Coherent sub-THz Spin Pumping from an Insulating Antiferromagnet

*Vaidya et al. Science **368**, 160–165 (2020)*

Enrique del Barco
Department of Physics – UCF Orlando

delBarco LAB
Nanomagnetism and Spintronics

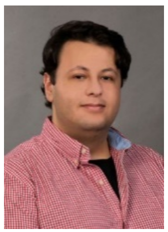
Work done in collaboration with:

David Lederman (University of California – Santa Cruz)
Ran Cheng (University of California – Riverside)
Arne Brataas (Norwegian University of Science and Technology)
Hans van Tol (National High Magnetic Field Laboratory / NHMFL – Tallahassee/FL)


College of Sciences
53 attoseconds
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FSU • UF • LANL
UCF
ORLANDO
NASA

www.delbarcolab.com

delBarco LAB
Nanomagnetism and Spintronics


Justin Zakhary

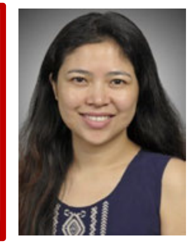

Ran Liu

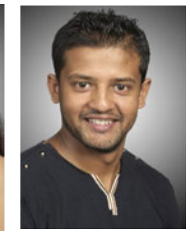

Cameron Nickle

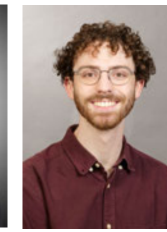

Francis Adoah


Yan Liu

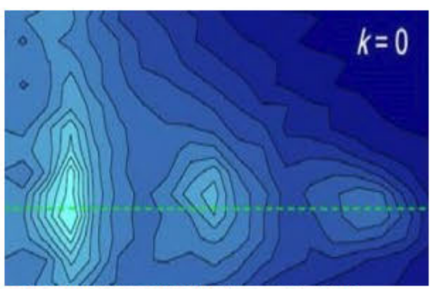

Jaesuk Kwon


Priyanka Vaidya


Gyan Khatri

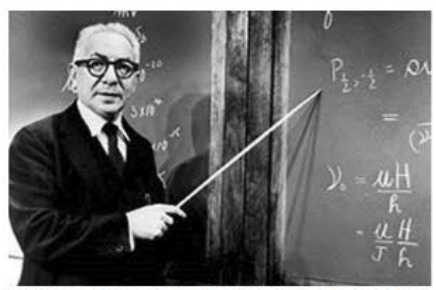

Greg Fritjofson

MOLECULAR MAGNETISM – QUANTUM DYNAMICS OF SPIN



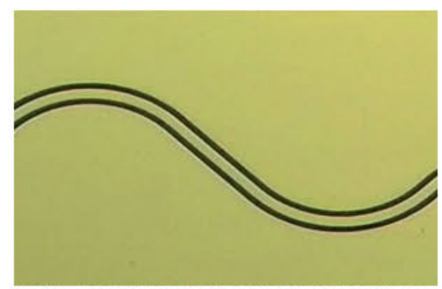
QUANTUM TUNNELING OF SPIN

Low-nuclearity molecules allow for a full numerical treatment of the multi-spin Hamiltonian, where degrees of freedom associated with the individual ions can be adequately tested.



RABI OSCILLATIONS IN ANISOTROPIC SPINS

The commutation between spin anisotropy operators leads to complex dynamics where the magnetic state of the molecule may develop excited precessional states.



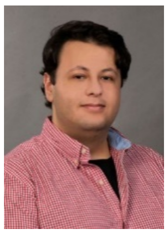
SPIN QUANTUM ELECTRODYNAMICS

High-Q superconducting resonators designed with nano-constrictions may allow the coupling a photon cavity mode with a single molecular spin.

www.delbarcolab.com

delBarco LAB

Nanomagnetism and Spintronics



Justin Zakhary

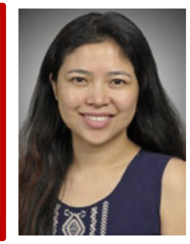
Ran Liu

Cameron Nickle

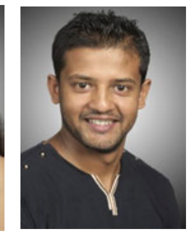
Francis Adoah

Yan Liu

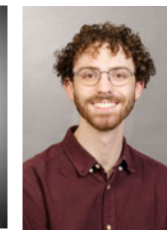
Jaesuk Kwon



Priyanka Vaidya

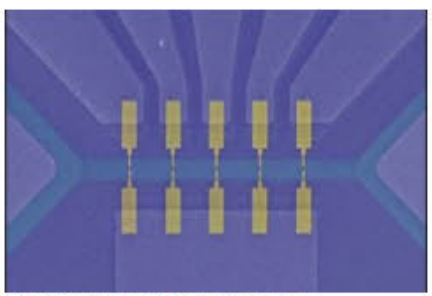


Gyan Khatri



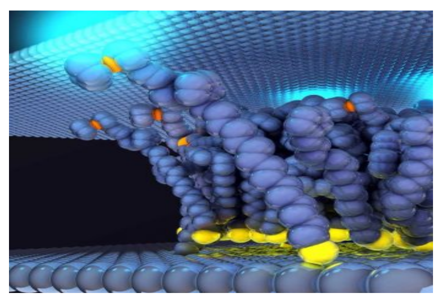
Greg Fritjofson

MOLECULAR ELECTRONICS – SINGLE-MOLECULE TUNNEL JUNCTIONS



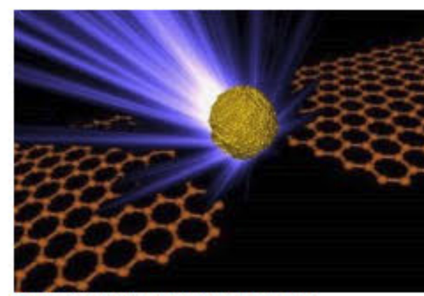
SINGLE-ELECTRON TRANSISTORS

Fabrication of electromigration-broken three-terminal single-electron transistors for transport spectroscopy at the individual molecule level.



CHARGE RECTIFICATION IN MOLECULAR TRANSISTORS

Study of charge rectification in tunnel junctions bridged by molecular chains including a ferrocene active conductive unit placed asymmetrically within the chain.



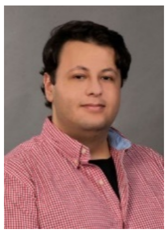
OPTOELECTRONICS AT THE NANOSCALE

Study of the transport properties of individual noble-metal nanoparticles in the presence of optical irradiation inducing plasmonic resonance.

www.delbarcolab.com

delBarco LAB

Nanomagnetism and Spintronics


Justin Zakhary

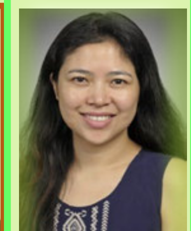

Ran Liu

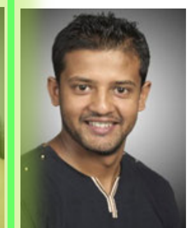

Cameron Nickle

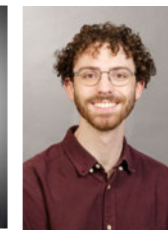

Francis Adoah


Yan Liu

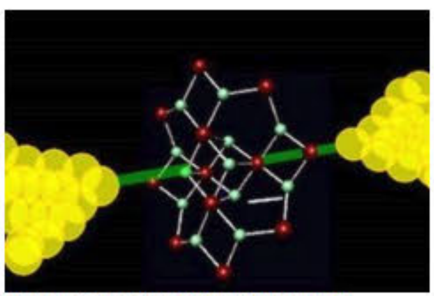

Jaesuk Kwon


Priyanka Vaidya


Gyan Khatri

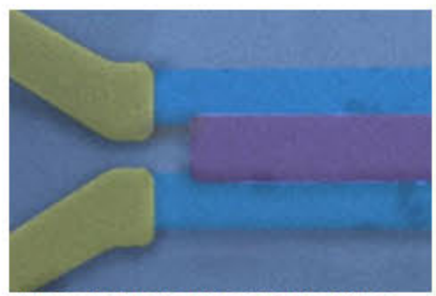

Greg Fritjofson

NANOSCALE SPINTRONICS – 0D, 2D and 3D SPIN TRANSPORT



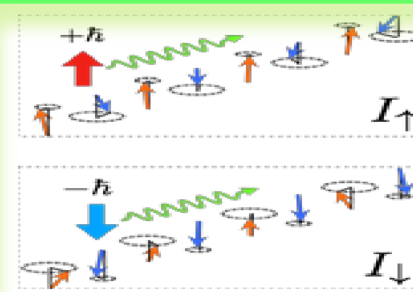
SINGLE-ELECTRON TRANSPORT THROUGH MOLECULAR MAGNETS

Investigation of the interplay between high-spin states of an individual SMM and conduction electrons in a three-terminal single-electron transistor.



TWO-DIMENSIONAL SPINTRONICS

An study aimed at understanding and controlling the injection of pure spin currents in graphene-based spintronics devices.



ANTIFERROMAGNETIC SPINTRONICS

Terahertz spintronics with antiferromagnetic insulators.

Spin Pumping from AFM Insulator MnF_2

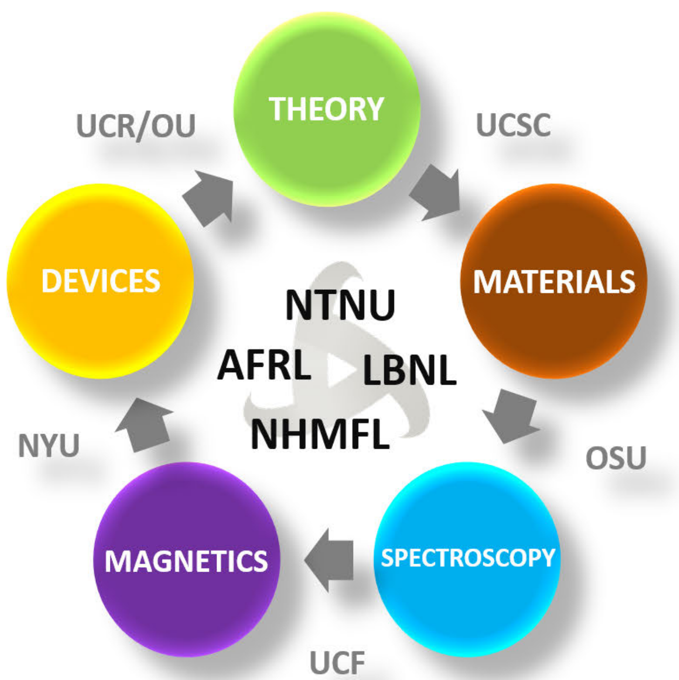
Terahertz Spintronics with Antiferromagnetic Insulators

delBarco LAB
Nanomagnetism and Spintronics

Collaborative Effort – Spintronics with AFM insulators

AFOSR

MURI TEAM



Experiment:

PI-Enrique del Barco (UCF)
PI-Chris Hammel (OSU)
PI-Andrew Kent (NYU)
C-Hans van Tol (NHMFL)
C-Simranjeet Singh (CMU)
C-Robert Peale (UCF)
C-Michael Chini (UCF)

Materials:

PI-David Lederman (UCSC)
PI-Fengyuan Yang (OSU)
C-Michael Page (AFRL)
C-Madhab Neupane (UCF)
C-Hendrik Ohldag (LBNL)

Theory:

PI-Ran Cheng (UCR)
PI-Andrei Slavin (OU)
C-Arne Brataas (NTNU–Norway)

Spin Pumping from AFM Insulator MnF_2

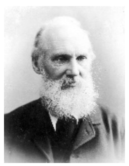
Terahertz Spintronics with Antiferromagnetic Insulators

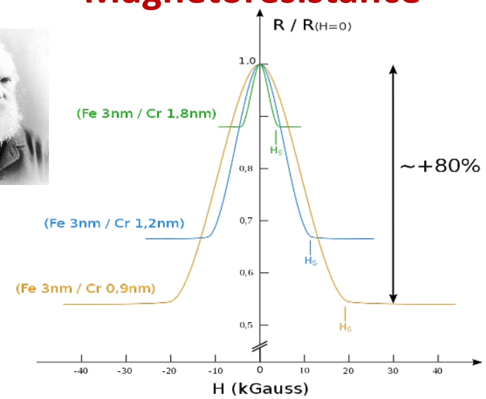
delBarcoLAB Nanomagnetism and Spintronics

What AFM materials have to offer in spintronics?

Ferromagnetic spintronics / STT–based MRAM

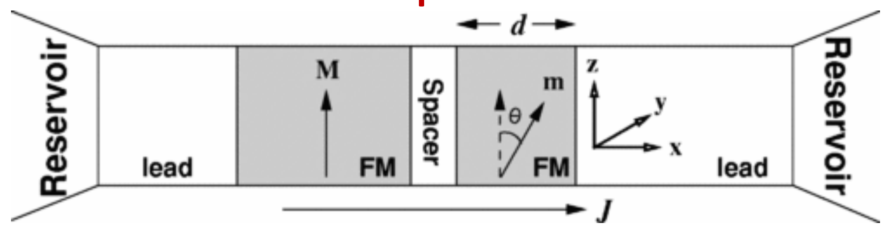
Magnetoresistance



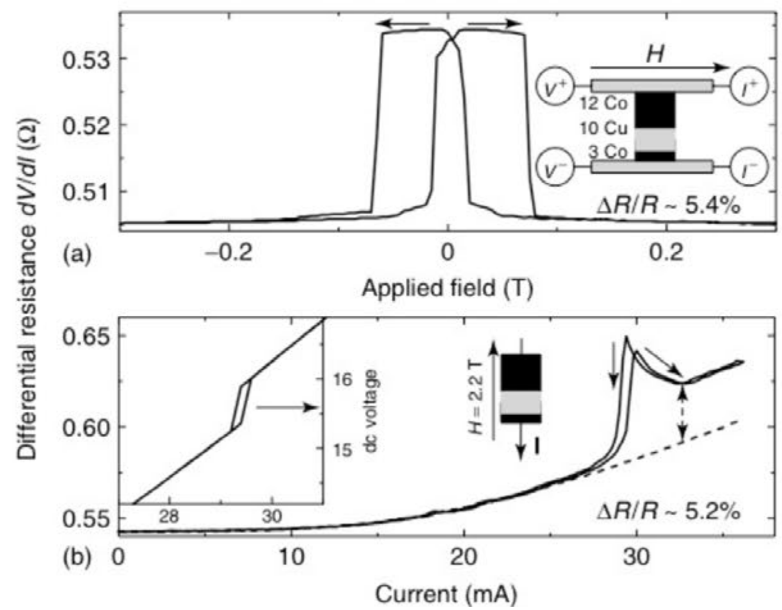


W. Thompson-5% (1856) 2007 Noble Prize: Fert-Grünberg-80% (1988)

STT spin valve

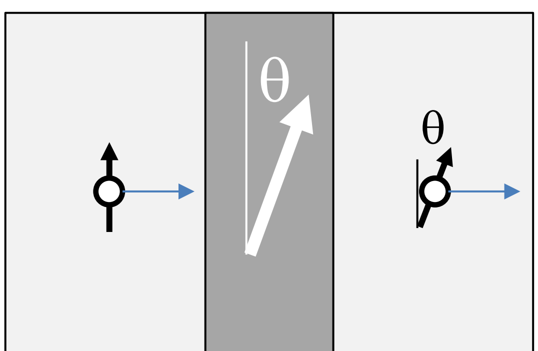


Jiang Xiao, A. Zangwill, and M. D. Stiles. PRB (2005)



Ozylmaz, Kent, Monsma, Sun, Rooks, and Koch. PRL (2003)

Spin Transfer Torque



Slonczewski (1989), (1996) and Berger (1996)

Spin Pumping from AFM Insulator MnF_2

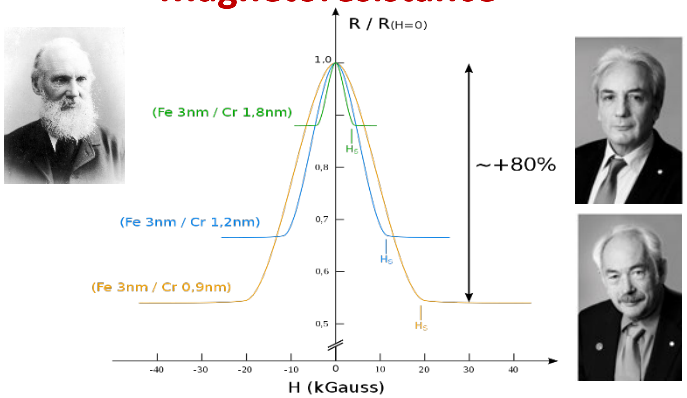
Terahertz Spintronics with Antiferromagnetic Insulators

delBarco LAB Nanomagnetism and Spintronics

What AFM materials have to offer in spintronics?

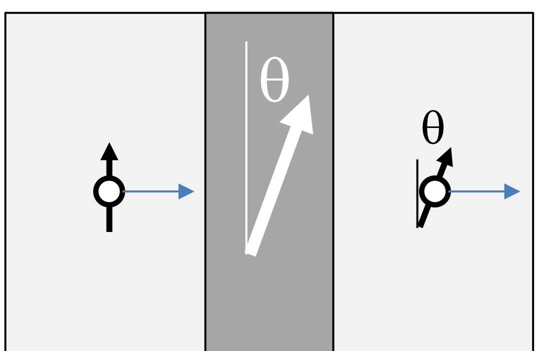
Ferromagnetic spintronics / STT–based GHz oscillator

Magnetoresistance

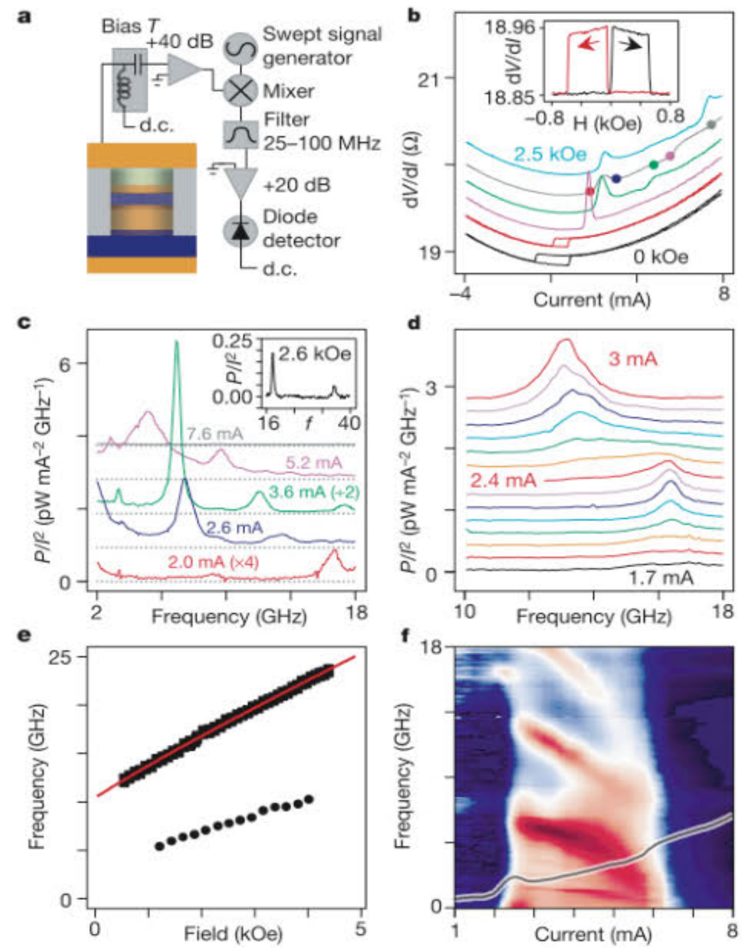


W. Thompson-5% (1856) 2007 Noble Prize: Fert-Grünberg-80% (1988)

Spin Transfer Torque



Slonczewski (1989), (1996) and Berger (1996)



Kiselev et al. Nature (2003)

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

- ✓ f = 0.3-3 THz
  Operation in the THz gap

- ✓ No stray fields / No cross-talk
- ✓ nm-scale magnon waves
  Miniaturization of magnonic circuits

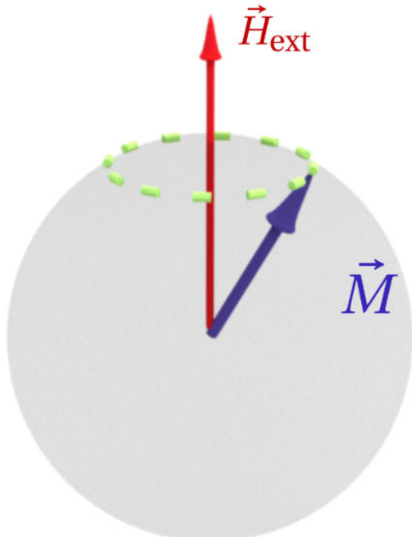
- ✓ Group velocity of magnons $\propto \sqrt{f}$
  Faster data transmission rates

- ✓ High frequency / Short Times
  Fast operations (picoseconds)

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?



$$H_{ext} \approx 1\mathrm{T}$$

$$\omega_{FMR} = \gamma\sqrt{H_{ext} H_{dip}} \approx 1 - 20\,\mathrm{GHz}$$

Ferromagnet

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

delBarcoLAB Nanomagnetism and Spintronics

What AFM materials have to offer in spintronics?

TUNABLE AFM OSCILLATOR

Cheng et al. PRL 2016 / Khymyn et al. Sci. Rep. (2017)

damping — Spin torque

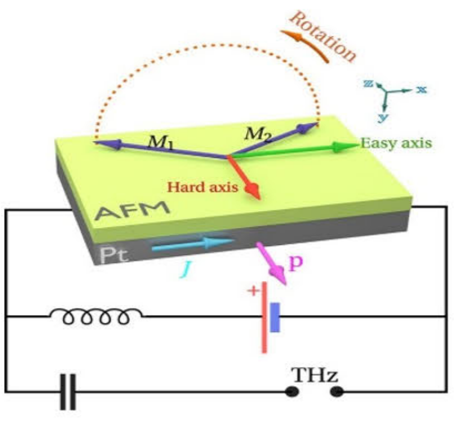
$$d\mathbf{M}_1/dt = \gamma[\mathbf{H}_1 \times \mathbf{M}_1] + \frac{\alpha}{M_s}[\mathbf{M}_1 \times d\mathbf{M}_1/dt] + \frac{\tau}{M_s}[\mathbf{M}_1 \times [\mathbf{M}_1 \times \boldsymbol{p}]],$$

$$d\mathbf{M}_2/dt = \gamma[\mathbf{H}_2 \times \mathbf{M}_2] + \frac{\alpha}{M_s}[\mathbf{M}_2 \times d\mathbf{M}_2/dt] + \frac{\tau}{M_s}[\mathbf{M}_2 \times [\mathbf{M}_2 \times \boldsymbol{p}]]$$

$$\mathbf{H}_1 = \frac{1}{M_s}\left[-\frac{1}{2}H_{\mathrm{ex}}\mathbf{M}_2 + H_h\mathbf{n}_h(\mathbf{n}_h \cdot \mathbf{M}_1) - H_e\mathbf{n}_e(\mathbf{n}_e \cdot \mathbf{M}_1)\right]$$

$$\mathbf{H}_2 = \frac{1}{M_s}\left[-\frac{1}{2}H_{\mathrm{ex}}\mathbf{M}_1 + H_h\mathbf{n}_h(\mathbf{n}_h \cdot \mathbf{M}_2) - H_e\mathbf{n}_e(\mathbf{n}_e \cdot \mathbf{M}_2)\right]$$

exchange — biaxial anisotropy



Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

TUNABLE AFM OSCILLATOR

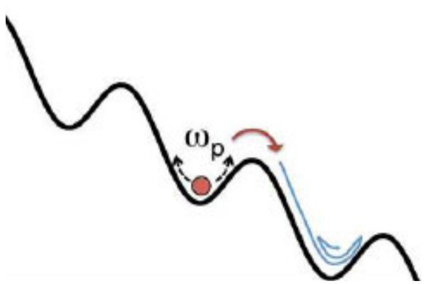
Cheng et al. PRL 2016 / Khymyn et al. Sci. Rep. (2017)

$$\vec{l} = \frac{M_1 - M_2}{2M_s} = \vec{x}\cos\phi(t) + \vec{y}\sin\phi(t)$$

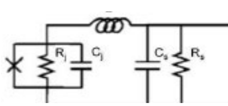
$$\underbrace{\frac{1}{\omega_{ex}}\ddot{\phi}}_{\text{exchange}} + \underbrace{\alpha\dot{\phi}}_{\text{damping}} + \underbrace{\frac{\omega_e}{2}\sin 2\phi}_{\text{anisotropy}} = \underbrace{\sigma j}_{\text{Spin torque}}$$

exchange (inertia=«mass») **damping** **anisotropy** **Spin torque**

Tilted washboard potential

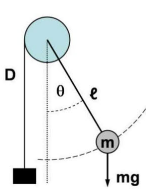


RC Joshepson Junction

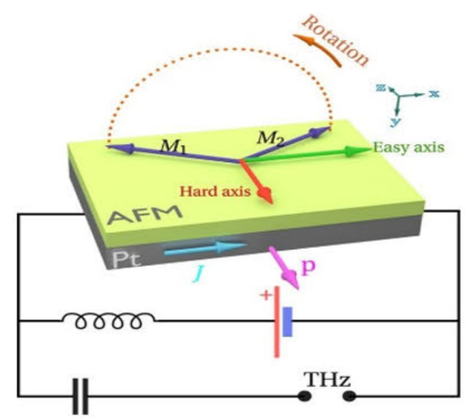


$$\ddot{\phi} + \frac{1}{RC}\dot{\phi} + \omega_J^2 \sin\phi = \omega_J^2 \gamma$$

Torqued pendulum



$$\Theta\ddot{\theta} + \Gamma\dot{\theta} + mg\ell\sin\theta = D$$



Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

TUNABLE AFM OSCILLATOR

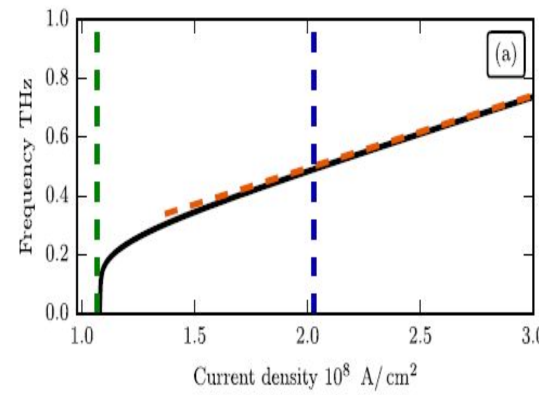
Cheng et al. PRL 2016 / Khymyn et al. Sci. Rep. (2017)

Super-critical regime: Driven dynamics

(above a threshold current)

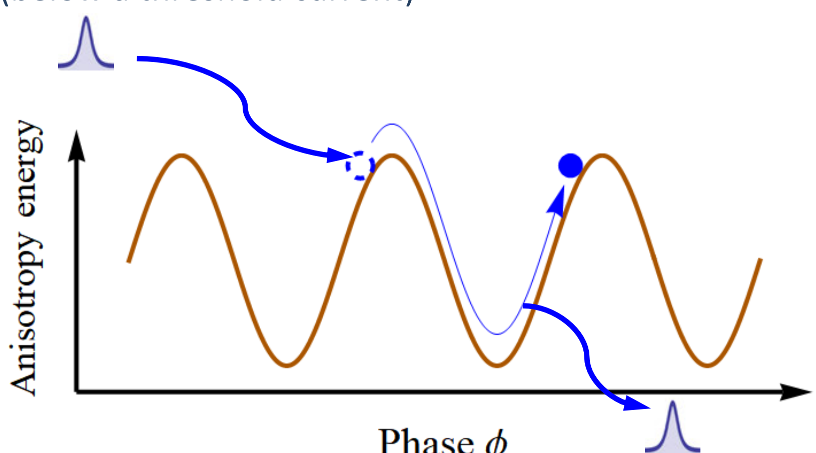
$$j_1^{th} = \frac{\omega_e}{2\sigma}.$$

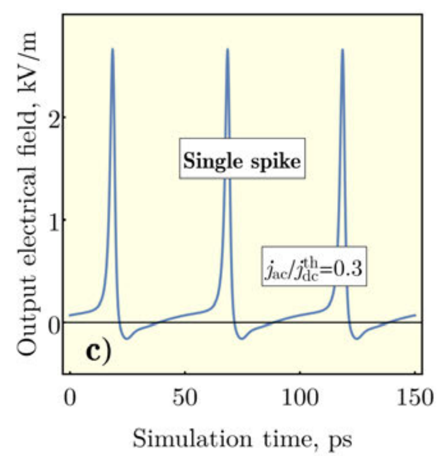
$$\dot{\phi}(t) \approx \frac{\omega_{gen}}{2} + \frac{\omega_e \omega_{ex}}{4\sqrt{\alpha^2 \omega_{ex}^2 + \omega_{gen}^2}} \cos \omega_{gen} t$$



Sub-critical regime: Inertial dynamics

(below a threshold current)





Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Nanomagnetism and Spintronics

What AFM materials have to offer in spintronics?

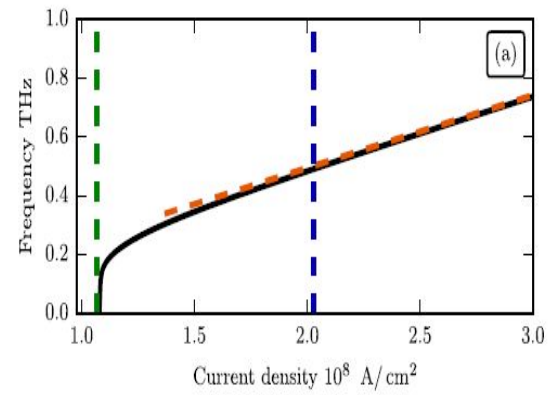
TUNABLE AFM OSCILLATOR

Cheng et al. PRL 2016 / Khymyn et al. Sci. Rep. (2017)

Super-critical regime: Driven dynamics
(above a threshold current)

$$j_1^{\text{th}} = \frac{\omega_e}{2\sigma}.$$

$$\dot{\phi}(t) \approx \frac{\omega_{\text{gen}}}{2} + \frac{\omega_e \omega_{\text{ex}}}{4\sqrt{\alpha^2 \omega_{\text{ex}}^2 + \omega_{\text{gen}}^2}} \cos \omega_{\text{gen}} t$$



CONDITIONS

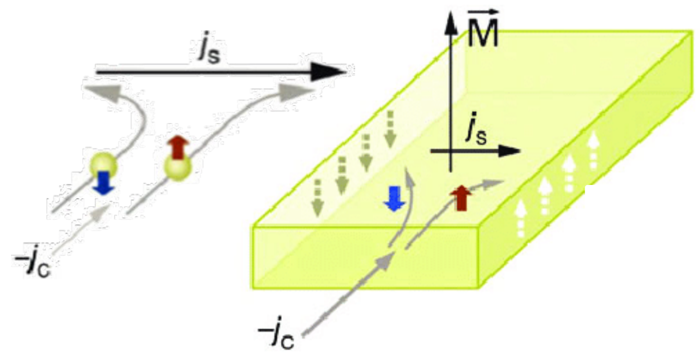
- **Single domain AFM**
- **Very specific magnetic anisotropy and AFM/NM device configuration**
- **Low anisotropy**
- **Efficient spin injection – Spin transfer torque**
  (Threshold charge current in Pt/NiO > 10^8 A/cm^2)

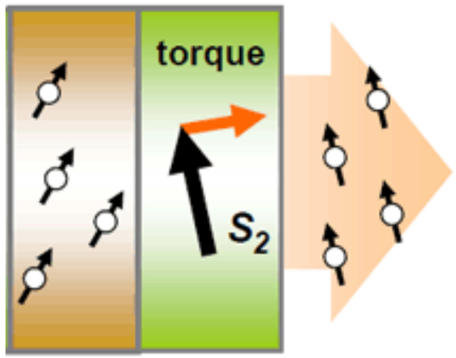
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

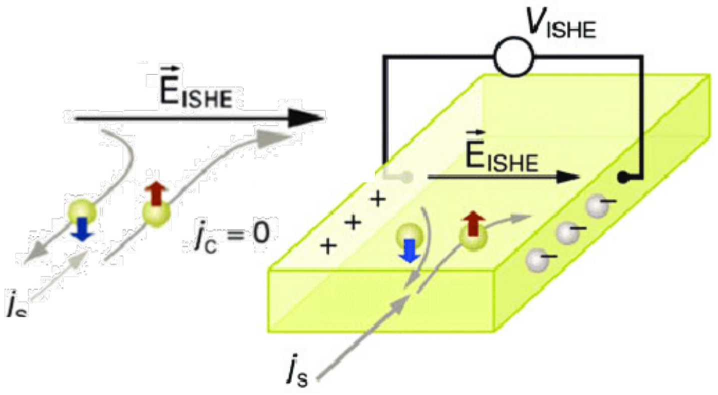
Spin-Charge interconversion with AFMs

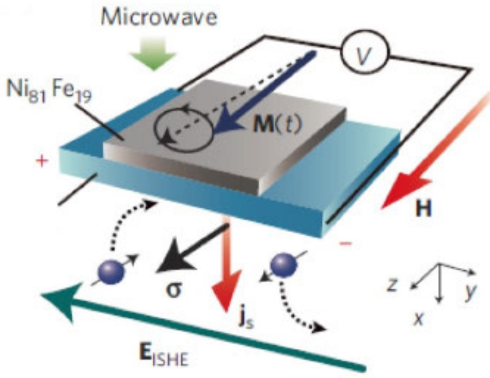
Spin Hall Effect (SHE) + Spin Transfer Torque (STT)





Inverse Spin Hall Effect (ISHE) + Dynamical Spin Pumping (DSP)





Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Magnetization dynamics in a uniaxial antiferromagnet (*e.g.*, MnF_2)

Free energy (macrospin)

$$F = \hbar\omega_E \mathbf{m}_1 \cdot \mathbf{m}_2 - \hbar\omega_H \mathbf{e}_z \cdot (\mathbf{m}_1 + \mathbf{m}_2) - \tfrac{1}{2}\hbar\omega_A \left[(\mathbf{m}_1 \cdot \mathbf{e}_z)^2 + (\mathbf{m}_2 \cdot \mathbf{e}_z)^2 \right]$$

exchange — magnetic field — anisotropy

Equations of motion

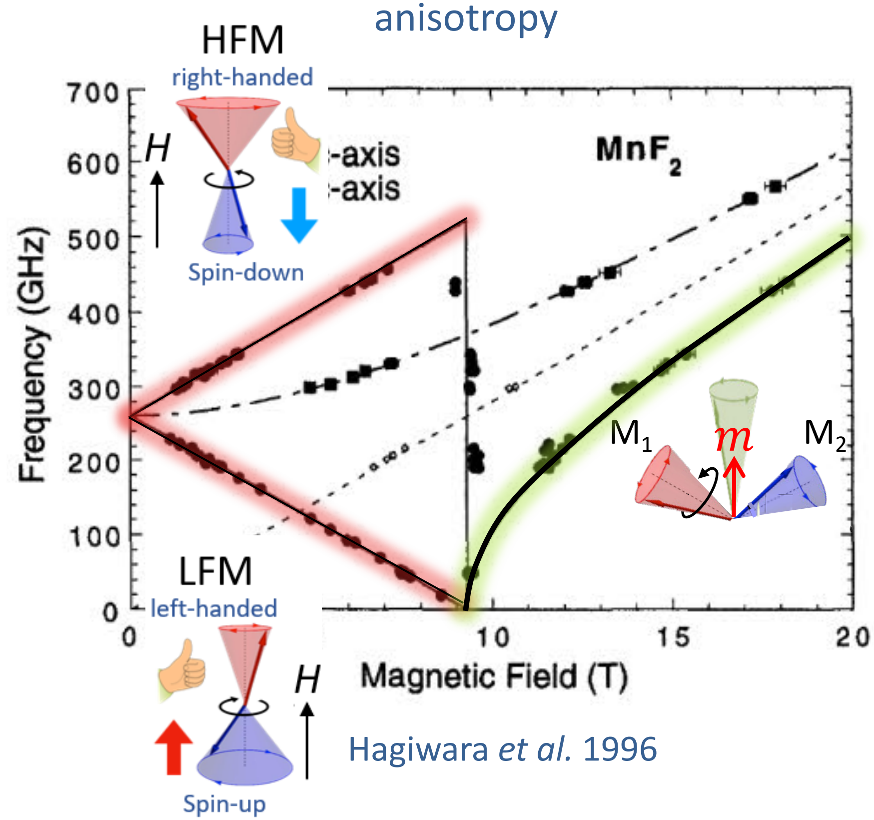
$$\dot{\mathbf{m}}_1 = \mathbf{m}_1 \times \left[-\omega_E \mathbf{m}_2 + \omega_H \mathbf{e}_z - \omega_A \mathbf{e}_z (\mathbf{m}_1 \cdot \mathbf{e}_z) \right]$$

$$\dot{\mathbf{m}}_2 = \mathbf{m}_1 \times \left[-\omega_E \mathbf{m}_1 + \omega_H \mathbf{e}_z - \omega_A \mathbf{e}_z (\mathbf{m}_2 \cdot \mathbf{e}_z) \right]$$

Resonance frequency

$$\omega_{res} = \gamma\mu_0 \sqrt{H_A(2H_E + H_A)} \pm \gamma\mu_0 H$$

$$\omega_{res} = \gamma\mu_0 \sqrt{H^2 - 2H_E H_A}$$



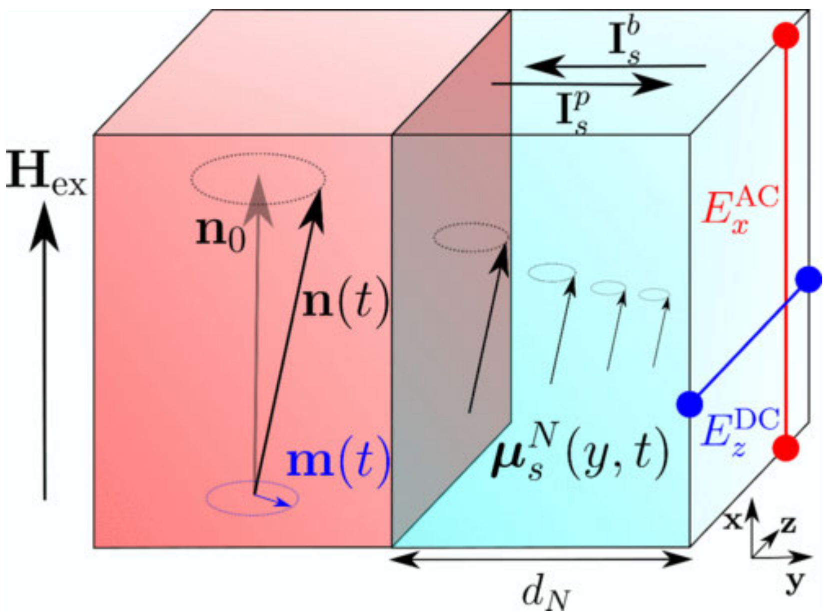
Hagiwara *et al.* 1996

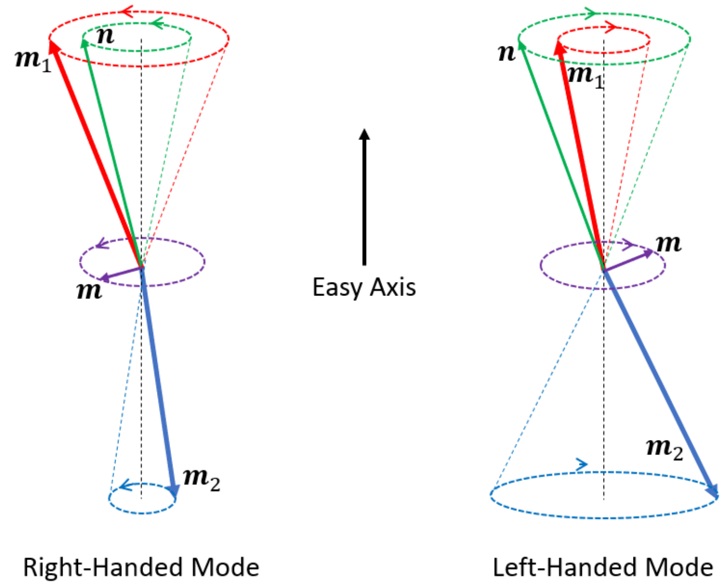
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

Cheng/Braatas PRL 113, 057601 (2014)





$$I_s \propto \mathbf{m}_1 \times \dot{\mathbf{m}}_1 + \mathbf{m}_2 \times \dot{\mathbf{m}}_2$$

$$\mathbf{m}_1 = -\mathbf{m}_2$$
$$\dot{\mathbf{m}}_1 \sim -\dot{\mathbf{m}}_2$$

$$\boldsymbol{n} = \frac{(\boldsymbol{m}_1 - \boldsymbol{m}_2)}{2}$$

Staggered Magnetization

$$I_s \propto \boldsymbol{n} \times \dot{\boldsymbol{n}}$$

$$\boldsymbol{m} = \frac{(\boldsymbol{m}_1 + \boldsymbol{m}_2)}{2}$$

Net Magnetization

$$I_s \propto \boldsymbol{m} \times \dot{\boldsymbol{m}}$$

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

Cheng/Braatas PRL 113, 057601 (2014)

$$F = \hbar\omega_E \mathbf{m}_1 \cdot \mathbf{m}_2 - \hbar\omega_H \mathbf{e}_z \cdot (\mathbf{m}_1 + \mathbf{m}_2) - \tfrac{1}{2}\hbar\omega_A\left[(\mathbf{m}_1\cdot\mathbf{e}_z)^2 + (\mathbf{m}_2\cdot\mathbf{e}_z)^2\right] + \delta F$$

a.c. field

$$\delta F = (\mathbf{m}_1 + \mathbf{m}_2)\cdot\left[\omega_{Hx}\mathbf{e}_x\cos(\omega t + \theta_x) + \omega_{Hy}\mathbf{e}_y\cos(\omega t + \theta_y)\right]$$

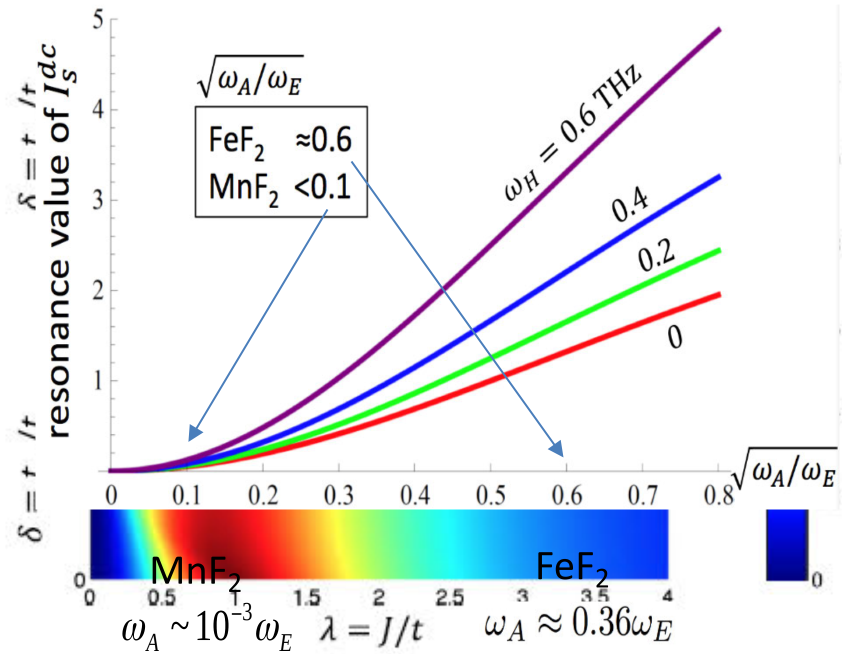
$$\frac{e}{\hbar}\boldsymbol{I}_s = G_r(\boldsymbol{n}\times\dot{\boldsymbol{n}} + \boldsymbol{m}\times\dot{\boldsymbol{m}}) - G_i\dot{\boldsymbol{m}}$$

Spin pumping (at resonance $\omega=\omega_R$, $\omega_H=0$)

$$\mathbf{m}_1\times\dot{\mathbf{m}}_1 + \mathbf{m}_2\times\dot{\mathbf{m}}_2 = \sqrt{\frac{\omega_A}{\omega_E}}\frac{1}{\alpha^2}\frac{\omega_{Hx}\omega_{Hy}}{\omega_E}\sin(\theta_x - \theta_y)$$

anisotropy enhancement

polarization dependence (no SP with linear)

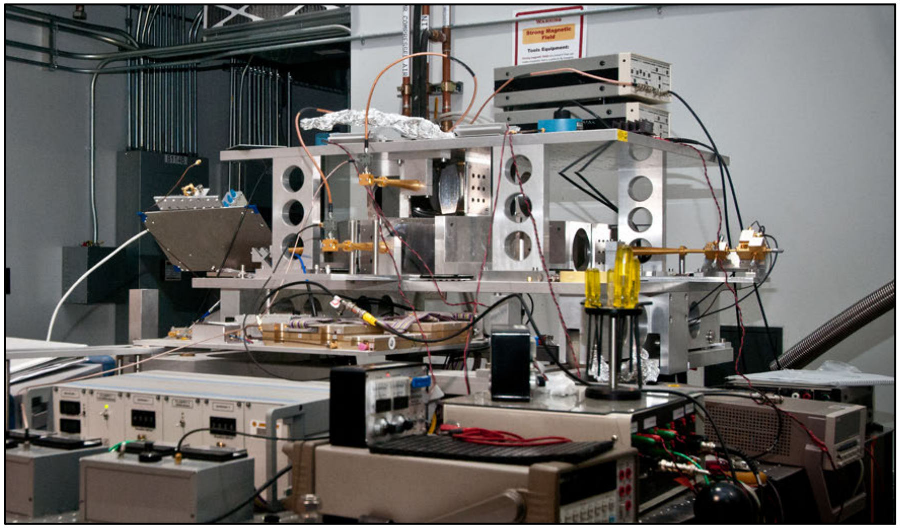


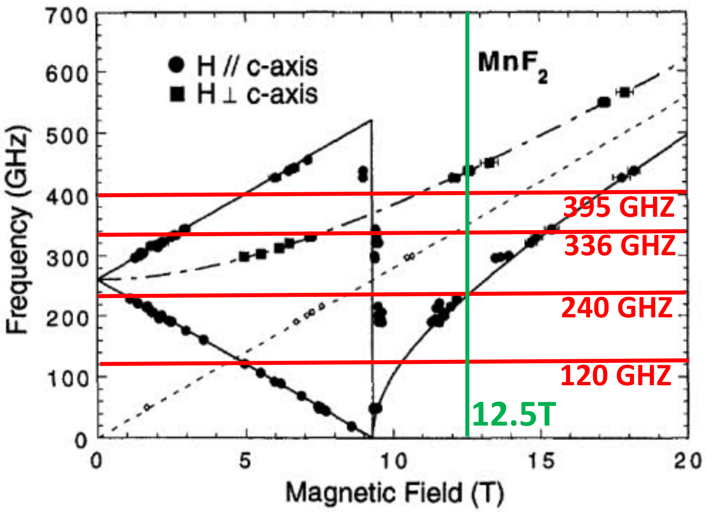
Spin Pumping from AFM Insulator MnF_2

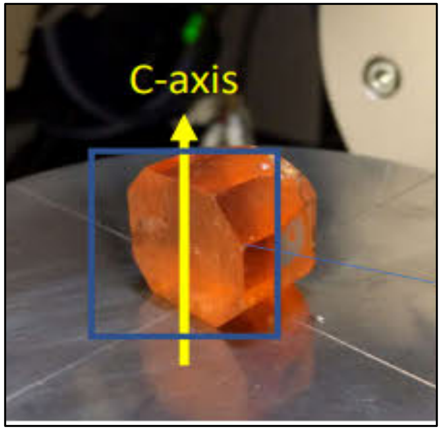
Terahertz Spintronics with Antiferromagnetic Insulators

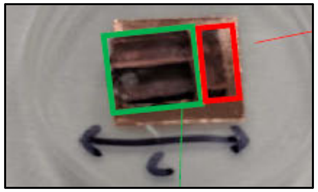
Spin pumping at MnF_2/Pt interfaces

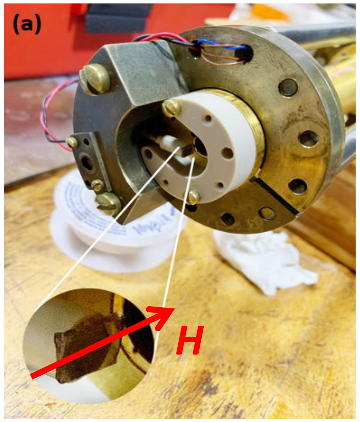
UCF/UCSC/UCR/NTNU/NHMFL results - MnF_2(300µm+10nm)/Pt(4nm)

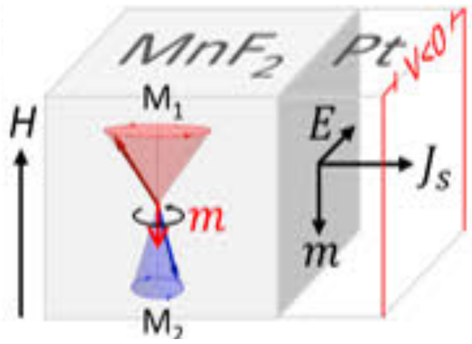










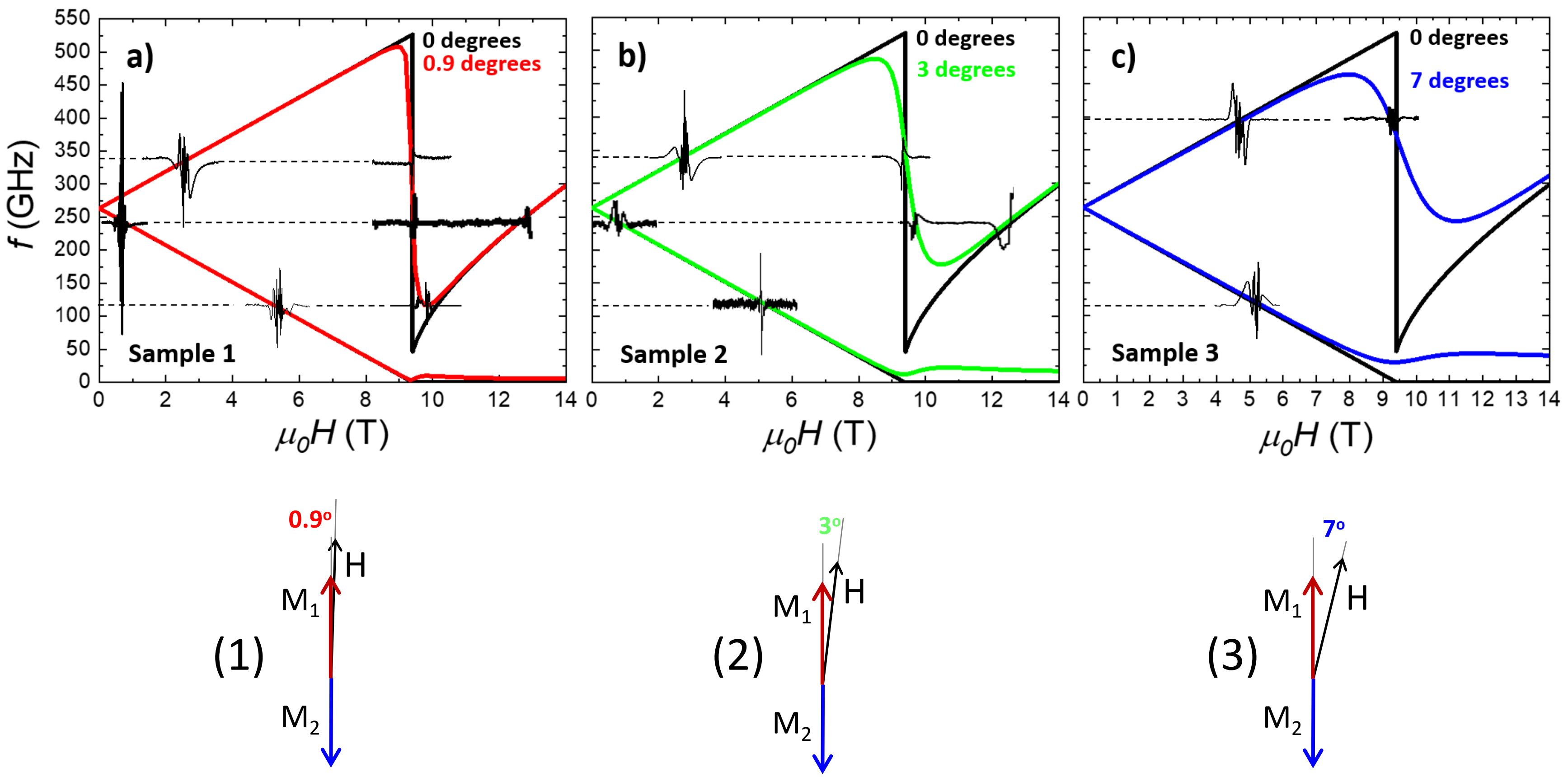


Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

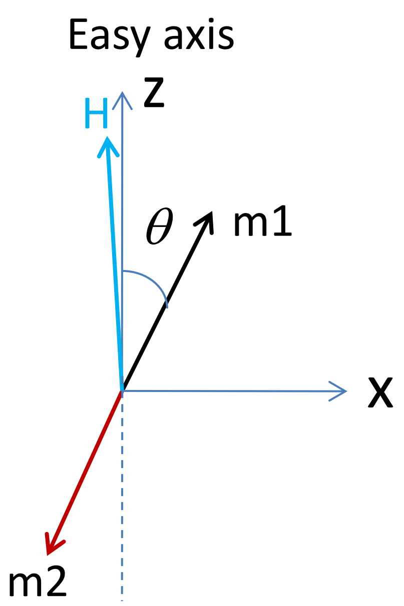
EPR SPECTROSCOPY



Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces



$$\frac{\mathrm{d}\mathbf{M}_i}{\mathrm{d}t} = -\gamma\left[\mathbf{M}_i \times \mu_0 \mathbf{H}_{\mathrm{eff},i}\right] - \alpha\frac{\gamma}{M}\left[\mathbf{M}_i \times \left[\mathbf{M}_i \times \mu_0 \mathbf{H}_{\mathrm{eff},i}\right]\right]$$

$$H_{eff} = H_{ex} + H_k + H + H_p$$

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

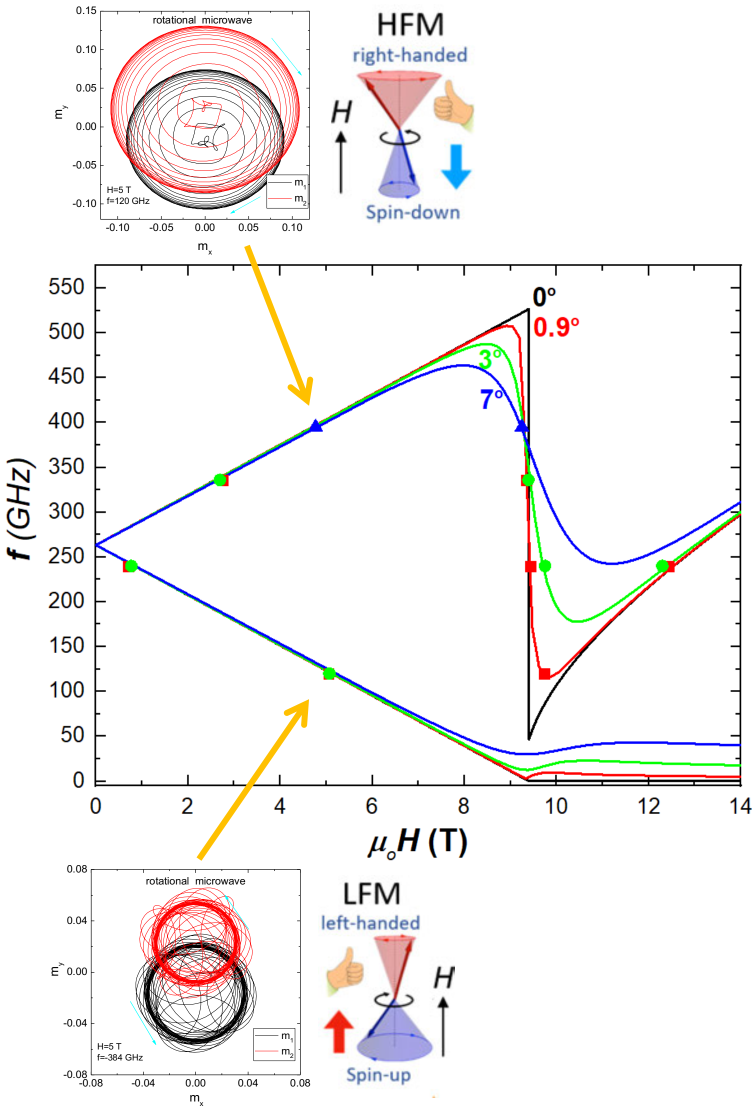
$M_s = 0.06T$

$H_E = 47.05T$

$H_A = 0.8T$

$\gamma = \gamma_e$

$\alpha = 0.001$



Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

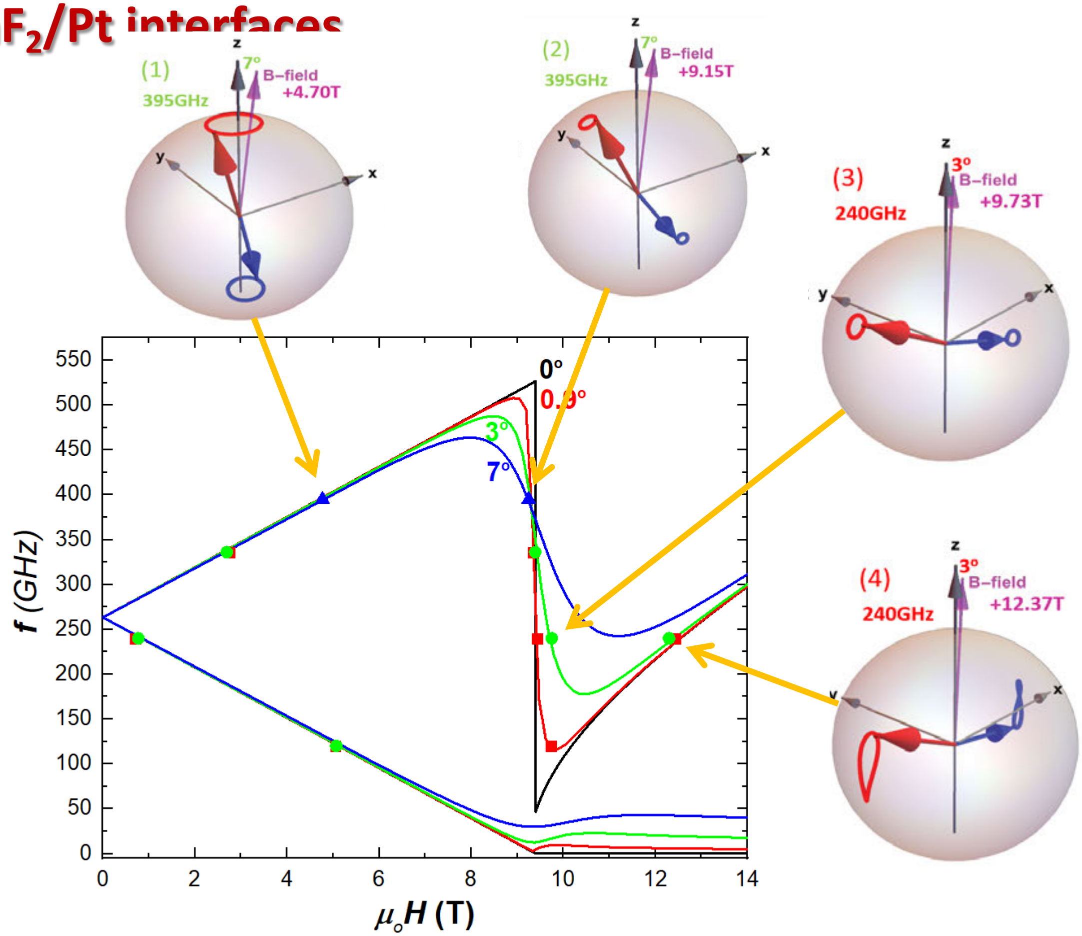
M_s = 0.06T

H_E = 47.05T

H_A = 0.8T

$\gamma = \gamma_e$

α = 0.001

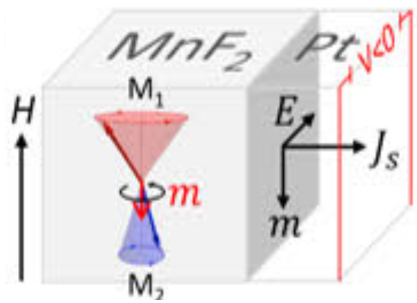


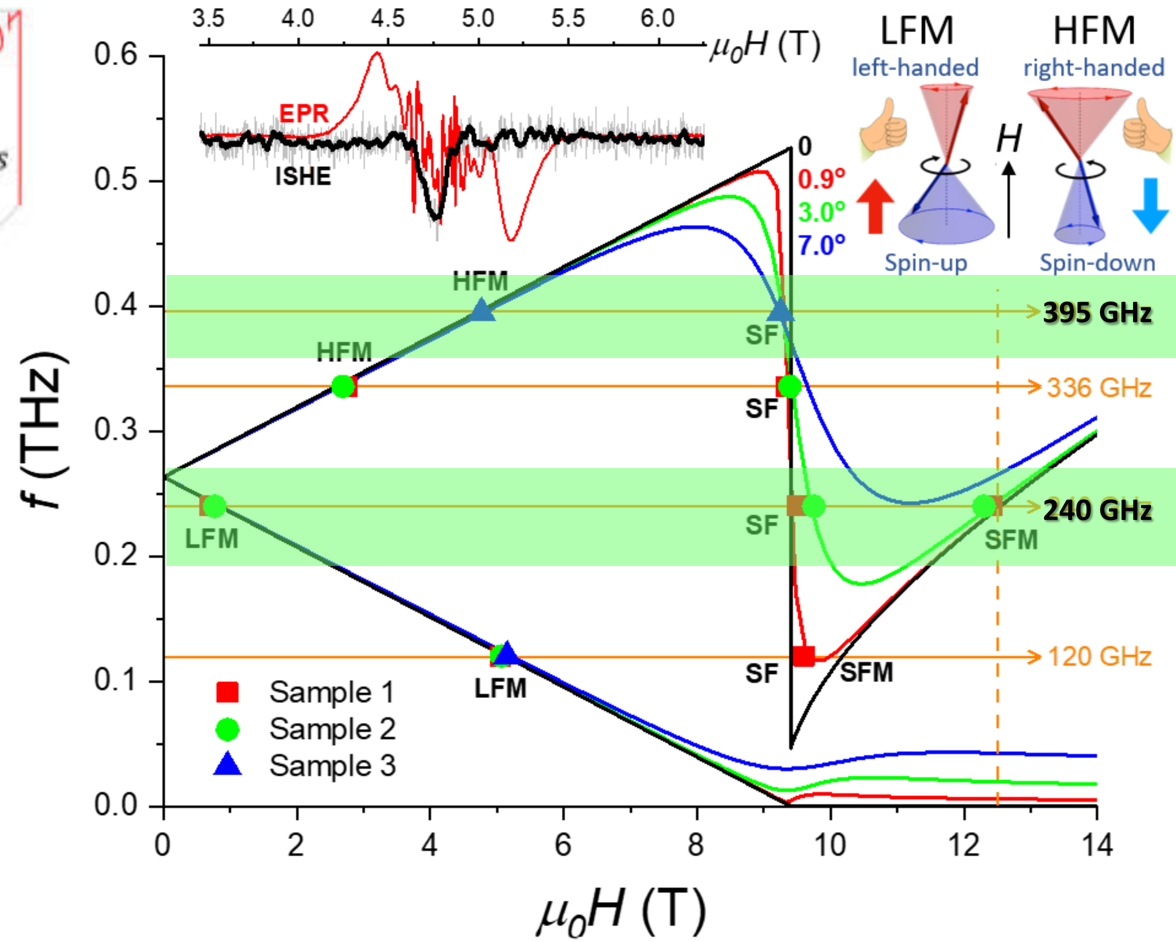
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS





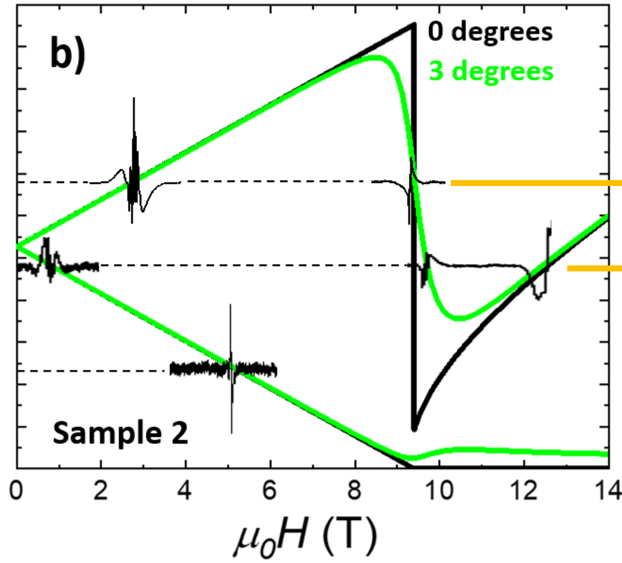
Nanomagnetism and Spintronics

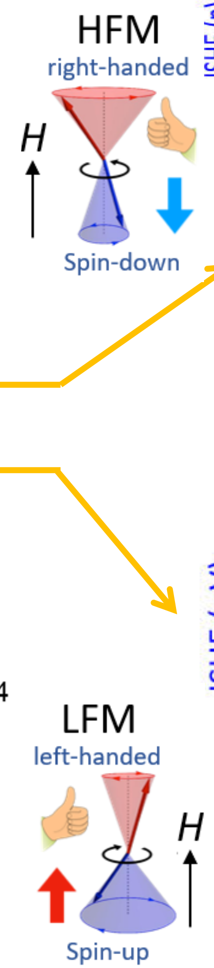
Spin Pumping from AFM Insulator MnF_2

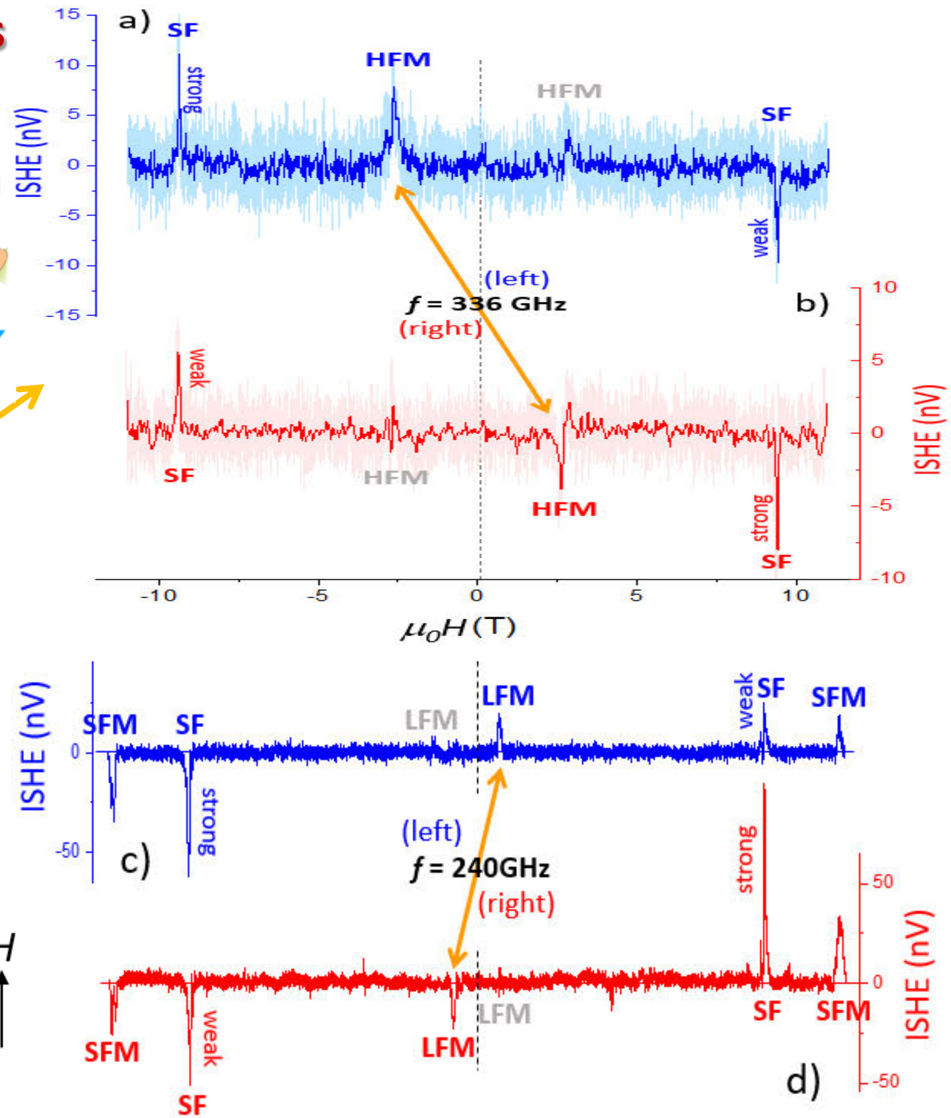
Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS







Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

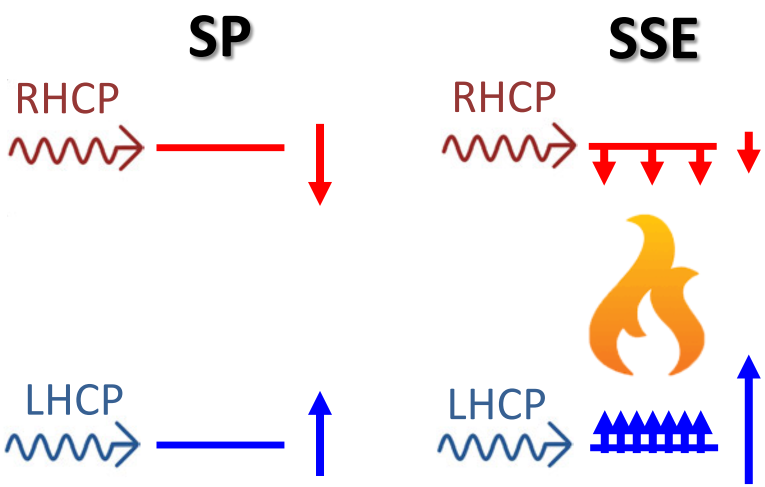
ISHE SIGNALS

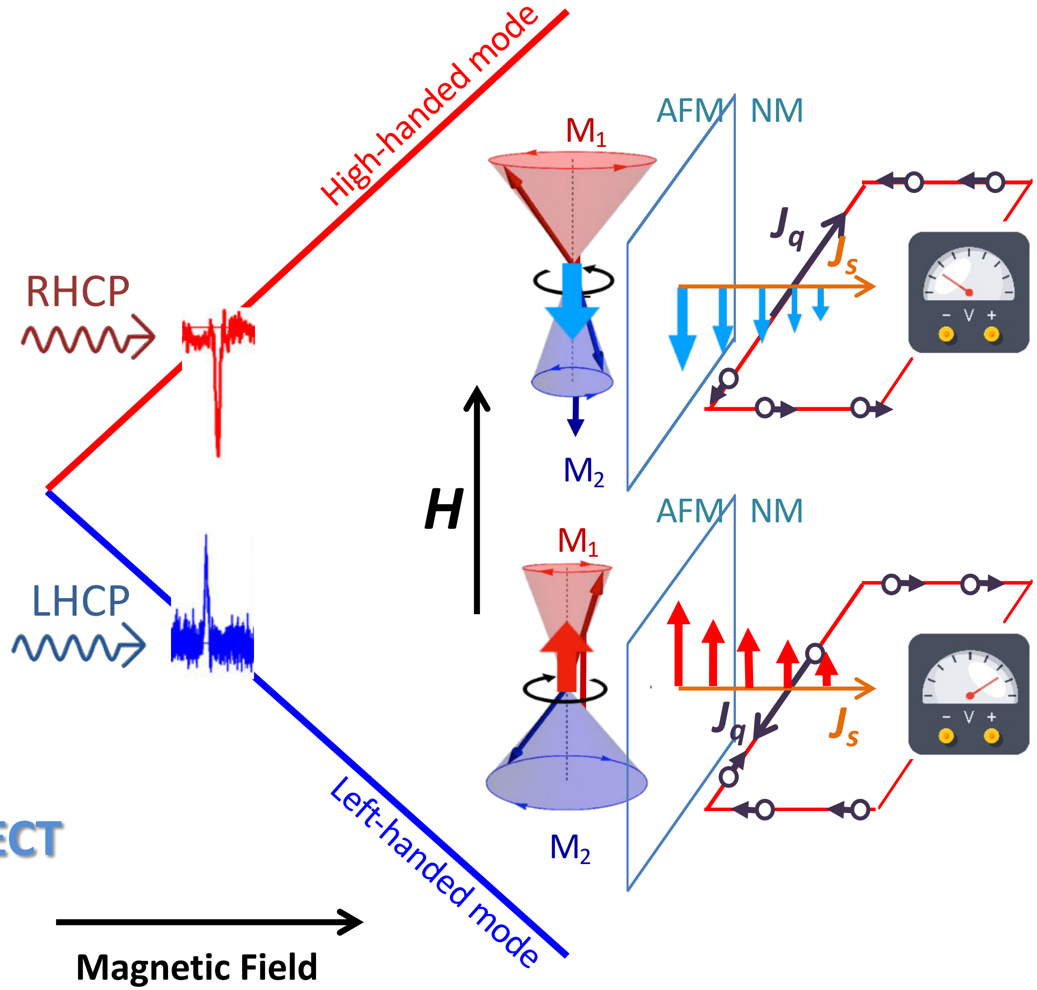
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS





PROOF of COHERENT SPIN PUMPING

NOT INCOHERENT SPIN SEEBECK EFFECT

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

delBarcoLAB Nanomagnetism and Spintronics

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS

SPIN-MIXING CONDUCTANCE

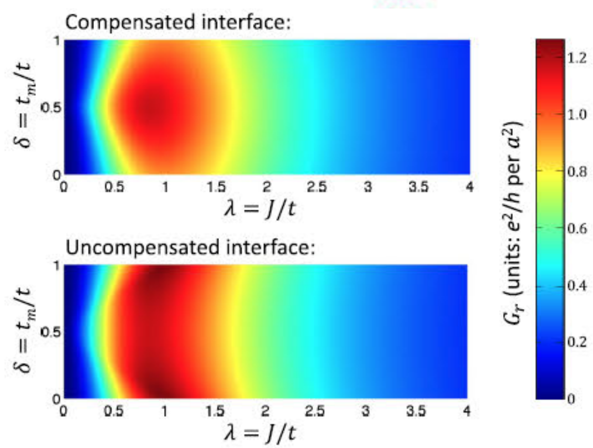
$$V_{ISHE} = L\theta_S \left(\frac{H_A}{H_E}\right)\left(\frac{\lambda}{d_N}\right)\frac{\hbar e(\gamma B_\perp)^2}{\alpha^2\omega_R}\frac{g_r \tanh\frac{d_N}{2\lambda}}{h\sigma + 2\lambda e^2 g_r \coth\frac{d_N}{2\lambda}}$$

$\frac{H_A}{H_E} \approx 1.8\%$
$\alpha \approx 0.5\times10^{-3}$
$d_N \approx 4$ nm
$\theta_s \approx 0.04$
$\lambda \approx 4$ nm
$\sigma \approx 2\times10^6$ S/m
$B_\perp \approx 200$ mG
$V_{ISHE} \approx 25$ nV

$$\boldsymbol{g_r \approx 4.3\times10^{18}\, m^{-2}}$$

$\approx \mathbf{1}\ \boldsymbol{e^2/h}$ per unit cell area

Similar than in FM/Pt interfaces!



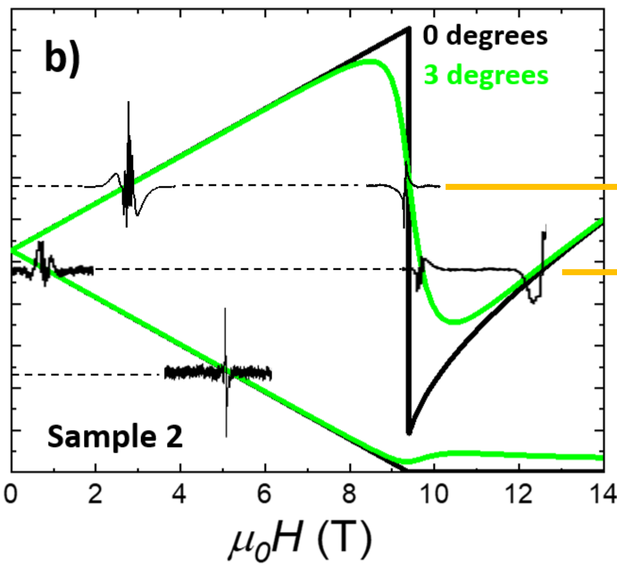
Spin Pumping from AFM Insulator MnF_2

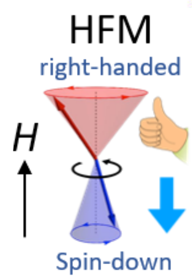
Terahertz Spintronics with Antiferromagnetic Insulators

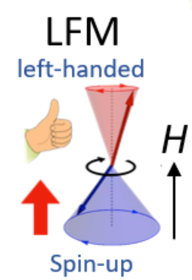
delBarco LAB
Nanomagnetism and Spintronics

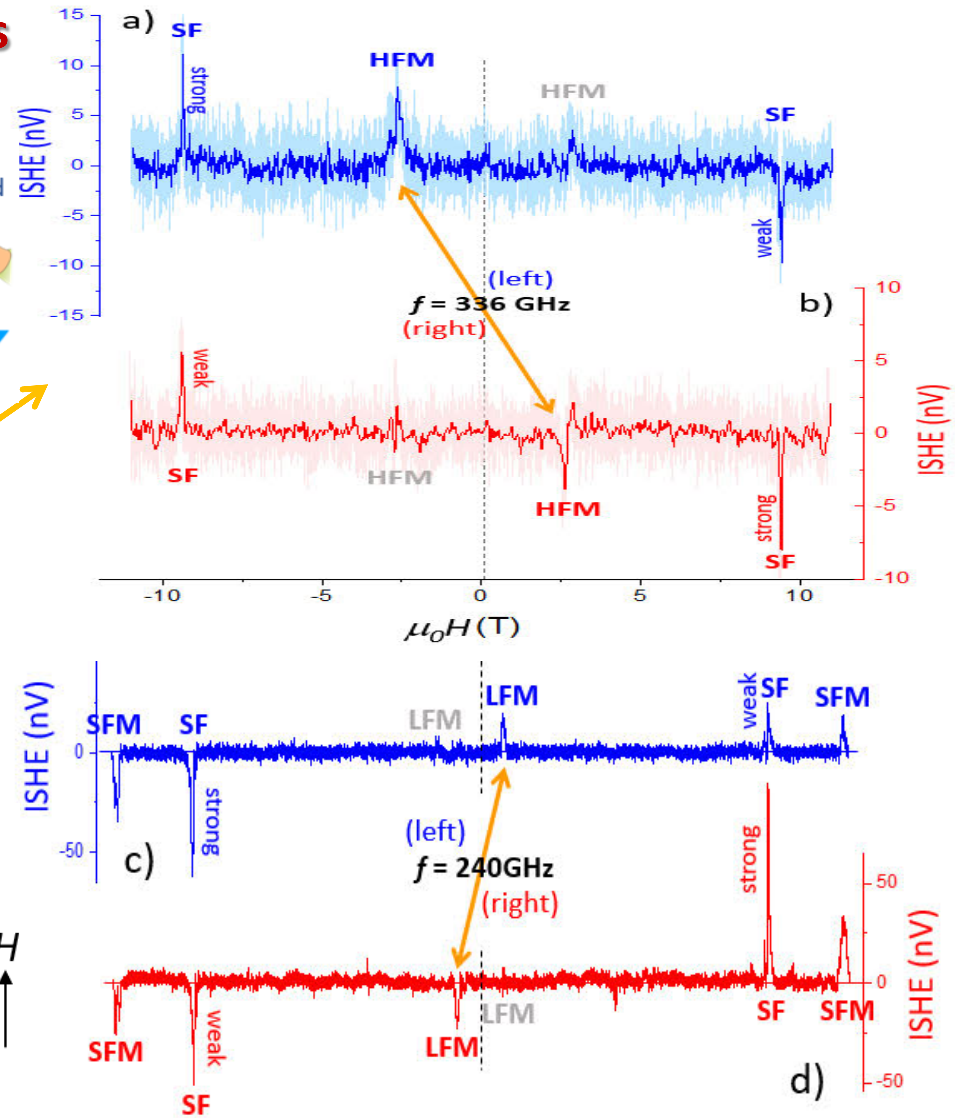
Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS







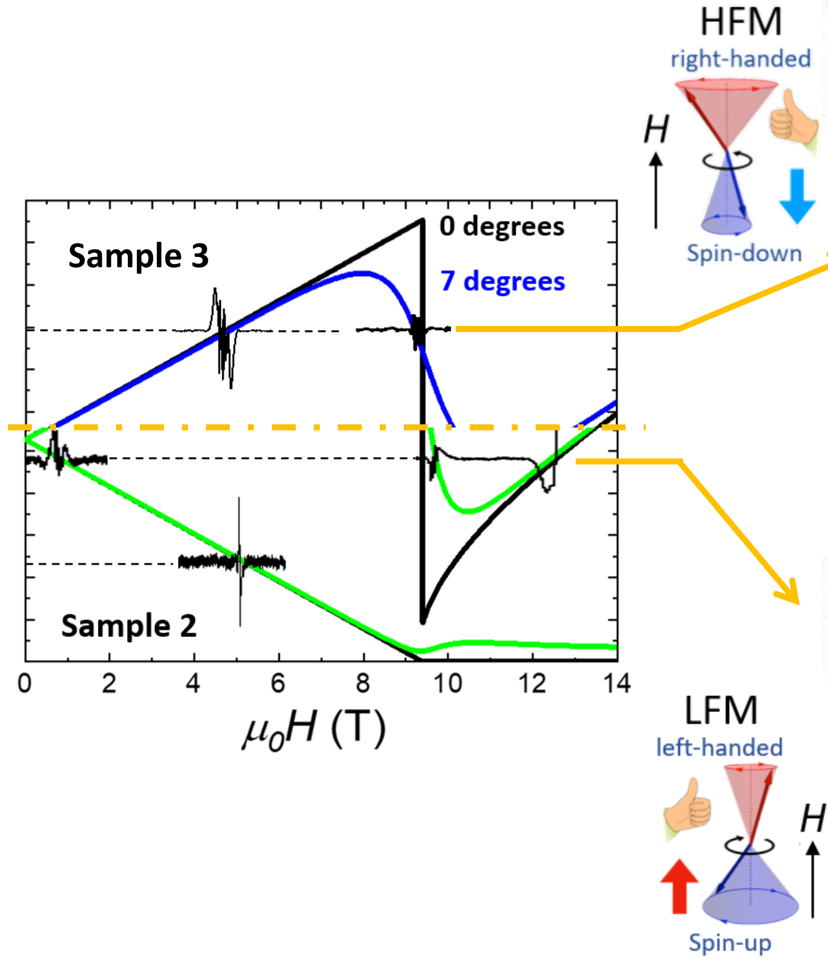


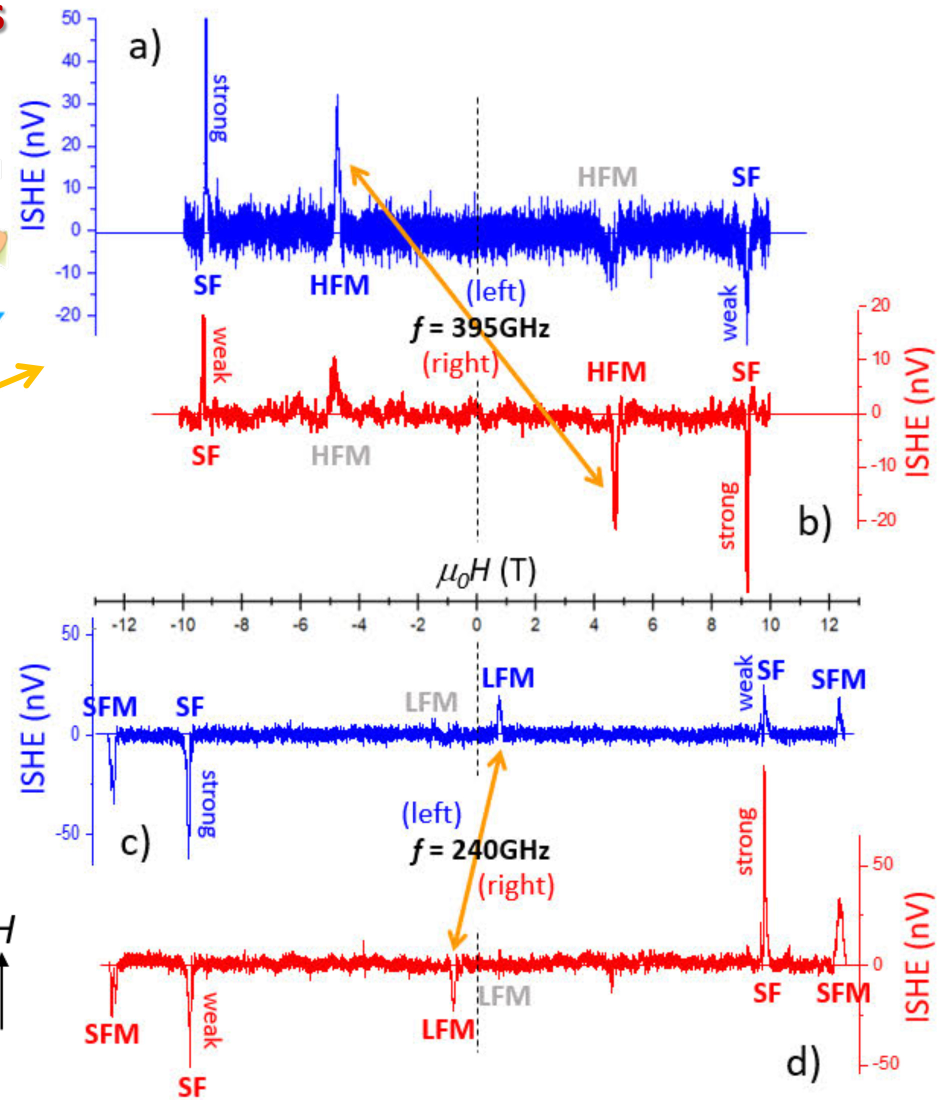
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS



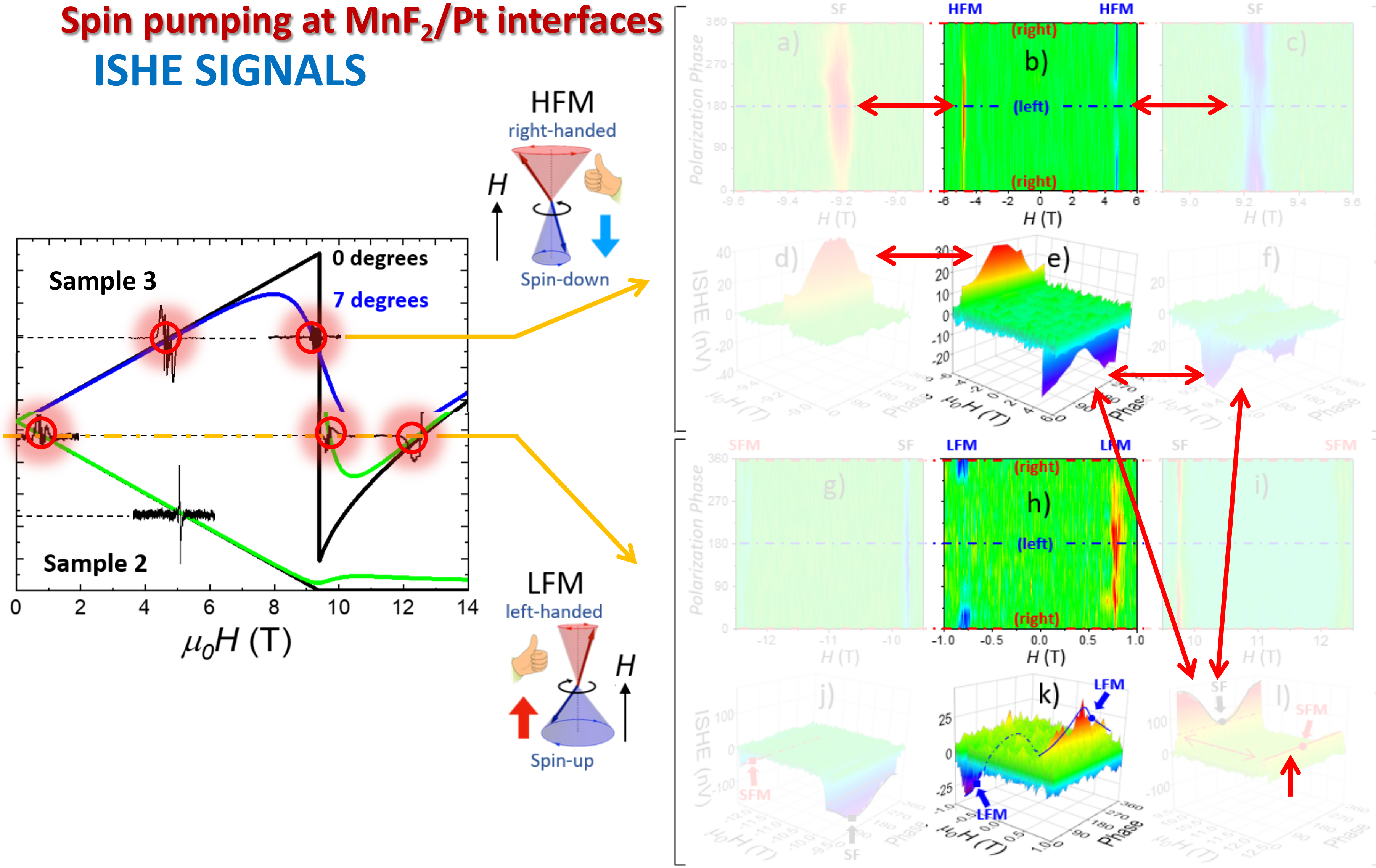


Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS



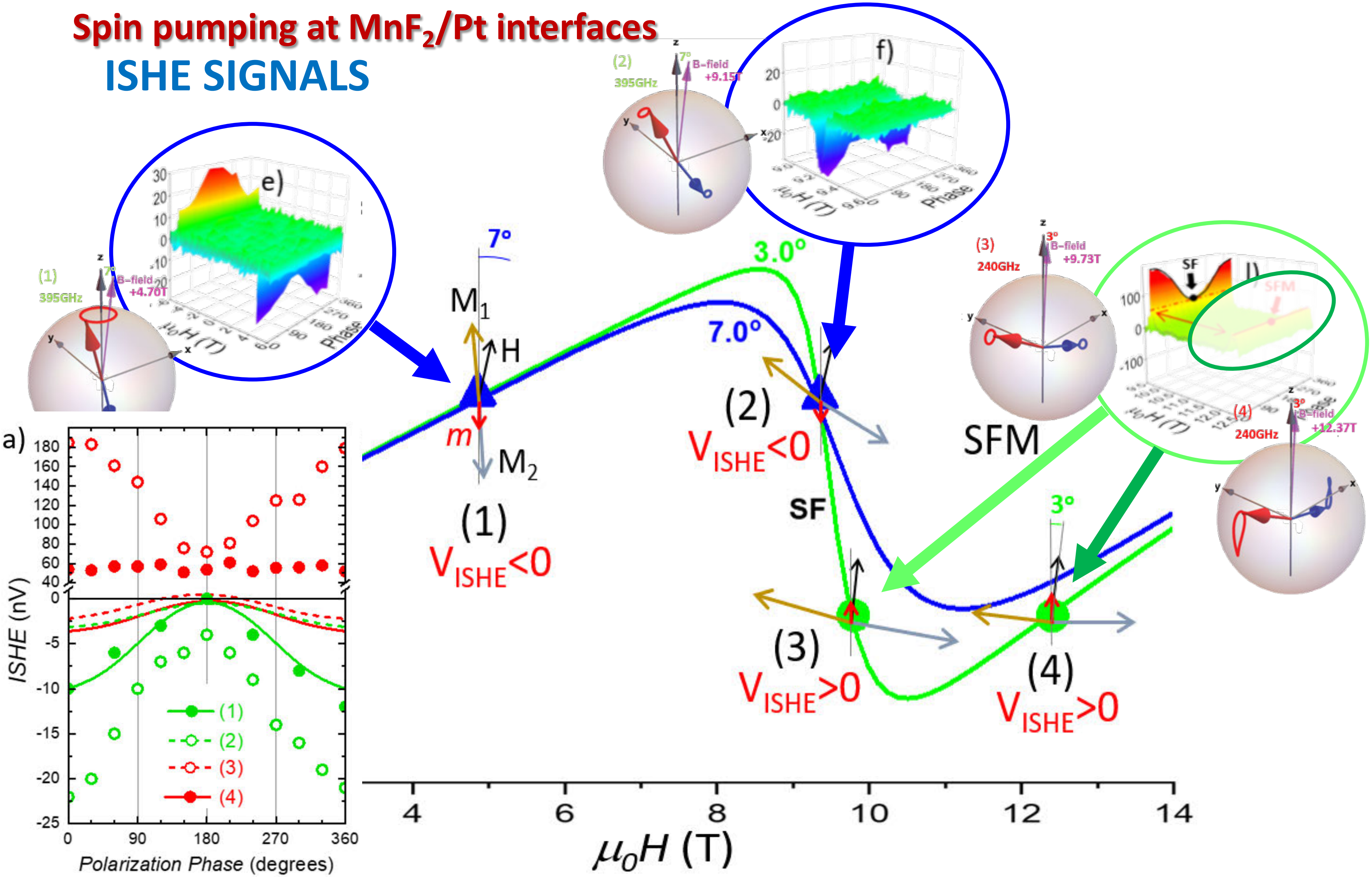
delBarco LAB
Nanomagnetism and Spintronics

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

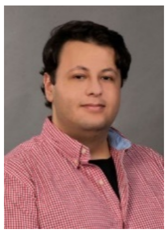
Spin pumping at MnF_2/Pt interfaces

ISHE SIGNALS



www.delbarcolab.com

delBarcoLAB
Nanomagnetism and Spintronics


Justin Zakhary


Ran Liu

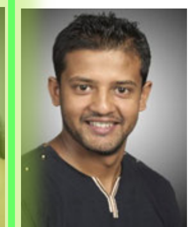

Cameron Nickle

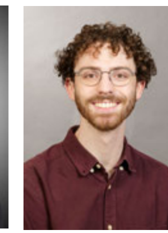

Francis Adoah


Yan Liu


Jaesuk Kwon


Priyanka Vaidya


Gyan Khatri


Greg Fritjofson

THANKS

Work done in collaboration with:

David Lederman (University of California – Santa Cruz)
Ran Cheng (University of California – Riverside)
Arne Brataas (Norwegian University of Science and Technology)
Hans van Tol (National High Magnetic Field Laboratory / NHMFL – Tallahassee/FL)