Liquid metals in energy technology

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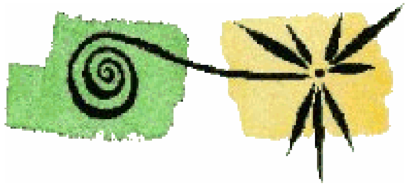


Content

- Technical appearance of liquid metal flows
    - Conventional conversion processes and
    - nuclear engineering
- Specific properties of liquid metals
- Measurement techniques in liquid metals
- Turbulent heat exchange
    - Analogies between momentum and heat exchange & Closure methods for turbulent heat flux
    - Examples: Backward facing step, heated pipe, heated rod
- Turbulent free surface flows
- Engineering -Pumps
- SUMMARY and outlook

Technical Liquid Metal flows

- Liquid metals are known to mankind since about 6000 years (natural Mercury)
- They are refined and casted since more than 4000 years (bronze, copper)
- Production of iron started in Turkey since 3000 years
- Alumina and alloy production on large scales in the last 200years

Liquid mercury in glass capsule

Bronze casting

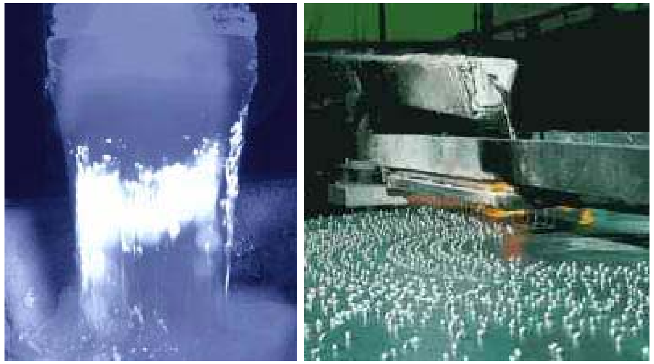
Raw iron refinement

- Industrial interest:
  - Adaptive materials with certain properties for specific use in e.g. car insdustry, aeronautics, etc. like AlLi-alloys
  - Minimization of primary energy input during refinement
  - Higher demand on quality of surfaces and reduction of number of secondary machining processes

Requirements:

→ Measurement techniques, heat transport phenomena, free surface shape

phase change problems



Alumina preparation for casting

Liquid metals in energy conversion

- Conventional systems
  - Solar towers
  - Coolant for high heat flux components
  - Surface conditioning
- Nuclear systems
  - Fusion reactors
    - ITER (liquid metal cooled blankets, divertors, HEX)
    - IFMIF (International Fusion Material Irradiation Facility)
  - Fission systems
    - ADS (Accelerator Driven Systems aimed to minimize nuclear waste production)
    - Fast breeders (lead or sodium cooled)
  - Nuclear physics

Conventional: Solar Towers or Heliostats

Basic Principle

- Solar furnace using a tower to receive the focused sunlight
- Collected from a set of mirrors
- Heat stored by circulating liquid metals or salts in containers (preferred Na or $NaNO_3$ KNO_3)
- Energy conversion in steam cycle.

PS10 Sevilla-
Spain ($11MW_{el}$)

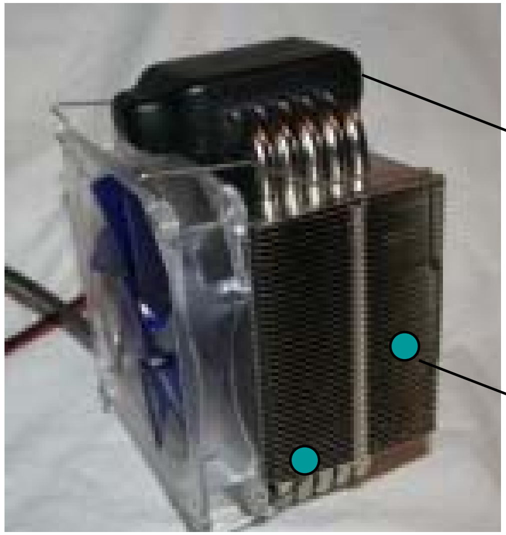
Conventional: High performance HEX

Background: CPU-Cooling

- trend towards higher frequencies (computing power) and
- miniaturization yields high surface powers with
- degradation by melt of electric circuits

⇨ Forced convective cooling with low ΔT in chip structures

⇨ Use of liquid metals (NaK, GaInSn)



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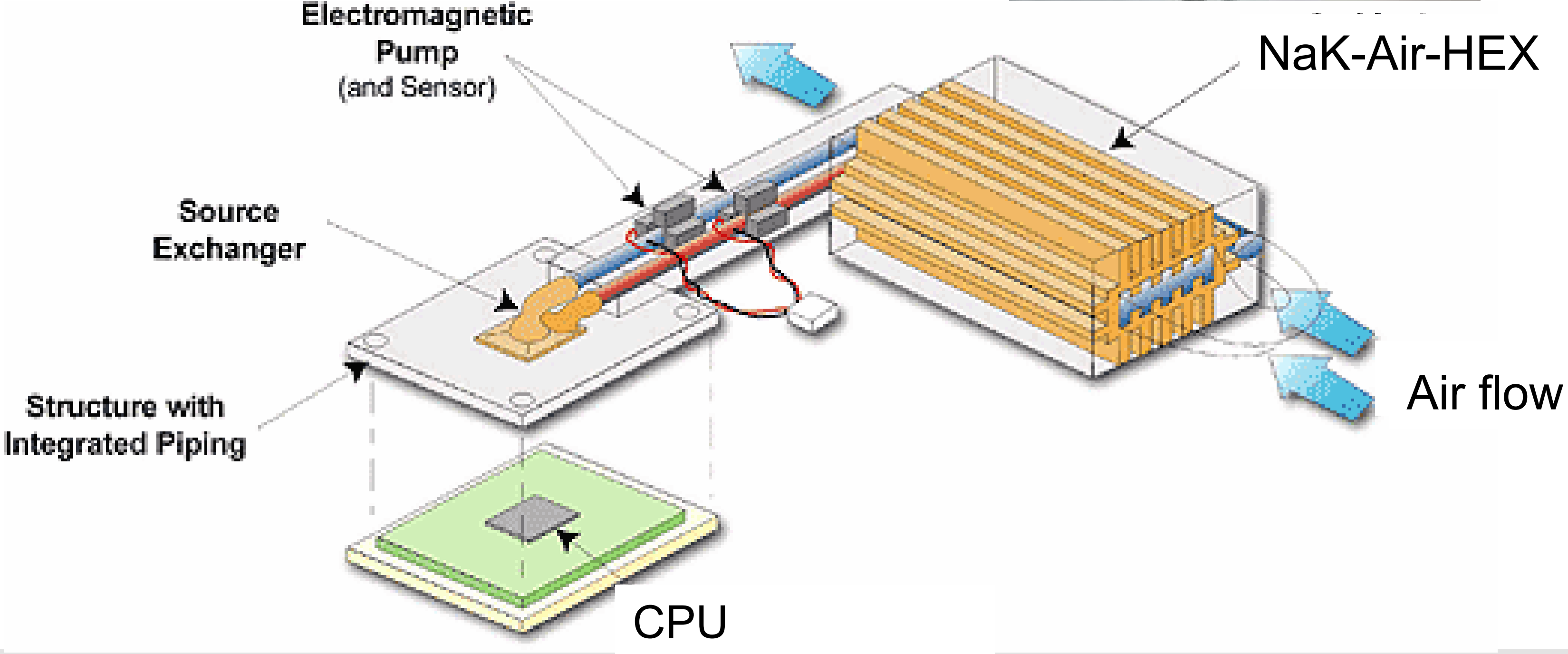
NaK-EM-Pump

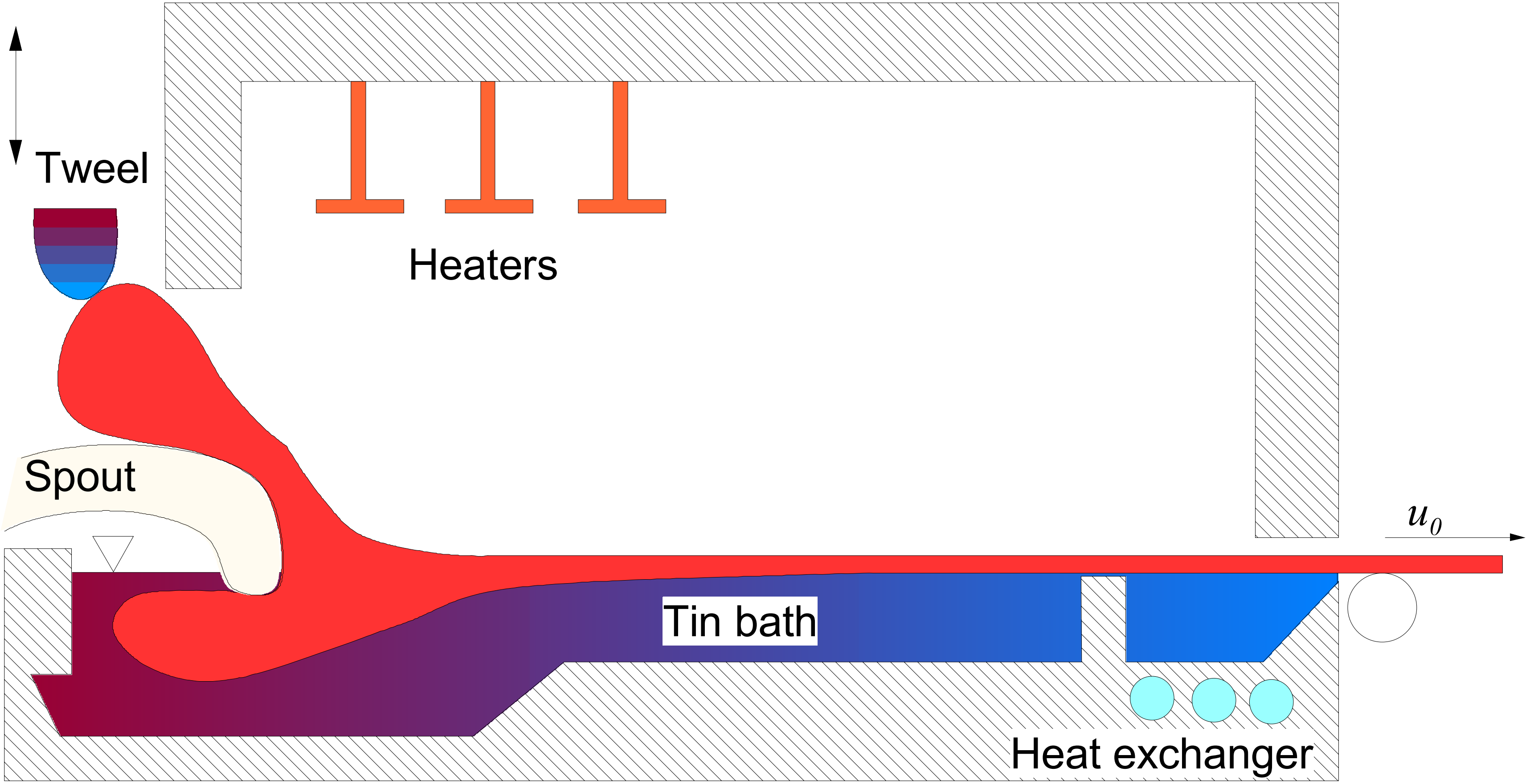
CPU-Cooling



Conventional: Floating glass process

Production of highly flat glasses (inventor Pilkington, 50´s)

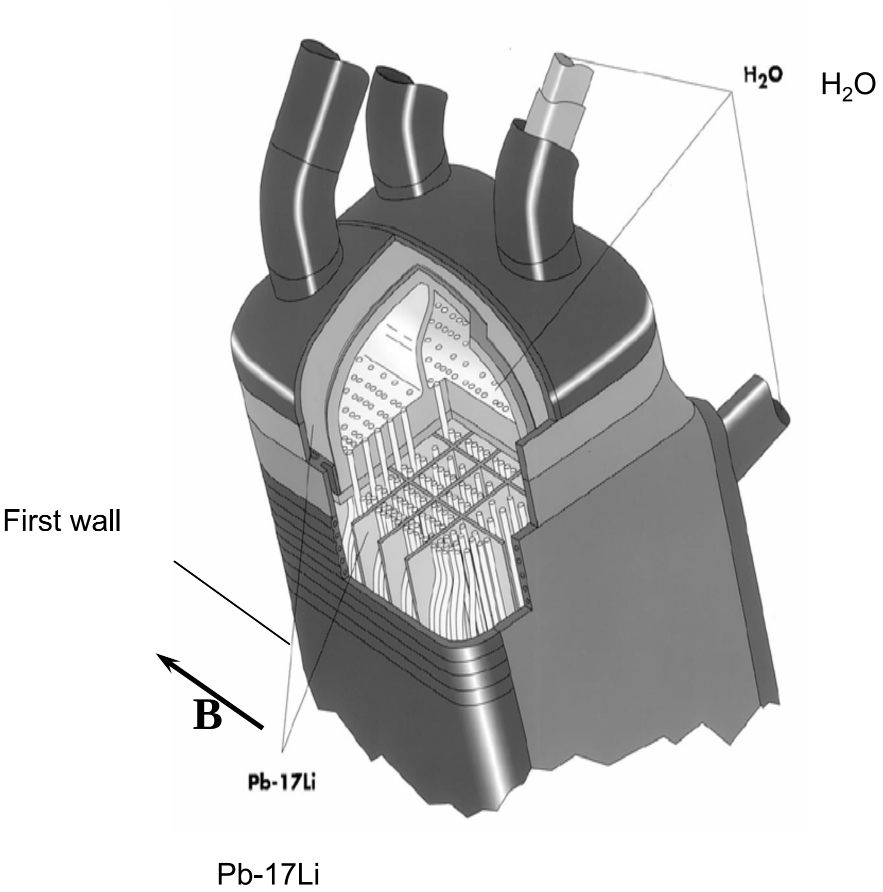
- Molten glass ejected to tin bath
- Inmiscible glass and liquid metal
- Controlled homogeneous cooling along axis

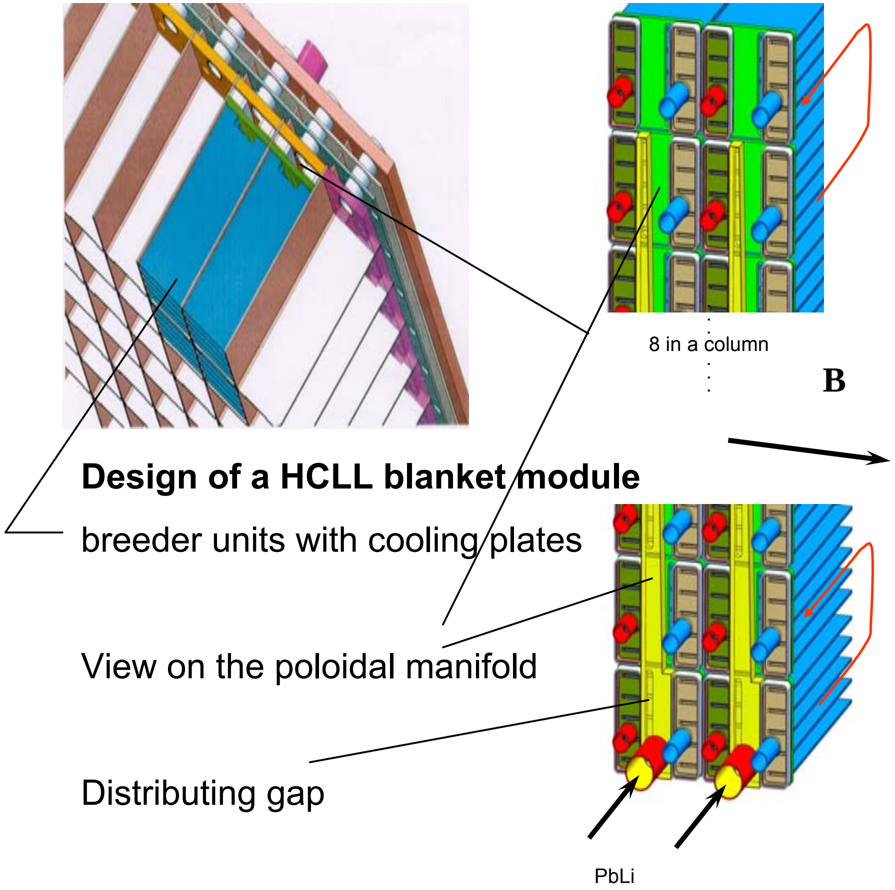


Fusion: LM Blankets for ITER

Blankets:

- Heat Removal
- Breeding Tritium
- Shielding magnets





a) Water cooled blanketWCLL, Giancarli et al. 2000

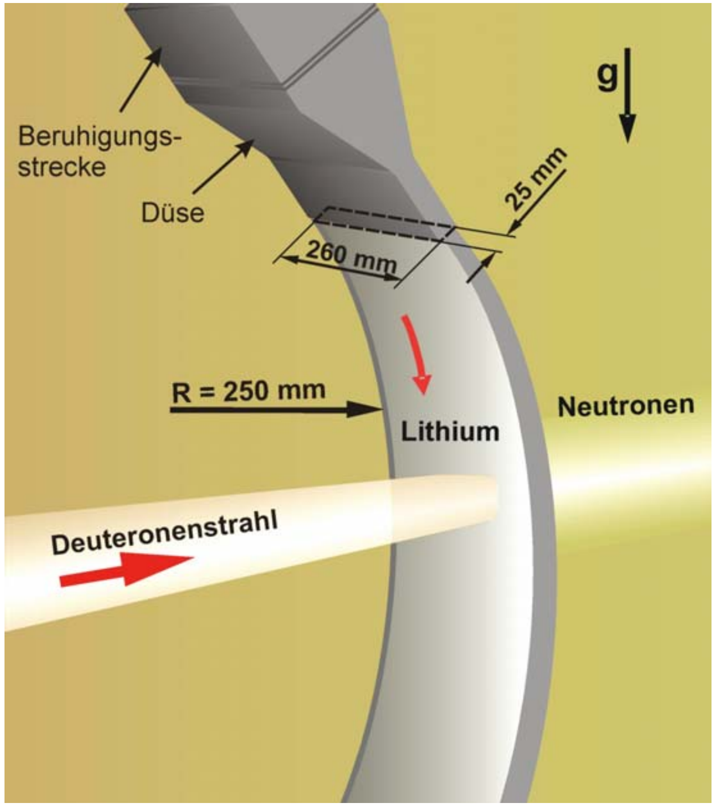
b) Helium cooled blanket HCLL, Giancarli et al. 2000

Fusion: IFMIF (Int. Fusion Material Irradiation Facility)

Targets:
- Secondary particle production (neutrons, fragments,..)
- Heat removal

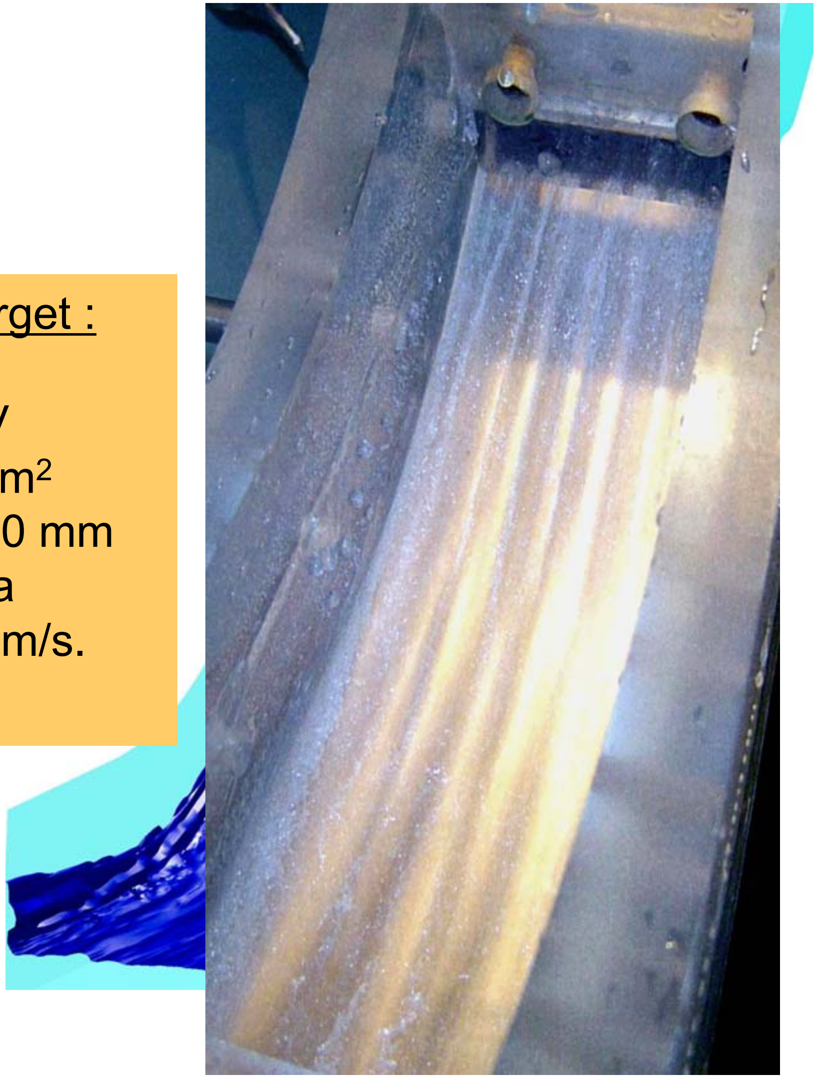
Development Structure

- ensure film height to attain neutrons with a
- flow velocity avoiding Li boiling in vacuum.



Conditions for IFMIF/Li-Target :

D+ beam energy	40MeV
Averaged heat flux	1 GW/m^2
Beam area	50x200 mm
Vacuum at surface	10^{-3} Pa
Li flow velocity	10-20 m/s.



Fission: MYRRAH

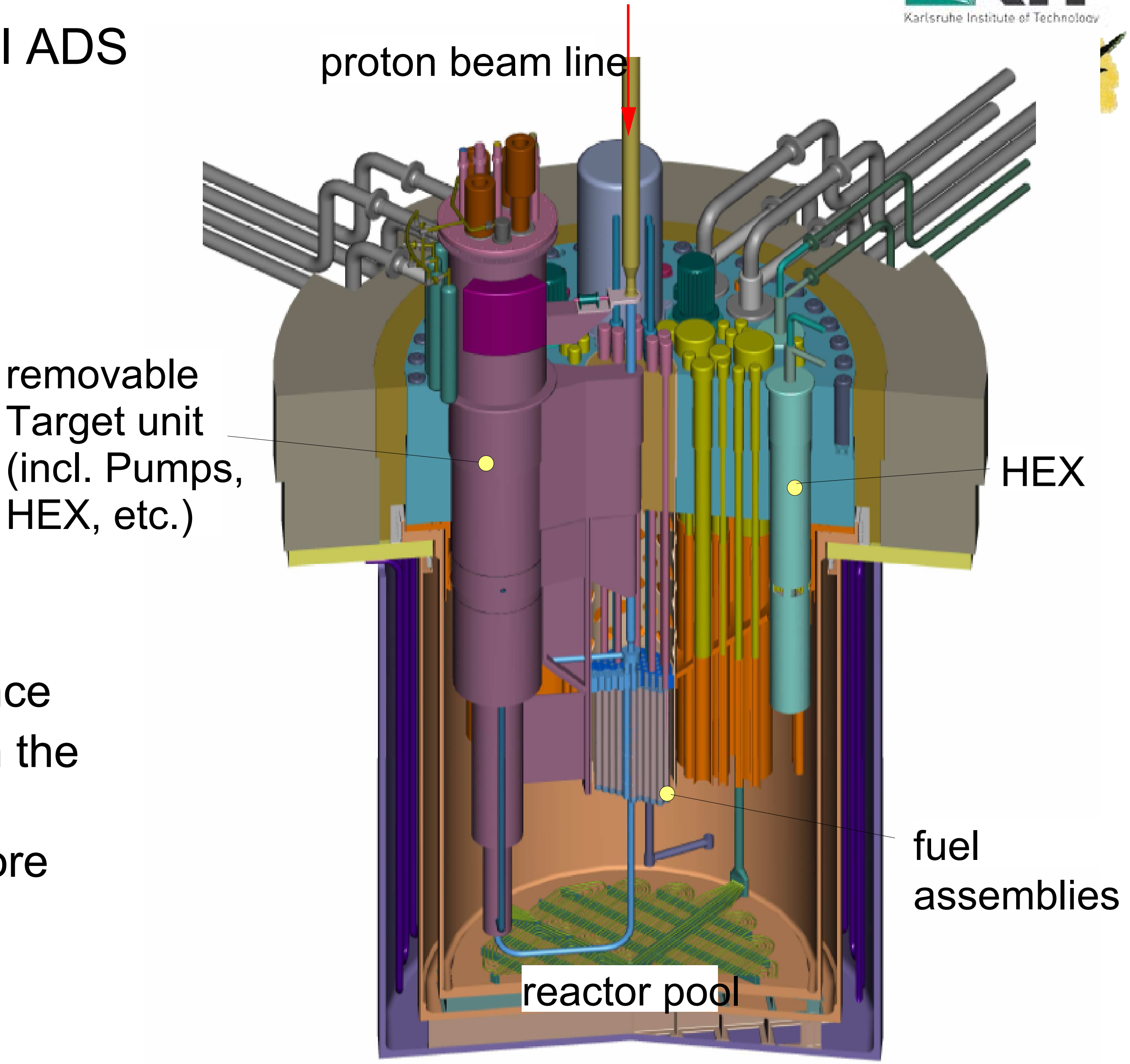
- a planned 50MW Experimental ADS

Features

- Free surface target
- Criticality k_{eff}~0.95
- Thermal power P_{th}=50MW
- Proton beam 350MeV at 5mA
- Lead bismuth cooled

Critical issues

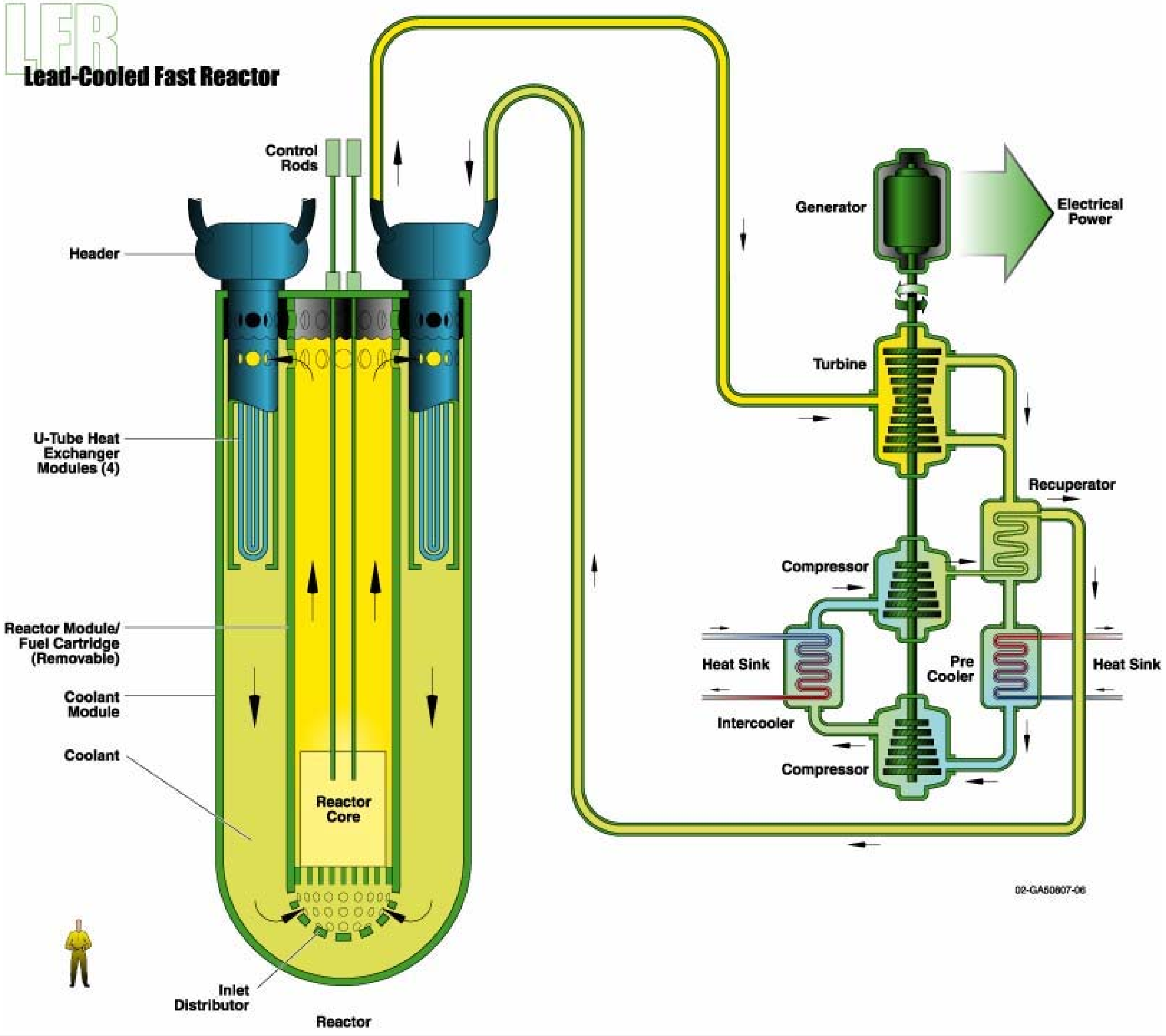
- Free surface flows with turbulence
- Mixed convection (Buoyancy) in the core
- LM technology in Target and Core
- Instrumentation and monitoring



Fission: Fast Reactors (Na/Pb cooled)

Challenges

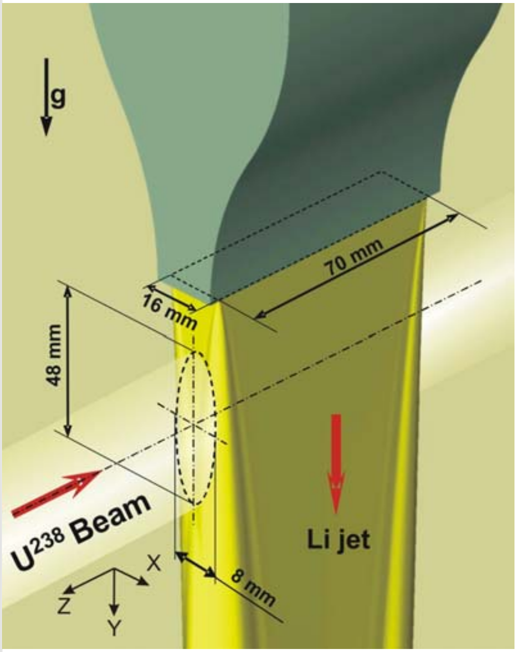
- Potential capability for transmutation
- High Temperature application (electricity and hydrogen prod.)
- Single phase heat transfer in the primary system
- Component development and monitoring at high temperatures



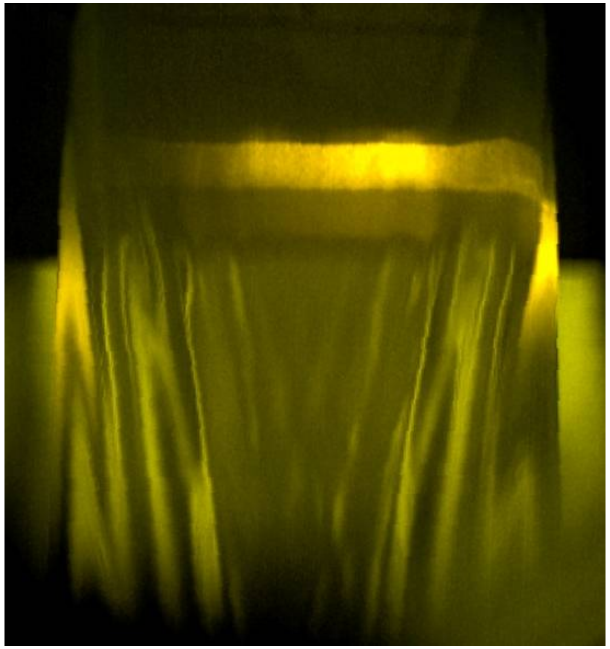
Nuc. Physics: Super-FRS-Target

- Ion accelerator at GSI (U^{238}-Ions, 10^{12} Particles/Spill, 2GeV, Puls duration 50ns) for particle physical experiments for medical applications (www.gsi.de/fair/index.html)
- Solid targets faile since the instantaneous power release: 12 kJ/50 ns ➔ 240 GW
- Generation of a stable Li-Jets in direction of gravity field

Set-Up



water u_0=2.5m/s



sodium u_0=2.5m/s

Specific properties of liquid metals

GENERAL FEATURES

- opaque, totally reflecting
- high temperatures,
- corrosive,
- large surface tension
- high thermal conductivity

HEAVY LIQUID METALS

- high density
- low kinematic viscosity,

		Unit	Pb^{45}B^{i55}	Lithium	Water
melting point at 0.1 MPa		[°C]	125	180.5	0
boiling point at 0.1MPa		[°C]	1670	1317	100
			300°C	300°C	25°C
density	ρ	[kg/m^3]	10325	505	1000
heat capacity	c_p	[J/(kgK)]	146.33	4279	4180
kinematic viscosity	ν	[m^2/s]·10^{-7}	1.754	9	9.1
heat conductivity	λ	[W/(m K)]	**12.68**	**29.2**	0.6
electric conductivity	σ_{el}	[A/(V m)] ·10^5	**8.428**	**33.5**	2·10^{-4} (tap)
thermal expansion coefficient	α	/	**6.7·10^{-3}**	**43.6·10^{-3}**	6·10^{-3}
surface tension	σ	[N/m]·10^{-3}	**410**	**421**	52 (tap)

Specific properties of liquid metals

Conservation equations

- mass, $\nabla \cdot \vec{u} = 0$
- momentum, $\frac{d\vec{u}}{dt} = f - \frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{u}$,
- energy, $\frac{dT}{dt} = \frac{\lambda}{\rho c_p}\nabla^2 T + \frac{\mu}{\rho c_p}\Phi$.

Force ratio		$X_{PbBi(300°C)}$/ $X_{Water(25°C)}$	$X_{Li(300°C)}$/ $X_{Water(25°C)}$	Energy ratio		$X_{PbBi(300°C)}$/ $X_{Water(25°C)}$	$X_{Li(300°C)}$/ $X_{Water(25°C)}$
Reynolds	$\mathrm{Re} = \frac{u \cdot l}{\nu}$	**5**	0.98	Peclet	$Pe = \frac{u \cdot l}{\kappa}$	**0.017**	**0.01**
Weber	$Wb = \frac{\rho \cdot u^2 \cdot l}{\sigma}$	1.31	0.062	Eckert	$Ec = \frac{u^2}{c_p \cdot \Delta T}$	28.6	0.98
Grashof	$Gr = \frac{g \cdot \alpha \cdot \Delta T \cdot l^3}{\nu^2}$	**30**	**7.4**	Fourier	$Fo = \frac{l^2}{\kappa \cdot t}$	0.017	0.01
Material ratio							
Prandtl	$\mathrm{Pr} = \frac{\nu}{\kappa}$	$\frac{0.02}{6.3}$	$\frac{0.05}{6.3}$	heat conduct. $[m^2/s]$	$\kappa = \frac{\lambda}{\rho \cdot c_p}$	**58.5**	**94.1**

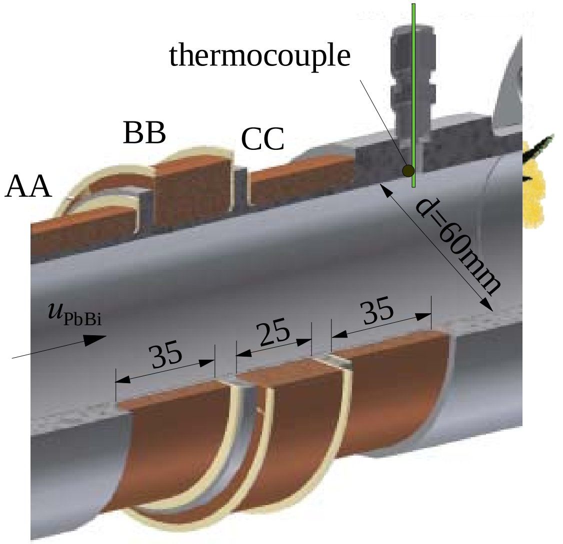
Specific properties

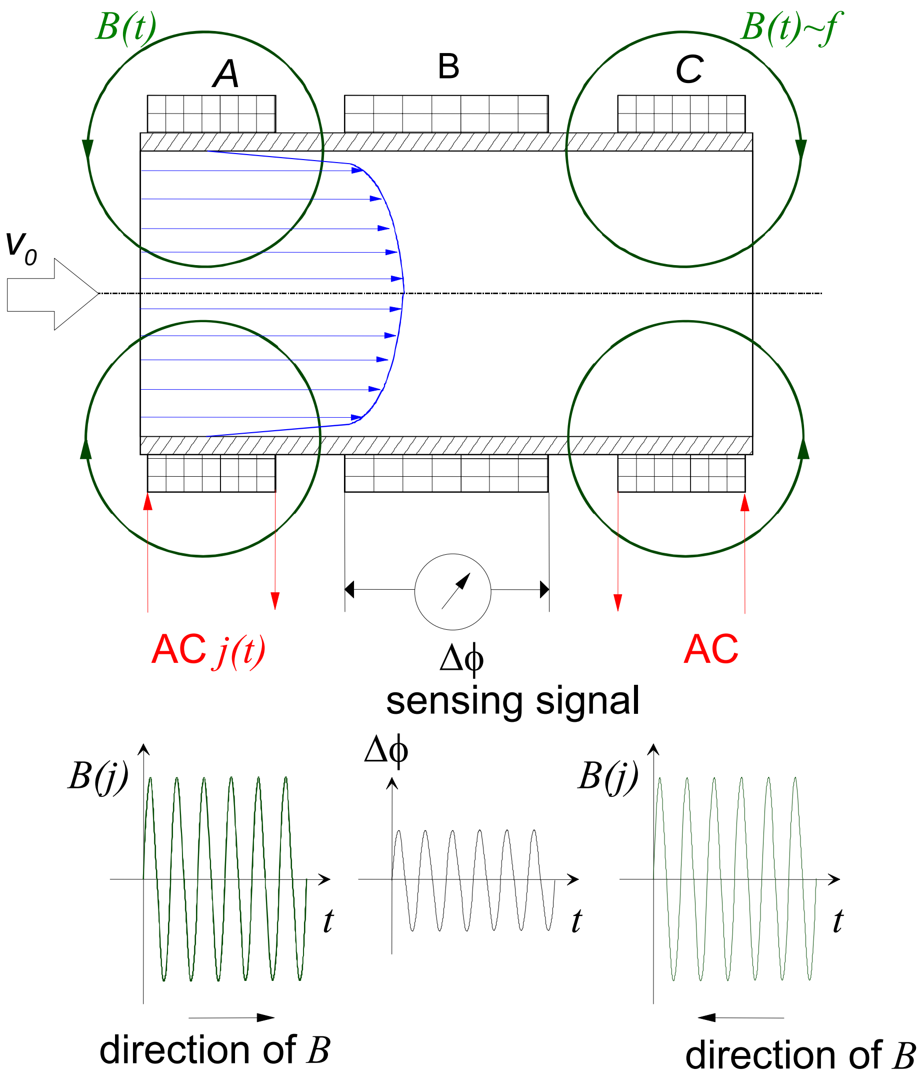
Consequences

- Nearly all technically relevant heavy liquid metal flows are **turbulent**.
- Due to large surface tension free jets shrink rather rapidly (**stability**)→**time scale** of u-field and shape **separates**.
- Small viscosity yields large Grashof numbers (**influence of buoyancy** in nearly all heat transfer experiments).
- Heat conduction is preferred to convection leading to a **scale separation** of thermal and viscous boundary layer (problematic for turbulence models).

Measurement: Flow rate

Electro-magnetic frequency flow meter (EMFM)





Measurement principle

- Dragging of magnetic fields lines by the flow (RMS-Value ~*Q*)

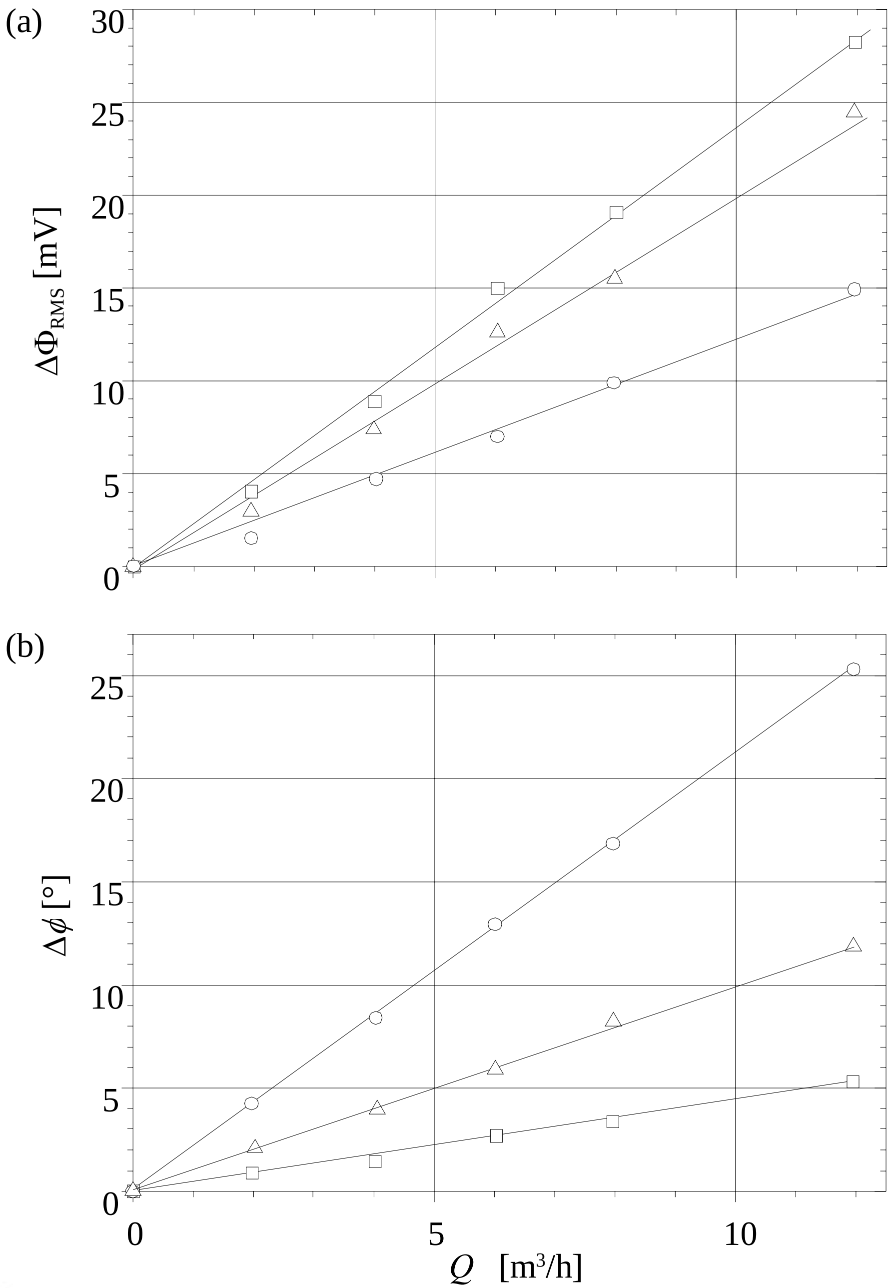
$$\mathrm{Re} = \frac{v_0 \cdot d}{\left(\frac{1}{\mu\sigma}\right)}$$

- Determination of flow direction by sign of signal
- Determination of time delay between Emitter-Sensor
  (or Phase Angle) $\Delta t \sim Q$

⇨ **2 independent gross-output quantities for *Q***

Th. Schulenberg, R. Stieglitz, NED 2009.

Measurement: Flow rate-EMFM



Design wishes

- High penetration depth δ of field B into duct (-> low f f=frequency AC current supply)
- High magnetic field strength (high $\Delta\Phi_{RMS}$)
- Large amount of windings (~n n=wire turns)

Counter arguments

- Low f yield high sensitivity to ambient stray signals
- High B modifies the flow Hartmann number Ha<<1 (Ha=(EM-forces/viscous forces))

$$Ha = d \cdot B \sqrt{\frac{\sigma}{\rho\nu}}$$

- Too large f yield skin-effect

$$f\, d^2\, \mu\, \sigma << 1$$

Measurement: Intrusive methods

Pitot and Prandtl tubes

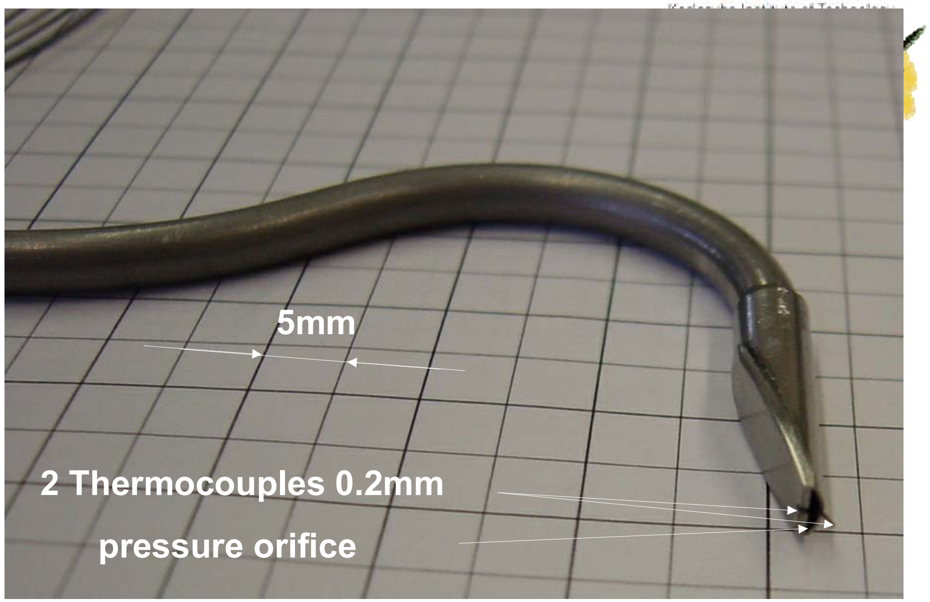
- measurement of pressure or pressure differences in fluid domains (coupled with TC)

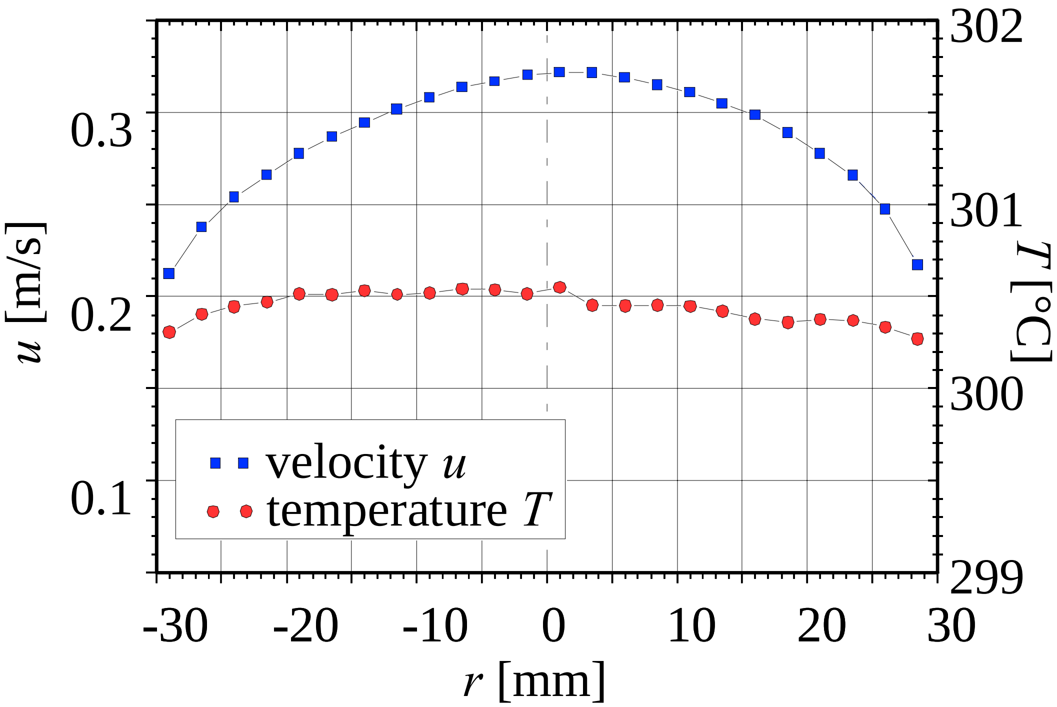
Advantages

- Sufficient time resolution.
- Simple set-up.

Disadvantages

- Disturbance of flow (intrusive method).
- Limited spatial resolution (boundary layer).
- Several corrections required.
- High fabrication effort in miniaturizing
- Sophisticated fill and drain necessary.
- Variable measurement ranges necessary for resolution of smallest fluctuations.
- Only one component measurable (flows in complex geometries ?)





Measurement :Ultra-Sound Doppler Velocimeter (UDV)

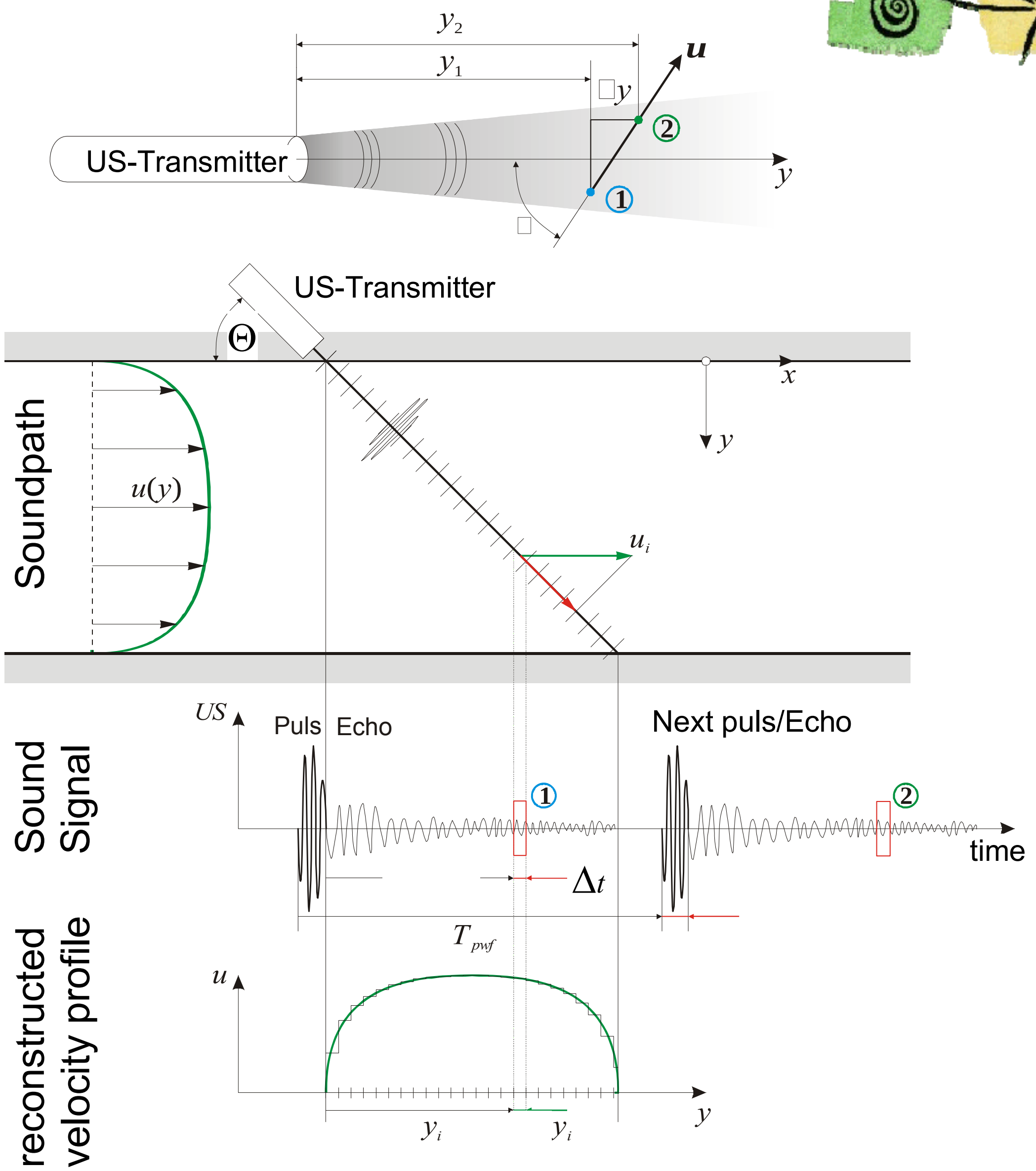
Principle (particle tracking)

- Distance change from sensor due to motion from 1→2 between two pulses.
- Determination of the time difference from the phase shift between received echoes

➡ Velocity at a discrete distance

Profile

- Separation of sound path in time intervals (gates Δt) allows recording of a velocity profile. Therefore,
  - Coupling of a time t_i with a measurement position
  - Determination of the local velocity u_i in the interval i



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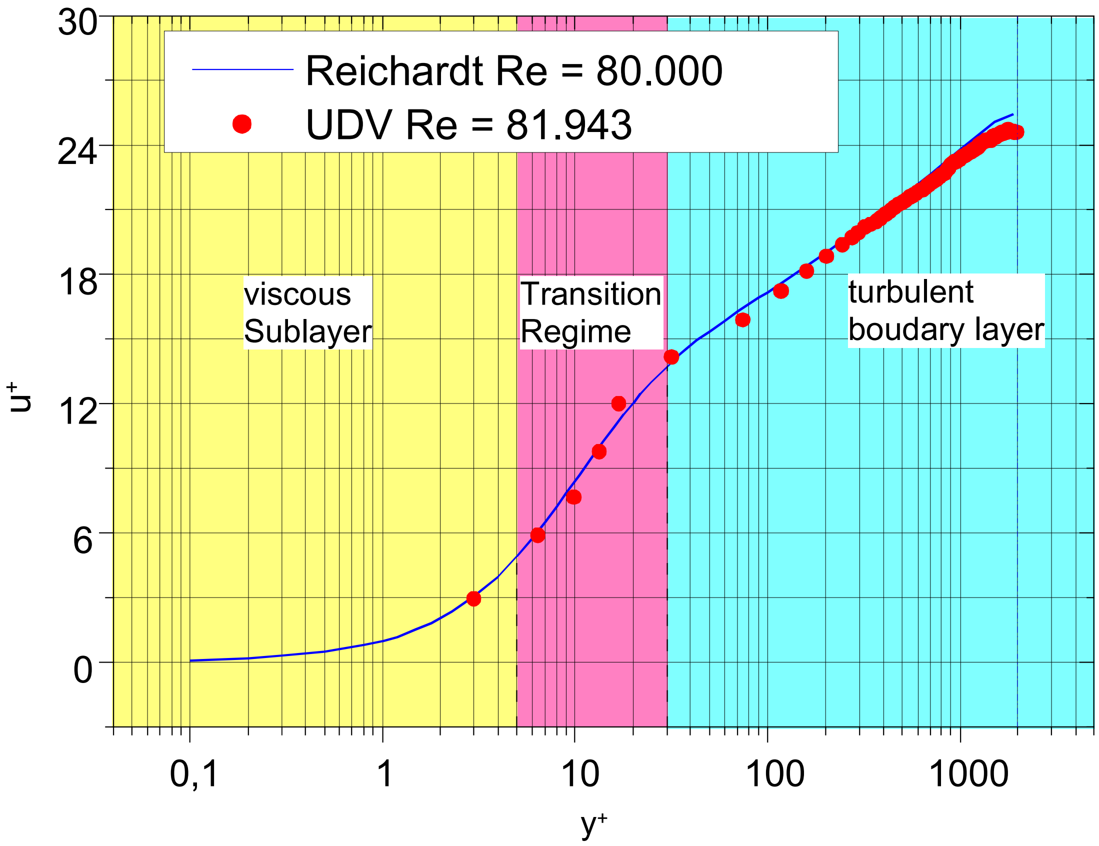
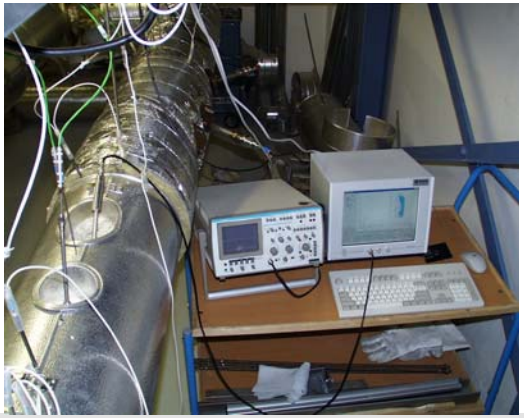
Measurement: UDV (2)





UDV-Sensor developed in cooperation with FZR

Result in the boundary layer

- All parts of the viscous boundary captured by UDV
- Max. deviation in the transtion regime of 5%
- UDV-measurements possible into the viscous sublayer (y^+=3   ~46μm)
- Temporal resolution currently up to 30Hz

Problems

- Long-term wetting of the sensor
- Temporal resolution (Turbulence spectra)
- What are the scattering particles ?
- More effective wave guides (Temperature, sound losses)
- Enhancement of math algorithm effectivity
- Only applicable in isothermal flows.
- Only one velocity component (3D-flows ?)

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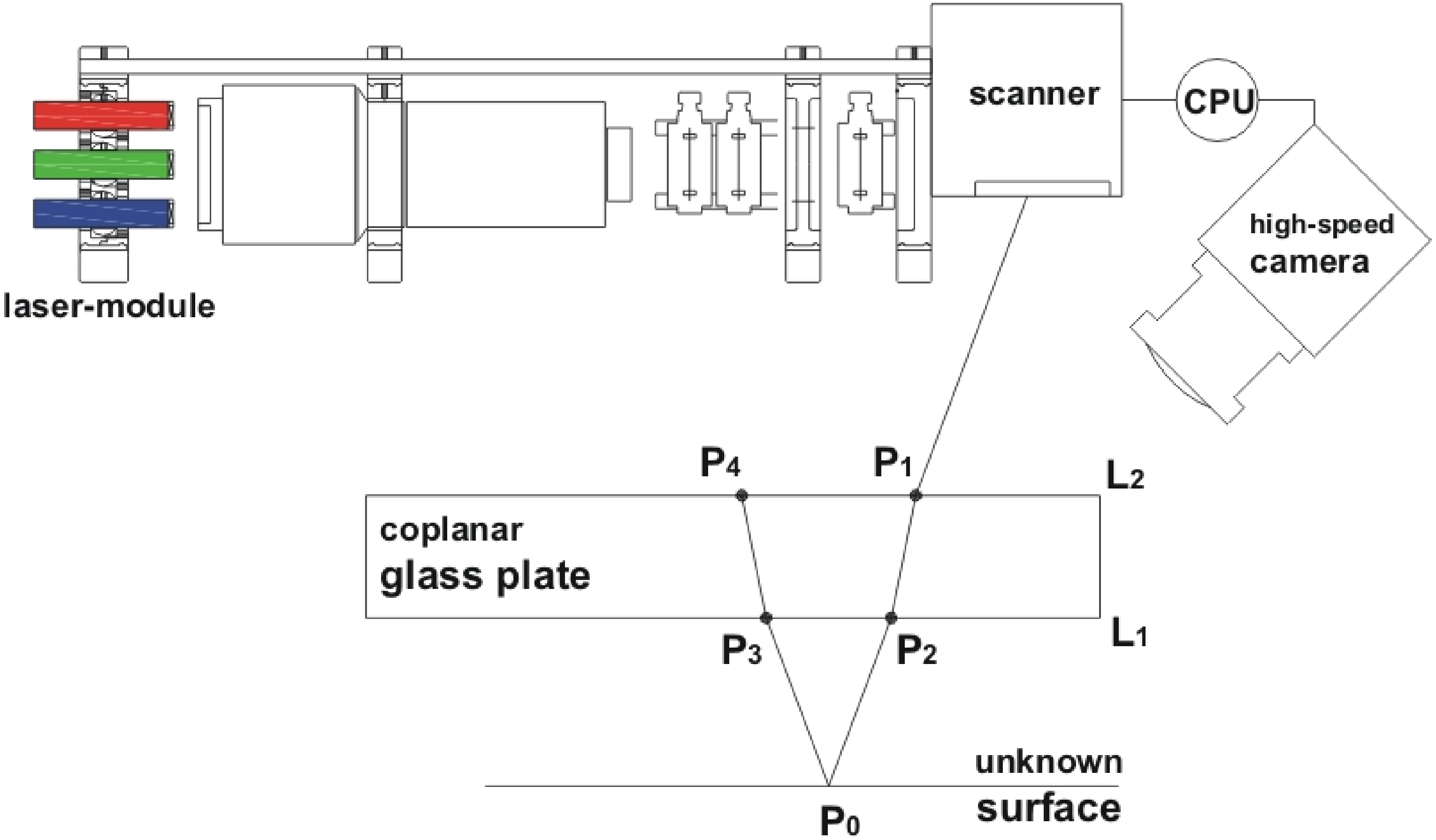
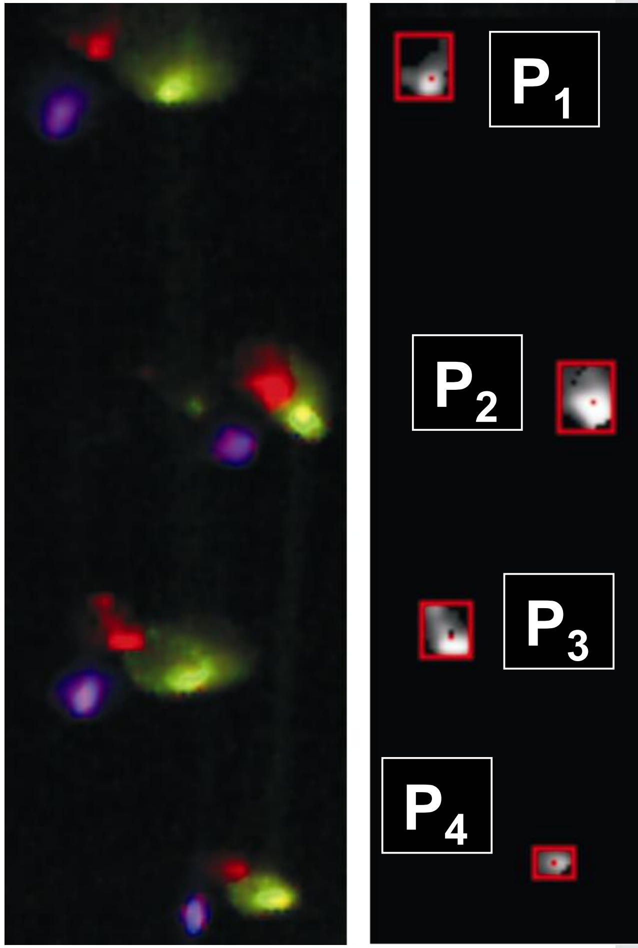
Measurement- Free surface detection

- **Optical method containing**
  - Color encoding (error estimate, filtering, cross-correlation)
  - Scanner (point, line and area acquisition)
  - High speed camera

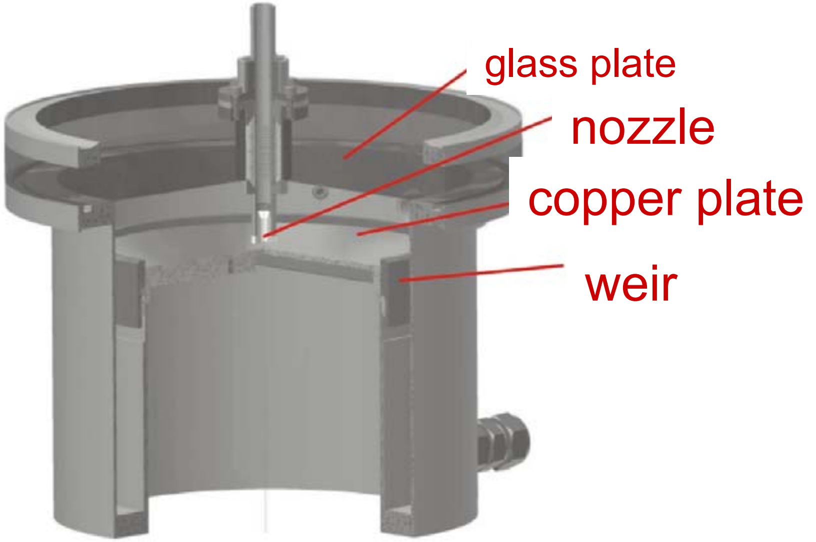


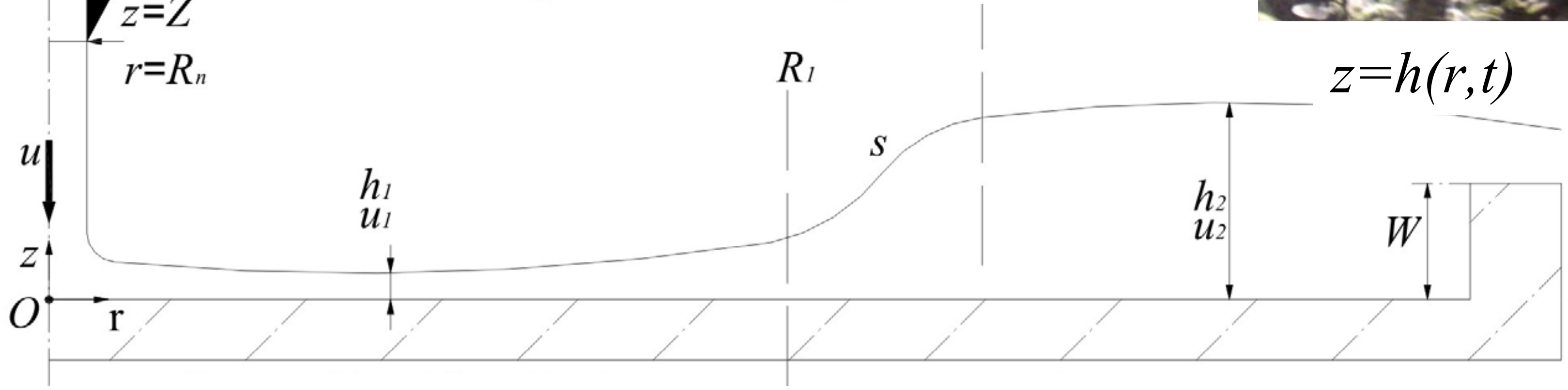


Measurement- Free surface detection

Validation:
- Circular Hydraulic Jump
- eutectic $Ga^{68}In^{20}Sn^{12}$

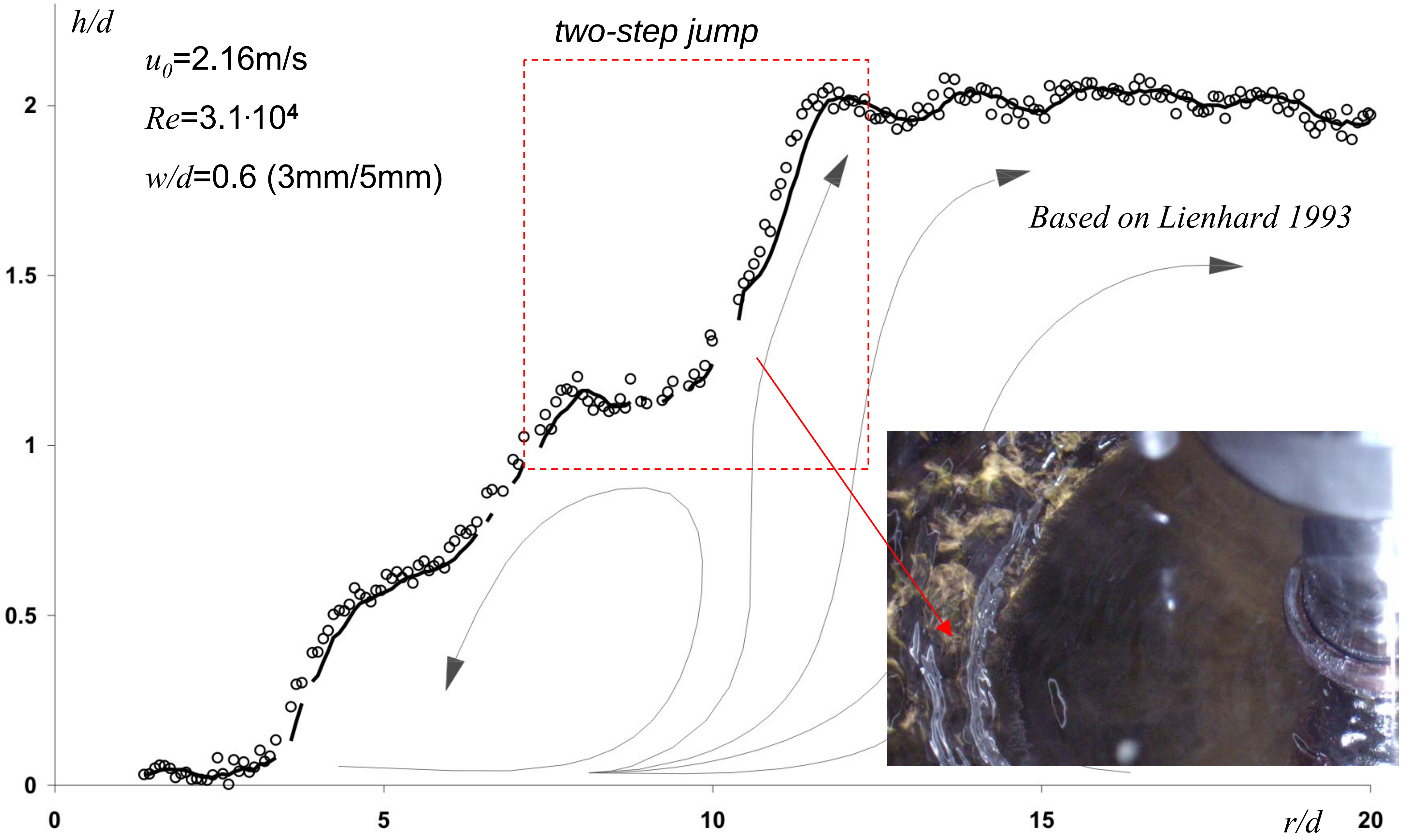
→ Goal: Measurement ***h(r,t)***





Supercritical flow regime $Fr>1$ Subcritical flow regime $Fr<1$

Measurement- Free surface detection



u_0=2.16m/s

Re=3.1·10^4

w/d=0.6 (3mm/5mm)

two-step jump

Based on Lienhard 1993

Turbulent heat transfer : General

- Turbulent energy equation

$$\rho c_p\left(\bar{u}\frac{\partial \bar{T}}{\partial x}+\bar{v}\frac{\partial \bar{T}}{\partial y}\right)=-\frac{\partial}{\partial y}\left(-\lambda\frac{\partial \bar{T}}{\partial y}+\rho c_p\overline{v'T'}\right) \quad ,$$

- Analogous to turbulent viscosity $\varepsilon_M=\mu_t/\rho$ a turbulent heat flux appears and thus
- a turbulent eddy heat diffusivity $\varepsilon_H=\lambda_t/(\rho\, c_p)$ can be defined,

⇨ the turbulent Prandt number Pr_t

$$Pr_t=\frac{\varepsilon_M}{\varepsilon_H}=f\left(Re,\,Pr,\,{}^{y}\!/_{R}\right)=\frac{\overline{u'v'}}{v'T'}\,\frac{\frac{\partial T}{\partial y}}{\frac{\partial u}{\partial y}}$$

<u>Consequences</u>

- Pr_t is far of being a constant (in reality a tensor)
- Difficult to measure directly, since it is a measure of
  - dimensions and
  - available sensor sizes as well as the
  - temporal resolution)
- Involves several modelling problems

Turbulent heat transfer : General

Closure methods for turbulent heat flux

- Semi-empirical models of zero and first order developed since late fourties yield mostly to **Reynolds analogy** results and to $Pr_t = f\,(Pr,\ \varepsilon_M / \nu)$ (**momentum-field≈temperature field**).
- Turbulent Prandtl Pr_t number from **analytic solutions** account for the statistics of the turbulence field (see Yakhot et al., 1987), but only applicable to simple geometries problematic with buoyant flows.

$$\left[\frac{\left(Pr_{eff}^{-1} - 1.1793\right)}{\left(Pr^{-1} - 1.1793\right)}\right]^{0.65} \left[\frac{\left(Pr_{eff}^{-1} + 2.1793\right)}{\left(Pr^{-1} + 2.1793\right)}\right]^{0.35} = \frac{1}{\left(1 + \varepsilon_M / \nu\right)} \quad \text{with} \quad Pr_{eff} = \frac{\left(1 + \varepsilon_M / \nu\right)}{\left(\dfrac{\varepsilon_M / \nu}{Pr_t} + \dfrac{1}{Pr}\right)} \quad .$$

- Turbulent heat transport **modelling by** means of **transport equations** (e.g. the turbulent fluxes $\overline{u_i' T'}$ temperature variance $\overline{T'^2}$, and its dissipation $\varepsilon_{T'}^{2}$ (TMBF –model) but each higher level of modelling leads to new constant and triple correlations a priori not known. Potential Solution approach:
  Determination of constants and triple correlations from
- Direct numerical simulation (DNS) of u- and T- field in simple geometries
- **CURRENT STATUS: sophisticated models for u-field but 0-dim. for T-field**

Turbulent heat transfer : Numerical methods

Benchmark problem: Backward facing step

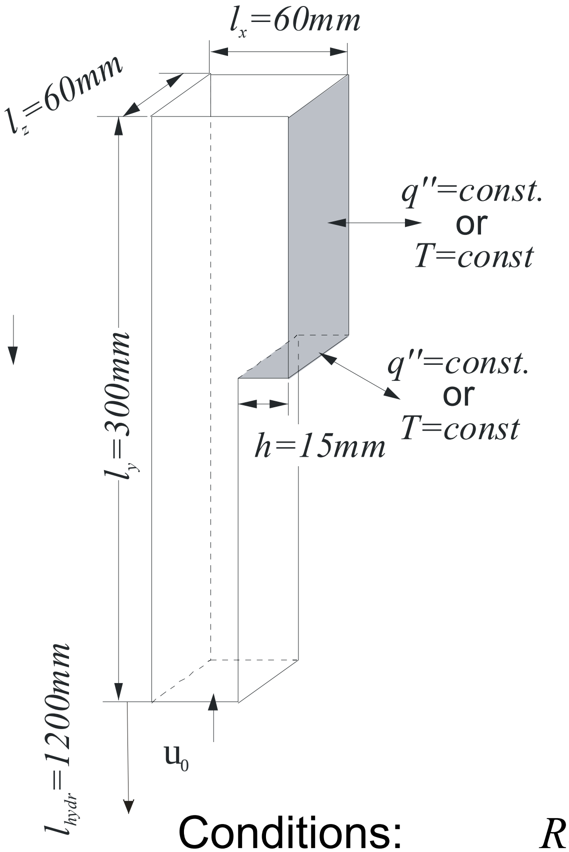
- Stratification problem (buoyancy) at large axial ΔT
- Flow separation at geometry discontinuities

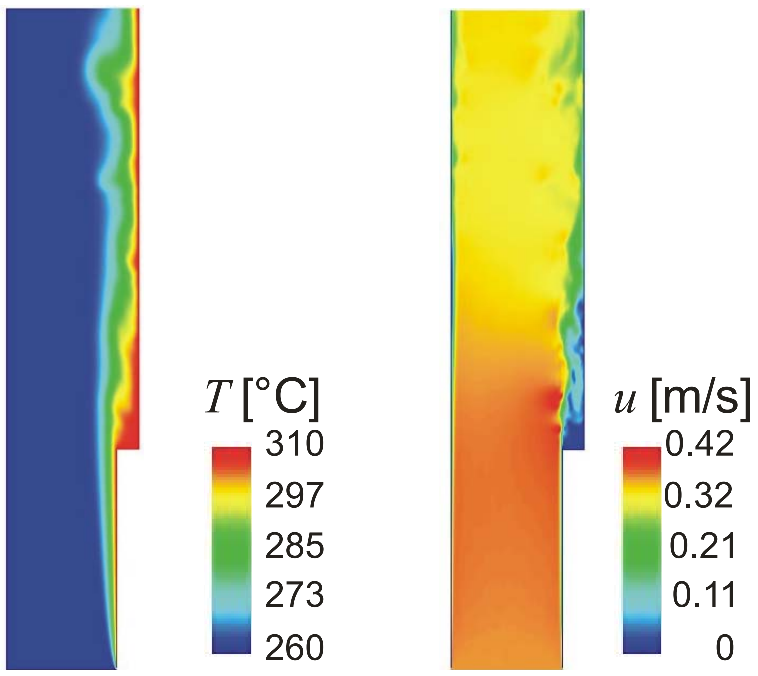
Approach

- Choice of small Pr-Fluid (Pr_{Sodium}=0.007) ⇨LES u-Field is DNS of T-Field

Goal

- Validity limits of CFD codes
- Development of advanced turbulent heat flux models
- Reliability threshold of design correlations

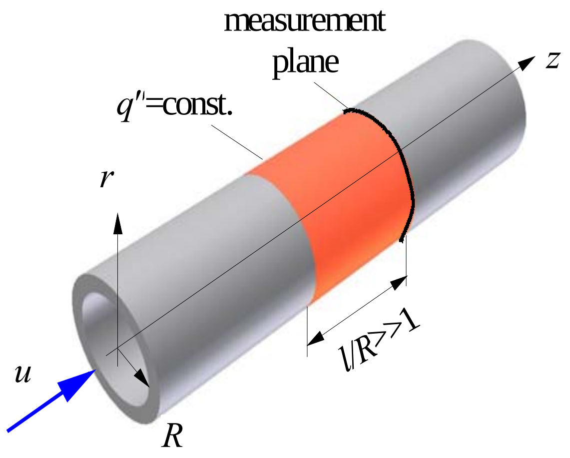


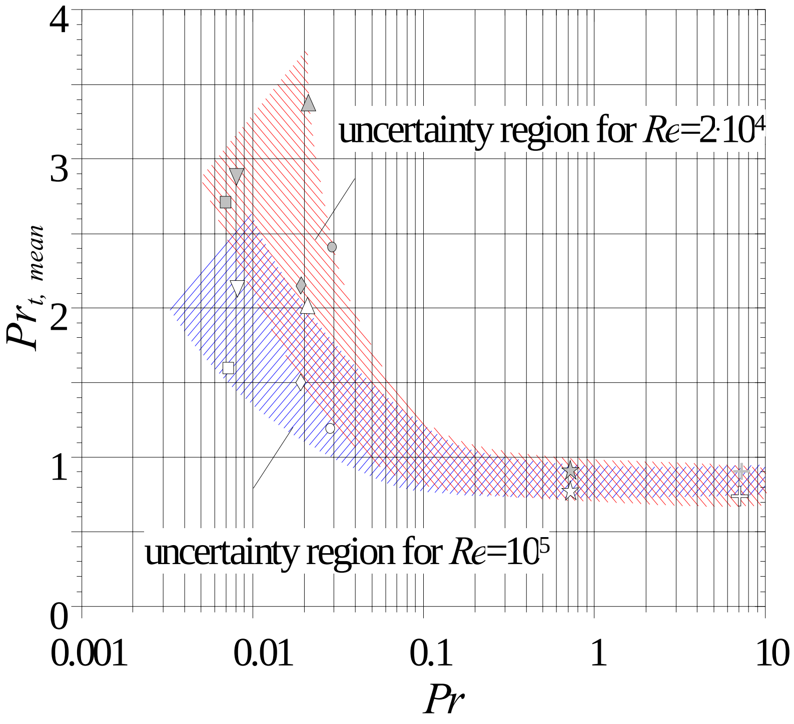


Conditions: Re=10^4, T=310°C=const., T_{in}=260°C

Turbulent Heat Transfer : Heated Pipe

- Fully developed turbulent (hydraulically and thermally) flow heated with a constant heat flux at different Reynolds (Re) and molecular Prandtl numbers (Pr)

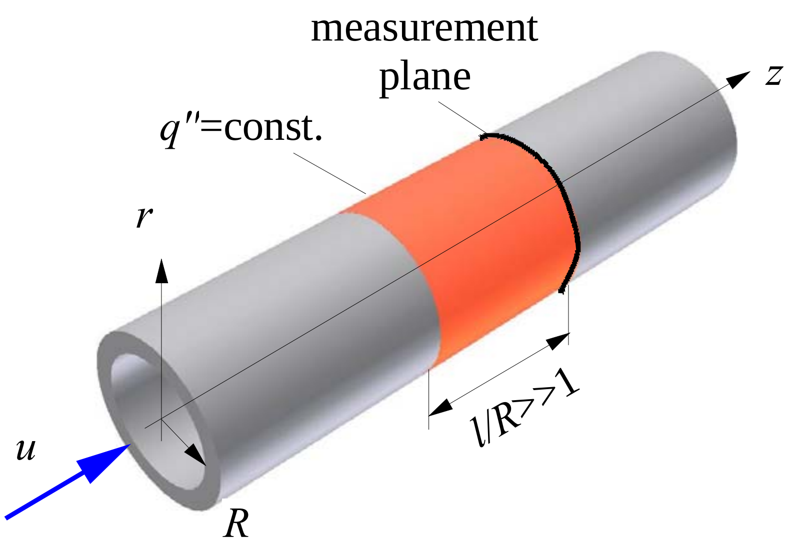


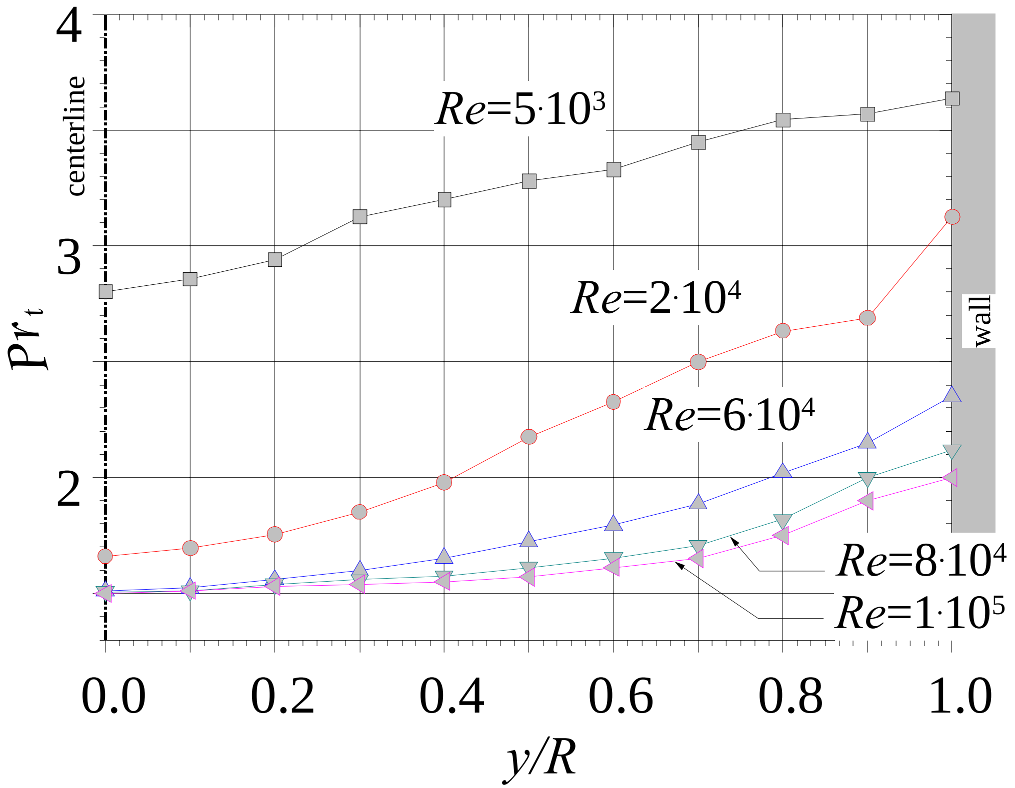


- Result:
  - Mean turbulent Prandtl number ($Pr_{t,mean}$) depends on molecular Prandtl number Pr.
  - Mean turbulent Prandtl number ($Pr_{t,mean}$) is a function of the Reynolds number Re.
  - But, for model development an unacceptably large uncertainty exists.

Turbulent Heat Transfer : Heated Pipe

- Measured local turbulent Prandtl number (Pr_t) in a fully developed turbulent flow heated with a constant heat flux at different Reynolds (Re)

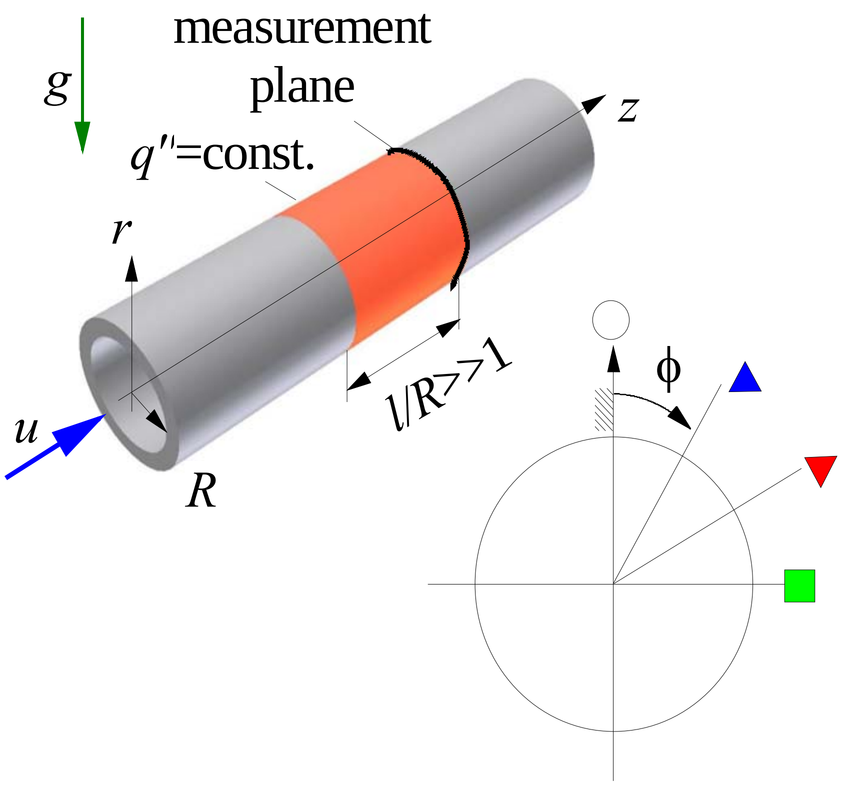


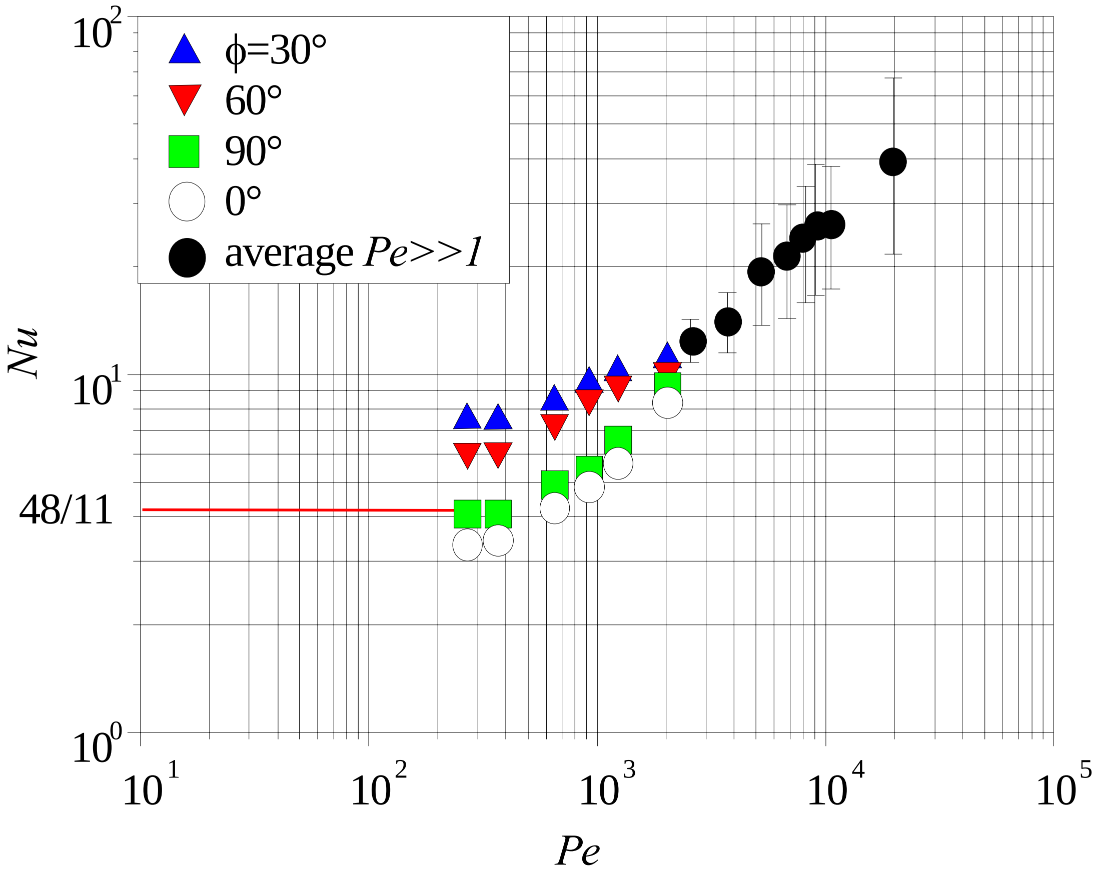


- Result:
  - Local turbulent Prandtl number (Pr_t) is a function of the Reynolds number Re **and** the radial coordinate y/R.
  - But, be careful with experimental data because boundary conditions and buoyancy play a considerable role.

Turbulent Heat Transfer : Heated Pipe

- The problem of free convection distortion. Liquid metals exhibit due to their large thermal expansion and low kinematic viscosity buoyancy distortion effects even at large *Re* (Hg, PbBi at $Re>10^5$)
- The horizontal pipe





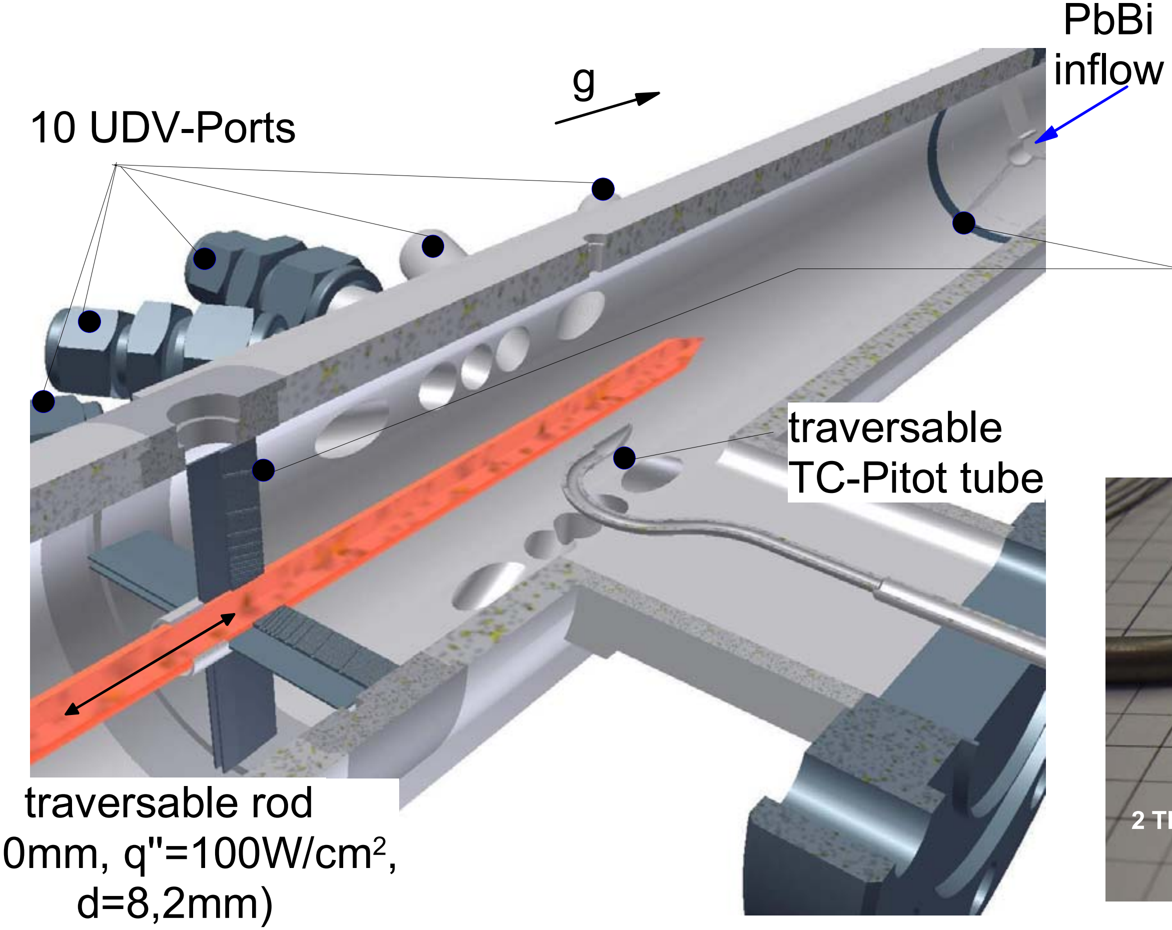
- Result:
  - Even large *Re* does not ensure a pure forced convective flow.

Turbulent Heat Transfer : Heated Rod

Background : Pin is single element of a fuel assembly

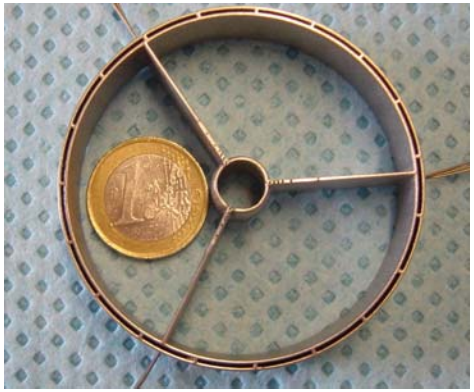
Scope : Turb. heat transfer in forced, mixed and buoyant convec. flows ($Re \rightarrow 6 \cdot 10^5$)

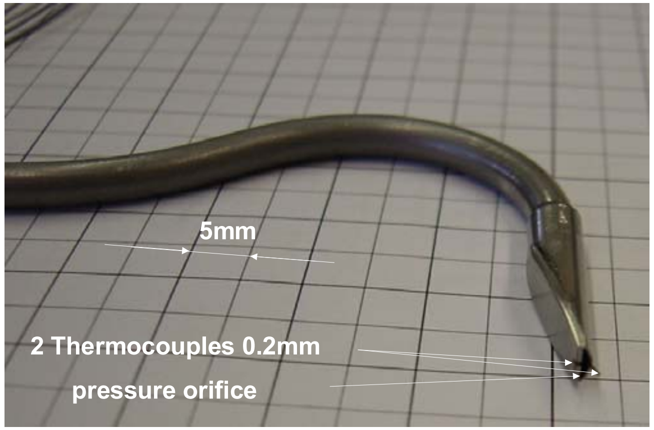
Measure:
- Development of models for turbulent heat flux;
- Determination of Nu-correlations;
- Evaluation of transitional regimes (model validity).



traversable rod (870mm, q''=100W/cm^2, d=8,2mm)

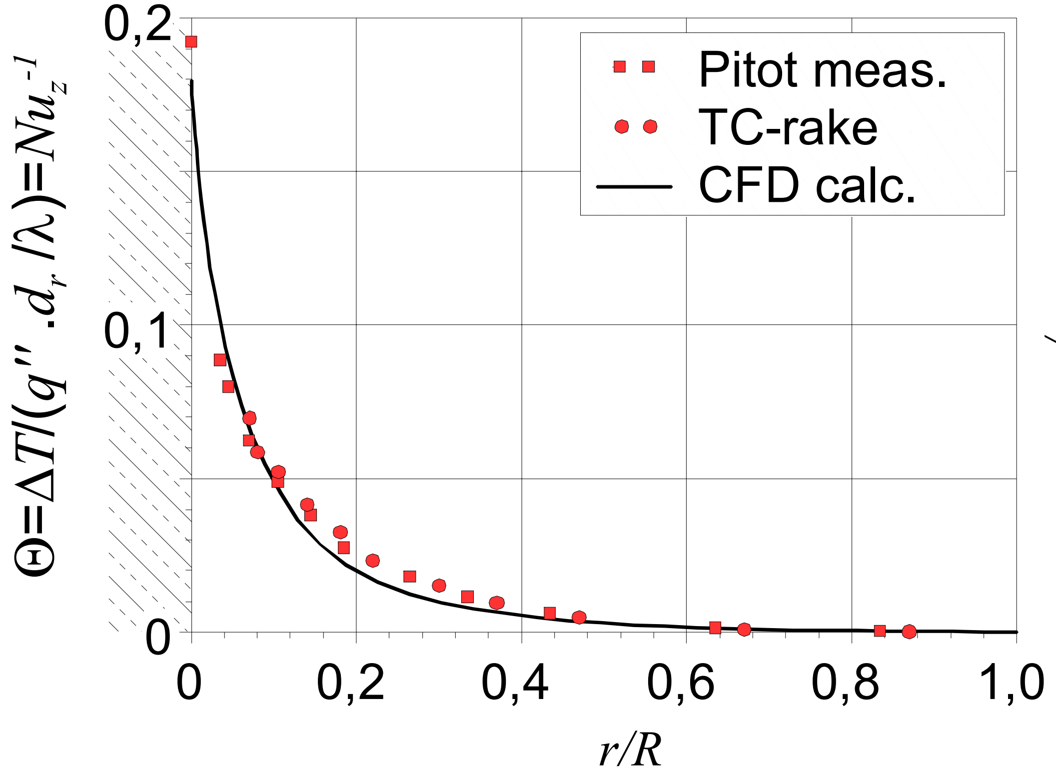
3 Rakes (60 TC´s, d=0.25mm)

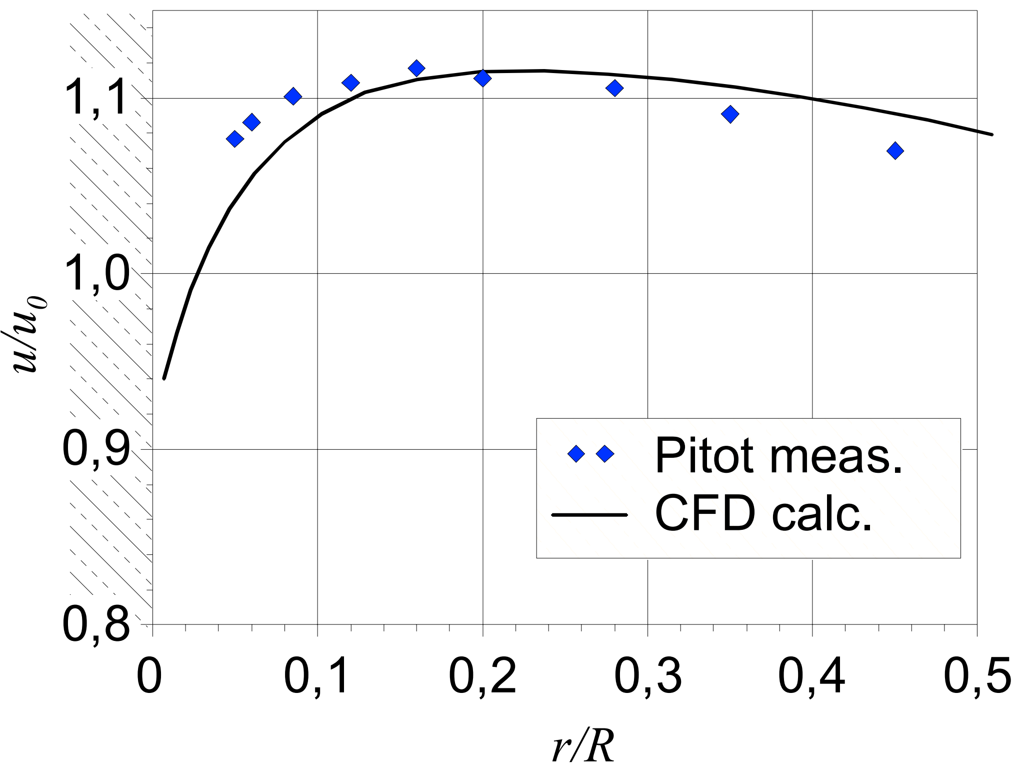




Turbulent Heat Transfer : Heated Rod

- CFD with SST-model , y^{+}~1 in heated part, but use of Reynolds-analogy with a prescribed & constant Pr_t (mostly Pr_t =0.9),





Conditions: $Re = 3.1 \cdot 10^5$, P_{HR} =9kW(~40W/cm²), d=8.2mm, T_{in}=300°C at z/d=51 (half heated length)

- Coincidence of measured and computed velocity.
- Resonable temperature agreement of CFD with Experiment at fluid- wall interface. But,
- Thermal boundary layer is thicker in experiment like expected (different heat fluxes).

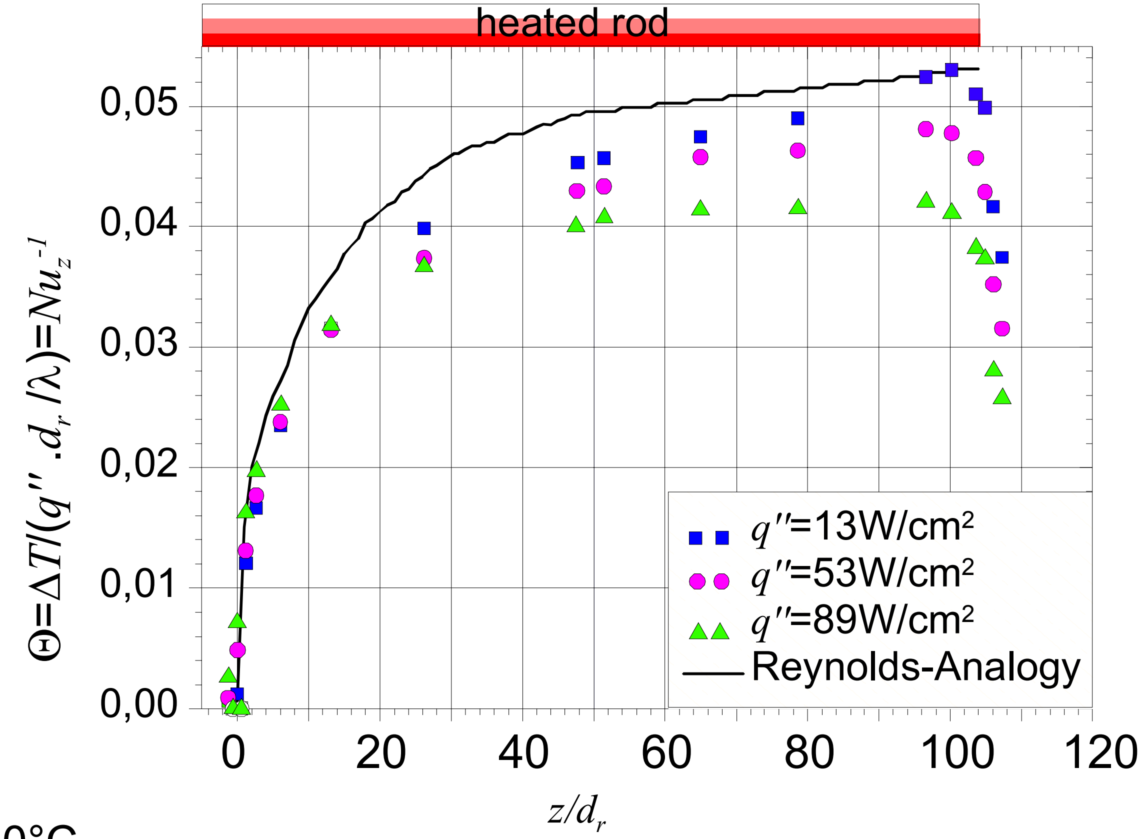
Turbulent Heat Transfer : Heated Rod

- Along the axis (z-direction) the temperature rise yields transition from

  forced convective heat transfer → mixed convective heat transfer
- At high heat fluxes along the flow path second transition occurs

  mixed convective heat transfer → buoyancy dominated heat transport
- Each transition alters turbulent heat fluxes in **wall normal distribution** and **magnitude**

⇨ Adequate turbulent heat flux models must be developed



Conditions: $Re = 7.7{\cdot}10^4$, d=8.2mm, T_{in}=300°C

Turbulent heat transfer: Summary

Turbulent heat exchange modelling

- State of the art Pr_t-correlations in codes!,
- Better buoyant flow modeling (+Qualified user),
- At least ASM based turbulent heat flux models ($u'T'$)
- DNS required to improve and validate advanced heat flux models to be embedded in commercial codes

Measurement techniques

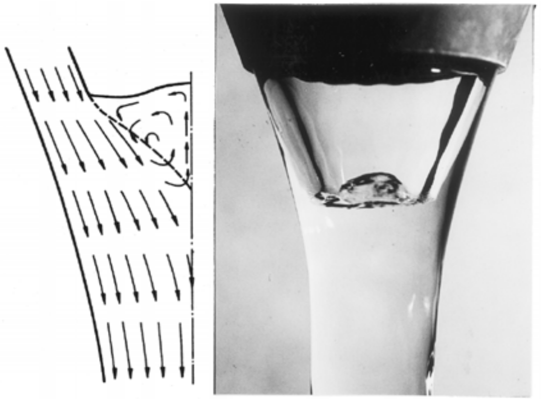
- Improved sensors to capture local flow velocities (accuracy, multi-components and spatial and especially temporal resolution, best non-intrusive)
- Defined benchmarks (regarding CFD,LES and DNS but also related to the BC´s with supplementary water experiments)

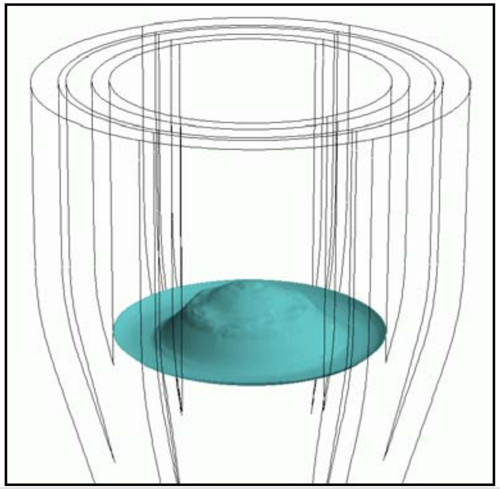
Turbulent free surface flows

Different types of free surface targets under development

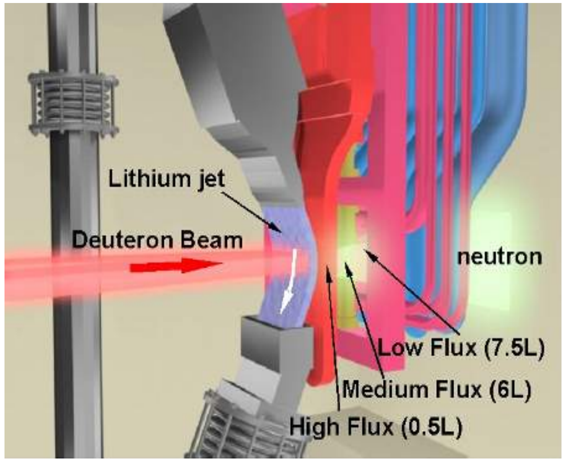
- Geometry driven designs (MYRRAH)
- Semi-bounded designs relying on centrifugal stabilization (IFMIF, FRANZ)
- Gravity driven designs (FAIR, DIRAC)

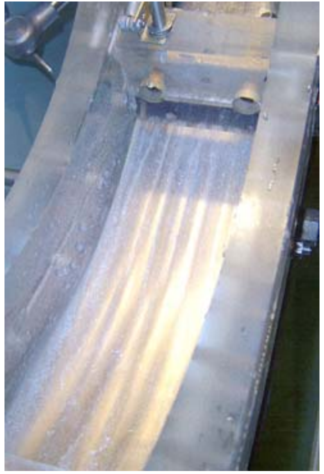
Myrrah-type target

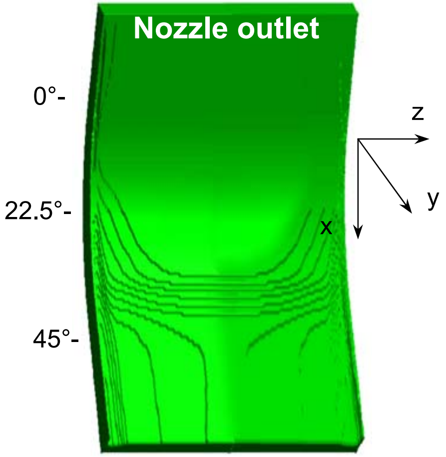




IFMIF-type target

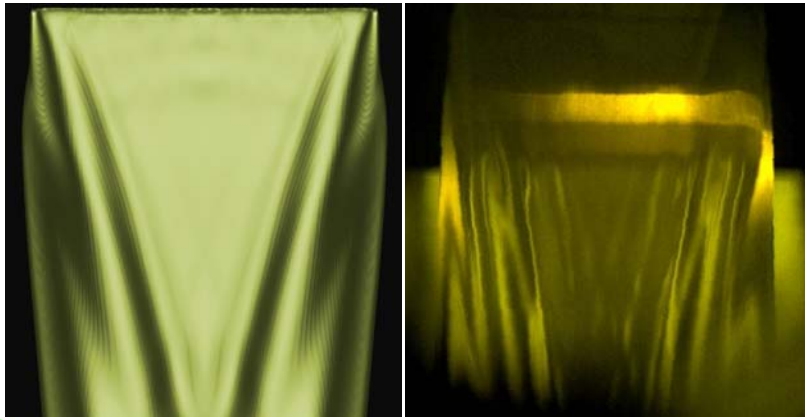


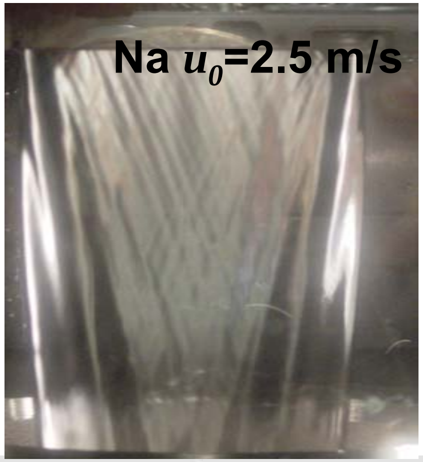




FAIR-type target

Water u_0=2.5 m/s





Turbulent free surface flows

Problems-CFD

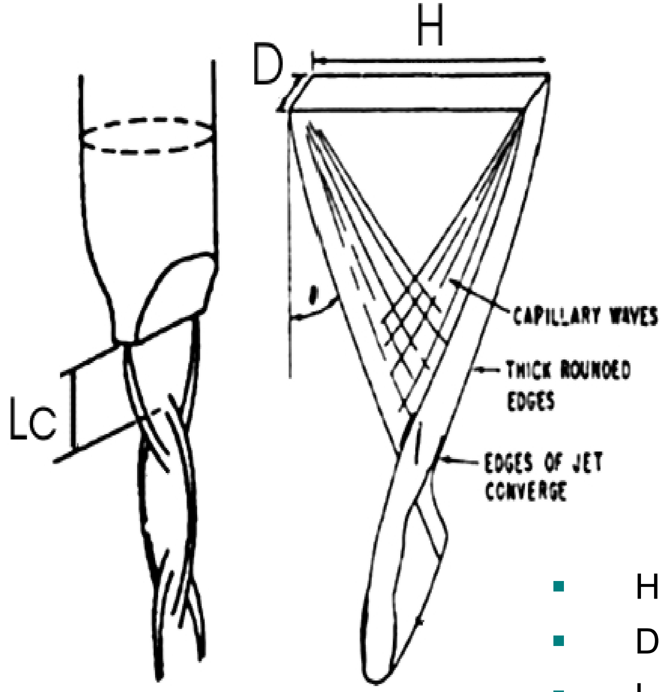
- Different statistics of u and h-field (damping times/diffusion times).
- Large density differences between liquid and gas phase ($\rightarrow\infty$ for vacuum).
- Coupling of turbulent u-field with h-field (lack of adequate models: e.g. level-set methods)
- Scale separation of u and h (viscosity<<surface tension)
- Potential phase transition requires LM adapted cavitation models.
- Flow mostly transient → time step given by p- and u-fluctuations.
- Complex geometries of induce secondary flows (e.g. edges, curved planes) leading to large computation times.

Problems Experiment

- Development of rree surface detection sensors with high temporal & spatial resolution
- Lack of experiments with simultaneous u and h-field measurements (unknowns statistics and diffusion times)

Turbulent free surface flows- faucet problem

- Surface tension contracts the stream
- Shear stress/surface tension in causes inversion of jet (twist)
- At discontinuities capillary waves are generated.



- H ≡ jet depth
- D ≡ Jet thickness
- L_C≡ contraction length

$$L_c = \frac{v \cdot H}{2}\left(\frac{\rho}{\sigma}\cdot\frac{\pi\cdot D}{16}\right)^{1/2} = \left(\frac{\pi\cdot We}{16}\right)^{1/2}\cdot\frac{H}{2}$$

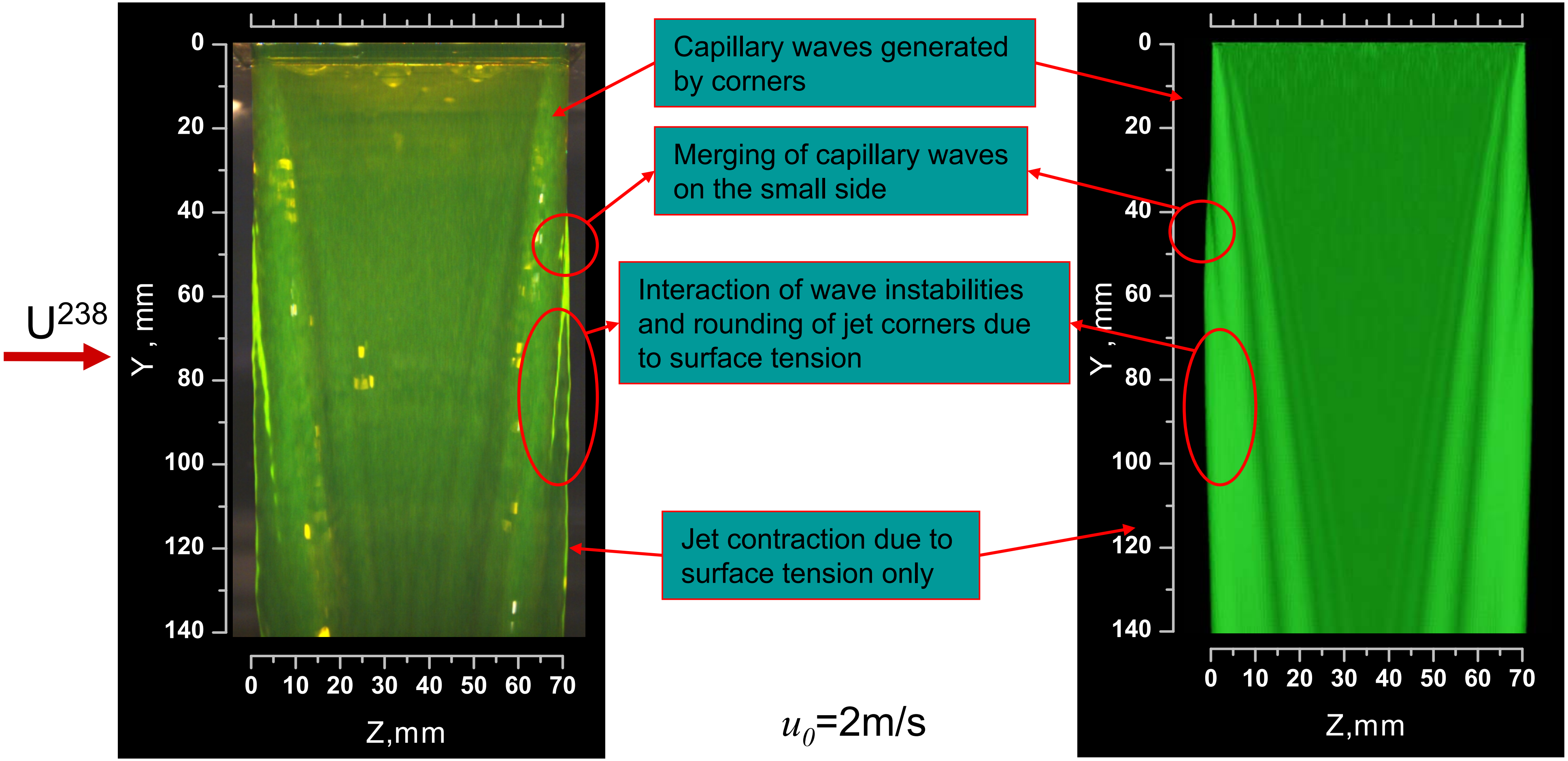
u_0=0.2 m/s

5 m/s

Turbulent free surface flows- faucet problem

Problem described by:

- Weber number
- Geometry ratios
- Surface roughness
- Nozzle inflow, pressure oscillations, …….



Capillary waves generated by corners

Merging of capillary waves on the small side

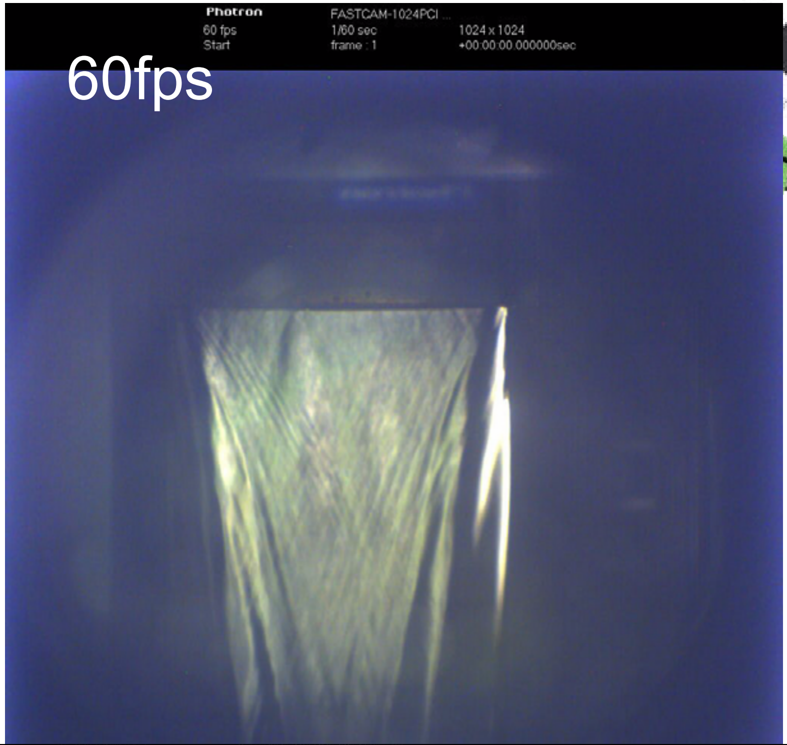
Interaction of wave instabilities and rounding of jet corners due to surface tension

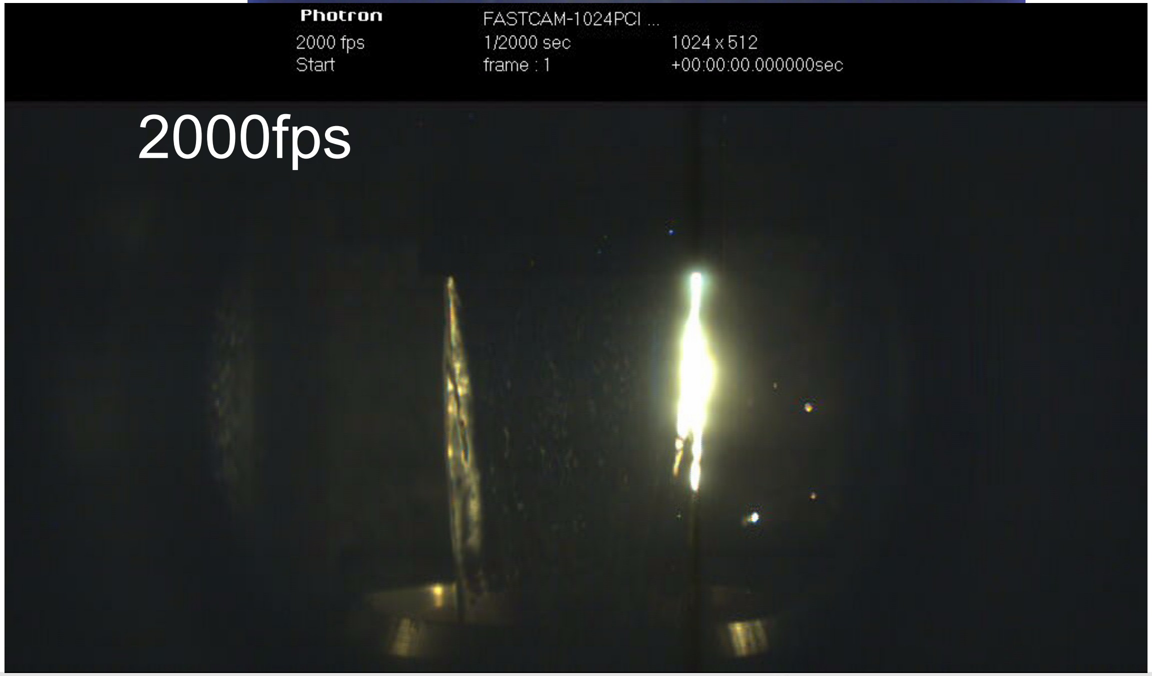
Jet contraction due to surface tension only

u_0=2m/s

Turbulent free surface flows

- RANS model simulations are suitable to predict mean surface shape (interaction of steady events).
- LES or DNS must used to capture temporal effects
  - Flow detachment
  - Velocity osciallations
  - Görtler vortices



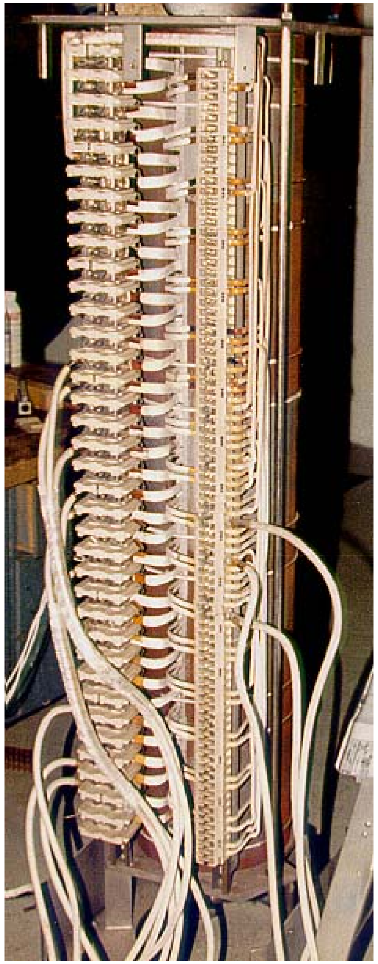


Vertical Sodium jet with u_0=2.5m/s

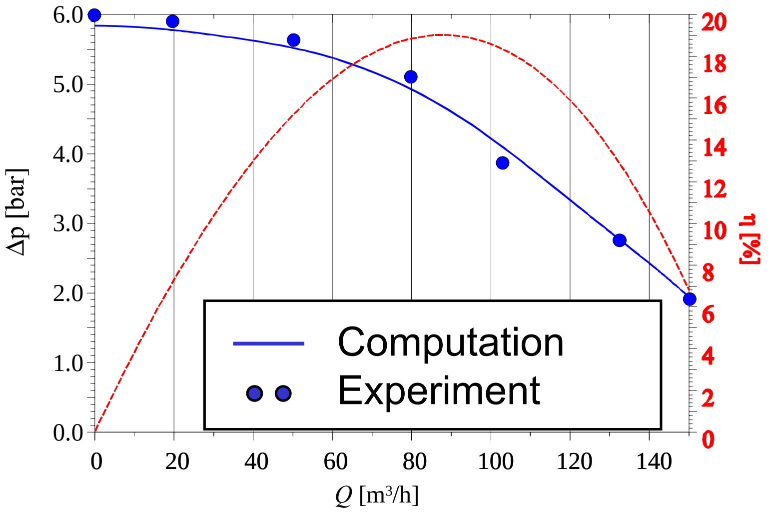
Liquid metal components

- Design, Computation and Construction of MHD pumps

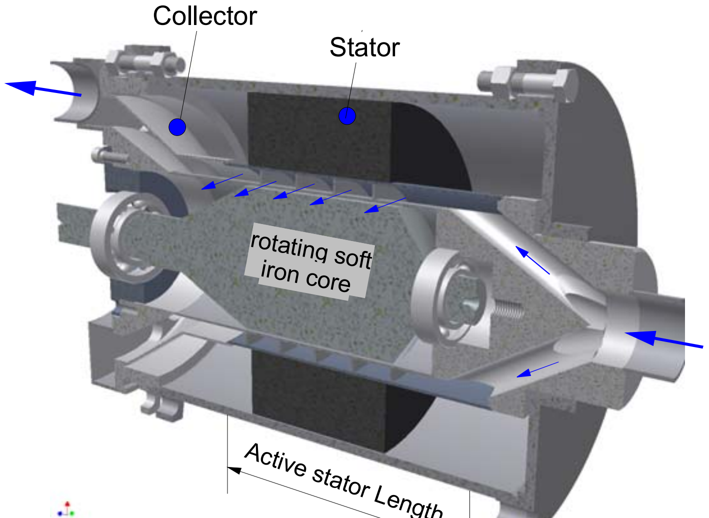
Annular Linear Induction Pump (ALIP)

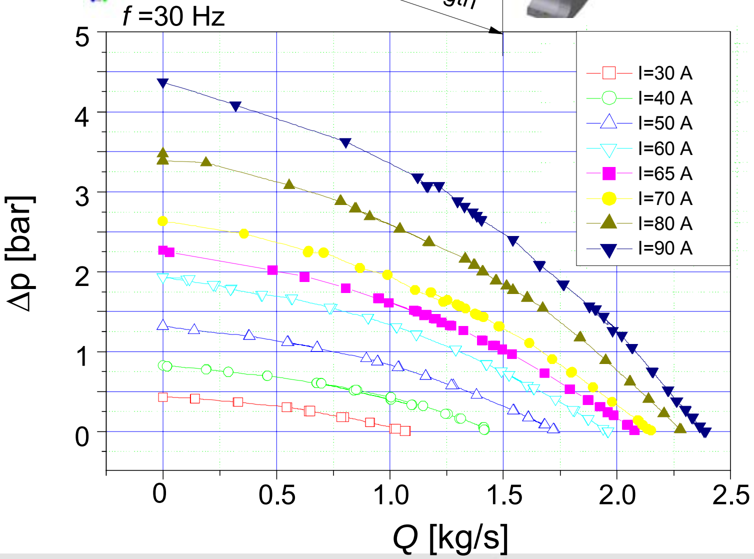


Sodium -ALIP



ACHIP –Alternating Current Helical Induction Pump)





Summary

- Liquid metal operated fusion and fission exhibit in many fields similar features originating mainly from the specific properties of the liquid metals.
- Commercial CFD-tools exhibit considerable deficits in MHD flows, heat transfer problems and free surface flows in low Prandtl number fluids even in the steady case because of
  - Strong anisotropic turbulence due to geometry, heat load,…
  - Scale separation of the boundary layers BL (viscous BL<< thermal BL,…)
  - Deficits of adequate coupling of free surface modeling with turbulence modeling
- The progress in measurement techniques achieved in the past decade enabled a first access to the rather complex flow phenomena occurring in the individual problems.
- This development process enables to define generic experiments aimed to
  - Develop more advanced physical models for the heat transfer and free surface problems.
  - To generate a data base and local correlations (for heat transfer) for the design of complex innovative nuclear systems.

SUPPLEMENTARY FIGURES

Nuc. Physics:
MEGA-WATT PILOT Experiment (MEGAPIE)

Demonstration of a high power

liquid metal cooled spallation target

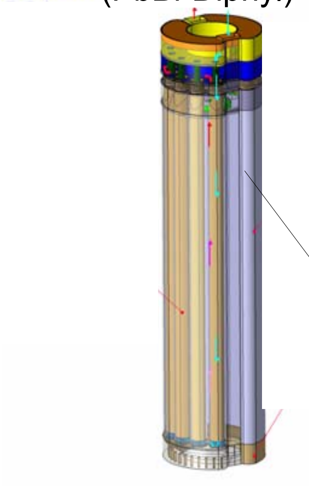
- Power: 1MW in 82 Litres $Pb^{45}Bi^{55}$
  PbBi-Inventory (incl. pump, HEX,
  gas system and instrumentation)
- irradiated from July-Dec. 2006
- Potential $\Delta\Phi$=630MeV, I=1.4mA

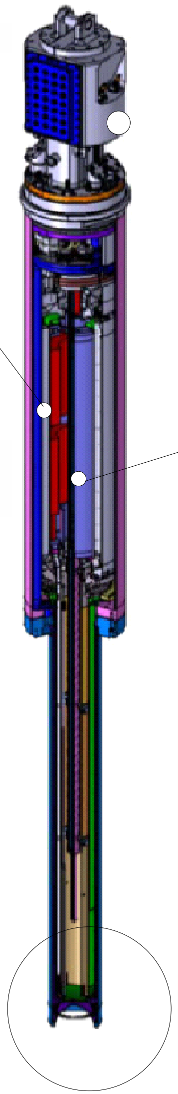
Crucial aspects

Thermalhydraulics of the components
especially the heat loaded target shell

*Megapie.web.psi.ch

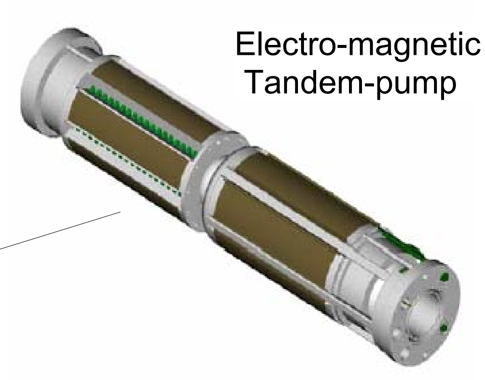
Pin-HEX
(PbBi-Diphyl)



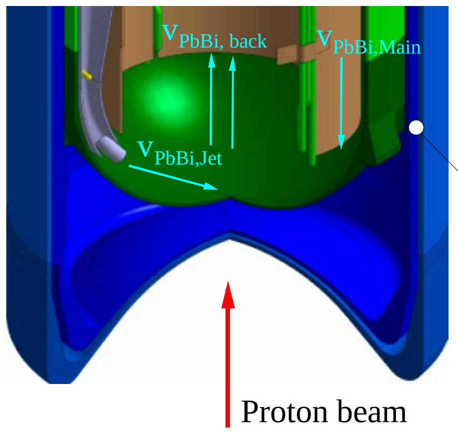


Head with media transfer and
electric connections

Electro-magnetic
Tandem-pump



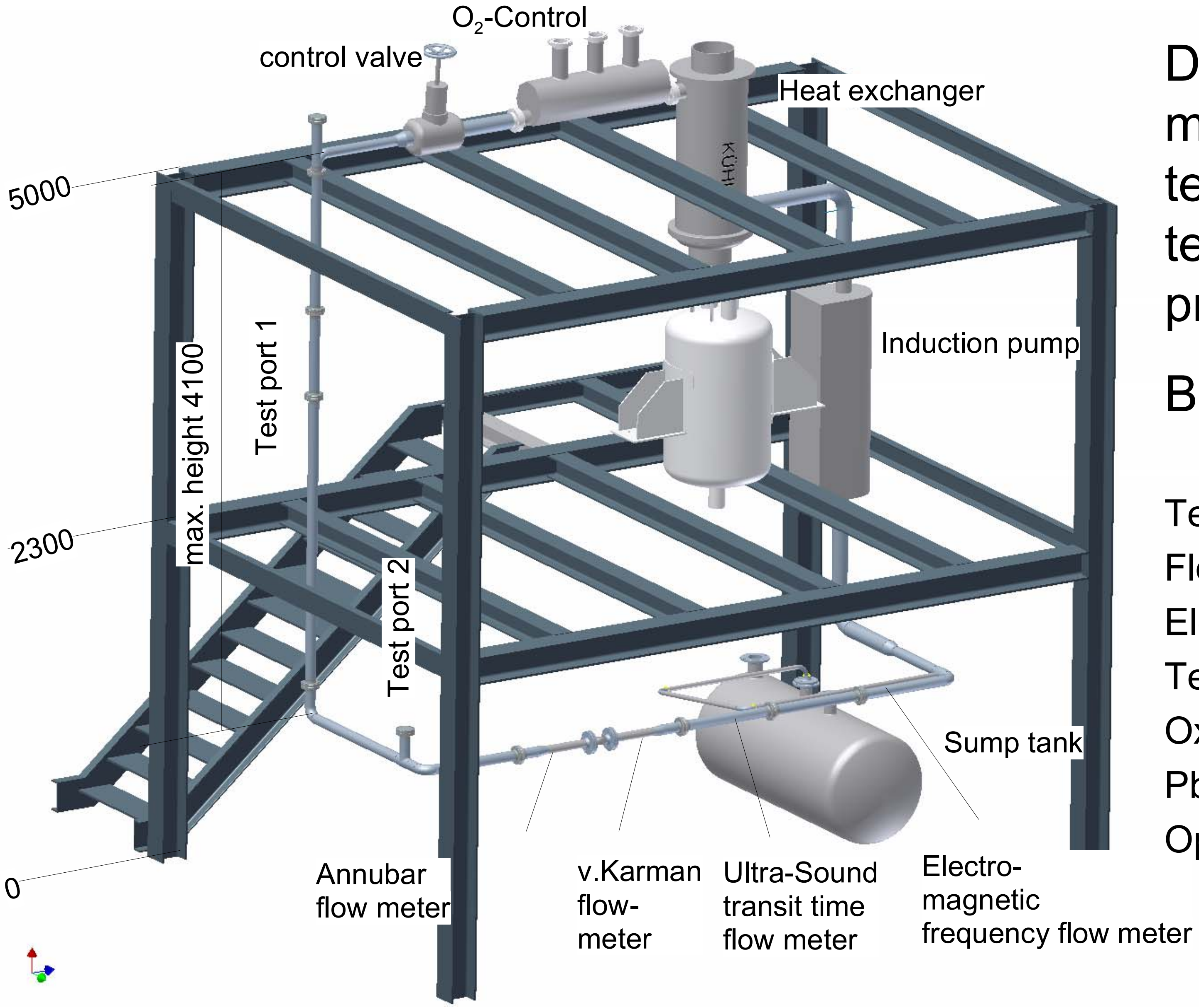
1:1 Targetsimulator
thermahydraulic
experiments in KALLA



Water cooled
safety hull

Proton beam

PbBi Loop THESYS



Development of measurement techniques for flow, temperature and pressures

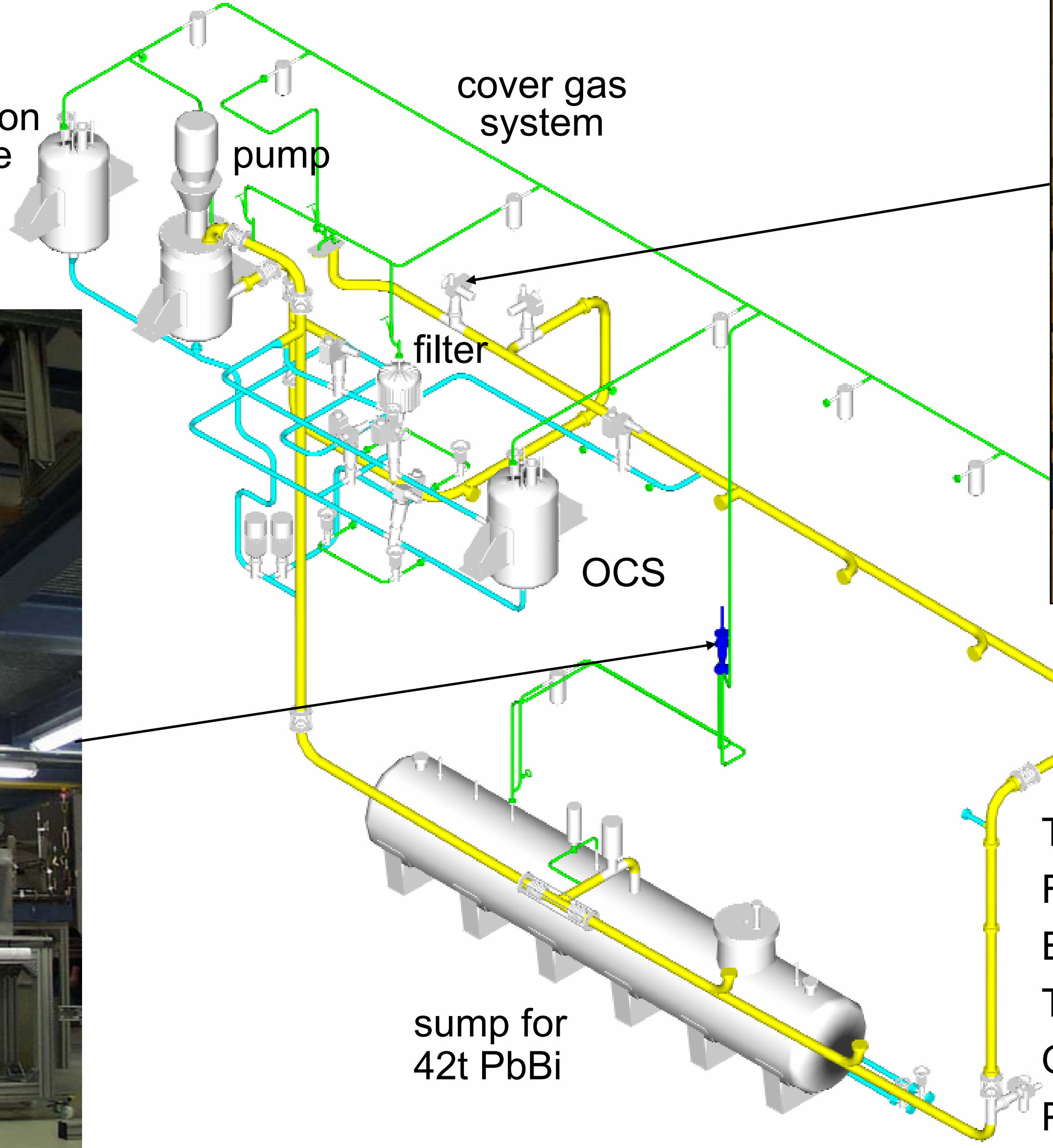
Benchmark experiments

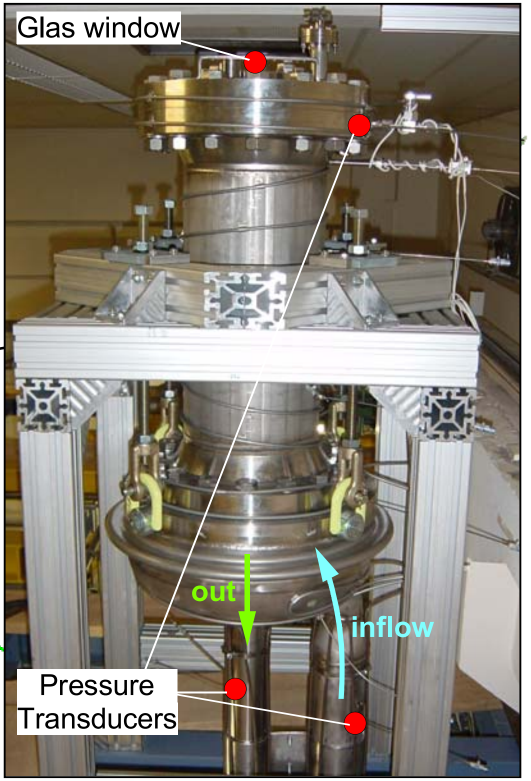
Temperature	200-550°C
Flow rate	16 m^3/h
Electr. power	250 kW
Test ports	2+2
Oxygen control	yes
PbBi inventory	300 l (3 t)
Operating hours	2000

Prototype Loop THEADES

Component Tests

MEGAPIE experiment





Free surface target experiment

Temperature	175-400°C
Flow rate	47 m^3/h
Electr. power	1200 kW
Test ports	2
Oxygen control	yes
PbBi inventory	4000 l (42 t)
Operating hours	3000

Corrosion PbBi-Loop CORRIDA

- Corrosion tests, 32 test specimen
- Mechanical tests
- Coating tests

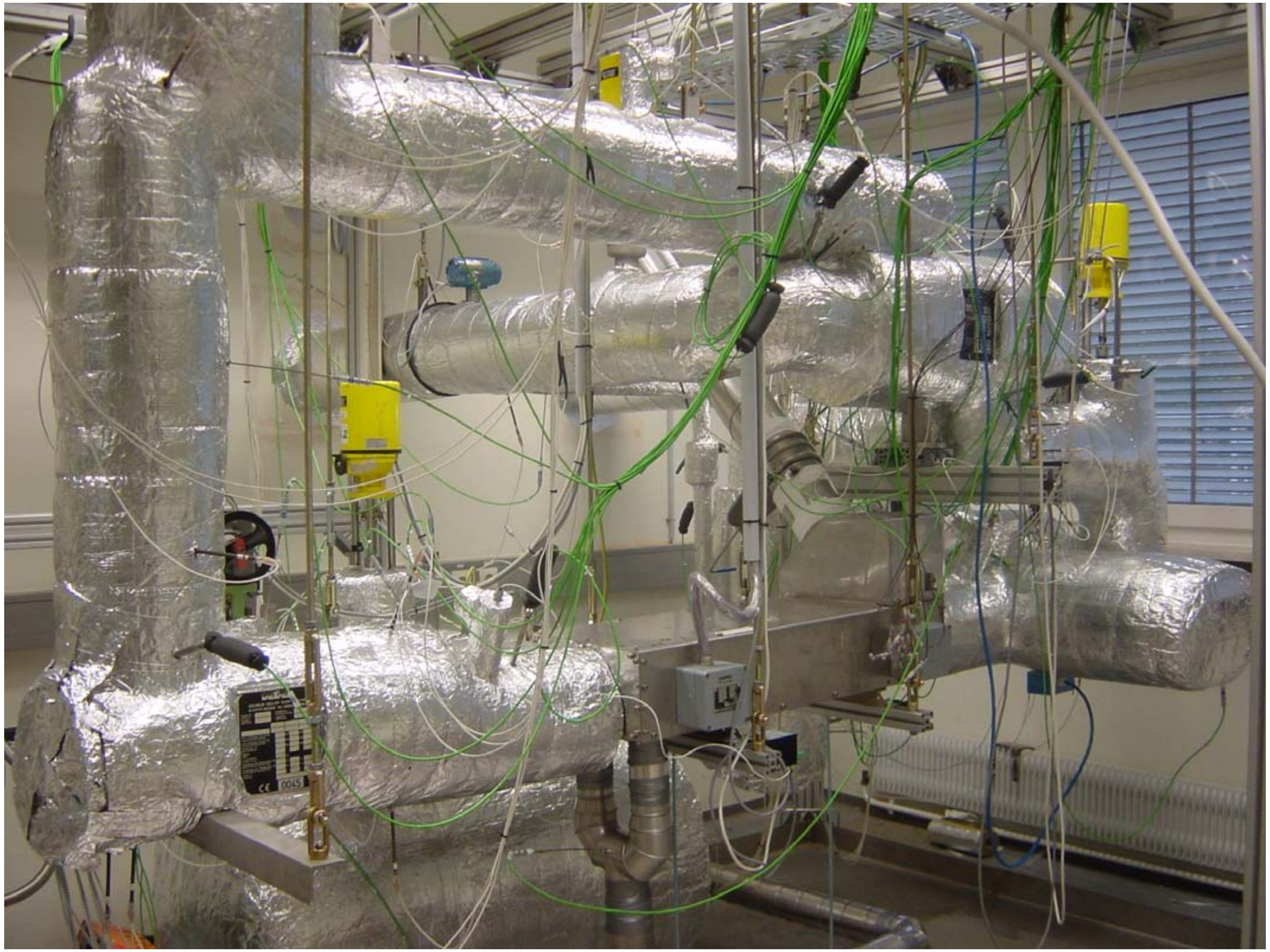
for beam windows and structural materials

Temperature	400-650°C
Flow rate	9 m^3/h
Electr. power	250 kW
Test ports	2
Oxygen control	yes
PbBi inventory	280 l (3 t)
Operating hours	17000

MHD Pump and Recuperator

Na- or Li-Loop ALINA

new



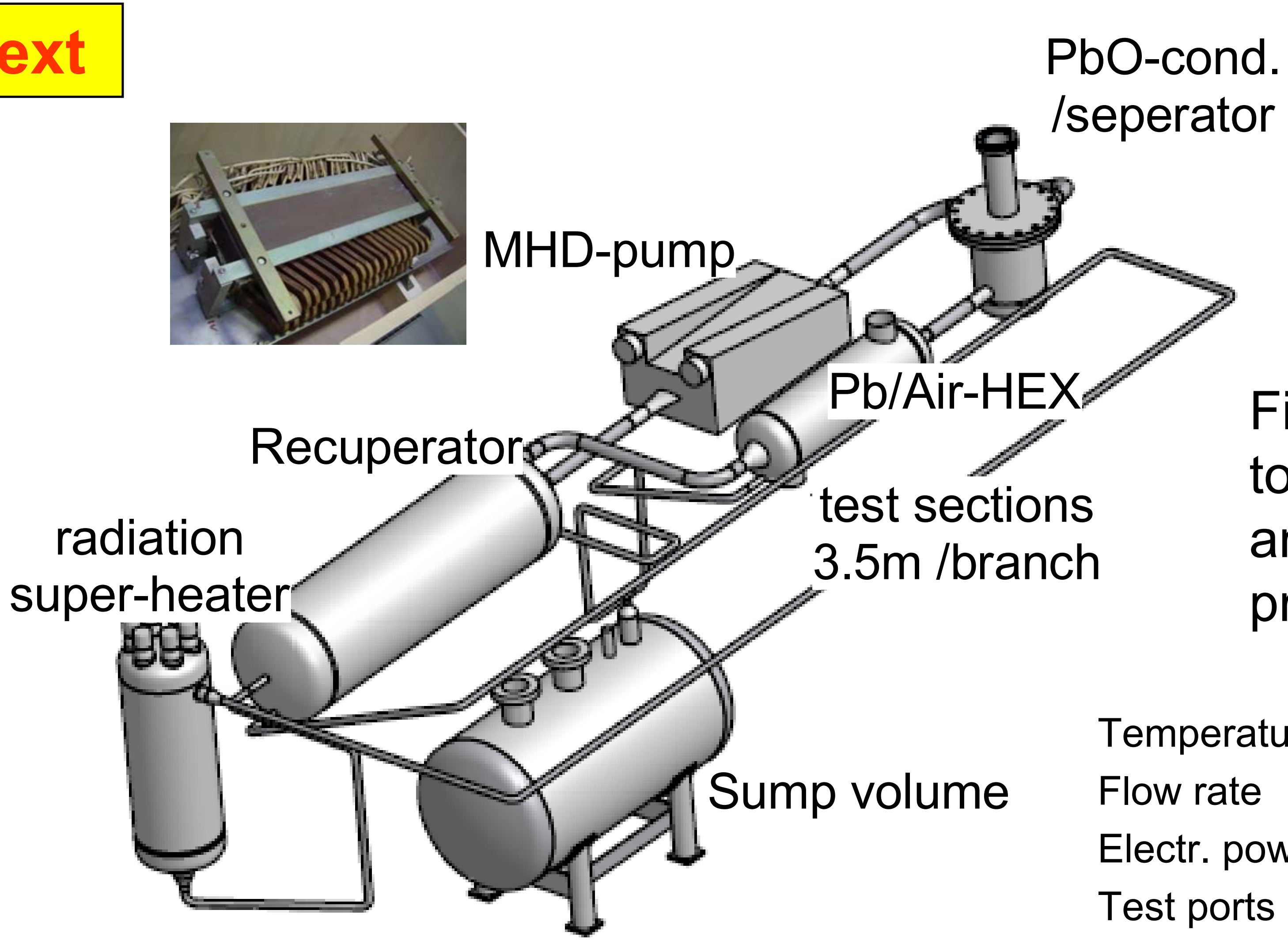
Test of windowless targets and small scale heat transfer tests for generic nuclear physics

Secondary Coolant: Diphyl/THT

Temperature	150-400°C
Flow rate	21 m^3/h
Electr. power	120 kW
Test ports	1
Na inventory	150 litres
Commissioning	2007

Pb-Loop TELEMAT

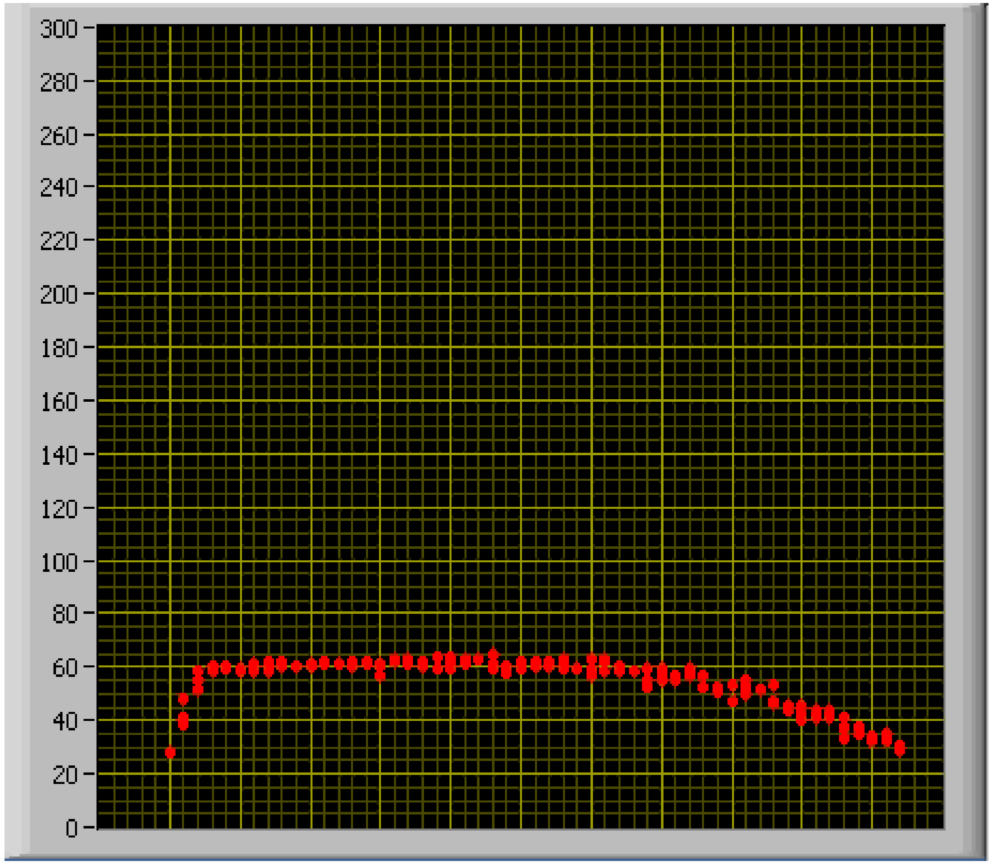
next



First tests planned to study corrosion and erosion problems in pure Pb

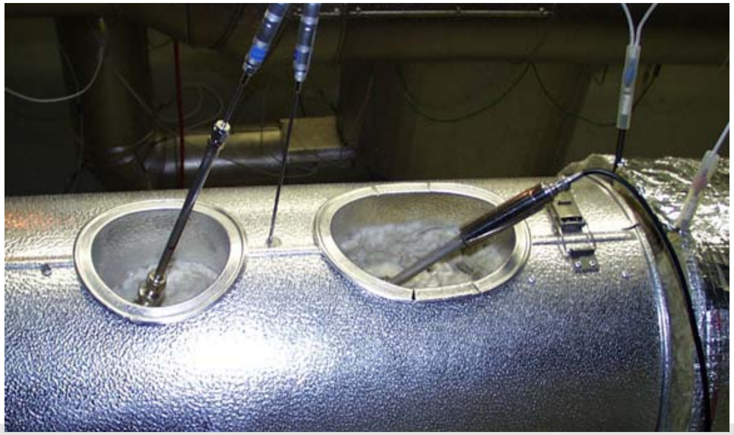
Temperature	400-750°C
Flow rate	2.1 m^3/h
Electr. power	110 kW
Test ports	2
Pb inventory	200 litres
Commissioning	2008

Velocity :Ultra-Sound Doppler Velocimeter (UDV)

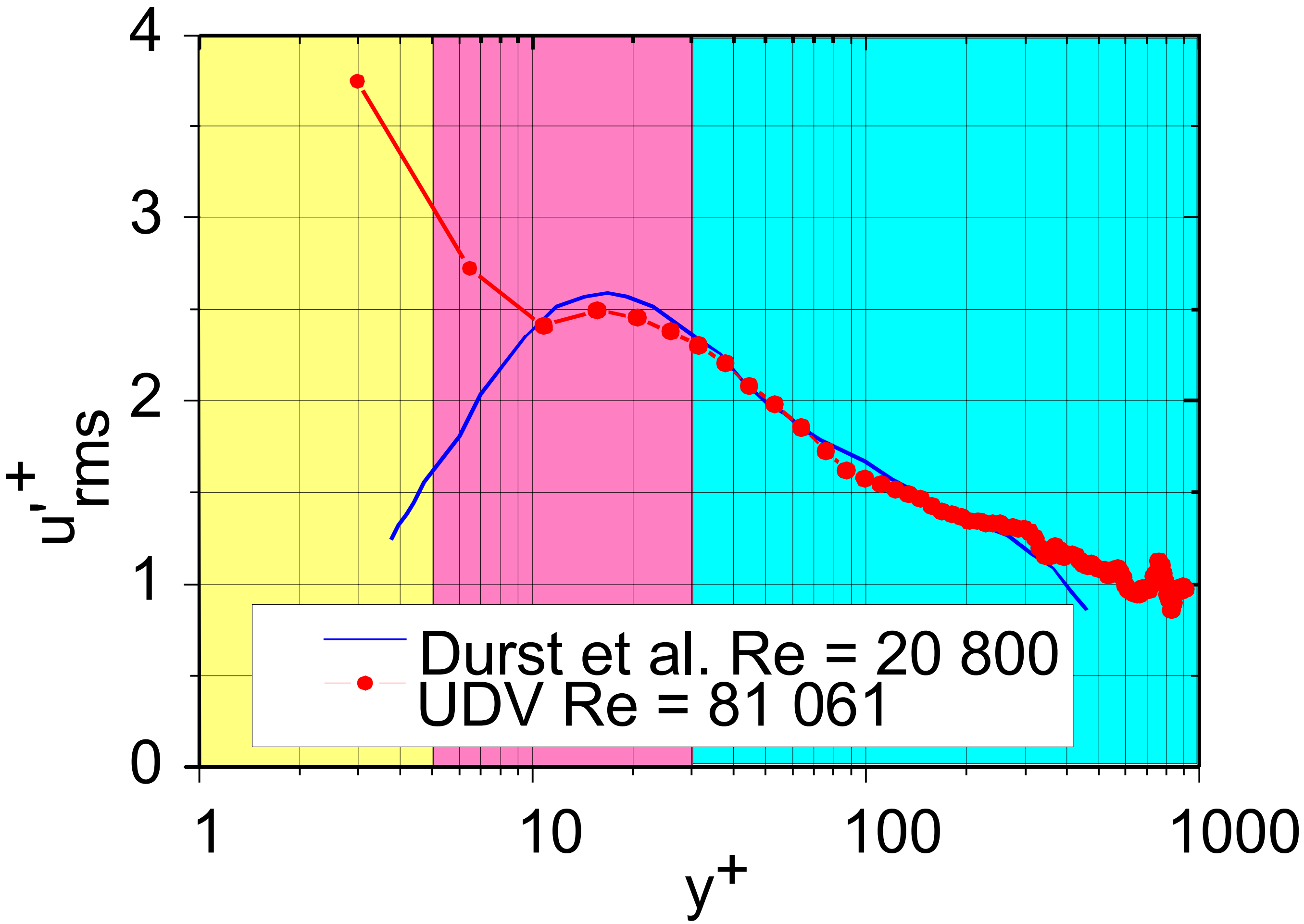


Transient start-up behaviour of
EM pump in THESYS Loop

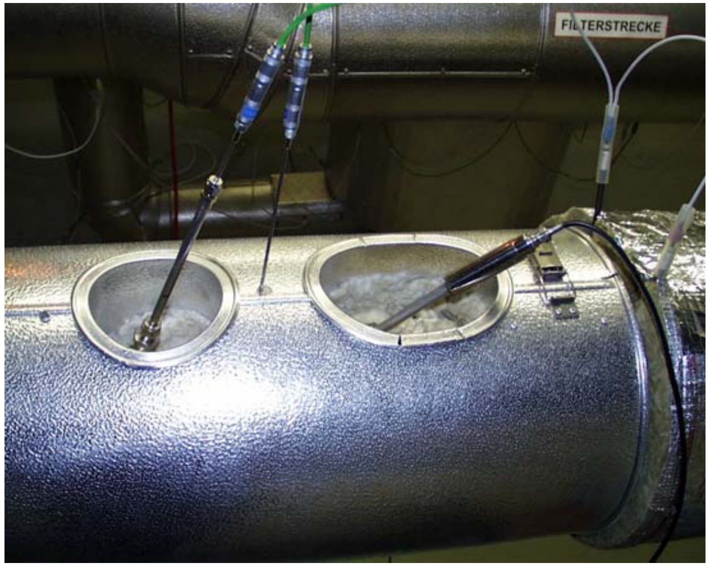
- Fluid temperature: 400°C
- Temperatur compensation durch (Wave Guide)
- Inclination angle: 45°
- Tube diameter: 60 mm

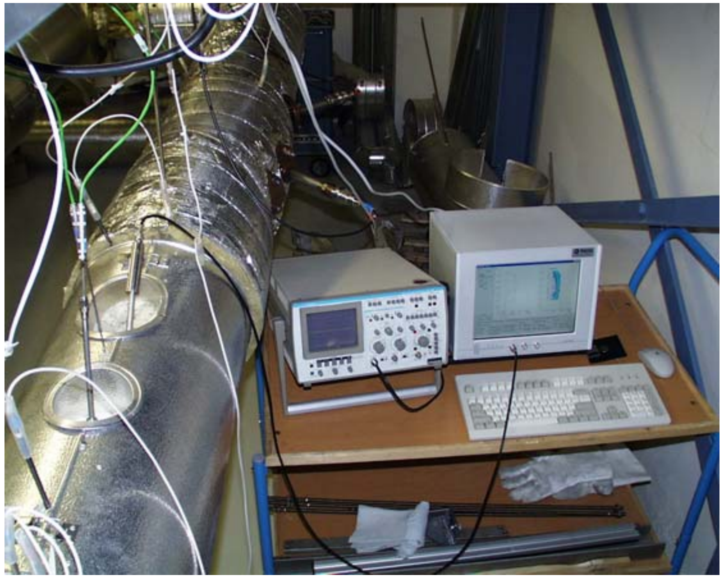


UDV Fluctuation measurements in boundary layer in a tube

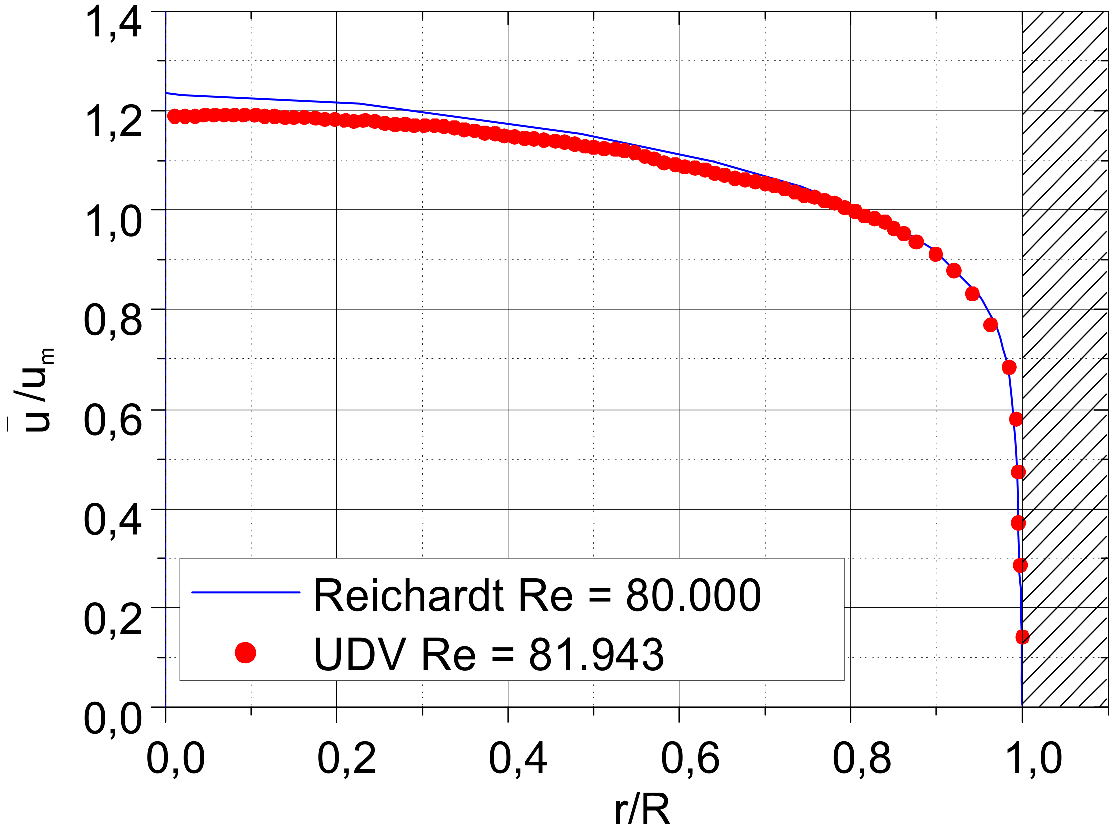


LM-Flow measurement





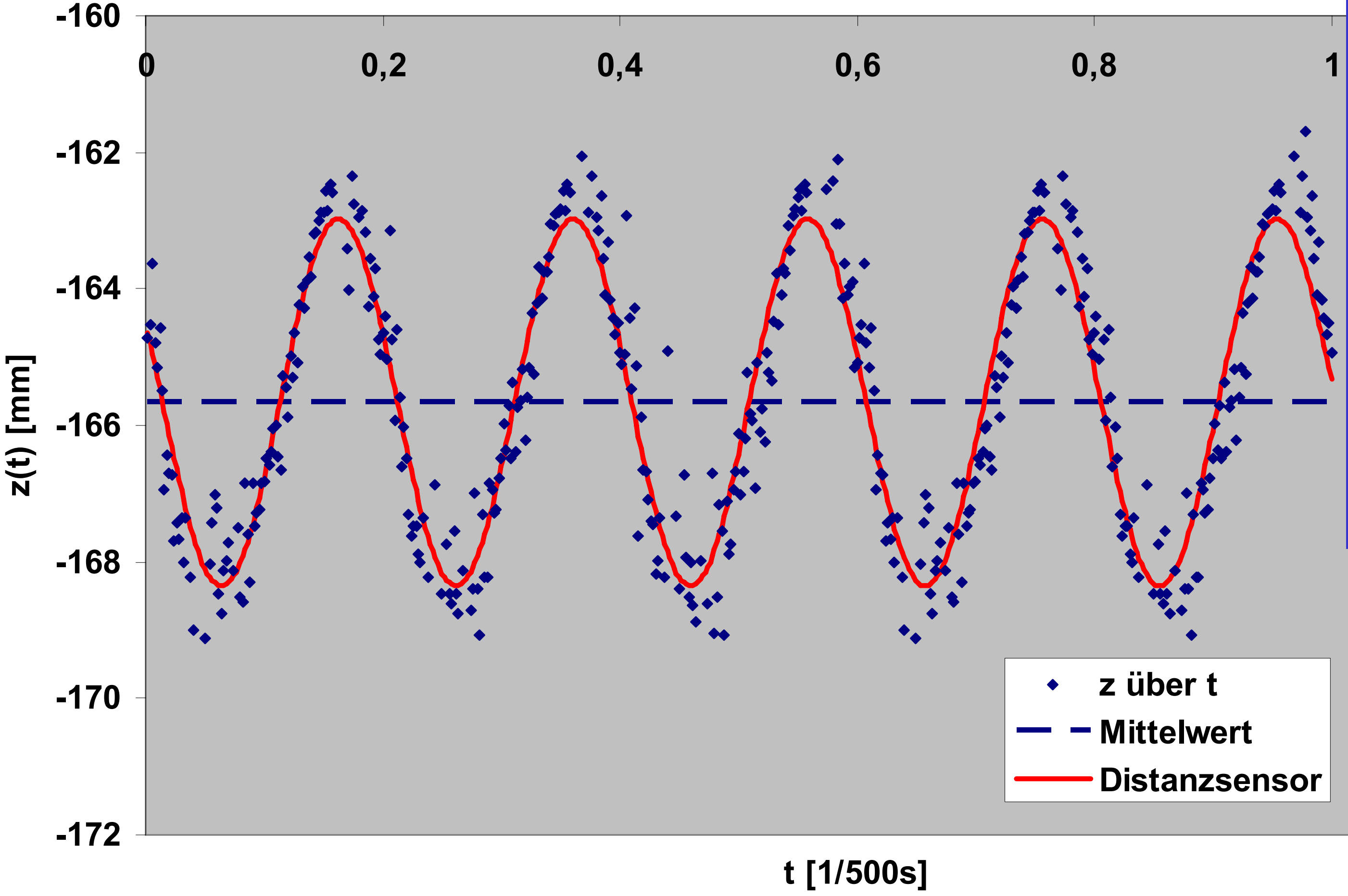
Ultra-Sound Doppler Velocimeter (UDV)



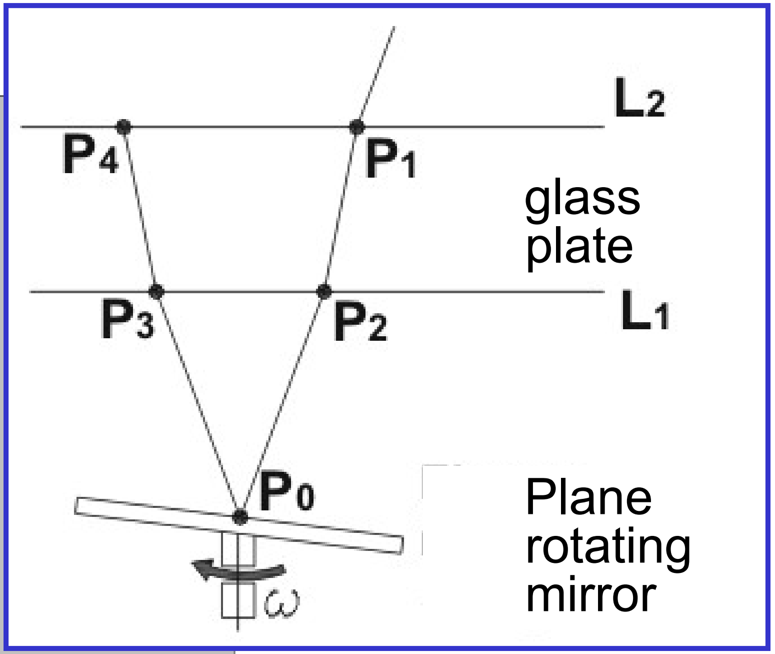
- Excellent agreement between measurement and literature profile
- Detailed resolution of the velocity profile
- Deviation from literature profile for r/R>0.6 less than 0.5%

PhD Thesis C.-H. Lefhalm 2004

LM-Free surface measurement



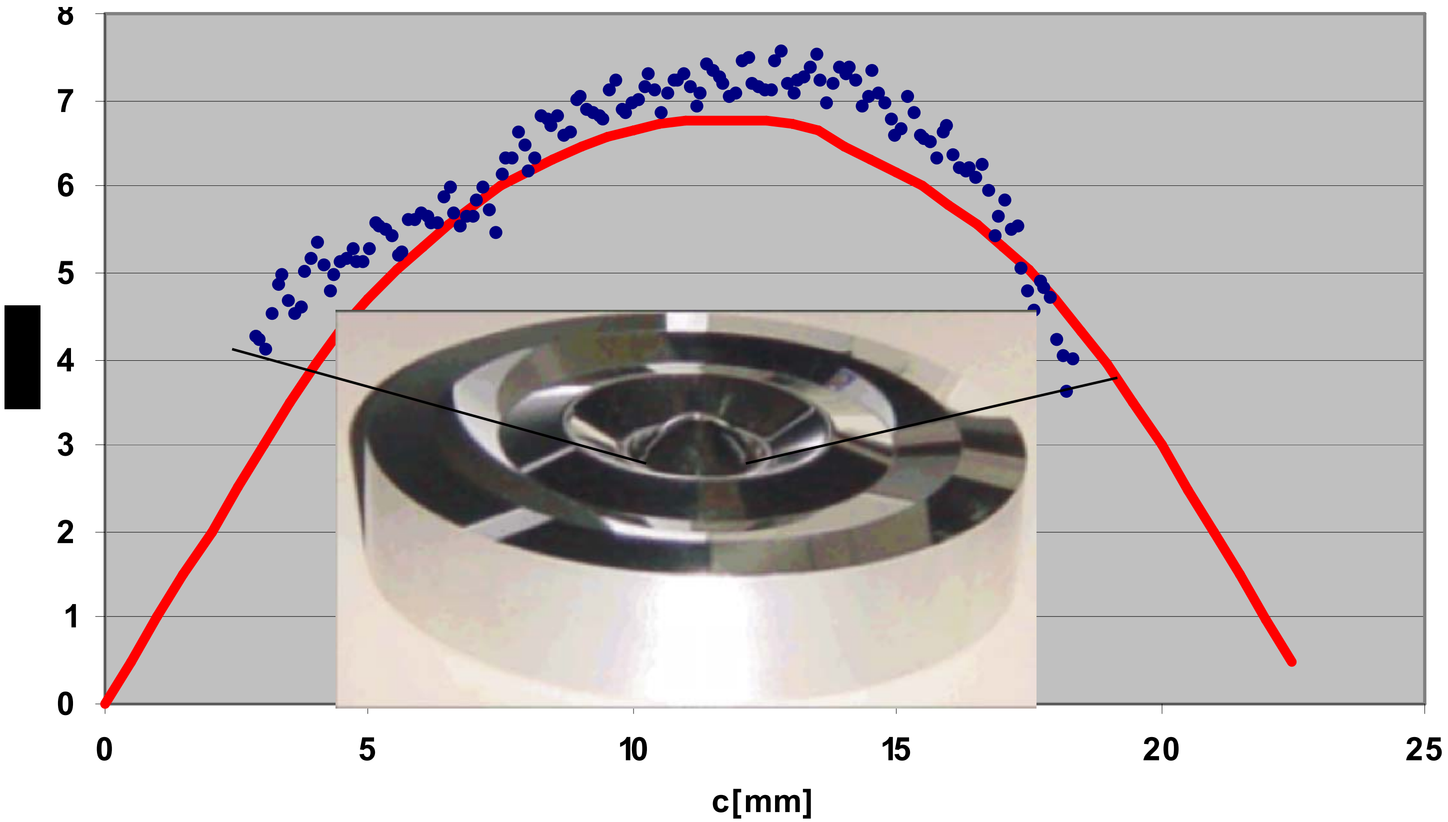
(rotating mirror)



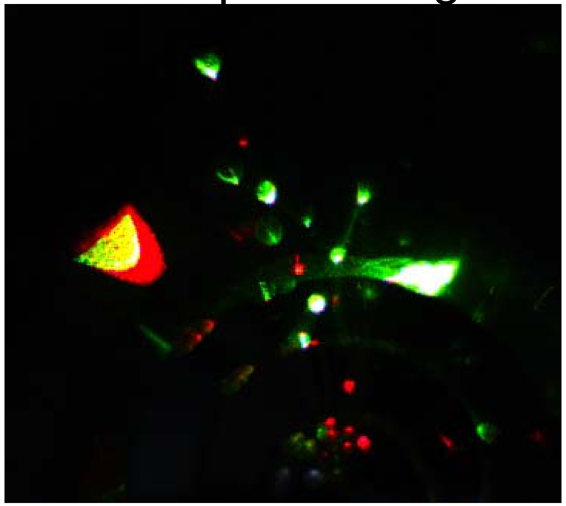
- **50Hz with 500fps**
- **92% valid Counts**
- **σ=0,57mm**

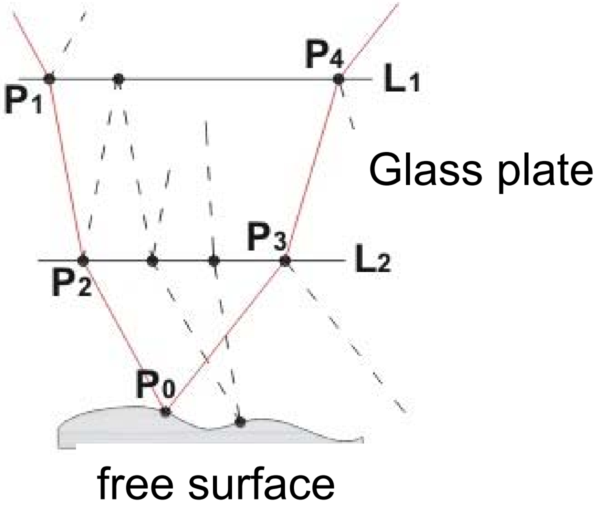
LM- free surface measurement

Validation at inclined known mirror surface



Typical frame picture before processing





Result

- Proof of principle (accuracy, spatial+temporal resolution) shown
- Optimization of algorithms (multiple reflection, calibration)
- Validation in LM experiment

CFD-Calculation strategies for liquid metal flows

Model-Procedure	Momentum	Heat	Time horizon	Comment
Mixed models	*k*-ε-model *k*-Ω-model hybrides (SST) (isotropic)	Reynolds Analogy Pr_t-correlations Pr_t=f(Re,Pr,y^+) +adequate wall functions for T^+	current near	isotropic in all scales WF, mesh,
TMBF model	*k*-ε-model (isotropic)	Transport equations $\overline{u'T'}, \overline{T'^2}, \varepsilon_{T'}$ (still problems with temp. variance dissipation)	near not in comm. codes	performance in conv. purely buoy. flow ? + low *Pe ?*
mixed higher order	kubic *k*-ε-model ASM RSM	Transport equations $\overline{u'T'}, \overline{T'^2}, \varepsilon_{T'}$ (Constants fort ransport eq. from DNS)	req. scientific benchmark	promising results (lacking exp. data)
Exact solution	DNS	DNS	future benchmark	

⬜	0th order direct coupling	🟩	2nd order Tensorial GDH
🟨	1st order Gradient diffusion hypotesis	🟥	exact solutions

- Model coefficients depend also (!) on *Re, Pr*, geometry
- Similar classification for LES