

# Localized Detection of Electron Spin Precession with Free Electrons

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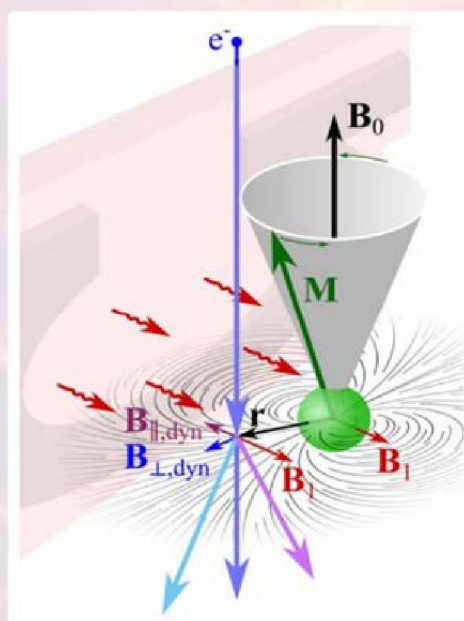
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Spin is a fundamental quantum property of matter, intrinsically linked to the electronic and chemical environment. Spin states can be coherently manipulated using microwave (MW) radiation, and spectroscopic methods such as electron spin resonance (ESR) and nuclear magnetic resonance (NMR) have provided profound insights into spin systems [1,2]. However, these conventional approaches typically probe the ensemble-averaged response of spins and therefore lack spatial resolution, limiting their ability to access local spin information within heterogeneous specimens

Here, we present SPINEM (Spin Electron Microscopy), a technique that integrates MW spectroscopy with transmission electron microscopy (TEM) to enable localized detection of spin excitations using a free-electron probe. Spin polarization is provided by the magnetic field of the pole piece ( $B_0 \approx 170$  mT). A custom-designed microresonator, implemented in a dedicated TEM holder [3], drives spin transitions at  $\approx 5$  GHz and induces a synchronous modulation of the electron beam (see Figure 1). This modulation enables phase-locked detection, isolating spin-precession-induced beam deflections with sensitivities down to the picoradian scale. By sweeping the polarizing  $B_0$  field across the resonance condition of the specimen, spatially resolved SPINEM spectra can be acquired with a lateral resolution of  $30 \mu\text{m}$  [4].

By uniting spin physics with high-resolution electron optics, SPINEM establishes a new platform for quantum electron microscopy. The technique enables sensitive and quantitative detection of spin excitations and opens a pathway toward spatially resolved mapping of spin excitations, providing access to local spin information beyond the reach of conventional methods.



**Figure 1:** SPINEM spectra are recorded by sweeping the static polarizing magnetic field ( $B_0$ ) through the resonance condition while keeping the driving magnetic field ( $B_1$ ) constant to preserve a stable phase reference. When resonance is reached, the sample's magnetization ( $M$ ) starts to precess, generating time-varying magnetic fields ( $B_{\text{dyn}}$ ) that deflect the electron beam.

## References

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