



ANTENNA DEVELOPMENT FOR MULTIFUNCTIONAL ARMOR APPLICATIONS USING EMBEDDED SPIN-TORQUE NANO-OSCILLATOR (STNO) AS A MICROWAVE DETECTOR

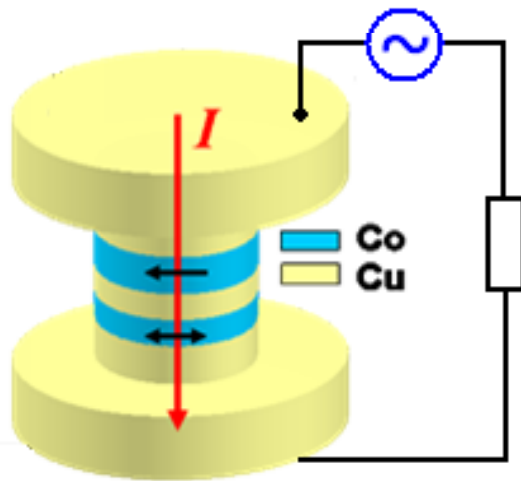
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SPIN-TORQUE DIODE EFFECT

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AC current excites magnetization precession
in the free layer (spin torque)



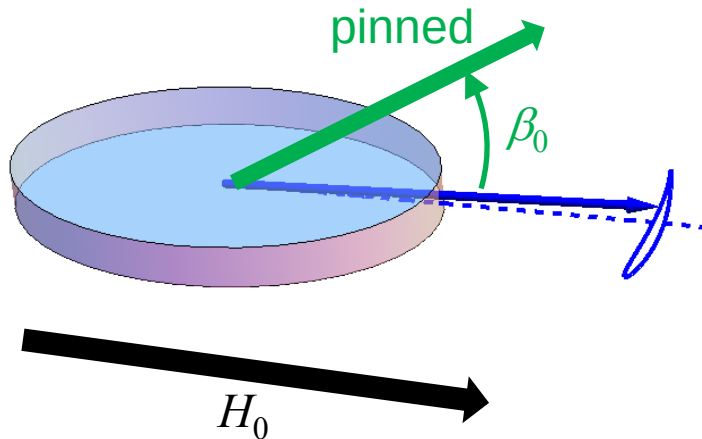
AC variations of the electrical resistance of the
structure (GMR/TMR/MTJ)



rectified dc voltage:

$$V_{\text{dc}} = \langle R(t) I_{\text{ac}}(t) \rangle$$

Standard “in-plane” spin-torque diode



Spin torque excites small-angle magnetization precession about equilibrium direction

- Resonance diode frequency $\approx$ FMR frequency ω_{FMR}
- Frequency range of detection $\approx$ FMR linewidth Γ
- Output voltage $\propto$ square of the input current I_{ac} (quadratic detector)
- Efficiency strongly depends on the angle β between magnetizations of the free and pinned layers

$$V_{\text{dc}} \propto \frac{I_{\text{ac}}^2 \sin^2(\beta_0)}{\Gamma^2 + (\omega - \omega_{\text{FMR}})^2}$$

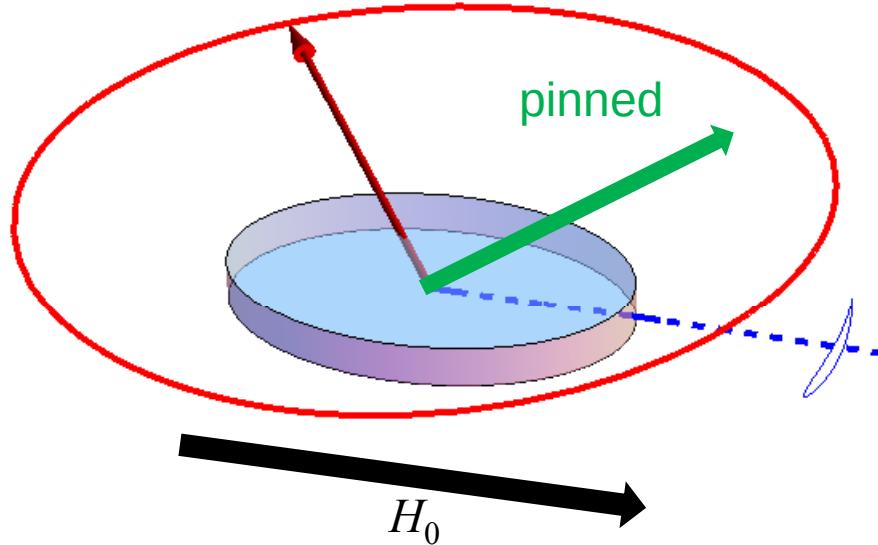
Diode sensitivity:

$$\kappa = \frac{\text{output voltage}}{\text{input power}} \sim 1000 \frac{\text{mV}}{\text{mW}}$$

C. Wang et al., JAP **106**, 053905 (2009)

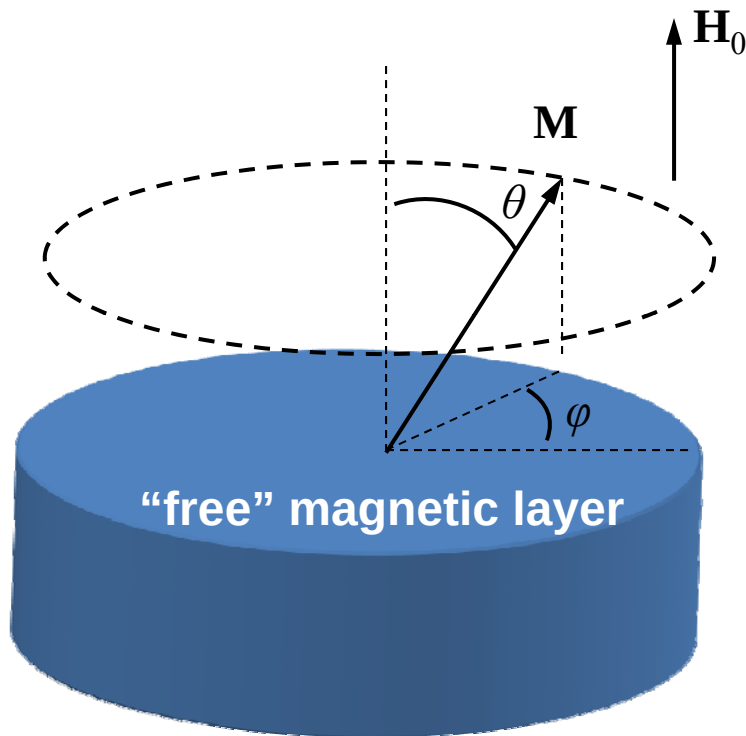
“Out-of-plane” spin-torque diode

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*Spin torque **can** excite
large-angle out-of-plane
magnetization precession*

Theoretical model



- Free layer – circular pillar (no in-plane anisotropy) radius 50 nm, thickness 1 nm
- Resistance: $R_0 = \Delta R = 1 \text{ k}\Omega$
- Bias magnetic field – perpendicular to the plane, **smaller than the saturation field**, $H_0 < 4\pi M_s$
- Magnetization of the pinned layer – in plane (along x axis)
- No dc bias current

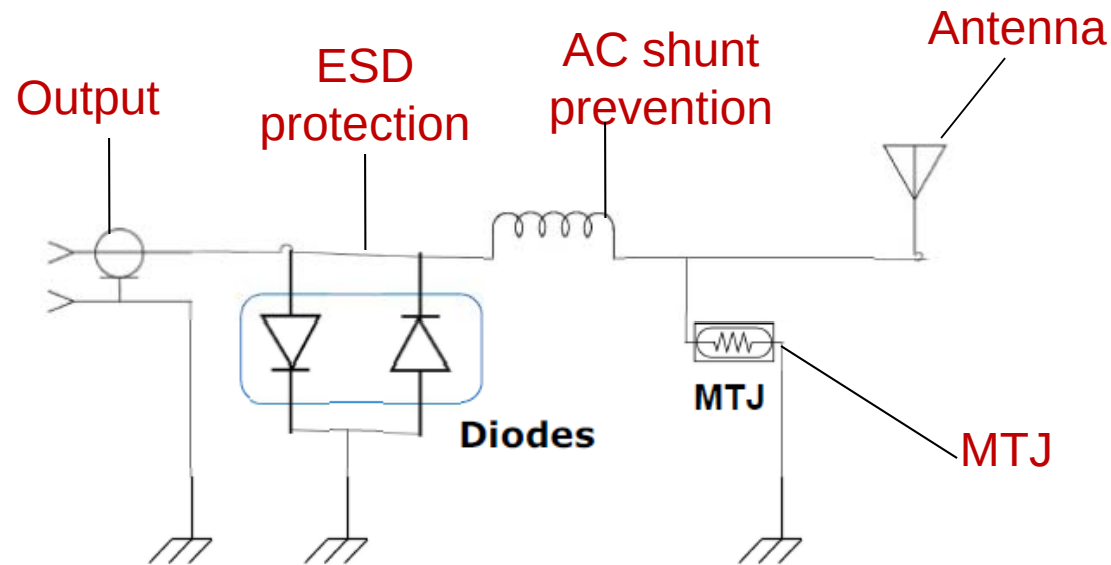
Angular dependence of the resistance:

$$R(\beta) = R_0 - \frac{\Delta R}{2} \cos \beta$$

$$\cos \beta = \cos \theta(t) \cos \phi(t)$$

Block- Diagram of the Spintronic MTJ Sensor

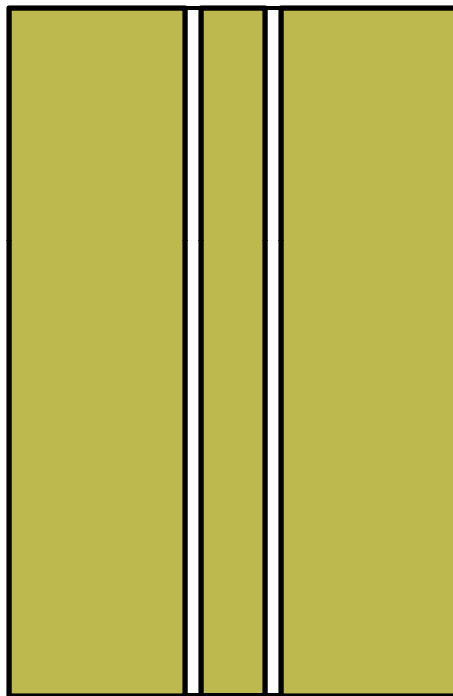
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Spintronic microwave sensor circuit design includes:

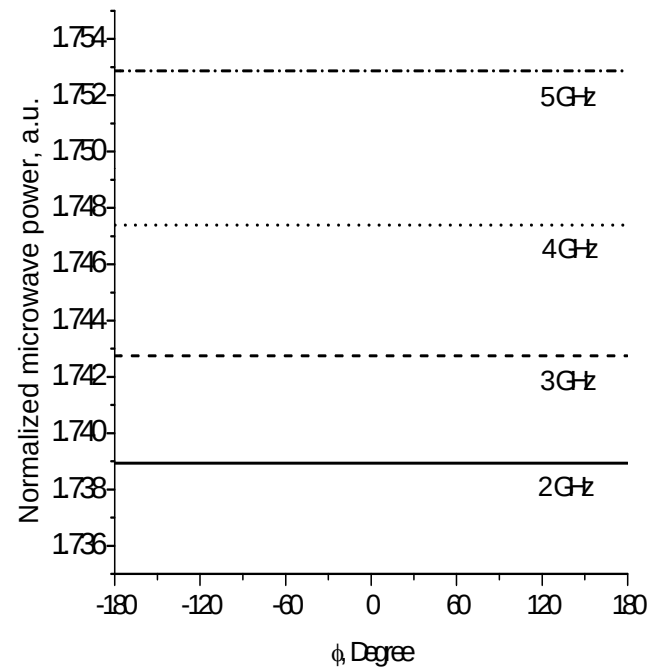
- Coplanar Waveguide (CPW) antenna
- Magnetic Tunnel Junction (MTJ) detector
- ESD protection circuit

Design of the sensor antenna

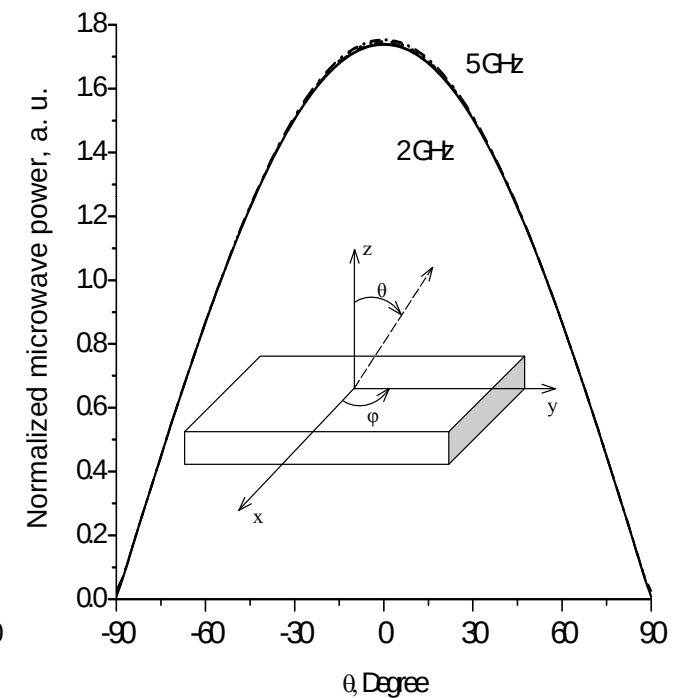


Coplanar waveguide (CPW) antenna

In-plane angle

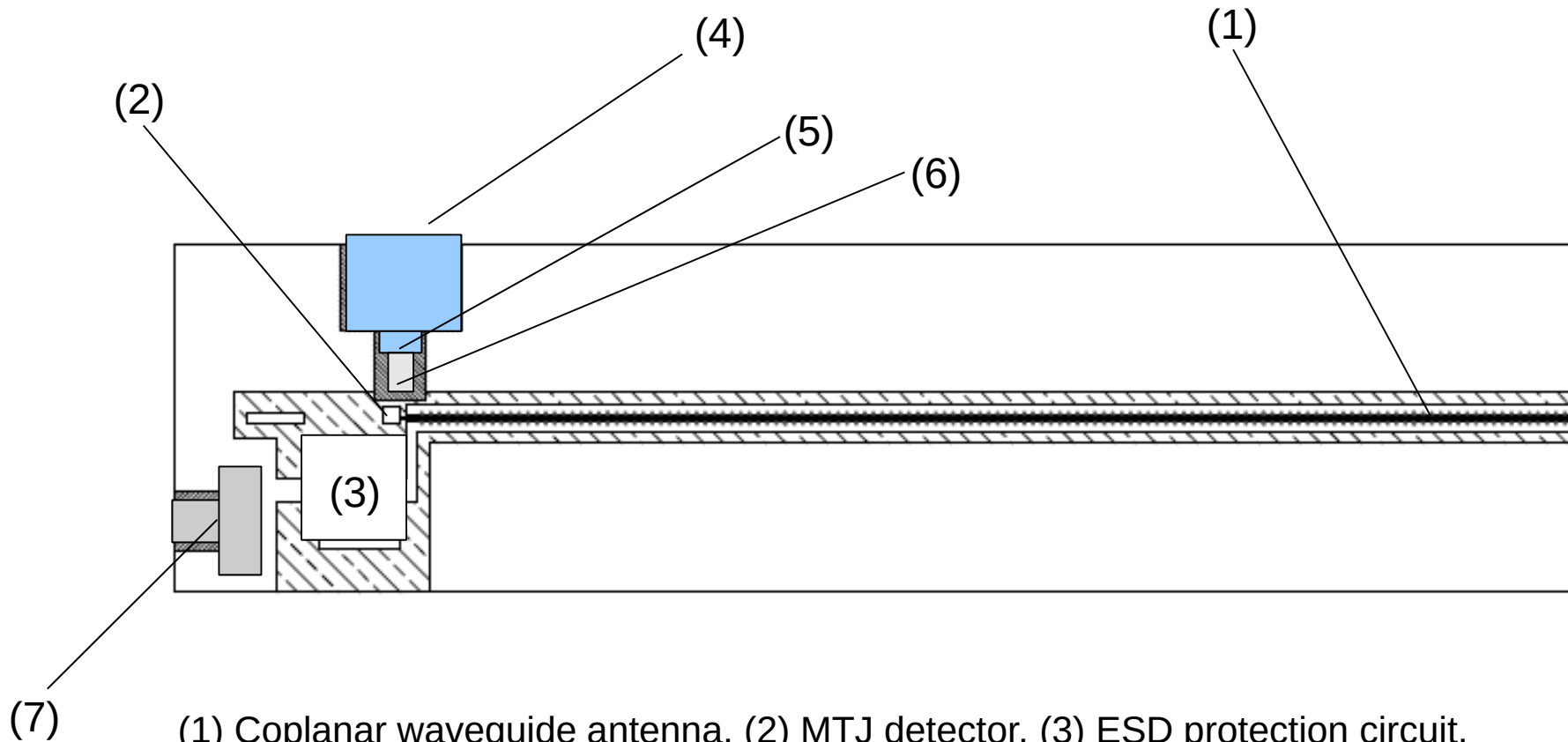


Out-of-plane plane angle



Projections of the CPW antenna directional diagram

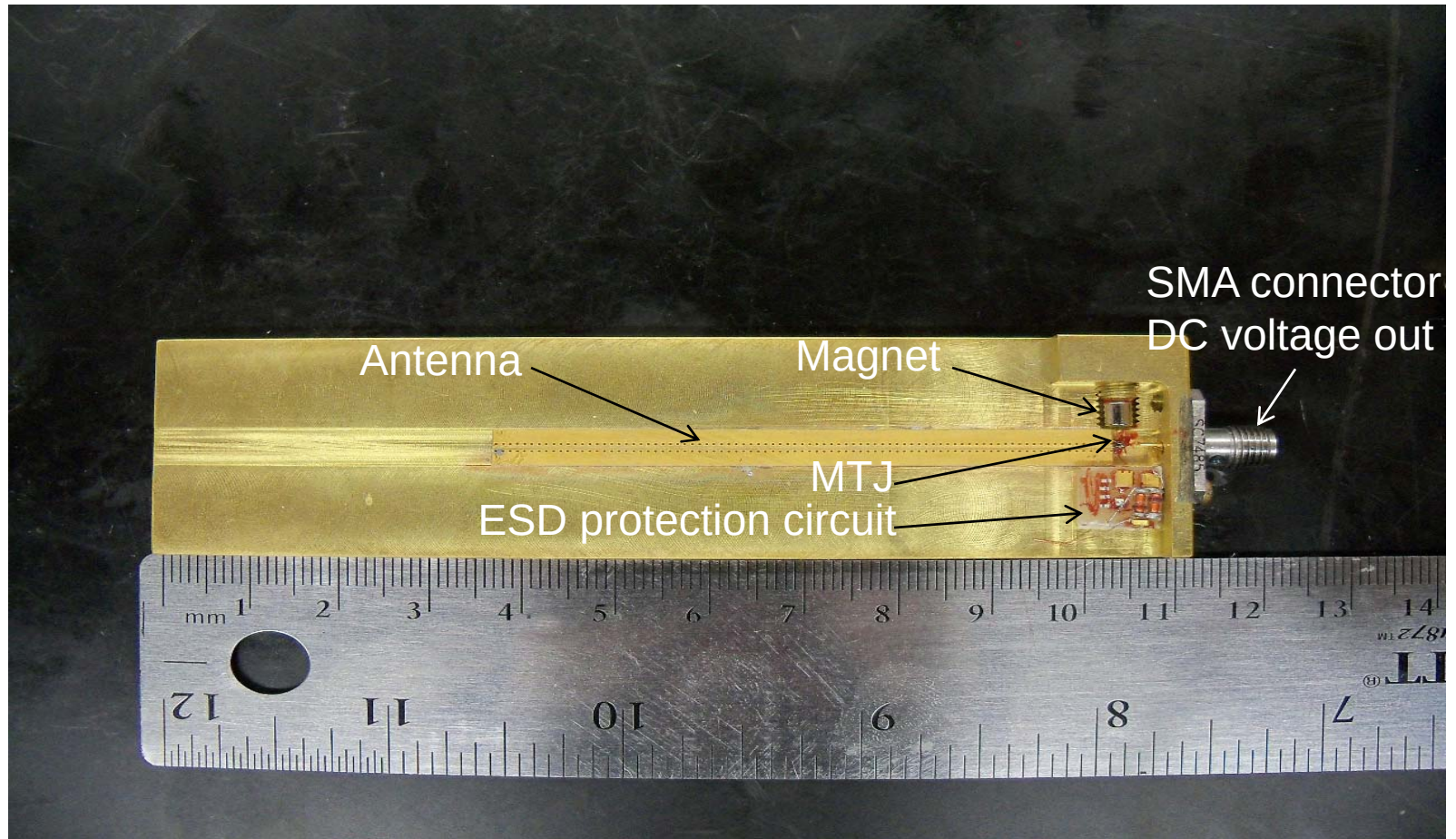
Design of the MTJ sensor



(1) Coplanar waveguide antenna, (2) MTJ detector, (3) ESD protection circuit, (4) brass screw holder, (5) brass set-screw, (6) magnet, (7) SMA connector.

Fabricated Spintronic MTJ Sensor

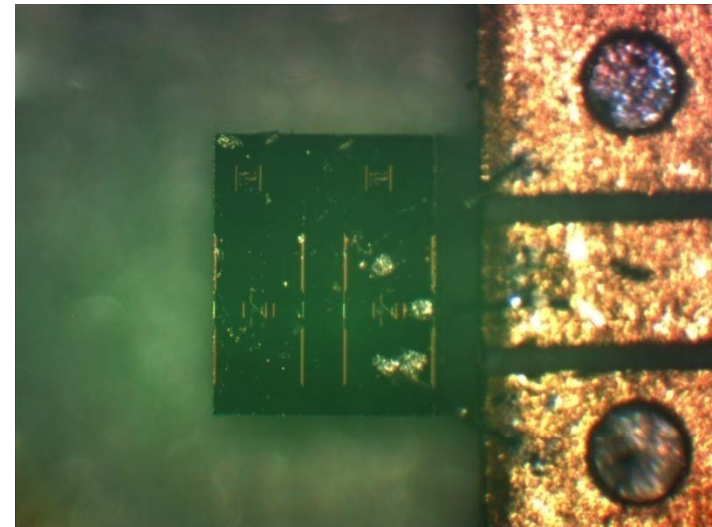
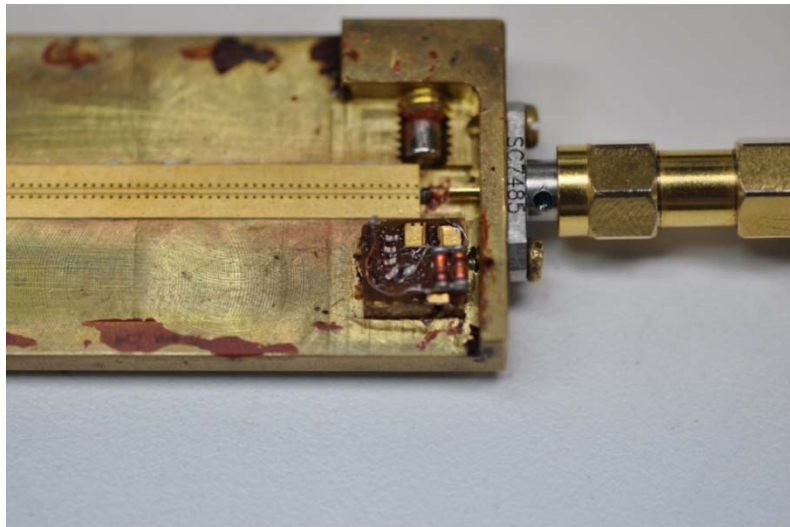
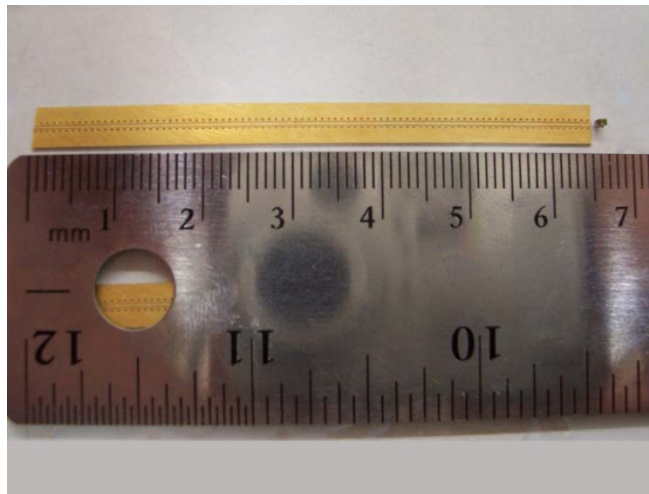
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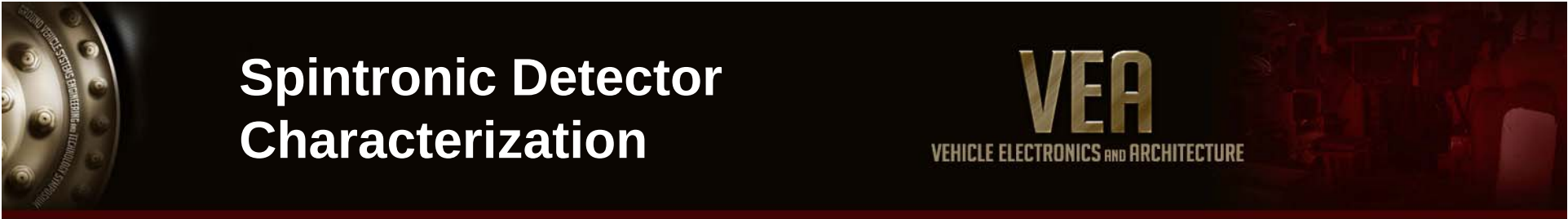


MTJ Detector with CPW Antenna

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Spintronic Detector Characterization

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- 1 – 6 GHz initial scan done to determine approximate resonance frequency
 - A group detectors with in-plane magnetization: focused scans at 4-6 GHz
 - B group (out-of-plane detectors): focused scans at 1-3 GHz
- 10 Detectors were tuned for maximum sensitivity using the adjustable magnet (set screw from 0 to 3 turns at 1/2 turn increments)
- Multiple peaks were present in some detector plots.
- B group out-of-plane detectors typically had a higher output voltage (5B was the best detector with approximately 6.5 mV output voltage).
- The absolute value of the extrema represented the voltage magnitude
- Tuning the magnet on the B group changed both the sensitivity and the resonance frequency. For the A group, it only changed the sensitivity.

Spintronic Detector Test Setup

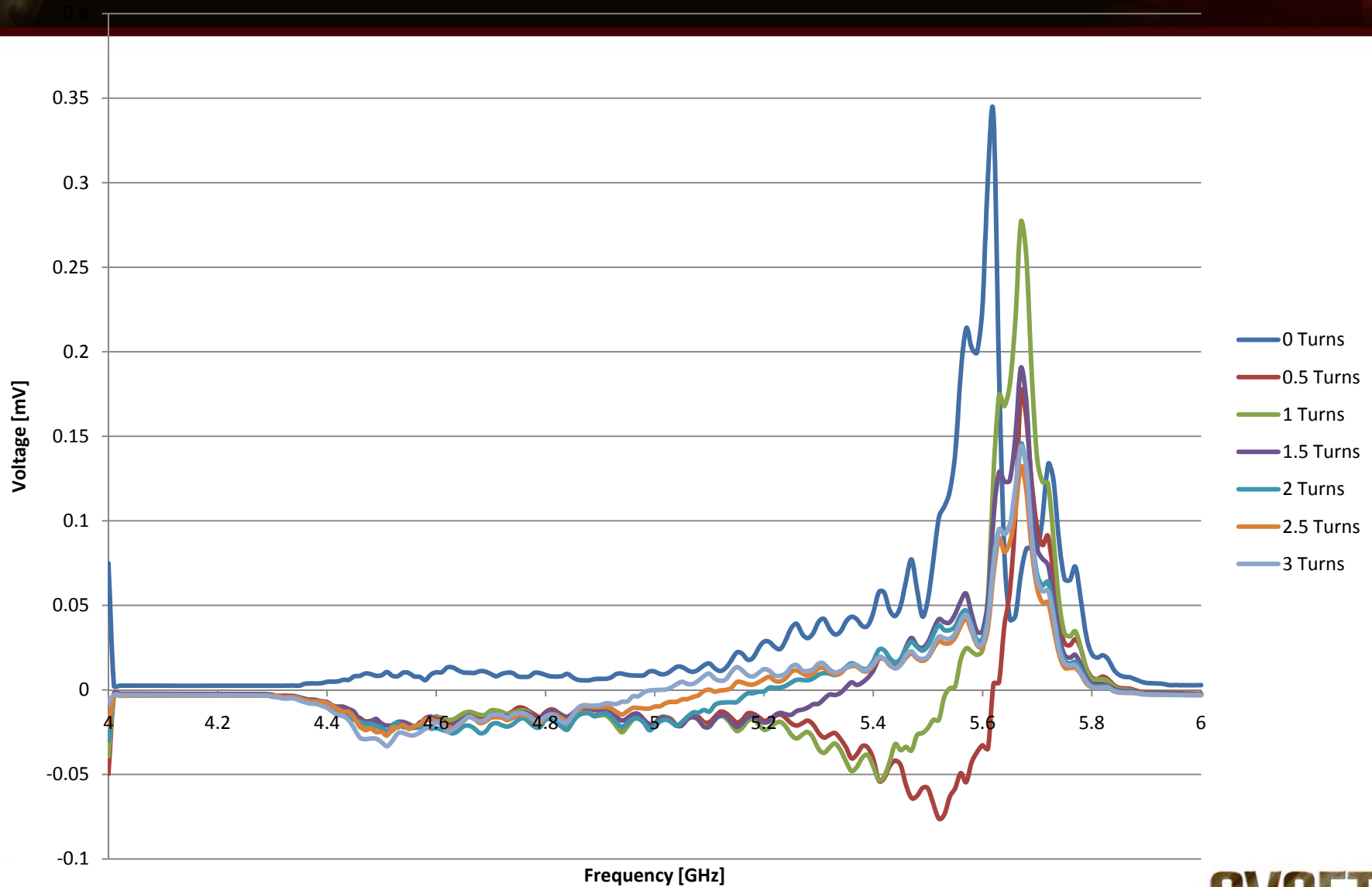
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Detector Characterization: 4A

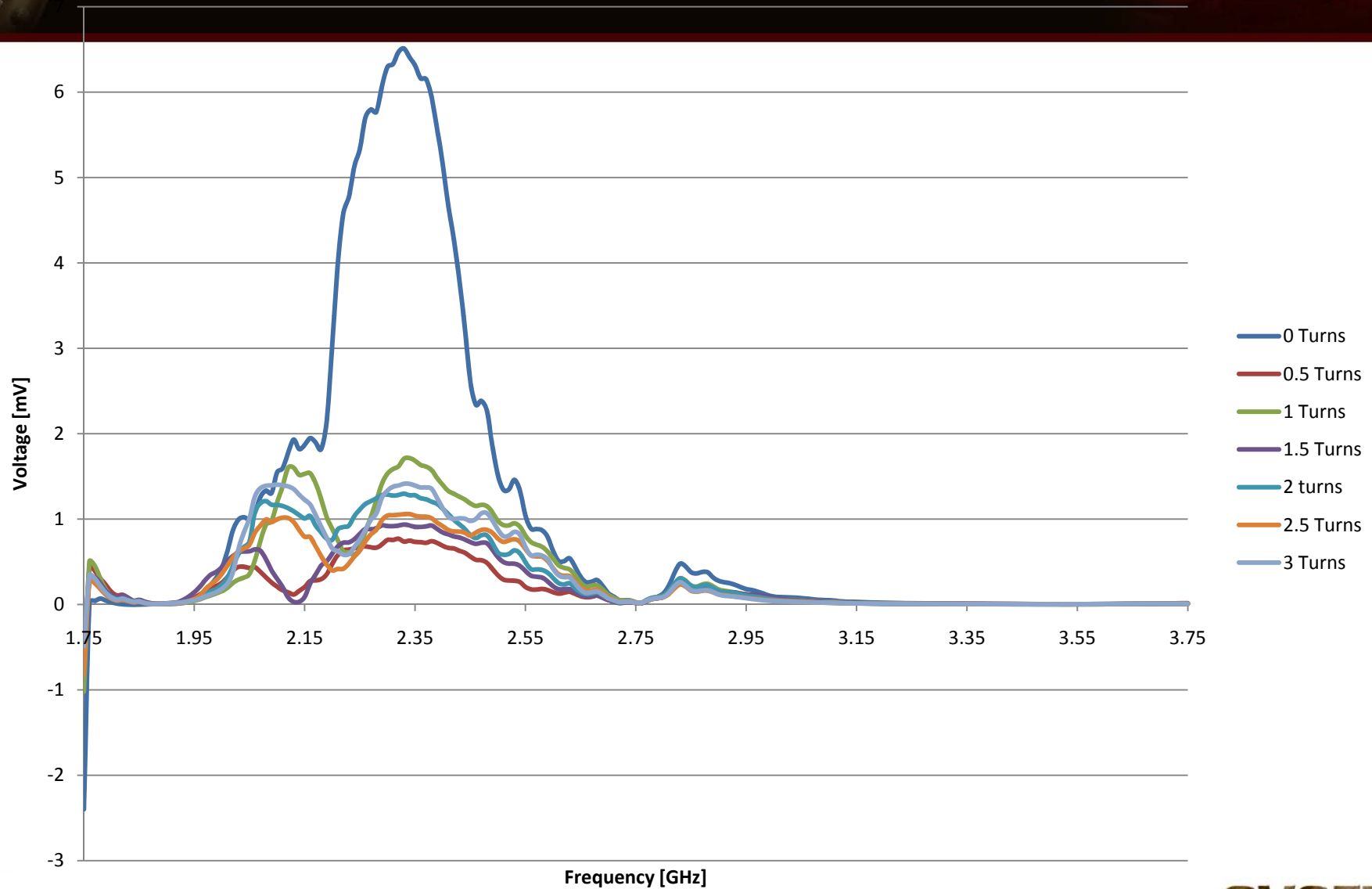
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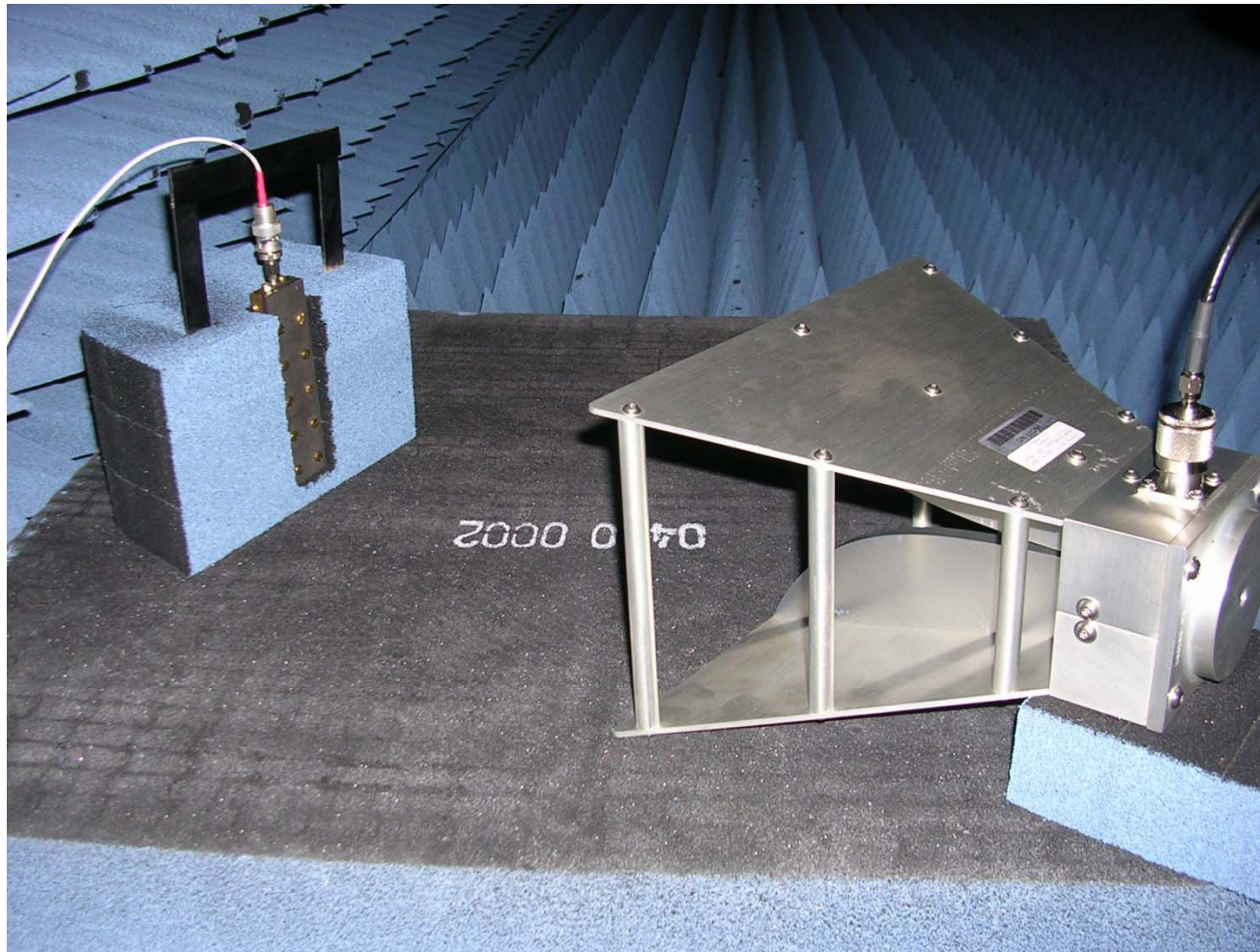
Spintronic Detector Characterization: 5B

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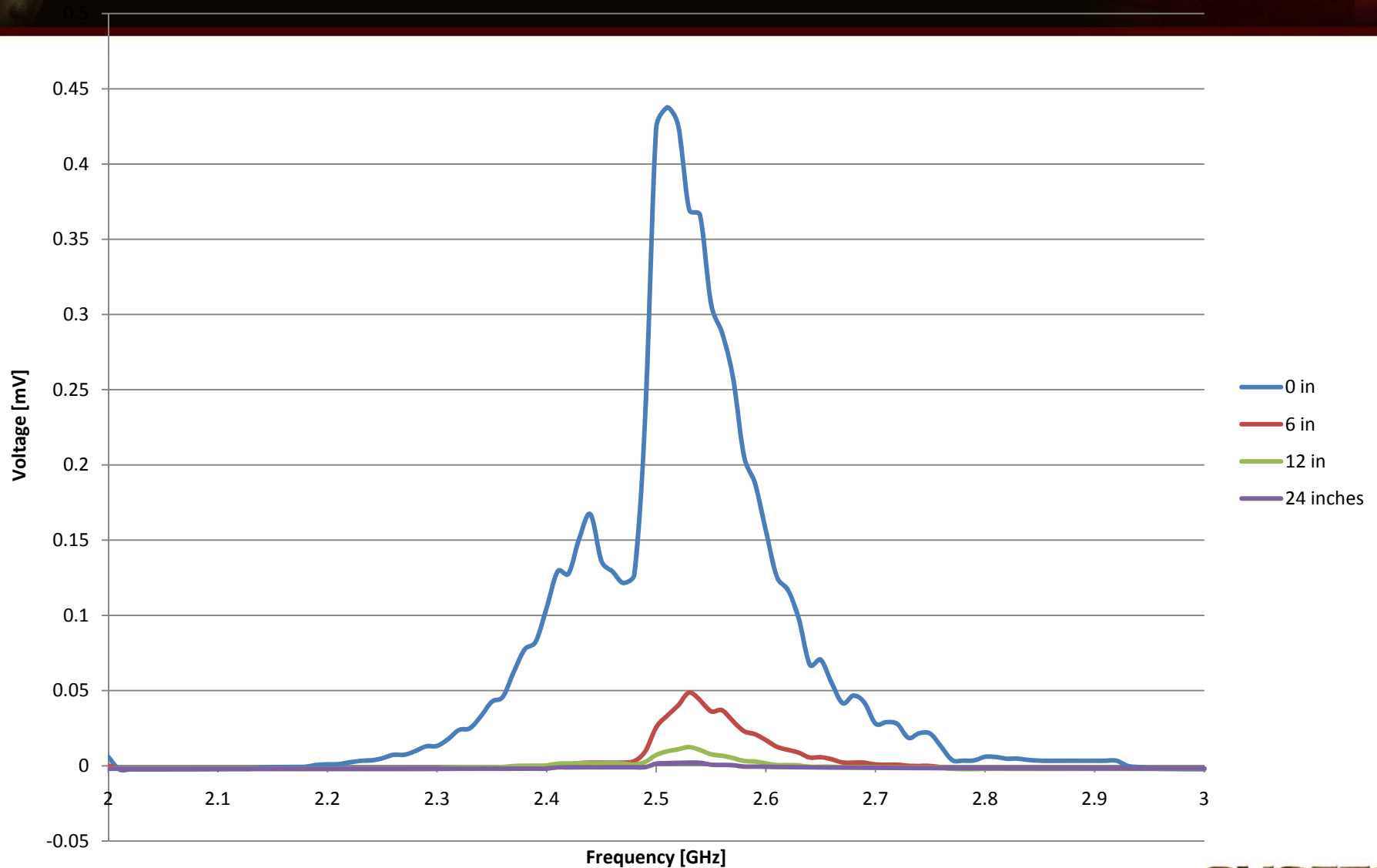
Spintronic Detector Test Inside the Anechoic Chamber

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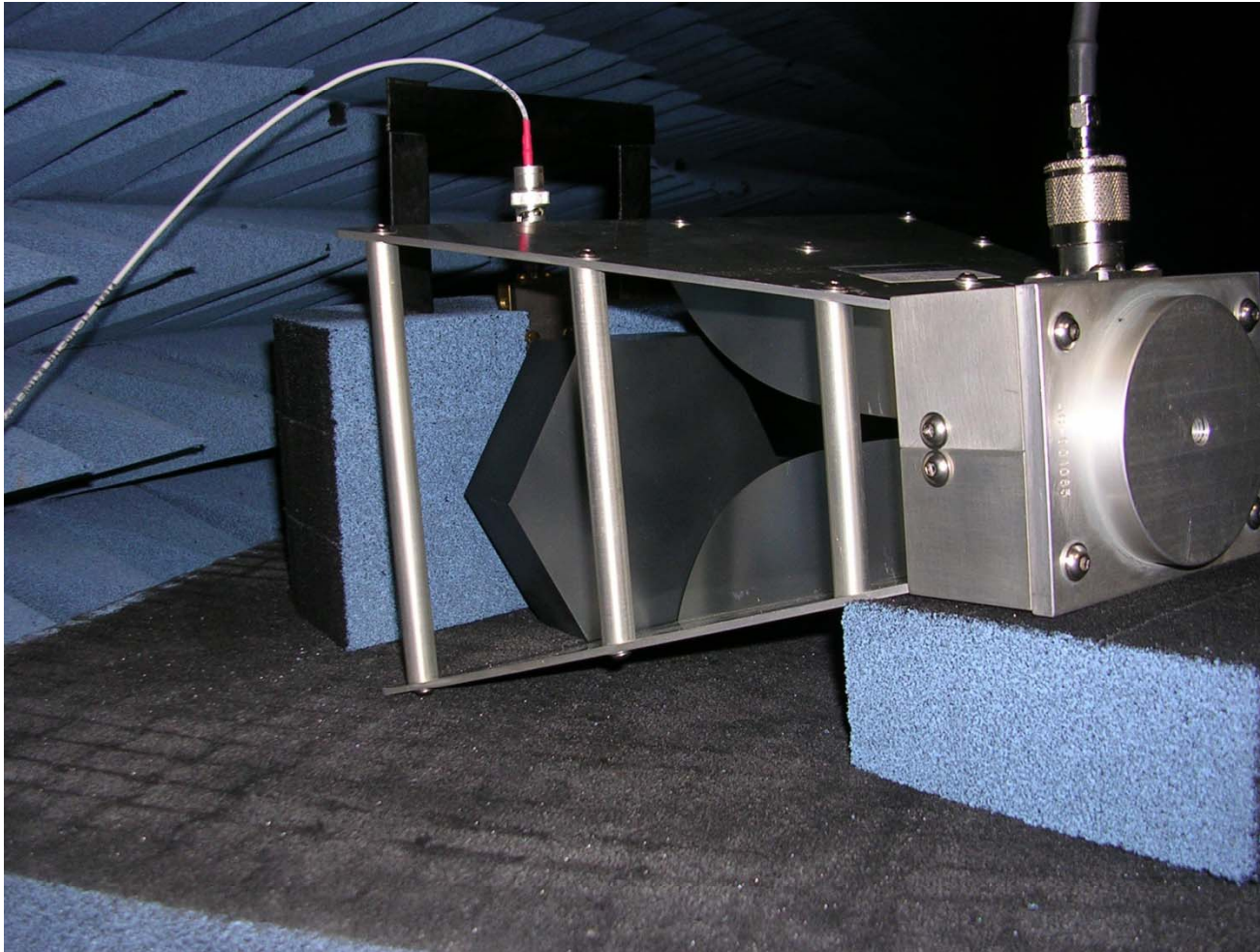
Detector Distance Testing Inside the Anechoic Chamber

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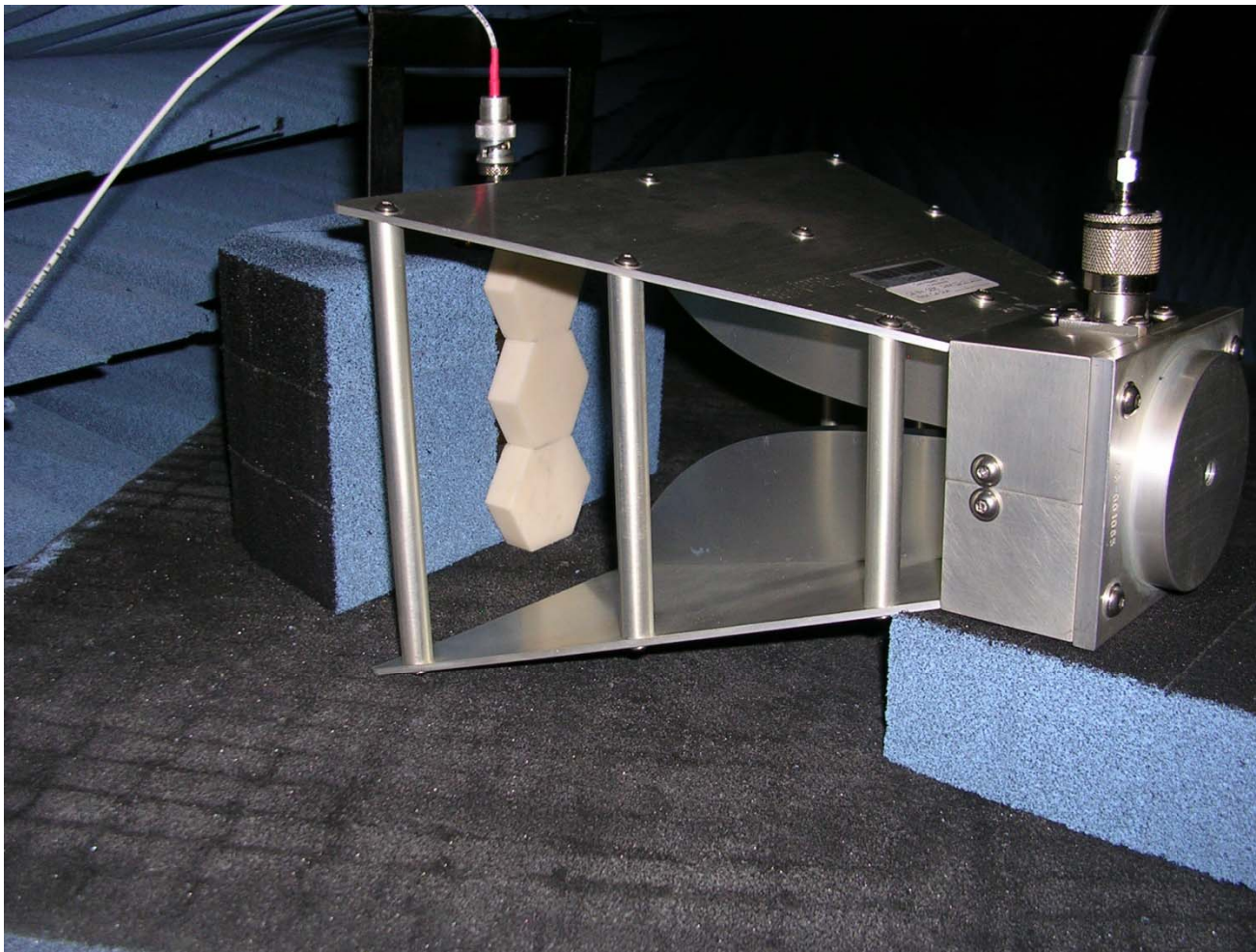
Detector Characterization inside the Anechoic Chamber: Obstacle Comparison - SiC

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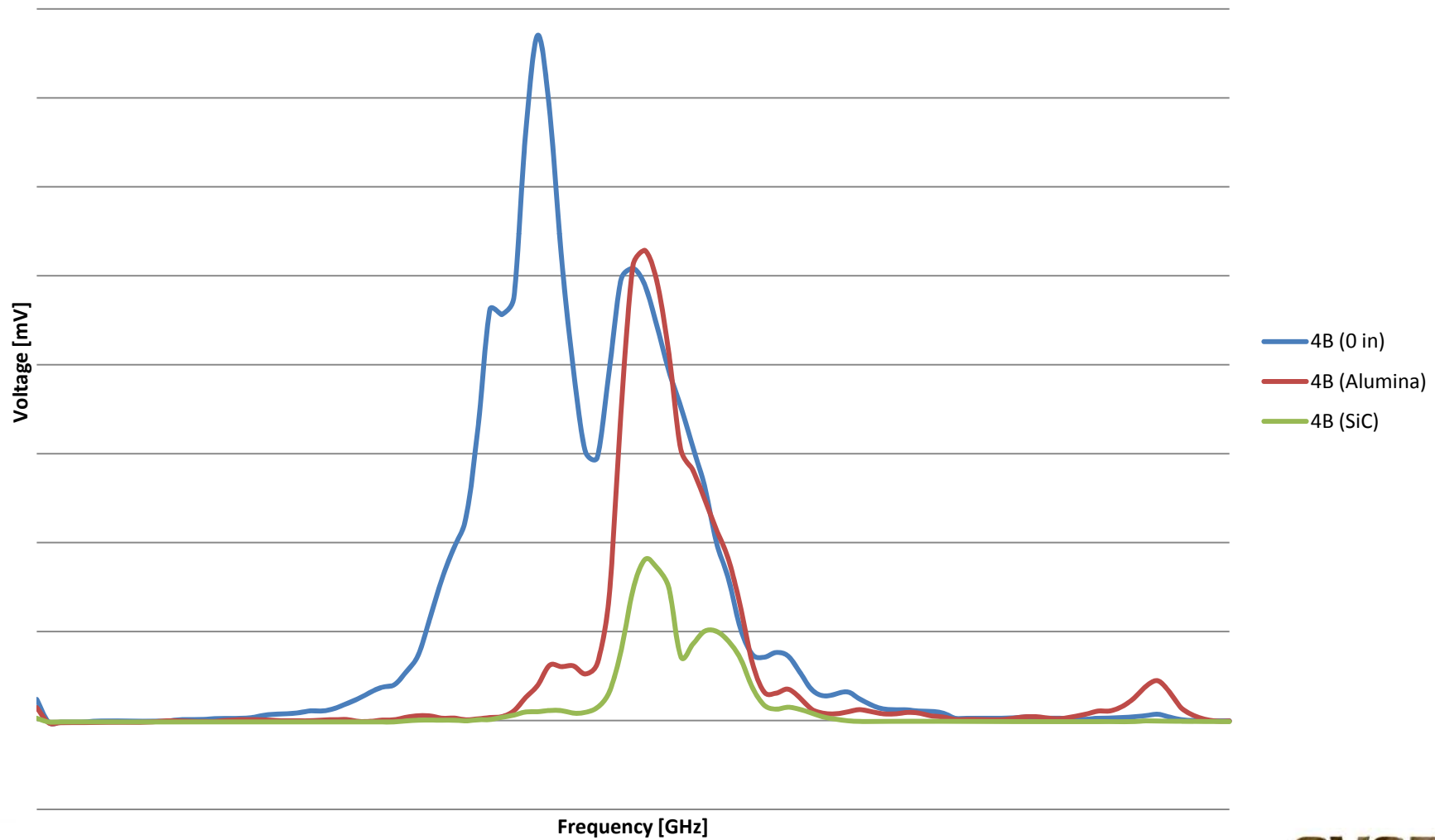
Detector Characterization inside the Anechoic Chamber: Obstacle Comparison - Alumina

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Detector Characterization: Obstacle Comparison

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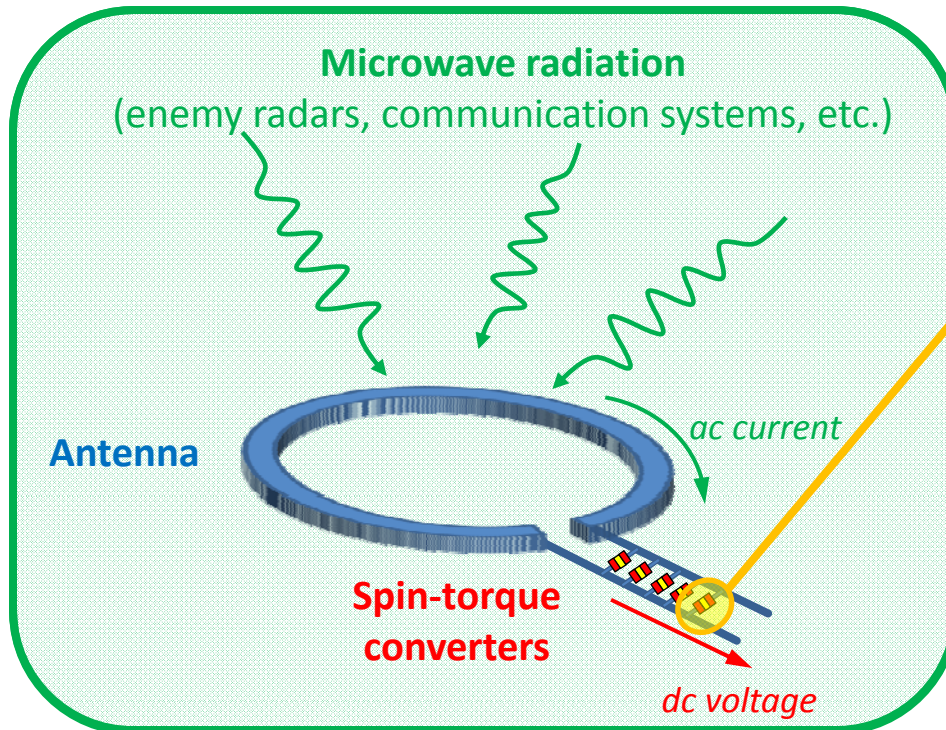
SUMMARY

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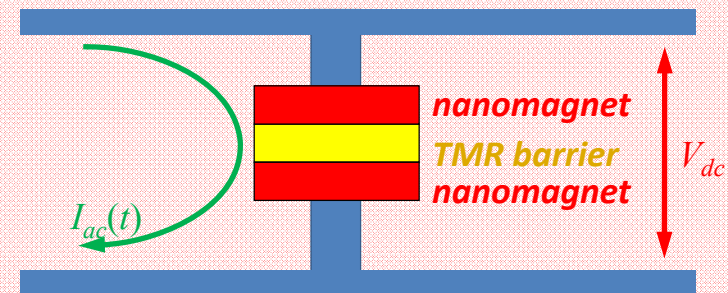
- We proposed a novel regime of operation of a spin-torque diode, based on excitation of **large-angle out-of-plane magnetization precession**.
- The specific features of the proposed spin-torque diode are:
 - **Higher output voltage** (>1 mV).
- The out-of-plane precession regime might be responsible for extremely high diode efficiencies observed in recent experiments.
- **CPW antenna was used as a feed line to the detector**. The transmitting antenna was a commercial horn antenna.
- Ten spintronic detectors of microwave radiation were built and tested at TARDEC.
- We are in the process of integrating of these radar detectors into armor.
- There will be more tests performed at TARDEC when integration is completed.
- Arrays of spintronic radiation-hard detectors have two important applications: analysis of frequencies of incoming signals and RF energy harvesting.

Microwave energy harvesting

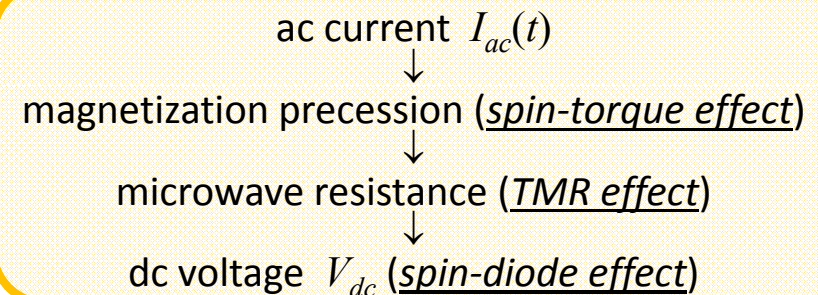
Energy harvesting device



Spin-torque ac/dc converter



Operation principle



Estimated efficiency (per converter):

$$P_{out,dc} = TMR^2 \frac{P_{in,ac}^2}{I_{cr}^2 R_0}$$

$TMR \sim 0.3$ – tunneling magnetoresistance
 $I_{cr} \sim 1$ mA – critical spin-torque current
 $R_0 \sim 1$ k Ω – electrical resistance

$$P_{in,ac} = 0.1 \text{ mW} \rightarrow P_{out,dc} = 1 \text{ } \mu\text{W}$$



Research Collaborators and Acknowledgements

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- TARDEC Research Team: Dr. Thomas Meitzler (Team Leader, Research Engineer), Dr. Elena Bankowski (Research Engineer) & Mr. Steven Zielinski (Engineer).
- Oakland University Research Team: Dr. Andrei Slavin (Chair, Physics Department), Dr. Vasil Tiberkevich (Research Associate Professor).
- We would like to thank Dr. Ilya Krivorotov (Assistant Professor), University of California at Irvine, and his research group for manufacturing prototype spintronic MTJ diodes for our experiments.
- We would like to thank TARDEC Director Dr. Grace Bochenek, the Chief Scientist Dr. Dave Gorsich and GVSS Associate Director Mr. Steve Knott for their support of this innovative research project.

Backup Slide: Expressions defining the antenna directional diagram

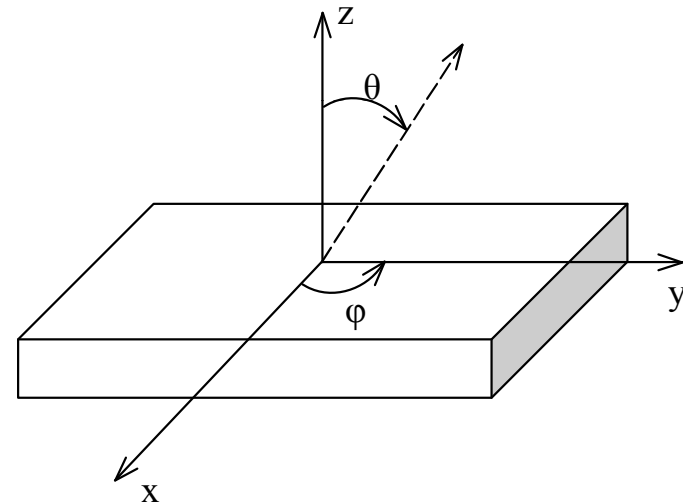
$$P(\theta, \phi) = \frac{1}{240\pi} \left(|E_\theta(\theta, \phi)|^2 + |E_\phi(\theta, \phi)|^2 \right)$$

Dependence on the in-plane angle

$$P_\theta(\phi) = \sqrt{\frac{P(\theta, \phi)}{P_0}} \Big|_{-180^\circ \leq \phi \leq 180^\circ, \theta = \text{const}}$$

Dependence on the out-of-plane angle

$$P_\phi(\theta) = \sqrt{\frac{P(\theta, \phi)}{P_0}} \Big|_{-90^\circ \leq \theta \leq 90^\circ, \phi = \text{const}}$$



$$P_0 = \frac{1}{8\pi} \operatorname{Re} \int_0^\pi d\theta \int_0^{2\pi} d\phi \left(E_\theta H_\phi^* - E_\phi H_\theta^* \right) \sin \theta$$