Spin-wave interference patterns created by spin-torque oscillators

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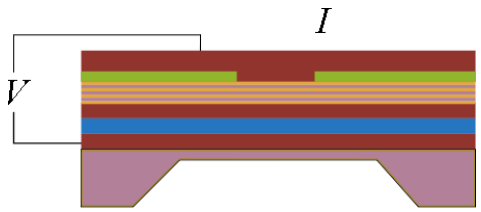
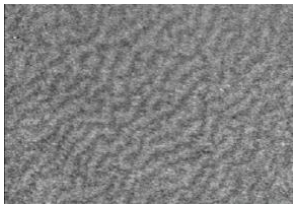
Outline

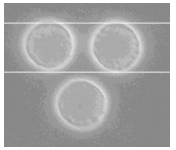
- Imaging spin-wave patterns created by STOs



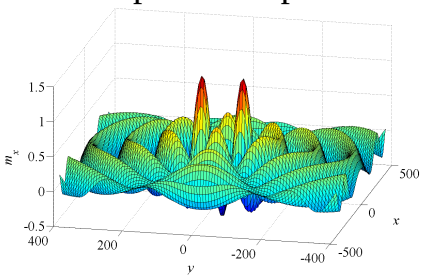
XMCD



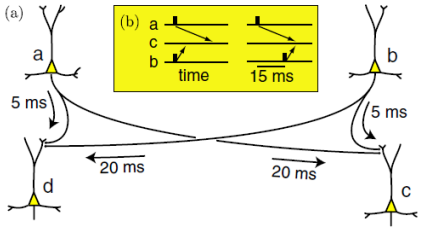
SEM

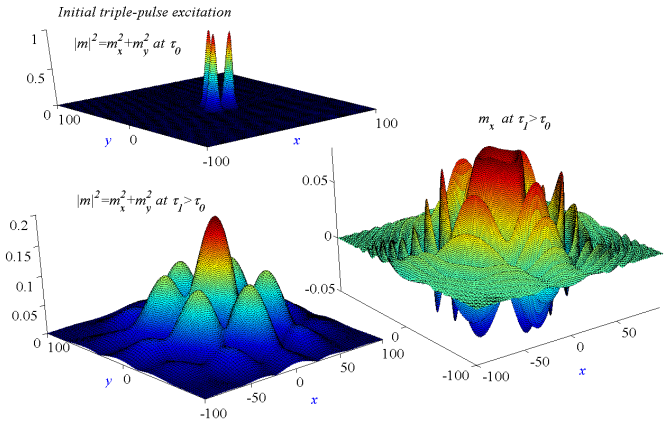


Spin-wave pattern



- Spin-wave diffusive patterns to implement memory units and computation



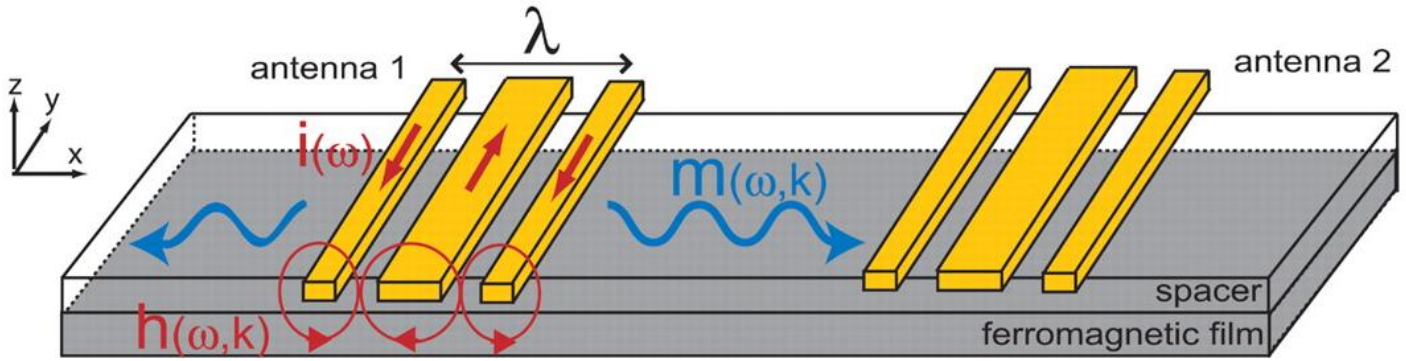


[Macià et al. Xiv:1009.4116]

Magnetic excitations in FM thin films

rf-fields

- Non-localized excitation
- Small amplitude
- Provide directionality

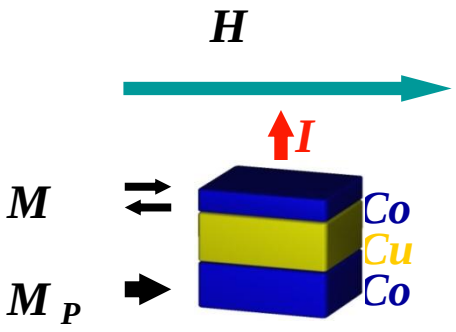


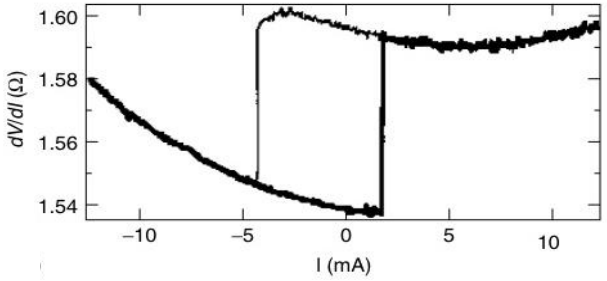
From Science (2008) **322,** 410

Magnetic excitations in FM thin films

Spin-polarized currents

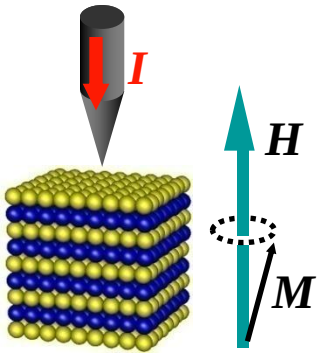
➔ Hysteretic Switching of M

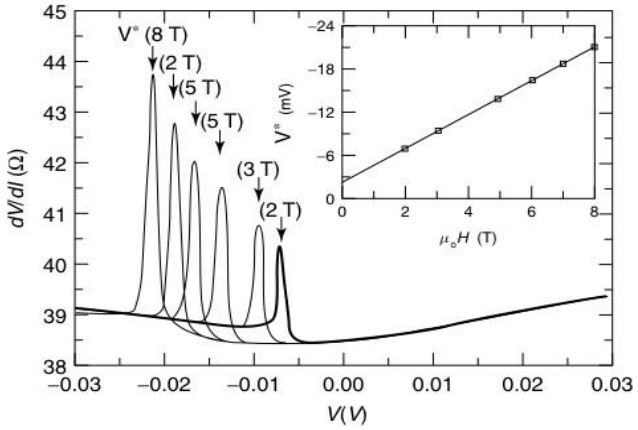




J.A. Katine et al. ; J. Grollier et al. … (1000)

➔ Precession of M





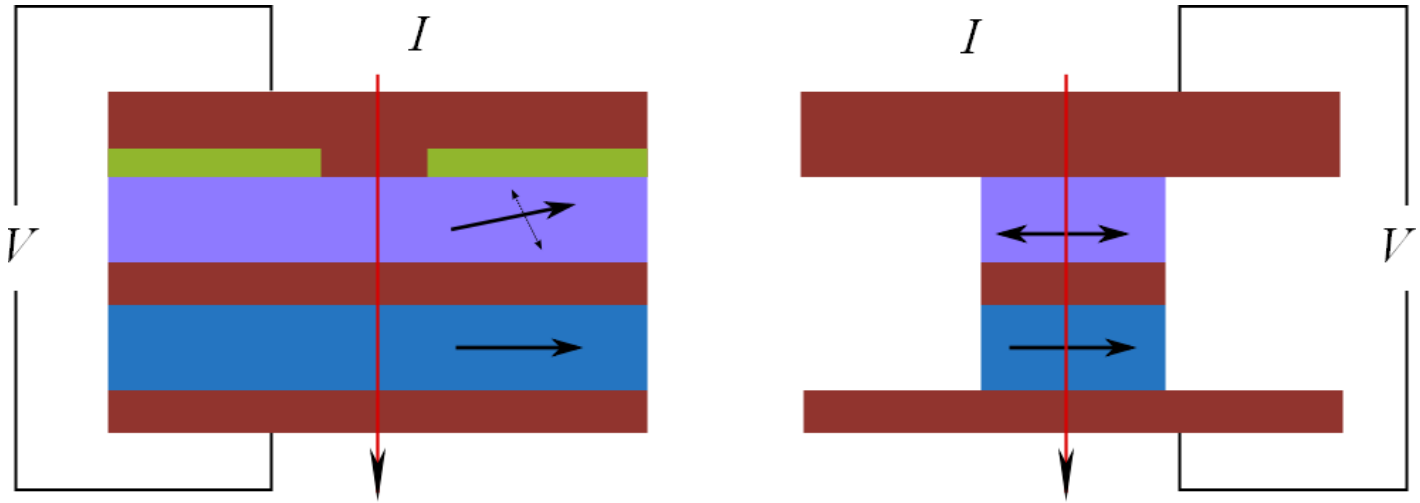
M. Tsoi et al. ; E.B. Myers et al.; Y. Ji et al., … (1998)

- Localized
- Large amplitudes excitations
- Provide NO preferred directions

Experimental Geometries

Spin transfer nano-oscillator (STO)

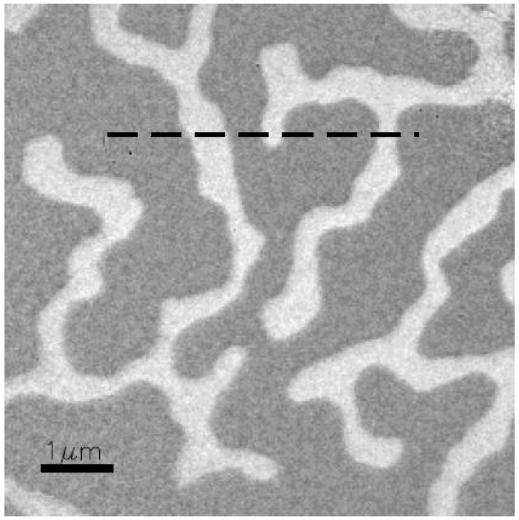
Nano pillars



In-plane radius ~ 20 – 200 nm
Current ~ 1 – 10 mA
Current density ~ 10^6 – 10^8 A/cm2

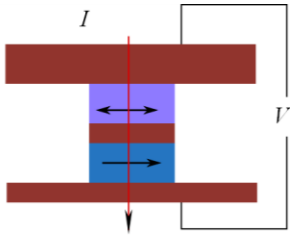
Imaging magnetic dynamics (XMCD)

Imaging magnetic domains

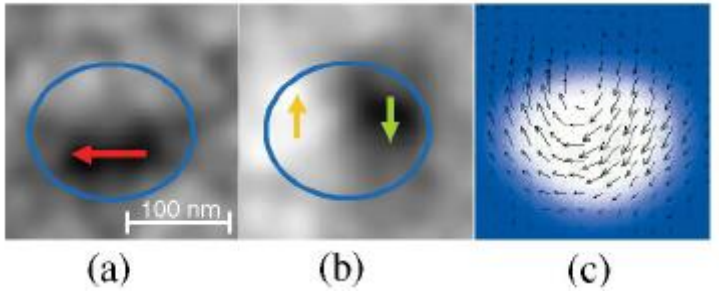


Fischer Z. Phys. B 101, 313–316 (1996)

Time-resolved measurements (XMCD) of the magnetic switching process

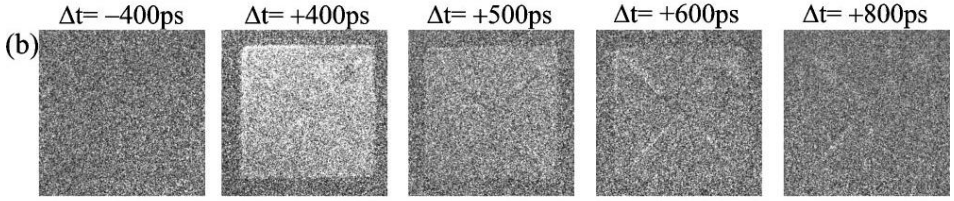


2nm Py



PRL 96, 217202 (2006)

Imaging of fast magnetization dynamics in magnetic nanostructures



Appl. Phys. Lett., Vol. 84, No. 17 (2004)

- Reversal process not uniform: Few domains involved

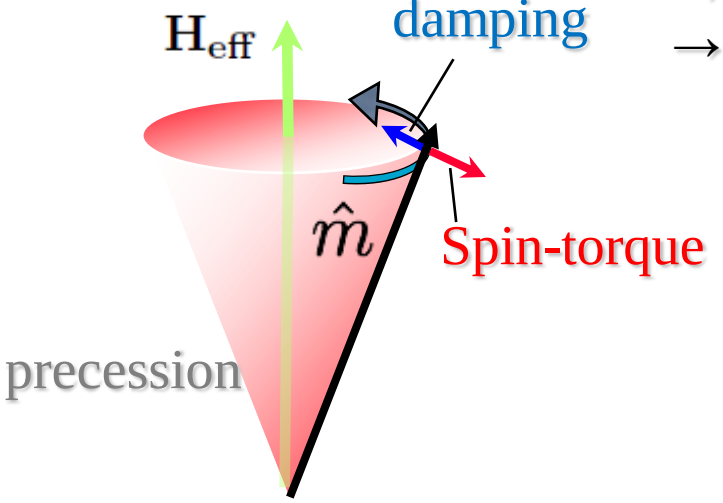
Dynamics: LLG + Spin-Torque (= LLGS)

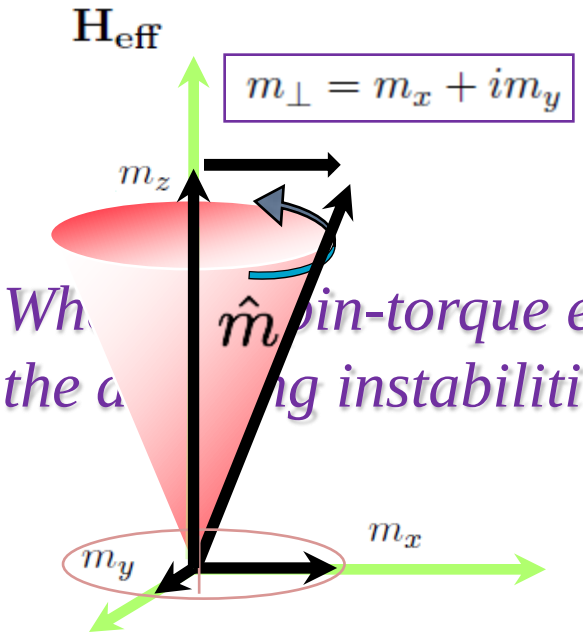
$$\frac{\partial \mathbf{M}}{\partial \tau} = -|\gamma|\mu_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} - \alpha \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) + \beta(\mathbf{x}) \mathbf{M} \times (\mathbf{M} \times \mathbf{m}_{\mathbf{f}}),$$

$\mathbf{H}_{\text{eff}}(\mathbf{H}_0, \mathbf{H}_D, \nabla^2 \mathbf{M})$

→ Applied field
→ Demagnetizing field
→ Exchange field

β(x) defines contact sizes and locations and depends on the current intensity, the layer thickness and the spin polarization



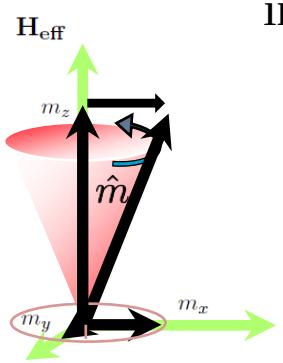


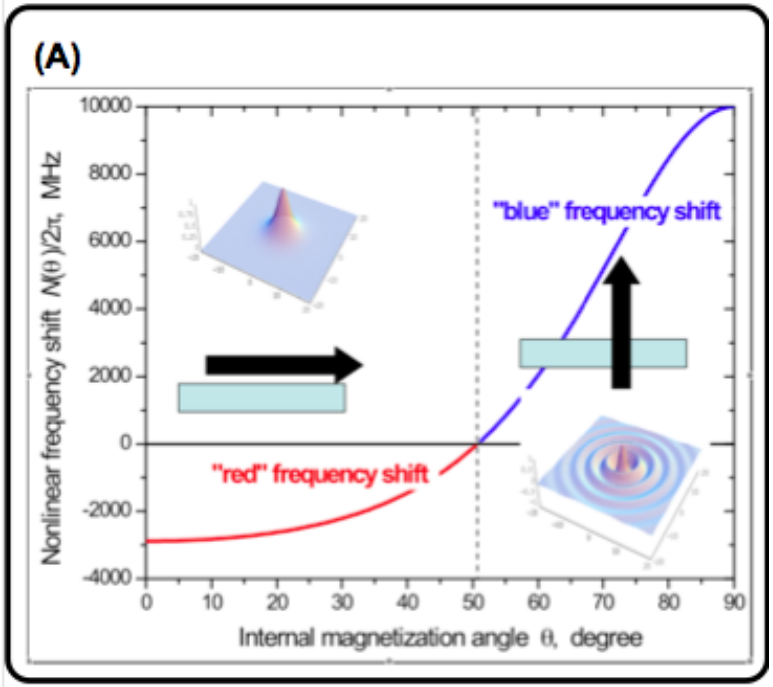
Wh pin-torque exceeds the c ng instabilities occur

Dynamics: Localized-delocalized modes

Static component decreases with the increasing oscillation amplitude.

$$m_z = \sqrt{1 - |m_\perp|^2}$$





FMR out-of-plane magnetization

$$\omega = \gamma(H - 4\pi M_{\text{eff}} m_z) \qquad \omega\uparrow$$

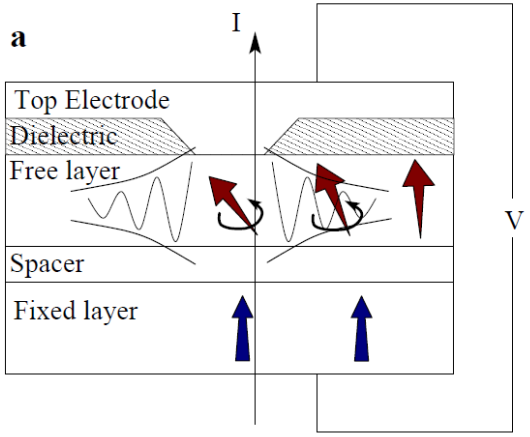
FMR in plane magnetization

$$\omega = \gamma\sqrt{H(H + 4\pi M_{\text{eff}} m_z)} \qquad \omega\downarrow$$

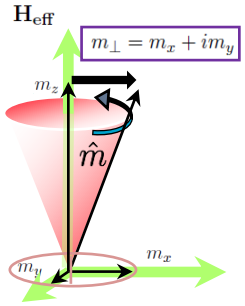
$$4\pi M_{\text{eff}} = 4\pi M_s - \frac{2K_\perp}{M_s}.$$

Slavin, PRL 95, 237201 (2005)

Patterning the spin-waves

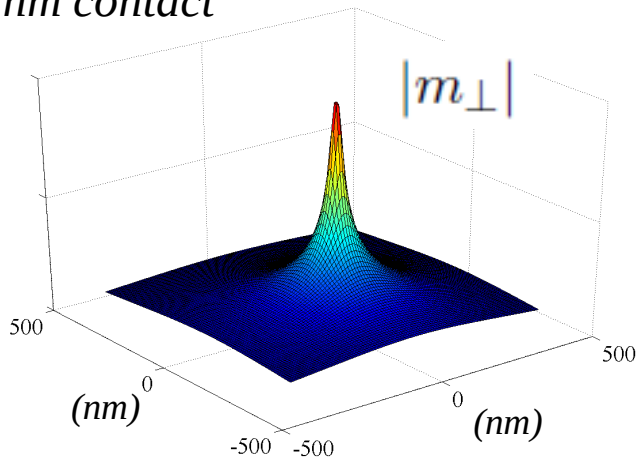


Can they be imaged?

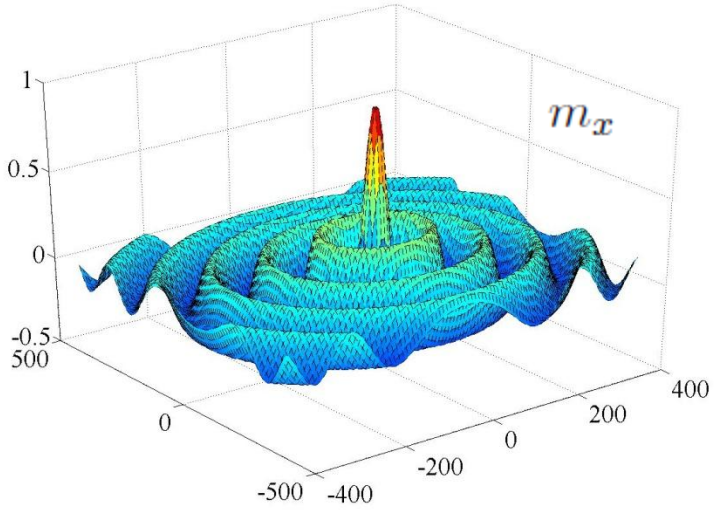


Modeling LLG for small perturbations

20 nm contact



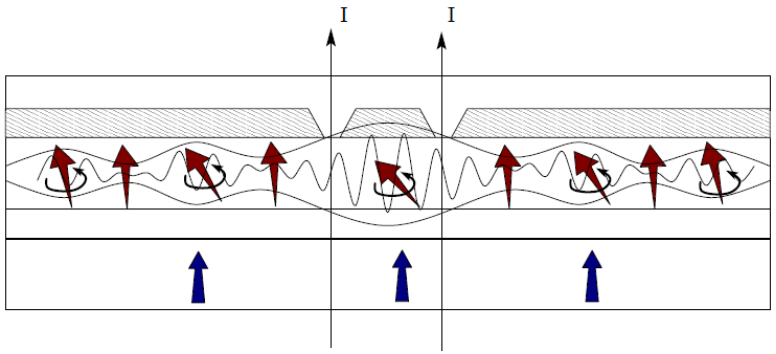
NO time-resolve imaging needed

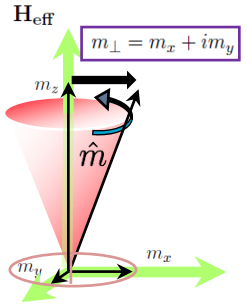


Time-resolved measurements NEEDED

- Contact size controls the patterns λ ~ 5r
- diffusions ~ microns

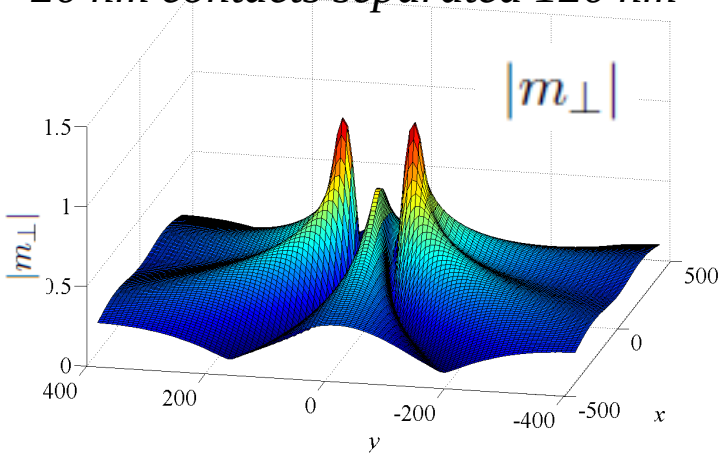
Patterning the spin-waves

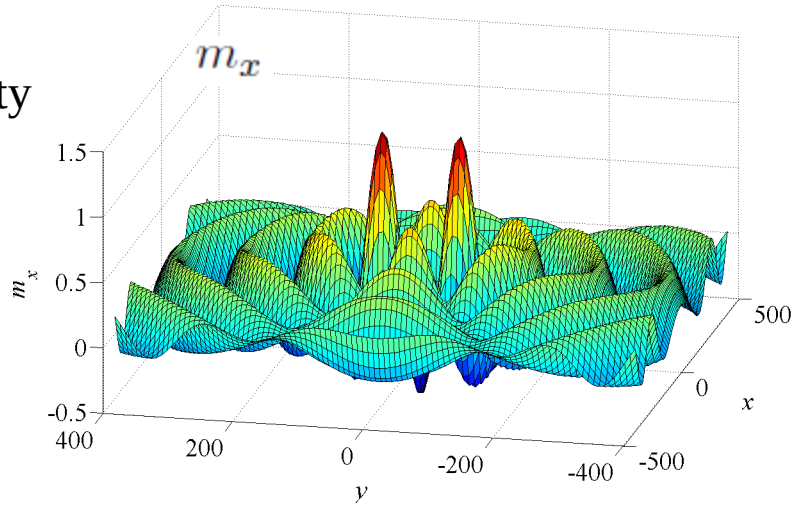




Spin waves interfere and enhance activity in certain locations

20 nm contacts separated 120 nm





- Contact size and distance allow pattern creations.
- Enhancement of activity in some regions

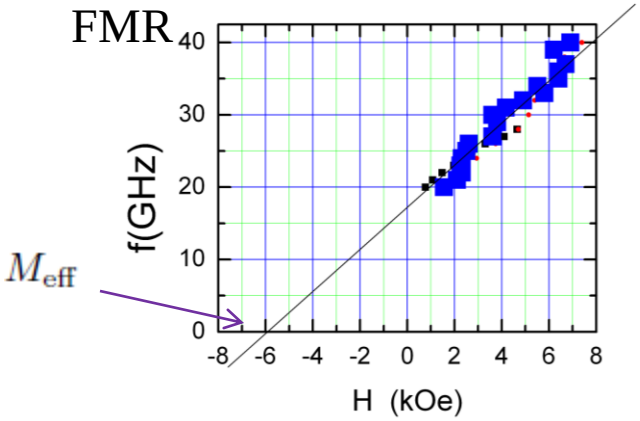
STO design: the magnetic film

Free layer: (0.2Co|0.6Ni) x n

Spacer: 10 Cu

Fixed layer: 10 Py

FMR

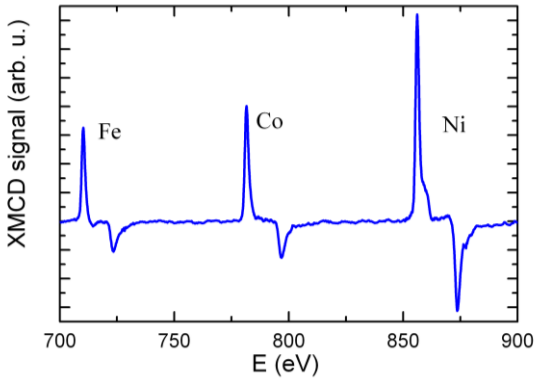


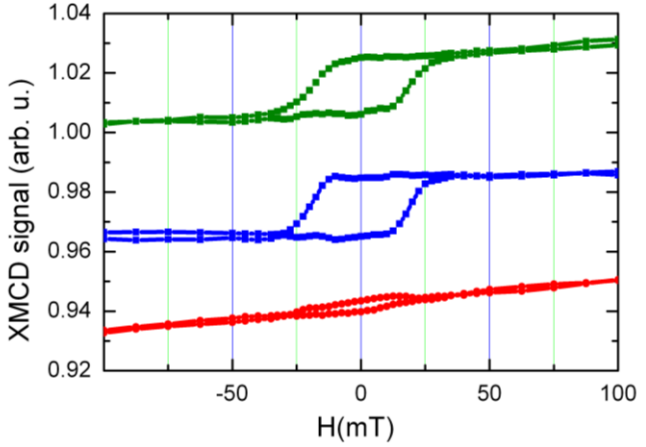
$$\omega = \gamma(H_0 - 4\pi M_{\text{eff}} m_z)$$

$$4\pi M_{\text{eff}} = 4\pi M_s - \frac{2K_\perp}{M_s}.$$

→ Out-of-plane anisotropy

XMCD



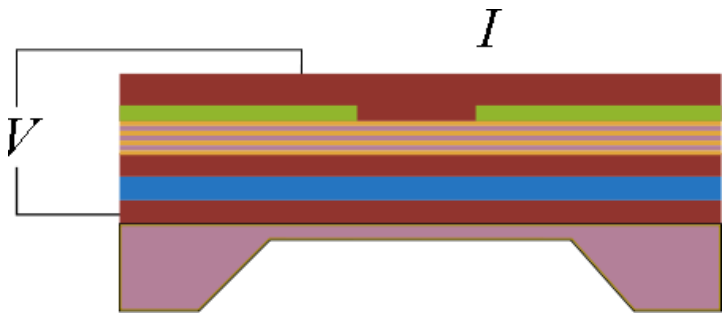


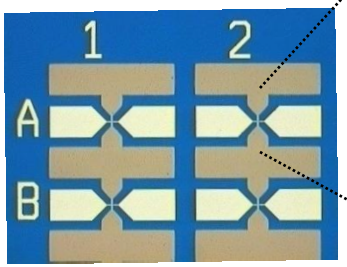
Ni

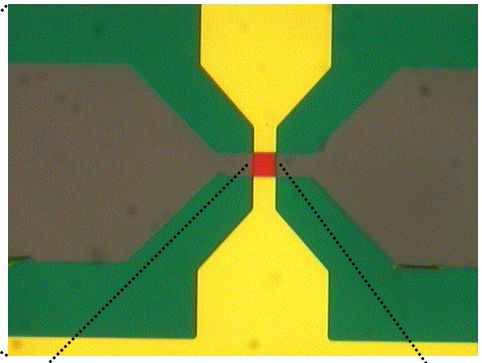
Co

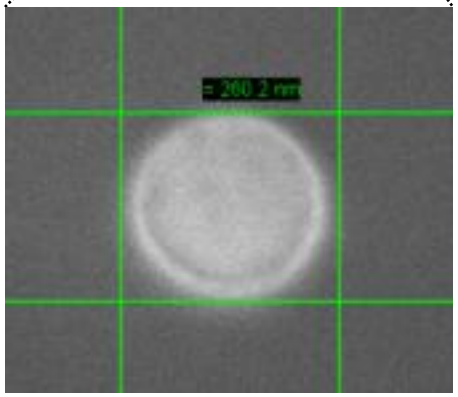
Fe

STO design: the STNOs

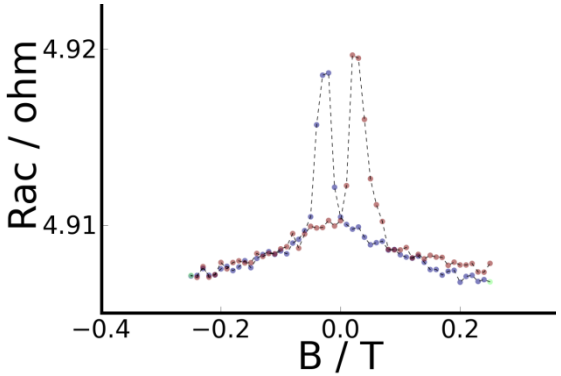




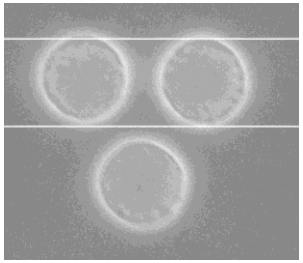


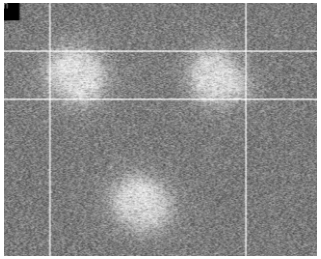


Different configurations

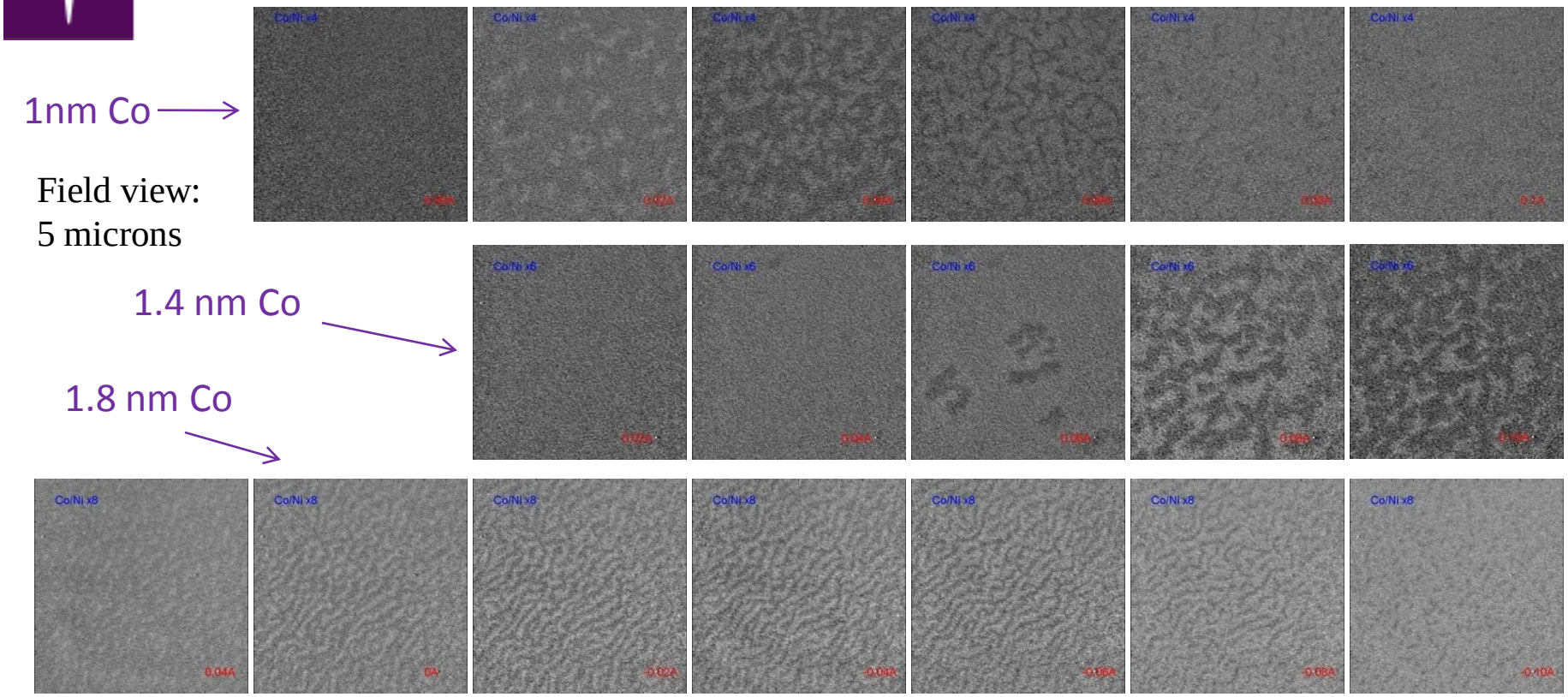


R=125 nm





Imaging the magnetic film, XMCD



Perpendicular applied field after saturation

H=0 T *H=6 mT* *H= 12mT* *H=18 mT* *H=24 mT* *H=30 mT*

- We have fabricated STOs, measured excitations, and resolved magnetization patterns in 1nm Co films.

Memory and computation with spin-wave patterns created by STOs

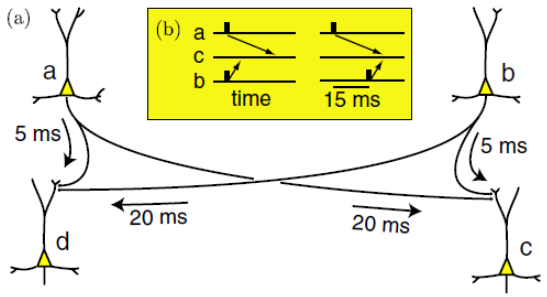
Polychronous wavefront computation ⟷ Computing with delays

Izhikevich, Int.Jour. of Bif. & Chaos (2009) 19:1733

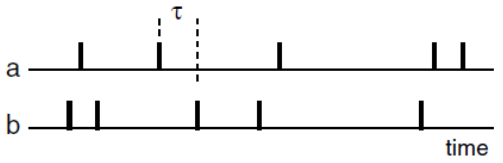
Computation paradigms that considers the importance of spatial propagation and axonal delays

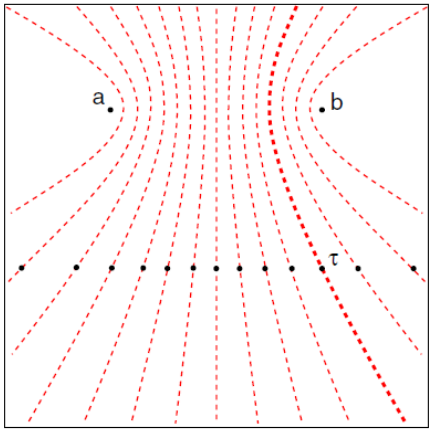
The key ingredients for PWC are

- A medium supporting interference patterns of propagating activity
- Transponders that can sense incident activity and respond by generating a propagating wave

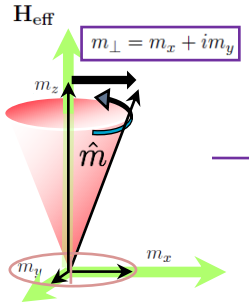


Detection of the inter-pulse interval

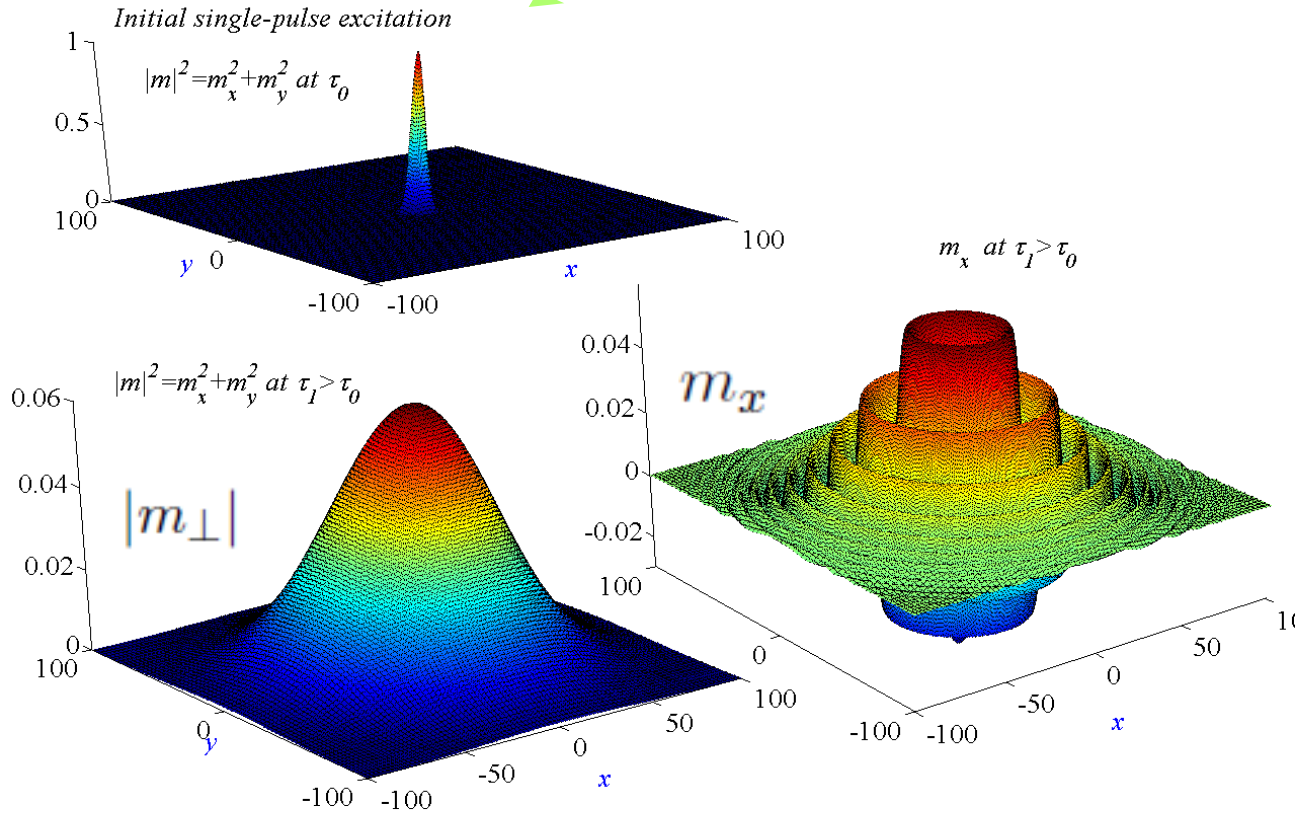




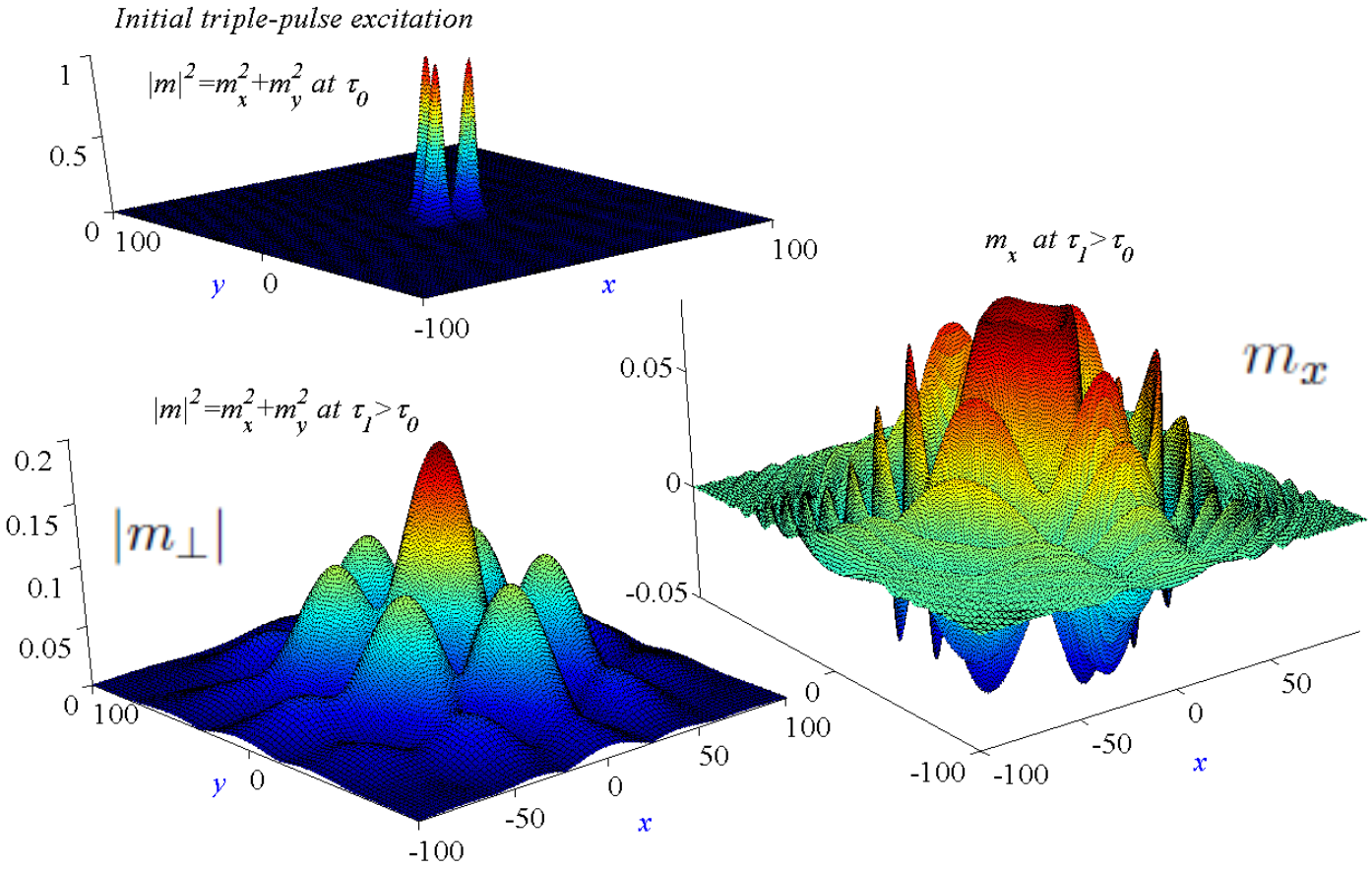
Propagating patterns; Pulsing STOs

Pulse STO → 

→ Relaxation patterns



Propagating patterns; Pulsing the more-than-one STO



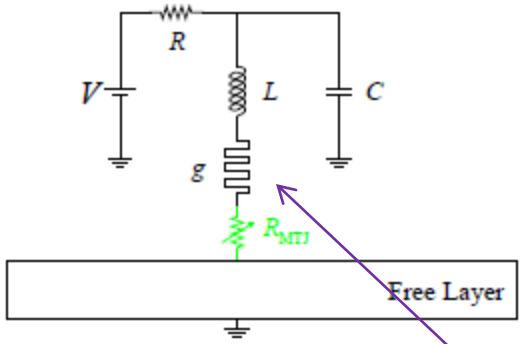
Transponders; Reverberating Activity

To use the spin-wave patterns for computation we need:

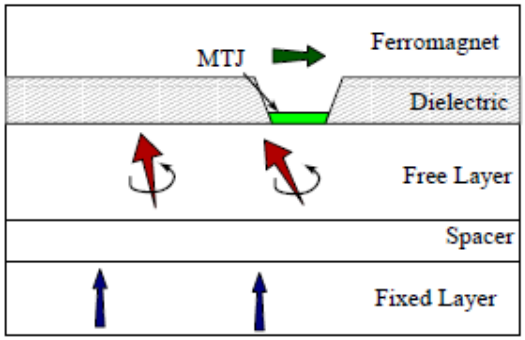
- Detecting spin-wave activity
- Responding by creating new activity

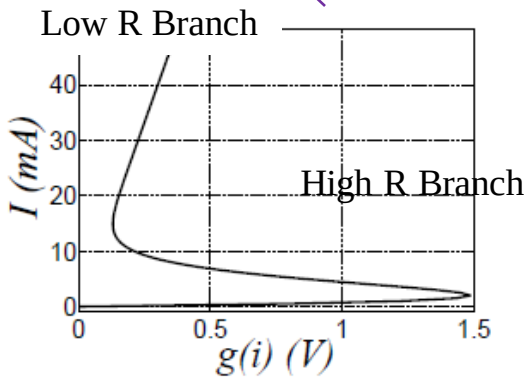
→ Transponders

•It is basically an integrate-and-fire circuit, where a storage device accumulates charge that is discharged rapidly when a certain threshold level is achieved.



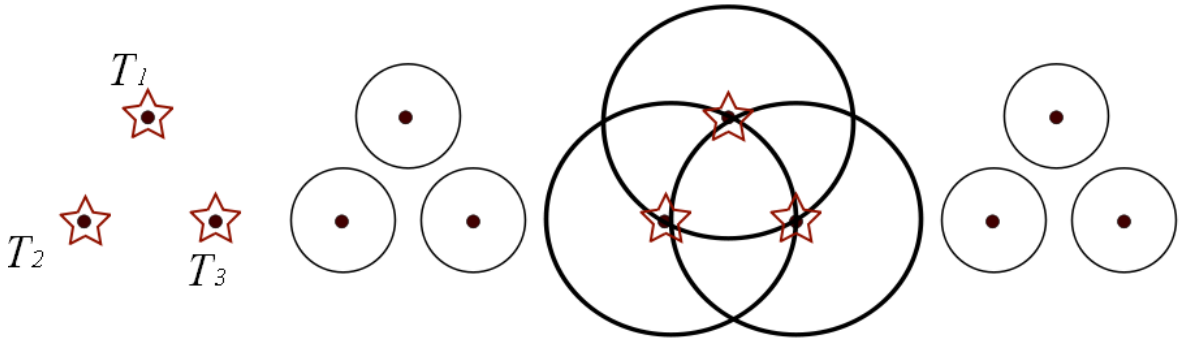
GMR-TMR





Polychronous wavefront computation with STNO

1. Reverberating structures



Several configurations can maintain stable reverberating activity, and hence, serve as memory unit.

2. Look-up tables

Scalable structures, 3D!

Programming transponder arrangements having graded reverberating frequencies: look-up tables.

Macià et al. arXiv:1009.4116

NYU

Summary

- Fabricated STOs and studied their characteristics
- Imaged 1nm-thick Co Layer
- Modeling shows that spin-wave packets can be tailored in STO arrays
- Provides a means of implementing Polychronous Wavefront Computation. *Macià et al. arXiv:1009.4116*