A Physically Unclonable Function (PUF) Using Micromagnets and NV Magnetic Imaging
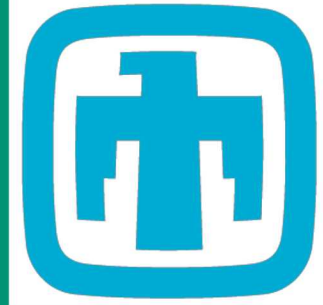
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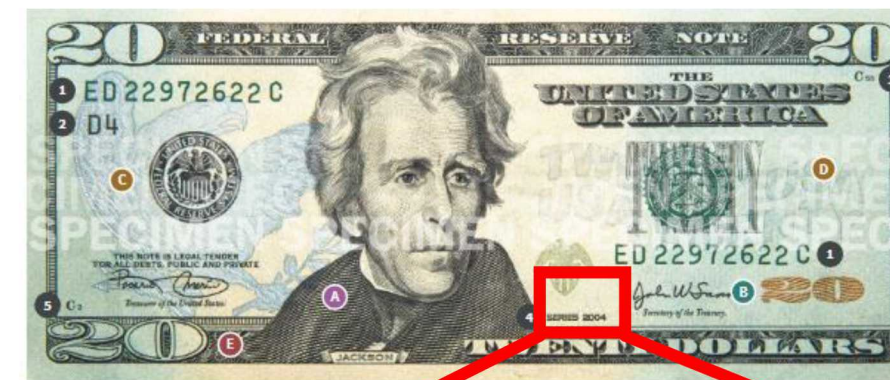
H71.00340
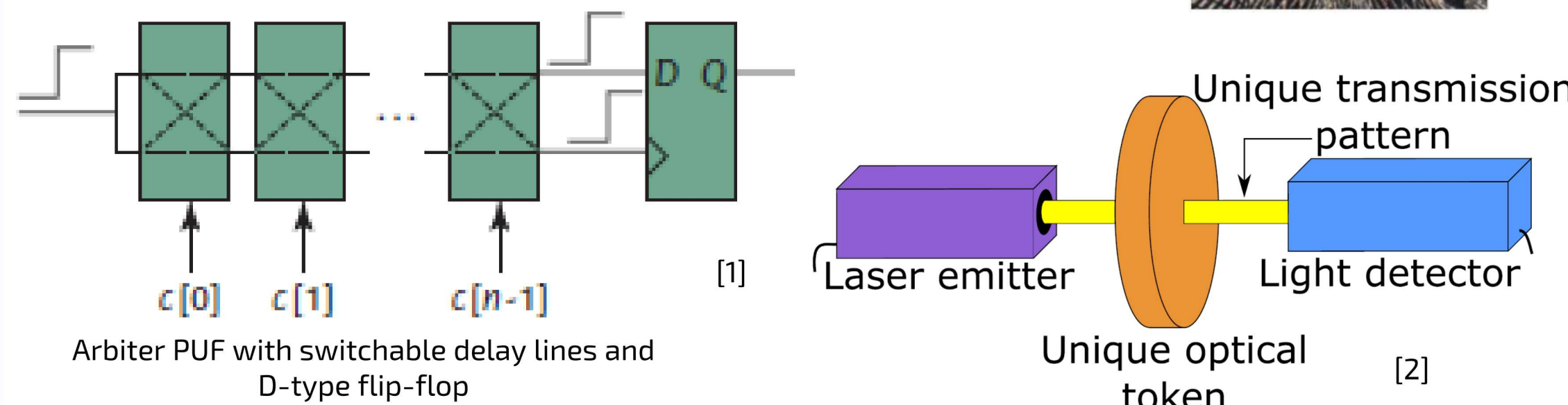SANDXXXX-XXXXX

Introduction to PUFs

- Anti-counterfeiting hardware security measure

- Desired properties
  - Easy to produce
  - Difficult to duplicate
  - Easy & reproducible readout
  - Low-cost & resilient

Anti-counterfeiting fibers in a banknote

SERIES 2004

Arbiter PUF with switchable delay lines and D-type flip-flop

$c[0]$ $c[1]$ $c[n-1]$ [1]

Unique transmission pattern

Laser emitter   Light detector

Unique optical token [2]

- Our approach: fabricated array of ferromagnetic rods
  - Random magnetic moment orientations
  - NV diamond widefield magnetic imaging readout
  - Image analysis

Micromagnet fabrication

- Recipe:
  - e-beam lithography on resist
  - Develop
  - Nickel deposition
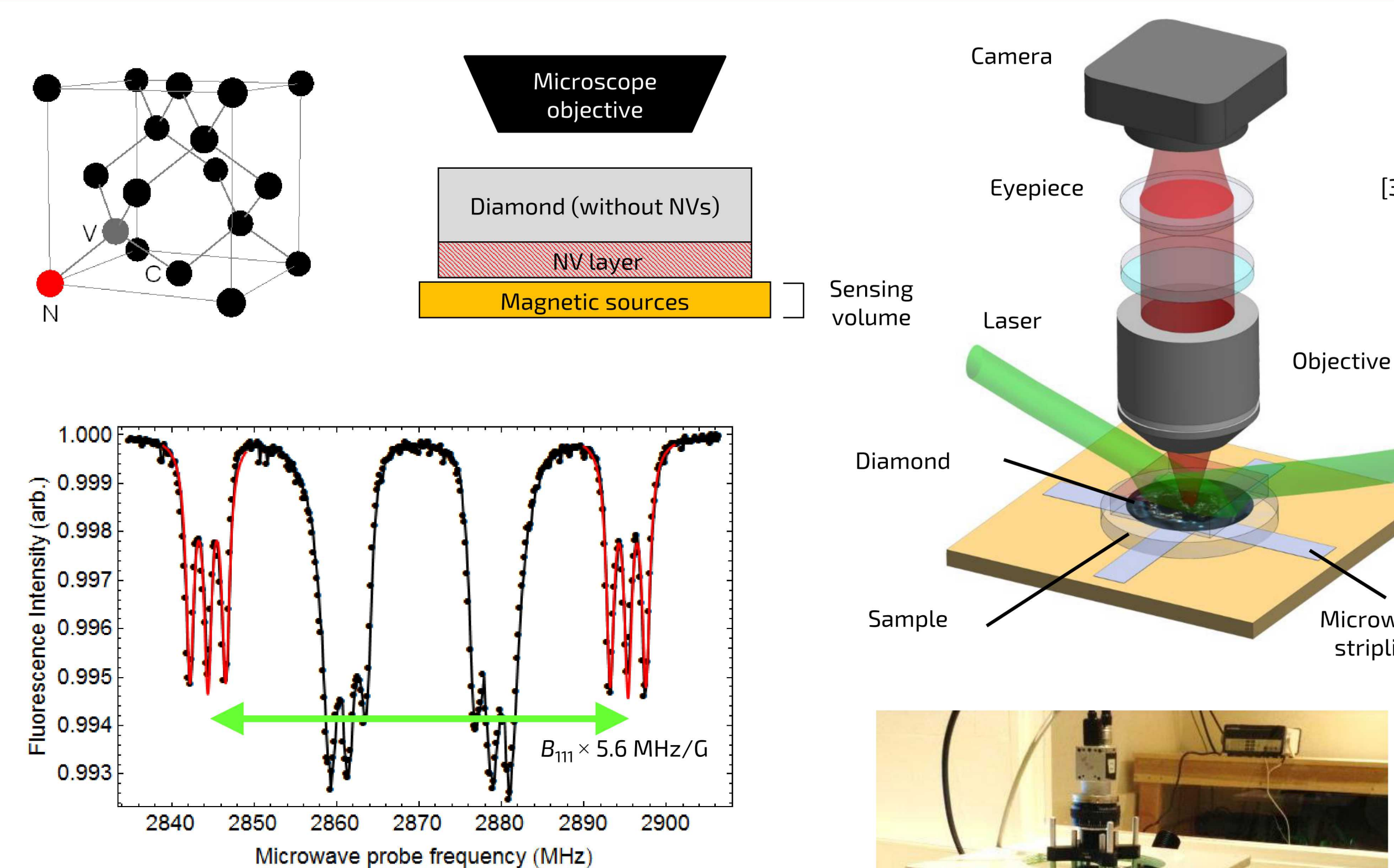 - Liftoff
  - Al_2O_3 protective layer

Diamond chip
Ni micromagnets on Si
10 µm
10 µm
Silicon substrate
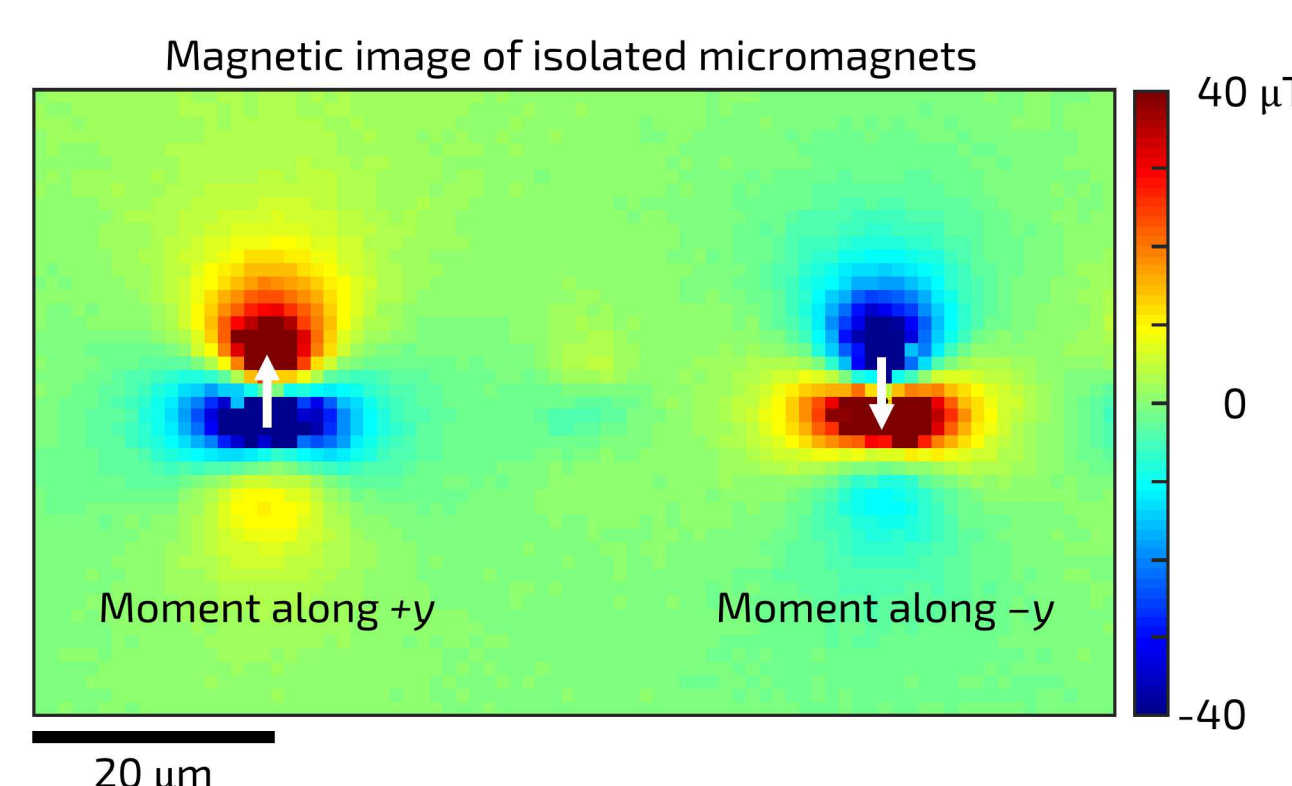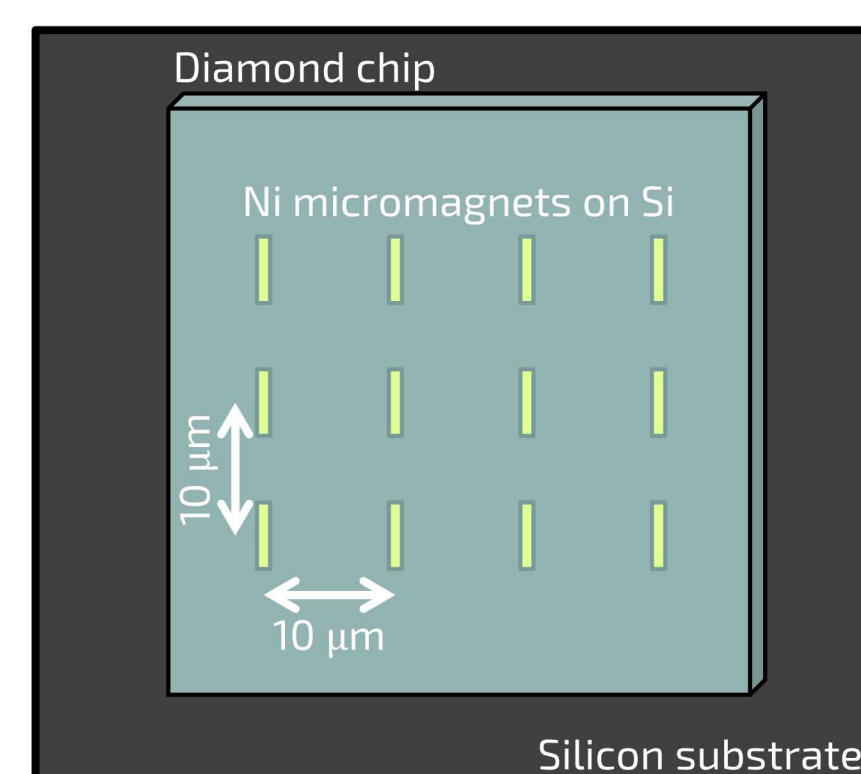
10,000 micromagnets in a 100x100 array
(1 mm × 1 mm, 4 µm × 1 µm each)

Magnetic image of isolated micromagnets

Moment along +y   Moment along −y

20 µm

- Rod-shaped micromagnets; easy axis along ±y

- Dipole-like magnetic field map

NV magnetic microscopy

Microscope objective
Diamond (without NVs)
NV layer
Magnetic sources
Sensing volume

N   V   C

Camera
Eyepiece [3]
Laser
Objective
Diamond
Sample
Microwave stripline

$B_{111} \times 5.6$ MHz/G

Fluorescence Intensity (arb.)

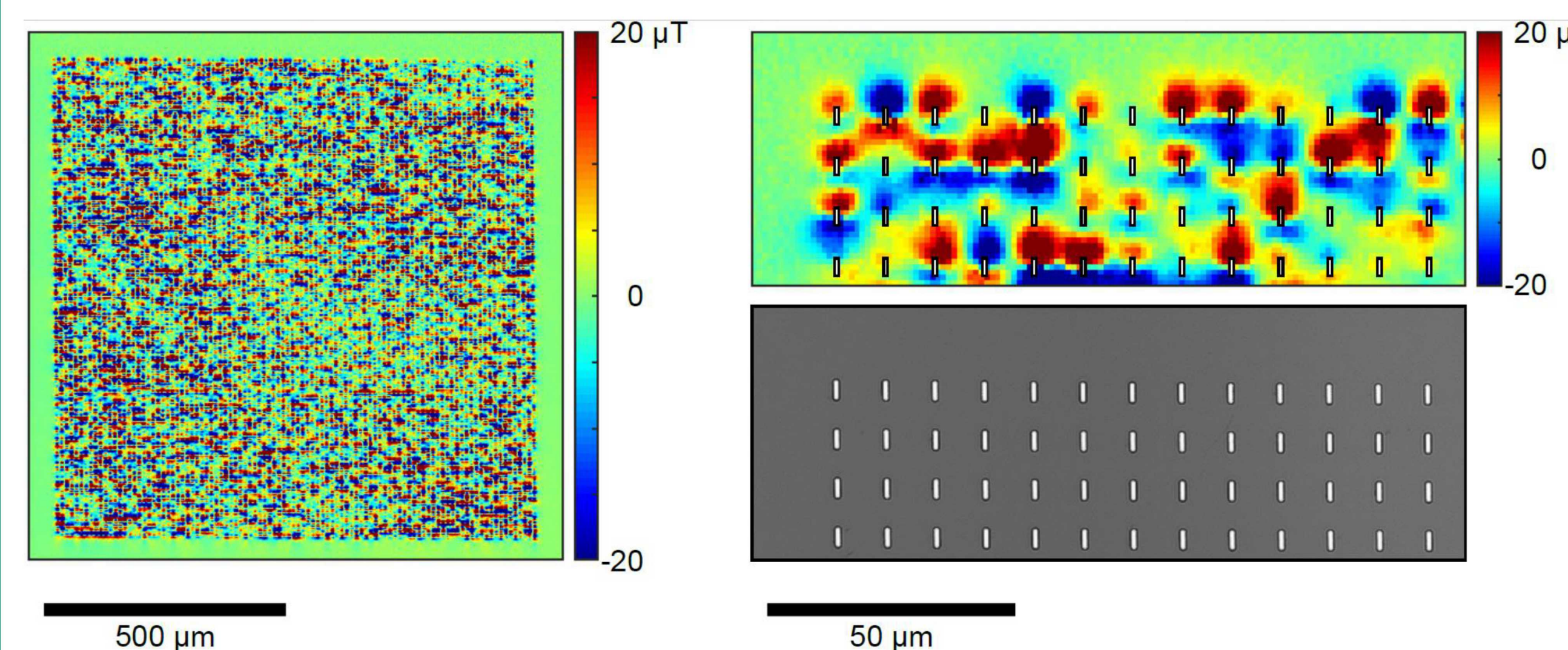Microwave probe frequency (MHz)

- Advantages:
  - Widefield readout; no raster scanning
  - Works in ambient conditions
  - Few-micron NV-target separation
  - Overlay optical & magnetic images
  - Few-mm FOV, micron-scale resolution
  - High magnetic moment sensitivity
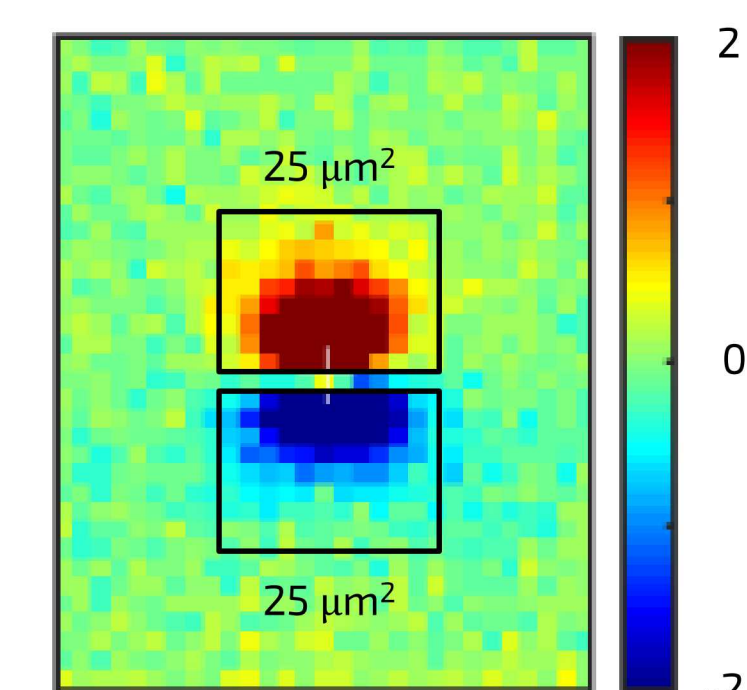 - Sensitive to deep sources
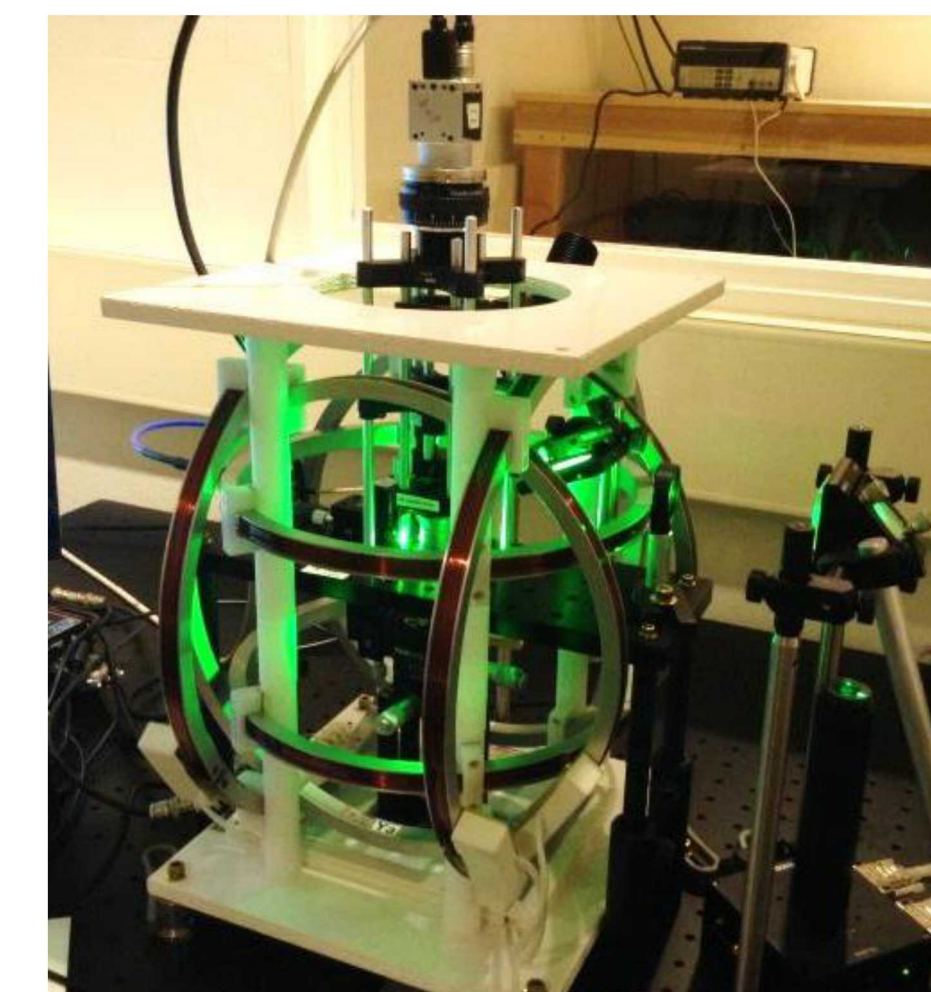
Example micromagnet PUF image

20 µT
20 µT
−20
500 µm   50 µm

25 µm²
25 µm²
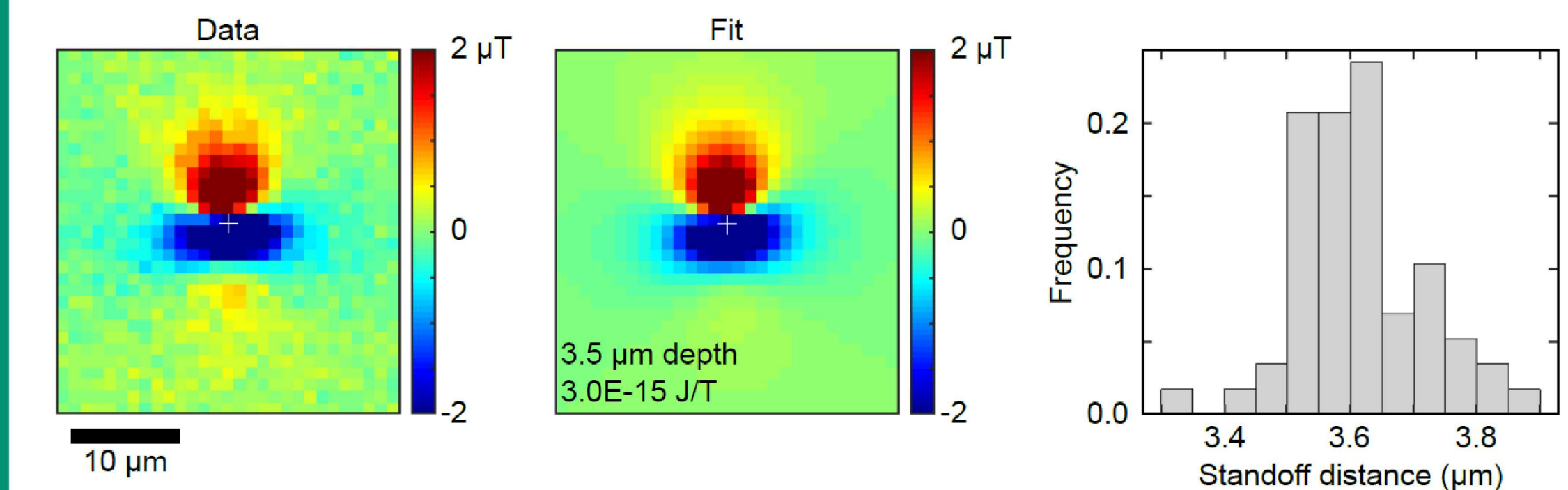2 µT
−2

- Image analysis:
  - Convert from B_{111} map to B_z map
  - Find edges with convex hull
  - Rotate micromagnet array to be square
  - Cut into 100×100 single-dipole boxes
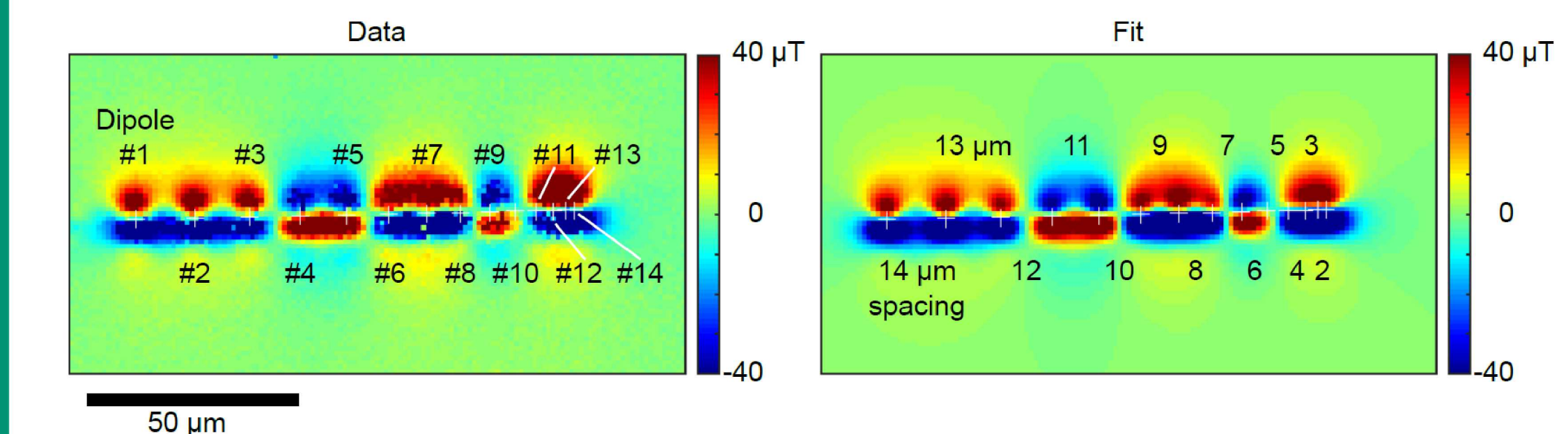 - Calculate $\Delta B = \sum B_{top} - \sum B_{bottom}$
  - Generate bit string

Performance specs

- Up to few-second readout time

- 3.6 µm NV-micromagnet standoff distance

Data   2 µT   Fit   2 µT
0   0
−2   −2
3.5 µm depth
3.0E-15 J/T
10 µm

Frequency
Standoff distance (µm)

- Closest-resolvable separation is ~5 µm

Data   40 µT   Fit   40 µT
Dipole
#1 #3 #5 #7 #9 #11 #13
13 µm   11   9   7   5   3
0   0
#2 #4 #6 #8 #10 #12 #14
14 µm spacing   12   10   8   6   4   2
−40   −40
50 µm

- Passes most NIST randomness statistical tests

Statistical Test	p-value	Result	Comments
Frequency	0.023821	Pass	
Block Frequency	0.036802	Pass	
Runs	0.000000	Fail	Bit string values fluctuate too slowly
Longest Run	0.465732	Pass	
Rank	0.862457	Pass	
Discrete Fourier Transform	0.066457	Pass	
Non-Overlapping Template	-	-	138 out of 148 tests pass
Overlapping Template	0.241223	Pass	
Maurer's Universal	-	-	Too few bits to evaluate
Linear Complexity	0.543677	Pass	
Serial ($\nabla \psi_m^2$)	0.059629	Pass	
Serial ($\nabla^2 \psi_m^2$)	0.311516	Pass	
Approximate Entropy	0.000503	Fail	
Cumulative Sums Forward	0.027787	Pass	[4]
Cumulative Sums Reverse	0.036550	Pass	
Random Excursions	-	-	Too few bits to evaluate
Random Excursions Variant	-	-	Too few bits to evaluate

Outlook

- Investigate materials, micromagnet dimensions, and NV layer thickness

- Characterize robustness to the environment

References

1. T. Bauer and J. Hamlet, IEEE Security & Privacy 12 6 97-101 (2014)
2. T. McGrath et al., Appl. Phys. Rev. 6 011303 (2019)
3. D. R. Glenn et al., Geochem. Geophys. Geosyst. 18, 8 (2017).
4. A. Rukhin et al., NIST Special Publication 800-22 Revision 1a (2010).
5. P. Kehayias et al., in prep. (2020).