Supporting Information for Mechanical control of individual superconducting vortices

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The SQUID's point spread function (PSF)

The flux image is a convolution between the magnetic signal and the SQUID's PSF. The magnetic field from a single vortex at a certain height above the surface, for heights larger than, the London penetration depth λ, can be modeled by a magnetic monopole at a height λ below the surface. The z component of the magnetic field at height h above the surface is given by

$$B_z(x,y) = \frac{\Phi_0}{2\pi} \frac{h+\lambda}{\left(x^2+y^2+(h+\lambda)^2\right)^{3/2}}$$

where Φ_0 is one flux quantum.

The SQUID signal, in units of flux, is the magnetic field lines that are captured by the pickup loop. The pickup loops of the SQUIDs we use are 0.5-3 µm in diameter. The PSF is closely related to the pickup loop's shape and can be roughly represented by a keyhole (a disk with a rectangle at the top). In Figure S1, we demonstrate how the circular shape of $B_z(x,y)$ of a single vortex is distorted by the keyhole-shaped PSF.

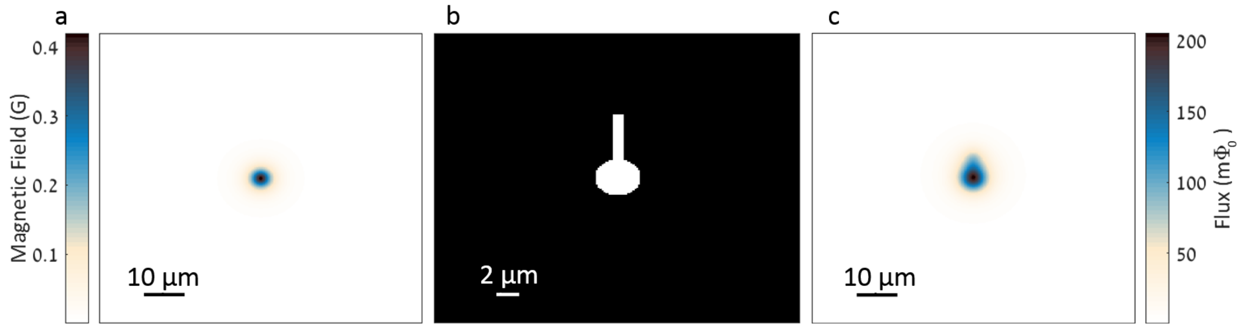

Figure S1: Convolution of the magnetic signal of a single vortex and the SQUID's PSF. a*, The z component of the magnetic field from a vortex, calculated for λ = 0.3 µm and h = 2.5 µm.* ***b****, Sketch of the SQUID's PSF, approximated by a keyhole shape.* ***c****, Convolution of panels a and b.*

SQUID imaging of an isolated vortex

Each vortex carries one flux quantum, Φ_0. The flux signal at each pixel depends on the area of the pickup loop and the height above the sample. The angle between the SQUID chip and the sample is set by the alignment of the experiment. For most SQUID experiments the alignment angle is set to be around 2.5° in order to bring the pickup loop as close as possible to the sample. For the experiments described in this work, the tilt angle between the chip and the sample was set to $\geq 4°$ in order to ensure that the tip of the silicon chip made contact with the sample (rather than the pickup loop). This angle sets the minimal height of the pickup loop above the sample to 1-2 µm. Figure S2a shows a flux image of an isolated vortex, with an alignment angle of 2.5°. In Figure S2b, we integrate the signal as a function of the distance from the center of the vortex, until a full signal of Φ_0. Figure S2d shows a flux image of an isolated vortex, imaged further from the surface (alignment angle of 4.5°). The vortex signal is spread over a larger area and the value of each pixel is smaller. As expected, integrating the signal yields Φ_0 (Figure S2e).

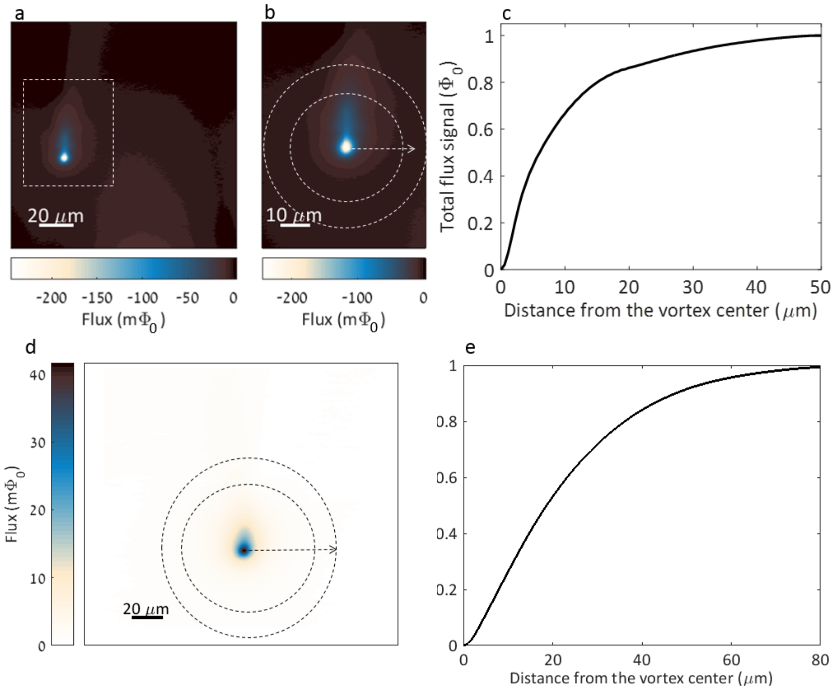

Figure S2: SQUID imaging of an isolated vortex. a*, SQUID flux image of a single vortex, imaged with SQUID alignment of 2.5°*. The signal spans over 240 mΦ_0. ***b****, A zoomed image on the area marked by dashed square in a.* ***c,*** *Flux signal integrated over a disk with its origin at the center of the vortex, as a function of the disk's radius, as illustrated by the dashed circles in b. The total signal from an isolated vortex is one Φ_0.* ***d,*** *An isolated vortex, imaged with SQUID alignment of 4.5°. The signal spans over 40 mΦ_0 due to the pickup loop height above the sample.* ***e,*** *The total integrated flux signal is one* Φ_0.

The center of the vortex and the filter used in this study

In the current study we are mainly interested in the location of each vortex. For some figures, we used a filter in order to clear magnetic background or to highlight the location of the vortex. Figure S3a shows the vortex from Figure S2d after subtraction of a Gaussian filter. This subtraction naturally affects the flux signal, which no longer integrates to a full Φ_0 (Fig. S3b). Note that the flux values span a smaller range and the radii of the vortex seem smaller. However, removing the Gaussian filter does not affect the location of the vortex (Fig. S3c).

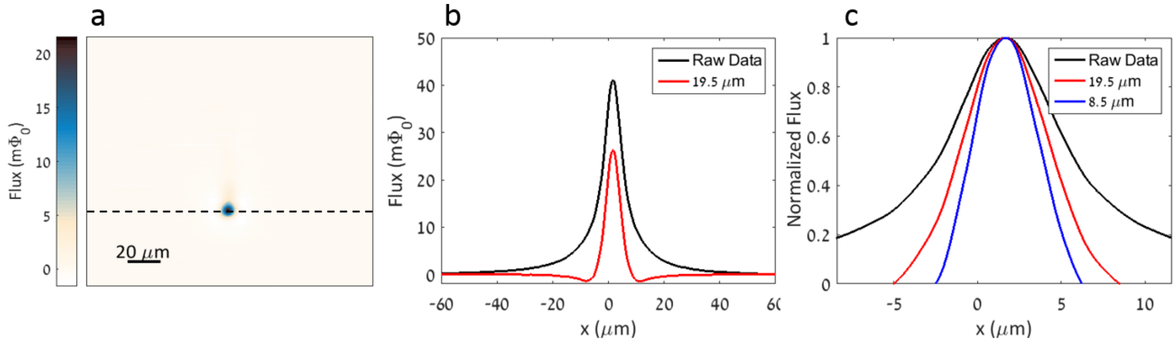

***Figure S3: Subtraction of a filter. a**, Data from Figure S2d after subtraction of a Gaussian filter of 19.5 μm. **b**, Cross section through the center of the vortex (dashed line in panel a). Flux signal of the filtered image (red) is lower than the signal from the raw data (black). **c**, The same cross section for raw data (black), and filters of 19.5 μm (red) and 8.5 μm (blue). Data are normalized to maximal value in order to demonstrate that detection of vortex location is not affected by the filter.*

When vortices are close together and their signals overlap, subtracting a Gaussian makes it easier to determine the location of each vortex automatically. In Figure S4, we demonstrate this technique by combining the raw flux image of an isolated vortex imaged a few microns above the surface with a 1.8 μm pickup loop. We shifted the signal of each vortex to demonstrate the overlap and the effect of the filter.

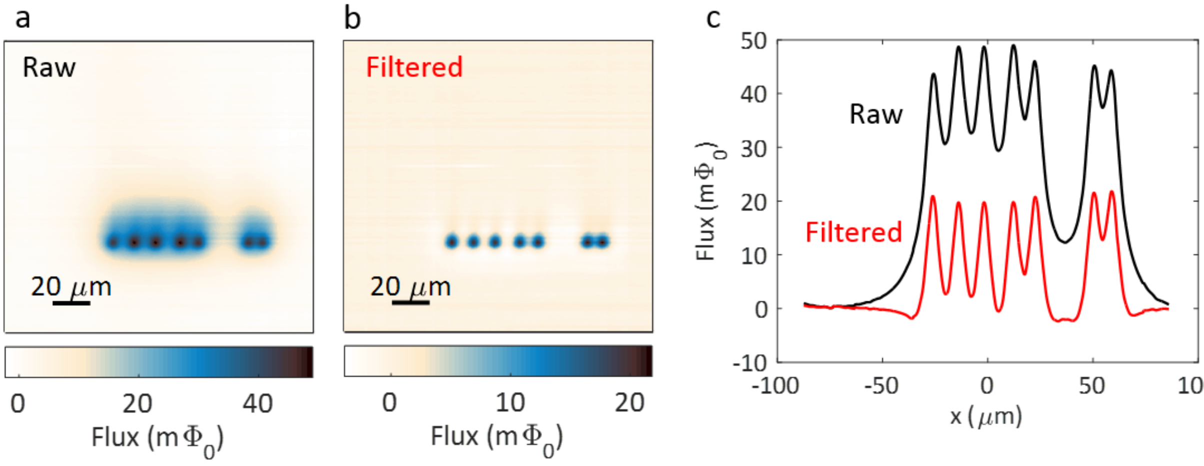

***Figure S4: Determining the locations of adjacent vortices. a**, Flux signal from an isolated vortex placed at different locations to demonstrate the overlap between signals. **b**, The same matrix after application of a 20-μm Gaussian filter. **c**, Horizontal cross-section through the center of the vortices.*

Expanded data presentation for Figure 1 of the main text

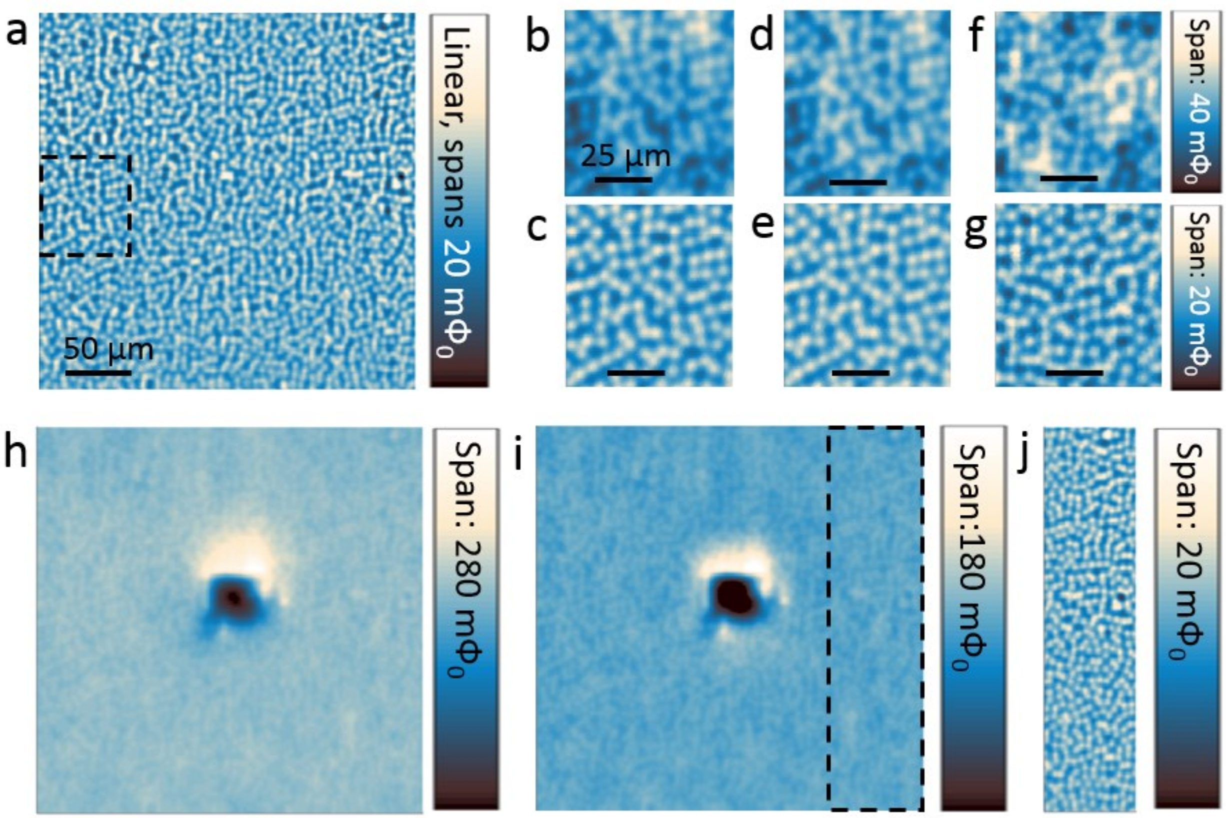

***Figure S5: Expanded presentation of data from Figure 1 of the main text. a**, Data from Figure 1b of the main text. Vortex configuration in an NbN thin film imaged at 4.2 K with no contact. **b-c**, The area marked by a dashed square in (a) is replotted as (b) raw data and (c) filtered data as demonstrated in Figure S3. **d-e**, The same region extracted from the data shown in Figure 1c of the main text. Vortices from the center of the area moved after scanning in contact (Fig. 1c of the main text). Here we demonstrate that vortex configuration in areas that were not scanned in contact (the dashed square in a) remain unchanged, shown in (d) raw and (e) filtered data. **f-g**, The same region extracted from the data shown in Figure 1d of the main text. New vortices generated on the same region sit in new locations in the (f) raw and (g) filtered datasets. **h-j,** Raw (h) and filtered (i) data from Figure 1c of the main text. The area marked by a dashed rectangle is plotted again in (j) with a zoomed scale bar, illustrating the configuration of individual vortices in these data.*

In Figure 1b of the main text, we used the filter described in Figure S3 to clarify the locations of the vortices. In Figure S5(b-g), we zoom in on part of the picture (dashed square in Fig. S5a) to demonstrate the use of the filter; raw data (Fig. S5b) and filtered data (Fig. S5c) are given for the same vortices.

Figures S5d (raw data) and S5e (filtered data) show the same region after a different region was scanned in contact. These data are shown in Figure 1c of the main text with different range of color scale values. In Figure S5, which includes a zoomed color scale, the data demonstrate that vortices outside the region that was scanned in contact did not move. Figures S5f (raw data) and S5g (filtered data) show the same region after thermocycling around the superconducting transition in order to generate new vortices. The new vortices sit in new random locations. These data also appear in Figure 1d of the main text.

The overall signal of the data in Figures S5h-j (also shown in Fig. 1c of the main text) spans a much larger set of color scale values because vortices that cleared out of the contacted area accumulated outside that area. The modulation of signal in the area that was not contacted by the SQUID tip has a much smaller amplitude (20 mΦ_0), due to overlapping signal from nearby vortices.

Expanded data presentation for Figure 2 of the main text

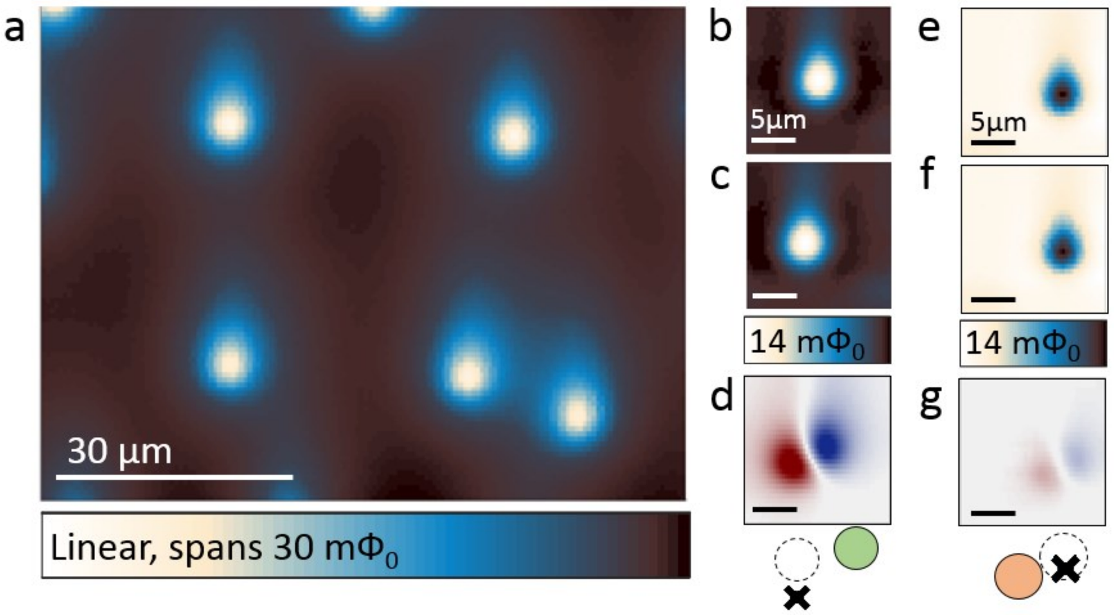

***Figure S6: Expanded presentation of data from Figure 2 of the main text. a**, Raw flux data from isolated vortices imaged without contact at 4.2 K. **b**, Flux image (raw data) of one vortex from panel a, imaged without contact. **c**, A second image of the same area, without contact, after tapping once near the vortex in panel b. The vortex displaced nearly 2 µm and is visible when comparing panels b and c. **d**, The differential image, similar to the images shown in Figure 2 of the main text. The vortex jumped in the direction of the tap. The cartoon below the images shows the position of the contact points (X) relative to the initial location of the vortex (green circle). **e-f**, A different vortex with opposite polarity displaced by 250 nm. The movement was difficult to detect by comparing the raw data in e and f, but was visible in the differential image (g).*

The location of the vortex is determined by finding its maximum signal. The fact that the PSF can be rather large does not affect our ability to identify the center of the vortex. Vortex displacement can be easily detected by subtracting images (raw data). Large displacements result in large signals. The ability to detect small displacements is limited only by flux noise (1-10 µΦ_0/√(Hz) at 1 Hz) and by mechanical vibrations.