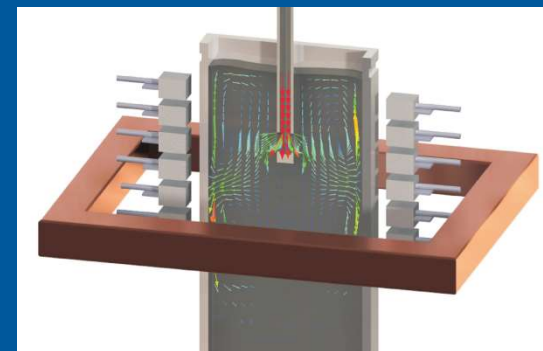# Flow measurements in liquid metals

Sven Eckert

Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Many thanks to:

Thomas Wondrak, Matthias Ratajczak, Nico Krauter,
Klaus Timmel, Sven Franke, Thomas Gundrum,
Frank Stefani, Phillip Büttner, Thomas Richter,
Natalia Shevchenko …

Measurement quantities

| Quantity	Sensor
Pressure	Fiber optical sensors
Flow rate	Inductive flow meter
Local velocity	Mechanical devices Potential probe (turbulent spectra)
Flow field (1D/2D/3D)	Ultrasound Doppler Velocimetry Contactless Inductive Flow Tomography
Multi-phase flows	Resistance probes Fibre optical sensors Ultrasound Transit Time Technique X-ray / neutron radioscopy Mutual Inductance Tomography
Free surface level	Ultrasound methods Optical methods Inductive methods

non-invasive but contact needed

contactless

Resistive probes for local gas detection

- Insolated rod with small electrical contact at the sensor tip

- Sensor inserted into the melt

- Current flows through the liquid to the sensor top

- Gas bubbles are insulator

- Sensor signal: on/off (contact time of bubble)

- Sensors with two tips: bubble velocity

- Sensor design challenges:
  - electrical insulation
  - length of the tip
  - corrosion of the tip
 - mechanical stability
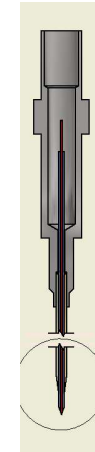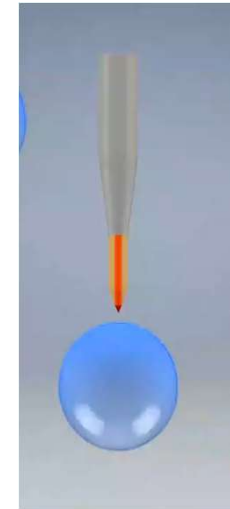
sensor design with mounting

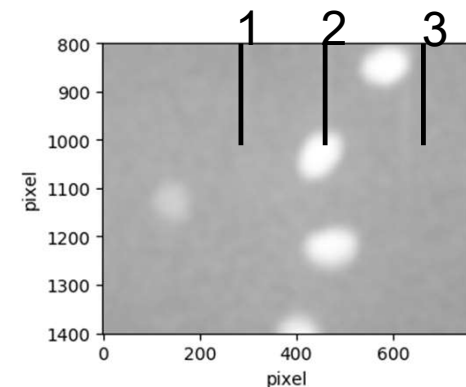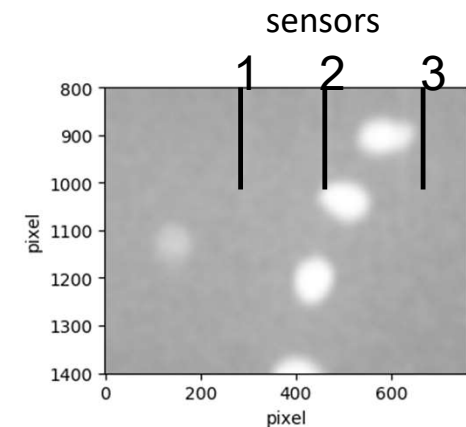2 tips   1 tip

DRESDEN concept

HZDR
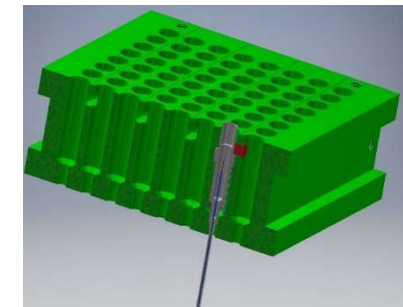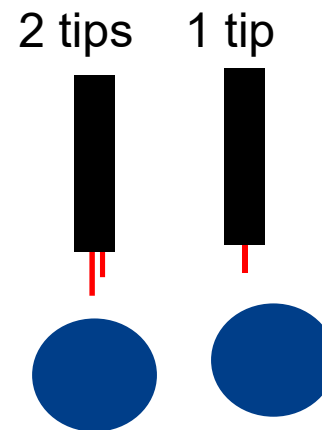
Resistive probes: validation by X-ray visualization

- Vessel cross section:
  140 mm x 12 mm

- Liquid metal: GaInSn

- 3 sensors inserted at the top

- Spacing 10 mm

- Argon gas injection
  at the bottom

- 1 – 10 kHz data sampling

- Synchronization with the camera

- Results:
  - negligible effect on the flow
  - bubble not centered
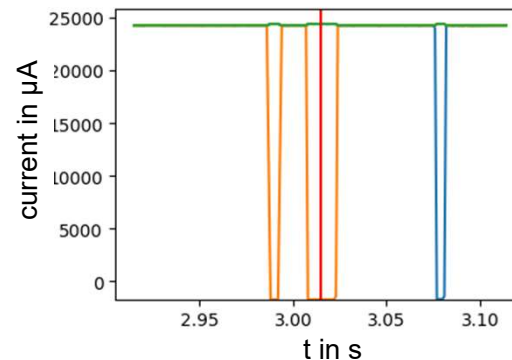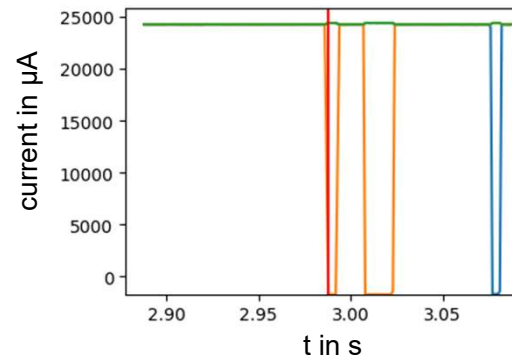
Potential Probe
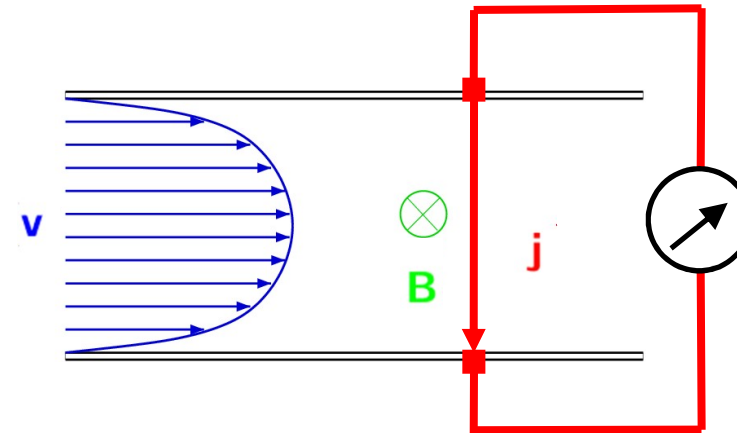
- Two electrodes with distance L in contact with the fluid

- Magnetic field **B** generated by a small magnet incorporated into the probe or externally applied

- Ohm's law for moving conductors

$$\mathbf{j} = \sigma(\mathbf{v} \times \mathbf{B} - \nabla\varphi)$$

- Measured voltage:

$$\Delta\varphi = c_w \cdot L \cdot |\mathbf{B}| \cdot v$$

- Calibration factor: c_w

- Small response time 500 Hz: turbulent fluctuations

- Challenges:

  - Invasive

  - Prone to electrical interfering signals: nV (!)

Ultrasound Doppler Velocimetry (UDV)

- Transmission of multitude of ultrasonic bursts

- Burst reflected at scattering particles
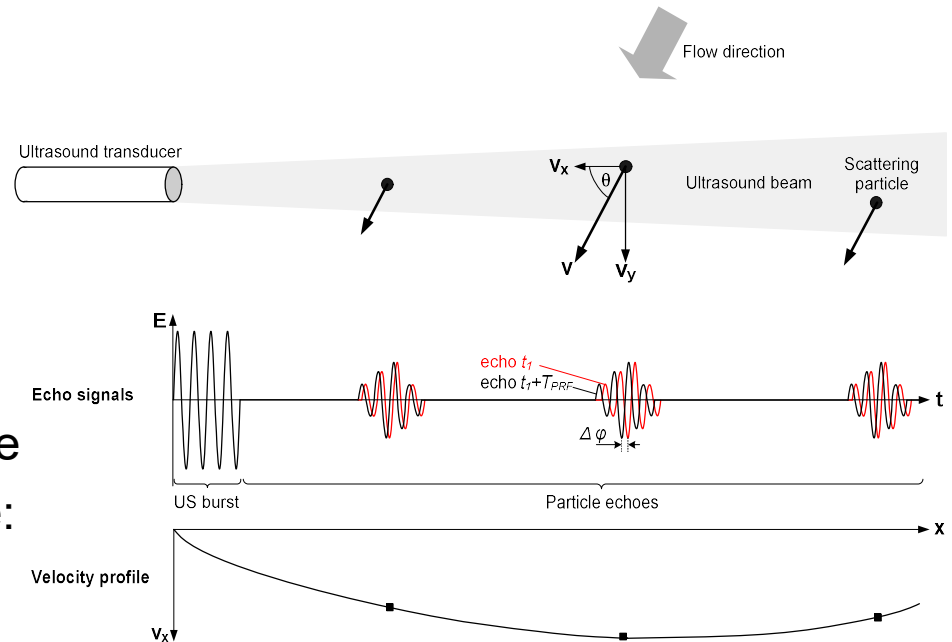
- Position of scattering particle:

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

c sound velocity

- Phase-shift between successive particle echoes referred to pulse repetition time:

$$v_x = \frac{c \cdot \Delta\varphi}{4\pi \cdot f_0 \cdot T_{prf}}$$

- Instantaneous velocity profile

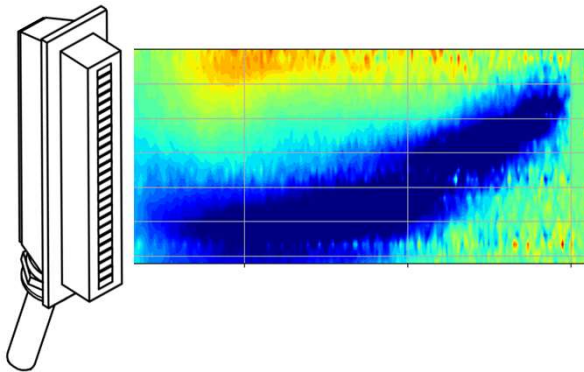 - 1 mm/s … 10 m/s
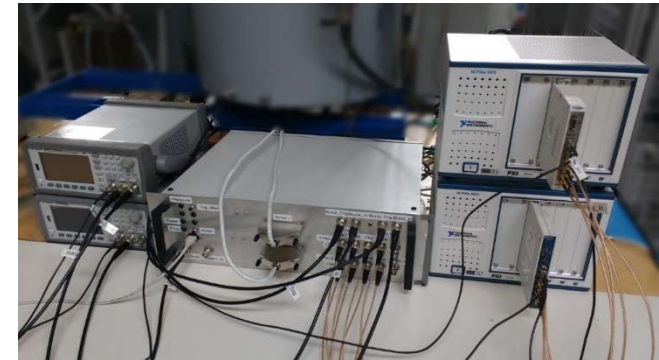
  - 20 - 30 Hz

- Can operate through wall

Doppler angle θ: $v = v_x \cos\theta$

Y. Takeda, Ultrasonic Doppler velocimetry profile for fluid flow (2012) Springer

Ultrasound sensor array

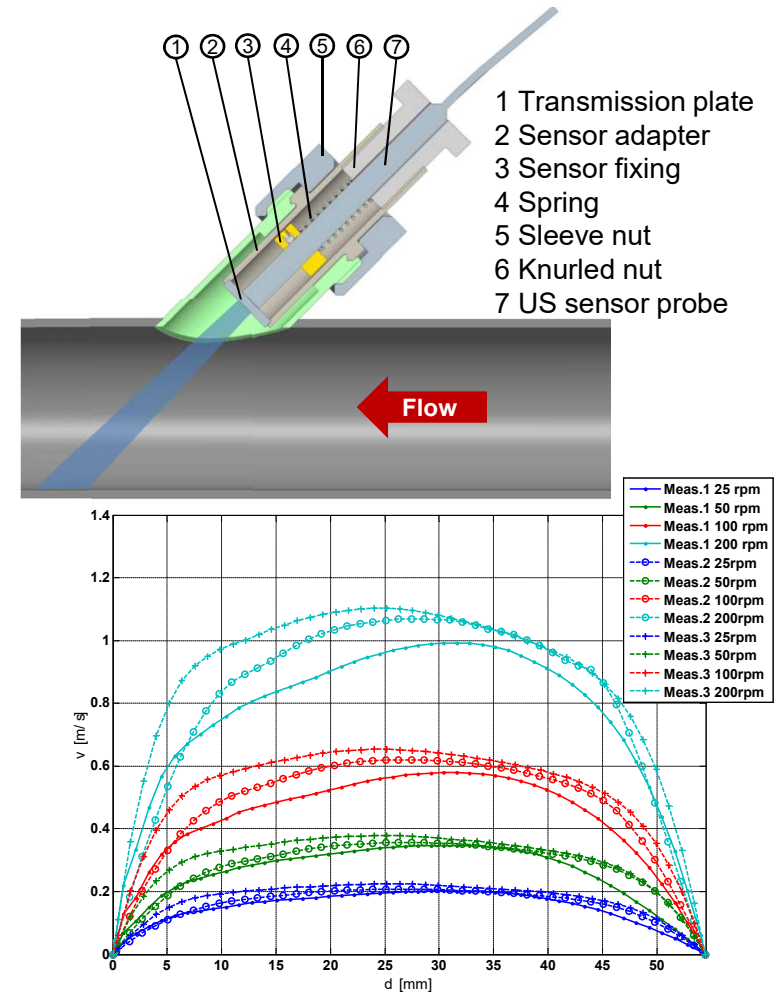|	state of the art	new array
Imaging dimensions	2D-1C	≥ 2D-2C
Measuring lines	≤ 21	≥ 48
Meas. line sampling	sequential	parallel
Measurement rate	5 fps	≥ 30 fps
Measuring line pitch	≥ 8 mm	< 3 mm

- Up to 4 linear transducer arrays
- Measuring plane: 67× 67 mm^2
- Measurement grid: 24 × 24 vectors
- Grid pitch: 2.7 mm
- Spatial resolution: ≈ 3 m
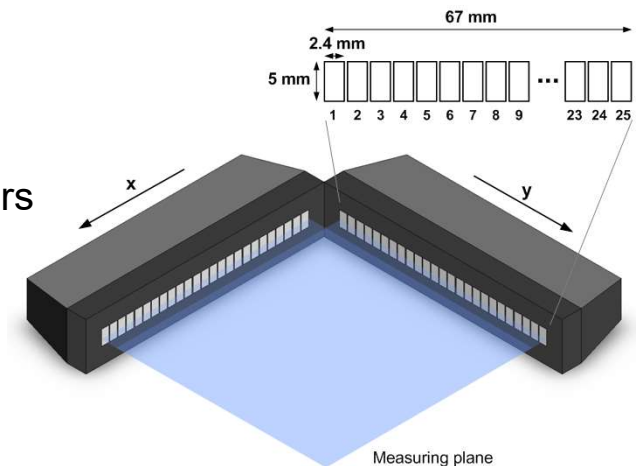
S. Franke et al., Ultrasonics (2013)

UDV: High temperature probes

- Temperature < 230°C

- Housing

  - protection from chemical corrosion
  - simple probe exchange during operation
  - removable for renewal of wetting
  - spring compensate thermal expansion
  - special treatment of housing tip to ensure wetting

- Measurement in a SnBi melt at 200 °C

1 Transmission plate
2 Sensor adapter
3 Sensor fixing
4 Spring
5 Sleeve nut
6 Knurled nut
7 US sensor probe

Flow

UDV: Wave guide sensor
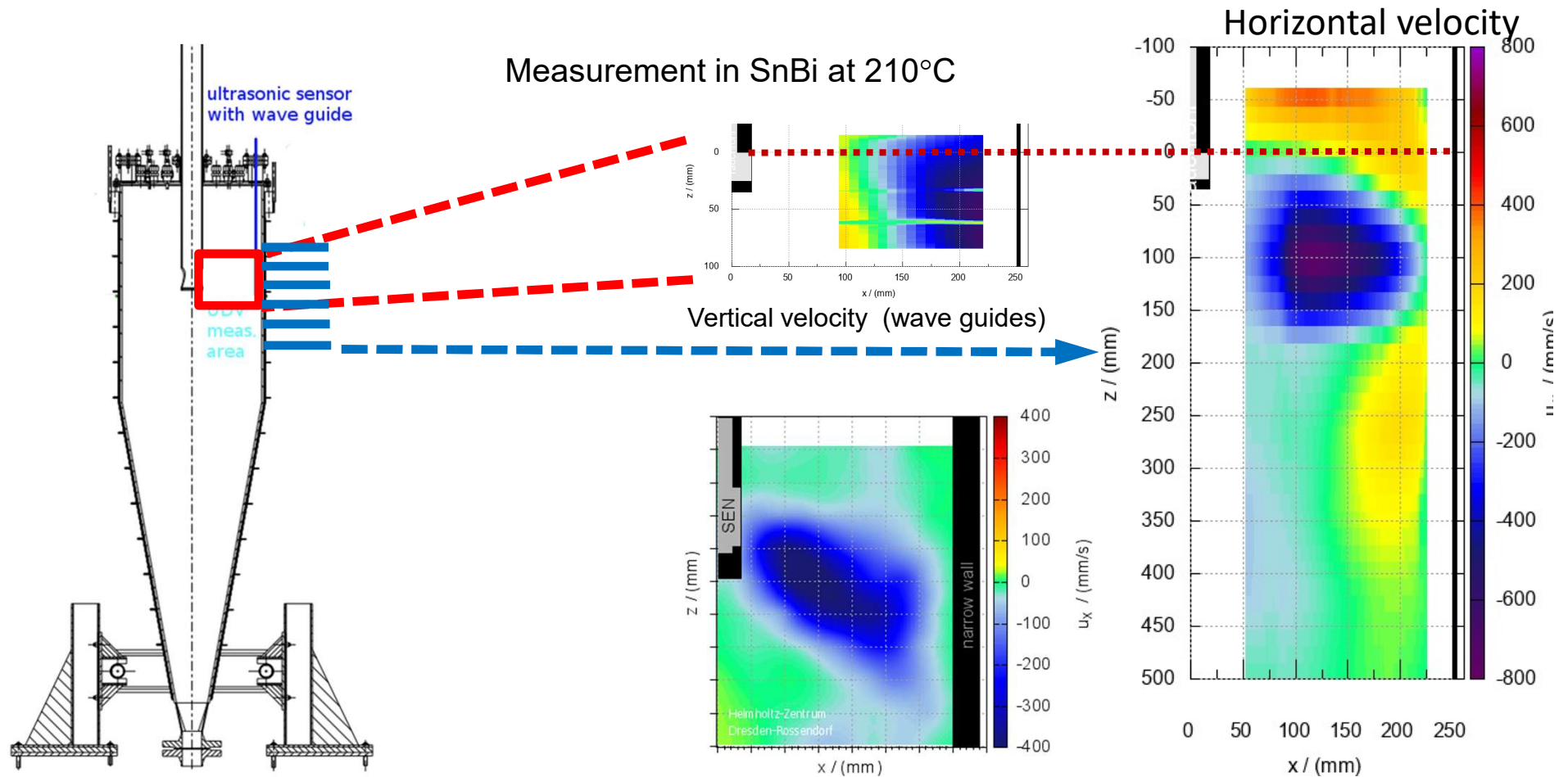
- Temperature < 700 °C

- Temperature gradient along wave guide

- Wave guide made of stainless steel foil (0.1 mm) axially wrapped

- Special treatment of the wave guide tip to ensure good wetting

- Prevent unwanted propagation modes
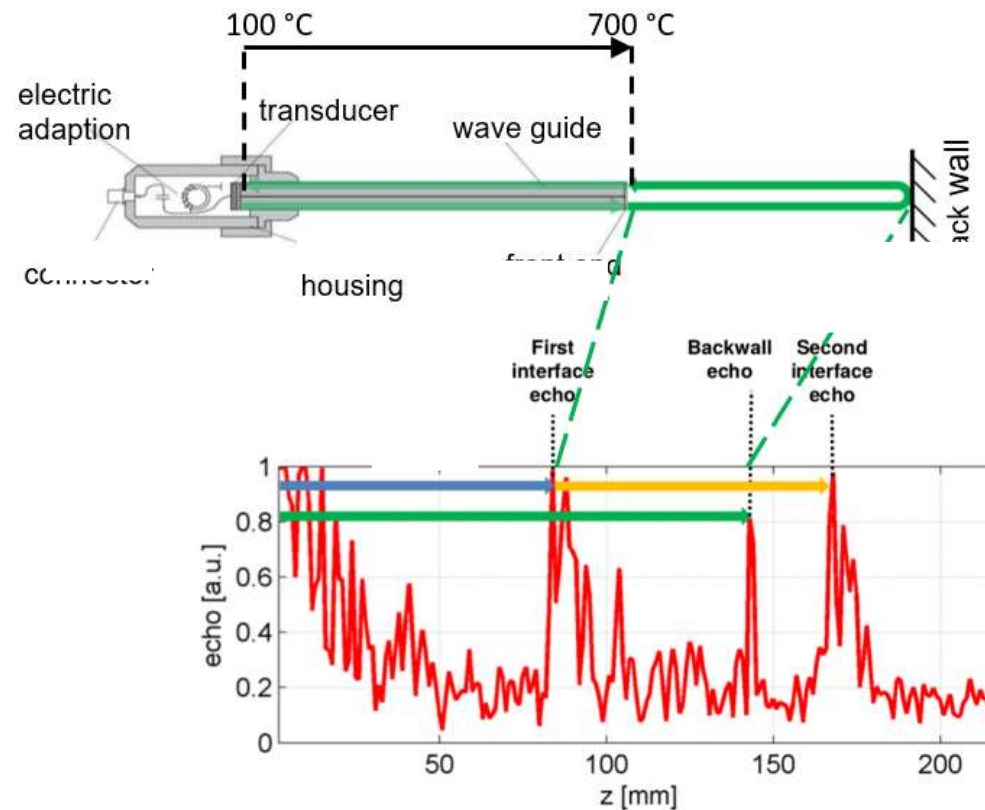
corrosion

UDV: Example at LIMMCAST

Measurement in SnBi at 210°C

Vertical velocity (wave guides)

Horizontal velocity

Ultrasound transit time technique (UTTT)

- Measurement procedure for one sensor:

    1. Send ultrasound impulse into the melt

    2. Listen to the echo

- Reflection at the outer surface of the bubble

- Measure time of flight of the impulse: t_b

- Distance between sensor and outer surface x_b:

$$x_b = \frac{c t_b}{2}$$

c sound velocity

- Information:

    - Spatial distribution of bubbles

   - Velocity of bubbles

    - Bubble diameter
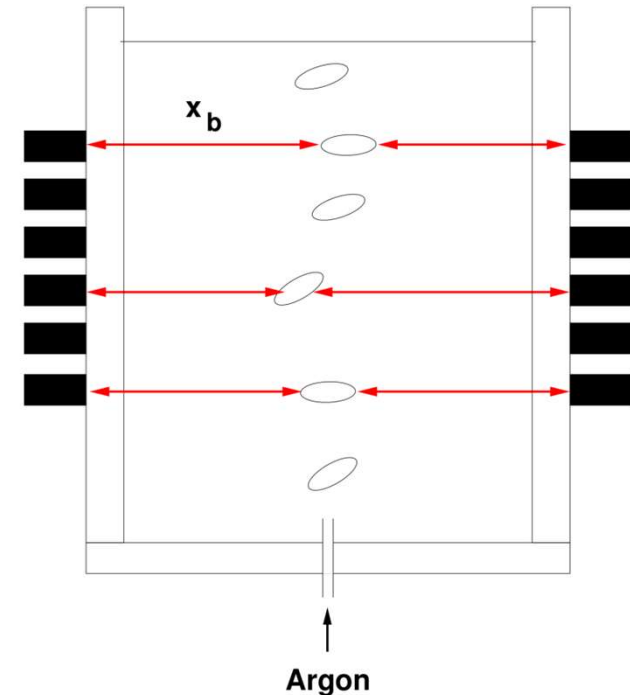
T. Richter et al., Nucl. Eng. Des. 291 (2015)

DRESDEN concept

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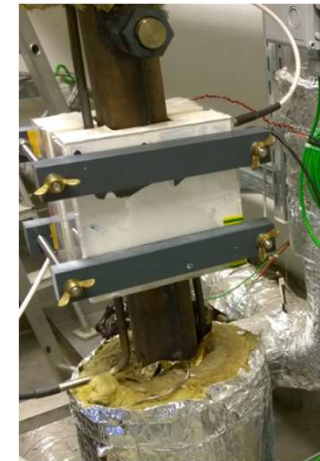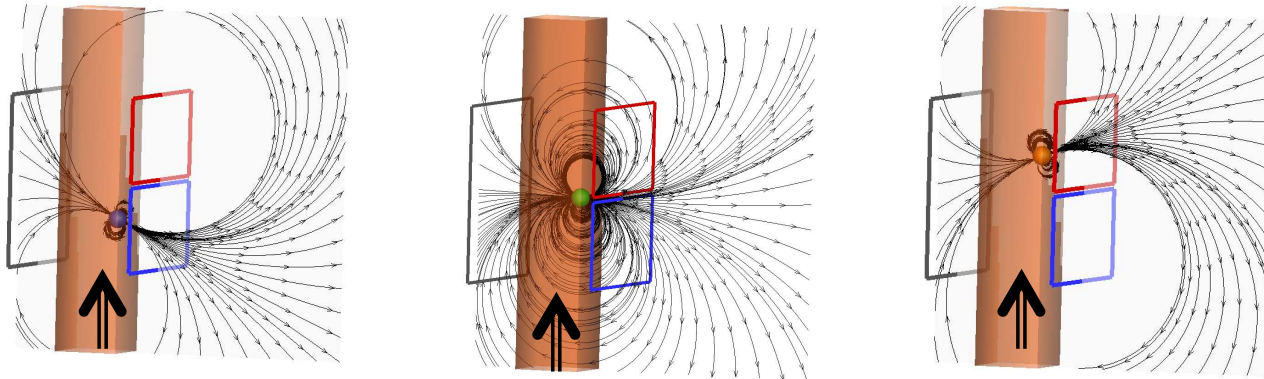# UTTT: Example in GaInSn path of single bubbles

- Flat vessel: 144 mm × 12 mm with h = 144 mm

- Static magnetic field perpendicular to the wide face of the container 0 – 300 mT

- Comparison with X-ray radiography

- Measurement at 5 vertical positions

- Bubble diameter
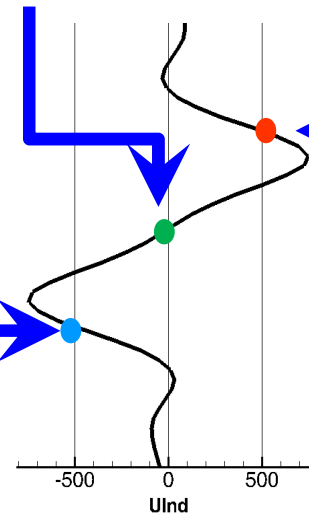
  0   mT: d = 4.8 mm
  300 mT: d = 5.2 mm
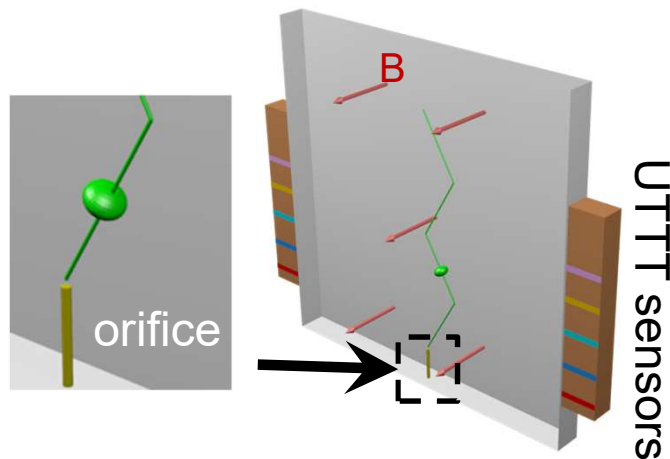
T. Richter et al., IJFM 104 (2018)

bubble position ■
bubble diameter ●
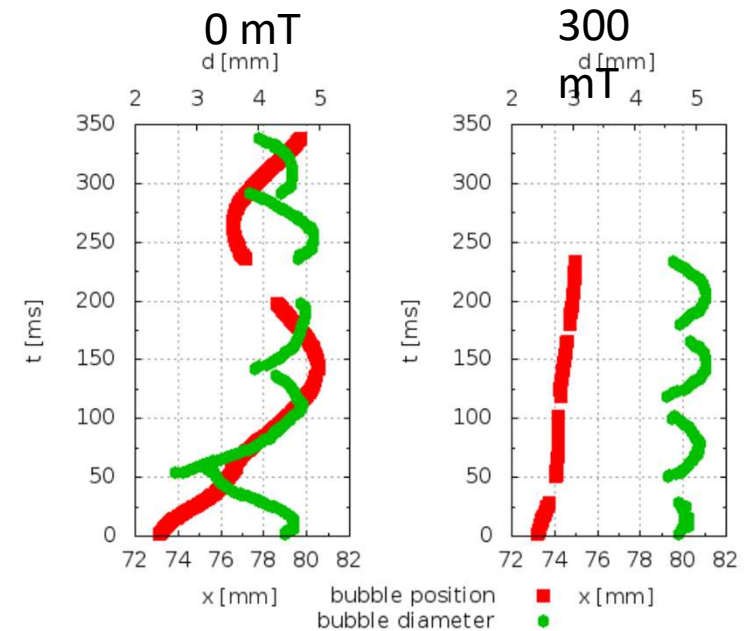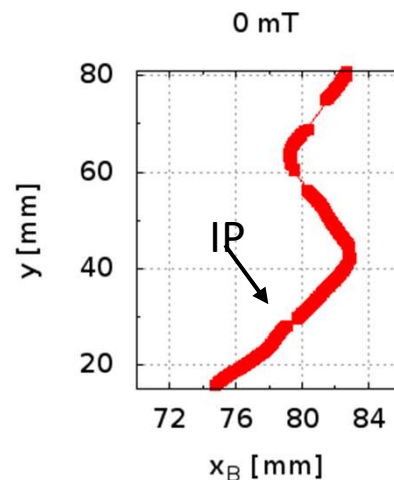
Inductive bubble detection

- Transmitting coil (black), frequency 10 – 200 Hz

- Planar gradiometer on opposite side (red and blue)

- Measured signal is zero, if the pipe is only filled with metal
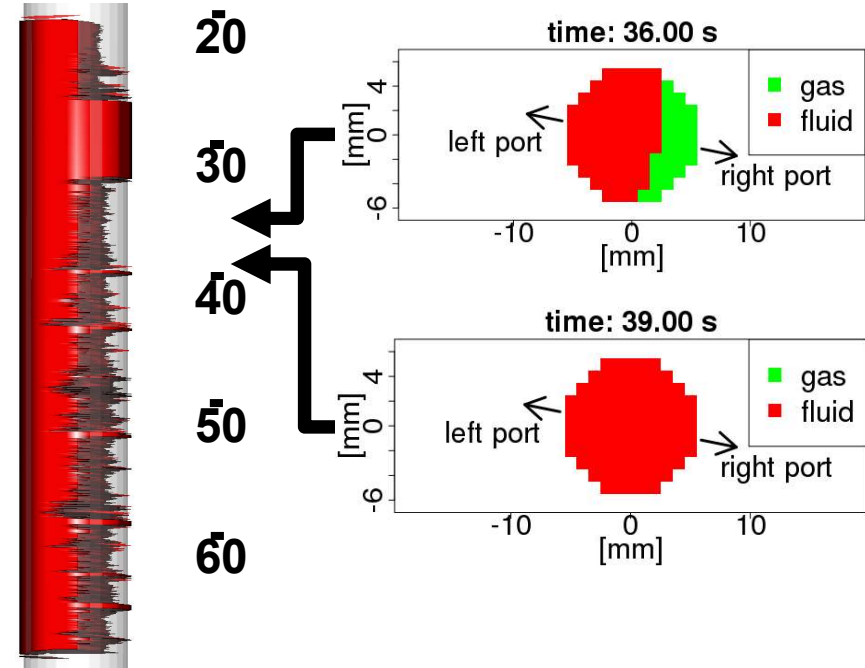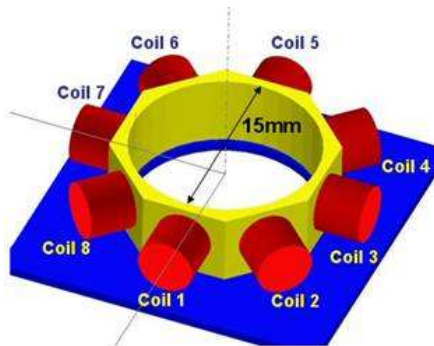
T. Gundrum et al., Sensors 16 (2016)

- Bubble deforms eddy currents inside the melt

- Deformed magnetic field is recorded by the sensor

- Typical S-shaped signal for a single bubble traversing the sensor volume

Mutual inductance tomography (MIT)

- Developed at the University of Manchester

- Measurement of the conductivity distribution in one cross section

- 8 sensing coils

- Temporal resolution about 20 – 40 frames per second

- Nonlinear inverse problem

N. Terzija et al., Flow Meas. Instrum. 22 (2011)

T. Wondrak et al., MMTB 42 (2011)

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# Two phase flows in pipes

- Argon gas / liquid steel distribution:
    - Shape of the jet
    - Bubbles inside the jet
- Difficult to reconstruct **both** properties at the same time using only MIT
- In collaboration with University of Bath:
    - **Capacitance tomography**: shape
    - **MIT**: bubbles
- Feasibility study for the application of capacitance tomography for liquid metals
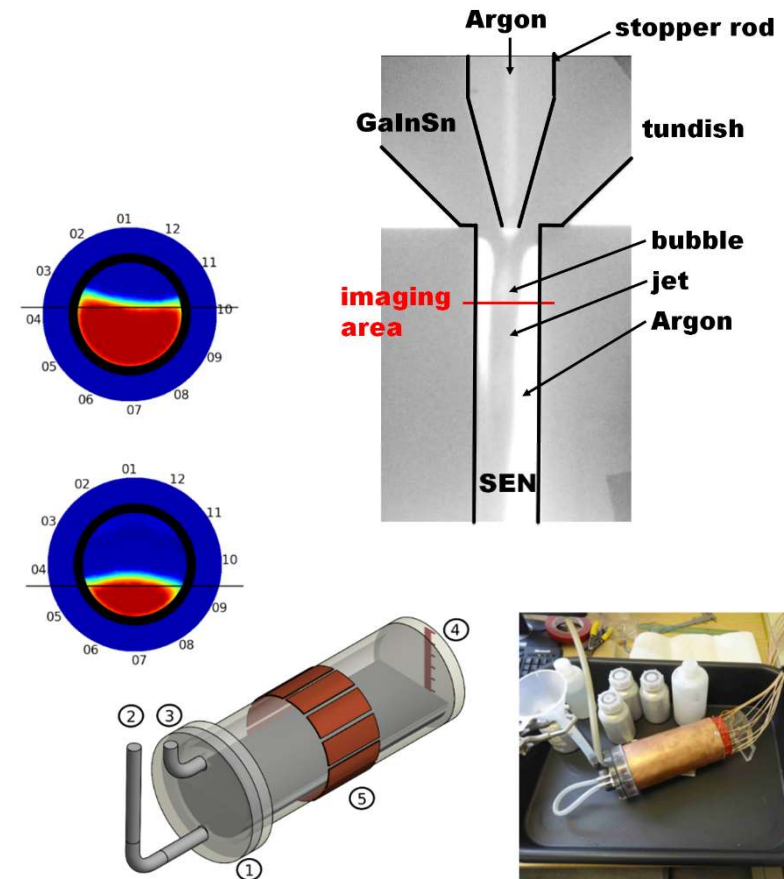
T. Wondrak et al., Meas. Sci. Technol. 28 (2017)

Contactless Inductive Flow Tomography (CIFT)

1. Exposing the flow **v** to an externally applied
   magnetic field **B**

M. Ratajczak et al, Philos. Trans. R. Soc, A 374 (2016)

T. Wondrak et al., Flow Meas. Instrum. 62 (2018)

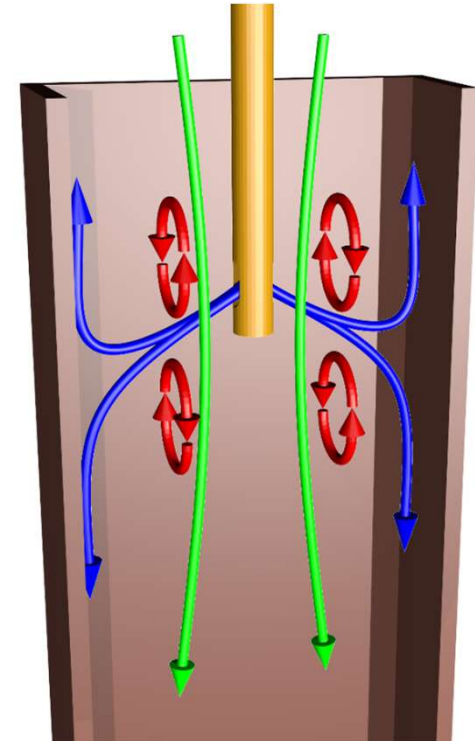# Contactless Inductive Flow Tomography (CIFT)

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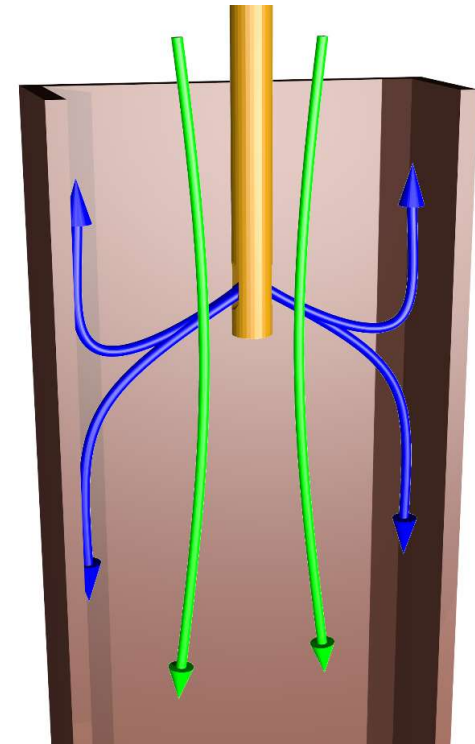
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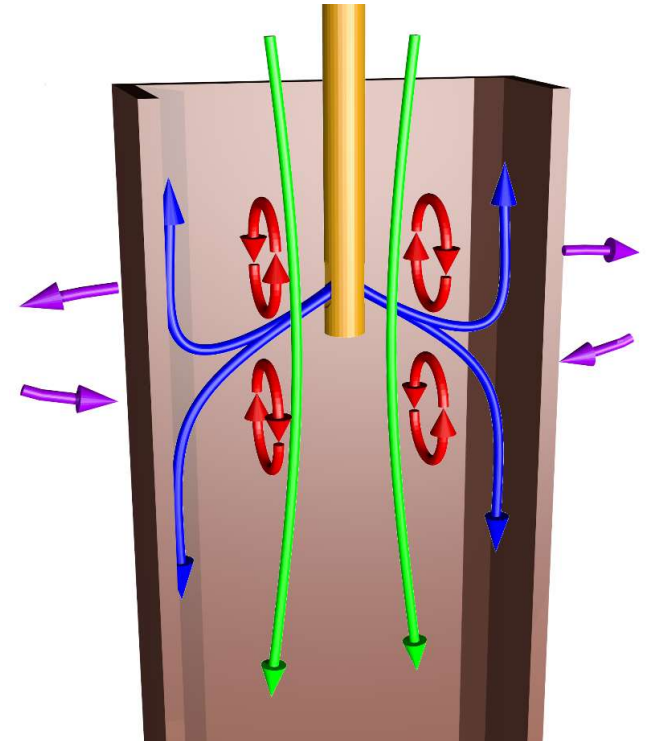
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3. Flow Induced magnetic field

$$\mathbf{b}(\mathbf{r}) = \frac{\mu_0 \sigma}{4\pi} \iiint_V \frac{(\mathbf{v}(\mathbf{r}') \times \mathbf{B}(\mathbf{r}') - \nabla\varphi(\mathbf{r}')) \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

M. Ratajczak et al, Philos. Trans. R. Soc, A 374 (2016)

T. Wondrak et al., Flow Meas. Instrum. 62 (2018)

DRESDEN concept

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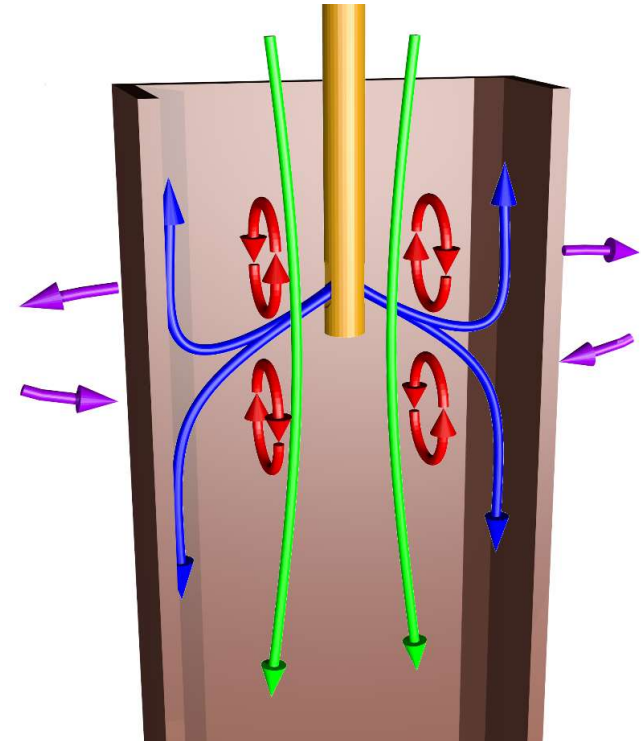
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4. Measurement of the magnetic field outside the melt

M. Ratajczak et al, Philos. Trans. R. Soc, A 374 (2016)

T. Wondrak et al., Flow Meas. Instrum. 62 (2018)

# Contactless Inductive Flow Tomography (CIFT)

1. Exposing the flow **v** to an externally applied magnetic field **B**

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4. Measurement of the magnetic field outside the melt

5. Reconstruction of the velocity field from the measured induced magnetic fields (linear inverse problem)
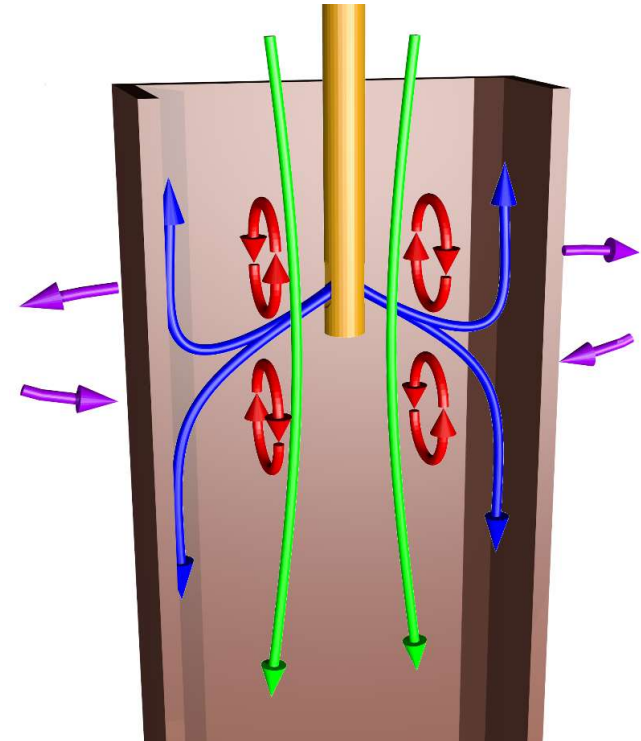
M. Ratajczak et al, Philos. Trans. R. Soc, A 374 (2016)
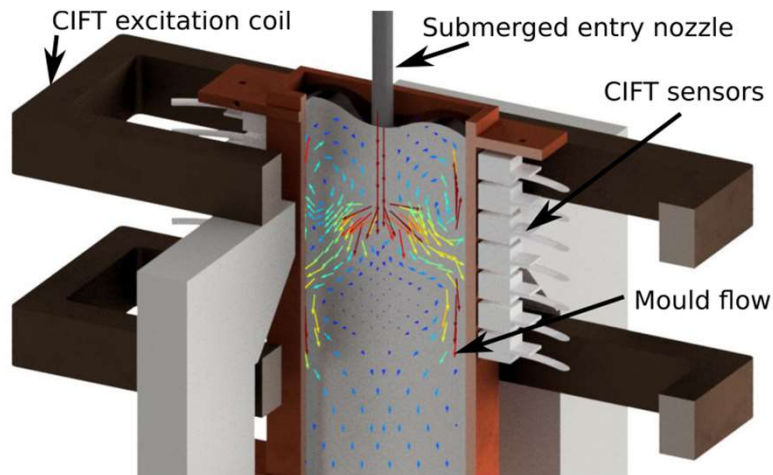
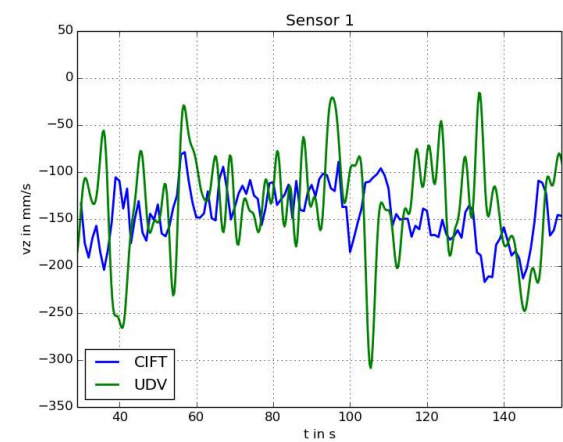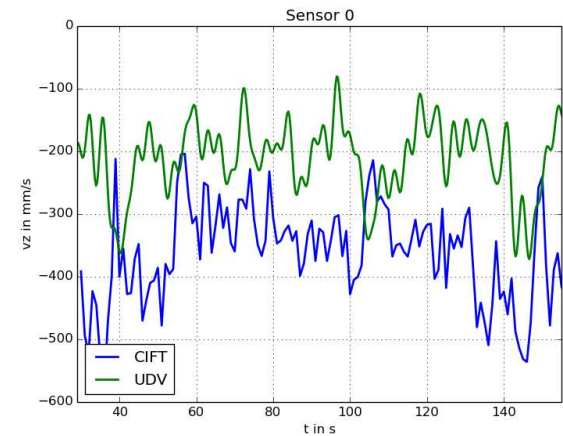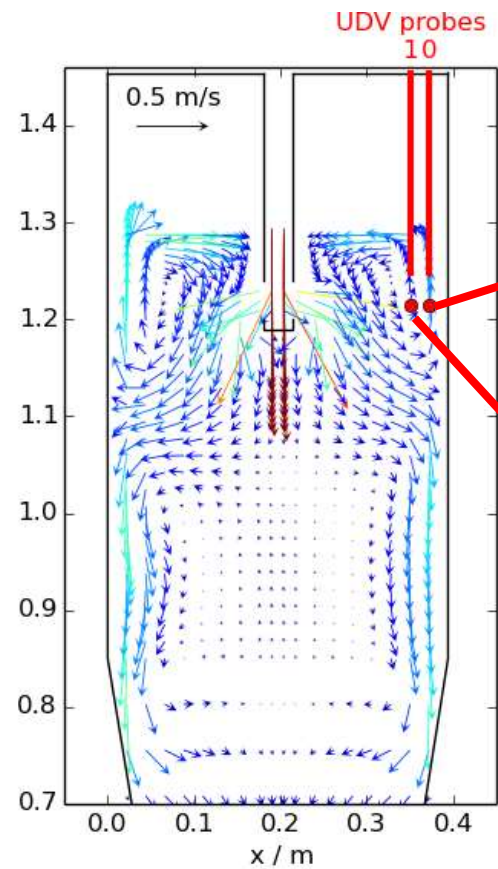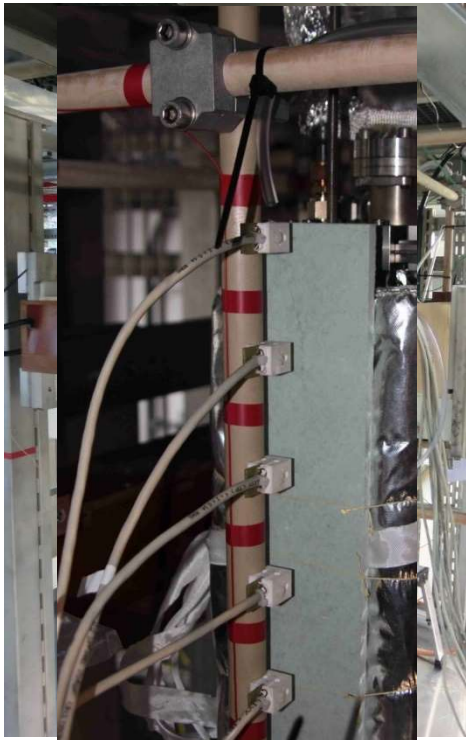T. Wondrak et al., Flow Meas. Instrum. 62 (2018)

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CIFT with electromagnetic brake
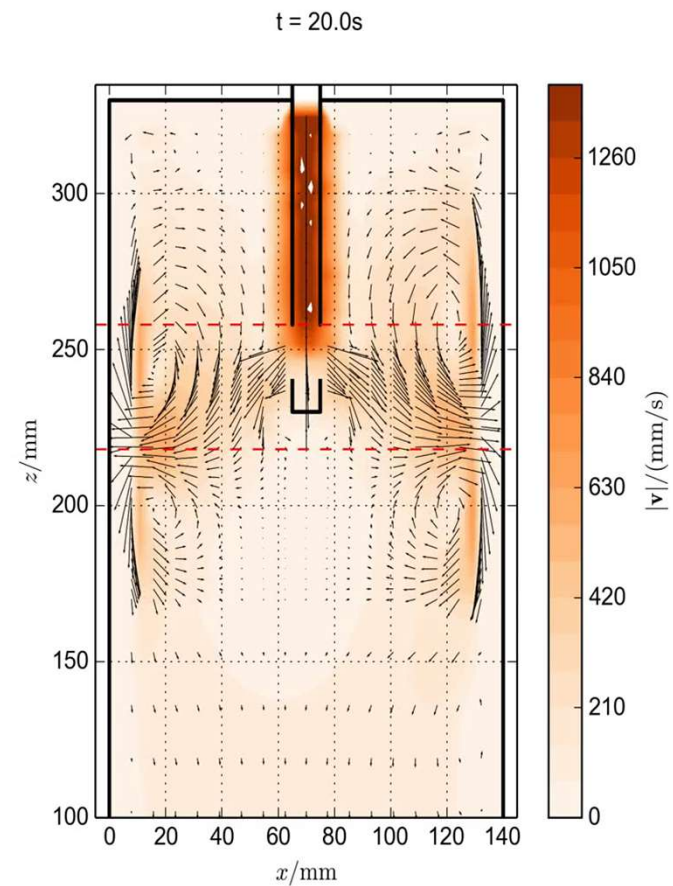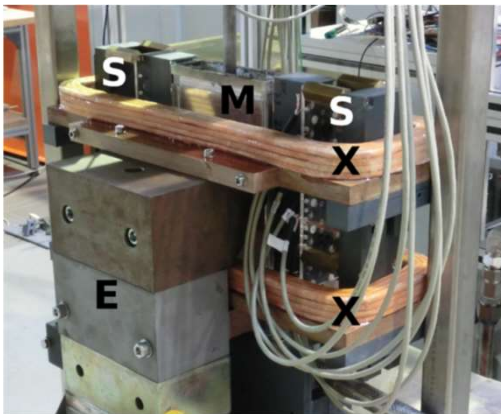
Example LIMMCAST

Tomographic sensors for control

- European Training Network:
  Smart tomographic sensors for
  advanced industrial process
  control (TOMOCON)

- **Tomographic measurement**
  - CIFT: flow in the mould
  - MIT/ECT: two-phase flow in
    SEN

- **Actuators**
  - Gas injection
  - Strength of the EMBr

- **Control objectives**
  - Double roll preferred
  - No asymmetric flow
  - Constant position of the jet
  - Constant filling degree of the
    SEN
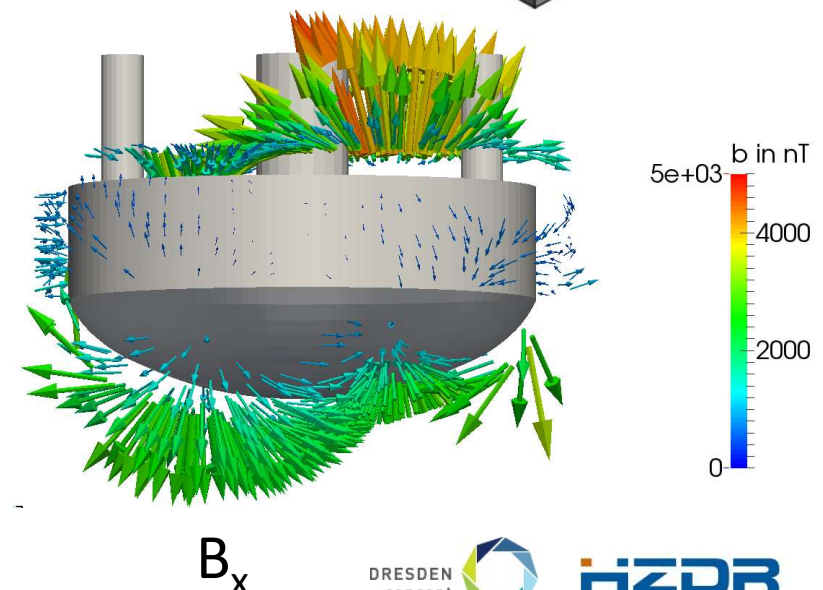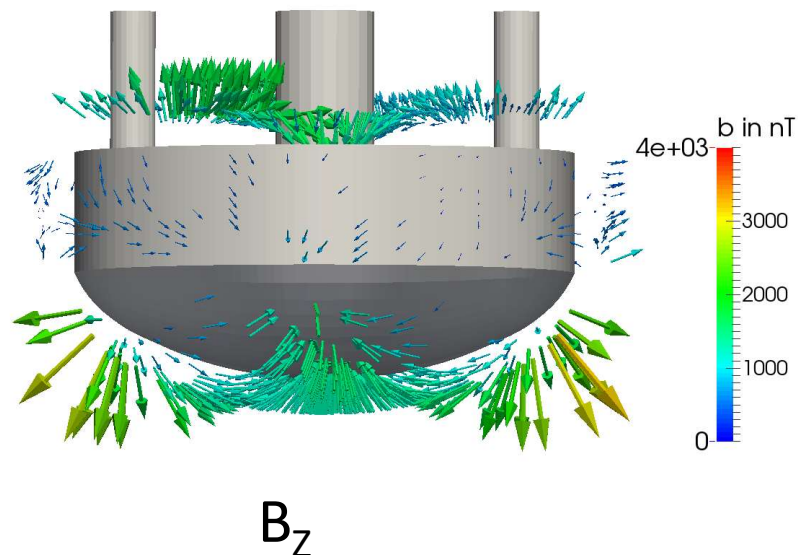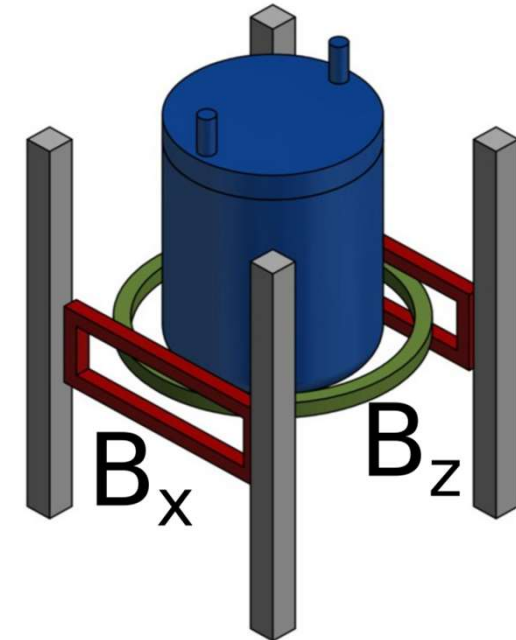 - Constant velocity at the
    meniscus
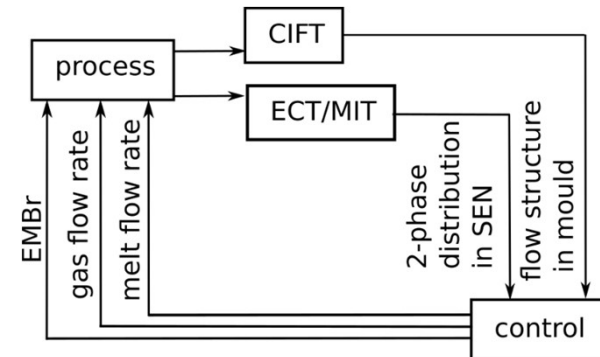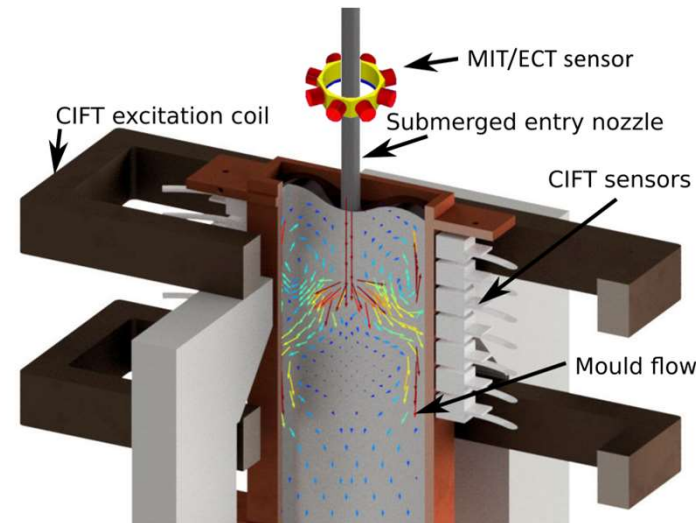
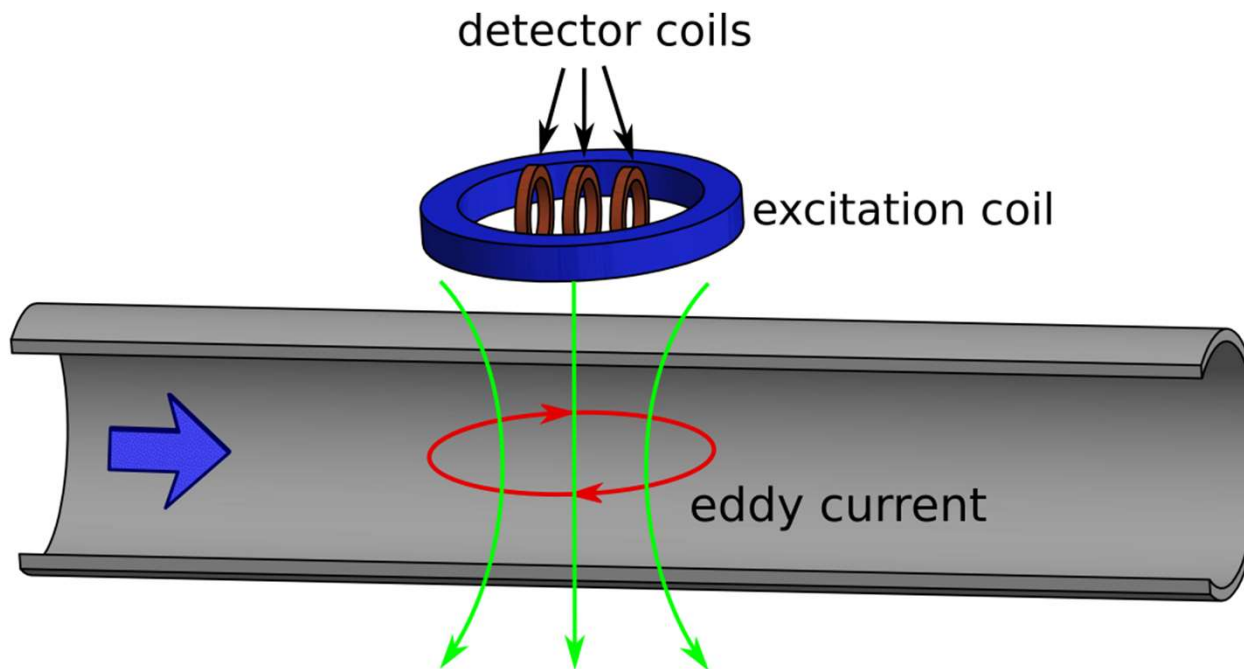# Proposal of the application of CIFT to ESCAPE
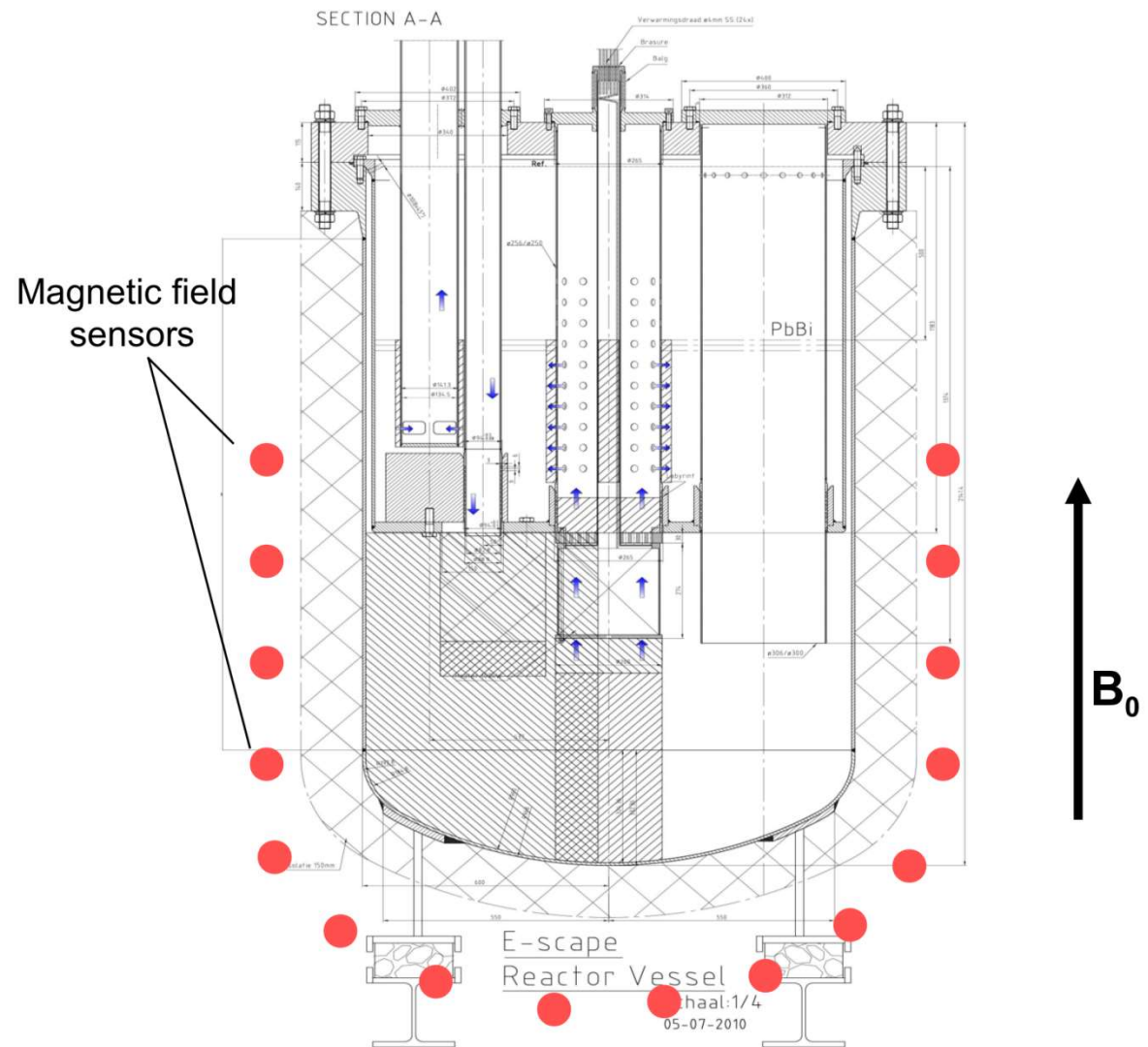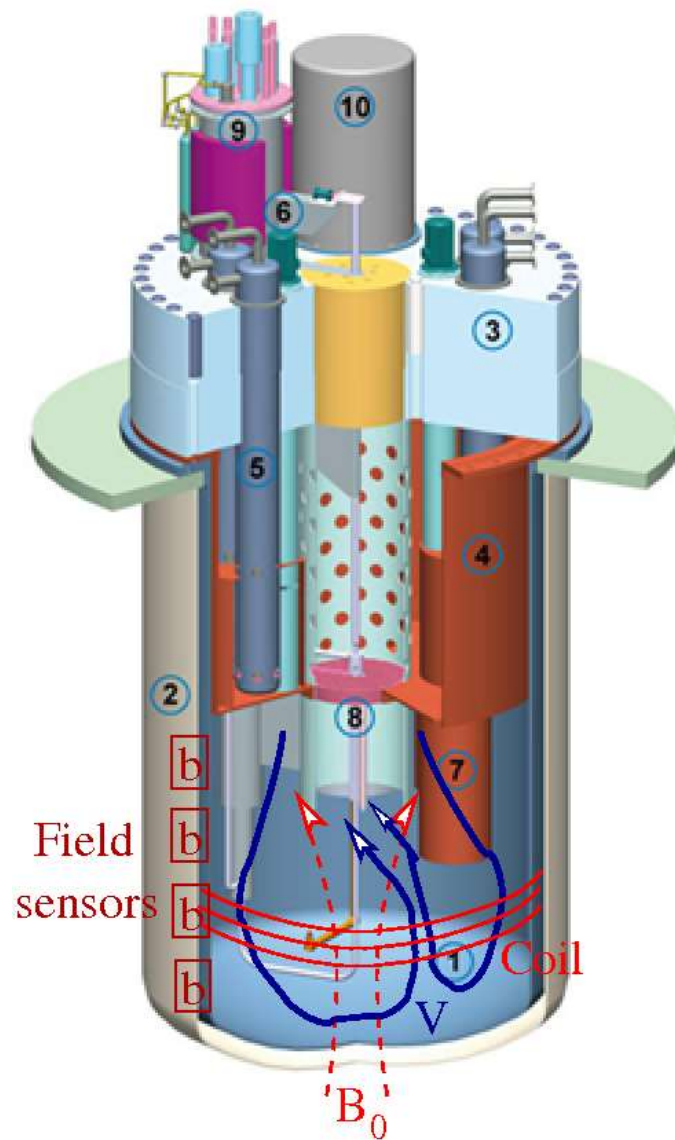
CIFT for ESCAPE: Forward problem

- Two applied magnetic fields (1 mT)

- Frequency 0.5 Hz

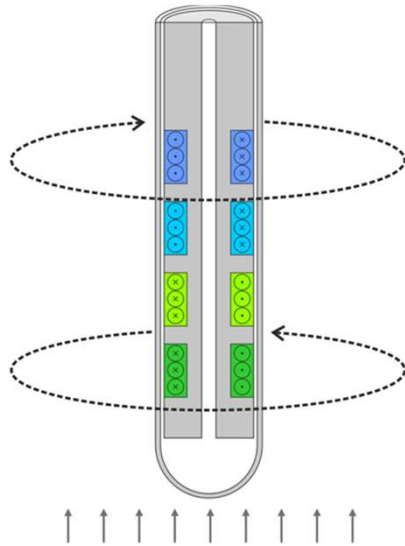- Flow induced magnetic field: 1 μT

B_z

B_x

Transient eddy current flow meter (TEC-FM)

- Pulsed external magnetic field generates a transient eddy current
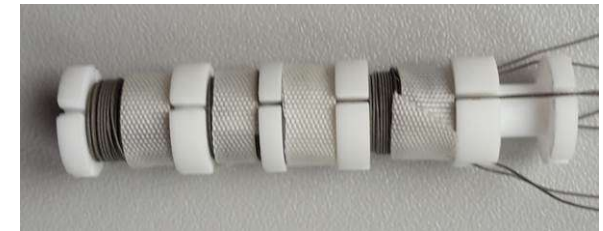- Continuous tracking of a flow-advected transient eddy
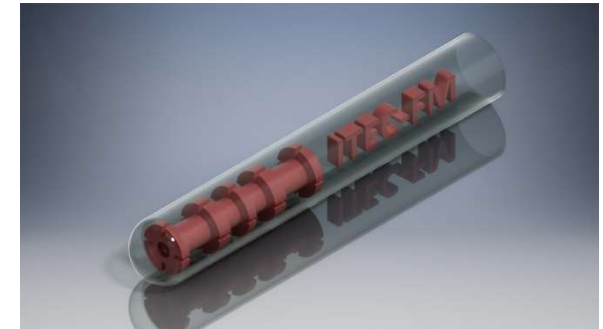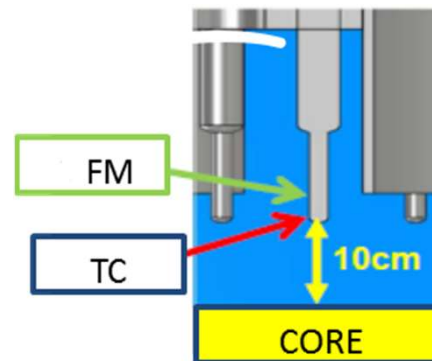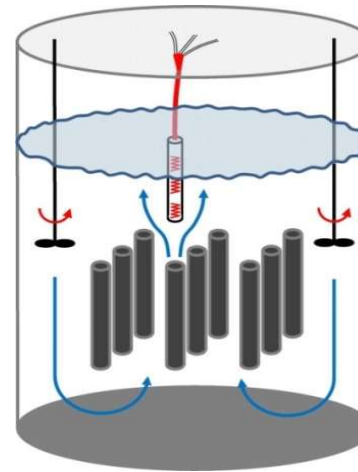

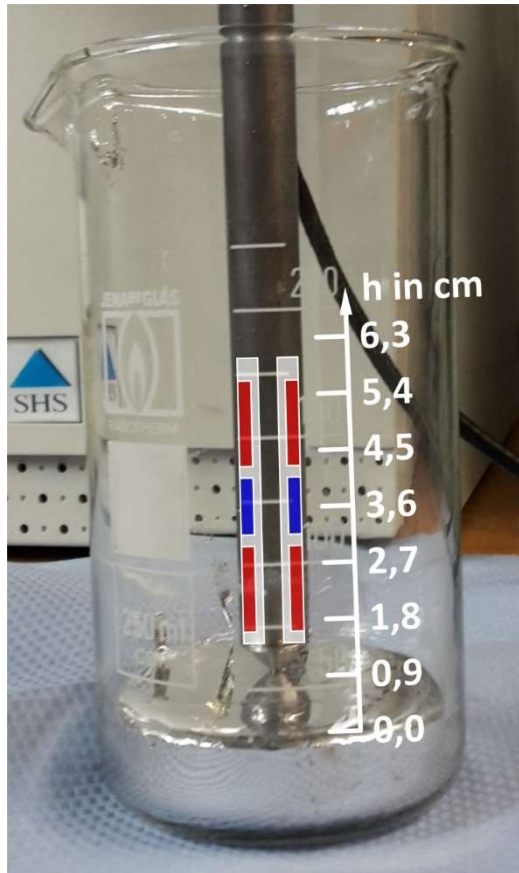J. Forbriger et al., Meas. Sci. Technol. 26 (2015)

Immersed sensor (ITEC-FM)

- Immersed TEC-FM for the purpose of local blockage detection
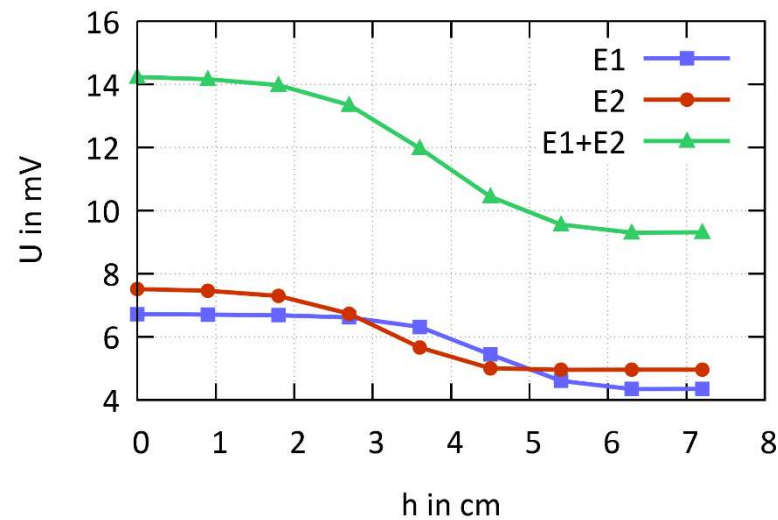- 2 excitation coils
- 2 detection coils

N. Krauter et al., Meas. Sci. Technol. 28 (2017)
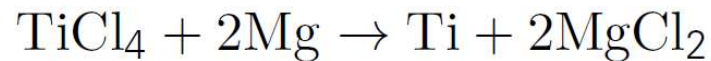
Immersed level sensor

- preliminary measurement witch velocity sensor in GaInSn
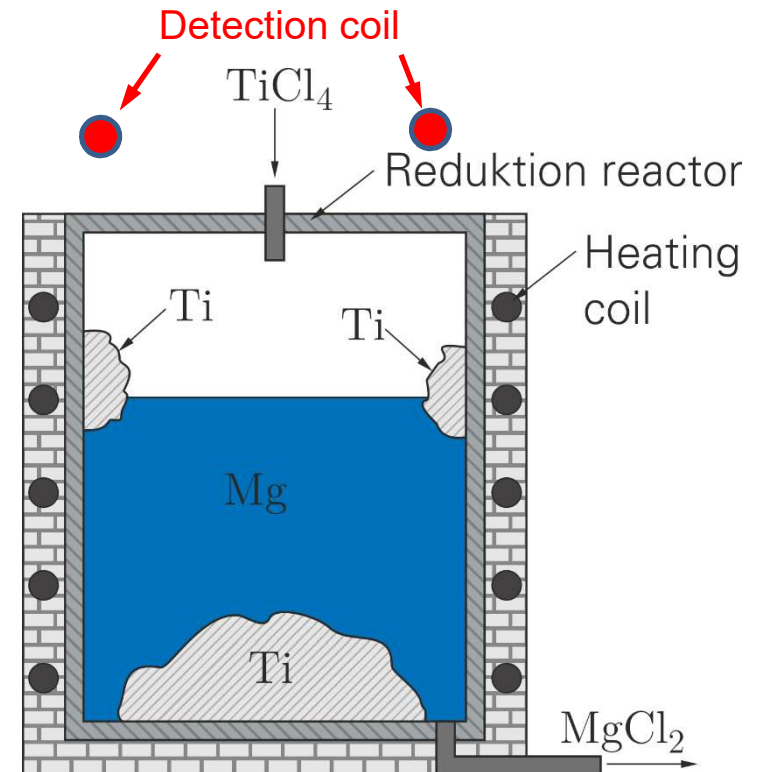- linear dependency of U(h) between 2,7 cm and 4,5 cm

Level measurement for titanium production (Kroll process)

- Exothermal reaction on the free surface of liquid Mg

$$TiCl_4 + 2Mg \rightarrow Ti + 2MgCl_2$$

- Temperature of 850 °C

- Titanium sponge deposits on the bottom and walls of the reduction reactor

- Titanium sponge interferes with the inductive level measurement because it has a similar electrical conductivity to liquid magnesium

- Heating coils are excitation coils

- One large coil at the top of the reactor

- Non linear inverse problem: database containing the induced voltage for a huge range of parameter combinations
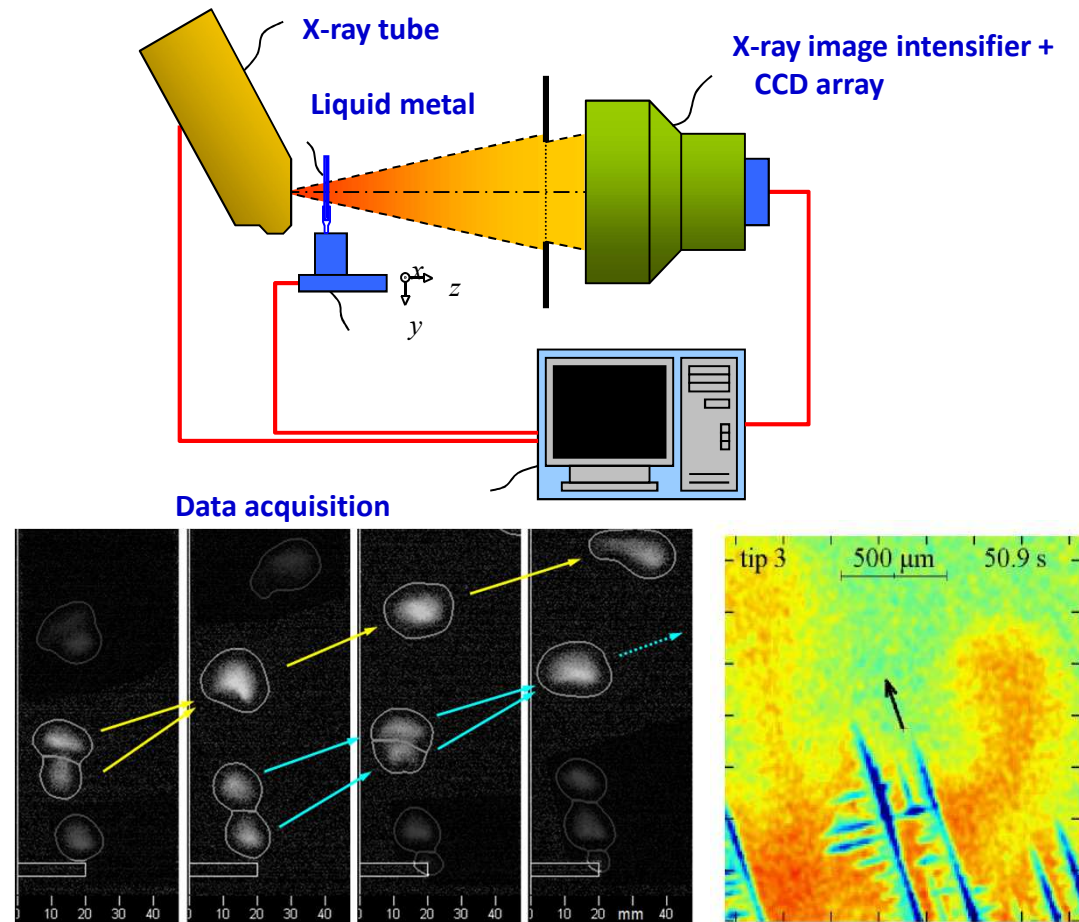
Detection coil

TiCl$_4$

Reduktion reactor

Heating coil

Ti

Ti

Mg

Ti

MgCl$_2$

N. Krauter et al., MMTB 49 (2018)

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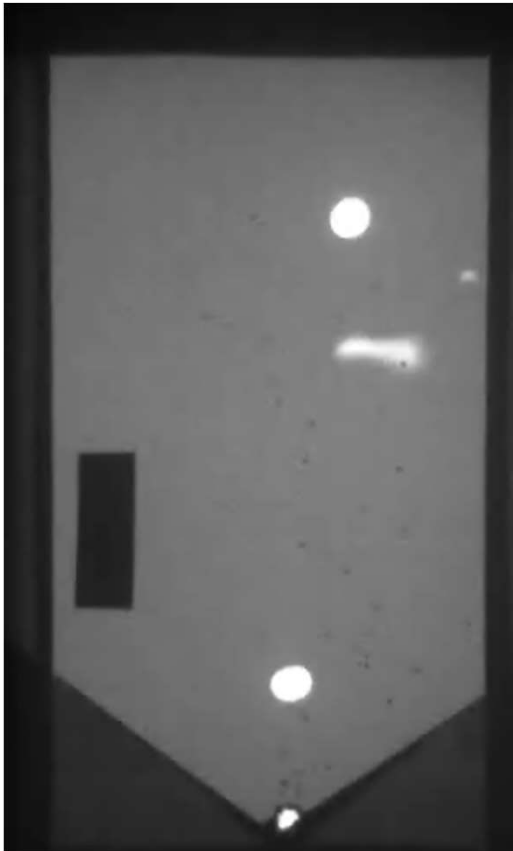Sven Eckert | Institute of Fluid Dynamics | www.hzdr.de

X-ray radiography

- Attenuation of the X-ray depends on the density ρ of the material

- Visualization of bubbles
  - bubble size and shape
  - bubble trajectory

- Visualization of solidification

- High density of liquid metals:
  GaInSn: < 15 mm thickness

N. Shevchenko et al., J. Cryst. Growth 417 (2015)

X-ray tube

Liquid metal

X-ray image intensifier + CCD array

Data acquisition

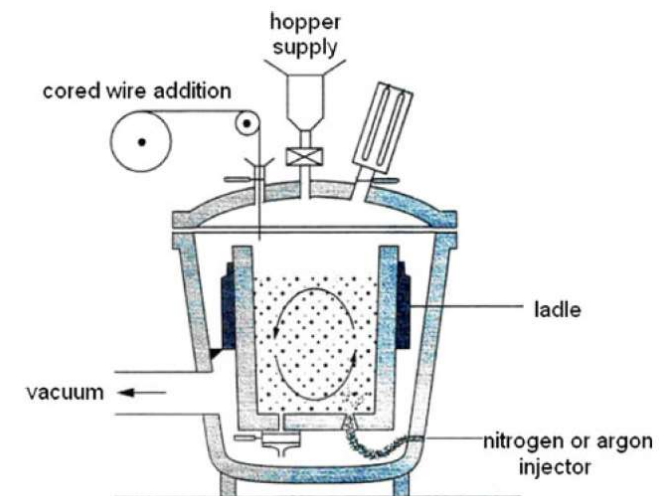tip 3   500 μm   50.9 s

Liquid metal flotation

- Removal of inclusions
- Shear-driven coalescence of particles
- Particle capturing by rising gas bubbles

Cooperation with Technical University Dresden
+ French partners (Nancy and St. Etienne)

Background: Flow control during solidification

Melt flow: natural convection (thermal, solutal)
Forced convection (electromagnetic stirring)

Freckle defect in a turbine blade

1 mm

[A.F. Giamei (1997)]

Freckle formation triggered by mesoscopic convection

Conclusions

- Flow measuring in liquid metal flows is still a challenging task

- Some progress has been achieved in recent years

- Velocity fields can be measured now with reasonable temporal and spatial distribution, however, technical solutions for a robust instrumentation under industrial conditions are still rare

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Many thanks for your attention!