Alignment of spindle-shaped particles in a liquid jet studied by SAXS experiments.

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Motivation

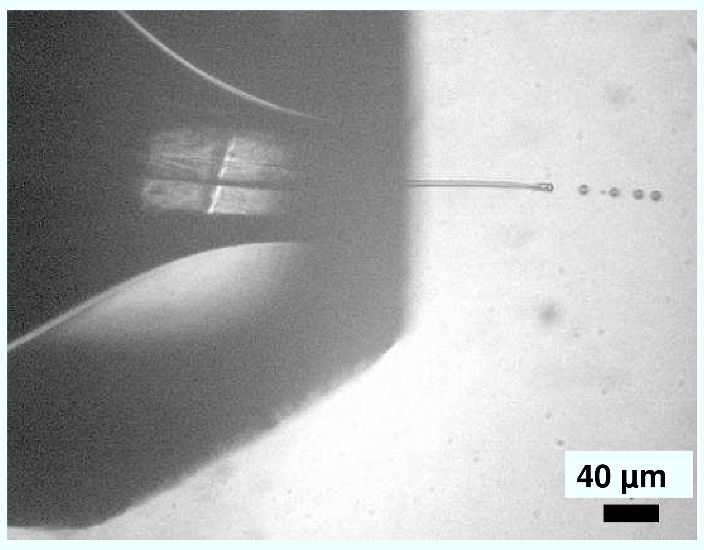
Colloidal dispersions under shear show non-Newtonian behavior, based on their microstructure, which influences macroscopic parameters, e.g. viscosity and density[1, 2]. Research has focused mainly on dispersions of spherical particles studied by rheological methods[3]. However, particle shape anisotropy introduces additional effects[3,4]:

a) The local fluid flow around a non-spherical particle is different from that around a spherical particle.
b) Non-spherical particles can orient themselves affecting the properties of the dispersion.
c) The particles' shape may additionally influence the particle-particle interactions.

Spindle-shaped hematite colloids (α-Fe_2O_3) are an excellent test case to study alignment of particles under shear using x-rays, as the characterization of such particles with x-ray scattering is well understood.[5]

Microfluidic liquid jets[6] allow the unique possibility to investigate spatially confined nanoscale objects under shear. This experiment provides new insights in nano-rheology studies of spindle-shaped particles due to high shear rates $\dot{\gamma} > 10^5\ s^{-1}$ as compared to conventional rheometers.[7]

Injection device

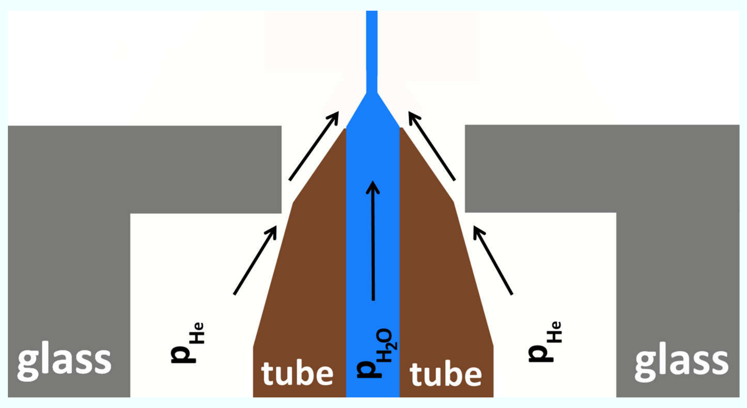


Microscope image of a GDVN producing a liquid jet.

Gas dynamic virtual nozzle (GDVN)[6]
- Coaxially flowing gas compresses jet
- Jet thickness down to 1 µm
- Vacuum conditions ~ 10^{-3} mbar
- Small sample amount ~ 100 µl/h

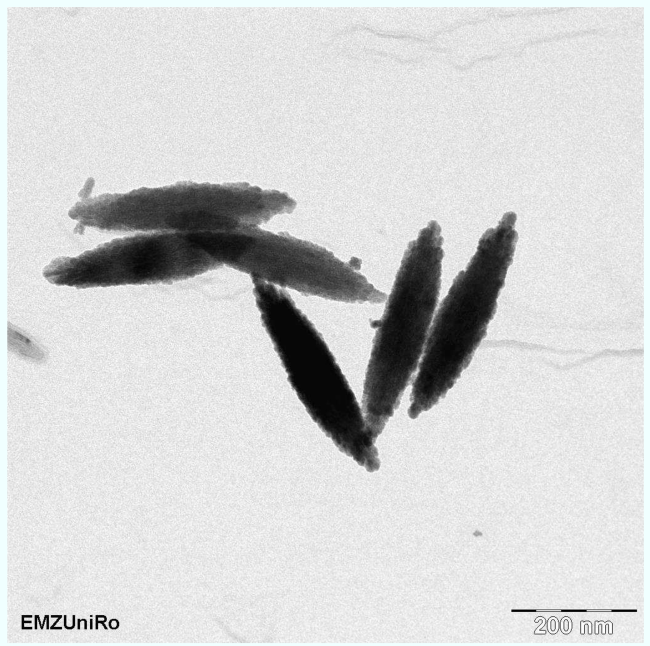
Gas dynamic virtual nozzles (GDVN)[6] employ a gas flow to compress water jets to thicknesses down to 1 µm. This technique allows to inject diluted sample particles without clogging.

The nozzle consists of a melted glass capillary that provides a tiny hole at its flat tip and a flexible fused silica tube that is grinded at one end. The liquid sample is pressed through the tube while the gas streams through the glass plenum.



Schematic drawing of the tip of a GDVN.

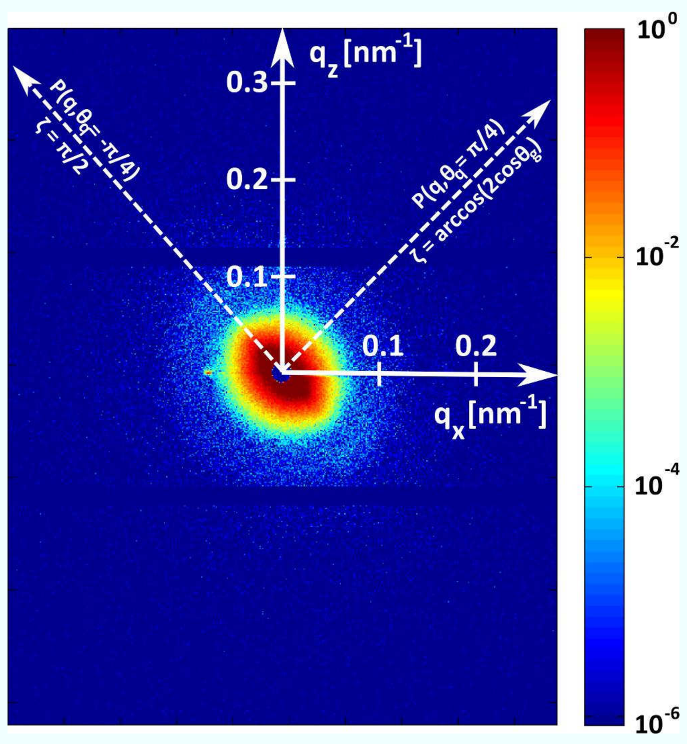
Spindle-shaped hematite colloids



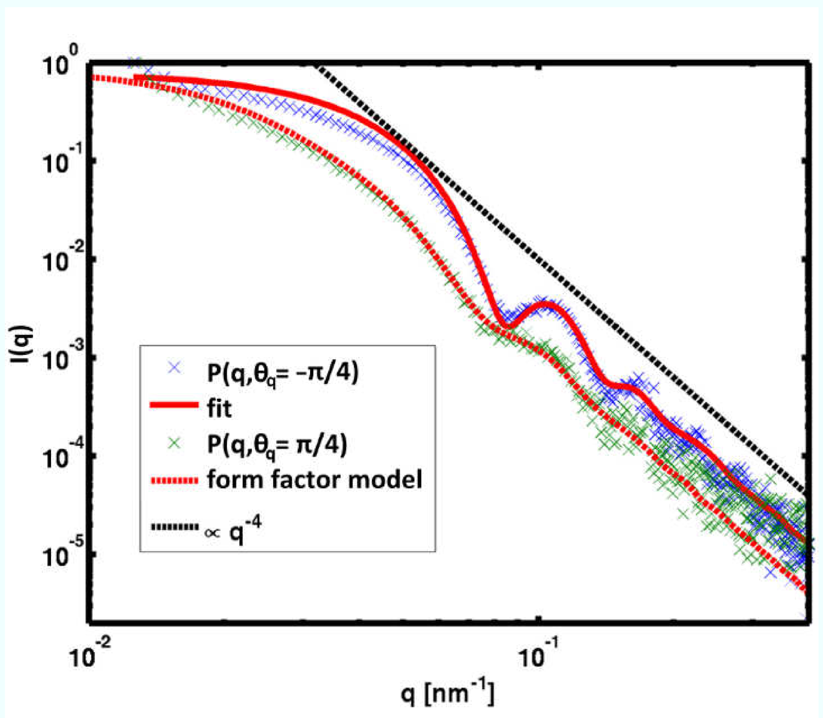
TEM-image of spindle-shaped hematite nano-particles.

Colloidal dispersion:
- Spindle-shaped hematite particles
- Dispersed in water
- Spindle size: 324 x 108 nm
- Concentration: 1 vol.%

Characterization of colloidal particles:
- Particle alignment by magnetic field perpendicular to the long axis
- Small angle x-ray scattering at beamline P10 / PETRAIII
- Anisotropic pattern corresponding to short and large semi-axes
- Analysis of scattering signal with form factor model[5,7]

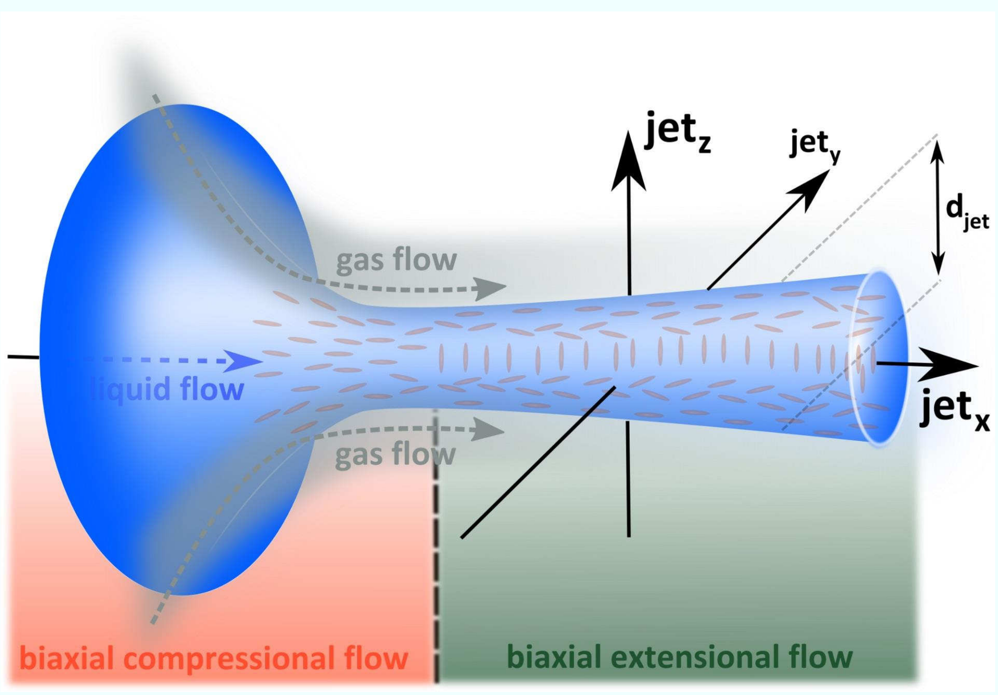


SAXS pattern of spindle shaped hematite particles under a magnetic field.[5]



Fit of form factor profiles of hematite particle aligned by a magnetic field.[5]

Different shear stresses along the jet



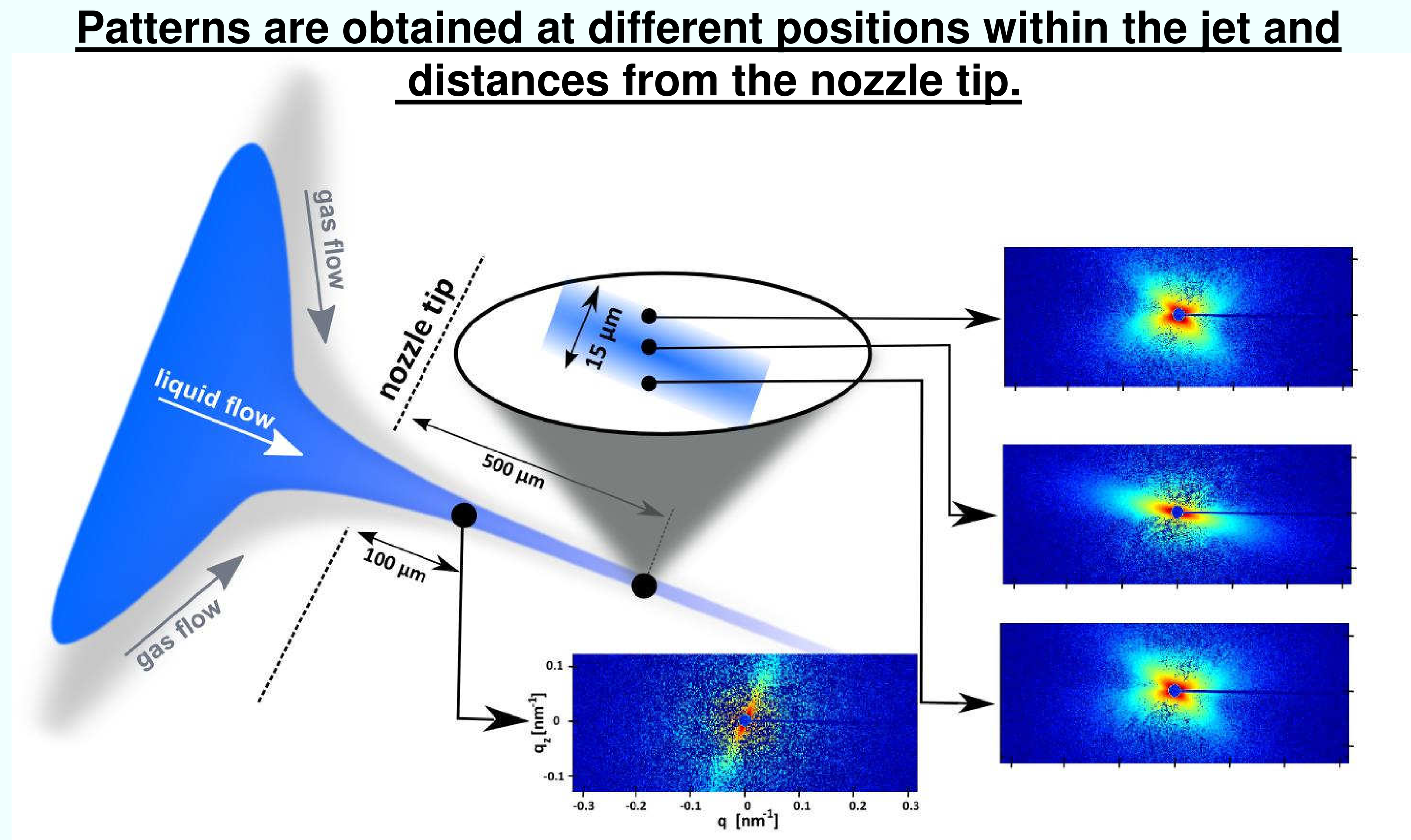
Schematic overview about the compressional and extensional flow regime in liquid jet.

Compressional shear flow[1]
- Gas flow compresses liquid jet parallel to y- and z-axis
- Flow configuration leads to particle alignment parallel to x-axis

Extensional shear flow[1]
- Gas pressure decreases
- Liquid jet expands parallel to y- and z- axis
- Flow configuration leads to particle alignment in expansion plane (y-z-axis)

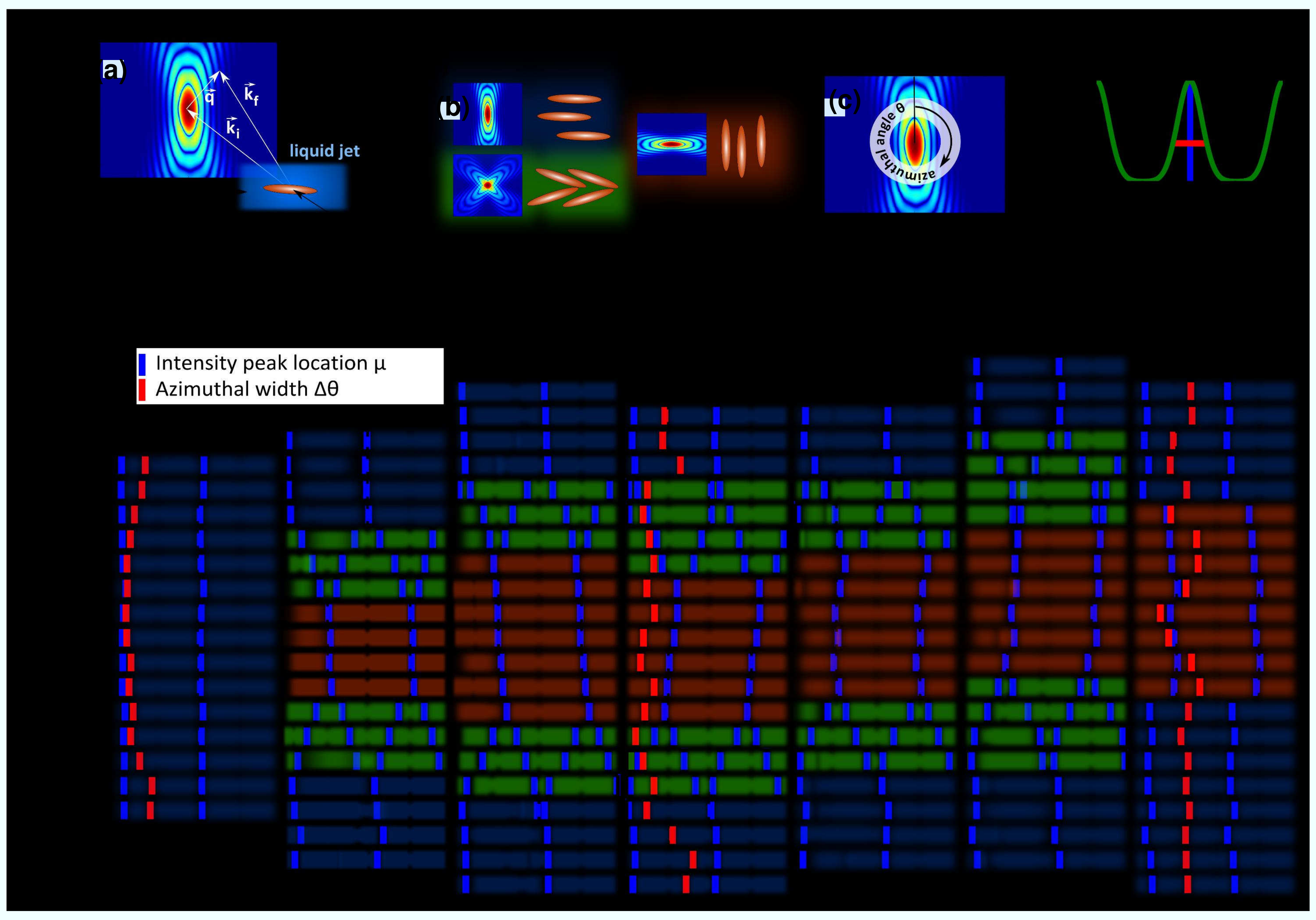
Inhomogeneous alignment of spindles in the jet

Patterns are obtained at different positions within the jet and distances from the nozzle tip.



Schematic overview of the measured form factors at different jet positions. Experiment performed at P10/ PETRAIII with Pilatus 300k at an x-ray energy of 7 keV.[7]

Regimes of spindle orientation within a jet with respect to fluid flow



(a) Form factor of spindle aligned parallel to the fluid flow; **(b)** Possible orientations of spindles with respect to fluid flow differentiated by the intensity patterns : Parallel (Blue); Mixed (Green); Perpendicular (Pink) ; **(c)** Radially-averaged intensity as a function of azimuthal angle, θ at q=0.05 nm^{-1} for spindles parallel to fluid flow. The intensity peak location μ (blue) provides the alignment of spindles *(parallel, perpendicular or mixed)*, and the peak width $\Delta\theta$ (red) presents the degree of orientation. **(d)** Spindle orientation with respect to fluid flow within the liquid jet (jet_z) at different distances from nozzle (jet_x). We show the intensity peak locations (blue) as a function of jet_x and jet_z. We also show $\Delta\theta$ (red) at select positions.[7]

Rotation velocity and estimating shear rate[8]:
- Typical flow rate: 10 µl/min
- Diameter of jet ~ 15 µm
- Angular velocity ~ $10^3\ s^{-1}$
- => Estimate shear rate[8] $\dot{\gamma} > 10^5$ Hz.

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