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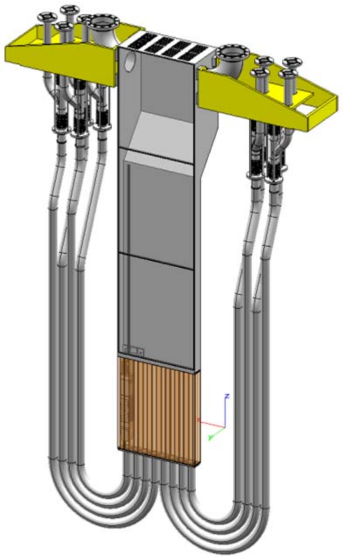
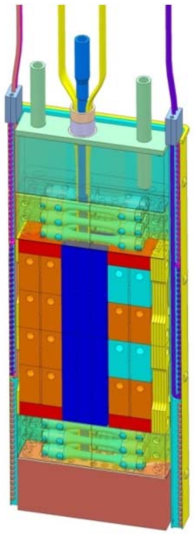
Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase

Frederik Arbeiter et al., ICFRM-17, 11.-16. October 2015, Jülich

Institut für Neutronenphysik und Reaktortechnik, Gruppe Messtechnik und Experimentelle Methodik (INR-MET)





Contents

- HFTM Functions and Requirements
- Engineering Design and Analyses
- Manufacturing of Prototypes
- Validation tests in helium loops and the BR2 reactor
- Outlook for further development
- Conclusions

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International Fusion Materials Irradiation Facility
IFMIF – Mission and Concept

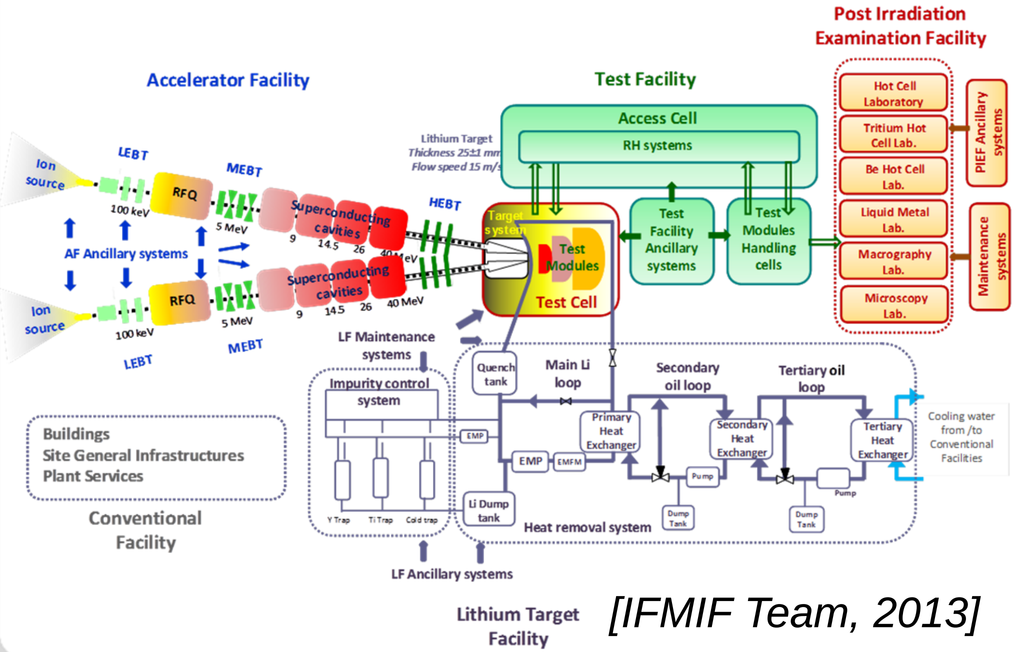
Mission: provide material data irradiated at fusion relevant neutron spectrum for design, construction, licensing and safe operation of a fusion DEMO Reactor.

IFMIF facility components:

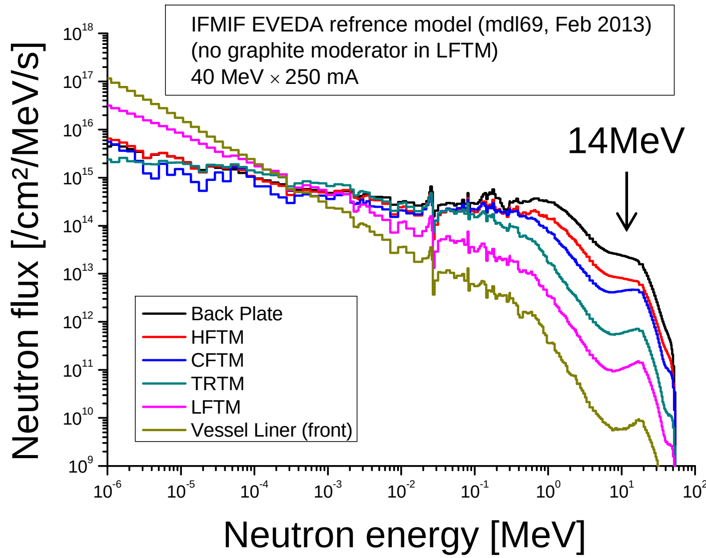
➔A suitable **neutron source** by the d,Li stripping reaction.

➔A set of mission-relevant **irradiation experiments.**

➔An **efficient & safe environment** for irradiated materials production and examination.



[IFMIF Team, 2013]

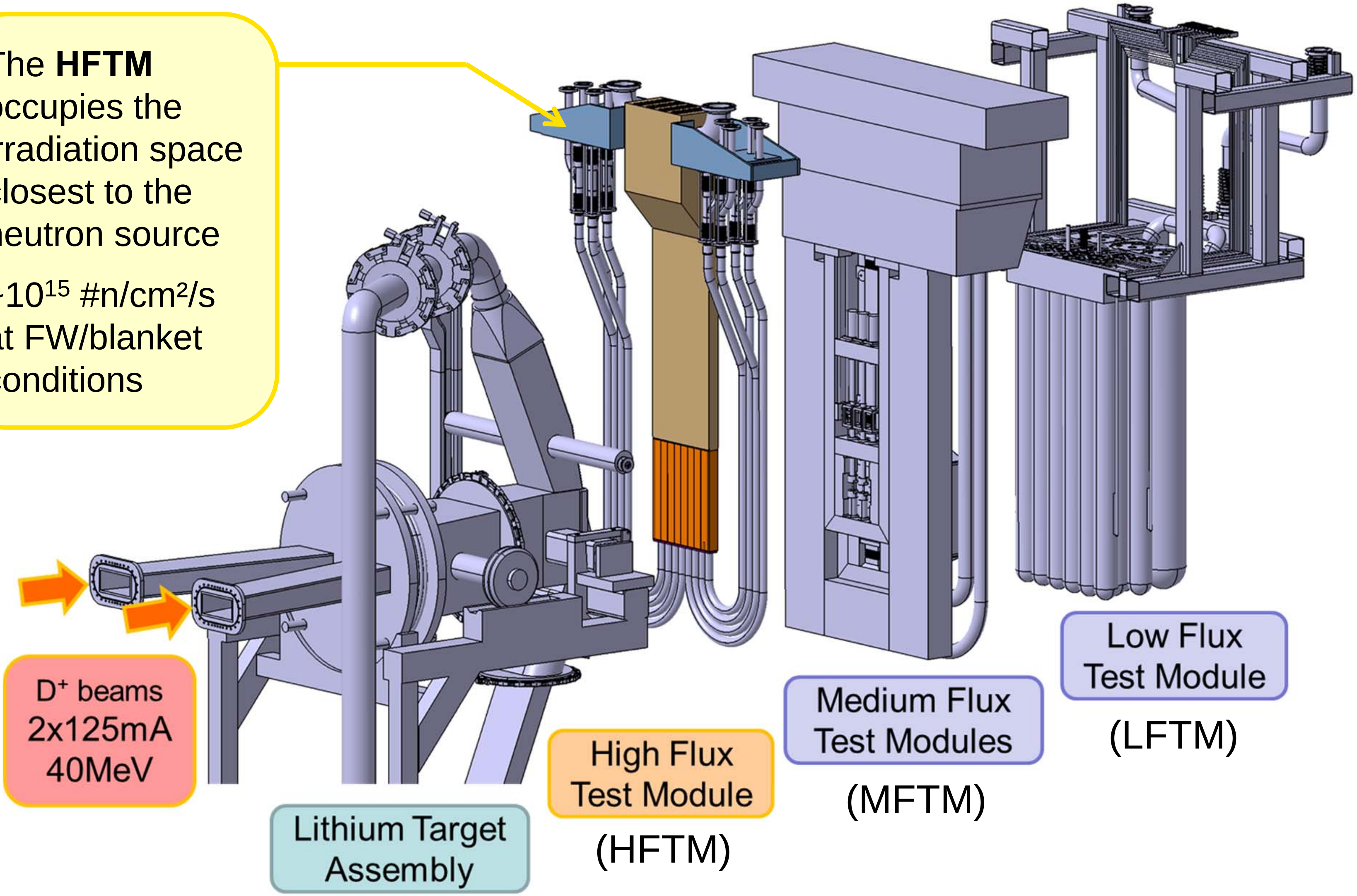


[K. Kondo, KIT, 2013]

Irradiation experiments in the IFMIF Test Cell

The **HFTM** occupies the irradiation space closest to the neutron source

~10^{15} #n/cm²/s at FW/blanket conditions



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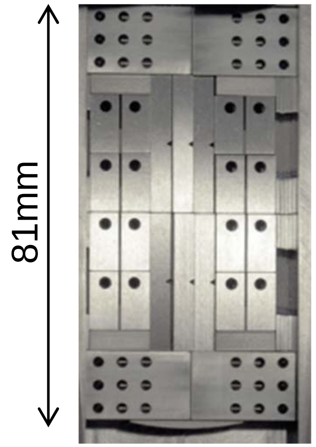
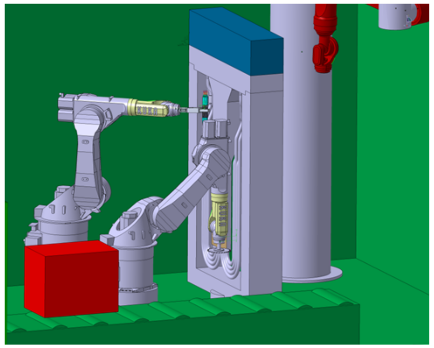
HFTM functions and requirements



80 SSTT specimens
in specimen stack
81 x 40 x 9.5 mm³
of 1 irradiation capsule

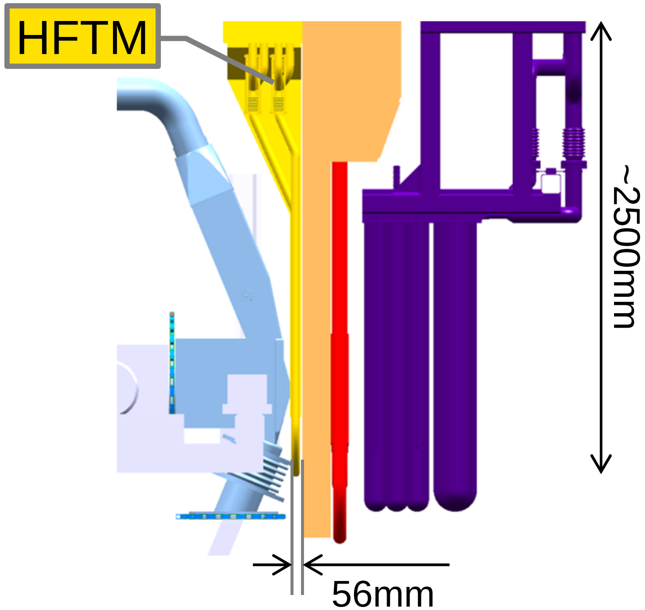


HFTM disassembly

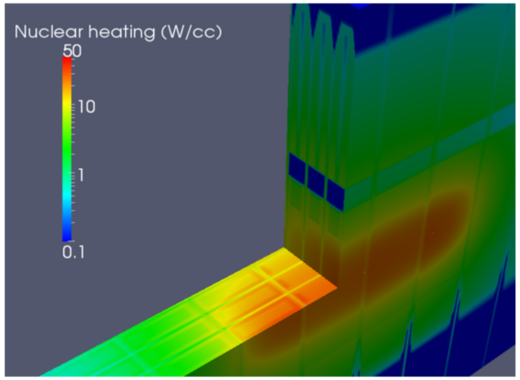
- To irradiate qualified **SSTT** specimens of **RAFM** steels in sufficient quantity/rate for IFMIF mission
- Irradiation temperatures in the range **250°C ≤ T_{irr} ≤ 550°C** (for RAFM steels)
- Maintain low temperature spread **(+/-3% of T_{irr}** in 80% of specimen stack and **temporal stability**)
- Design for component lifetime of **1 year , 50dpa**, meet RAMI requirements
- Integrate with **IFMIF plant requirements** (remote handling, (dis)assembly in hot cells, safety, waste disposal

HFTM design constraints and paradigms

- The geometry of the IFMIF neutron source/radiation field suggests a **flat cuboid** as irradiation space
- Limited building space : 56mm + 2x 2mm gap reserved for the HFTM in the „stack“ of irradiation experiments ➔ **a slender structure** avoiding protrusions (flanges etc.) Low pressure **minichannel He-cooling** chosen.
- A radiation source with limited extension and possible temporal variations requires **neutron reflectors** to limit flux gradients and **active temperature control**



HFTM installation space



Nuclear heating distribution

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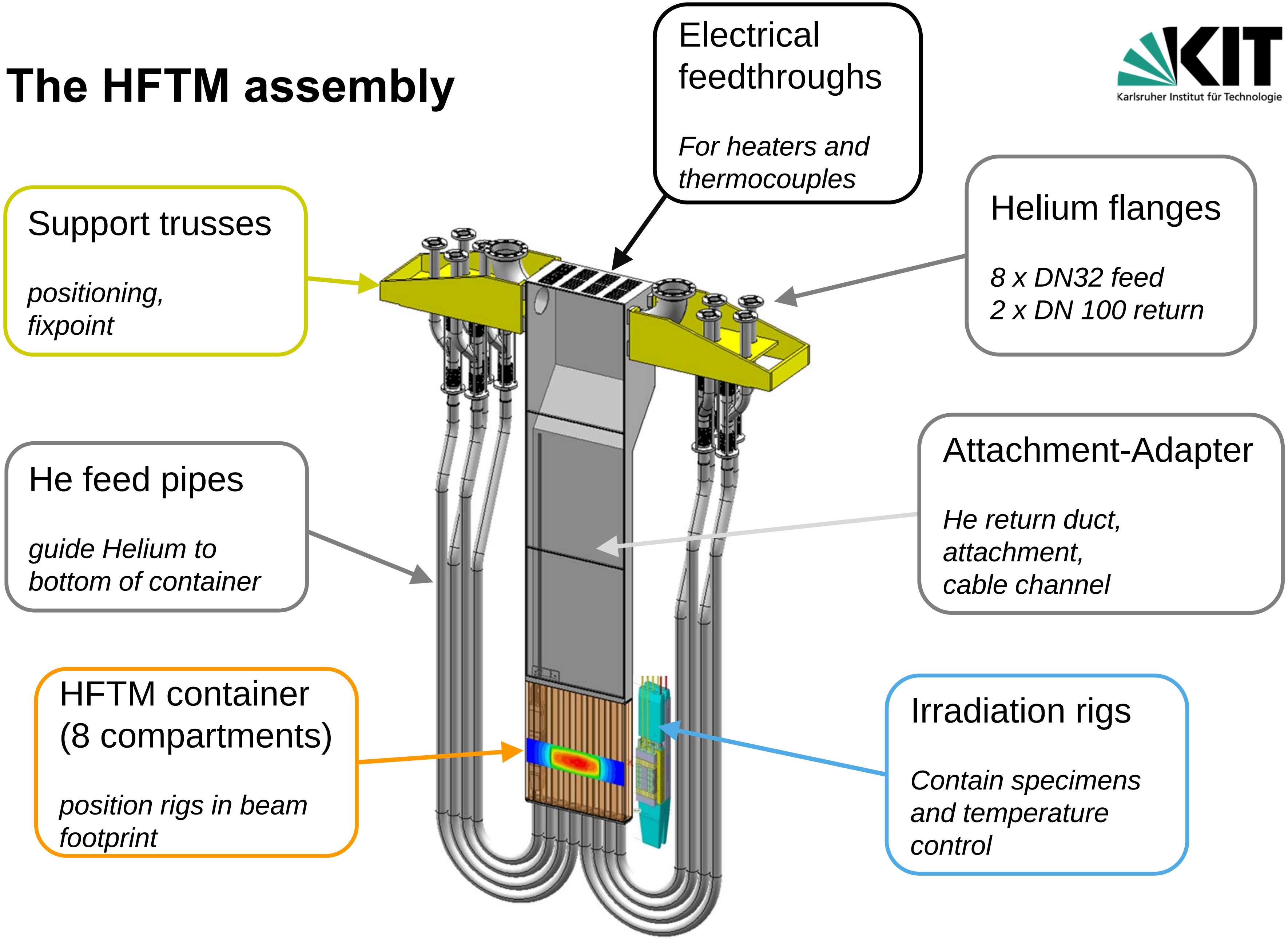
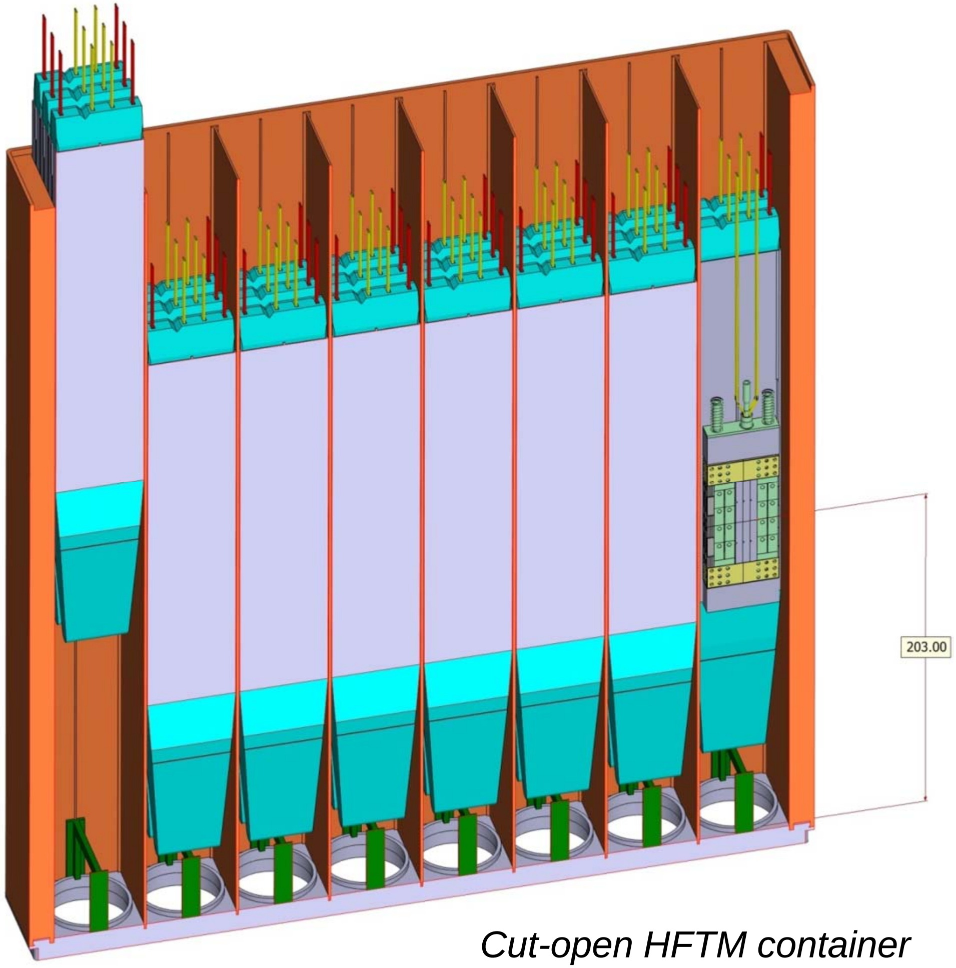
The HFTM assembly



HFTM container and irradiation rigs



Cut-open HFTM container
with 8 compartments, each with 3 irradiation rigs

Functions & Requirements:

- Position the rigs in the beam footprint
- Guide the helium coolant
- Widthstand the internal pressure
- Act as saftey barrier

Features:

- Subdivision into 8 „compartments“
- Wire-cut EDM from solid block
- Built from AISI 316L steel
  RCC-MRx : 53dpa @ < 375°C
- 2mm outer wall thickness
- Spring loaded rig downholders

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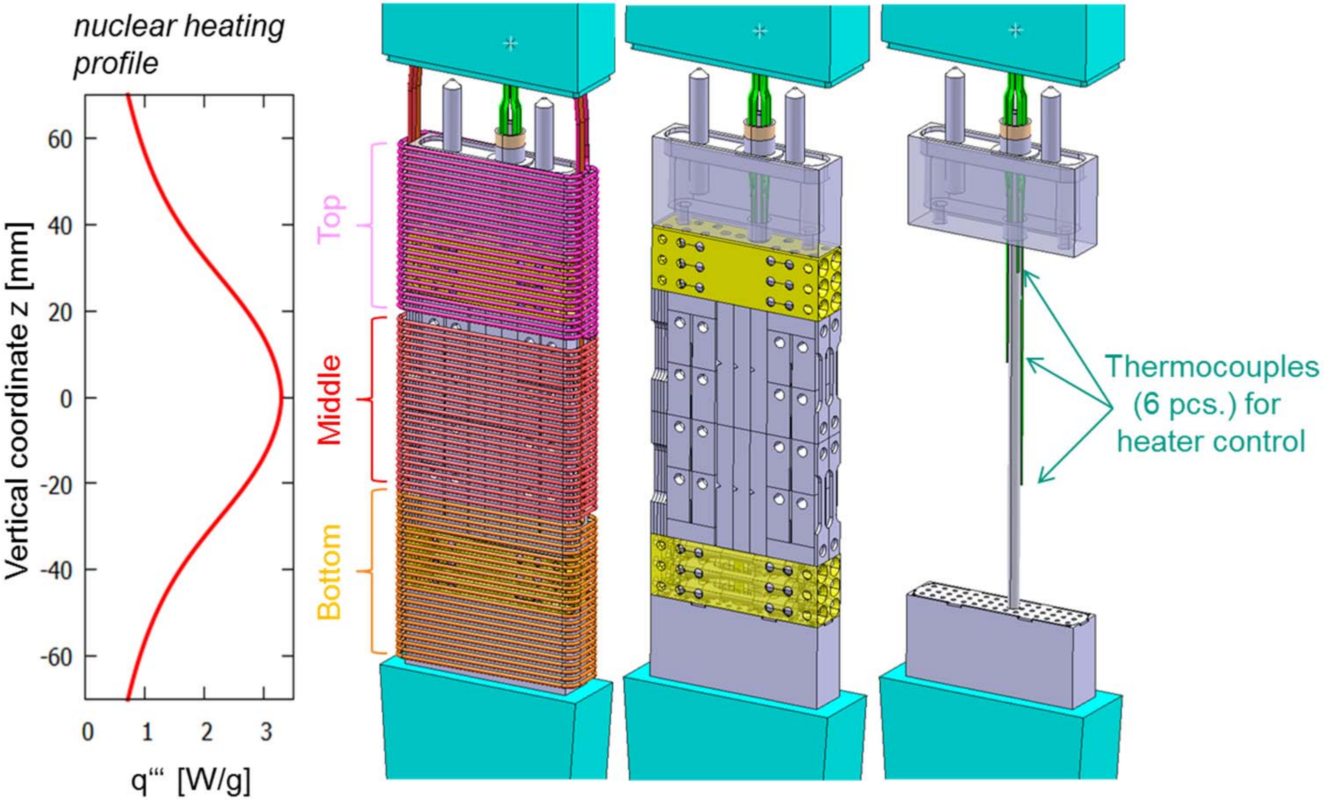
Capsule temperature control



Three (individually controlled) **electrical heater circuits** are used to

(1) balance the **axial profile** of the nuclear heat release

(2) balance **temporal variations** of the beam power

They are guided by 3 thermocouple measurement positions.

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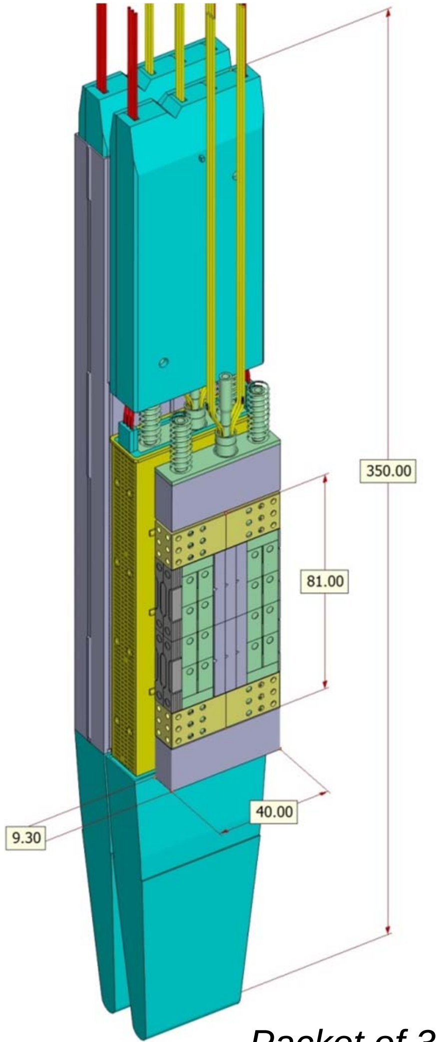
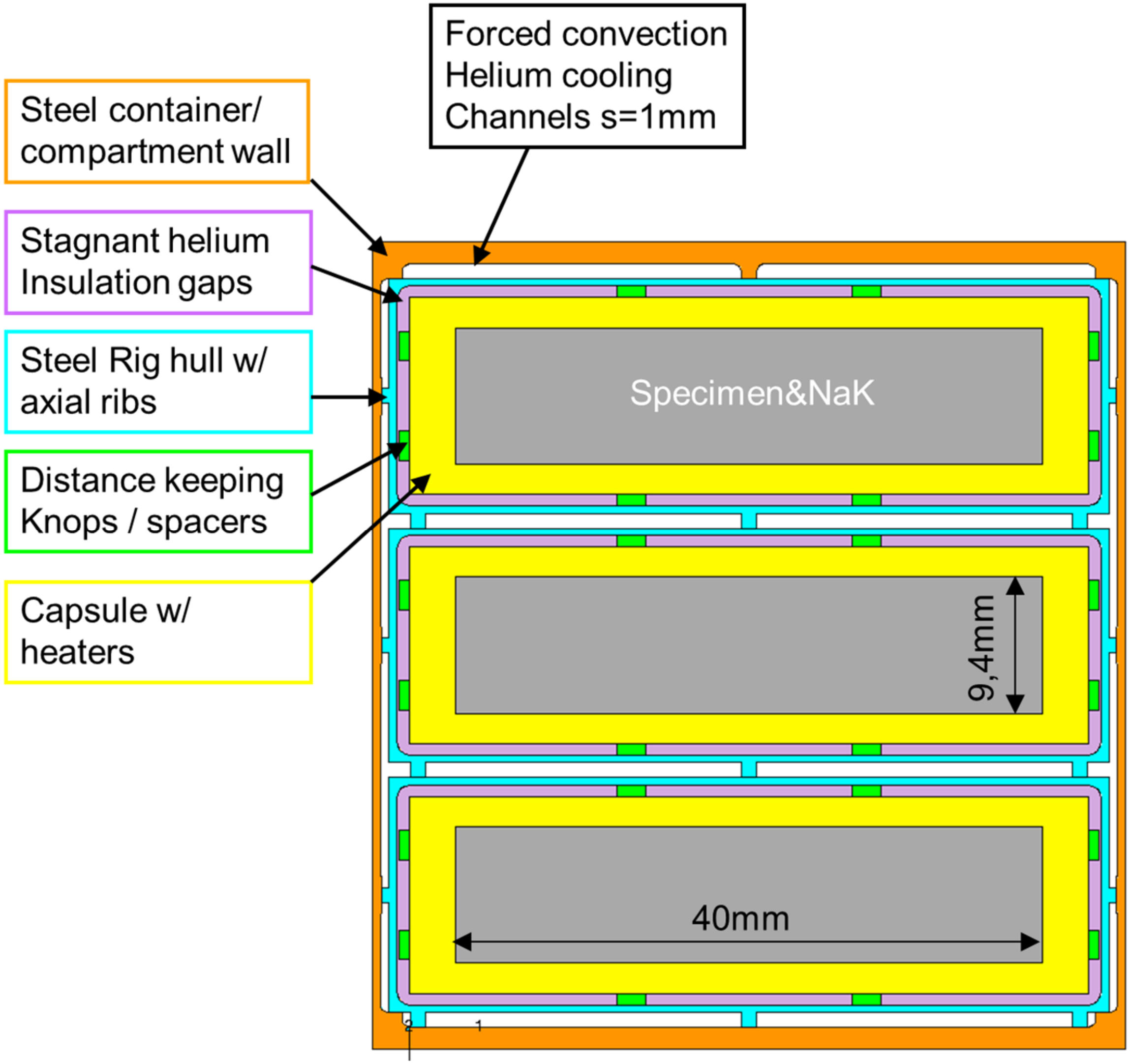
Rig packet in compartment

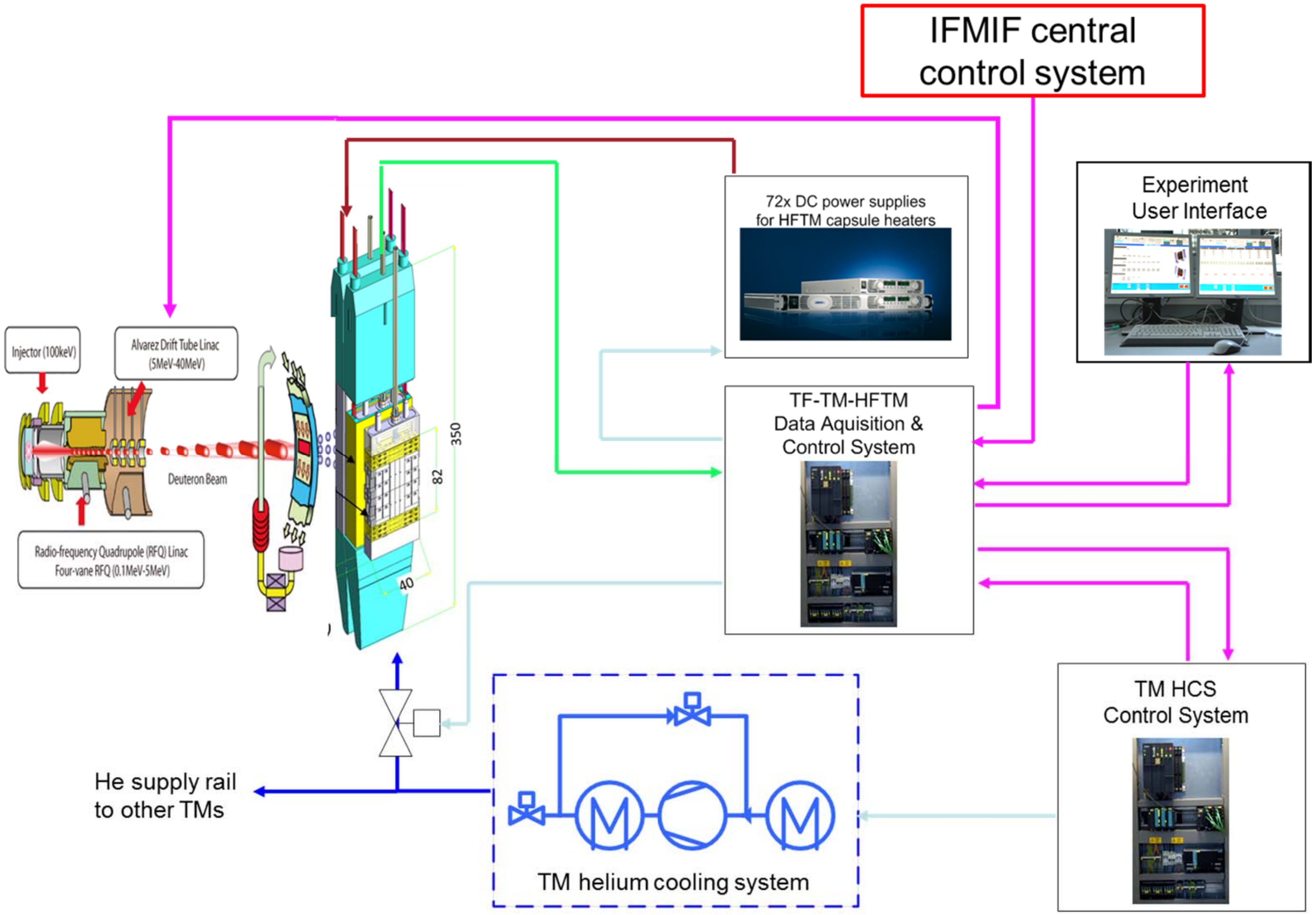


Packet of 3 rigs (stripped layers)



Cross section through 3 rigs inside compartment

Control system architecture



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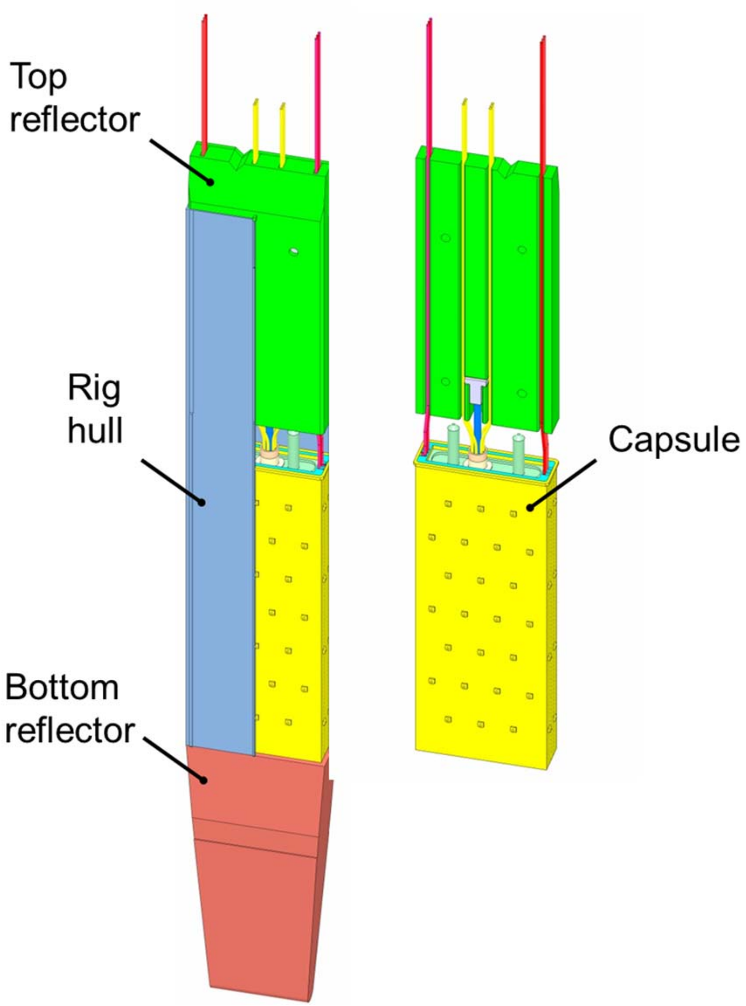
Irradiation rig with capsule



Cut-open irradiation rig with capsule

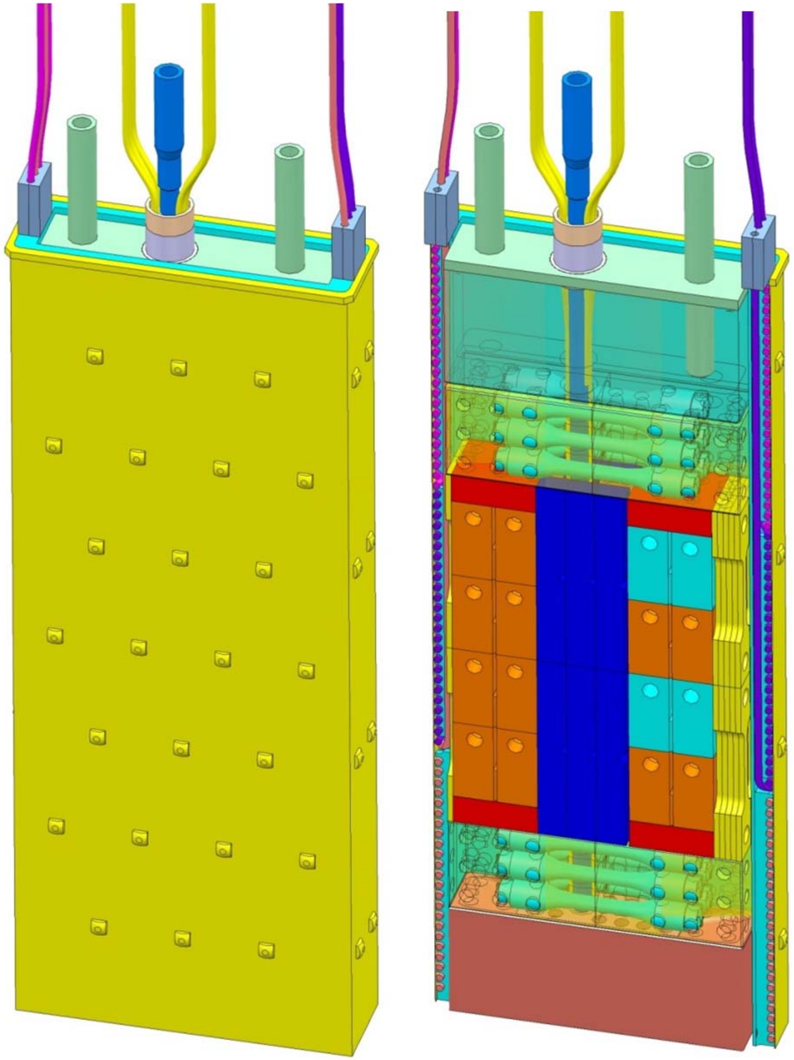
Functions & Requirements

- Contain the capsule
- Implement insulation gaps around the capsule
- Guide the helium coolant
- Provide neutron reflectors

Features:

- Contain the capsule in a thin rig hull
- Insulation gap between capsule and rig is defined by knops on the capsule
- Built from AISI 316L steel
- Upper reflector is built from two half-shells to insert the capsule wires

The irradiation capsule



Left: outside skin with knops. Right: specimens

Functions & Requirements

- Contain ~80 SSTT specimens
- Allow irradiation between 250-550°C
- Maintain „isothermal“ irradiation conditions
- Hermetical confinement of contents

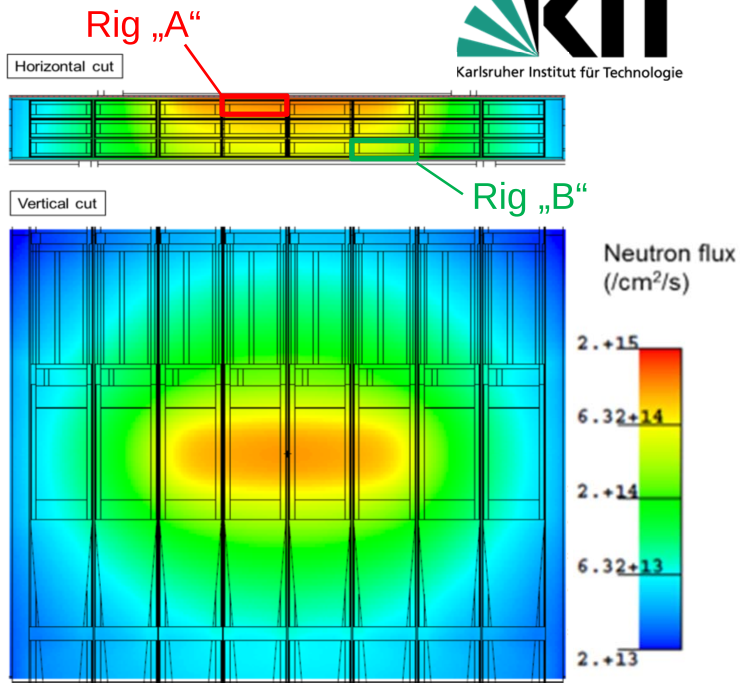
Features

- Box-type design
- Sample volume 81mm x 40mm x 9.3mm
- Made of RAFM (Eurofer97/F82H)
- Equipped with 3 THERMOCOAX heaters
- Instrumented with 6 Type-K TCs
- Specimens immersed in liquid NaK-78
- Knops on the surface to define insulation gap

Nuclear design analyses

- Nuclear analyses performed with McDeLicious-11 and FENDL-3 nucl. data library
- Detailed geometry model generated with McCAD

After 11 months:
Decay heat per rig (t=0, 1.6kg) : 48W
Activity per rig 3E+14Bq



Map of neutron flux

	Global max.	Rig „A“	Rig „B“	DEMO BZ
Neutron flux [/cm²/s]	2E15	9E14	4E14	6E14 ... 1E14
Nuclear heating [W/cm³]	40	25	11	10 ... 0.5
Struct. damage rate [dpa/fpy]	50	33	12	11 .. 0.6
He production [appm/dpa]		12.5	12.8	11 .. 2.3

[K. Kondo, U. Fischer, P. Pereslavtsev, KIT]

Thermal design analyses

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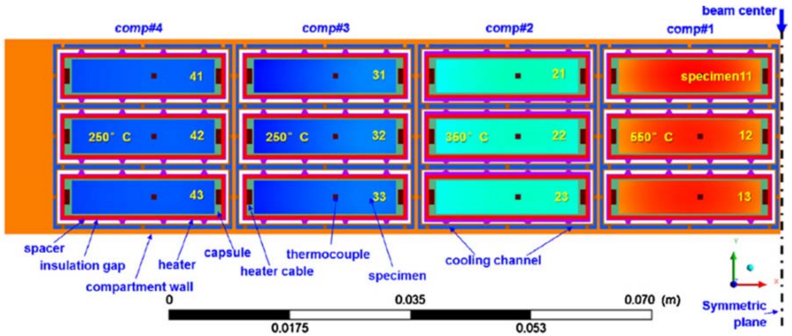
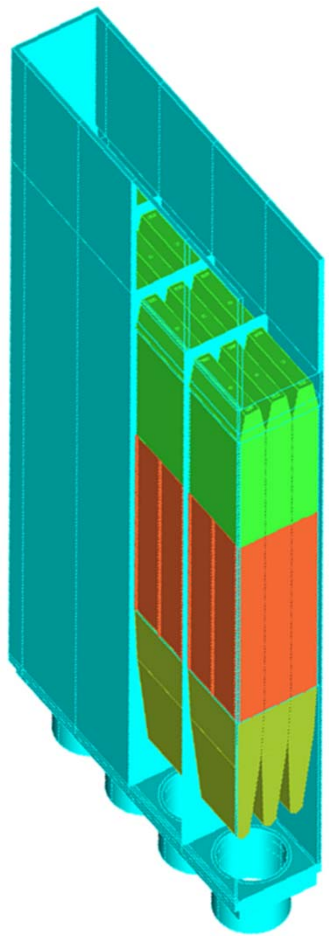
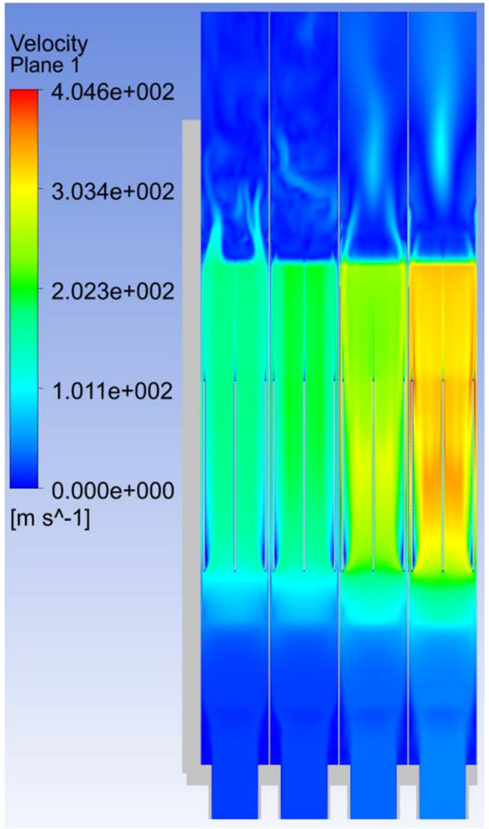
Simulation features: *[Y. Chen, KIT]*

- ½ HFTM container, approx. 10‘000‘000 cells
- For some simulations individual resolved specimens
- „EVEDA“ neutron beam profile
- CFX V 13.0, adapted turbulence models in each compartment, according to validation results
- Radiation and contact heat resistances are considered, natural convection on container





Geometry model for container with 12 rigs



Result for helium gas flow

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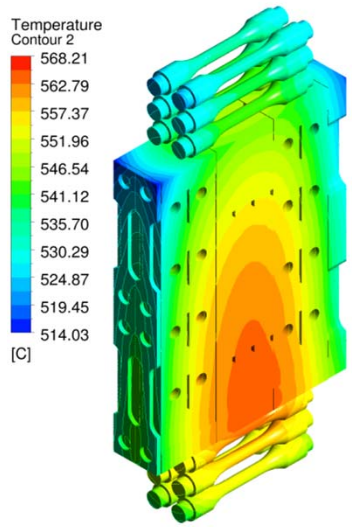
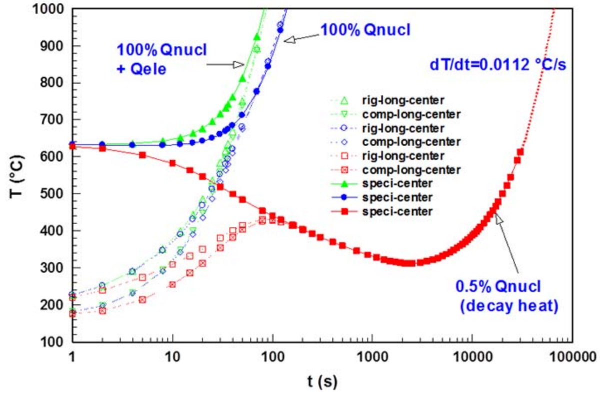
Thermal design analyses

Summarized outcomes:

- Temperature spread in specimen stacks < 3% achieved in >97% of capsule volume
- Influence of NaK on temperature field: without NaK spread increases ~10K
- Container temperature < 160°C
- Grace time for LOCA with decay heat: several hours
- Intervention time scale for control with beam on : ~10s



3D temperature map with resolved specimens



Transient behaviour

Irradiation campaign in the BR2 reactor

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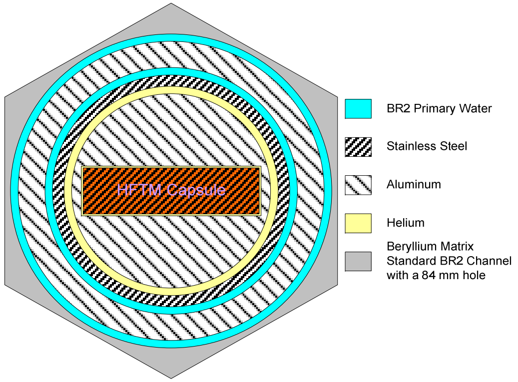
Objectives:

- Build 3 fully functional irradiation capsules, complete with NaK filling and specimens
- Irradiate capsules and specimens at comparable nuclear heating (up to 3W/g)
  - Heater control
  - Heater lifetime
- Practice specimen retrieval in hot cell conditions

3 Irradiation capsules



Irradiation rig for BR2
[P. Jacquet, SCK-CEN]

Specimen stack assambly

NaK filling in Glovebox

Irradiation campaign in the BR2 reactor

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Main outcomes:

- 3 capsules were built, but some damages had occurred (heaters, one caps. without NaK) during manufacturing
- Irradiation was done for 3 BR2 irradiation-periods:
  - Capsule #1 cycling 250-440°C
  - Capsule #2 static 390°C
  - Capsule #3 static 250°C (without NaK)
- Several heaters failed (mainly such with pre-damage)
- The cycling capsule weld seam ruptured after ~650 cycles
- The rise of the heater wire resistance saturated at about 10%
- The capsules were dismantled from the rig, NaK was purged and specimens retrieved.

➔ Manufacturing experience and irradiation results triggered a long list of necessary improvements for capsule design.

➔ Main points concern the heaters.

Manufacturing of the HFTM prototype

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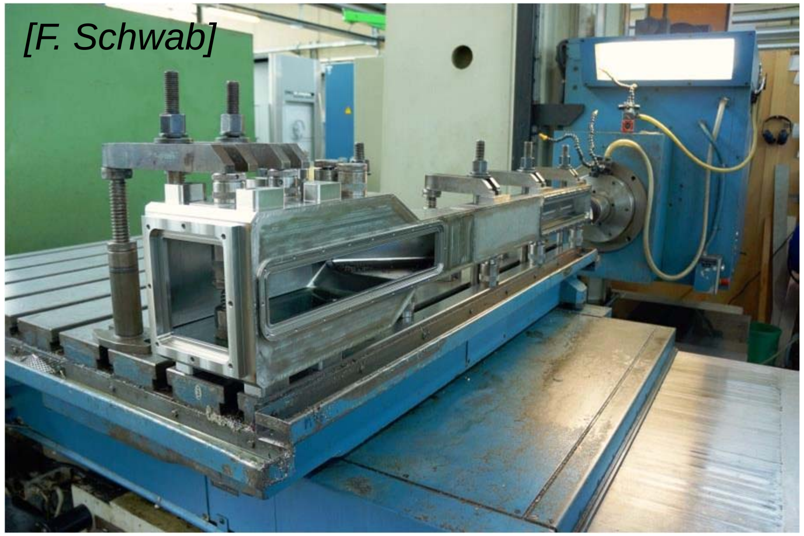
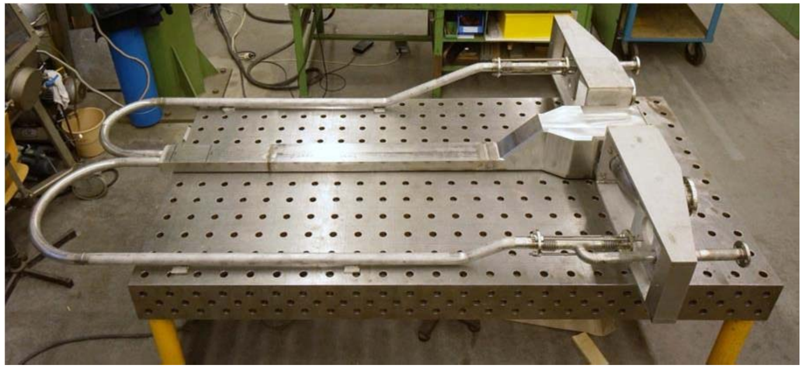
- The prismatic container with internal compartments was manufactured by wire-cut EDM
- The attachment adapter was machined from 2 large parts of 316L steel
- The final assembly was TIG welded



Machining of HFTM attachment adapter

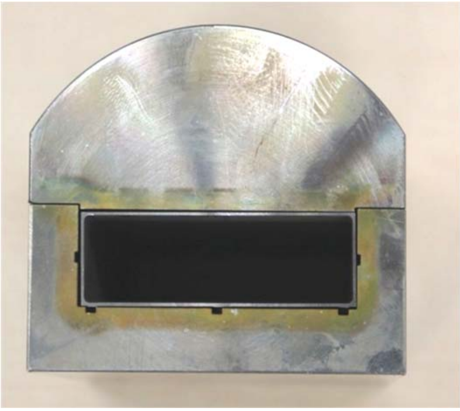
Container fabricated by wire-cut EDM



HFTM assembly after final welding

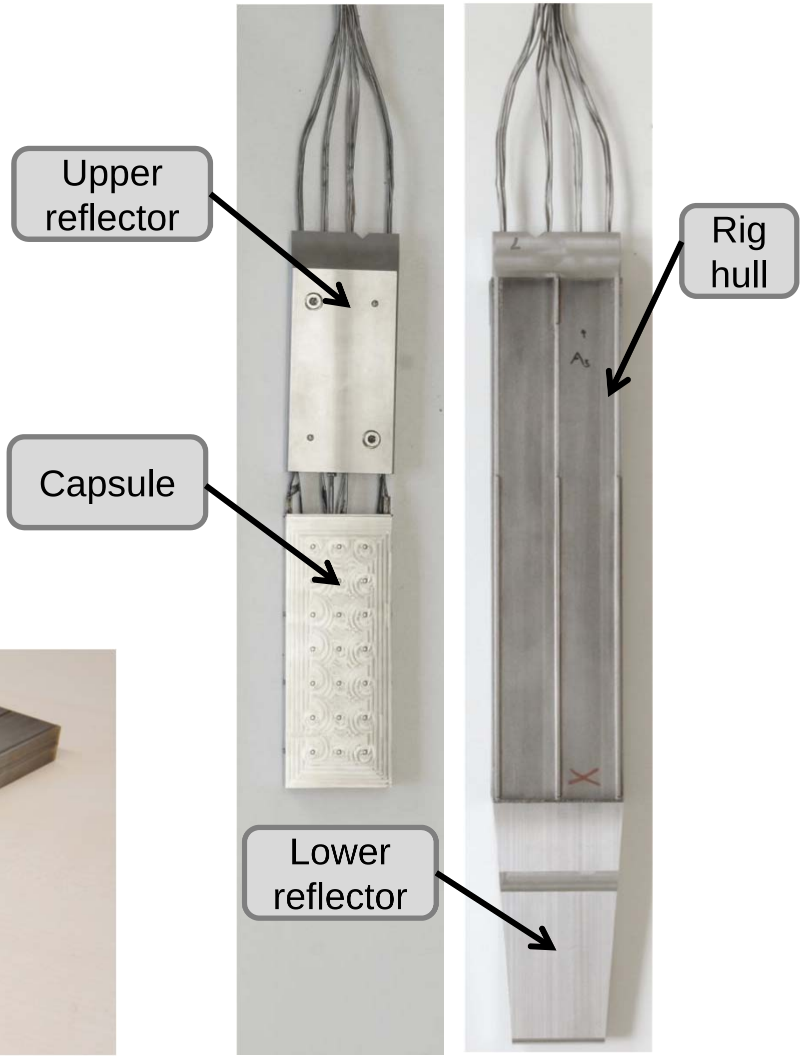
Manufacturing of rig prototypes

- The key component is the rig-hull, a prismatic body with 0.5mm wall thickness
- The lower neutron reflector is welded to the rig hull
- The upper neutron reflector encloses the capsule cabling and is inserted into the rig hull.



Rig hull manufacturing

Rig hull single part (ribs on surface)



Rig assembly

The HELOKA-LP helium loop facility

Main features:

[G. Schlindwein]

Gas-parameter	HELOKA-LP	HFTM
Massflow	12 – 120g/s	96g/s
Pressure	0.3 – 0.6MPa	0.3MPa
Temperature	20 – 250°C	50°C

- Driven by 350kW screw type compressor
- Siemens Simatic S7 control systems
- ~350 channels for data acquisition
- 36 x 1.5kW DC sources for heaters

➔Taken to service 12/2009

➔ Dedicated test facility for the HFTM

➔ Operation yields experiences for IFMIF He loops

HELOKA-LP Test environment

HELOKA-LP 350kW compressor

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The HFTM double compartment experiments

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Objectives:

- Demonstrate themal-hydraulic properties of the HFTM:
  - temperature range
  - control stability
  - temperature spread
- Investigate mechanical behaviour (strains, flow induced vibrations)

➔ 17 thermocouples per capsule measure the temperature distribution in the specimen stack

➔ The HFTM body is instrumented with strain gages, displacement- and temperature sensors

➔ Nuclear heating (in the capsules) is substituted by a variable slope heater cartridge

Installation of the HFTM-DC in HELOKA-LP

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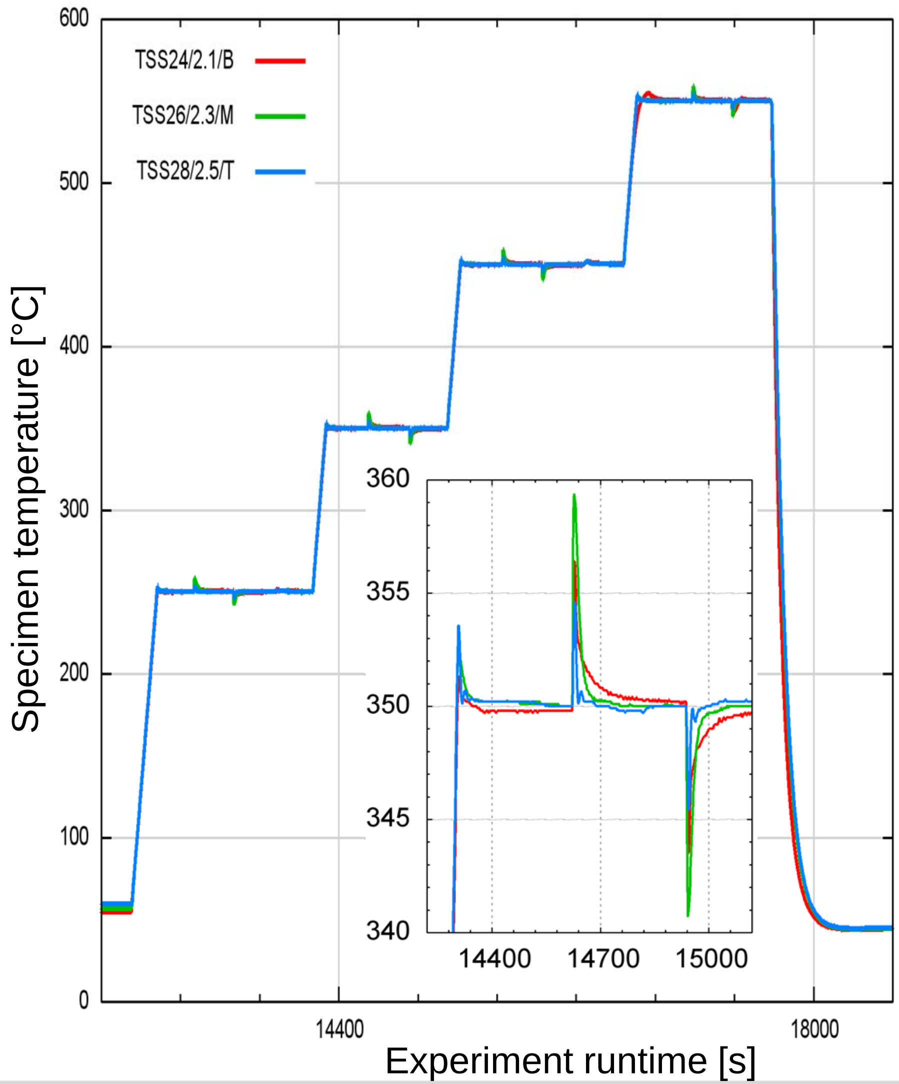
Thermal performance in HELOKA-LP

Transient behaviour:

- The full required temperature range **250-550°C** was demonstrated!
- The temperature control is swift and precise:
  - heat-up with 1K/s
  - cool down **550-200°C in 109s**
  - Setpoint-jump overshoot < 4K
  - Beam-on/off **overshoot < 10K**



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Thermal performance in HELOKA-LP

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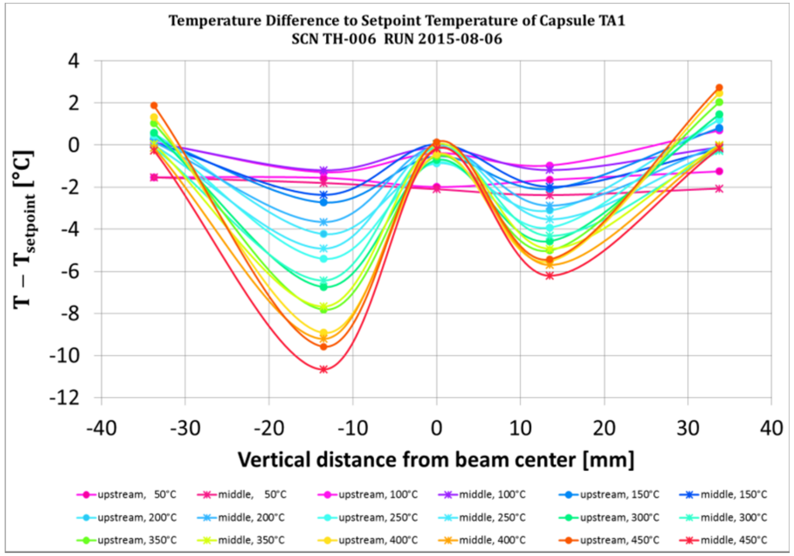
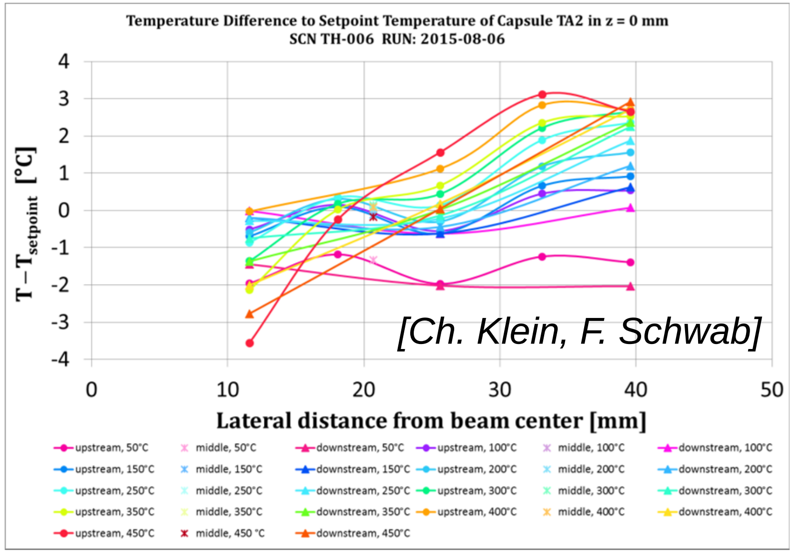
Temperature field in specimen stack:

- In the axial coordinate, the temperature spread is < 15K
- In the transversal coordinate, the temperature spread is < 8K
- The maximum observed deviation from the setpoint temperature is 1.5% (3% allowed)

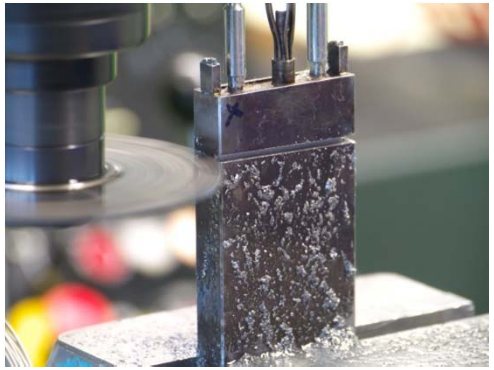




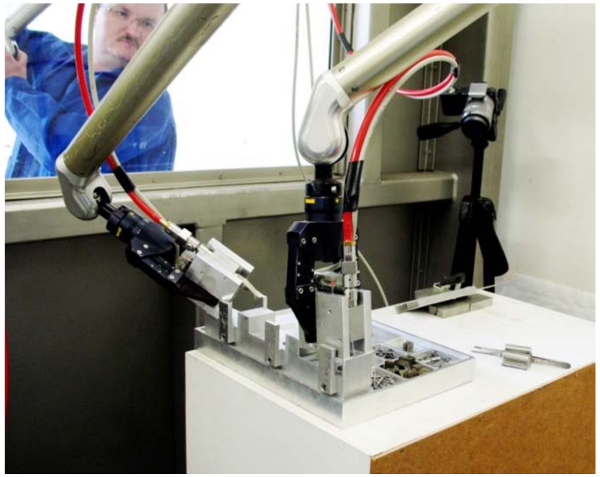
➔ All thermal requirements of the HFTM are met

Complementing studies : specimen handling

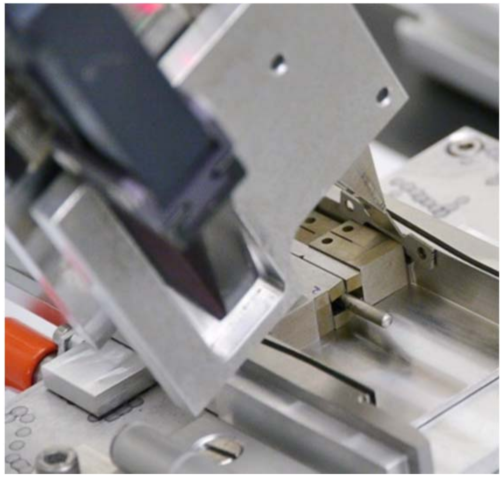
- The complete processes of specimen insertion & retrieval were demonstrated
- In case of re-irradiation, specimen insertion/retrieval must be performed in hot cells
- Specimen stack assembly was practiced with hot cell manipulators and adapted gripper tools
- Total time for specimen stack assembly is about 2 hours



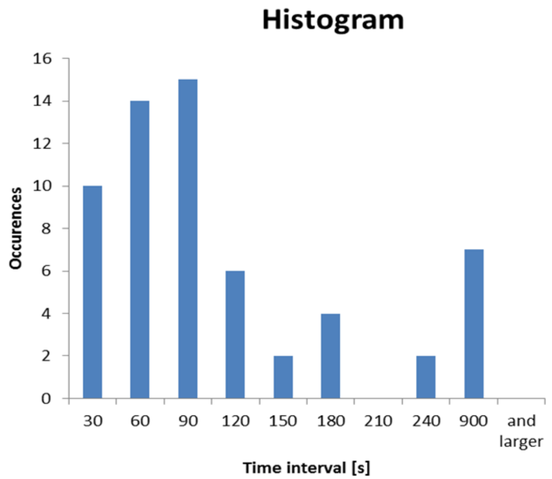
Cutting of capsule for specimen retrieval



Manupulator-based handling of SSTT specimens



Gripper handling a 0.76mm thick flat tensile specimen



Experience on required specimen handling times

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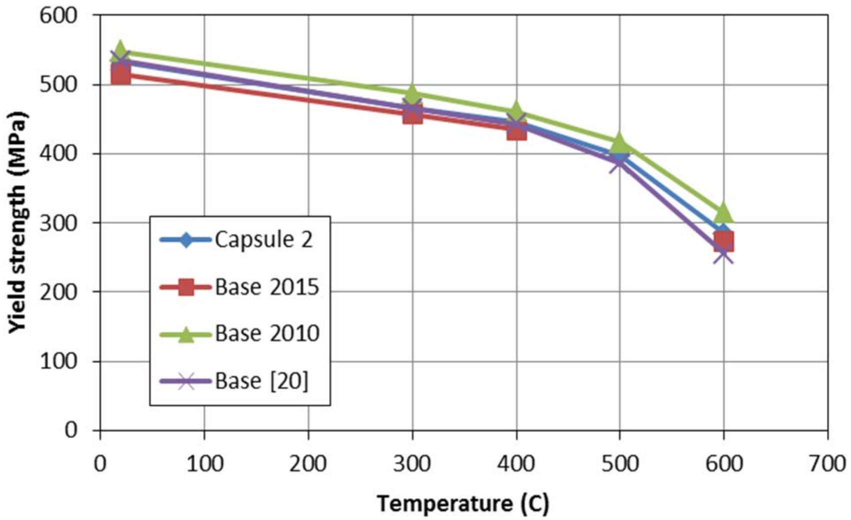
Complementing studies : NaK corrosion & wetting

- Two capsules with Eurofer specimens immersed in NaK-78 were operated 3 / 6 months at 470-500°C cycl.
- After retrieval, specimens were investigated optically, mechanically, and by SEM/Energy Dispersive X-Ray
- Cleaning by Ethanol and ultrasound

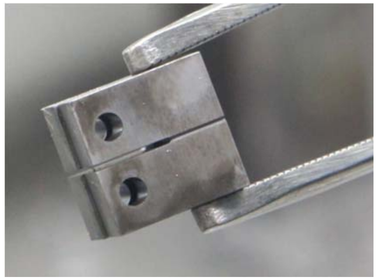
➔ Influenced layer was limited to max. 5µm

➔ No effect in mechanical properties

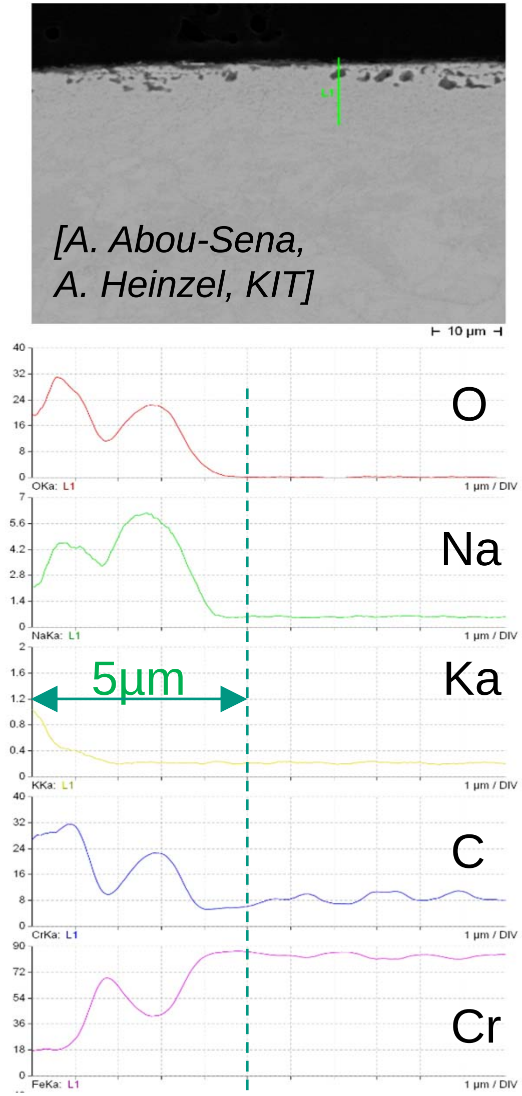


Comparison of base / NaK exposed materials

NaK film after retrieval



Cleaned specimen



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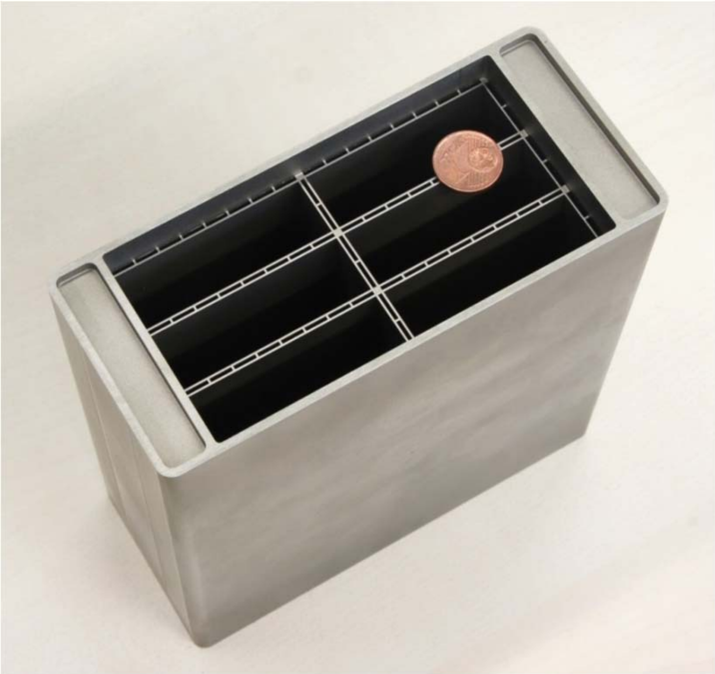
Conclusions

- The HFTM was developed according to the IFMIF EVEDA specifications and user requirements
- Analyses characterize all nuclear (material testing and operation relevant) properties and engineering properties
- Prototypes of all relevant components were fabricated
- Integrated function of all components was demonstrated by the tests of the HFTM prototype in the HELOKA-LP helium loop
- Complementing studies gave results on NaK handling, specimen handling/insertion/retrieval, NaK corrosion, thermal hydraulics
- The prototype fabrication and tests (especially irradiation in BR2) delivered many specific hints on improvements, such as capsule lifetime

Outlook on further development

The HFTM development continues in the frame of EUROFUSION WPENS (DONES):

- Improvements for capsule lifetime to be implemented and tested.
- The HFTM body will be adapted to the DONES environment
  - relieved space requirements
  - 50% of nuclear heating



Integrated channels HFTM body (fabrication test)

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IFMIF

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Thank you for your attention !