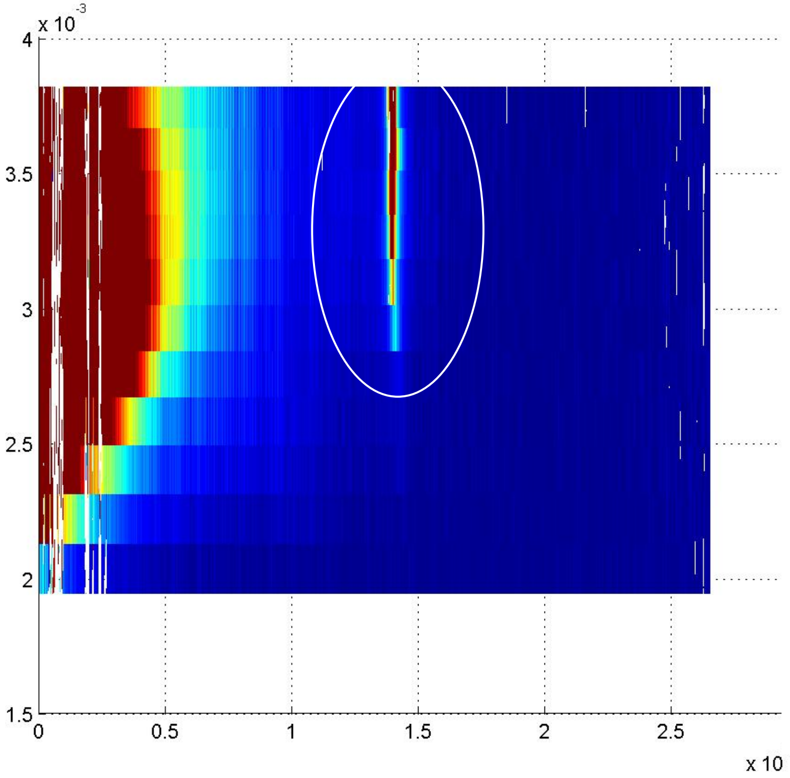
Large Shield to Shield Passive Gap for Large H_{perp}

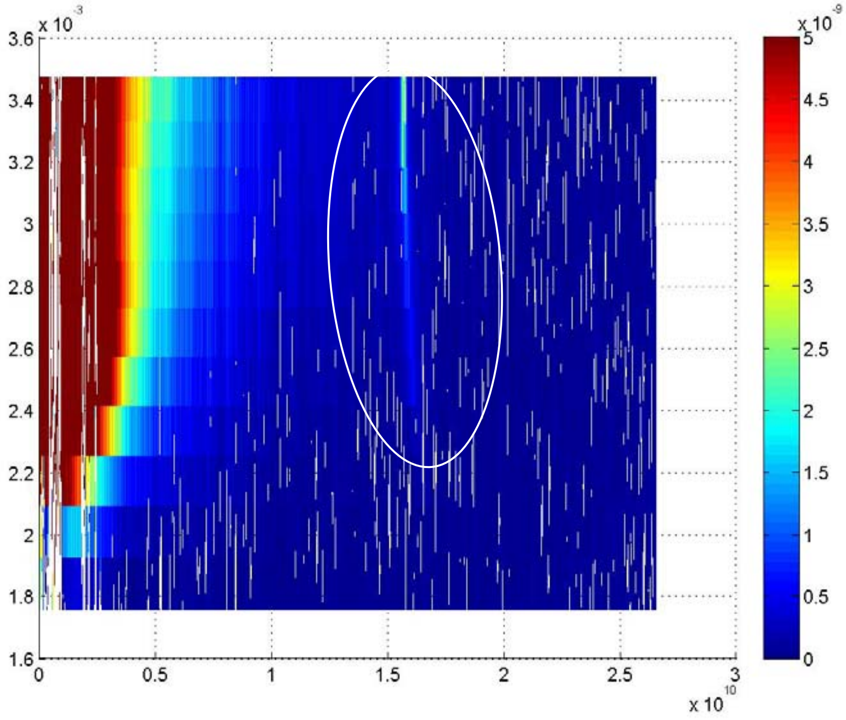
- **Simulations show increase in frequency for $H_{perp} > 5$ kOe**
- **$H_{perp} = H_{applied}(G_{passive}/G_{active})$**
- **$F_{-3dB} = 1/(2\pi R_{sto} C_{passive}) \sim 5$ Ghz**



Frequency (horizontal axis) vs Current for WD STOs

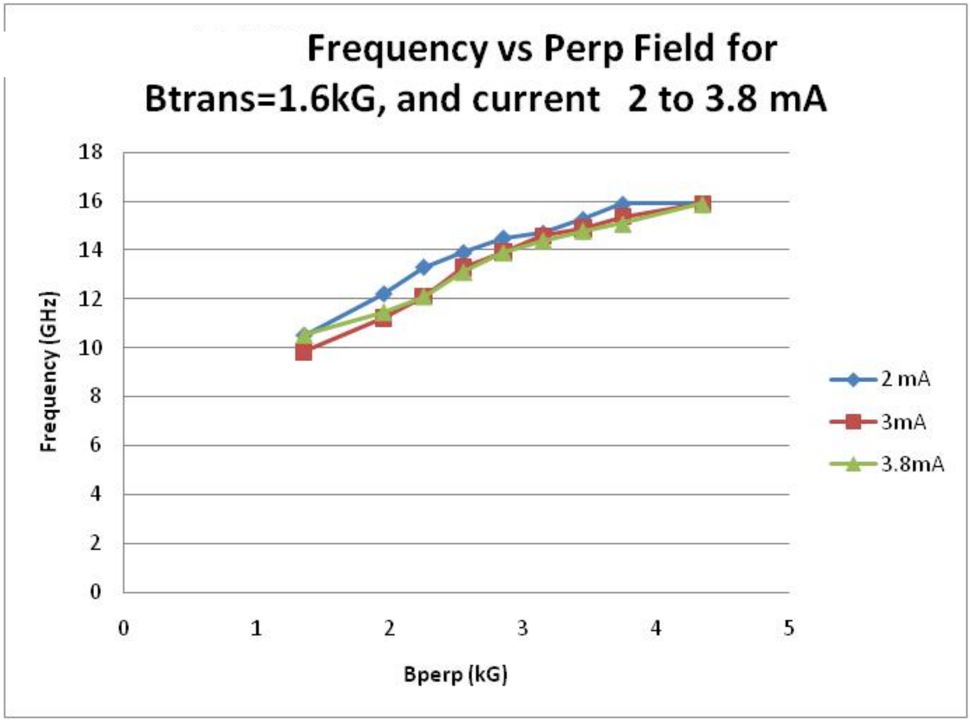
- ~2.5kOe perpendicular to film
- Weak current(vert) dependence of freq (horiz) as seen in simulations
- M19H and M19J have strong narrow lines at 14 and 16 GHz in 2.8 kOe perp. to film and 1.6 kOe perp. to ABS



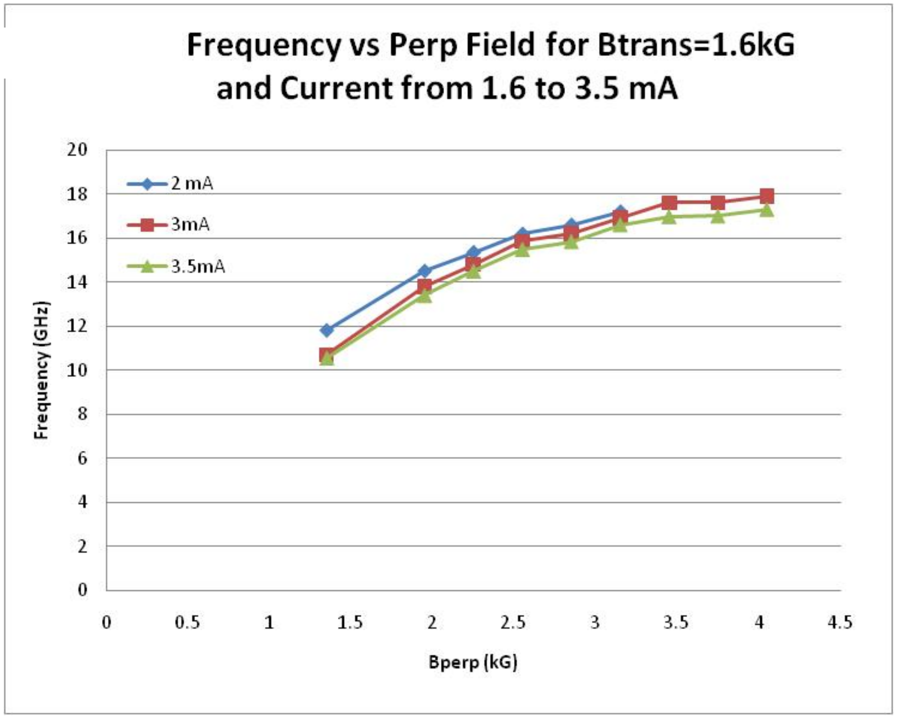


Neighboring parts are very similar

- Weak current dependence on frequency and strong dependence on field
- Slope break at ~ 2.8 kOe is expected from saturation of the read shields resulting in the loss of the x3 gain from the gap ratio(x4) and proximity to the ABS (x.75)



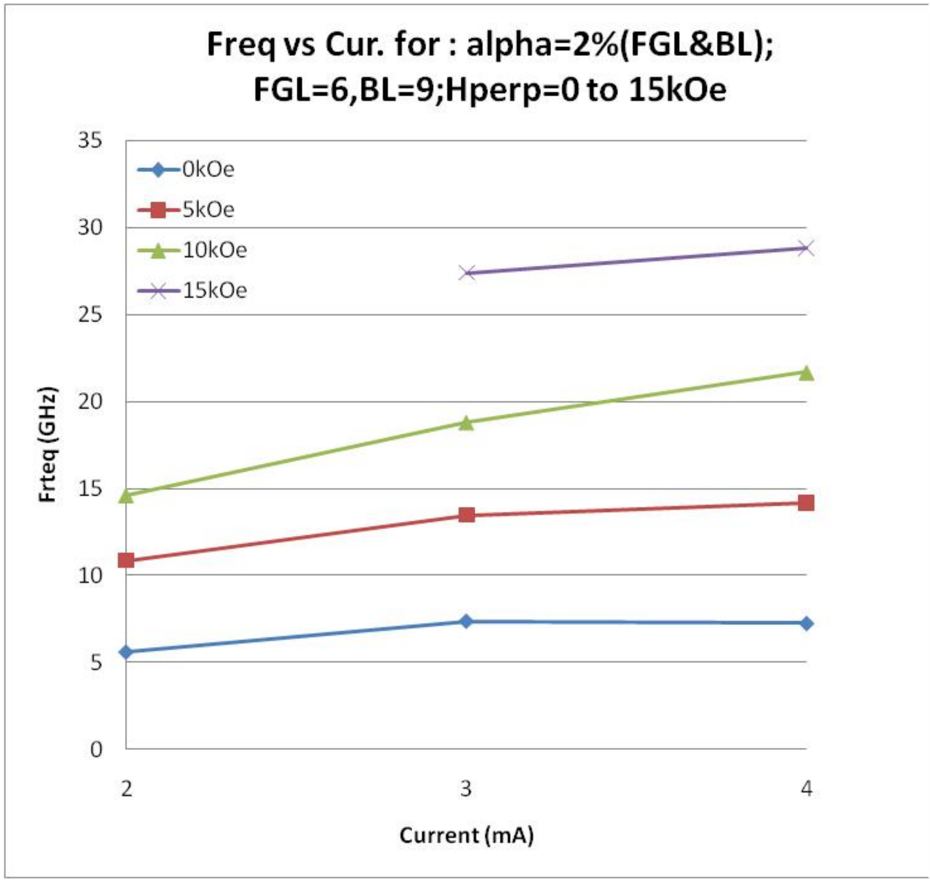
Frequency vs Perp Field for Btrans=1.6kG, and current 2 to 3.8 mA

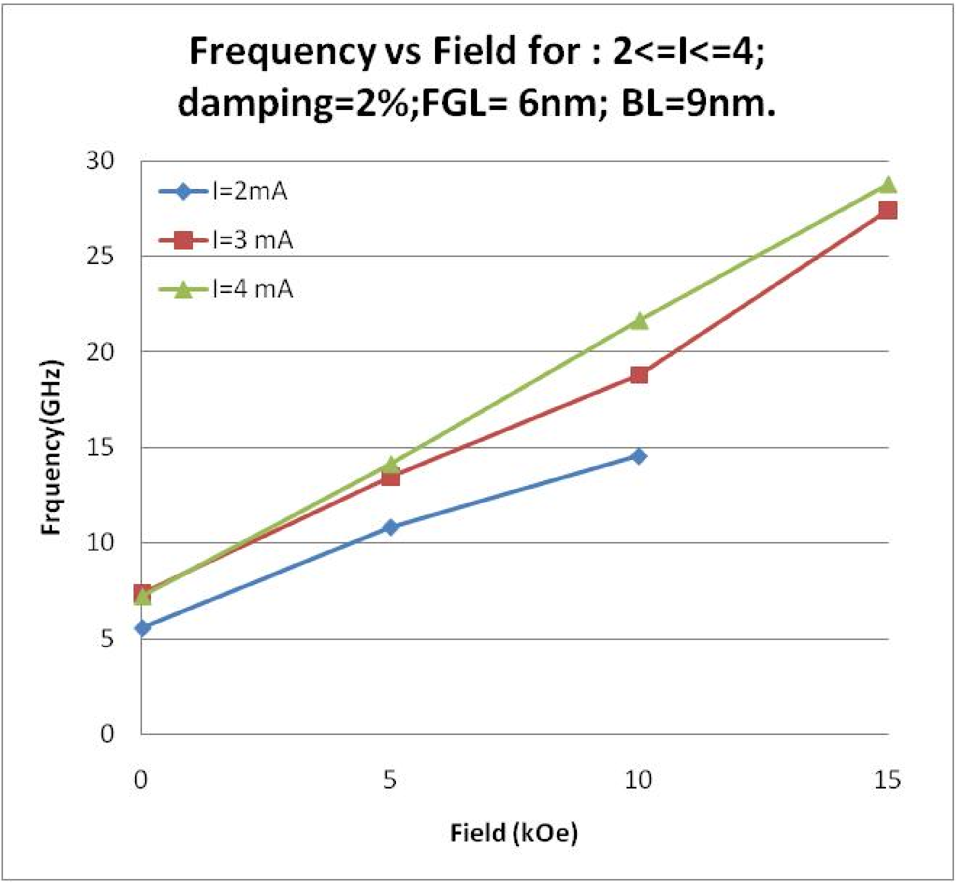


Frequency vs Perp Field for Btrans=1.6kG and Current from 1.6 to 3.5 mA

Simulation of Frequency vs Current and Field

- **Strong field dependence**
- **Weak current dependence causes tuning problem**

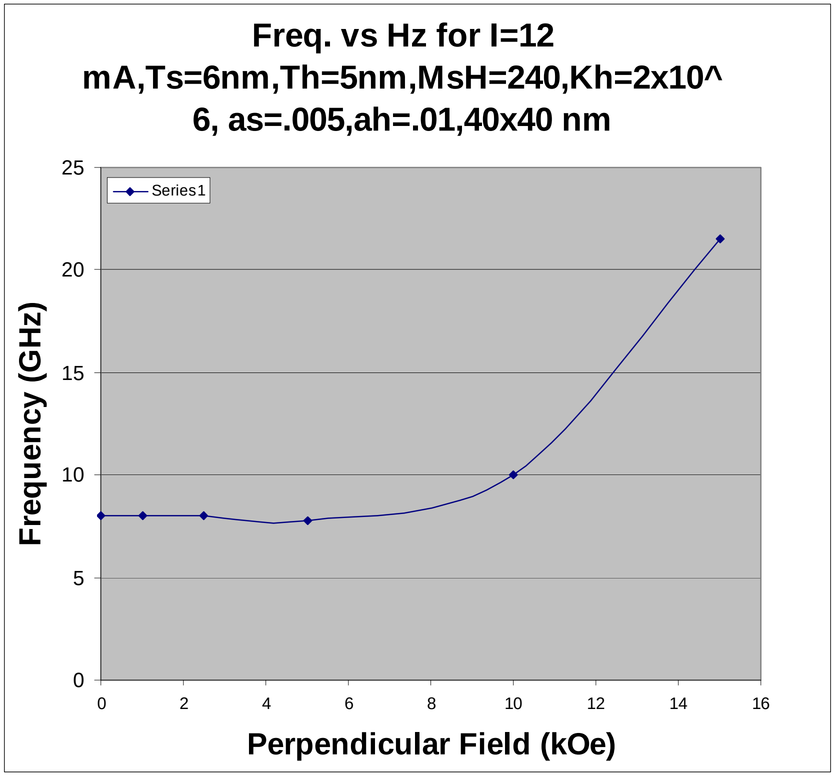




Some STO Simulation Results

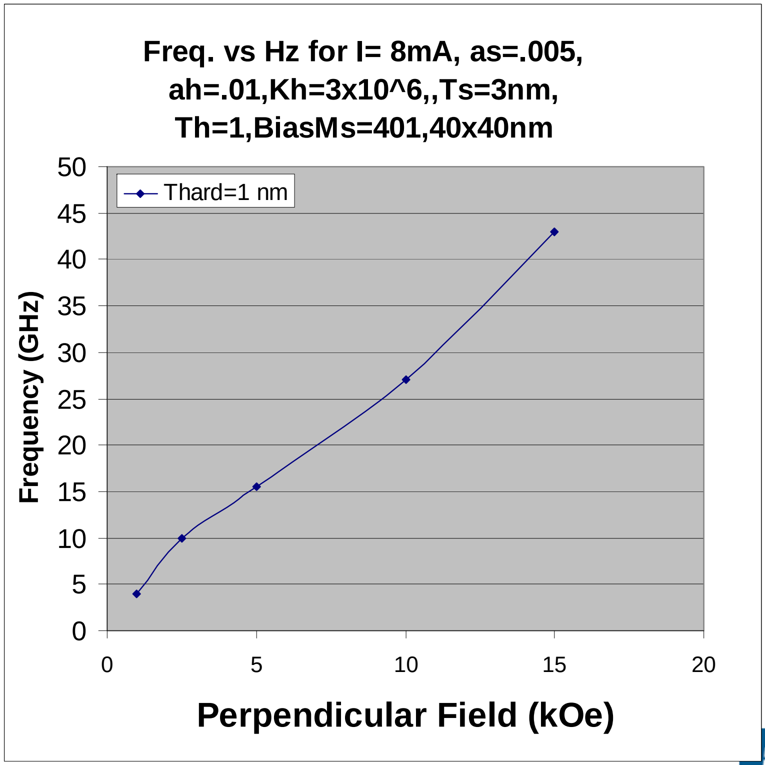
- **For thin Bias Layers**
  - Freq. ~ H_{perp}
  - Unstable for $H_{perp} = 0$
- **For thick bias layers**
  - Freq. constant for $H_{perp} < H_{threshold}$
  - $H_{threshold}$ increases with Bias Layer thickness

Bias Layer Thickness = 5 nm



Freq. vs Hz for I=12 mA,Ts=6nm,Th=5nm,MsH=240,Kh=2x10^6, as=.005,ah=.01,40x40 nm

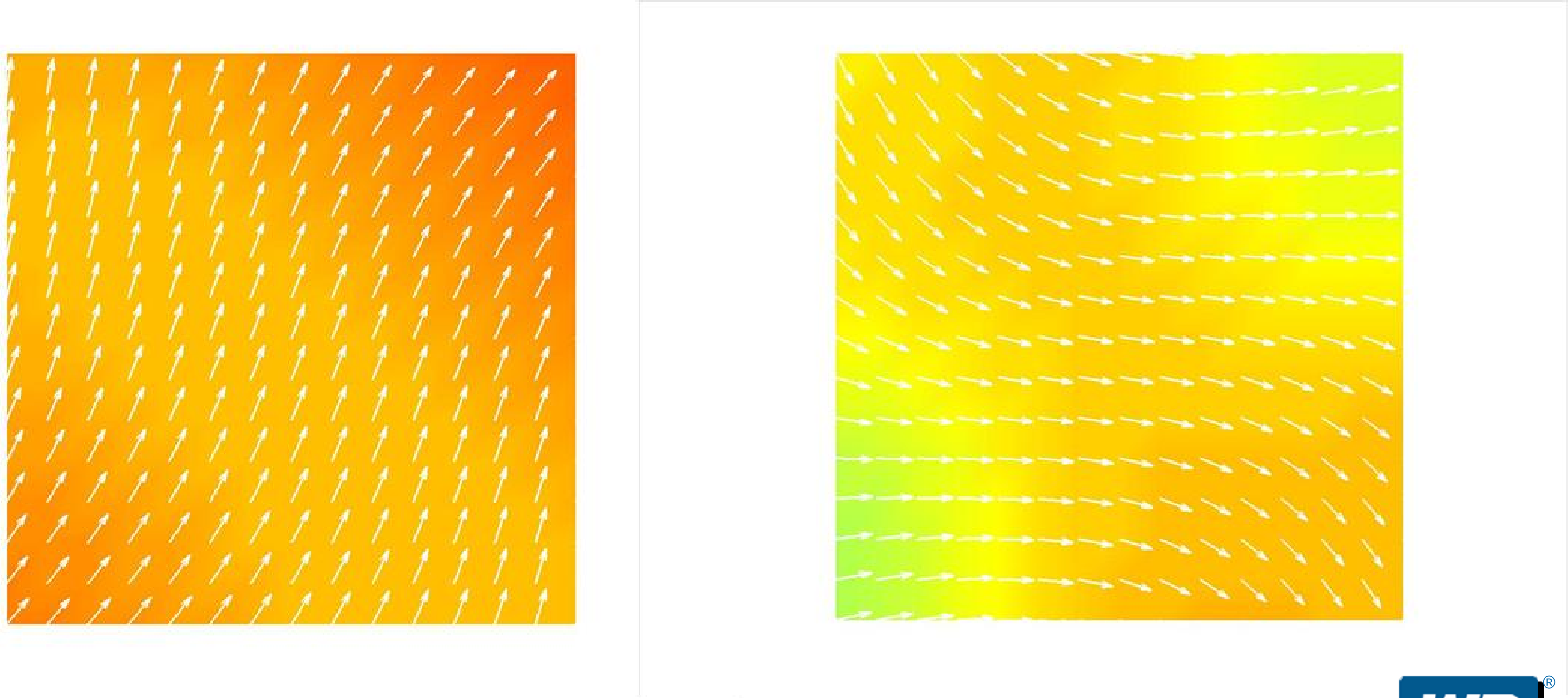
Bias Layer Thickness = 1 nm



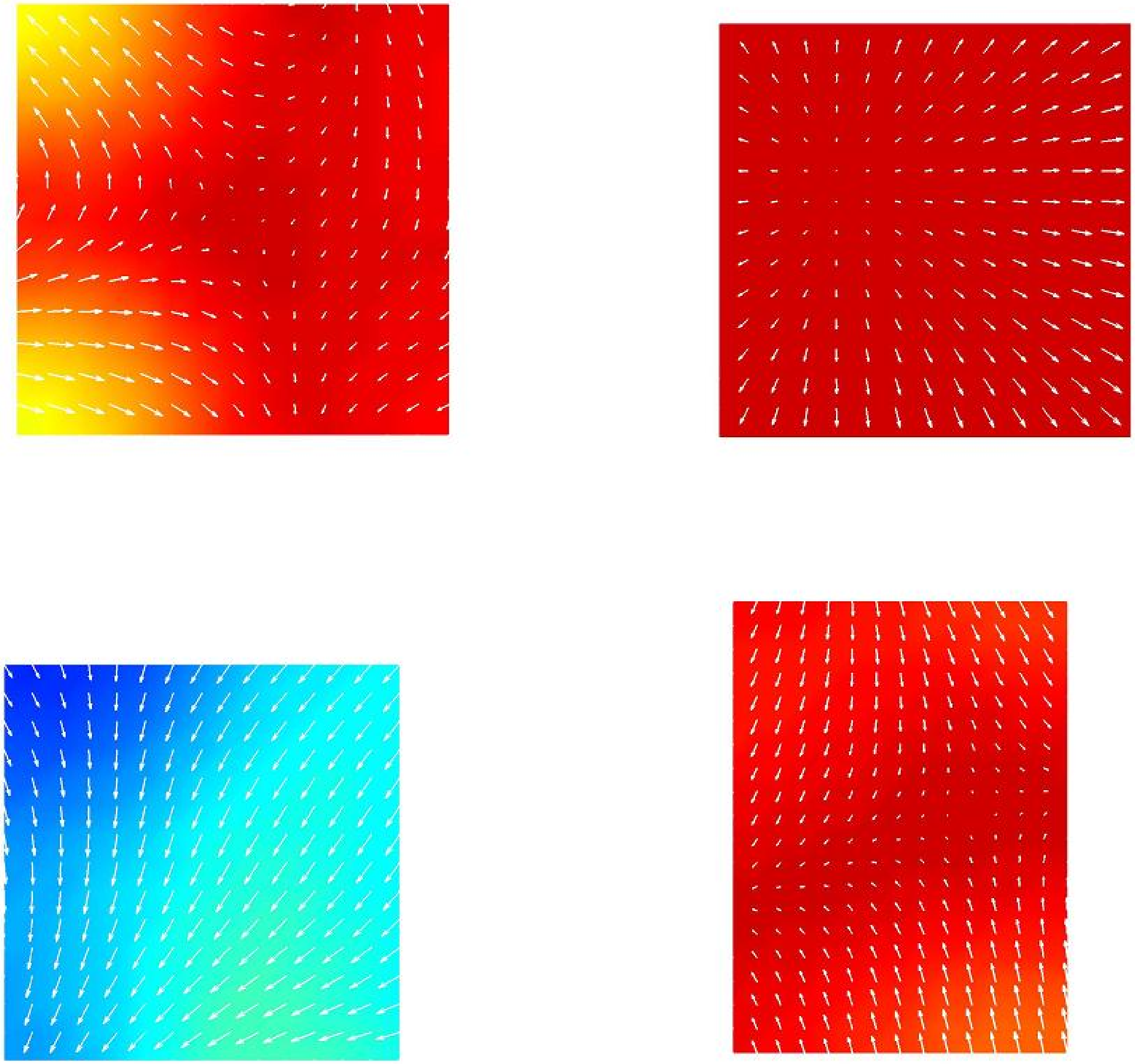
Freq. vs Hz for I= 8mA, as=.005, ah=.01,Kh=3x10^6,,Ts=3nm, Th=1,BiasMs=401,40x40nm

STO magnetization at two currents (3 and 5 mA)

- **As current increase**
  - Frequency increases
  - Curling increases
  - A point of gross instability is reached eventually

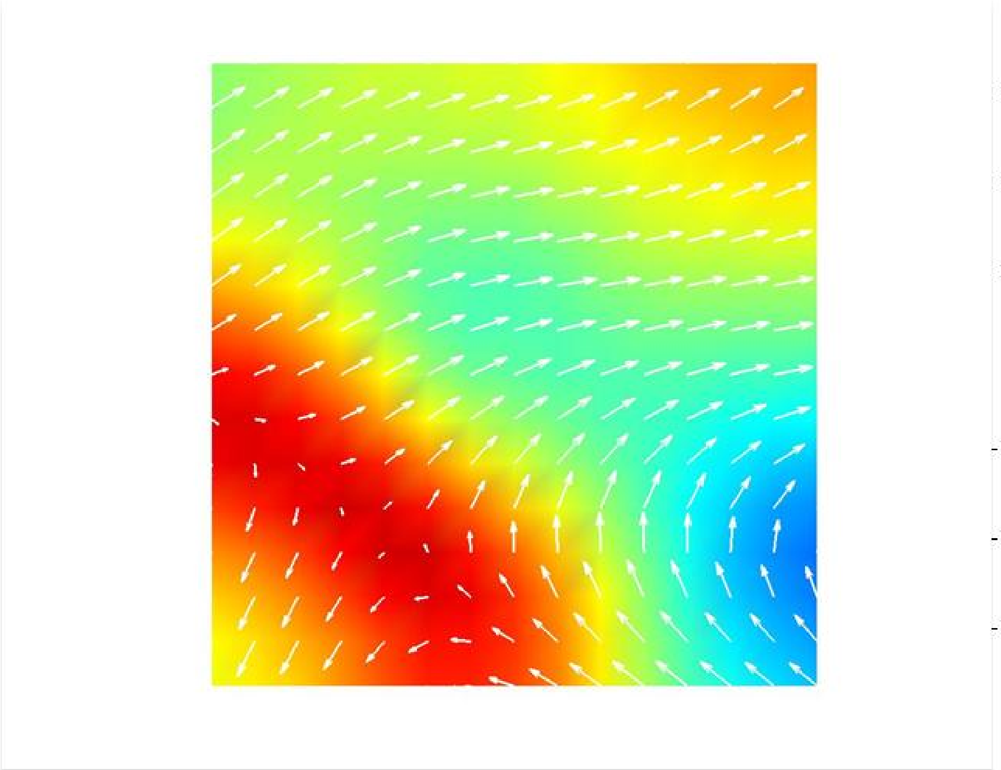


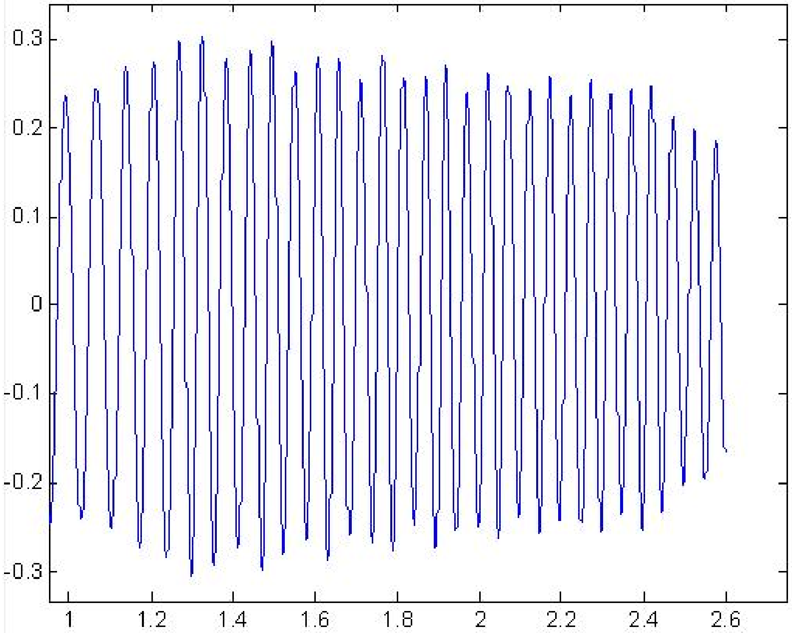
There are many ways to be wrong



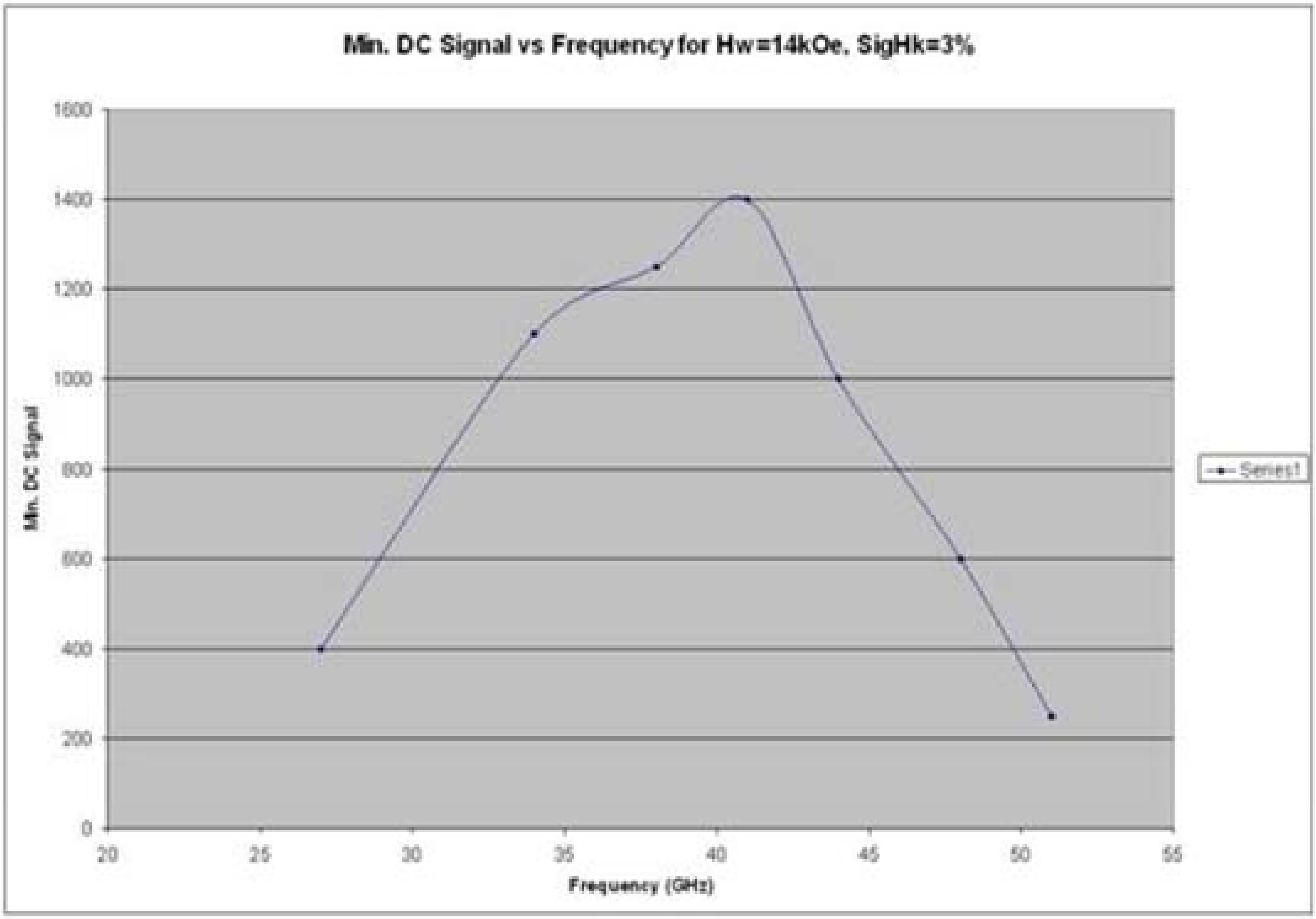
Unstable STO oscillation from highly curled magnetization

- **Frequency variation from 19 to 23 GHz**
- **Amplitude modulation of 55% full range**

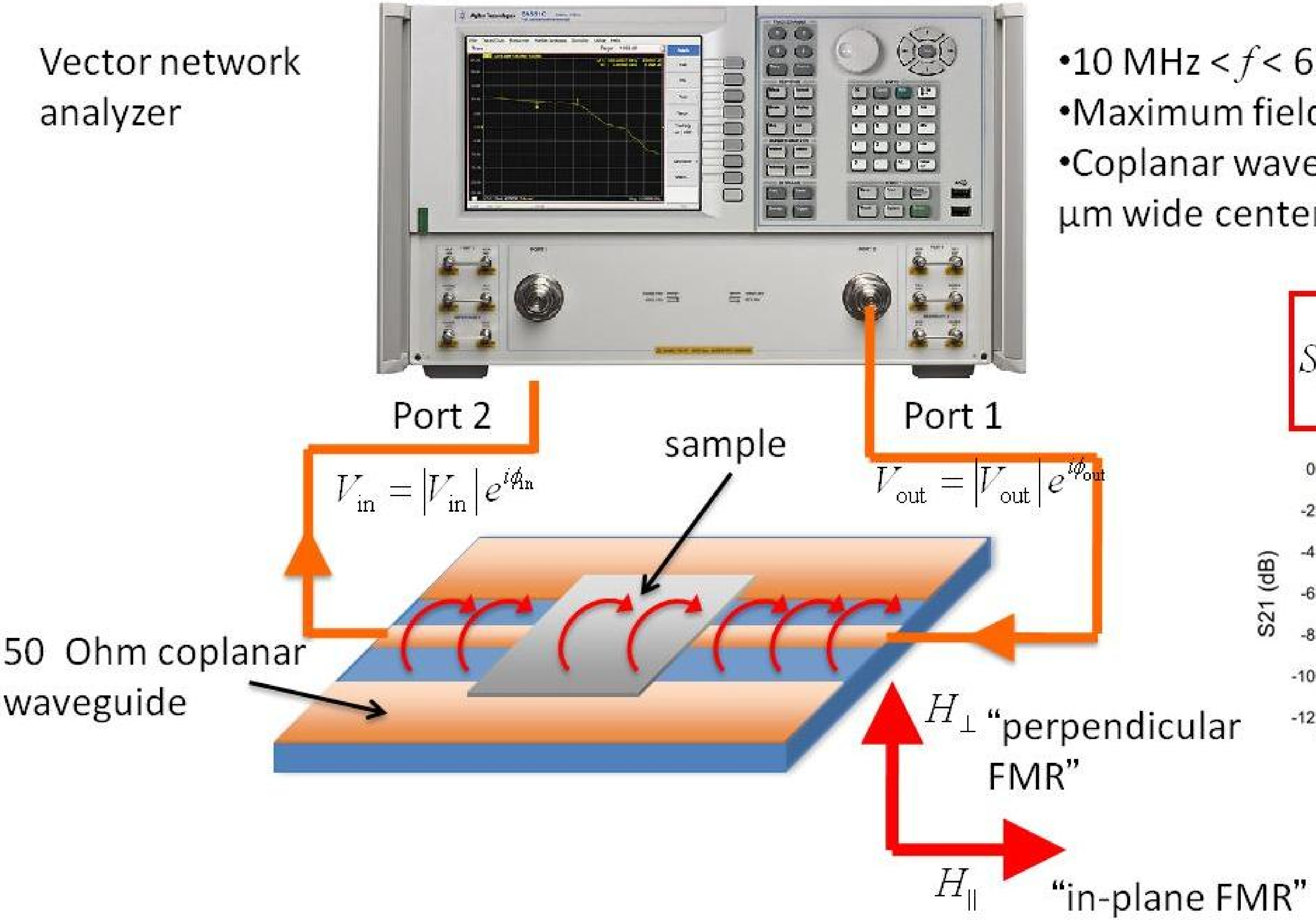




STO must be well tuned to the media

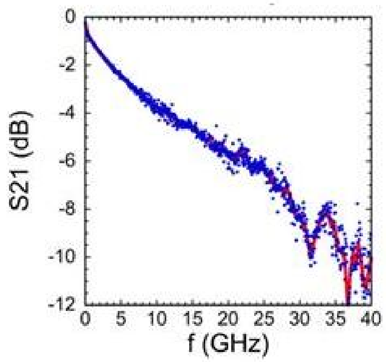


NIST VNA-FMR (10MHz to 67GHz)

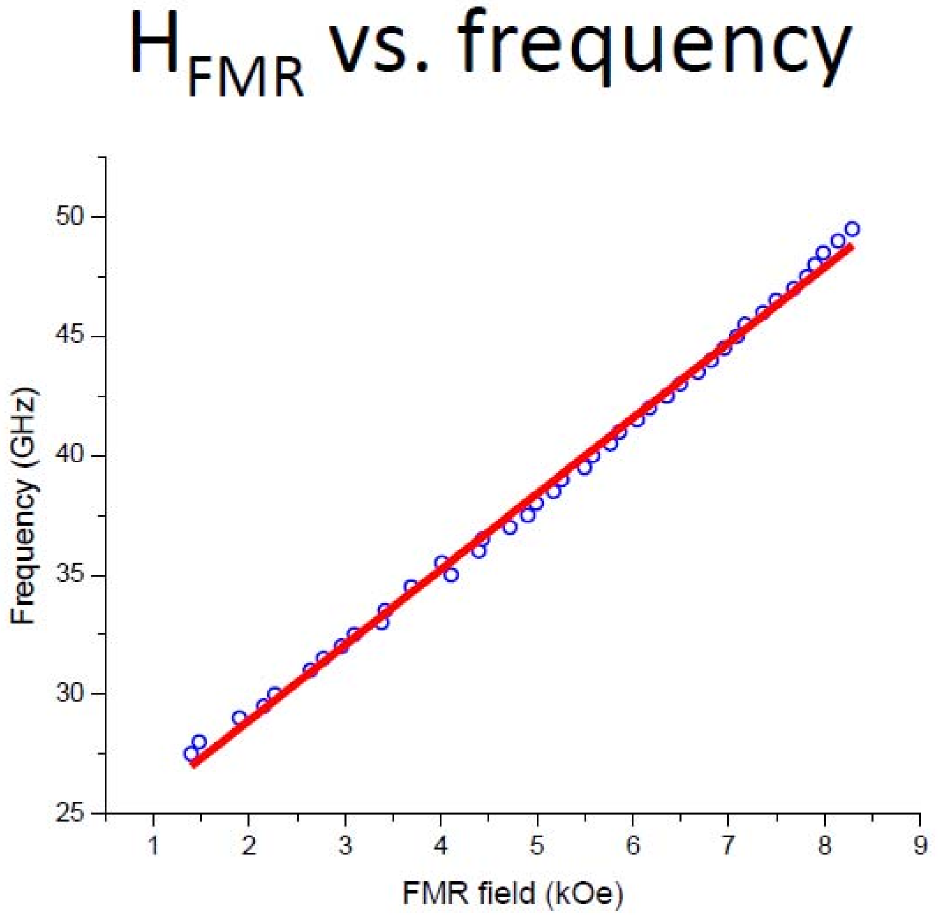


- 10 MHz < f < 67 GHz
- Maximum field: 2.4 T
- Coplanar waveguides with 100 µm wide center conductor

$$\boxed{S_{21} = \frac{|V_{\text{in}}| e^{i\phi_{\text{in}}}}{|V_{\text{out}}| e^{i\phi_{\text{out}}}} \propto \chi}$$

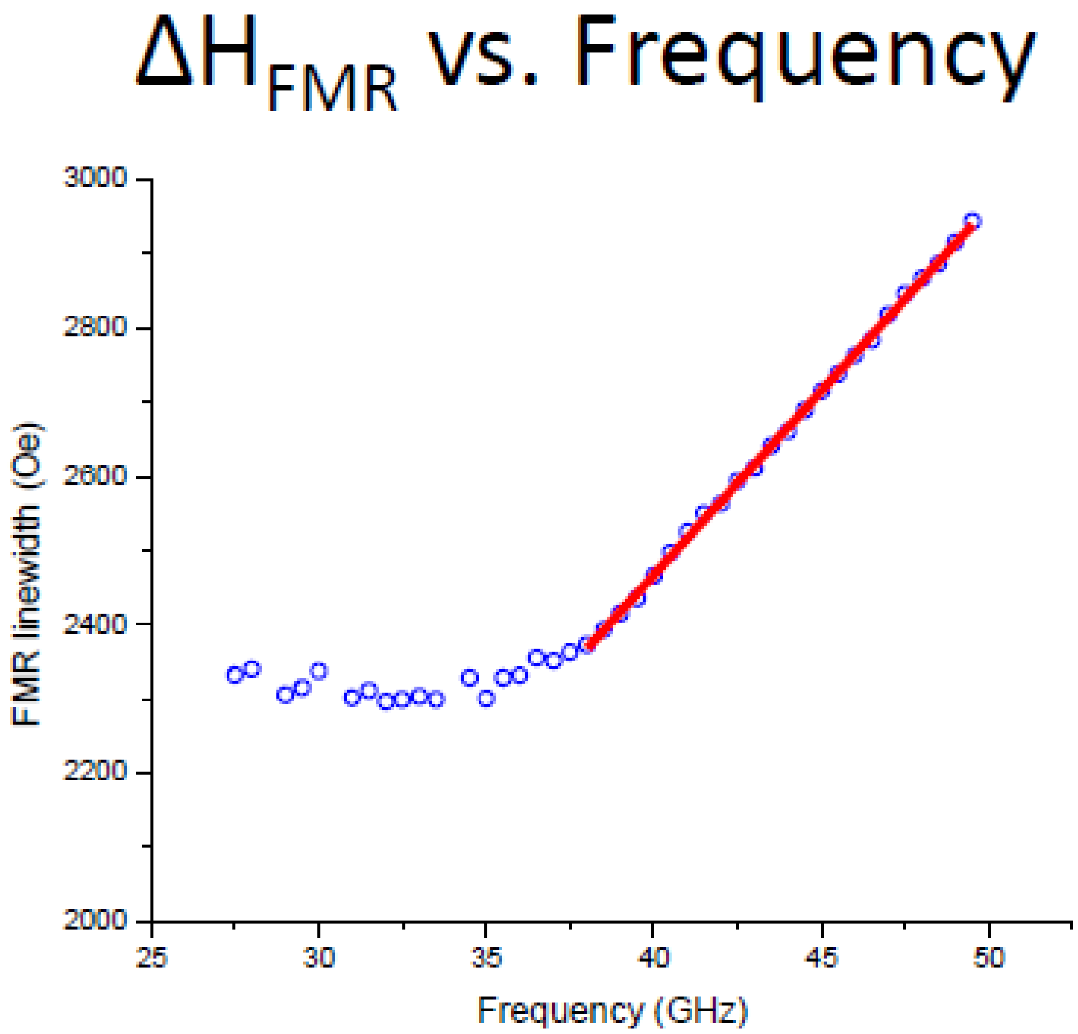


CSU Frequency vs Field Results



$$\gamma = 3.16\ MHz/Oe,\ H_k = 14862\ Oe,\ 4\pi M_s = 7738\ G$$

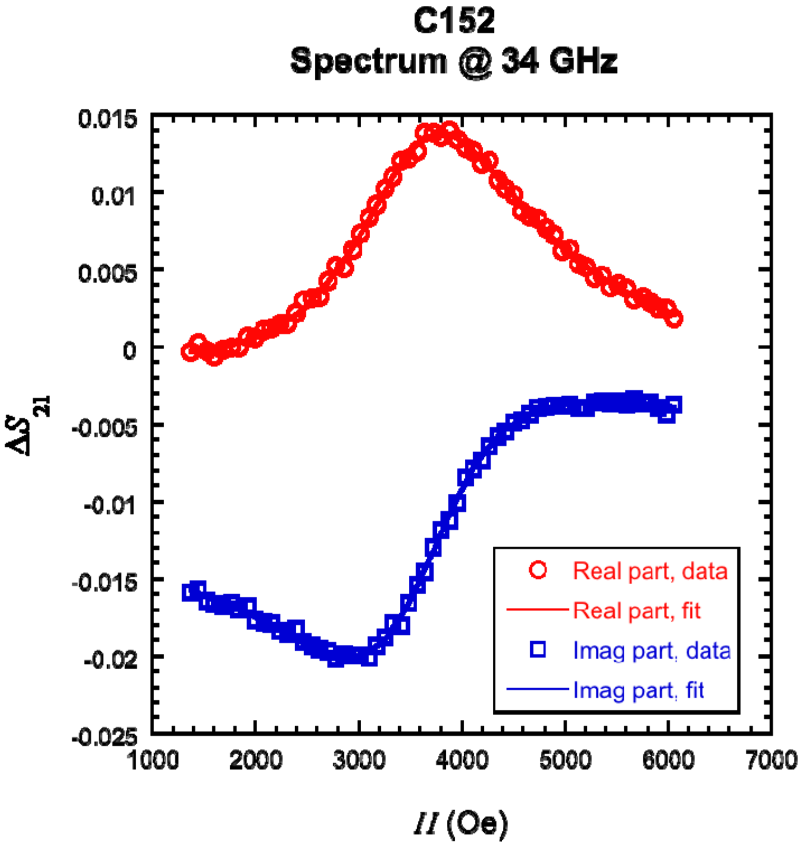
CSU Line Width Results



ΔH_{FMR} vs. Frequency

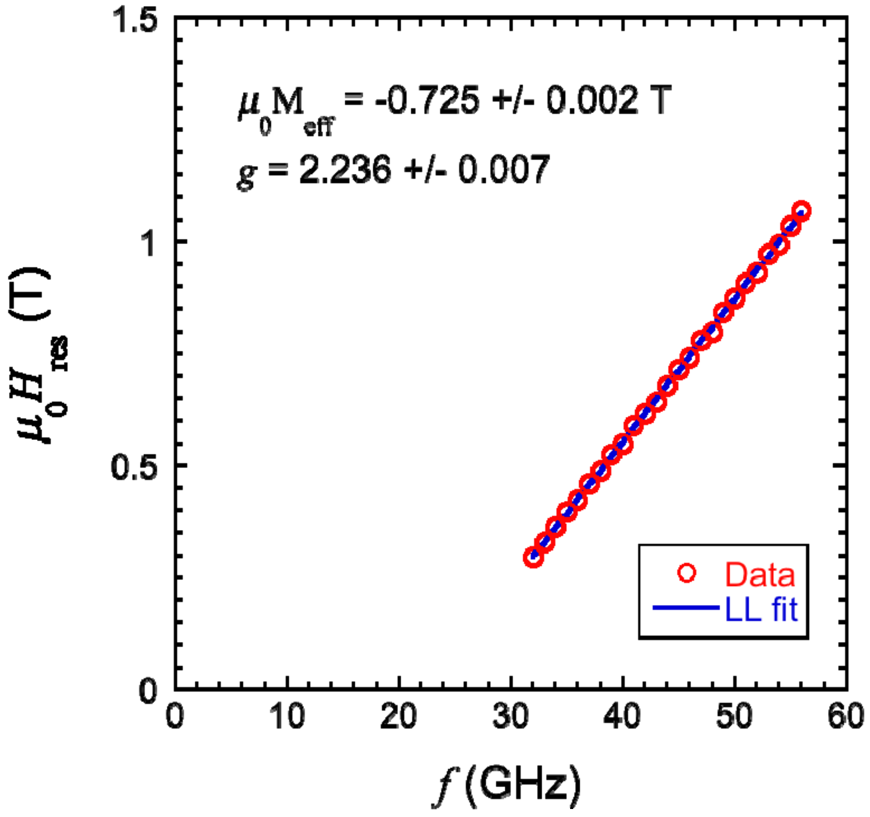
$$38\ GHz \sim 49.5\ GHz,\ \alpha = 0.079,\ \Delta H_0 = 479.5\ \mathrm{Oe}$$

NIST Bolder FMR spectra for media sample



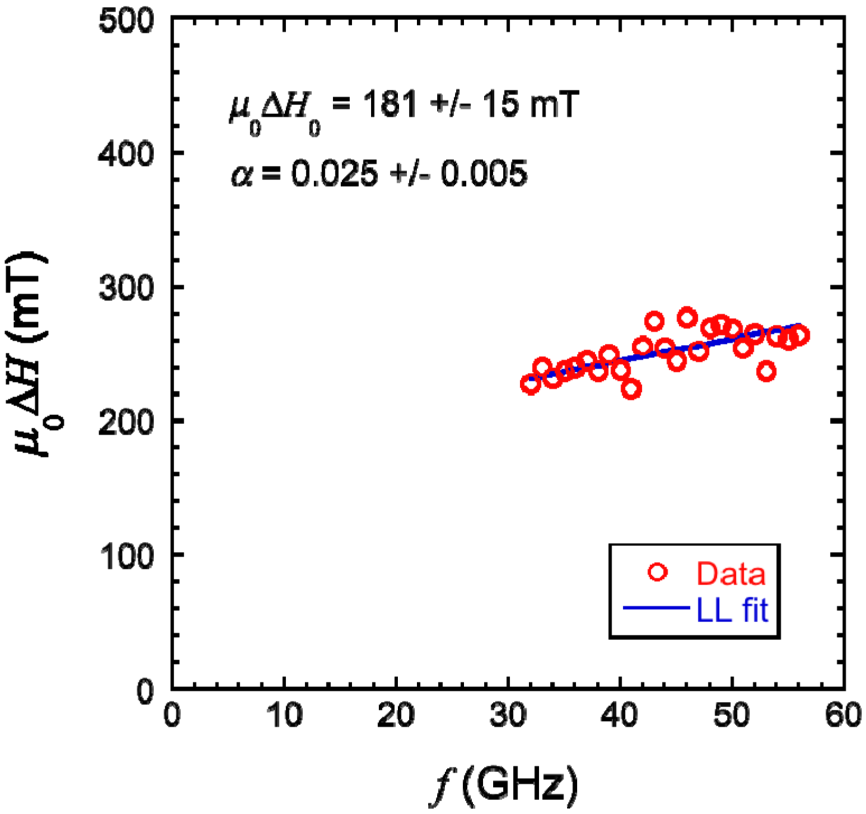
- Simultaneous fit of real and imaginary parts of susceptibility.
- 2000 – 3000 Oe linewidths. (Huge!)
- Excellent fit to LL spectral shape.

NIST Bolder Extracted spectroscopic parameters



- Extremely precise determination of effective anisotropy and orbital contribution to moment.
- Large g is not unexpected for films with large perpendicular anisotropy.
- Exact determination of zero-field resonance frequency.

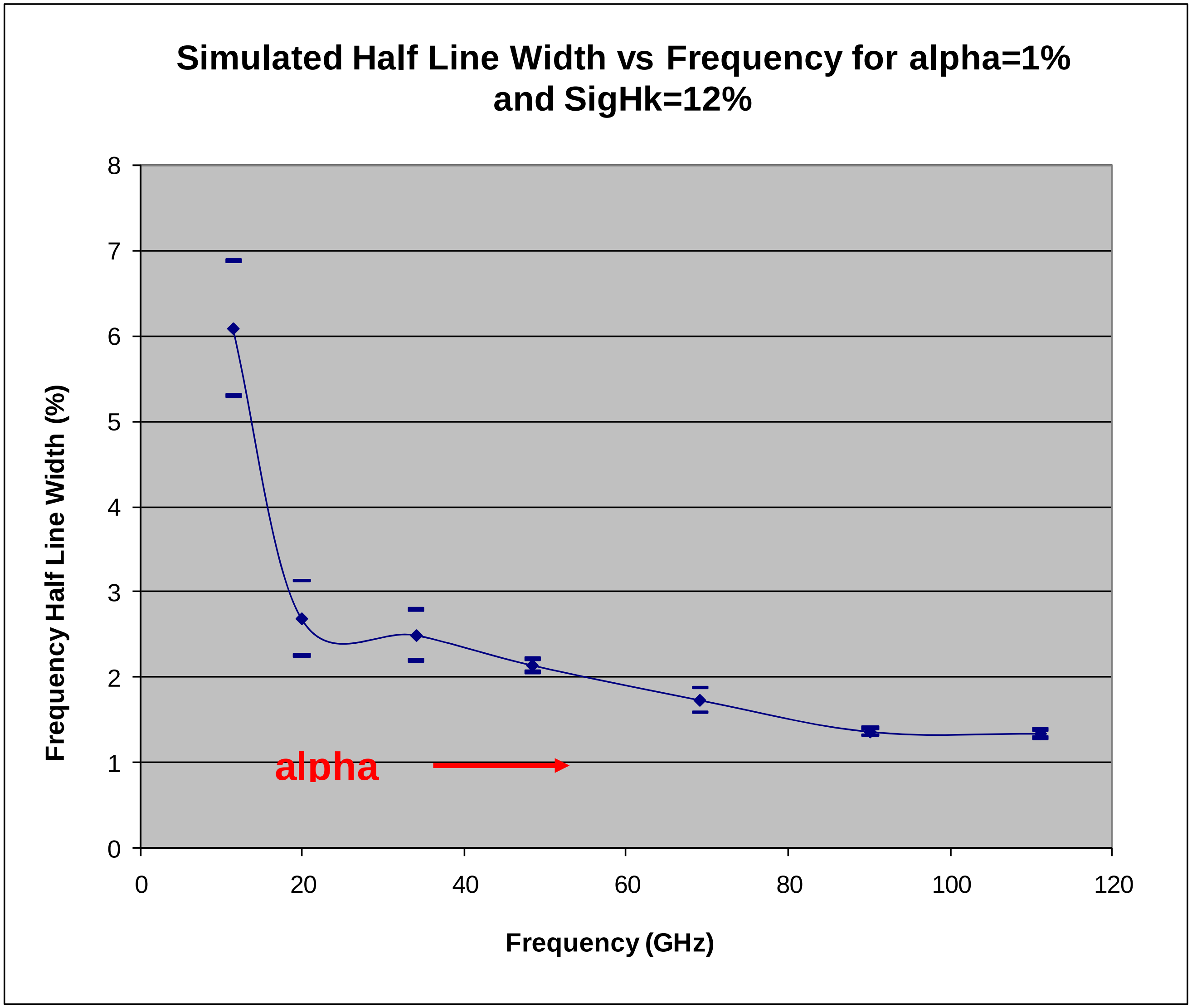
NIST Bolder Linewidth vs. frequency: Damping



- Huge linewidths. (Largest we've ever measured!)
- Slight increase over measured frequencies: Most of linewidth due to inhomogeneous broadening, not damping.

WD FMR Line Width Simulation with α=1% and σHk=12%

- Intern-granular exchange coupling strongly suppresses σHk at positive fields

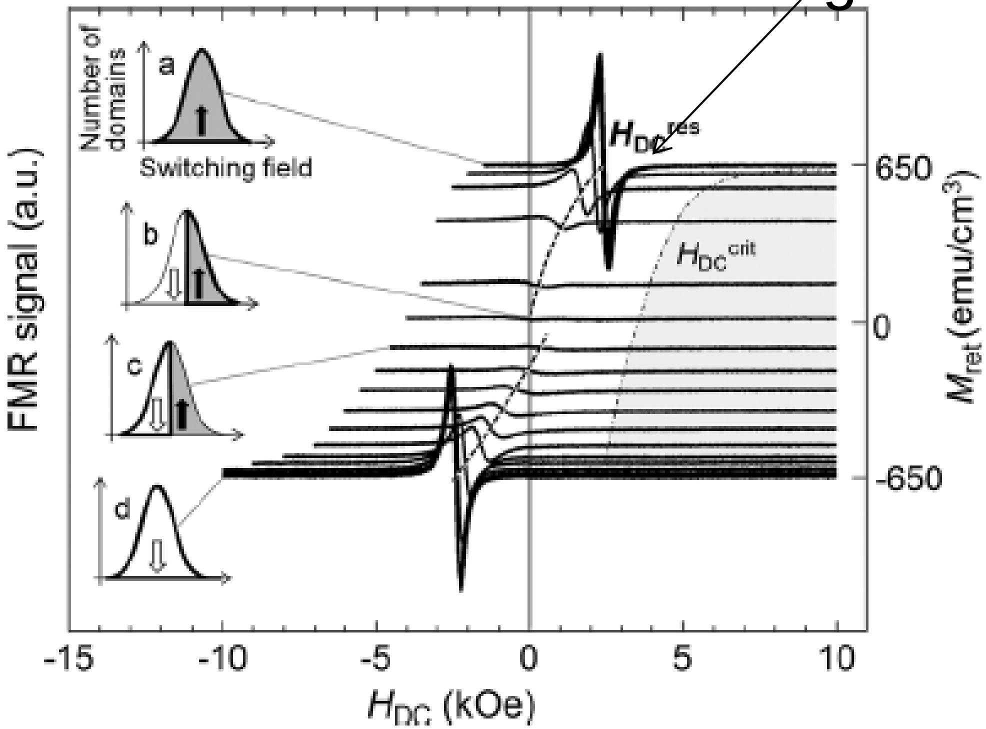


Ferromagnetic resonance analysis of internal effective field of classified grains by switching field for granular perpendicular recording media

Shintaro Hinata, Shin Saito, and Migaku Takahashi

Citation: J. Appl. Phys. **111**, 07B722 (2012); doi: 10.1063/1.3679466

Width gives $\alpha+\sigma H_k$ = **2.3%**



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JApplPhys_111_07B
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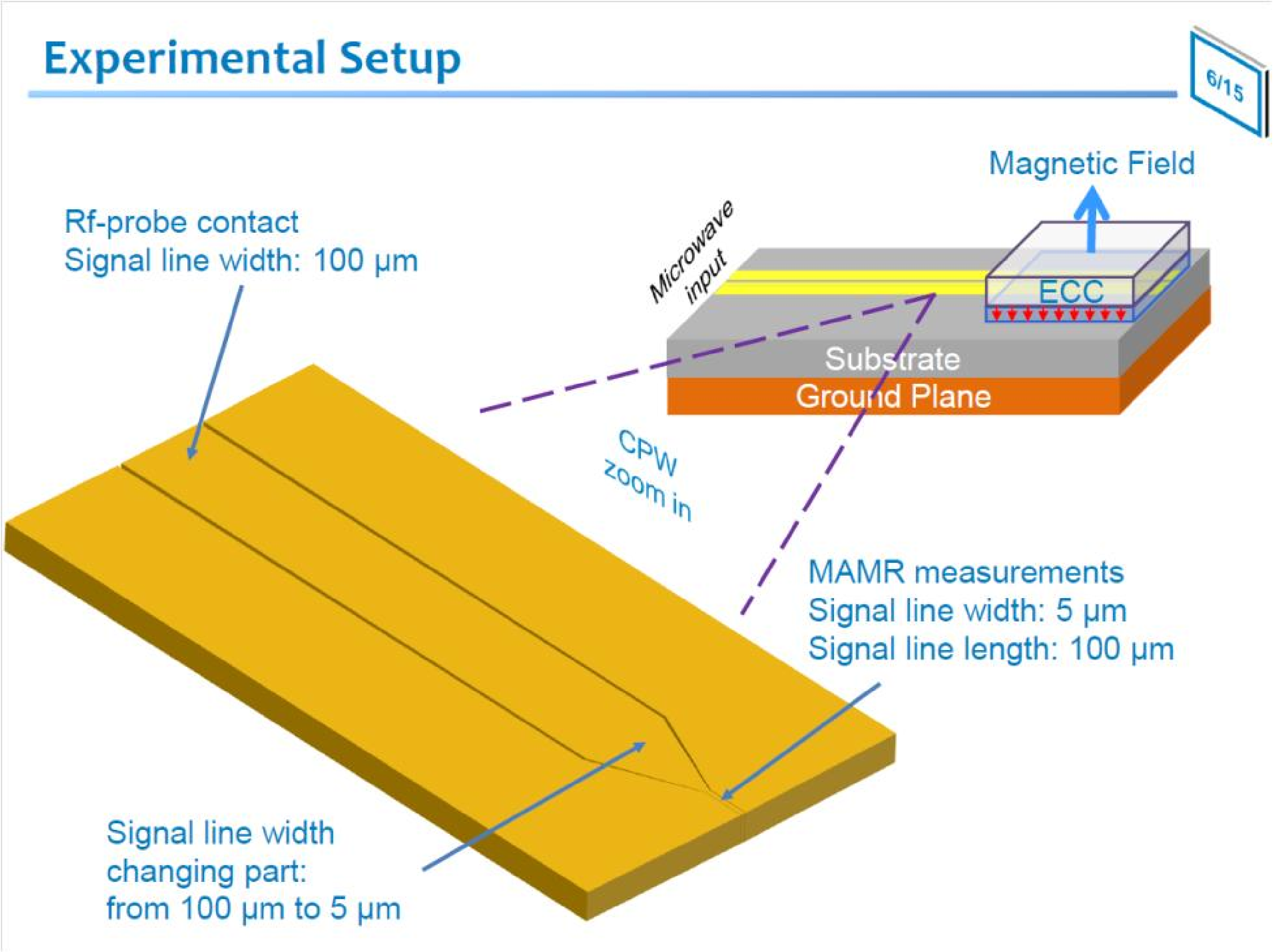
FIG. 4. FMR signals for the media II. Right vertical axis shows M_{ret} of the medium. Dash-dotted line indicates envelope of H_{DC}^{crit}. a–d: switching field distribution histograms when M_{ret} is equal to M_s, nearly 0, and $-M_s$, respectively.

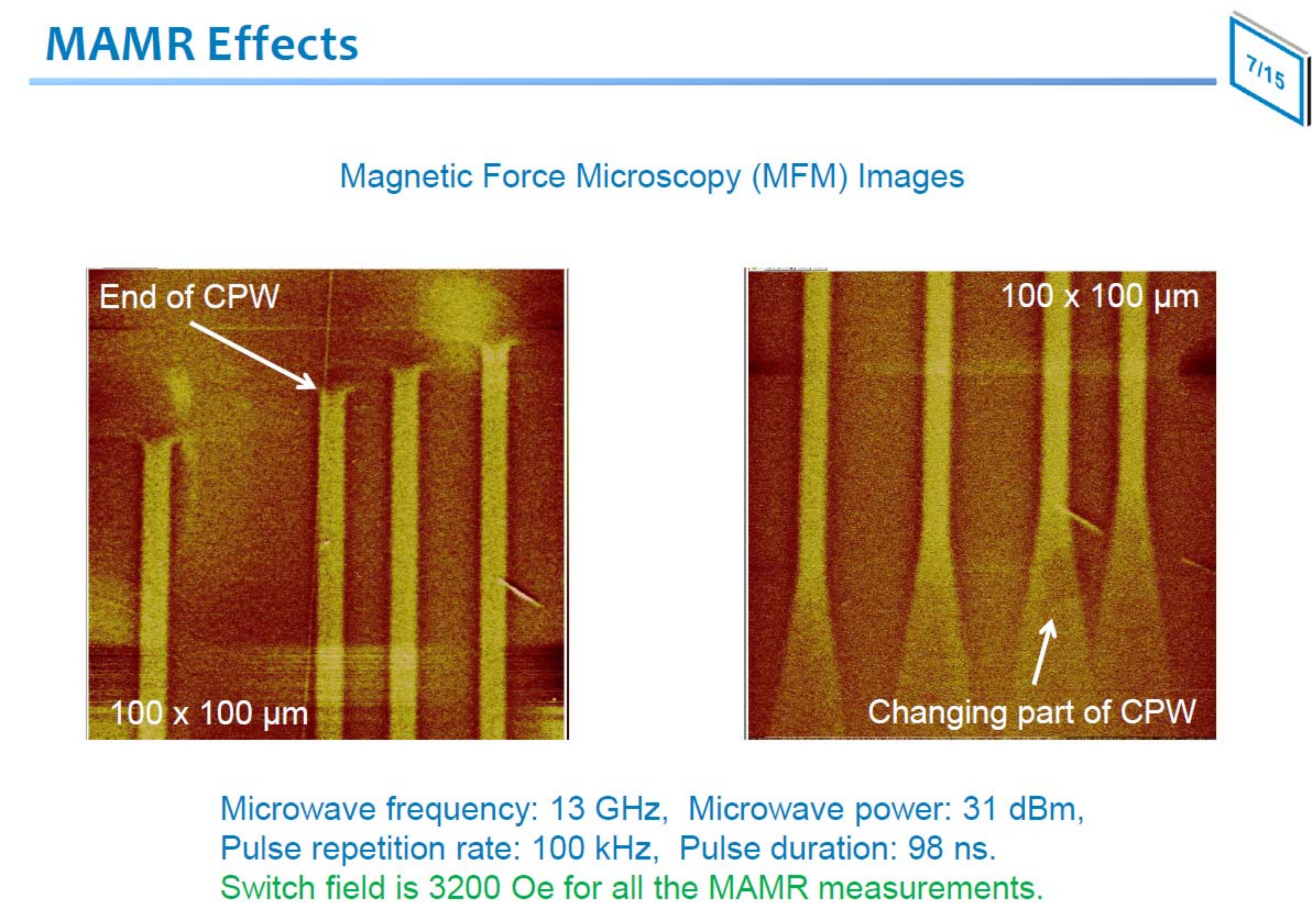
Media FMR Study Preliminary Conclusions

- FMR will ultimately be able to get sound measurements of damping, anisotropy field and anisotropy field dispersion but more work needs to be done with high intergranular exchange coupling
- CSU and NIST measurements on the same sample (C152) disagree significantly
  - **CSU α = 7.9%**
  - **NIST α = 2.5% +/-0.5%**
- Tohoku U. FMR result on CoPtCr line width gives alpha=2.3%
- All the above have sigma Hk contamination

CSU Micro-Loop MAMR (Prof. Mingzhong Wu and Lei Lu)



CSU Micro-Loop MAMR (Prof. Mingzhong Wu and Lei Lu)



MAMR Effects

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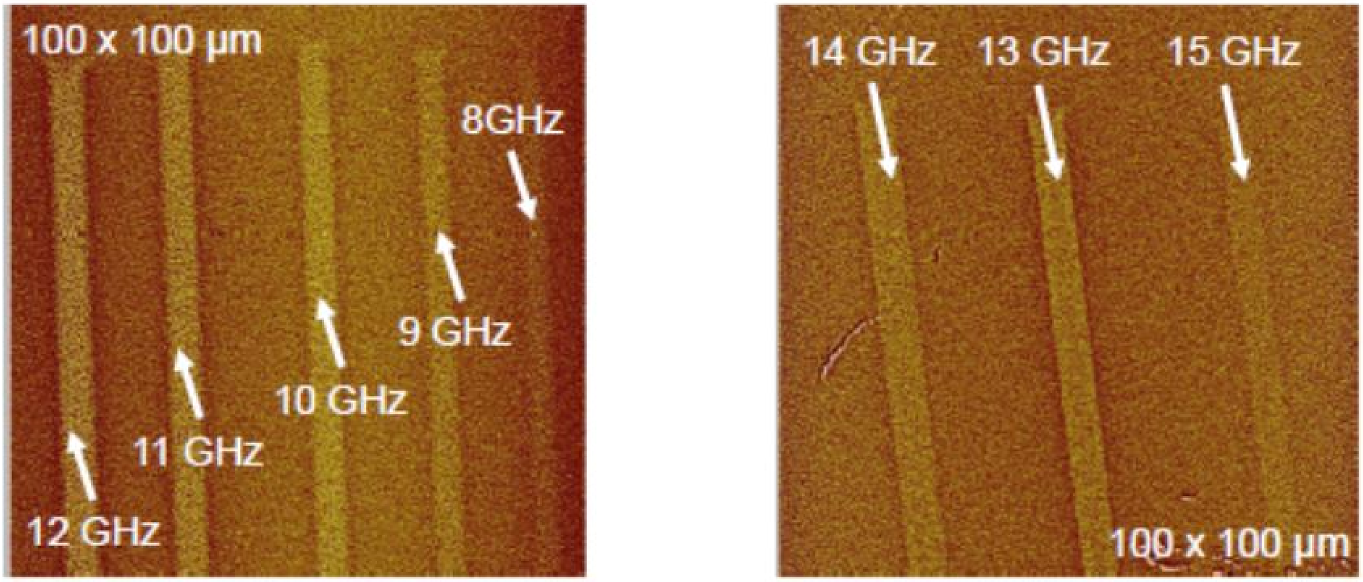
Magnetic Force Microscopy (MFM) Images

Microwave frequency: 13 GHz, Microwave power: 31 dBm,
Pulse repetition rate: 100 kHz, Pulse duration: 98 ns.
Switch field is 3200 Oe for all the MAMR measurements.

CSU Micro-Loop MAMR (Prof. Mingzhong Wu and Lei Lu)

Different Microwave Frequencies

Microwave Power: 31 dBm, Pulse repetition rate: 0.1 kHz, Pulse duration: 11 ns.



We observed MAMR effects with a frequency range from 8 to 15 GHz.

Conclusions

- **MAMR can provide an insurance policy for the performance and reliability issues of competing approaches**
  - Much smaller heads and media change
  - Buy time to debug other technologies
  - Can probably do >2 Tb/Sq”
    - Reduce required head field ~40%
    - Increase head field ~30% with wide write pole and no side shields
    - x2 increase in writeable Hk → ~ **x2 AD increase**
- **MAMR has to be done just right (it is a Goldilocks technology)**
  - STO optimized to media
    - frequency matched to media with the right deep gap field
    - Right Ms*Thickness for the FGL
  - Essential media modifications
    - Higher anisotropy with smaller grains while maintaining low sigma Hk
    - Other proprietary refinements
- **Critical mass of industrial investment is needed for MAMR to happen**