Some recent developments in the field of liquid metal measuring techniques and instrumentation

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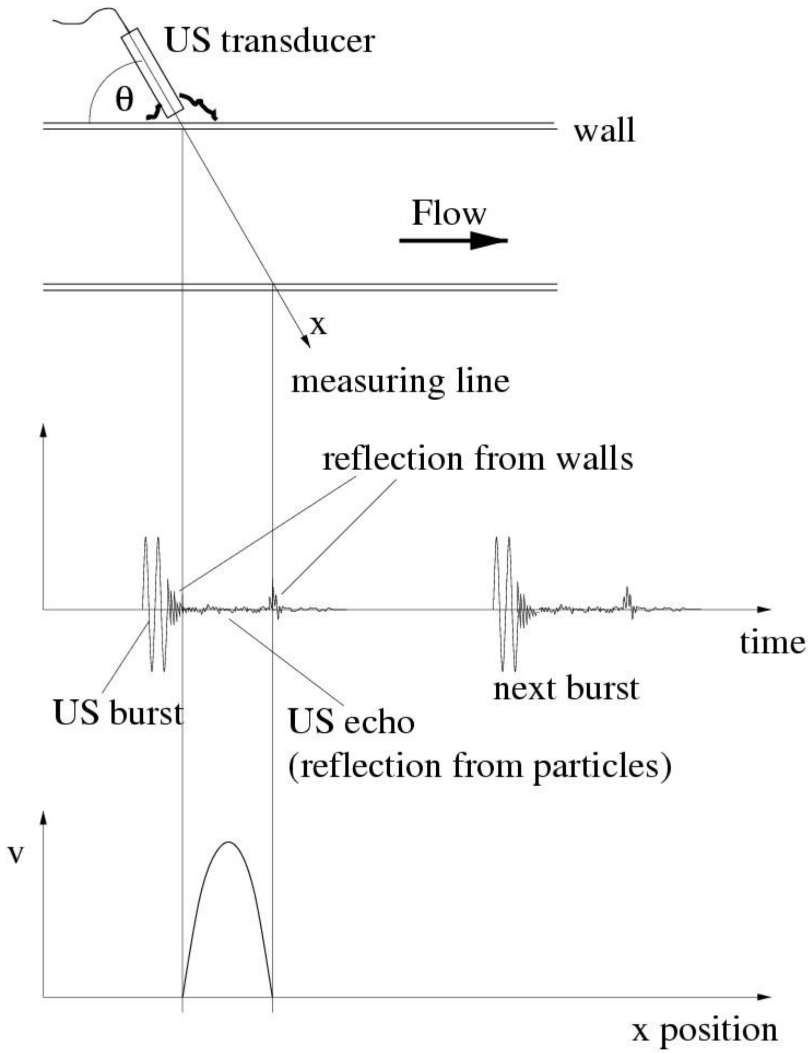
- **Ultrasound Doppler Velocimetry (UDV)**
  - Instantaneous measurement of linear velocity profiles
- **Inductive Flowmeter**
  - Flow rate measurements
- **Contactless Inductive Flow Tomography (CIFT)**
  - Reconstruction of a fully 3D flow structure
- **X-Ray Radiography**
  - Visualization of flows showing differences in density

Ultrasound Doppler Velocimetry (UDV)



Pulse-echo method:

- information about the position
  - ⇨ time of flight measurement

$$x = \frac{ct}{2}$$

- information about velocity
  - ⇨ Doppler relation

$$v = \frac{c \cdot f_D}{2 \cdot f_0}$$

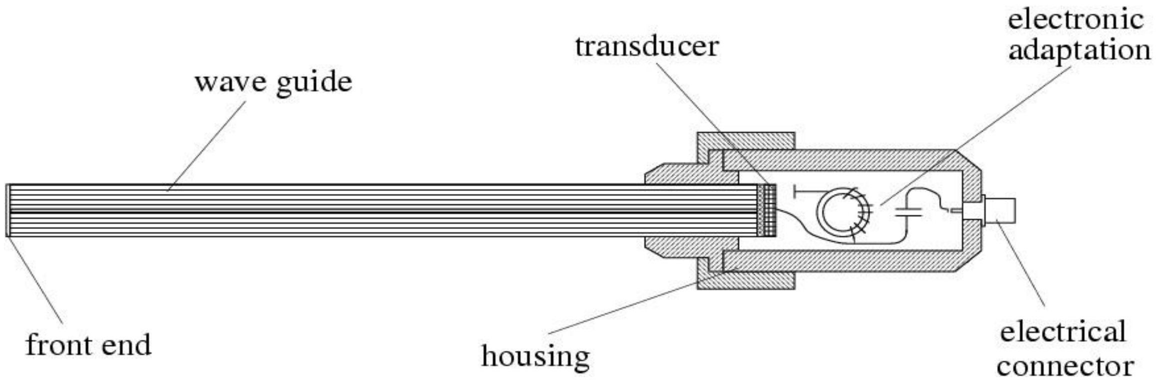
(c - sound velocity, f_D - Doppler frequency, f_0 - ultrasound frequency)

Y. Takeda, Nucl. Techn. (1987)

Y. Takeda, Nucl. Eng. Design (1991)

Application at high temperatures

- Piezoelectric transducer coupled on an acoustic wave guide made of stainless steel
- Ultrasonic frequency 2...5 MHz
- Maximum temperature ≈ 700°C
- Stainless steel foil (0.1 mm) axially wrapped
  Length 200 - 1000 mm
  Outer diameter 7.5 mm



S. Eckert, G. Gerbeth, V.I. Melnikov, Exp. Fluids (2003)

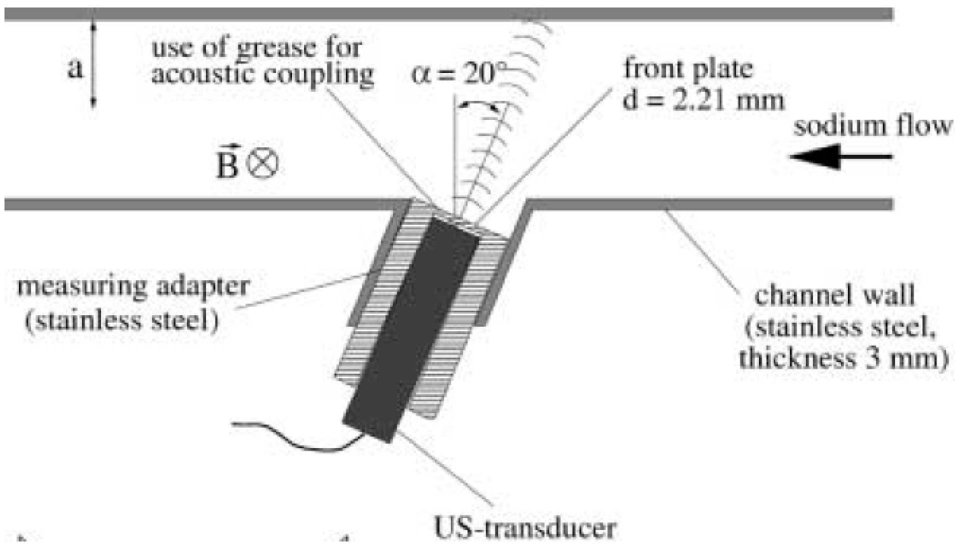
Coupling through the wall

- Wetting of the inner wall
- Acoustic impedance (λ/4 condition)

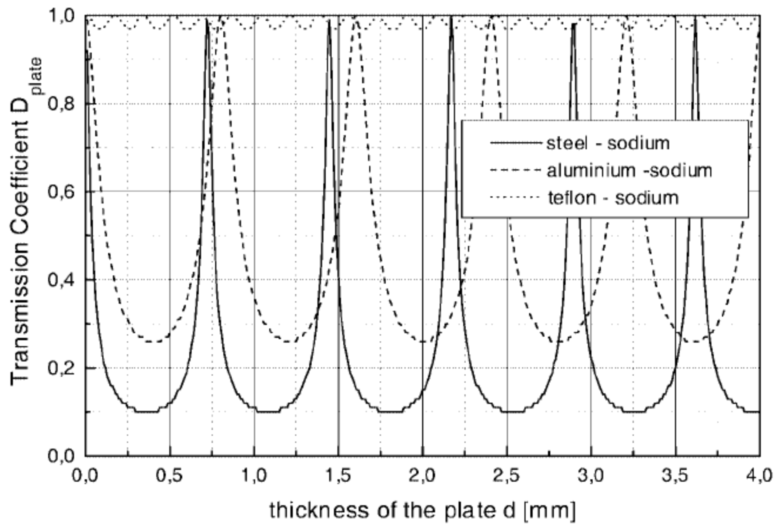
Transmission coefficient *D* (parallel plate)

$$D = \frac{1}{\sqrt{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 \frac{2\pi d}{\lambda}}}$$

$$m = Z_{Fl}/Z_W \; (Z = \rho c_{sound})$$



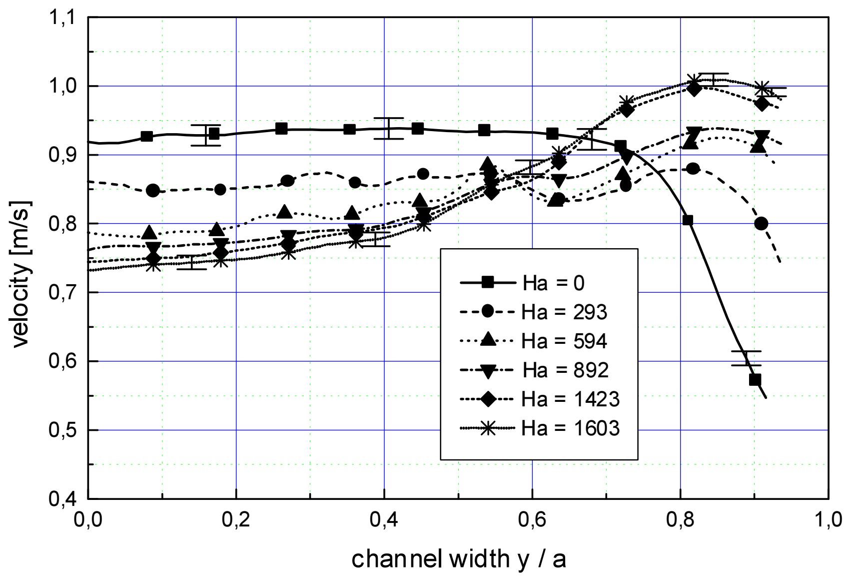
S. Eckert, G. Gerbeth, Exp. Fluids (2002)

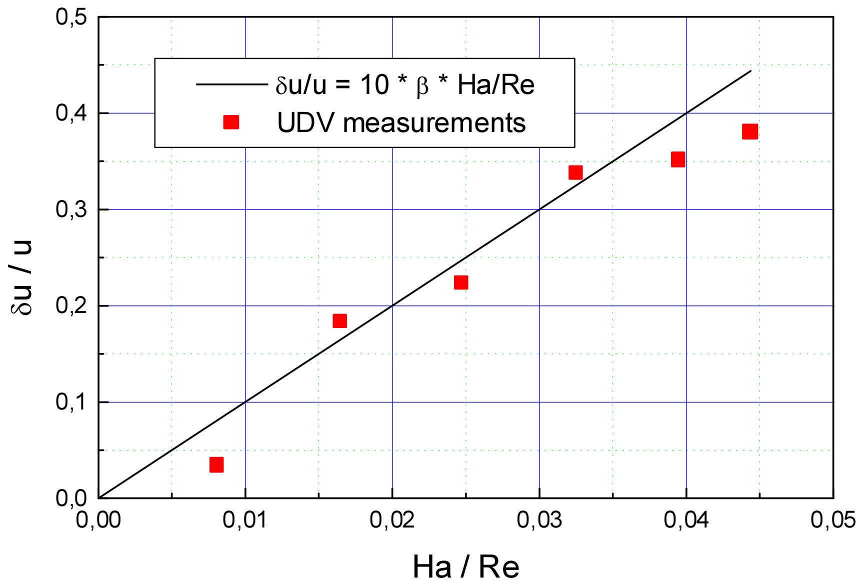


maximum at d/λ = n/2 (n = 1, 2, 3…)

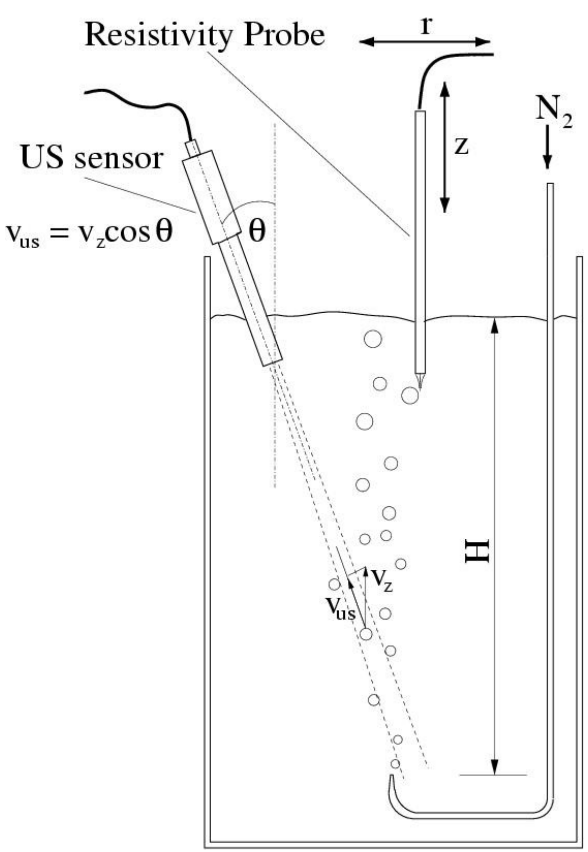
Results

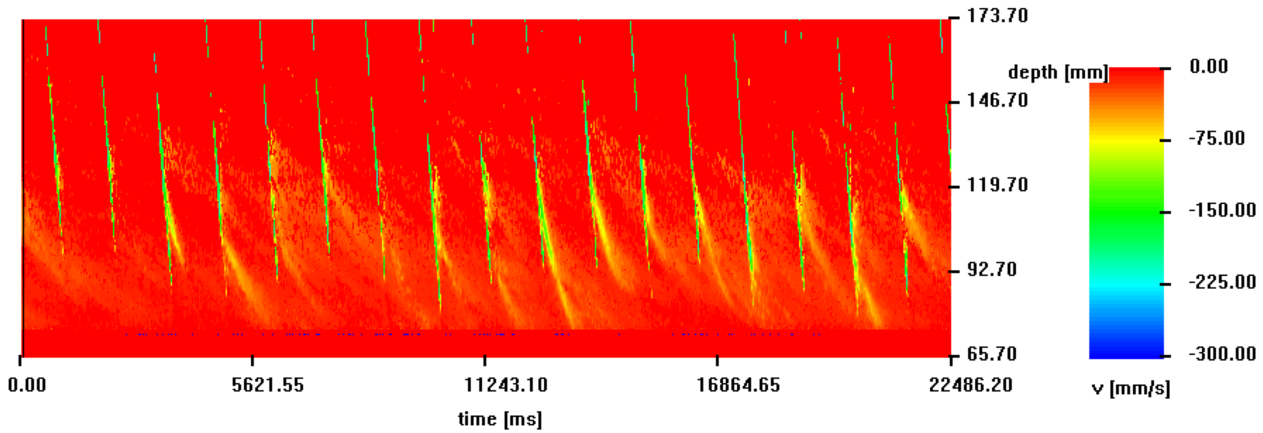
- Modification of the flow profile by a transverse magnetic DC field
- Agreement with theoretical predictions



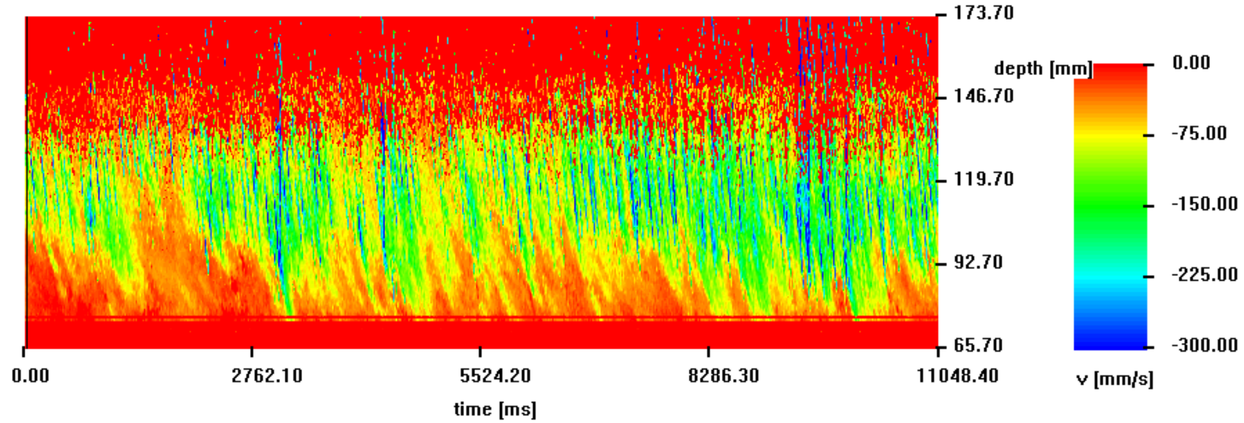


S. Eckert, G. Gerbeth, Exp. Fluids (2002)



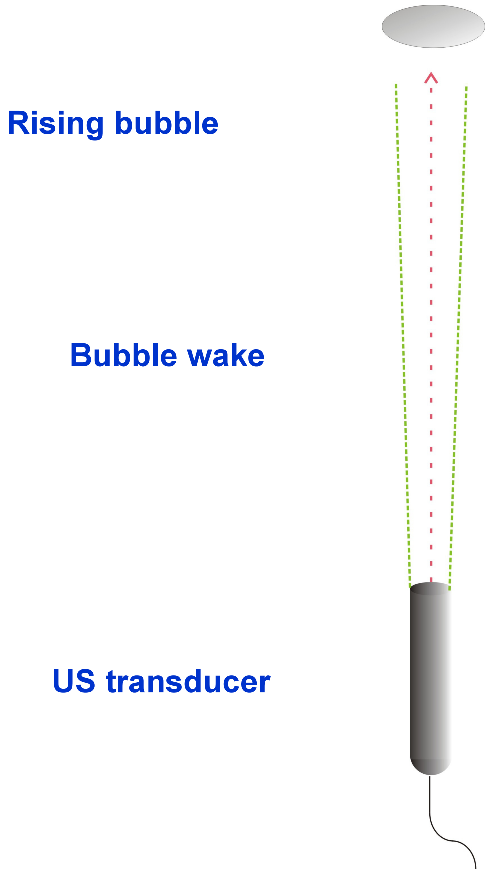


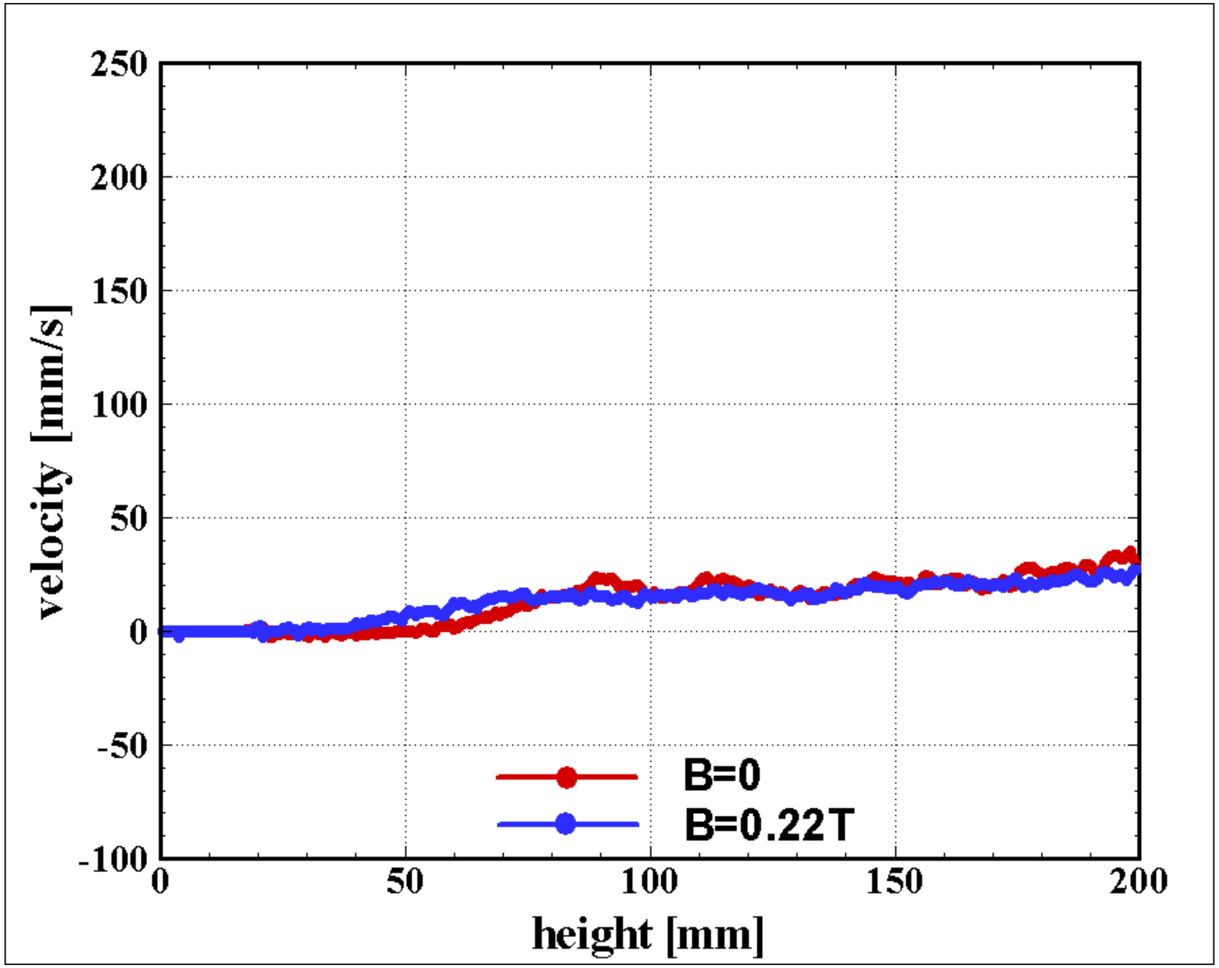
(a) $Q_g = 0.04\ cm^3/s$



(a) $Q_g = 1.2\ cm^3/s$

PbBi, 250 °C, gas injection through single orifice: $d_o = 0.5$ mm



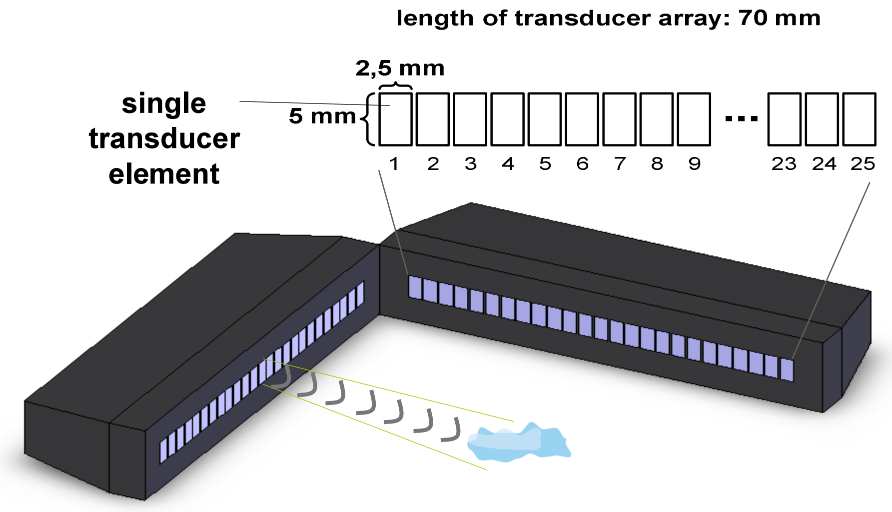


C. Zhang, S. Eckert, G. Gerbeth, Int. J. Multiphase Flow (2005)

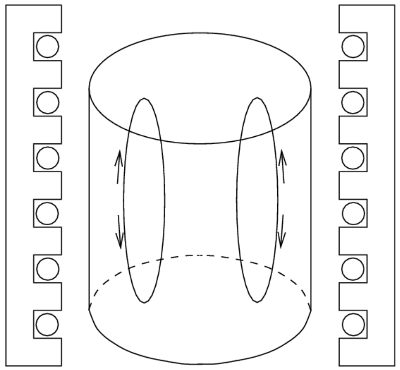
Outlook UDV: Flow mapping using transducer arrays

Goals

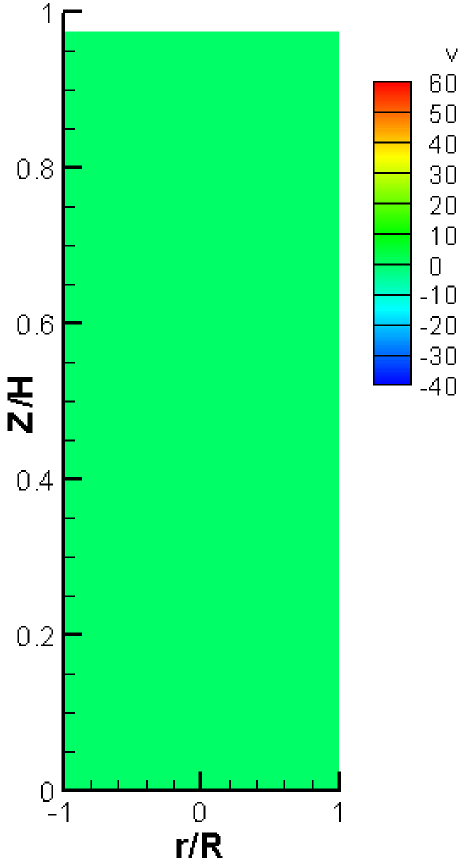
- 2D(3D) flow field
- Multiple velocity components
- High spatial and temporal resolution



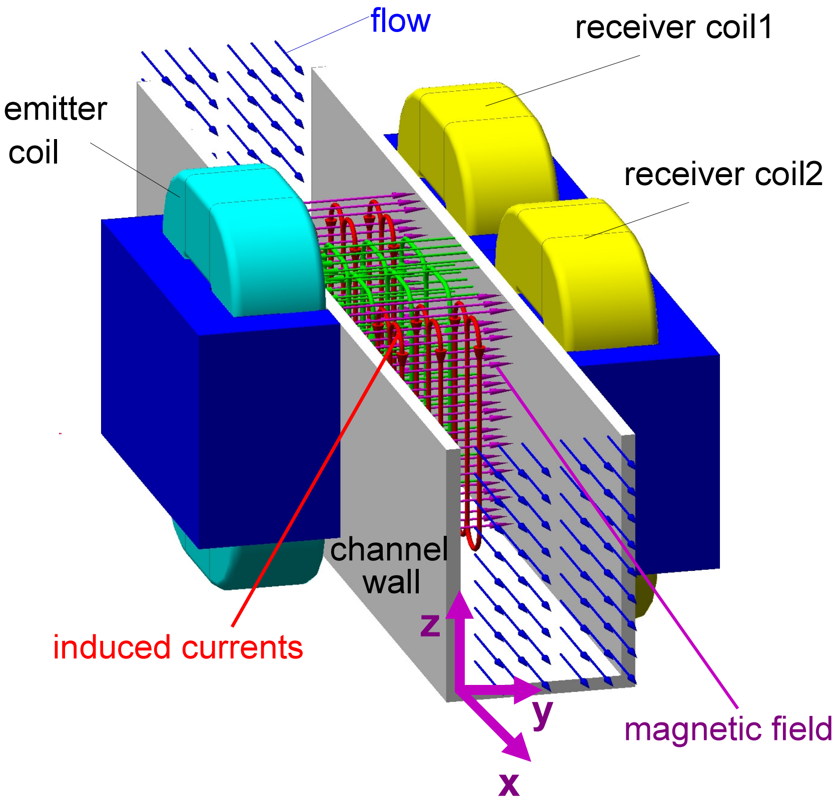
Example:
Electromagnetic melt stirring by AC magnetic fields



GaInSn, cylindrical vessel
(∅ 90 mm, H = 220 mm)
Traveling magnetic field



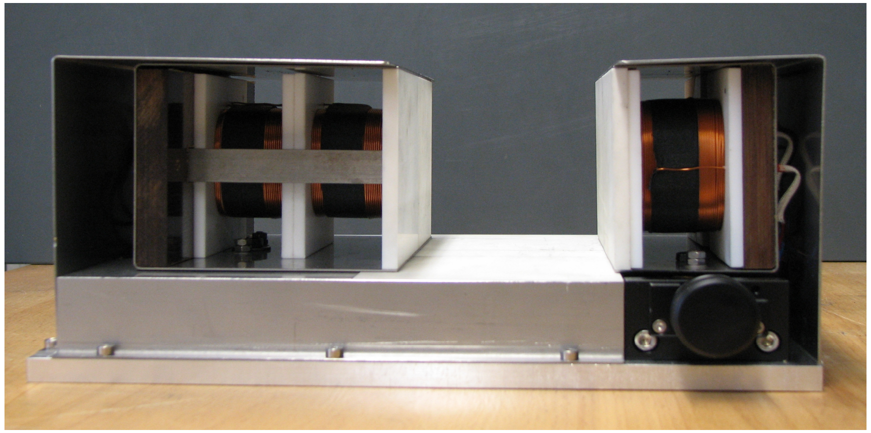
Inductive Flowmeter



- Perturbation of the magnetic field due to the flow
- Voltage/Phase shift is proportional to the flowrate
- High temporal resolution
- Can be applied at high temperatures

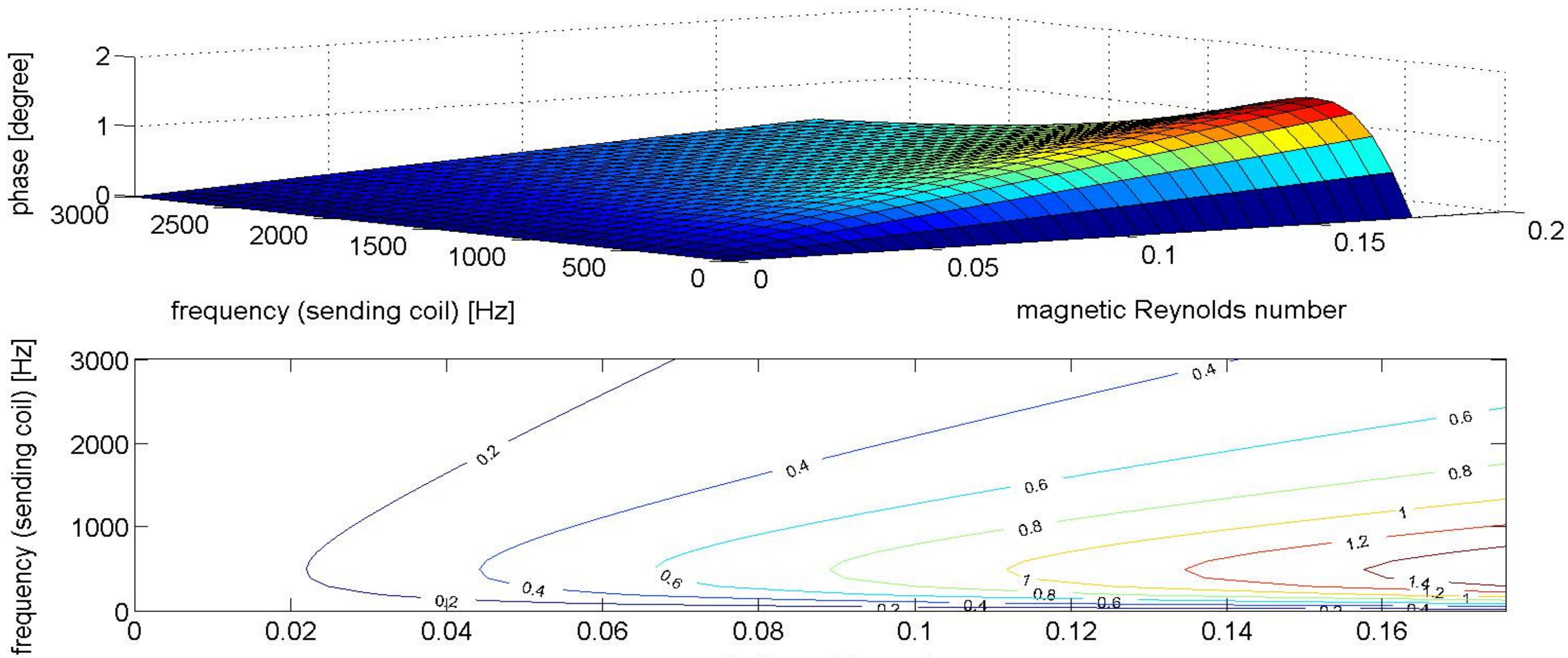
J. Priede, D. Buchenau, G. Gerbeth, 5th Int. Conf. on EPM, Sendai (2006)

- Ceramic material, Macor (T_{max} = 800°C)
- Coil windings are protected by a double layer of polyamide (T_{max} = 260°C)
- Channel width and zero position of the coils are adjustable in steps of 10 µm

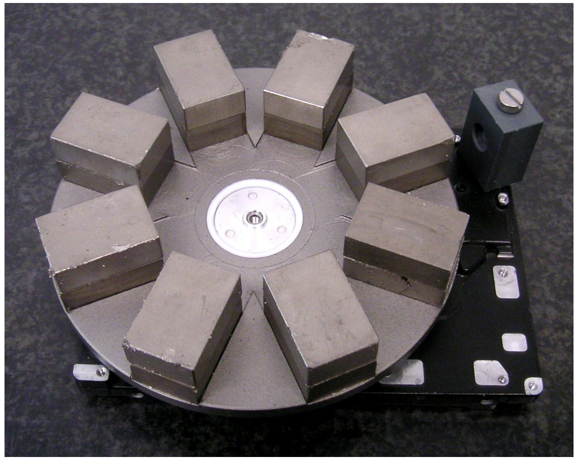


$$\Delta\phi = \arctan\left(\frac{2 f\tau \, \mathrm{Re}_m}{1+(\omega\tau)^2(1+\mathrm{Re}_m/\pi)}\right)$$

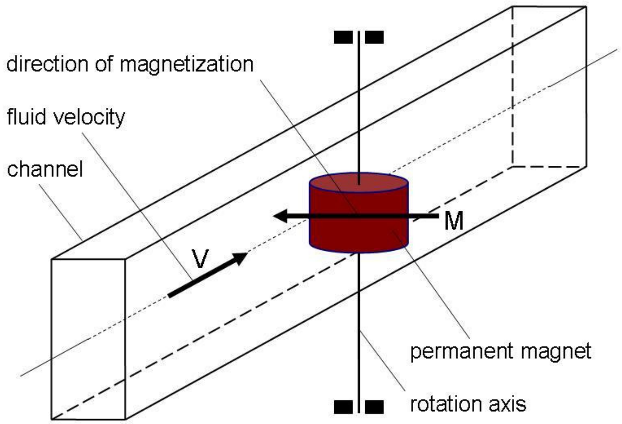
material: $Pb_{44}Bi_{56}$, diameter of the channel: 54.5mm
velocity: 1 m/s – magnetic Reynolds number: 0.058

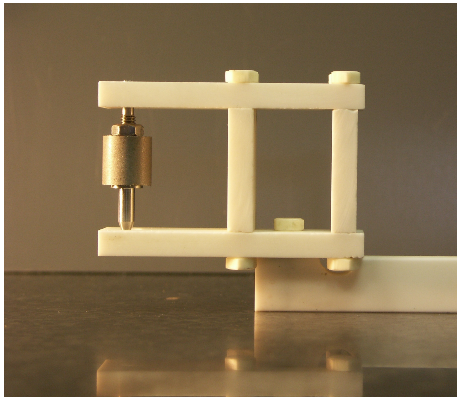


Inductive Flowmeter: Rotating magnets



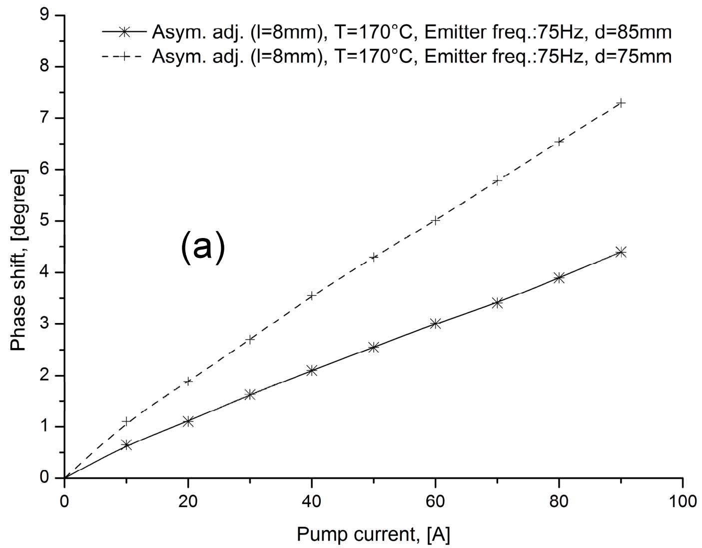
I. Bucenieks , 5th Int. PAMIR Conference, Ramatuelle (2002)



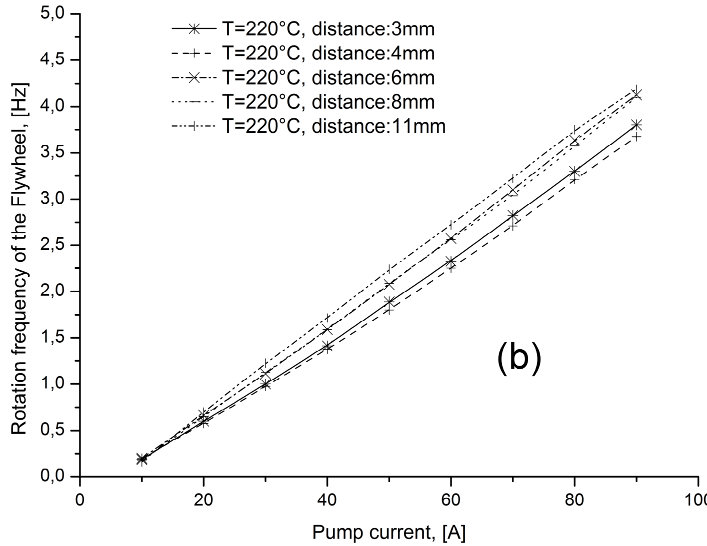


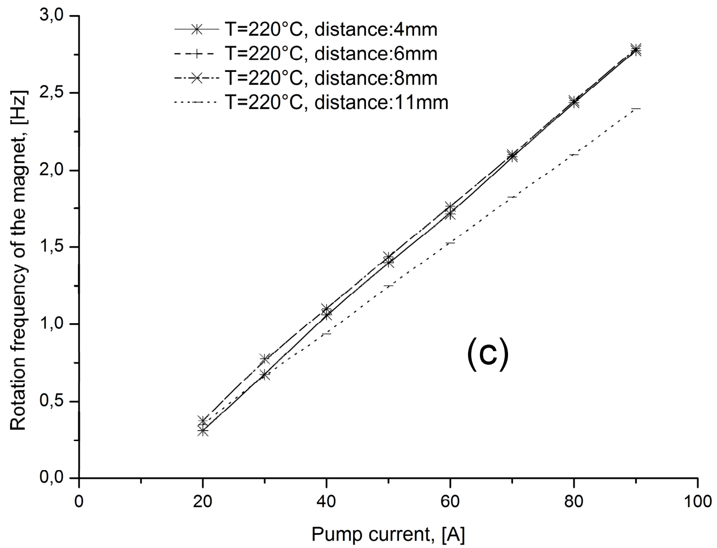
J. Priede, D. Buchenau, G. Gerbeth, Magnetohydrodynamics (2009)

Flow rate as a function of the pumping power:
(a) Phase-shift sensor
(b) Magnetic fly wheel
(c) Single magnet rotary flow meter



Problem: calibration vs. flow rate





Contactless Inductive Flow Tomography (CIFT)

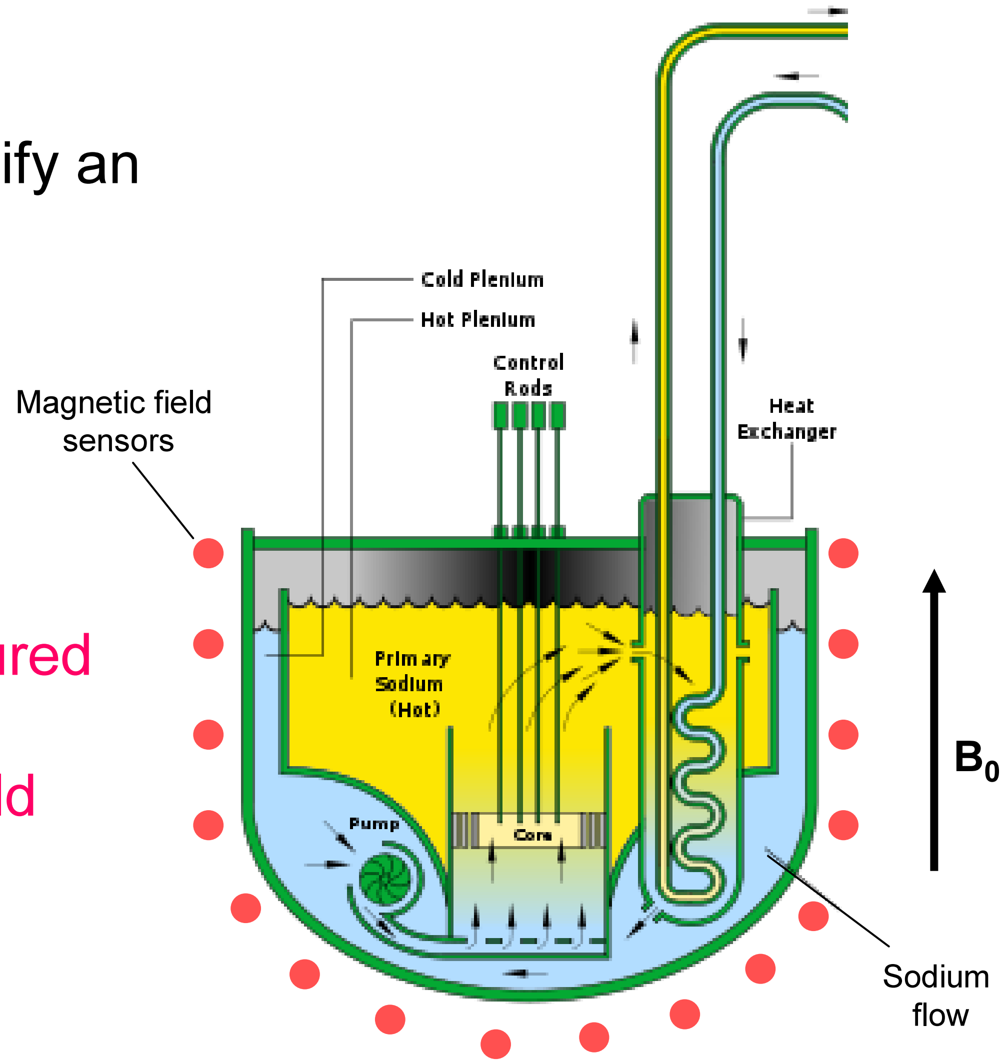
- An existing flow field will modify an applied magnetic field:

  $\mathbf{B}=\mathbf{B}_0+\mathbf{b}$, $\mathbf{b}\sim R_m\,\mathbf{B}_0$

  $(R_m=\mu\sigma L v)$

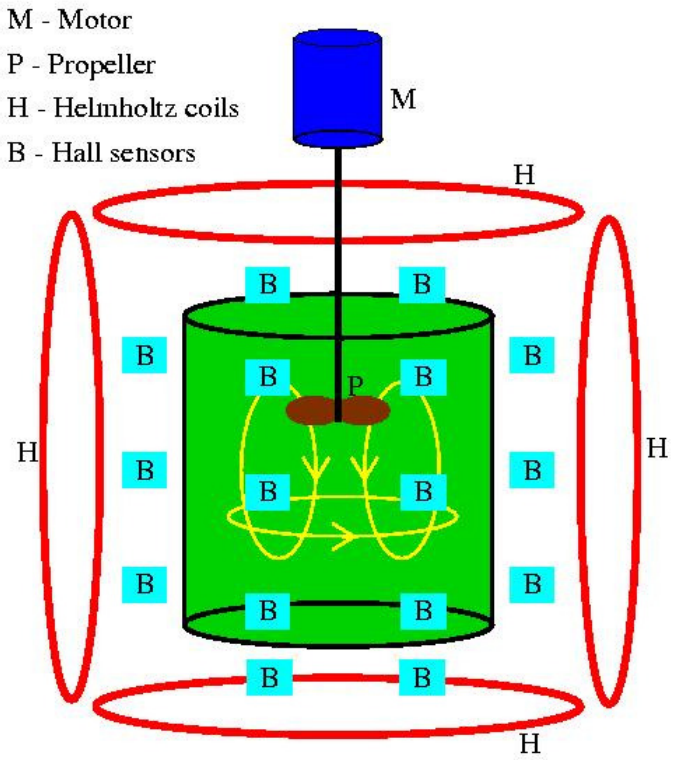
  e.g. the magnetic field measured outside the melt contains information about the flow field

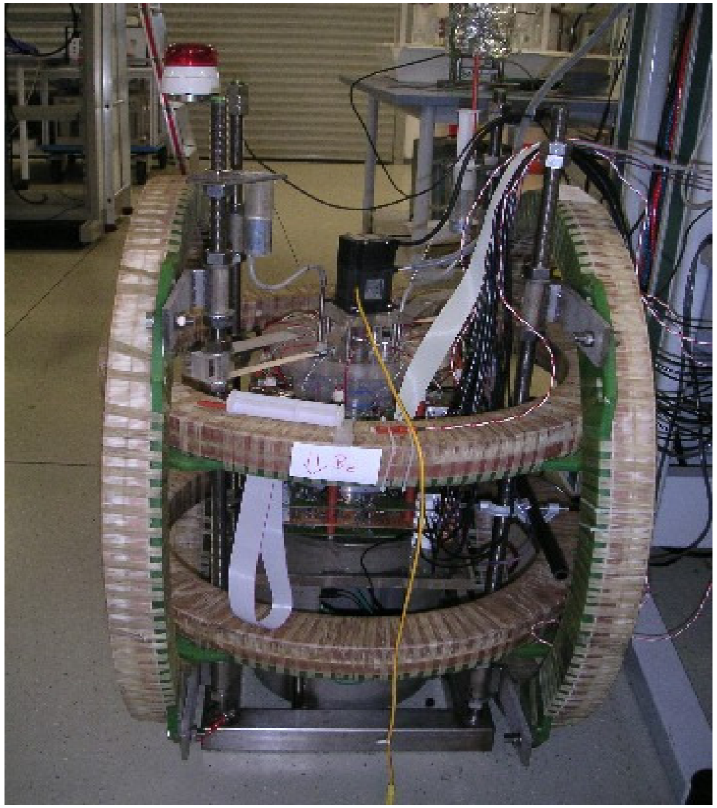
- $Rm \sim 10^{-3}$ ➔ $b \sim O(\mu T)$



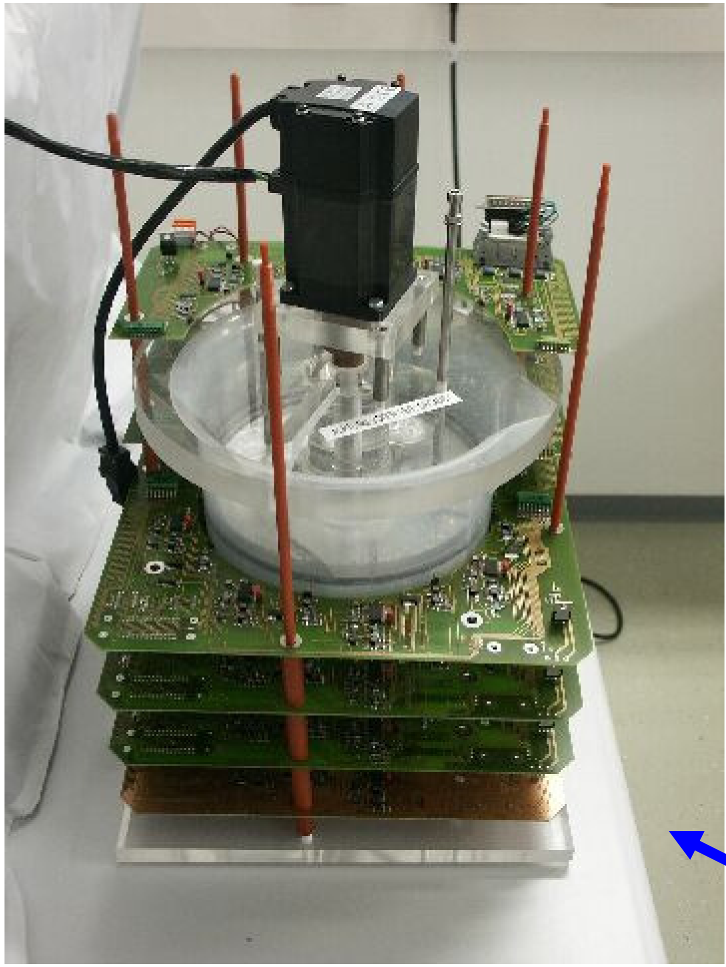
Example: SFR

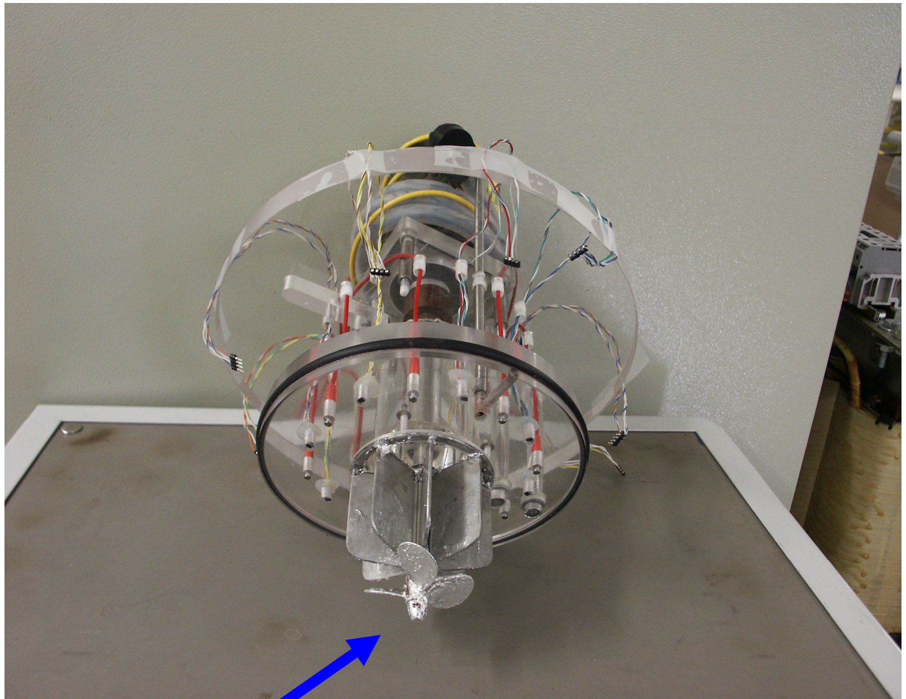
F. Stefani, G. Gerbeth, Inverse Problems (1999, 2001)
F. Stefani, T. Gundrum, G. Gerbeth, Phys. Rev. E. (2004)





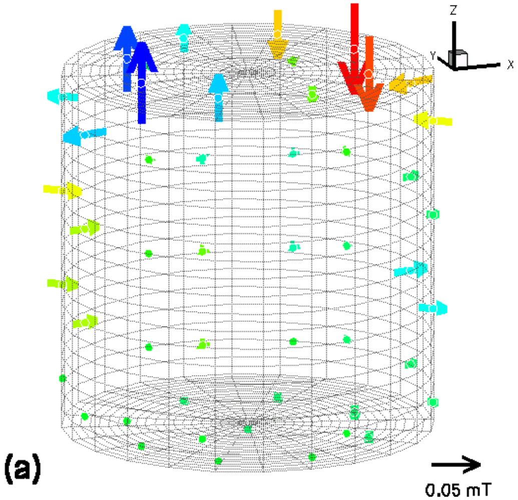
- Cylinder filled with InGaSn
  (D = 180 mm , H = 180 mm)
- Magnetic field: two pairs of Helmholtz coils
  10mT
- 48 Hall sensors
  (KSY44-Infineon, resolution 1 μT)
- Mechanical stirrer (2000rpm)
  max. velocity ~ 1 m/s



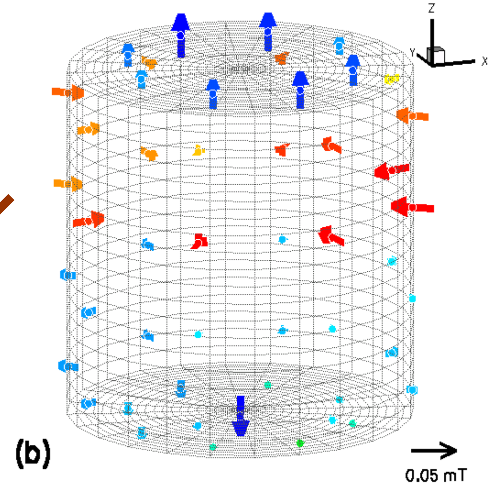


Lid with stirrer and motor

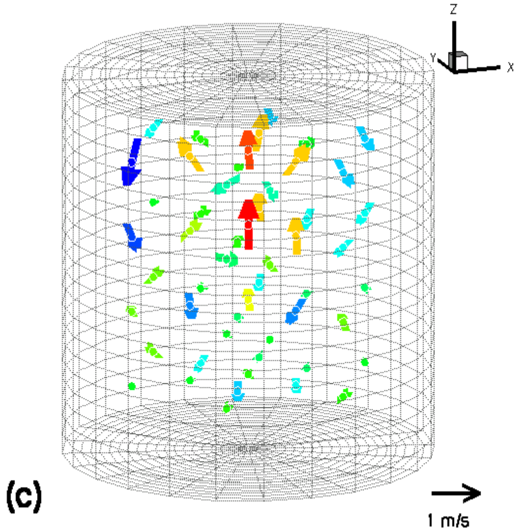
Vessel, electronic equipment



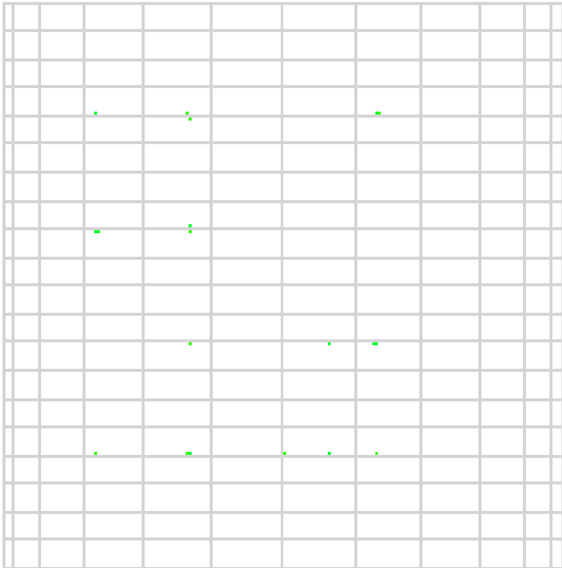
Induced magnetic field for transverse primary field

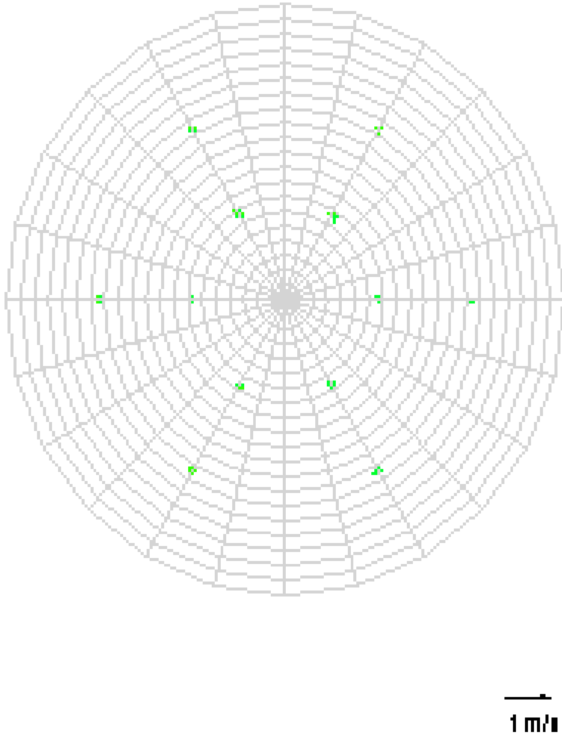


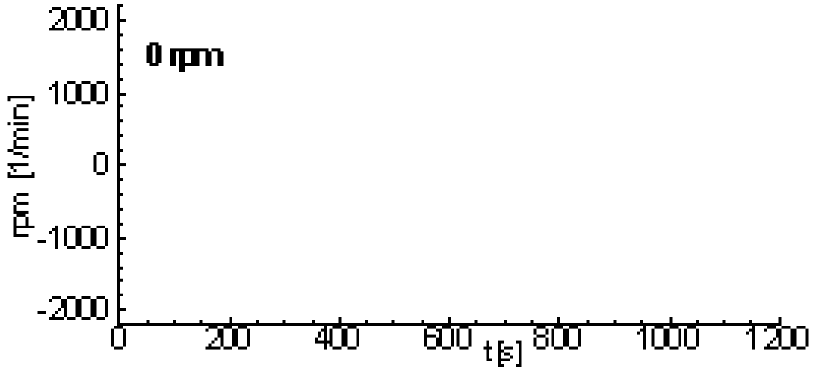
Induced magnetic field for axial primary field



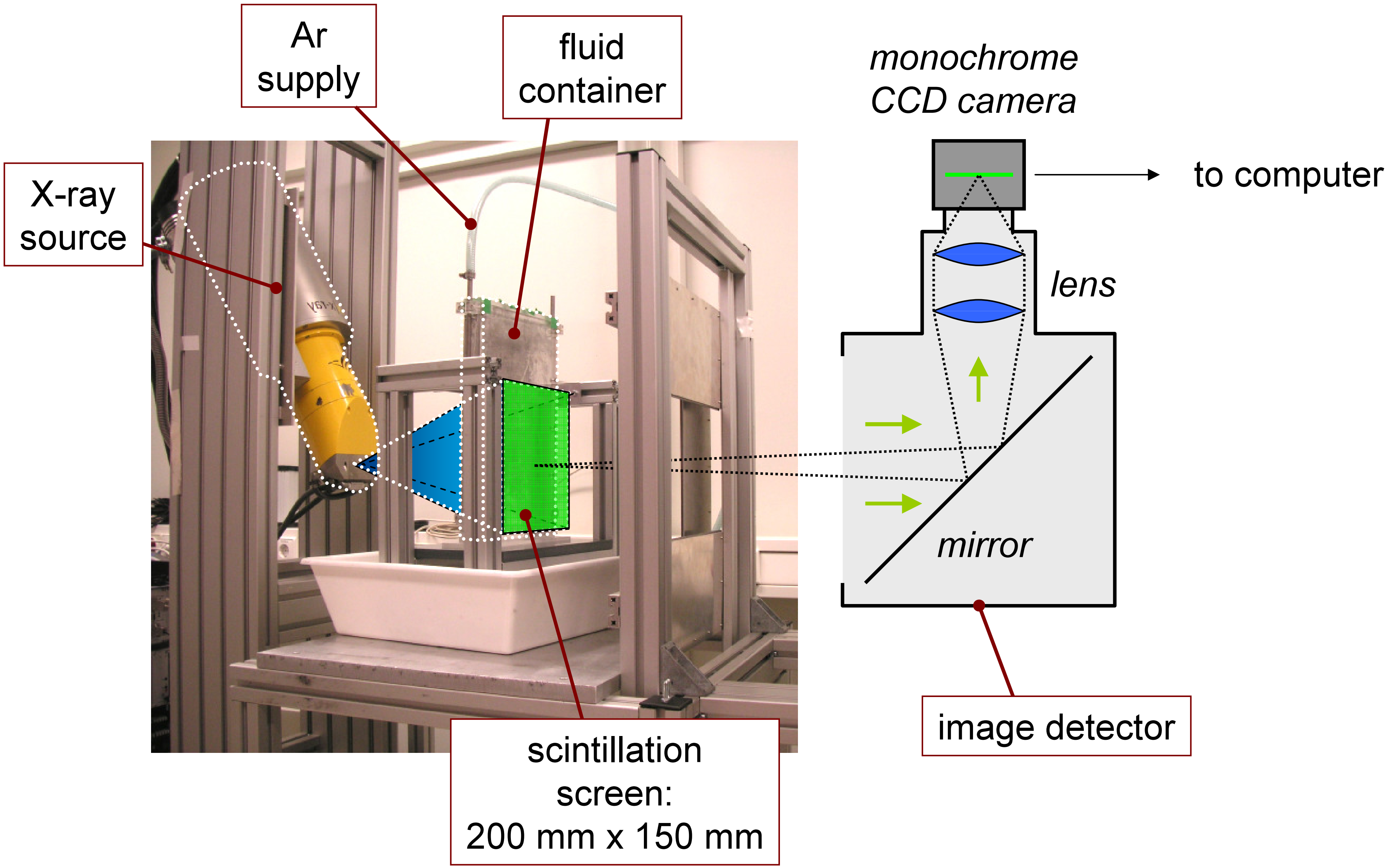
Reconstructed velocity field

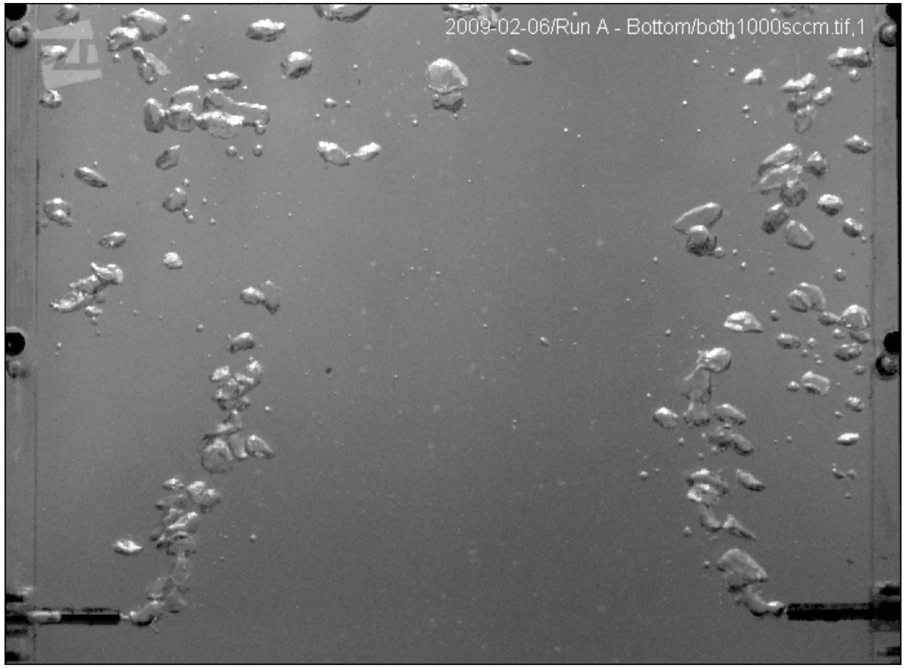




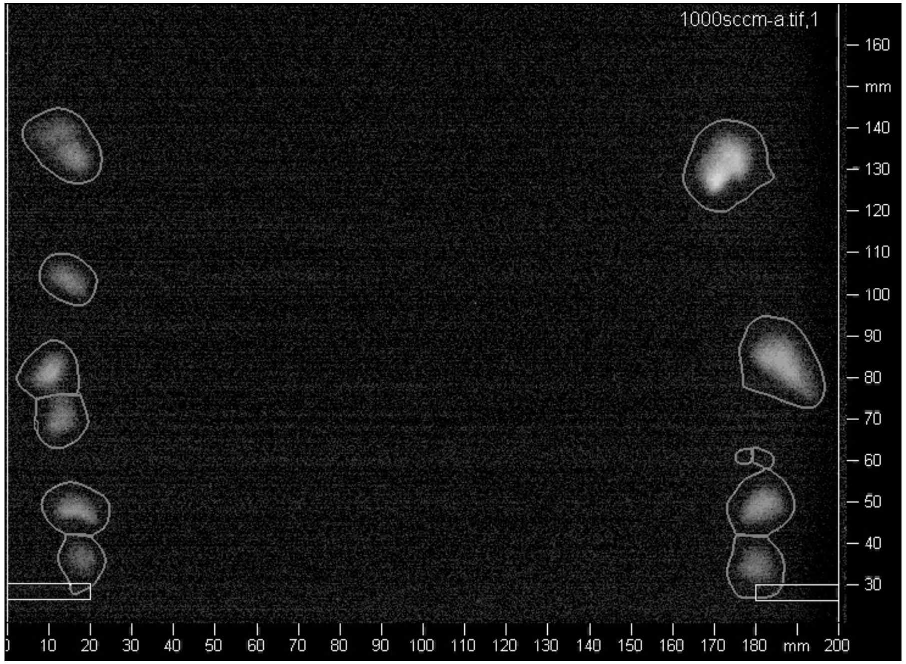

0 rpm
rpm [1/min]
2000
1000
0
-1000
-2000
0
200
400
600
800
1000
1200
t[s]

X-Ray Radiography


Ar
supply
fluid
container
X-ray
source
monochrome
CCD camera
to computer
lens
mirror
image detector
scintillation
screen:
200 mm x 150 mm



Water-Air



GaInSn-Argon (X-Ray)

Gas flow rate 1000 cm^3/s

- **Ultrasound Doppler Velocimetry (UDV)**
  - Instantaneous measurement of linear velocity profiles, flow mapping
  - Non-invasive method, but, not contactless
  - Measurements through the channel
- **Inductive Flowmeter**
  - Flow rate measurements
  - Contactless method
  - Calibration
- **Contactless Inductive Flow Tomography (CIFT)**
  - Reconstruction of a fully 3D flow structure (several seconds)
  - Contactless method
  - Arrangements: external field, field sensors
- **X-Ray Radiography**
  - Visualization of flows showing differences in density
  - Restricted fluid volume

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Thank you for your attention!