HFML

University of Nijmegen

Magnetic Manipulation of Functional Molecular Materials

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IMM

Radboud University Nijmegen

IN DEI NOMINE FELICITER

Magnetic Tools & Materials

Homogeneous magnetic fields

⇓

Orientation

(anisotropy required)

Magnetic field gradients

⇓

Levitation

polymers

peptides

proteins

molecular dyes

biological tissue

polymer liquid crystals

supramolecular aggregates

liquid crystals

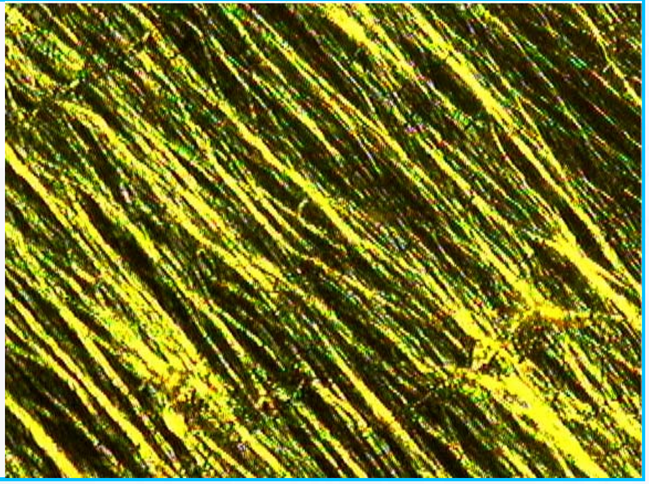
Outline

Part I: Magnetic Levitation

- Principle of Levitation
- Magneto-Archimedes effect
- Supression of convection

Part II: Magnetic Orientation

- Principle of Orientation
- Liquid Crystals
- Supramolecular self-assemblies



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Science in High Magnetic Fields

Part I: Magnetic Levitation

Utilizing forces in gradient magnetic fields

Outline

- Explanation of principle
- Magneto-Archimedes effect
- Suppression of convection

Applications:

- magnetic separation
- tuning effective gravity
- microgravity
- crystal growth

Magnetic energy (isotropic objects)

$$E(B) = -\int_0^B \mathbf{m} \cdot d\mathbf{B} = -\frac{\chi V}{2\mu_0} B^2$$

$$\mathbf{m} = \frac{\chi V}{\mu_0} \cdot \mathbf{B}$$

m = induced magnetic moment
χ = magnetic susceptibility
B = magnetic field
V = Volume object

Paramagnetism: $\chi \approx 10^{-3}$, χ *positive*

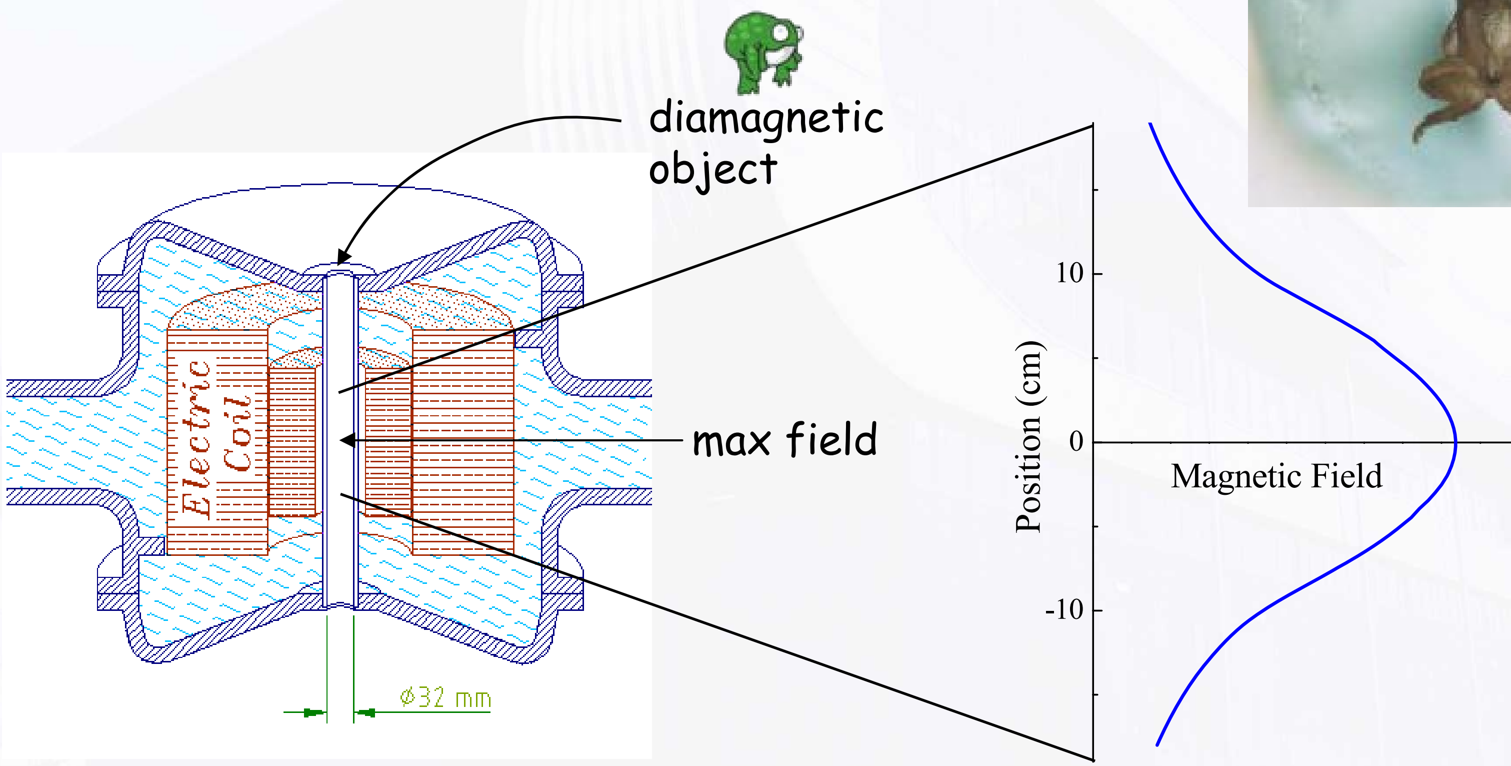
⇒ energy decreases with field
⇒ force towards high fields

Diamagnetism: $\chi \approx -10^{-5}$, χ *negative*

⇒ energy increases with field
⇒ force towards low fields

Diamagnetic levitation

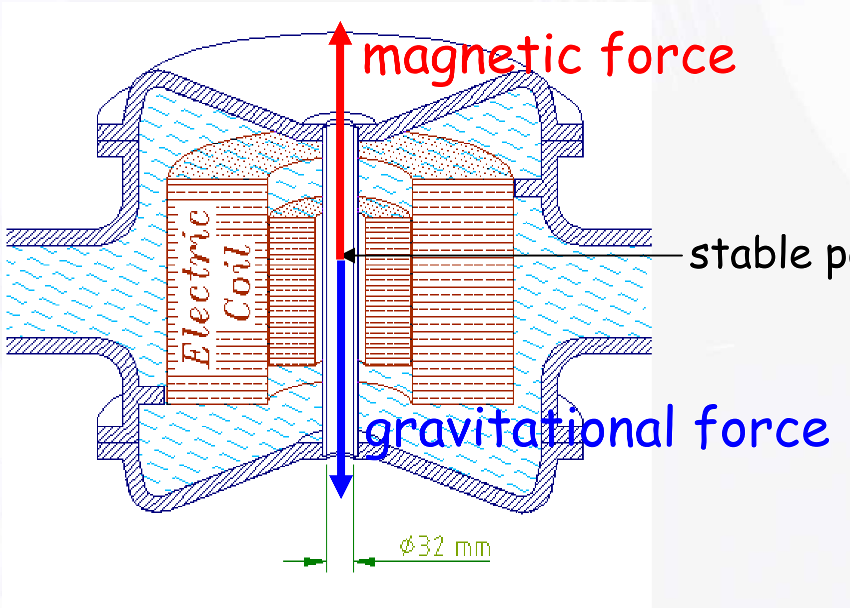
Magnetic levitation in a field gradient:



Beaugnon et al., Nature **349**, 470 (1991); J. Phys. III **1**, 1423 (1991)
Geim, Physics Today, Sept. 1998, 36-39

Diamagnetic levitation

Magnetic levitation in a field gradient:



Beaugnon et al., Nature **349**, 470 (1991); J. Phys. III **1**, 1423 (1991)
Geim, Physics Today, Sept. 1998, 36-39

Diamagnetic levitation

$$F_{mag} = -\frac{\partial E(B)}{\partial z} = -\frac{\partial}{\partial z}\left(-\frac{\chi V B^2}{2\mu_0}\right)$$

$$= \frac{V\chi}{\mu_0} B(z) \frac{dB(z)}{dz}$$

$$F_{gravity} = -V\rho\, g$$

diamagnetic object

levitation:

$$B(z)\frac{dB(z)}{dz} = \frac{\rho}{\chi}\mu_0 g$$

$$\boldsymbol{F_g + F_{mag} = 0}$$

Beaugnon et al., Nature **349**, 470 (1991); J. Phys. III **1**, 1423 (1991)
Geim, Physics Today, Sept. 1998, 36-39

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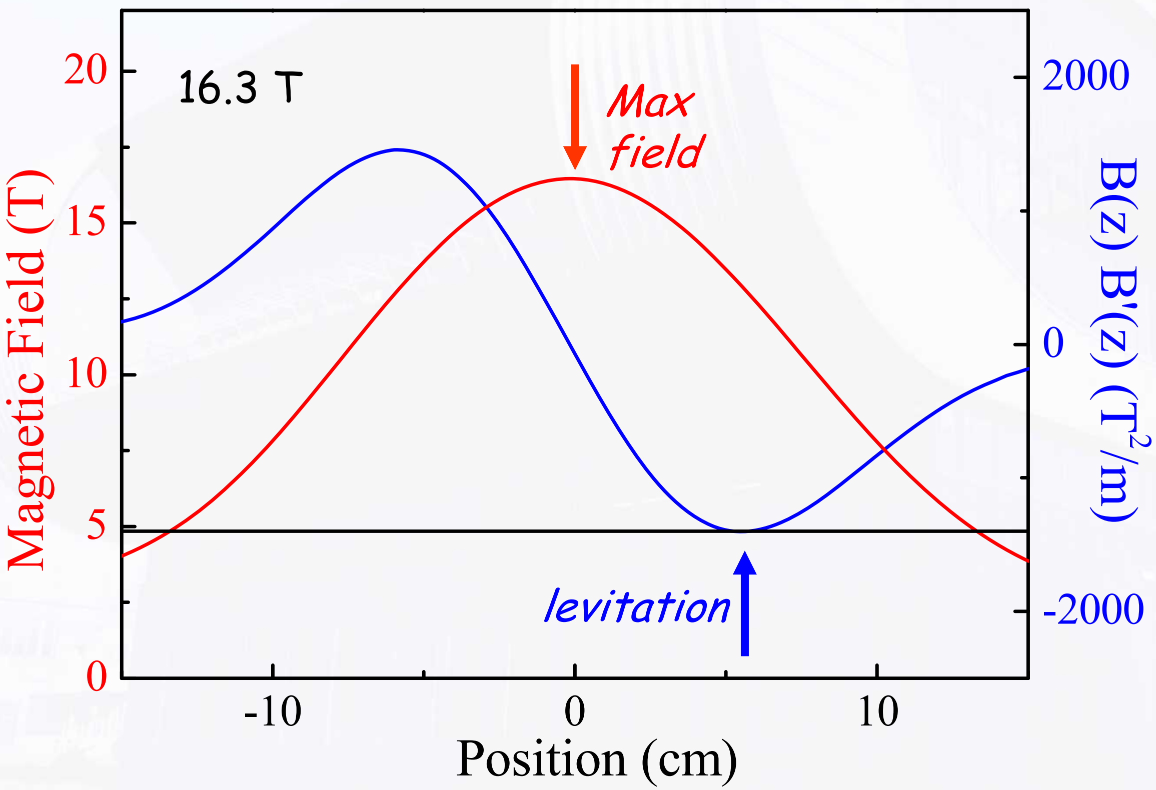
Diamagnetic levitation

$$B(z)\,B'(z) = \frac{\rho}{\chi}\,\mu_0 g$$



Water:

ρ = 10^3 kg/m^3
χ = -8.8 10^{-6}

$\Downarrow$

$\frac{\rho}{\chi}$ = -1.14 10^8 kg/m^3

$\Downarrow$

$B(z)B'(z) \cong$ -1400 T^2/m

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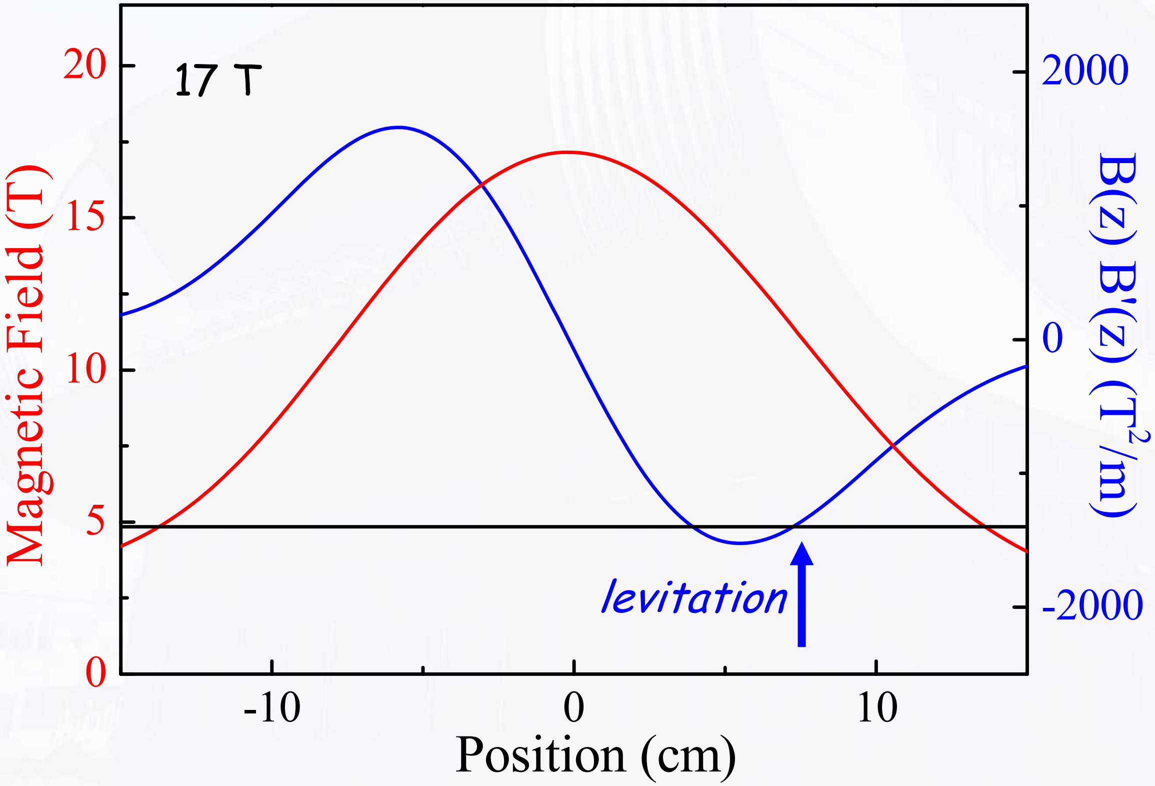
Diamagnetic levitation

$$B(z)\,B'(z) = \frac{\rho}{\chi}\mu_0 g$$



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Diamagnetic levitation

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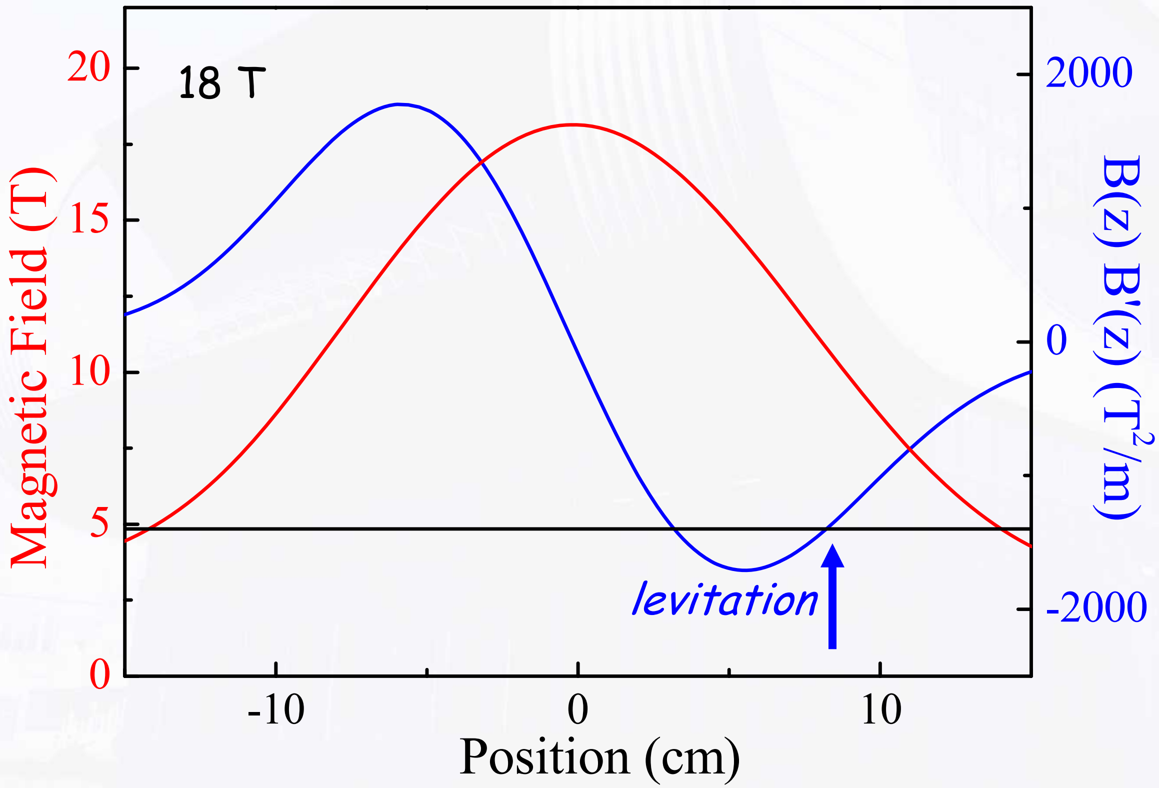

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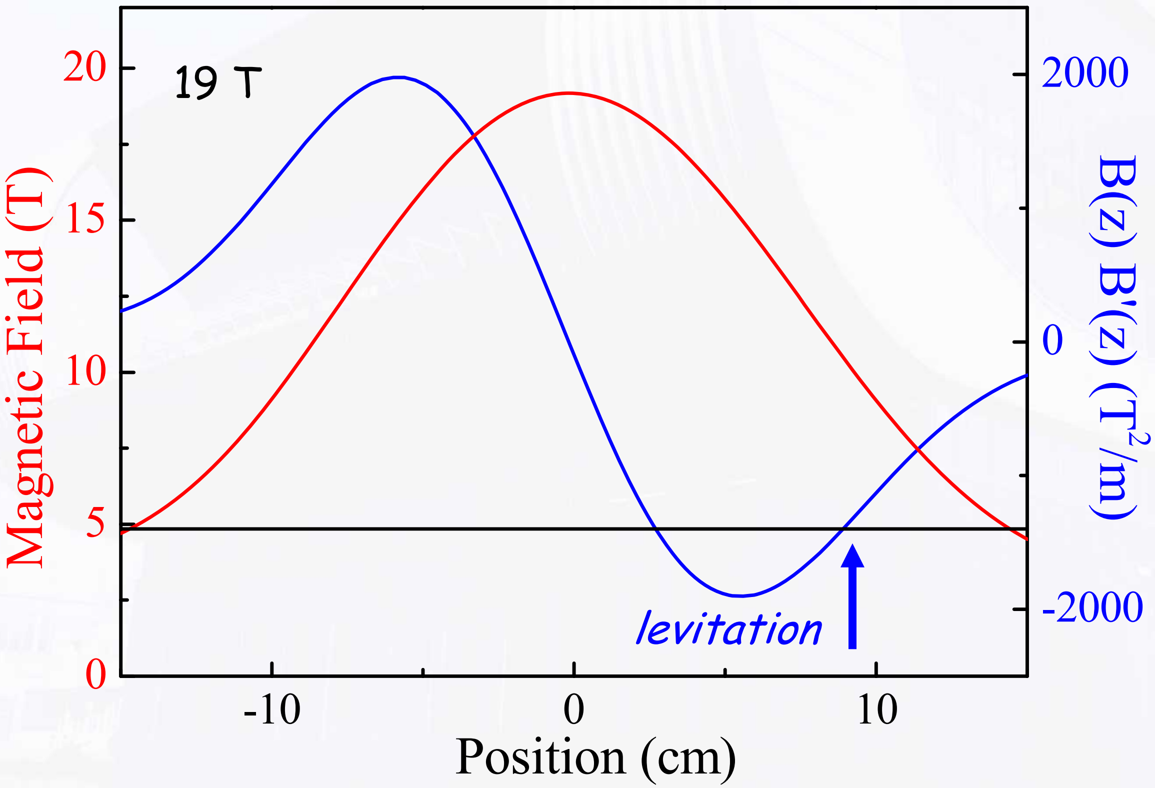

Water:

$\rho = 10^3$ kg/m^3
$\chi = -8.8\ 10^{-6}$

$\Downarrow$

$$\frac{\rho}{\chi} = -1.14\ 10^8 \text{ kg/m}^3$$

$\Downarrow$

$$B(z)B'(z) \cong -1400 \text{ T}^2/\text{m}$$

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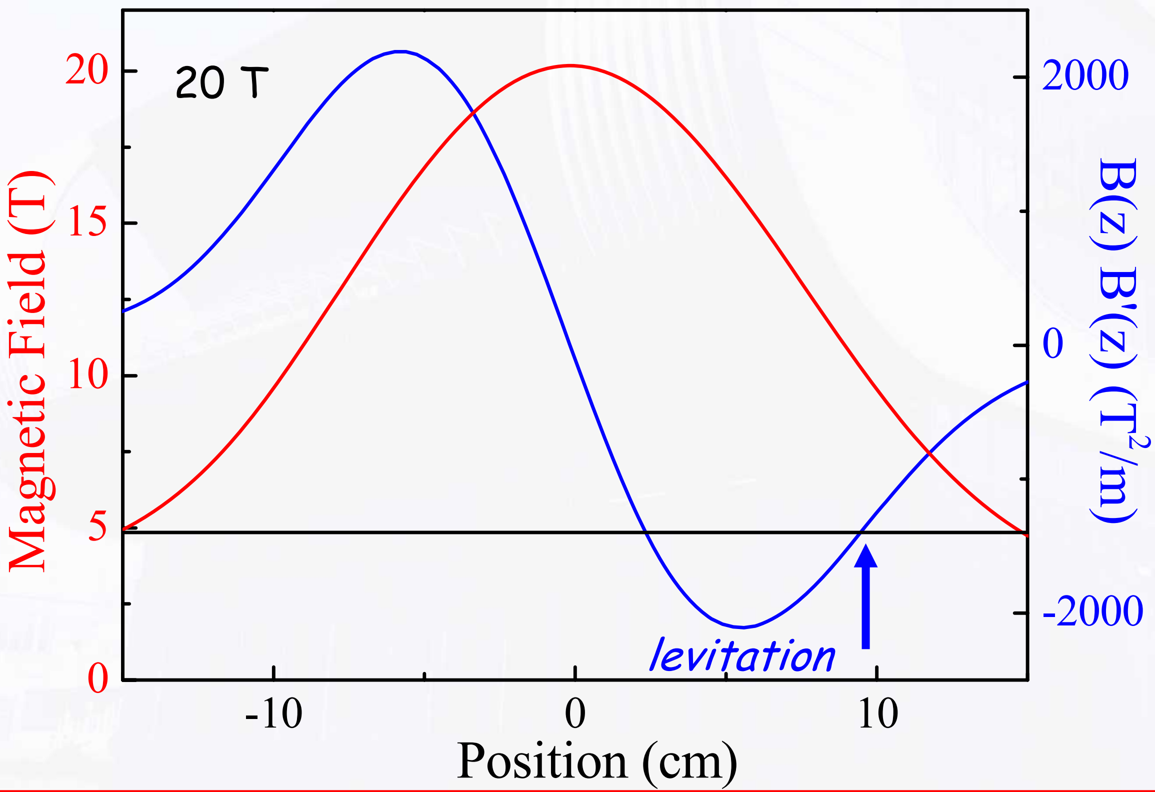
Diamagnetic levitation

$$B(z)\,B'(z) = \frac{\rho}{\chi}\,\mu_0 g$$



Water:

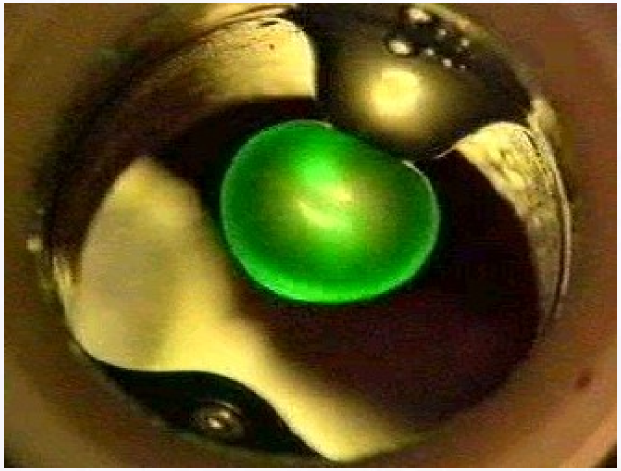
ρ = 10³ kg/m³
χ = -8.8 10⁻⁶

$\Downarrow$

$\frac{\rho}{\chi}$ = -1.14 10⁸ kg/m³

$\Downarrow$

$B(z)B'(z) \cong$ -1400 T²/m



See movies on HFML website: **www.hfml.science.ru.nl**

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Stability of levitation

Stable levitation requires a restoring force

$$E(\mathbf{r}) = mgz - \frac{\chi V}{2\mu_0} B^2(\mathbf{r})$$

$$\mathbf{F}(\mathbf{r}) = -\nabla E(\mathbf{r})$$

$$\oint \mathbf{F}(\mathbf{r}) \cdot d\mathbf{S} < 0 \quad \Rightarrow \quad \nabla \cdot \mathbf{F}(\mathbf{r}) < 0$$

for diamagnets: $\nabla^2 B^2(\mathbf{r}) > 0$

for paramagnets: ~~$\nabla^2 B^2(\mathbf{r}) < 0$~~

$$\nabla \cdot \mathbf{B} = 0 \text{ and } \nabla \times \mathbf{B} = 0$$

$$\Downarrow$$

$$\nabla^2 B^2(\mathbf{r}) \geq 0$$

Stable levitation of paramagnets is impossible

Berry and Geim, Eur. J. Phys. **18**, 307 (1997)

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Levitation: vertical and horizontal stability

Vertical stability: $\dfrac{\partial F(\mathbf{r})}{\partial \mathbf{z}} < 0 \quad \Rightarrow \quad \dfrac{\partial^2 B^2(\mathbf{r})}{\partial \mathbf{z}^2} > 0$

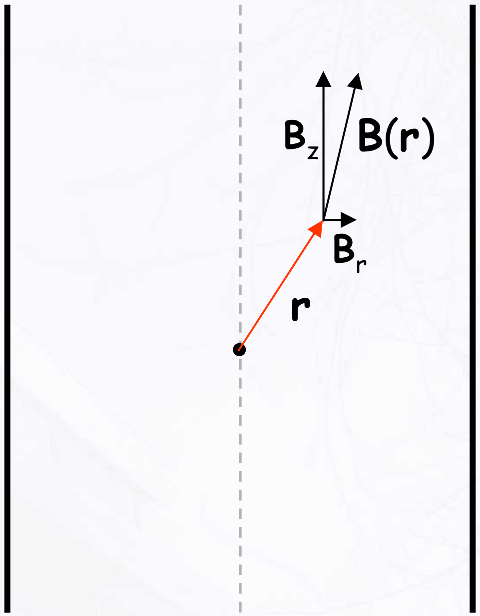
magnetic potential: $\mathbf{B}(\mathbf{r}) = \nabla \phi(\mathbf{r})$

on-axis terms: $\phi(0,0,\mathbf{z}); \dfrac{\partial \phi(0,0,\mathbf{z})}{\partial \mathbf{z}}; \dfrac{\partial^2 \phi(0,0,\mathbf{z})}{\partial \mathbf{z}^2};\ldots$

$$\nabla \cdot \mathbf{B}(\mathbf{r}) = 0 \Rightarrow \nabla^2 \phi(\mathbf{r}) = 0$$

$$\frac{\partial^2 \phi(0,0,\mathbf{z})}{\partial \mathbf{x}^2} = \frac{\partial^2 \phi(0,0,\mathbf{z})}{\partial \mathbf{y}^2} = -\frac{1}{2}\frac{\partial^2 \phi(0,0,\mathbf{z})}{\partial \mathbf{z}^2}$$

$$\phi(\mathbf{r}) \approx \phi(0,0,\mathbf{z}) - \frac{1}{4}\left(\mathbf{x}^2 + \mathbf{y}^2\right)\frac{\partial^2 \phi(0,0,\mathbf{z})}{\partial \mathbf{z}^2} + \ldots$$



Vertical stability: $D_{vert.} = B'(\mathbf{z})^2 + B(\mathbf{z})B''(\mathbf{z}) > 0$

Horizonal stability: $\dfrac{\partial^2 B^2(\mathbf{r})}{\partial \mathbf{r}^2} > 0 \qquad D_{hor.} = B'(\mathbf{z})^2 - 2B(\mathbf{z})B''(\mathbf{z}) > 0$

Berry and Geim, Eur. J. Phys. **18**, 307 (1997)

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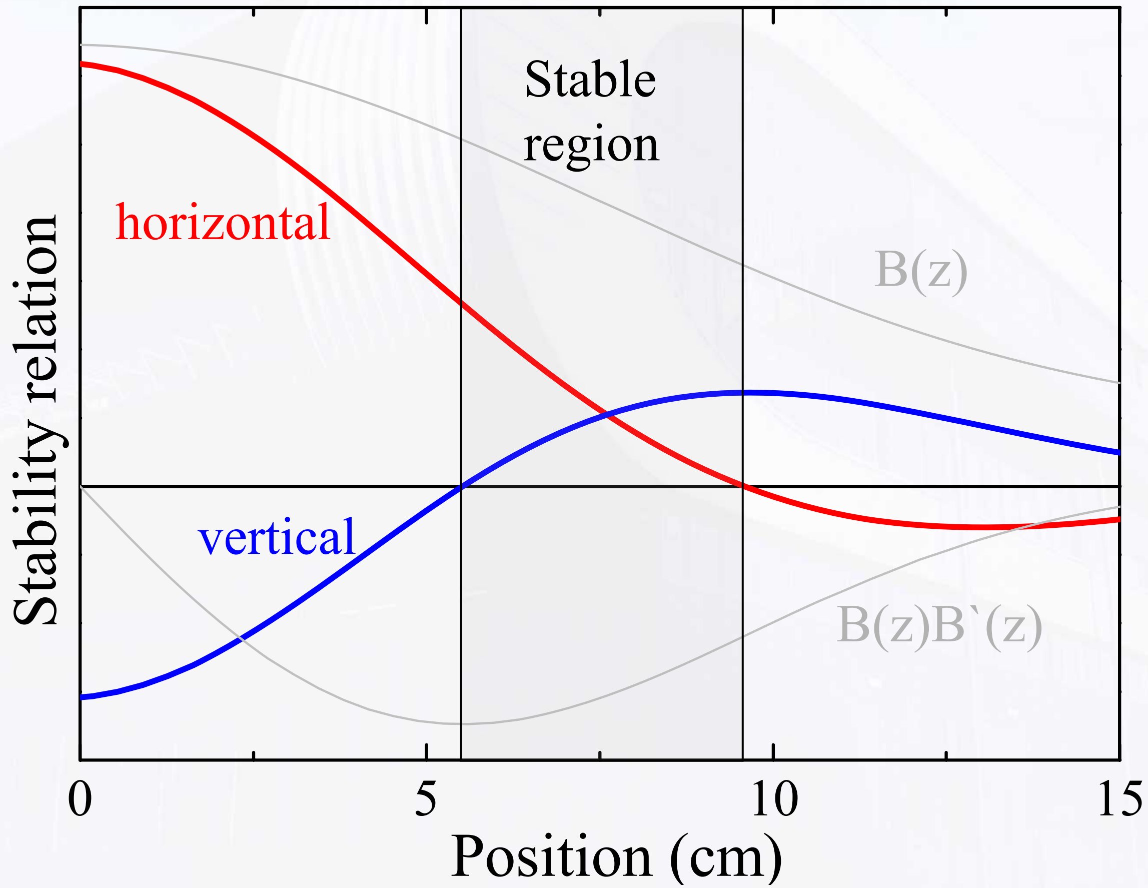
Levitation: vertical and horizontal stability

$$D_{vert.} = B'(z)^2 + B(z)B''(z) > 0 \quad \text{and} \quad D_{hor.} = B'(z)^2 - 2B(z)B''(z) > 0$$



Berry and Geim, Eur. J. Phys. **18**, 307 (1997)

Magneto-Archimedes effect

$$F_{tot} = \frac{V\chi}{\mu_0} B(z)B'(z) - V\rho g \quad - \frac{V\chi_{med}}{\mu_0} B(z)B'(z) + V\rho_{med}\, g$$

magnetic and normal buoyancy forces

levitation:

$$\frac{V(\chi - \chi_{med})}{\mu_0} B(z)B'(z) - V(\rho - \rho_{med})g = 0$$

$$\Downarrow$$

$$B(z)B'(z) = \frac{\rho - \rho_{med}}{\chi - \chi_{med}} \mu_0 g$$

χ_{med}, ρ_{med}

Levitation enhanced in paramagnetic medium

For example in: *air, oxygen*
pressurized oxygen
liquid oxygen

Ikezoe et al., Nature **393**, 750 (1998)
Catherall et al, Nature **422**, 579 (2003)

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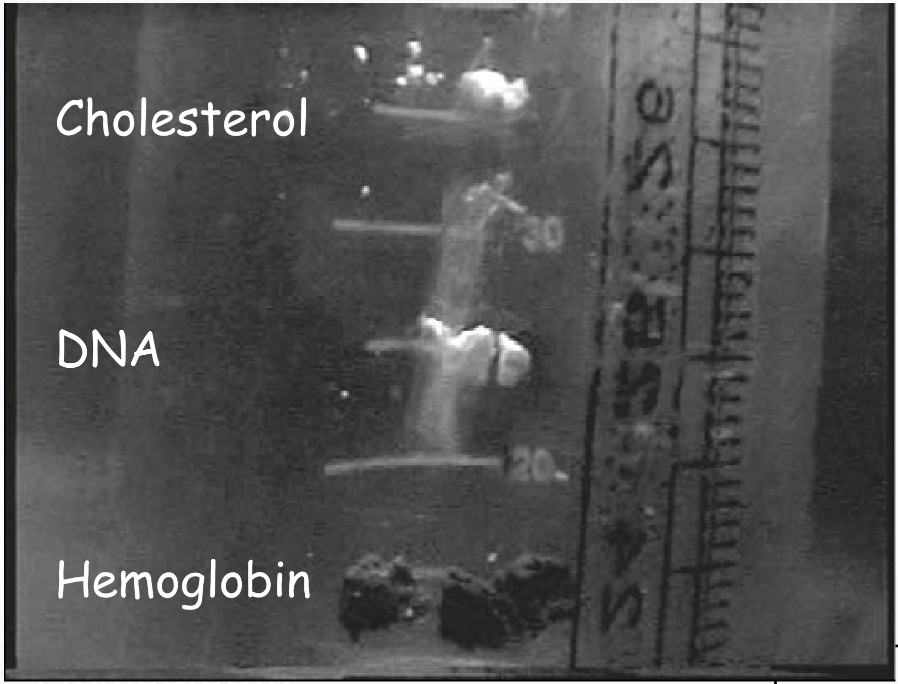
Magneto-Archimedes separation

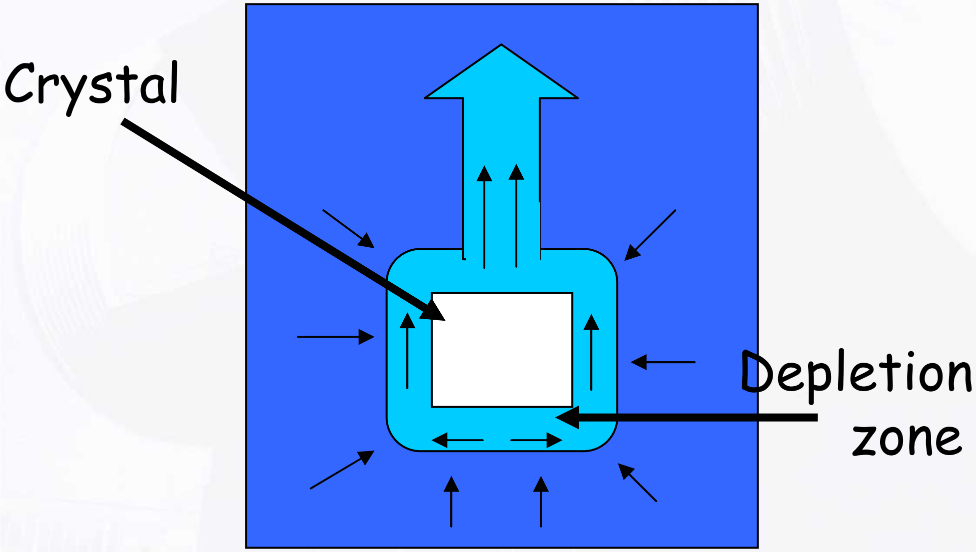


	ρ (kg/m^3)	χ (10^{-6})	ρ/χ (10^8 kg/m^3)	$B\nabla B$ (T^2/m)
Water	1000	-8.8	1.14	-1401
Hemoglobin	1330	-3.38	3.93	-4850
Fibrinogen	1570	-6.12	2.56	-3162
Cholesterol	1020	-7.61	1.34	-1652
DNA	1280	-4.99	2.56	-3162

Hirota et al., Physica B **346**, 267 (2004)
See also: Catherall et al, Nature **422**, 579 (2003)

Microgravity application: crystal growth

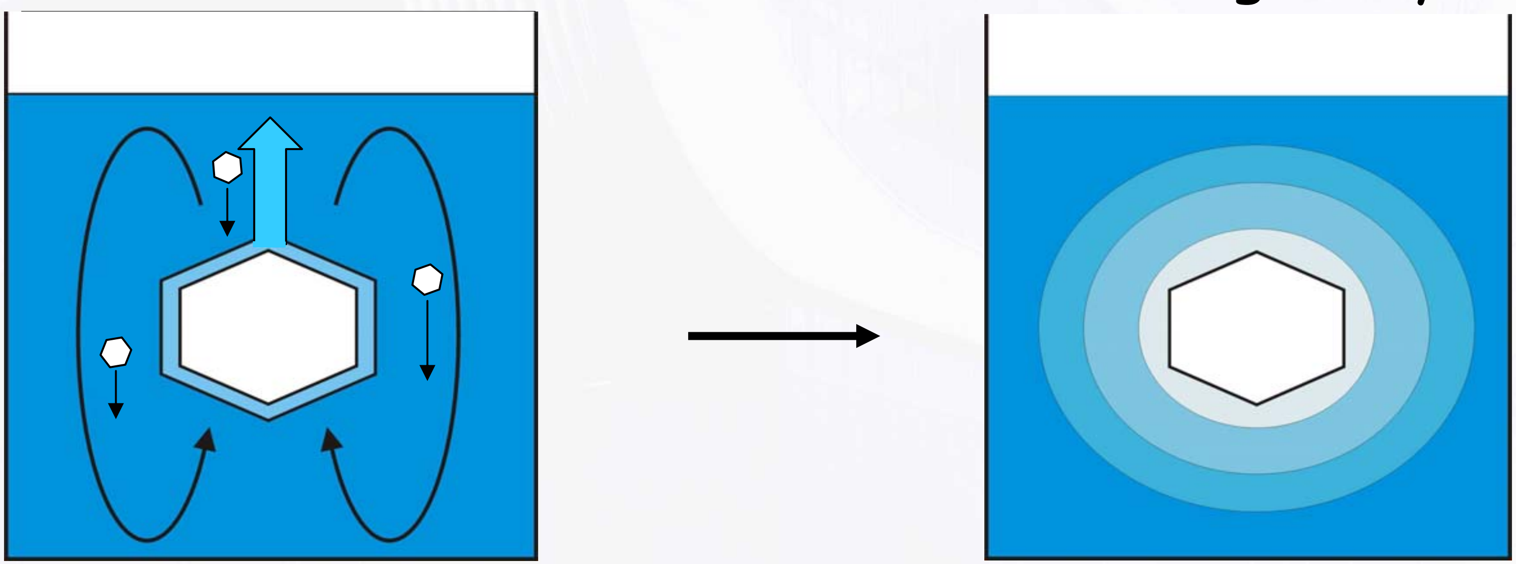
- High supersaturation
- Mass transport & Fluid dynamics



Microgravity application: crystal growth

- High supersaturation
- Mass transport & Fluid dynamics
- Sedimentation

Microgravity

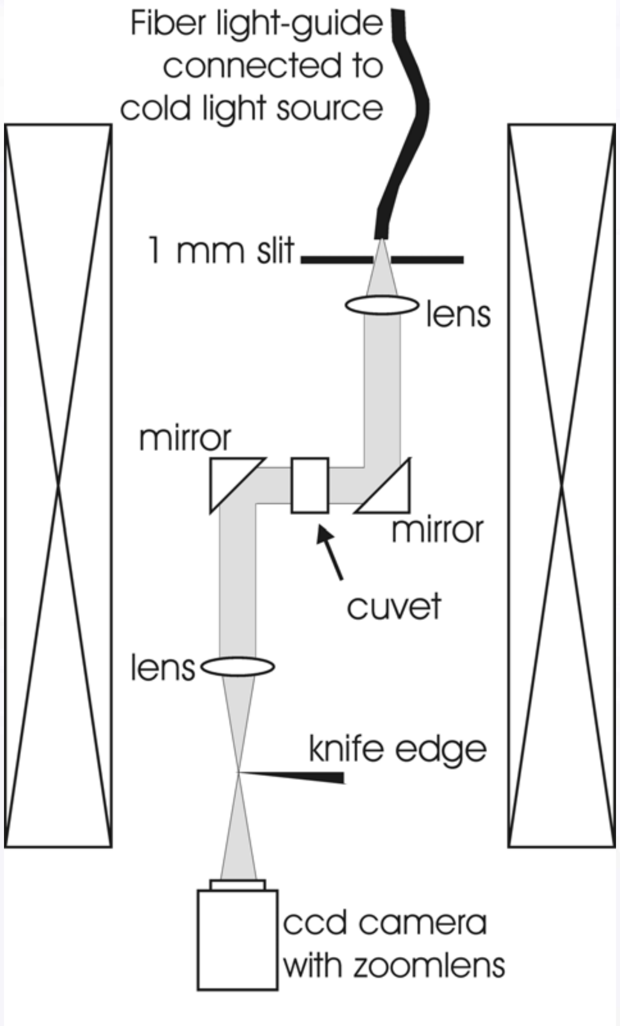


Magnetic field gradients ?

Schlieren microscope

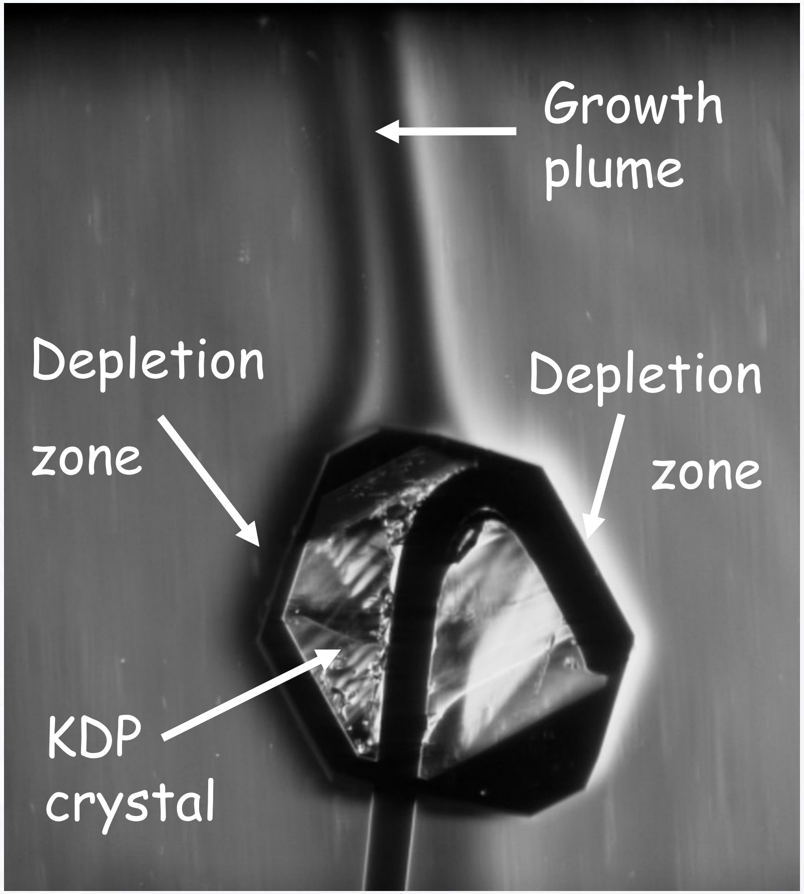
The Schlieren insert:

- 32 mm bore 20 T magnet
- NA = 0.08, Theoretical resolution of 6.5μm
- Field of view ~ 4.5mm



Schlieren microscopy of growth plume

Example: Growing KDP (KH_2PO_4) crystal



Local variations in:
concentration *c*
and thus in the
refractive index *n*

Schlieren microscopy

$$I \propto \frac{\partial n}{\partial x} \propto \frac{\partial c}{\partial x}$$

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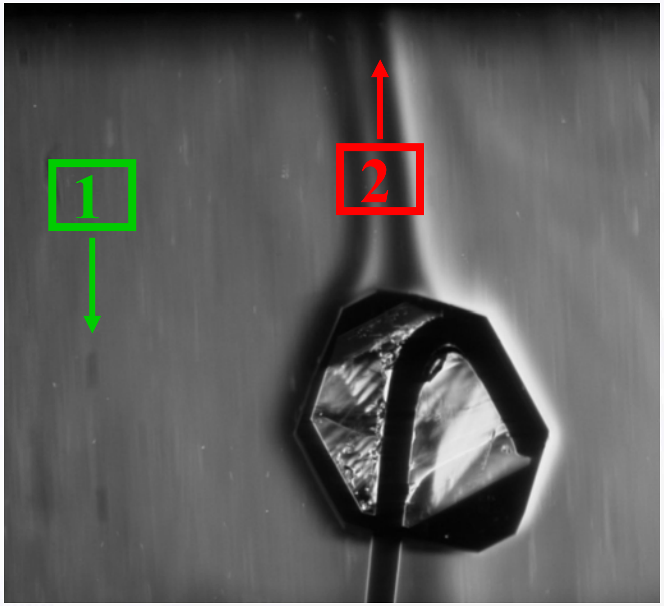
Damping convection



No convection if: $F_2(z) - F_1(z) = 0$

$$F_{mag}(z) = \frac{V\chi}{\mu_0} B(z)B'(z) \quad F_{gravity}(z) = -V\rho g$$

Balance of forces if

$$B(z)B'(z) = \frac{\Delta\rho}{\Delta\chi}\mu_0 g \qquad \begin{aligned}\Delta\rho &= \rho_2 - \rho_1 \\ \Delta\chi &= \chi_2 - \chi_1\end{aligned}$$

For small variations in c: $\rho(c) = \rho_0 + \alpha c\,;\ \chi(c) = \chi_0 + \beta c$

$$\Rightarrow B(z)B'(z) = \frac{\alpha}{\beta}\mu_0 g \qquad g_{eff} = g\left[1 - \frac{\beta}{\alpha\mu_0 g} B(z)B'(z)\right]$$

Appl. Phys. Lett. **87**, 214105 (2005)
Cryst. Gr. Des. **6**, 2275 (2006)

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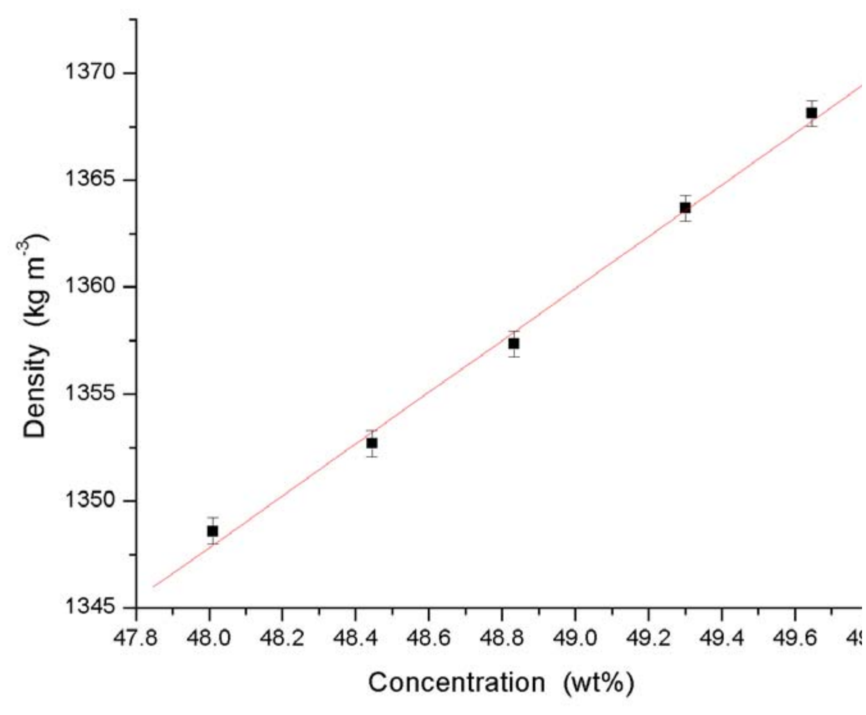
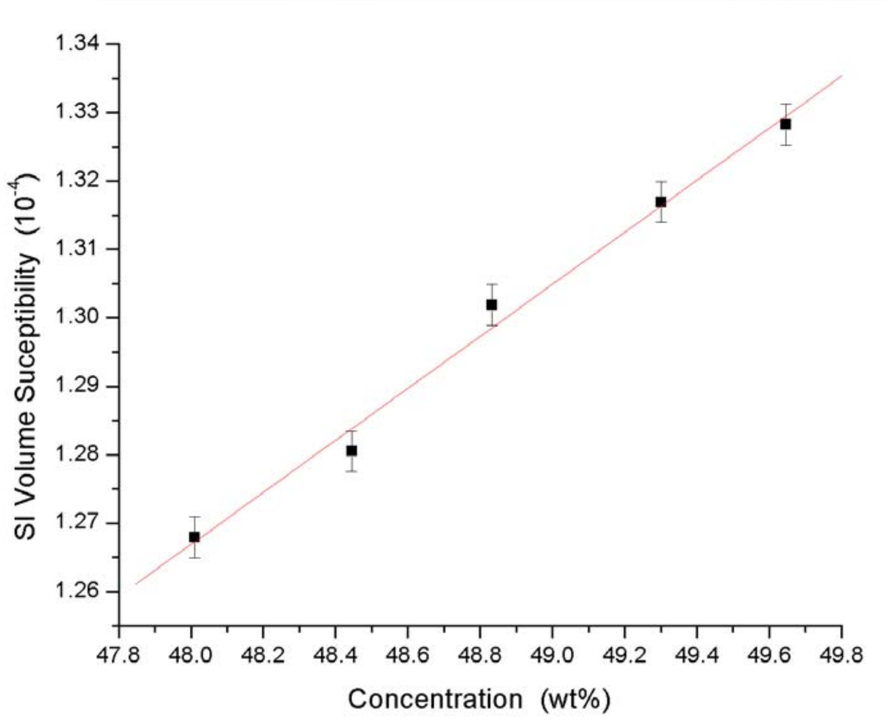
Paramagnetic $NiSO_4$ hexahydrate





$\alpha = 12.1 \pm 0.5$ kg m^{-3} wt%$^{-1}$ $\beta = (+3.8 \pm 0.2) \times 10^{-6}$ wt%$^{-1}$

$$B(z)B'(z) = +39 \pm 3 \text{ T}^2 \text{ m}^{-1}$$

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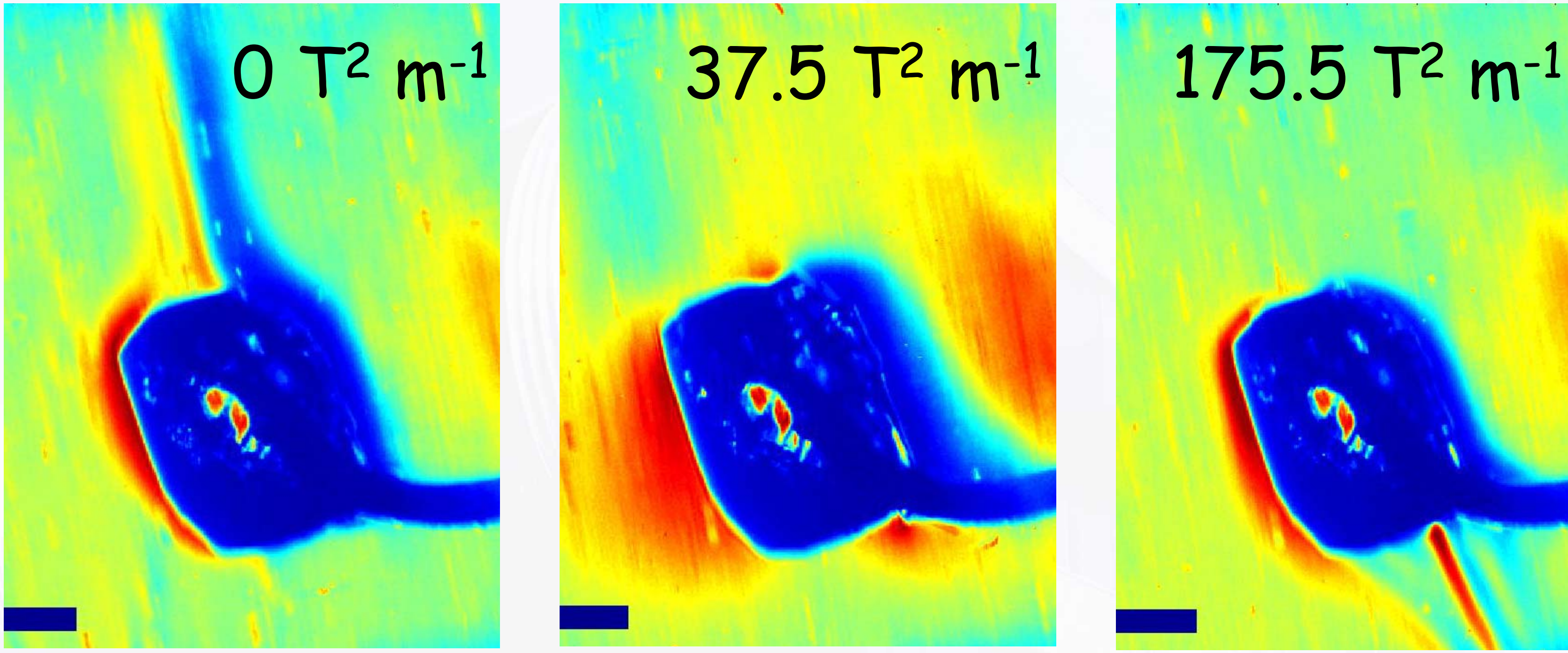
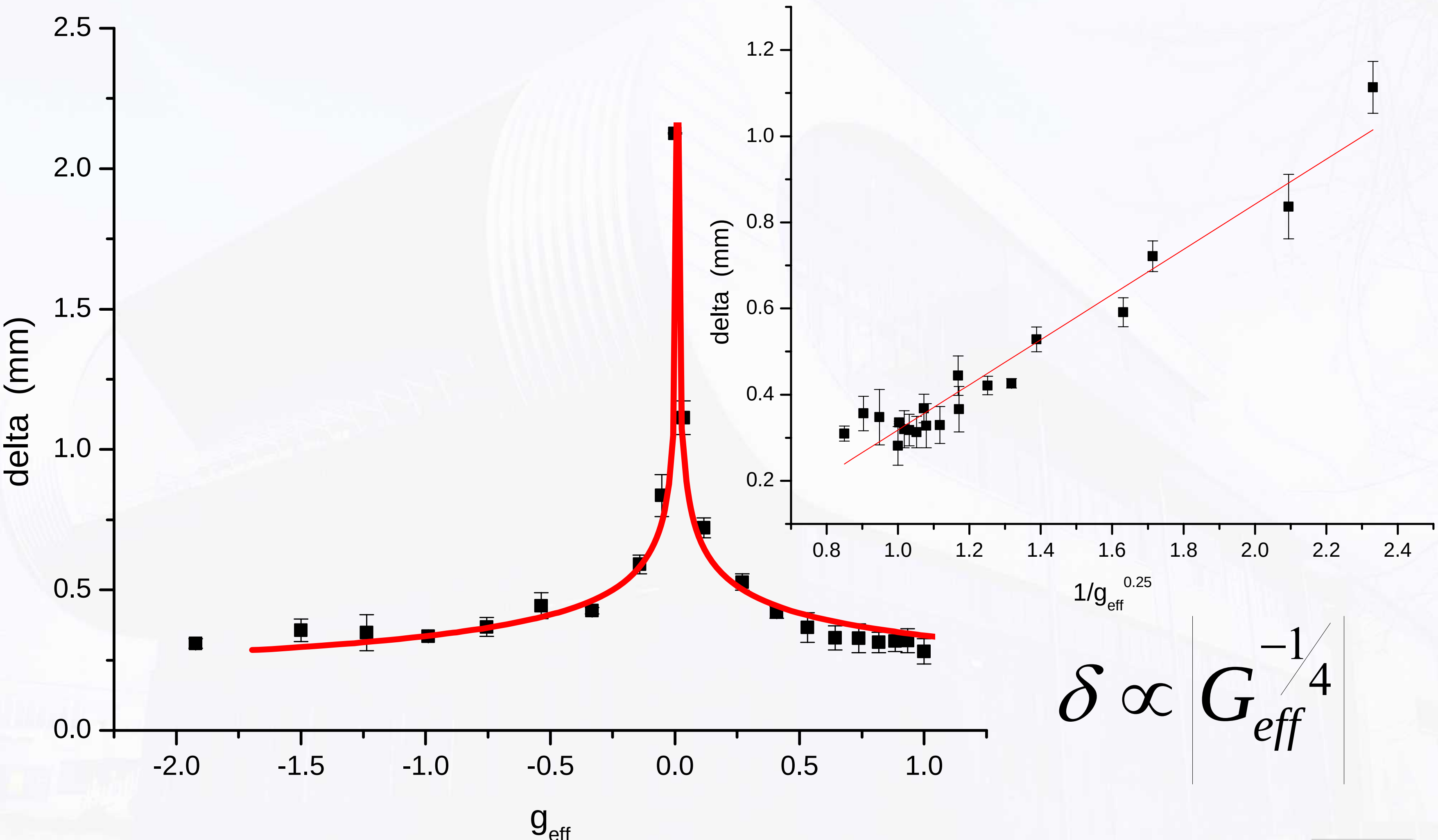
Tuning effective gravity



$g_{effective} = 1\ g$	$g_{effective} = 0\ g$	$g_{effective} = -3.5\ g$
Normal growth	No Plume!	Plume downwards
Plume upwards	Large depletion zone!	

Appl. Phys. Lett. **87**, 214105 (2005)
Cryst. Gr. Des. **6**, 2275 (2006)

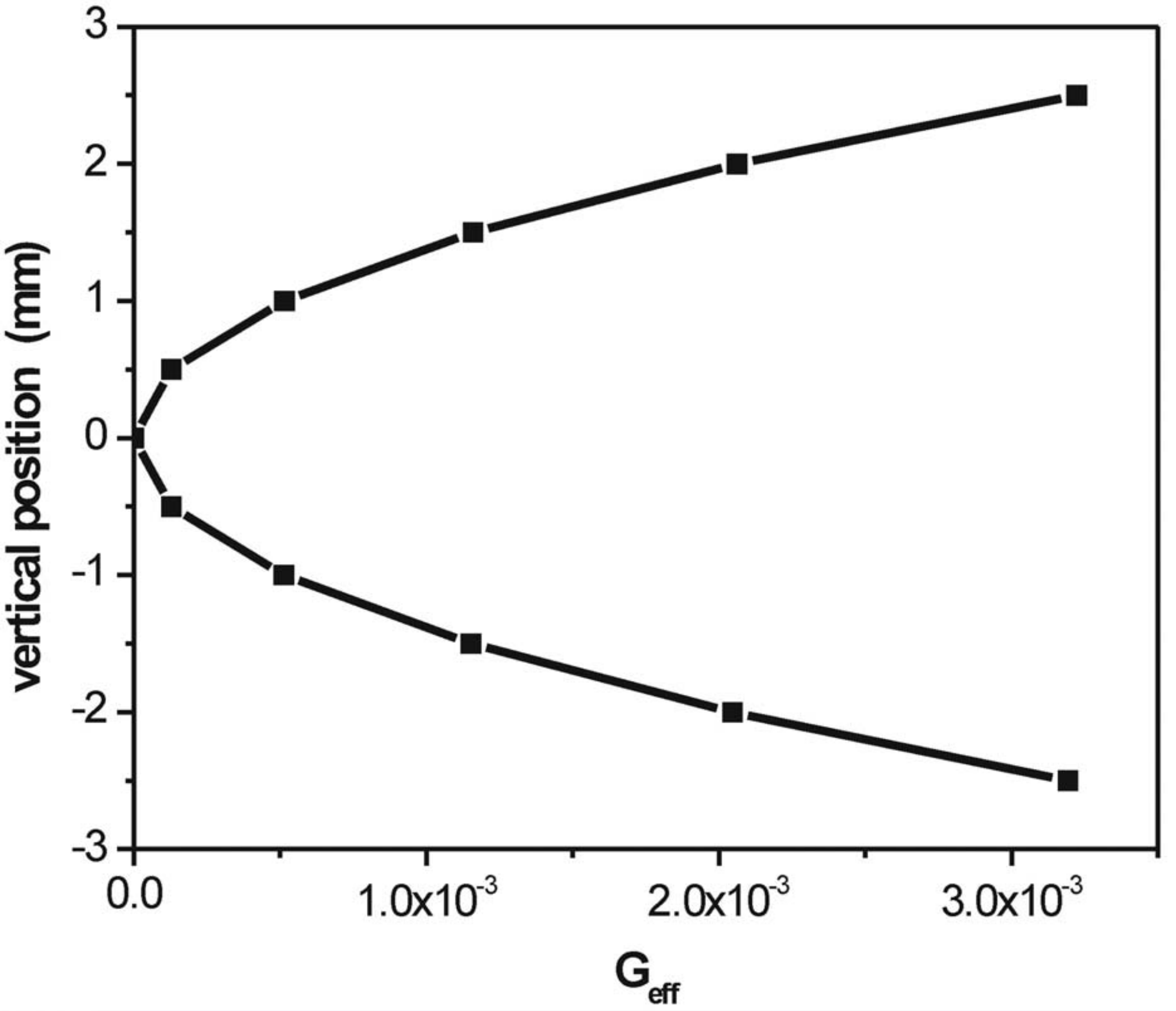
Width of depletion zone



$$\delta \propto \left| G_{eff}^{-1/4} \right|$$

Cryst. Gr. Des. **6**, 2275 (2006)

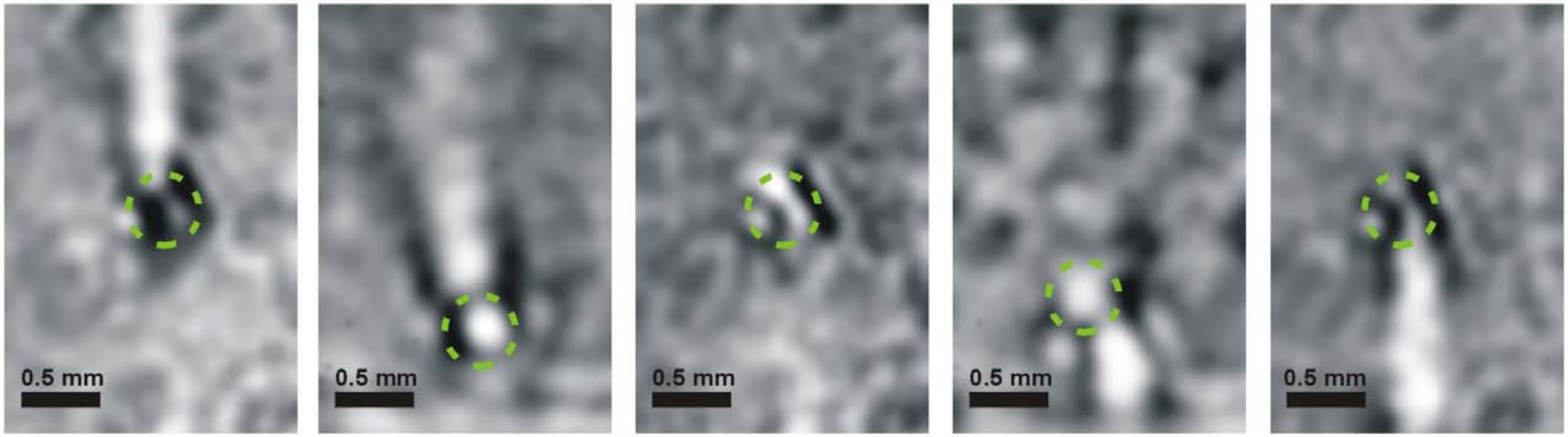
Microgravity ?



Milligravity

is sufficient to
dampen convection

It also works for diamagnetic Lysozyme !



B_0	0	26.0	27.0	27.5	29.0 T
$B_z B'_z$	0	-4130	-4450	-4630	-5140 T^2/m
G_{eff}	1	0.07	0	-0.04	-0.15

growth of Lysozyme crystals in tunable gravity

Appl. Phys. Lett. **90**, 264105 (2007)

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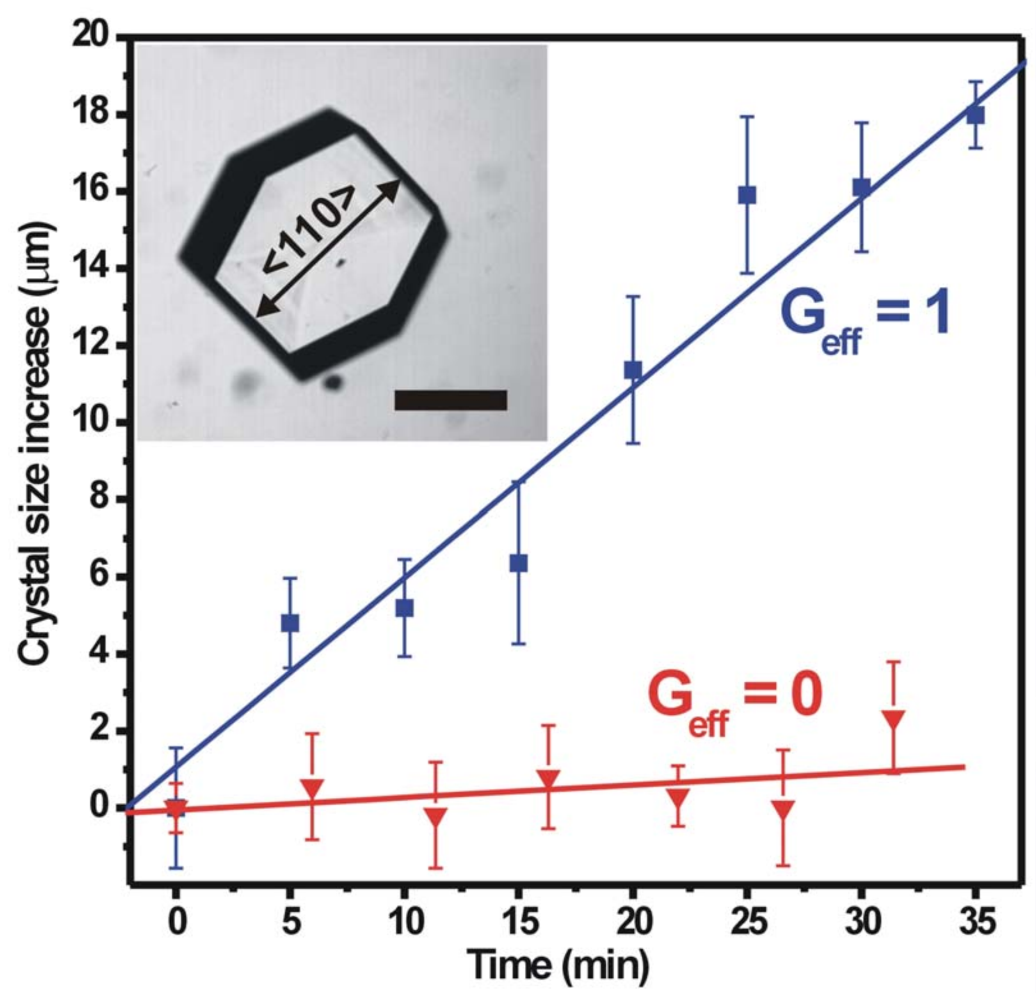
Growth rate in reduced gravity



Appl. Phys. Lett. **90**, 264105 (2007)

Conclusions Part I

- regular magnetic levitation

$$B(z)\,B'(z) = \frac{\rho}{\chi}\,\mu_0 g$$

- magneto-archimedes effect

$$B(z)\,B'(z) = \frac{\rho - \rho_{med}}{\chi - \chi_{med}}\,\mu_0 g$$

- suppression of convection

$$B(z)\,B'(z) = \frac{\alpha}{\beta}\,\mu_0 g$$

$$\rho(c) = \rho_0 + \alpha\, c;\ \chi(c) = \chi_0 + \beta\, c$$

Magnetic field is a powerful tool to tune effective gravity

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