Condensation of magnons driven by thermal gradients

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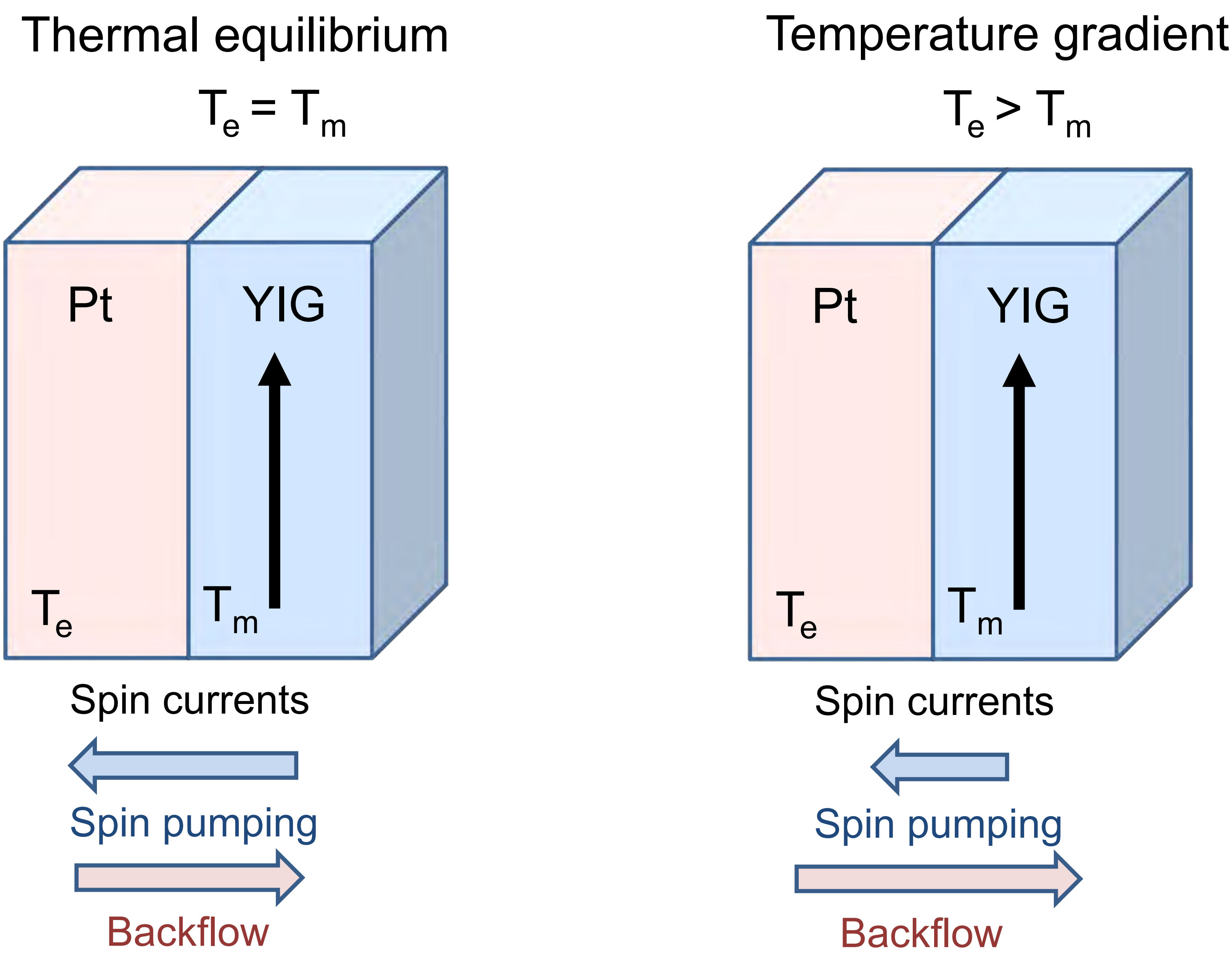
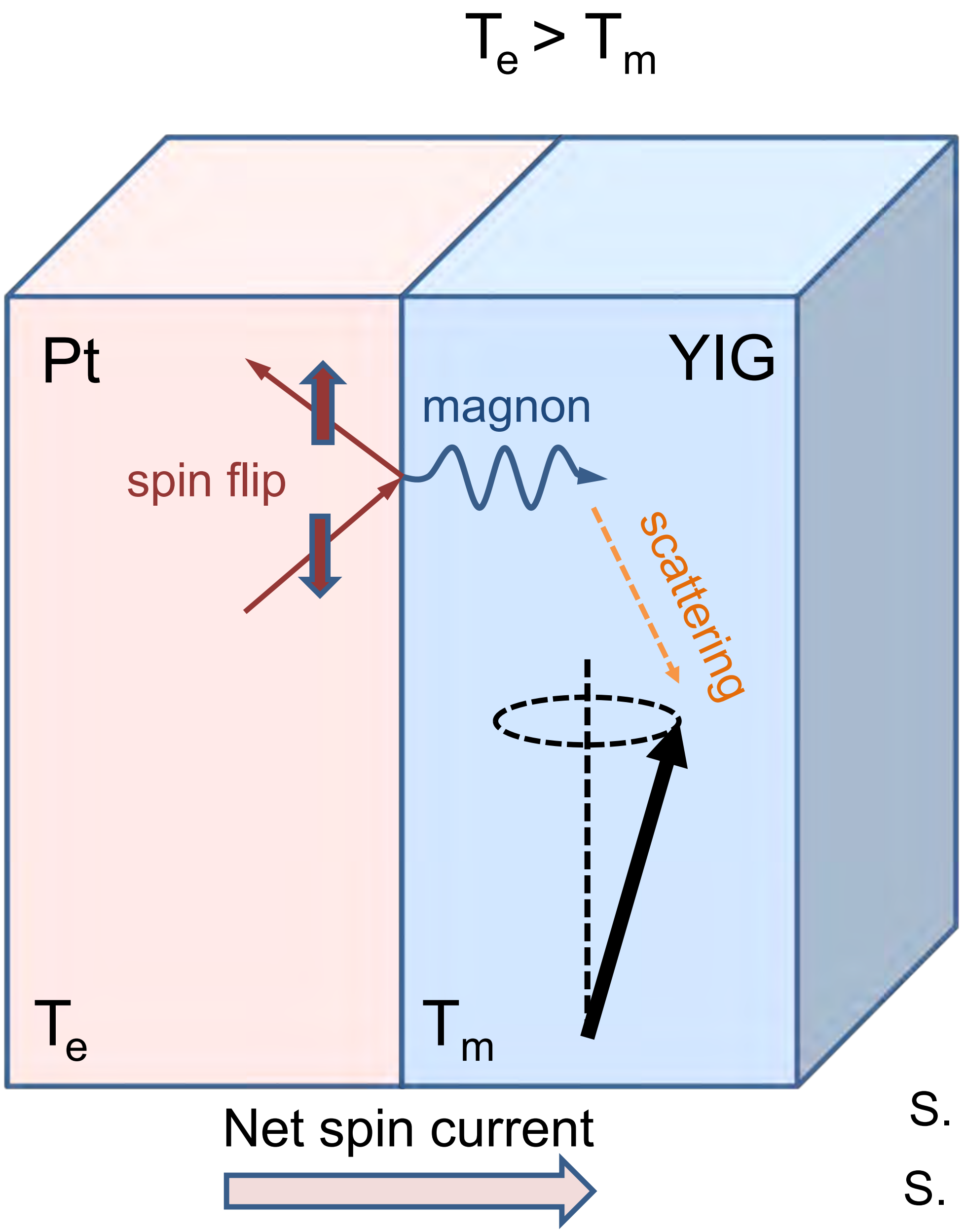
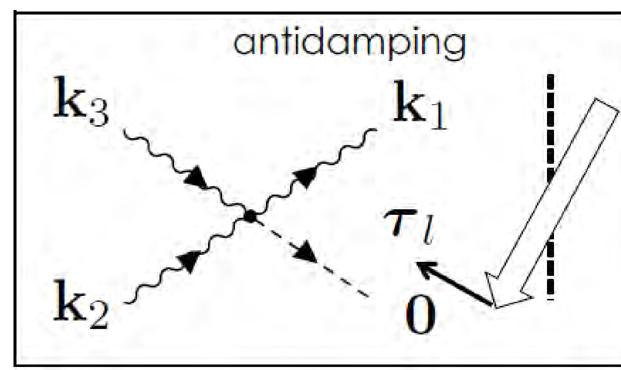
Thermal spin currents in YIG/Pt bilayers



Magnon condensation driven by ∇T



- Spin current generates quasi-equilibrium cloud of incoherent magnons
- Nonlinear magnon scattering populates quasi-uniform mode
- Macroscopic coherent occupation of quasi-uniform mode above a critical current (condensation)



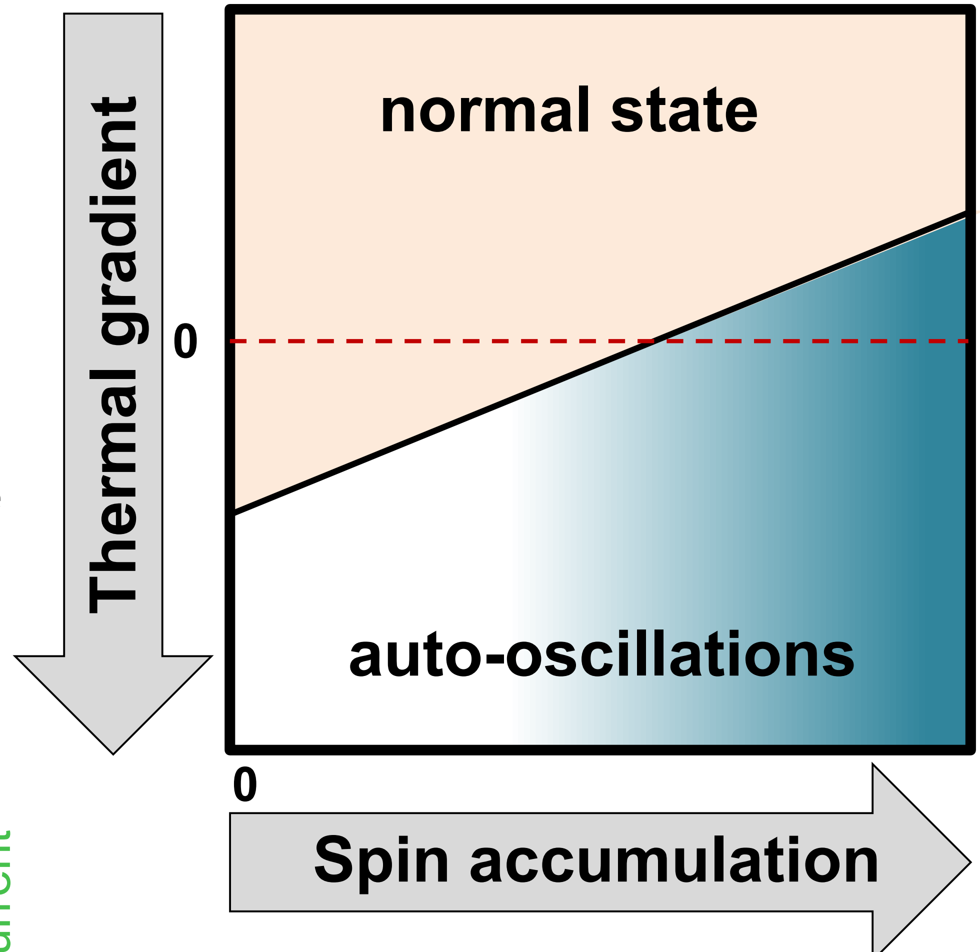
S. Bender et al., PRB (2014)

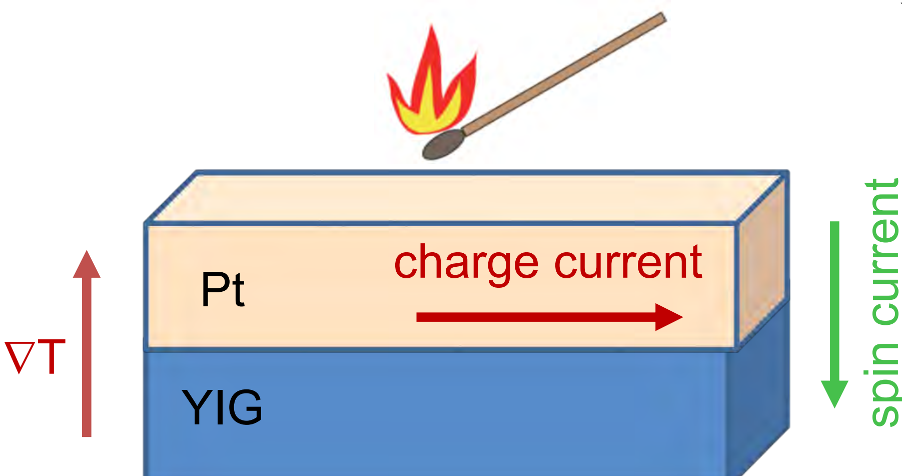
S. Bender and Y. Tserkovnyak, PRB (2016)

Magnetization auto-oscillation by pure spin currents

- Magnetization auto-oscillations can be achieved by injecting pure spin current into insulating ferromagnet
- Two sources of spin current:
  - spin accumulation due to spin Hall effect
  - spin Seebeck current due to temperature gradient

Theoretical phase diagram

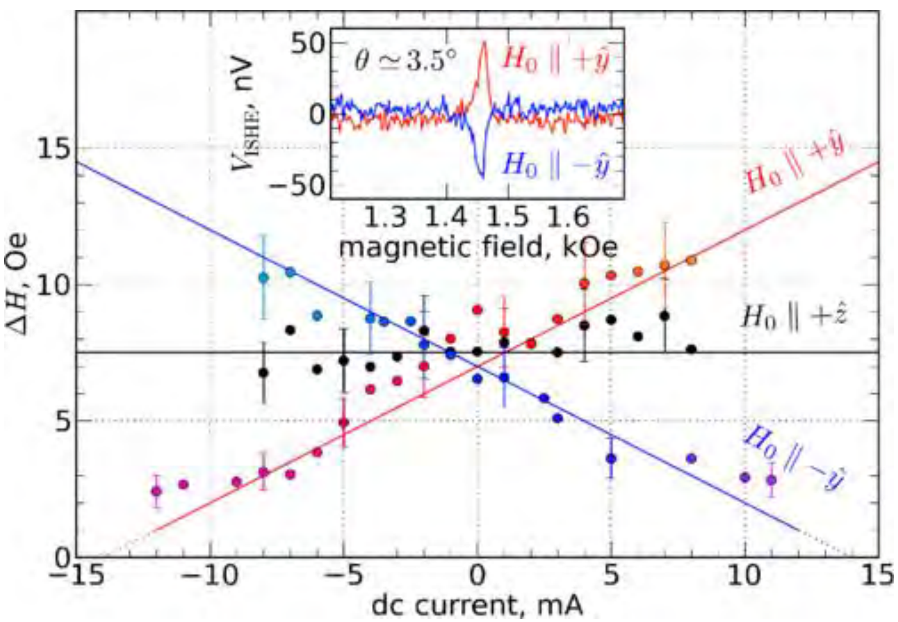




S. Bender et al., PRB (2014)

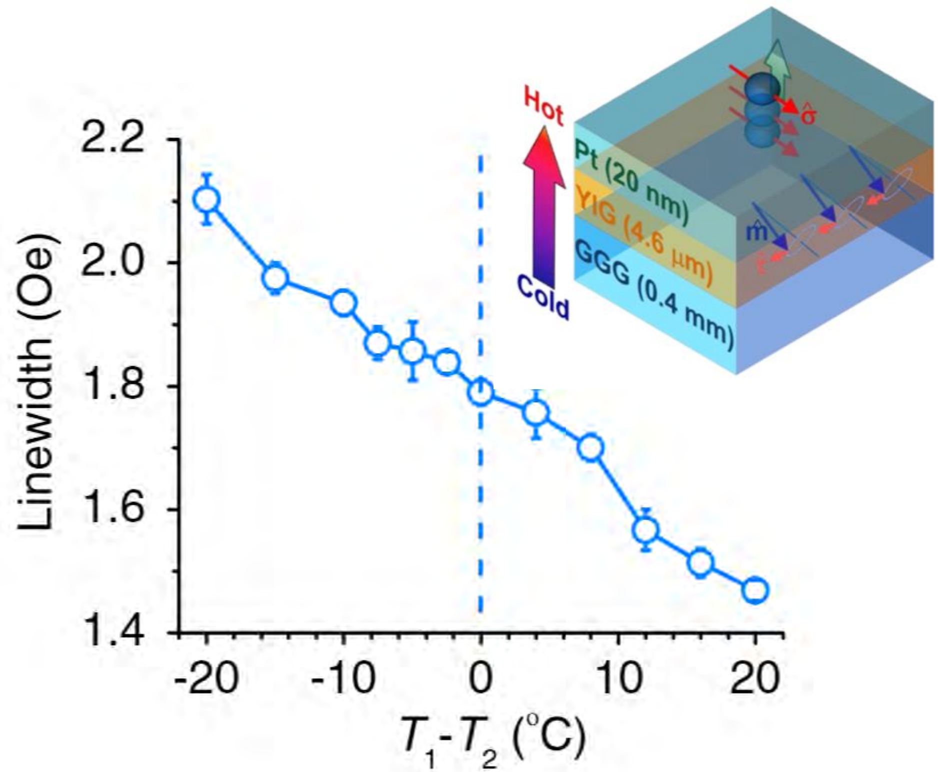
Linewidth control in YIG/Pt

Control of linewidth in YIG/Pt via spin Hall current



Hamadeh et al, PRL (2014)

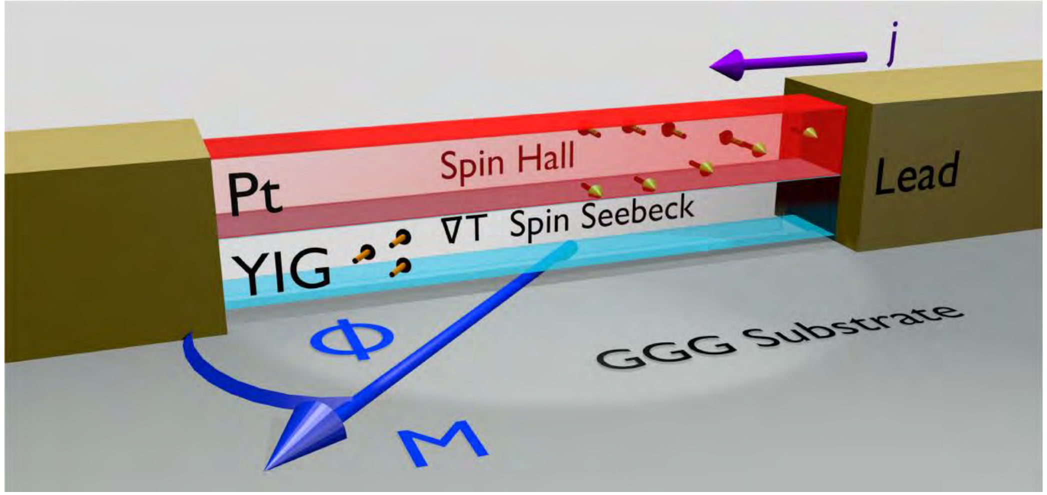
Control of linewidth in YIG/Pt via spin Seebeck current

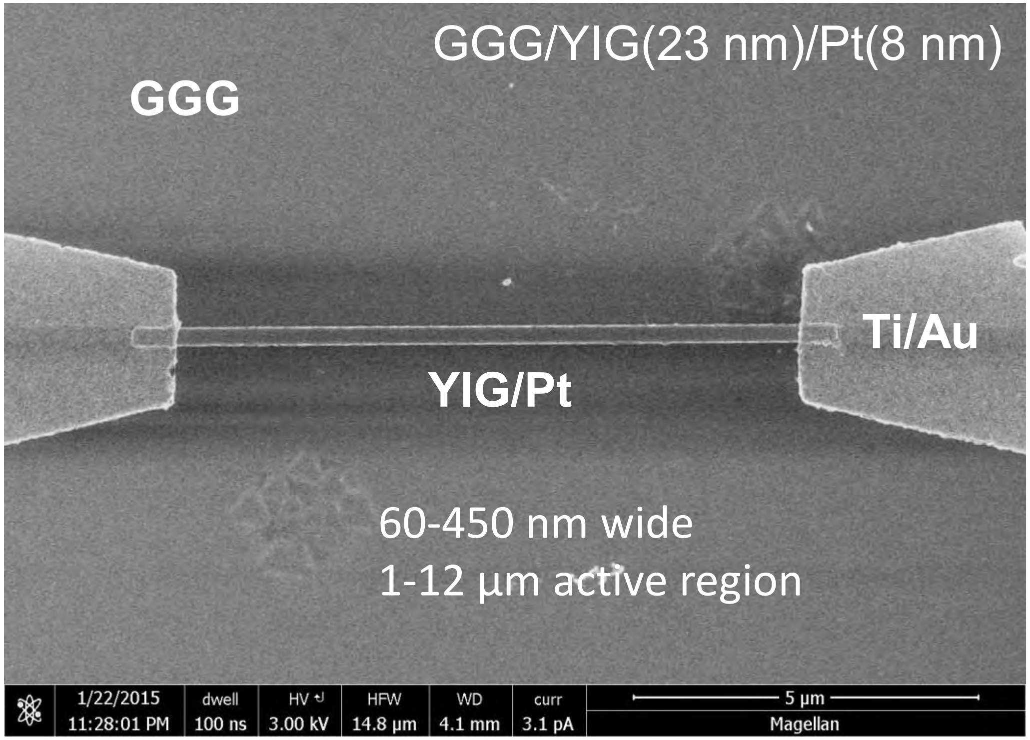


L. Lu et al., PRL (2012)

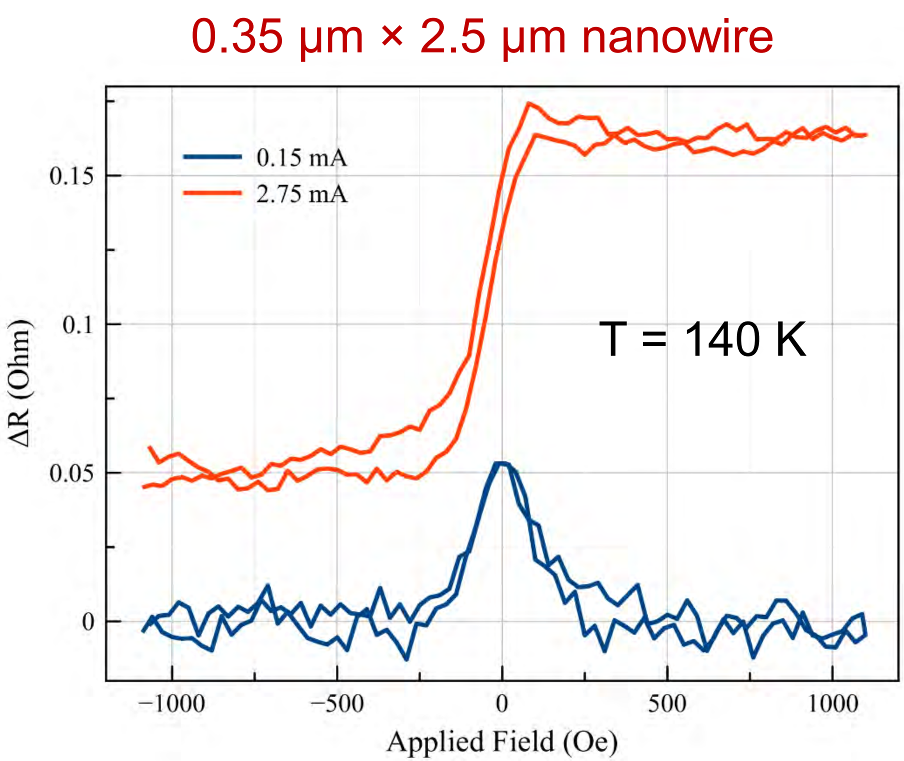
YIG/Pt nanowire devices

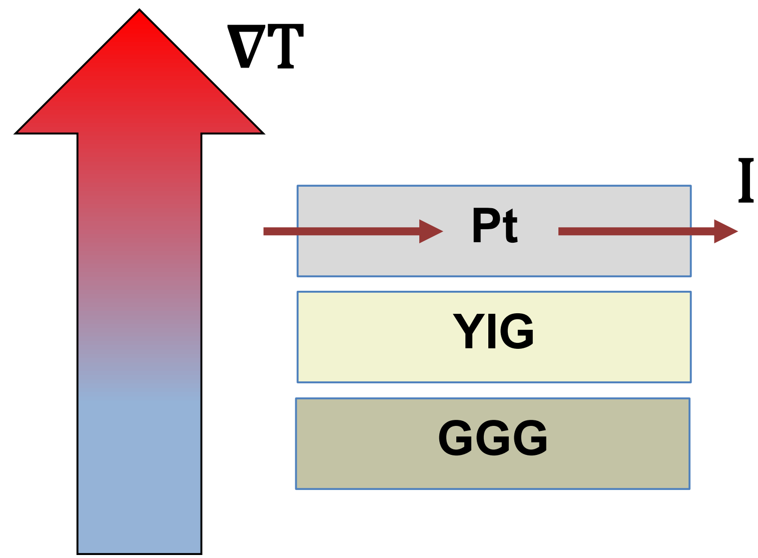
- YIG/Pt bilayer nanowire devices
- High current densities can be applied to Pt wire
- Large vertical temperature gradient ∇T due to high resistivity of the Pt layer
- Combination of spin Hall and spin Seebeck currents





Spin Hall and spin Seebeck magnetoresistance



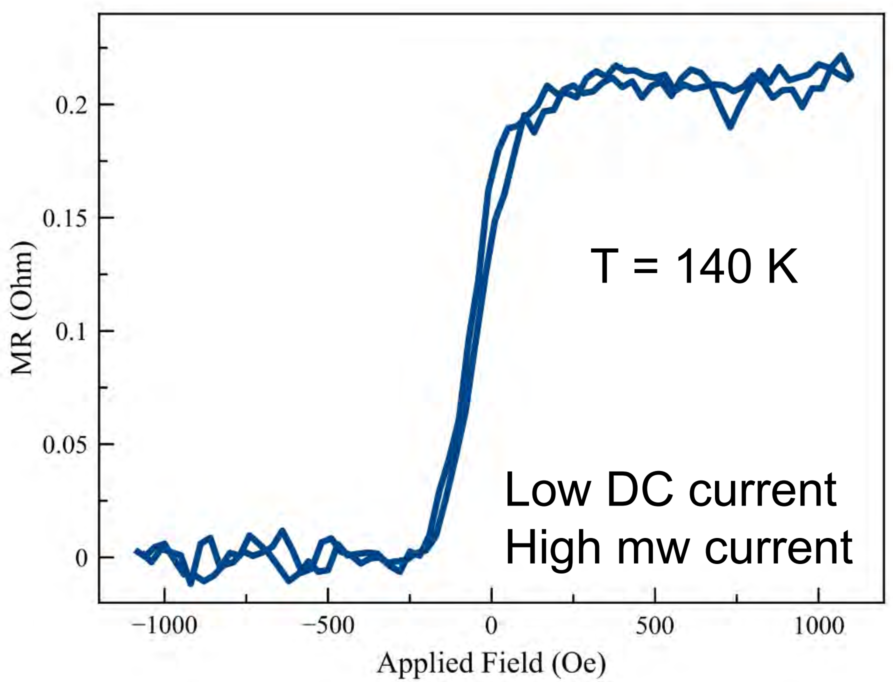


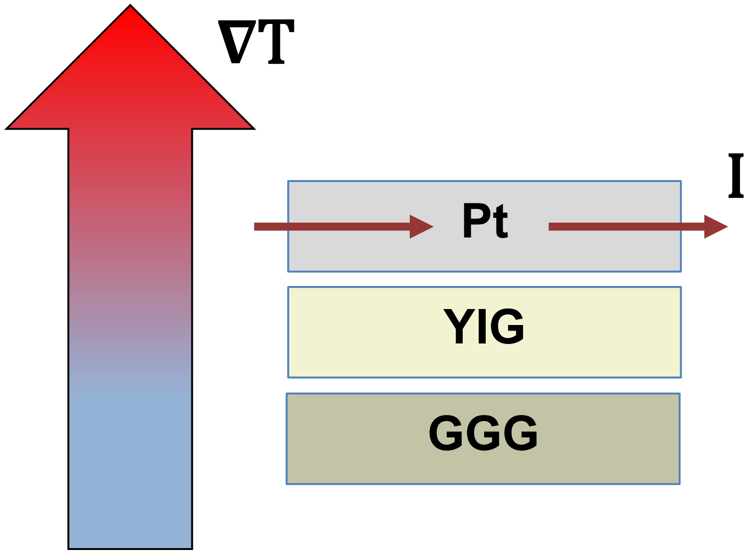
- **Spin Hall magnetoresistance** 0.005-0.012%
- **Spin Seebeck magneto-resistance** ~ ∇T

[1] Nakayama et al., PRL (2013)
[2] Marmion et al., PRB (2014)
[3] Miao et al., PRL (2014)
[4] Schreier et al., APL (2013)
[5] D. Meier et al. AIP Adv. (2016)

Spin Seebeck magnetoresistance

0.35 μm × 2.5 μm nanowire





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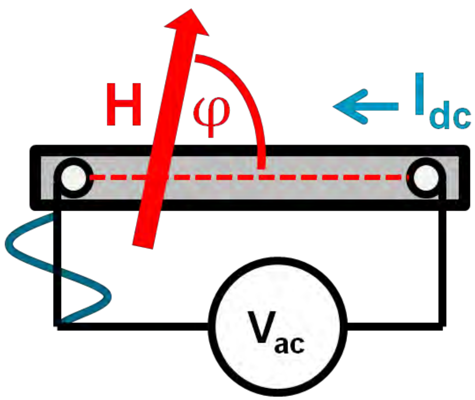
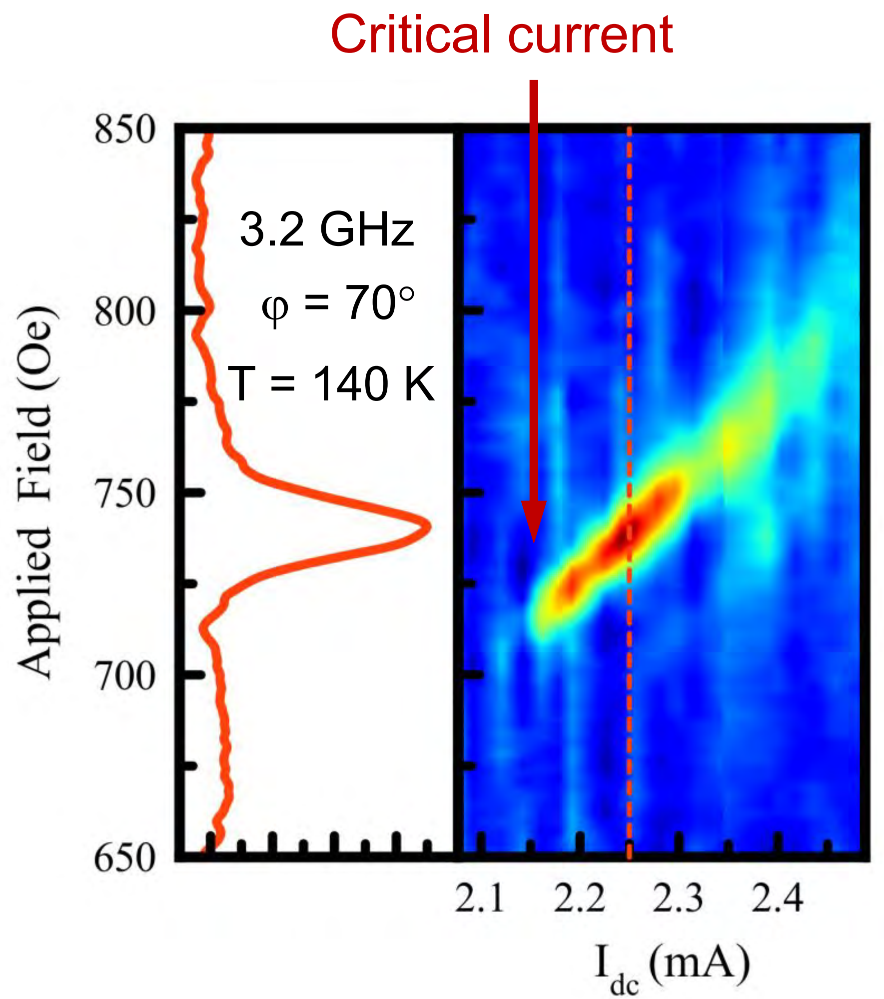
Microwave emission from the nanowire device



- Small MR: emission power is typically sub-femtoWatt
- Conventional frequency-swept spectrum analyzer measurements insufficient
- Reliable method of measuring emission is sweeping magnetic field at fixed detection frequency



0.35 μm × 2.5 μm nanowire

Angular dependence of critical current

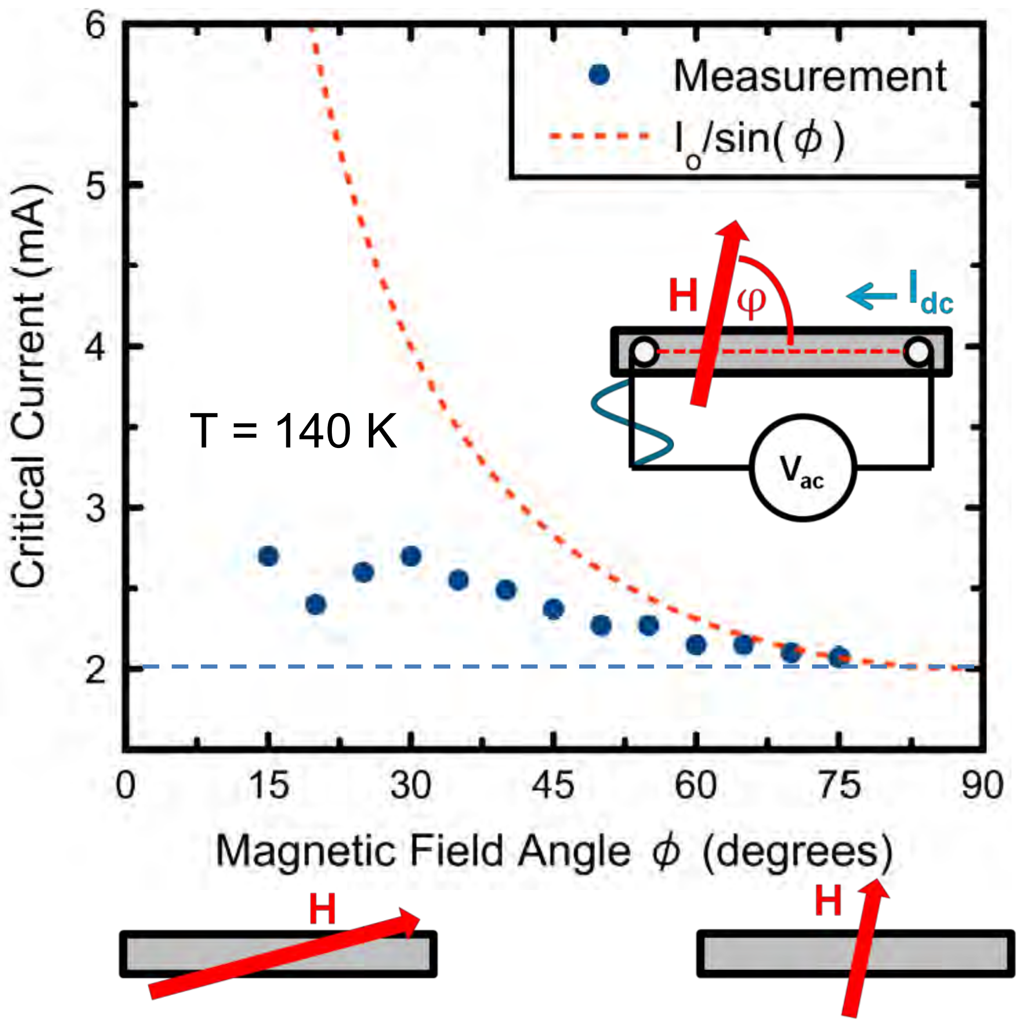
- Angular dependence of I_c due to spin Hall current:

$$I_c(\varphi) = \frac{I_{c0}}{\sin(\varphi)}$$

- I_c due to spin Seebeck current is expected to be independent of φ:

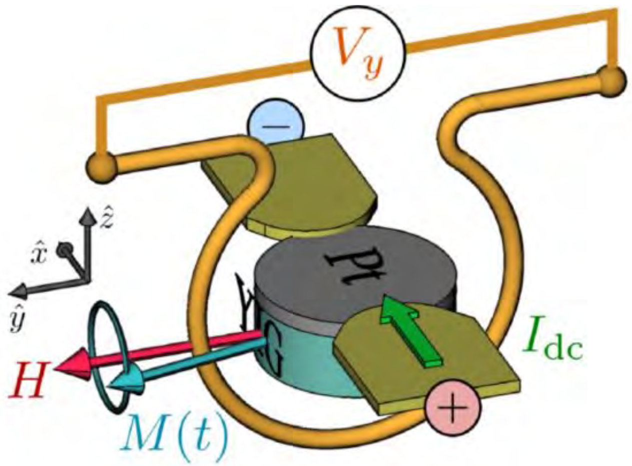
$$I_c(\varphi) = const$$

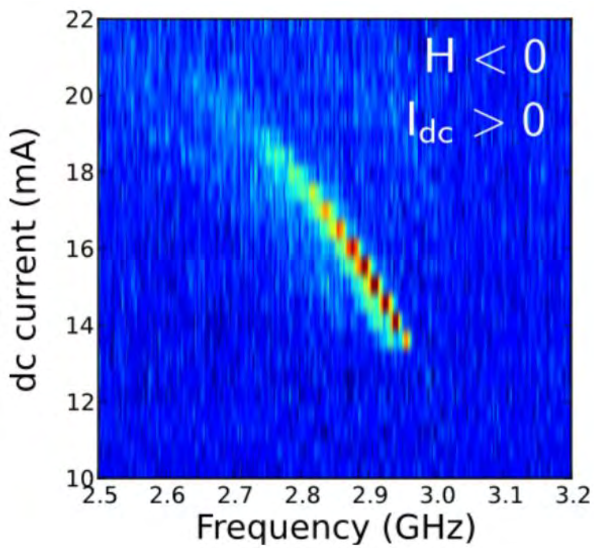
- Our data suggest that both spin Hall and spin Seebeck currents are important for excitation of self-oscillations

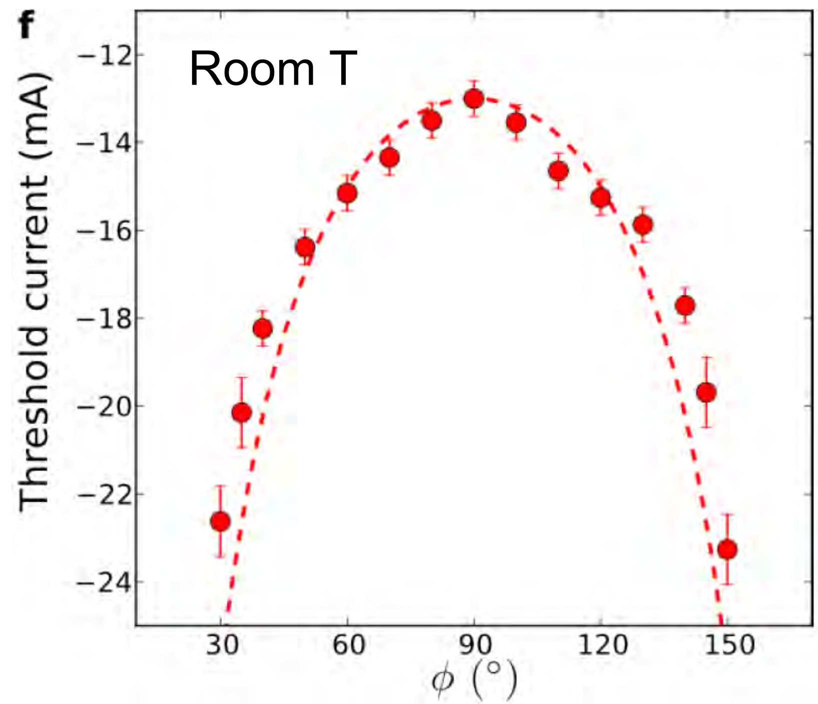


CNRS group results

- YIG/Pt microdisk ST oscillators studied by CNRS group closely follow the 1/sin(φ) critical current dependence





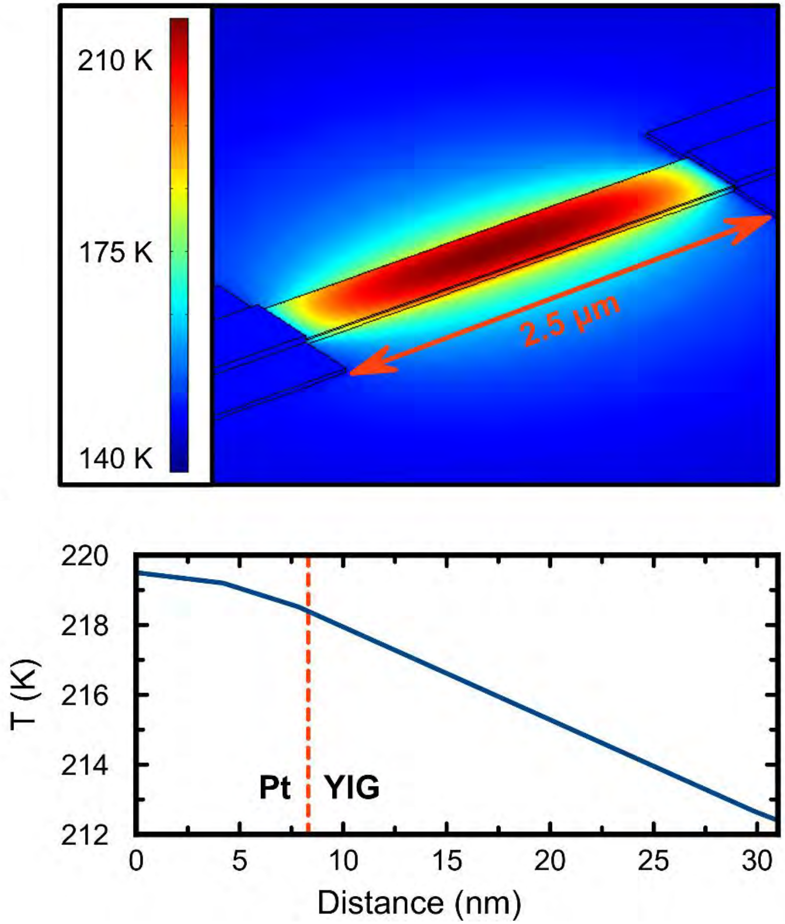


$$I_c(\varphi) = \frac{I_{c0}}{\sin(\varphi)}$$ fits the data well

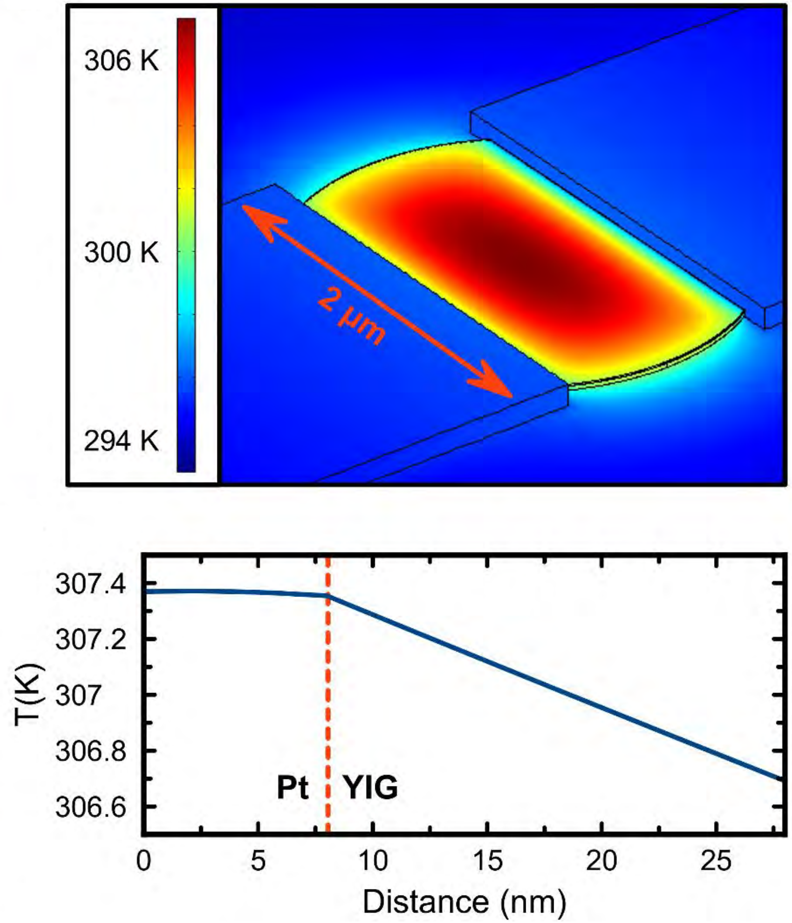
M. Collet et al., Nat. Comm. (2015)

Temperature profile simulations

UC Irvine YIG/Pt devices



CNRS YIG/Pt devices



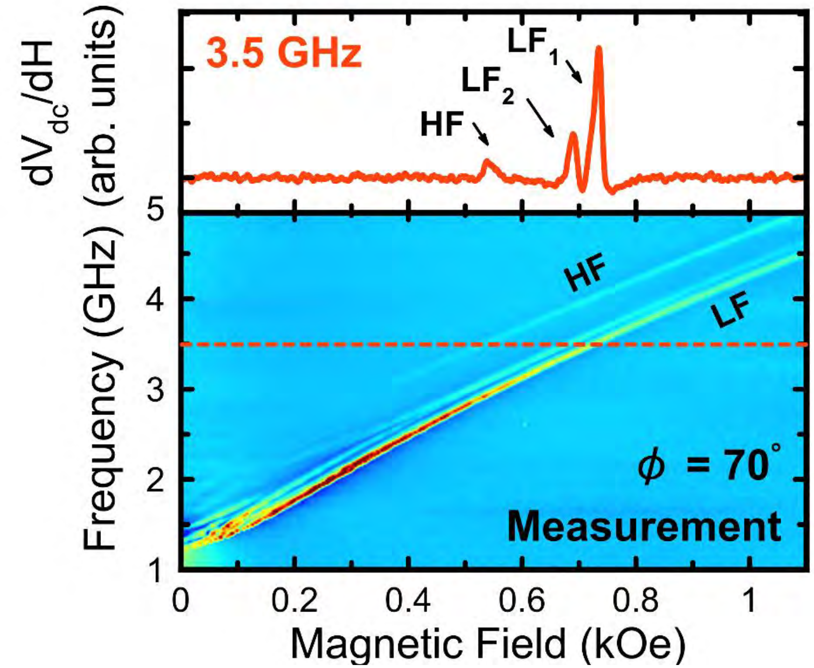
∇T in YIG ~ 0.26 K/nm

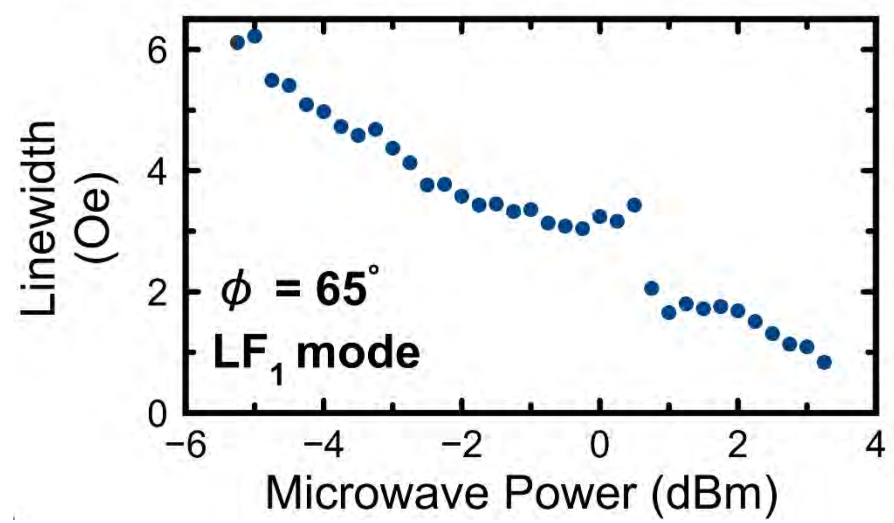
∇T in YIG ~ 0.033 K/nm

@ critical current

Spin torque ferromagnetic resonance

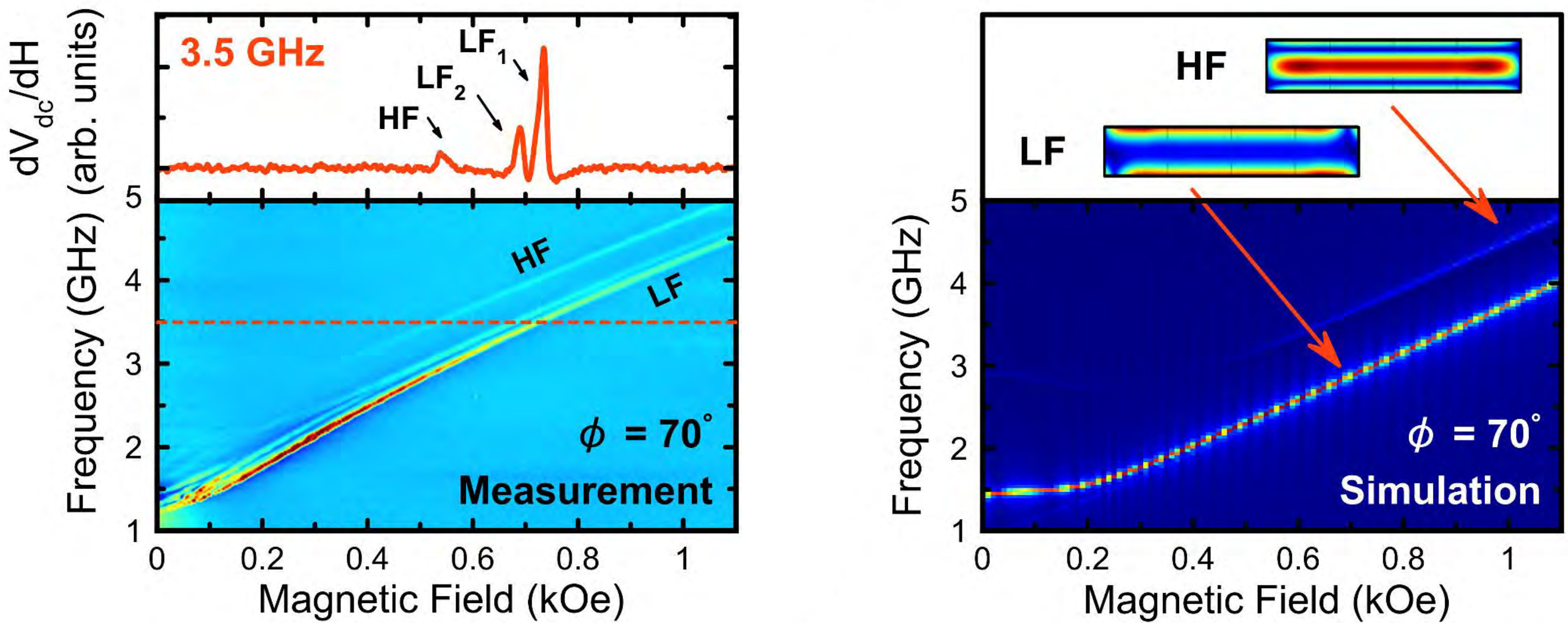
- ST-FMR spectra can be measured in our YIG/Pt nanowire devices
- Due to small MR, ST-FMR signals are only seen at large microwave power
  - μ-wave generates Ohmic heat and spin Seebeck current
  - truly linear FMR regime is not achievable
- Only qualitative analysis of the measured spectral linewidth is possible





Mode identification

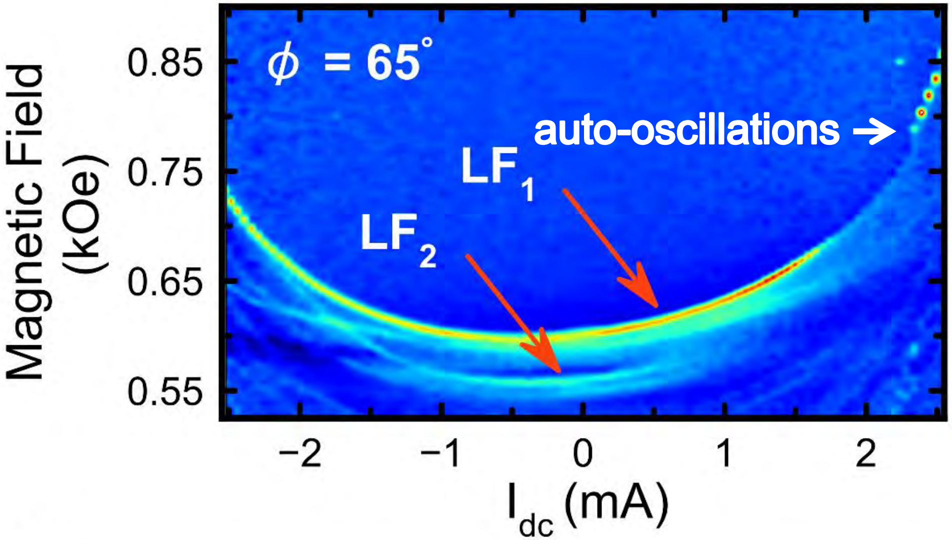
- Micromagnetic simulations of the spin wave spectra reveal two dominant low frequency modes
- Same modes are observed in ST-FMR measurements

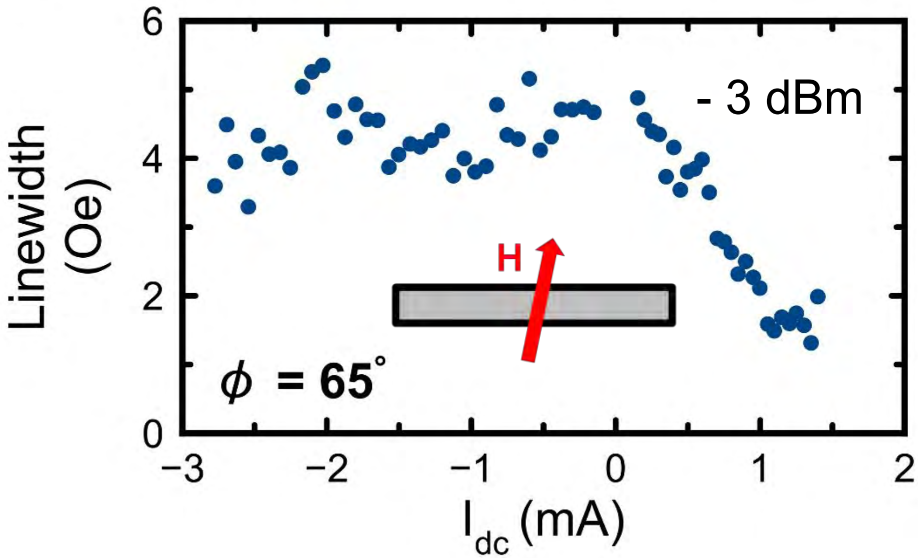


- The LF mode seen in the experiment and simulations has edge character
- Auto-oscillations of the LF_1 mode are seen in the experiment

Linewidth versus bias current, near hard axis

- Near hard axis, the asymmetry in the linewidth versus current is apparent
- This asymmetry is due to combined action of spin Hall and spin Seebeck torques





SH – damping
SS – antidamping

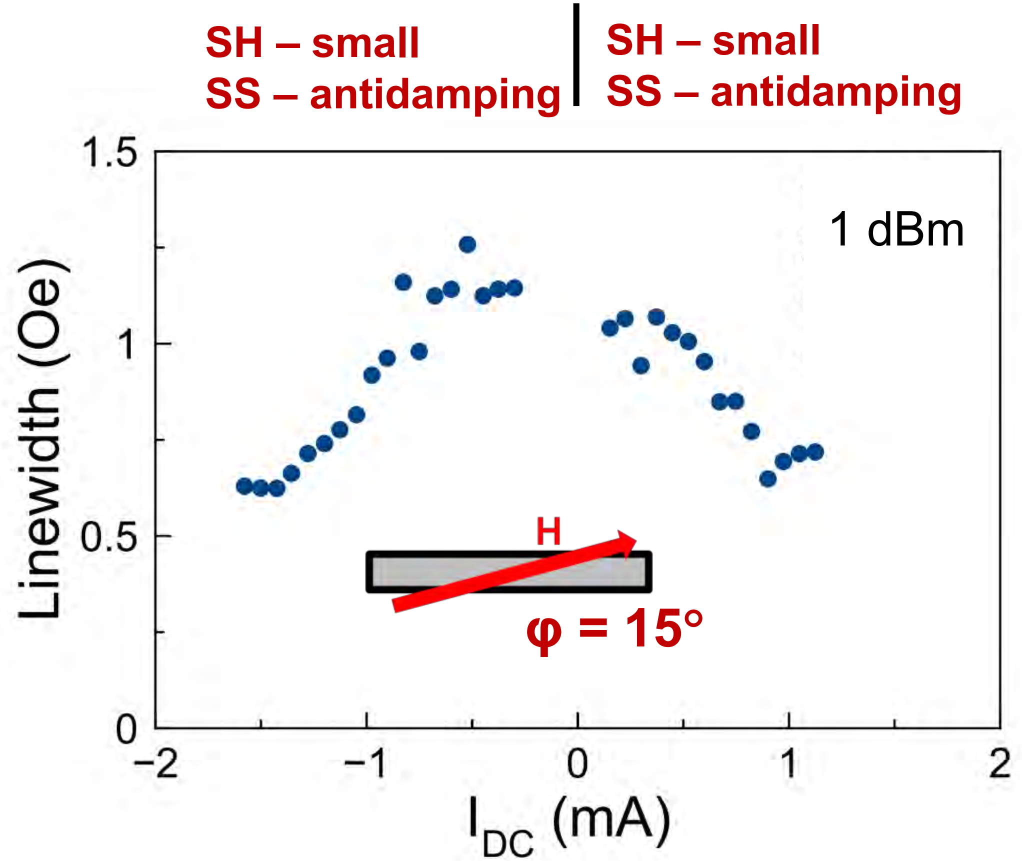
SH – antidamping
SS – antidamping

Linewidth versus bias current, near easy axis

- For magnetization nearly parallel to the wire axis, spin Hall antidumping is inactive

- Yet, strong decrease of the linewidth is observed for both current polarities

- The data are consistent with anti-damping arising from spin Seebeck current alone (symmetric in current)



Summary

- Observed current-driven auto-oscillations of magnetization in YIG/Pt nanowire devices
- The critical current shows weak angular dependence
- Large Ohmic heating in Pt results in large temperature gradient across YIG film – high density of spin Seebeck current
- Auto-oscillations in YIG/Pt nanowire devices are driven by combined action of spin Hall and spin Seebeck currents

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