MYRRHA Core Component Testing in Heavy Liquid Metal Coolant

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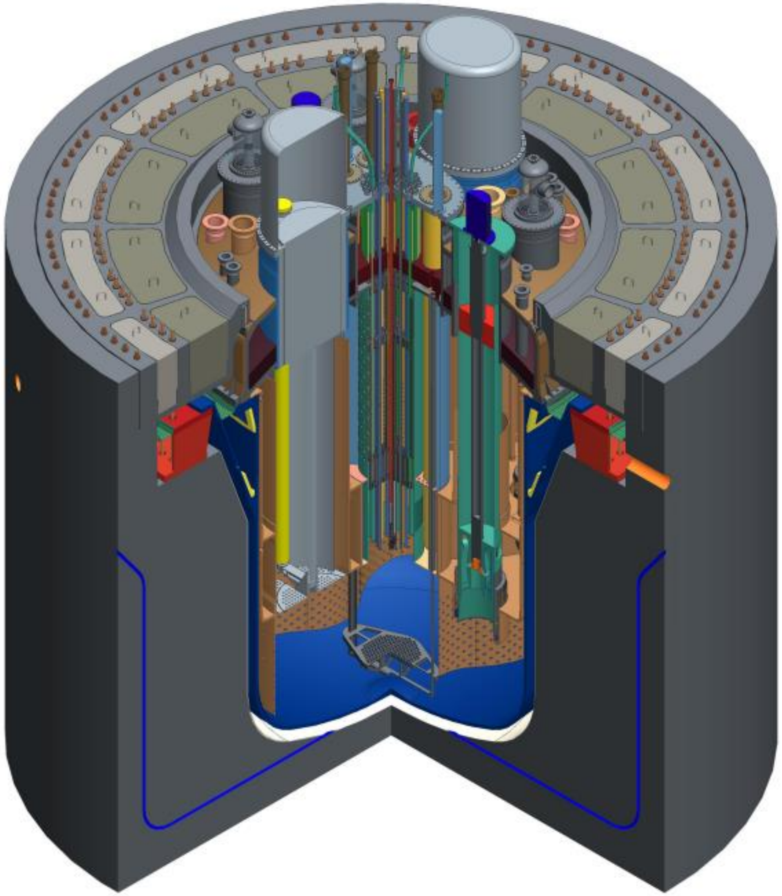
EU DuC = N

MYRRHA @ SCK•CEN

- MYRRHA = **M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications
- Characteristics
  - Critical and Accelerator Driven System mode
  - Lead Bismuth Eutectic coolant
- Purpose
  - Fast spectrum irradiation facility (after BR2)
  - European technology pilot plant for LFR
  - P&T demonstration in ADS



MYRRHA R&D program

- R&D program required for engineering design, safety and licensing
- Knowledge of the thermal hydraulic and hydrodynamic behaviour of all core components is of high importance
- Model experiments are necessary for understanding the physics, for validating numerical tools and to qualify the design for the licensing.
- SCK•CEN have established numerous collaborative partnerships within EC FP7 and H2020 projects:
  - KIT
  - NRG
  - ENEA
  - CRS4
  - VUB & UGent

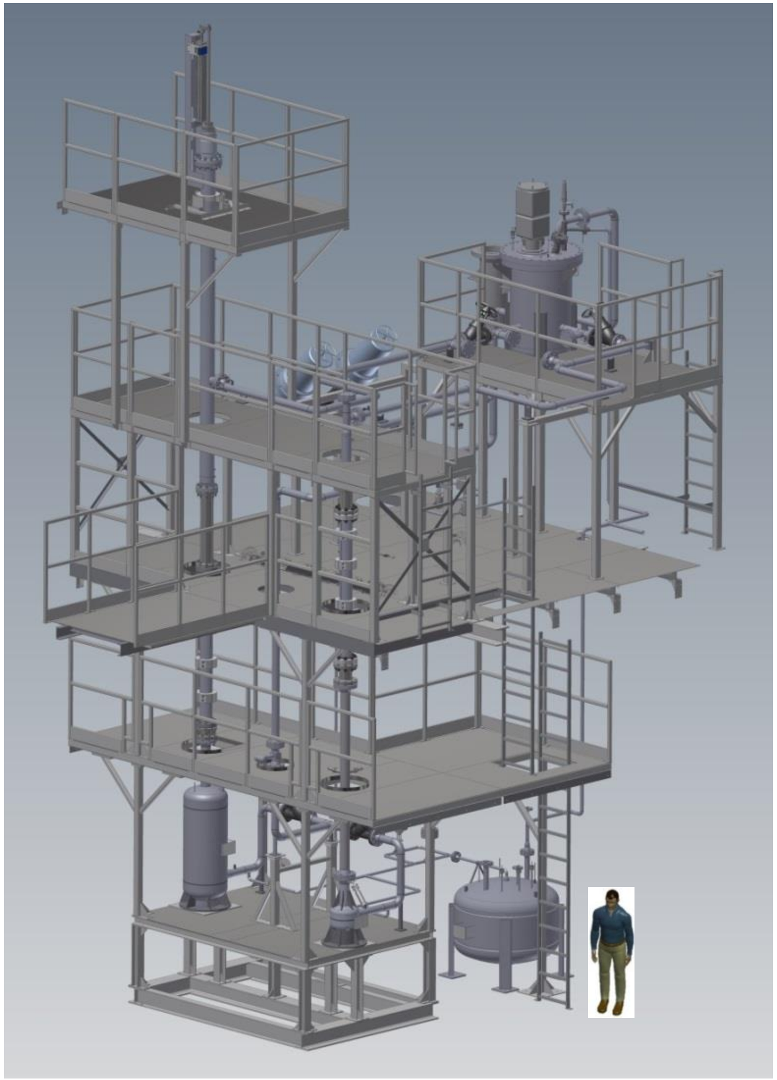
Core component testing

- **<u>Fuel assembly</u>** experimental and numerical investigation of:
  - Pressure drop characterisation of a full-scale 127-pin bundle – SCK•CEN (experimental), NRG (numerical)
  - Thermal hydraulic heat transfer coefficient characterisation of a 19-pin heated bundle – KIT, ENEA (experimental), NRG (numerical)

    Forced convection

    Natural and mixed convection
  - The safety relevant thermal-hydraulic behaviour of the fuel assembly with a partial internal blockage – KIT (experimental), NRG (numerical)
  - Flow induced vibration
- **<u>Control rod</u>**
  - Full-scale hydrodynamic experimental testing in LBE – SCK•CEN
  - Numerical dynamic CFD analysis – CRS4

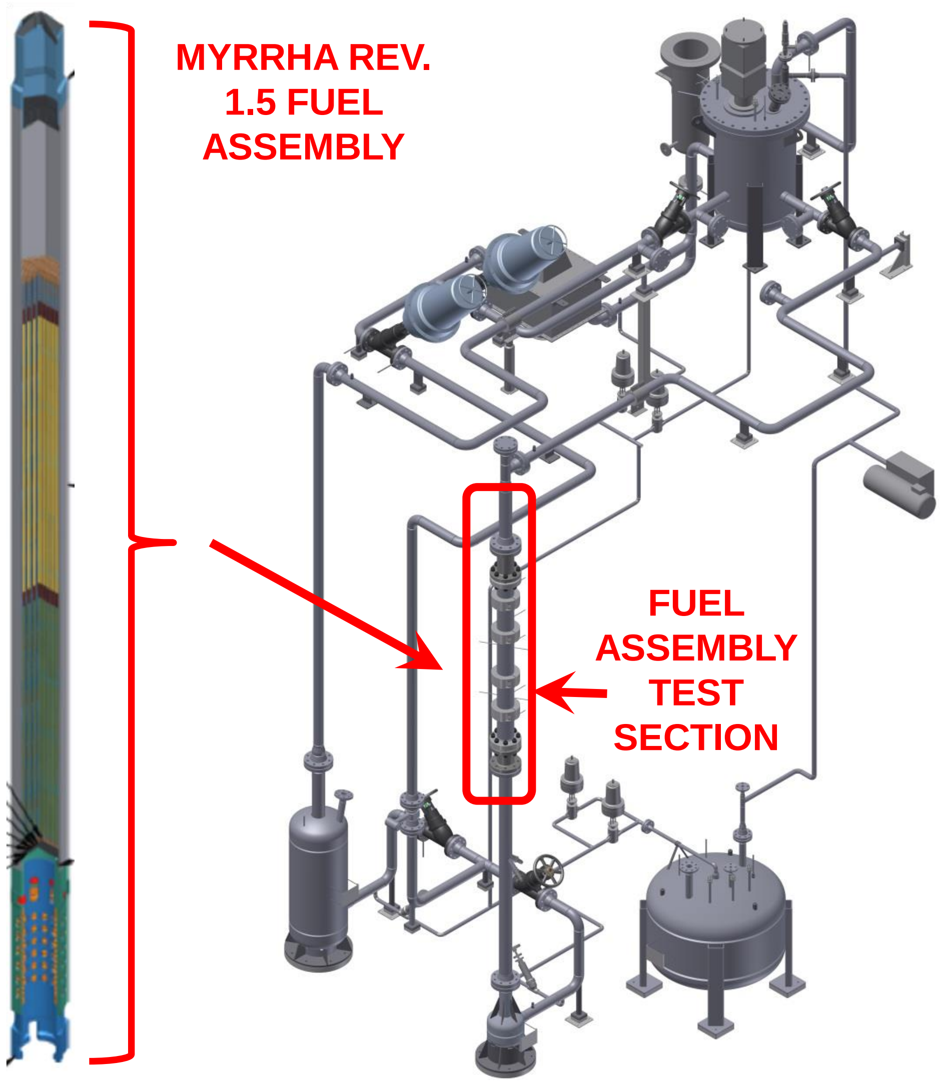
COMPLOT LBE Facility



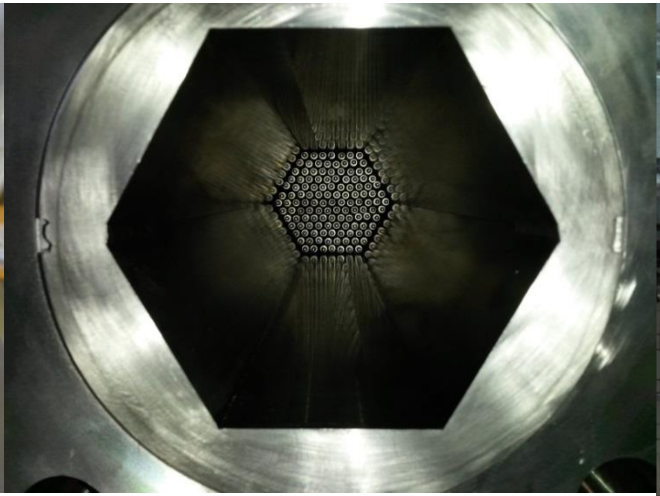
Parameter	Value
Design Pressure (Bar)	16
Material	316L
Operational temperature range (°C)	200 - 400
Flow rate range (m3/h)	1.24 - 36
Flow rate range (kg/s)	3.6 - 104.7
LBE Volume (litres)	~ 800
Installed tracing (kW)	75

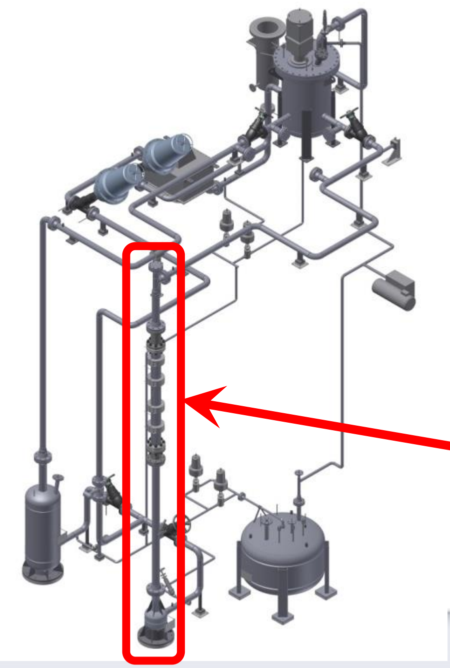
Fuel Assembly ΔP Test Section

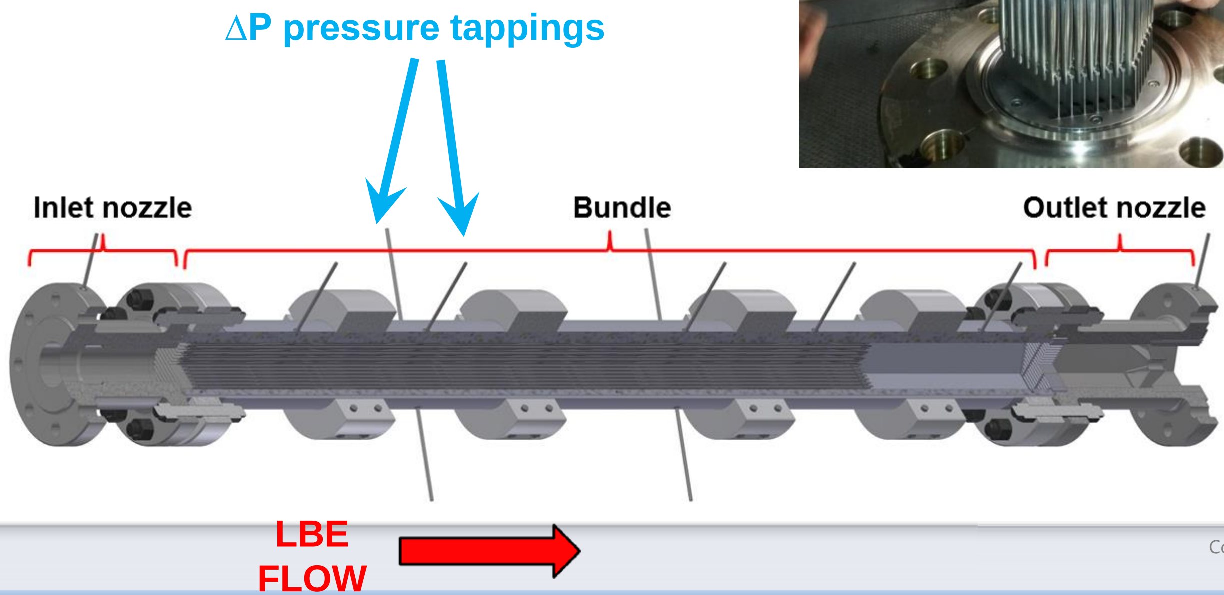
- Helical wire-spacer to preserve spacing between adjacent pins
- Primary system pressure losses dominated by the FA pressure drop:
  - Defines the primary pump specifications
  - Determines free surface level difference
  - Defines the natural convection flow rate => passive decay heat removal
- Test section: 1:1 MYRRHA scale (127 wire-wrapped pins)
  - Empty pins – all in 316L
  - Pressure tappings for differential pressure measurements



Fuel Assembly ΔP Test Section

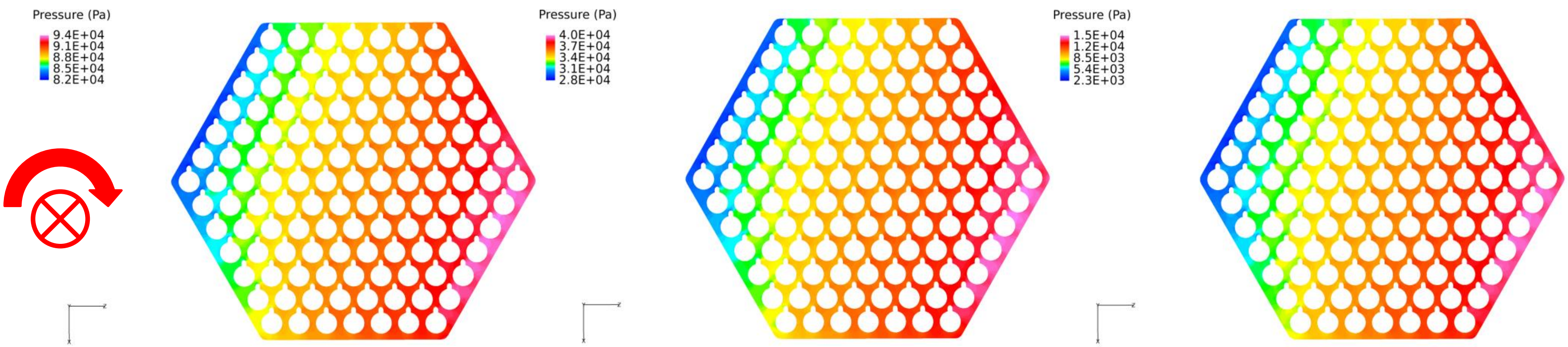






Pre-test CFD analysis

- Characteristic transverse pressure profile evident: periodic across axial positions in multiples of the wire-wrapper pitch i.e. 1.75·H, 3.75·H, 4.75·H

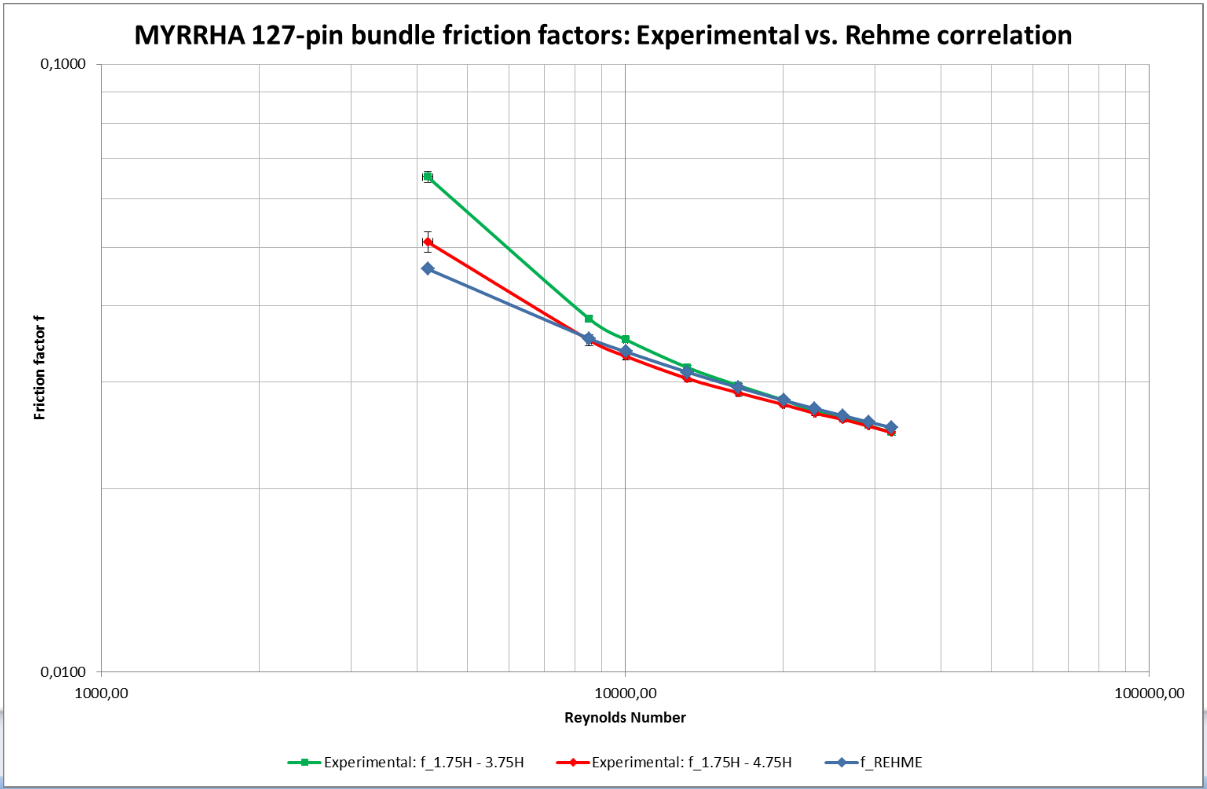


1.75·H **3.75·H** **4.75·H**

- Local minimum and maximum pressure regions: consistent maximum difference ~12 kPa (~44% of the axial pressure drop over one wire pitch)
  - Characteristic global swirl motion at the periphery associated with wire-wrapped assemblies

FA ΔP Experimental results: Comparison with correlations

- Correlations (f vs Re):
  - Rehme (1973)
  - Cheng and Todreas (Simplified and detailed) (1986)
  - Baxi and Dalle Donne (1981)
- Rehme (1973) correlation most suitable: consistently over predicts the measured data by 1-2% (except at the lowest flow rate; Re = 4,200)*
  - Rehme correlation is intended for transition and turblent regime



Re_{bdl} x 10^3	% error (Rehme)	% error (CTD)	% error (CTS)	% error (BDD)
4,20	-9,70	-14,11	-1,82	-6,93
8,53	0,62	-3,94	12,52	1,29
10,02	1,76	-2,65	14,55	3,54
13,14	2,46	-2,06	16,10	5,46
16,44	2,00	-7,59	10,80	5,40
20,03	1,67	-6,75	11,81	5,04
23,00	1,80	-6,00	12,70	4,96
26,04	1,42	-5,90	12,83	4,27
29,13	1,61	-5,38	13,45	4,10
32,23	1,99	-4,78	14,17	4,10

***Kennedy et al., Experimental investigation of the pressure loss characteristics of the full-scale MYRRHA fuel bundle in the COMPLOT LBE facility, 2015, NURETH-16, Chicago.**

Experimental results: Comparison with CFD

- CFD analysis under predicts the average presure drop over one wire pitch, and the corresponding friction factor by approximately 12 – 13%
  - Experimental mass flow rate was 71,73 kg/s compared with the 71,4 kg/s used in the CFD model

Variable	Experiment	CFD	% difference
$\Delta P_{wirepitch}$ 1.75H-3.75H (mbar)	307,20 ± 1,03	270,05	-12,09
$\Delta P_{wirepitch}$ 1.75H-4.75H (mbar)	307,11 ± 2,54	265,53	-13,54
$f_{1.75\text{-}3.75}$ $(x10^{-3})$	24,77 ± 0,12	21,79	-12,05
$f_{1.75\text{-}4.75}$ $(x10^{-3})$	24,76 ± 0,23	21,42	-13,49

- The CFD model predicts a lower average wire-wrapper pressure drop across 3 wire pitches, than that across 2 wire pitches => similar trend seen in the experimentally measured values but only at lower flow rates (in absolute pressure terms)
  - Likely attributed to flow development through the bundle

- **ONGOING AND FUTURE EXPERIMENTS: Repeatability and influence of temperature**

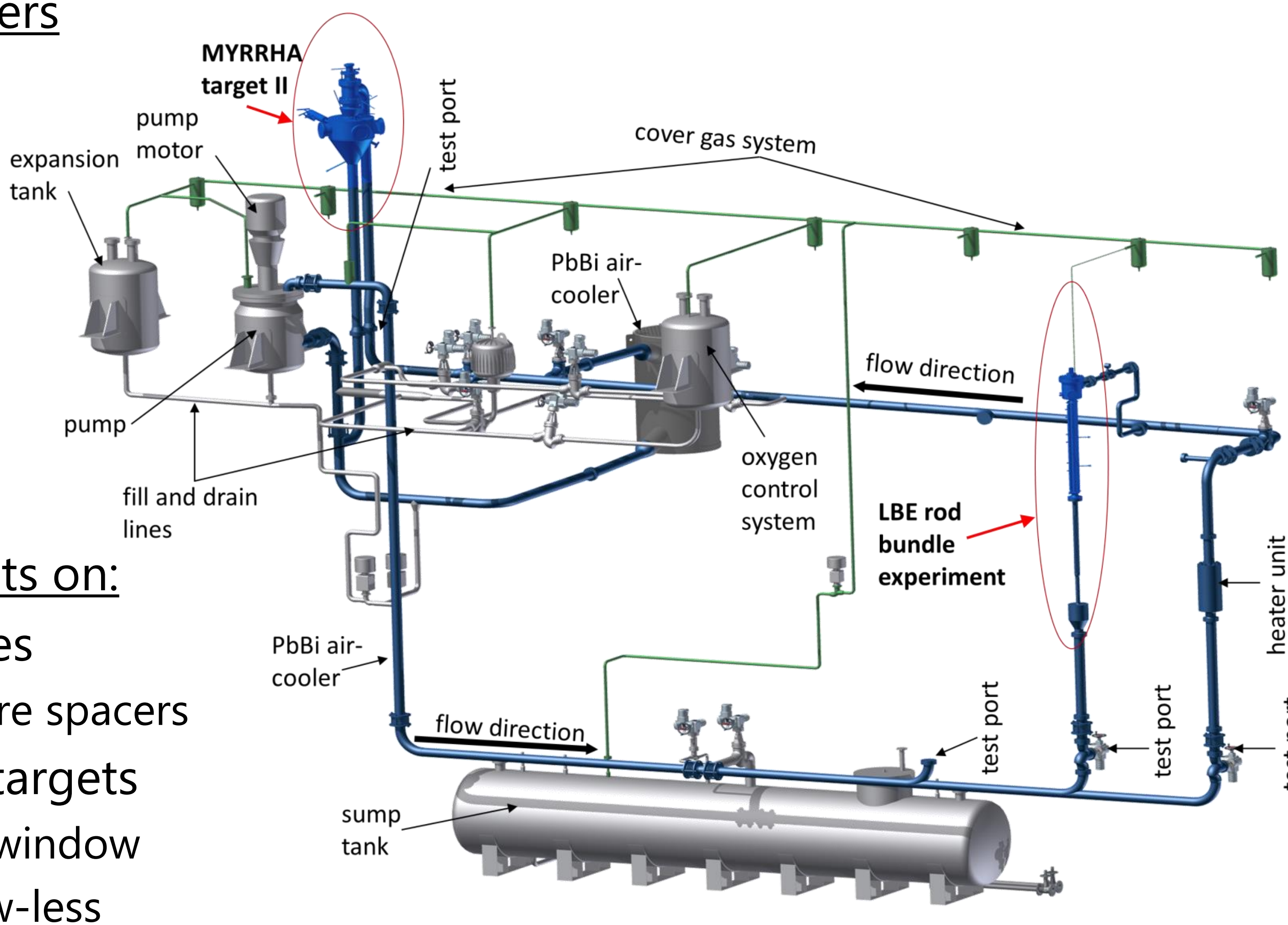
Experimental facility THEADES: Forced circulation

Max. parameters

- 450°C
- 47 m^3/h
- 5,9 bar
- 500 kW
- h=3.4 m

TH Experiments on:

- Rod bundles
  - Grid/wire spacers
- Spallation targets
  - Target window
  - Window-less



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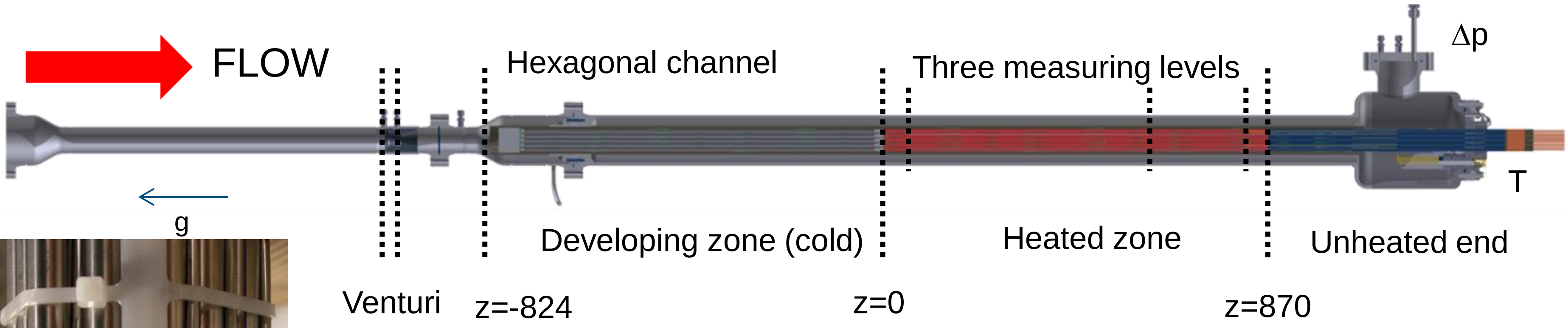
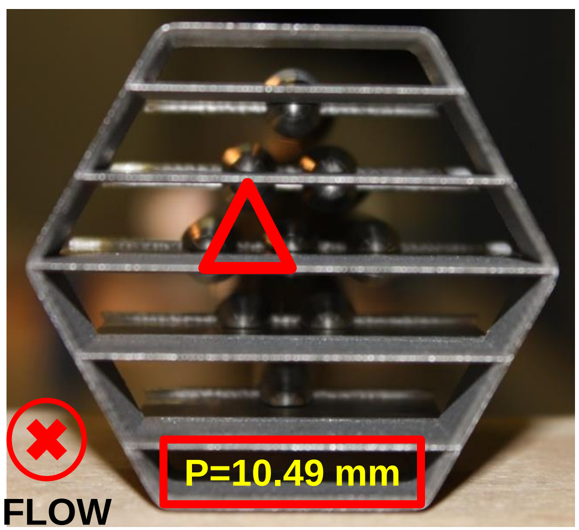
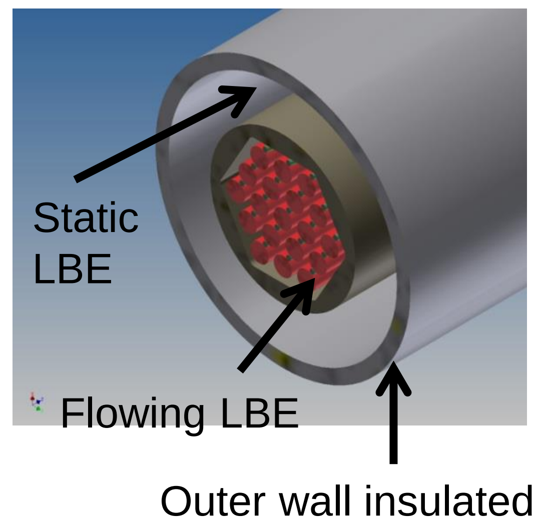
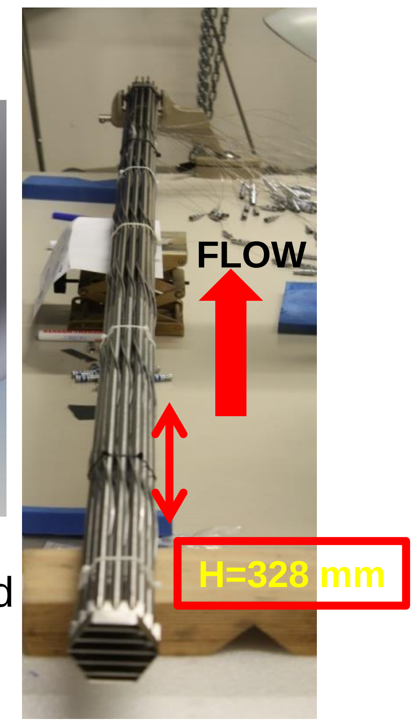
Test section: 19-rod bundle with wire spacers









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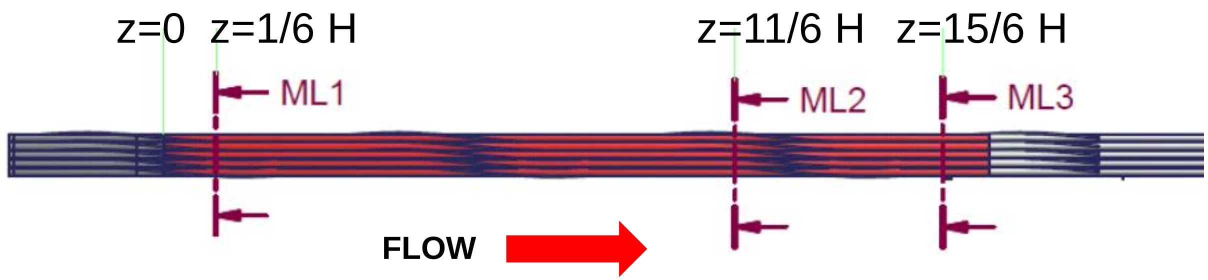
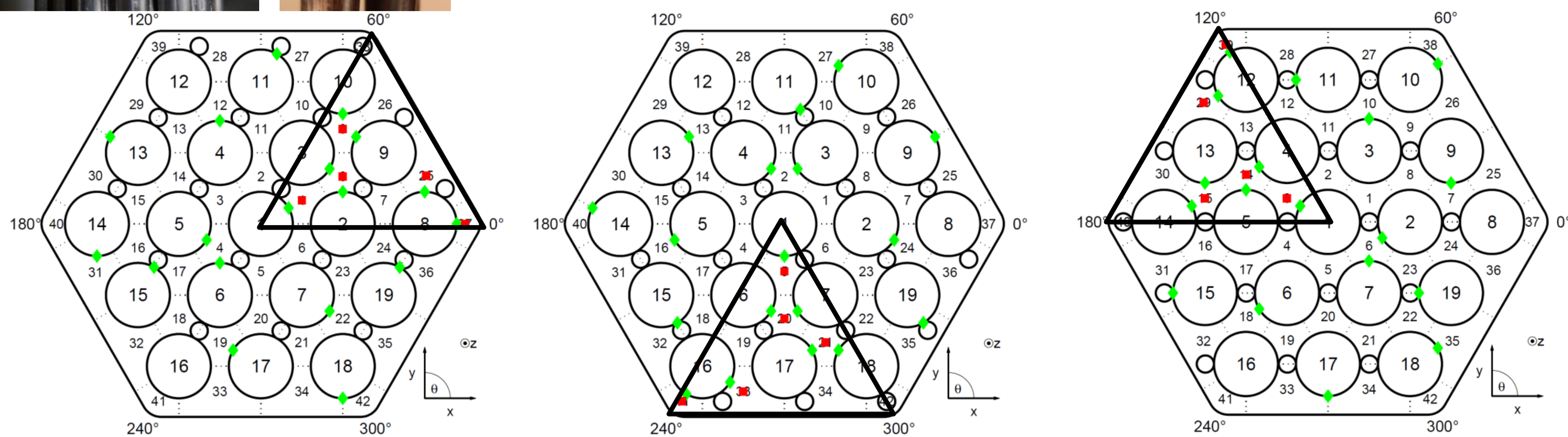
Instrumentation: local T at the wall and fluid

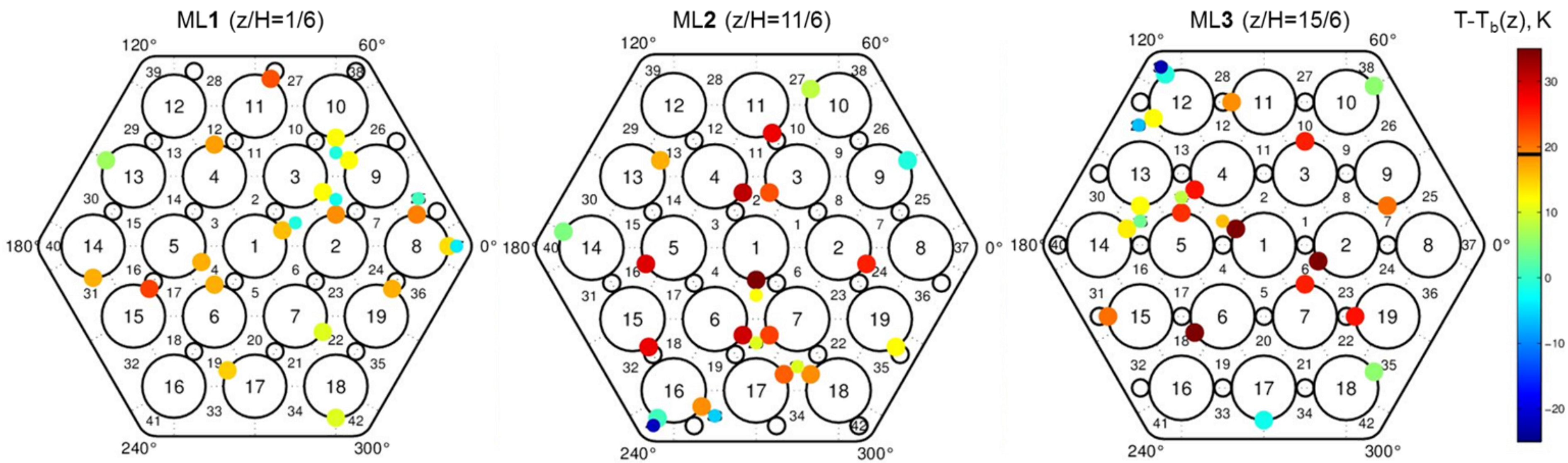




- 3 measuring levels
- Symmetrical sectors
- 3x18 Twall (0.5 mm)
- 3x5 Tsch (0.25 mm)
- #11, #15 and #19 are behind the wire

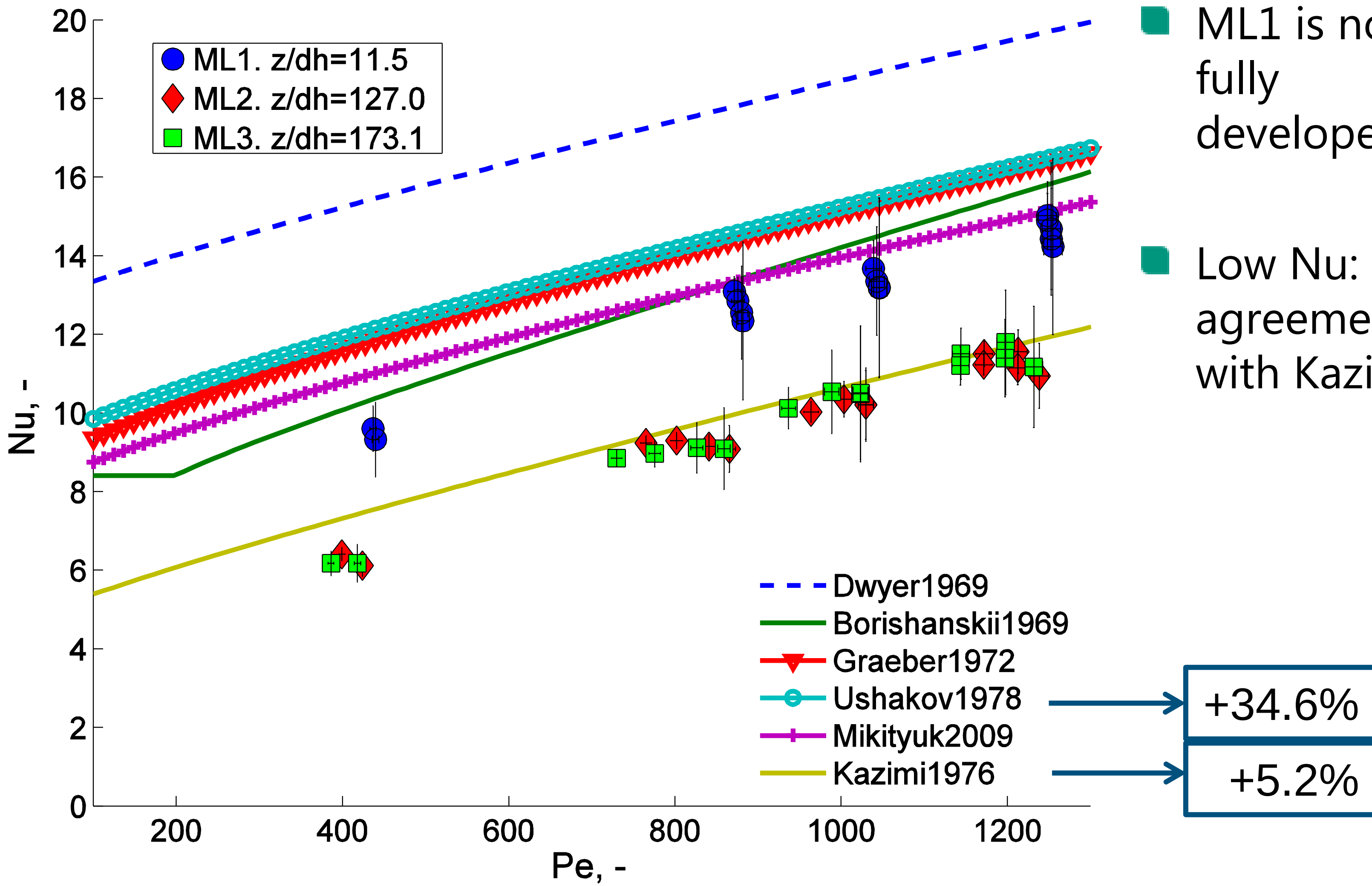
Results for a reference case: $T - T_b(z)$

- T_{in} = 200°C
- Re_m = 38 100
- m = 16 kg/s
- Pe_m = 980
- Q = 197 kW
- q_w = 462 kW/m^2



- ML1: $T_f \leq T_b$ at all sub-channel centers → developing region
- ML2 and ML3: inner region hotter than outer one, as expected
- Hot spot behind the wires is not critical

Mean heat transfer coefficient: Nu vs. Pe

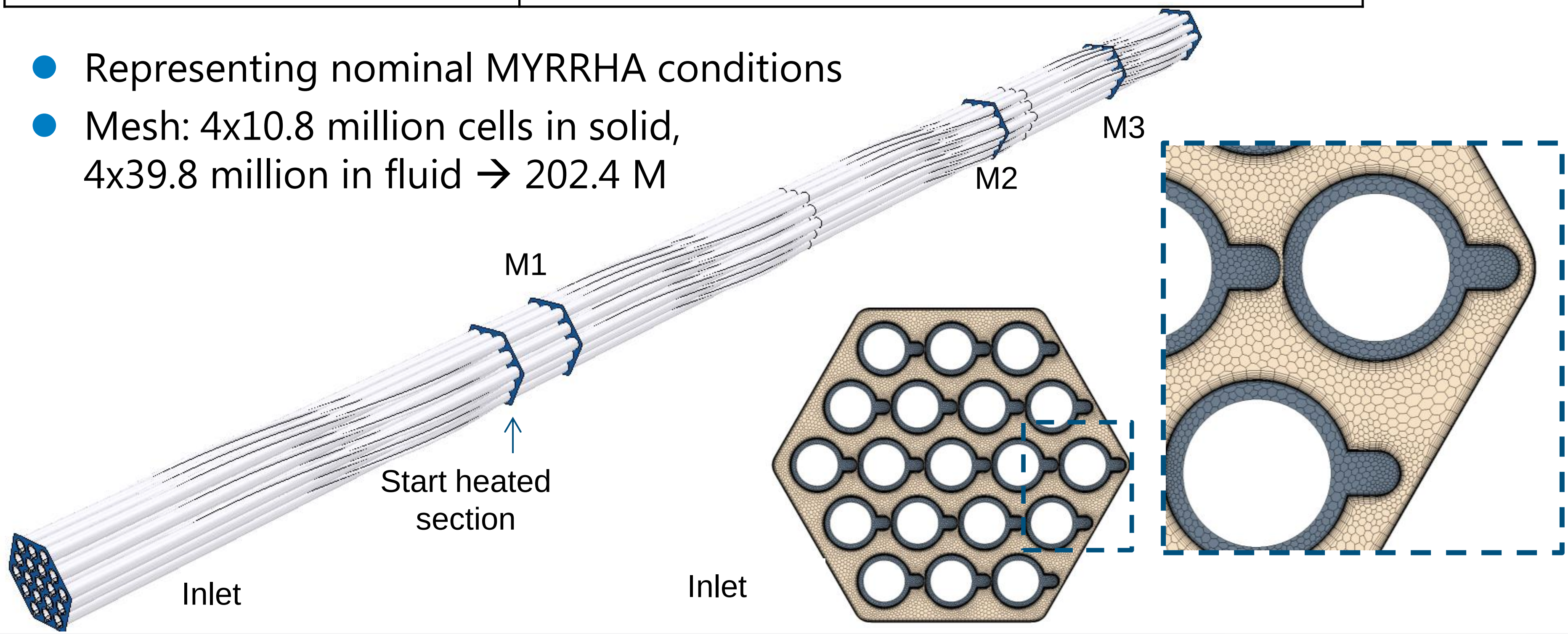


- ML1 is not fully developed
- Low Nu: best agreement with Kazimi

Post-test CFD simulation THEADES

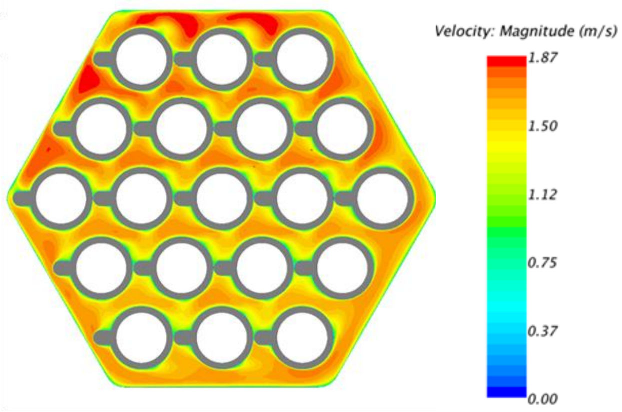
Property	Setting
Code	STAR-CCM+ 10.2
Turbulence model	SST k-ω
Fluid	LBE, temperature dependent properties (LBE handbook 2007)
Steel	Temperature dependent properties (ITER material handbook)
Mean y+	0.9
Turbulent Prandtl number	0.9

- Representing nominal MYRRHA conditions
- Mesh: 4x10.8 million cells in solid, 4x39.8 million in fluid → 202.4 M

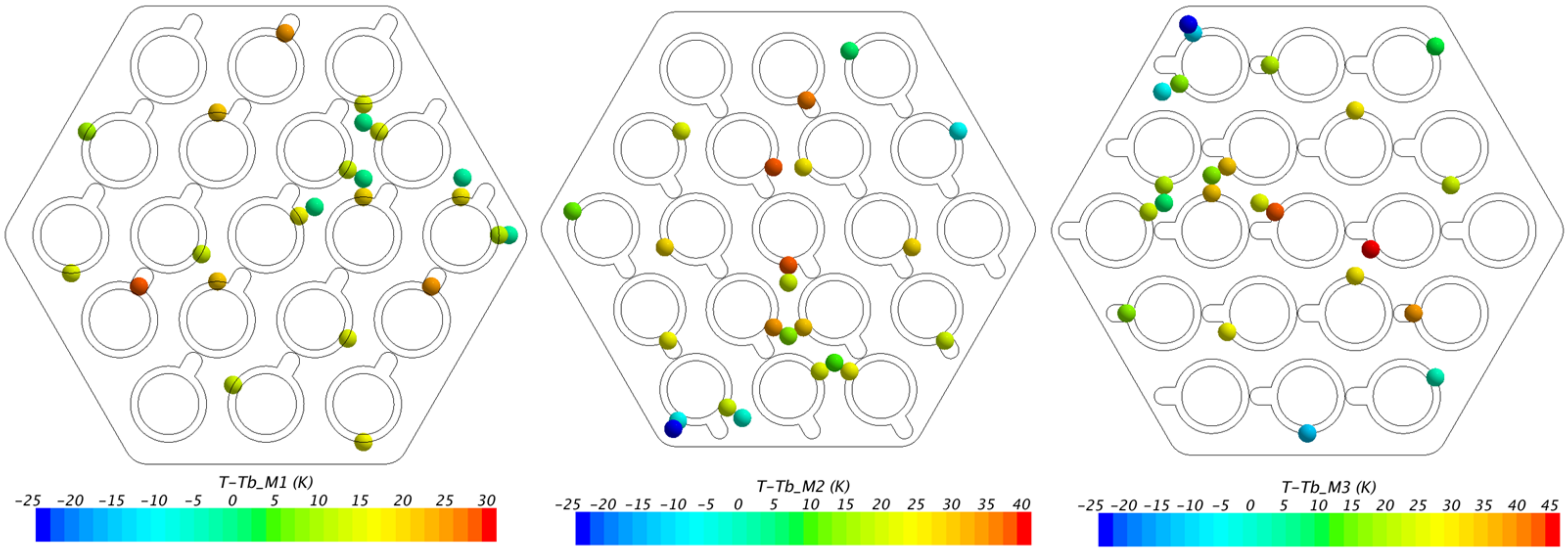


CFD results: comparison with experiment*

- Pressure drop underestimated with respect to experiments by 15-19%
- Nusselt number within 10% of the experiments



*Pacio et al., Thermal-hydraulic study of the LBE-cooled fuel assembly in the MYRRHA reactor: experiments and simulations, 2015, NURETH 16, Chicago

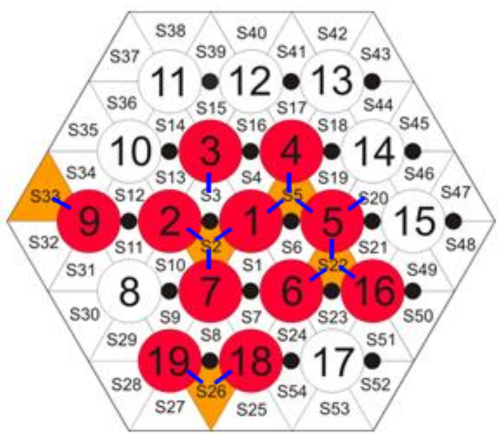


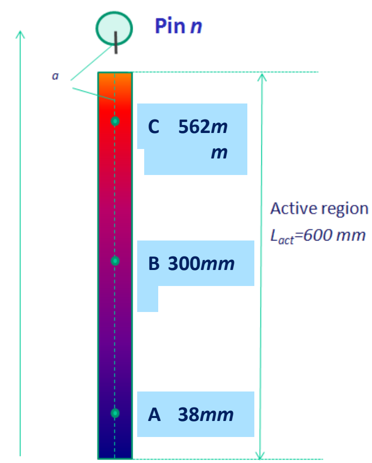
Comparison: experiments, CFD, correlations

	ΔP_1, mbar	ΔP_2, mbar	Nu_1, -	Nu_2, -	Nu_3, -
Experiment	211.5	215.5	13.61	10.02	10.12
+/-	0.7 (0.34%)	0.8 (0.37%)	0.86 (6.3%)	0.26 (2.6%)	0.53 (5.2%)
CFD 1(sol.)	179.2	173.6	13.02	9.49	9.11
Diff. %	-15.3%	-19.4%	-4.3%	-5.3%	-10.0%
CFD 2 (fl)	179.4	173.7	13.71	9.45	8.94
Diff. %	-15.2%	-19.4%	0.7%	-5.7%	-11.6%
CTS	212.8	209.7			
Diff. %	+0.6%	-2.7%			
Ushakov			15.4	15.0	14.9
Diff. %			+13.1%	+49.7%	+47.2%
Kazimi			10.8	10.4	10.3
Diff. %			-20.6%	+3.8%	+1.8%

NACIE facility: Mixed & NC

- Rectangular loop, two vertical pipes 8*m* long and two horizontal pipes 2.4*m* long (O.D. 2.5”);
- A **Shell and tube HX** with two sections, operating range 5-250 *kW*;
- An argon **gas injection device** to provide the driving force to enhance the circulation;
- A **Fuel Pin Simulator** (19-pins wire-spaced arranged in triangular lattice) of ***235 kW*** maximum power;

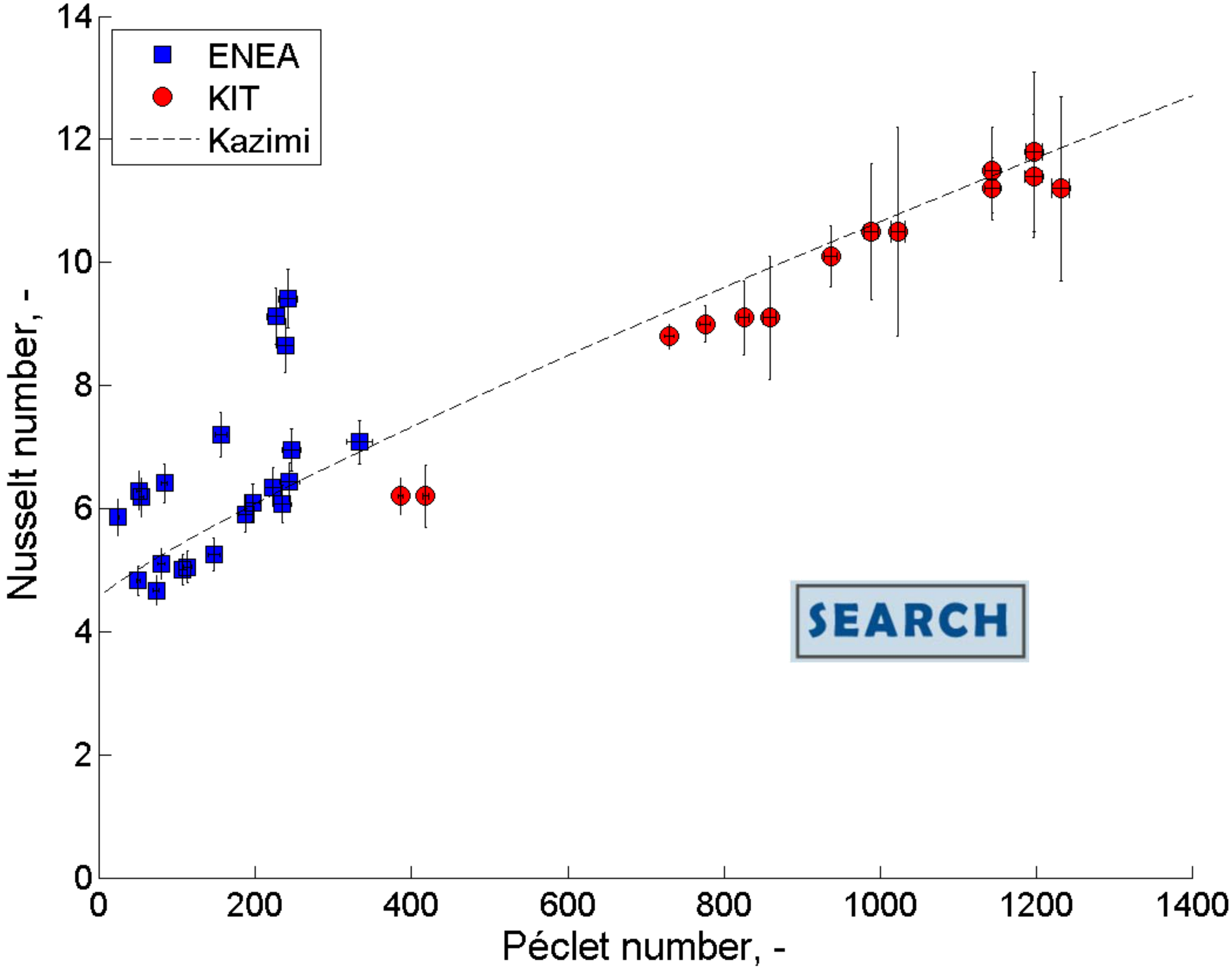




D_{pin}	6.55 mm
P	8.4 mm
P/D	1.2824
d	1.75 mm
P_{wire}	262 mm
L_{tot}	2000 mm
L_{active}	600 mm
$D_{H,nom}$	3.84 mm

- Refer to presentation in Session 4 by Alessandro Del Nevo (ENEA): “Heat transfer on HLM cooled wire-spaced fuel pin bundle simulator”

KIT and ENEA results

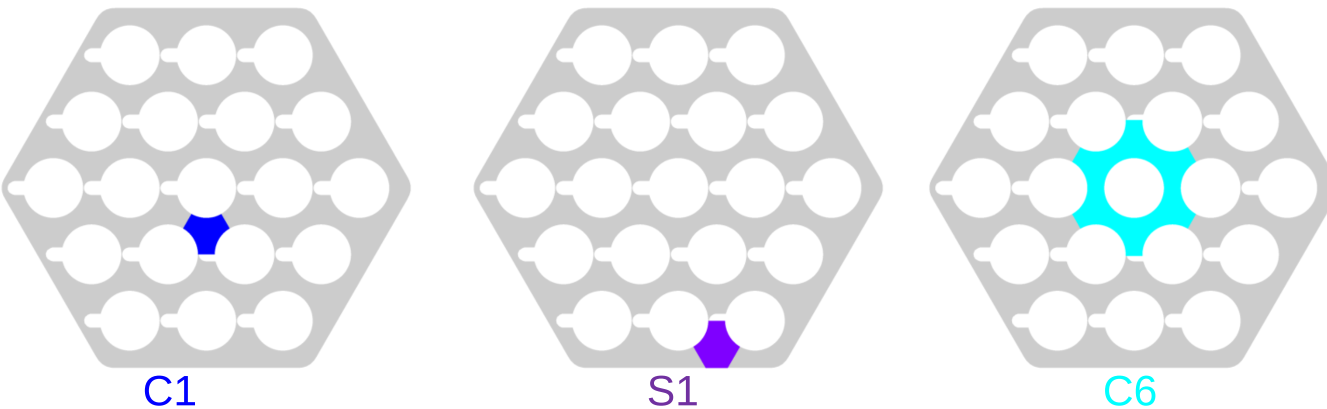


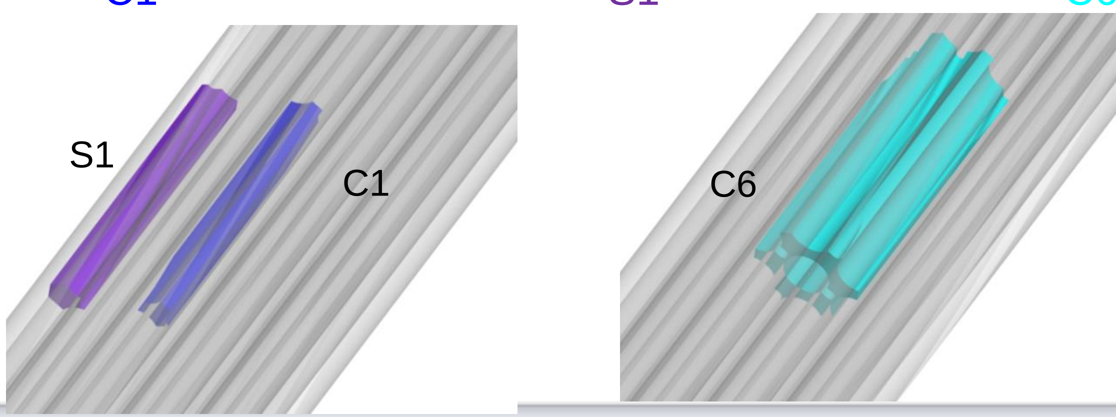
Conclusions: bundle heat transfer

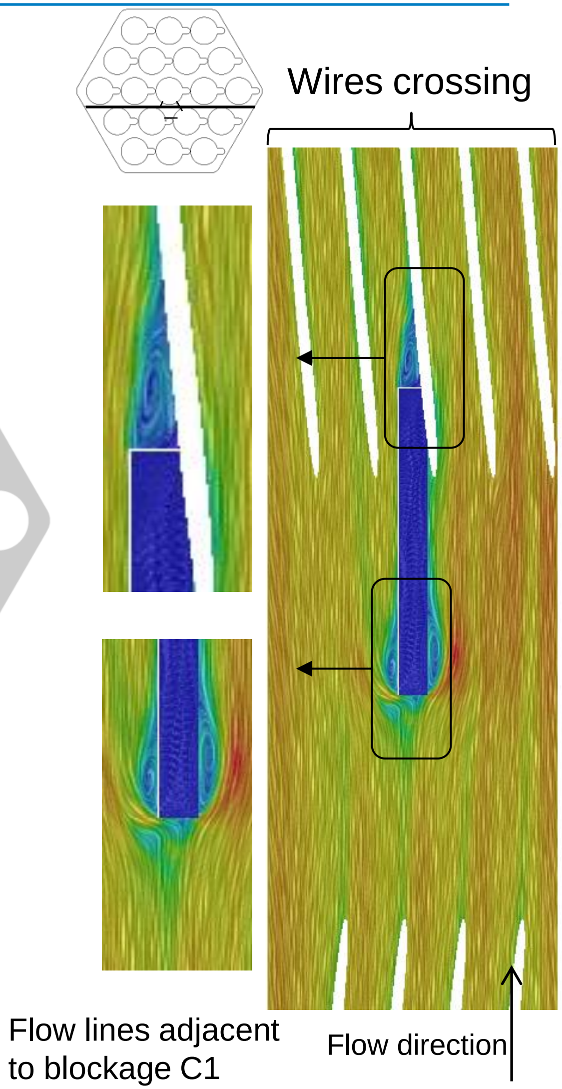
- Temperature profile likely not fully developed at ML1 ($T_f \leq T_b$)
- Difference between local and section averaged Nu
  - Local Nu dependent on rank and relative position of the wire
  - Inner regions are hotter than the outer ones
- Local hot spots occur behind the wire
  - At the central pin or in the first ring (ML2 and ML3)
- Section averaged Nu in agreement with Kazimi and Carelli correlation
- Further in depth analysis required to determine an appropriate correlation

Bundle blockage: Pre-test CFD simulations

- MAXSIMA WP3:
  - Check experimental feasibility
  - What is the influence of various blockages
- Three blockages defined (C1, S1, C6)
- Solid blockages with conductivity of 1 W m^{-1} K^{-1}

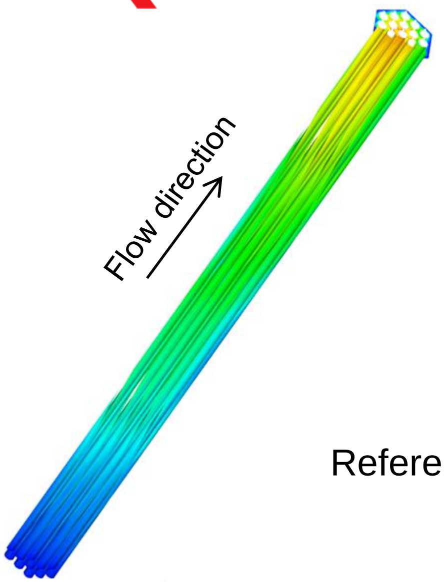




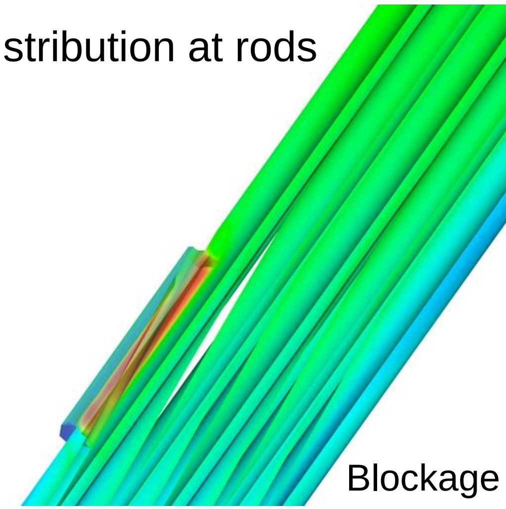


Pre-test blockage simulations: temperature results

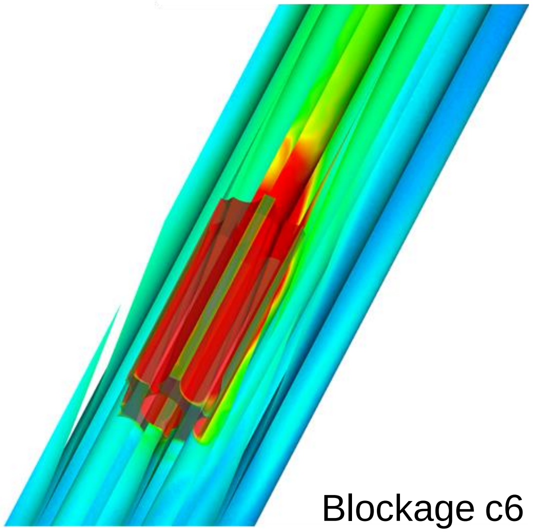
Temperature distribution at rods



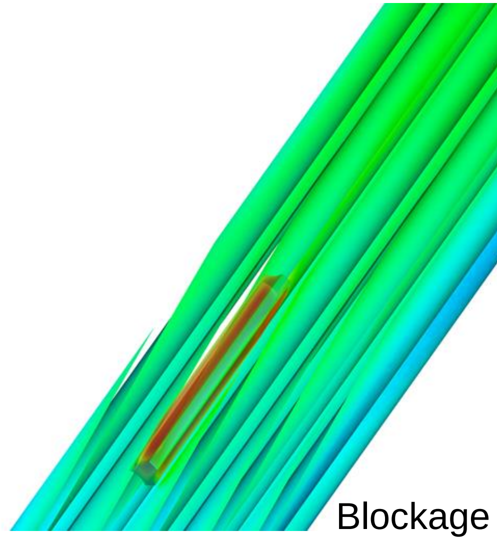
Reference



Blockage c1



Blockage c6



Blockage s1

Temperatures due to blockages C1 and S1 are experimentally feasible at nominal MYRRHA conditions.

Temperatures due to blockage C6 are too large.

Experiment with nominal MYRRHA cooling and 20% MYRRHA power is feasible for blockage C6.

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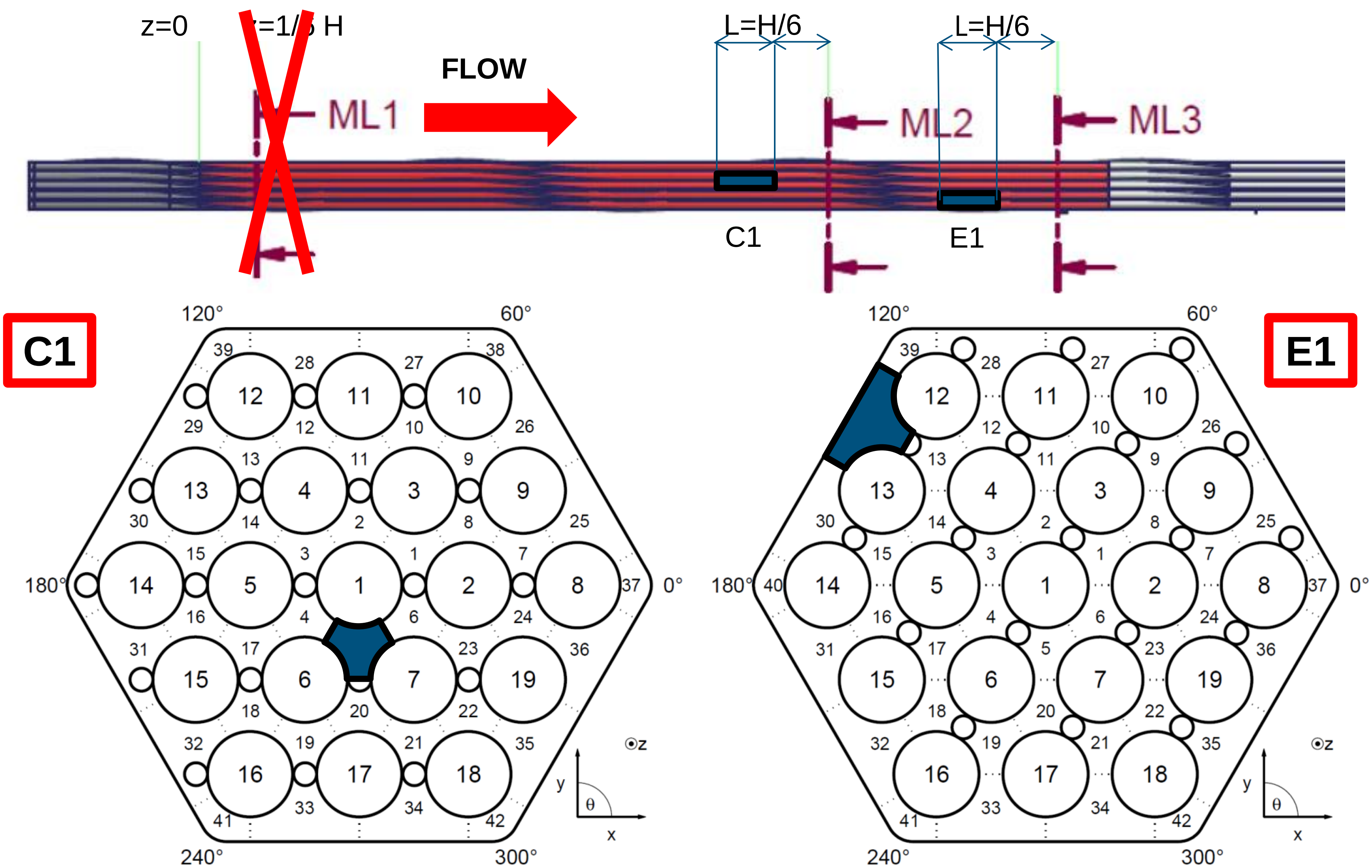
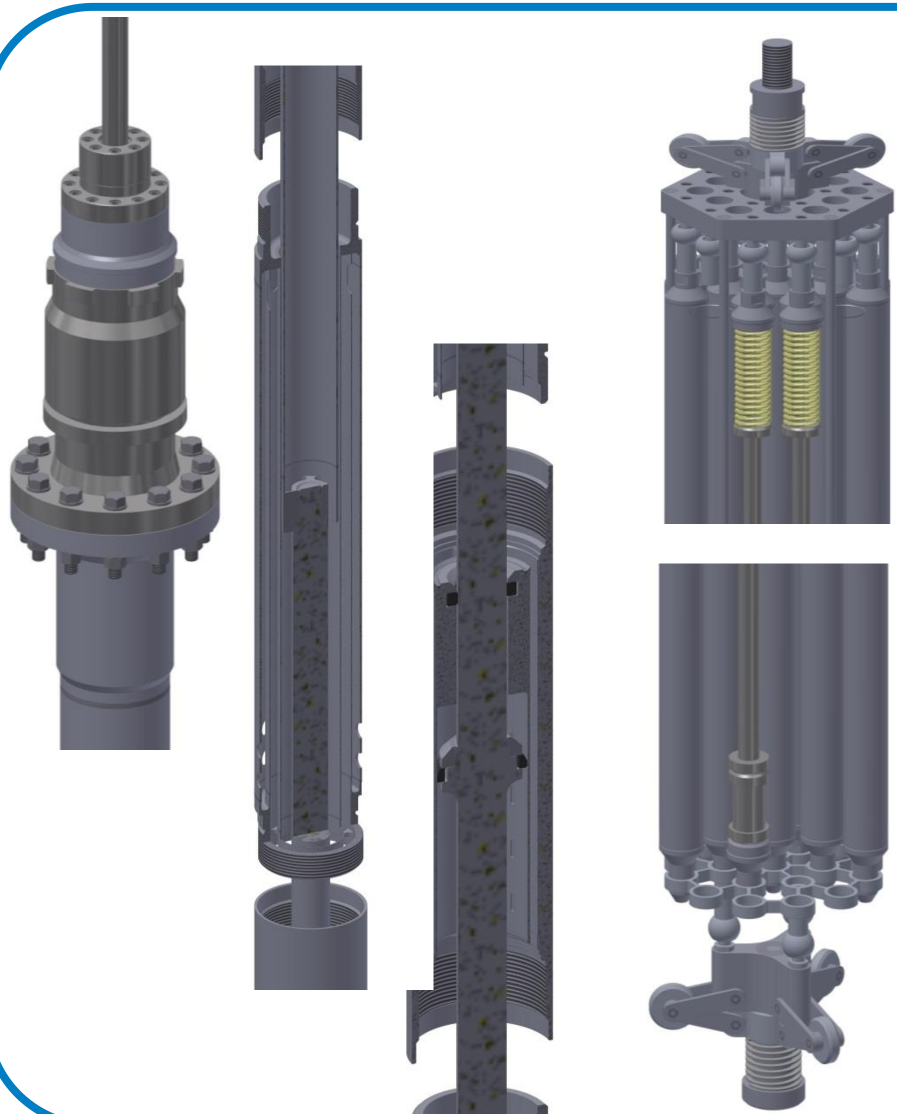
Experimental blockage setup



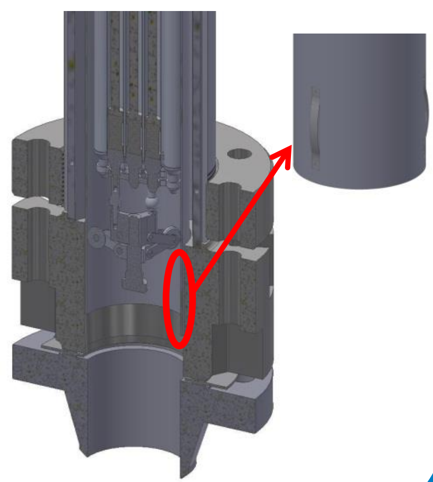
Control rod – Experimental and numerical approach

- MAXSIMA WP3 - Task 3.2: Safety Rod System Tests in Heavy Liquid Metal (HLM)
  - SCK•CEN
- Test and qualify the buoyancy driven control rods in MYRRHA
  - Unique concept of passive insertion under the influence of buoyancy
  - Full-scale hydraulic tests in the COMPLOT test facility (SCK•CEN)
  - Bundle displacement vs time (Full flow & no flow)
  - Hydrodynamic behaviour (insertion time < 1 s)
- Input to Task 3.4 - CFD Simulation of Safety/Control Rod system (CRS4)

Control Rod Test Section: Guide tube and internals



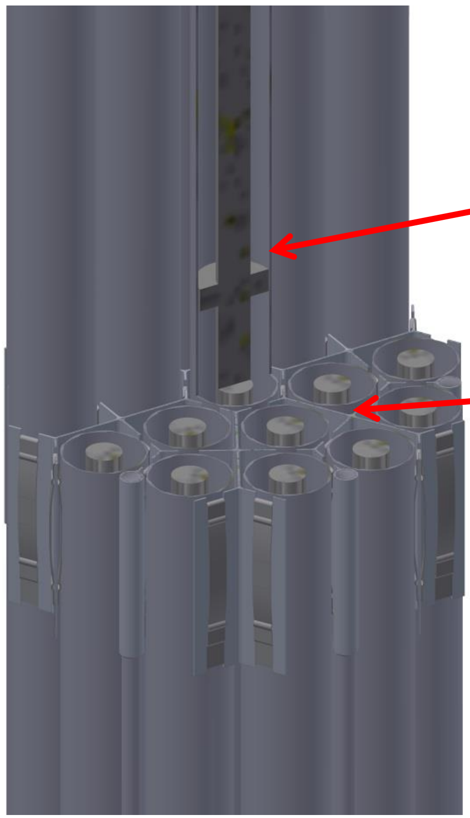
* Some design features were very slightly modified to fit standard available tube sizes

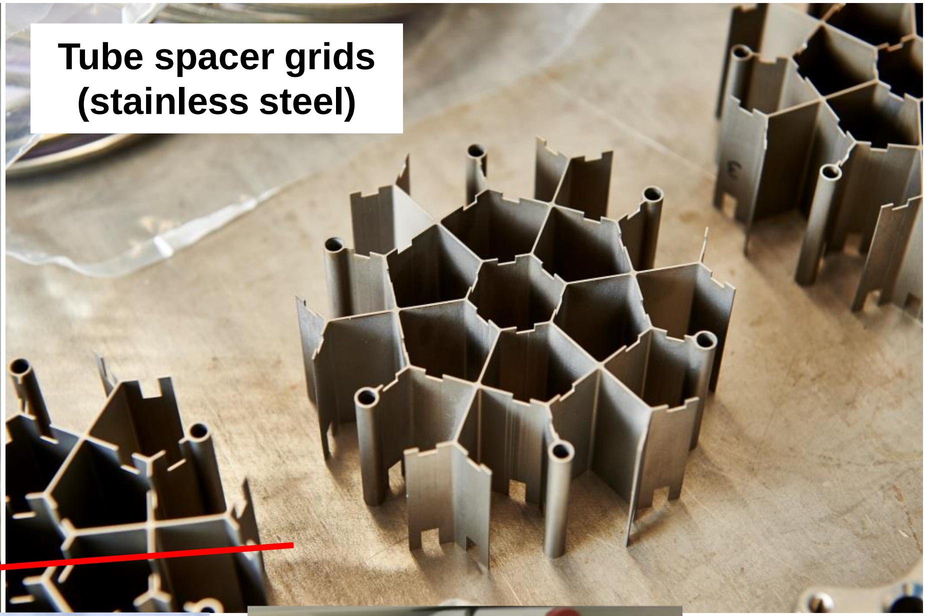


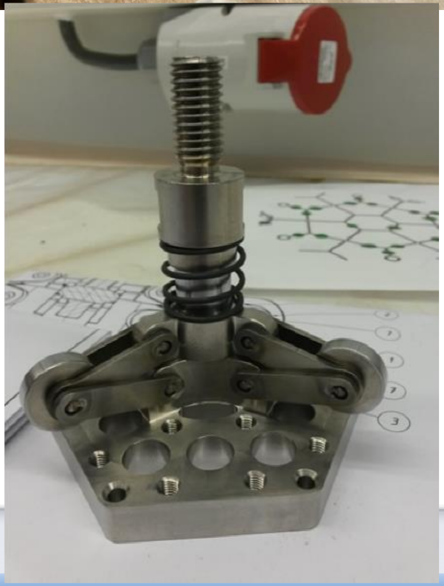
Outer shell assembly

Inner guide tube assembly

Control Rod Test Section: Bundle components





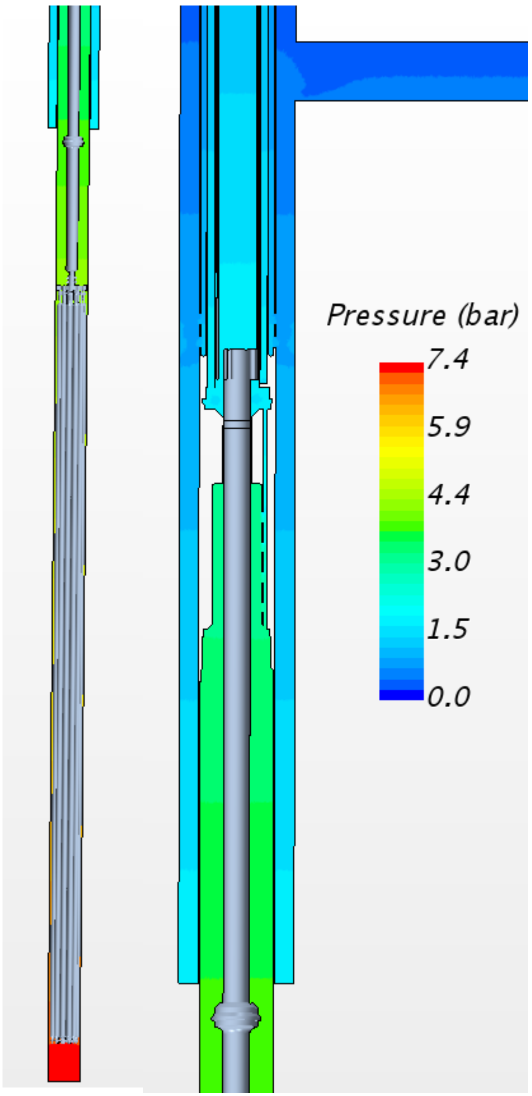


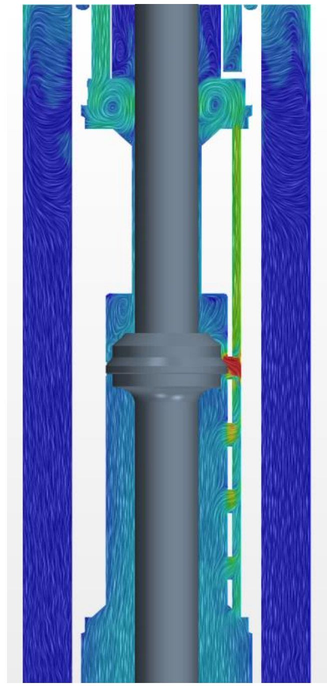
Instrumentation

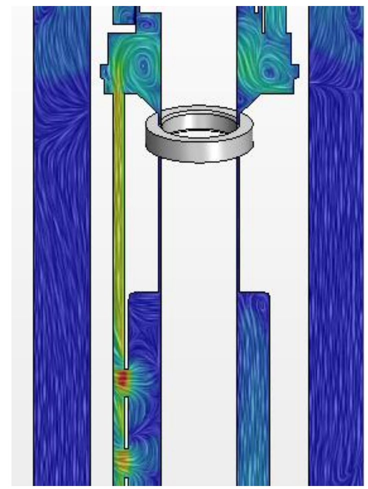
- Rod bundle insertion maintained by pneumatic actuator and electromagnet mechanism

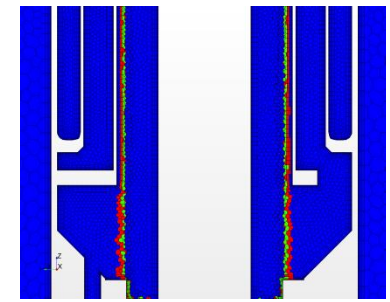
- Instrumentation
  - Laser displacement sensor
    - 0 – 750 mm
    - 2.5 kHz
    - Resolution = 50 μm
  - Load cell measures steady state buoyancy force
  - Steady state inlet pressure: Remote seal transducer
  - Steady state LBE levels:
    - inlet buffer tank (ΔP transducer)
    - outlet plenum (ΔP transducer)
    - In the guide tube (bubble tube)

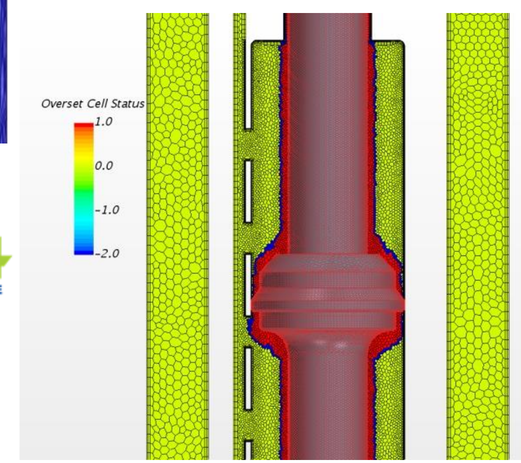
Control Rod : CFD model for steady state & insertion







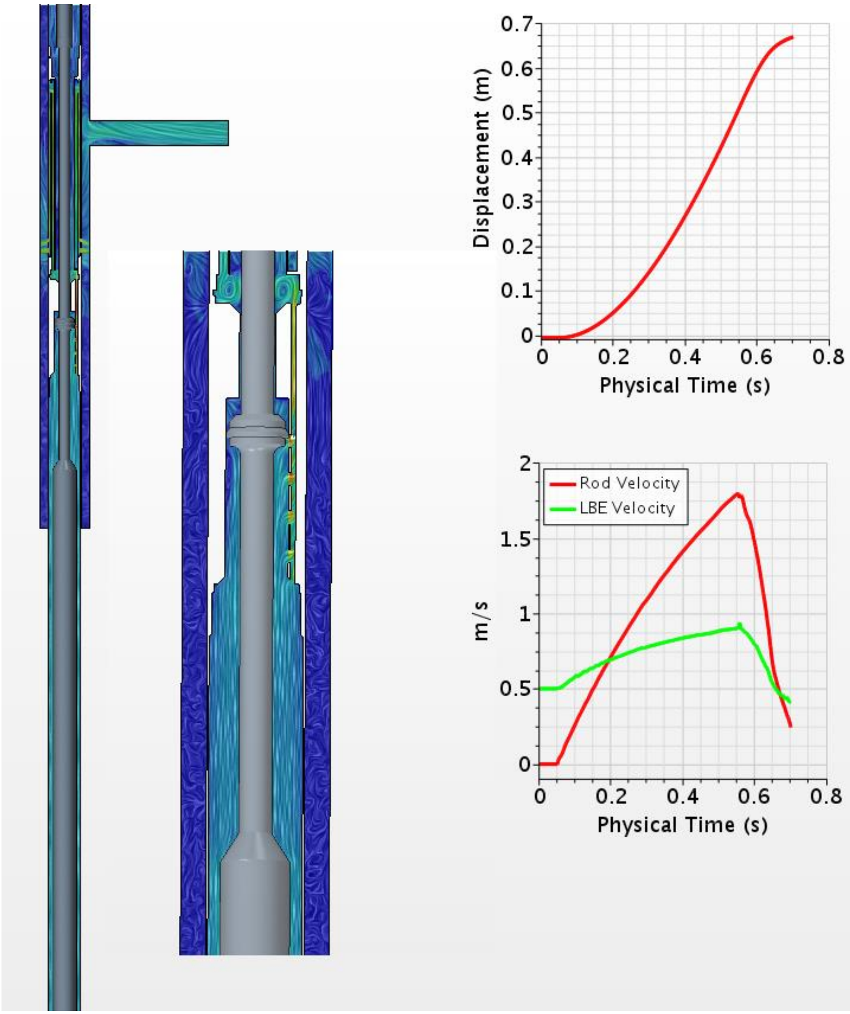




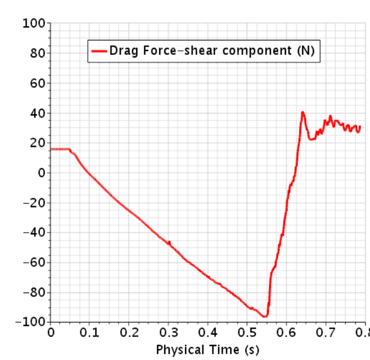
- Overlapping grids in STAR-CCM+
- Hydraulic damper effect modeled
- Narrow gaps in the flow pattern
- Good agreement mesh density-geometrical accuracy
- Zero Gap volumetric interface
- Full flow 18 kg/s for half domain

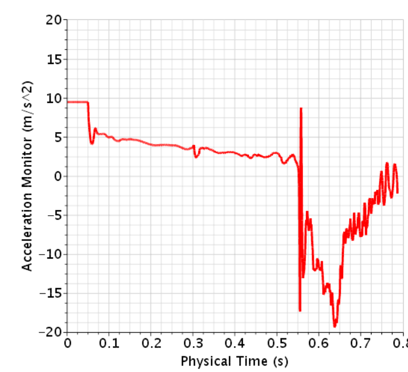
- 1-inactive cells
- 0-active cells
- -2-acceptor cells

CR insertion with 2-way coupling motion from force balance

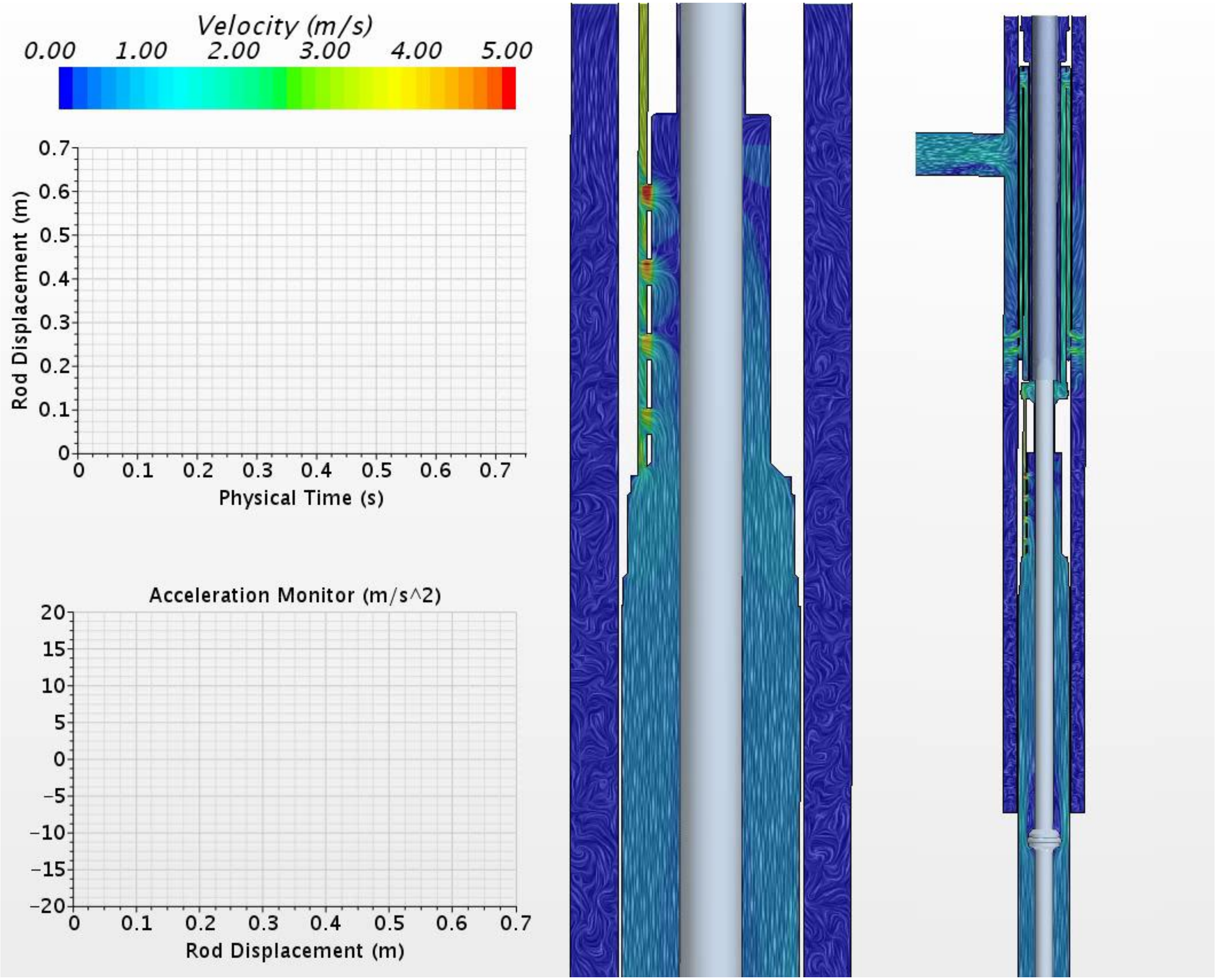


- a=resultant force/mass
- F_R=Drag (Shear + Dynamic pressure) + Buoyancy (Static pressure) – Gravitational force
- The acceleration is integrated in time and the resulting velocity is given to rod.
- The shear curve shows a consistent sign reversal as the bundle is faster/slower then the LBE.

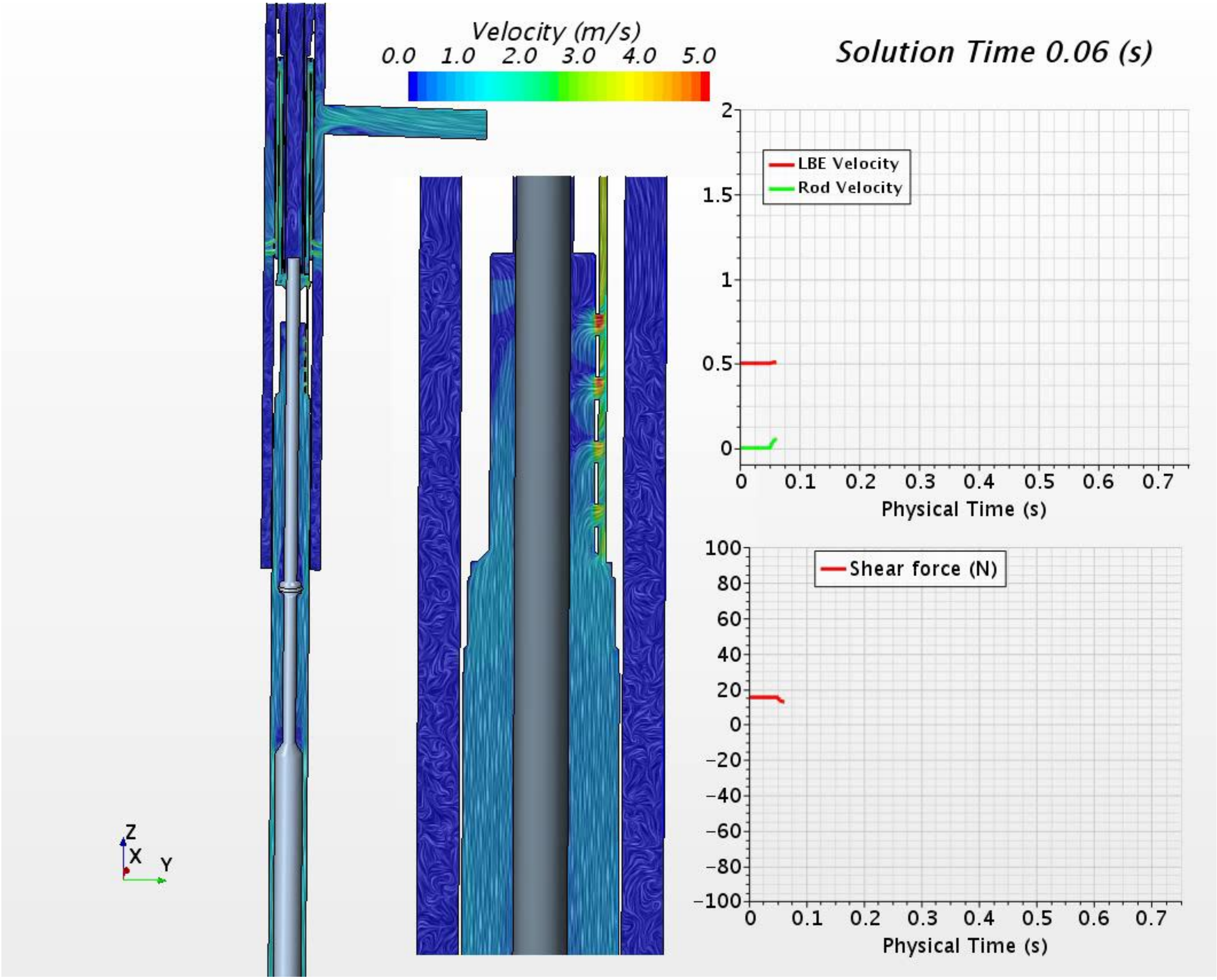




CR insertion: CFD animations (1)



CR insertion: CFD animations (2)



Conclusions & future work

- Fuel assembly
  - Experimental results quantify the predicting performance of existing correlations and numerical CFD analysis
    - bundle pressure drop: Good agreement with correlation/s – further full-scale tests at different LBE temperatures
    - bundle heat transfer coefficients: Further in depth analysis required to assess local vs averaged Nu – possibility for correlation development
  - Safety relevant bundle blockage experimental results expected soon
  - Experimental and numerical flow induced vibration investigation: MYRTE WP3

- Control rod
  - Full-scale experimental proof of principle: MAXSIMA WP3 (Results expected Q2 2016). Input to numerical analysis.
  - Numerical dynamic CFD analysis: mature model methodology, to be validated by experiments.

Flow induced vibration

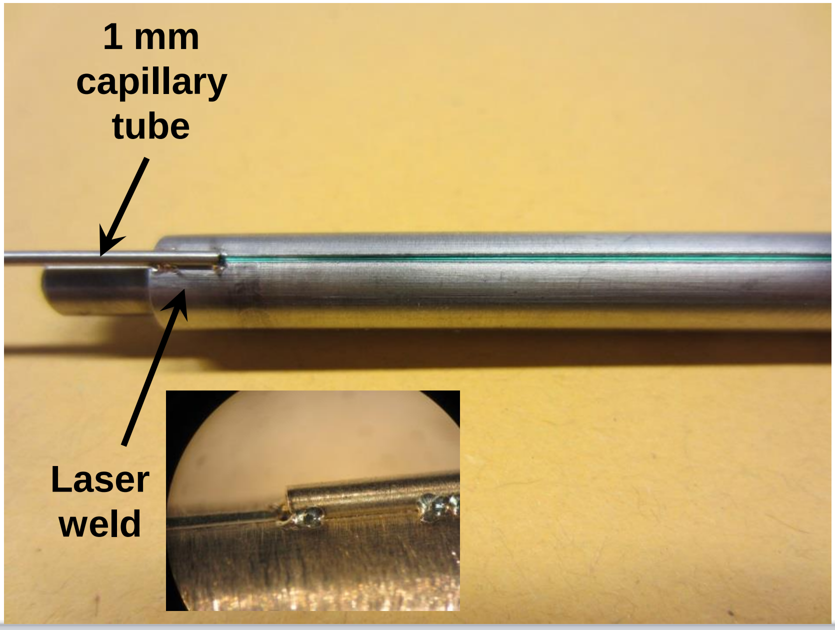
- MYRTE (H2020) Task 3.2: MYRRHA fuel assembly thermal hydraulics
  - Subtask 3.2.1.1 Fuel pin vibration experiments (SCK•CEN)

- Investigate fluid-structure interaction and mechanical fretting
- Characterise the flow-induced vibration (FIV) modal characteristics of the MYRRHA bundle
  - Full-scale experimental tests in the COMPLOT test facility (SCK•CEN)

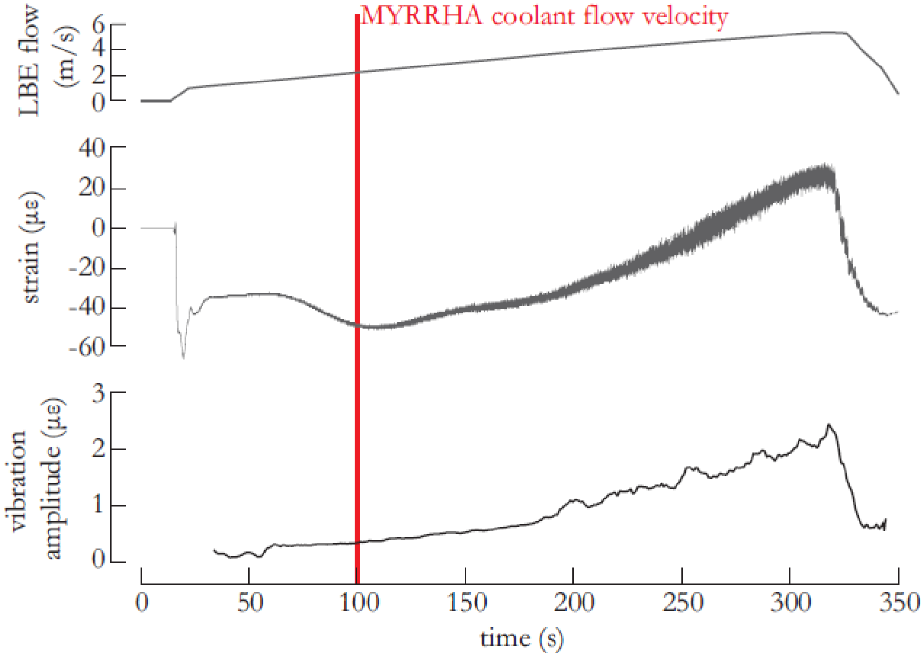
- Input to:
  - Task 3.2.1.2 – Fuel pin vibration simulations (Ugent and NRG)
  - Task 3.2.1.3 – Fretting experiments (KIT)

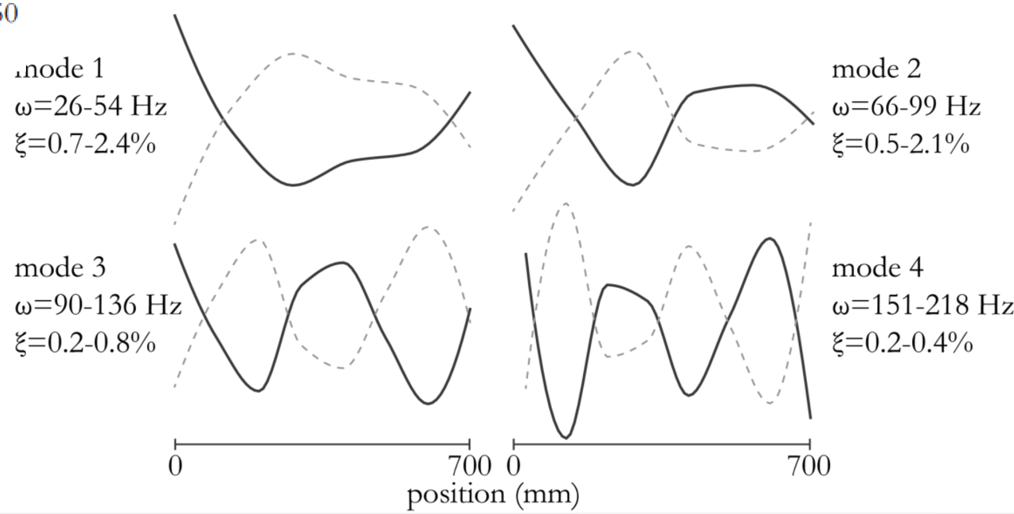
FBG instrumentation

- Optical fibres with Fibre Bragg Gratings (FBGs)
  - Type I draw tower gratings (Germanium doped)
  - Diameter = 200 µm
  - ORMOCER coated (rated for continuous operation up to 300 °C)
  - Mounted within a 250 µm groove

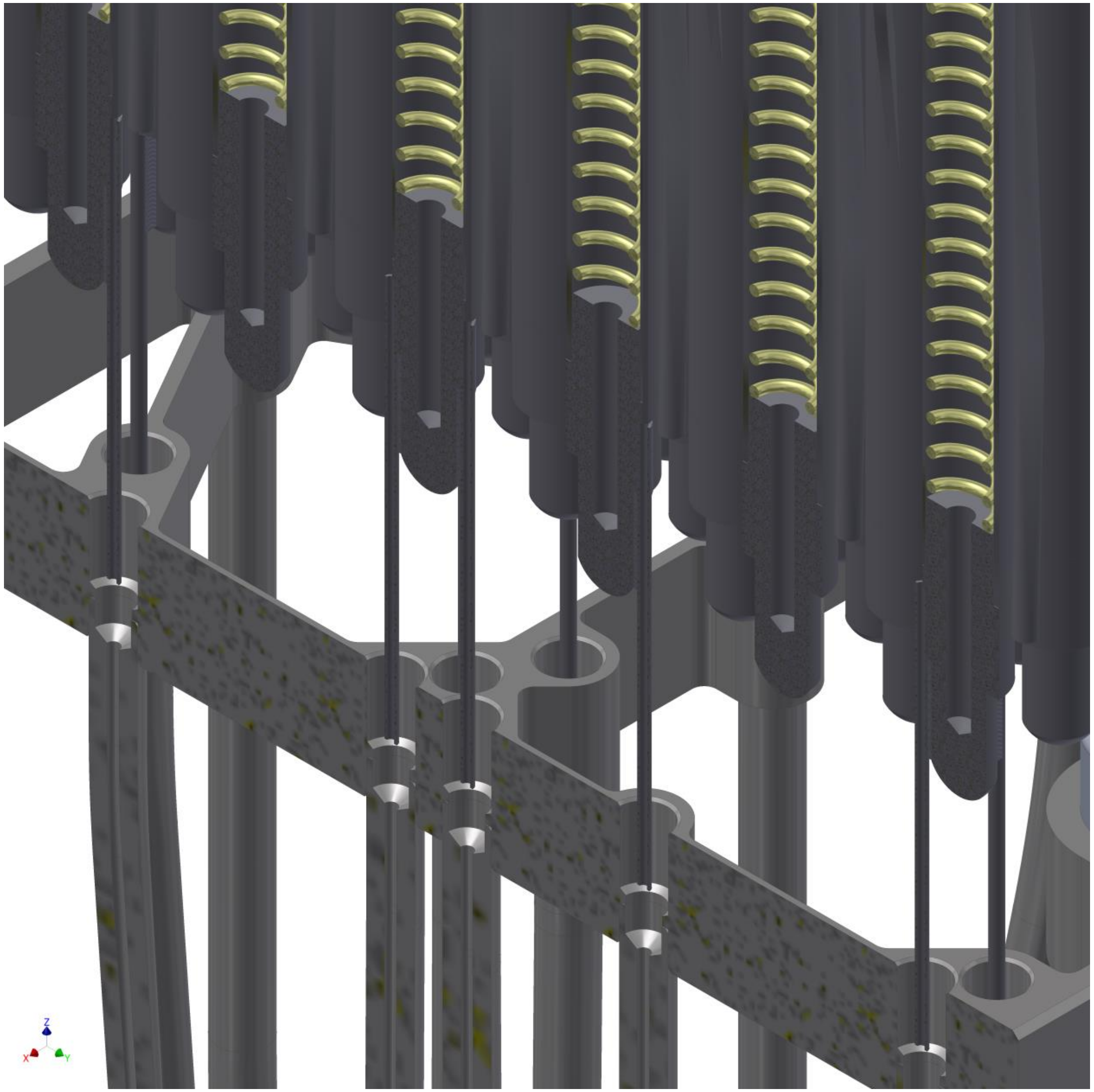


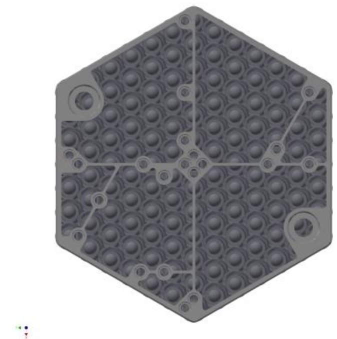
7-pin mock-up in Lilliputter LBE facility





Fibre feedthrough





Concept adopted from the earlier 7-pin experiment in LBE