Flow distribution and turbulent heat transfer in a hexagonal rod bundle experiment

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Introduction
Liquid metal cooled reactors (ADS)

Motivation

- Minimization of radiotoxicity of long lived fission products (Am,Cu,Np,..)

Realisation options

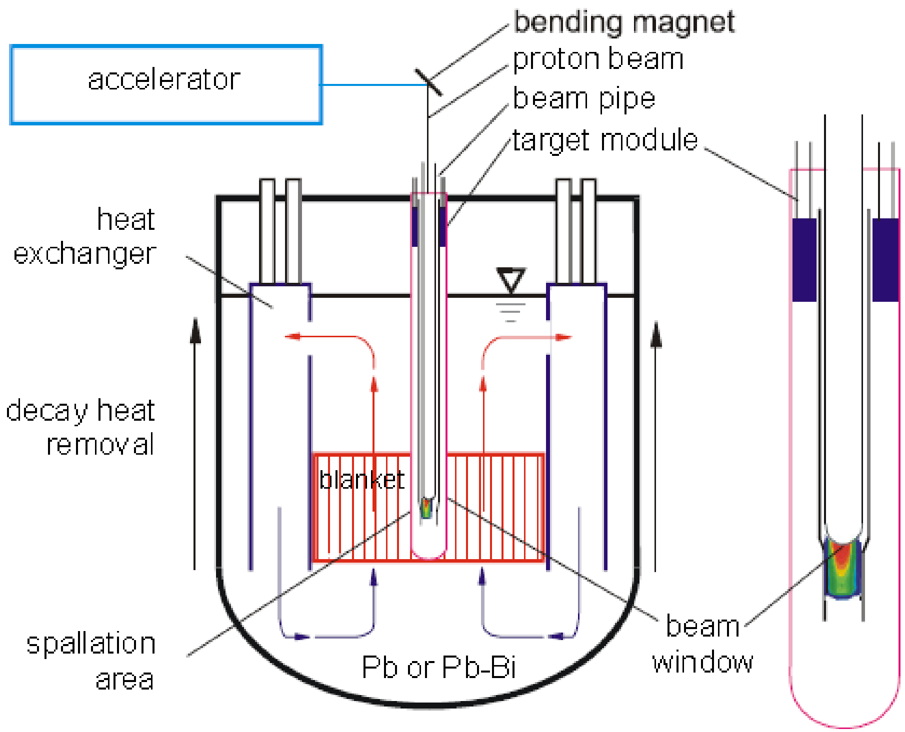
- Accelerator Driven Systems
- Fast critical reactors

Heavy liquid metal (Pb or LBE) as coolant

- High neutron production rate
- low reactivity

Open issues

- Turbulent liquid heat transfer of HLM along fuel pins and bundles



Sketch of ADS

Experimental overview:

Experimental campaign at KALLA in the framework of IP-EUROTRANS:

- LBE single rod experiment
    - Heat transfer for forced, mixed and buoyant convection
    - Test of heater performance
    - Validation and qualification of measurement techniques
- Water rod bundle experiment
    - Pressure drop in subchannels / rod bundle area
    - Fluid-structure-interaction (flow induced vibrations)
    - Validation and qualification of measurement techniques
    - 2dim flow distribution in sub channels (turbulent mixing)
- LBE rod bundle experiment
    - Pressure drop in subchannels / rod bundle area
    - Temperature distribution of the rod bundle in the forced convection regime
    - Heat transfer of the hexagonal rod bundle geometry

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ADS Fuel assembly design

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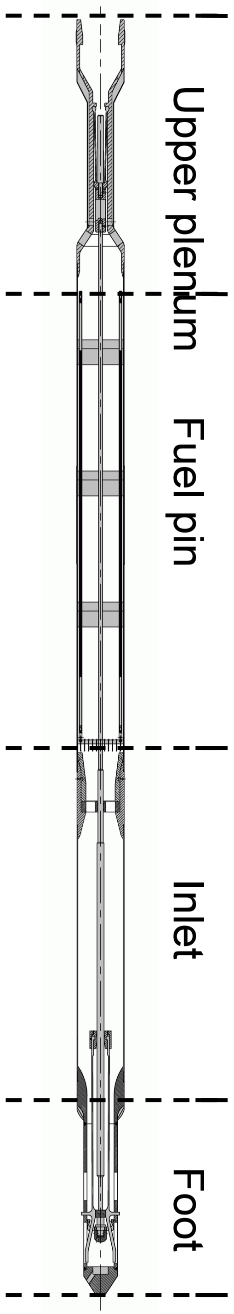
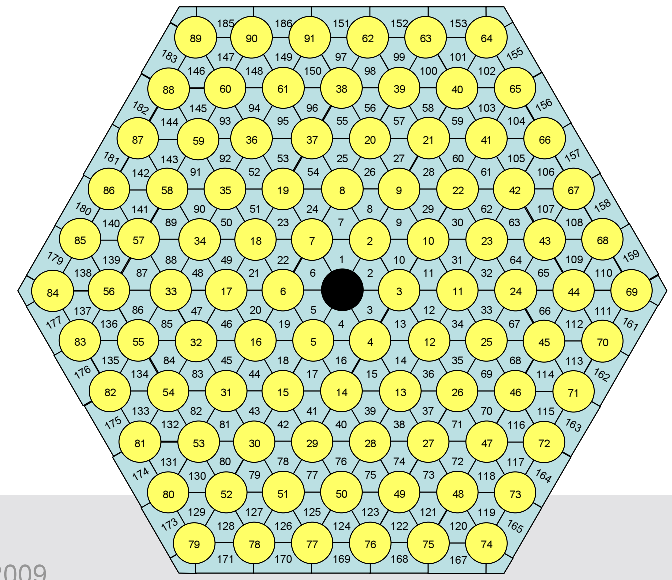
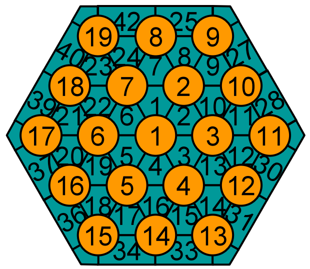
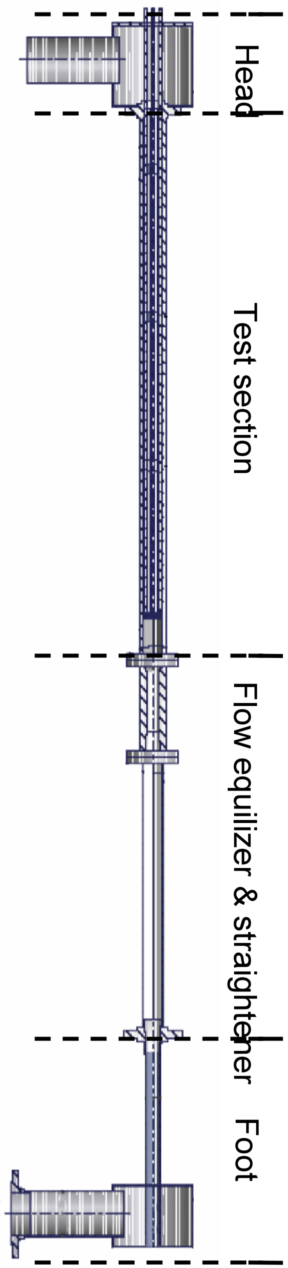


Parameter	PDS-XADS	Experiment	MYRRAH
Design of FA	hexagonal	hexagonal	hexagonal
Total Power	0.775 MW	0.43 MW	1.466 MW
Number of fuel pins	90	19	91
Pin diameter	8.5 mm	8.2 mm	6.55 mm
Pitch	13.41 mm	11.48 mm	8.55 mm
P/D ratio	1.57	1.4	1.3
Pin length	1272 mm	1272 mm	1200 mm
Active height	870 mm	870 mm	600 mm
Nr. of grid spacers	3	3	3
coolant mean velocity	0.42 m/s	2 m/s	2.5 m/s
mass flow	~ 40 kg/s	~ 26 kg/s	~ 71 kg/s
sub channel area	9330 mm²	1260 mm²	2760 mm²
mean heat flux	38 W/cm²	100 W/cm²	131 W/cm²
Inlet temperature	~ 300 °C	~ 300 °C	~ 200 °C
outlet temperature	~ 400 °C	~ 415 °C	~ 337 °C







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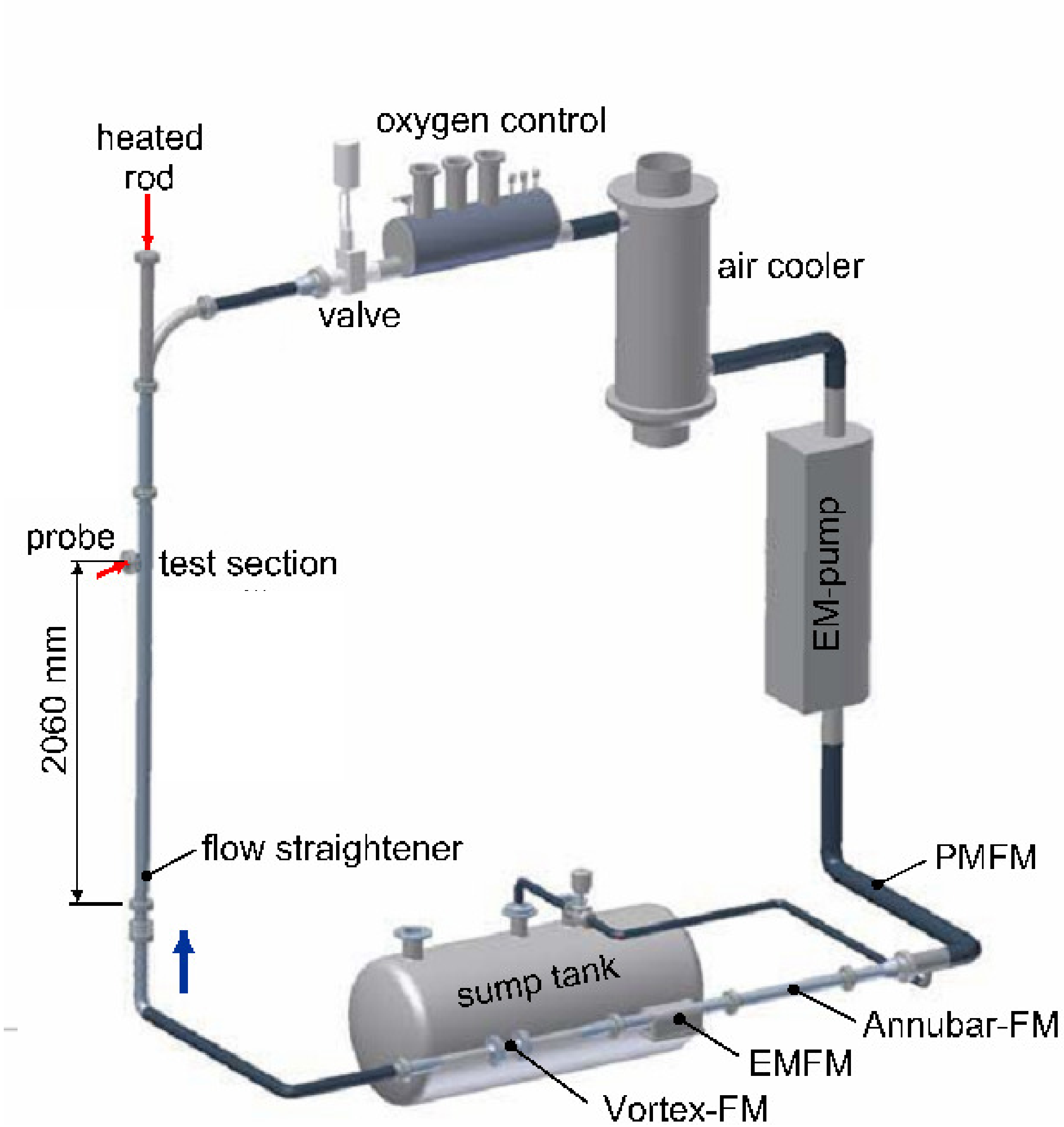
LBE Single rod experiment

Experiment carried out at
LBE Loop Thesys 2

Technology for
Heavy Liquid Metal
Systems
2nd Version

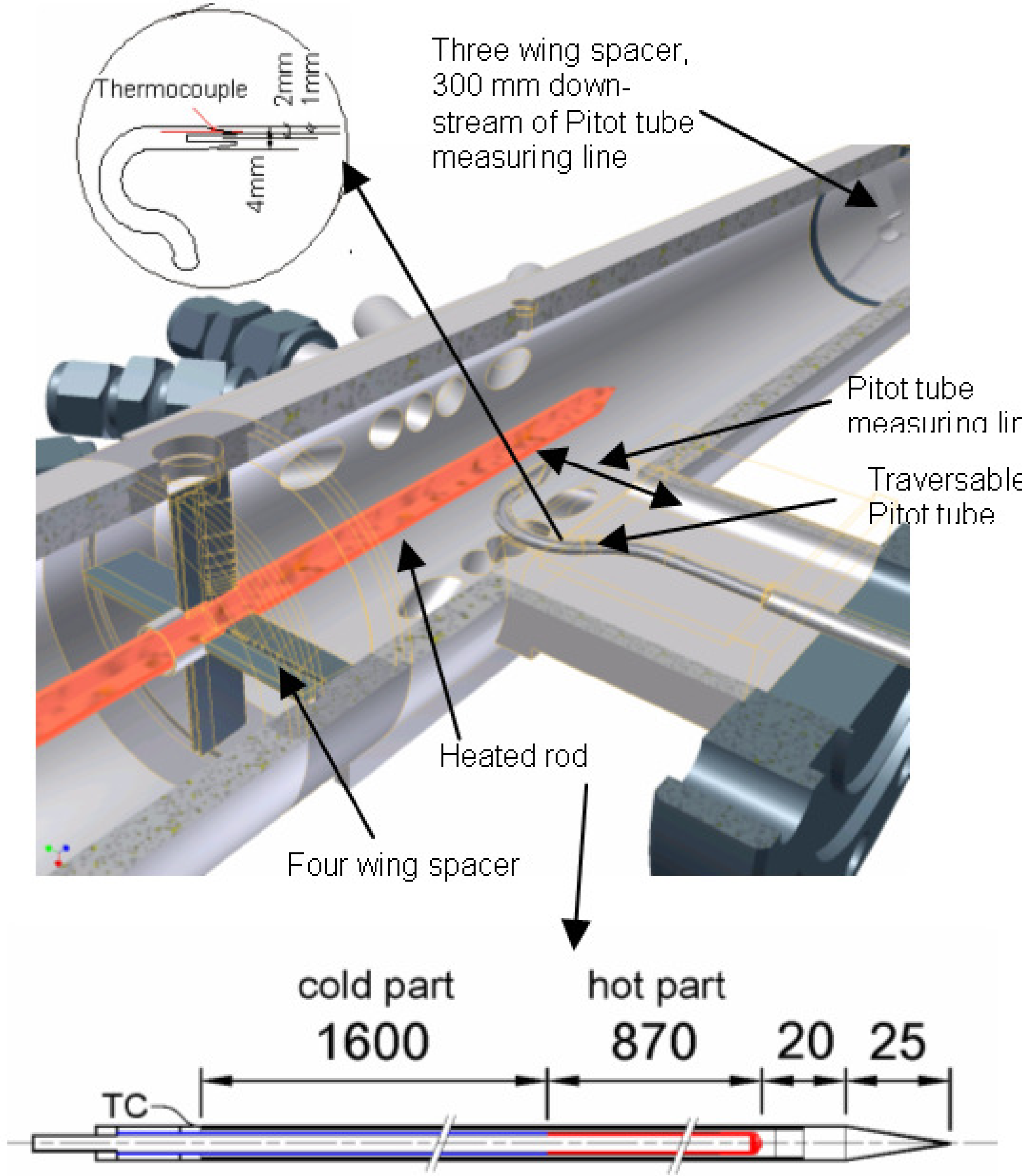
- Medium: $Pb_{45}Bi_{55}$
- Inventory: 222 l
- Flow rate: 2 - 14 m³/h
- Diameter: 60 mm
- 4 different flowmeter
  Accuracy + 0,5%
- Oxygen control



LBE Single rod experiment

- Single rod layout:
  - Total power 22,4 kW
  - heated length 870 mm
  - Power density 100 W/cm²
  - Rod diameter d_r 8,2 mm
  - Tube diameter D 60 mm

- Measurement Range:
  - Temperature 200°C - 400°C
  - Velocity 0 -1.6 m/s
  - Prantl 0,016 - 0,03
  - Reynolds $5{\cdot}10^4$ - $5{,}6{\cdot}10^5$



Results will be presented in Talk 6-16

"Turbulent liquid metal heat transfer along a heated rod within an annular cavity"

Water rod bundle experiment

Experiment carried out at
KALLA water loop

Technical details:

• Temperature	20°C - 100°C
• Flow rate	130 m³/h
• Pressure	14,7 bar
• H_2O inventory	8 m³

- Water rod bundle design identical with LBE rod bundle except for PMMA in active Zone needed for LDA measurements
- Isothermal experiment
- Measurement Range:

Velocity:	0.1 - 10 m/s
Reynolds:	10^3 - $9 \cdot 10^4$

Water rod bundle experiment

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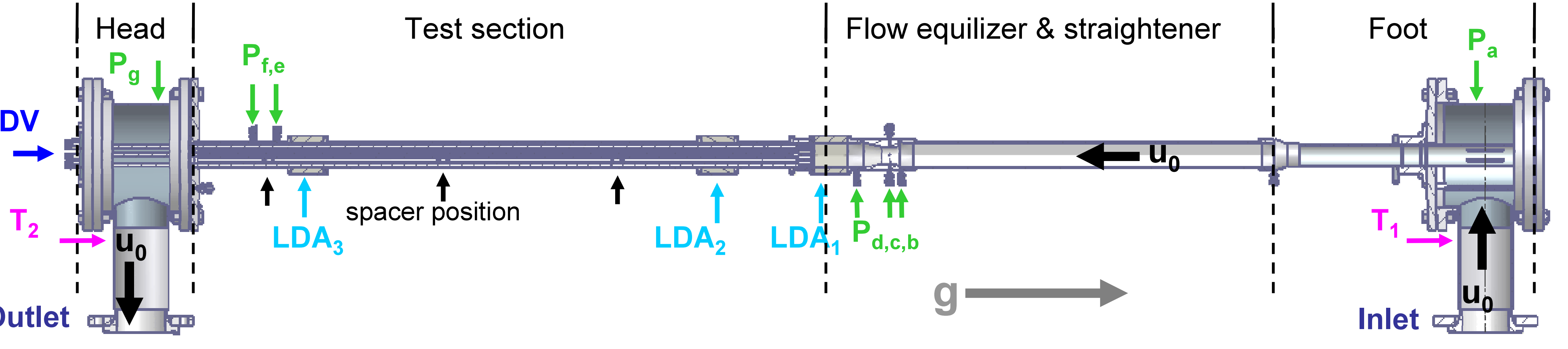
Sensor instrumentation:



Pressure measurements

- Fast pressure sensors P_a to P_g for component specific pressure loss, flow metering and vibration measurements

Temperature measurements

- Static temperature sensors T_1 and T_2 for overall temperature change

LDA velocity measurements

- LDA_1 downstream venturi nozzle for inlet conditions
- LDA_2 upstream fist spacer for lateral flow distribution due to the bundle
- LDA_3 downstream 2nd spacer for lateral redistribution

UDV velocity measurements

- Measurement in each sub Channel type

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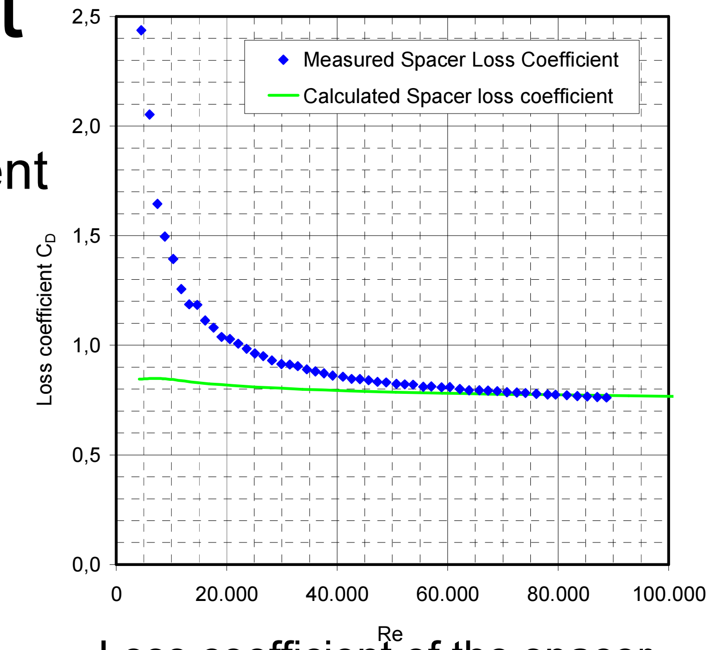
Water rod bundle experiment

Measurements of pressure loss P_a to P_g in different configurations to characterize loss coefficient of

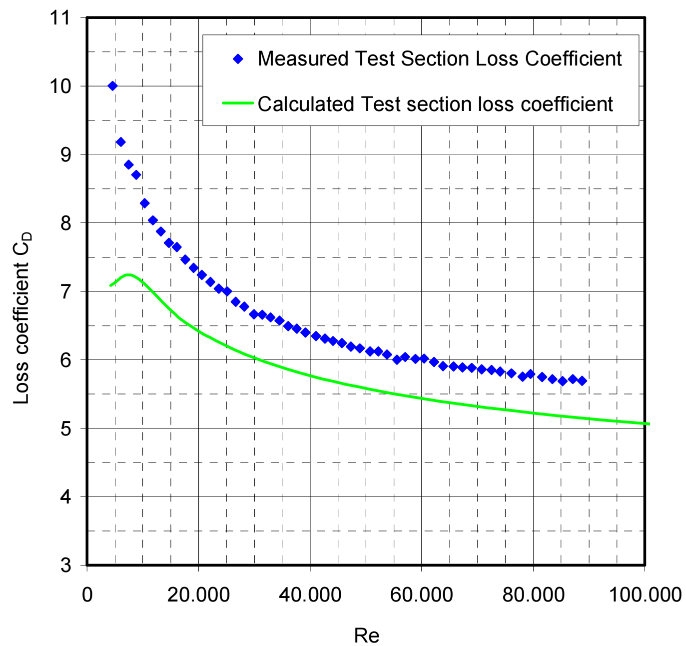
- Inlet section with foot and riser
- Flow straightener
- Test section
- Spacer

	Exp Pressure loss	Loss coefficient
Inlet section	0.60 bar	--
Flow straightner	0.66 bar	--
Spacer	0.38 bar	0.78
Test section	2.58 bar	5.7

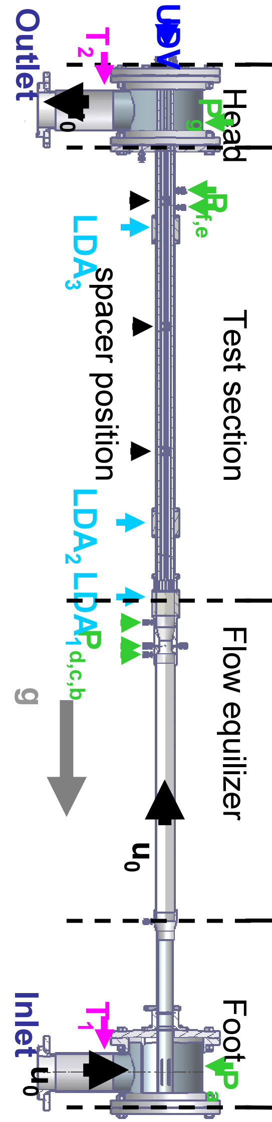
Experimental results of pressure loss measurements at max velocity of 10m/s (Re 88.000)



Loss coefficient of the spacer



Loss coefficient of the test section



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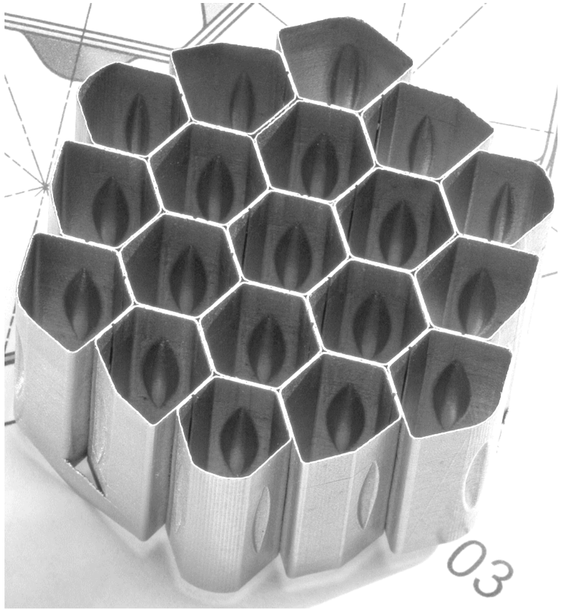
Water rod bundle experiment

Comparing experimental results:

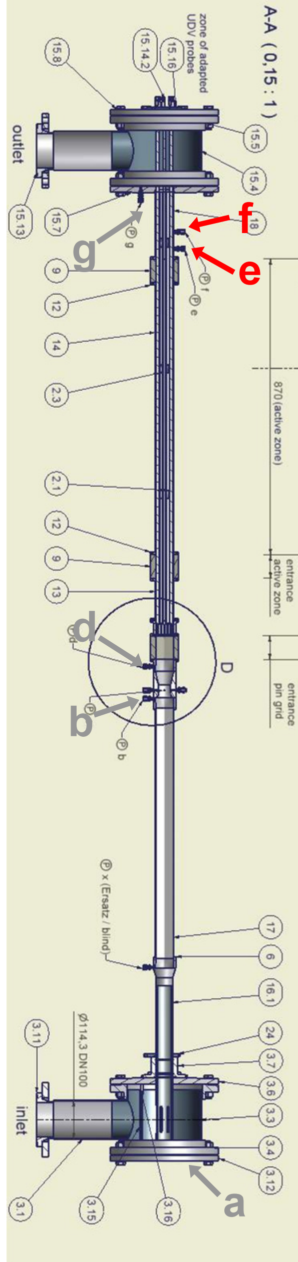
- Simple calculation of loss coefficient for used spacer given by average blockage ratio calculates a loss coefficient of 0.65

$$C_D = 7 \cdot \left(\frac{A_S}{A} \right)^2 \qquad C_D = \frac{\Delta p}{0.5 \cdot \rho \cdot u^2}$$



- Calculated pressure losses for water and lbe experiment:

	H_2O Exp.	LBE Exp 200°C	LBE Exp 300°C
Spacer pressure loss	0.38 bar	0.20 bar	0.20 bar
Test section pressure loss	2.58 bar	2.26 bar	2.21 bar



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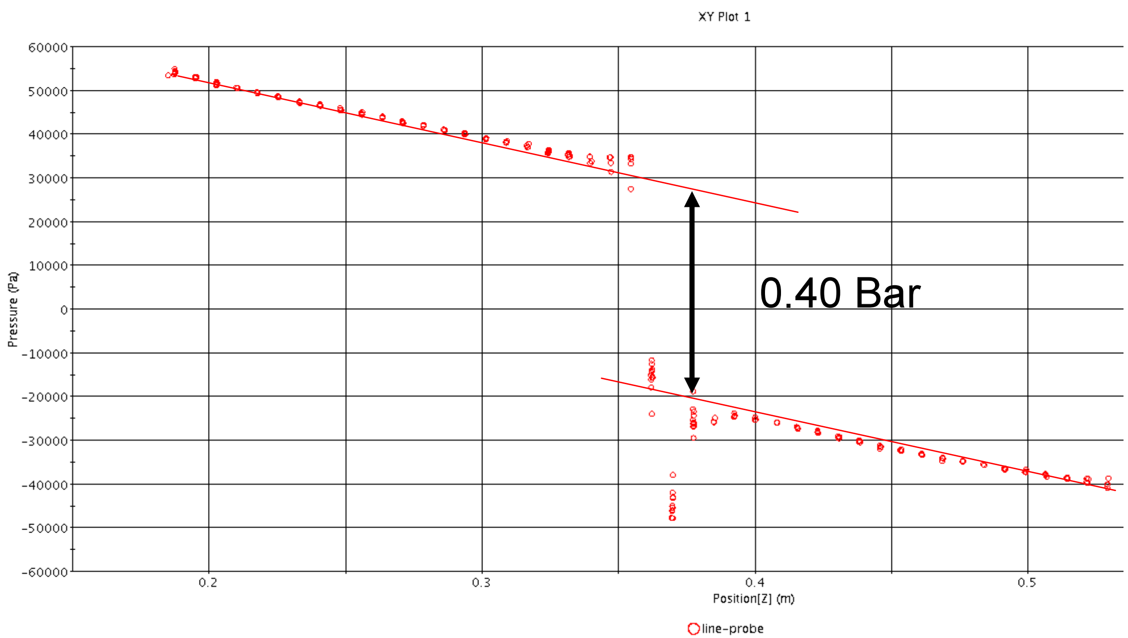
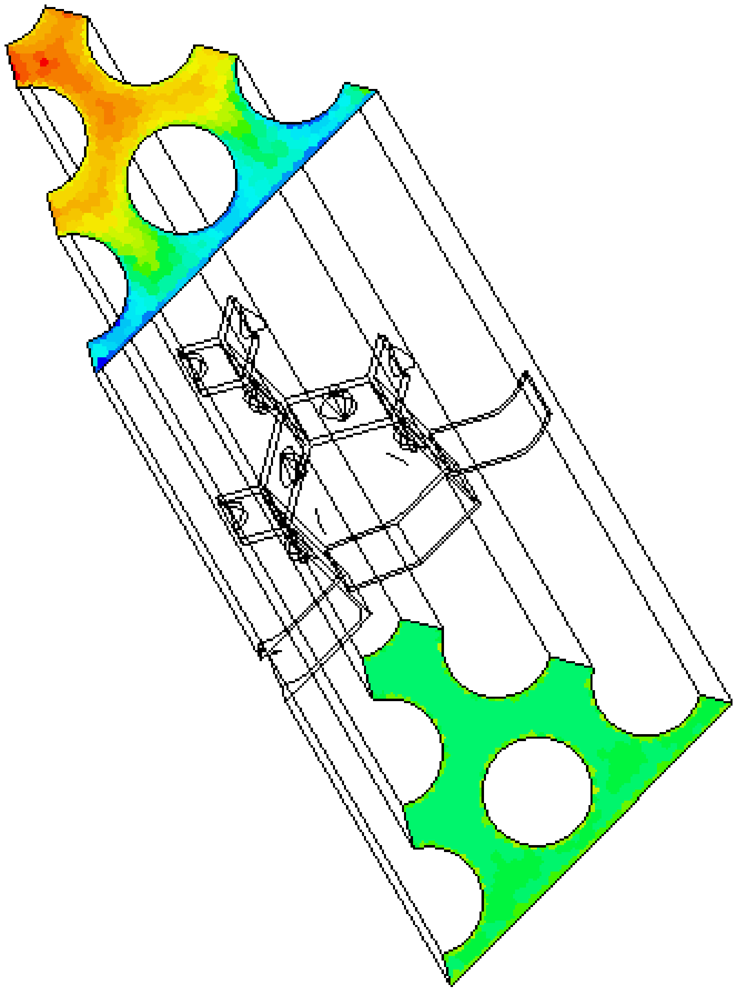
Water rod bundle experiment

CFD of the test section area

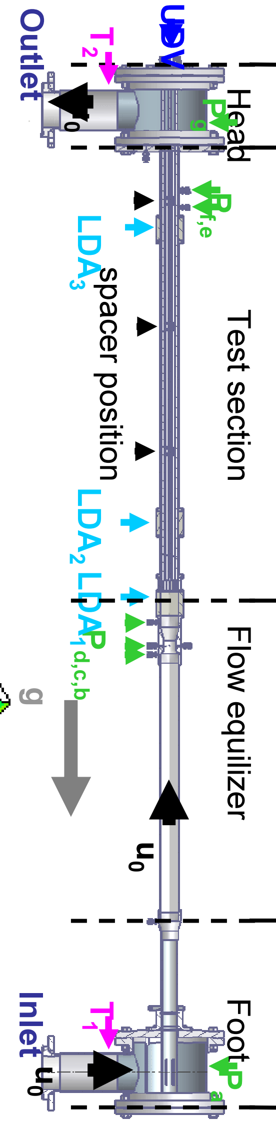
Calculated pressure loss of the spacer geometry agrees very well with measured pressure loss.



calculated pressure loss of the test section near a spacer



CFD 1/6 of the test section with modelled spacers
(1.2M cells, kε model)



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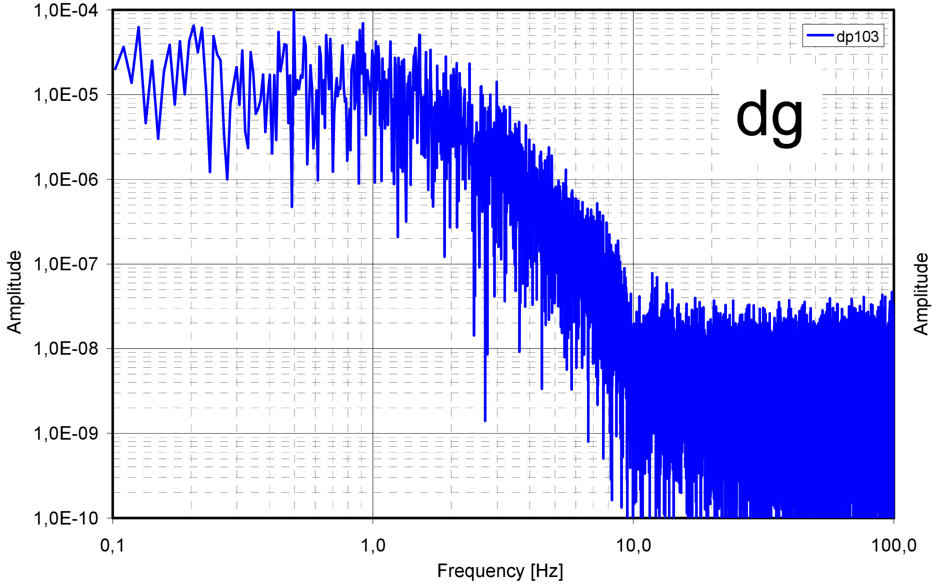
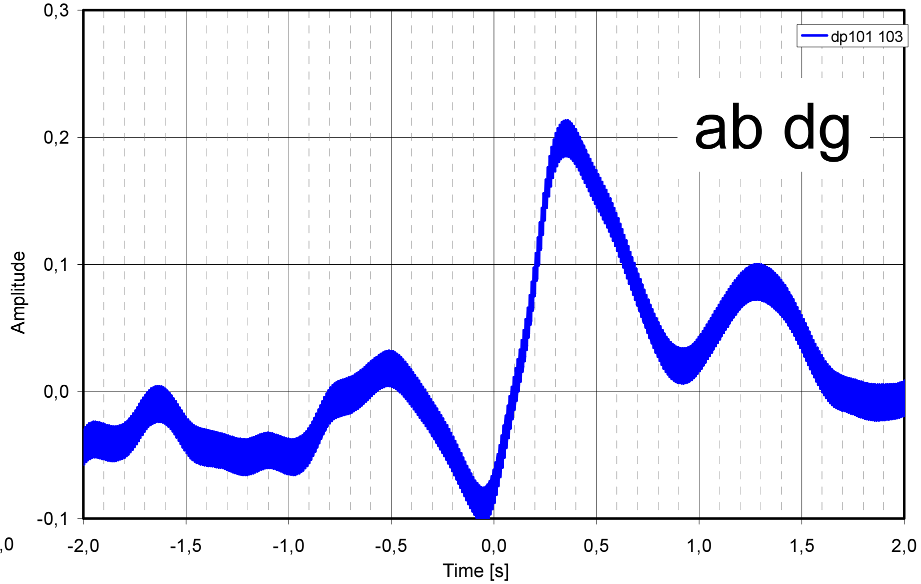
Water rod bundle experiment

Measurements of pressure loss on inlet and test section area with high time resolution:

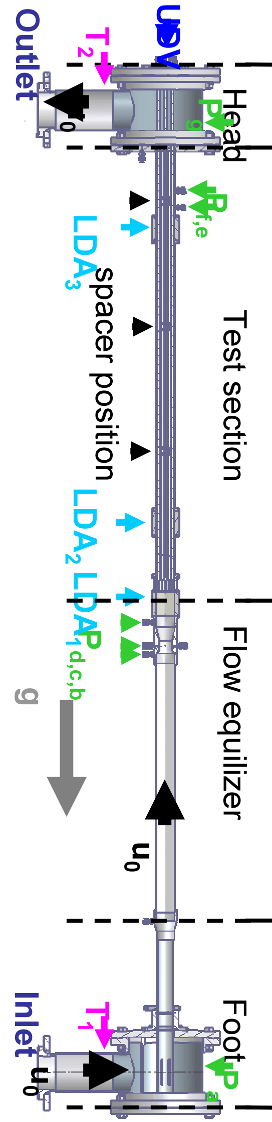
- Negligible influence of flow induced vibrations onto the experimental setup.



FFT of the time resolved pressure of the test section



Cross correlation calculation of the time resolved pressure of the inlet and test section



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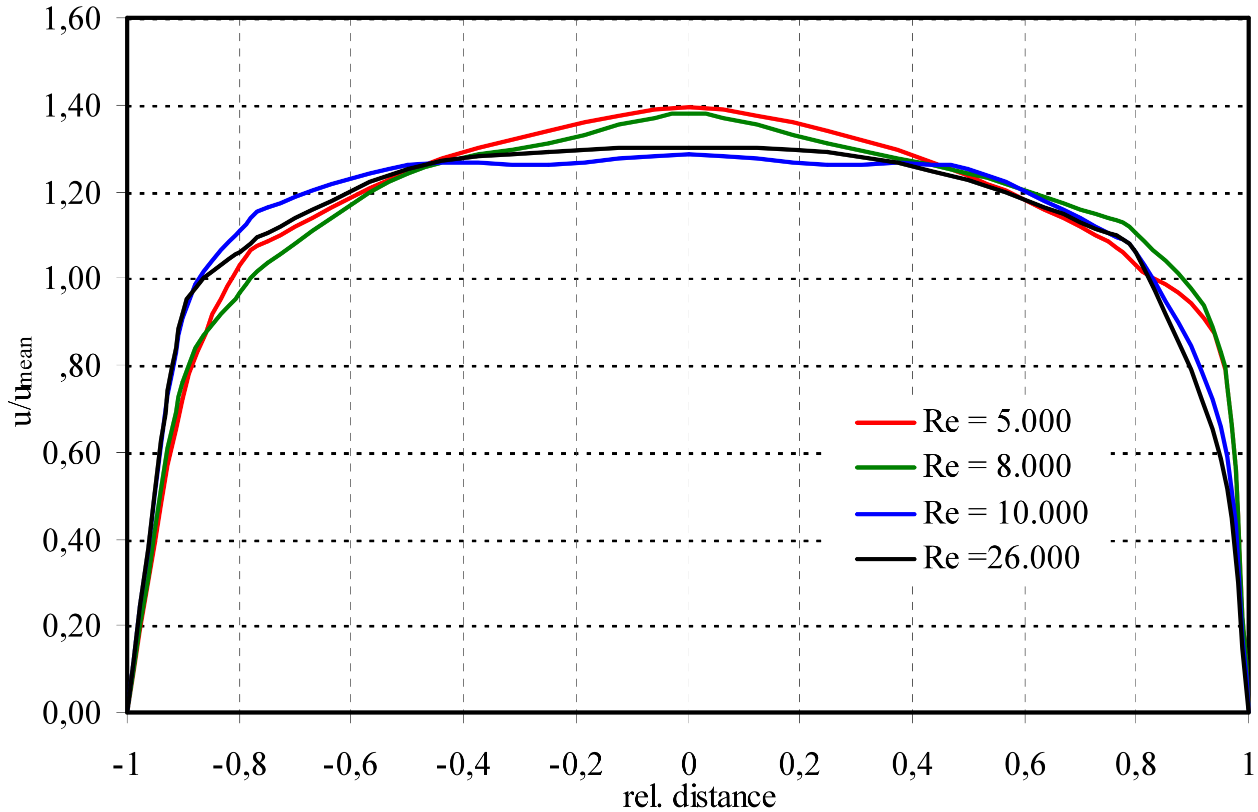
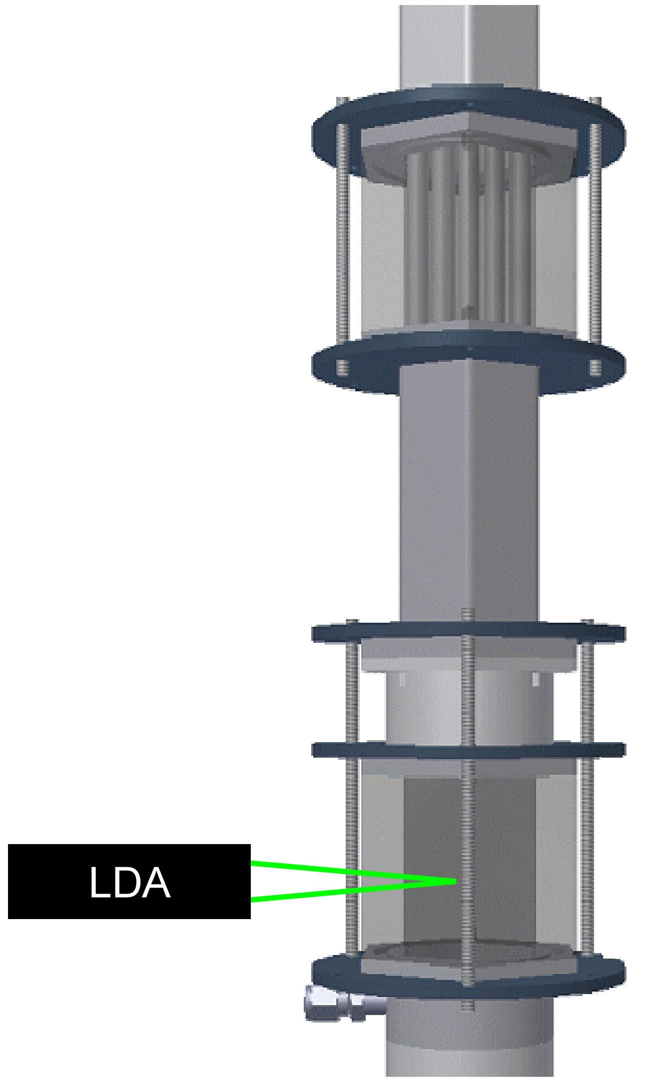
Water rod bundle experiment

LDA Measurements of 1d velocity downstream the venturi nozzle at the end of the flow straightening section :

- Symmetric flow distribution, flow conditionning works more reliable compared to the single rod experiment.



Normalized velocity profile downstream the venturi nozzle at the end of the flow straightening section



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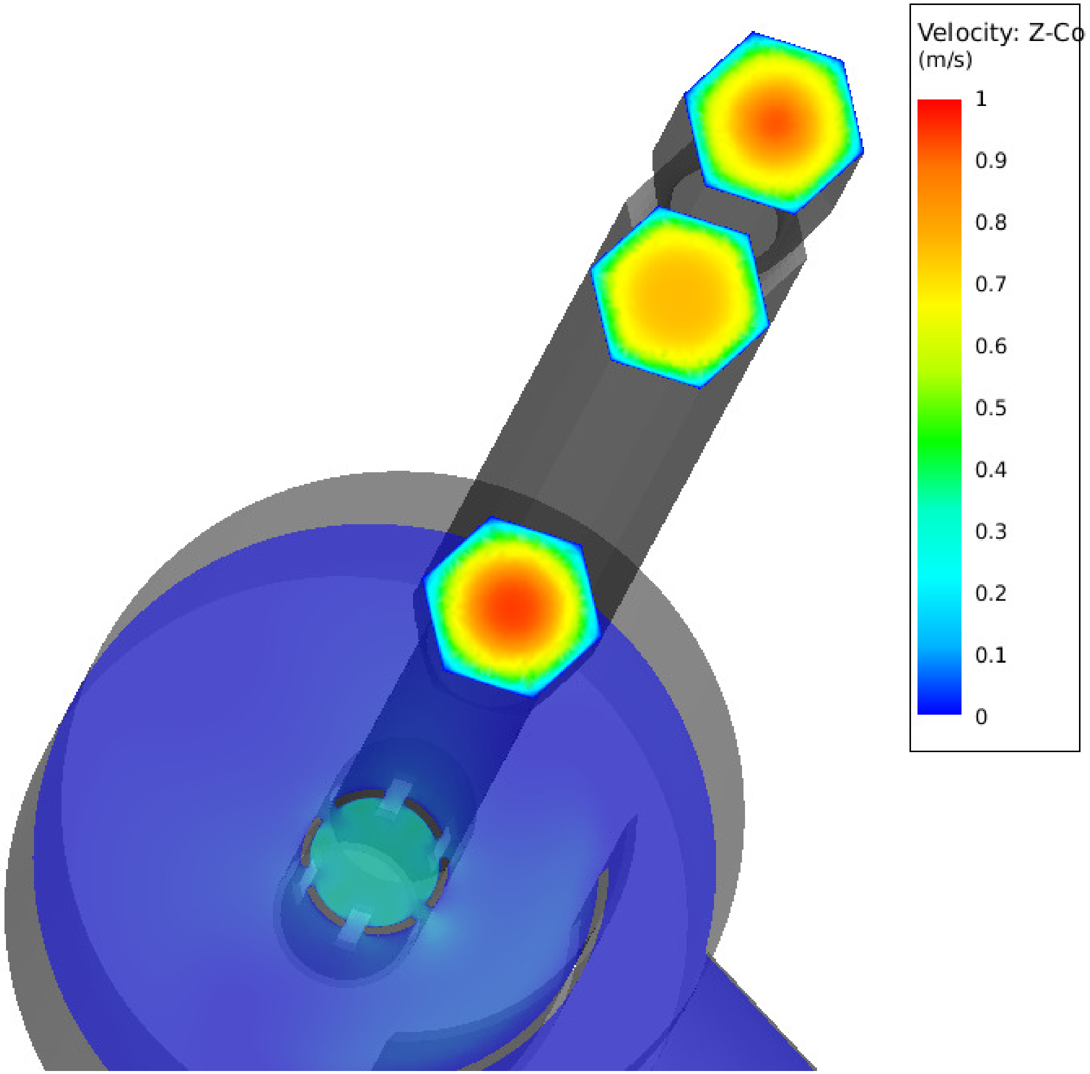
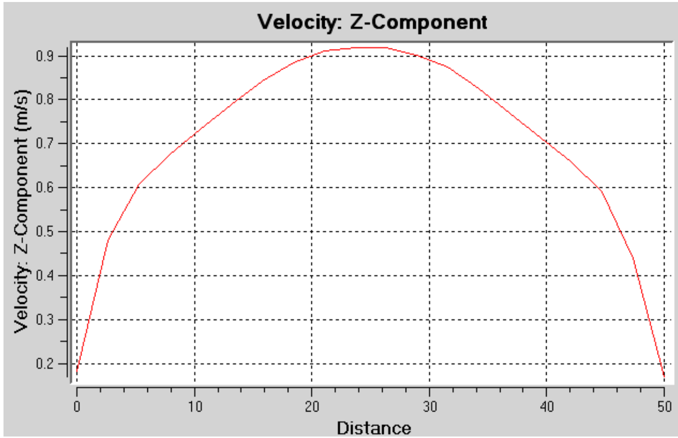
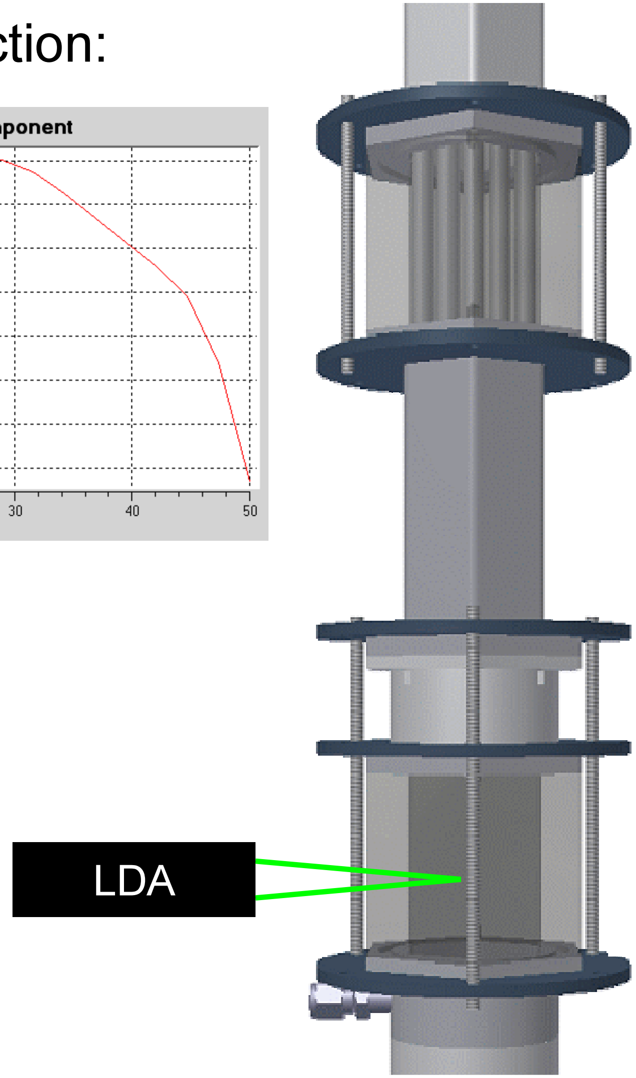
Water rod bundle experiment

CFD of the velocity profile at the end of the flow straightening section:







Velocity profile downstream the venturi nozzle at the end of the flow straightening section with Re 8000. (cfd with 960.000 cells , k ε model)

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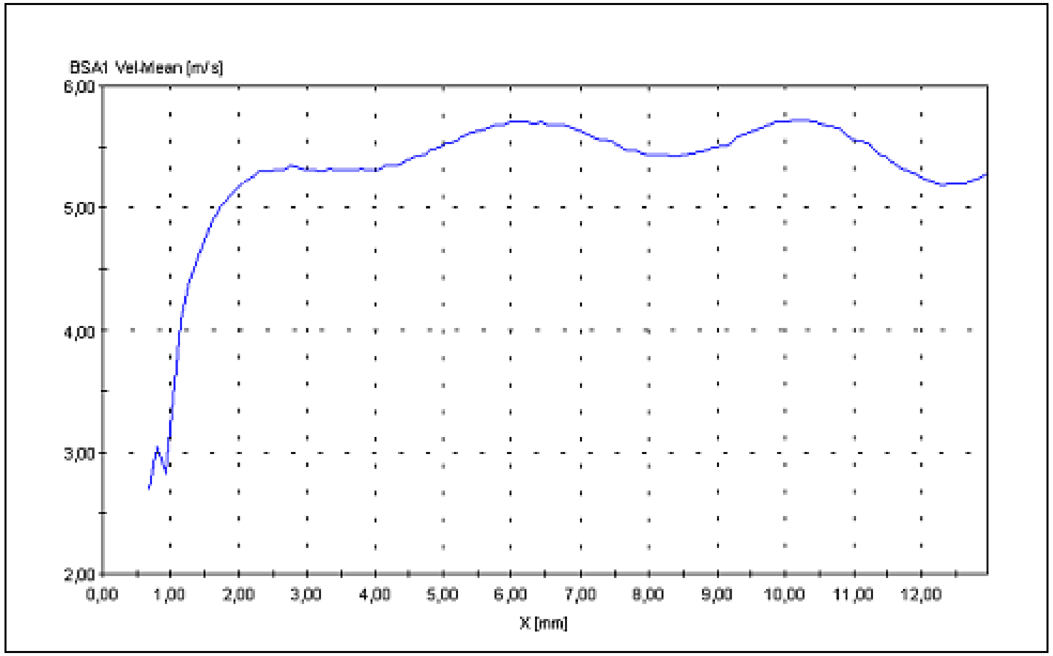
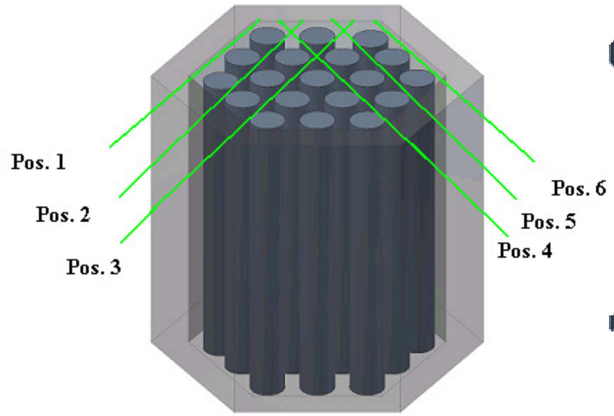
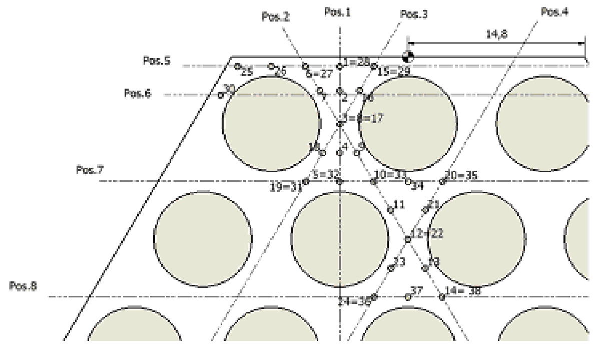
Water rod bundle experiment

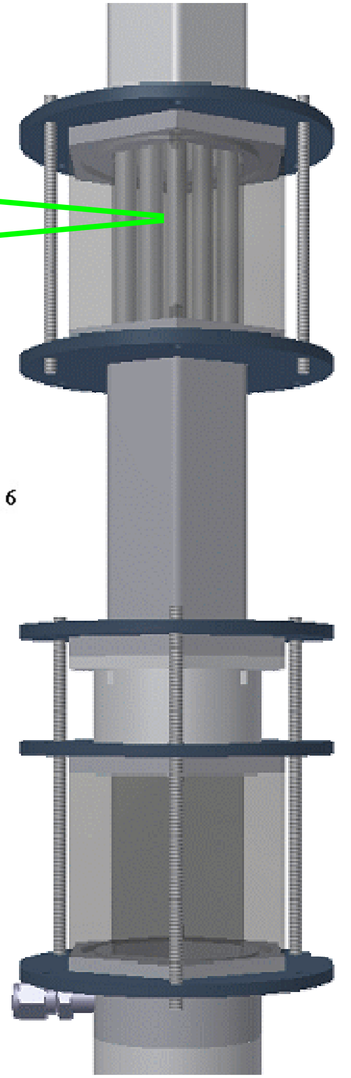
- 1d Measurements of the velocity profile in the testsection area:



1d velocity profile at the beginning of the testsection (5m/s Re 38000)







- 2d Measurements of the velocity profile in the testsection area are planned.
- Additional cfd planned.

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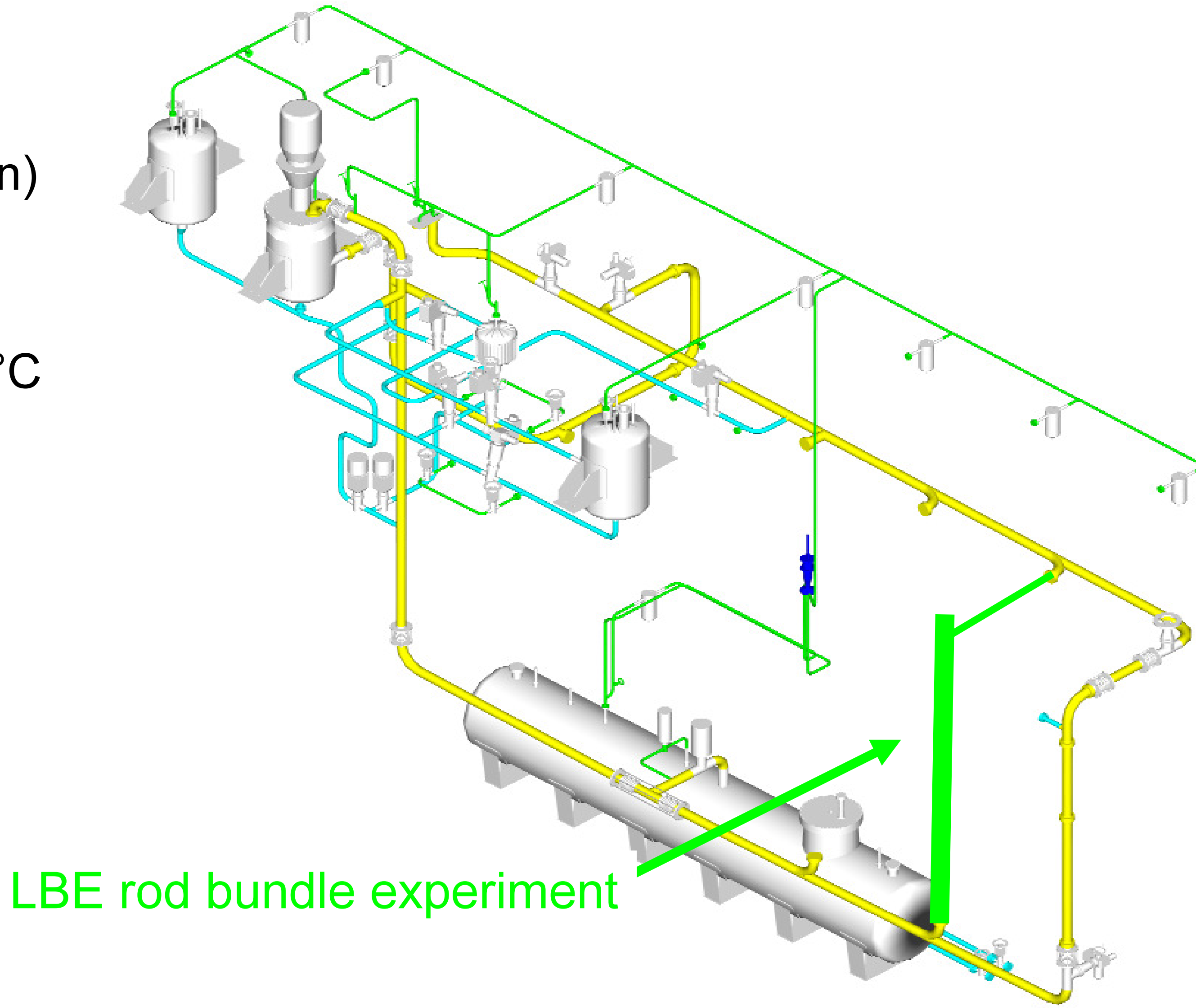
LBE rod bundle experiment

Experiment to be carried out at
LBE Loop THEADES
(*THE*rmalhydraulics and *A*ds *DES*ign)

Technical details:

- Temperature 190°C - 450°C
- Flow rate 47 m³/h
- Pressure 5,9 bar
- Test ports 3
- Usable height 3405 mm
- O_2 Control ☑
- LBE-Inventory 4 m³ (42 to)
- Tube diameter 107mm



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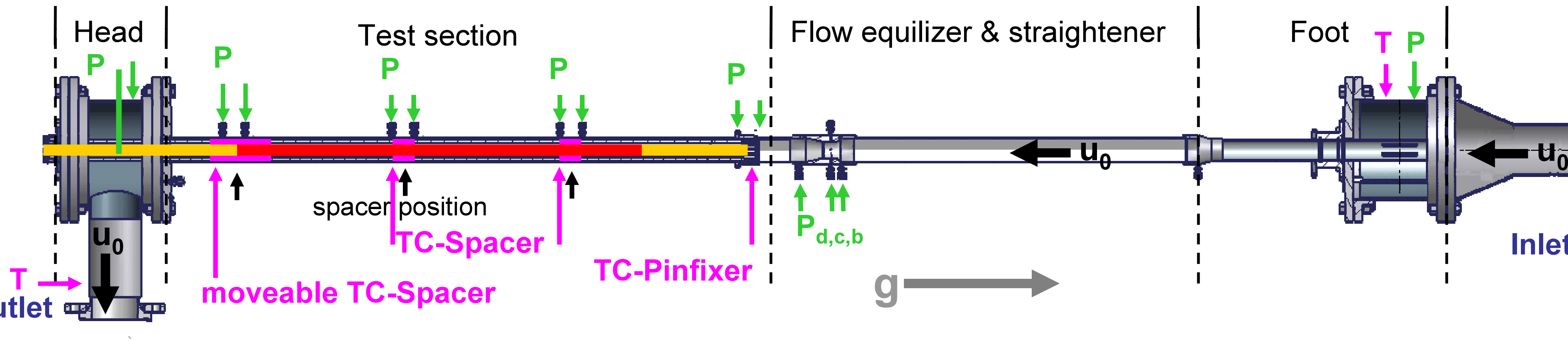
LBE rod bundle experiment

Sensor instrumentation:



Pressure measurements

- Fast pressure sensors for component specific pressure loss, flow metering and vibration measurements.
- Pitot tube for pressure distribution in sub channels

Temperature measurements

- Static temperature sensors T for overall temperature change
- Fast TC equipped spacer and Pinfixer for subchannel and rod surface temperature distribution

Conclusions

- Single rod experiments show a large influence of buoyancy on the velocity profile even at relatively high Reynolds Numbers while the temperature field is less influenced. This yields to an enhanced heat removal.
- Currently used Nusselt correlations are rather conservative.

- Water rod bundle experiments show very good agreement of measured pressure loss with numerical predictions in the fully turbulent flow regime whereas in the transitional regime secondary flow leads to a rising loss coefficient
- Measurements show negligible flow induced vibrations onto the setup

- LBE rod bundle experiments will be conducted soon and hopefully give new insights onto the heat transfer.

Acknowlegement

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