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

GVSETS

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SPIN-TORQUE DIODE EFFECT

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

↓

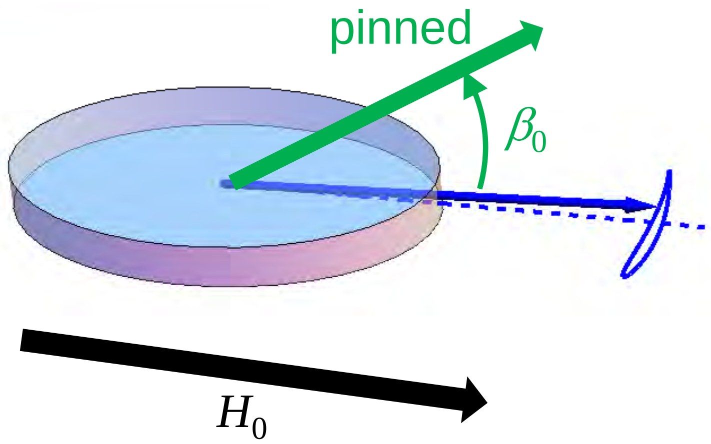
AC variations of the electrical resistance of the structure (GMR/TMR/MTJ)

↓

rectified dc voltage:

$$V_{\mathrm{dc}} = \left\langle R(t) I_{\mathrm{ac}}(t) \right\rangle$$

Standard "in-plane" spin-torque diode



Spin torque excites small-angle magnetization precession about equilibrium direction

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

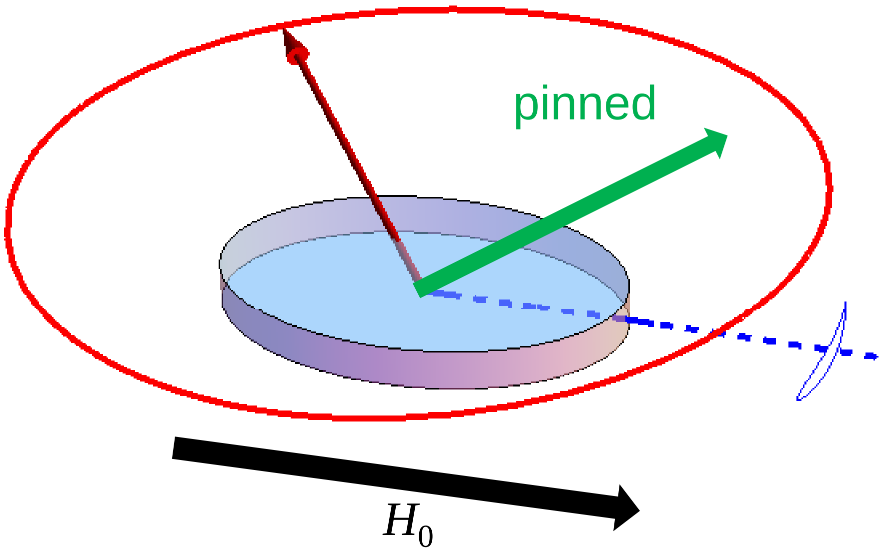
$$V_{\mathrm{dc}} \propto \frac{I_{\mathrm{ac}}^2 \sin^2(\beta_0)}{\Gamma^2 + (\omega - \omega_{\mathrm{FMR}})^2}$$

Diode sensitivity:

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

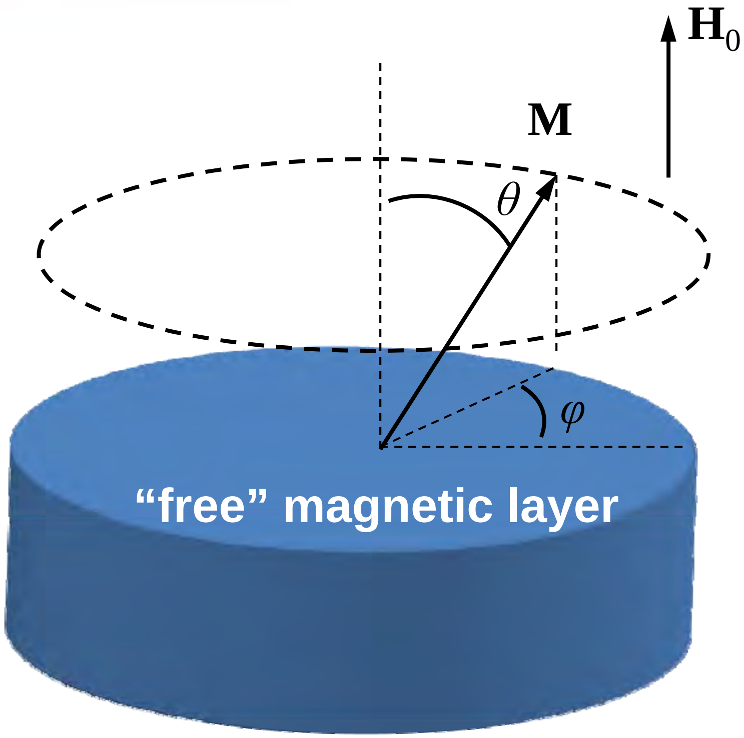
C. Wang *et al.*, JAP **106**, 053905 (2009)

"Out-of-plane" spin-torque diode



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

Theoretical model

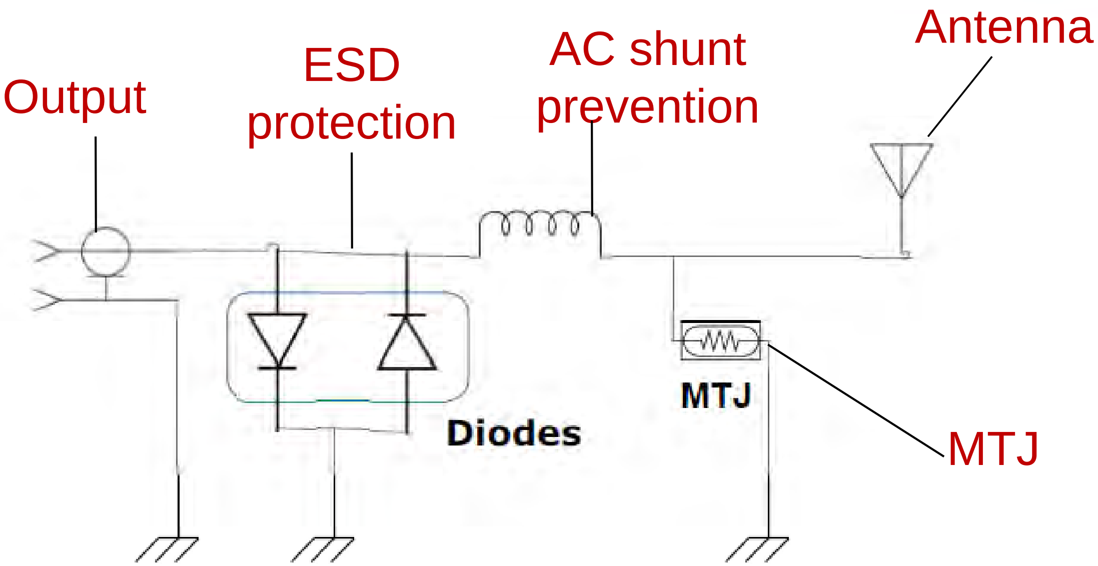


- Free layer – circular pillar (no in-plane anisotropy) radius 50 nm, thickness 1 nm
- Resistance: $R_0 = \Delta R = 1\ \mathrm{k}\Omega$
- Bias magnetic field – perpendicular to the plane, **smaller than the saturation field**, $H_0 < 4\pi M_s$
- Magnetization of the pinned layer – in plane (along *x*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

Angular dependence of the resistance:

$$R(\beta) = R_0 - \frac{\Delta R}{2}\cos\beta \qquad \cos\beta = \cos\theta(t)\cos\phi(t)$$

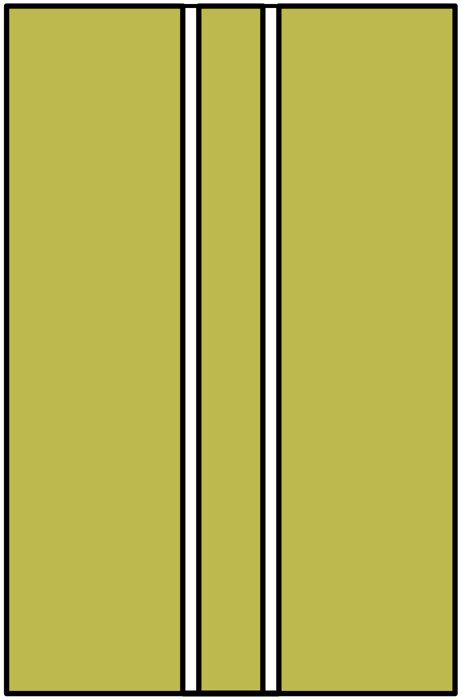
Block- Diagram of the Spintronic MTJ Sensor



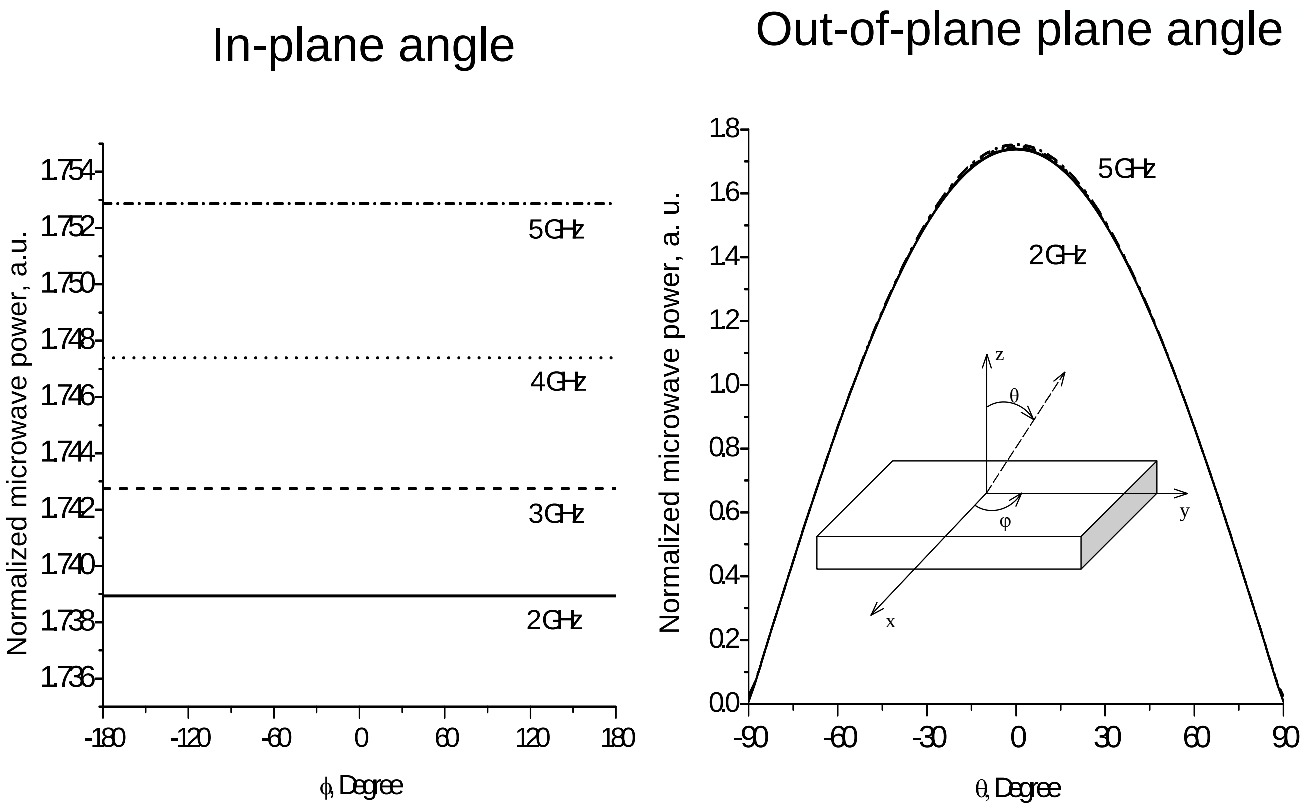
Spintronic microwave sensor circuit design includes:

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

Design of the sensor antenna



Coplanar waveguide (CPW) antenna

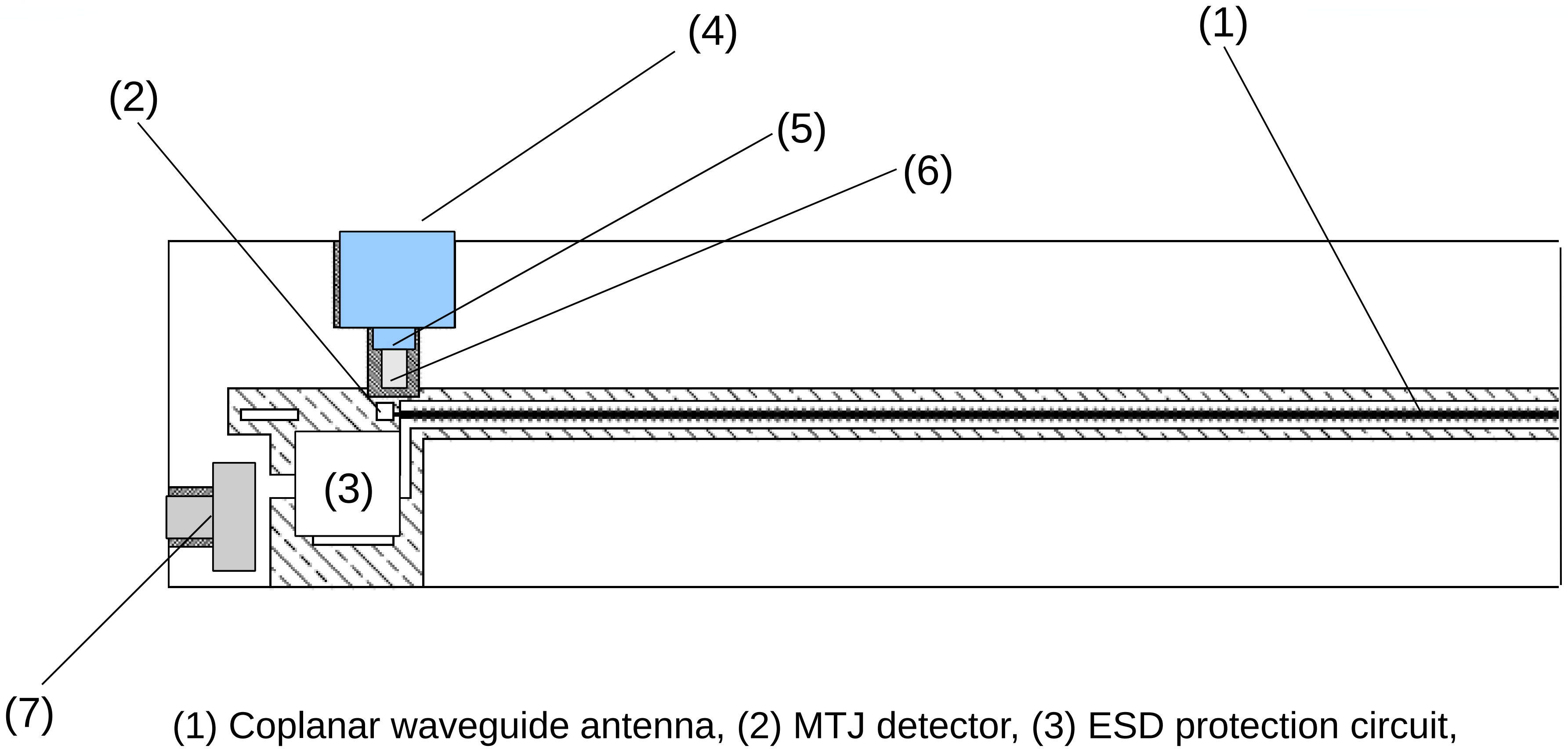


In-plane angle

Out-of-plane plane angle

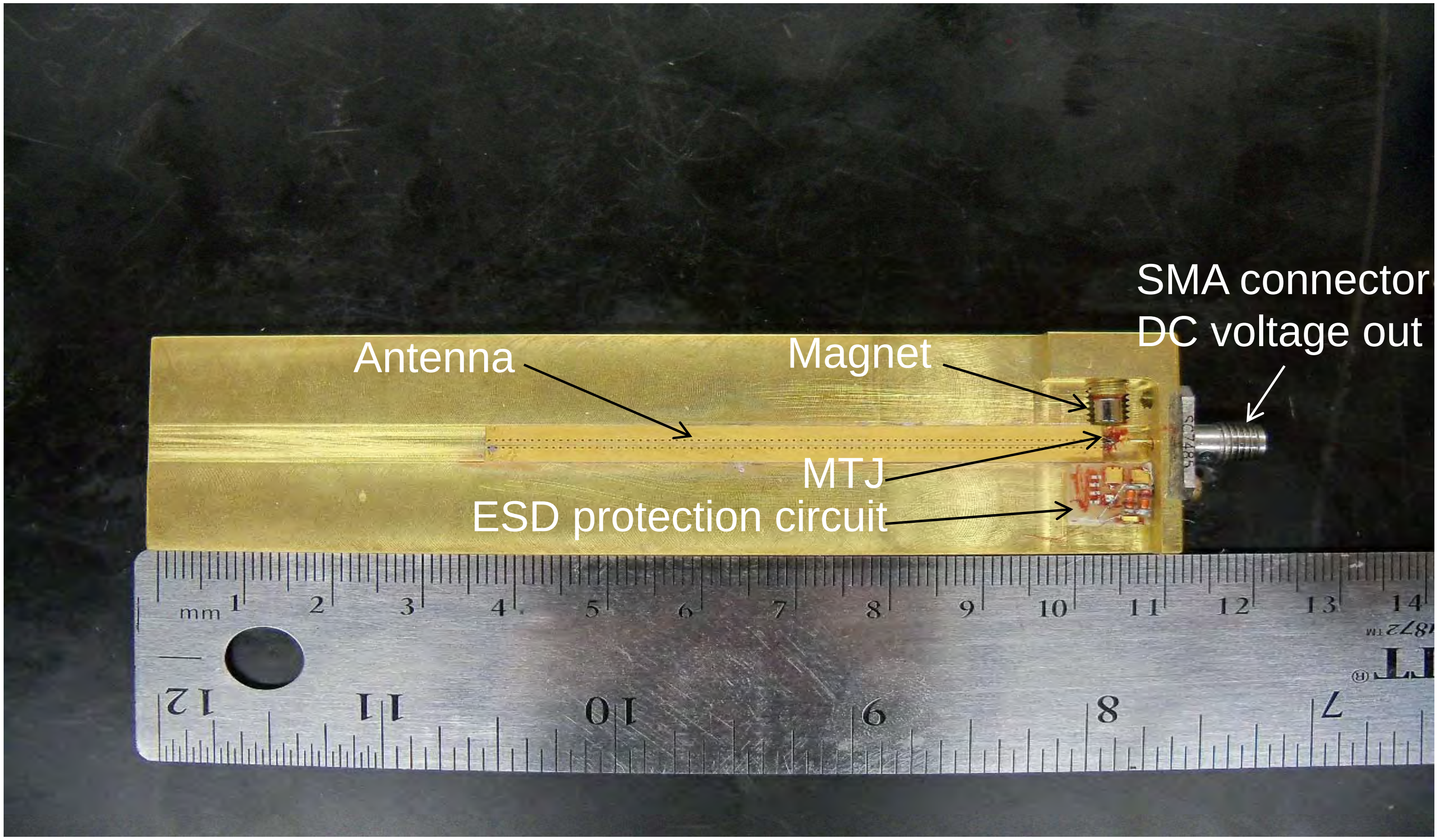
Projections of the CPW antenna directional diagram

Design of the MTJ sensor

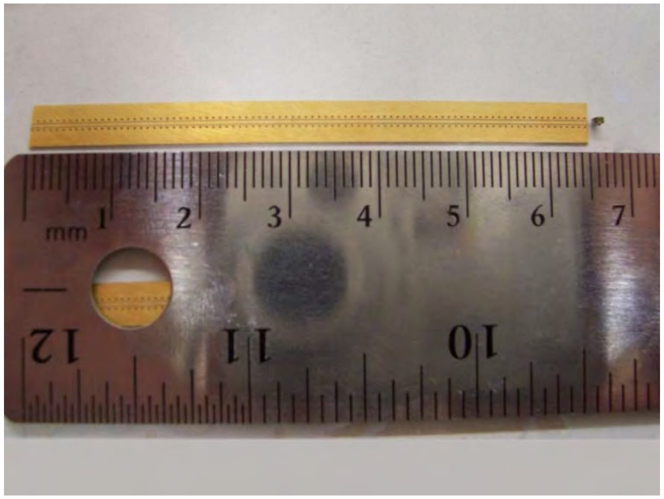


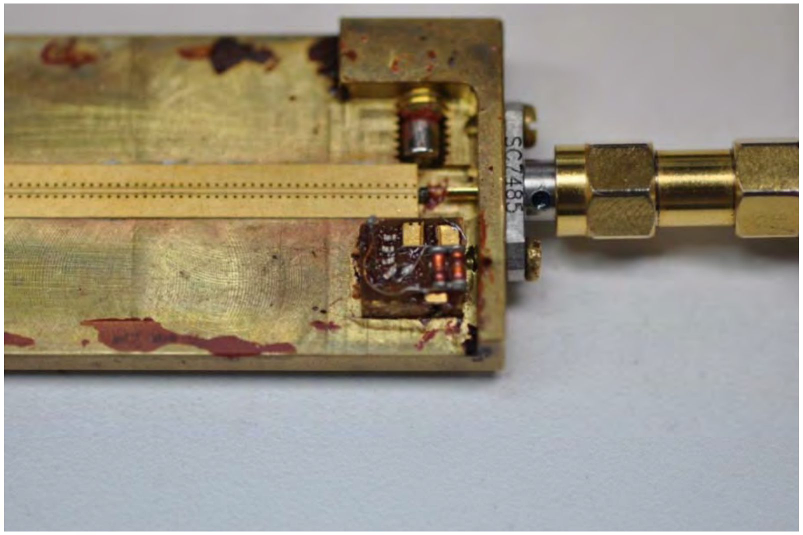
(1) Coplanar waveguide antenna, (2) MTJ detector, (3) ESD protection circuit, (4) brass screw holder, (5) brass set-screw, (6) magnet, (7) SMA connector.

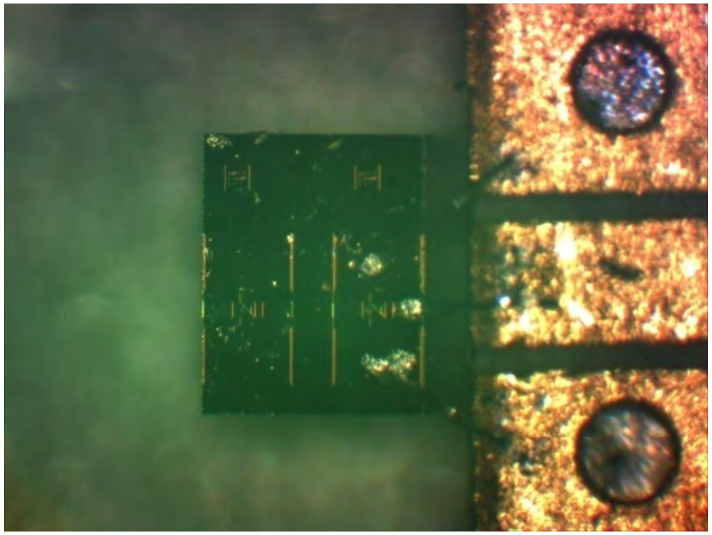
Fabricated Spintronic MTJ Sensor



MTJ Detector with CPW Antenna







Spintronic Detector Characterization

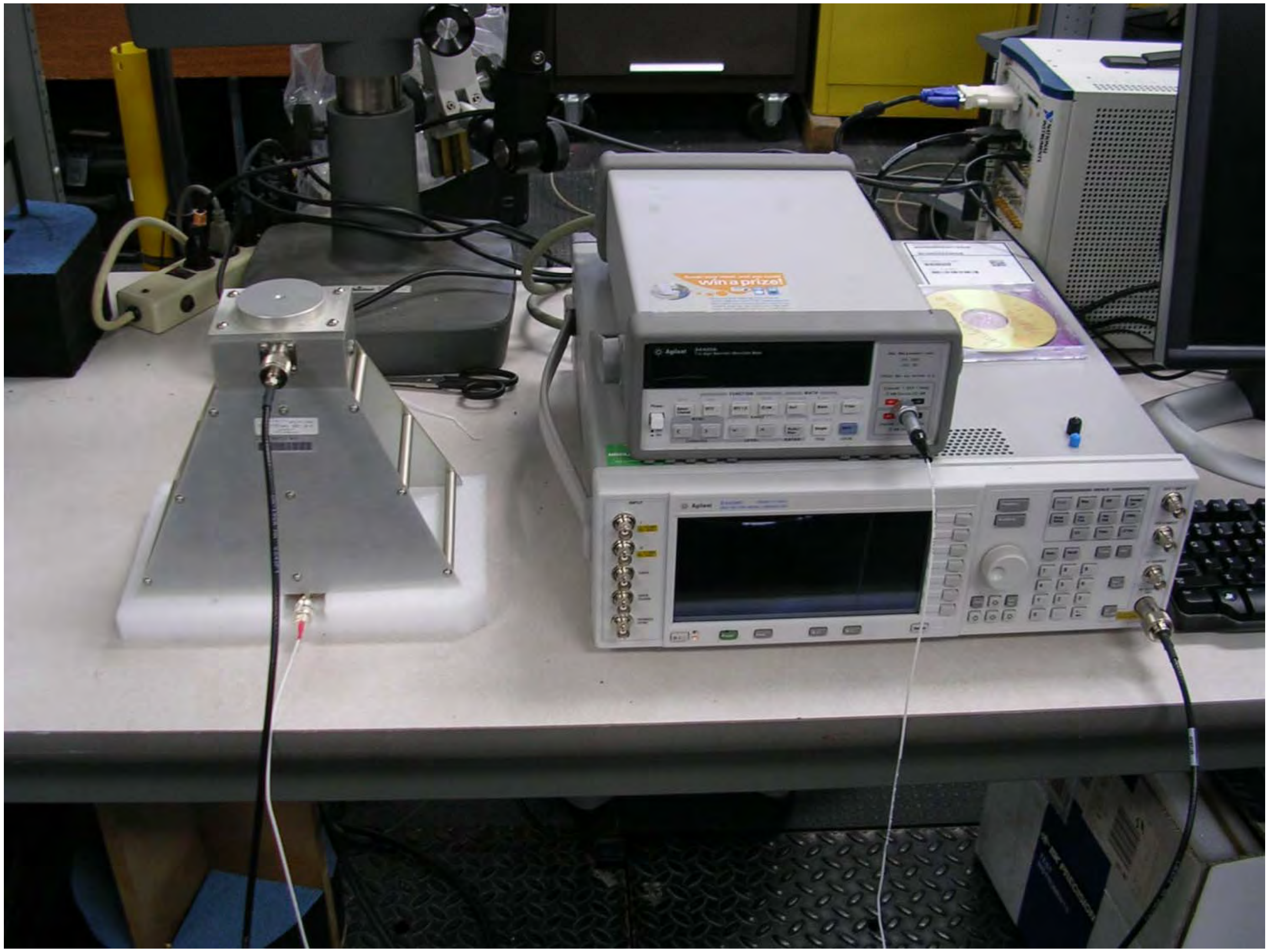
- 1 – 6 GHz initial scan done to determine approximate resonance frequency

  A group detectors with in-plane magnetization: focused scans at 4-6 GHz

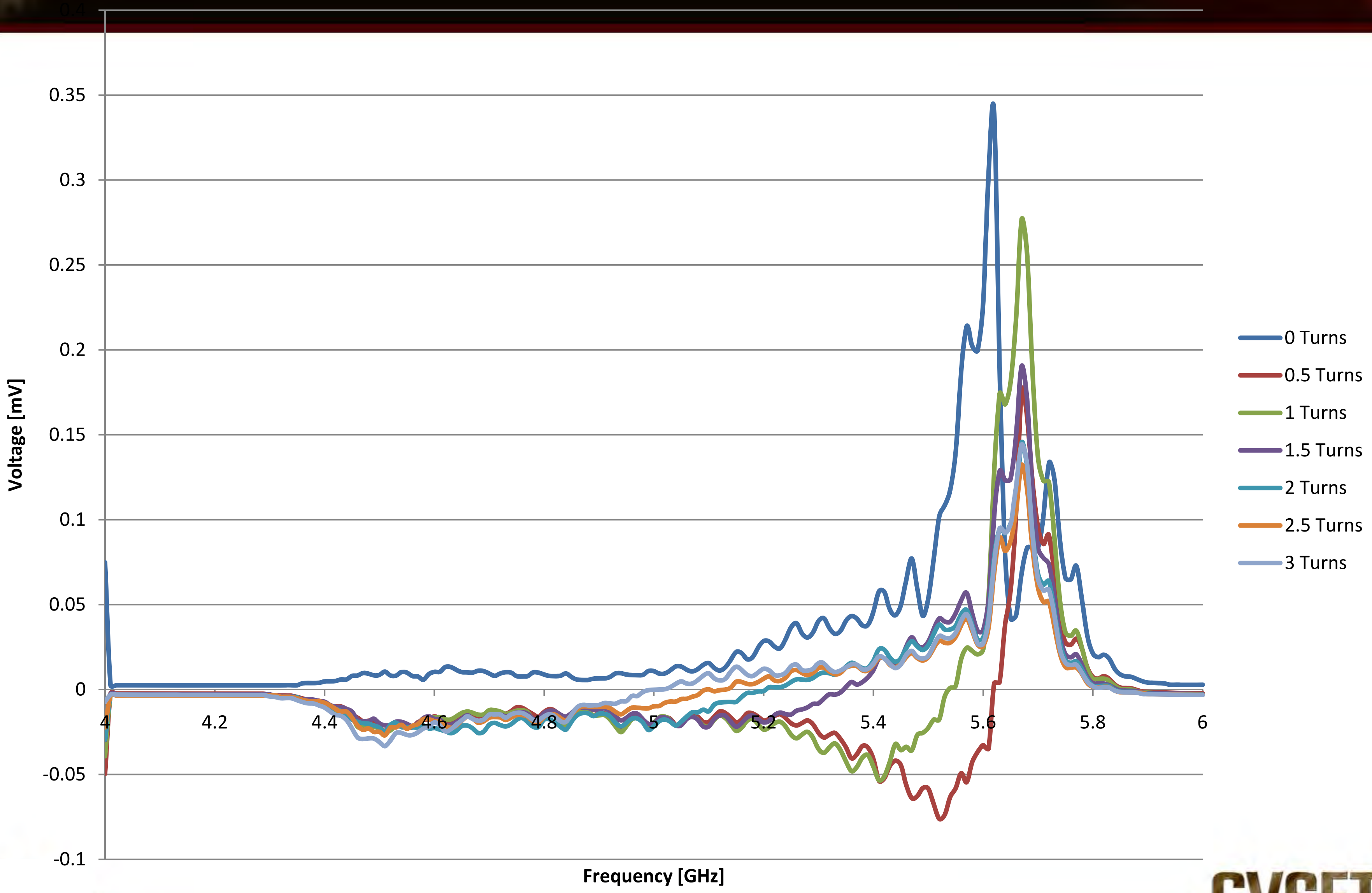
  B group (out-of-plane detectors): focused scans at 1-3 GHz

- 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.

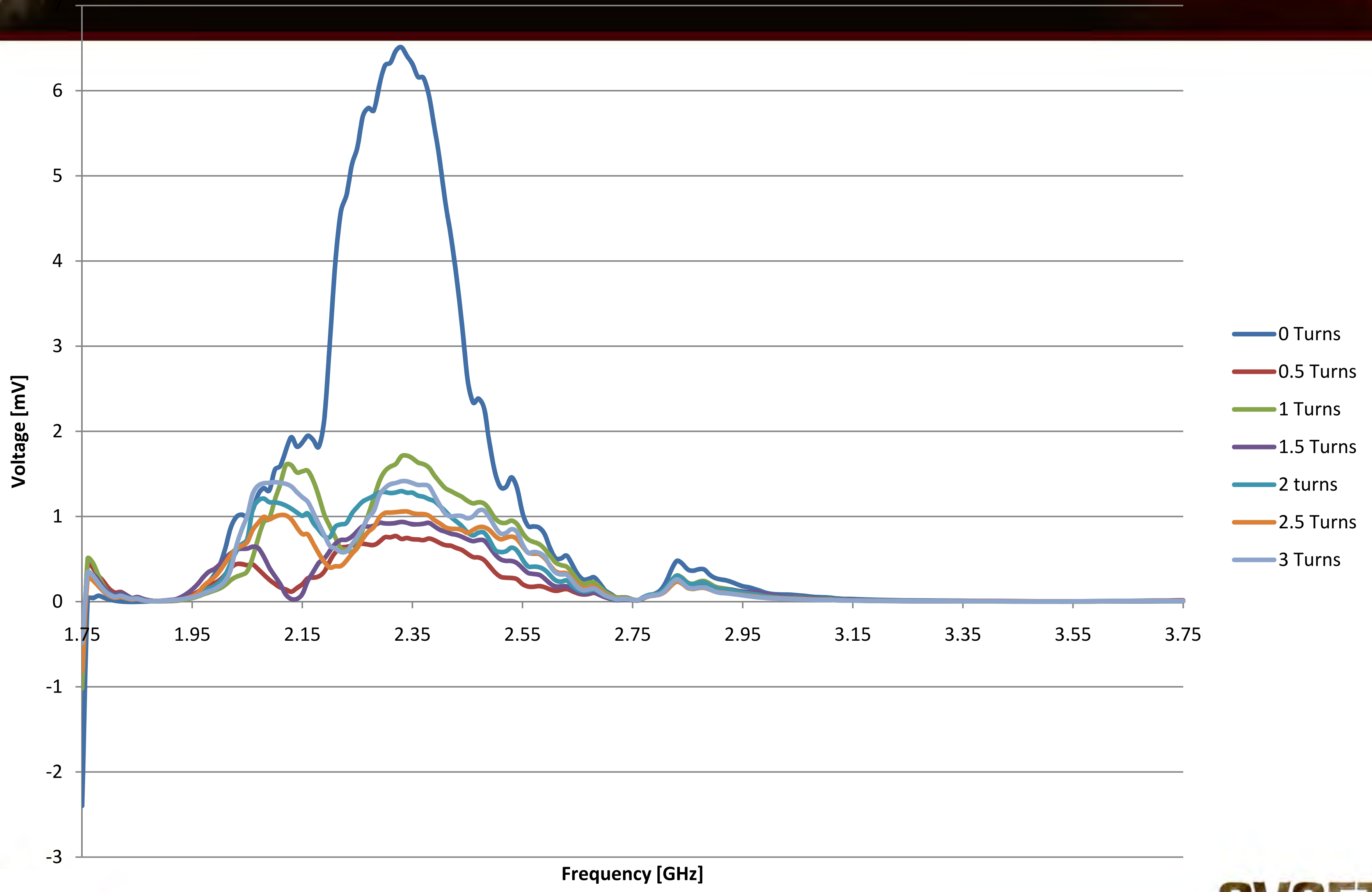
Spintronic Detector Test Setup



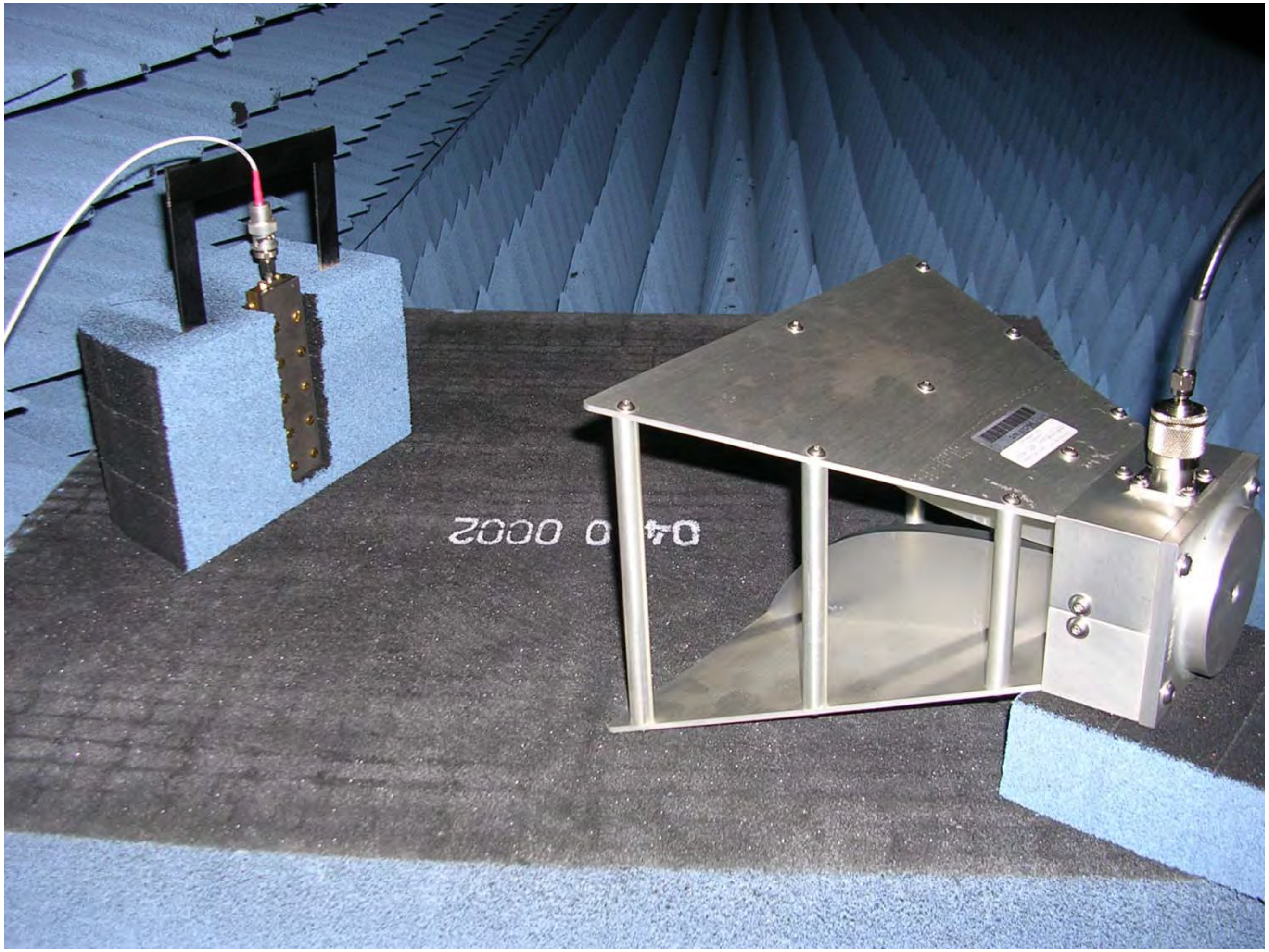
Detector Characterization: 4A



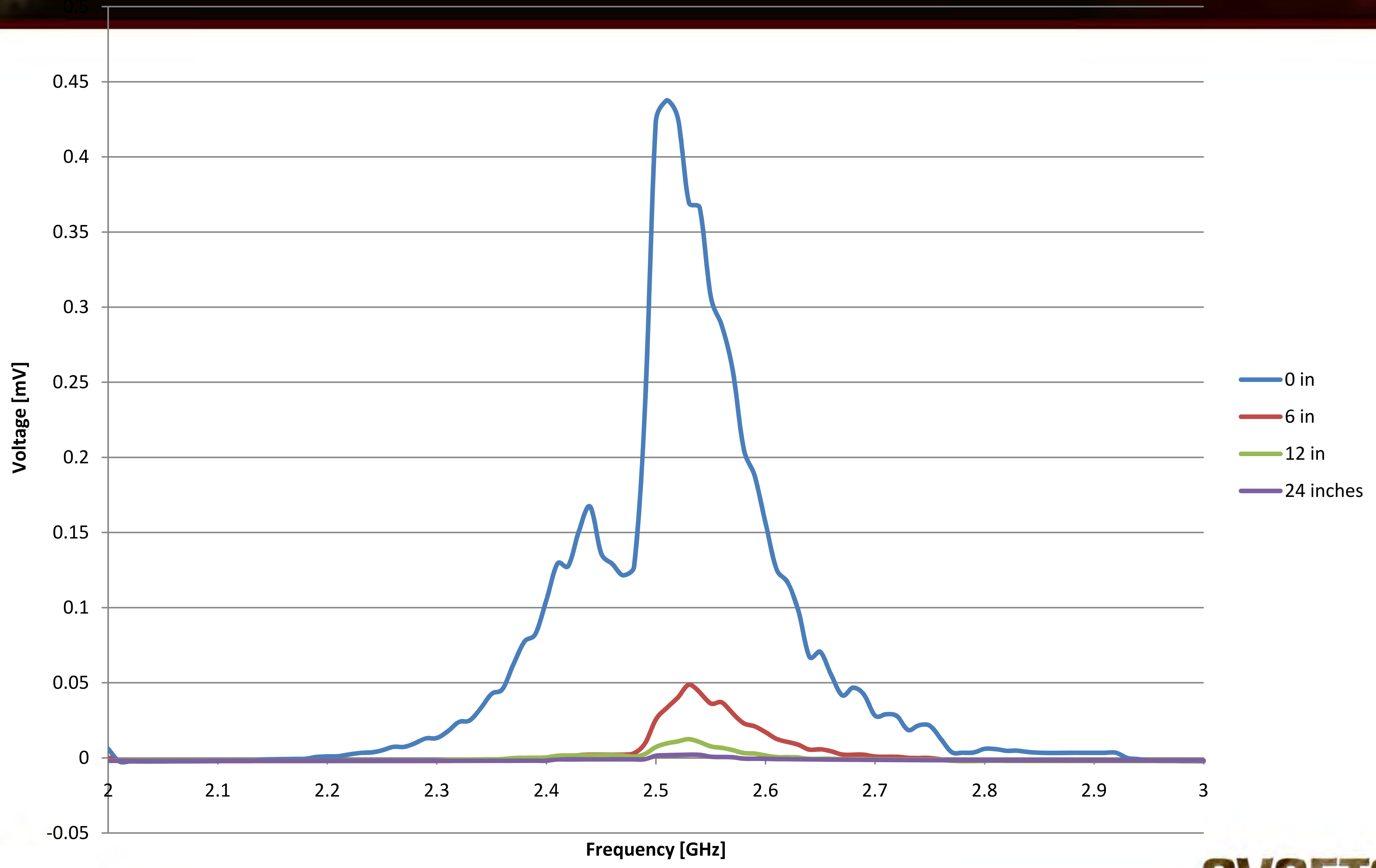
Spintronic Detector Characterization: 5B



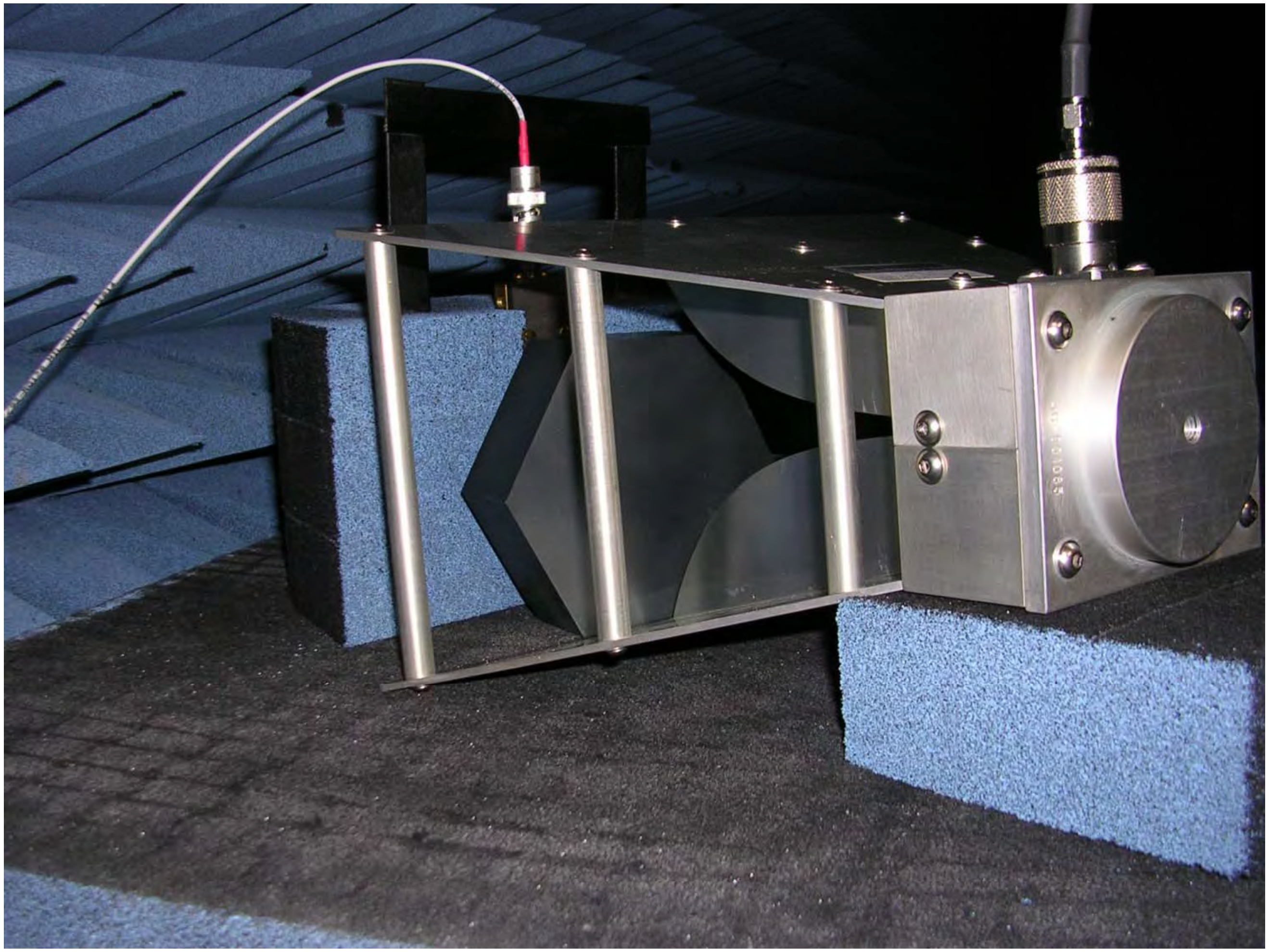
Spintronic Detector Test Inside the Anechoic Chamber



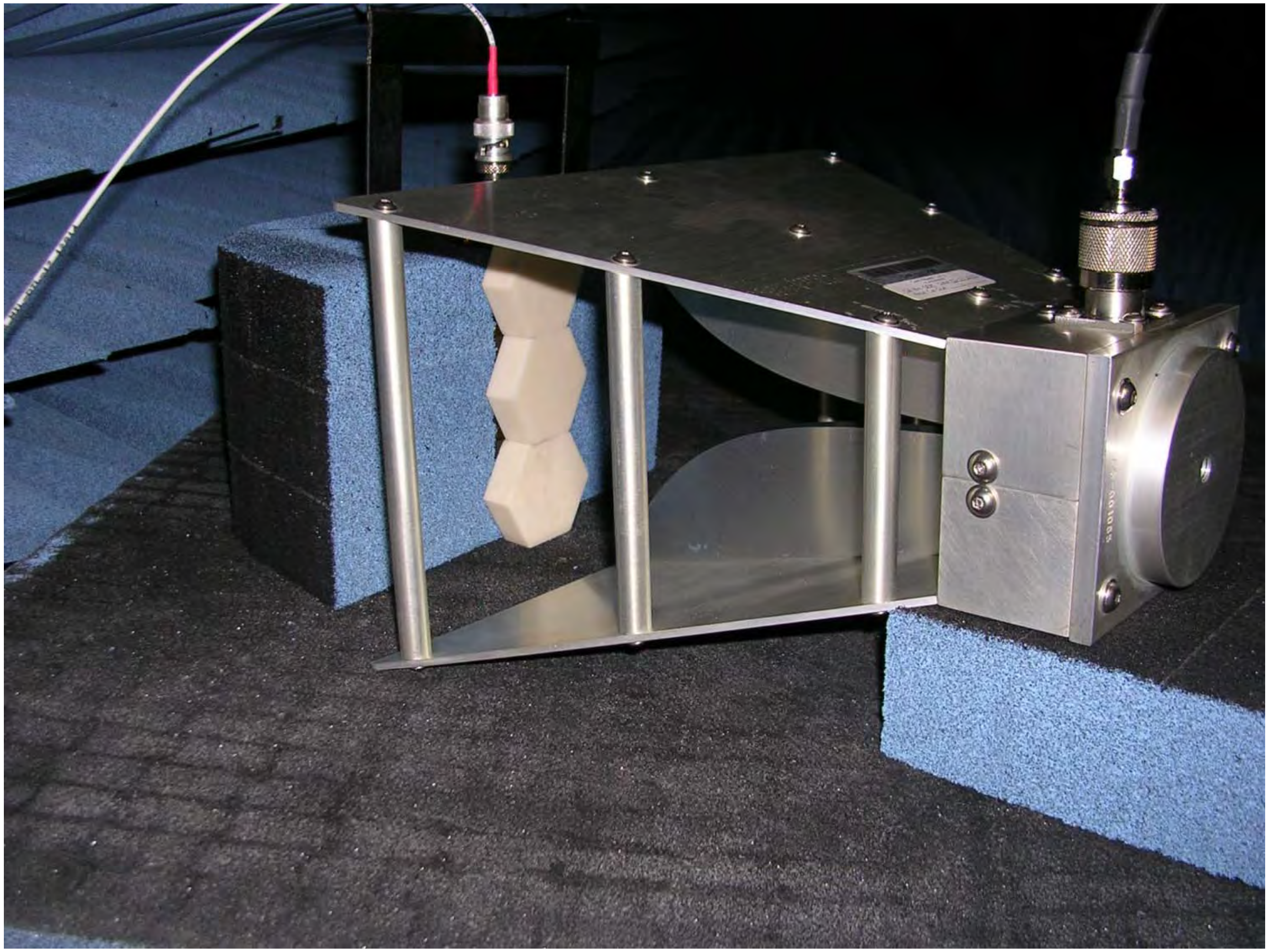
Detector Distance Testing Inside the Anechoic Chamber



Detector Characterization inside the Anechoic Chamber: Obstacle Comparison - SiC



Detector Characterization inside the Anechoic Chamber: Obstacle Comparison - Alumina



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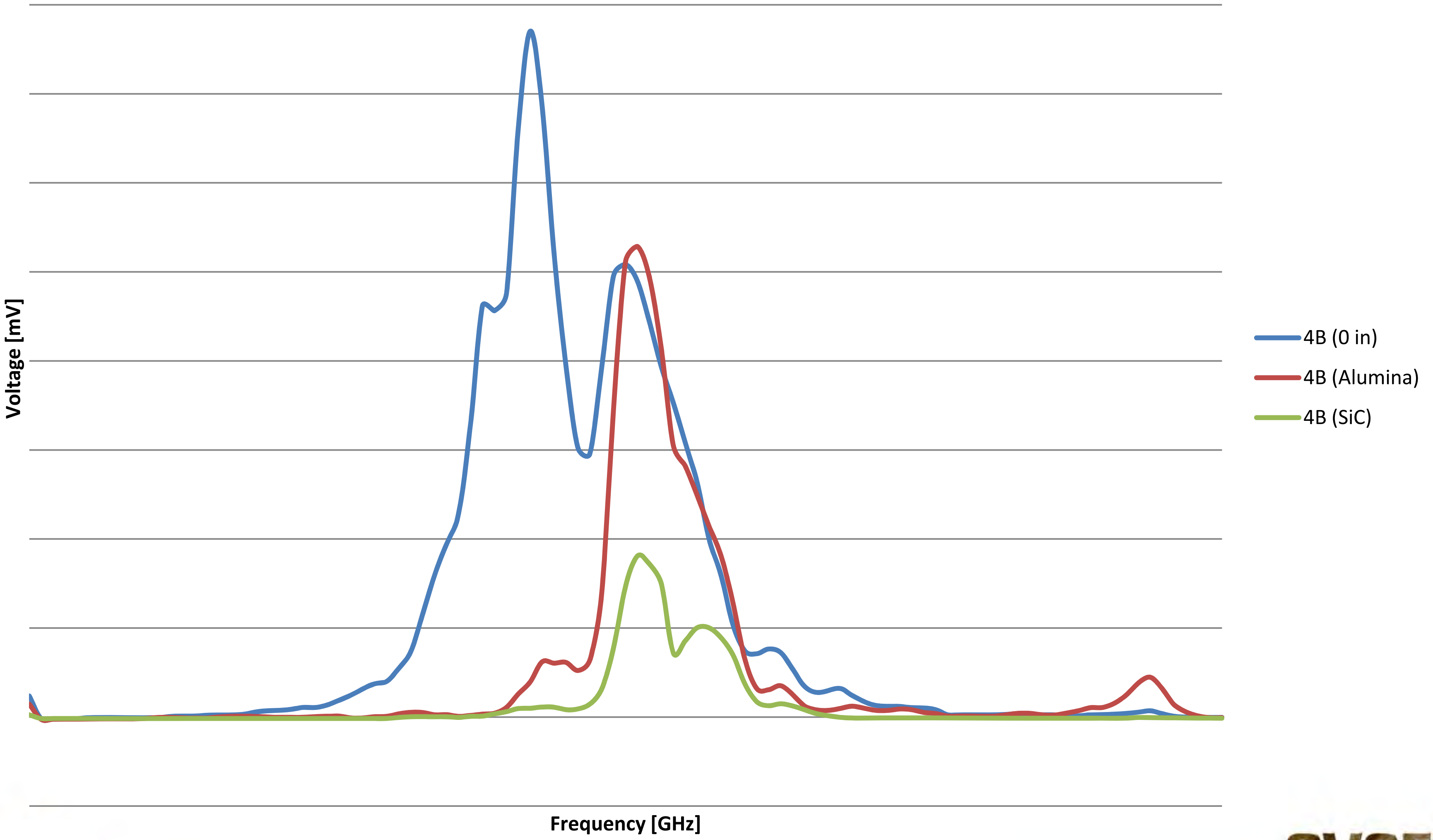
Detector Characterization: Obstacle Comparison

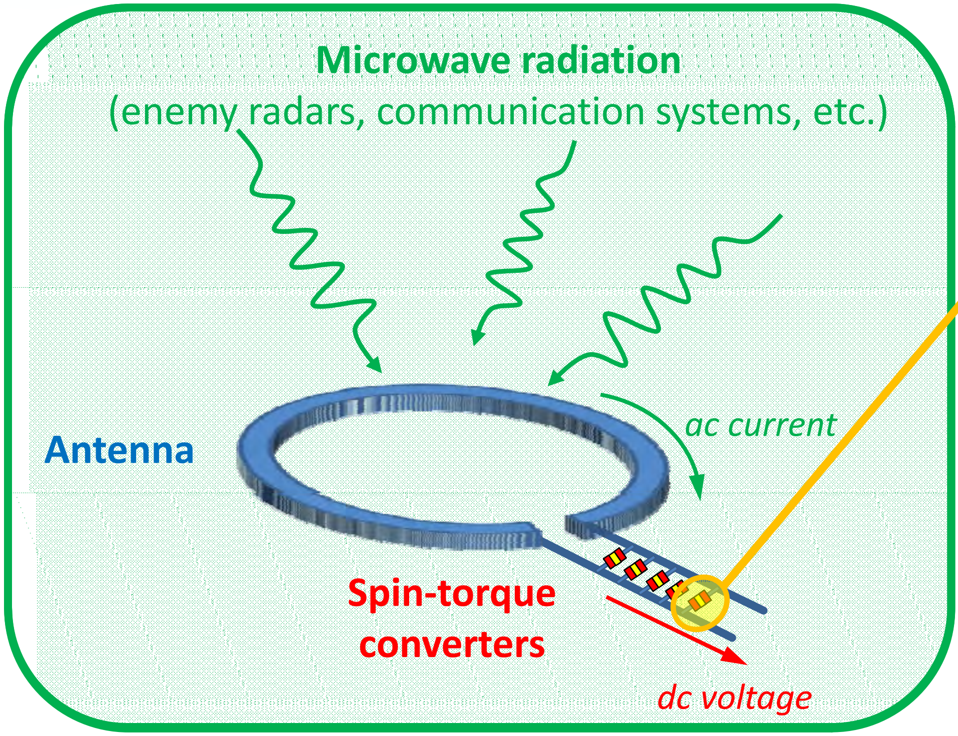


SUMMARY

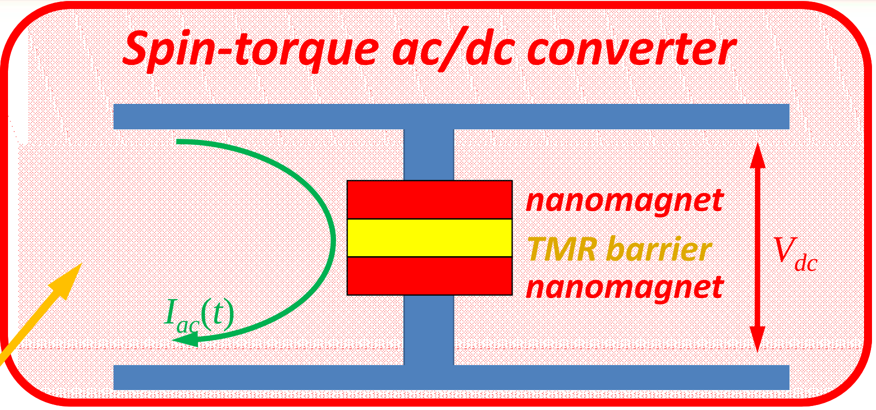
- We proposed a novel regime of operation of a spin-torque diode, based on excitation of large-angle out-of-plane magnetization precession.
- The specific features of the proposed spin-torque diode are:
    - Higher output voltage (>1 mV).
- The out-of-plane precession regime might be responsible for 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

ac current $I_{ac}(t)$

↓

magnetization precession (*spin-torque effect*)

↓

microwave resistance (*TMR effect*)

↓

dc voltage V_{dc} (*spin-diode effect*)

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
$R_0 \sim 1$ kΩ – electrical resistance

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

Research Collaborators and Acknowledgements

- 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.

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Backup Slide:
Expressions defining the antenna directional diagram

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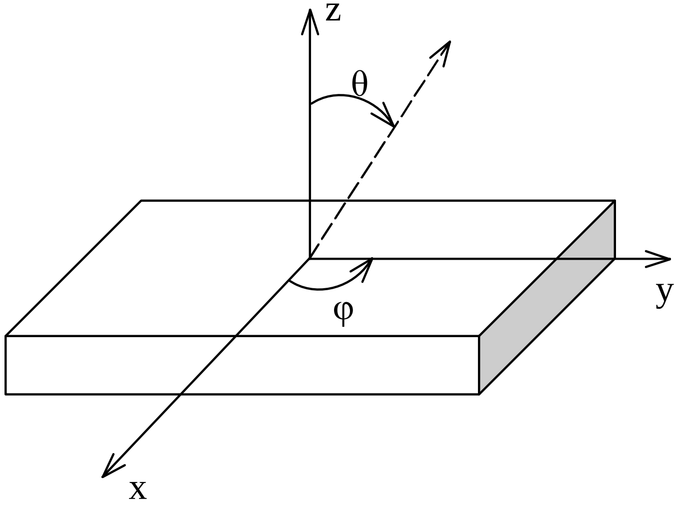
$$P(\theta,\phi)=\frac{1}{240\pi}\left(\left|E_{\theta}(\theta,\phi)\right|^{2}+\left|E_{\phi}(\theta,\phi)\right|^{2}\right)$$

Dependence on the in-plane angle

$$P_{\theta}(\phi)=\sqrt{\frac{P(\theta,\phi)}{P_{0}}}\Bigg|_{-180^{\circ}\le\phi\le 180^{\circ},\theta=const}$$

Dependence on the out-of-plane angle

$$P_{\phi}(\theta)=\sqrt{\frac{P(\theta,\phi)}{P_{0}}}\Bigg|_{-90^{\circ}\le\theta\le 90^{\circ},\phi=const}$$



$$P_{0}=\frac{1}{8\pi}\mathrm{Re}\int_{0}^{\pi}d\theta\int_{0}^{2\pi}d\phi\left(E_{\theta}H_{\phi}^{*}-E_{\phi}H_{\theta}^{*}\right)\sin\theta$$