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Nano MRI

Of all the different methods that have aimed to achieve nanometer to sub-nanometer 3D reconstructed images, MRFM has made the most progress. The method, however, has its limitations. The biggest limitation is a very low temperature, in the order of several Kelvin. Imaging living biological samples under such conditions may not be possible.

MRFM is based on ultra-sensitive force detection using a submicron magnetic tip on a cantilever. Several protocols have been used in experiments in order to couple the spin to the dynamics of the moving cantilever. One such method, the interrupted oscillating cantilever-driven adiabatic reversal protocol (iOSCAR), was successfully used to detect an isolated electron spin.

A schematic diagram of an OSCAR-type MRFM experiment for electron spin detection is shown in Figure 1.1. As shown in the figure, a submicron ferromagnet is placed on the tip of a cantilever and positioned close to an unpaired electron spin contained within the sample. An applied radio-frequency (rf) field serves to induce magnetic resonance of the spin when the rf field frequency matches the Larmor frequency. Because the magnetic field emanating from the tip is highly inhomogeneous, magnetic resonance is spatially confined to a thin bowl-shaped region called the "resonant slice".

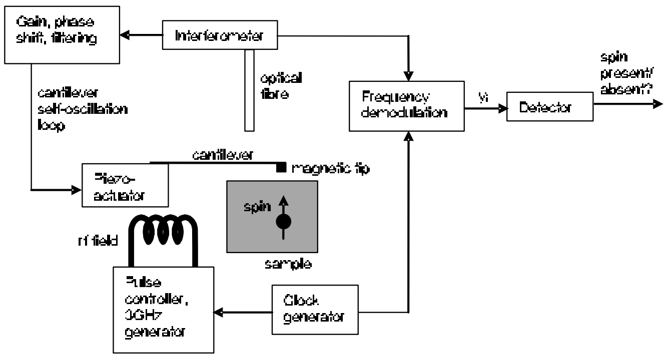

Figure 1.1. *Schematic of an OSCAR-type MRFM experiment for electron spin detection*

If the cantilever is forced into mechanical oscillation by positive feedback, the tip motion will cause the position of the resonant slice to oscillate. As the slice passes back and forth through an electron spin in the sample, the spin direction will be cyclically inverted due to an effect called adiabatic rapid passage [WAG 98]. The cyclic inversion is synchronous with the cantilever motion and affects the cantilever dynamics by changing the effective stiffness of the cantilever. Therefore, the spin–cantilever interaction can be detected by measuring small shifts in the period of the cantilever oscillation. This methodology has been successfully used to detect small ensembles of electron spins [MAM 03a, STI 01], and even a single spin [RUG 04].

In [MAM 03b], the point spread function (psf) of an MRFM tip is derived under the following assumptions:

– The tip can be modeled as a point dipole.

– The spins are undergoing cyclic adiabatic inversion (CAI).

– There is no spin–spin coupling.

– Energy-based measurements are taken.

Although Figure. 1.1 shows a horizontal cantilever, experiments use a vertical cantilever vibrating in the x direction. A horizontal cantilever cannot vibrate too closely to the sample surface; otherwise, van der Waals and electrostatic forces will draw the tip onto the surface and break the cantilever [STO 97]. The psf for a vertical cantilever vibrating in the x direction is given by

$$H(x,y,z) = \begin{cases} \left(\frac{G(x,y,z)}{G_0}\right)^2 \left(1 - \left[\frac{s(x,y,z)}{x_{\text{pk}}}\right]^2\right) & |s(x,y,z)| \leq x_{\text{pk}} \\ 0 & |s(x,y,z)| > x_{\text{pk}} \end{cases}, \quad [1.1]$$

where x_{pk} is the peak amplitude and G_0 is a normalizing constant [MAM 03b]. Let $r = \sqrt{x^2+y^2+z^2}$, then

$$s(x,y,z) = \frac{B_{\text{res}} - B_{\text{mag}}(x,y,z)}{G(x,y,z)}, \quad [1.2]$$

$$B_{\text{mag}}(x,y,z) = \sqrt{\left(\frac{3xzm}{r^5}\right)^2 + \left(\frac{3yzm}{r^5}\right)^2 + \left(\frac{m(2z^2-x^2-y^2)}{r^5} + B_{\text{ext}}\right)^2} \quad [1.3]$$

and $G = \frac{\partial}{\partial x} B_{\text{mag}}$, which is

$$G(x,y,z) = \frac{1}{2B_{\text{mag}}(x,y,z)}\Bigg(- \frac{90m^2x^3z^2}{r^{12}} - \frac{90m^2xy^2z^2}{r^{12}} + \frac{18m^2xz^2}{r^{10}} + 2\left[-\frac{2mx}{r^5} - \frac{5mx(-x^2-y^2+2z^2)}{r^7}\right] \times \left[B_{\text{ext}} + \frac{m(-x^2-y^2+2z^2)}{r^5}\right]\Bigg). \quad [1.4]$$

The parameter set listed in Table 1.1 is used to illustrate the 3D MRFM psf. Slices of the MRFM psf, which in their 3D form resemble a traffic cone, are illustrated in Figure 1.2–1.4 at three different z values. As z increases, the psf shrinks in the x–y plane as well as decreasing in intensity. The 2D MRFM psf is an x–y slice of the 3D psf. Note that the interior of the 2D MRFM psf is zero; thus, the noiseless MRFM response of an electric spin consists of two crescents facing each other.

Parameter		Value
Description	Name	
Amplitude of external magnetic field	B_{ext}	8.817×10^3 G
Value of B_{mag} in the resonant slice	B_{res}	10^4 G
Radius of tip when modeled as a sphere	R_0	3 nm
Distance from tip to sample	d	3 nm
Cantilever tip moment[a]	m	1.923×10^5 emu
Peak cantilever swing	x_{pk}	0.246 nm
Maximum magnetic field gradient[b]	G_{max}	406.9 G/nm

[a]Assuming a spherical tip.
[b]Assuming optimal sample position.

Table 1.1. *Parameters used to illustrate the MRFM psf*

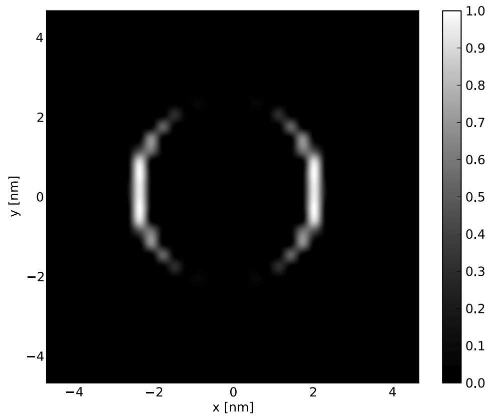

Figure 1.2. *Slice in the x–y plane at z = 6 nm*

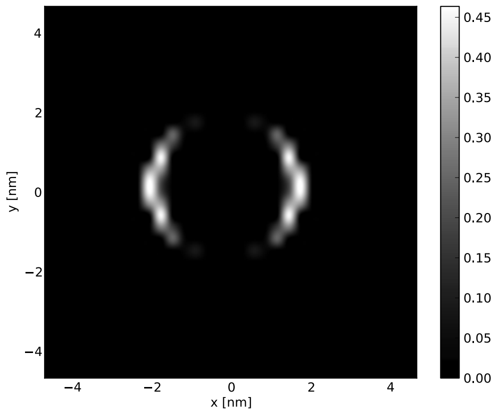

Figure 1.3. *Slice in the x–y plane at z = 6.361 nm*

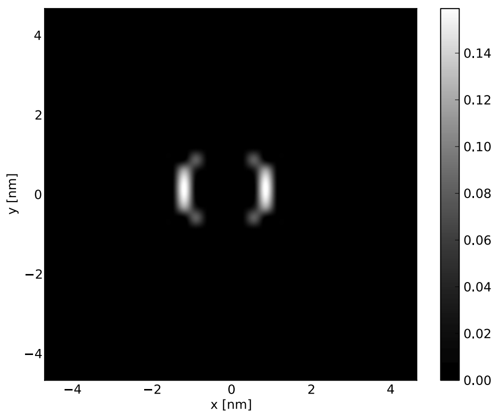

Figure 1.4. *Slice in the x–y plane at z = 6.722 nm*