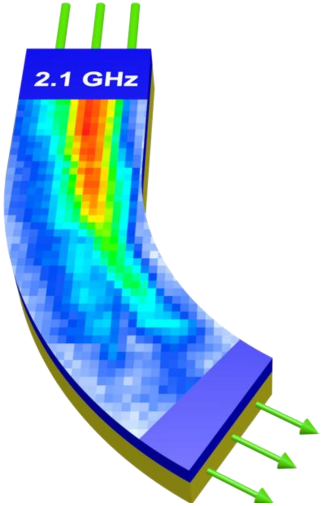
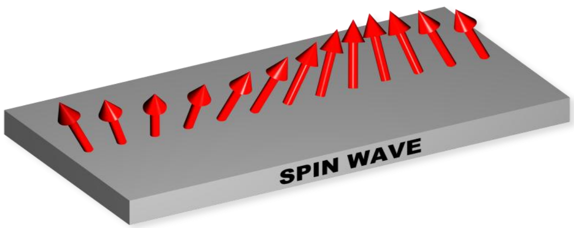
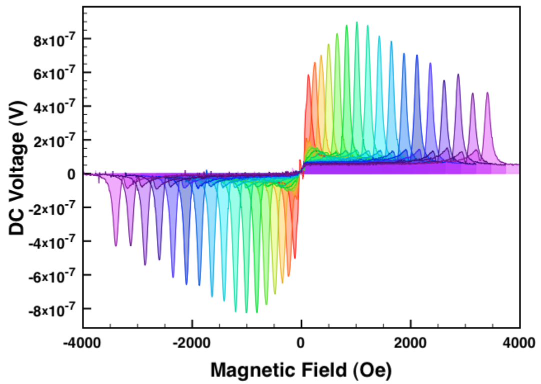
Electric Control and Detection of Spin Waves





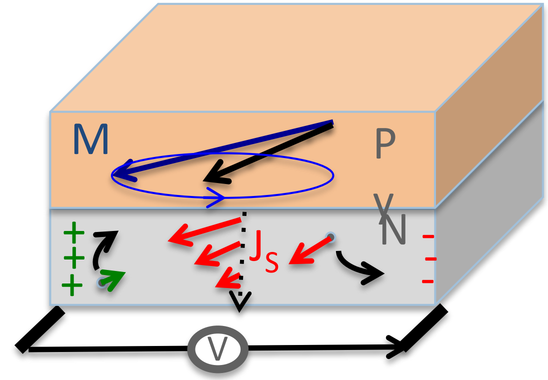


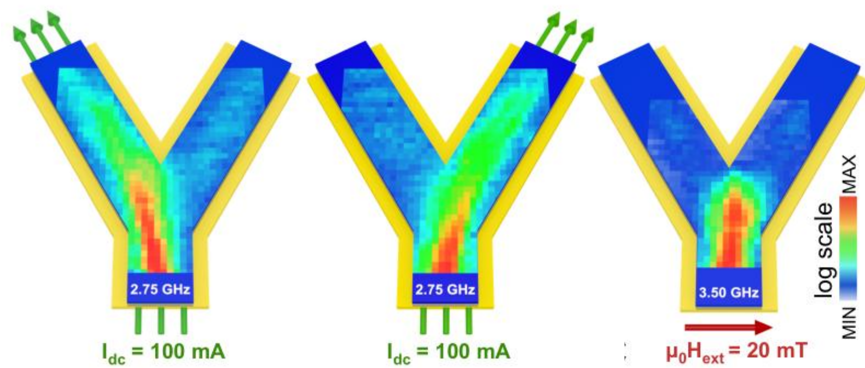
Axel Hoffmann

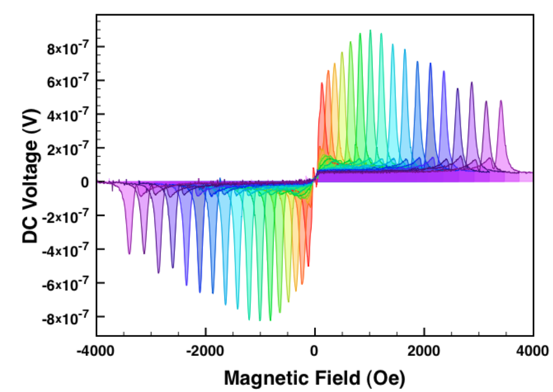
Materials Science Division
Argonne National Laboratory

Outline

- Spin Hall Effects
- Manipulating Spin Waves
- Thermoelectric Detection of Spin Waves
- Conclusions



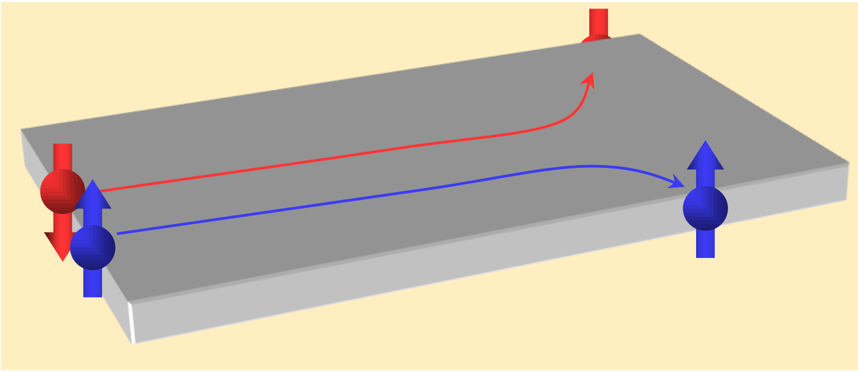


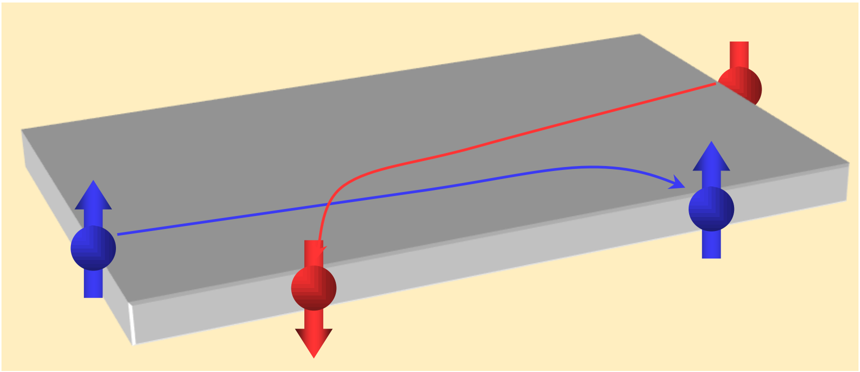


Spin Hall vs. Inverse Spin Hall

M.I. Dyakonov & V. I. Perel, *Sov. Phys. JETP Lett.* **13**, 467 (1971); J.E. Hirsch, *Phys. Rev. Lett.* **83**, 1834 (1999)

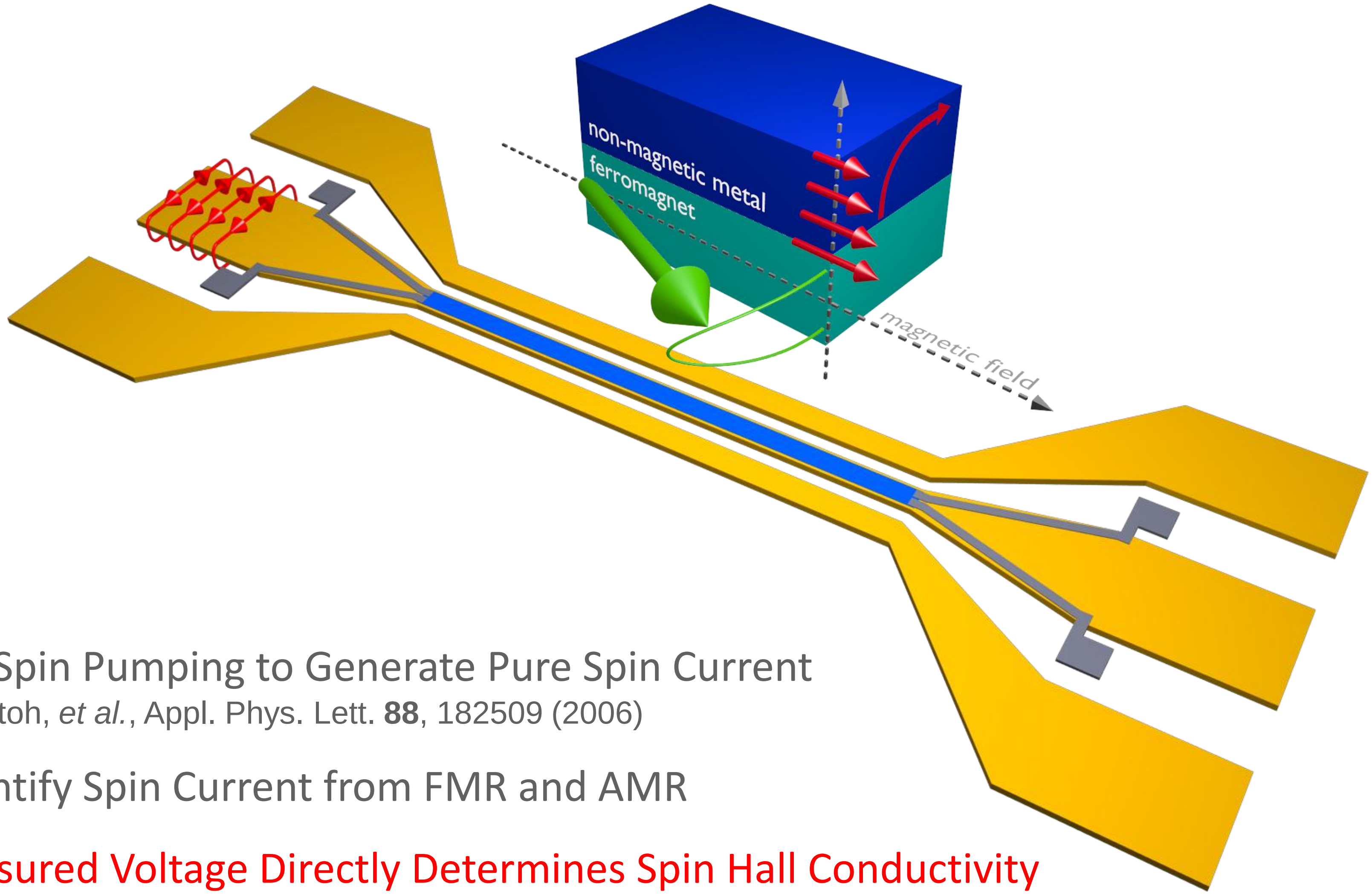
Spin Hall		Inverse Spin Hall
Charge Current		**Spin Current**
⇓	**Spin Dependent Scattering**	⇓
Transverse Spin Imbalance		**Transverse Charge Imbalance**





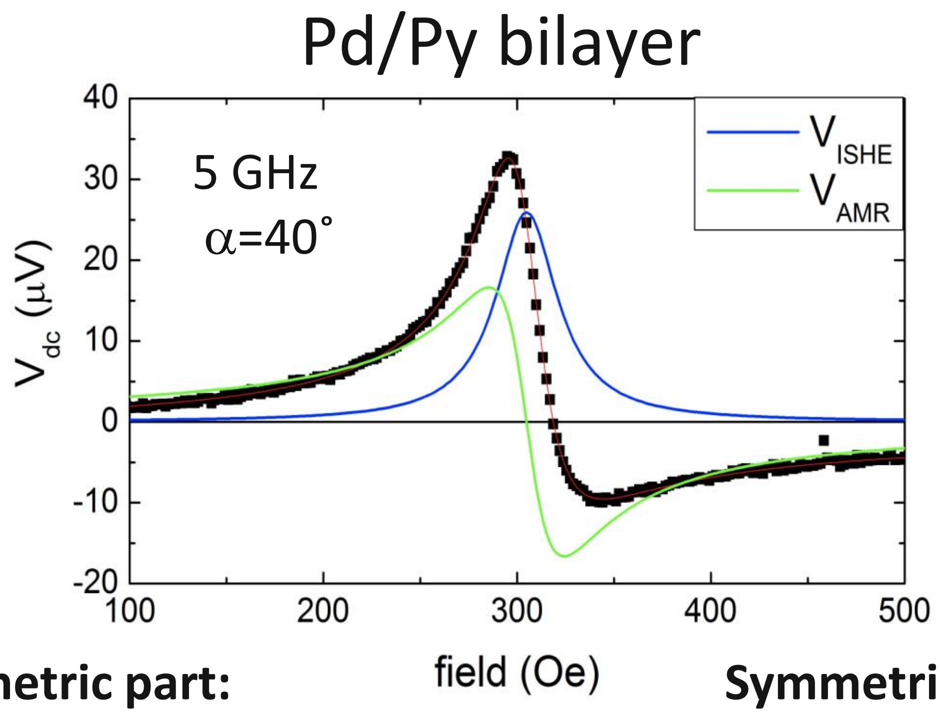
Recent Review: **Axel Hoffmann, IEEE Trans. Magn. 49, 5172 (2013)**

Combine Spin Pumping and Inverse Spin Hall Effect



- Use Spin Pumping to Generate Pure Spin Current
  E. Saitoh, *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)
- Quantify Spin Current from FMR and AMR
- Measured Voltage Directly Determines Spin Hall Conductivity
  O. Mosendz, *et al.*, Phys. Rev. Lett. **104**, 046601 (2010); Phys. Rev. B **82**, 214403 (2010)

Typical *dc* Voltage Spectrum



Antisymmetric part:

Symmetric part:

Anisotropic Magnetoresistance

$$V_{AMR} \propto I_{rf}^{Py} \Delta R_{AMR} \sin 2\theta \sin 2\alpha \cos \varphi_0$$

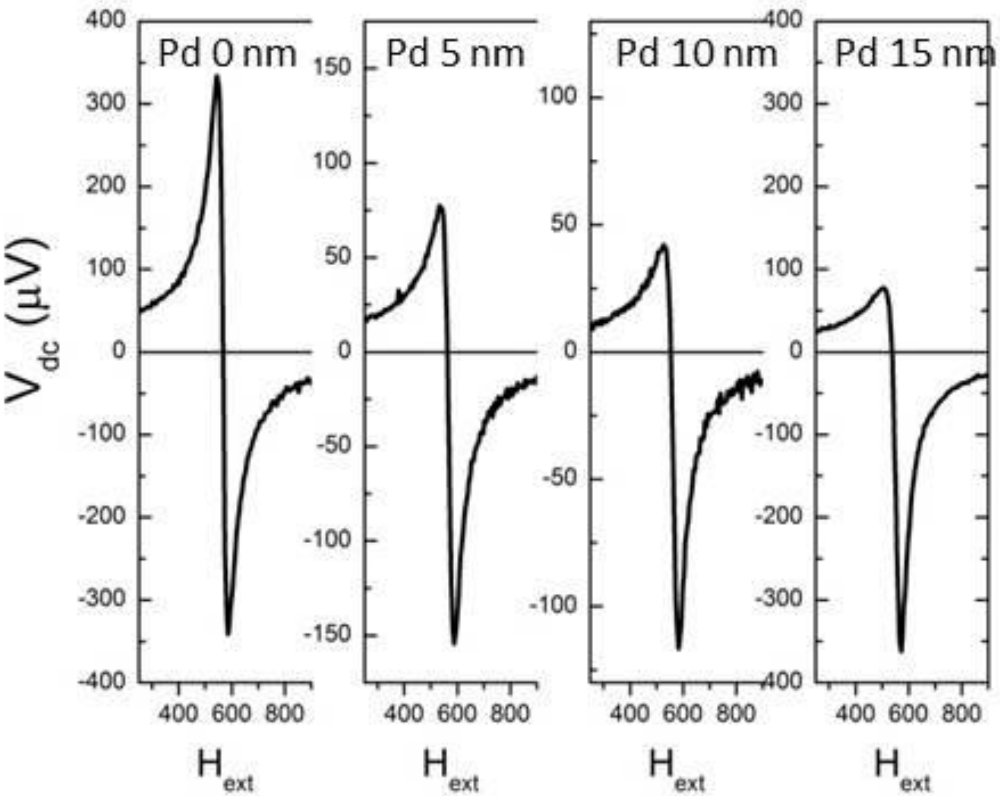
Spin Hall Effect

$$V_{ISHE} \propto -\gamma \frac{L}{\sigma} \frac{\lambda_s}{t_N} g_{\uparrow\downarrow} f \sin^2 \theta \sin \alpha$$

O. Mosendz, *et al.*, Phys. Rev. Lett. **104**, 046601 (2010); Phys. Rev. B **82**, 214403 (2010)

Non-Magnetic Layer Thickness

V. Vlaminck *et al.*, Phys. Rev. B **88**, 064414 (2013)



$$\frac{V_{ISHE}}{V_{AMR}} = \frac{\gamma e E w g_{\uparrow\downarrow} \lambda_s R_F}{R_{CPW} I_{CPW} \Delta R_F} \frac{h_{rf}}{\Delta H} \frac{\rho_F L}{t_F} \tanh\left(\frac{t_N}{2\lambda_s}\right)$$

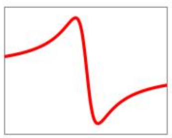
As Pd thickness increases: Signal becomes more symmetric, i.e., ISHE-like

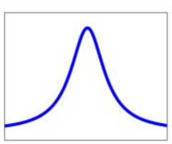
Determine Spin Diffusion Length in Pd and Pt

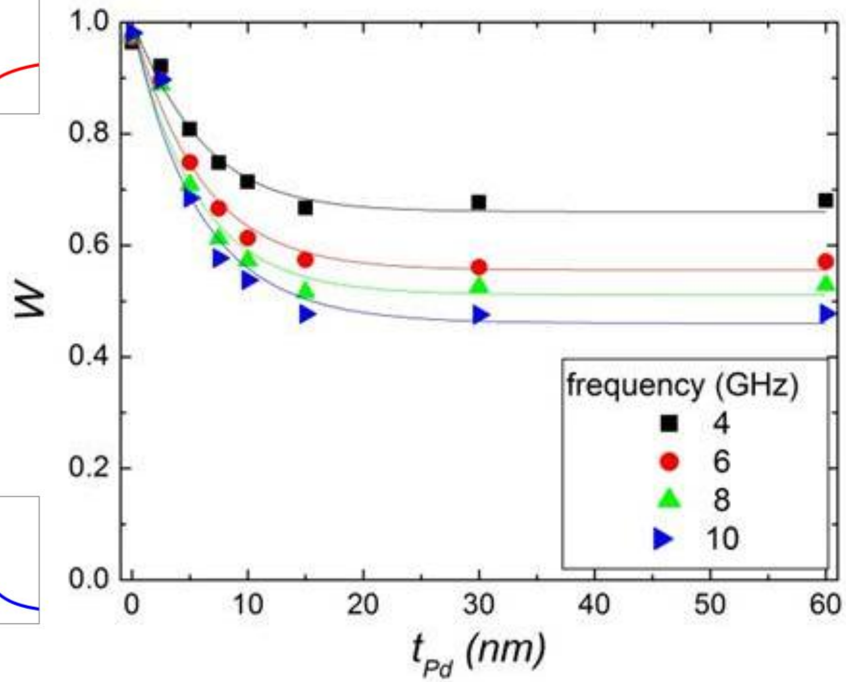
V. Vlaminck *et al.*, Phys. Rev. B **88**, 064414 (2013)

$$V = wV_A + (1 - w)V_S \qquad w = \frac{1}{1 + V_{ISHE}/V_{AMR}} \qquad \frac{V_{ISHE}}{V_{AMR}} \propto \tanh\left(\frac{t_N}{2\lambda_s}\right)$$

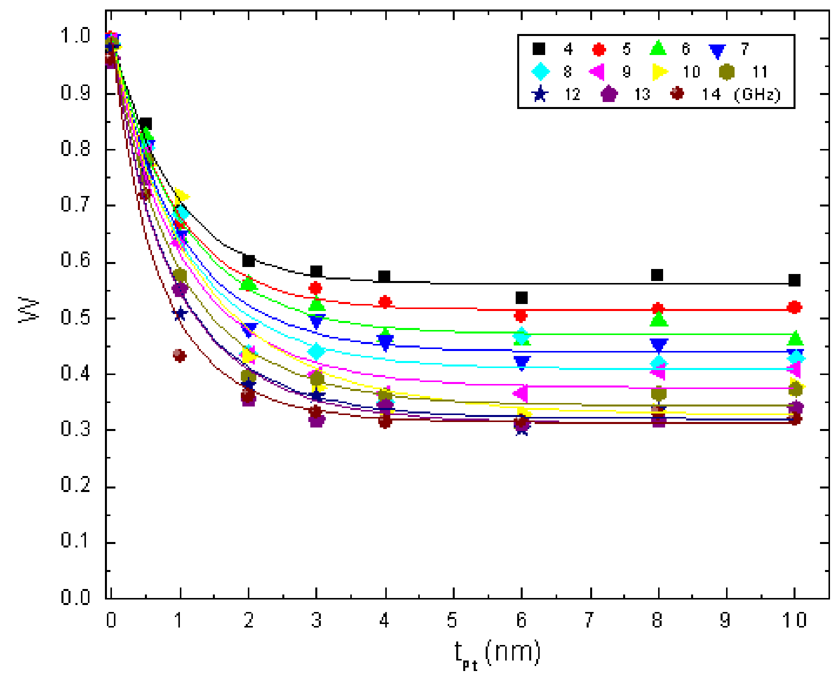
Pd







Pt



$$\lambda_S(Pd) = 5.5 \pm 0.5\ \text{nm} \qquad \lambda_S(Pt) = 1.2 \pm 0.5\ \text{nm}$$

Determine Spin Hall Angle for Many Materials

Phys. Rev. Lett. **104**, 046601 (2010); Phys. Rev. B **82**, 214403 (2010); Phys. Rev. B **88**, 064414 (2013)

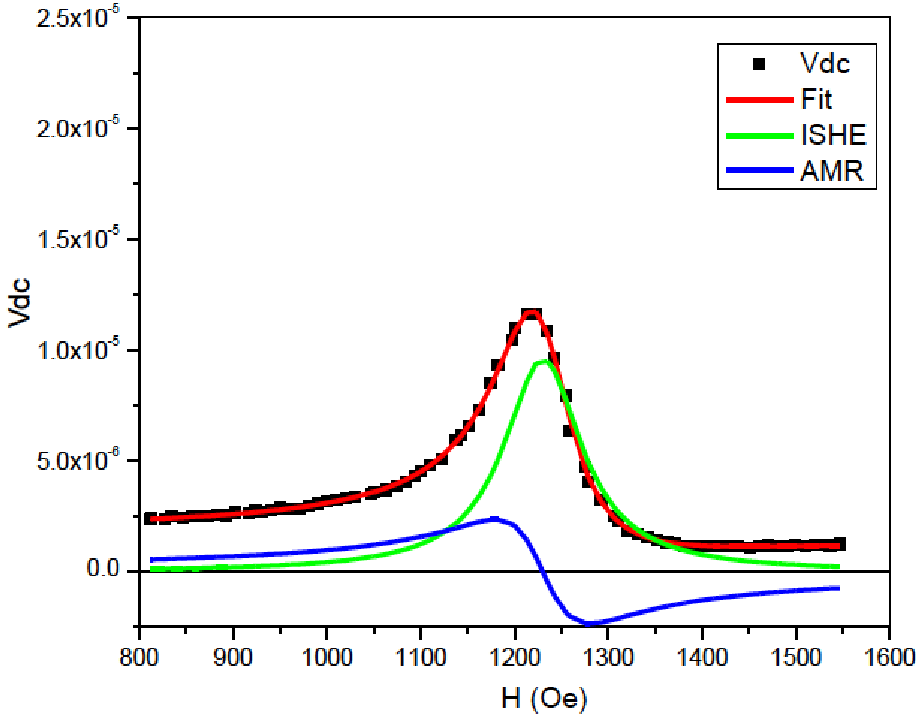
4d	Mo $\gamma = -0.05\% \pm 0.01$	• • •		Pd $\gamma = 1.2\% \pm 0.3$	
5d	Ta γ very small and negative	• • •	Ir $\gamma \approx 1\%$	Pt $\gamma = 9.4\% \pm 0.5$	Au $\gamma = 0.3\% \pm 0.1$

Technique readily adapted to any material!

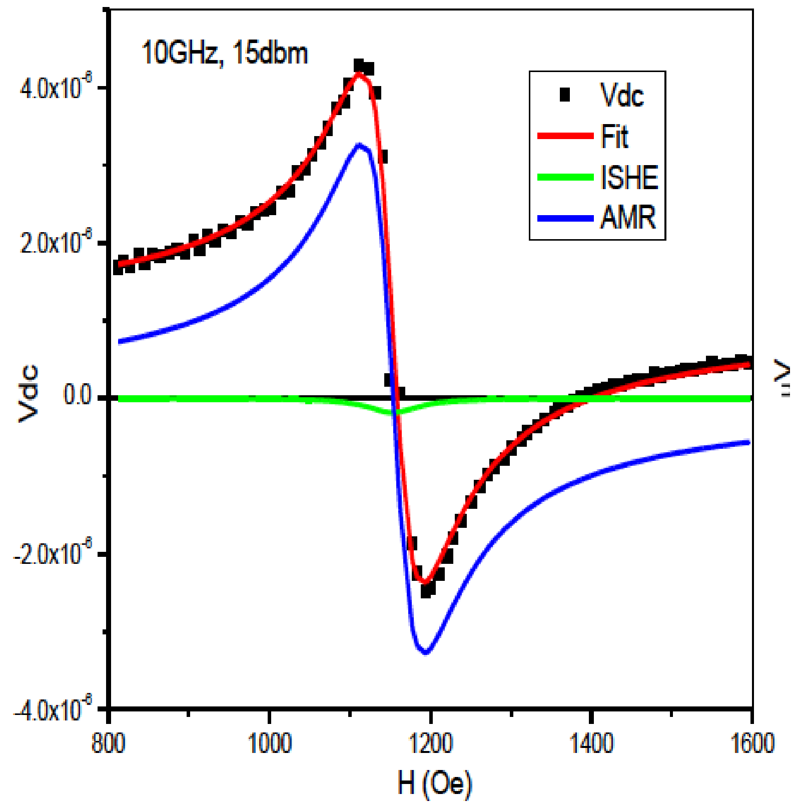
Giant Spin Hall Effect in Ta?

Compare raw data

Pt

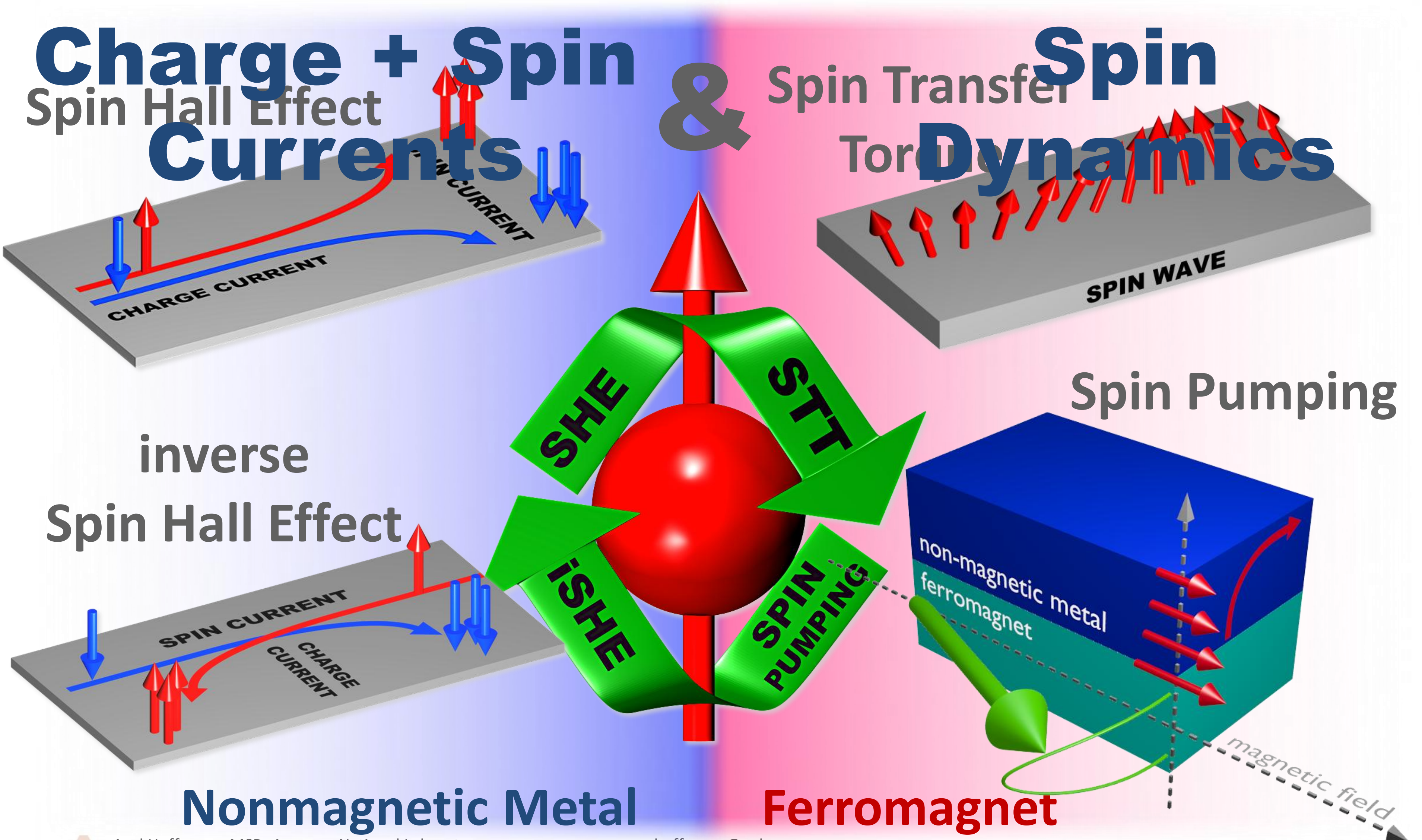


Ta



Spin mixing conductance, spin diffusion length, something else?

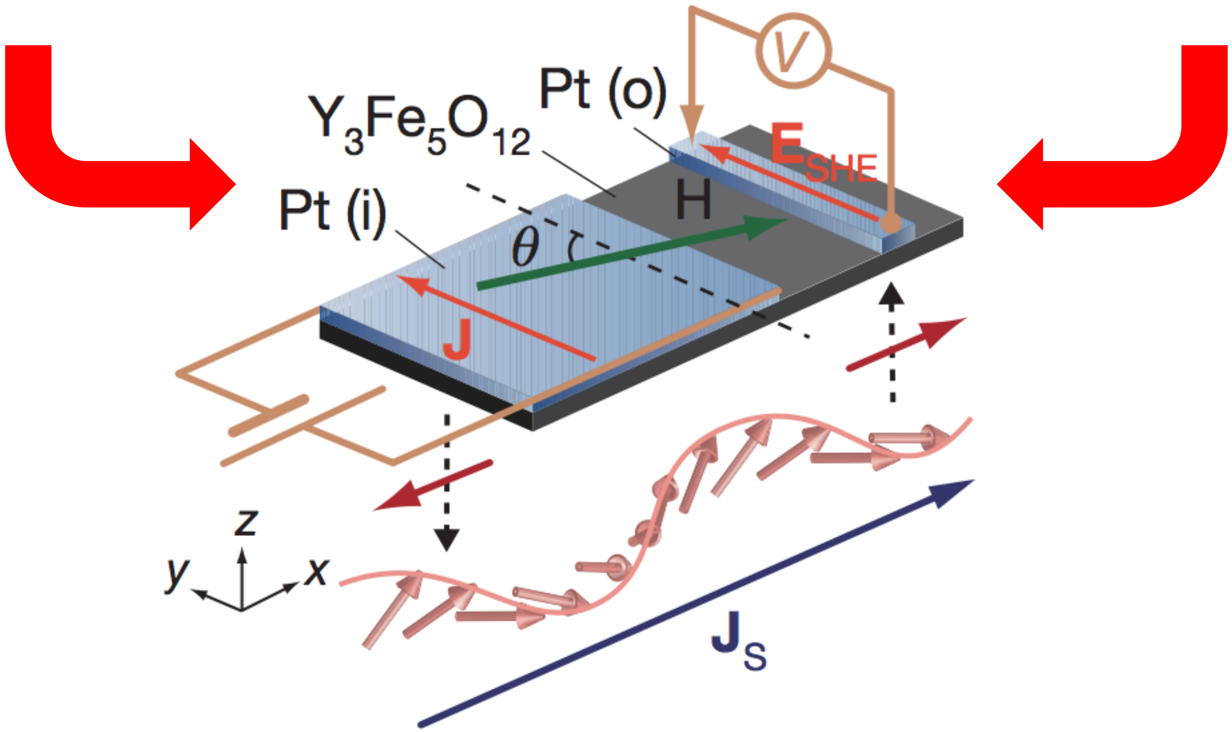
Spin Hall Effects are Key Enabling Phenomena



Spin Currents in Insulators

Use Direct Spin Hall Effect to excite magnetization dynamics

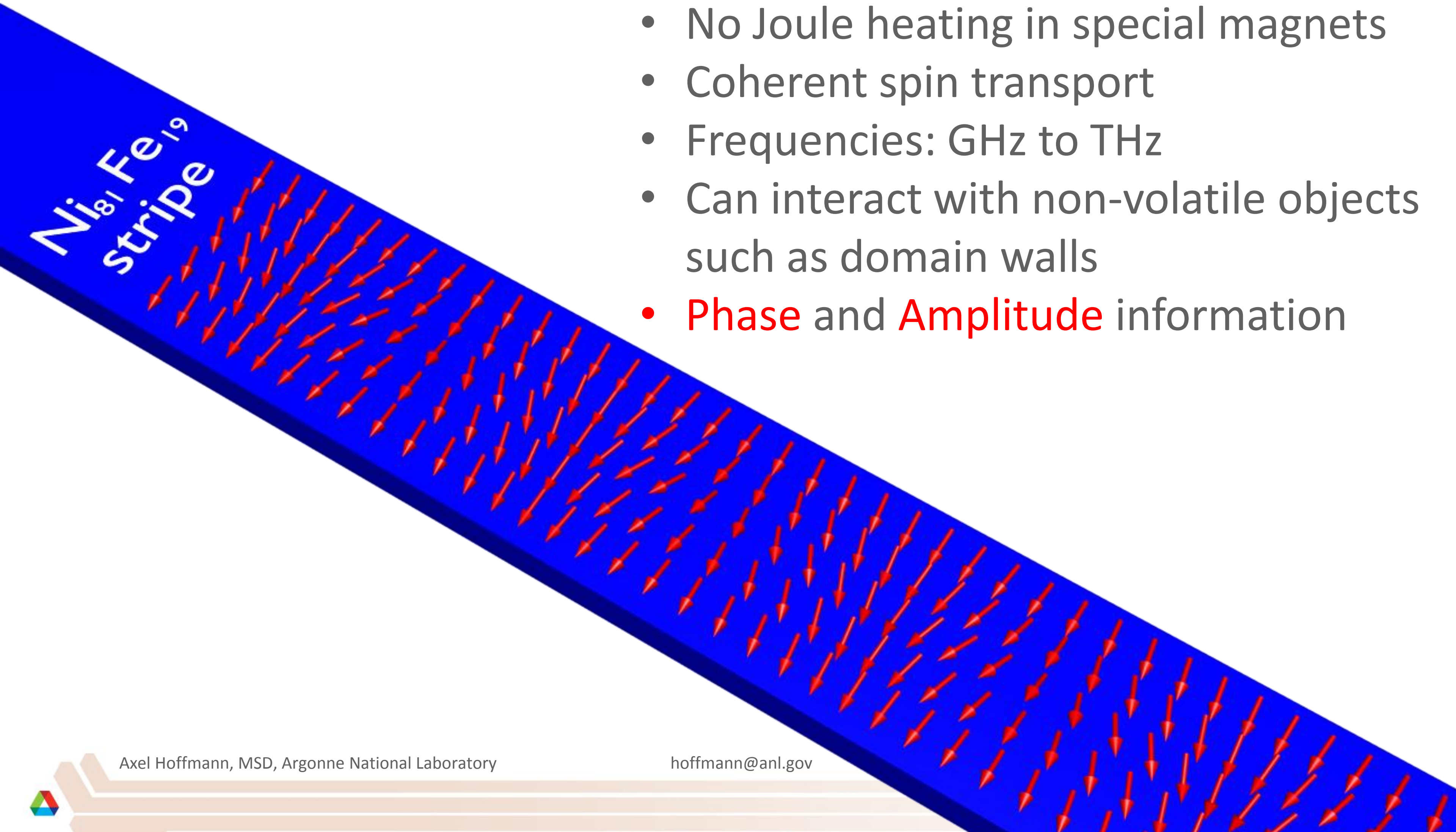
Use Inverse Spin Hall Effect and Spin Pumping for detection



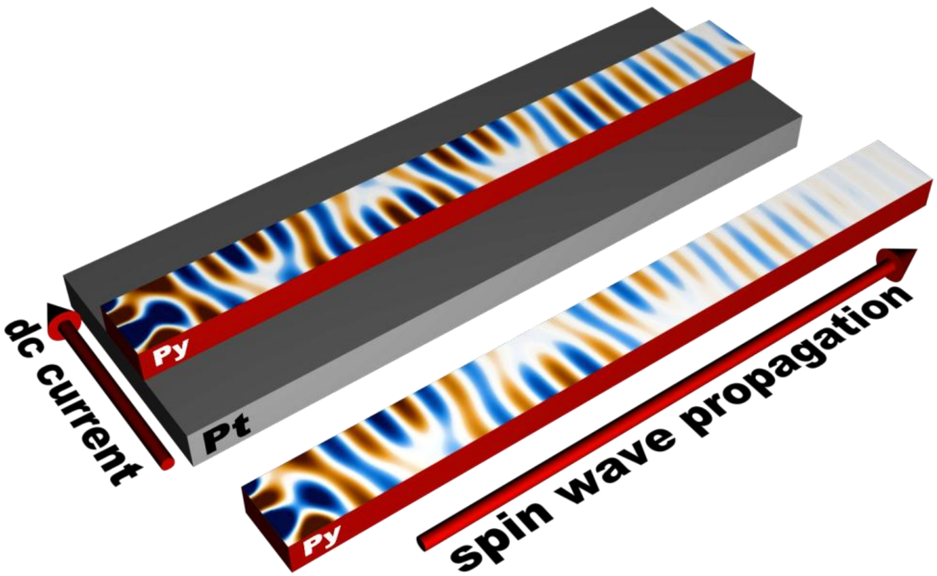
Y. Kajiwara *et al.*, Nature **464**, 262 (2010)

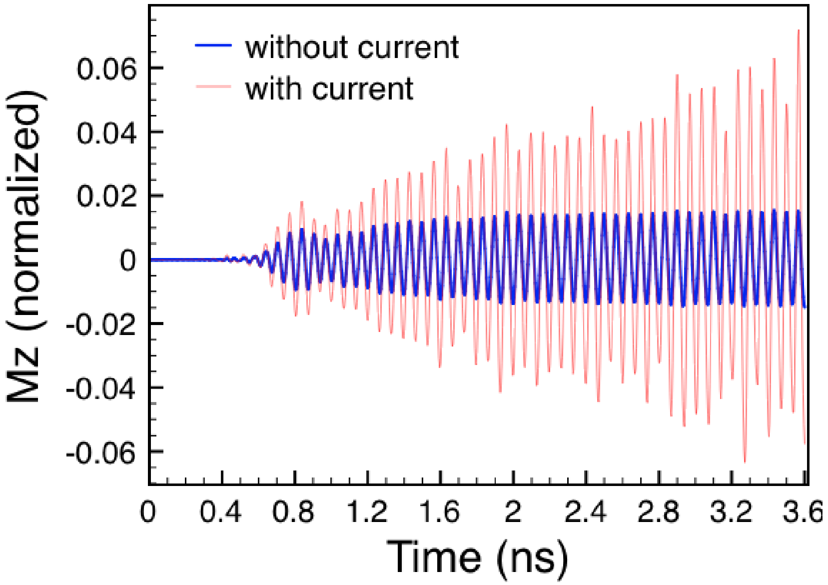
Why Spin Wave Transport?

- Decay length orders of magnitude larger than for diffusive spin currents
- No Joule heating in special magnets
- Coherent spin transport
- Frequencies: GHz to THz
- Can interact with non-volatile objects such as domain walls
- Phase and Amplitude information



Using Spin Hall Effects to Amplify Spin Waves





- Spin Hall effects generates spin accumulation at interface with ferromagnet
- Spin torque from spin accumulation can compensate intrinsic damping

What about Oersted fields?

or

How to send a spin wave around a corner

K. Vogt *et al.*, Appl. Phys. Lett. **101**, 042410 (2012)

Magnetic Field Dependence of Spin Waves

$$\omega(k,\varphi) = \frac{\gamma\mu}{2\pi}\sqrt{(H_{eff} + \lambda_{ex}k^2)(H_{eff} + \lambda_{ex}k^2 + 4\pi M_s F_{00}(k,\varphi))}$$

dipolar interaction

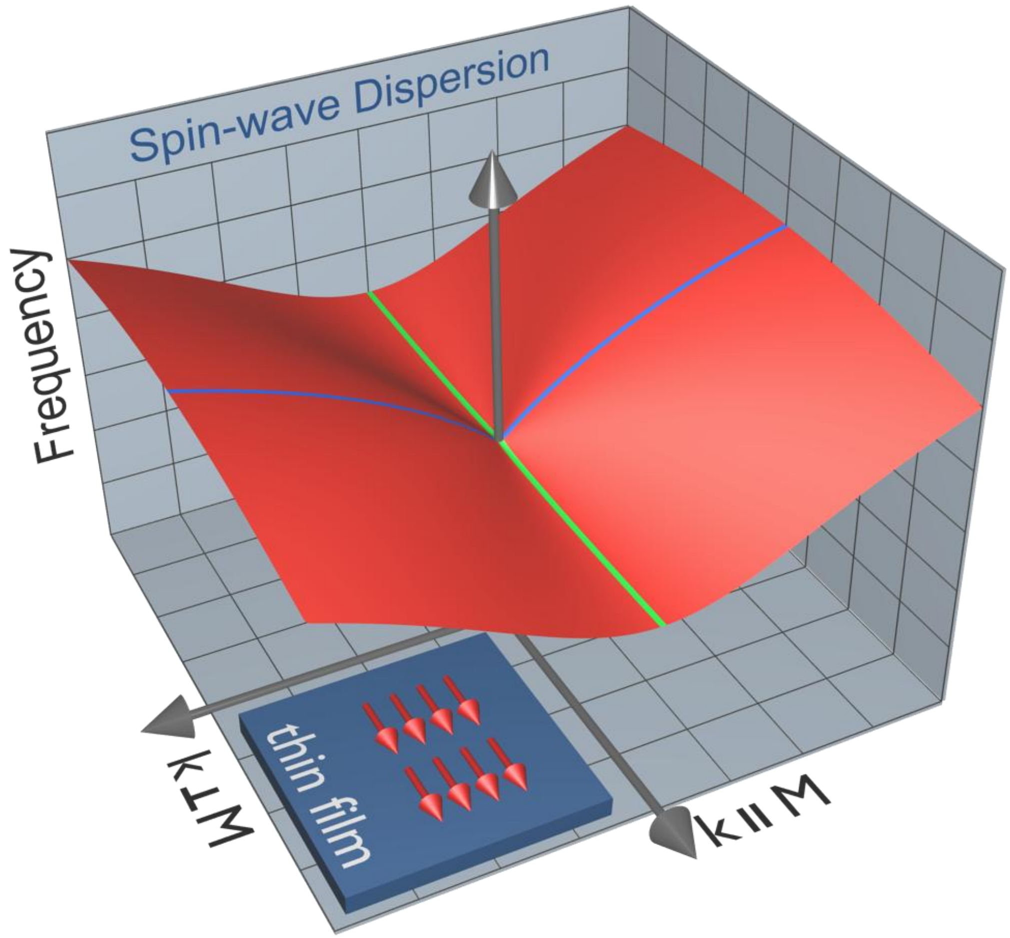
exchange interaction

k ⊥ M:

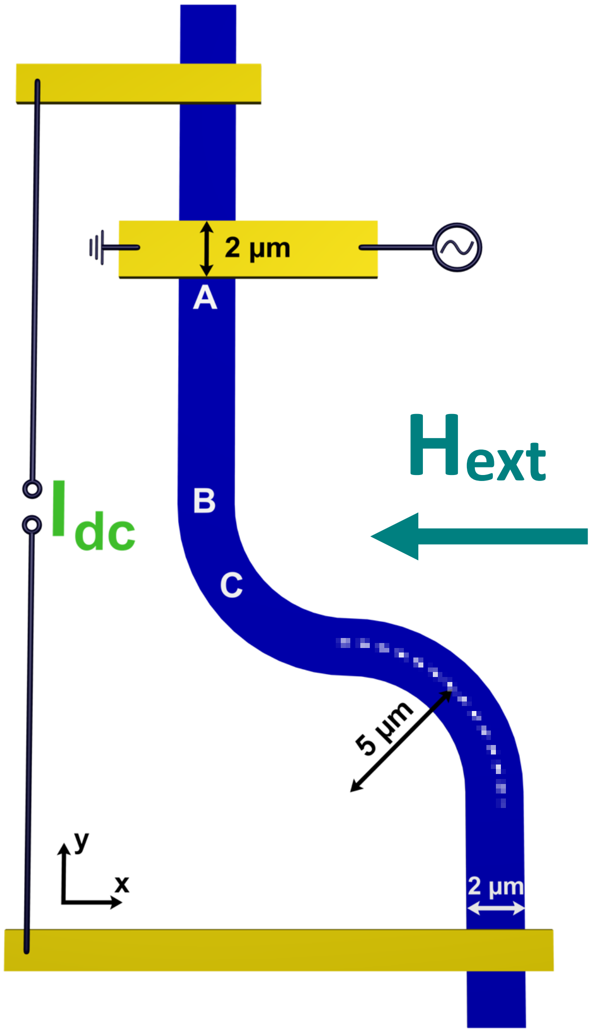
- positive dispersion
- high group velocity

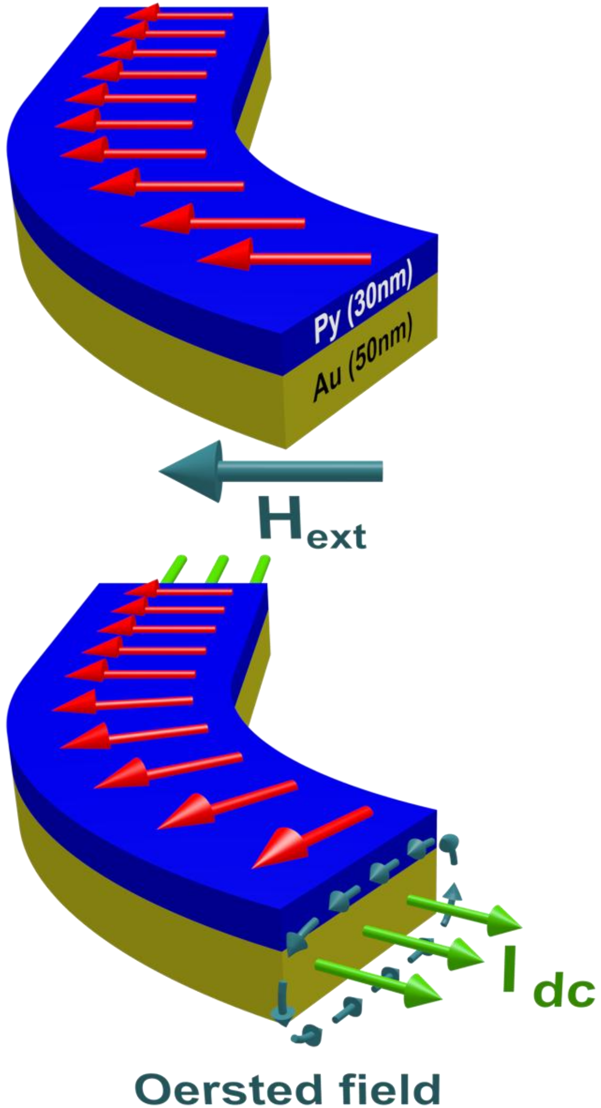
k || M:

- negative dispersion
- small group velocity



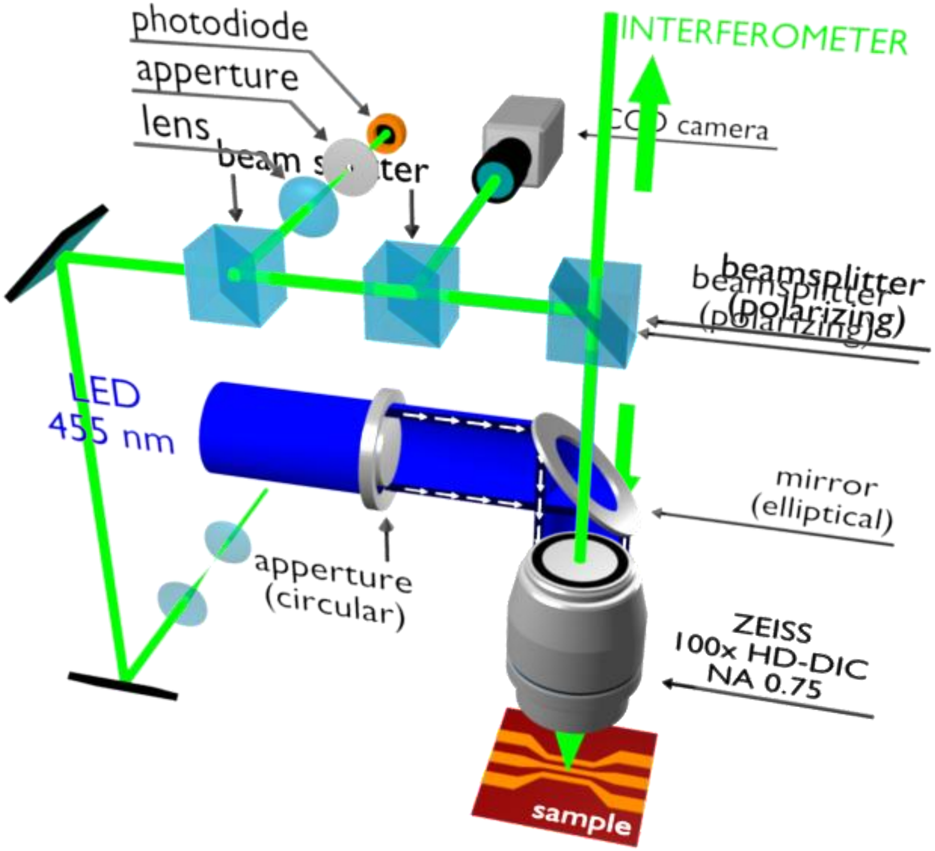
Can a Spin Wave turn a corner?





K. Vogt *et al.*, Appl. Phys. Lett. **101**, 042410 (2012)

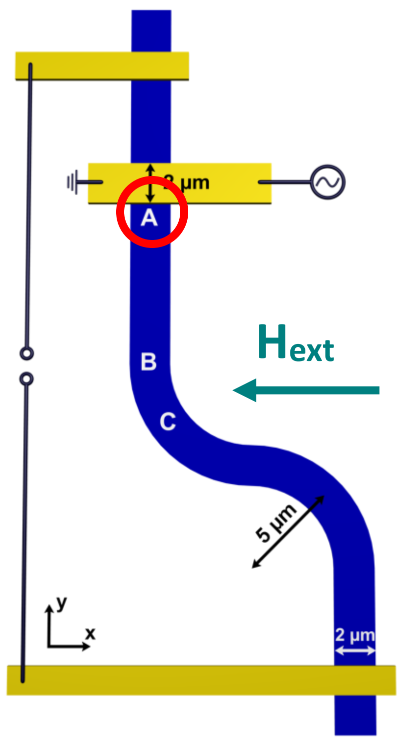
Brillouin Light Scattering Microscopy



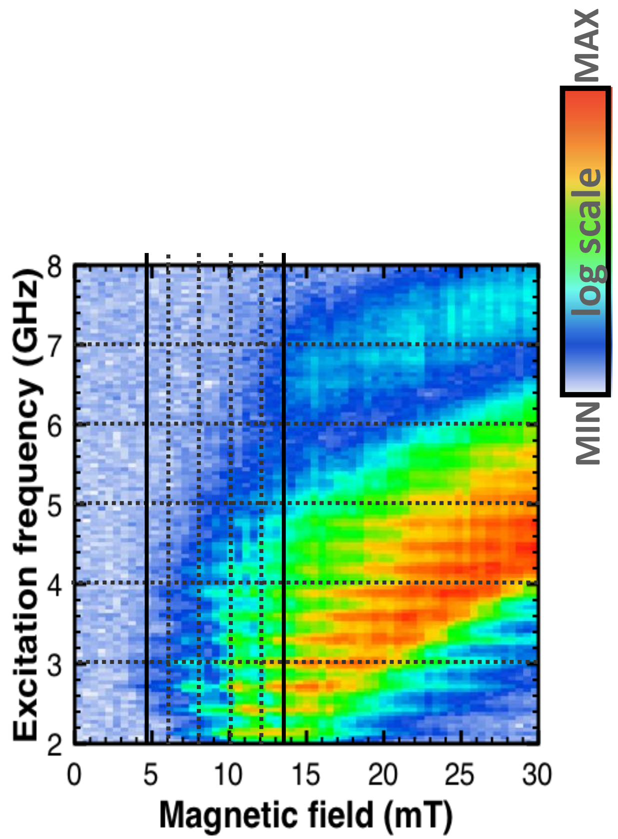
- optical resolution: 250 nm
- 2D scanning stage for sample

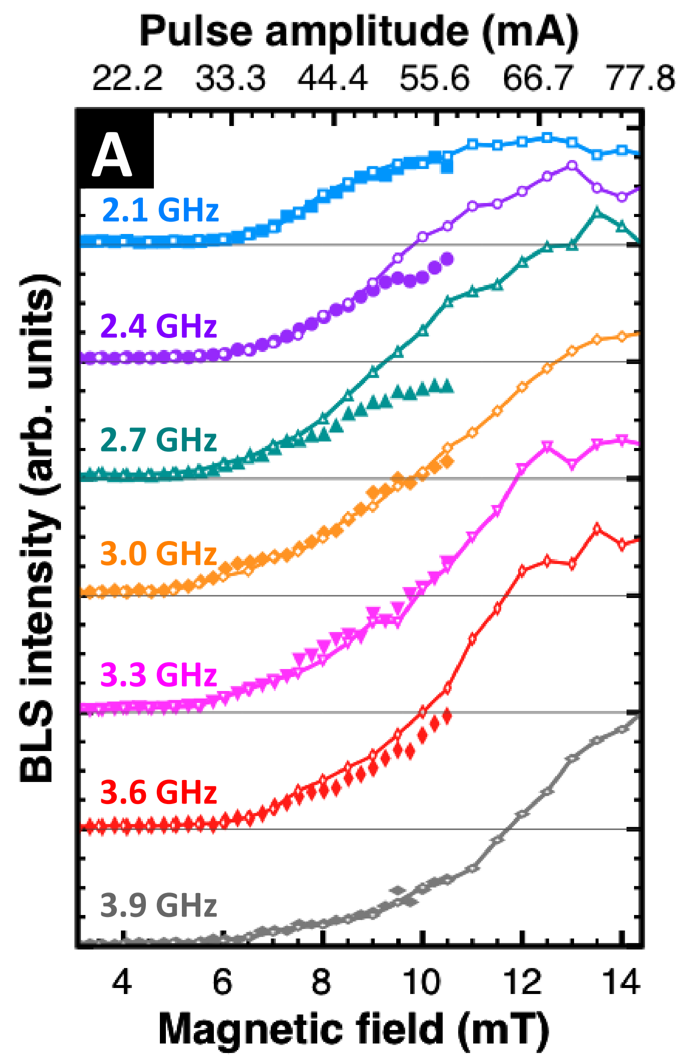
- controlling sample position while measuring
- active stabilization via pattern recognition
- accuracy: *better than 20 nm*

Mapping excitation with Brillouin Light Scattering

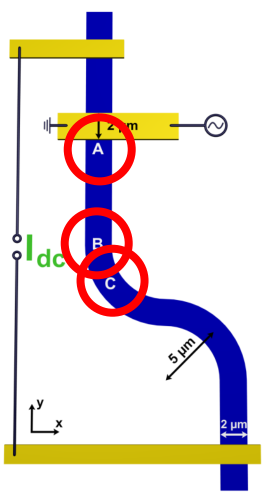


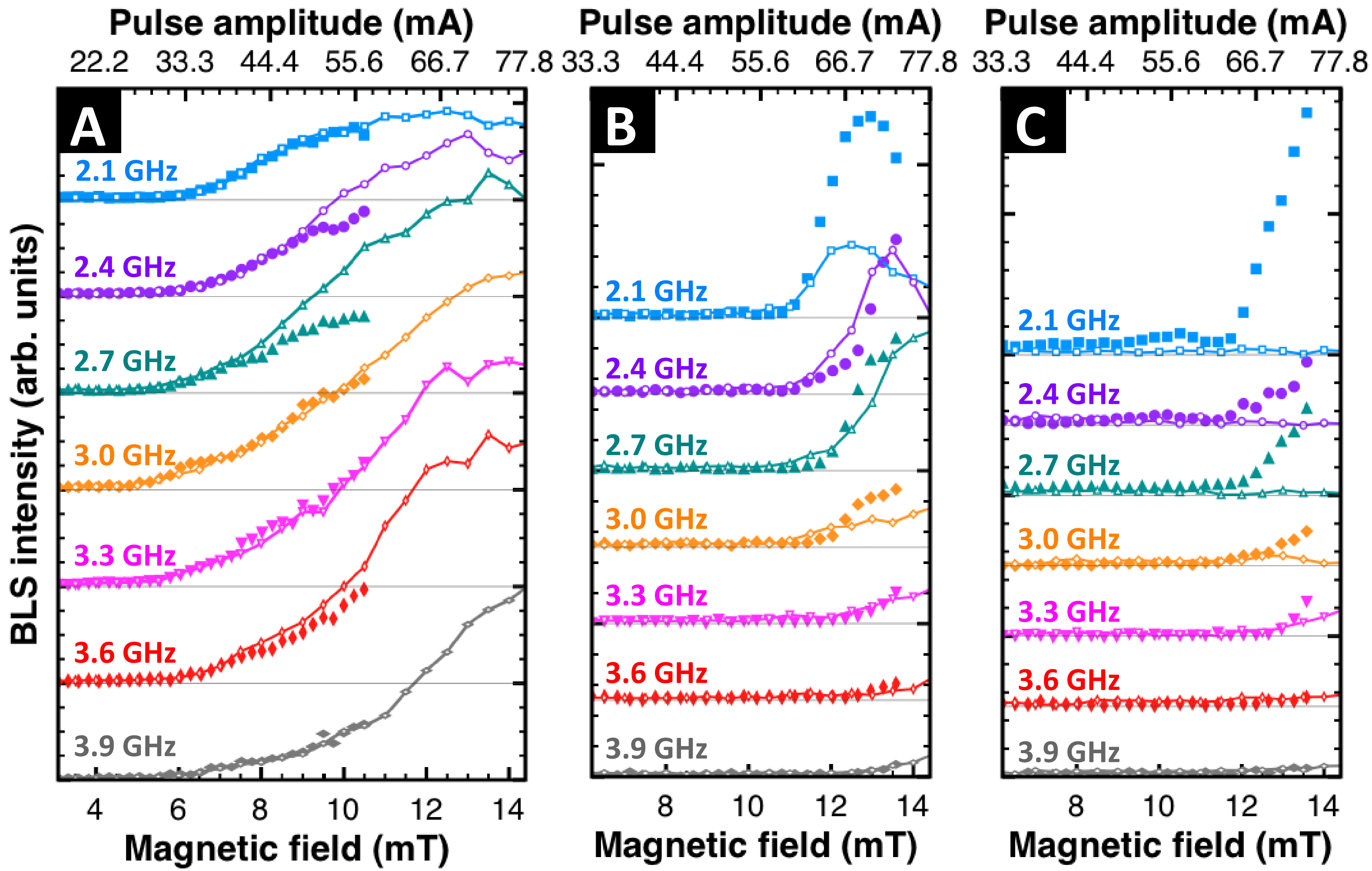
K. Vogt *et al.*,
Appl. Phys. Lett.
101, 042410 (2012)





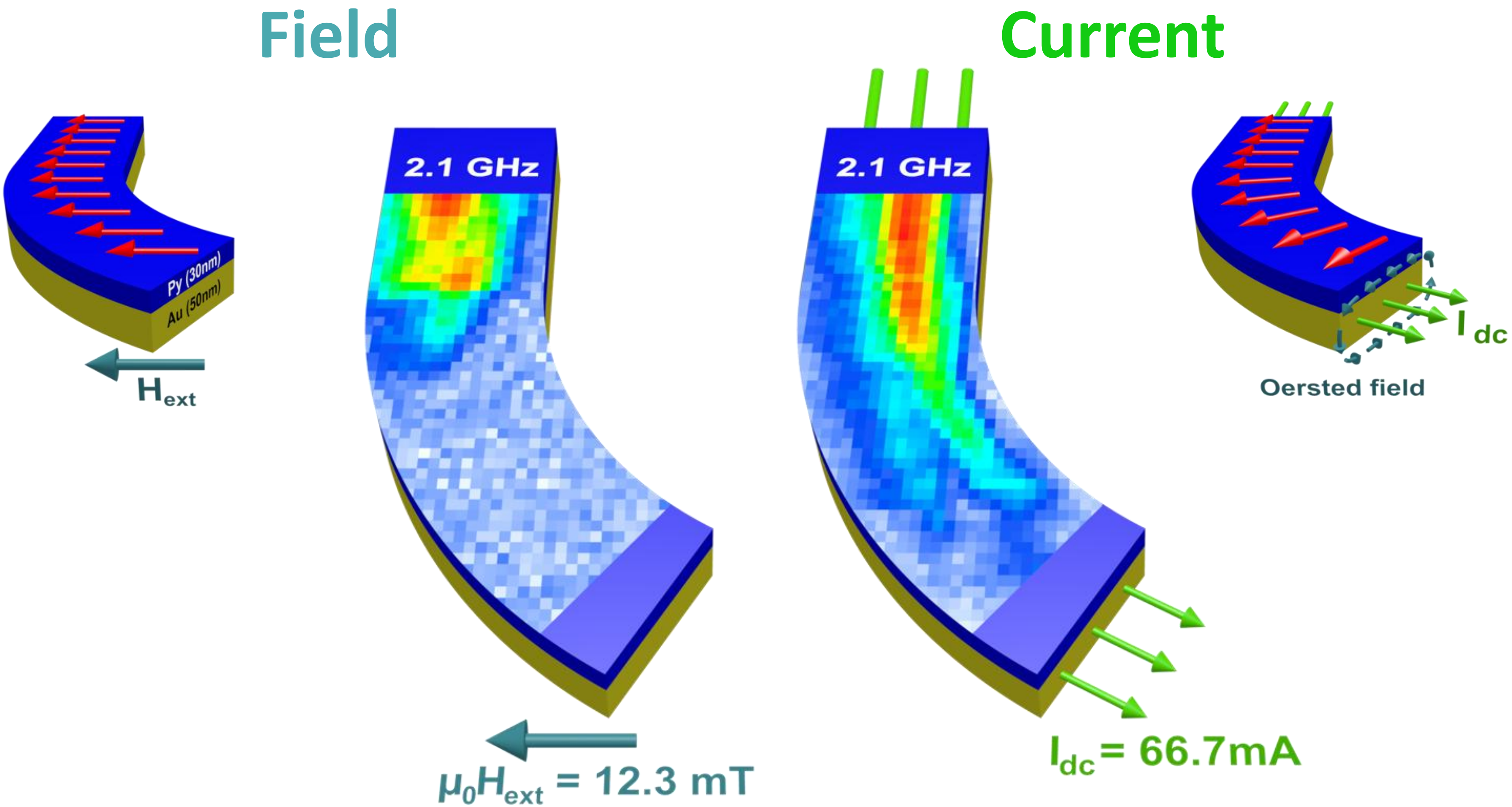
Spatial Dependence





K. Vogt *et al.*,
Appl. Phys. Lett.
101, 042410 (2012)

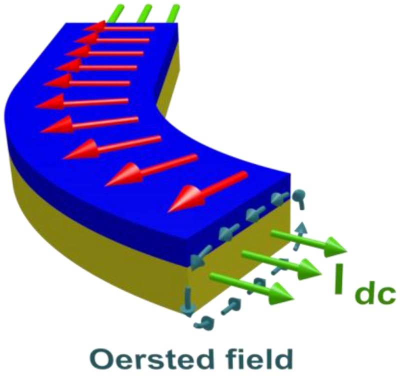
Spin Wave Propagation

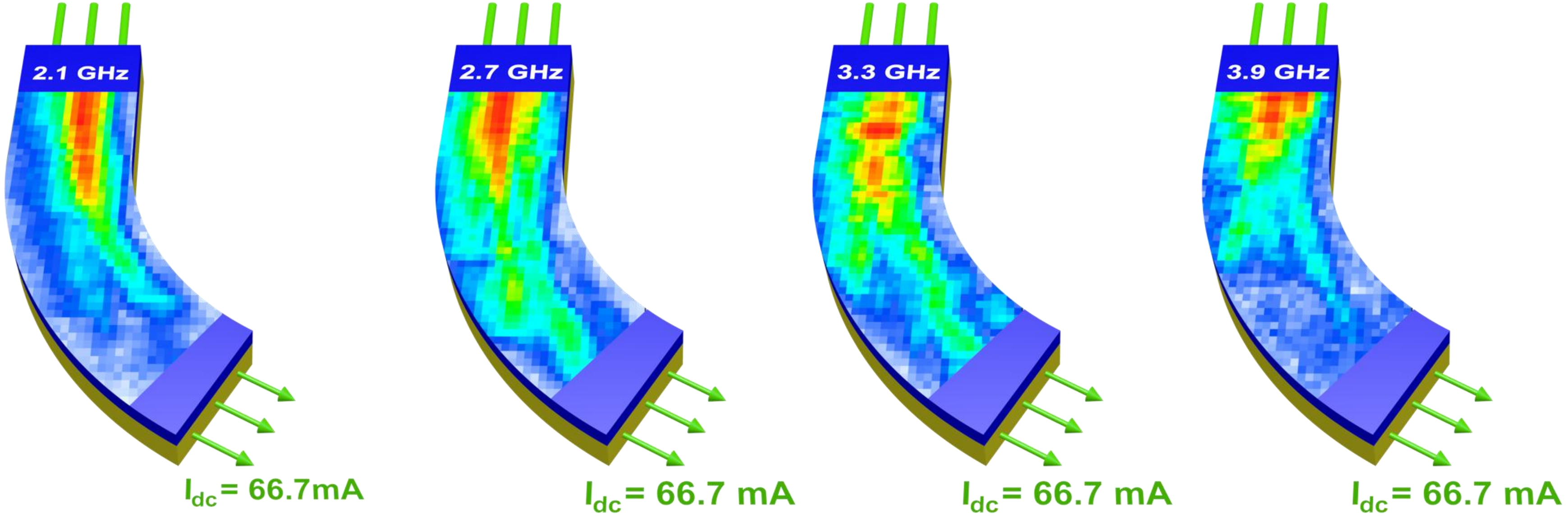


- Better spin-wave guidance with the applied direct current

K. Vogt *et al.*, Appl. Phys. Lett. **101**, 042410 (2012)

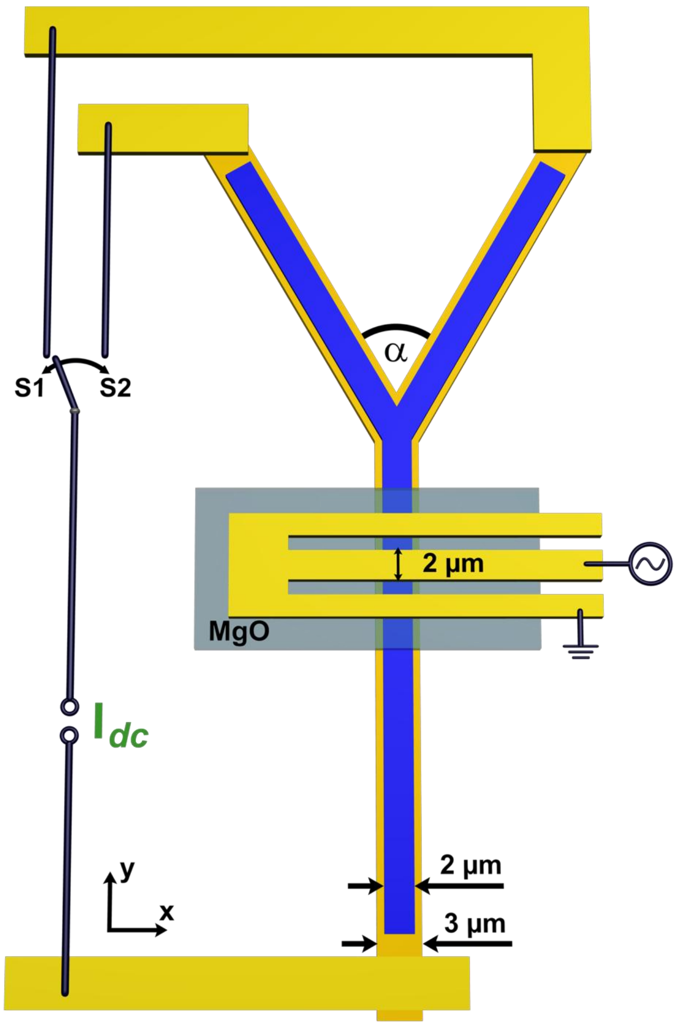
Wave Vector Dependence





Spin-Wave Multiplexer

Sample Design



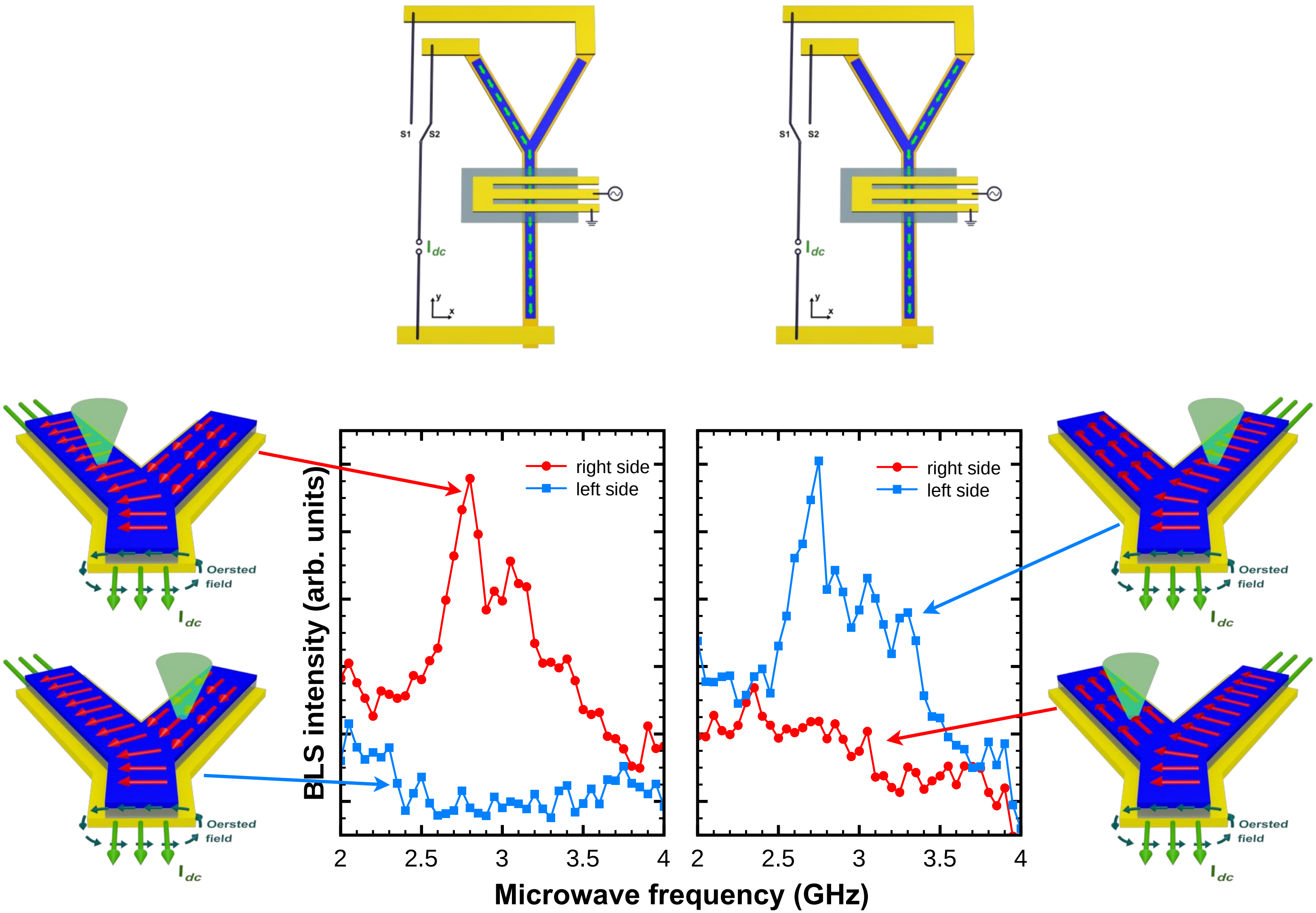
General Idea:

- use electric current (**one input**) to switch spin-wave propagation between two arms of a Y-structure (**two outputs**)

Sample Geometry:

- 2 µm wide and 30 nm thick spin-wave conduit made from Py
- 3 µm wide and 50 nm thick Au line insulated with 50 nm MgO from Py
- angles of 30°, 60° and 90°

Spin-Wave Multiplexer

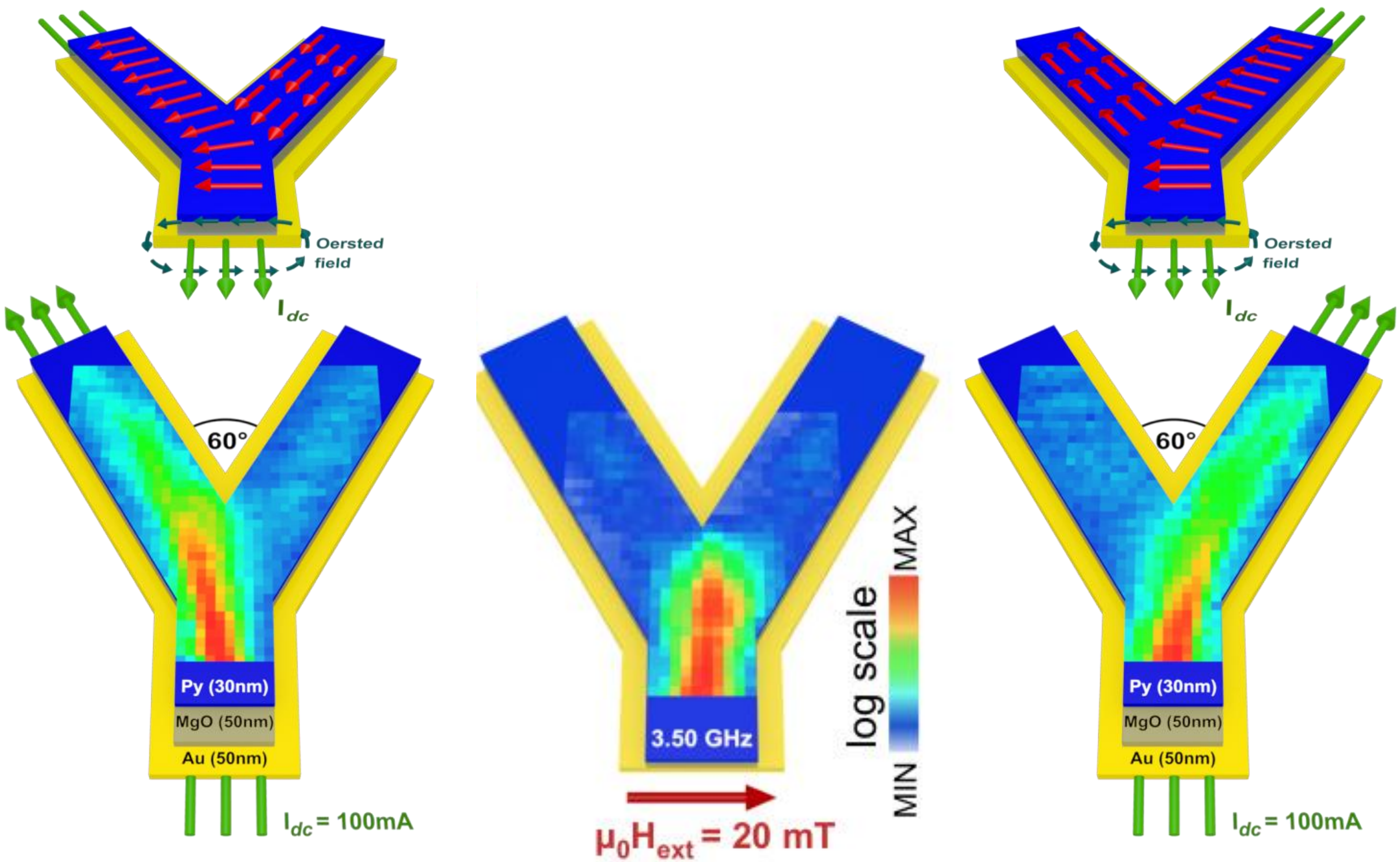


Axel Hoffmann, MSD, Argonne National Laboratory hoffmann@anl.gov

Spin-Wave Multiplexer

Electric Current in Left Arm

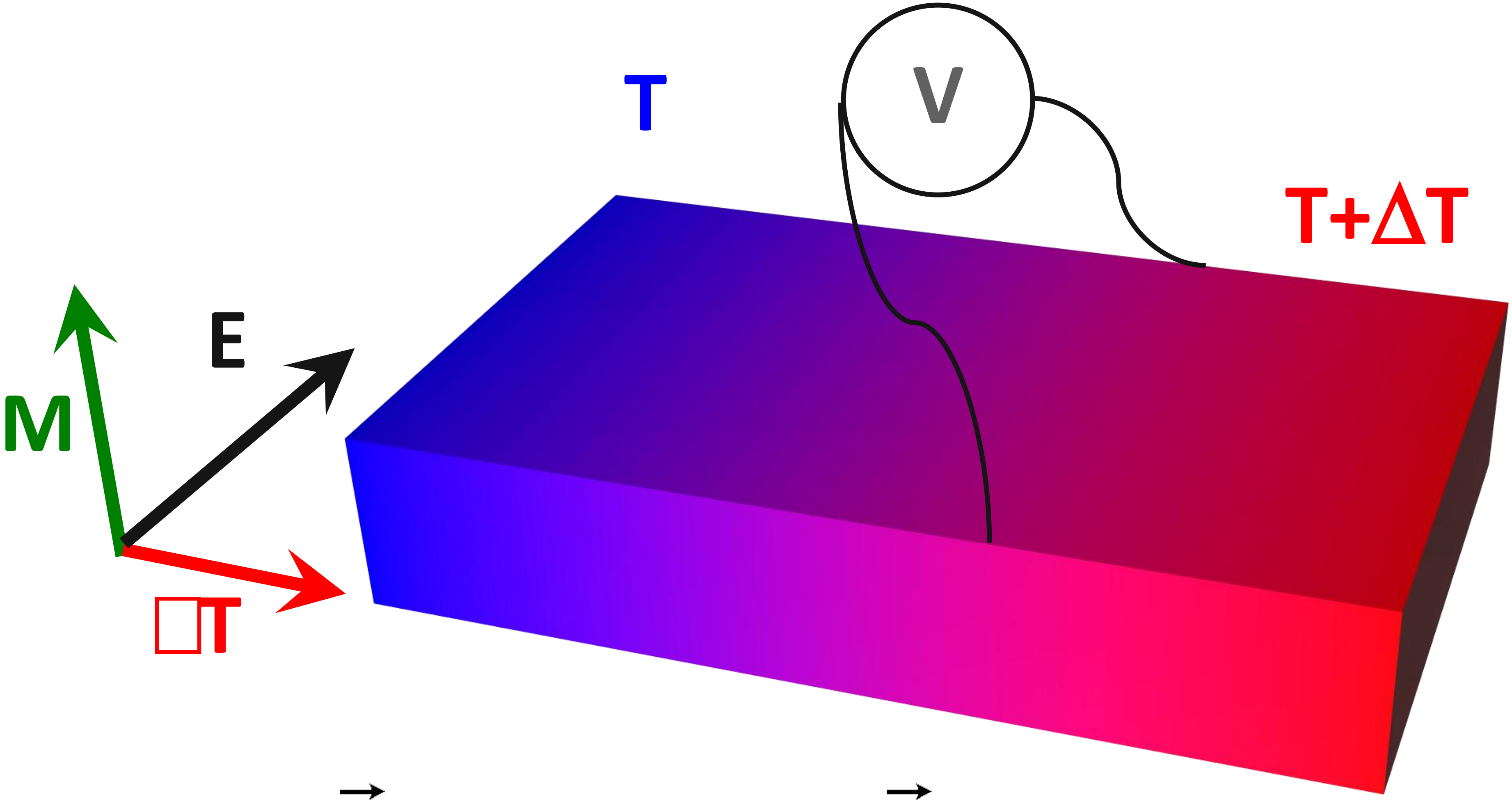
Electric Current in Right Arm



⇨ **Spin waves only propagate in arm where electric current is flowing**

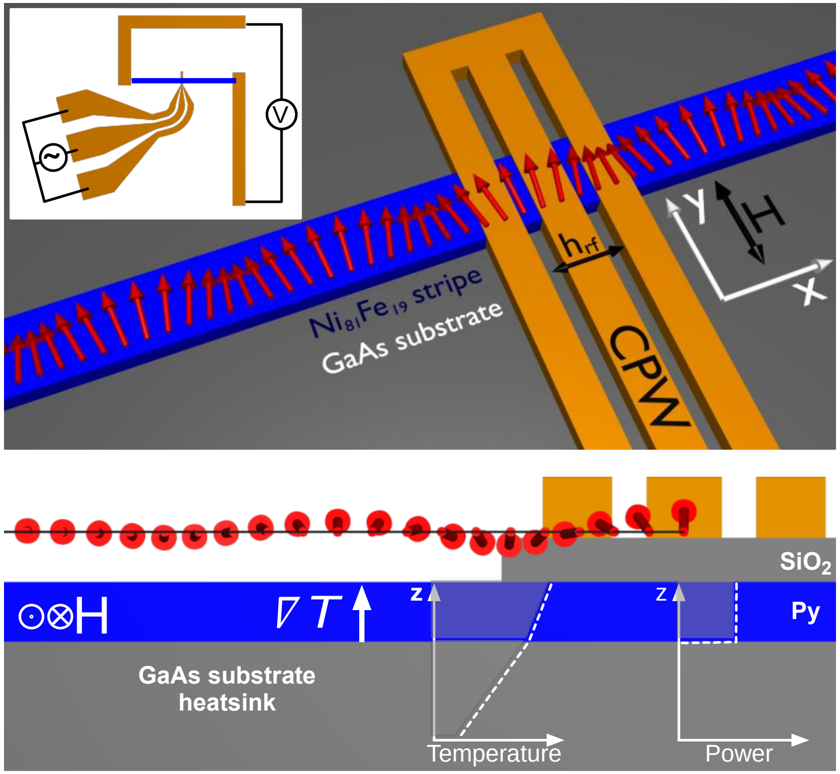
Thermoelectric Detection of Spin Waves

Anomalous Nernst Effect

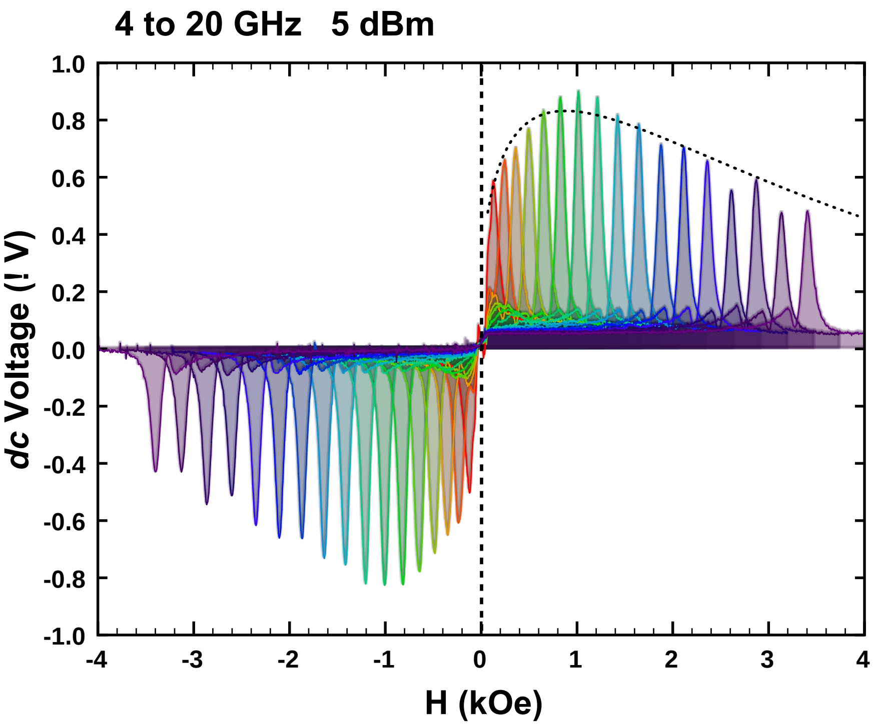


$$\vec{E}_{ANE} = -N m_0 \vec{M} \times \nabla T$$

Damping of Spin Waves Generates Heat



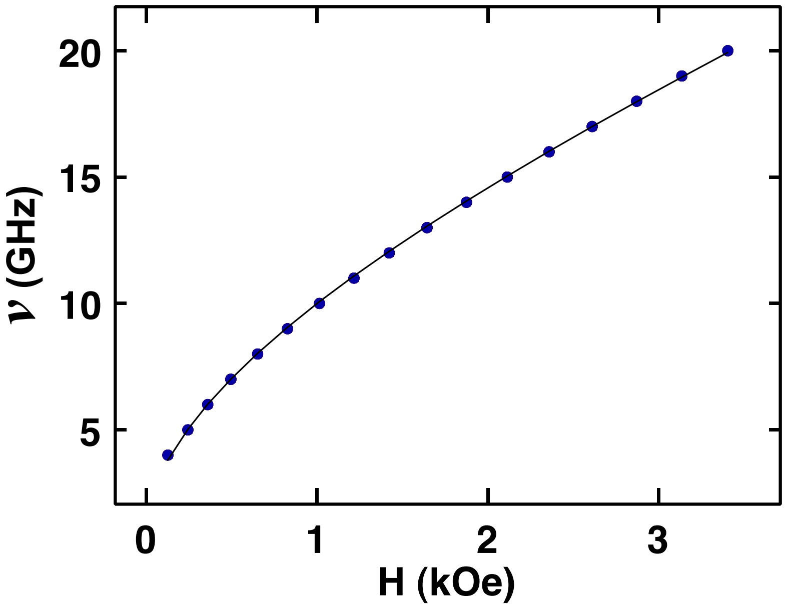
H. Schultheiss *et al.*, Phys. Rev. Lett. **109**, 237204 (2012)



- Dissipated Energy increases with ω
- Losses at higher ω due to impedance mismatch

Damping of Spin Waves Generates Heat

Peak position follows Kittel equation

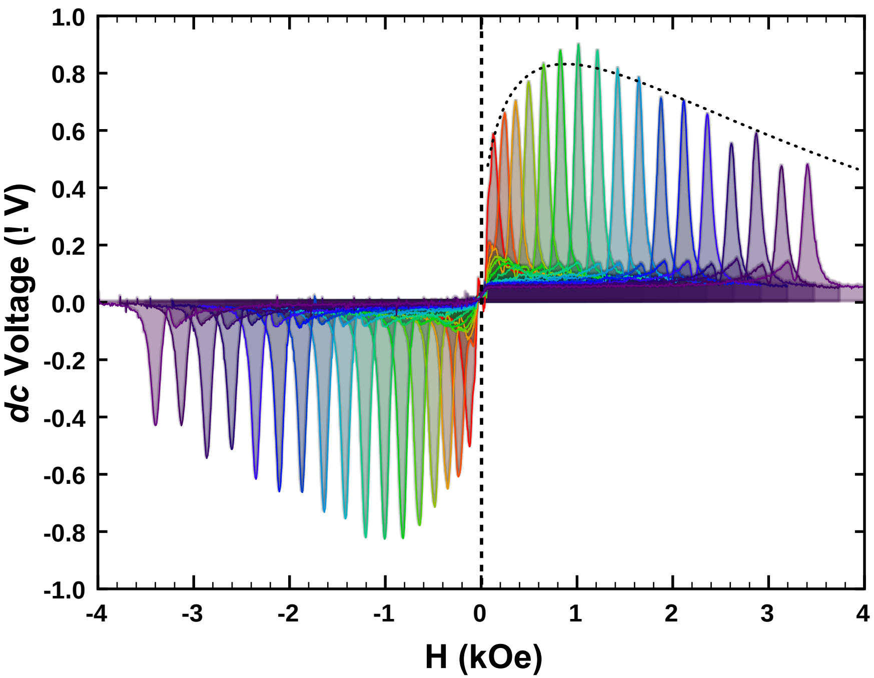


$$\nu^2 = \left(\frac{\gamma}{2\pi}\right)^2 [H - (N_x - N_y)M_s][H - (N_x - N_z)M_s]$$

M_s = 905 kA/m

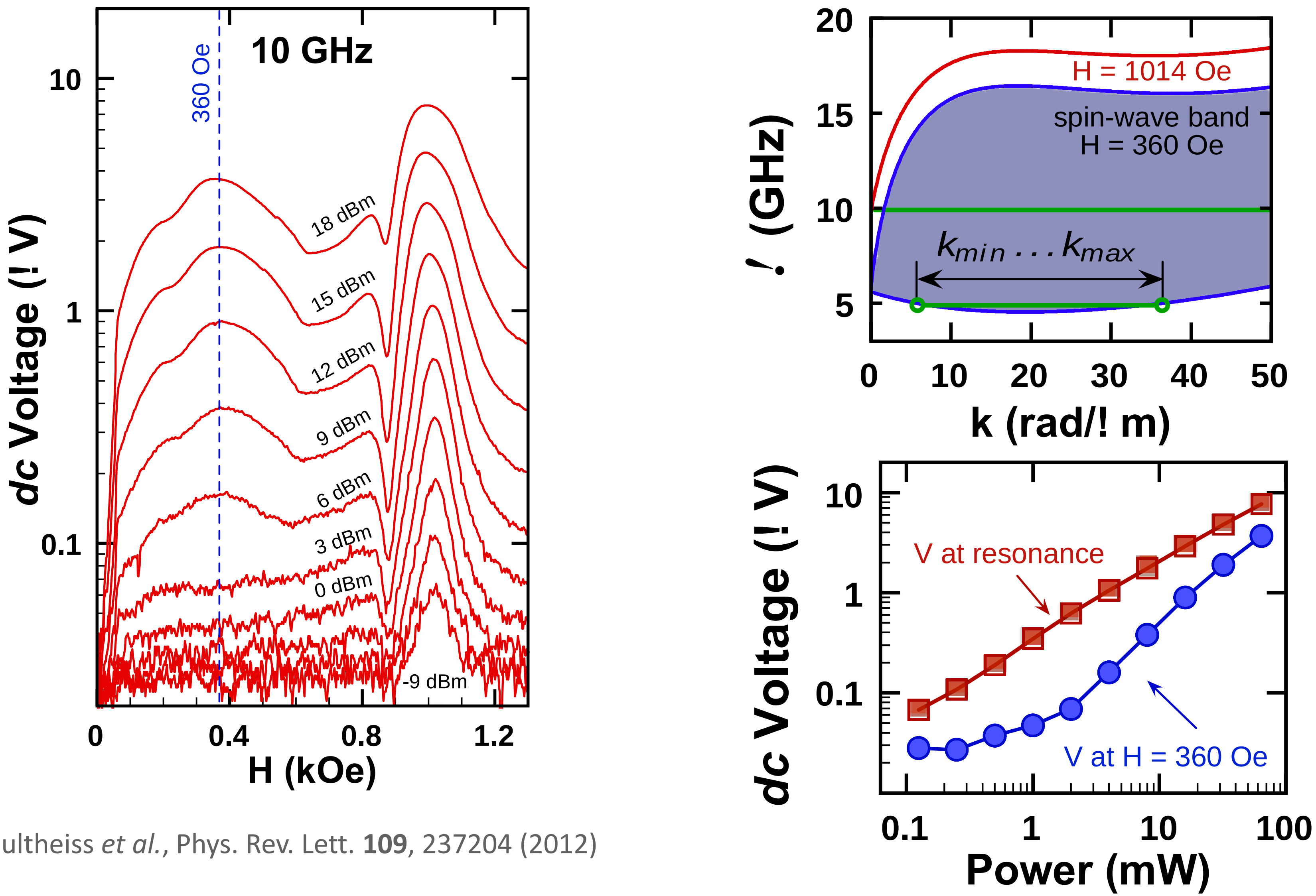
H. Schultheiss *et al.*, Phys. Rev. Lett. **109**, 237204 (2012)

4 to 20 GHz 5 dBm



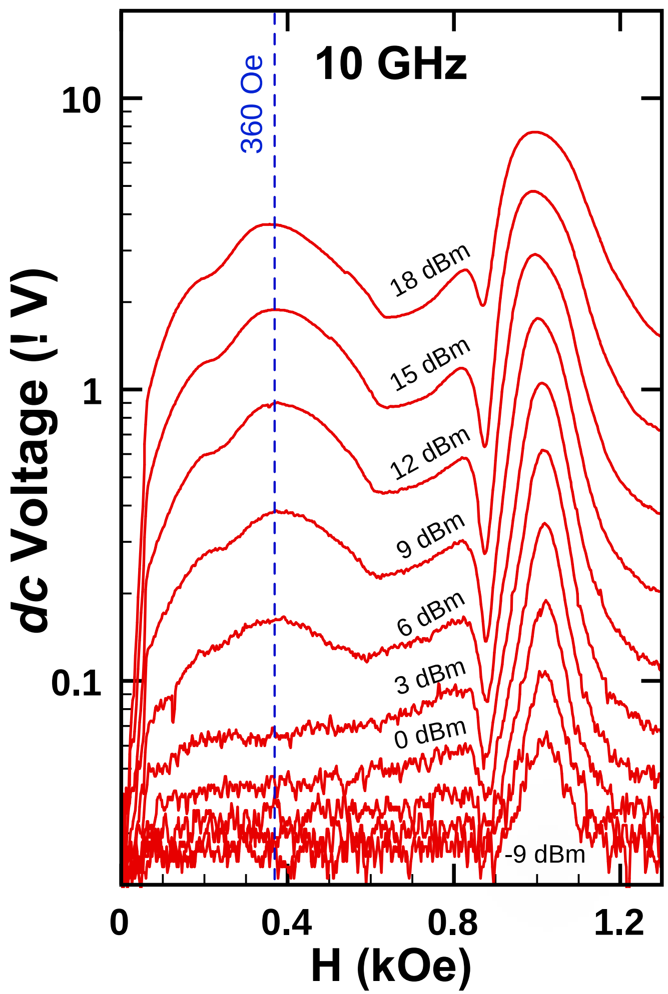
- Dissipated Energy increases with ω
- Losses at higher ω due to impedance mismatch

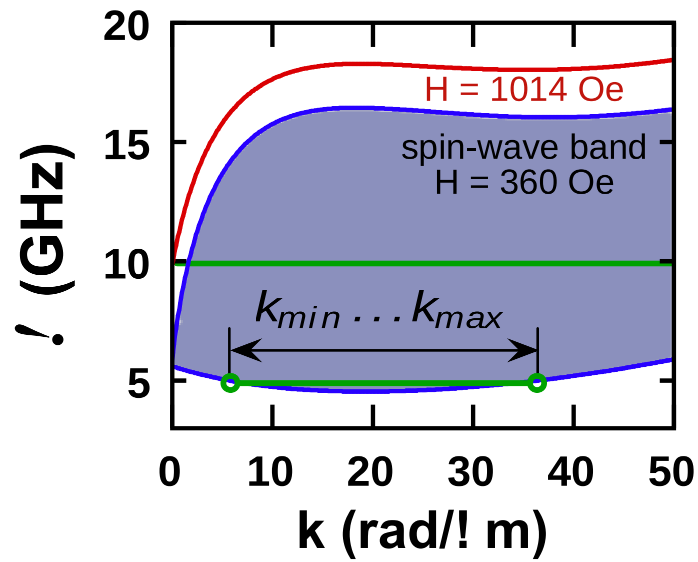
Allows Detection of nano-Spin Waves



H. Schultheiss *et al.*, Phys. Rev. Lett. **109**, 237204 (2012)

Allows Detection of nano-Spin Waves





- 100 Oe corresponds to a minimum wavelength of 125 nm!
- Detection is practically independent of wavelength

H. Schultheiss *et al.*, Phys. Rev. Lett. **109**, 237204 (2012)

Thanks to

Wei, Zhang, John E. Pearson,
Frank Y. Fradin, and Sam D. Bader
Argonne National Laboratory

Oleksandr Mosendz, Shikha Jain
HGST a Western Digital Company

Vincent Vlaminck
Universidad San Francisco de Quito

Gerrit E. W. Bauer
Delft University of Technology and
Tohoku University

Helmut Schultheiß
Helmholtz-Zentrum
Dresden-Rossendorf

Katrin Vogt, Thomas Sebastian,
and Burkard Hillebrands
Technische Universität
Kaiserslautern

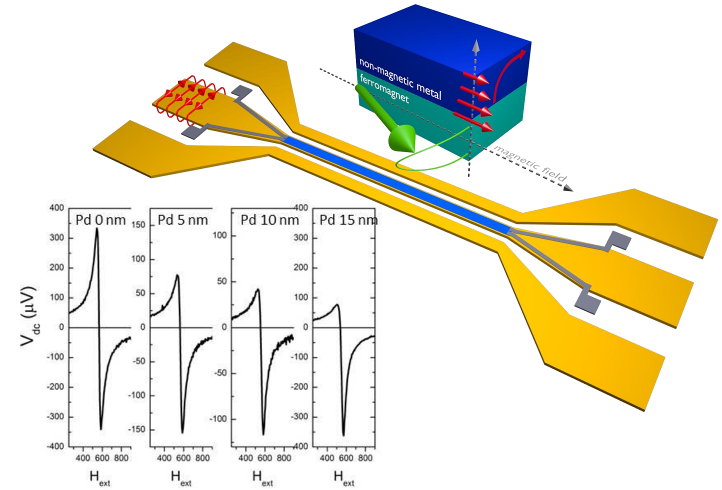
Sebastian Gliga
ETH Zürich

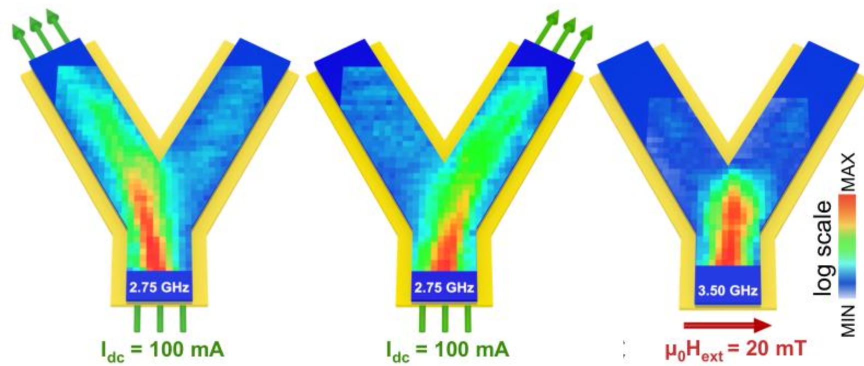
Financial Support

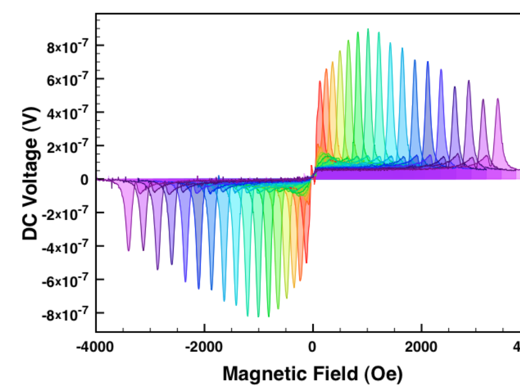
DOE-BES

Conclusions

- Spin Hall Effects
  - Converts charge into spin currents and enables spin injection into insulators
  - Spin Diffusion Lengths
    - Pd: 5.5 nm; Pt: 1.2 nm; Ir: ≈0.5 nm
  - See only small effects with Ta
- Spin Waves
  - Can be guided around corners by Oersted fields
- Thermoelectric Detection of Spin Waves
  - Damping of spin waves results in *dc* voltages
  - Enables detection of very short wavelengths







58th Conference on Magnetism and Magnetic Materials

Dates

Nov 4-8, 2013

Location

Sheraton Denver Downtown
Denver, Colorado

Chairs

Conference: Axel Hoffmann
hoffmann@anl.gov

Program: Andrew Kent
andy.kent@nyu.edu
Suzanne te Velthuis
tevelthuis@anl.gov

58
Denver 2013

AIP
American Institute of Physics

IEEE