

Proceedings Article

# Stimulated Emission Depletion (STED) Magnetic Particle Imaging

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## Abstract

Magnetic Particle Imaging (MPI) enables in vivo magnetic nanoparticle detection for cell tracking and molecular imaging, but human-sized scanners only reach 5-10 mm resolution, insufficient for precise localization. We searched for the donut focal spot by adding a direct current offset stimulation magnetic field in the direction of the excitation field and receiver coil in MPI. When the offset stimulation field is greater than the excitation field amplitude, a donut-shaped focal spot can be formed and the donut radius increases with the offset field amplitude. The formation of the donut focal spot was theoretically evaluated and simulated on phantom images. Optimized STED factor-based PSF subtraction yielded smaller full width at half maximum (FWHM), enabling sub-millimeter resolution reconstruction.

## I. Introduction

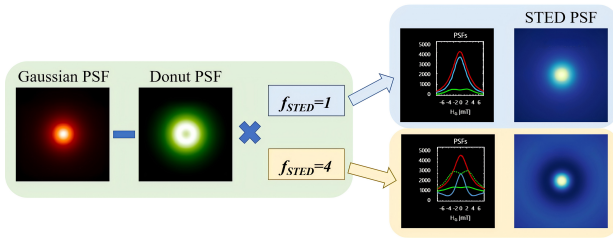
Magnetic Particle Imaging (MPI) is a new in vivo method first proposed in 2005 [1], which can sensitively detect magnetic nanoparticles without ionizing radiation and is used in fields such as T cell tracking [2]. Stimulated Emission Depletion (STED) fluorescence microscopy, proposed by Professor Hell in 1994 [3], achieves super-resolution by adding a circular ring-based PSF to the regular Gaussian PSF. This study thus proposes a high-resolution MPI method by searching for donut-shaped focal spots via an offset excitation magnetic field. By applying an optimized STED factor in the subtraction of the donut PSF from the regular Gaussian PSF, a much

smaller PSF could be obtained for deconvolution-based image reconstruction.

## II. Methods and materials

### II.1. Theory

In STED-MPI, we combine a cosine excitation field with a collinear stimulation DC magnetic field along the field free line (FFL). The imaging space is covered by two orthogonal gradient fields in a typical FFL-based MPI scanner. We assume that the alternating excitation field has a period  $T$  and an amplitude  $H_{AC}$ . The stimulation field was defined as an offset direct-current field  $H_{DC}$  in the



**Figure 1:** An STED factor can be used to generate a much smaller PSF than the bright Gaussian PSF during the focal modulation process.

$z$ -direction. The selection gradient fields  $G$  forming the FFL are in the  $x$ - $y$  plane.

The  $n$ th stimulated emission signal frequency component along the  $z$ -direction can be calculated as:

$$S_{n,z} = \frac{-2i}{T} \frac{\partial M_z(Gr)}{\partial H_z} * \left( U_{n-1} \left( \frac{H_{DC}}{H_{AC}} \right) \sqrt{1 - \left( \frac{H_{DC}}{H_{AC}} \right)^2} \right), \quad (1)$$

where  $M_z$  is the magnetization along the  $z$ -direction,  $r = \sqrt{x^2 + y^2}$  is the distance to the origin of the  $x$ - $y$  plane, and  $U_{n-1}$  is the Chebyshev polynomial of the second kind.

## II.II. Simulation

In STED PSF simulation, the Gaussian focal spot and donut focal spot were subtracted to generate a smaller PSF (Figure 1). An STED factor is used during subtraction of two focal spots,

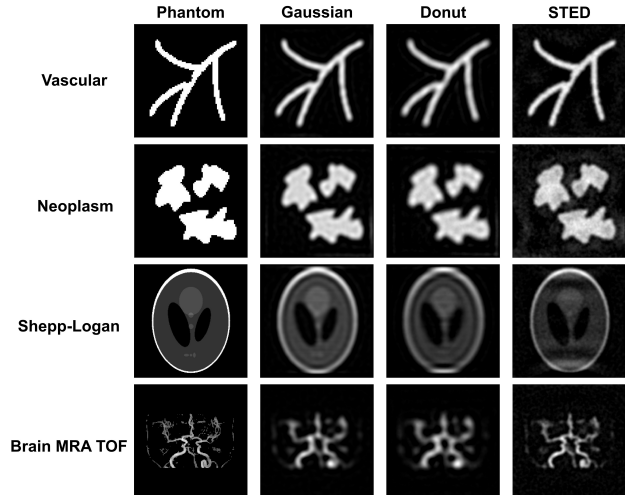
$$PSF_{STED} = PSF_{Gaussian} - f_{STED} \cdot PSF_{Donut}. \quad (2)$$

In this study, a 0% DC offset was set as the Gaussian PSF. A 105% DC offset was selected as a donut PSF and an STED factor of 1.9 was chosen for STED PSF generation.

The selection field was used to form an FFL perpendicular to phantom images, which was moved point by point throughout the entire field of view (FOV) for signal generation. The Richardson-Lucy deconvolution algorithm was used to generate higher-resolution images. The reconstructed image quality was evaluated using the root mean square error (RMSE), peak signal-to-noise ratio (PSNR), and structural similarity index (SSIM).

## III. Results and Discussion

The reconstructed phantom images using the STED-MPI method and deconvolution algorithm exhibited higher quality than Gaussian-based or donut-based images, as visualized in Figure 2 and quantitatively indicated in Table 1. The STED-PSF-based images exhibited higher resolution and contrast than the Gaussian-PSF-based images. The resolution of the STED-PSF-based images was about 0.62 mm on the bar pattern phantom images.



**Figure 2:** Reconstructed phantom images from Gaussian, donut, and STED kernels.

**Table 1:** Reconstructed image quality assessment in STED-MPI phantom simulation

Phantom PSF style	RMSE		PSNR		SSIM	
	Gaussian	STED	Gaussian	STED	Gaussian	STED
Vascular	7.77	4.00	69.52	82.92	0.263	0.851
Neoplasm	9.91	4.90	67.18	79.21	0.256	0.695
Shepp-Logan	8.85	5.97	67.26	74.91	0.296	0.523

## IV. Conclusion

This study proposed high-resolution MPI based on a small donut-shaped focal spot and the STED microscopic imaging principle. The donut focal spot can be generated by adding a large offset stimulation field parallel to the excitation and receiver directions. A focal spot modulation technique and deconvolution algorithm can be used to improve MPI image resolution.

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## References

- [1] B. Gleich and J. Weizenecker. Tomographic imaging using the non-linear response of magnetic particles. *Nature*, 435(7046):1214–1217, 2005.
- [2] R. E. Tay, L. P. S. T. Pang, K. E. Low, H. C. Tay, C. M. Ho, B. Malleret, O. Röttschke, M. Olivo, and Z. W. Tay. High-efficiency magnetophoretic labelling of adoptively-transferred t cells for longitudinal in vivo magnetic particle imaging. *Theranostics*, 14(16):6138–6160, 2024.

- [3] S. W. Hell and J. Wichmann. Breaking the diffraction resolution limit by stimulated emission: Stimulated-emission-depletion fluorescence microscopy. *Optics letters*, 19(11):780–782, 1994.