HGF-Activities for liquid metal fast reactor systems

M. Daubner, S. Gordeev, M. Haselbauer, W. Hering, W. Jäger, A. Onea, J. Pacio, S. Perez, A. Ponomarev, A. Rineiski, V. Sanchez, Th.Wetzel - presented by **R. Stieglitz**
S. Eckert [*1], E. Fridman [*1], G. Gerbeth [*1], U. Hampel [*1], S. Kliem [*1]

[*1] **Helmholtz Center Dresden-Rossendorf**

Institute for Neutron Physics and Reactor Technology (INR)

Content

- **Fast Reactor R&D in the Helmholtz-Programm PoF-III**
- **Advanced measurement techniques**
- **Infrastructures**
- **Thermalhydraulics**
- **Safety assessment**

HELMHOLTZ ASSOCIATION
LIMTECH Alliance

FR research in Helmholtz-Programm PoF-III

- **PoF-III Funding Period 2015-2019**
- **FR –Research and Development embedded in Waste Management Strategies (subtopic 1.2)**
  - Scenario studies
  - Partitioning
  - **Transmutation and safety assessment of transmuting reactors (spent nuclear fuels-SNF)**
  - Waste conditioning by cermic matrices
  - Nuclear legacy waste and decommssioning

➡ **Substantial reduction compared to previous funding period**
  - declining core design activities (e.g. abdication of KAPROS)
  - reduced effort in safety analysis
  - reorientation of experimental program towards neighbouring R&D fields
  - enhanced engagement in EU-Programs (**only** to be complemented by nat. funds)
- **Contributing Centers**
  - Helmholtz Center Dresden Rossendorf (HZDR)
  - Karlsruher Institute of Technology (KIT)

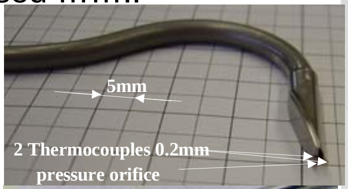
General capabilities

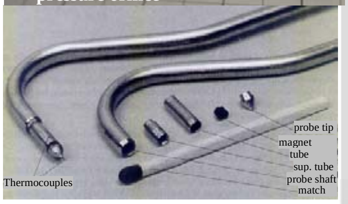
- **Flow rate**
- **Velocity measurement**
- **Flow visualization -2 phase flow**
- **Flow field reconstruction**

ADVANCED INSTRUMENTATION TECHNIQUES

How to measure in liquid metals ?

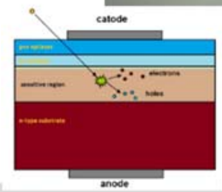
- **Flow rate** – electro-magnetic, D*p*, UTT, momentum based ……..
- **Visualization techniques**
  - direct – X-Ray tomography
  - indirect – CIFT,
    Utra-sound-transient time (UTT),….
- **Velocity**
  - direct – Pitot-Tube (Δp)
    – magnetic potential probes (MPP)
    – fibre-mechanics





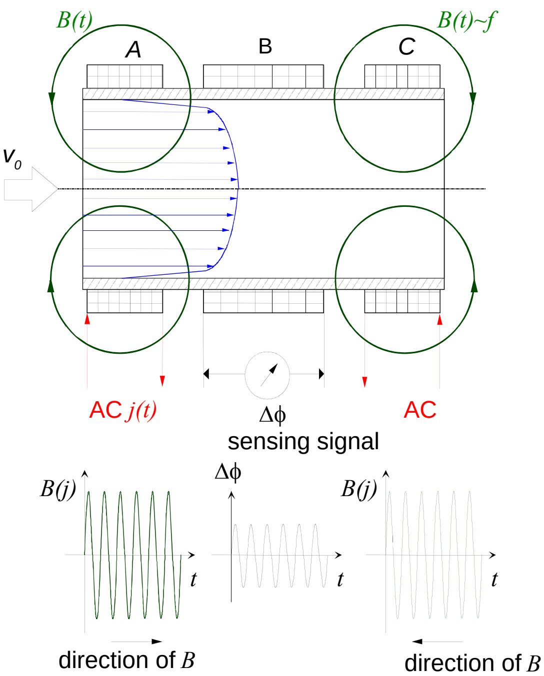
  - Non-intrusive – Ultra-sound doppler velocimetry (UDV), multi units ➡ mapping
- **Surfaces /2-phase**
  - direct – resistance probes
  - indirect – X-ray, UTT
    – optic means for surfaces

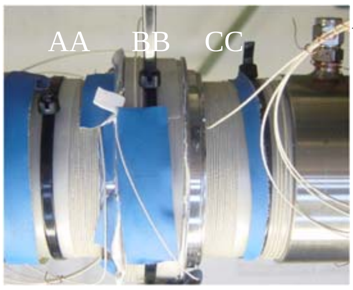
- **Neutronic core monitoring**
  - fission chambers
  - semi-conductors- SiC based- diode (SPND)
    (neutron-generator available)

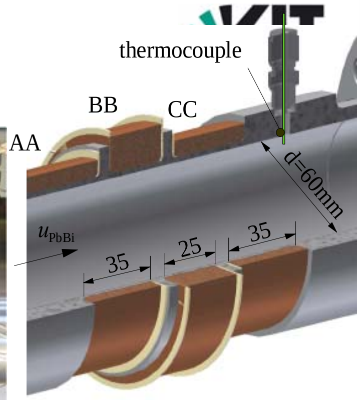


Flow rate

Electro-magnetic frequency flow meter (EMFM)







Measurement principle

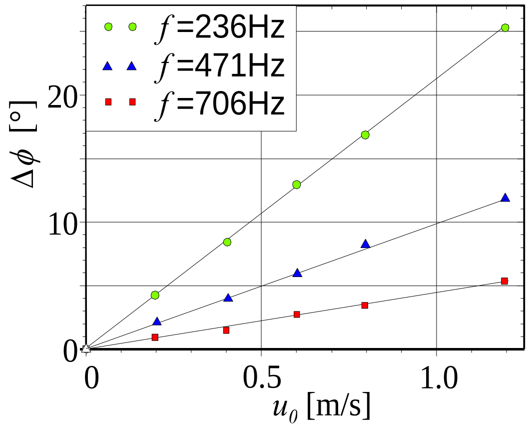
- Dragging of magnetic fields lines by the flow (**RMS-Value ~*Q***)

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

- flow direction given by sign of signal
- time delay between Emitter-Sensor (or Phase Angle) $\Delta t \sim Q$
- ➡ **2 independent gross-output quantities for *Q***

Th. Schulenberg, R. Stieglitz, NED 2010.

Flow rate-EMFM



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

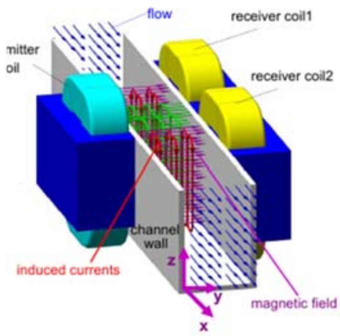
- low f yield high sensitivity to ambient stray signals
- high B modifies the flow Hartmann number Ha<<1 (Ha=(EM-forces/viscous forces))

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

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

Other designs

- clamp on systems (validation in liquid Al !!!)



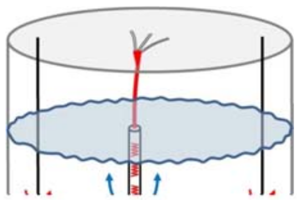
Local velocity – miniaturized EMFM

Goal: sensor downstream rod bundle to measure local flowrate

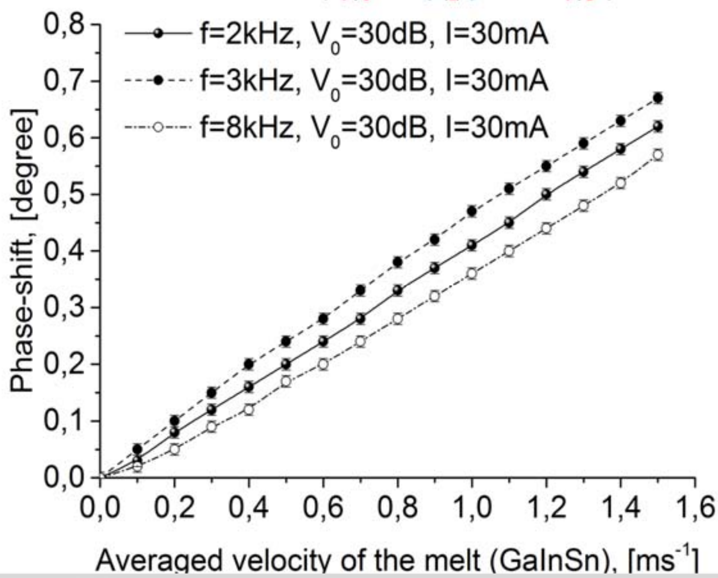
Requirements:

- velocity range: 0…4 m/s
- resolution: ± 0.1 m/s

near sensor flow

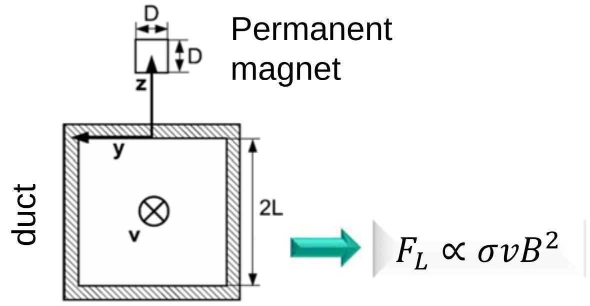


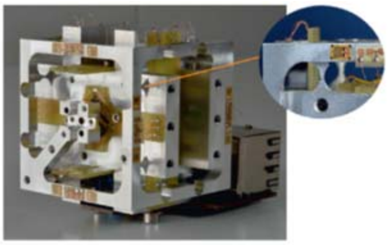
Sensors ϕ=6,12mm tested in GaInSn flow



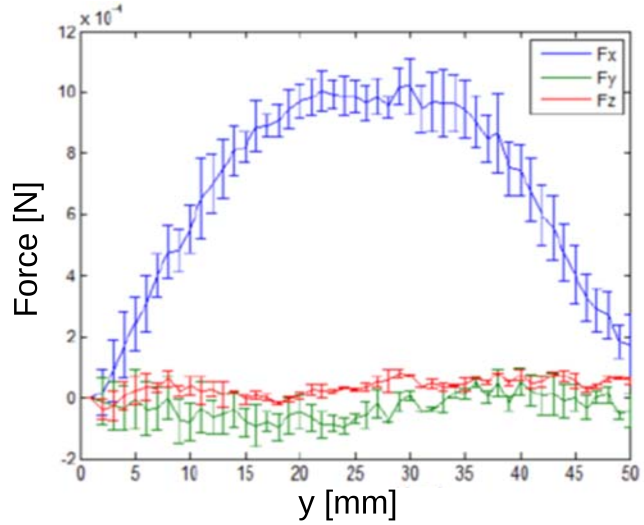
Local velocity - Lorentz Force Flowmeter (L2F2)

- Measurement of force/torque via permanent magnet close to the wall
- Force equal to Lorentz force F_L in flow
- Force/torque depended on near wall velocity
- New Multi-degree of freedom sensor: all 3 components of torque and force





multi degree of freedom sensor



Proof of principle @ GALINKA facility (TUI)

Local flow velocity - UDV

Ultra-Sound Doppler Velocimeter (UDV)

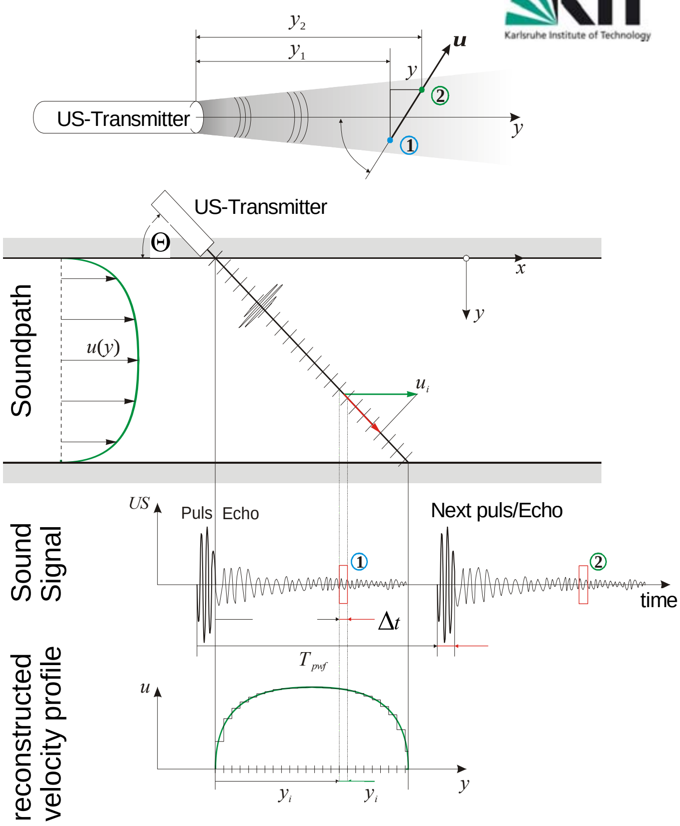
Principle (particle tracking)

- 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

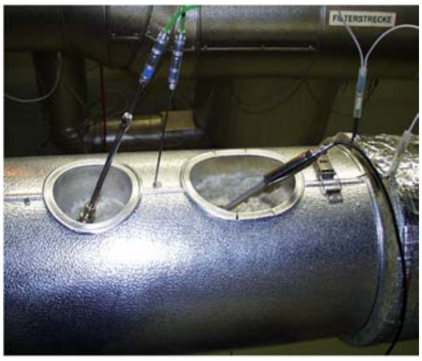
⇨ Velocity at a discrete distance

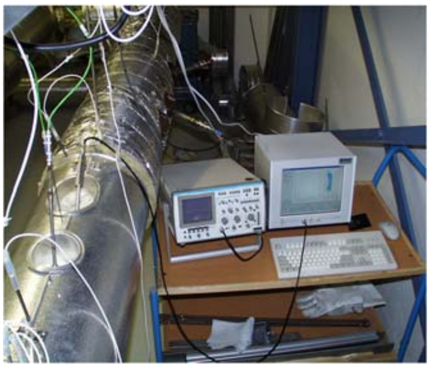
Profile

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

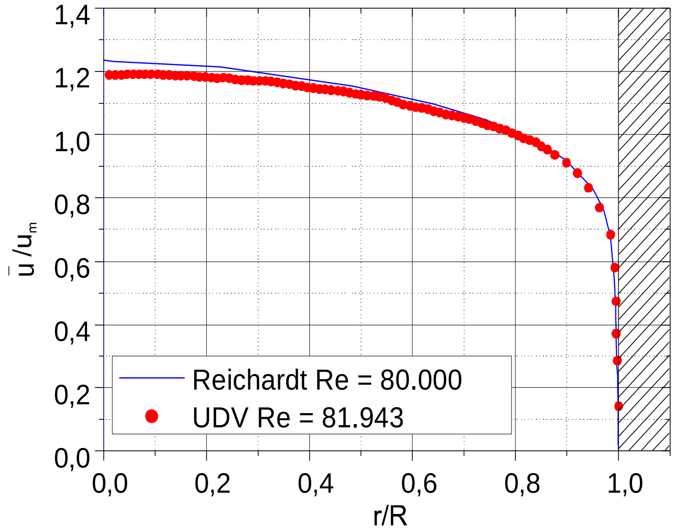


Local flow velocity





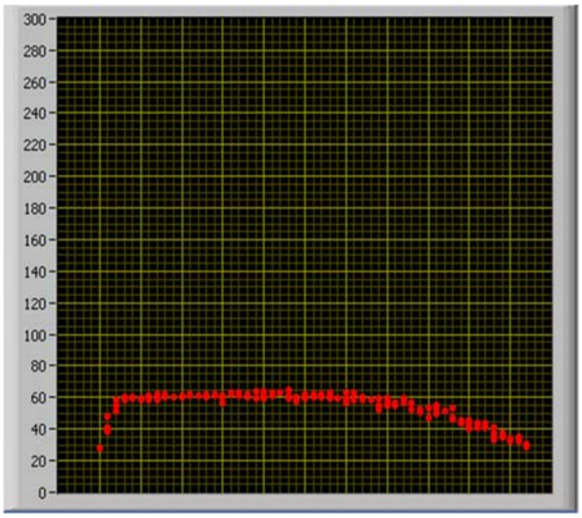
Ultra-Sound Doppler Velocimeter (UDV)-Validation



- 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)

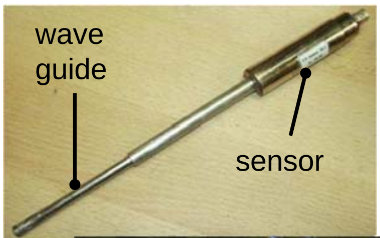
Local flow velocity



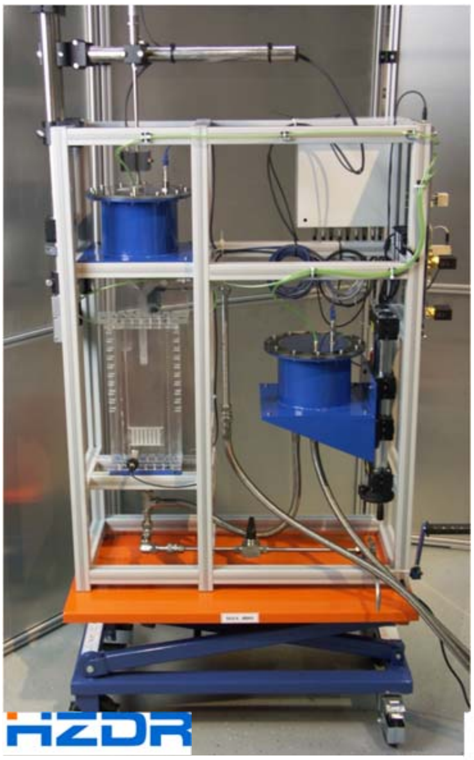
Transient start-up behaviour of EM pump in THESYS Loop

Ultra-Sound Doppler Velocimeter (UDV)

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

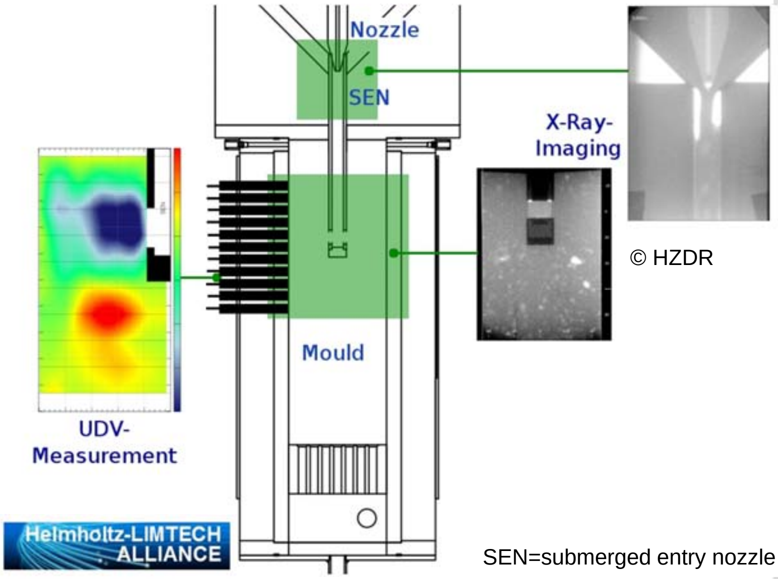


Flow visualization- 2 phase-flow –X-Ray

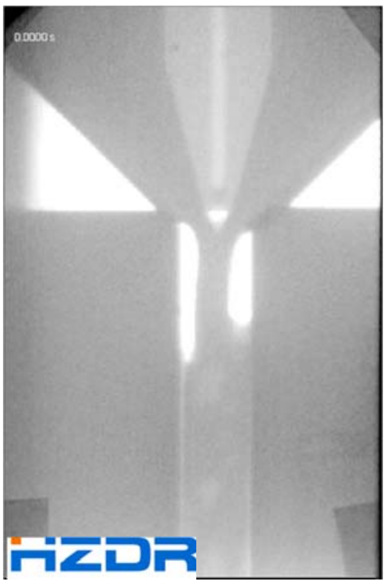


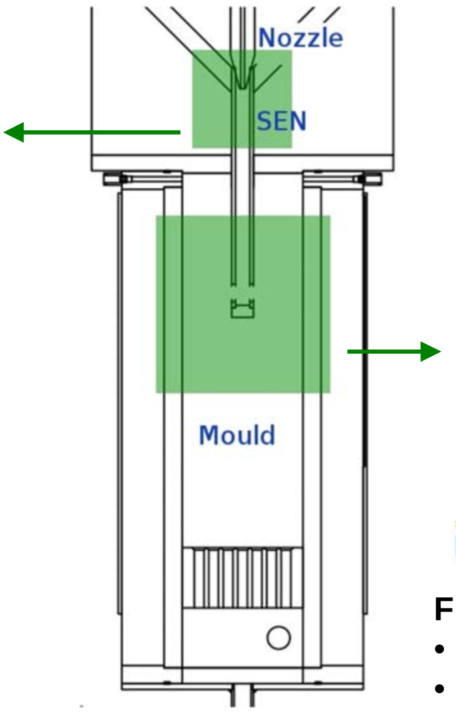
Main feature:
- X-ray visualization of two-phase flows
- Restriction of the mold size in beam direction

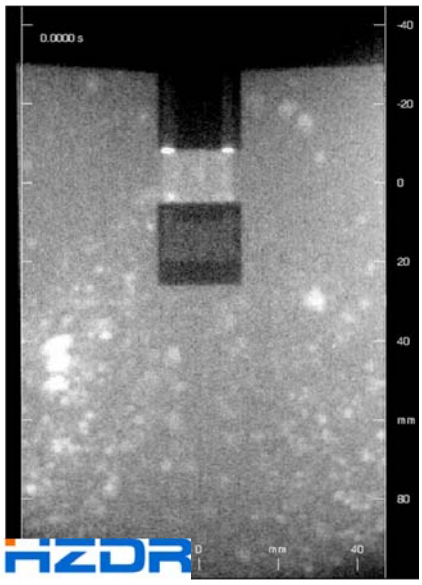
Example : LIMMCAST @ HZDR



Flow visualization- 2 phase-flow –X-Ray







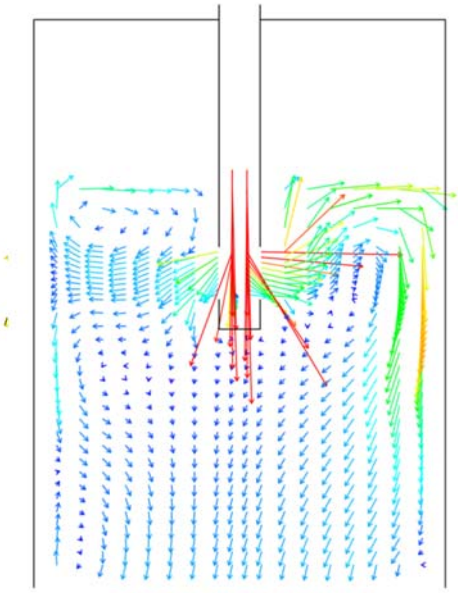
Complex flow regimes

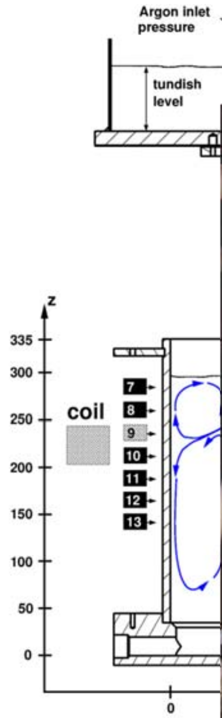
Flow rates:
- Ar: 1,7 cm^3/s
- Liquid metal: 120-130 ml/s

Flow field reconstruction - CIFT

Contactless Inductive Flow Tomography (CIFT)

- flow field **v** modifies externally applied magnetic field **B**
- Measured magnetic field outside melt contains information on flow field
- Reconstruction of velocity field by measured induced magnetic fields b





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

F. Stefani et al., Phys. Rev. E (2004) 70, 056306
T. Wondrak et al, Meas. Sci. Technol. (2010) 21, 045402

➡ higher resolution by use of externally applied AC magnetic fields B

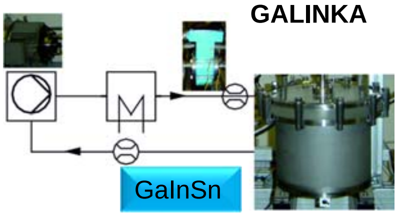
Technology systems

- **loop facilities**
- **material and qualification stands**

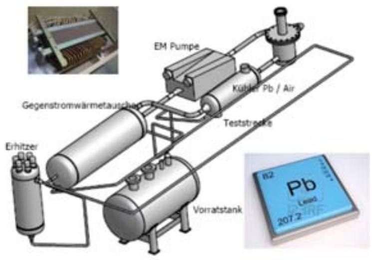
INFRASTRUCUTRES

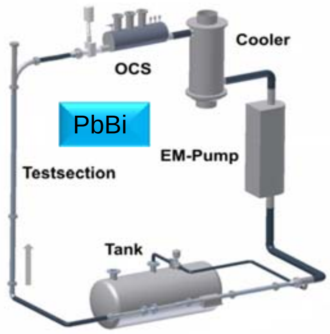
Infrastructures –loop facilities

Table-top/proof of principle | **Laboratory scale** | **Pilot-scale (proto-typical)**

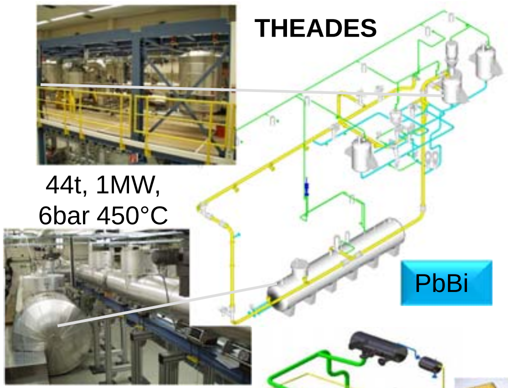


TELEMAT





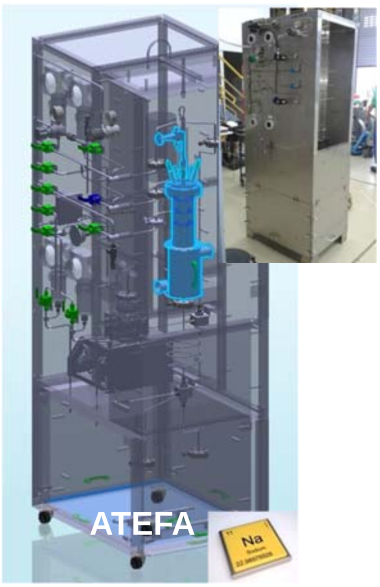
THESYS
2t, ~200kW,
4 bar, 450°C



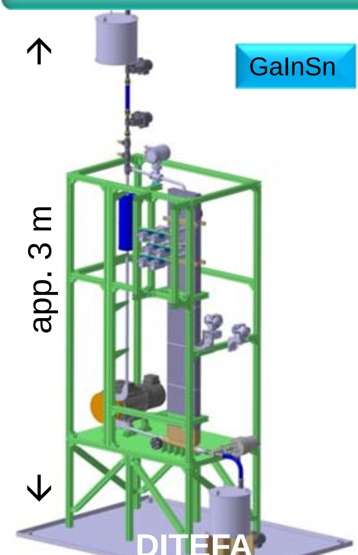
Available liquids
- Lead, PbBi-eutectics, tin
- Gallium-Indium, tin
- Sodium, NaK,

Infrastructures –technology development

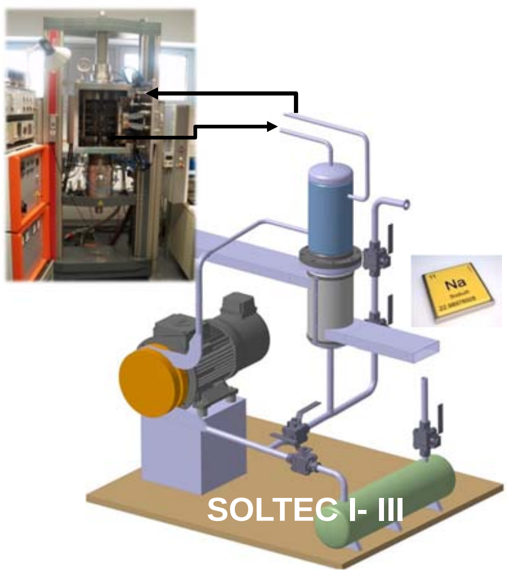
Phase transition (boiling) | **Flow phenomena** | **Materials in flowing LM**



- Sodium boiling (thermal-electric energy conversion)
- Instrumentation qualification



- transitional flow evaluation
- proof of principle instrument.
- qualification CFD and systems codes (TRACE, ASTEC-Na*)
- education & training



- steel corrosion qualification* up to 1000K
- creep tests
- stress corrosion cracking

Infrastructures –material qualification

Material corrosion	Coolant control	Coolant conditioning

COSTA = COrrosion test stand for STagnant liquid lead Alloys

- Operative since : 1997
- Pb or Pb-Bi
- Equipped with O_2-control
- Influence of protection layers and coatings on corrosion

KOSIMA: Karlsruhe Oxygen Sensor In Molten Alloys.

- Operative since: 1998
- Pb or Pb-Bi
- Equipped with O_2-control
- Development and calibration of oxygen sensors

KOCOS: Kinetics of Oxygen COntrol Systems

- Operative since: 1999
- Pb or Pb-Bi
- Equipped with O_2-control
- Diffusion coefficient and mass exchange rates for oxygen

Features

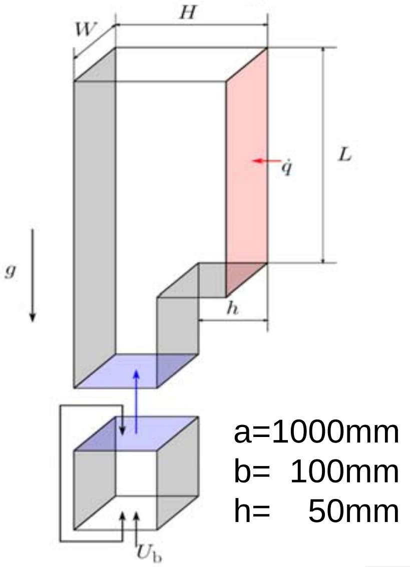
- **Generic phenomena (micro-scale)**
- **FR –FA flow experiments**
- **System tool qualfication**

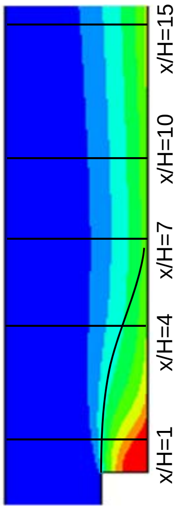
THERMAL-HYDRAULICS

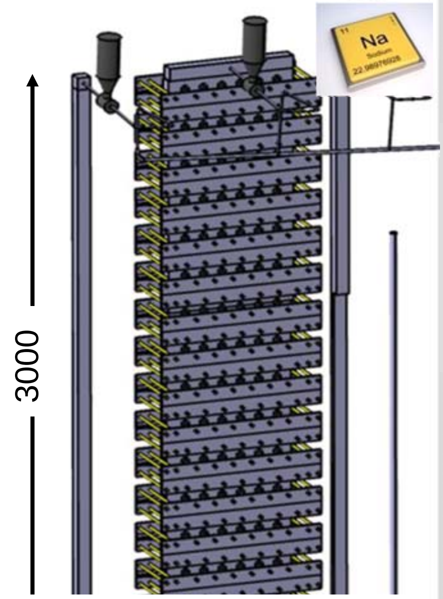
Thermal-hydraulics –Generic science

Vertical Backwards Facing Step (BFS)

- Identification of the **transition regimes**
- **Development** , improvement of **anisotropic heat flux** and momentum **models** (DNS, LES and RANS)
- Enhanced **engineering correlations**







Sodium (*Re*=5·10³)

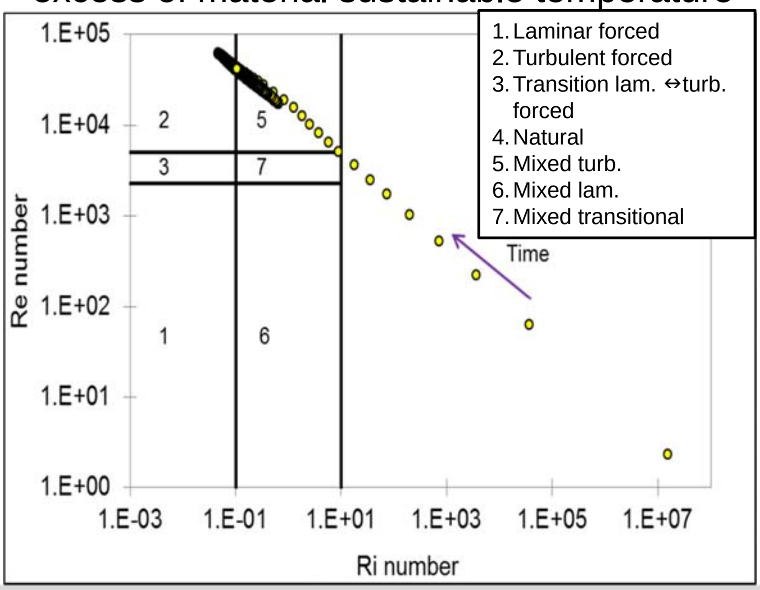
- T_{wall} in recirculation zone too low
- Temperature prediction in developing region adequate

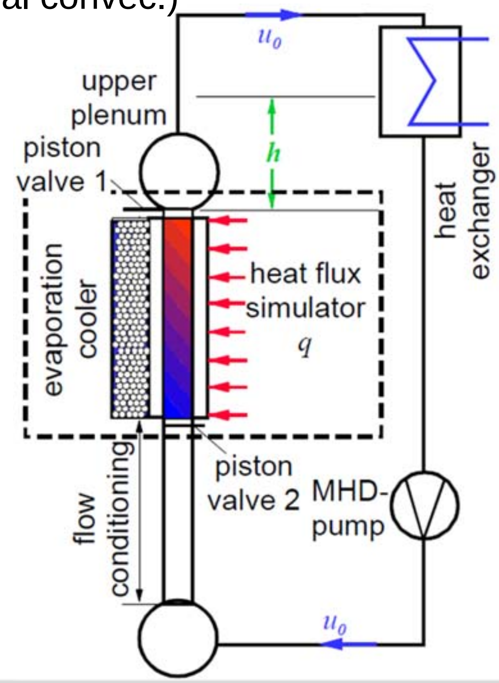
Helmholtz-LIMTECH ALLIANCE

Thermal-hydraulics –Generic science

Transitional Flows

- during start-up, shut-down or LOFA
- flow regimes altered (forced ➡ mixed ➡ natural convec.)
- instabilities in the heat removal
- excess of material sustainable temperature





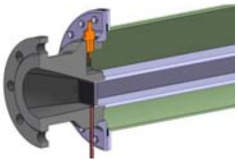
Thermal-hydraulics –Generic science

Transitional flows

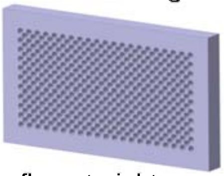
- InGaSn-Loop
- volume of ~ 16 l
- Counter-Current Water-InGaSn HEX
- Test section: 22 x 220 x 2000 (DxWxH,mm)
- Electro-magnetic pump

Goals:

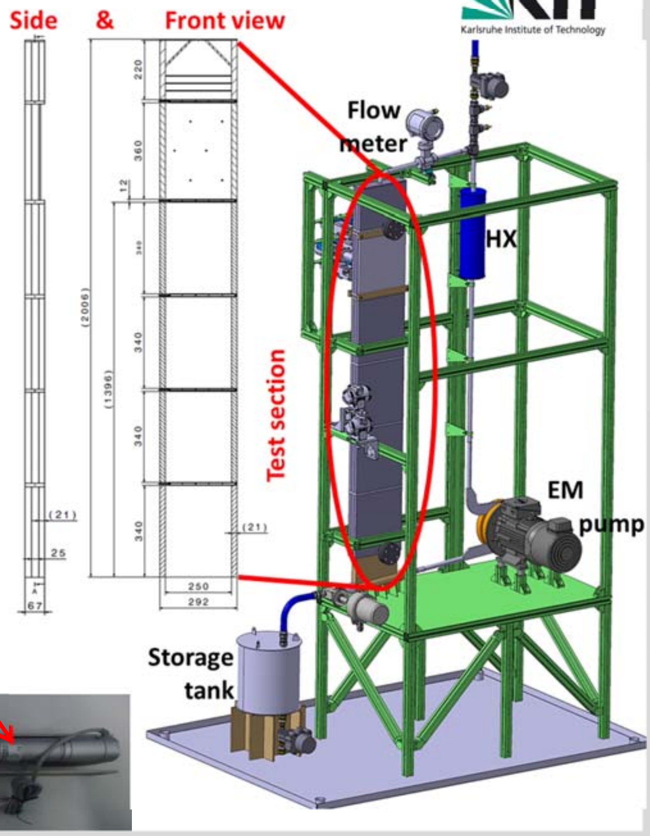
- Identification of transitional states
- Qualification of measurement devices
- Asset for education and training



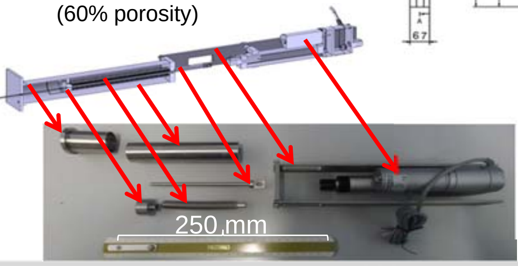
transition
circular- rectangular



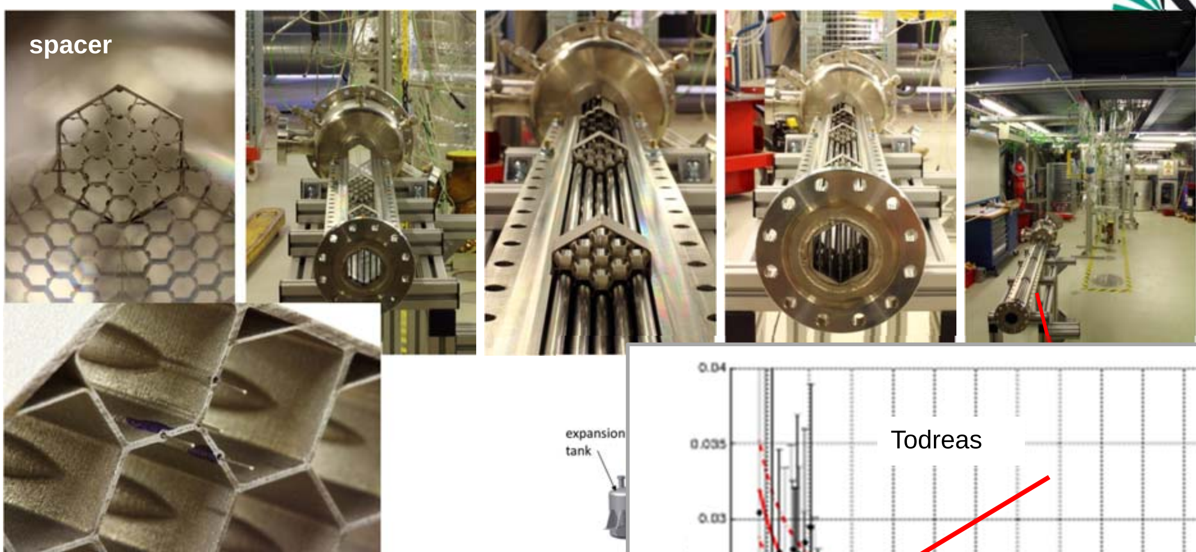
flow straightener
(60% porosity)

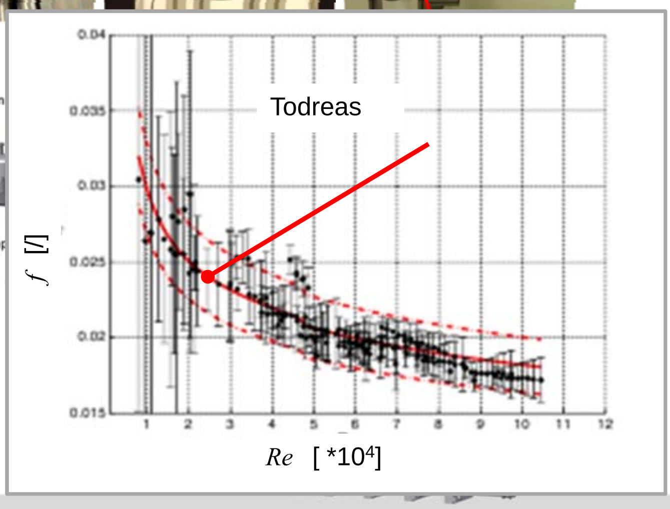


fabrication sample



Thermal-hydraulics – FA experiments





Hexagonal FA with spacers

P/D= 1.4 , D =8.2mm, h=870mm
19 Pins, Q_{el}=440kW, q''=1MW/m^2

Results

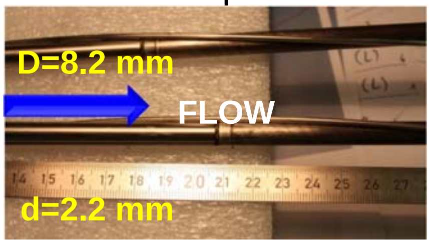
- Nu-Numbers 20% higher than Miktiyuk

J. Pacio et al. / Nuclear Engineering and Design 273 (2014) 33–46

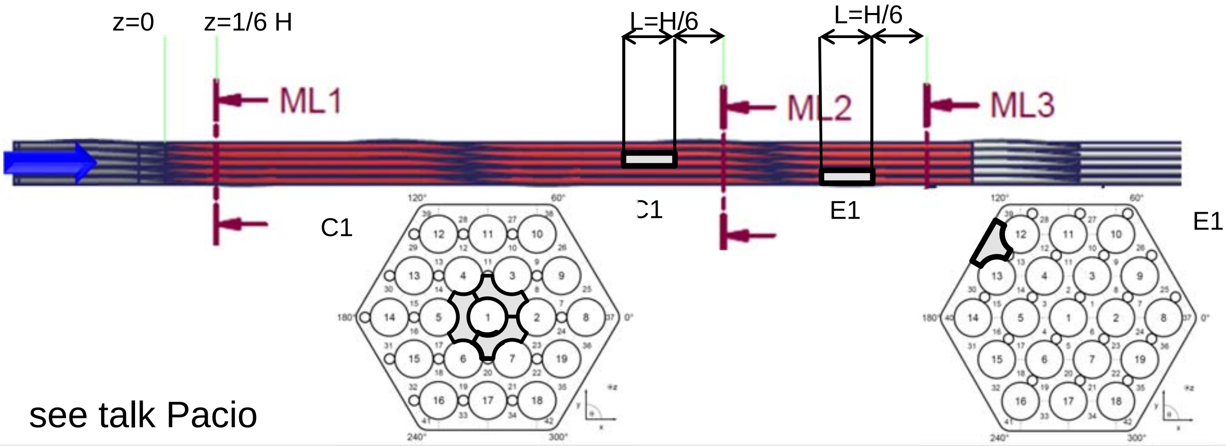
Thermal-hydraulics –FA experiments

Consecutive further elaboration

- FA- with wire wraps P/D=1.29



- Now FA with partial blockage

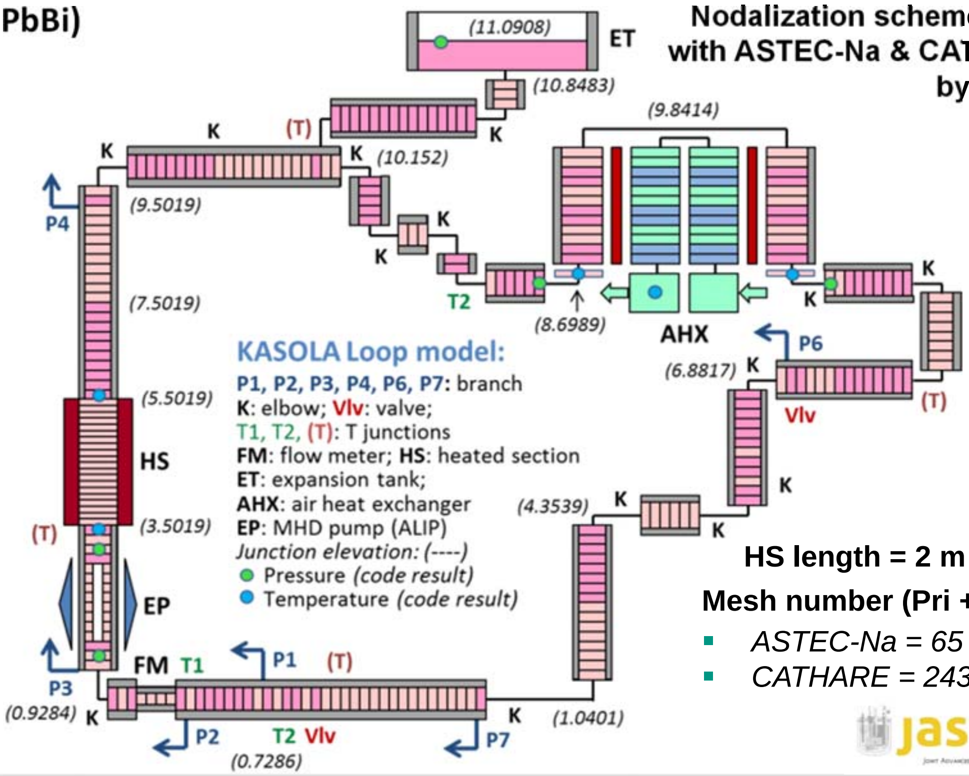


- see talk Pacio

Thermal-hydraulics –loop simulation

- **More reliable loop system description in Na (counterpart to LACANES (PbBi)**

Nodalization scheme used with ASTEC-Na & CATHARE by ENEA



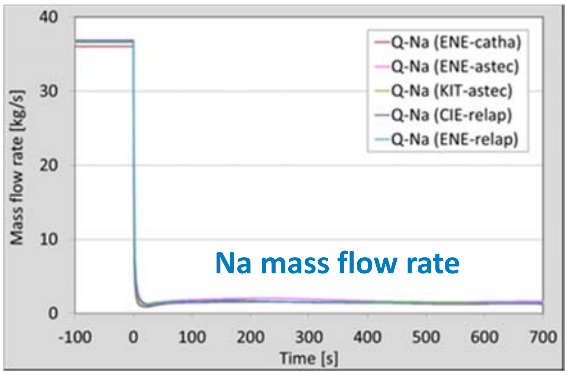
HS length = 2 m

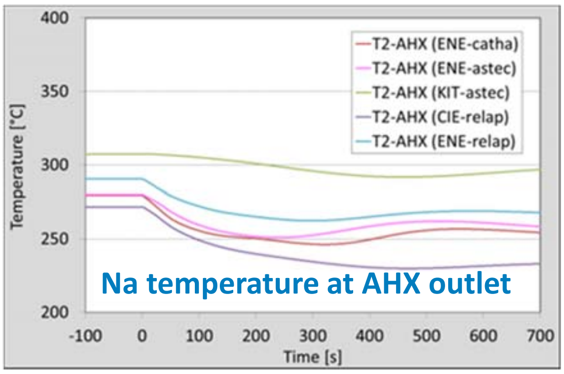
Mesh number (Pri + Sec):

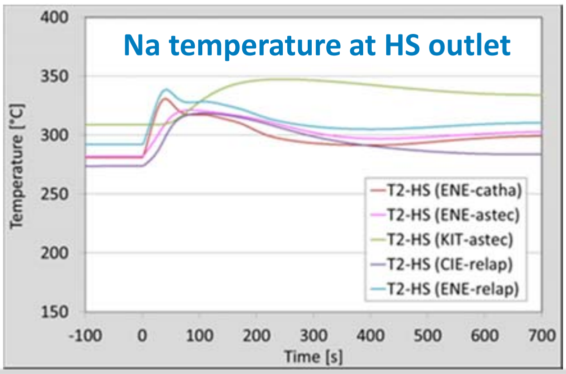
- *ASTEC-Na = 65 + 14*
- *CATHARE = 243 + 26*

Thermal-hydraulics –loop simulation

- **Anticipated ULOF starting at 80 kW power**







- All codes predict NC primary mass flow rate around 4% of nominal one
- Large margin against primary temperature safety limit *(T = 550 °C)* and the risk of sodium freezing *(T_{sol} ~ 100 °C)*

Expertise fields

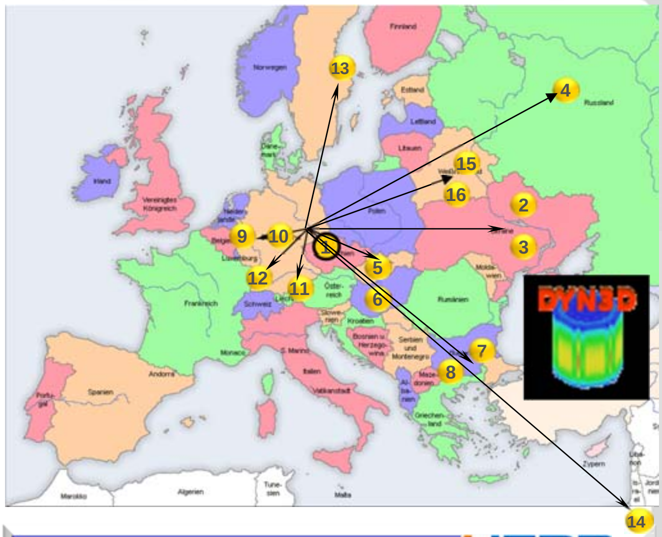
- **Design basis events (from core ➔ system)**
- **Accident analysis (from failure ➔core degradation)**
- **Containment behavior**

SAFETY ASSESSMENT

Design basis events – DYN3D

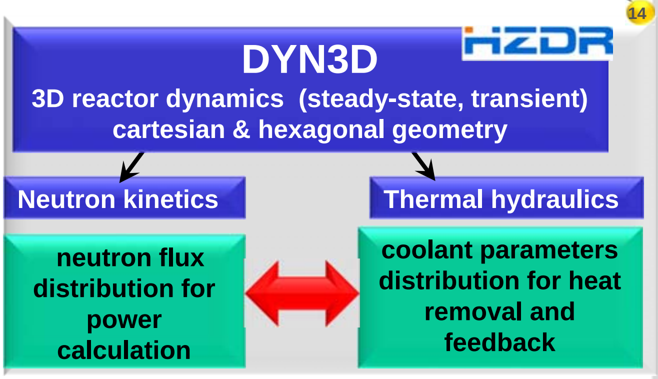
Coupled N-TH simulation by DYN3D

- developed at HZDR for safety analysis of LWR cores
- validated code versions for Western PWR's, BWR's and Russian VVER reactors



Extension of DYN3D to FR'systems focussing on:

- XS generation methodology
  Validation of DYN3D by fast reactor experiments
- models for thermal expansion effects
  - Axial thermal expansion of the fuel rods
  - Radial thermal expansion of the diagrid



Design basis events – DYN3D

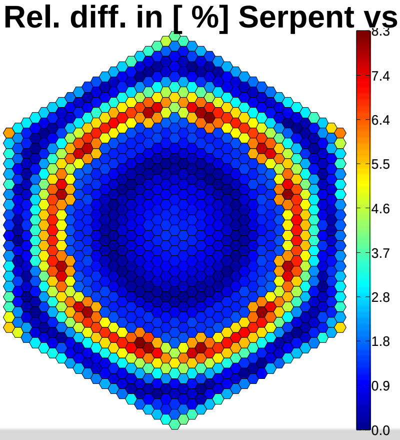
Neutronic analysis of the BFS-73-1 critical assembly using DYN3D and Serpent

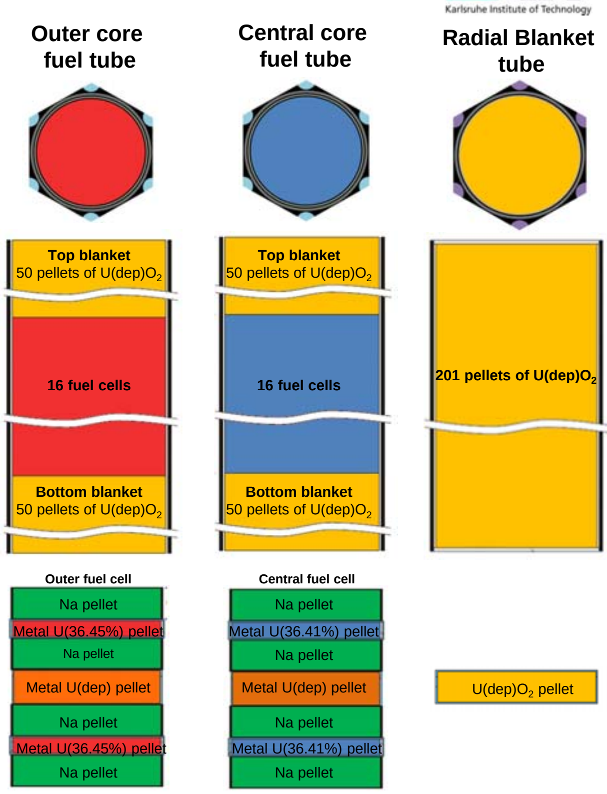
- **3D detailed assembly calculation**
  - DYN3D: diffusion calculations
  - Serpent: MC calculations
  - Generation of few-group XS for DYN3D
  - Reference solution

Assembly k_{eff}: Difference: -12 pcm

Assembly radial power distribution

Rel. diff. in [%] Serpent vs. DYN3D

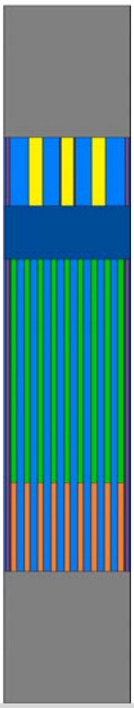


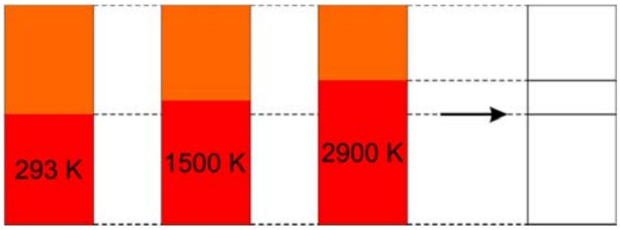


Design basis events – DYN3D

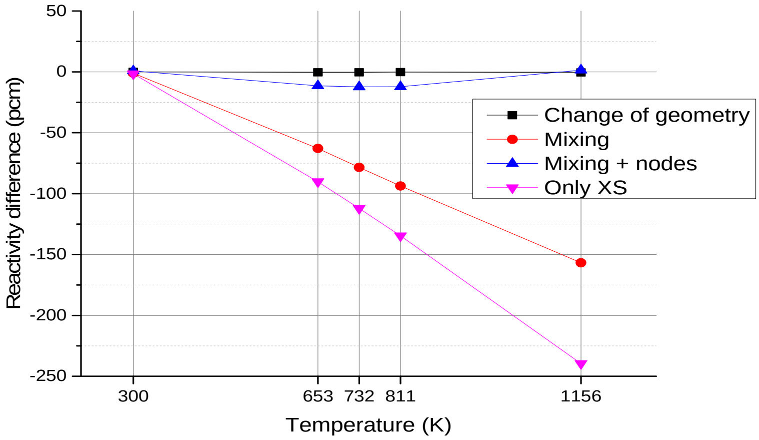
Axial fuel rod expansion model via mixing method:

- Approach: insertion of additional node after each expanding material interface





Example:
- Axial fuel rod expansion in one PHENIX assembly



➡ Reasonable agreement in terms of reactivity

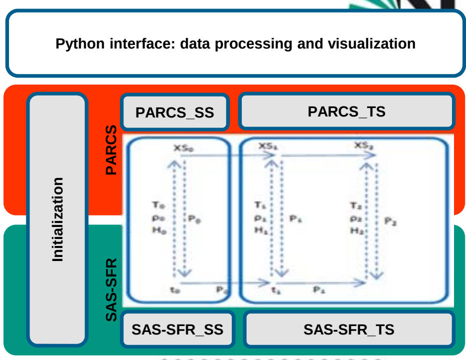
Design basis events - Coupling PARCS/SAS-SFR

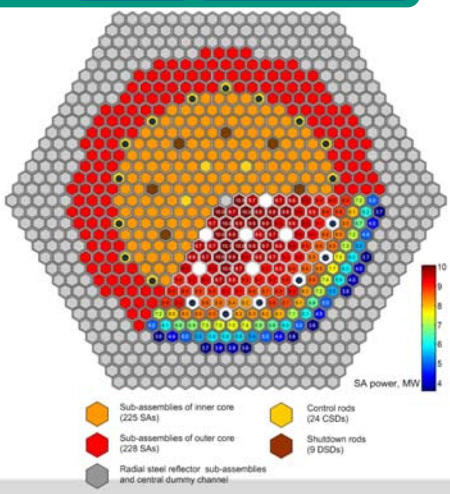
Methods applied

- “on-the-fly” XS generation system (“Sigma-0” method, 33 EG, all nuclides)
- data exchange procedure with time clocking
- geometry transfer, expansion model developed (independent axial representation in TH and N models and averaged fissile core height)

Capability to account reactivity feedbacks:

- fuel Doppler
- axial + radial expansion of pin & SA elements
- sodium density and void
- fuel and clad relocation





Validiation: **ESFR Reference Oxide** core, **BOL**

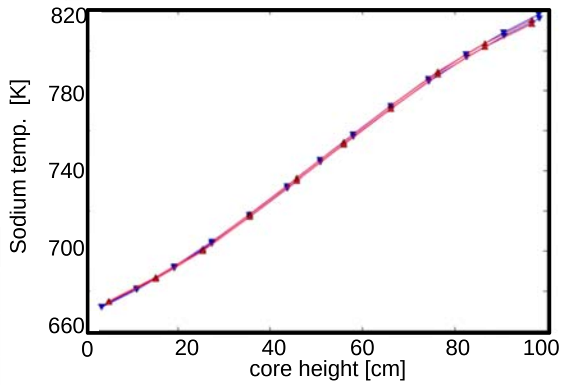
- models for 2 and 10 channels
- feedbacks for all important nodes of fissile height and upper core regions (UAB, UGP, USP)

PhD Ponomarev

Design basis events - Coupling PARCS/SAS-SFR

Steady state calculations

- Different independent axial representations
- Comparison: SAS-SFR , PARCS
- Updated node parameters (each iteration): fuel, clad, sodium masses + temp, axial node height



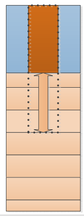
Comparisons with SAS-SFR/MCNP:

Parameter	SAS-SFR/MCNP	SAS-SFR/PARCS
K-effective (nom.)	1.0124	1.01195
Doppler constant, pcm	-1200	-1198
SVE active core	+1650	+1773
SVE active core + SP	-	+1650 (-123)

➡ steady state adequately depicted

Transient calculations –Validation cases

- CR insertion/ withdrawal (fig./table right)
- "Hypothetical" ULOF transient with 2.5 s pump half-time trip and 200% of nom.power
- Reference ULOF 10s (as in ESFR)



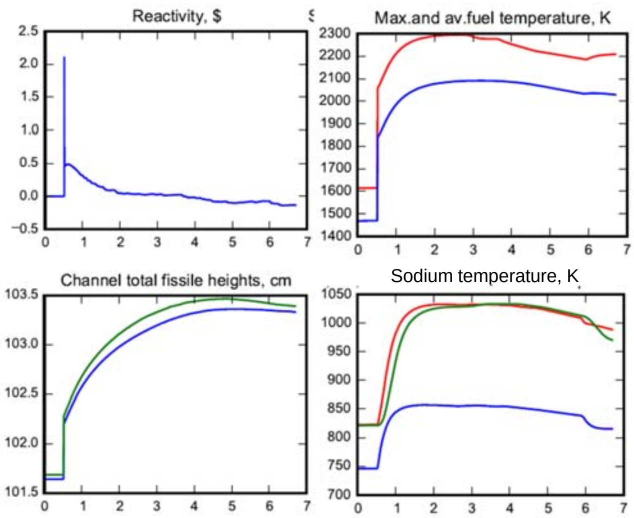
core config. (from top)	insertion/ withdrawal, [cm]	transient dynamic reactivity [$]		β [pcm]
		positive	negative	
1 mesh	10.17	0.81	-	
2 mesh	20.34	2.10	-1.51	249.88

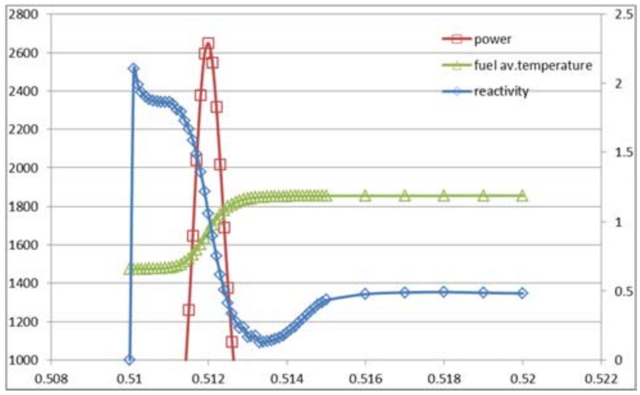
PhD Ponomarev

Design basis events - Coupling PARCS/SAS-SFR

Transient simulations results CR movement

- **Case #3** - outer CRs withdrawal: **2.10$**
  - power rapid increase by factor 2.65, radial power redistribution up to 8%
  - fuel failure occurred (few nodes in mid.plane): ch#2 at 2.596 s, ch#1 at 4.046 s





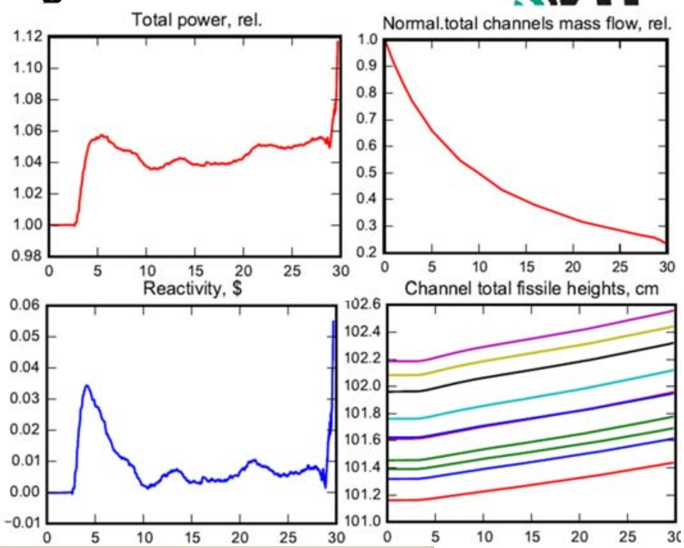
Design basis events - Coupling PARCS/SAS-SFR

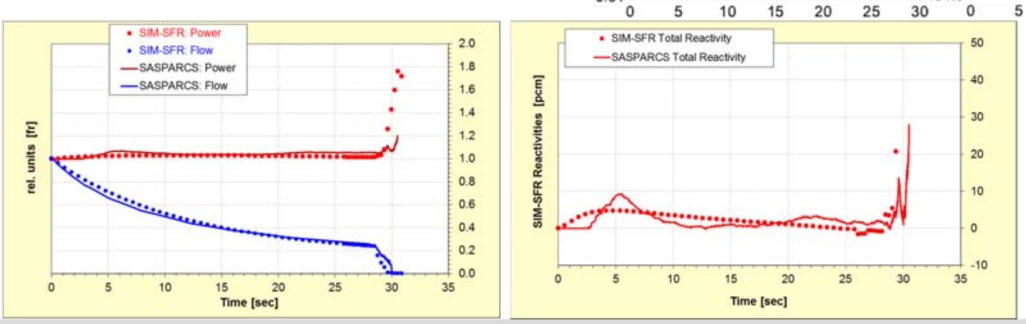
Transient simulations results reference ULOF

Case set-up
- nom.power 3600 MWth
- pump trip with 10 s half-time

Results
- shortest boiling time 27.35s
- boiling in almost all channels
- radial power shape change ~1.5%

Comparison with SIM-SFR
- good agreement with ESFR comparison (without CR drive lines effect)





PhD Ponomarev

Accidental safety analysis- Frame

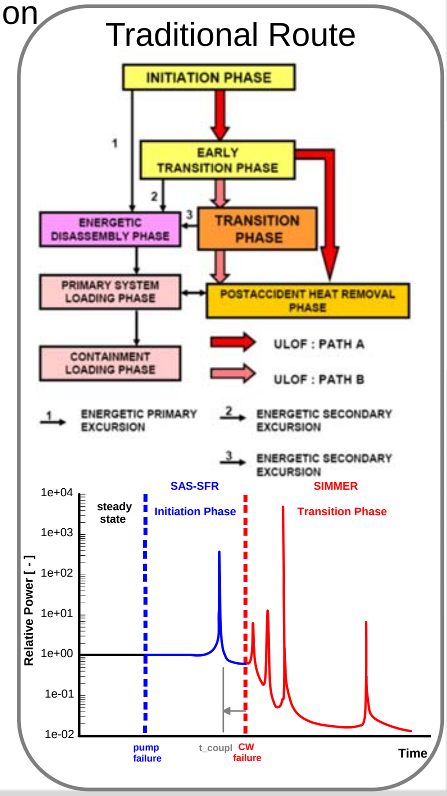
FR cores with TRU= core not in most reactive configuration
Re-criticality potential allow disruptive accidents (CDAs)

CDA described by 3 different phases :
- Initiation Phase (IP) ➡ can-wall failure
- Transition Phase (TP) ➡ creation of molten fuel pool,
- Expansion Phase (EP) ➡ mechanical energy release.

➡ Multi-physics description mandatory N/TH/SM

Options
- SAS4A/SAS-SFR- FRED (channel approach) for IP
- SIMMER for TP and EP
- SIMMER stand-alone simulation

Complementary approach
- **Model optimization in accidental codes mainly ASTEC**
  - boiling models, gap heat transfer, fission gas behaviour (axial fuel expansion, melting limits),clad mechanics
- **SIMMER improvements**
  - thermal expansion reactivity feedbacks (axial/radial)
  - reactivity effects due to fuel-steel mixing
  - fine mesh approach ➡ accountance for coherency effects



Accidental safety analysis- model improvement

Simulation of fundamental boiling experiments

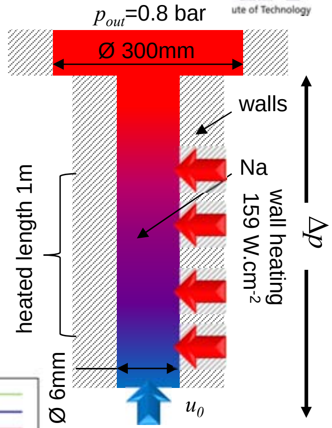
- Ispra Tubular Experiment (ITE)

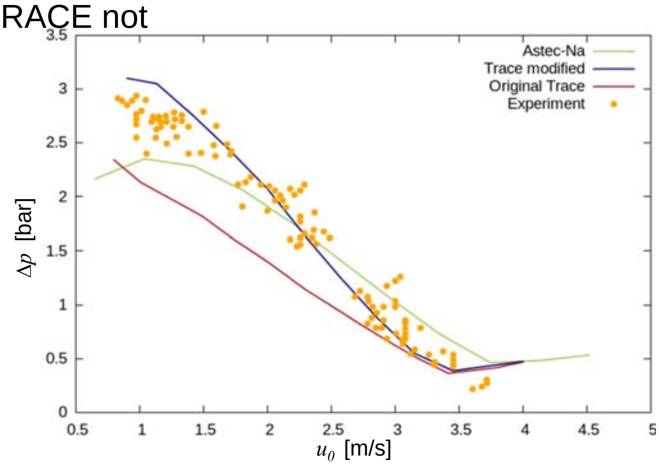
Approach

- modified Lockhart-Martinelli correlation for pressure regular two-phase pressure
- several flow quality factors investigated (from literature)

Results

- ➡ improved system provides better description
- ➡ original ASTEC, TRACE not conservative



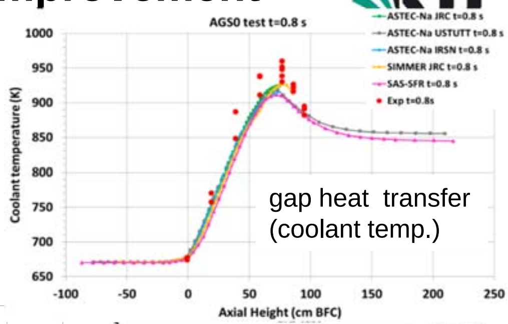


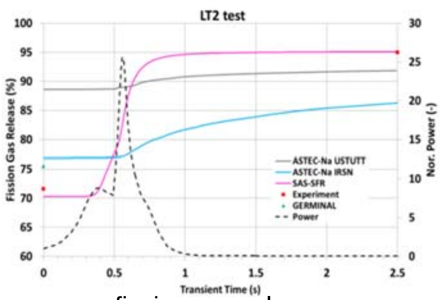
PhD Haselbauer

Accidental safety analysis- model improvement

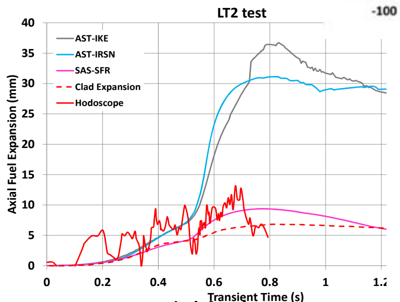
Approach

- identification of modelling deficits
- by code-to-code comparision complemented by experimental data

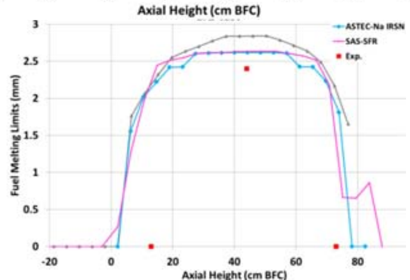




fission gas release



axial fuel exp.



fuel melting

Some Results

- gap heat transfer model validated
- fission gas model contains many parameters ➡ sensitivity analysis of some parameters
- axial fuel expansion overestimated ➡ visco-plasticity model now in ASTEC-Na V2.0
- ……

Accidental safety analysis- SIMMER developments

Simmer III, IV advancements

- modifications TH –SM Coupling
- advanced neutron physics description (incl. expansion, feedbacks)

coupling to structure mechanics for expansion phase simulation

Fluid Dynamics (TH)
- 8 velocity fields (7 for liquid, 1 for gas)
- Multi-phase, multi-component flow
- Phase transitions
- Flow regime (pool-channel)
- Interfacial area tracking
- EOS (various fuels, coolants, gases)
- Heat and mass and momentum transfer

C^4P
1968/560 Group Master Library
Basis: JEFF, JENDL, ENDF/B
Full Range Neutron Spectrum

Structure model
- General structure model
- Pin model (new fuels-development)
- Loop model (IHX & pumps)
- Axial + radial heat transfer
- Virtual structure model
- Structure disintegration
- Freezing on structures

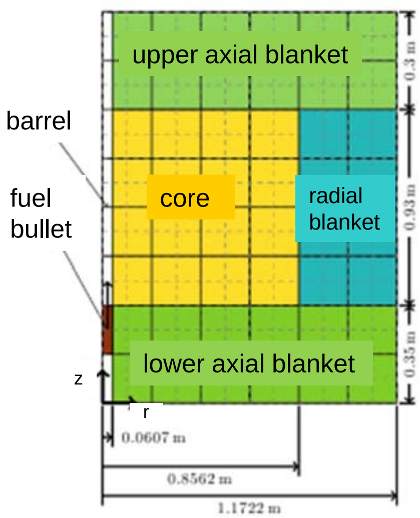
Neutronics
- Neutron transport (diffusion)
- improved quasi-static method
- Cross-section generation
- Heterogeneity treatment
- Decay heating
- movable neutron precursors
- external n.-source & source importance

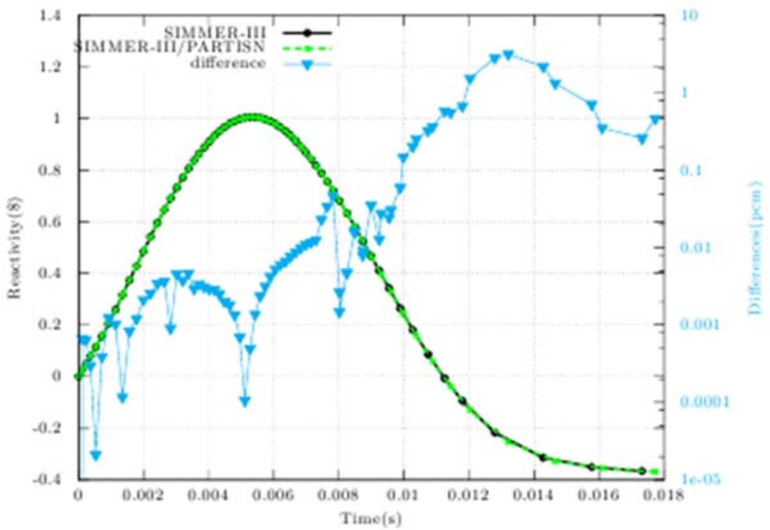
PARTISN neutron transport solver, heterogeneity, thermal exp. feedbacks

PhD Marcetti, Reineiski

Accidental safety analysis- SIMMER developments

- Performance assessment by Space Time Neutronics (STN) Benchmark





Results

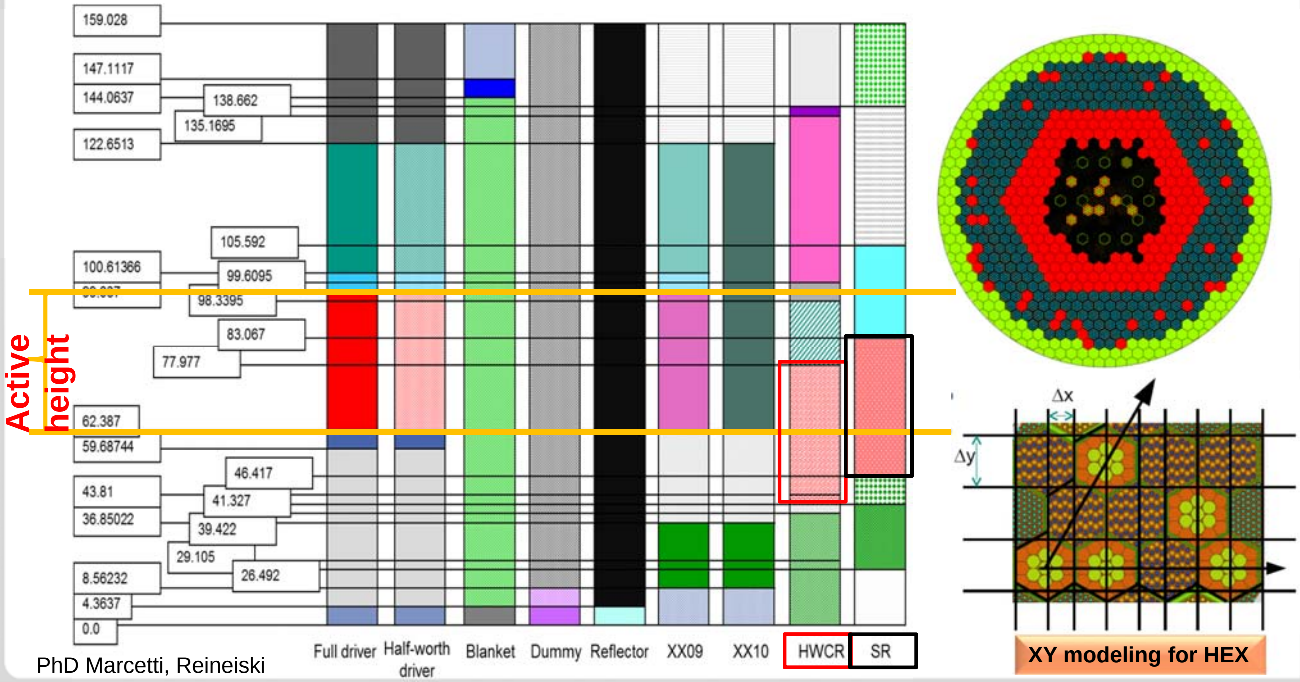
PhD Marcetti, Reineiski

- Excellent agreement in reactivity, flux, amplitude (<1% deviation)
- Similar performance for 2D ULOF of pool type LMFBR
- ➔ space-time-kinetics also with heterogenous approach validated

Accidental safety analysis- SIMMER developments

IAEA Benchmark (EBR-II Shutdown Heat Removal Tests) Results:

- Good agreement with partners **and** experiment, using HEX and XYZ models.
- Excellent performance of PARTISN XYZ model for criticality, reactivity effects, power profile



PhD Marcetti, Reineiski

Accidental safety analysis- Containment behaviour

Sodium fires (physical & chemical processes) in severe accidents
Approach: Validation of CONTAIN LMR wrt. single effect phenomena

- atmosphere thermodynamics including condensation and vaporization of sodium;
- reactions between sodium and oxygen or water (sodium spray or pool fires);
- sodium aerosol behaviour.

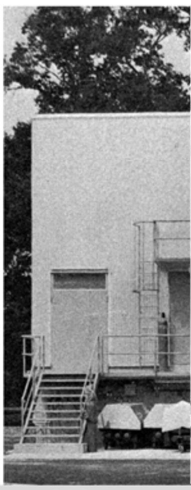
Reference FAUNA experiments @ KIT

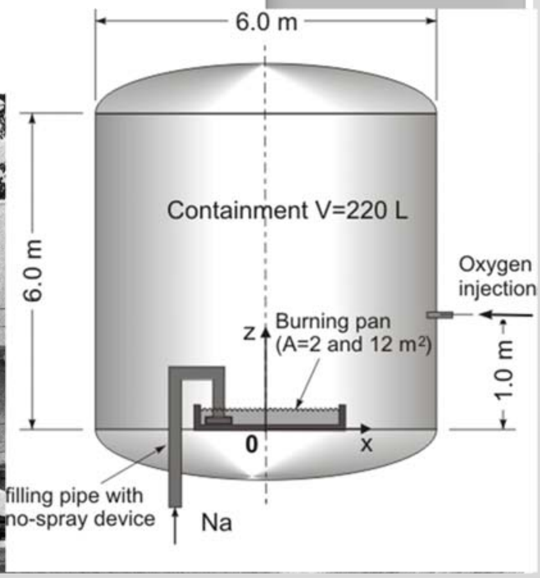
CONTAIN- Features

- oxygen diffusion model (pool-fire), spray fire models
- sodium combustion chemistry
- aerosol description (diffusion, graviational settling, agglomeration)

Burn chamber:
Volume 220m^3

experiment No.	F1	F2	F3
pool surface (m^2)	2	2	12
sodium (kg)	150	250	500
pool depth (mm)	90	150	50
c_{O2} (vol.%)	19-22	17-25	15-25
T_{start} (°C)	550	550	550
T_{Pan} (°C)	250	250	250



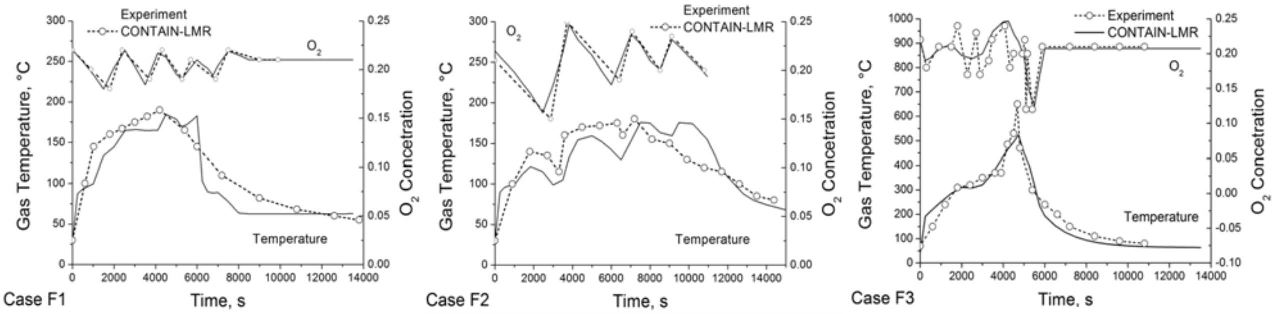


More information:

- Gordeev et al. 2014, CONTAIN-LMR simulation of sodium aerosol behaviour during sodium fires, ICAPP 2014.
- Cherdron W, 1985. Thermodynamic Consequences of Sodium Spray Fires in Closed Containments. Part 1. KfK 3829, Juni 1985

Accidental safety analysis- Containment behaviour

Computed vs. measured oxygen concentration and gas temperature in containment



measured vs. calculated average values of burning rates

Experiment	Experiment (kgNa/m² h)	CONTAIN-LMR (kg Na/m² h)
F1	29.5	30.
F2	21	28.5
F3	33	30

Results

- For F1 and F2 the max. gas temperature in second phase of pool fire over-predicted + cooling down more abrupt. (Reason: @ large pool depth crusting of the pool surface controls combustion process in second fire phase.
- ➡ incomplete combustion of sodium and slow cooling down of hot reaction residuals and unconsummated sodium.

OVERALL

- reasonable description of different sodium fire types
- More accurate prediction requires both experimental and numerical efforts

SUMMARY

- **SFR related R&D mainly conducted in frame of international programs (EU programs, bilateral cooperations) – focus reactor safety**
- **Participation in international context (IAEA, NEA-OECD), in particular for IAEA CRP projects desired – conceived as preservation of competence**
- **Technology development reduced in nuclear context but also contributions in future by R&D in complementary science fields**

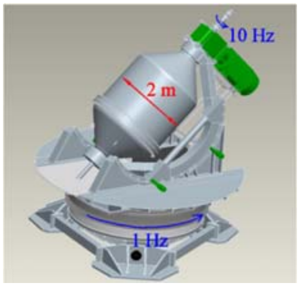
R&D focus

- Development of simulation tools to improve analytic capabilities
- Technology development as cornerstone of knowledge
- Safety assessment as mission of provisionary R&D in Helmholtz
- Education and training

DRESDYN

A European platform for dynamo experiments and thermohydraulic studies with liquid metals

Internal containment (~ 50% of the lab)
for a precession driven dynamo experiment



Building ready
first GaInSn experiments: spring 2016

START-UP 2016

Water pre-experiments : mid 2017
first Na experiments: 2017/2018

HZDR