Nanowire spin torque oscillator driven by spin orbit torques

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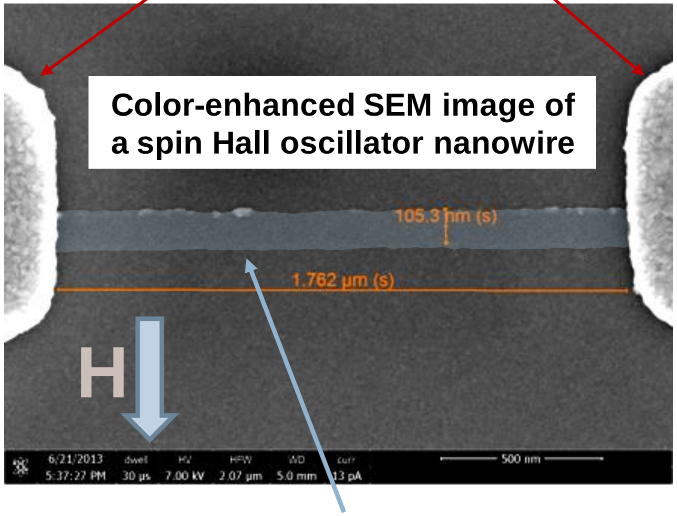
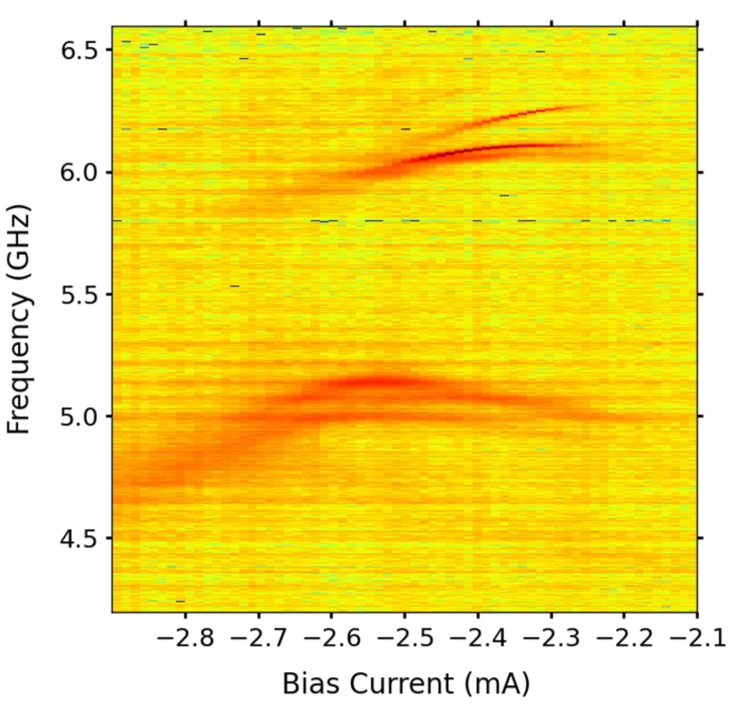
Au leads

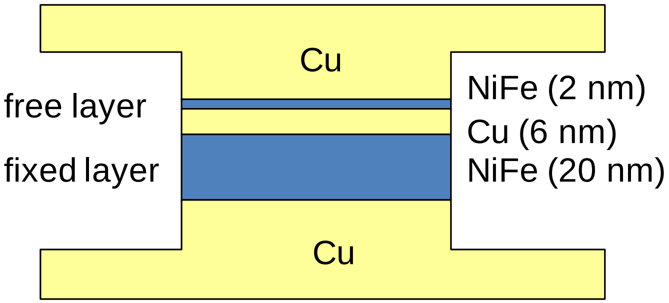


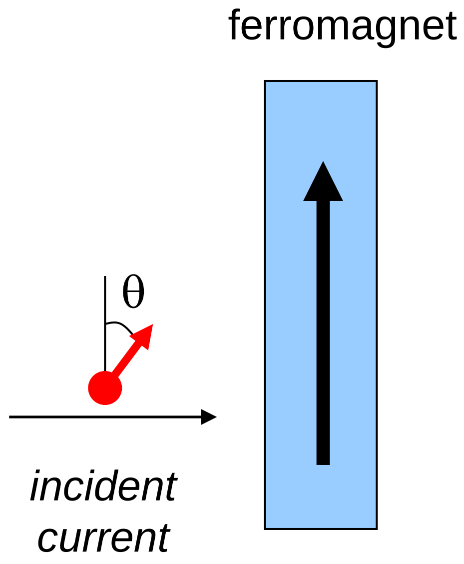
Color-enhanced SEM image of a spin Hall oscillator nanowire

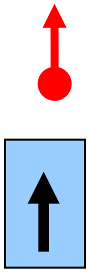
Pt/Py bilayer



Spin Transfer Torque Effect







- *electron magnetic moment*

- *local moment of ferromagnet*

-Spin-polarized current applied to a ferromagnet exerts torque on its magnetization

- Usually the effect is observed in nanoscale spin valves or magnetic tunnel junctions

-The physical origin of this torque is exchange interaction between spins of the current and local magnetization of the ferromagnet:

- Spin torque can be evaluated from the *conservation of angular momentum*:

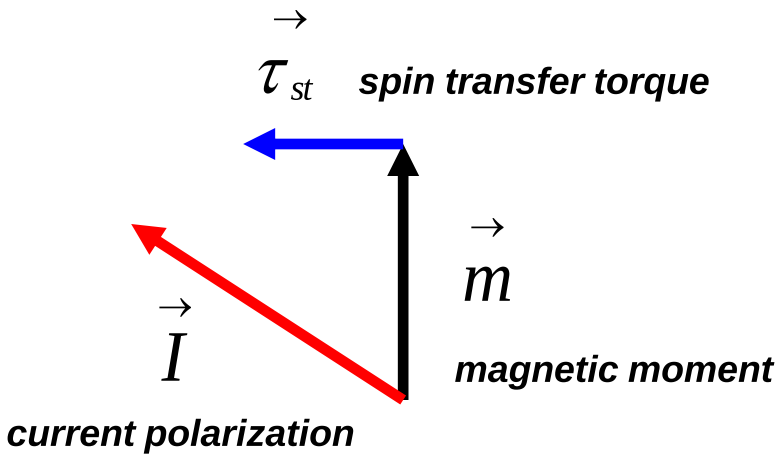
$$\tau_{ST} = \frac{dL_{in}}{dt} - \frac{dL_{out}}{dt}$$

Slonczewski, JMMM (1996)

Berger, PRB (1996)

Spin Torque

Spin torque can act on magnetization like extra damping or anti-damping



$$\vec{\tau}_{st} \sim \vec{m} \times \left(\vec{I} \times \vec{m} \right)$$

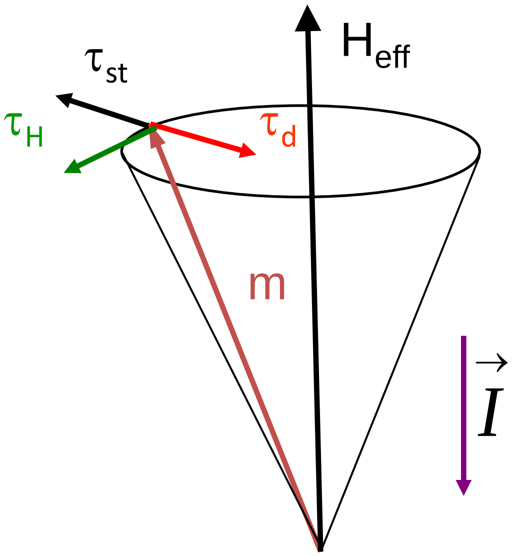
Landau-Lifshitz-Gilbert equation with spin torque term :

$$\frac{d\vec{m}}{dt} = -\gamma \cdot \vec{m} \times \vec{H}_{eff} + \frac{\alpha}{|\vec{m}|} \cdot \vec{m} \times \frac{d\vec{m}}{dt} + \eta(\theta) \cdot \vec{m} \times \left(\vec{I} \times \vec{m} \right)$$

Precession **Damping** **Spin Torque**

Magnetic Dynamics Induced by Spin Torque

Magnetic moment can either switch to a static state anti-parallel to the field or it can enter a dynamic state of steady precession.

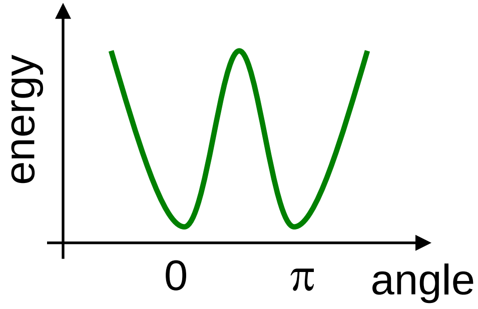


τ_H – field torque

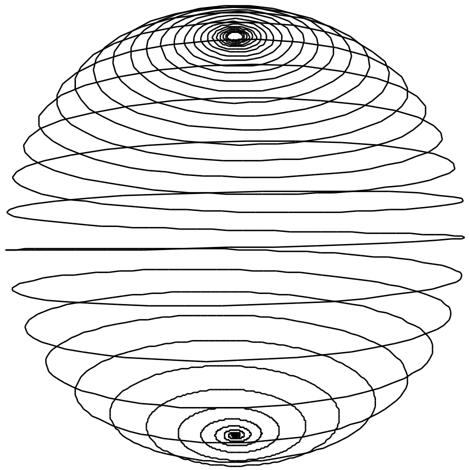
τ_d – damping torque

τ_{st} – spin transfer torque

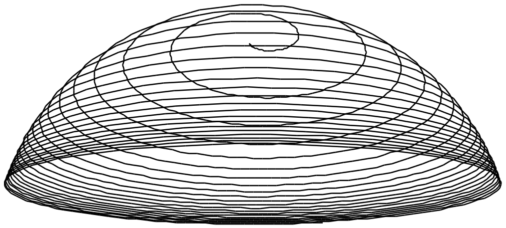
Uniaxial ferromagnet



switching

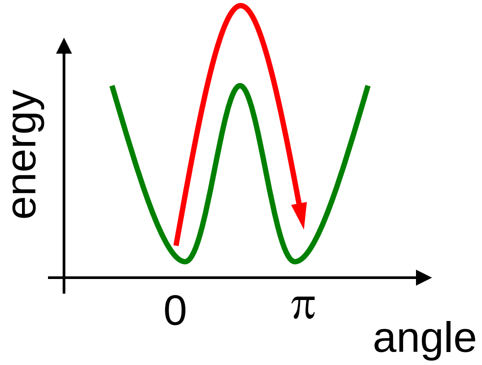


persistent precession

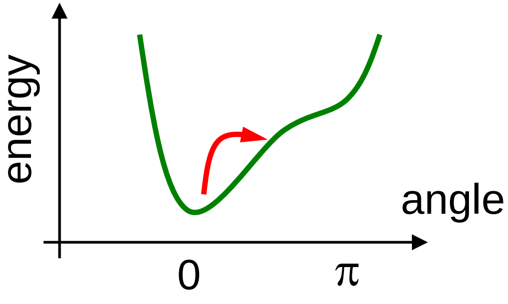


H_K – anisotropy field

$H = 0$

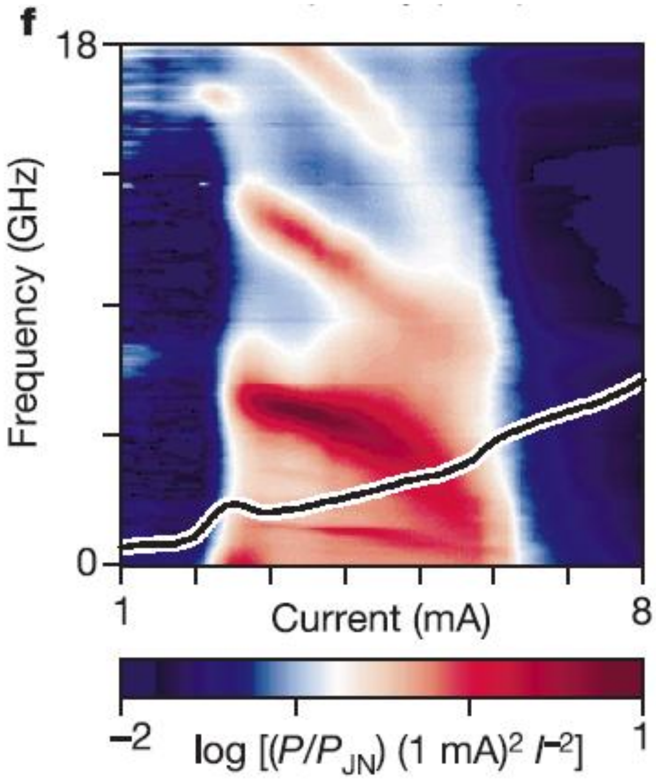


$H > H_K$

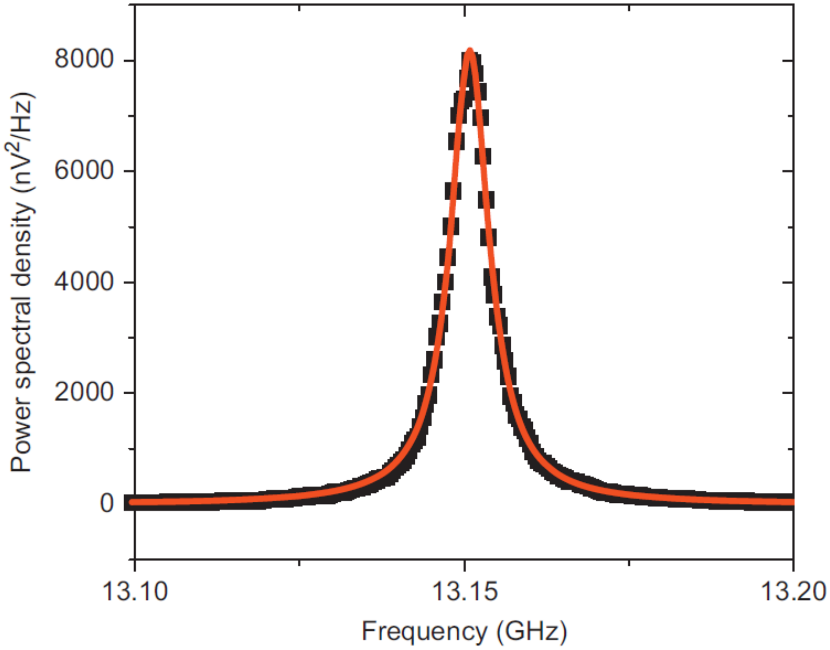


Spin Torque Oscillators

Self-oscillating magnetization in the free layer of spin valves generates microwave voltage signal at the frequency of oscillations (spin torque oscillators).



Kiselev et al. Nature (2003)



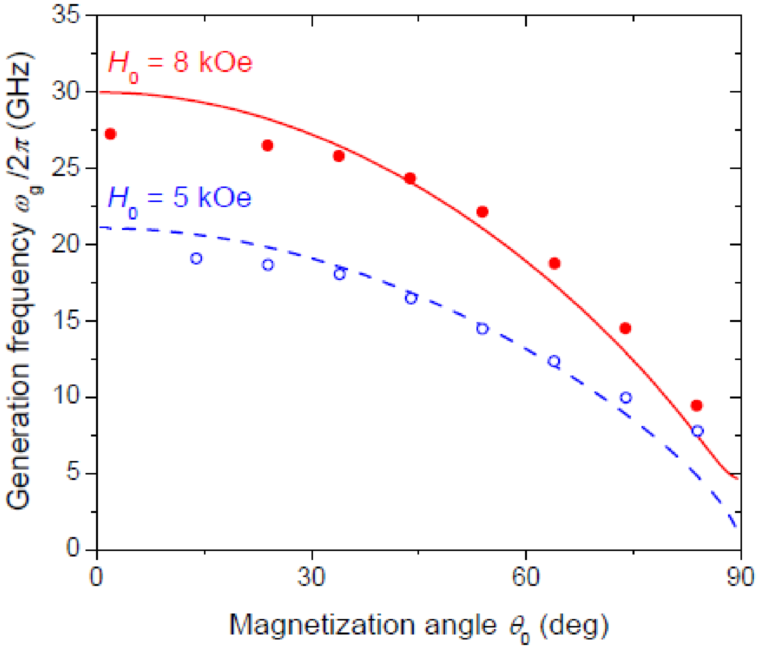
Rippard et al. PRL (2004)

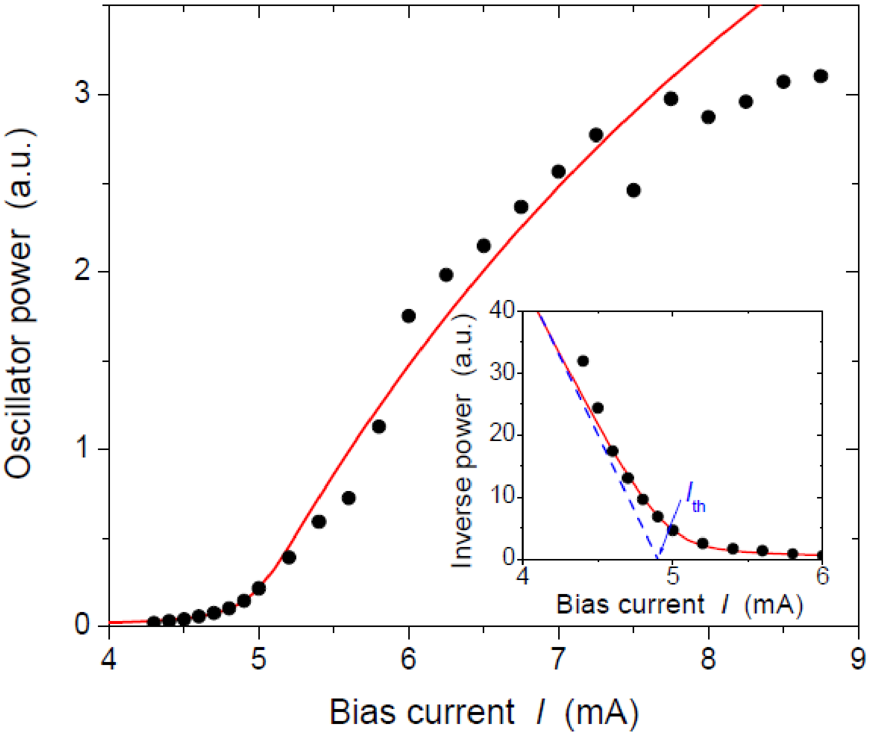
Properties of nanopillar spin torque oscillators

Assuming a single mode of self-oscillations is excited (e.g. quasi-uniform precession):

1. Amplitude of oscillations increases with current
2. Frequency of self-oscillations changes with the amplitude (nonlinear frequency shift):

$$\omega = \omega_0 - N|a|^2$$

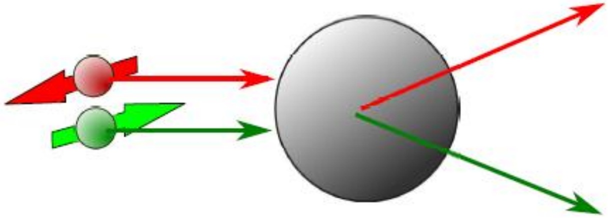


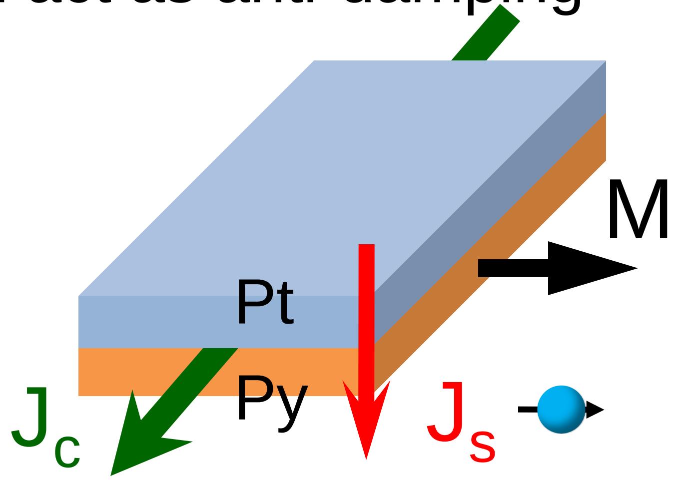


Tiberkevich and Slavin, review (2009)

Spin Hall Effect

- Spin Hall effect (SHE) is observed in materials with strong spin-orbit interactions such as Pt
- Electric current generates pure spin current flowing perpendicular to the electric current
- Pure spin current can be injected into an adjacent ferromagnetic film and apply spin torque to the ferromagnet (pure interfacial spin torque is possible as well)
- This spin orbit (SO) torque can act as anti-damping

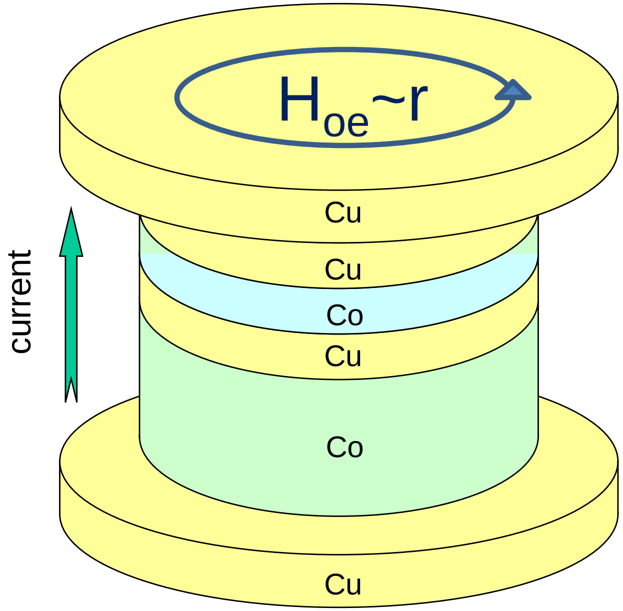


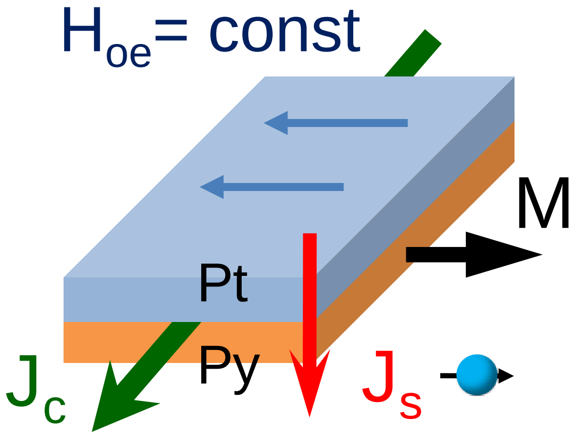


Spin torque oscillator dimensions

In spin valves with vertical current, Oersted field at the periphery increases linearly with the system size

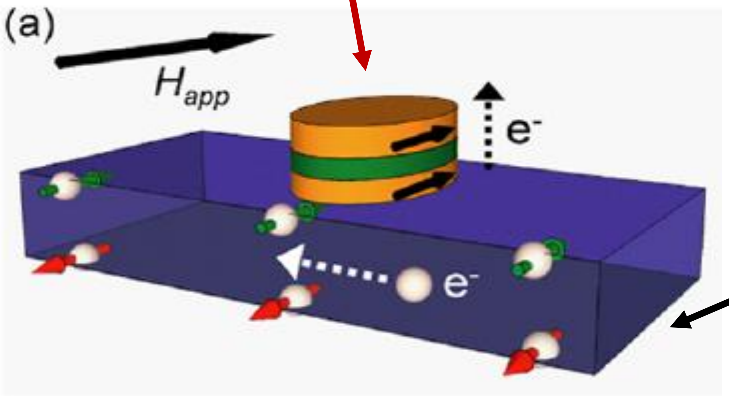
- In μm-scale spin valves, the Oersted field at periphery reaches a fraction of Tesla at the critical current density. This forces magnetization into a vortex state.
- In SO bilayers, the Oersted field is proportional to the charge current density and is independent of the system size. Oersted field at the critical current is small (a few mT) and uniform.
- Can we realize μm-scale oscillators with SO torques?





Auto-oscillations of a nanomagnet by SO torques

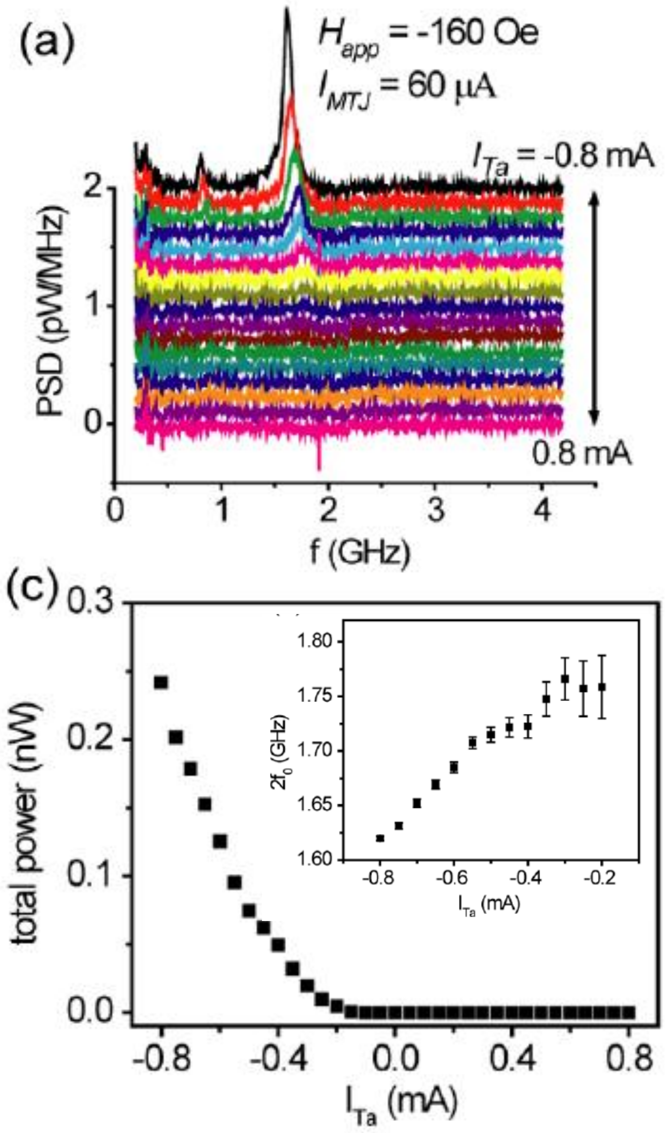
Nanoscale magnetic tunnel junction



Ta

Liu et al. PRL 109, 186602 (2012)

Microwave signal emission

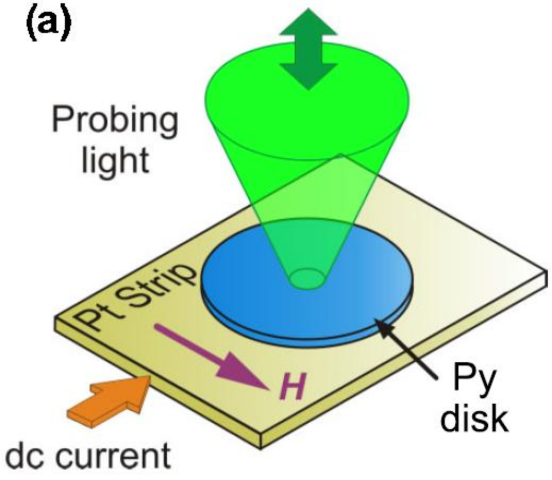


Cornell group demonstrated excitation of self-oscillations of a CoFeB nanomagnet driven by spin orbit torque from current in Ta

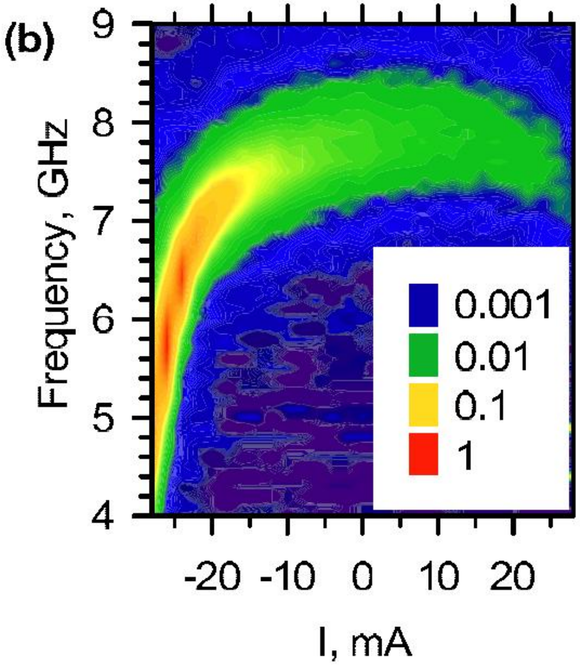
Similar to conventional nanopillar spin valve devices (0D object – ferromagnetic nanodot)

Auto-oscillations in extended thin film ferromagnet?

- Is it possible to excite self-oscillations in a macroscopic uniformly magnetized ferromagnetic film?
- Anti-damping SO torque gives this opportunity because Oersted fields are small and homogeneous
- Muenster group answered this question by using Brillouin light scattering measurements



Py disk diameter 2 μm

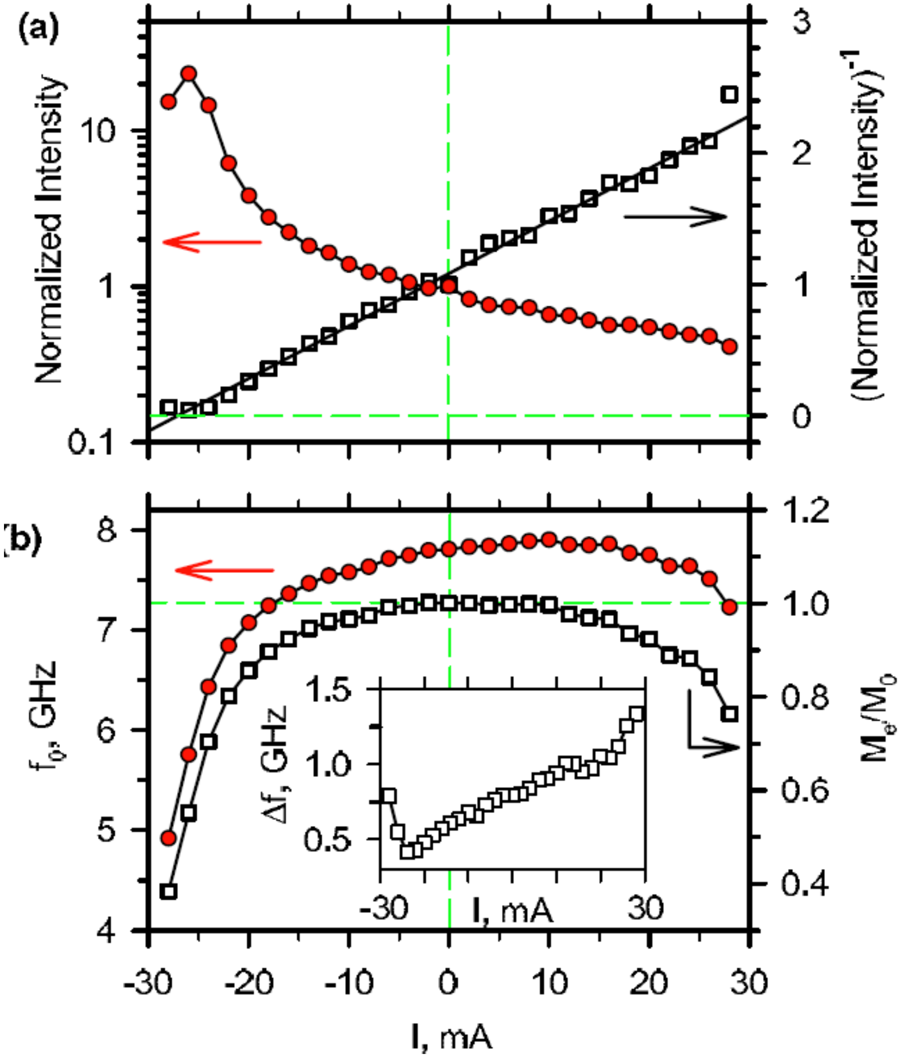


Large frequency shift is observed for one current polarity.

Is this shift due to excitation of the quasi-uniform mode self-oscillations?

Demidov et al., PRL ***107****, 107204 (2011)*

Auto-oscillations in extended thin film ferromagnet?



Demidov et al., PRL ***107****, 107204 (2011)*

Signal intensity (proportional to the power $|a|^2$ of the quasi-uniform mode fluctuations) increases by a factor of 25 compared to zero bias current

For *I* > 26 mA, signal intensity starts to decrease while the frequency continues to decrease.

This is inconsistent with the expected nonlinear frequency shift for the uniform mode:

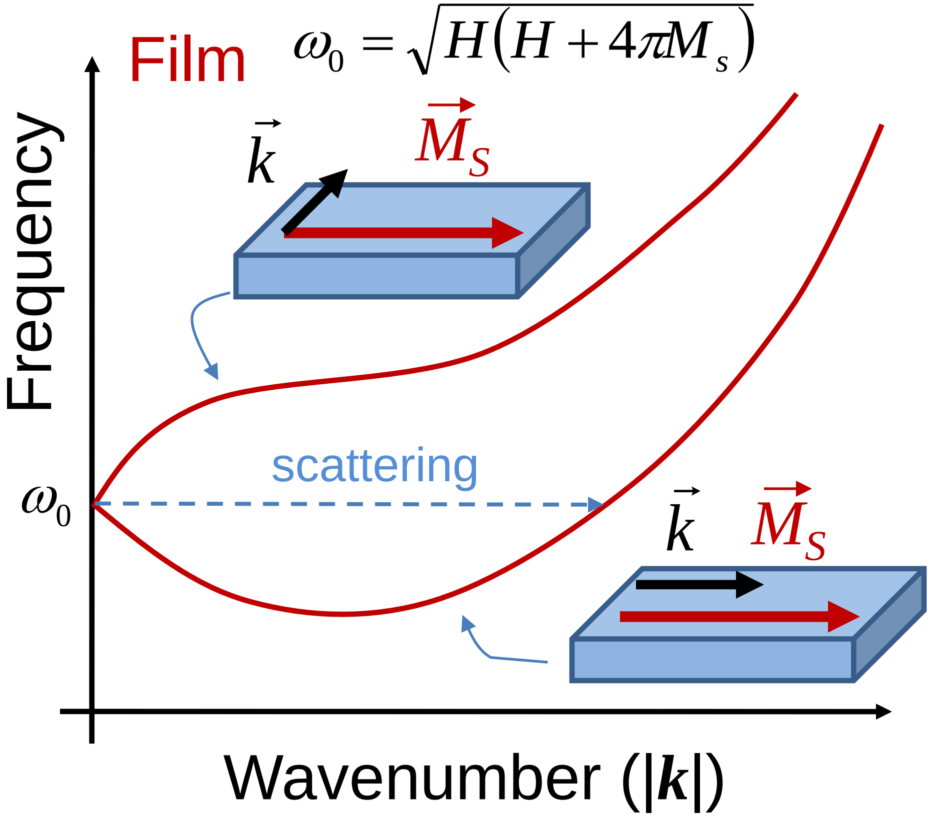
$$\omega = \omega_0 - N|a|^2$$

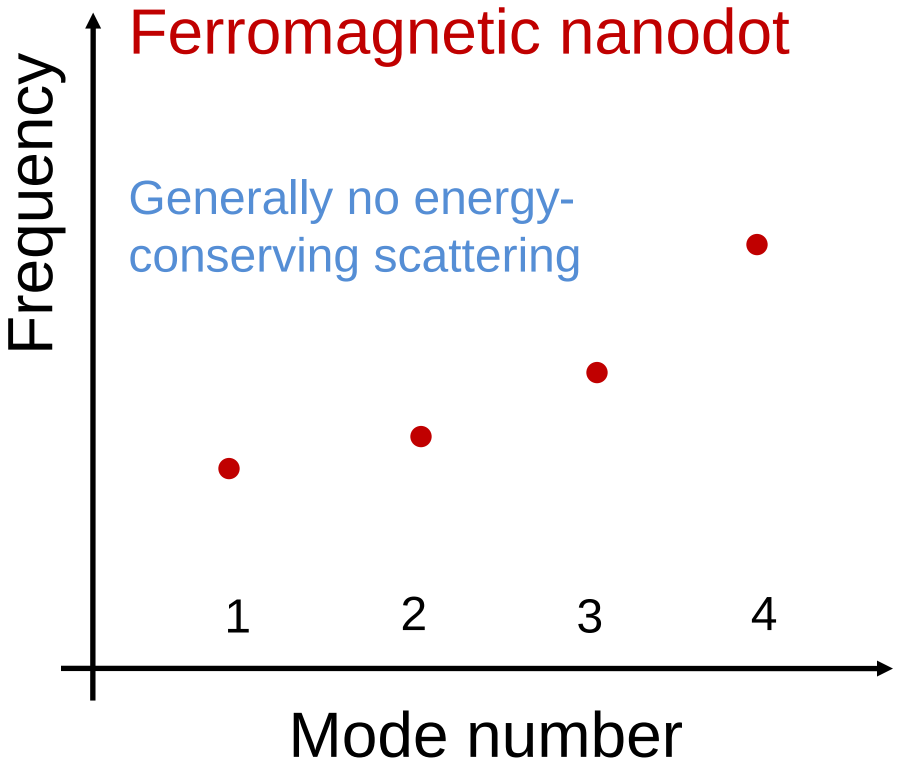
Spin wave dispersion relation in thin film

Textbook spin wave (magnon) dispersion in a ferromagnet:

$$\omega = Dk^2$$

Dipolar interactions make the spin wave dispersion strongly anisotropic and add linear terms in ***k***



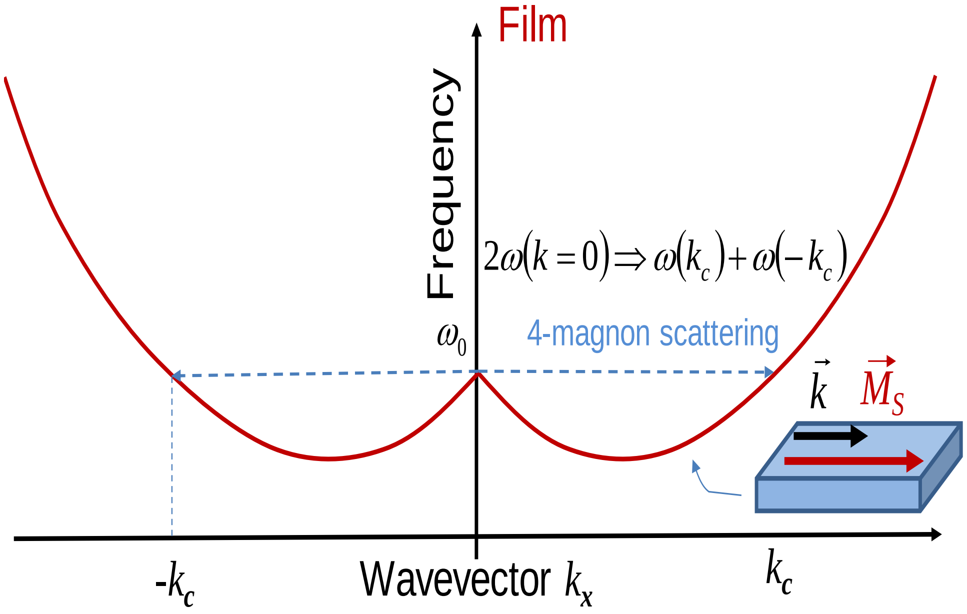


Origin of the frequency shift

A likely explanation is reduction of magnetization M_s due to generation of short-wavelength magnons: $\omega_0 = \sqrt{H\left(H + 4\pi M_s\right)}$

In a range of directions of $\boldsymbol{k}$ near $\boldsymbol{M_s}$, 4-magnon scattering is allowed with conservation of energy an momentum.

Such types of nonlinear scattering manifest themselves as additional (nonlinear) damping for the quasi-uniform mode and reduction of magnetization.



In extended film, the critical current for self-oscillations is never reached due to nonlinear magnon scattering

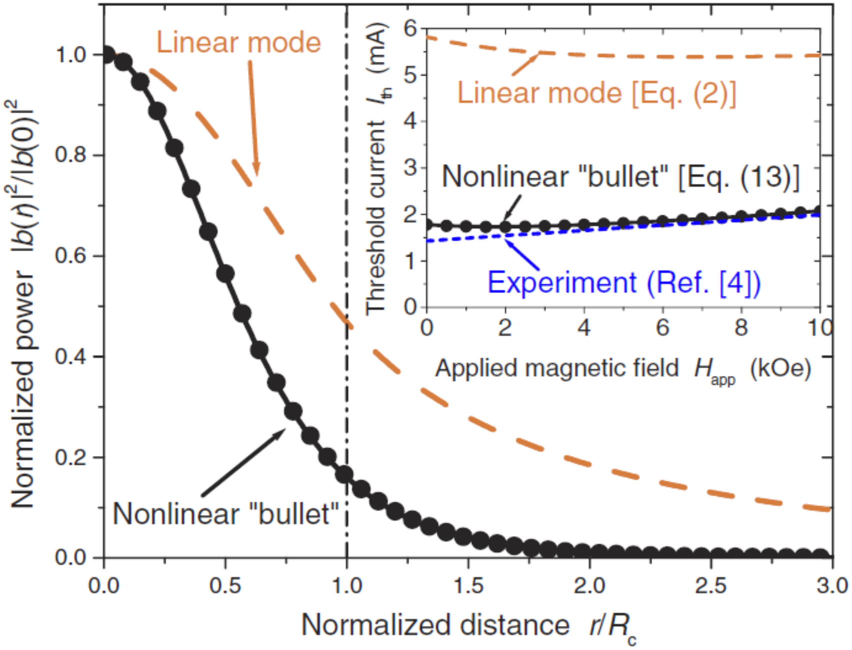
Beating nonlinear scattering

Can one beat nonlinear scattering?

A possible way – excitation of an intrinsic localized mode (called spin wave bullet)

$$b(t,r) = B_0\psi(r/\ell)e^{-i\omega t}$$

$$\psi'' + \frac{1}{x}\psi' + \psi^3 - \psi = 0,$$



The bullet solution is stable only above a critical amplitude b_c

$$\omega_b = \omega_0 - N'|b|^2$$

Tiberkevich and Slavin, PRL ***95****, 237201 (2005)*

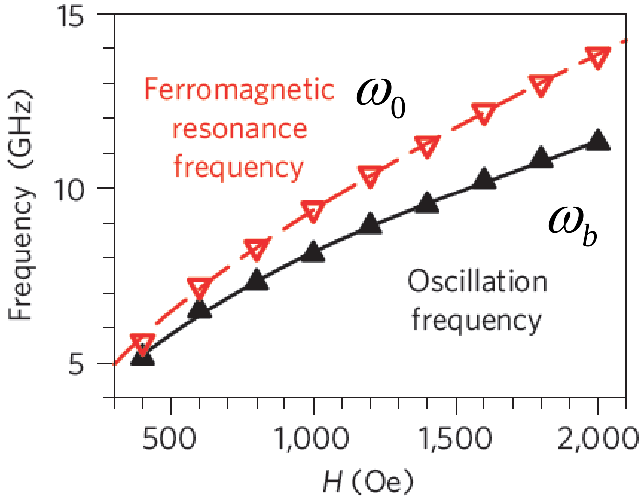
This solitonic mode frequency ω_b is below the bottom of the spin wave dispersion (suppressed 4-magnon scattering)

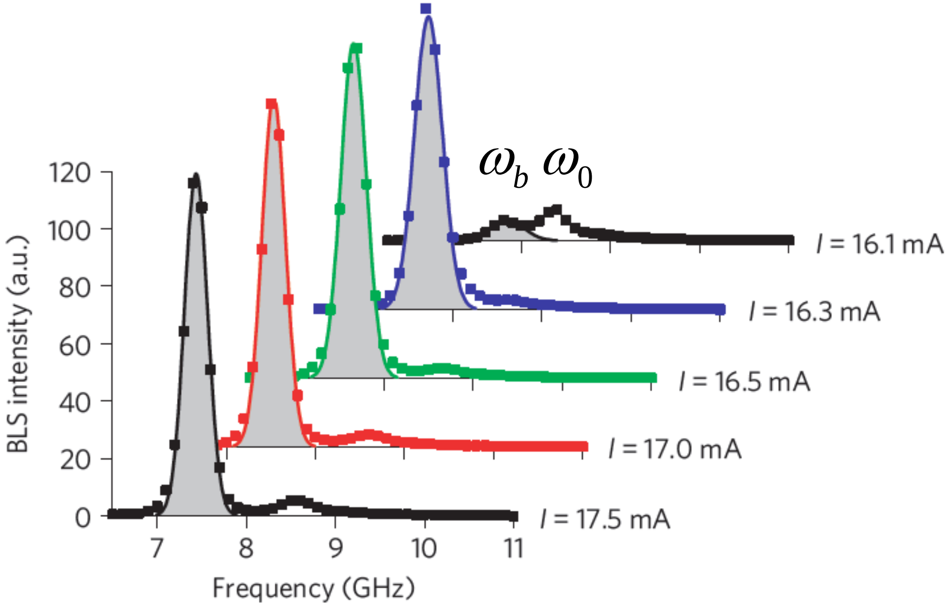
Exciting the bullet mode in a film

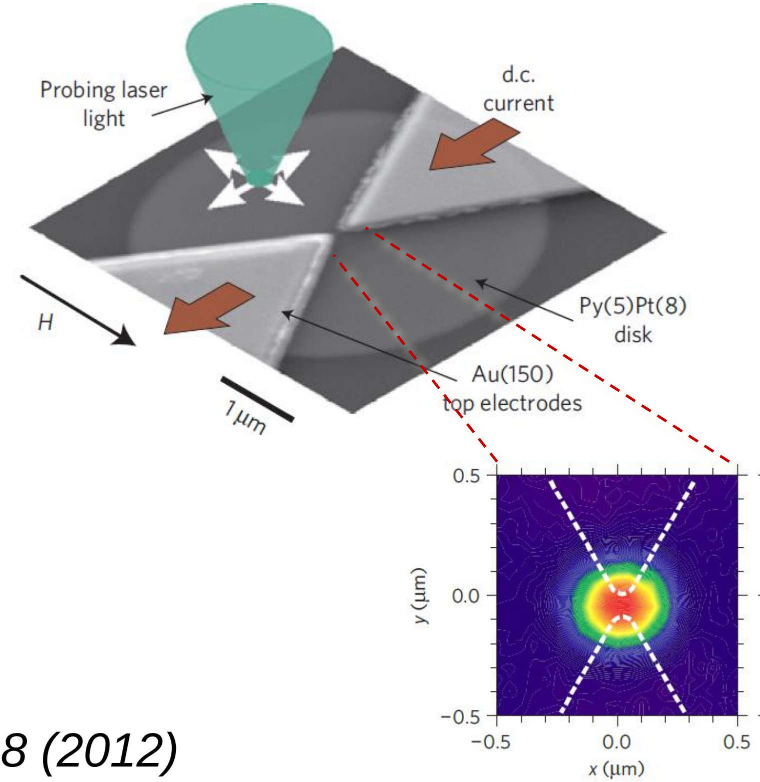
-SW bullet is excited by confining current to small region (planar point contact)

- A bullet is excited abruptly with a large amplitude and low frequency, as expected

- Bullet size does not exceed 100 nm





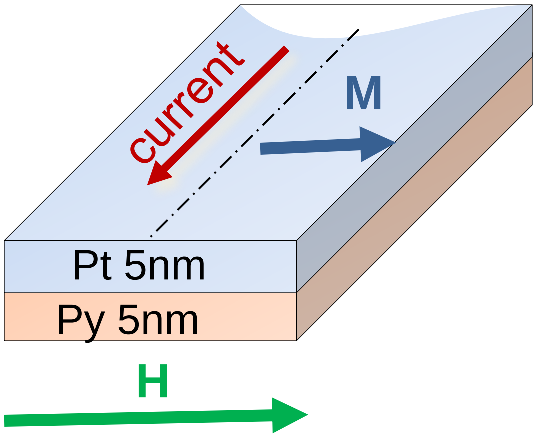


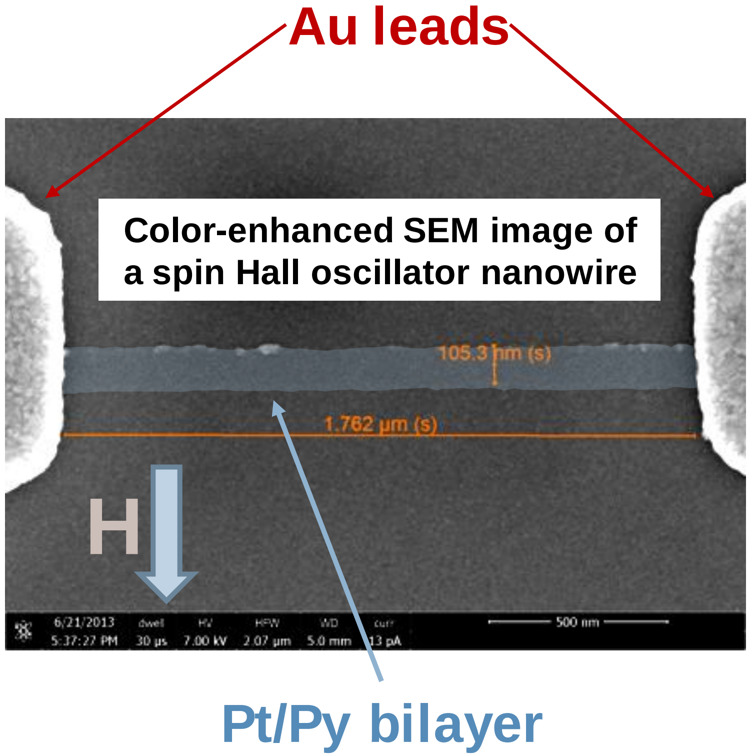
Demidov et al. Nat. Mater. 11, 1028 (2012)

Self-oscillations at μm length scales?

- So far, all spin torque driven self-oscillations are limited to nanometer-scale regions (either nanomagnets or self-localized nonlinear intrinsic modes)
- Self-oscillations are not excited in extended thin films
- Is there hope of exciting self-oscillations in extended ferromagnetic systems (useful for e.g. magnonics)?

The answer is yes – we observed self-oscillations in μm long Pt/Py nanowires (100 – 200 nm wide)

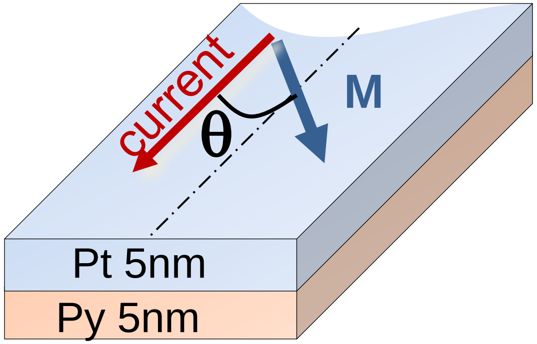


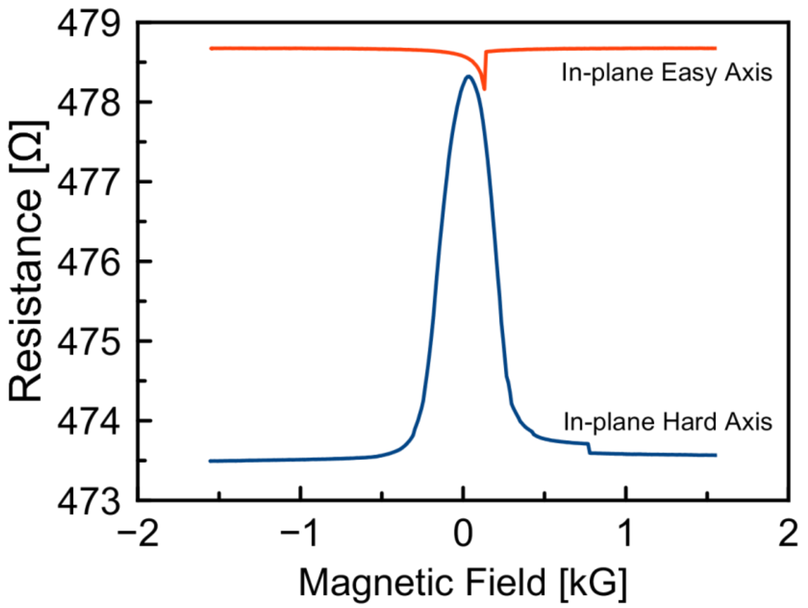

Color-enhanced SEM image of a spin Hall oscillator nanowire

Anisotropic magnetoresistance characterization

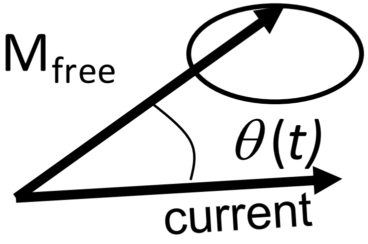
Anisotropic magneto-resistance (AMR)

$$R = R_0 + \Delta R \cos^2(\theta)$$

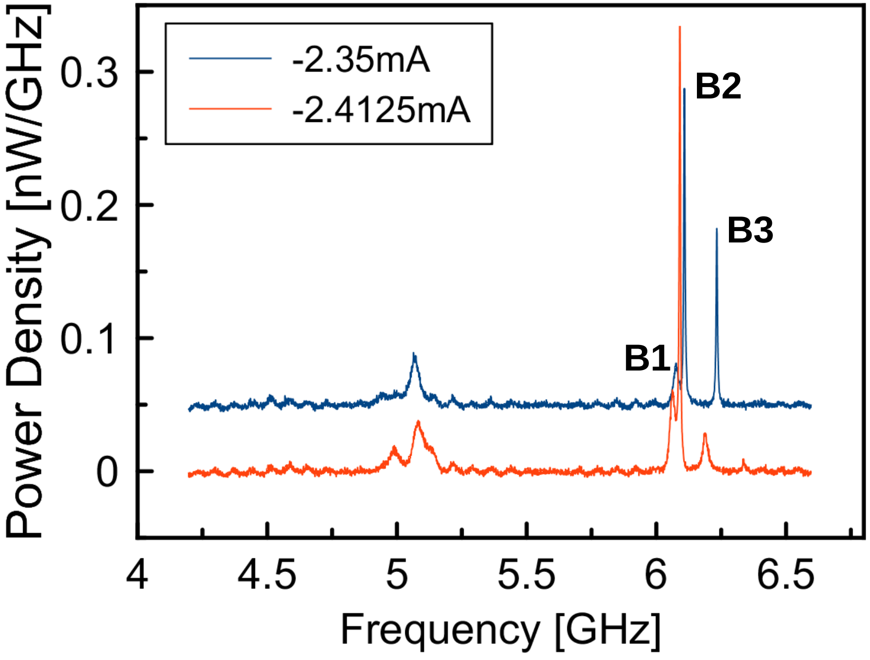




If self-oscillations are induced, the current-biased sample will generate microwave voltage at the oscillation frequency



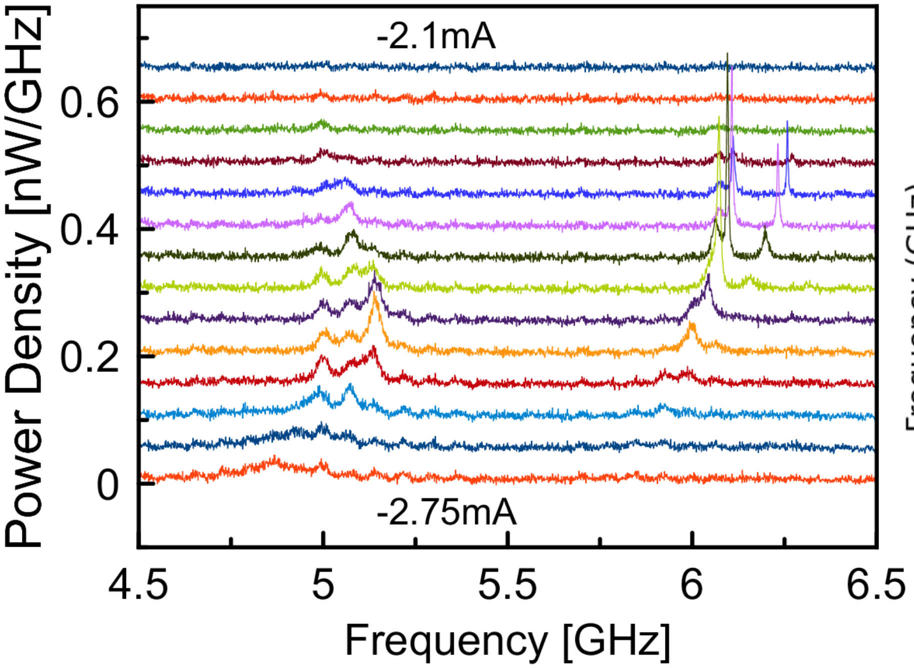
$$V(t) = I \cdot R(\theta(t))$$

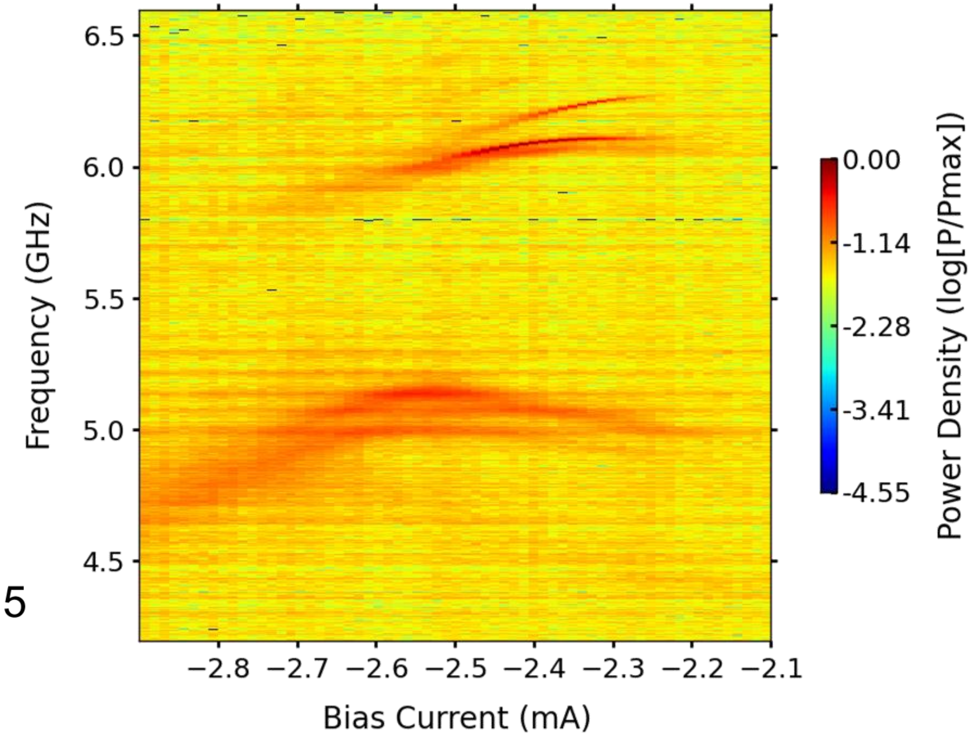


Microwave generation

- Above a critical current of ~ 2.1 mA, two modes of self-oscillations are observed (with some finer-scale mode splitting)

- The maximum amplitude of the signal is large (corresponds to the maximum precession cone angle ~ 10°)





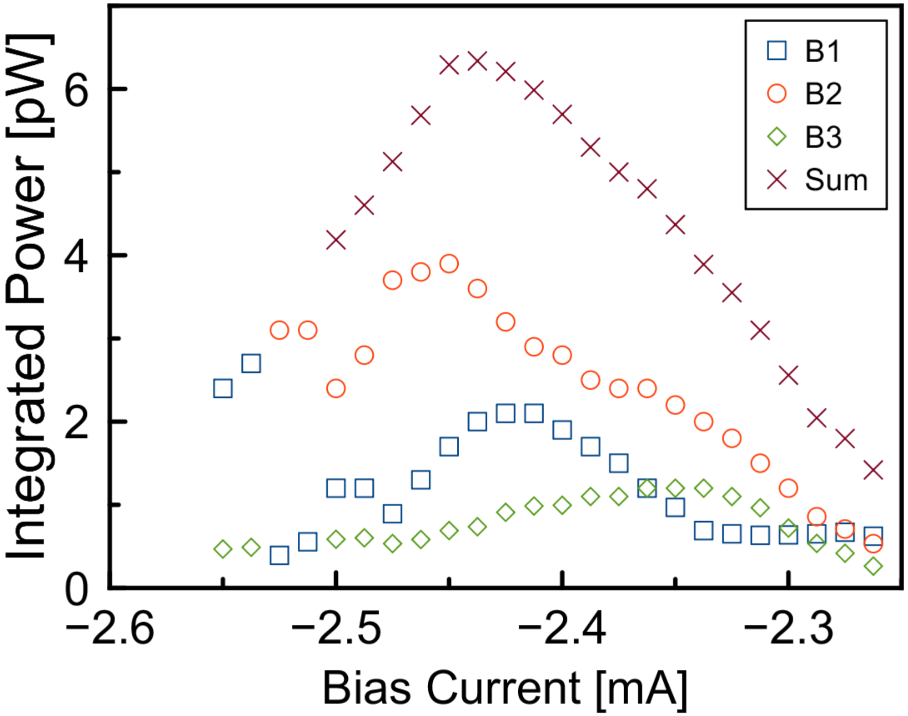
Excited modes

- We measure the spectrum of low-energy, long wavelength spin wave eigen-modes in these sample by resistively detected spin wave resonance

-We find that the frequencies of the self-oscillatory modes at the critical current are identical to the frequencies of spin wave eigenmodes

-The excited self-oscillatory modes at the critical current are long wavelength spin wave eigenmodes of the system (not spin wave bullet)

- Integrated power increases gradually (unlike the case of spin wave bullet)

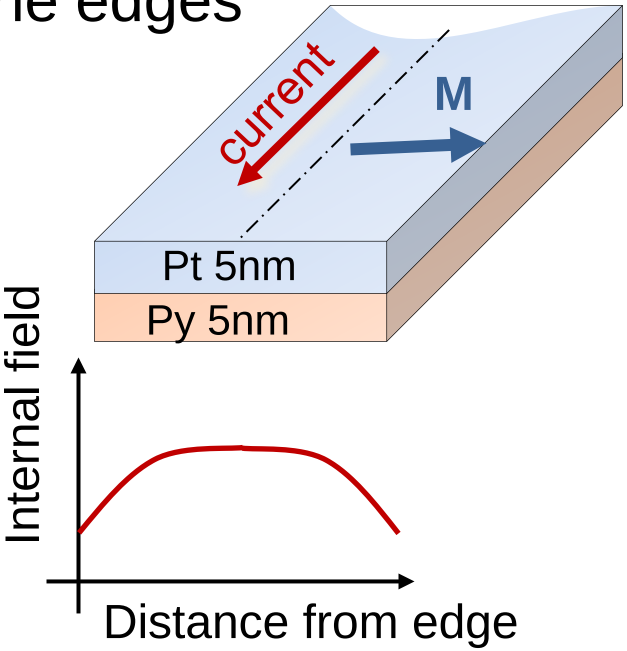


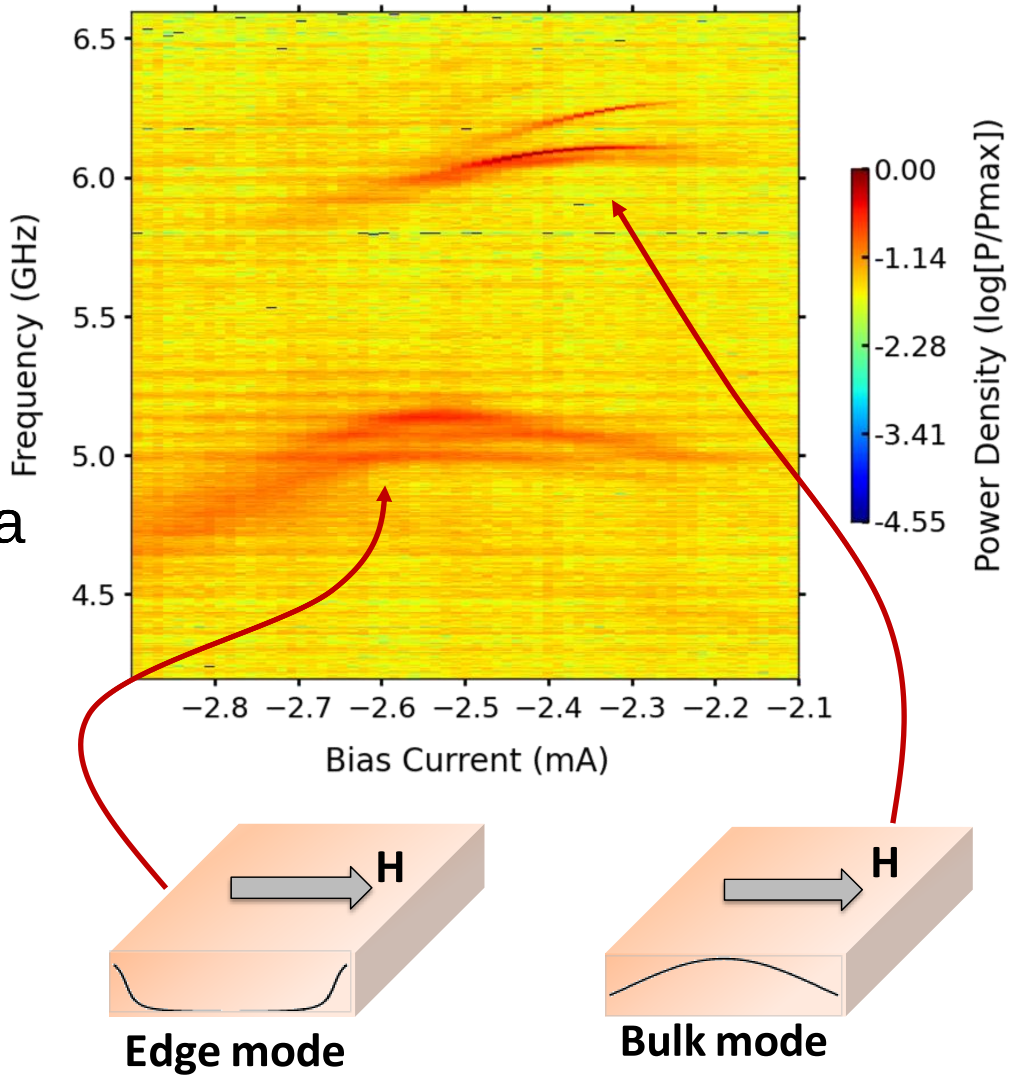
Spin wave eigenmodes

Spin wave eigenmodes for transversely magnetized ferromagnetic wires are known:

- bulk modes (high frequency)
- edge modes (low frequency)

The edge mode forms because internal magnetic field is inhomogeneous and has minima at the edges



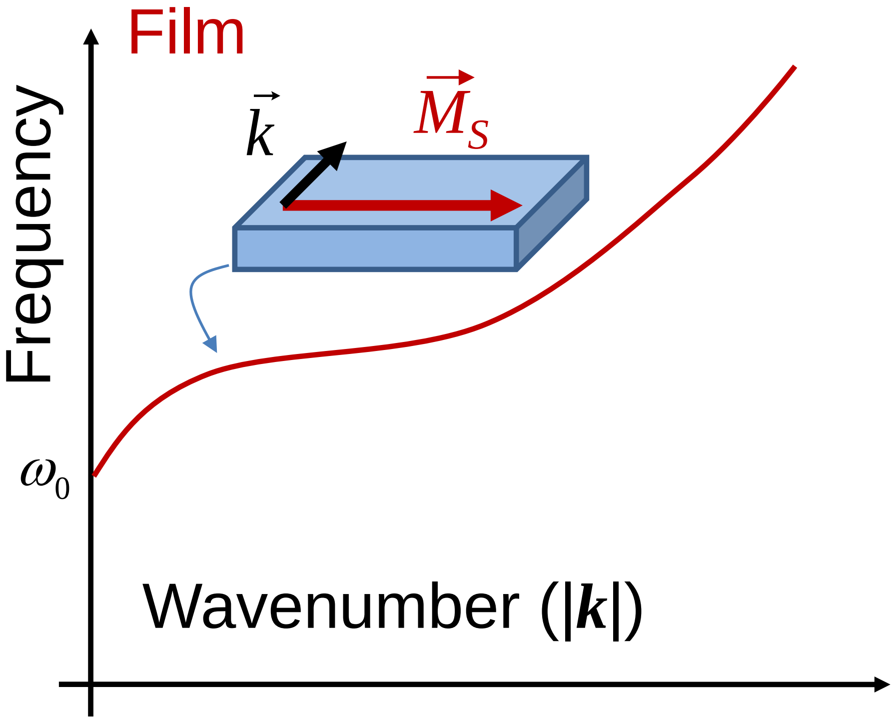


Amplitude maximum at the wire edge

Amplitude maximum at the wire center

Reduction of magnon scattering in nanowires

- Dispersion relation for the nanowire modes is qualitatively similar to the film dispersion for waves propagating perpendicular to magnetization



-The slope of the dispersion curve is positive, which means that 4-magnon scattering of the quasi-uniform mode is suppressed

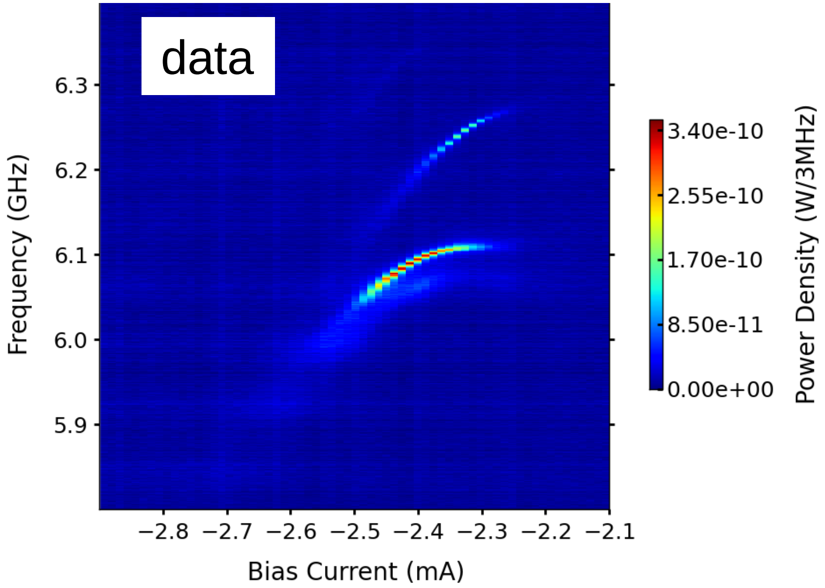
- The suppression of the 4-magnon scattering and reduction of the phase space for nonlinear magnon scattering in nanowires is the likely origin of stabilization of self-oscillations

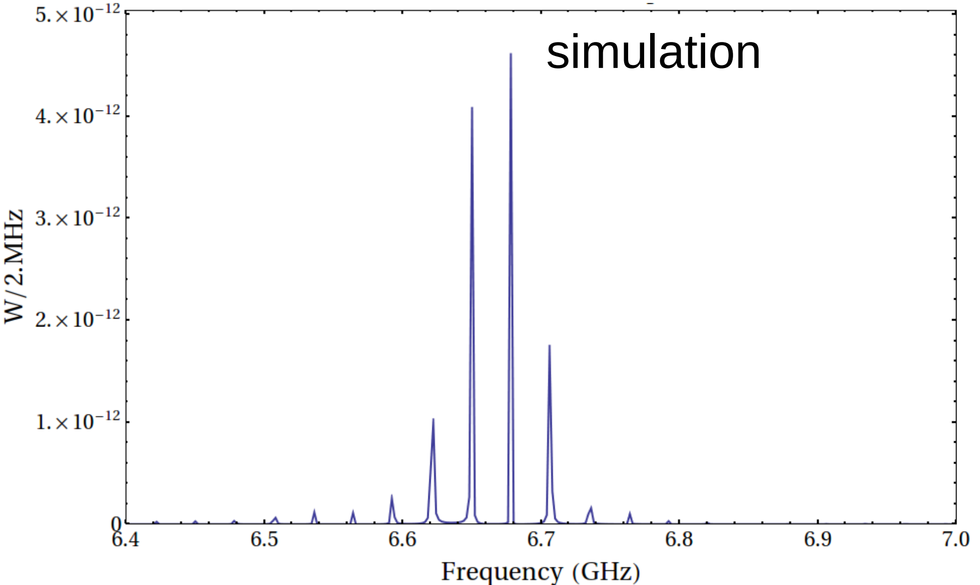
The origin of fine splitting

- To understand the origin of fine splitting of the modes, we solve the micromagnetic LLG equation with SO torques at T=0

- A frequency comb is observed due to the active region of the wire forming a resonator (~ 2 μm long)

- The experimentally seen comb does not show regular spacing and the splitting is somewhat larger than in simulations. We attribute this to partial mode localization (in the linear regime) due to magnetic spatial inhomogeneities of the wire.





Summary

- Antidamping-like spin orbit torque can drive magnetization self-oscillations in Py/Pt bilayer nanowires
- Unlike 2D thin film geometry, the 1D nanowire geometry allows excitation of long-range (μm - scale) self-oscillations of magnetization
- The excited self-oscillatory modes directly emerge from spin wave eigenmodes (bulk and edge modes) of the nanowire (non-solitonic modes)
- We argue the spin wave spectrum in the nanowire geometry reduces the phase space for nonlinear magnon scattering and thereby enables coherent self-oscillatory dynamics

STARnet DARPA NSF SRC NRI