Supplemental Information

Magnetic field calibration

To calibrate the orthogonality of the magnetic field from each pair of solenoids (Channel 1 and Channel 2) we generate a single chain of 10~15 particles and observe its orientation under a DC field with a single solenoid pair. In the presence of any background magnetic fields (e.g. nearby equipment, earth's magnetic field), varying the voltage will change the orientation of the chain. Observing changes in the chain angle under varying voltages allows us to calibrate the direction of the field. The difference in the chain angle between 5V and -5V is the maximum angle difference (MAD). The MAD on one channel will change monotonically as the voltage changes on the other channel unless the voltage on the other channel is equal to the cancellation voltage. The cancellation voltages for Channel 1 and Channel 2 are 0.455V and 0.210V respectively and are added on each channel for the experiment. The orthogonalization of 90.01±0.11 degrees is then achieved after a series of minor adjustments of the coil direction. Calibration of the magnetic field is confirmed by Fig. S1, where the chain angle remains fixed while varying the voltage on a single channel.

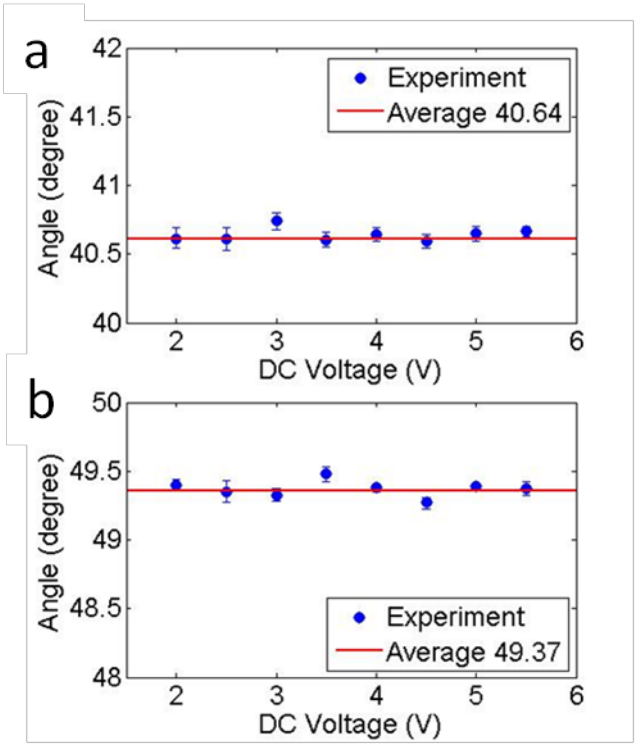

Fig. S1 The single chain orientation for channel (a) 1 and (b) 2