ARTICLE TYPE

Strong vortical flows generated by the collective motion of magnetic particle chains rotating in a fluid cell – Electronic Supplementary Information

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Movies

Video S1 shows the observed phenomenon of the collective motion of rotating particle chains. Video S2 shows the influence of field gradients on a collection of vertically rotating magnetic 10 particle chains. Video S3 shows the transition of a cloud of

- rotating magnetic particle chains to a steady state vortical flow. Video S4 shows the different regimes of the collective motion of particles. Video S5 shows the triaxial control of the cloud of rotating magnetic particle chains. Video S6 shows the induced ¹⁵ fluid flow actuated by a cloud of magnetic particle chains.
- Finally, Video S7 shows mixing using a cloud of magnetic particles.

Time-dependent formation of collective particle motion

- ²⁰ In Fig. S1, the formation of a global vortex flow of microstirrers is plotted as a function of time. At t=0 s, a clockwise rotating vertical magnetic field (30 mT, 30 Hz) is applied and the magnetic particles at the bottom surface move to the left while the cloud of particles at the top surface moves to the right (t=18 s
- ²⁵ and t=28 s). After the cloud of particles reaches the opposite end of the cell, a stable and clockwise rotating vortex flow is established consisting of particle chains translating in opposite directions along the upper and bottom surfaces of the fluid cell (t=5 min). If we reverse the applied field, i.e. a counter-clockwise
- ³⁰ rotating magnetic field is applied, we observe the inverse translational movements for both the microstirrers and the cloud.

Triaxial control

In Fig. S2a, a biaxial (vertical) rotating magnetic field is applied and the formed vortex flow occurs within a band with a width of

³⁵ 3 mm. From numerical simulations (Fig.1(b) in the main article), a biaxial rotating magnetic field induces a band of high field strengths with a width of around 4 mm. Although the bandwidth of the experimental vortex flow is found to be smaller, both are in the same order. The 'band region' of high field strengths is ⁴⁰ responsible for the confinement of the magnetic particles within a

band along the entire length of the fluid cell. Experiments were conducted in which the 'band region' of high field strengths was broken down by superposing on top of the rotating vertical field, a rotating horizontal field of equal

- ⁴⁵ magnitude (30 mT) and equal frequency (30 Hz), i.e. a triaxial rotating magnetic field was created. As shown in Fig. 1(c), the critical `band region' is broken down into isolated islands, located near the horizontal poles. Experimentally (Fig. S2(b)), sedimented magnetic particles form large rotating aggregates ⁵⁰ translating towards the horizontal poles. Due to the closed volume, small backflows are observed at the upper surface of the fluid cell, allowing some of the clusters to escape. However, these backflows of clusters are eventually drawn into regions of highest field strengths, depleting magnetic particles in the cell ⁵⁵ center. The band region of high field strengths is restored by decreasing the magnitude of the horizontal magnetic field (≈7.5 mT). In accordance with the numerical findings (Fig. 1(d)), a stable but stretched vortex flow of magnetic micro-stirrers is formed (Fig. S2 c), due to the influence of the horizontal poles.
- 60 (Video S5).

It is interesting to explore the possibility of creating collective motion of particles when exposing the magnetic particle suspension to a triaxial magnetic field, i.e. the combination of a horizontal rotating magnetic field with a vertical rotating

- 65 magnetic field with unequal rotational frequencies. This is advantageous since such triaxial magnetic fields extend the motion of the particle chains to a larger volume rather than to be limited to a band as is the case with a single rotating magnetic field. To this end, the vertical magnetic field (30 mT, 30 Hz) is
- ⁷⁰ set dominant over the horizontal magnetic field (5mT, 300 Hz). On the macroscopic level and in accordance with above, the influence of the horizontal poles results in a stable but stretched vortex flow of magnetic colloidal particles (Fig. S2 d).

Biochemical assay protocol

75 Fig. S3 shows the biochemical assay protocol.

Notes and references

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Fig. S1 A clockwise rotating vertical magnetic field is applied (30 mT, 30 Hz) and the formation of a global induced vortex flow of ⁵ rotating magnetic particle chains is depicted as a function of time. The initial motion of the microstirrers at the bottom surface is towards the left and the resulting backflow at the upper surface of the fluid cell is towards the right. After the cloud of particles reaches the opposite end of the cell, a stable and continuous ¹⁰ clockwise rotating vortex flow is established.



Fig. S2 Bi- and triaxial control of rotating magnetic particle chains. (a) A single rotating vertical magnetic field (30 mT, 30 ⁵ Hz) is applied and the formed vortex flow of microstirrers is a band with a width of \$\sim\$3 mm. (b) A superposition of rotating vertical and horizontal magnetic fields with equal magnitude and equal frequency (30 mT, 30 Hz) for which the magnetic particles form large aggregates translating towards the horizontal poles,

- ¹⁰ depleting the cell center of magnetic particles. (c)-(d) The combination of a stronger vertical (30 mT, 30 Hz) and a weaker horizontal (7.5 mT, 30 Hz at (c) and 5 mT, 300 Hz at (d)) magnetic fields. Due to the influence of the horizontal poles, the formed vortex flow of rotating particle chains is stretched
- ¹⁵ compared to (a). Movies of the experiments can be found at Video S5.



Fig. S3 The steps of the biochemical assay protocol. The assay components are magnetic capture particles coated with Protein G

- s proteins and Goat anti-Mouse IgG assay targets marked with fluorescent labels. Magnetic particles (1) and the assay targets (2) are subsequently introduced into the fluid cell and a first reference measurement is performed, i.e. by acquiring the corresponding brightfield and fluorescence images of the
- ¹⁰ sedimented magnetic capture particles. Each image contains around 600 particles. Next (3), the magnetic particles are either allowed to remain sedimented (passive measurements) or they are magnetically agitated, thereby inducing strong and global vortical flows of fluid and particles. After each (actuation) time-period of
- ¹⁵ 5 min, bright-field and fluorescence images are taken. Utilizing the bright-field images, binary masks are constructed to differentiate between the magnetic particles (0, blue) and the surrounding fluid (1, red). The fluorescence image (data) contains the emitted intensities from the fluorescent targets. By combining
- ²⁰ the data and the mask, we obtain the net emitted fluorescence intensity from the magnetic capture particles, indicating the amount of the captured targets.