Microwave Measurements of Spintronic Devices

Matthew Pufall

William Rippard, Eric Evarts, Mark Keller

Magnetics Group

NIST-Boulder, CO

Outline

Ferromagnet-based Spintronics.

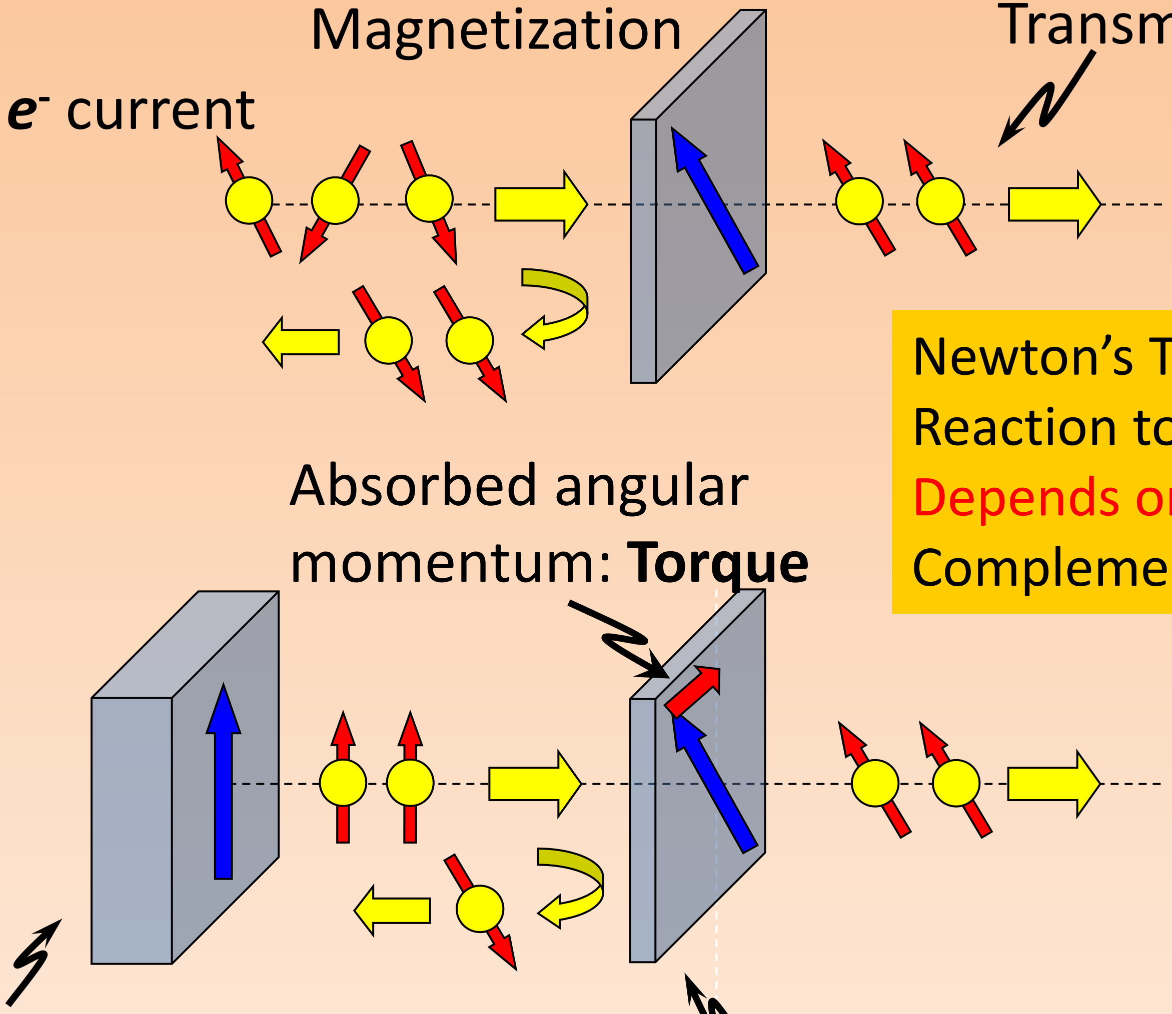
- **Ferromagnets:** Spin filters
- **Spin torque:** Fundamental interaction between spin current and ferromagnet

Device-level microwave measurements: Probe of structure/function.

- **Spin torque MRAM**
  - Correlate error rates to spectral behavior
- **Spin Torque Oscillators**
  - Phase locking, frequency noise
  - STOs as local probes of magnetization

Outlook & Future Challenges.

Spin Transfer: Angular Momentum Absorption



Magnetization

Incident e^- current

Transmitted e^- spins

Newton’s Third Law:
Reaction torque on ***M;***
Depends on **sign** of ***I***
Complementary effect: GMR

Absorbed angular
momentum: **Torque**

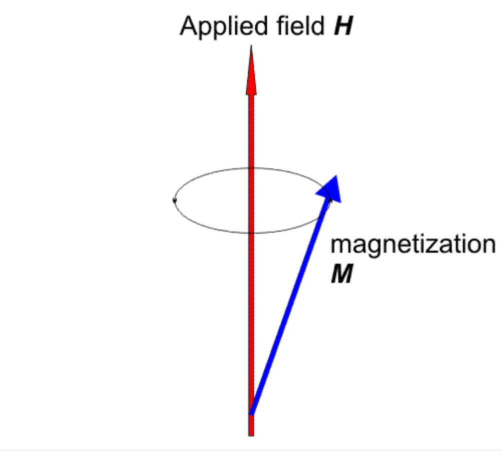
Polarizing layer (thick): “Fixed”

Active layer (thin): “Free”

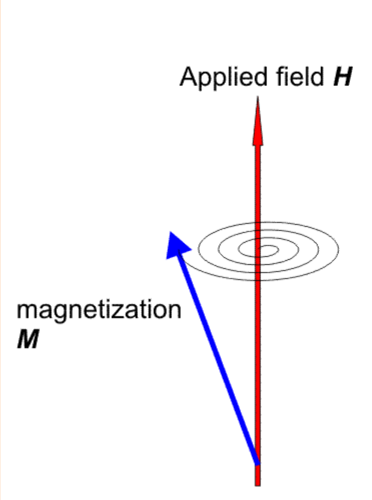
Magnetization Dynamics: Spin Torque

$$\boxed{\frac{d\vec{m}_1}{dt} = T_{Larmor} + T_{Damping} + T_{SpinTransfer}}$$

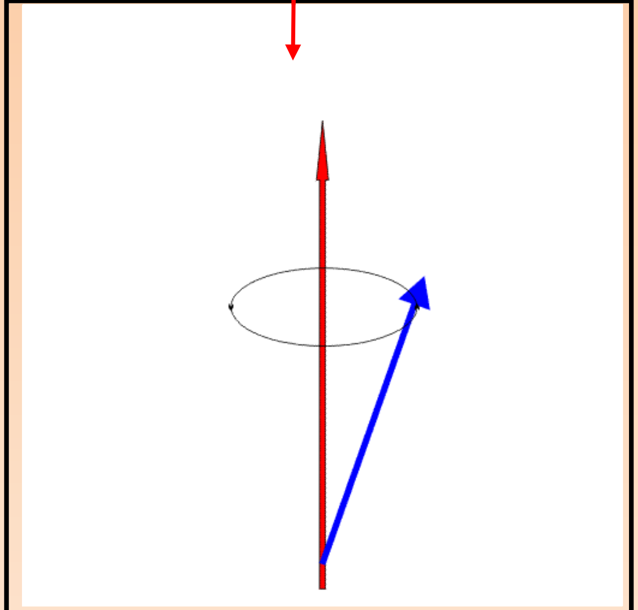
$$\frac{d\vec{m}_1}{dt} \propto \underbrace{-\vec{m}_1 \times \vec{H}_{eff}} \quad \underbrace{-\alpha\vec{m}_1 \times (\vec{m}_1 \times \vec{H}_{eff})} \quad \underbrace{+\beta J_{inj}\vec{m}_1 \times (\vec{m}_1 \times \vec{m}_2)}$$



Larmor term:
precession



Damping term:
aligns M with H



Spin torque can **counteract** damping!

$T_{Spin\ Transfer} \cong T_{Damping}$

$J \sim 10^7 A/cm^2$

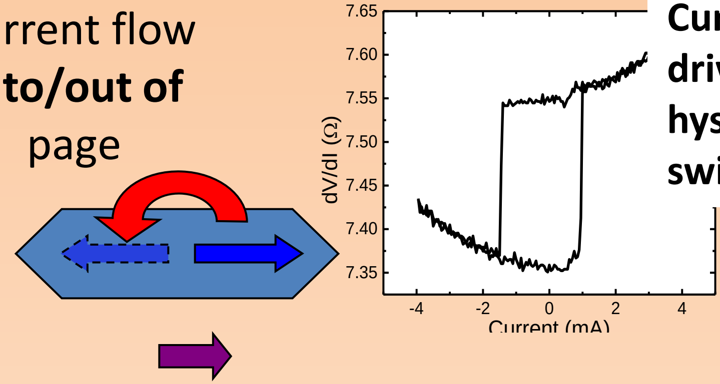
⇨ **Nanoscale effect: larger at smaller length scales**

Slonczewski, 1996

What does Spin-torque do?

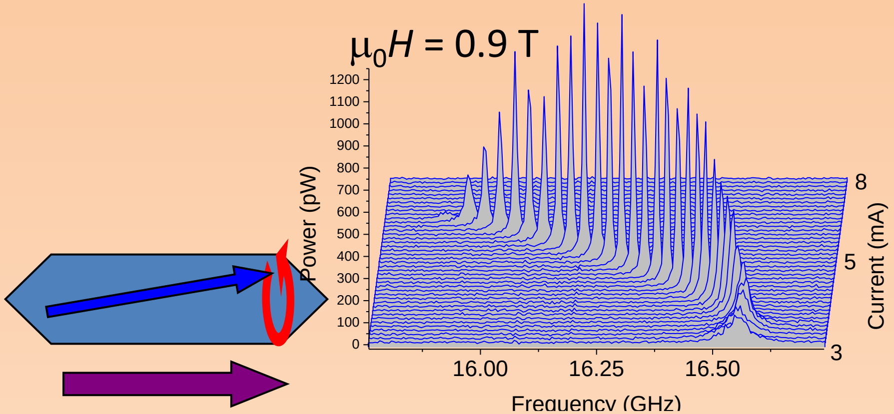
Sign of torque depends on direction of current flow: causes **motion of the magnetization**, depending on the magnetic configuration

Current flow **into/out of** page



Current-driven hysteretic switching

applied field ***H***



applied field ***H***

Microwave freq. power output

Bistable device (small fields): **Current-induced switching**

Monostable device (high fields): **Current-tunable Coherent magnetization precession**

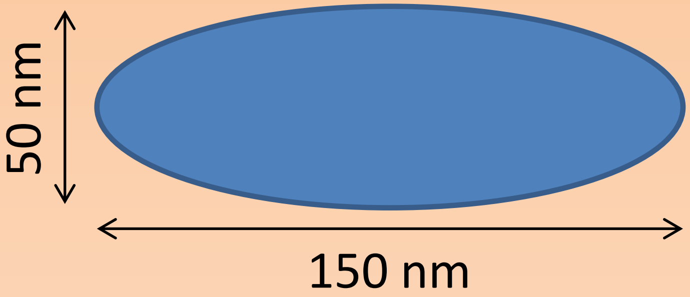
…fundamentally new way to manipulate magnetization

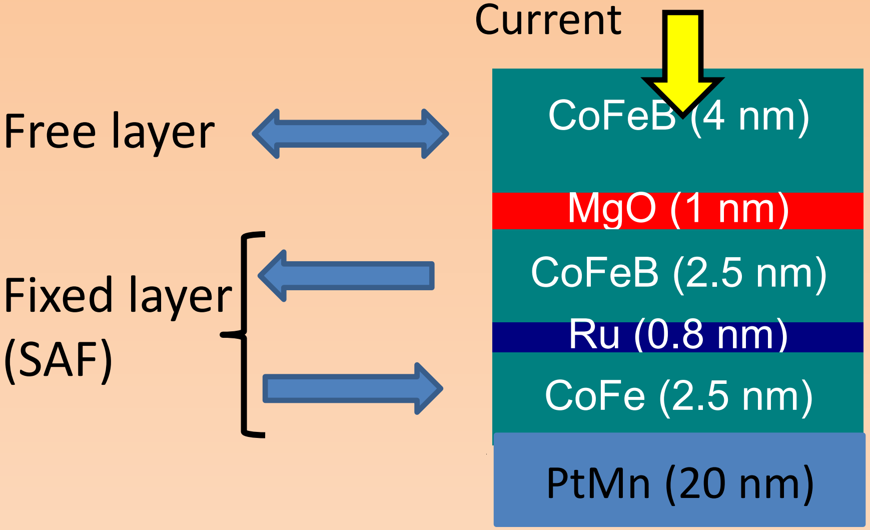
Spin torque Magnetic RAM.

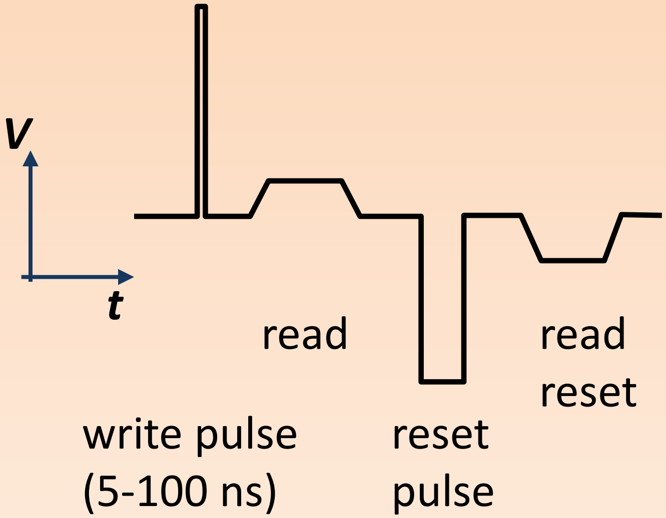
See also poster by Evarts, today

…Potential nonvolatile RAM: Need to determine details of switching

“Nanopillar” Schematics:



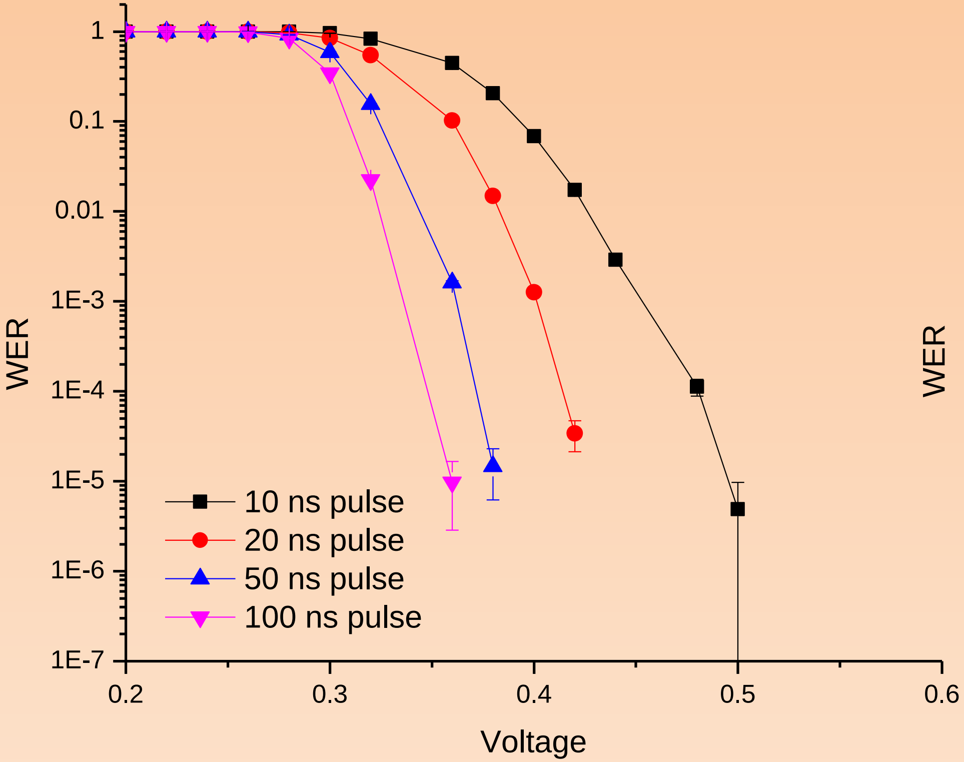




- Tunnel junctions: large MR (70%) & spin polarization
- Measure write error rate (WER) for large numbers of events: compare to two state (single domain) model
- Also can measure real-time switching trajectory (*R* vs. *t*)

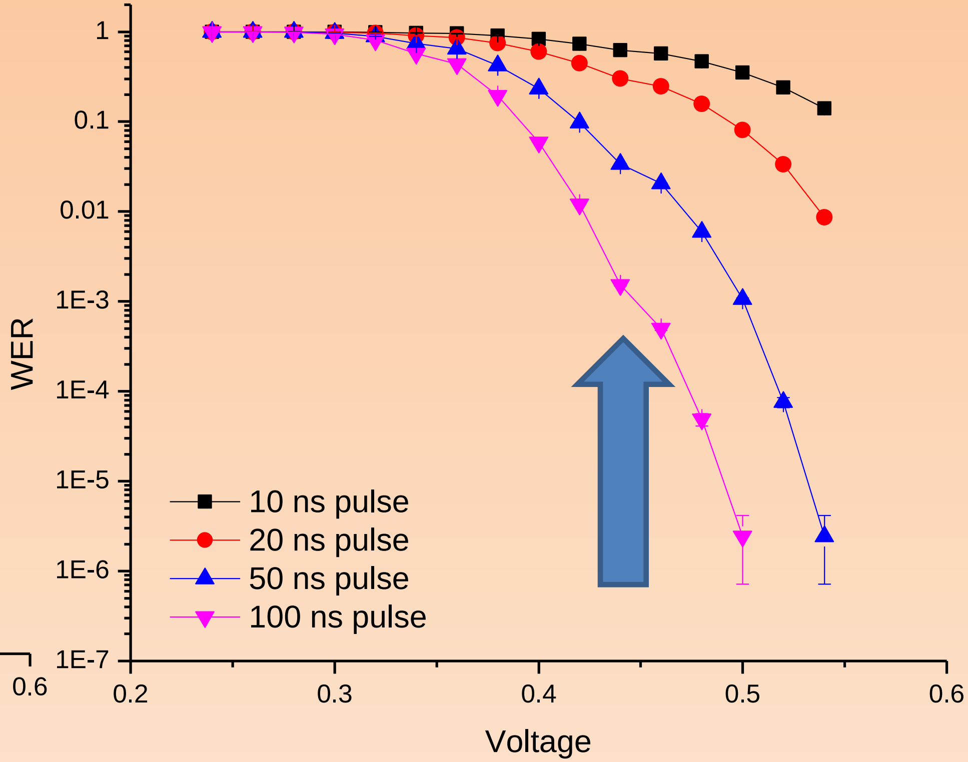
ST-MRAM: Write Error Rate Variations

Typical Device



- Largely follows single exponential expected from single domain
- Shorter pulses require higher voltage to achieve same error rate

‘Anomalous’ Device



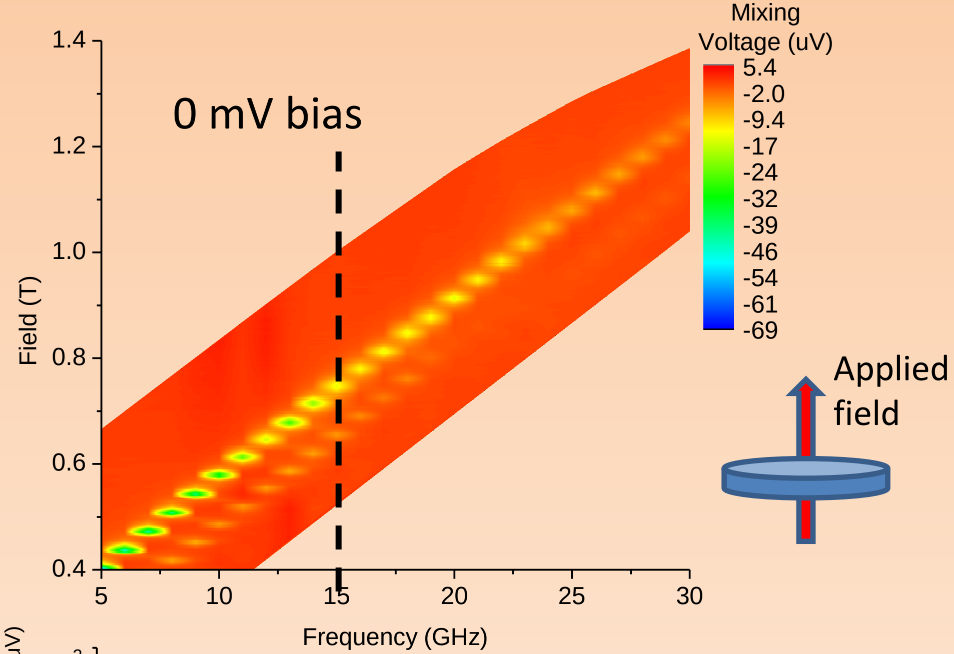
- Deviates from single exponential at higher biases
- Evidence of non single domain behavior?

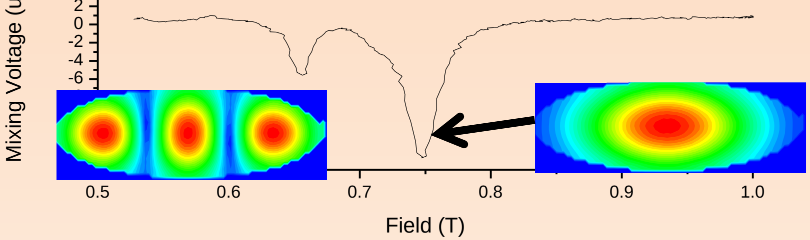
ST-MRAM: Resonance Spectra

ST-ferromagnetic resonance (ST-FMR):

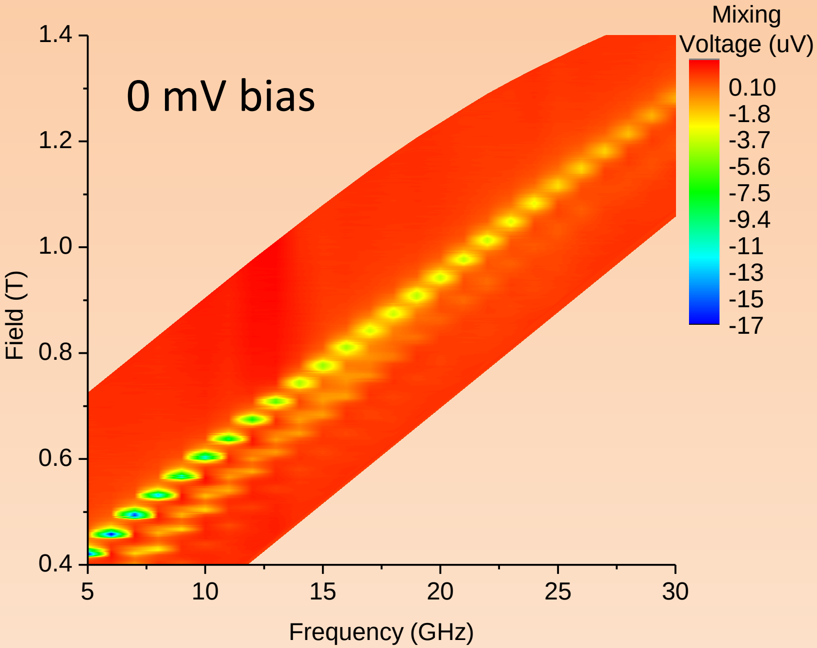
- Inject AC current, measure device response vs. ***f, H***
- Determine **resonant modes** of device

Typical Device





Anomalous Device

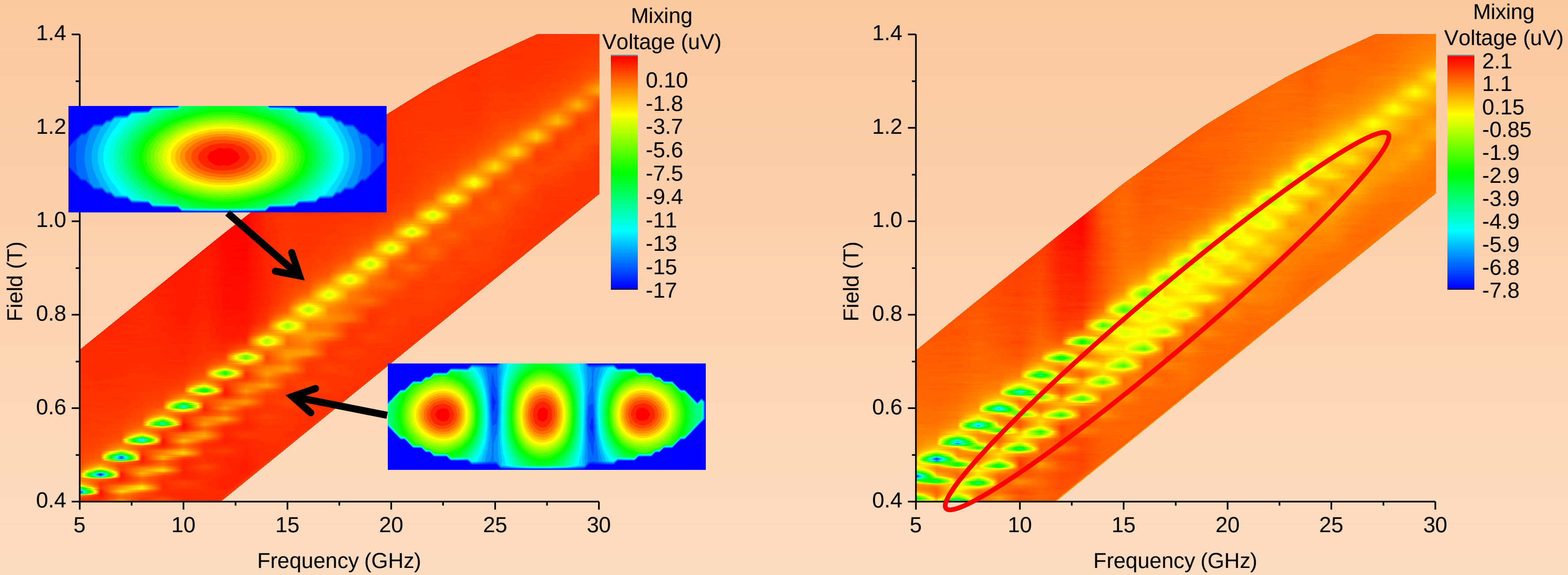


- ‘Typical’ and ‘anomalous’ devices have similar spectra at low bias
  → Implies similar ***physical*** structures

*Mode patterns determined with OOMMF micromag. simulator (oommf.nist.gov)

ST-MRAM: Spectra vs. Voltage Bias

Spectra of anomalous devices are function of voltage bias



0 mV bias

300 mV bias

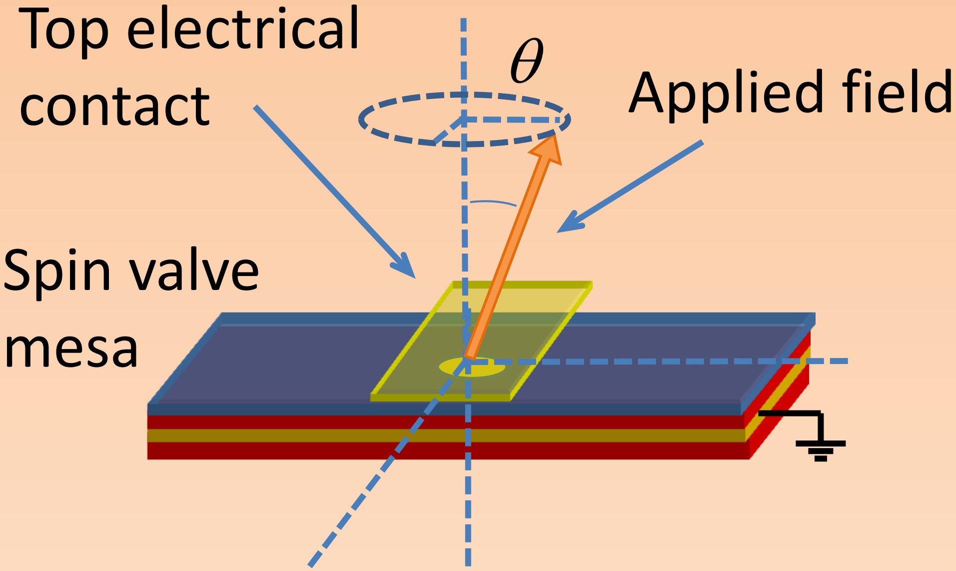
- Higher order modes excited at high bias: become similar in magnitude to fundamental mode
- Deviation from single domain spectra: deviation of WER

Linear response not solely responsible for variations: Requires measurements of full devices

*Mode patterns determined with OOMMF micromag. simulator (oommf.nist.gov)

Spin Torque Oscillators

Current concentrated by electrical lead: Magnetization is unpatterned

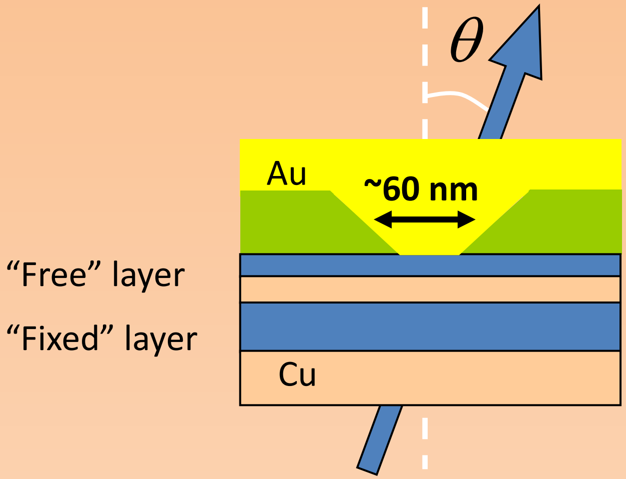


Top electrical contact

θ

Applied field

Spin valve mesa



θ

Au

~60 nm

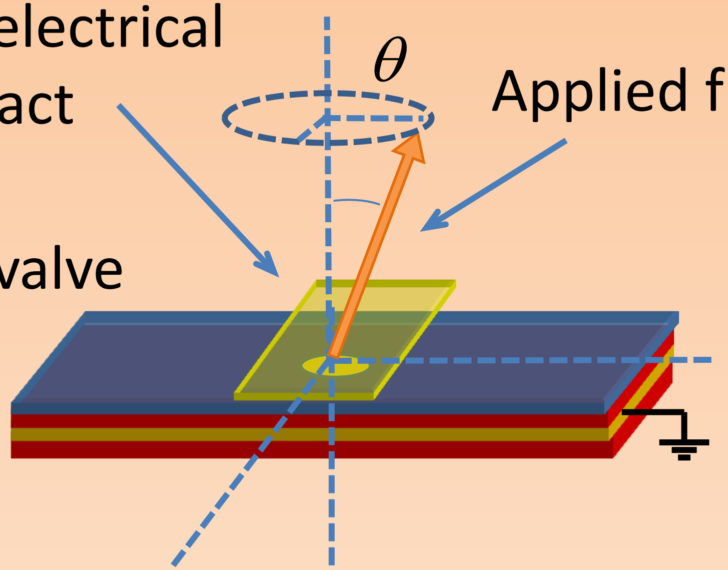
“Free” layer

“Fixed” layer

Cu

Spin Torque Oscillators

Current concentrated by electrical lead: Magnetization is unpatterned



Top electrical contact

Applied field

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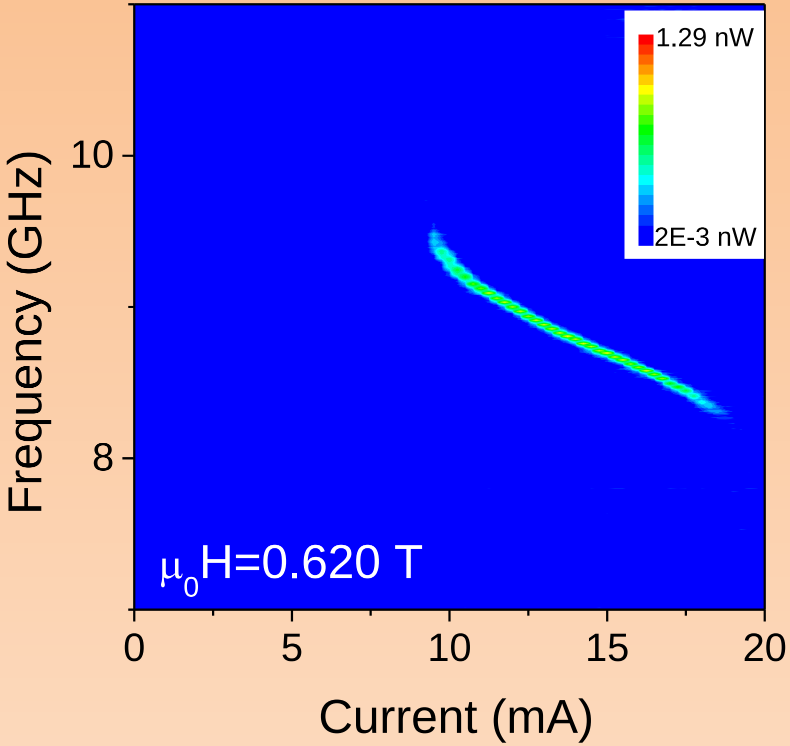
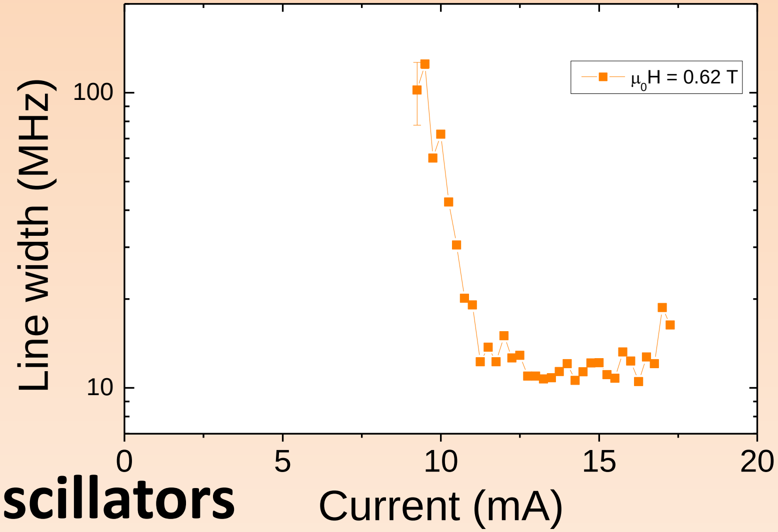


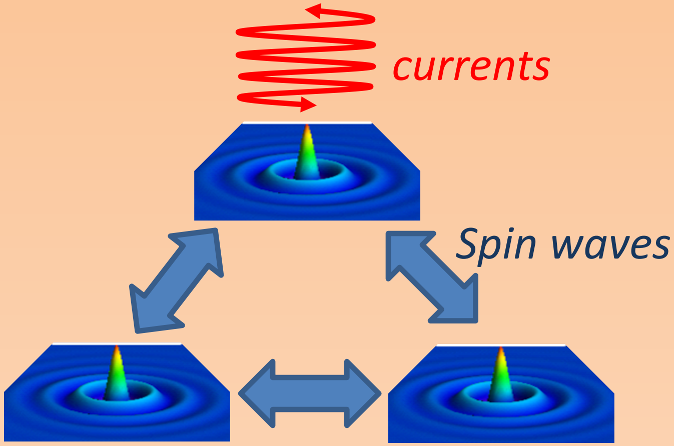


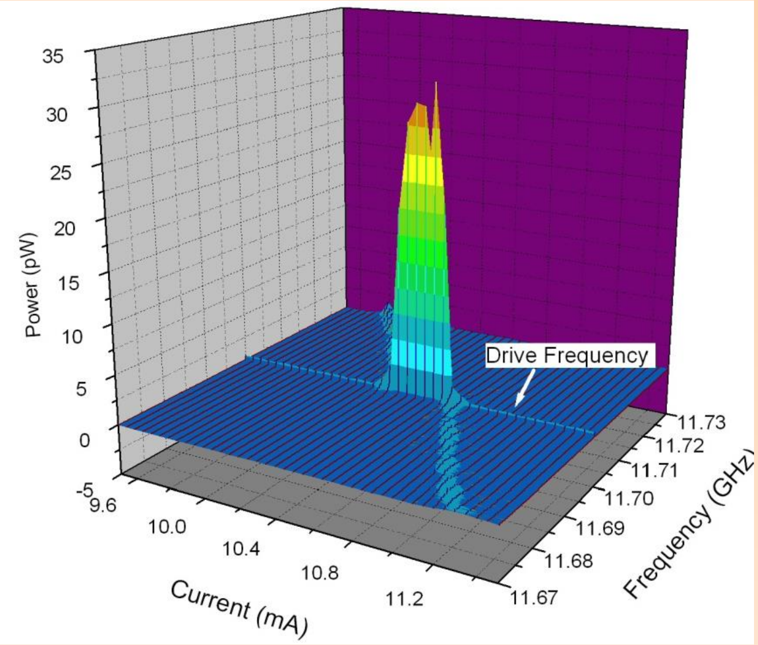
- DC current induces microwave precession
- Frequency tunable with current
- Line widths in 1-100 MHz range

…STOs are nonlinear, current tunable oscillators

STOs: Metrology Challenges (i.e., Why?)

Quantifying **nonlinear coupling** of STOs via currents, fields, and spin waves, to enable **large-scale arraying**—e.g., bio-inspired NonBoolean architectures*





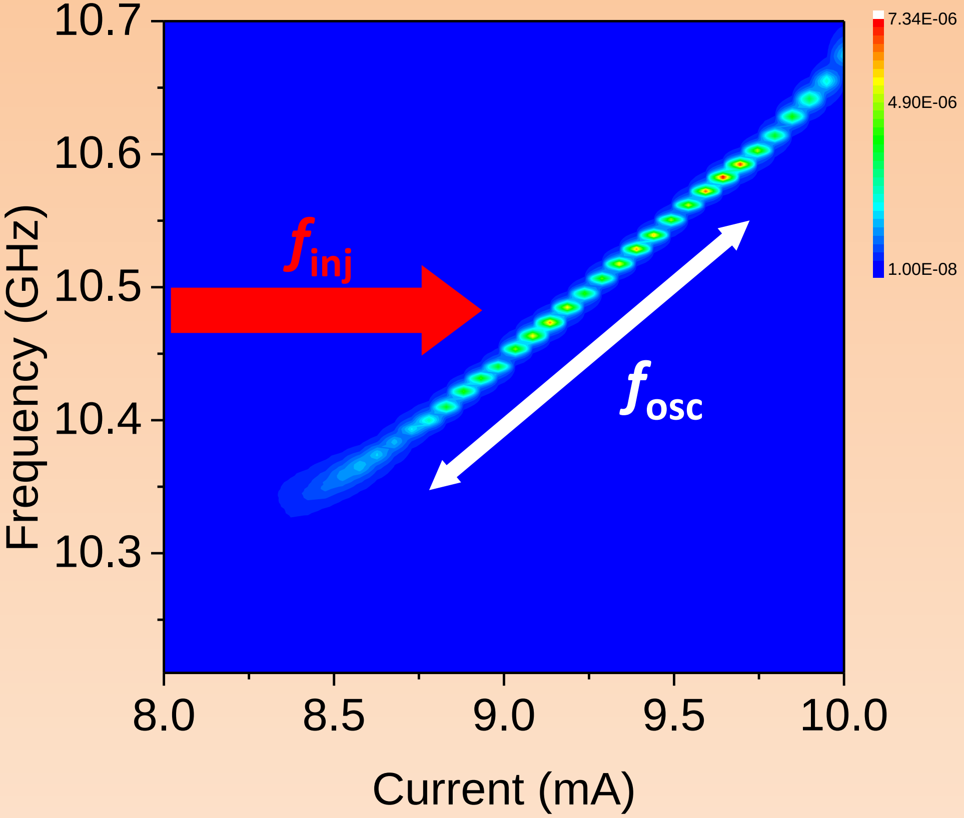
Understanding details of oscillations (line width, frequency, **phase noise**): dependence on **nanoscale** (magnetic) **structure**, defects, effects on phase locking

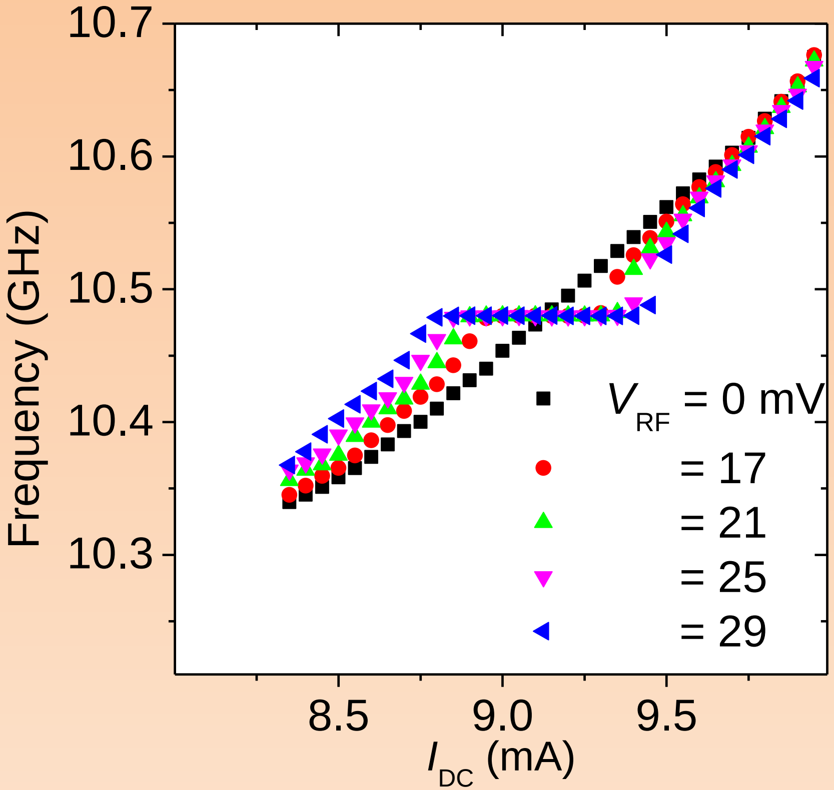
Measurements are of *magnetic devices* at nanometer scales, at frequencies >10 GHz

* Collab. with Intel, Notre Dame, Pitt., others

Injection Locking—CW microwaves

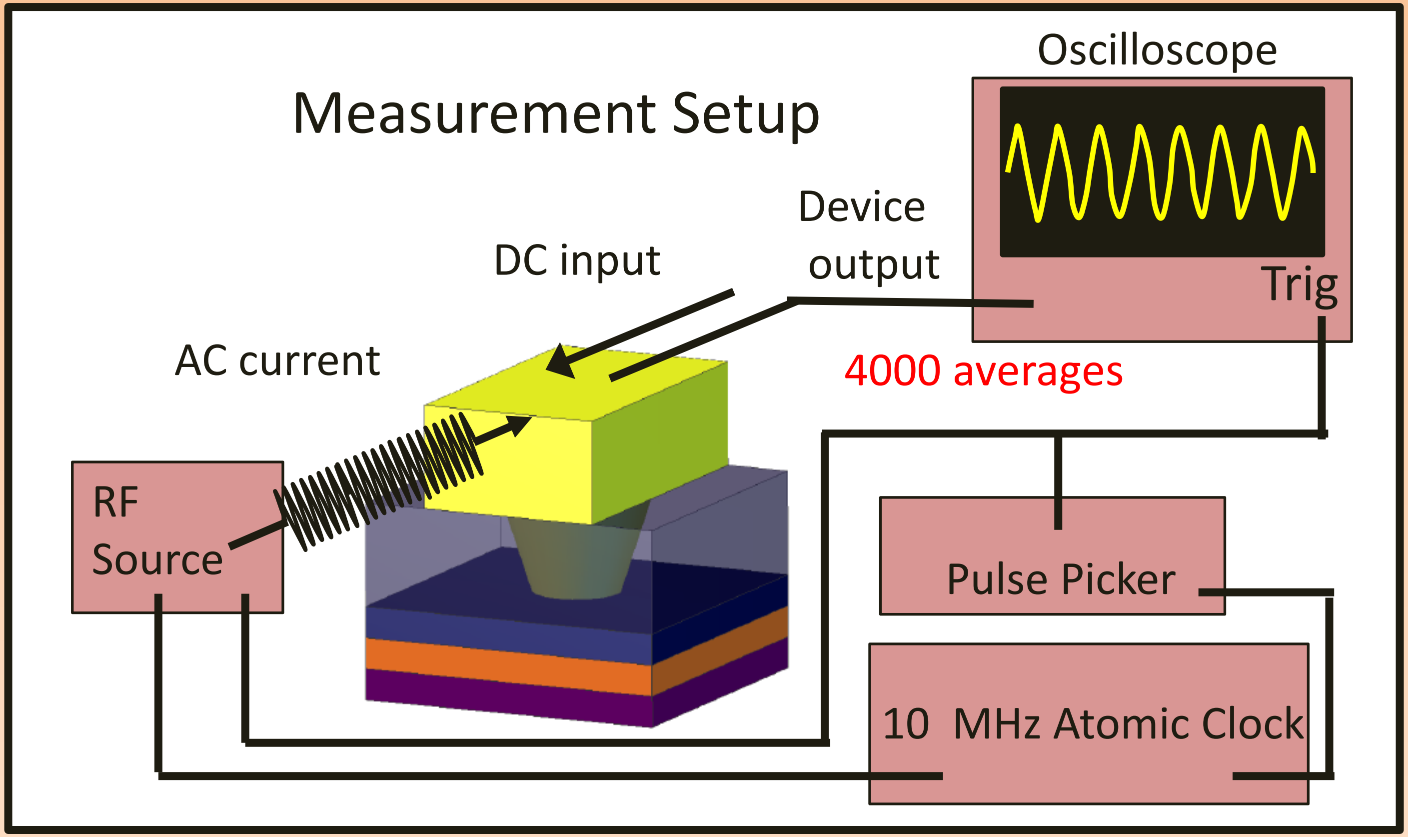
Inject AC spin current at f = 20.96 GHz, tune f_{osc}:





- Device locks to $f/2$ (= 10.48 GHz)
- Width of locking range (in frequency) depends on drive amplitude

Injection Locking: Time domain

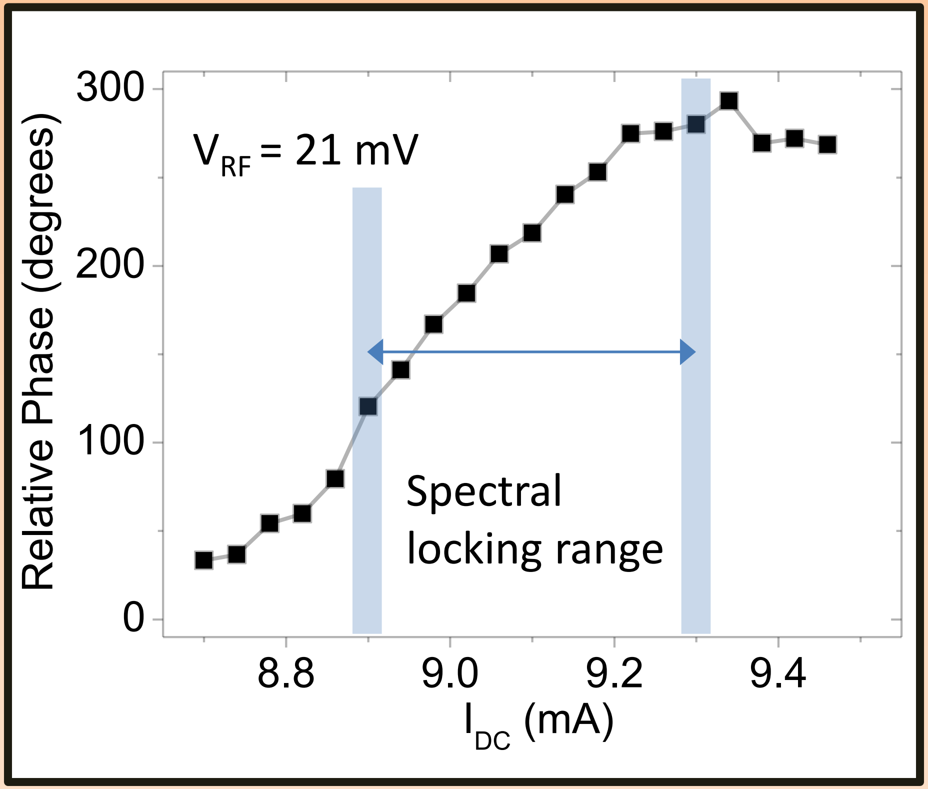


- Scope trigger coherent with microwave source:

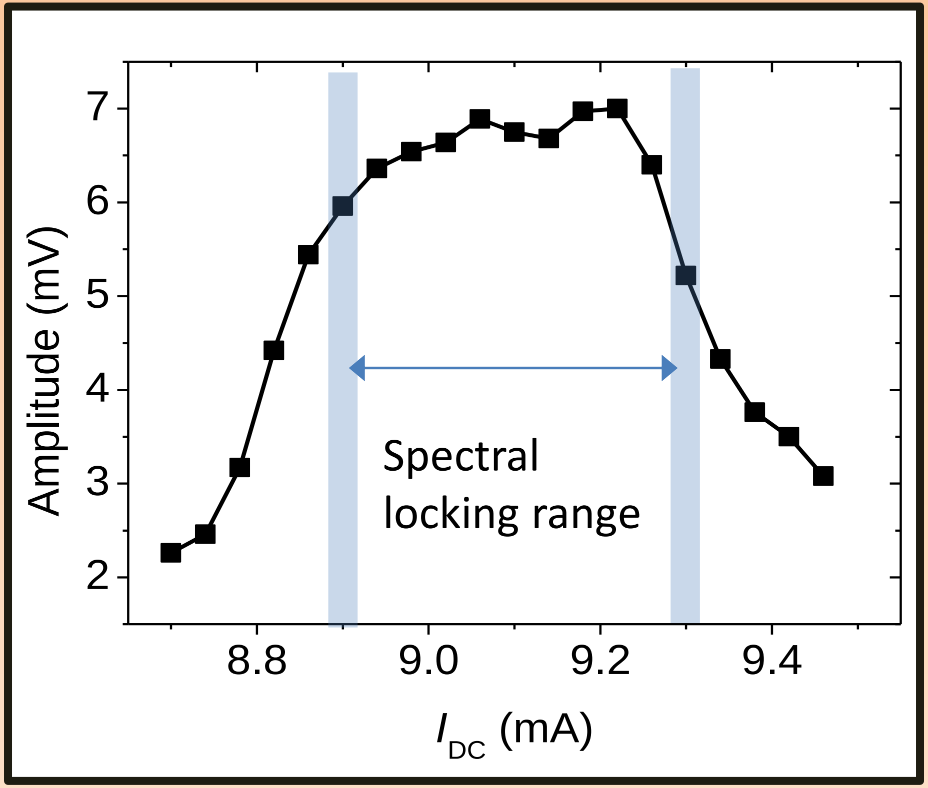
→ Any signal not coherent with microwaves will average to zero… determine phase vs. frequency difference

Phase and Amplitude vs. Frequency Difference

Phase vs. Bias



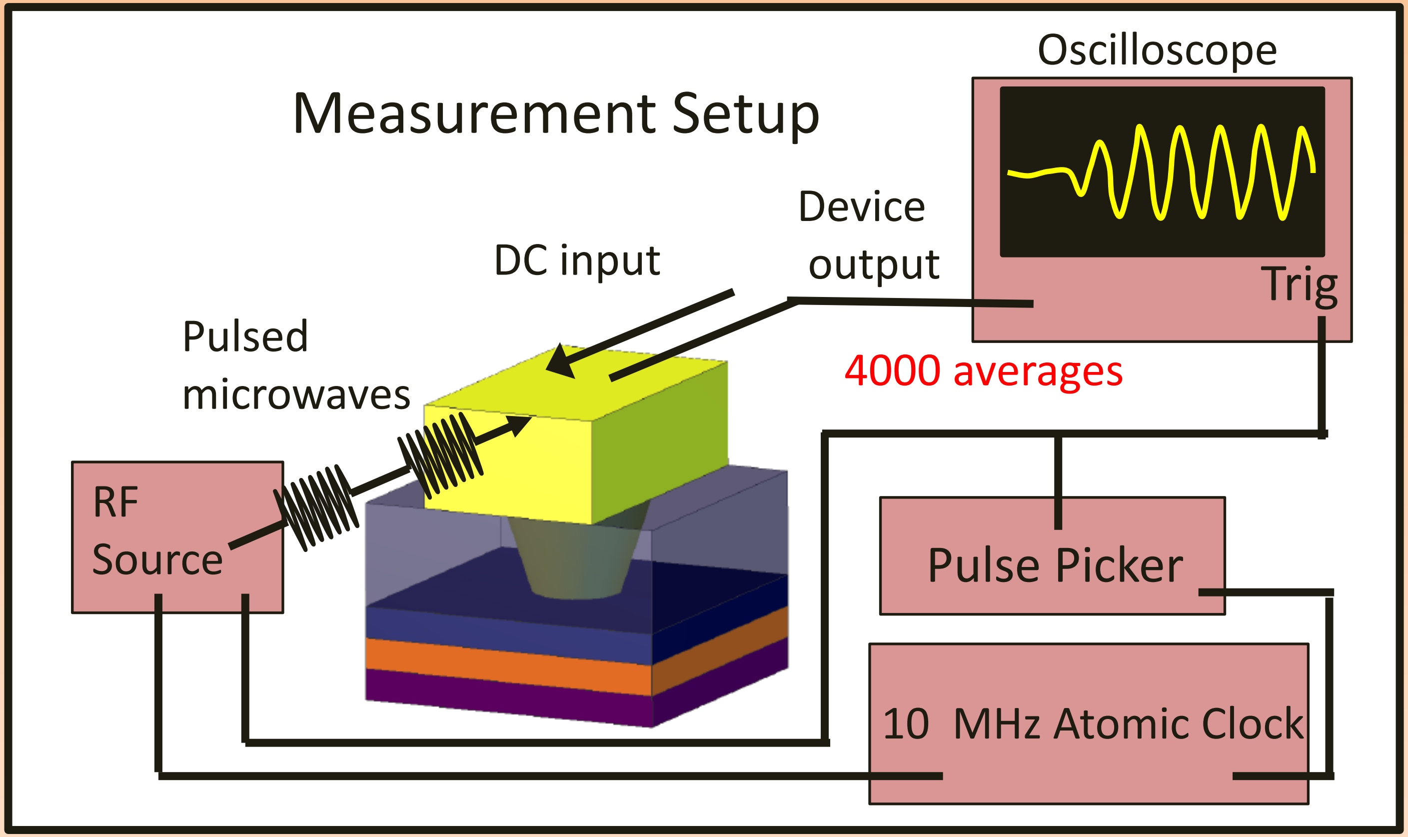
Avg Amplitude vs Δf



- Phase changes as a function of DC bias

- Amplitude ∝ time device is locked.
- Even when partially "locked" the STO maintains well-defined phase with the injected signal: **Stochastic process**

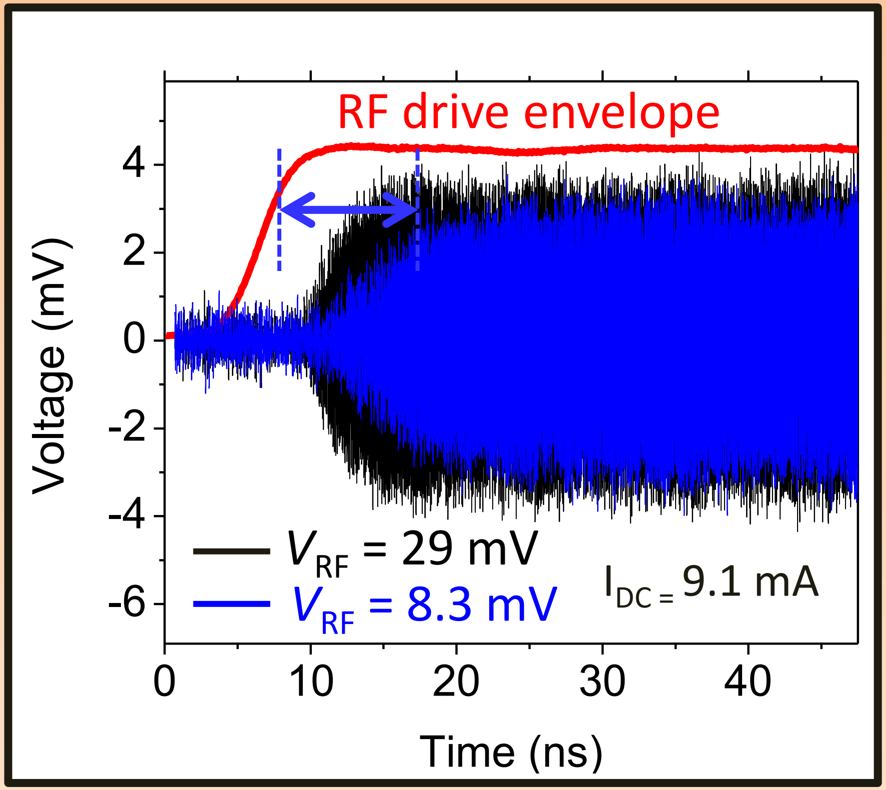
Pulsed Injection Locking: Time-to-lock



- Use a “pulse picker” to trigger scope and **gate RF source**
- Microwaves are pulsed: 100 ns on and 900 ns off , to allow device decoherence (≈ 80 ns required)

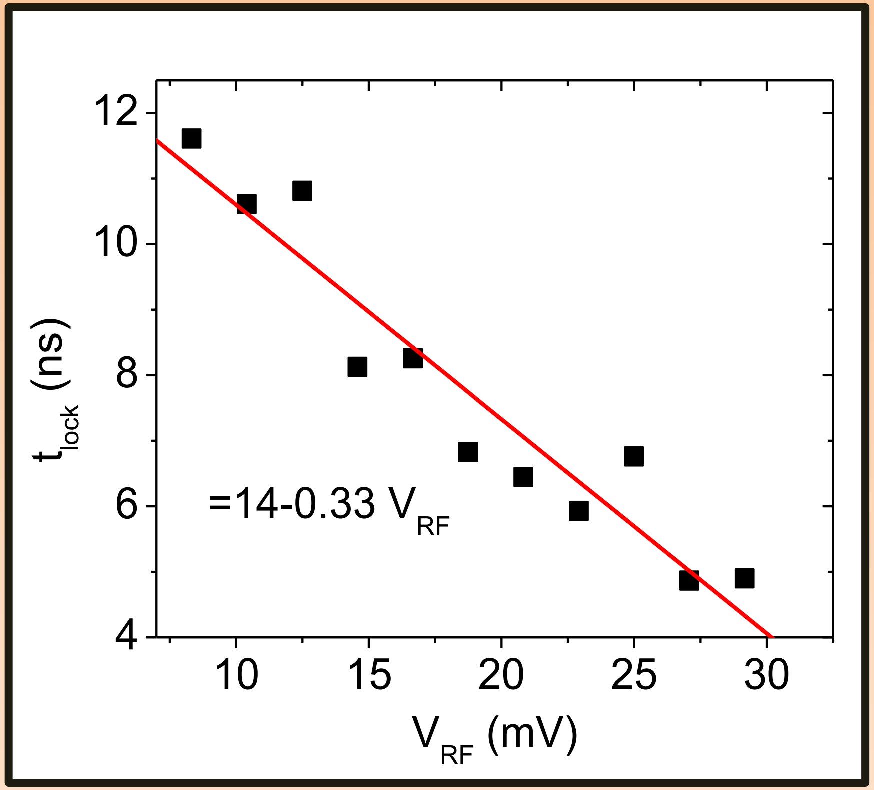
Time Required for Locking

Locking to Pulsed Microwaves



- Consider“locked” when envelope reaches 90% of steady-state amplitude.

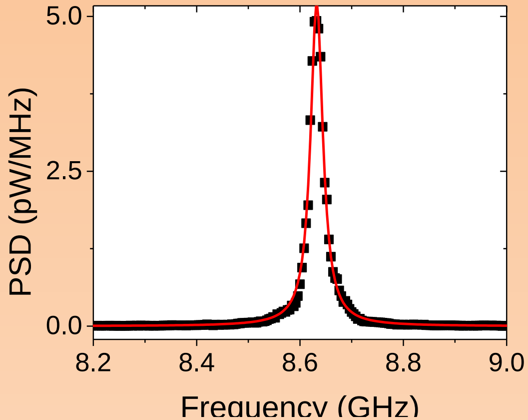
Locking Time vs. RF Voltage



- **Locking can occur in a few 10’s of cycles.**
- Locking time varies quasi-linearly with RF.
- Consistent with Adler ~ 1/V_{RF}.
- Minimum V_{RF} required to lock agrees with CW measurements.

Quantifying Oscillator Performance

$$V(t) = \left[V_0 + \varepsilon(t)\right]\sin\left[2\pi\nu_0 t + \phi(t)\right]$$



- **Simple method: Spectrum analyzer**
  - Measures power spectrum of *V*(*t*)
  - But, cannot separate $\varepsilon(t)$ and $\phi(t)$
  - May depend on measurement time
- **Better method: Direct measurement of $\phi(t)$ or $\nu(t)$**
  - Not affected by $\varepsilon(t)$
  - Power spectrum of $\phi(t)$ or $\nu(t)$ easy to compare with theory

	S_ϕ	S_ν
White phase noise	f^{0}	f^{2}
1/*f* phase noise	f^{-1}	f^{1}
Random walk of phase White freq. noise	f^{-2}	f^{0}
1/*f* freq. noise	f^{-3}	f^{-1}
Random walk of freq.	f^{-4}	f^{-2}

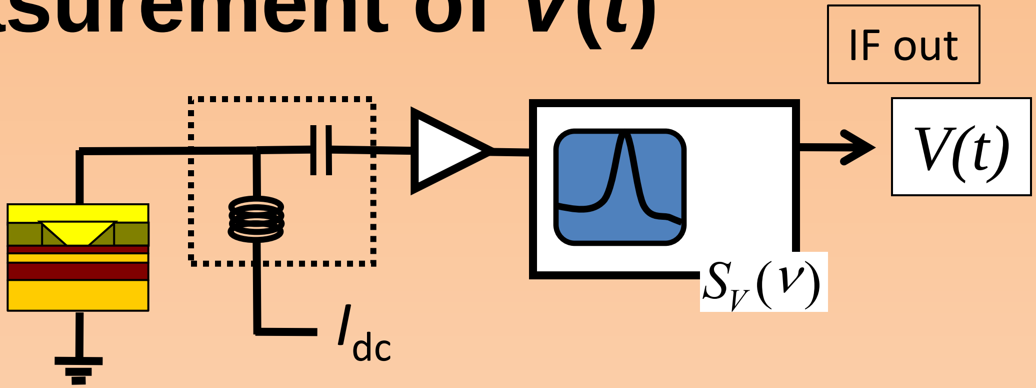
Refs:

Allan variance James Barnes and David Allan, 1964 (NIST)

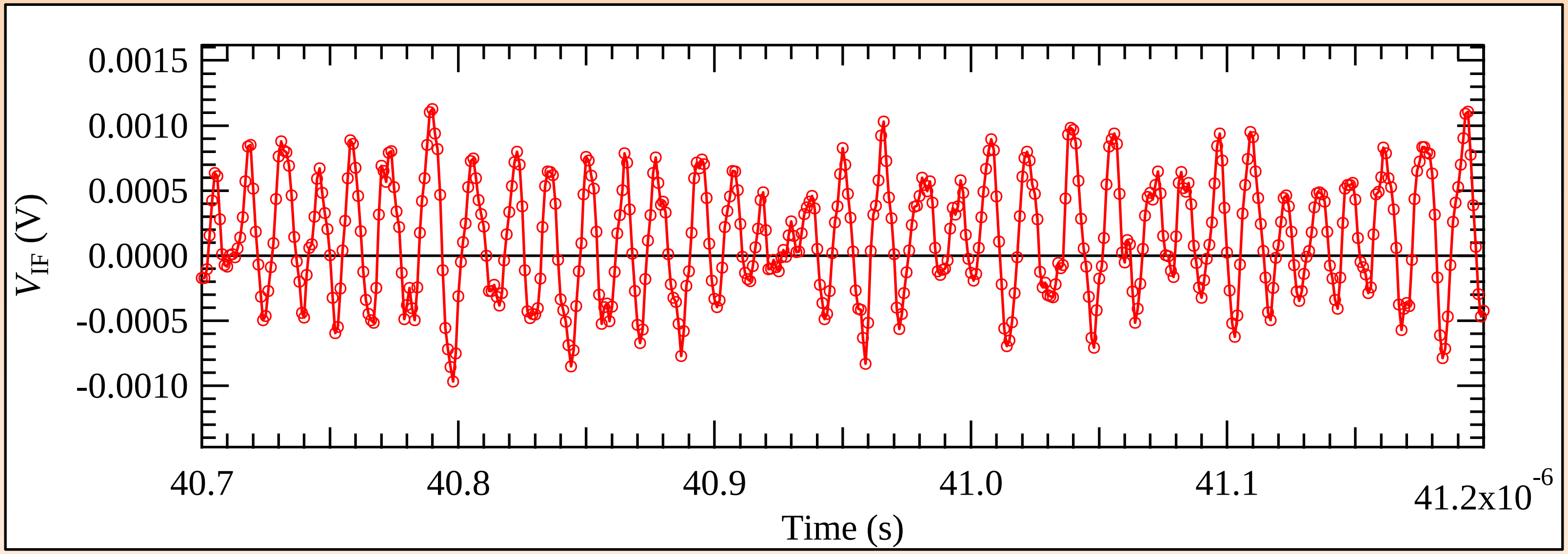
Collected papers NIST Technical Note 1337 (http://tf.nist.gov/general/publications.htm)

Phase noise tutorial http://tf.nist.gov/timefreq/phase/Properties/toc.htm

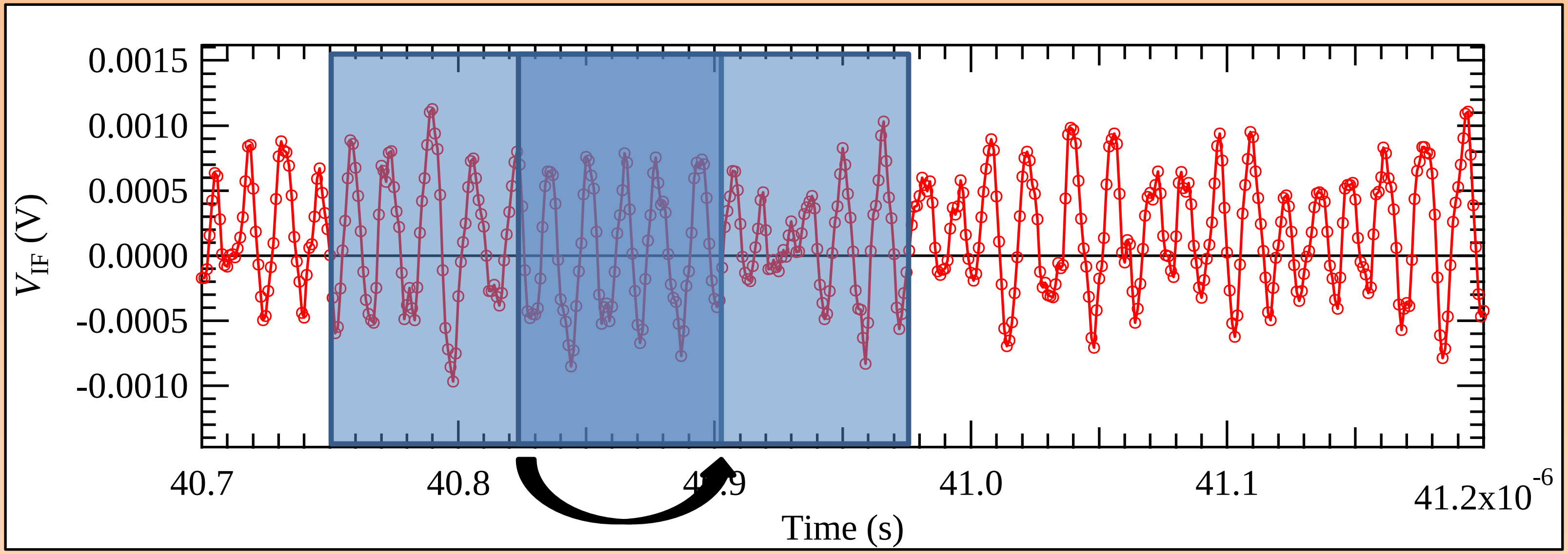
Measurement of *V*(*t*)



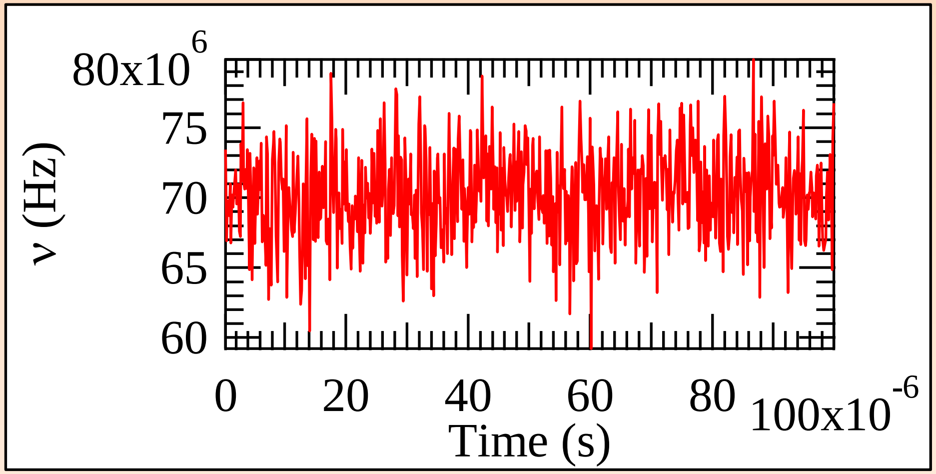
- Resonance is in 5-30 GHz range: directly digitize, or mix down to low frequency—use SA IF (70 MHz+/-30 MHz)
- Amplify, digitize at 1 GS/s (low pass filter @ 150 MHz)



Measurement of f(t): Sliding DFT



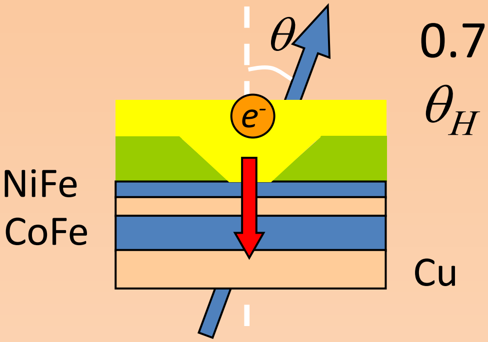
Discrete Fourier transform segments Δt in length, overlapping $\Delta t/2$ to generate $\nu(t)$:



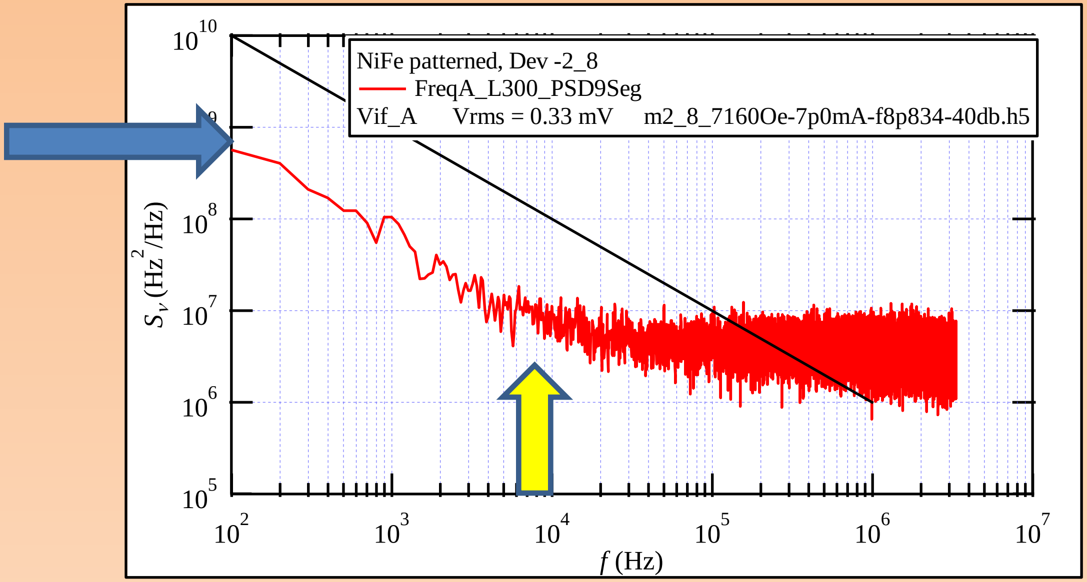
…DFT to get $S_\nu(f)$

Frequency Noise Spectra

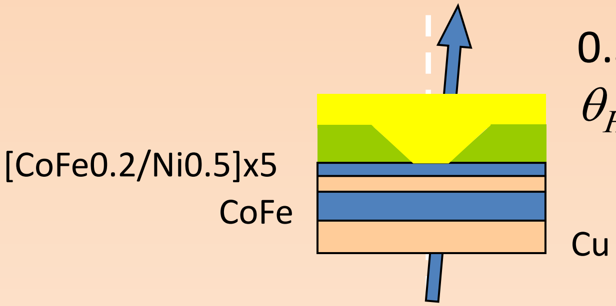
NiFe free layer



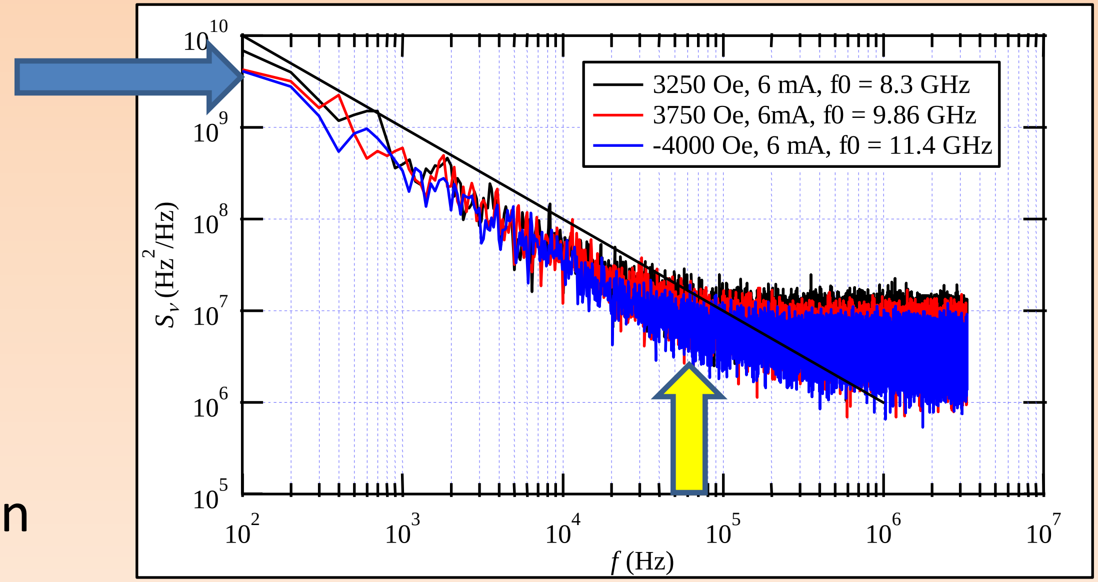
0.72 T,
$\theta_H = 10°$



CoFe/Ni multilayer F.L.



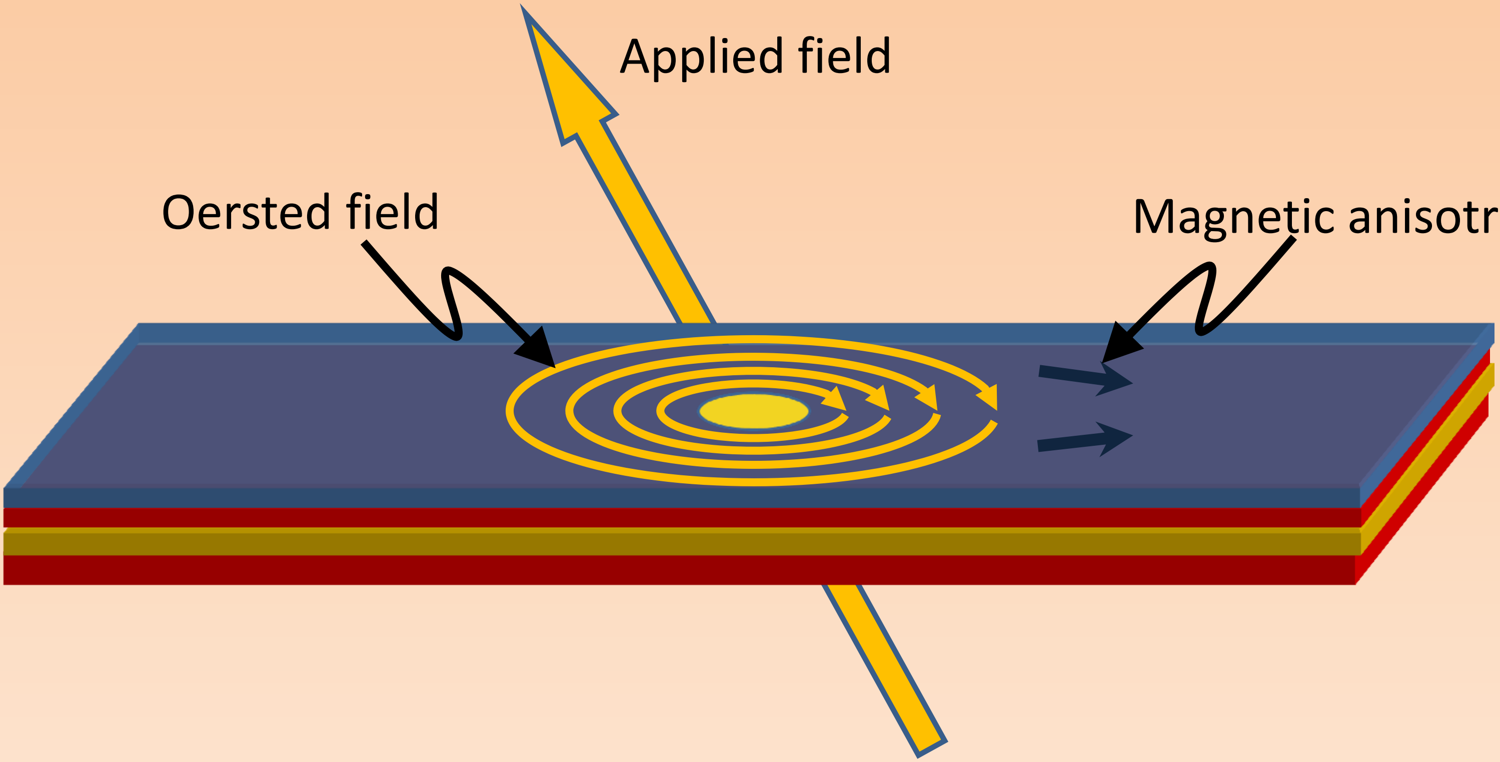
0.3 T
$\theta_H = 1°$



- 1/f variation **dependent on details of free layer**: Unknown relationship

STO: Probe of local magnetic environs

STOs respond to local (*nanoscale*) **net effective field**: Sum of external, current- and spin-induced, and local anisotropy fields

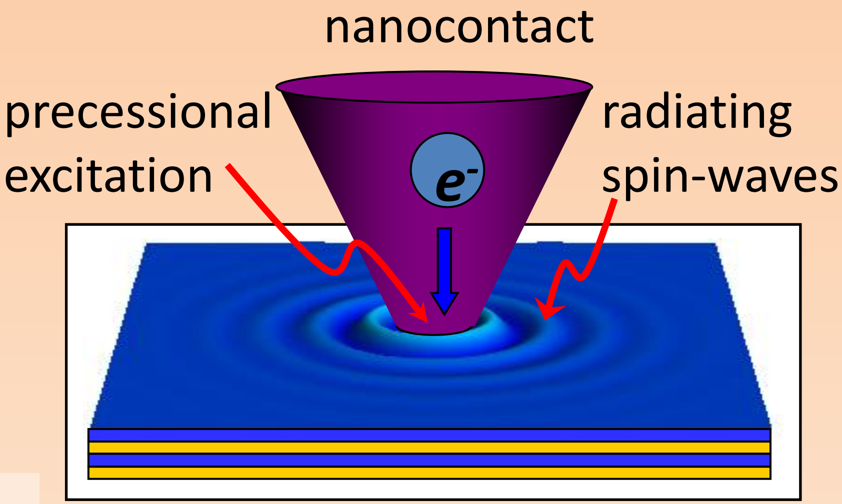


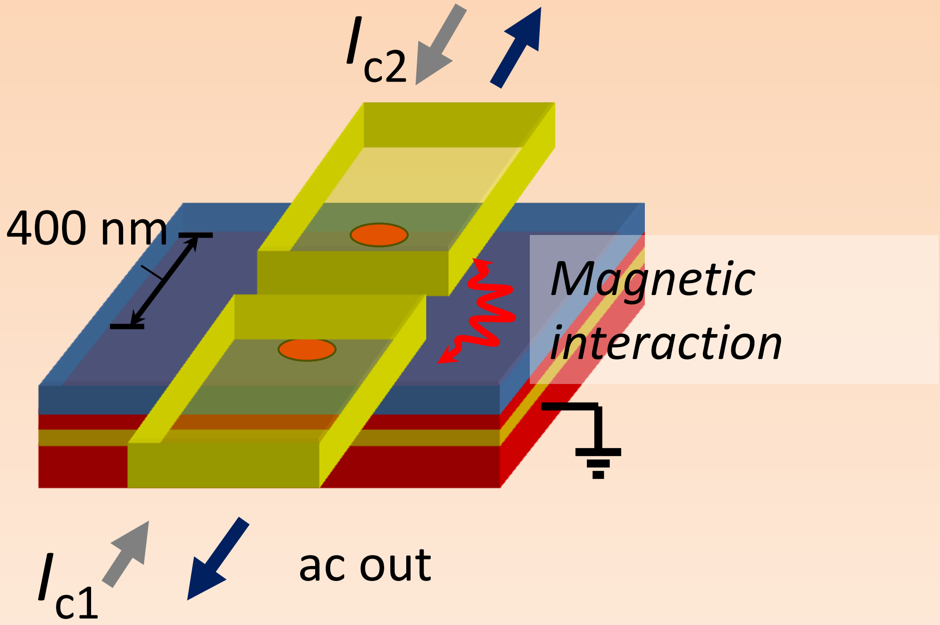
…Device/materials physics challenge: Controlling these fields to produce desired functional behavior

STOs: Mutual Phase Locking

Spin current induces local oscillation of ***M***: couples to surrounding medium → "spin waves"

- Mechanism for coupling oscillators without additional wiring layer
- Additional source/sink for dynamics: Larger effective volume

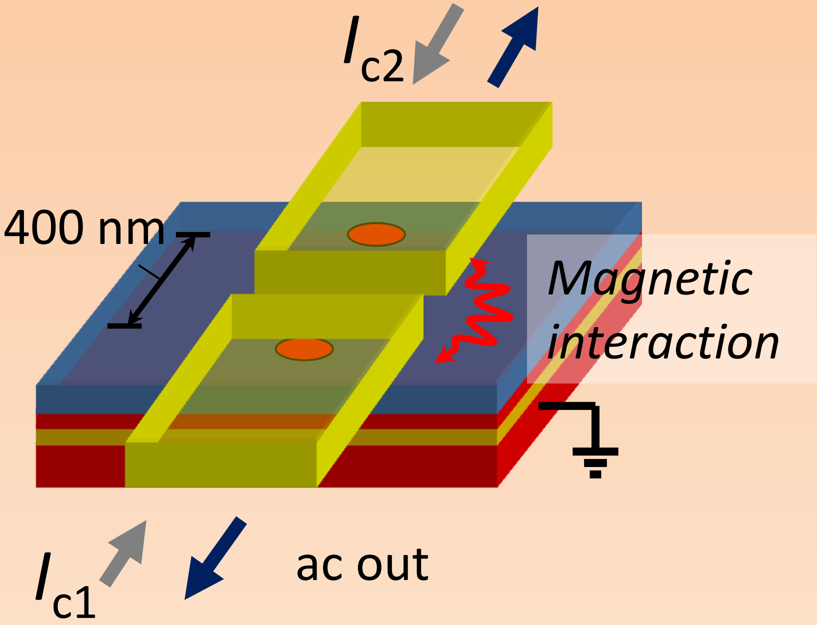


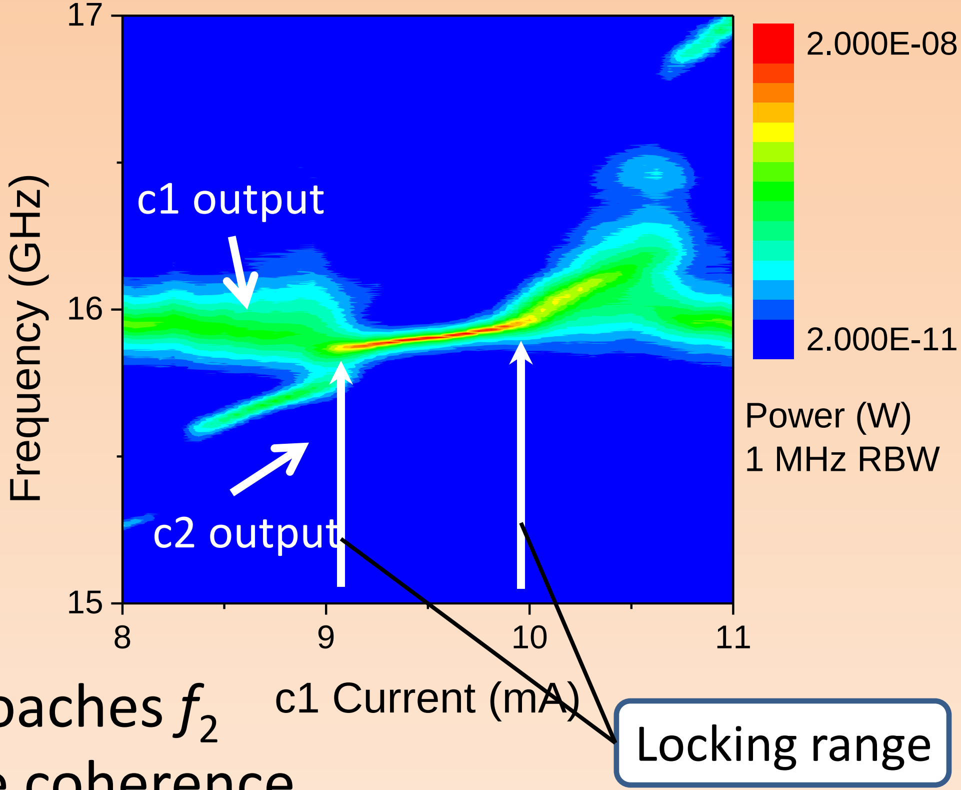


…Bias I_{c2}, sweep I_{c1}

STOs: Mutual Phase Locking

Spin current induces local oscillation of ***M***: couples to surrounding medium → “spin waves”





- Contacts phase lock when f_1 approaches f_2
- Combined power increases: phase coherence
- Line width narrows when locked: **Larger effective volume**

Future directions.

Metrology of **spin currents & transport** in multilayered/ heterogeneous systems:

- Spin orientation is not conserved: Many sources and sinks, transport is 3D
- Spin pumping
- Spin relaxation
- Spin accumulation

Need to be understood for efficient spin circuit design

Metrology of novel spin current sources:

- **Spin Hall Effect**—spin currents from **nonmagnetic** materials
- **Spin Seebeck effect**—spin currents driven by thermal gradients

Other Spintronics Efforts at NIST-Boulder.

RF-STM project (*Mitch Wallis and Pavel Kabos*)

- Calibrated RF-STM measurements at variable temperatures, high frequencies, with magnetic contrast: Potential to image spin waves, spin currents, doping profiles…

Nanomagnetism project (*Justin Shaw, Hans Nembach, Tom Silva*)

- FMR measurements of arrays and individual isolated magnetic elements
- Measurements of spin pumping, spin diffusion

Summary.

- **Spin-based devices have unique metrology challenges**

- Reliability and speed of ST-MRAM devices depend on magnetization dynamics
  - Potentially complicated dependence on **device nanostructure**

- STOs are current tunable, nonlinear, microwave oscillators
  - Potential applications in NonBoolean architectures, microwave circuits
  - Development depends on understanding **nonlinear device dynamics, coupling, & noise**

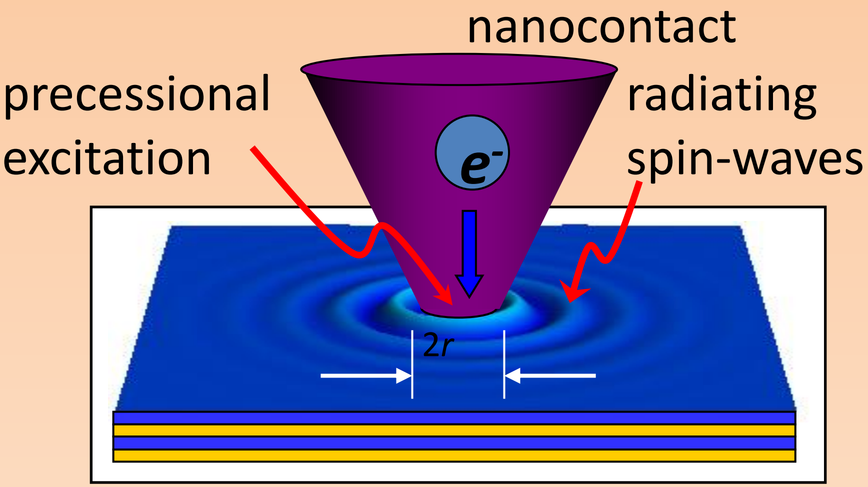
- Future devices will employ pure spin currents: New metrology challenges?

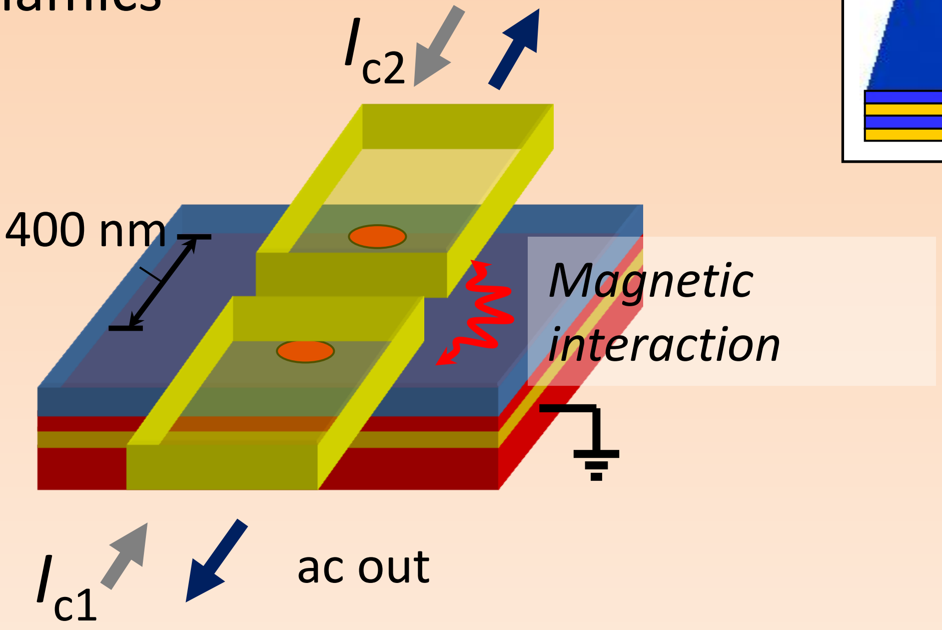
Bonus Slides!

STOs: Mutual Phase Locking

Spin current induces local oscillation of M: couples to surrounding medium → “spin waves”

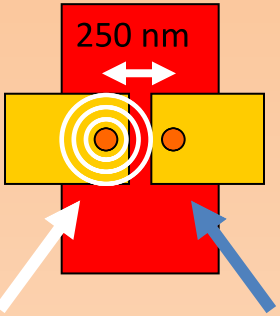
- Mechanism for coupling oscillators without additional wiring layer
- Additional source/sink for dynamics



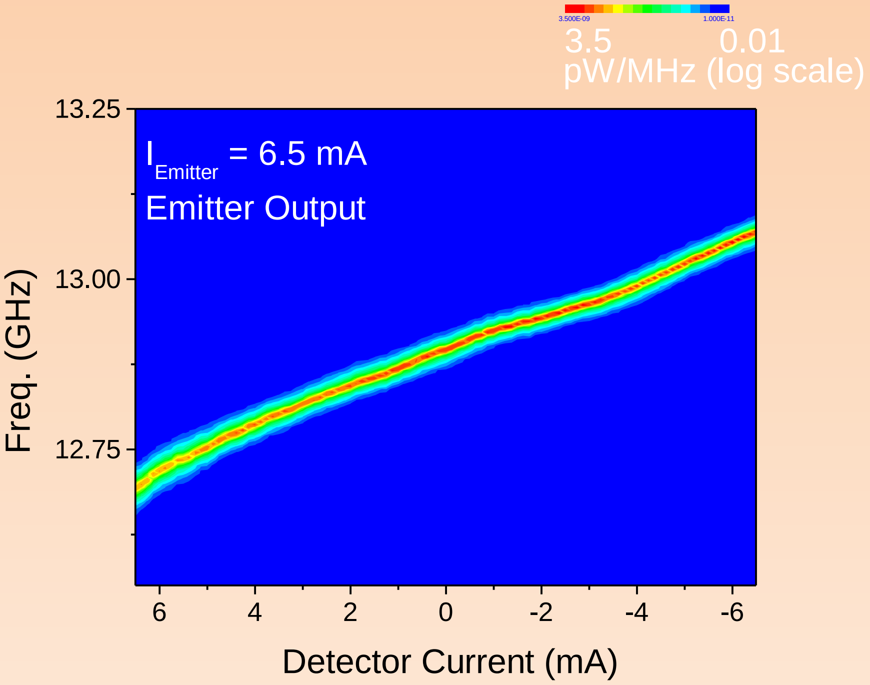


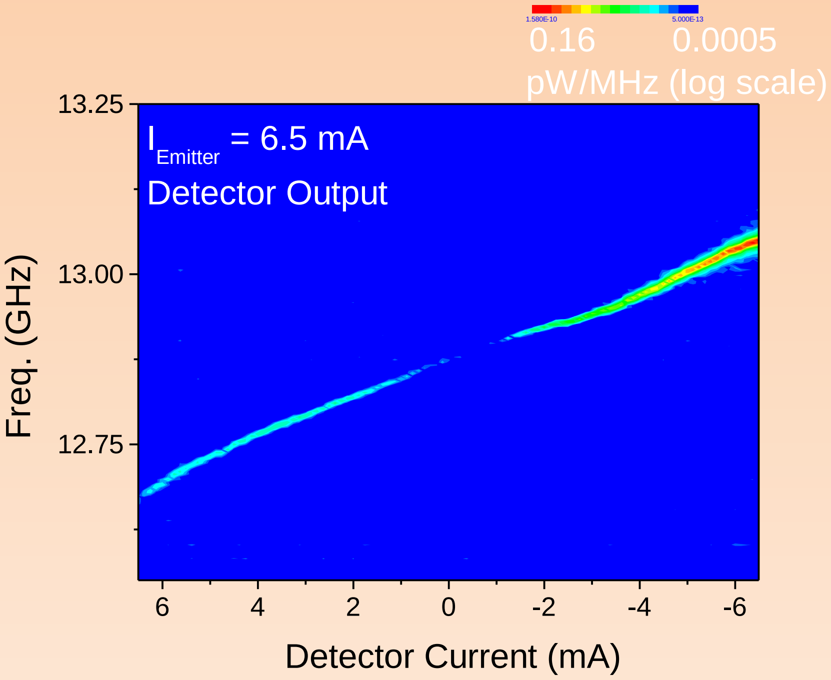
Detection of Spin Waves Using Nanocontact as Detector

Output from precessing (emitter) contact



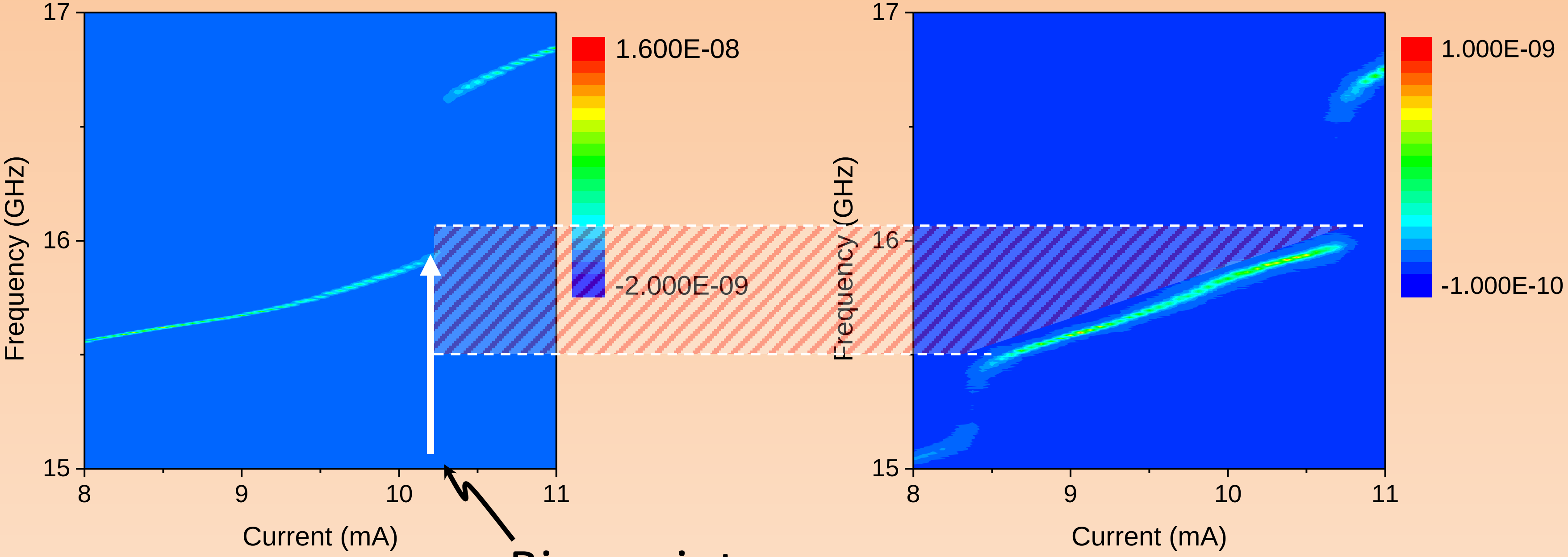
Measured output from detector contact





Spin waves radiated from one contact to the other: coupling mechanism?

Individual Contact Outputs:



contact c1 alone

contact c2 alone

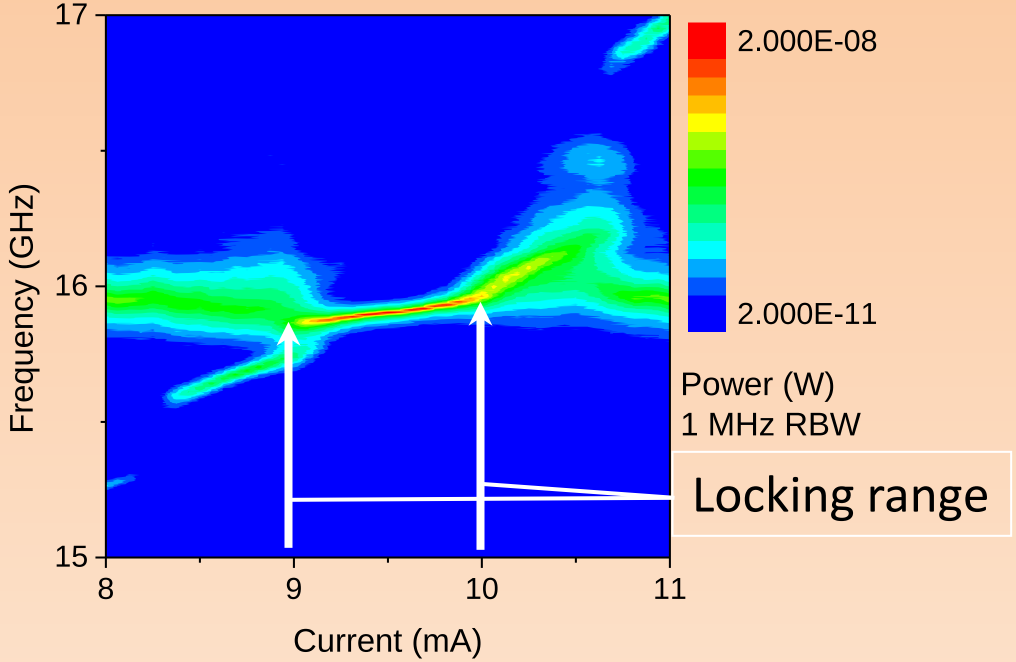
Bias point

…bias contact **c1**, **sweep** current through **c2**

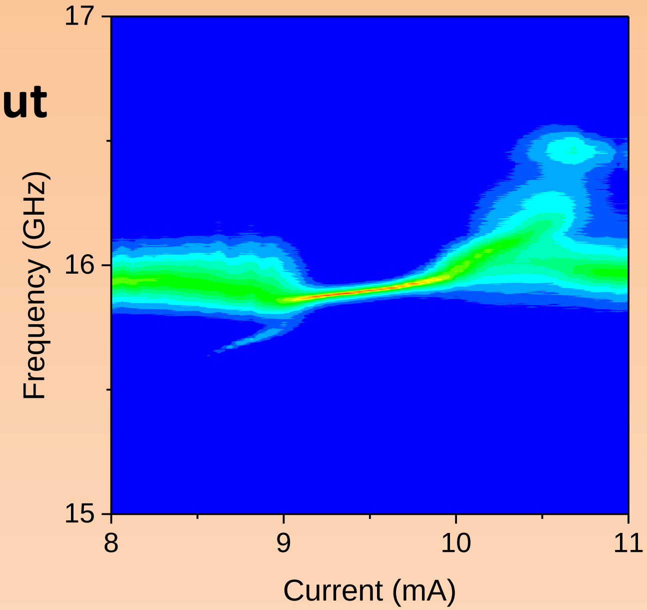
→ Look for interactions between oscillators

Mutual Phase Locking: Spectra

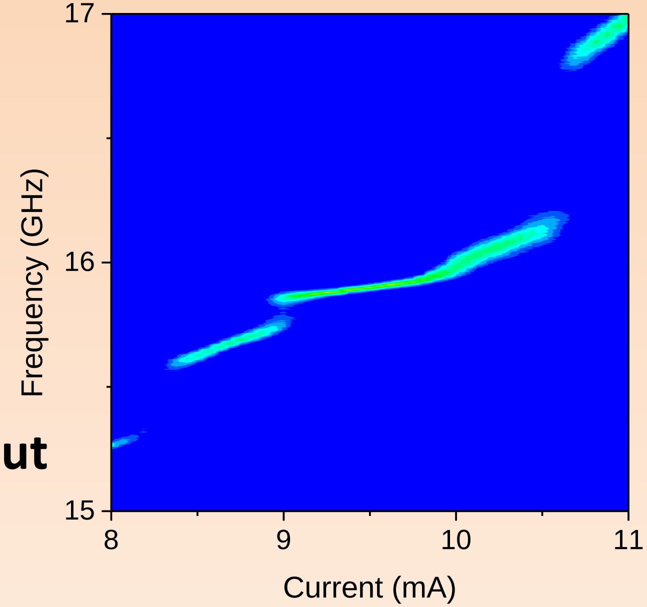
Both contacts measured



c1 output



c2 output



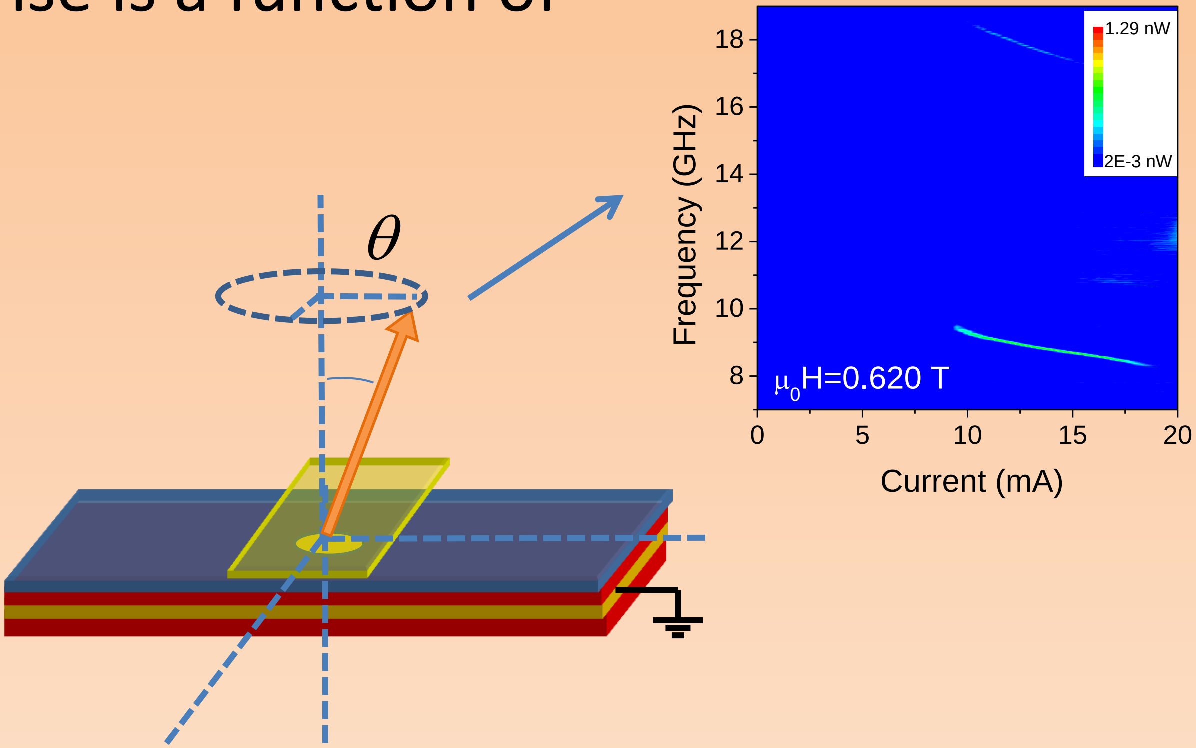
- Devices lock outputs from 9^{+}-10 mA
- Powers combine coherently:

  Need to understand mechanisms setting relative phases

Nature, Sept. 2005, PRL 2006.

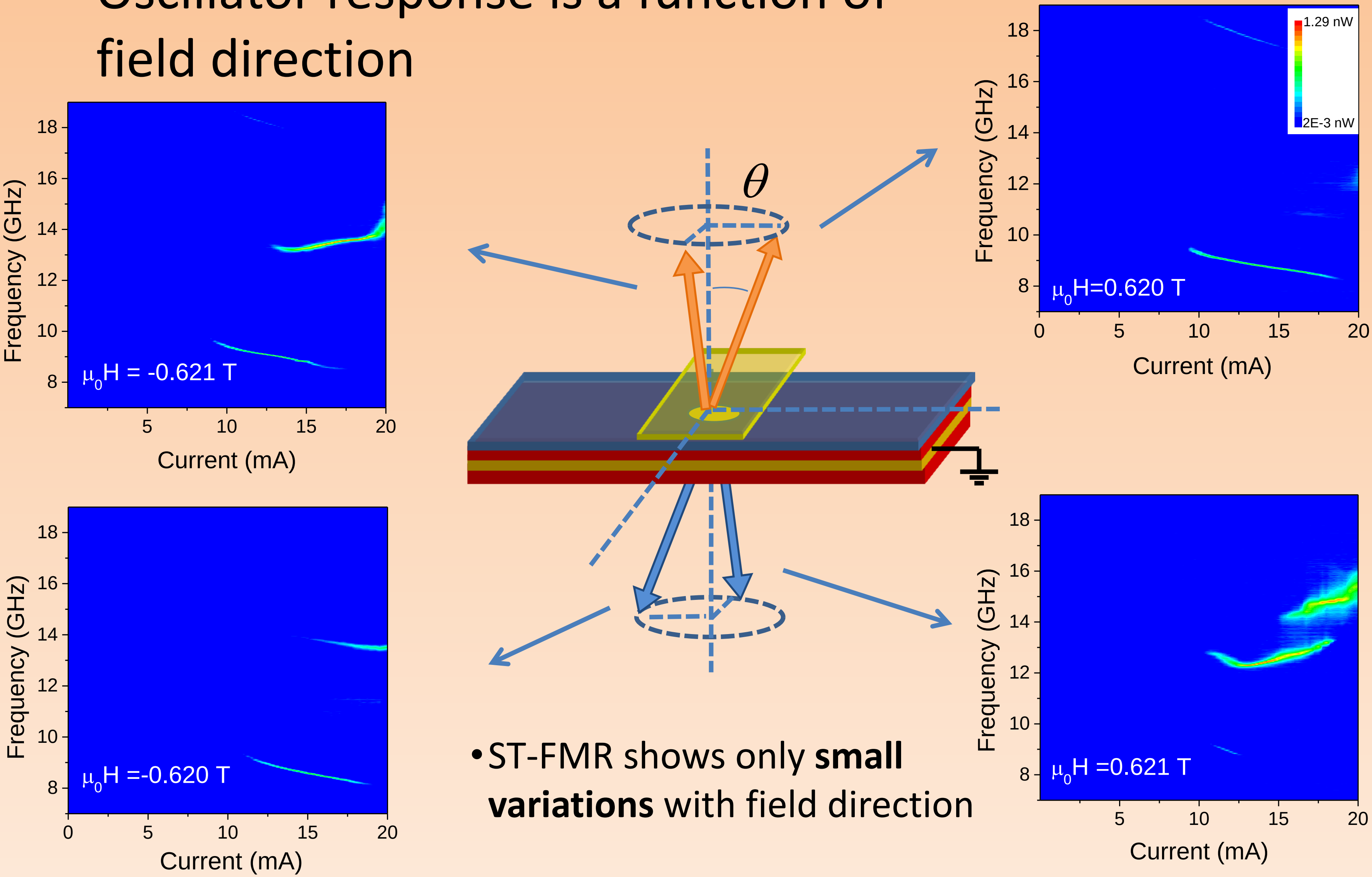
STOs: Probes of local magnetism

Oscillator response is a function of field direction



STOs: Probes of local magnetism

Oscillator response is a function of field direction



- ST-FMR shows only **small variations** with field direction