Karlsruher Institut für Technologie

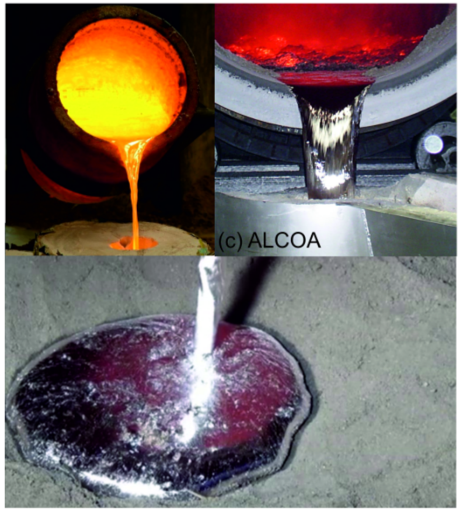
“Liquid metals in energy engineering”

R. Stieglitz, G. Gerbeth*[1], Th. Wetzel, E. Baake *[2], J. Fröhlich *[3]

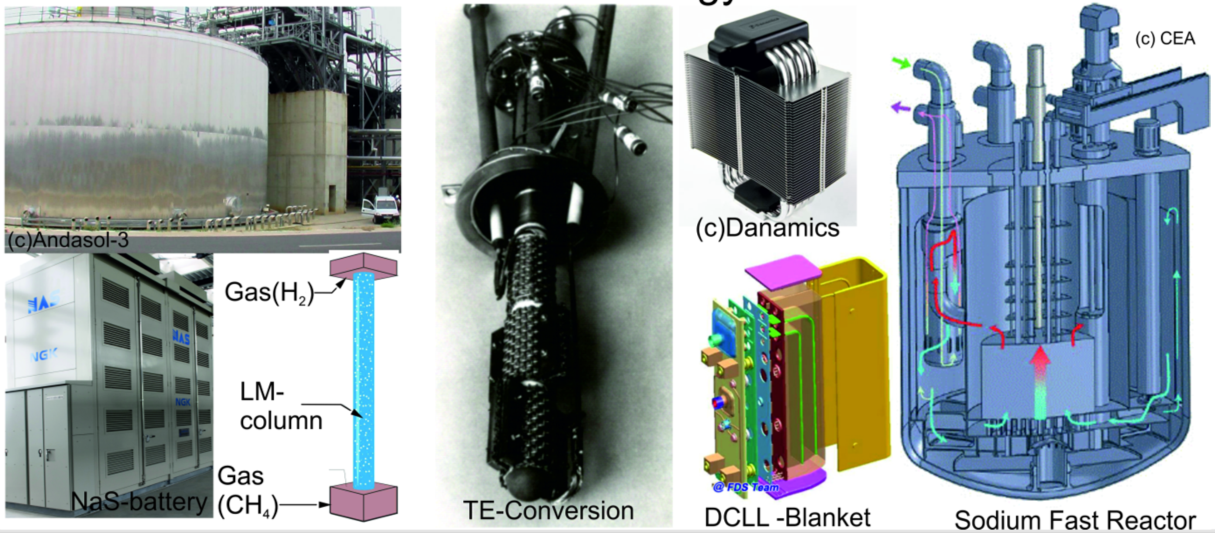
***[1] Helmholtzzentrum Dresden Rossendorf (HZDR)**
***[2] Leibniz Universität Hannover**
***[3] TU- Dresden**

Helmholtz-LIMTECH ALLIANCE

Processing/Refinement



Energy



Content

- **Where** liquid metals appear **?**
- **What** distiguishes liquid metals from others **?**
- **How to measure** in liquid metals ?
  - Problem of scalars,vectors associated with opaqueness
- Dynamics of transport in liquid metals
  - Momentum
  - Energy
  - Phases
  - Interaction with magnetic fields –Magnetohdyrodynamics (MHD)

– **Why** liquid metals behave different **?**

A glance at models, computational methods towards validation

- **Building** reliable liquid metal systems (some engineering) **?**
- **Summary**

Where ?

What ?

How ?

Why ?

Build ?

Technical Liquid Metal flows

Where ?

Karlsruher Institut für Technologie

History

- Liquid metals are known to mankind since about 6000 years (natural Mercury)
- Refinement & casting since more than 4000 years (bronze, copper)
- Iron production in Turkey since 3000 years
- Alumina and Al alloy production on large scales in the last 200years
- Human progress without liquid metals not imaginable

➡ **About 5% of electricity consumption in Europe by Al-production***

Industrial interest:

- Adaptive materials
- Minimization of primary energy input
- High demand on quality of surfaces

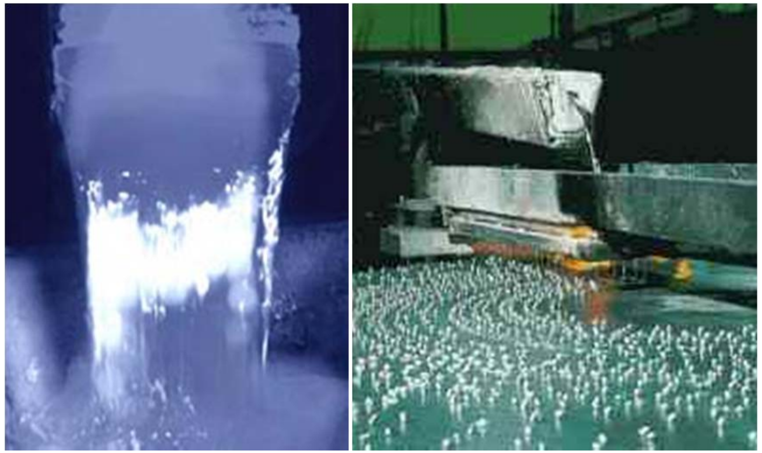
Requirements:

- Measurement techniques
- Transport phenomena
- Free surfaces
- Active components (engineering)
- phase change problems

Liquid mercury in glass capsule

Bronze casting

Raw iron refinement



Alumina preparation for casting

* www.world-aluminum.org

Conventional: High performance HEX

Where ?

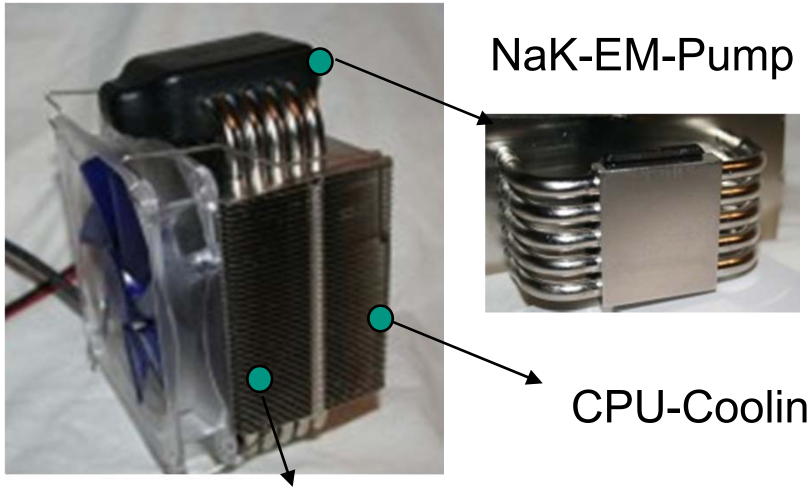
Background: CPU-Cooling

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

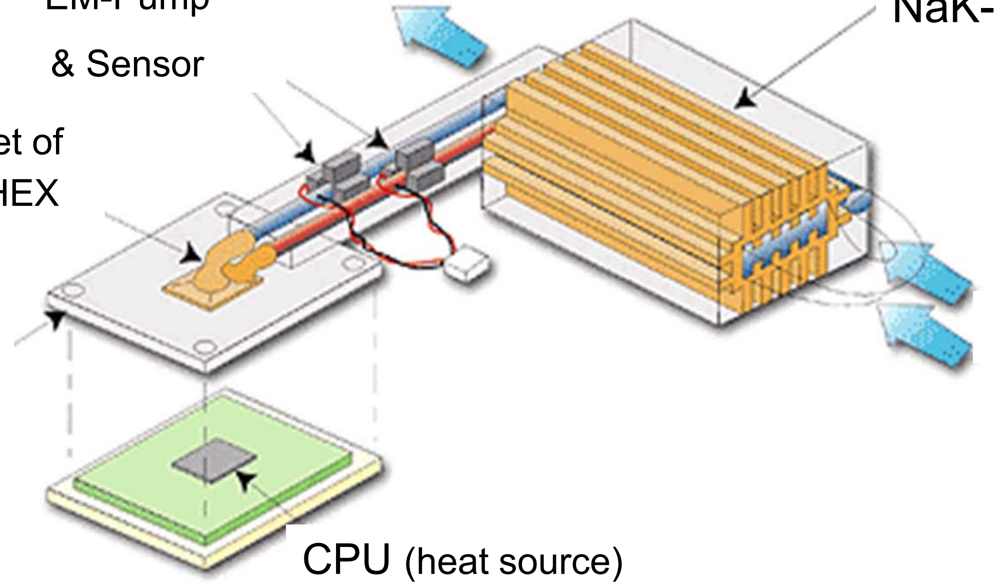
➡ Forced convective cooling with low ΔT in chip structures

➡ Use of liquid metals (NaK, GaInSn)

© DANAMICS LM10



NaK-Air-HEX



CPU (heat source)

Thermal storage in CSP -Plants

Where ?

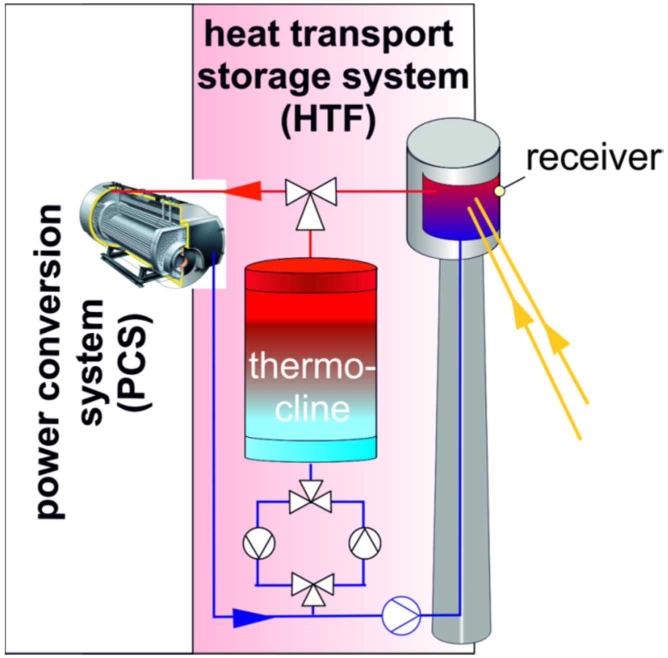
Motivation for liquid metals

- higher temperatures ➡ higher efficiency
- high conductivty ➡ high power density
- excellent heat transfer ➡ fast system response
- low pressure ➡ simple civil engineering

➡ Compact systems

Alkali metals

- direct thermo-elec. conversion ➡ efficiency gain



Fluid	Thermal oil at 300°C	Solar salt at 550°C	Air at 600°C, 1 bar	Na (600°C)	PbBi (600°C)	Sn (600°C)
T_{min} [°C]	12	228	-195	98	125	232
T_{max} [°C]	450	560	n.n.	883	1533	2687
ρ [kg/m^3]	812	1903	0,39	808	9660	6330
η [$mPa*s$]	0,22	1,33	0,03	0,21	1,08	1,01
c_p [$kJ/(kg\ K)$]	2,30	1,50	1,12	1,23	0,15	0,24
λ [$W/(m\ K)$]	0,11	0,52	0,06	63,0	12,8	33,8

Thermo- electric conversion

Principle

- β''-Alumina solid electrolyte
- Key process: Na-ionization
  (Δp across electrolyte)

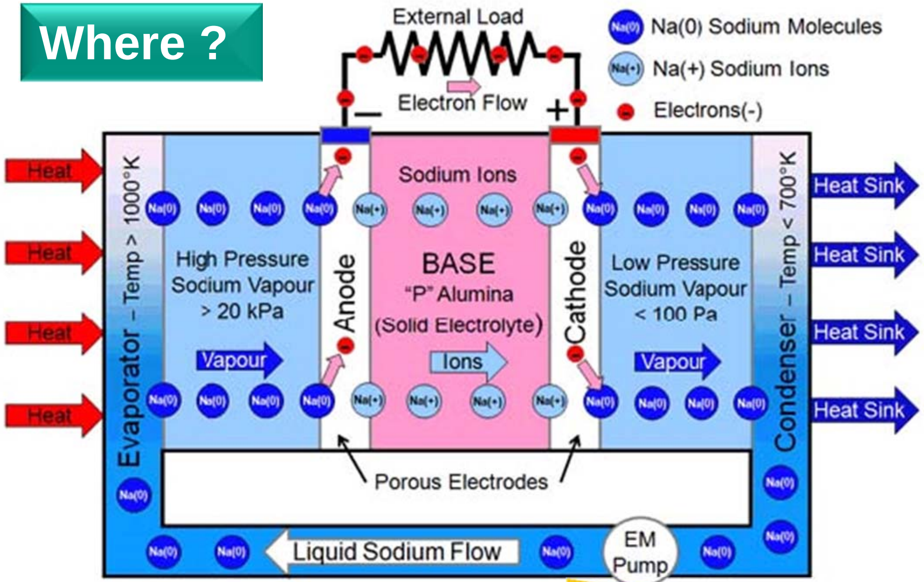
Na ➡ $Na^+ + e^-$

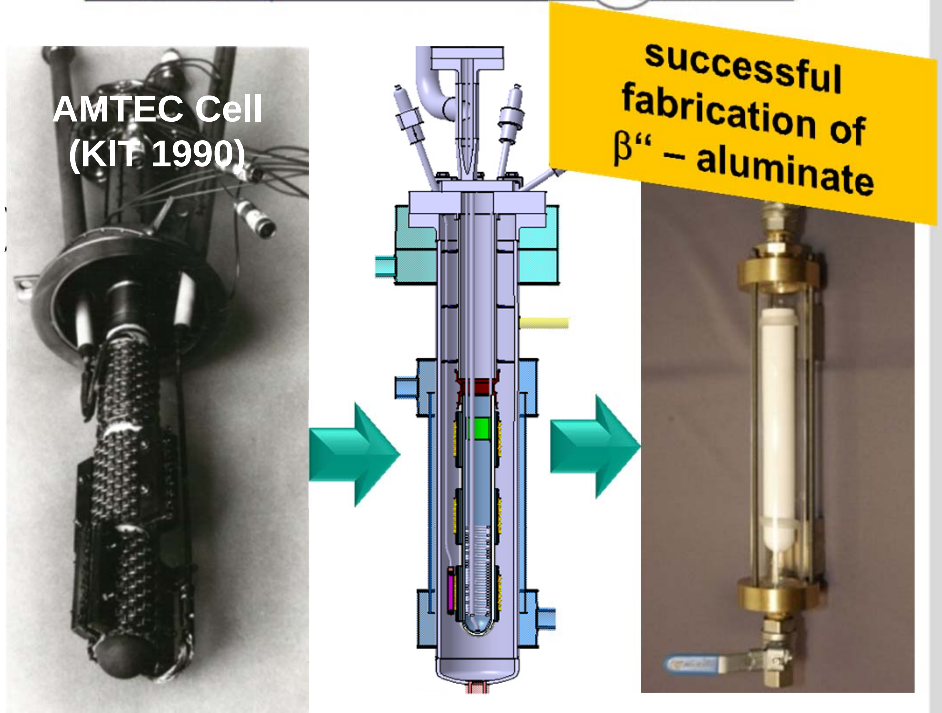
- Anode: p~1-2bar; T~600-1000°C
- Cathode: p < 100 Pa; T~200-500 °C

AMTEC perspective

- topping cycle of CSP Plant (η_{AMTEC}>30%)
- return heat sufficient for power plant operation (PCS and/or storage)

Where ?





H_2 production by thermal cracking of CH_4

Where ?

Motivation

- large electricity consumption of electrolysis
  @ fairly low efficiencies

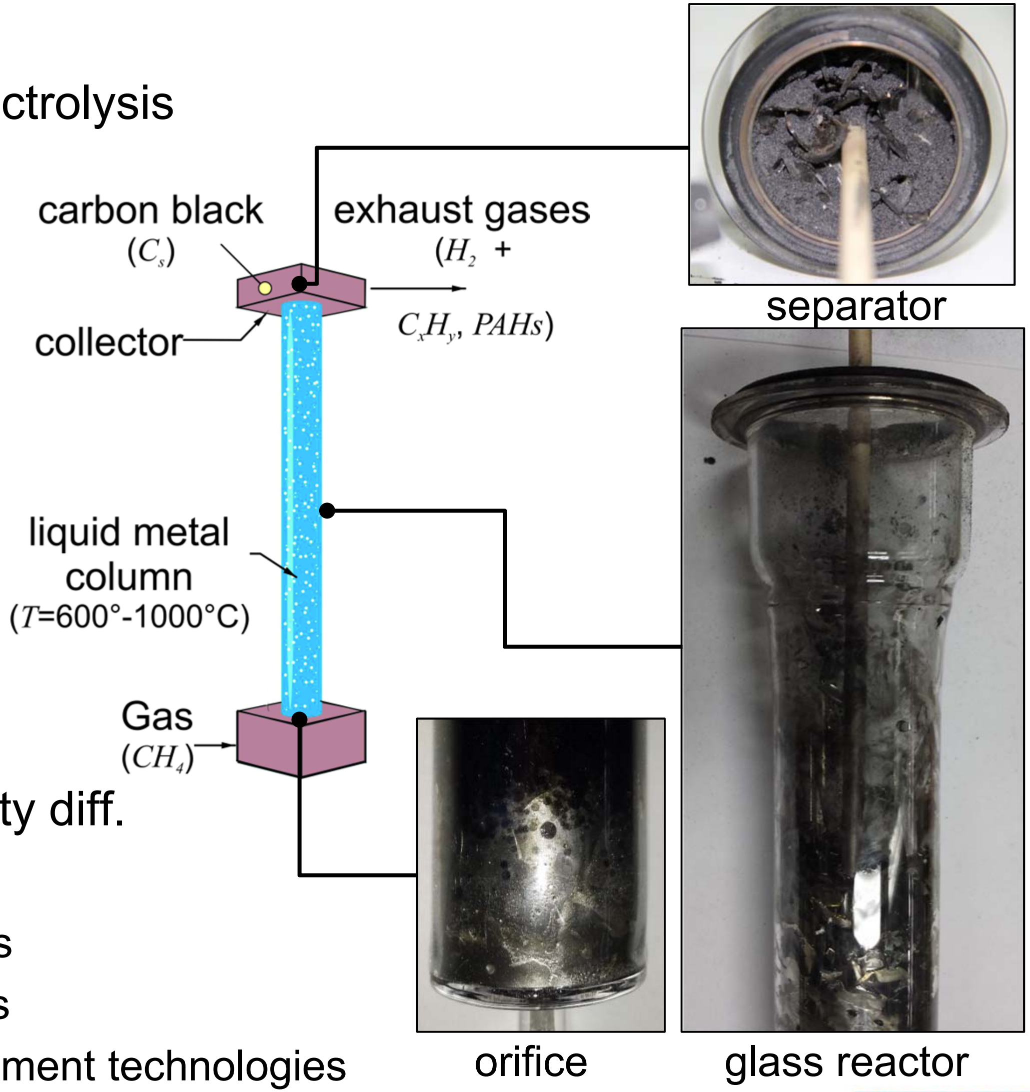
Idea

- enlarged reaction rates
  by high contact areas

$$CH_4 \leftrightarrow C + 2H_2 \quad + 74{,}85\, kJ/mol$$

Achievements &challenges

- ✓ CH_4 cracking success using Sn
- ✓ separation of C functional by density diff.
- efficiency to be improved
  - optimization of process parameters
  - understanding of bubble dynamics
  - experimental validation ➡measurement technologies



Liquid metal batteries

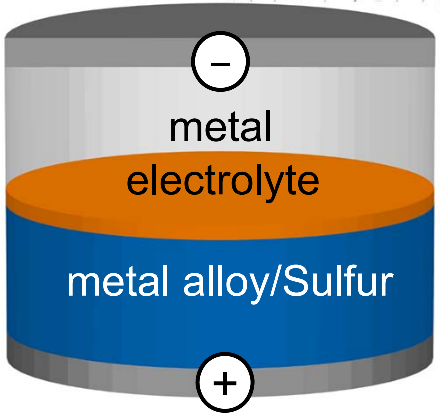
Where ?

„A quite old idea „

Advantages

- simple construction
- cheap abundant materials
- high current densites (>1kA/m^2 compared to Li$^+$ <10A/m^2)
- high cycle life time (hardly irrev. reactions)
- low energy costs \$/kWh*

Principle

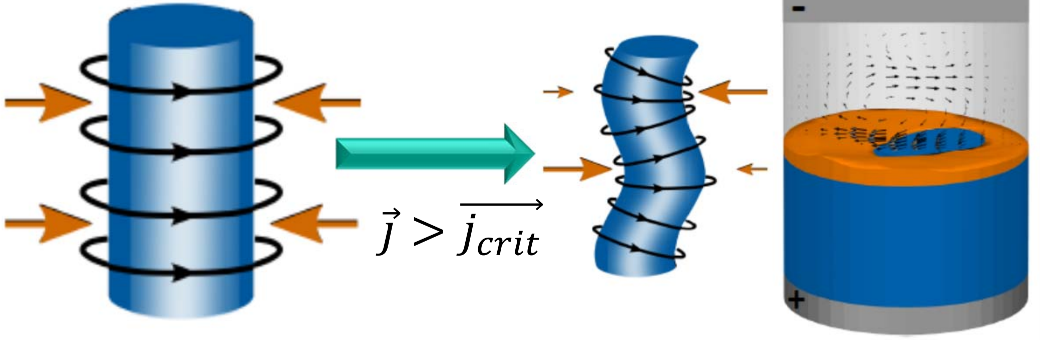


but

- high temperatures (>250°C)
- low cell voltage
- susceptible to flow instabilities
  - Tayler –Instability
  - Electro-Vortex flows
  - Marangoni-Convection
  - Rayleigh Benard- Convection
  - ….

$$\vec{F} = \vec{j} \times \vec{B}$$

Tayler-instability[*2]



- Commercial vendor in MWh range

© NGK-34MWh-Wind farm storage

*Kim et al., 2013, Chem. Rev.

[*2] Weber et al,2013 N.J.Phys

Nuclear Fission: Fast Spectrum Reactors (Na/Pb)

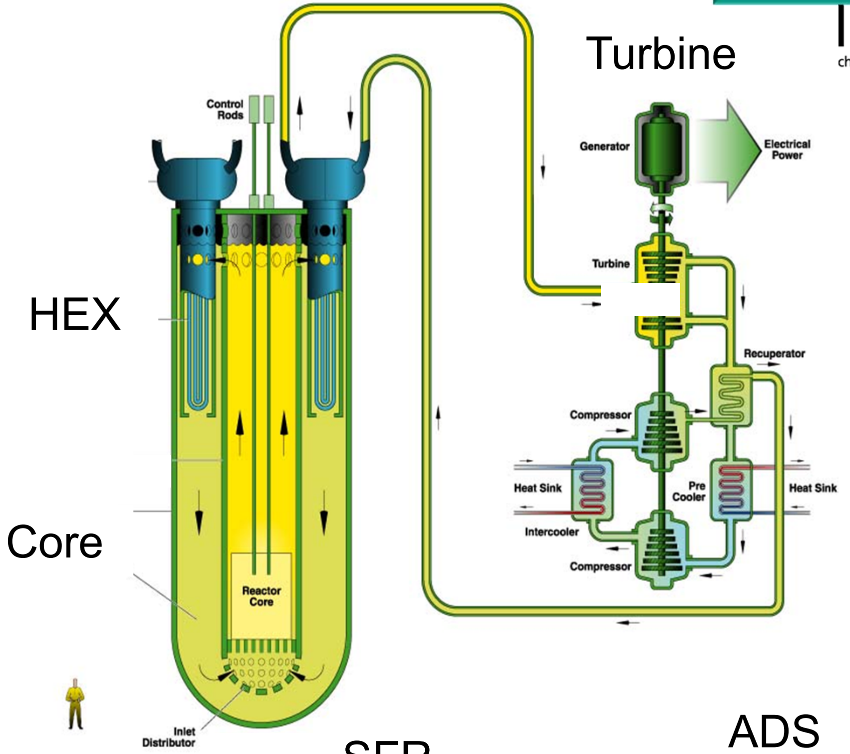
Where ?

Aim

- Potential for transmutation of MA (➡reduction of radiotoxicity
- Better nuclear fuel utilization

Utilization & challenges

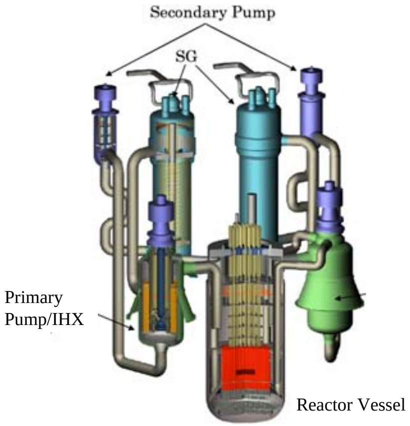
- High Temperature applications (electricity, hydrogen prod.)
- Single phase heat transfer in primary system.
- Liquid metal component development & monitoring at high temperatures.

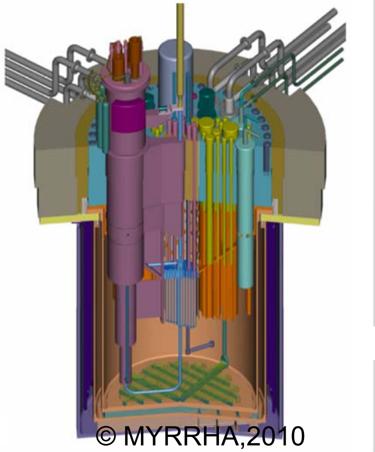


SFR

ADS


© Kundakulam NPP



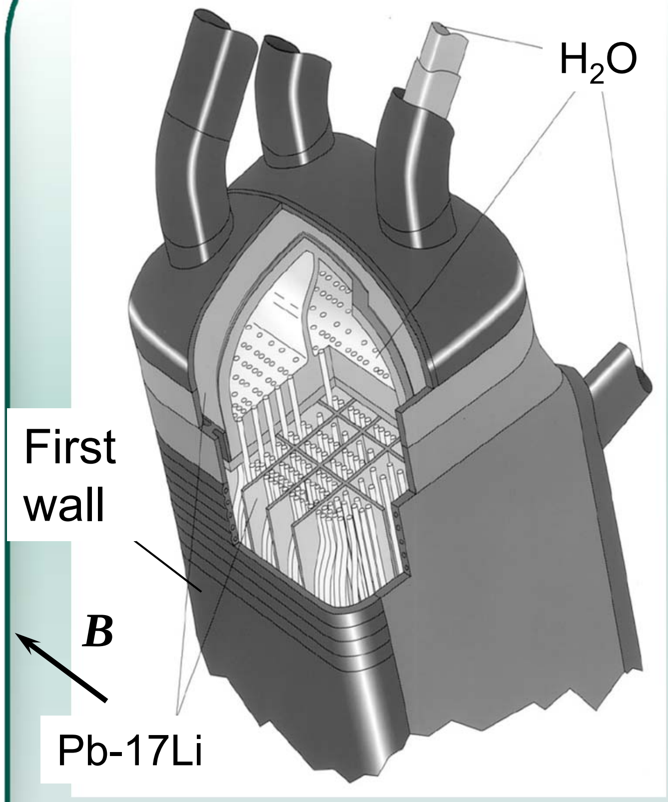

© MYRRHA,2010

Fusion: Liquid metal blankets

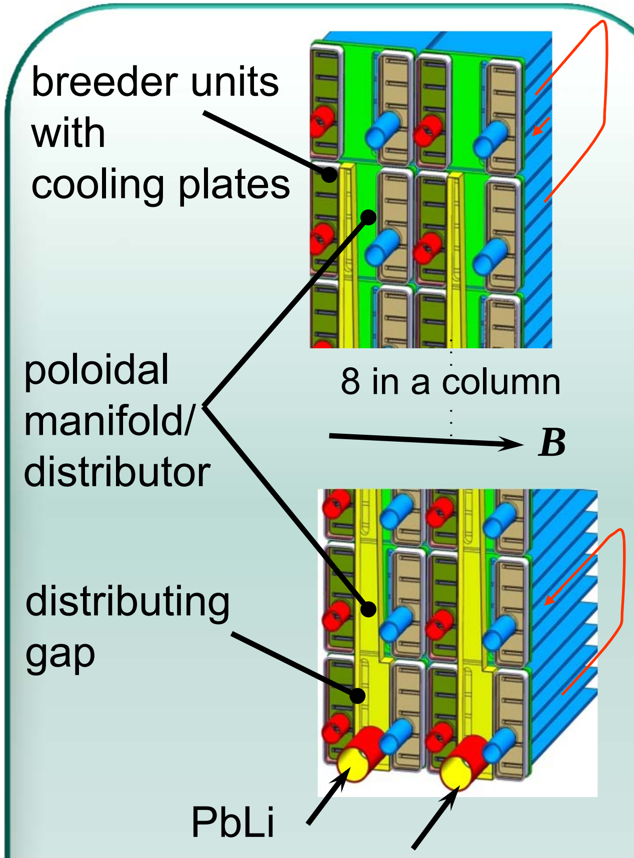
Where ?

Blanket functions:

- heat removal
- fuel breeding (by $Li - n$-multiplication by Pb)
- magnet shielding



a) Water cooled blanket - WCLL (Giancarli et al. 2000)



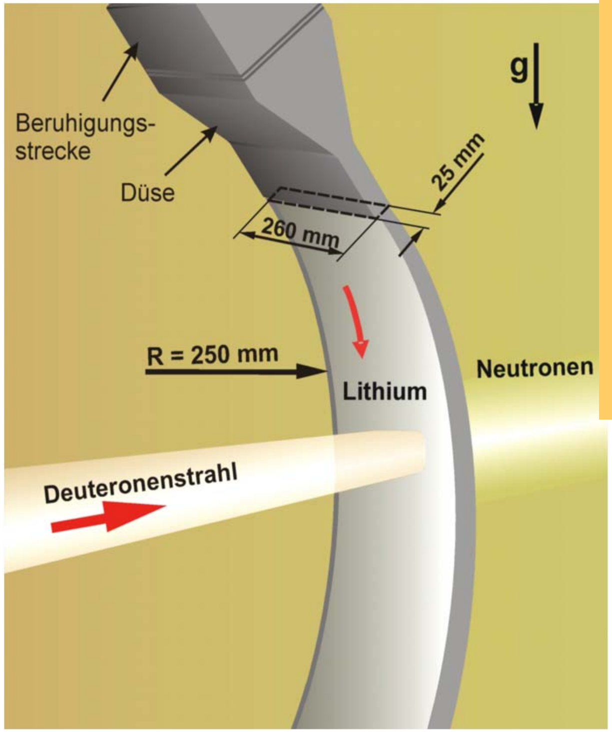
b) Helium cooled blanket HCLL (Giancarli et al. 2000)

Nuclear Fusion: IFMIF (Int. Fusion Material Irradiation Facility)

Where ?

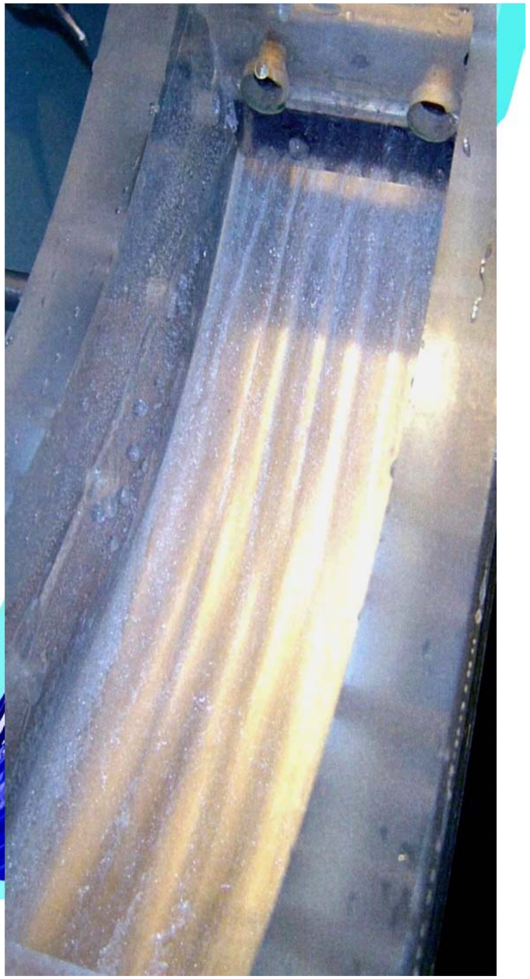
Targets:
- Secondary particle production (neutrons, fragments,..
- Heat removal

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.



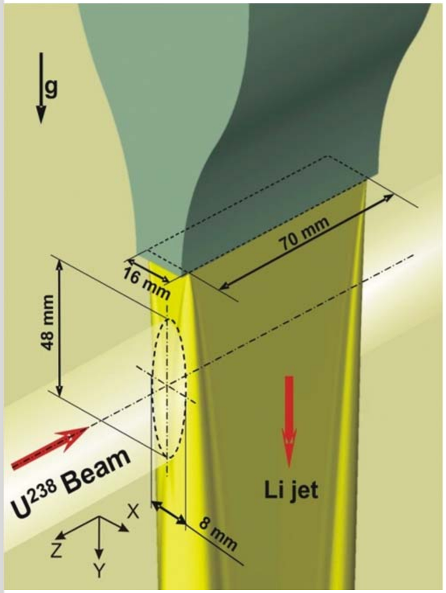
R. Stieglitz et al.

Nuclear Physics: Super-FRS-Target

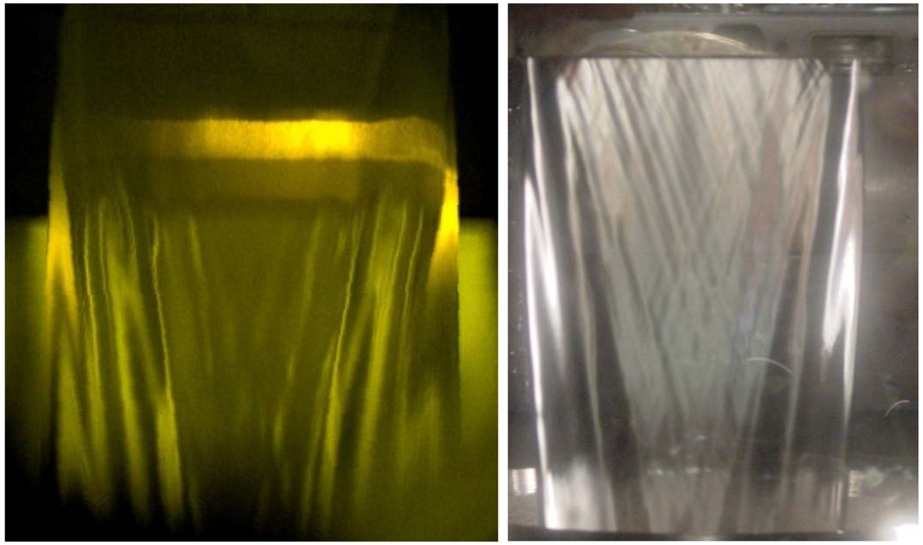
Where ?

- 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

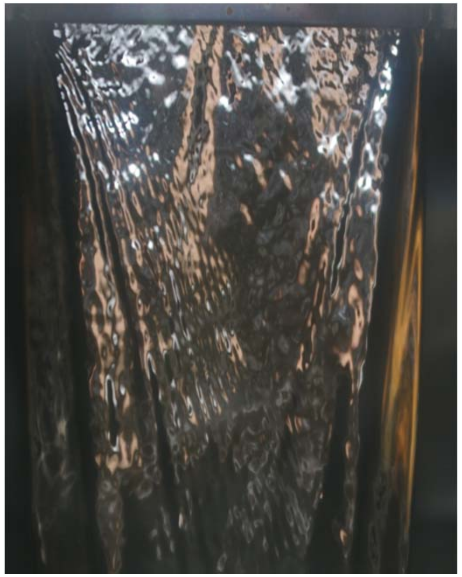
Set-Up



water u_0=2.5m/s

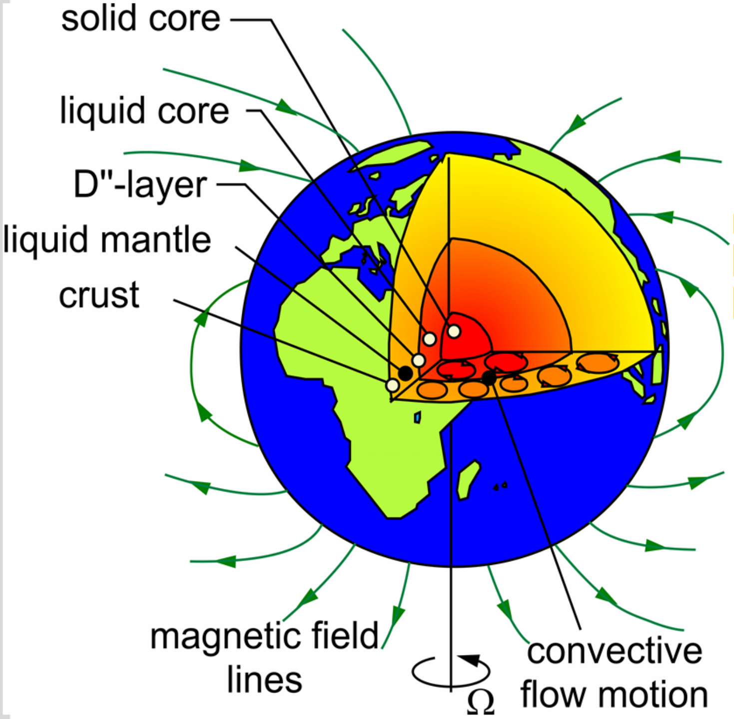


sodium u_0=2.5m/s

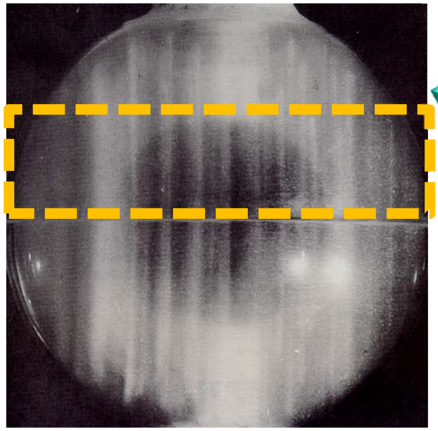


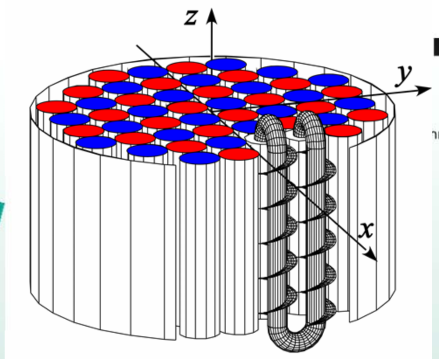
Planetary dynamos

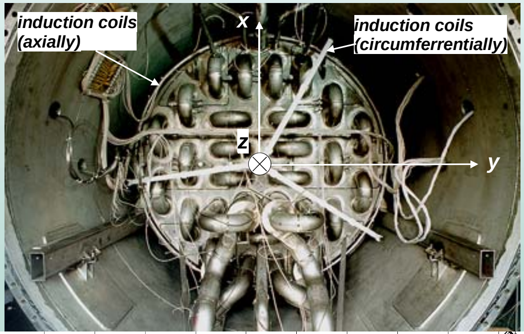
Where ?

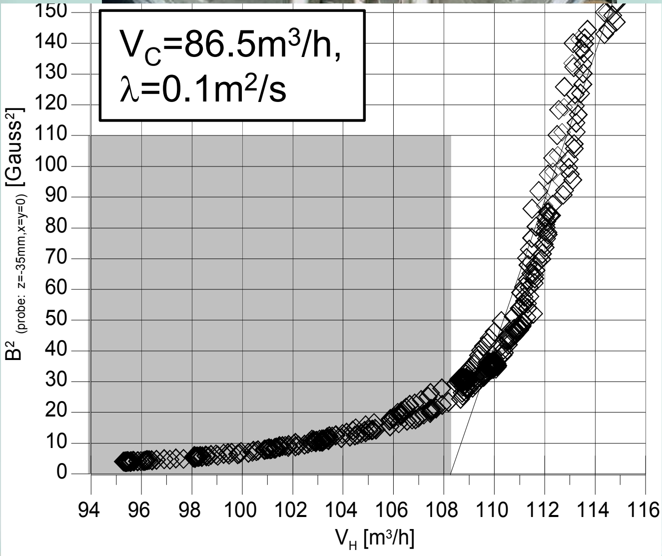


Carrigan ,1985









- exp. proof

Idea

- Coriolis-forces
- Eckman-pumping
- buoyant convection

→ kinemat. dynamo

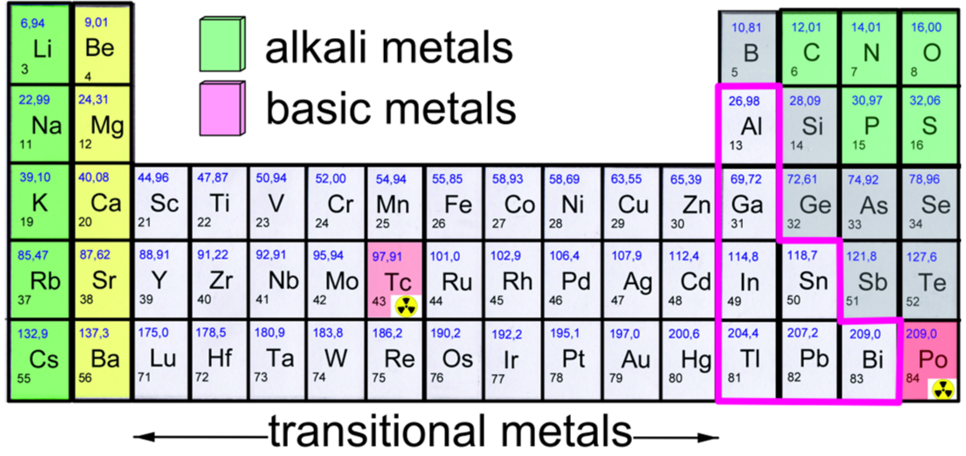
- approximation of flow pattern
- forced convection

* Stieglitz, 2000,2001 ; Phys.Fluids, Science

What distiguishes liquid metals from other liquids ?

Elements suitable for engineering ?

- alkali-metals (Li, Na,K+alloys)
- basic metals (Pb,Ga,Sn+alloys)



	Li	**Na**	**Na^{78}K^{22}**	**Pb**	**Sn**	**Pb^{45}Bi^{55}**	**Ga^{68}In^{20}Sn^{12}**	**Hg**
T_{melt} [°C]	180	98	-11	327	232	126	11	-39
$T_{boiling}$ [°C]	1317	883	785	1743	2687	1533	2300	356
ρ [kg/m3]*	475	808	750	10324	6330	9660	6440	13534
c_p [J/(kgK)]	416	1250	870	150	240	150	350	140
ν [(m^2/s)· 10^{-7}]	7.16	2.6	2.4	1.5	1.6	1.1	3.7	1.1
λ [W/(mK)]	49.7	67.1	28.2	15	33	12.8	16.5	8.3
σ_{el} [A/(Vm)·10^5]	23.5	50	21	7.8	15.9	6.6	8.6	5.7
σ [N/m·10^{-3}] @ T=300°C	421	202	110	442	526	410	460	436

* @ T=600°C, p=10^{5}Pa, except GaInSn, Hg (T=20°C)

What ?

What distiguishes liquid metals from other liquids ?

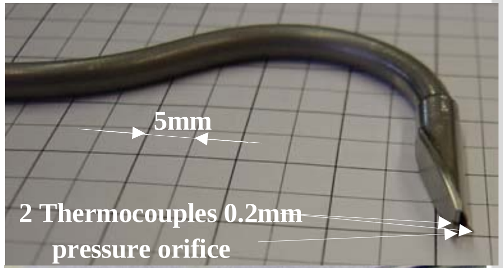
General findings ➡ technical impact

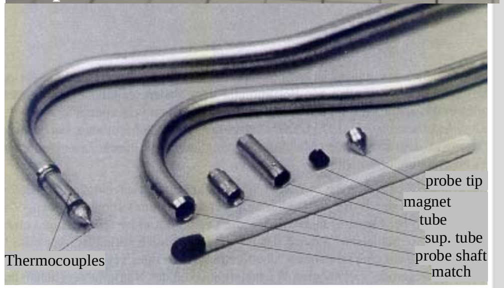
- low kinematic **viscosity** ➡ turbulent flow $(\nu_{H2O}\sim 10\text{-}6 m^2/s)$
- high **heat conductivity** ➡ scale separation of thermal from viscous boundary layer $(\lambda_{H2O}\sim 0.6 W/(mK))$
  ➡ time separation of temperature and velocity fluctuations (different damping !!!!)
- high surface **tension** ➡ different bubble transport/interaction mechanisms
  ➡ scale separation of velocity field and surface statistics (high retarding moment) $(\sigma_{H2O}\sim 52 mN/m))$
- high elec. conductivity ➡ velocity field modification by strong fields due to $(\vec{v}\times\vec{B})$ (Magnetohydrodynamics)
  ➡ measurement access by electromagnetic means
  ➡ pumping (MHD-Pumps) and/or flow control
- **opaque** ➡ no optical access
- high boiling points ➡ wide operational temperature threshold (ΔT)
- Complex **chemistry** ➡ alkali metals with Group V, VI,VII elements
  ➡ exotherm. reactions
  ➡ heavy metals weak reactions with Group V-VII but
  ➡ dissolution transitional metals (structure materials !!!)

How ?

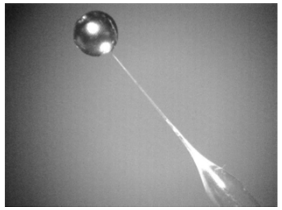
How to measure in liquid metals ?

- **Flow rate** – electro-magnetic, Δp, UTT, momentum based ……..
- **Visualization techniques**
  - direct – X-Ray tomography
  - indirect – CIFT,
    Utra-sound-transient time (UTT),….





- **Velocity**
  - direct – Pitot-Tube (Δp)
    – magnetic potential probes (MPP)
    – fibre-mechanics

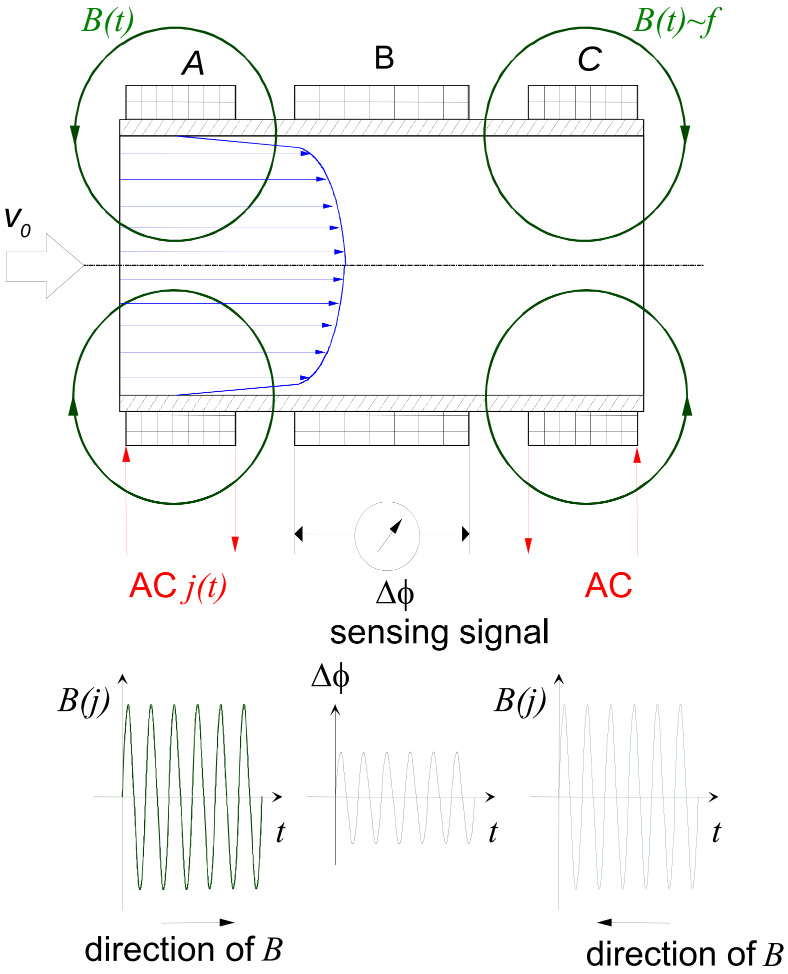


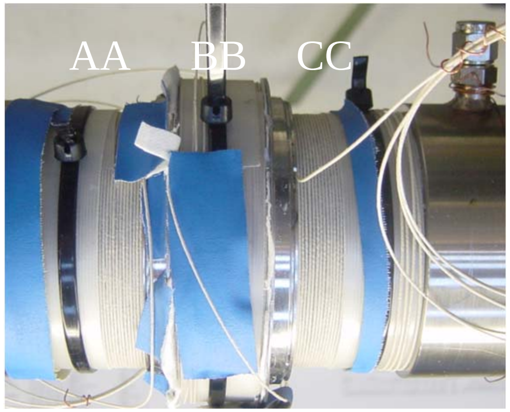
  - Non-intrusive – Ultra-sound doppler velocimetry (UDV), multi units ➡ mapping
- **Surfaces /2-phase**
  - direct – resistance probes
  - Indirect – X-ray, UTT
    – optic means for surfaces

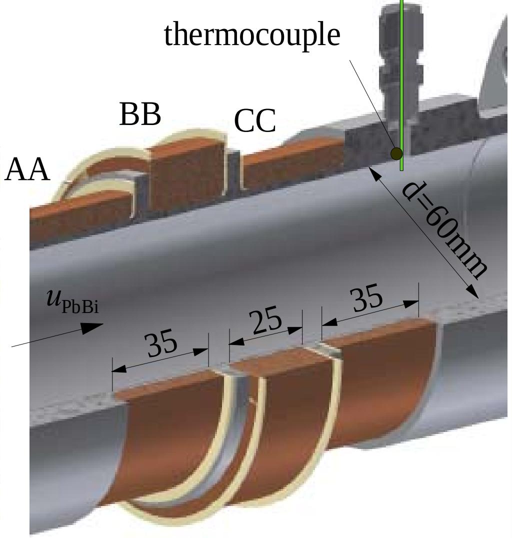
Measurement: Flow rate

How ?

Electro-magnetic frequency flow meter (EMFM)







Measurement principle

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

$$Re=\frac{u_0\cdot d}{\left(\frac{1}{\mu\sigma}\right)}$$

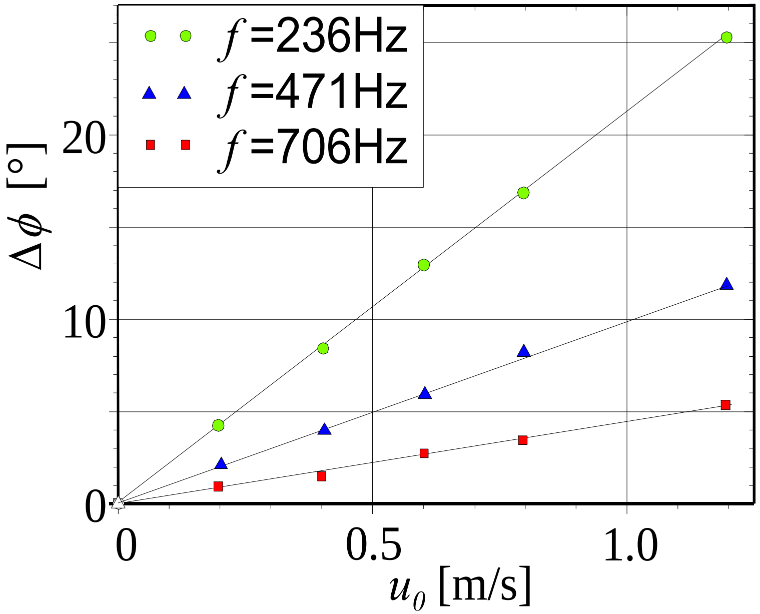
- flow direction given by sign of signal
- time delay between Emitter-Sensor (or Phase Angle) **Δ*t*~*Q***

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

Th. Schulenberg, R. Stieglitz, NED 2010.

Measurement: Flow rate-EMFM

How ?



Conds. : PbBi tube flow, T_0=200°C, Pr=0.02, d=60mm, I_0=410mA

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

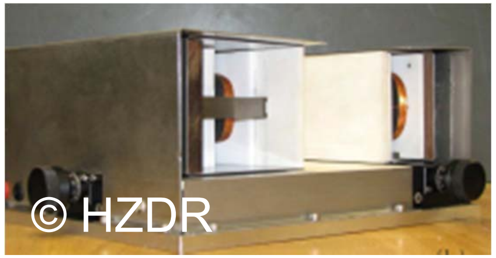
- Low f yield high sensitivity to ambient stray signals
- High B modifies the flow Hartmann number Ha<<1 (Ha=(EM-forces/viscous forces))

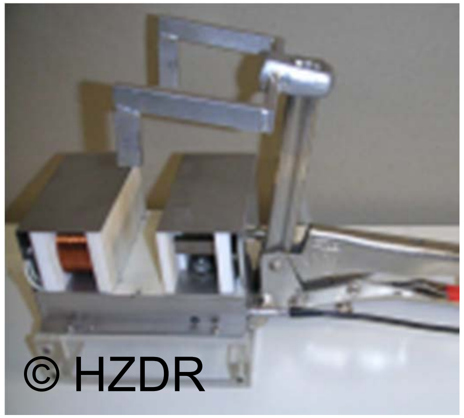
$$Ha = d \cdot B\sqrt{\frac{\sigma}{\rho\nu}}$$

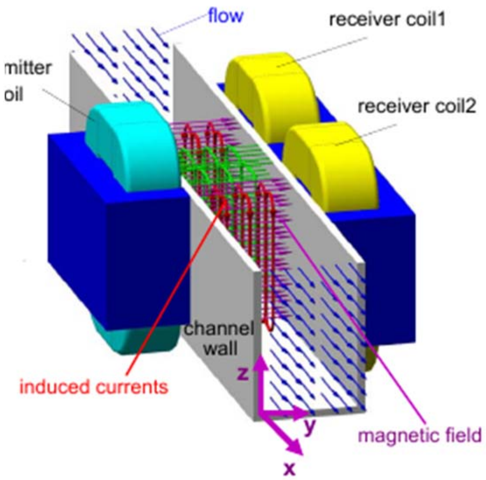
- Too large f yield skin-effect $f\, d^2\, \mu\, \sigma << 1$

Other designs

- clamp on systems

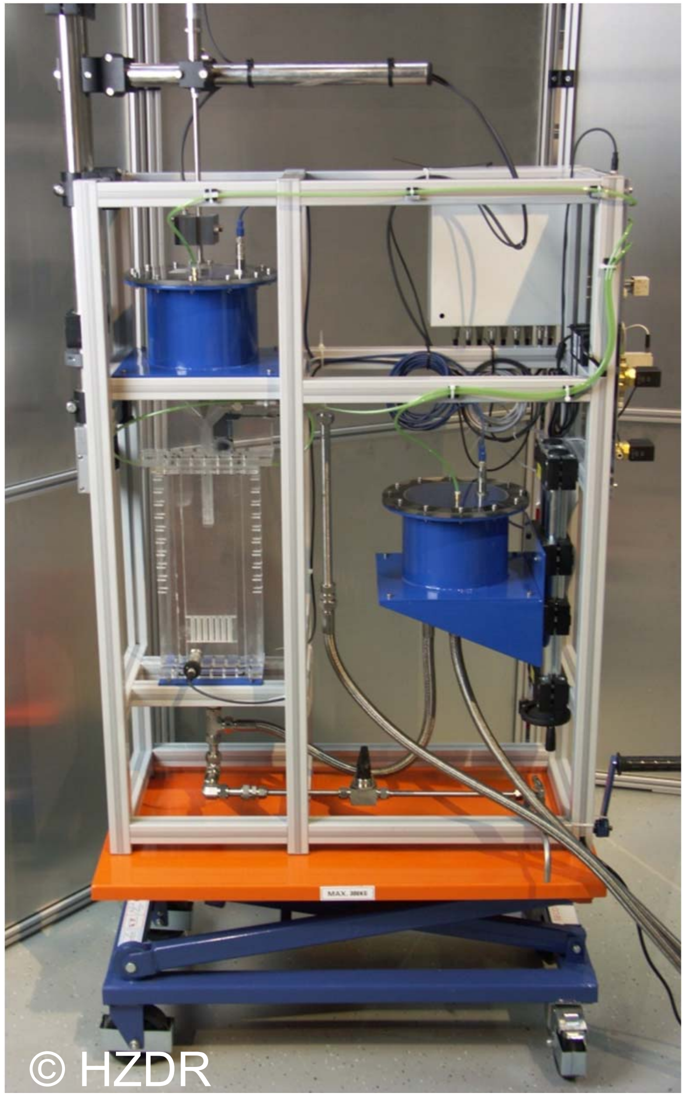






Measurement: flow visualization- 2 phase-flow

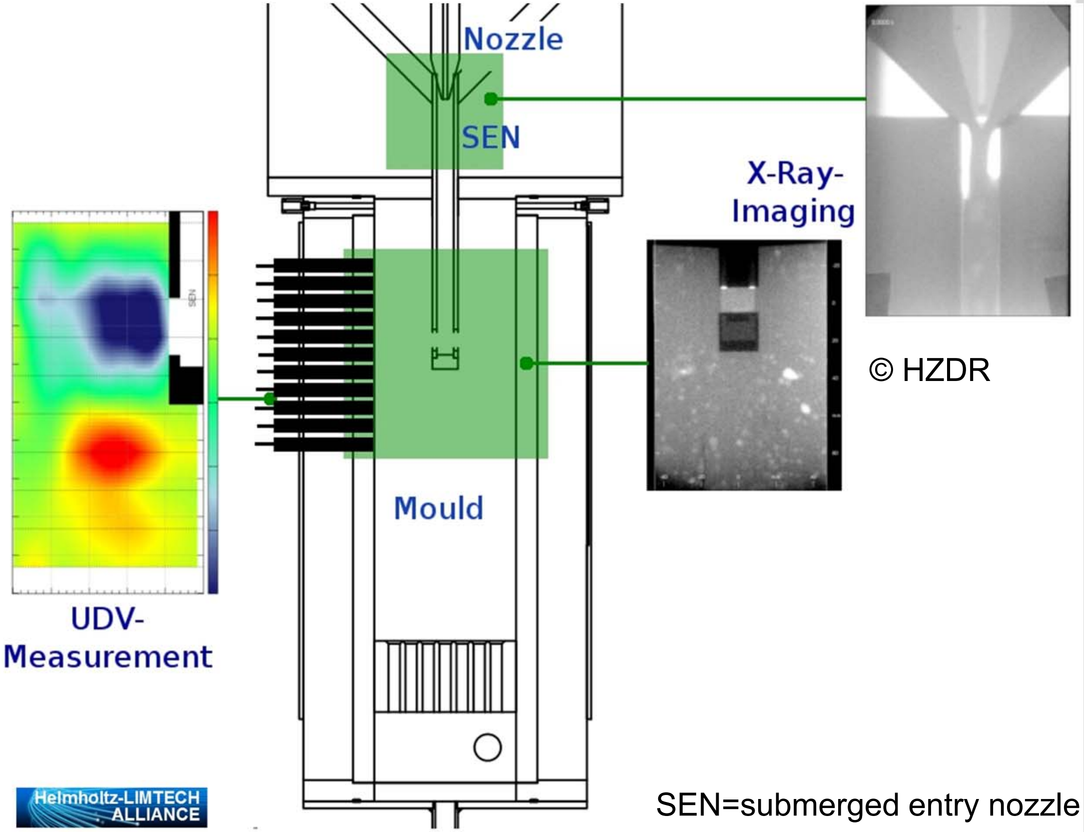
How ?



Main feature:

- X-ray visualization of two-phase flows
- Restriction of the mold size in beam direction

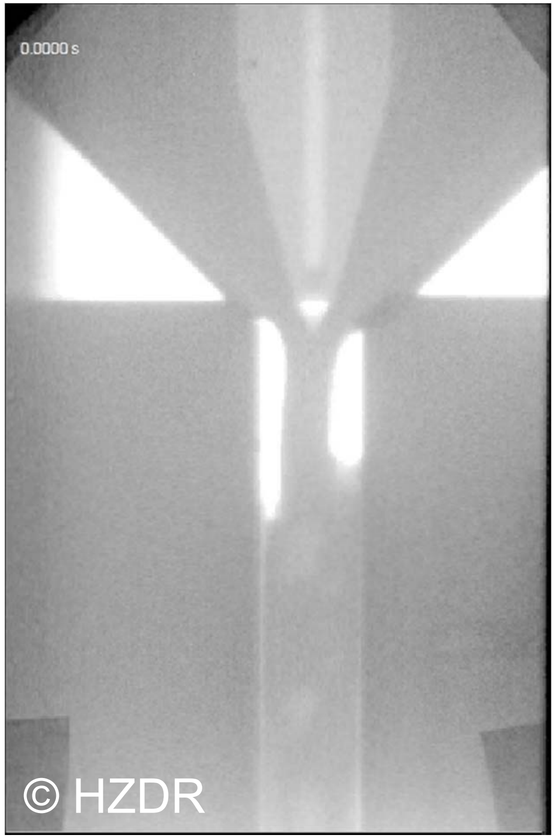
Example : LIMMCAST @ HZDR

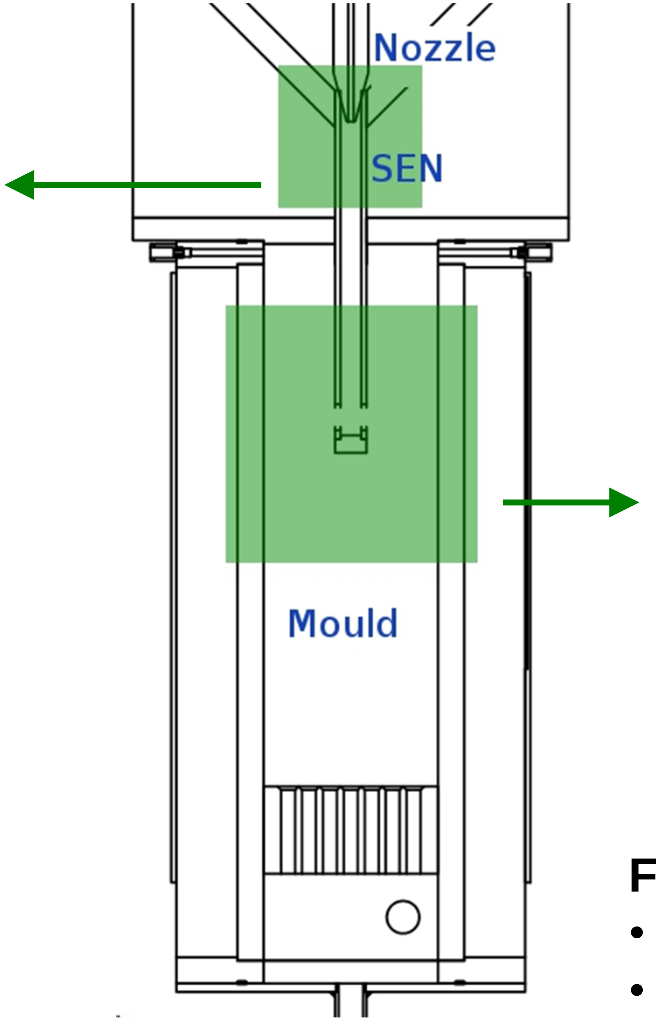


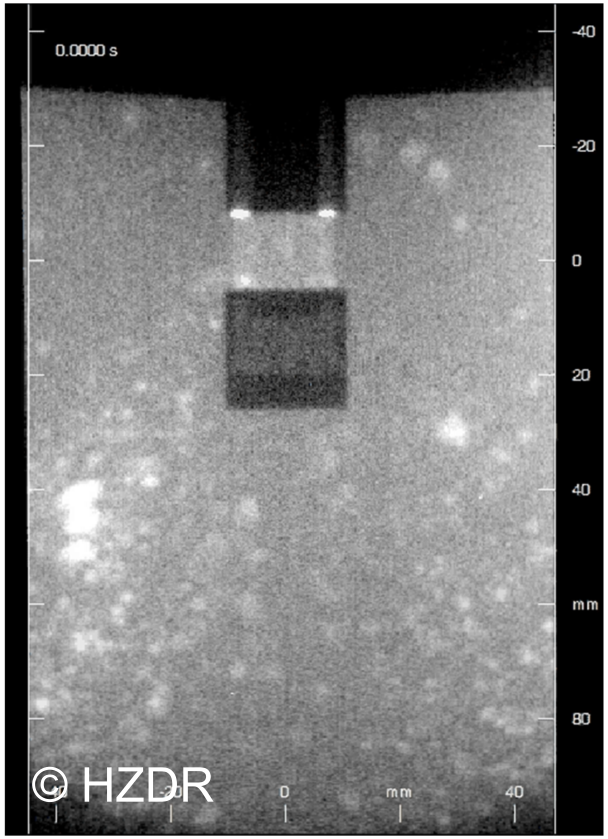
SEN=submerged entry nozzle

How ?

Measurement: flow visualization- 2 phase-flow







Complex flow regimes

Flow rates:

- Ar: 1,7 cm^3/s
- Liquid metal: 120-130 ml/s

Measurement :Flow velocity

How ?

Ultra-Sound Doppler Velocimeter (UDV)

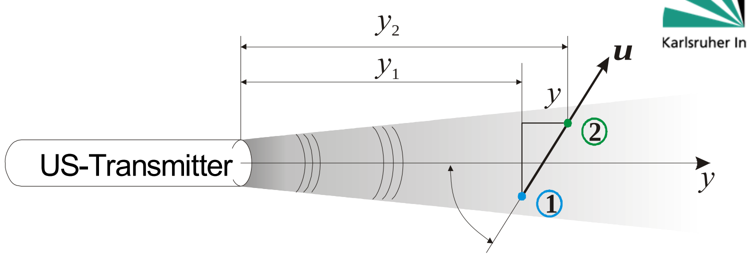
Principle (particle tracking)

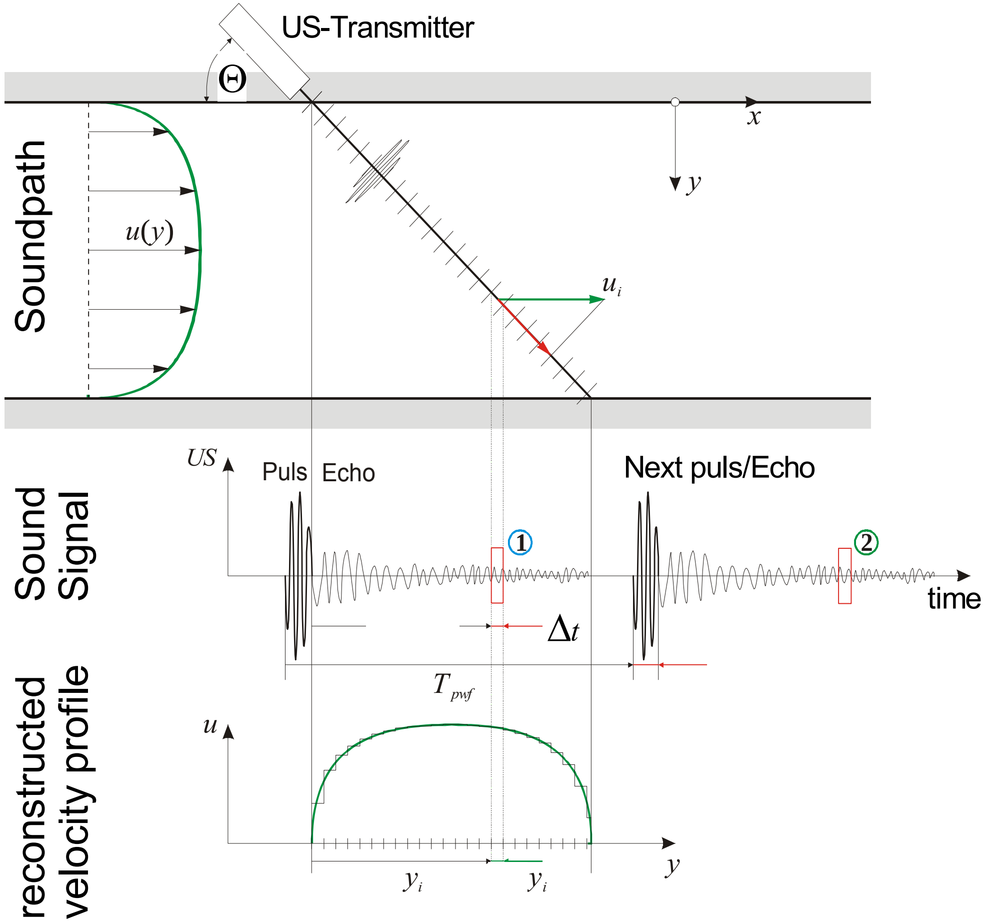
- Distance change from sensor due to motion from 1→2 between two pulses.
- Determination of the time difference from the phase shift between received echoes

⇨ 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

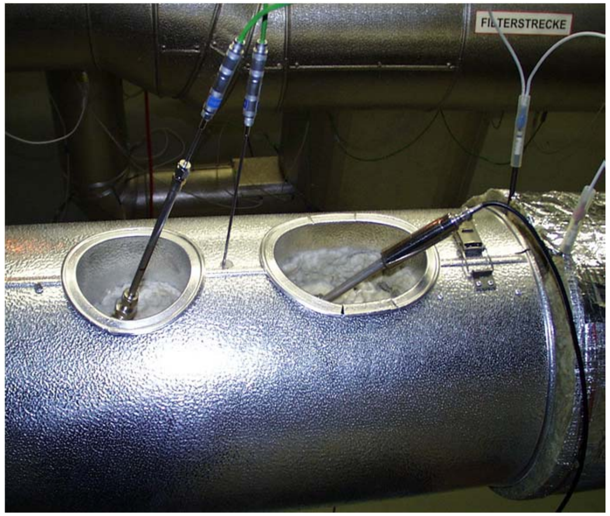


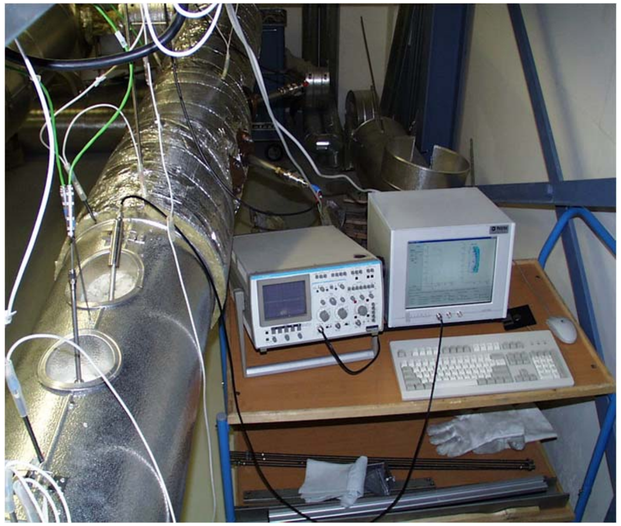


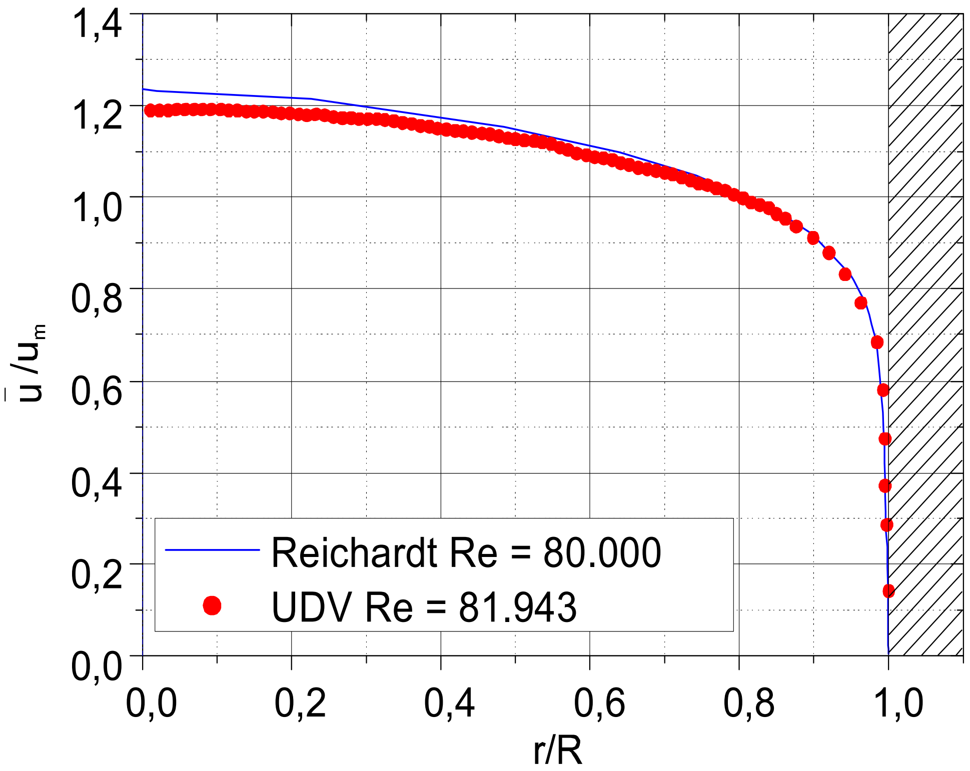
Measurement :Flow velocity

How ?

Ultra-Sound Doppler Velocimeter (UDV)-Validation





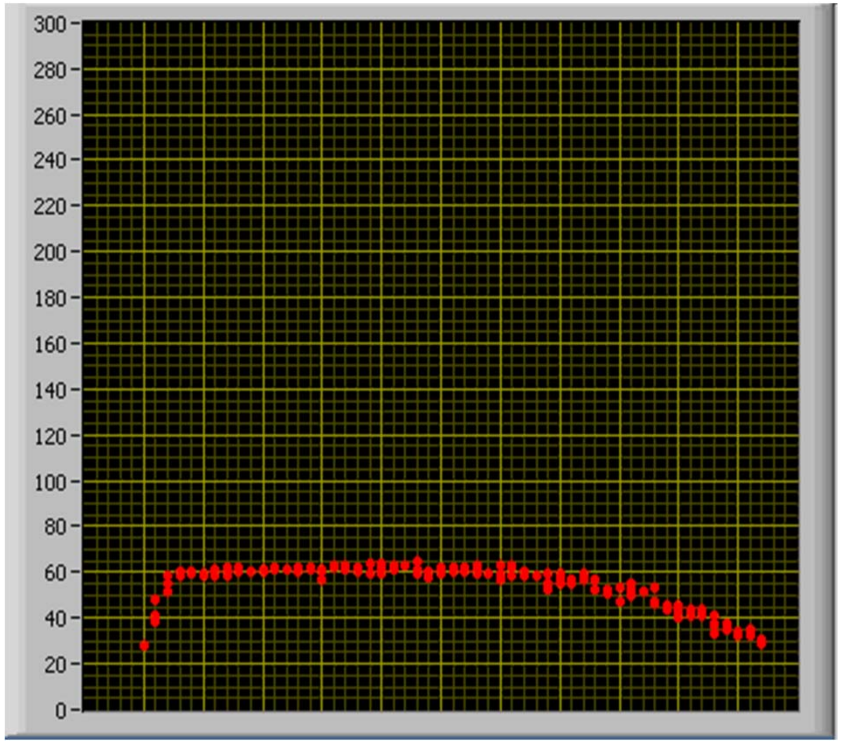


- Good agreement between measurement and literature profile
- Detailed resolution of the velocity profile
- Deviation literature profile for r/R>0.6 less than 0.5%

(Schulenberg&Stieglitz, NED, 2010)

How ?

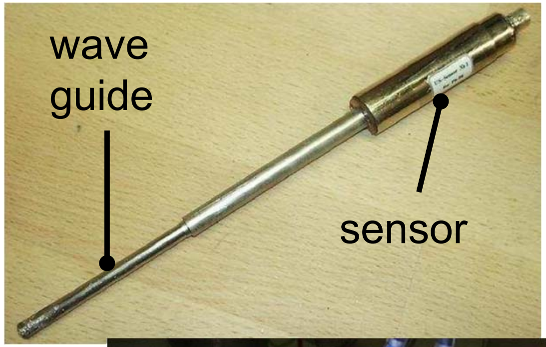
Measurement: Flow velocity

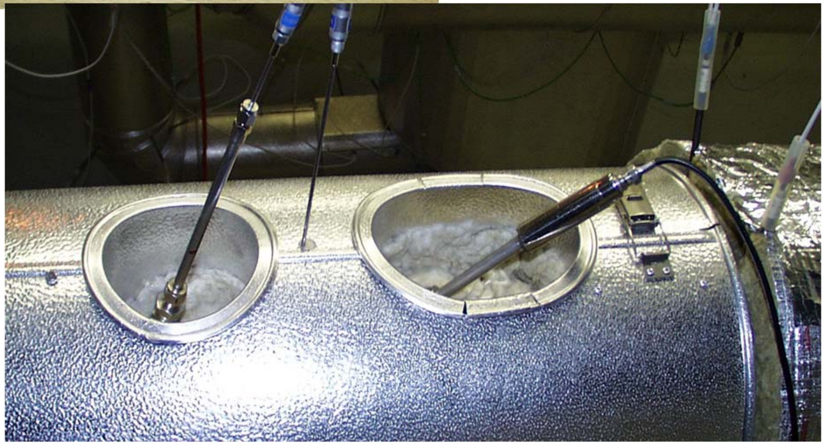


Transient start-up behaviour of EM pump in THESYS Loop

Ultra-Sound Doppler Velocimeter (UDV)

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





Measurement- flow mapping

How ?

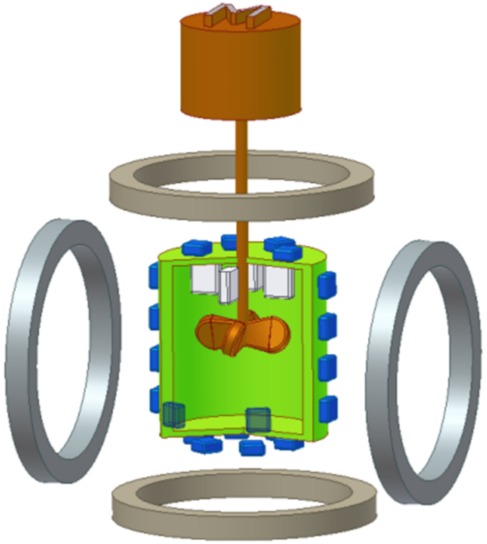
- Multi- UDC set-up
- Contactless-inductive flow tomography (CIFT)

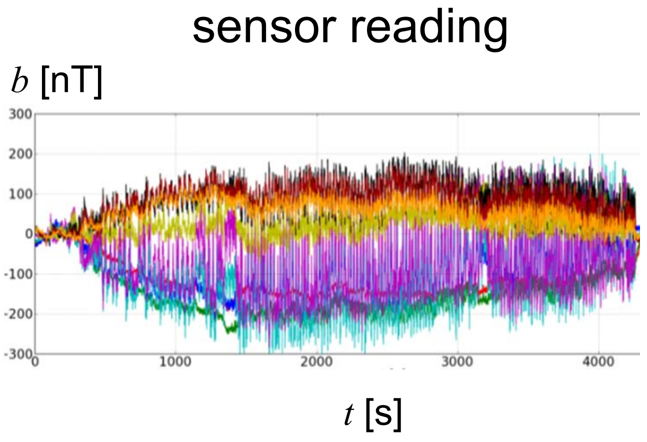
CIFT - Principle

- Measurement of induced magnetic field (Hall-sensors)

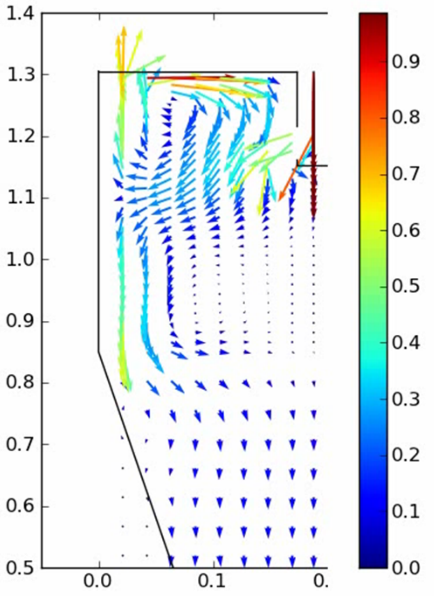
at given

- prescribed magnetic field
- numeric reconstruction





some computation



© HZDR

Stefani, Phys. Rev. 2004
Wondrak, Iron-Steel,making 2012

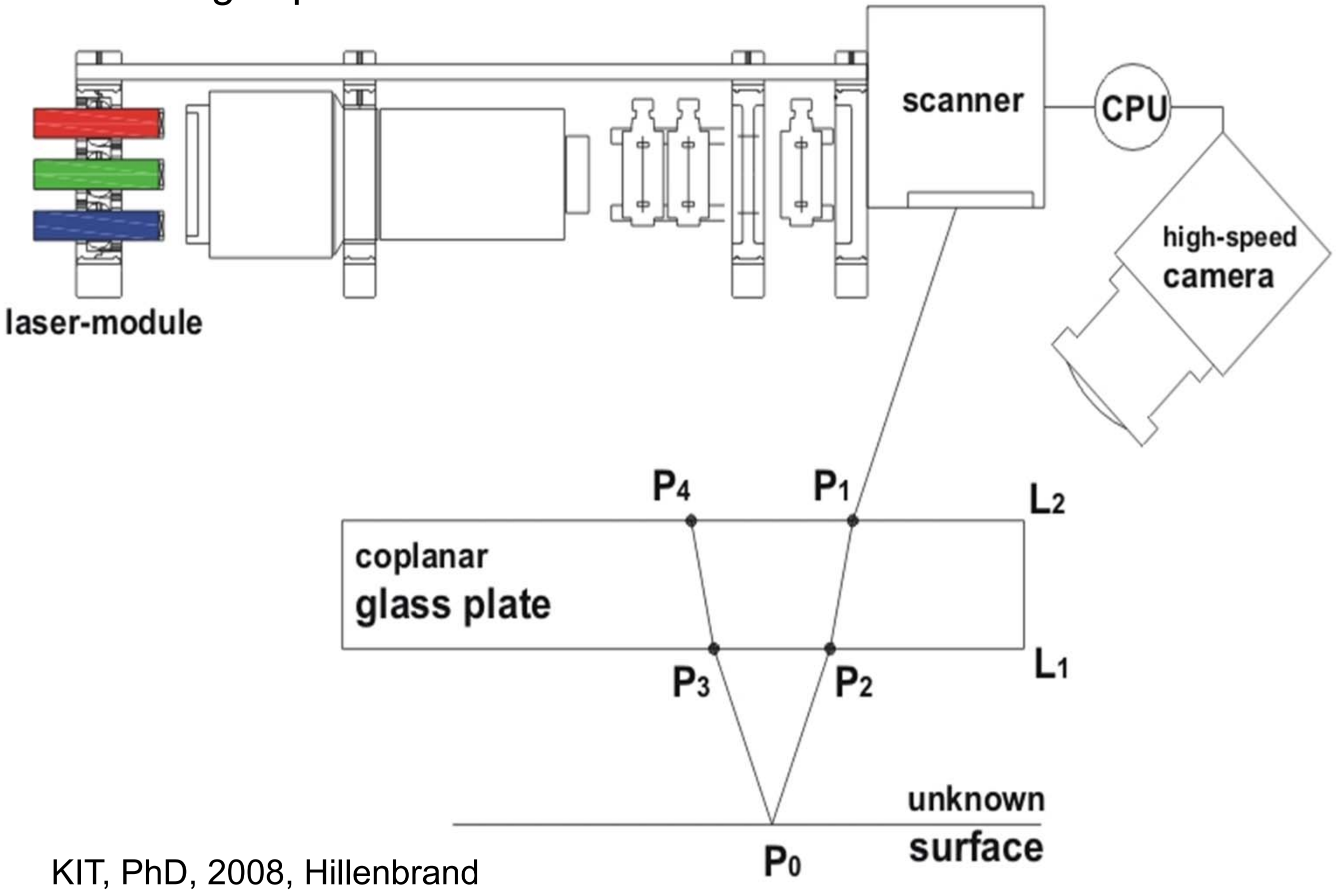
How ?

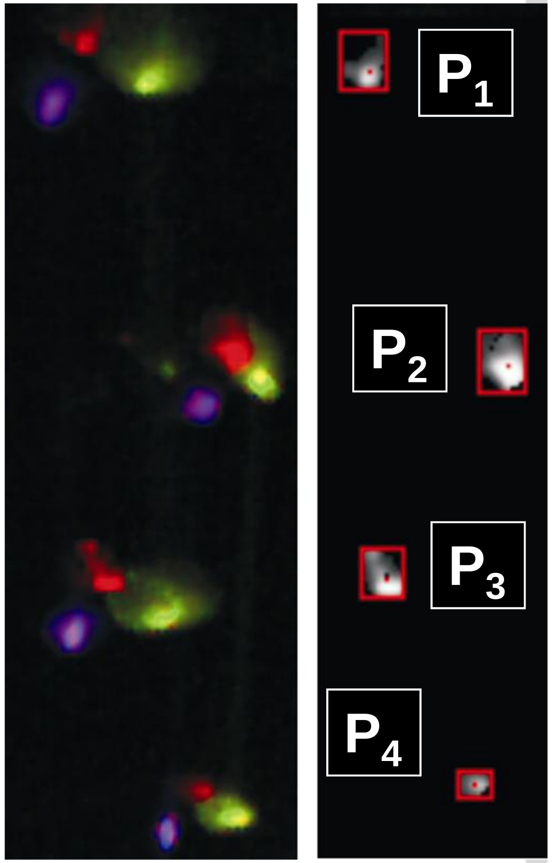
Measurement: Free surface detection

Optical method - Double-Layer-Projection (DLP)

Features:

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





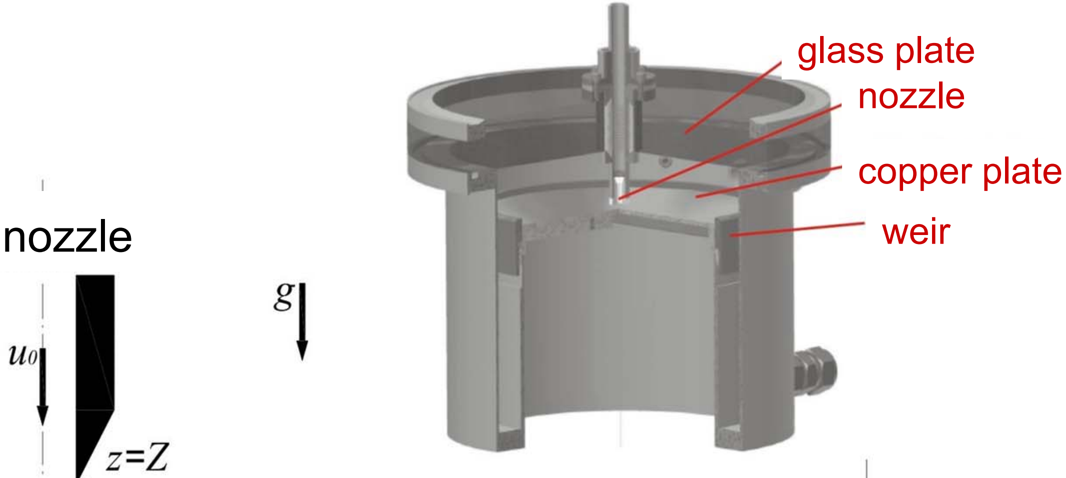
KIT, PhD, 2008, Hillenbrand

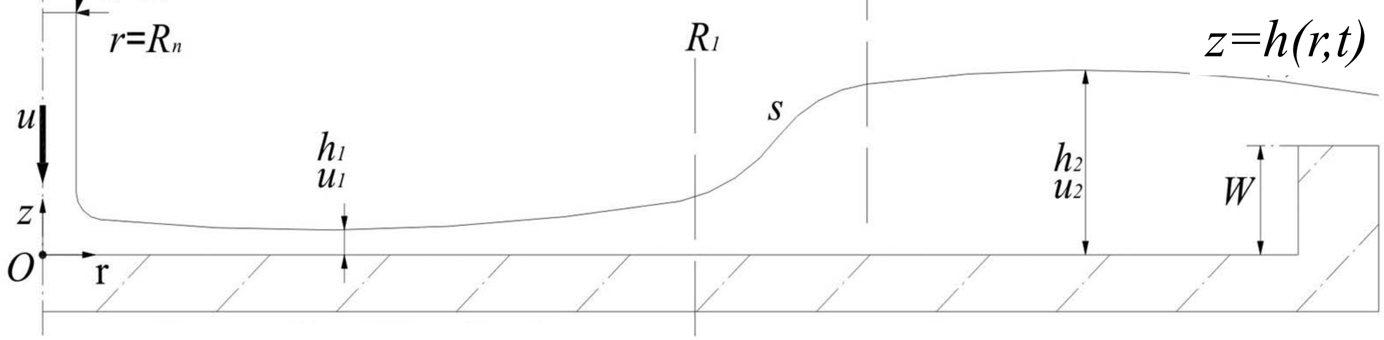
Measurement: Free surface detection-DLP

How ?

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

➡ Goal: Measurement $h(r,t)$

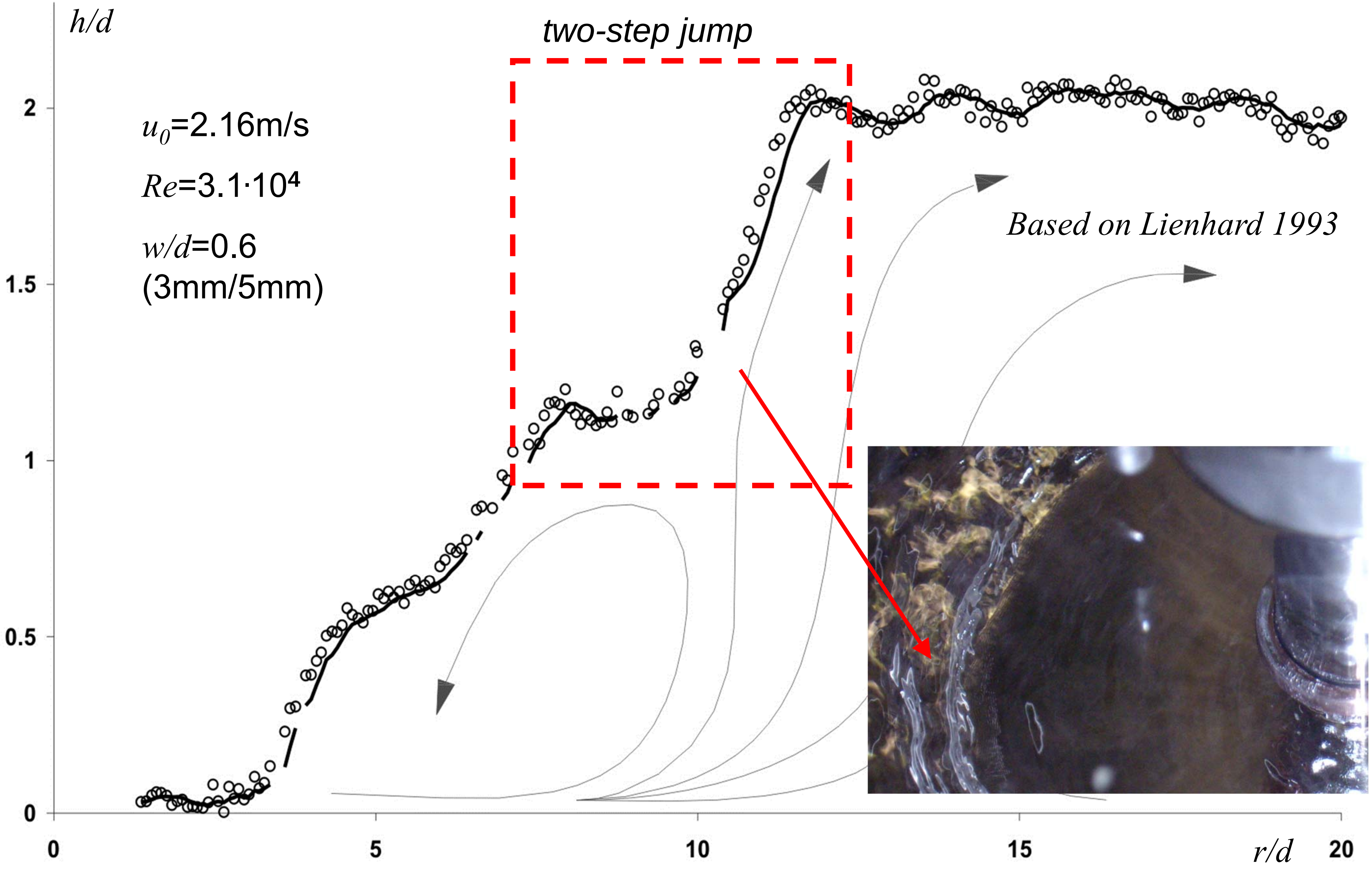




Supercritical flow regime $Fr>1$ Subcritical flow regime $Fr<1$

Measurement- Free surface detection-DLP

How ?



two-step jump

u_0=2.16m/s

Re=3.1·10⁴

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

Based on Lienhard 1993

Why ?

Dynamics of transport in liquid metals

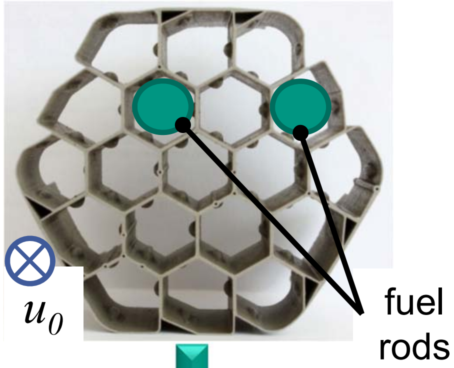
Why ?

Momentum transfer: numerical approach

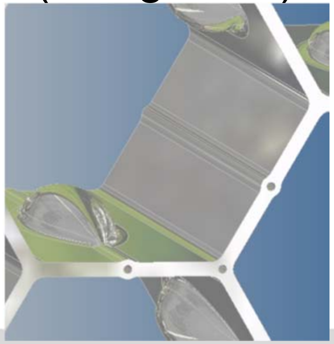
- At a first glance simple: put numerous cells (fluid, solids) in SA geometry
- But: with tremendous effort (correction terms) successful for low Re by CFD means

- **Example : Fluid assembly Flow (heated rods)**

real geometry

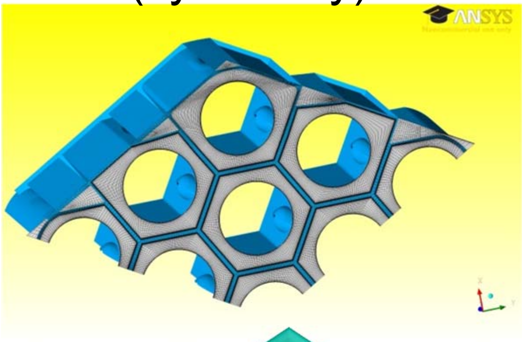


Transfer into solids (using CAD)

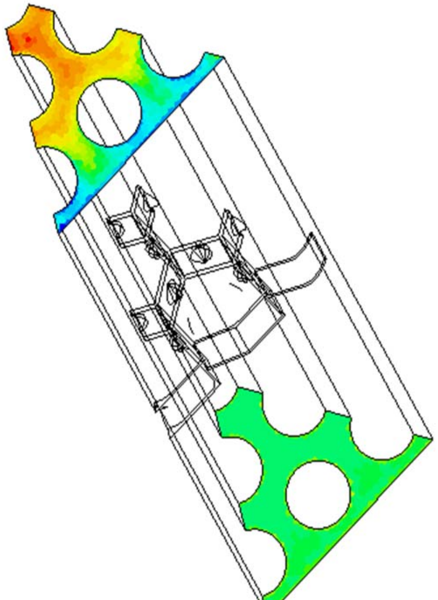


Segmented adapted meshing for fluid

120° fluid mesh (symmetry)



Extrusion to full length (here only 60° shown)



44 Million Cells,
6h CPU (Multi-core proc.)
y^+=5 core (≈0.2mm)
Boundary layers 0.01mm

Momentum transfer: numerical approach

Why ?

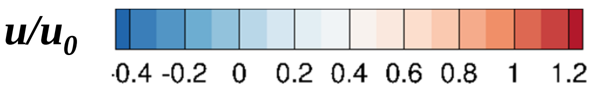
- **Momentum transport models based on averaging (e.g. $u = \bar{u} + u'$)**

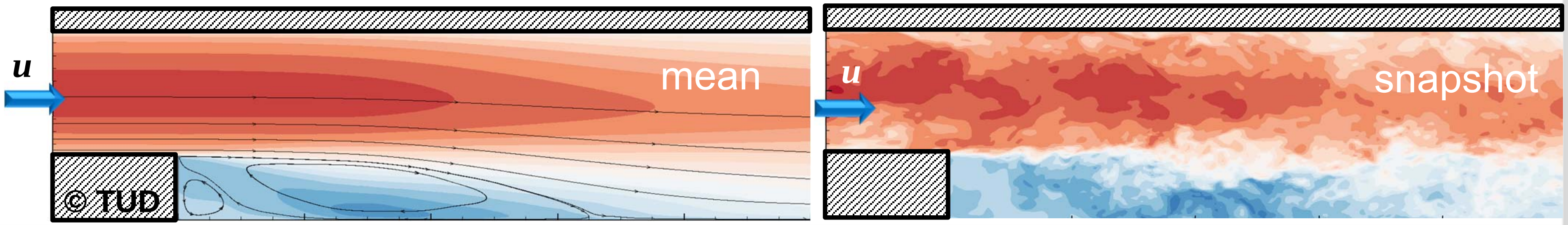
🟩 standard

▨ in development

Order	isotropic turbulent transport	anisotropic turbulent transport	No. of transport equations
1st	Gradient models, eddy diffusivity models		
	🟩 l mixing length models	l_i mixing length models	0
	🟩 k-l, k-ε, k-ω, SST, etc.		1,2, ...
	🟩 non-linear k-ε, V2-f and branches		2
		▨ ASM models with k-ε	2
2nd	transport equations for all second order closure moments		
		▨ equations for complete shear stress tensor	6+2

- ***Large Eddy Simulation* (LES + adequate subgrid scale modelling)**
- ***Direct Numerical Simulation* (DNS)**
  Example: Backward facing step Re=4.800





Turbulent momentum transfer: numerical approach

Why ?

- **Quality of CFD computations not defined by number of cells**

Reynolds averaged modelling of momentum transport

- Reynolds-Averaged Navier-Stokes (RANS) equations ➡ closure problem in convective term

$$\frac{\partial}{\partial x_i}\left(\overline{u_i}\cdot\overline{u_j}+\overline{u_i'\cdot u_j'}\right)$$

- Standard model assumption: gradient hypothesis

$$\overline{u_i'\cdot u_j'} = -\varepsilon_M^{ij}\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)$$

- Simplification **=** isotropic exchange coefficient

$$\overline{u_i'\cdot u_j'} = -\varepsilon_M\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)$$

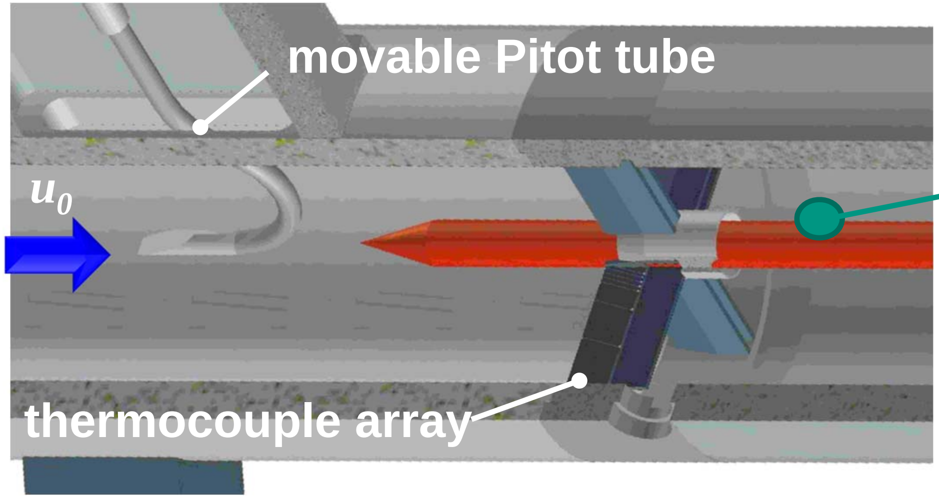
General

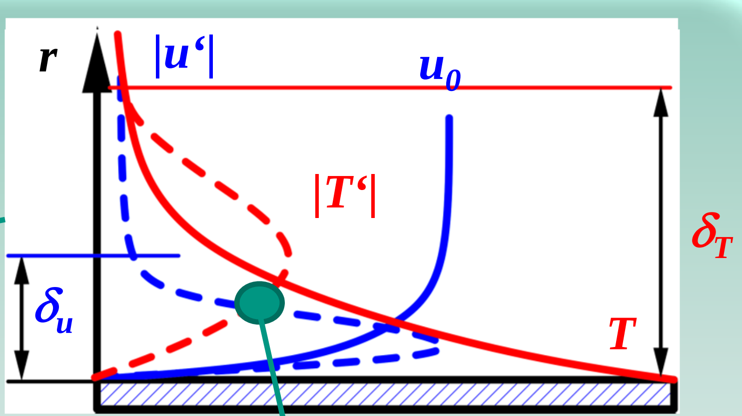
- Turbulent flow modelling demands qualified user (rather than computing power)
- **No substantial difference of liquid metals to ordinary liquids in bounded flows**

Energy transfer: some considerations

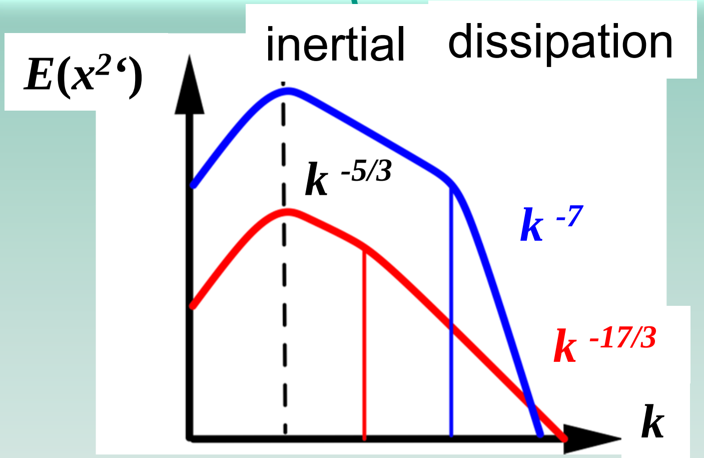
Why ?

- Observation: -high heat conductivity λ





- scale separation boundary layers $\delta_T > \delta_u$
- spatial statistics $r(T_{max}') \neq r(u_{max}')$



- different transport characteristics

Consequences

- turbulent heat transport necessitates dedicated turbulence modelling for
  - heat transport and
  - dissipation
- constant turbulent Prandtl number concept (Reynolds analogy) not correct (standard CFD-models)
- if more cells do not improve the results (super-slating of a soup!!!)

Energy transfer: numerical approach

Why ?

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

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

Consequences

- 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
- Hydraulic diameter concept is not valid (except for forced convection)

Energy transfer: numerical approach

Why ?

How to solve the closure problem of the turbulent heat flux?

- **Standard approximation: Gradient hypothesis**

$$\overline{u_i' T'} = -\varepsilon_H^i \frac{\partial T}{\partial x_i} \quad \rightarrow \quad \overline{u_i' T'} = -\varepsilon_H \frac{\partial T}{\partial x_i}$$

enforced isotropic exchange coefficient ε_H

- **Reynolds – Analogy (Standard in all CFD-Codes)**

$$\overline{u_i' T'} = -\underbrace{\varepsilon_H^i}_{\text{tensor}} \frac{\partial T}{\partial x_i} \approx -\frac{\varepsilon_M}{\underbrace{Pr_t}_{\text{constant}}} \frac{\partial T}{\partial x_i} \quad \text{with} \quad Pr_t = \frac{\varepsilon_M}{\varepsilon_H}$$

- **Consequences & typical problems (CFD Simulation with standard Pr_t =0.9)**
  - **u and T- Statistics completely different, Pr_t is function of Pr_t =(y, Re, Pr, Gr)**
  - **no anisotropic diffusivity**
  - **Missing transport characteristics (diffusor, recirculation flows, free jets)**

➡ Zero-dimensional approach is problematic only valid for forced convection (otherwise extremely qualified user required)

➡ **Use of more cells and computing will not help only modelling**

Energy transfer: numerical approach

Why ?

Direct numerical Simulation (DNS)

- only chance to obtain transport coefficients but
- limitation of Reynolds number (flow velocity)
- **Formulation of benchmark problems**

Backward facing step

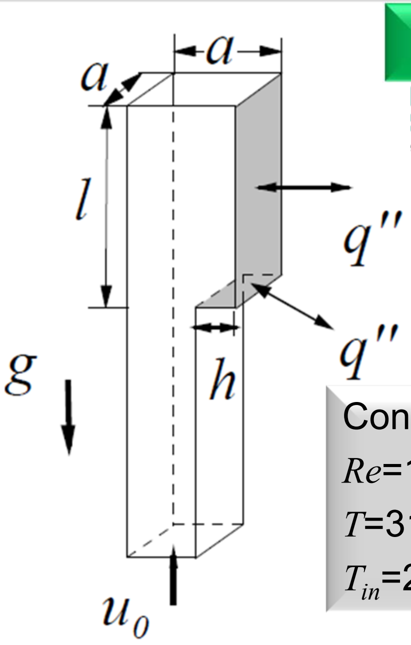
- Stratification problem (buoyancy) at large axial ΔT
- Flow separation at geometry discontinuities

Approach

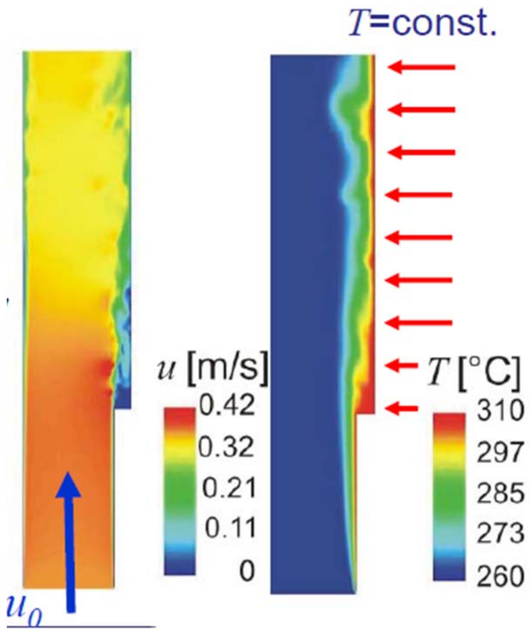
- Choice of small Pr-Fluid (Pr_{Sodium}=0.007)
- LES u-Field is DNS of T-Field

Goal

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



Cond's:
Re=10^4,
T=310°C=const
T_{in}=260°C



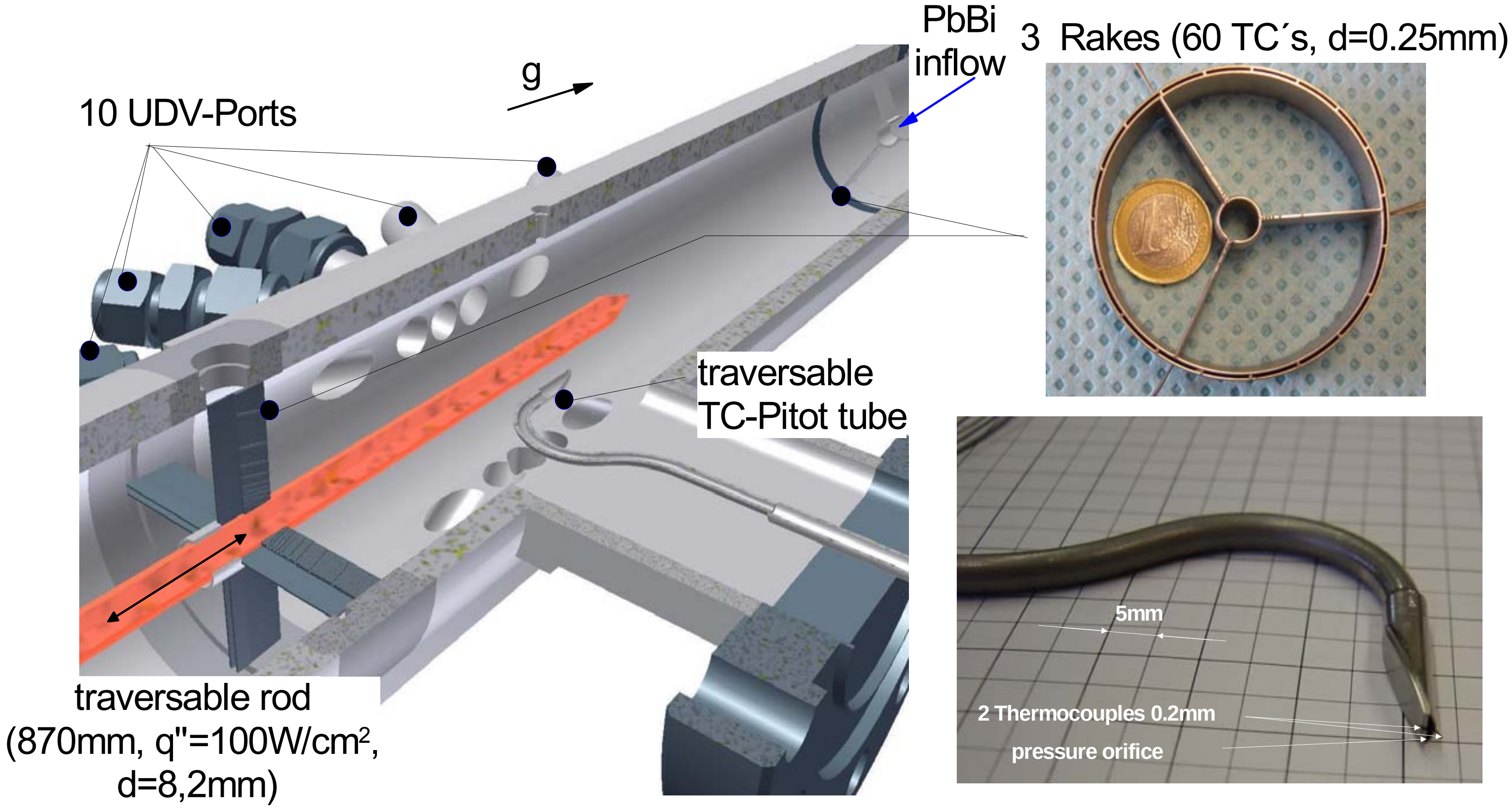
Energy transfer: Validation

Why ?

Background : Pin single element of fuel assembly

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

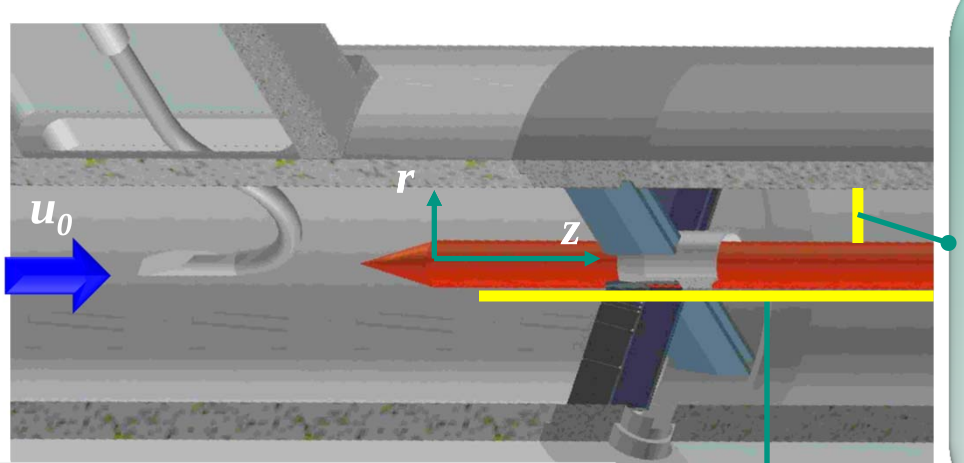
Measure:
- Development of models for turbulent heat flux;
- Determination of Nu-correlations;
- Evaluation of transitional regimes (model validity).



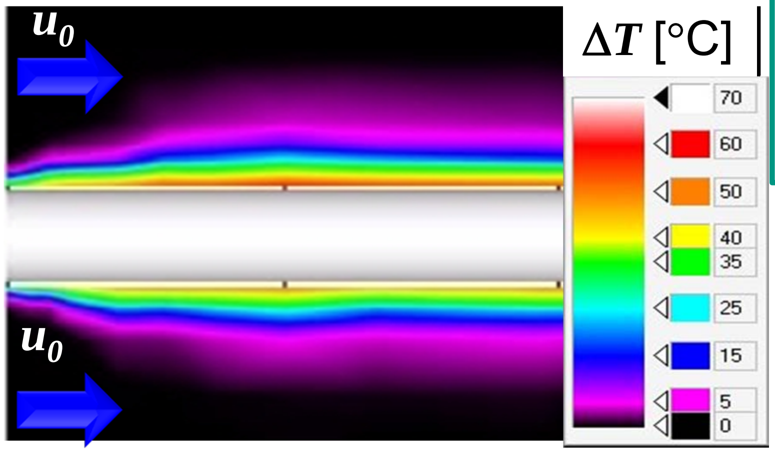
Why ?

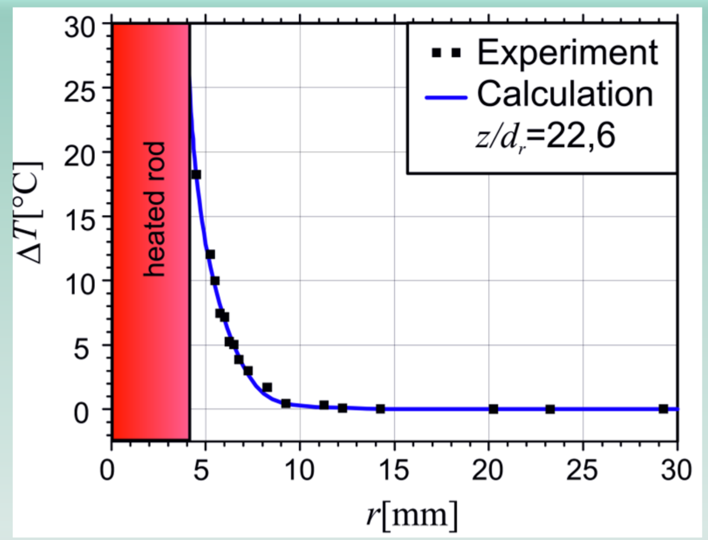
Energy transfer: “real world”

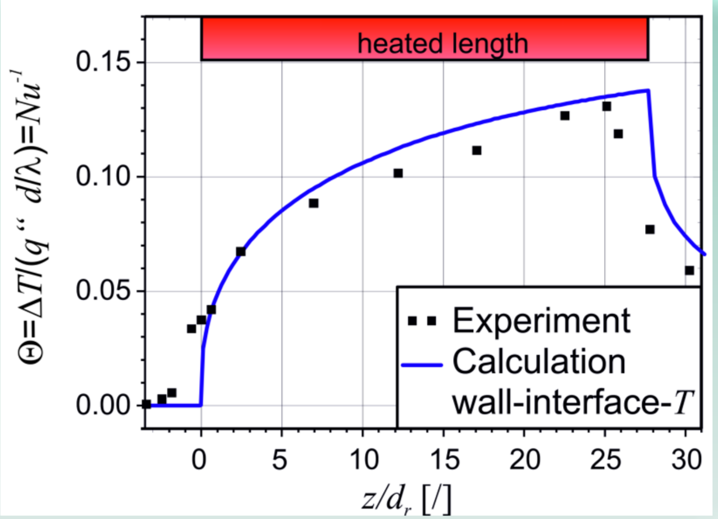
- Observation: -high heat conductivity λ



Conds:
Re = 3.1·10^5, q''=40W/cm^2,
PbBi @ T_{in}=300°C







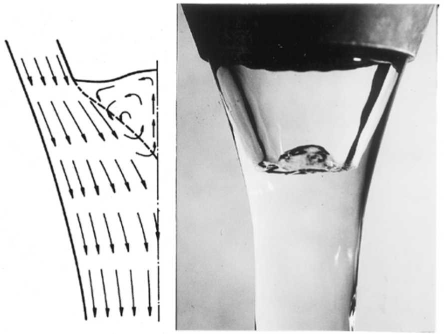
Liquid metals and free –surfaces

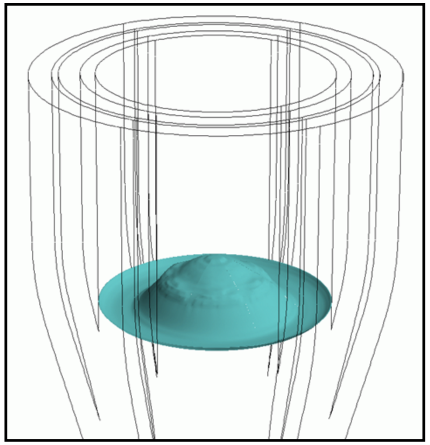
Why ?

Appearance:

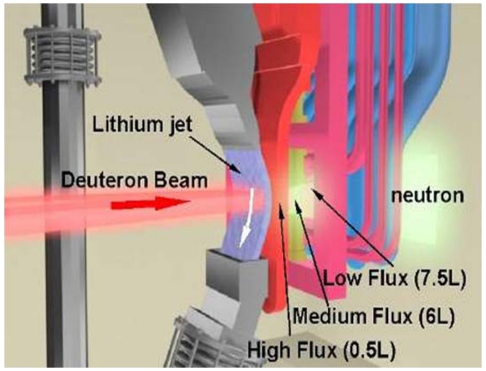
- Gas bubbles in flow (process engineering, in reactors, ……)
- Metal casting
- Nuclear targets

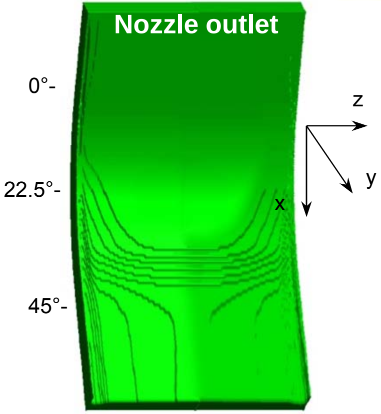
Myrrah-type target





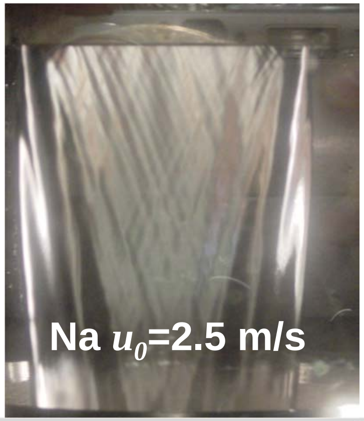
IFMIF-type target





FAIR-type target

Water u_0=2.5 m/s



Free surface flows

Why ?

Numerical challenges

- 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.

Experimental challenges

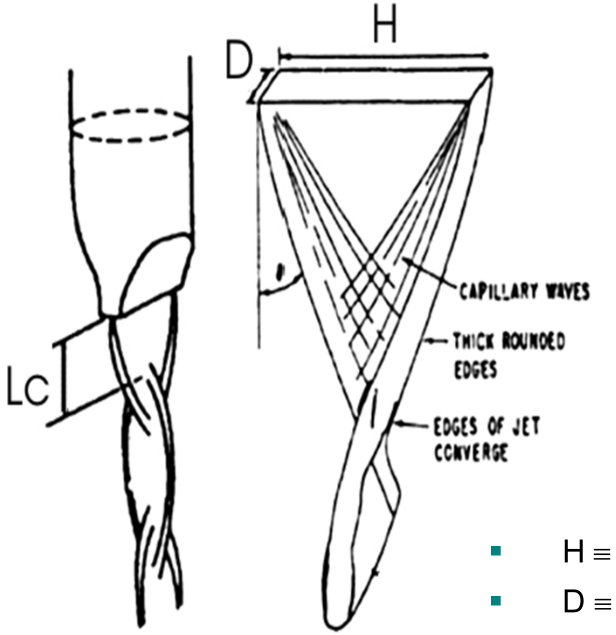
- Development of free surface detection **sensors** with high temporal & spatial resolution
- Lack of experiments with **simultaneous *u* and *h*-field measurements** (unknowns statistics and diffusion times)

Free surface flows- Phenomena

Why ?

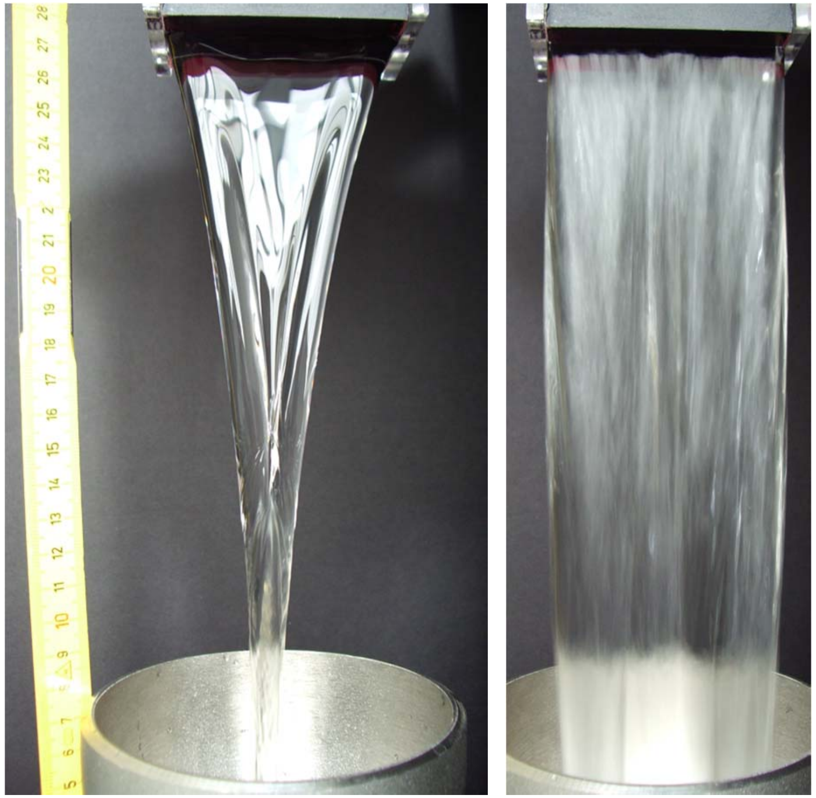
Observations

- 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

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



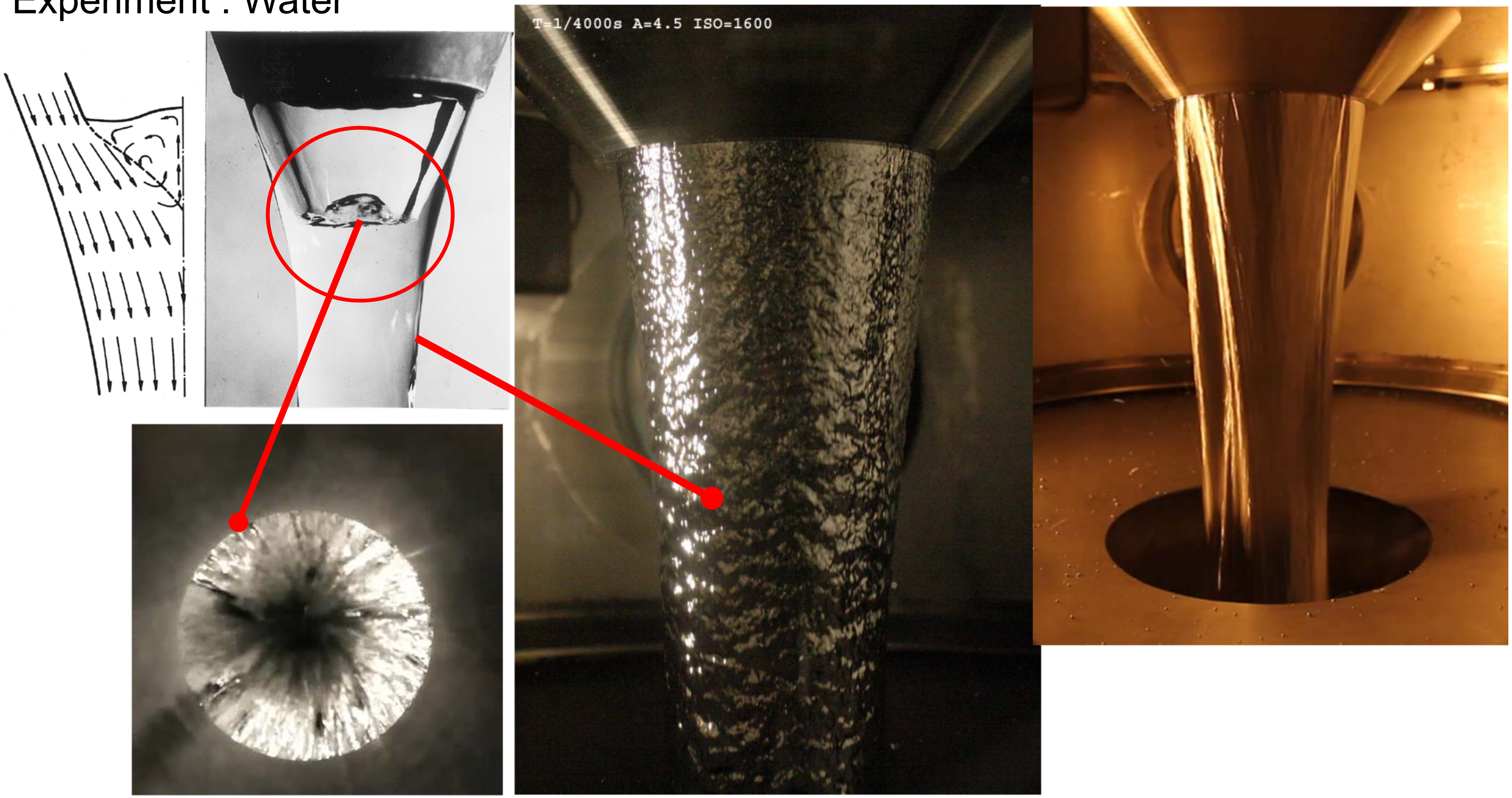
u_0=0.2 m/s 5 m/s

Turbulent free surface flows- Validation

Why ?

ADS Windowless Target: 2^{nd} Generation (MYRRHA)

Experiment : Water



Experiment : $Pb^{45}Bi^{55}$ (top view)

Experiment : $Pb^{45}Bi^{55}$ (side view)

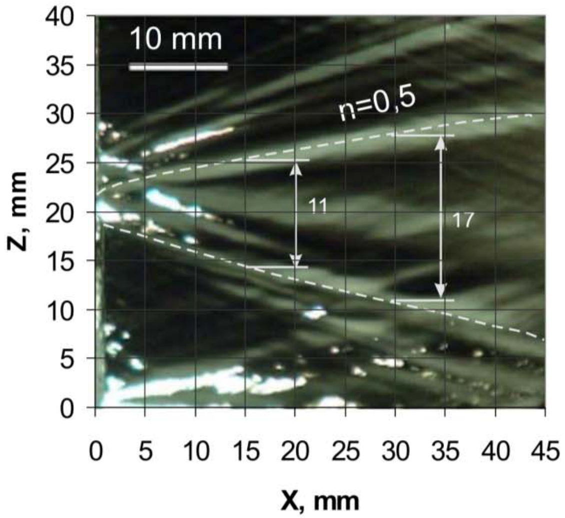
Free surface flows- Validation

Why ?

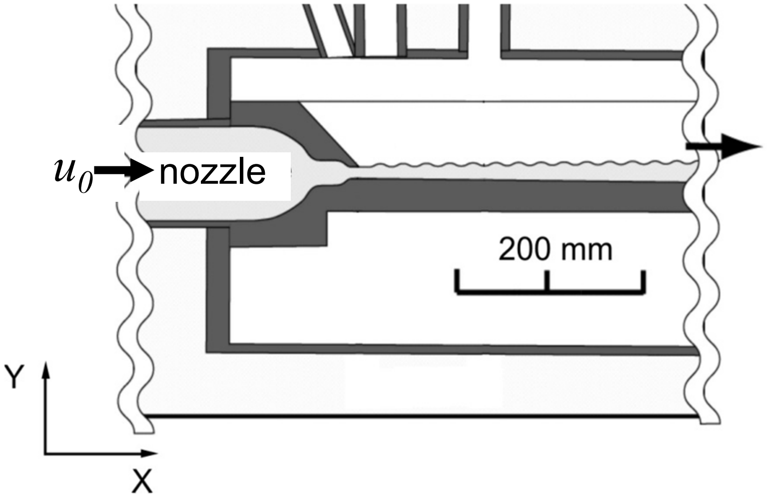
Example:

- Wave propagation on a liquid lithium surface
  caused by precipitation at the nozzle exit (Kondo et al. (2006) Osaka University)

Experiment **LES** **V2F (unsteady)**



Mean nozzle exit velocity U_0 =5m/s



Results

- Excellent agreement of numerical and experimental data for large scales
- LES allows resolution of fine structure

Free surface flows- Validation

Why ?

Target development FAIR:

- Acceptable agreement of steady state “mean” surface shape
- Convective instabilites can be captured by RANS methods
- Local unsteady phenomena require an LES

PhD Gordeev,2008;

Daubner, Stoppel, & KALLA DIRAC-Final Report, 2009

Example: sodium jet u_0=2,5m/s

Simulation Standard photo High speed cam. (2000fps)

Why ?

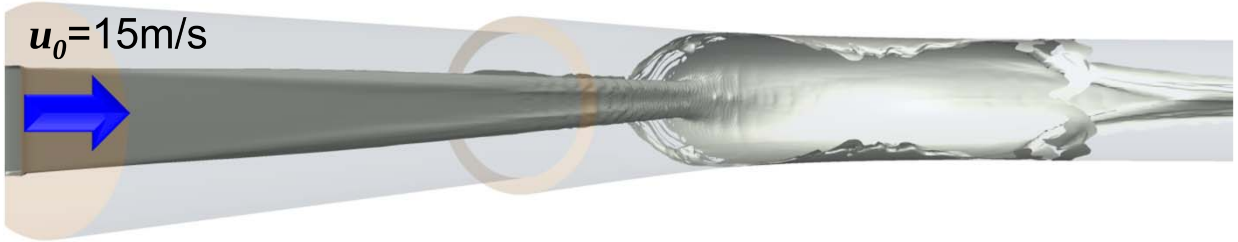
Free surface flows- Phenomena

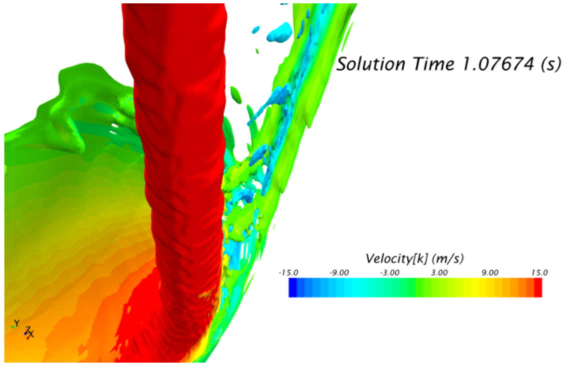
What happens for a free jet impinging on a surface ?

- splashing by momentum exchange
- Droplet generation generation
- Cavitation ?

Example: IFMIF –lithium flow entering the catcher

lithium jets with different u_0=5,15m/s , p=10^{-3}Pa

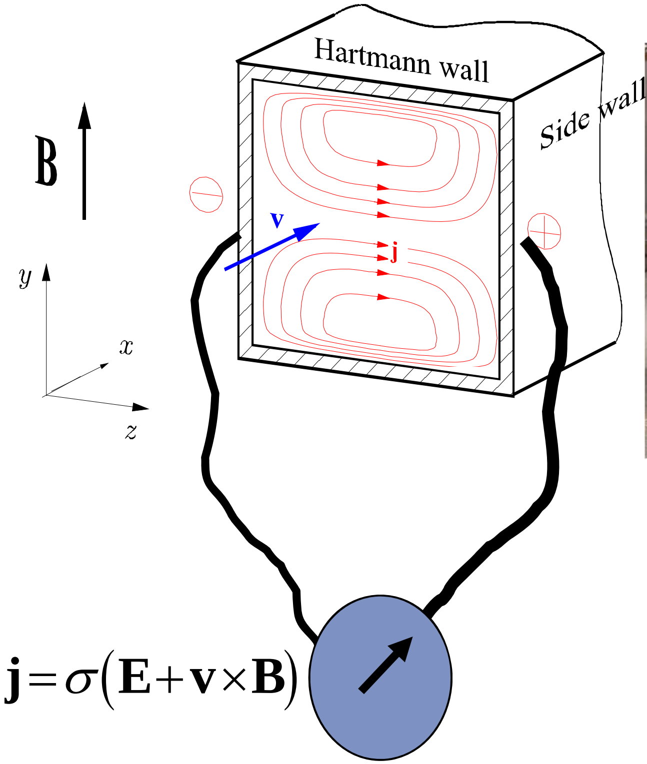




© Gordeev, 2014

Why ?

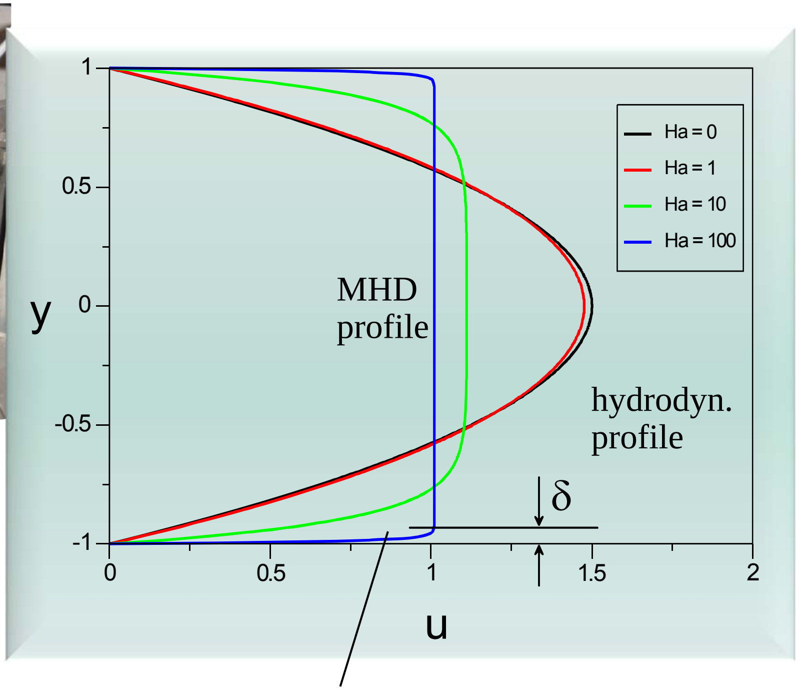
Interaction with magnetic fields - MHD-flows



$$\mathbf{j}=\sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B})$$

U [V]

Electro-magnetic flow meter



Development of extremely thin boundary layers $\delta \sim Ha^{-1}$

Leading parameter: Hartmann number Ha $\quad Ha = a\,B\sqrt{\dfrac{\sigma}{\rho\nu}} = \dfrac{EM - Forces}{viscous\ \ forces}$

Fusion: $Ha \sim O(10^4) \rightarrow$ flow is dominated by electromagnetic forces

Interaction with magnetic fields - MHD-flows

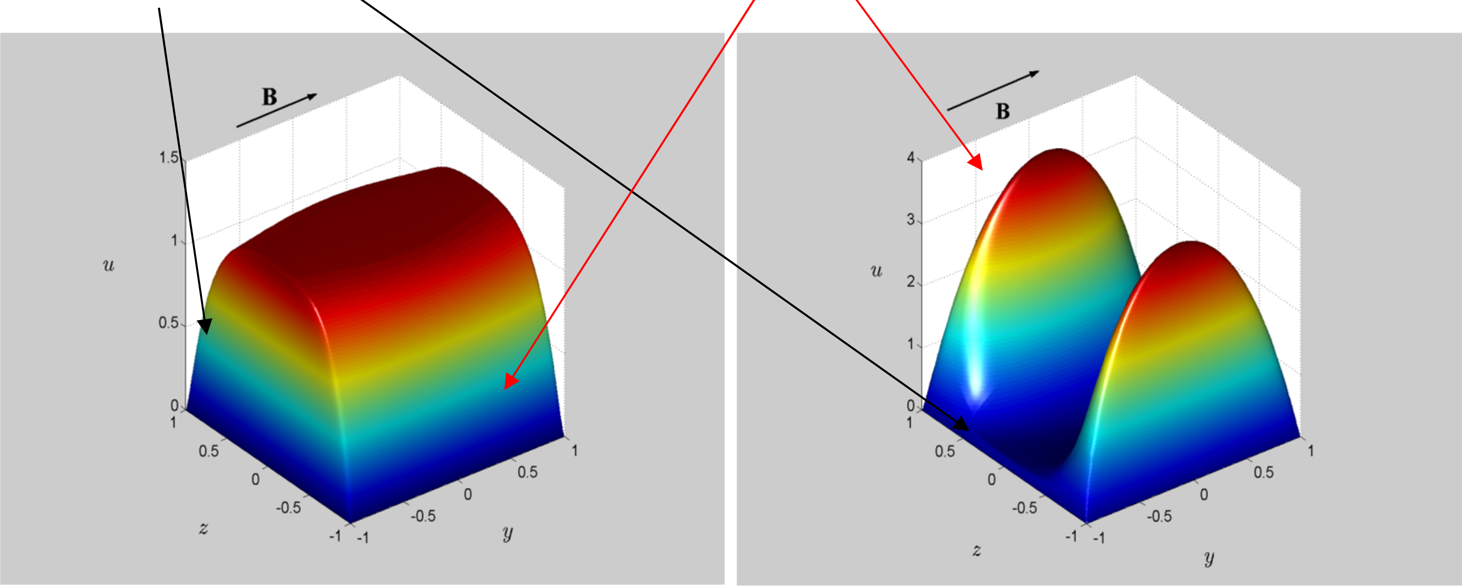
Why ?

Major phenomena

- Highly electr. conducting walls → high current densities → large Δp
- thin conducting walls → current density reduction → M-shaped velocity profiles (high jets <t walls || B)
- Electrically coupled ducts → superposition of currents → large scale current circulation → multi-channel effects (even larger Δp)
- Best in terms of velocity profile and Δp electrically insulated walls → $\Delta p \sim B$ are (neutron resistance ??)

Hartmann - layer $\delta \sim Ha^{-1}$

Side layer $\delta \sim Ha^{-1/2}$



Insulated Walls

Walls at y=±1 ideal conducting

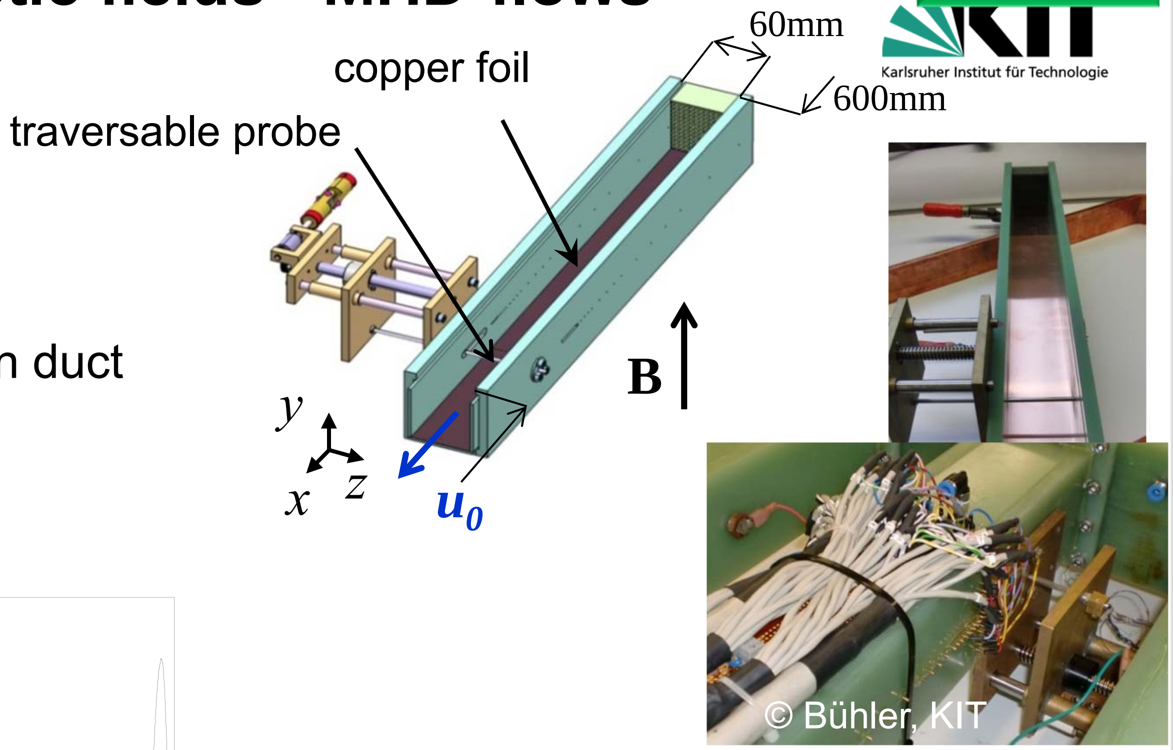
Interaction with magnetic fields - MHD-flows

Why ?

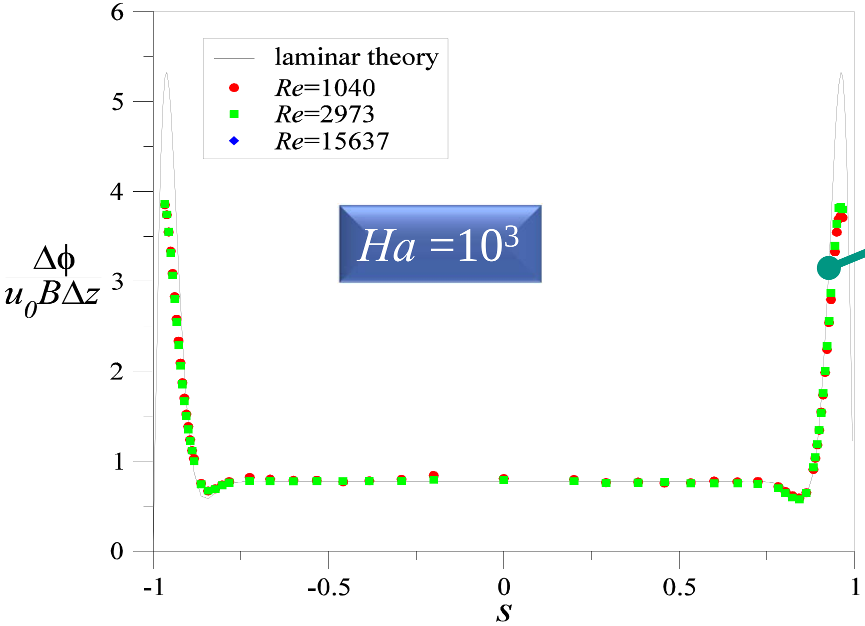
- Experimental validation

Set-up

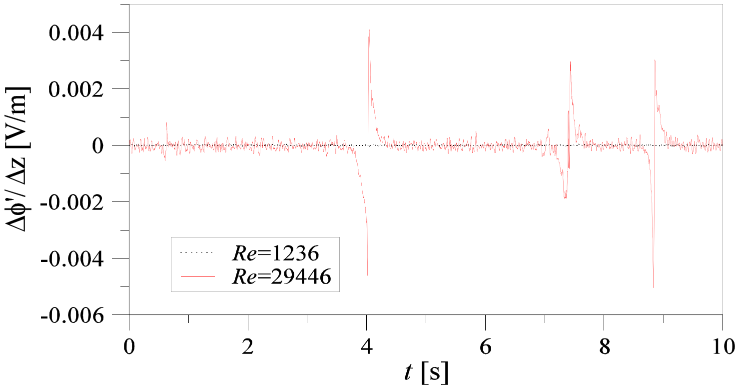
- $Ga^{68}In^{20}Sn^{12}$-model fluid
- electric potential on *Ha*-walls depict flow organization within duct



- Measured velocities



Could the jets get unstable ?

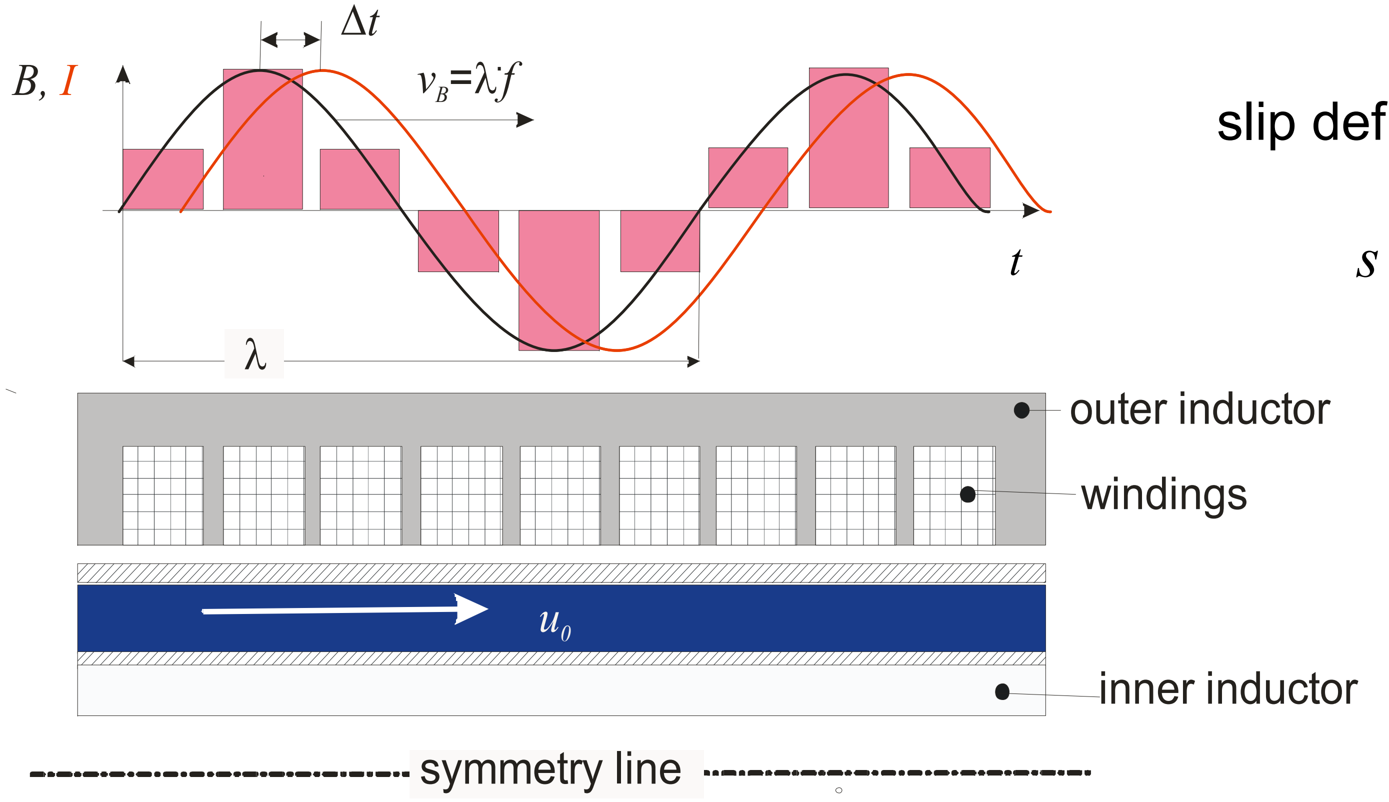


Engineering: LM-Pumps

Build ?

Liquid metal operated loops utilize often MHD-pumps, why ?

- Low maintenance costs (absence of sealings, bearings, moving parts),
- Low degratation rate of structure material,
- Simple replacement of inductor,
- Fine regulation of flow rate and pump characteristics (p'/p, $V'/V<<1$).
- Computations: Electrodynamics + MHD (Stieglitz, FZKA-6826)



slip definition s:

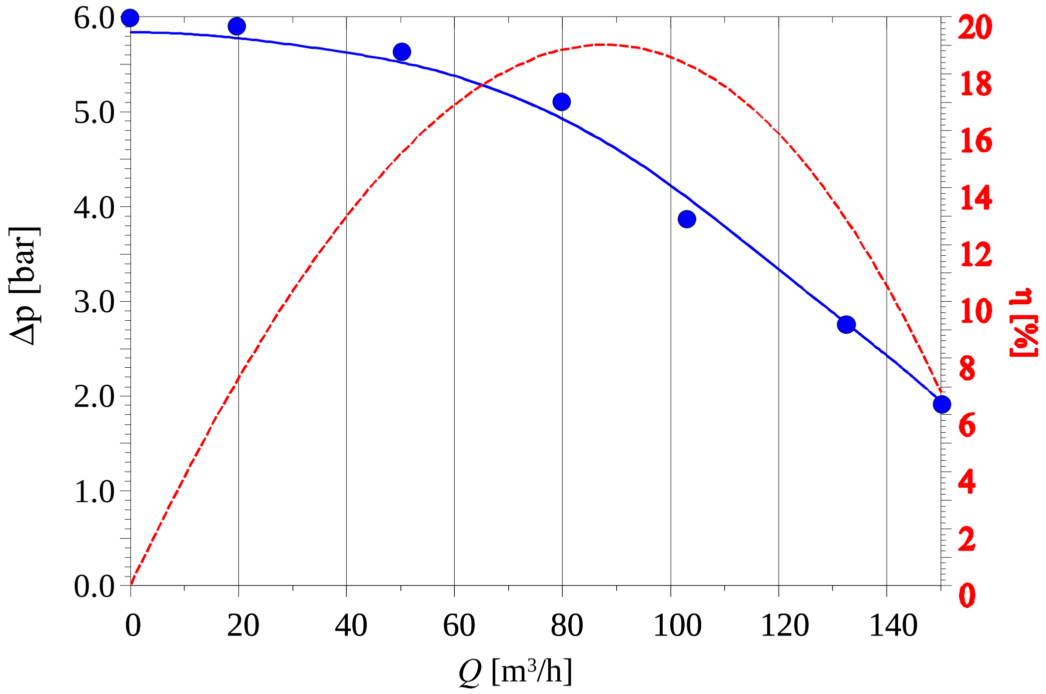
$$s=\frac{(v_B-u_0)}{v_B}$$

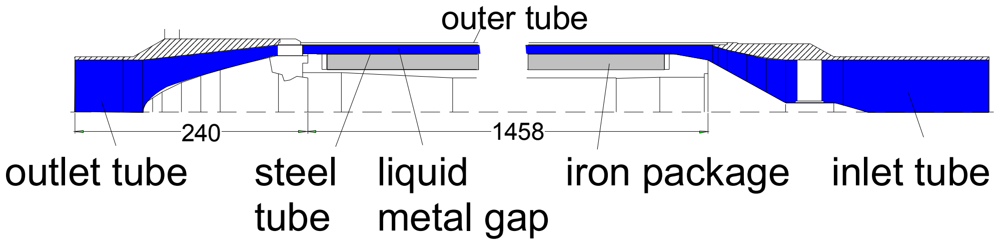
Build ?

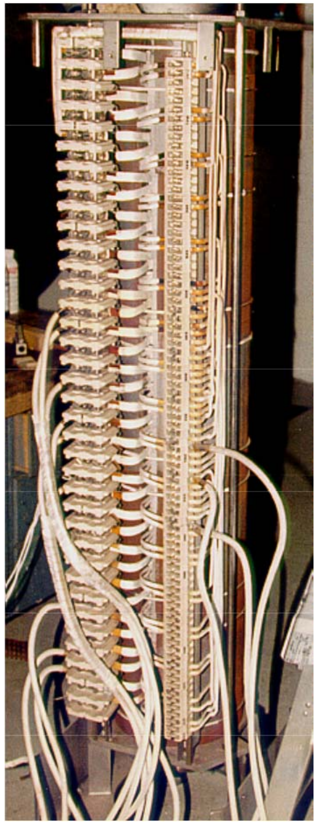
Engineering: LM-Pumps

Sodium operated Annular Linear Induction Pump (ALIP)

- Q at Δp 150m³/h …0.2MPa
- 115°<T<500°C



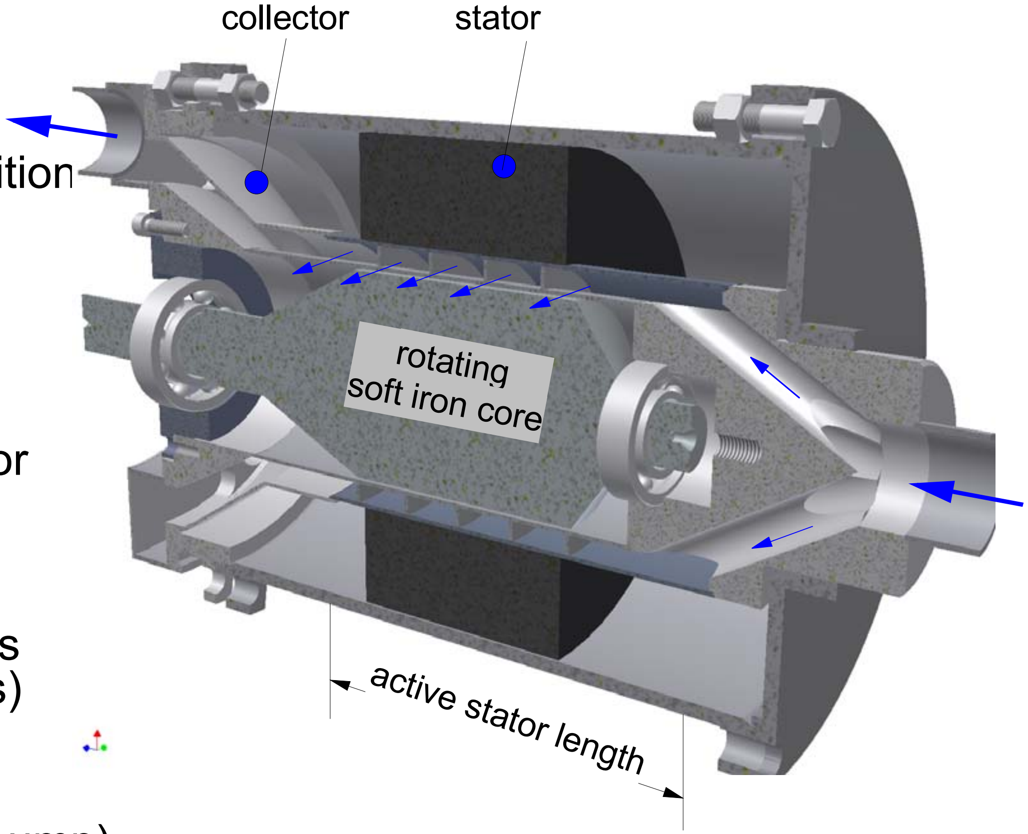




Engineering -Pumps

Build ?

Development of new pump types at KIT (ACHIP -Alternating Current Helical Induction Pump)



Motivation

- High price of EM-pumps, no competition
- Inspection, sealings
- complex set-up and loop integration

Ansatz

- Use of stator of asynchroneous motor (e.g. old pump, crane motor,….)
- design of liquid metal duct in stator
- Compensation of eddy current losses by rotating soft iron core (in bearings)

Advantages

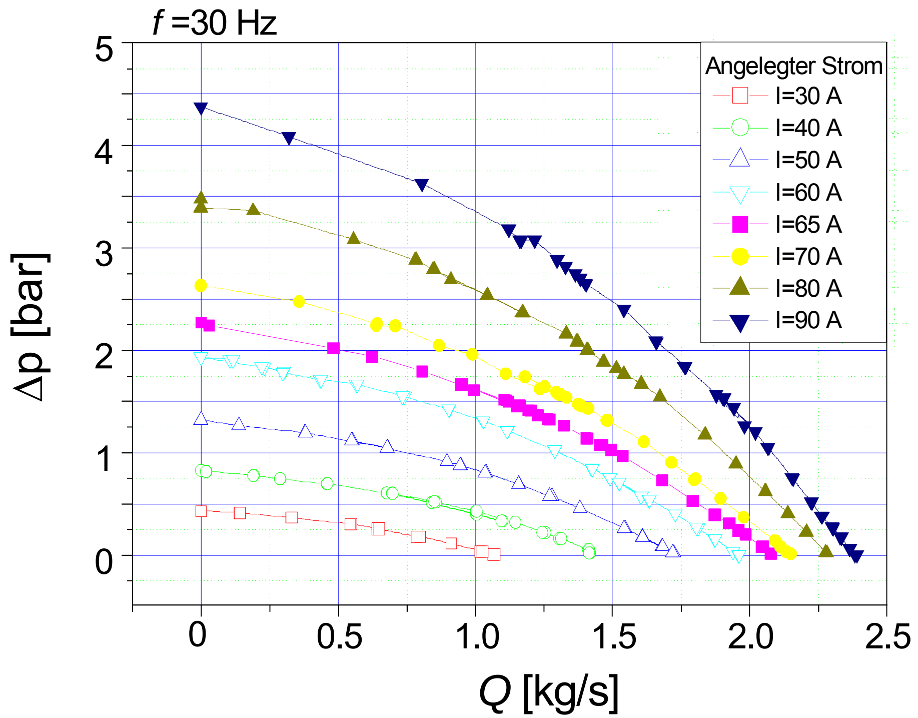
- Low construction price (1/10 to EM pump)
- No sealings, conventional parts, pumpin in both directions possible
- High reliability low pressureoscillations ($\Delta V/V$, $\Delta p/p$<<10%)

Build ?

Engineering -Pumps

Functional and performance tests of ACHIP

- Successful operation
- First shot : acceptable efficiency η_{max}=14% no optimization
- Next optimization
  - instead soft iron permanent magnets,
  - Use of 4 pole instead of 2 pole stator
- Resonable agreement between model and FOAK demonstrator



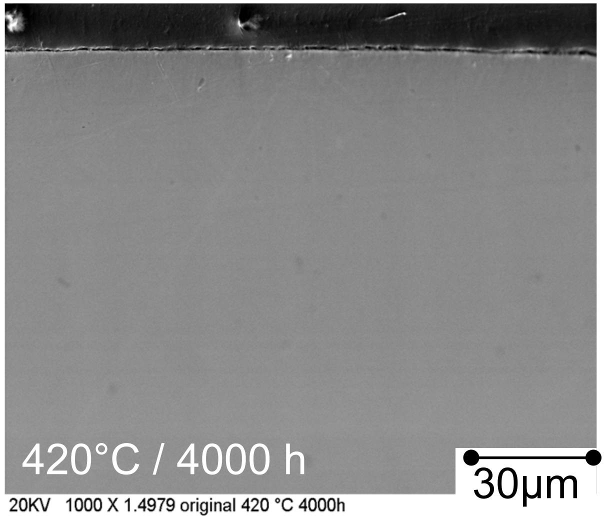
NaK pump in MEKKA @KIT

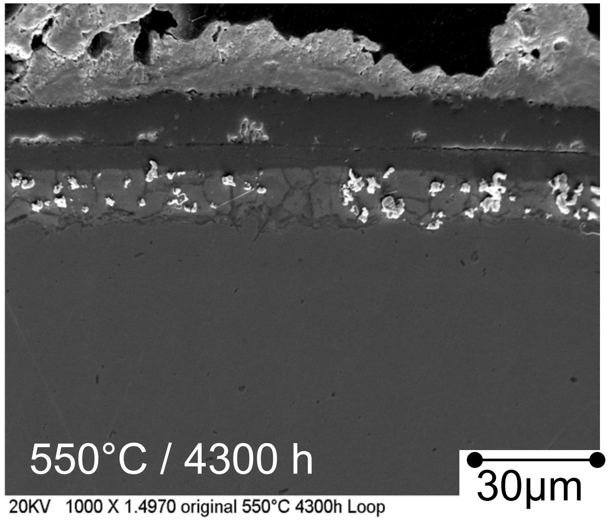
Engineering -Materials

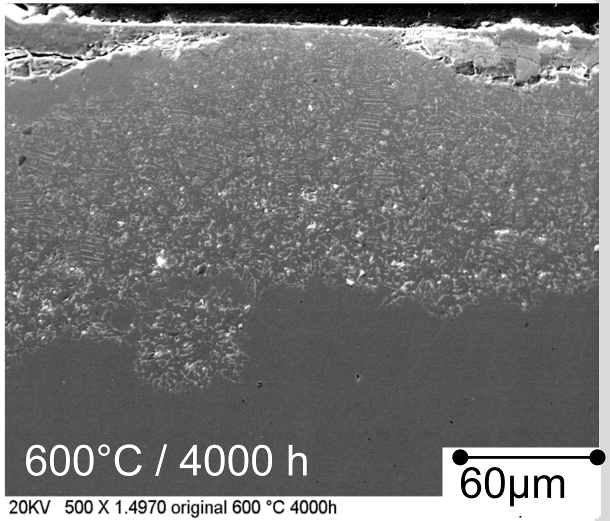
Build ?

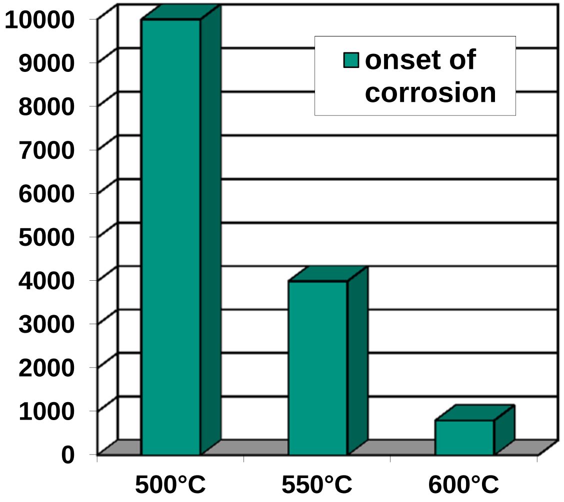
Material selection: Depends strongly on liquid

Example : Heavy liquid metal (here Pb^{45}Bi^{55})









Material

Austenitic steel (316L-type)

Influence of temperature on material compatibility

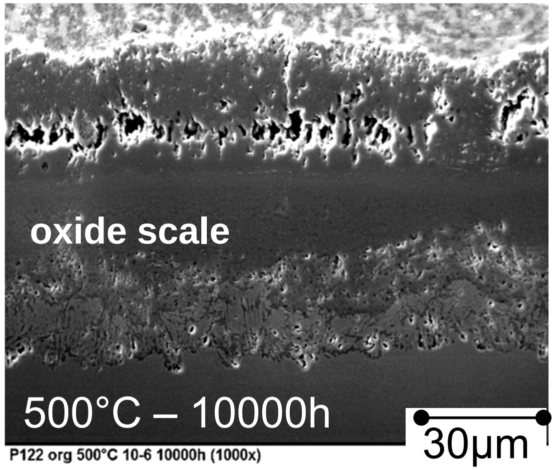
at optimal oxygen concentration 10^{-6} *wt%*

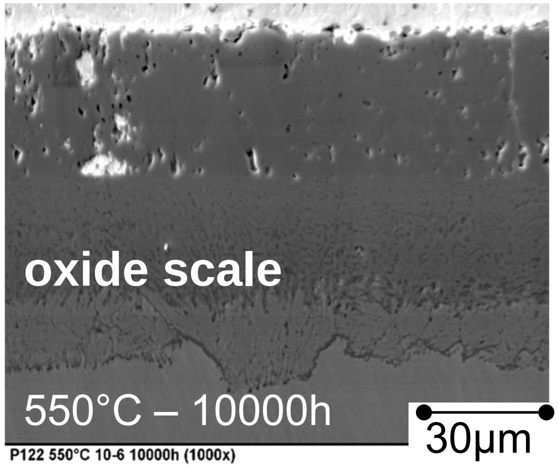
Result

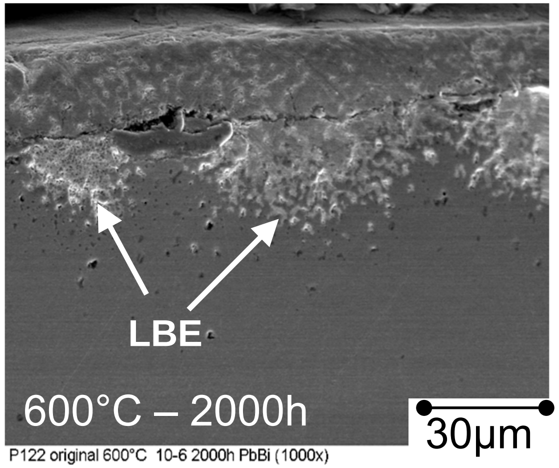
Austenitic steels operable without protection for temperatures below 500 °C

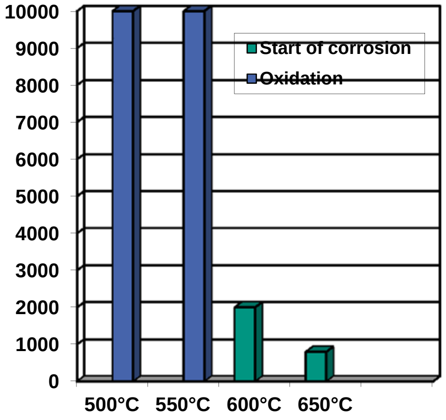
Engineering -Materials

Build ?









Material:

F/M steel (HCM12a -type)

Influence of temperature on material compatibility

at optimal oxygen concentration 10^{-6} wt%

Result

Martensitic steels operable below ≤ 550 °C.

huge oxidation rate: up to 50 -100µm/10.000 h

and frequent spallation of oxide scale.

- ➡ contamination of liquid metal
- ➡ reduced heat removal capability $(\lambda_{M_3O_4} = 1 W/mK)$

Summary

- Liquid metal flows exhibit features different to normal liquids due to their thermo-physical properties.
- Conventional computational fluid dynamics tools exhibit deficits in simulating MHD flows, heat transfer problems and free surface flows if not liquid metal adapted due to
  - 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 with turbulence modeling
- Recent progress in measurement techniques enables access to rather complex flow phenomena.
- Development process allows to define generic experiments focussing to
  - develop more advanced physical models.
  - generate a data base, local correlations for design of complex systems.
- Each liquid demands a dedicated material study to ensure a safe life time performance especially in a nuclear environment

Authors thank especially to the Helmholtz funding through

Helmholtz-LIMTECH
ALLIANCE