High-Sensitivity Magnetometry with Nitrogen-Vacancy Centers for Biomagnetic Signal Detection

Jonah A. Majumder, John F. Barry, Matthew H. Steinecker, Xingyu Zhang, Michael F. O'Keeffe, Linh M. Pham, Danielle A. Braje

MIT Lincoln Laboratory, Lexington, MA 02421, USA

Abstract

We present work towards a diamond-based sensor capable of measuring magnetic fields of biological strength, consisting of $\sim 10^{12}$ nitrogen-vacancy defects. We expect an optical shot noise-limited field sensitivity of approximately $200\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$, placing our device in a regime traditionally occupied only by SQUID and SERF magnetometers. Improvements rely on significantly lengthened T_2^* dephasing times, arising from engineering of diamond substrates and implementation of pulse sequences designed to mitigate problematic interactions. These performance enhancements, combined with the relative small size and simplicity of such a sensor, could provide a practical, inexpensive, and powerful alternative for biologically focused magnetometry.

BACKGROUND

What is a nitrogen-vacancy center?

The nitrogen-vacancy (NV-) center is a point defect in diamond with an atom-like energy level structure.

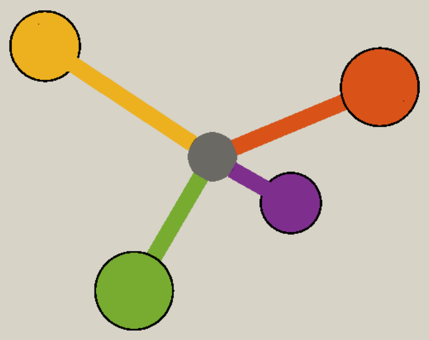
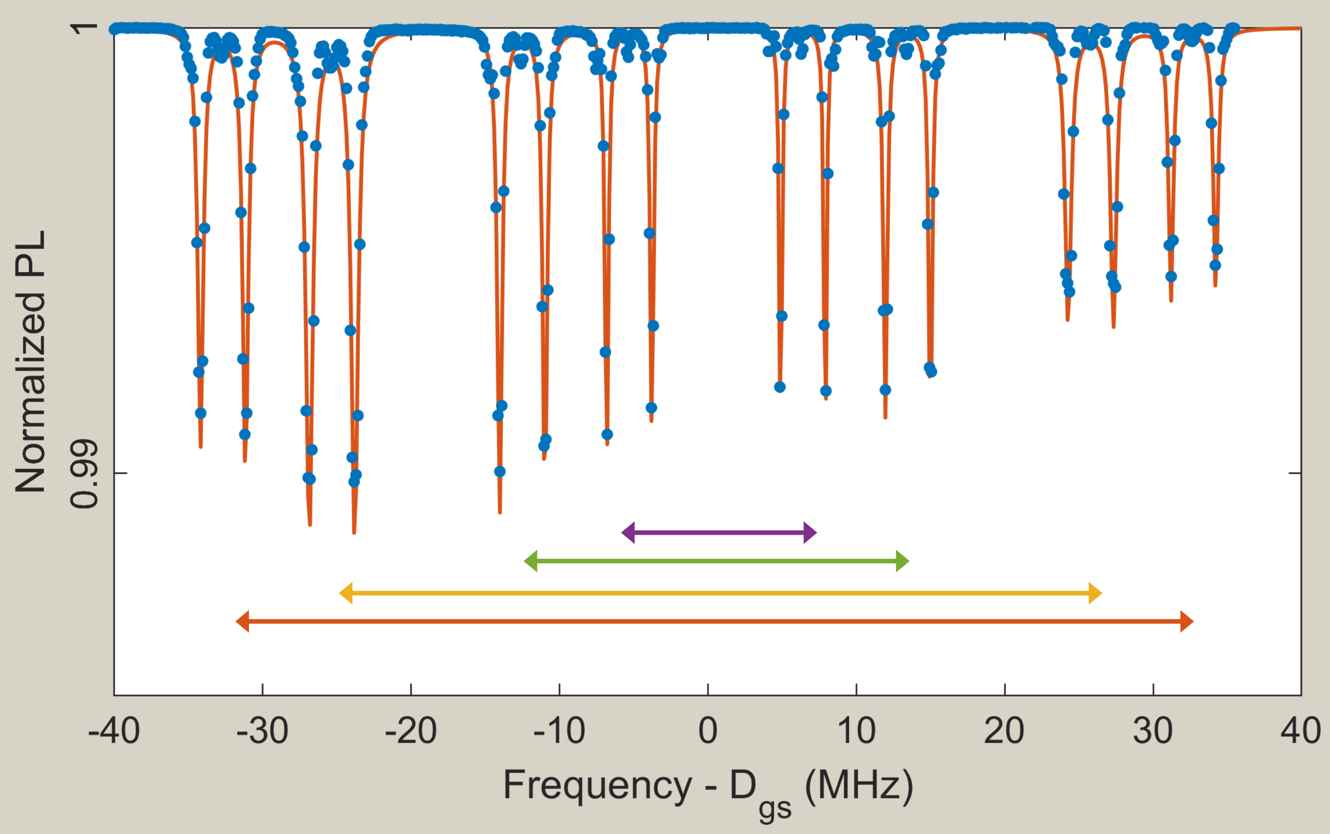
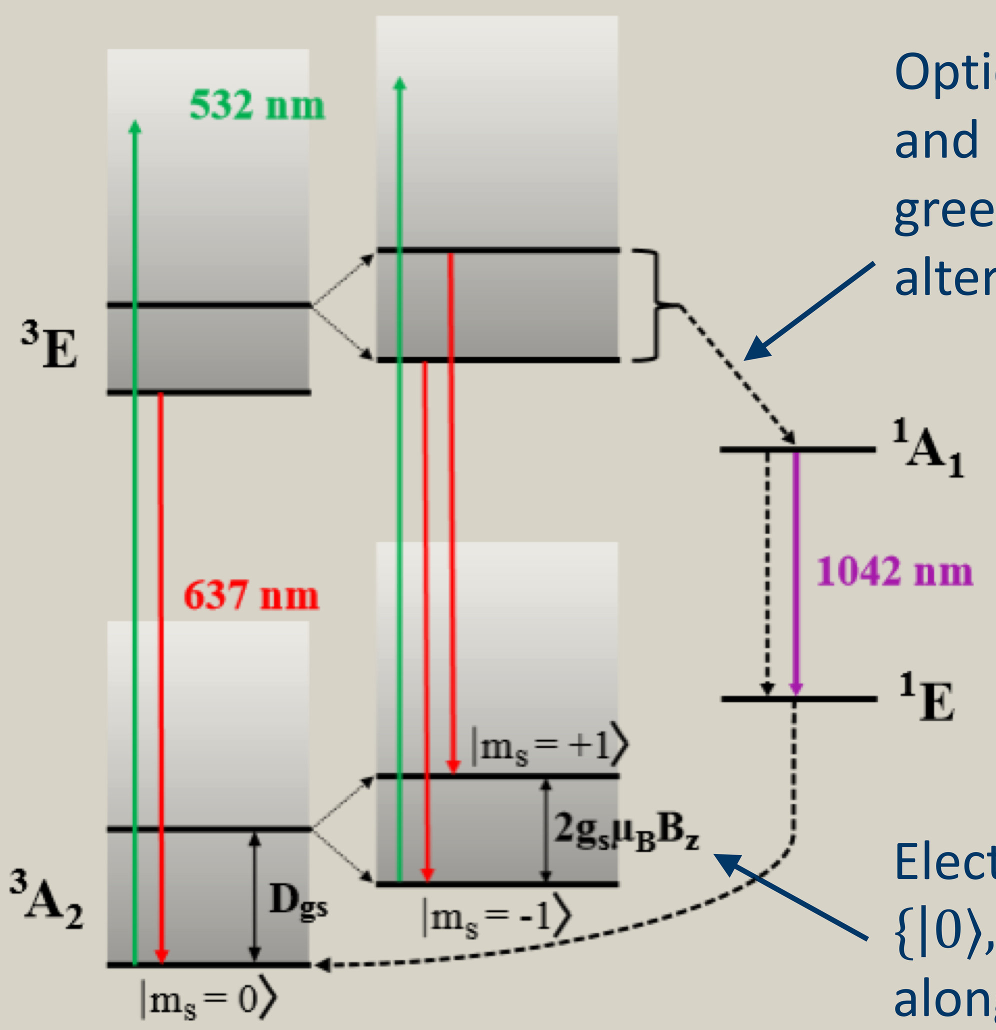


Figure 1: (Left) An illustration of the four possible NV- crystal orientations. (Below) Optically-detected electron spin resonance of an MIT Lincoln Laboratory (MIT LL) diamond in a nondegenerate magnetic field.





Optical polarization and readout with green light (from alternate decay path)

Figure 2: NV- energy level structure in an on-axis magnetic field. Upon being pumped with green light, the NV- fluoresces in red (adapted from [1]).

Electron spin triplet $\{|0\rangle, |\pm1\rangle\}$ quantized along crystal axis, with Zeeman splitting $\propto B_\parallel$ between $|\pm1\rangle$

Ground-State Spin Hamiltonian

$$\boxed{H_{gs}/\hbar = D_{gs}S_z^2 + B_z(\gamma S_z + \gamma_N I_z) + A_\parallel S_z I_z}$$

$$D_{gs} = 2.87\ \mathrm{GHz} \qquad A_\parallel = 3.03\ \mathrm{MHz}$$

$$\gamma = -28.0\ \frac{\mathrm{GHz}}{\mathrm{T}} \qquad \gamma_N = -4.32\ \frac{\mathrm{MHz}}{\mathrm{T}}\ [2]$$

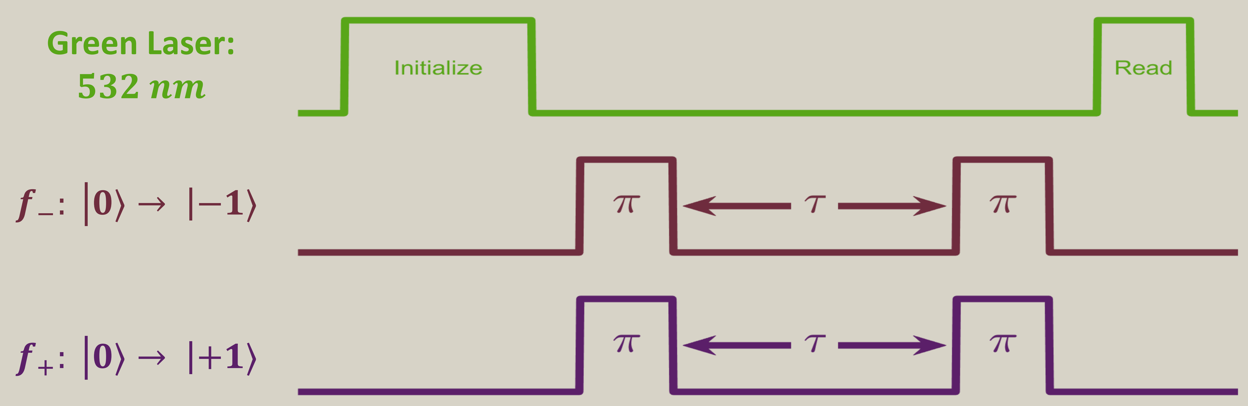
METHODS

Measurement in the *Double Quantum* (DQ) Basis

$$|\Psi_{DQ}^{+}\rangle = \frac{|-1\rangle + |+1\rangle}{\sqrt{2}} \qquad |\Psi_{DQ}^{-}\rangle = \frac{|-1\rangle - |+1\rangle}{\sqrt{2}}$$

The $|-1\rangle$ to $|+1\rangle$ energy splitting is proportional to B_z and *insensitive* to temperature, electric field, and crystal strain.

Ramsey-Type DQ Pulse Sequence



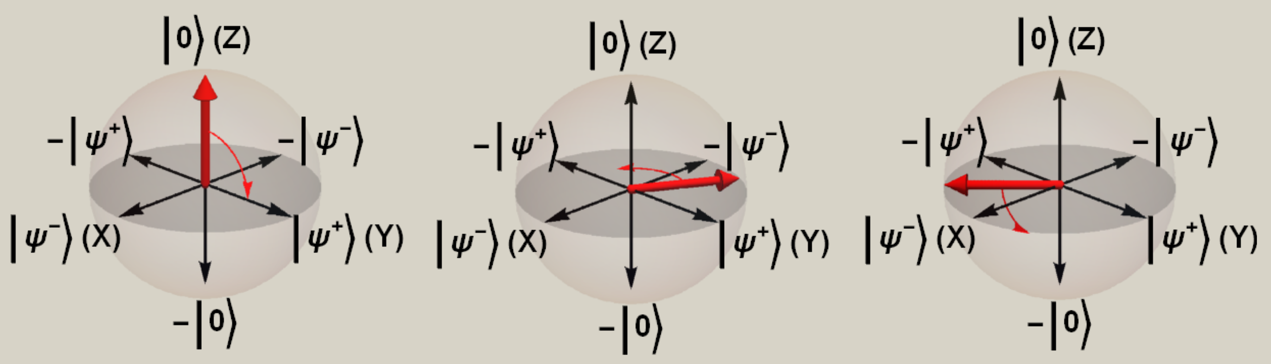
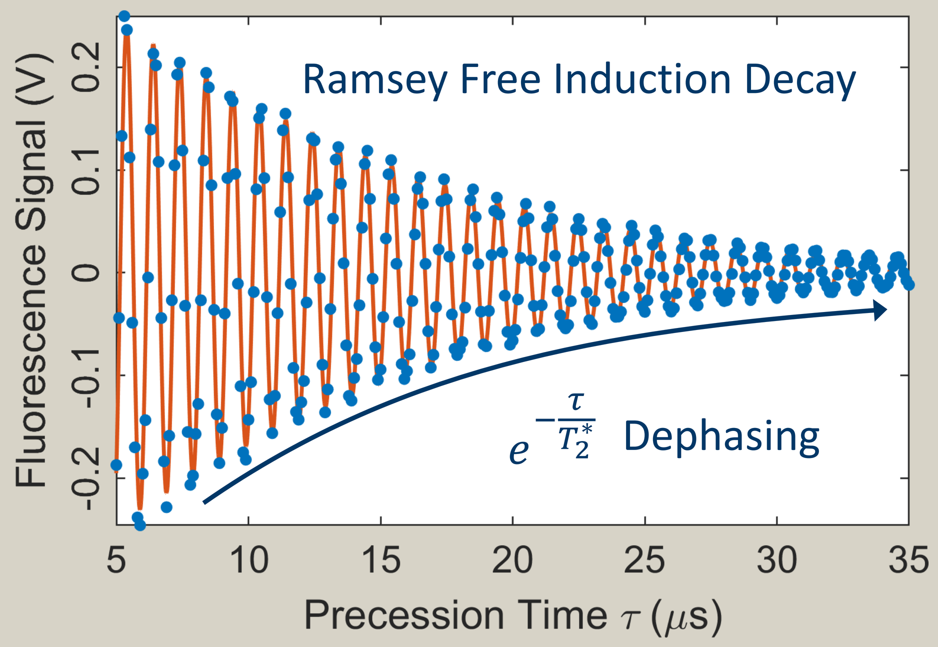
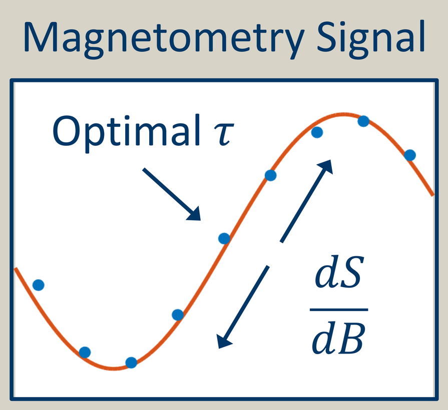


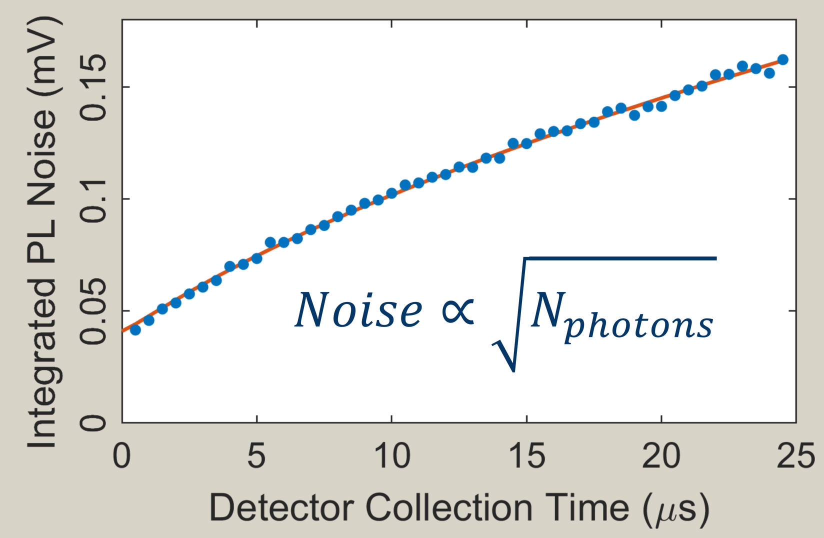
Figure 3: (Top) Pulse sequence diagram for a DQ Ramsey magnetometry scheme. (Middle) Corresponding state evolution on a DQ Bloch Sphere. (Below) Free induction decay (FID) data of an MIT LL diamond and origin of the magnetometry signal.





Optical Shot Noise-Limited Performance

$$\text{B-Field Sensitivity: } \eta_B = \frac{\hbar}{\gamma}\frac{e}{\Delta m_s\, C_{fl}}\frac{1}{T_2^*} \qquad [3]$$



Projected limit:

$$200\ \frac{\mathrm{fT}}{\sqrt{\mathrm{Hz}}}$$

Figure 4: Data illustrating the square root dependence of noise on photons collected, characteristic of Poissonian shot noise statistics.

APPLICATIONS

Biomagnetism

Cells in the brains and hearts of animals undergo rapid membrane depolarization, a process called an action potential. Action potentials travel as ions flow axially through the neuron or muscle cell. These events can be detected noninvasively by their magnetic signatures.

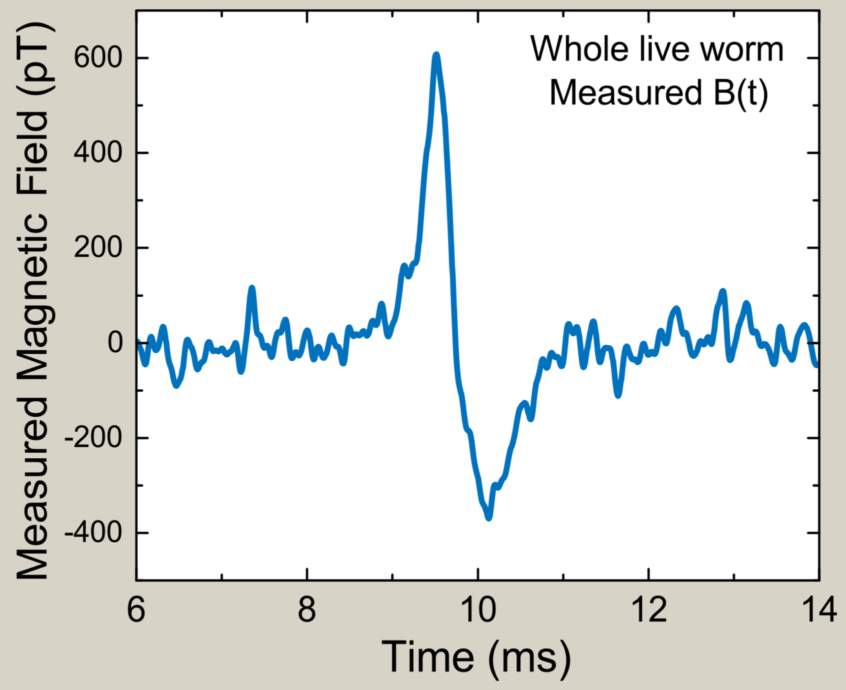
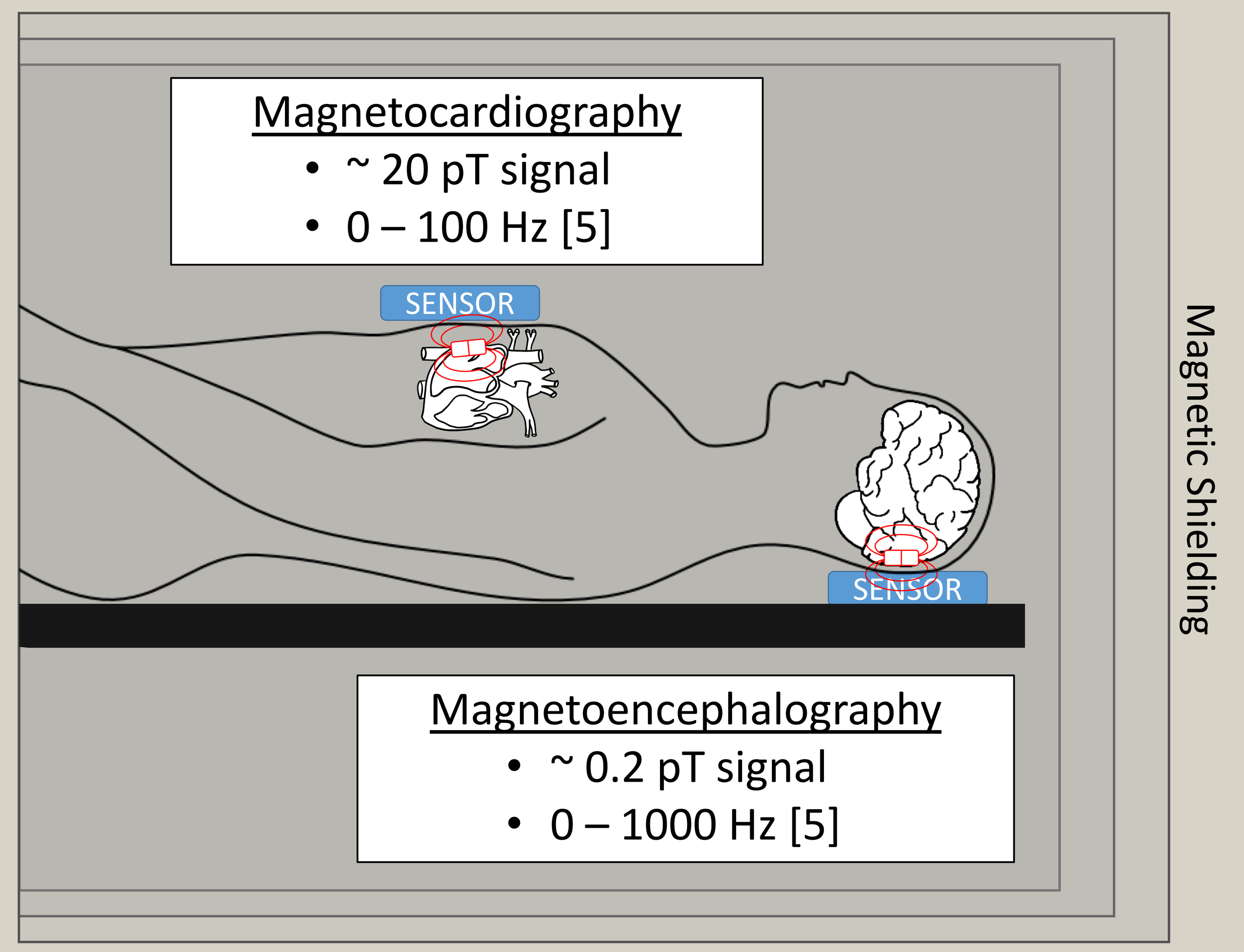


Figure 5: (Left) Example magnetic detection of an action potential in a marine worm (taken from [4]). (Below) Diagram illustrating the geometry of biomagnetic signal detection.



Ongoing Work

- Demonstrate measurement of human subject
- Further improve diamond properties for device performance
- Investigate techniques to surpass optical shot noise limit and compete with SQUID/SERF sensitivity

References

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