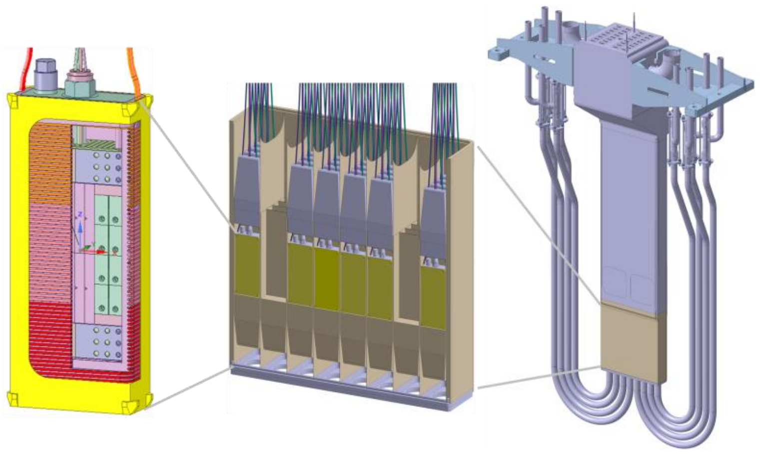
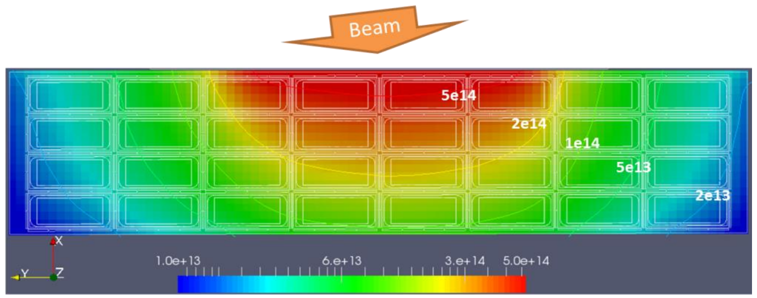
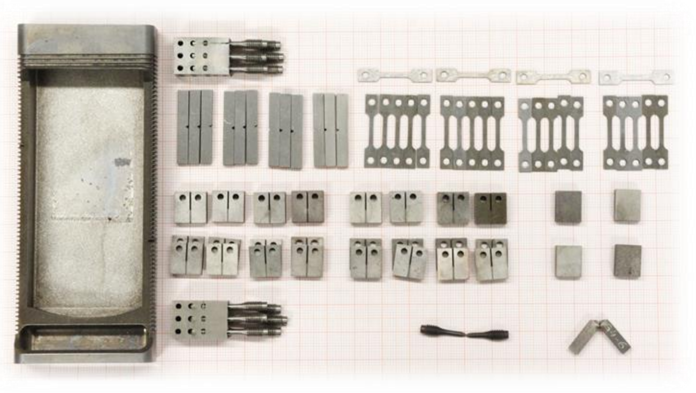
Irradiation capabilities at the IFMIF-DONES HFTM

Frederik Arbeiter, Yuefeng Qiu, and the IFMIF-DONES team





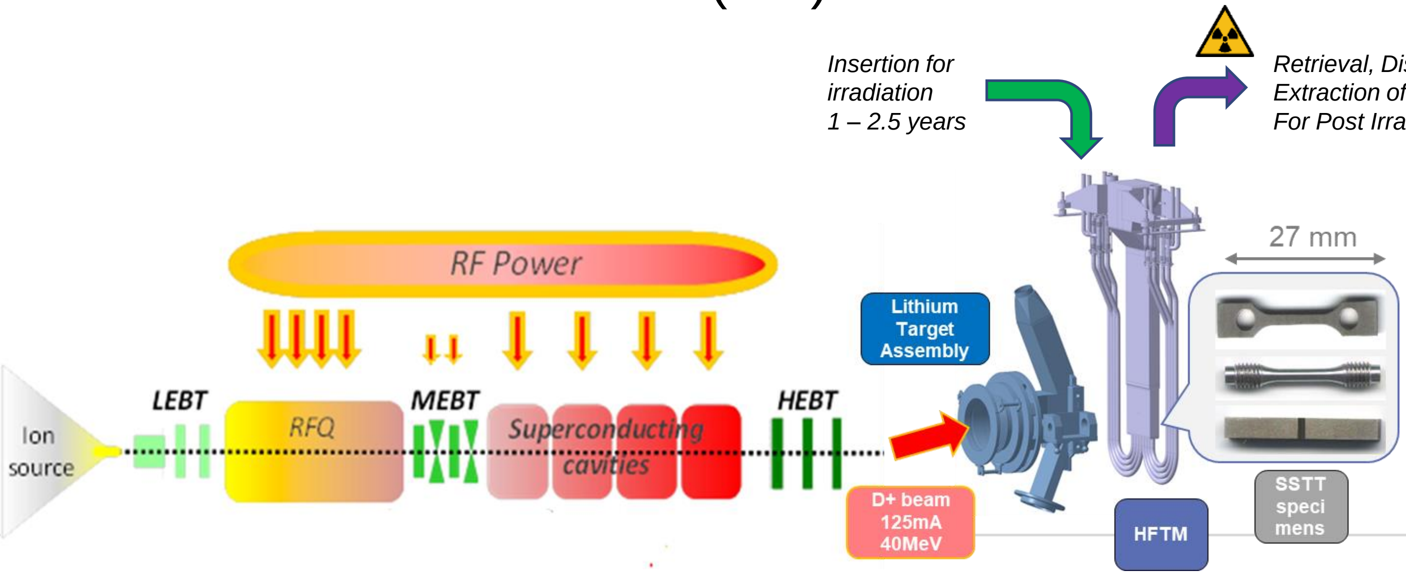


Mission of the DONES HFTM

HFTM = High **F**lux **T**est **M**odule

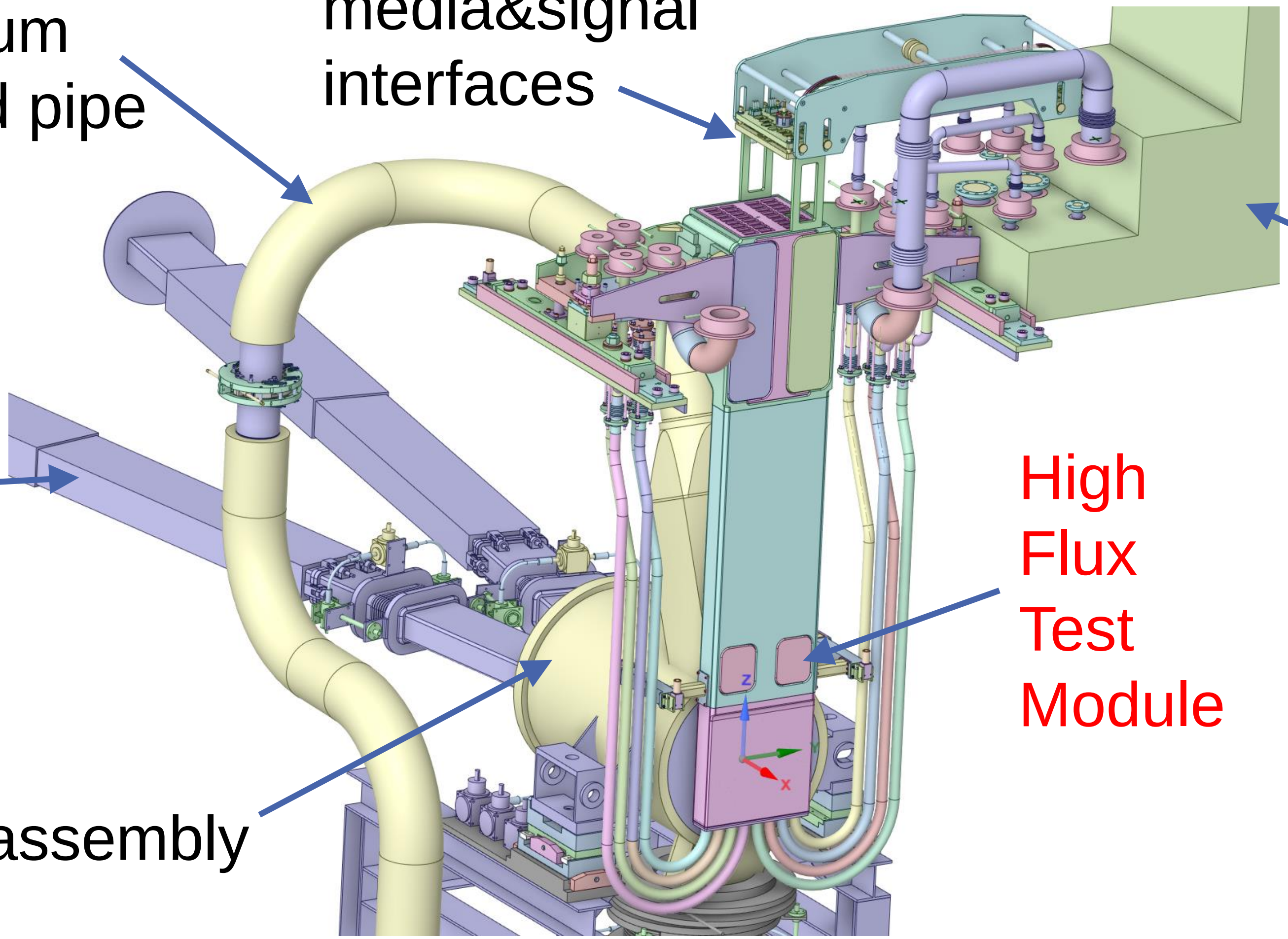
- Utilization of the **“high flux” region** directly behind the IFMIF-DONES neutron source
- Irradiation of (SSTT) specimens **for PIE**

The current development aims to facilitate the irradiation of SSTT specimens of **RAFM steels** (Eurofer, F82H, …) at conditions of the DEMO **First Wall** (FW)



Neutron flux
~5×10^{14} #/cm²/s

HFTM installed behind DONES Li-Target



Design driving requirements

Karlsruher Institut für Technologie

- Compatibility with high neutron flux / fluences
  ➔ required lifetime to 50 dpa, 2.5years

- Irradiation temperatures 250 – 550 °C

- Allowing well-controlled experiments & analyses
  ➔ sufficient monitoring (temperature, fluxes, fluences)
  ➔ low temperature spread (+/-3 %)
  ➔ temperature control independent of neutron source

- Maximization of irradiation payload
  ➔Shape compatibility with DONES neutron source & test cell
  ➔Minimization of parasitic volumes

Design driving parameters : consequences

- Volumetric heating q''' & imposed limits on temperature spread
  ➔ maximum "thickness" of specimen stack t_S

HFTM : limit of 3% at 2.4W/g limits specimen stack to ~14mm

- Ratio of electric heating vs. nuclear (gamma) heating
  ➔ possibility of temperature control
  ➔ heater lifetime limited by electric field

HFTM: to handle variable beam power and cool <200°C (defect "freezing") requires powerful heaters (max. 575W)

- Requested irradiation temperature level
  ➔ thickness of insulation (stagnant gas) gap

HFTM : gas gaps 0.2 – 0.8 mm

- Total released power, maximum allowed vessel temperature
  ➔ coolant flow rate (translates to coolant pressure head)

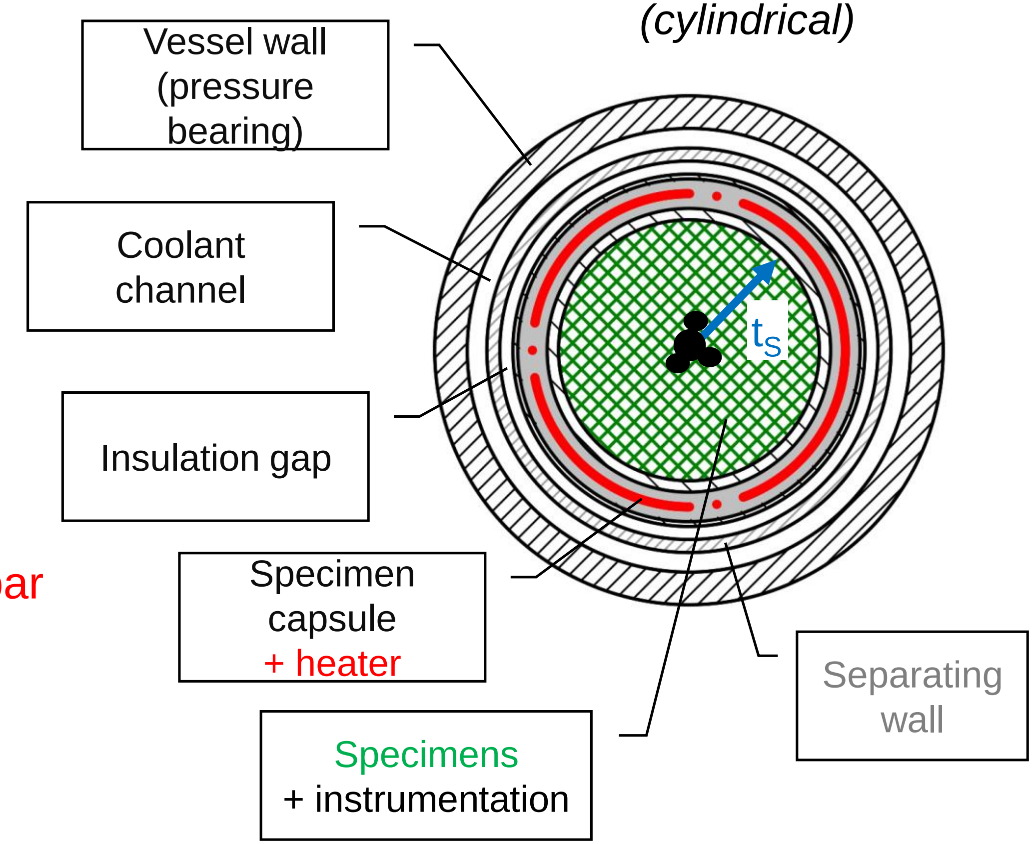
HFTM: 2.4W/g nuclear, T<160°C, requires He at 314m/s, Δp=0.9 bar

- Coolant pressure
  ➔ wall thickness of "body" / vessel

HFTM : 3.5 bara Helium, 2mm wall thickness

$$\Delta T \propto q''' \cdot \frac{t_S^2}{\lambda_S}$$

Generic temperature-controlled Irradiation setup (cylindrical)



HFTM characteristic features

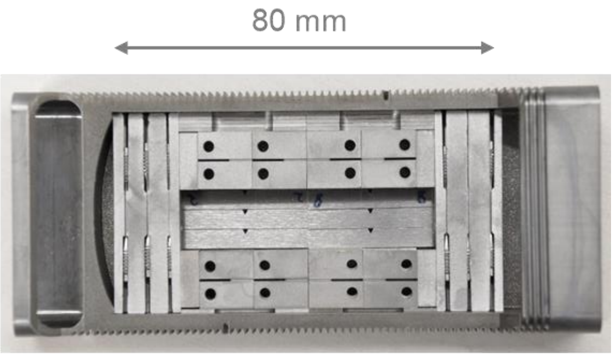
- Box-like structures (cuboid)
  ➔ increased specimen payload
  ➔ bending stresses

- Long slender shape
  ➔ move interfaces away from radiation footprint
  ➔ prone to deformations/deflections

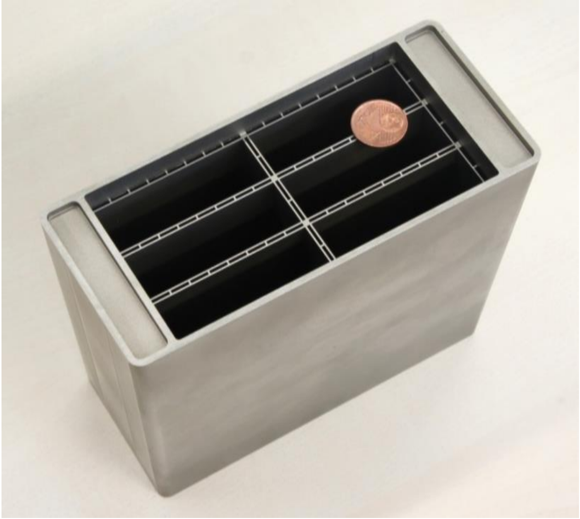
- Electric heating > 100% nuclear heating
  - allows full temperature control
  - consumes irradiation space, complicates manufacturing
  - may be a life-time limiting component

- Highly densified cross section
  ➔ Increased specimen payload
  ➔ challenging fabrication technology, assembly & QA

Balance between increasing raw specimen payload vs. effective irradiation capacity, which includes availability.



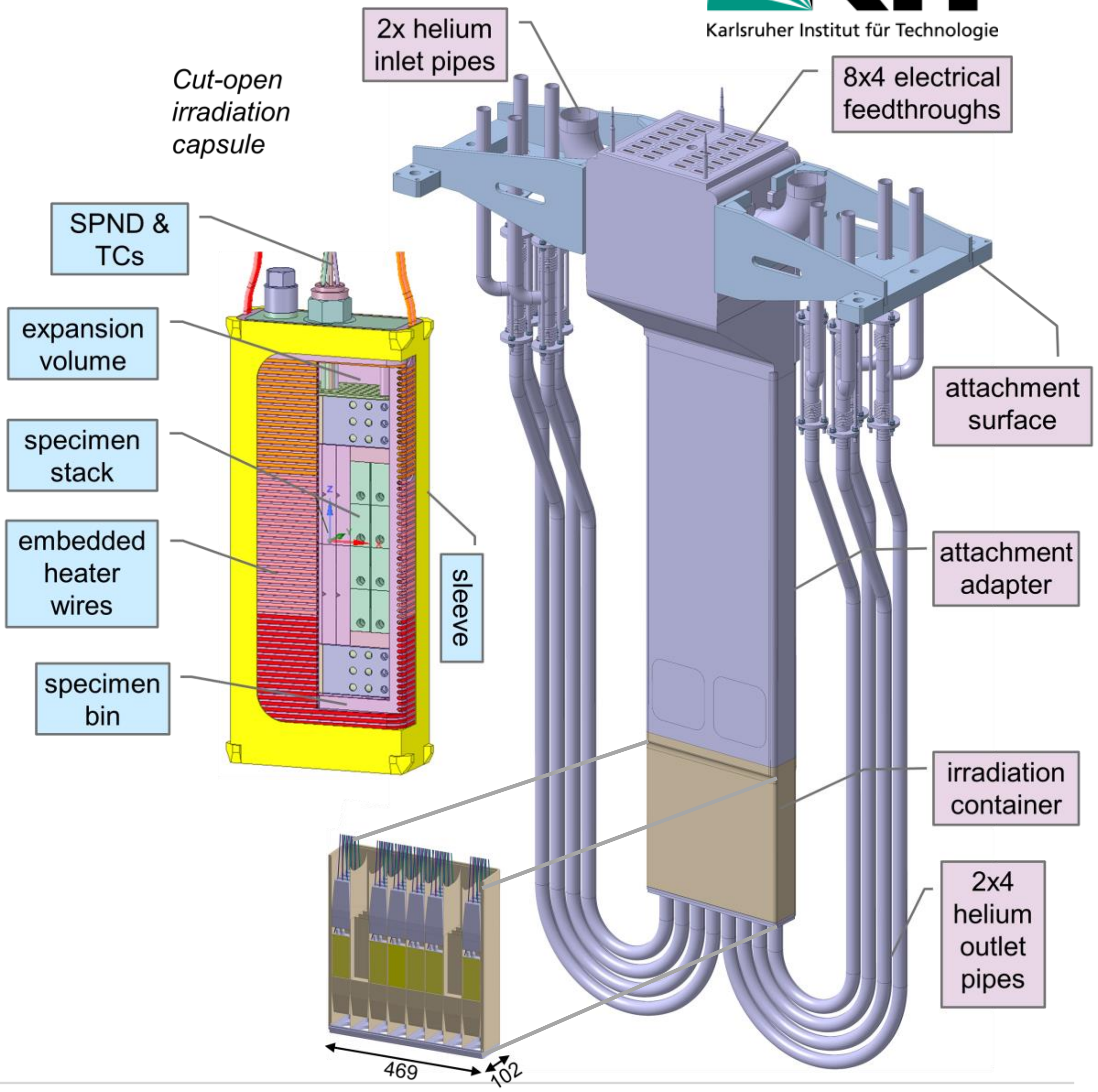
Cuboid specimen capsule: 80 SSTT specimens



HFTM body prototype with integrated minichannels

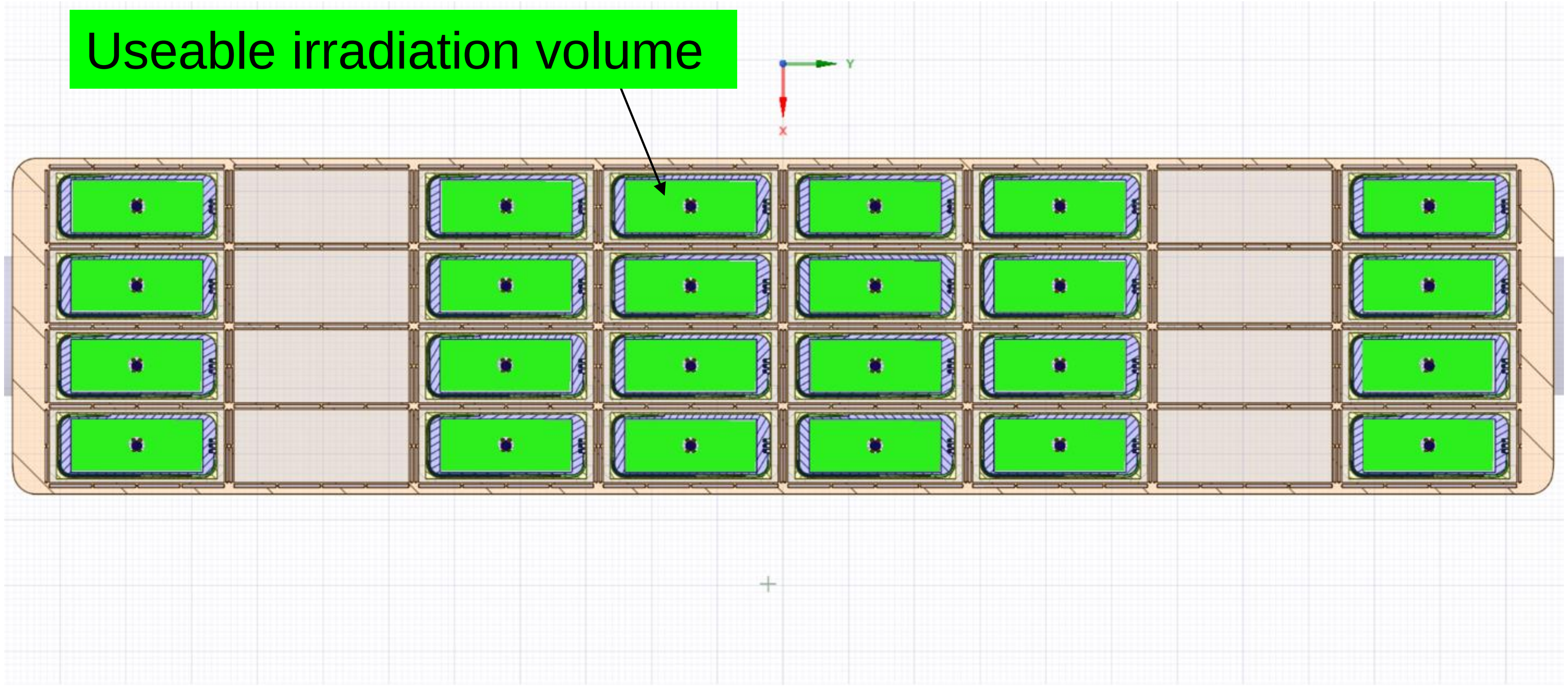
The HFTM overall design

- 2.6m high stainless steel body
- 16.9 kW complete nuclear heating
- Cooled by 180 g/s Helium at 3.5 bara, 50 °C
- Interfaces on the the top end
- Irradiation container on beam level
- Slots for 8x4 irradiation capsules
- Neutron reflectors (axial, lateral) are provided



Section through HFTM at beam level

Karlsruher Institut für Technologie

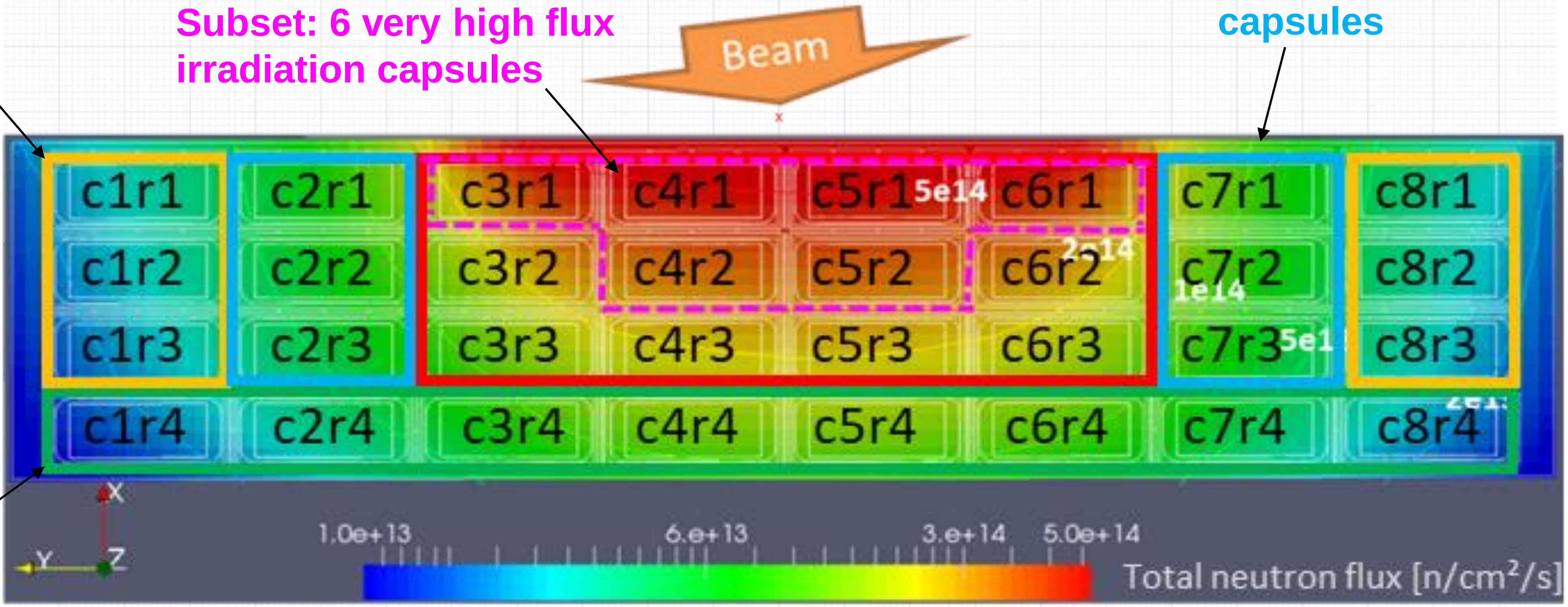


Section through HFTM at beam level

"companion" irradiation Capsules

12 *high-flux* irradiation capsules
Subset: 6 very high flux irradiation capsules

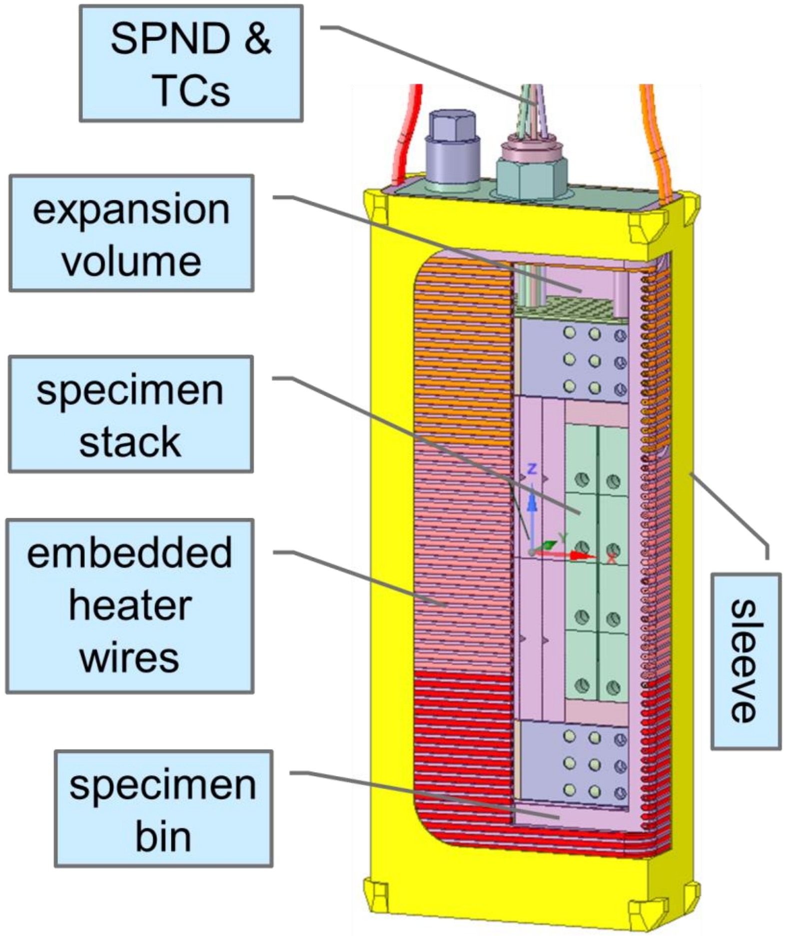
instrumentation capsules

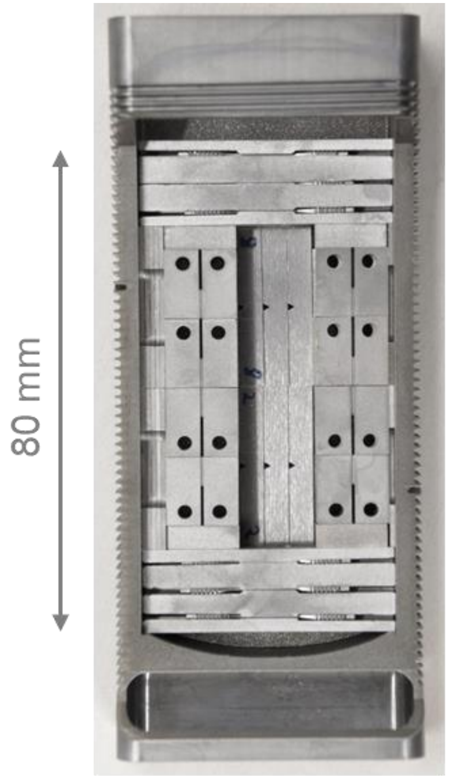


reflector capsules

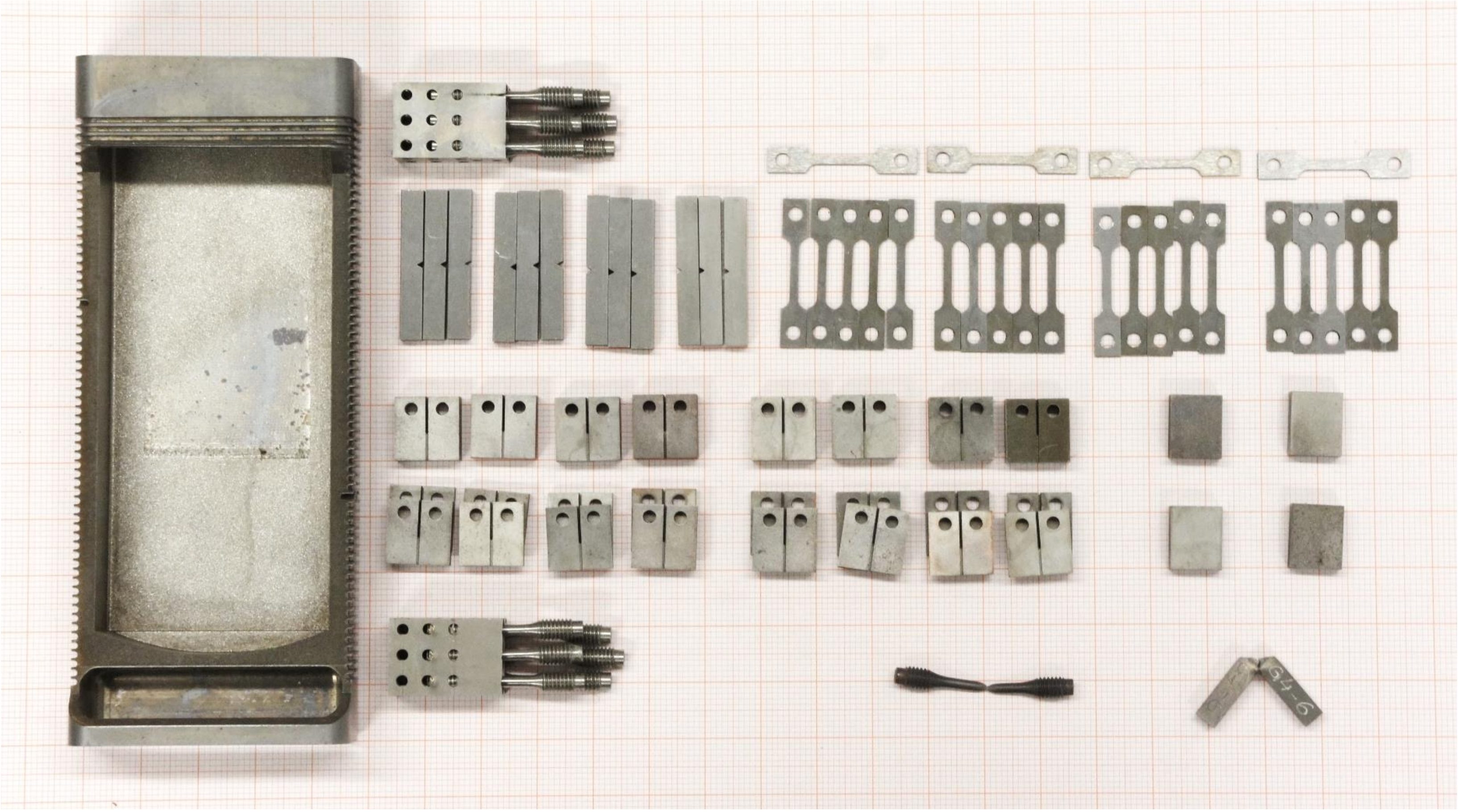
HFTM irradiation capsule

- Specimen payload 15x39x80 mm³ O(100) SSTT specimens per capsule
- Instrumentation by
  - 3x2 thermocouples
  - 1 central SPND
  - distributed activation samples
- 3 controlled electrical heater sections (up to 575W each)
- Body made by high temperature brazing from EDM-manufactrured Eurofer parts
- Filled with Sodium & evacuated

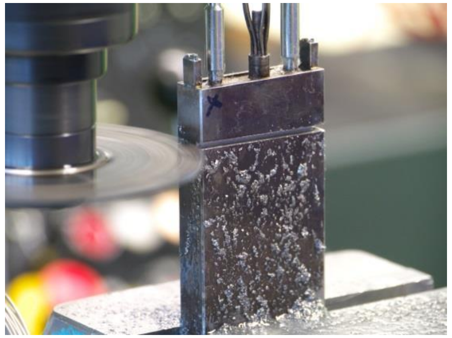
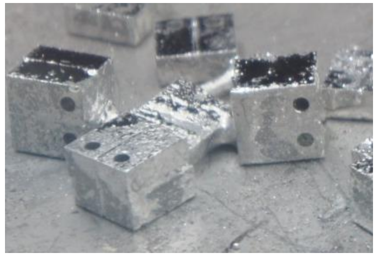
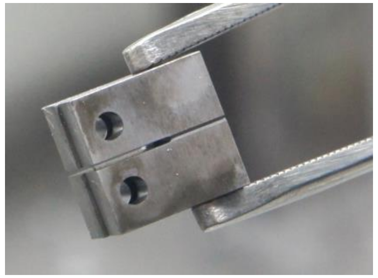




Example specimen payload



Specimen immersion in Sodium

- Specimen are immersed in Sodium to reduce the contact resistance (prevent overheated specimens)

➔ Sodium is filled at 400 °C after specimen loading

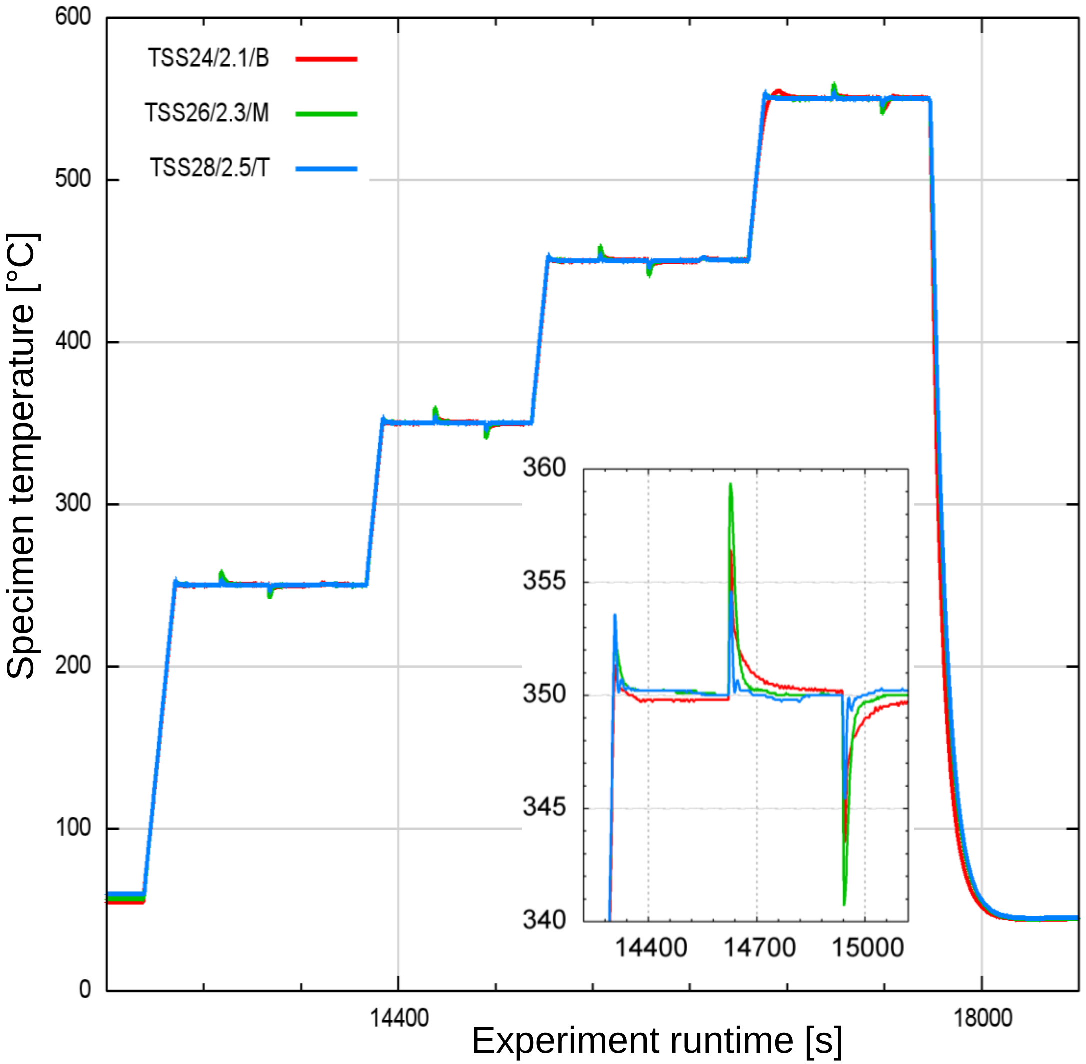
➔ Sodium needs to be physically (melting at 180-190 °C) and chemically (cleaning with alcohol) removed after irradiation

- Experience with NaK (Exposure 6 months at 500°C) showed influenced layer <5µm and no influence on tensile properties

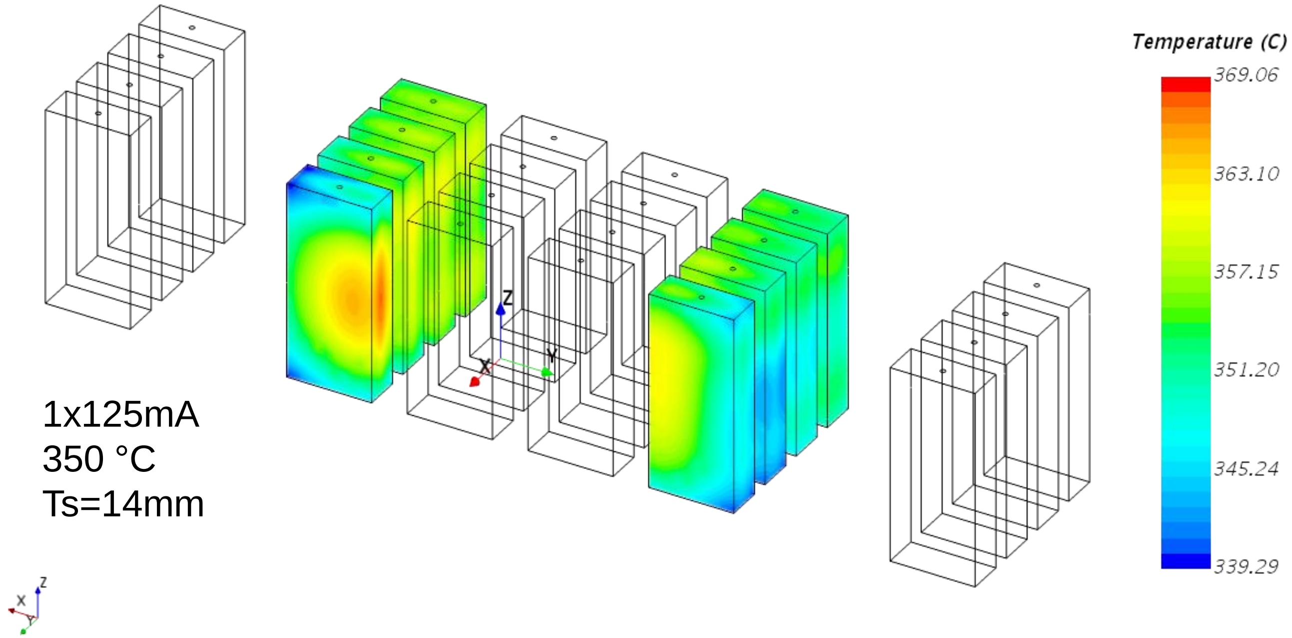
Experimental test in HELOKA-LP

Thermal behaviour:

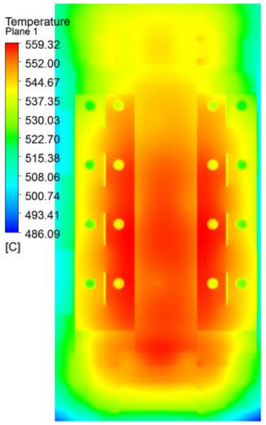
- The full required temperature range **250-550°C** was demonstrated!
- The temperature control is swift and precise:
  - heat-up with 1K/s
  - cool down **550-200°C in 109s**
  - Setpoint-jump overshoot < 4K
  - Beam-on/off **overshoot < 10K**
- A LOCA simulation with decay heat (substituted) showed several hours < 150°C



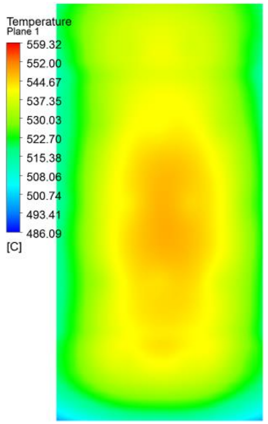
Temperature spread in specimen payload



1x125mA
350 °C
Ts=14mm



He-filling



NaK-filling

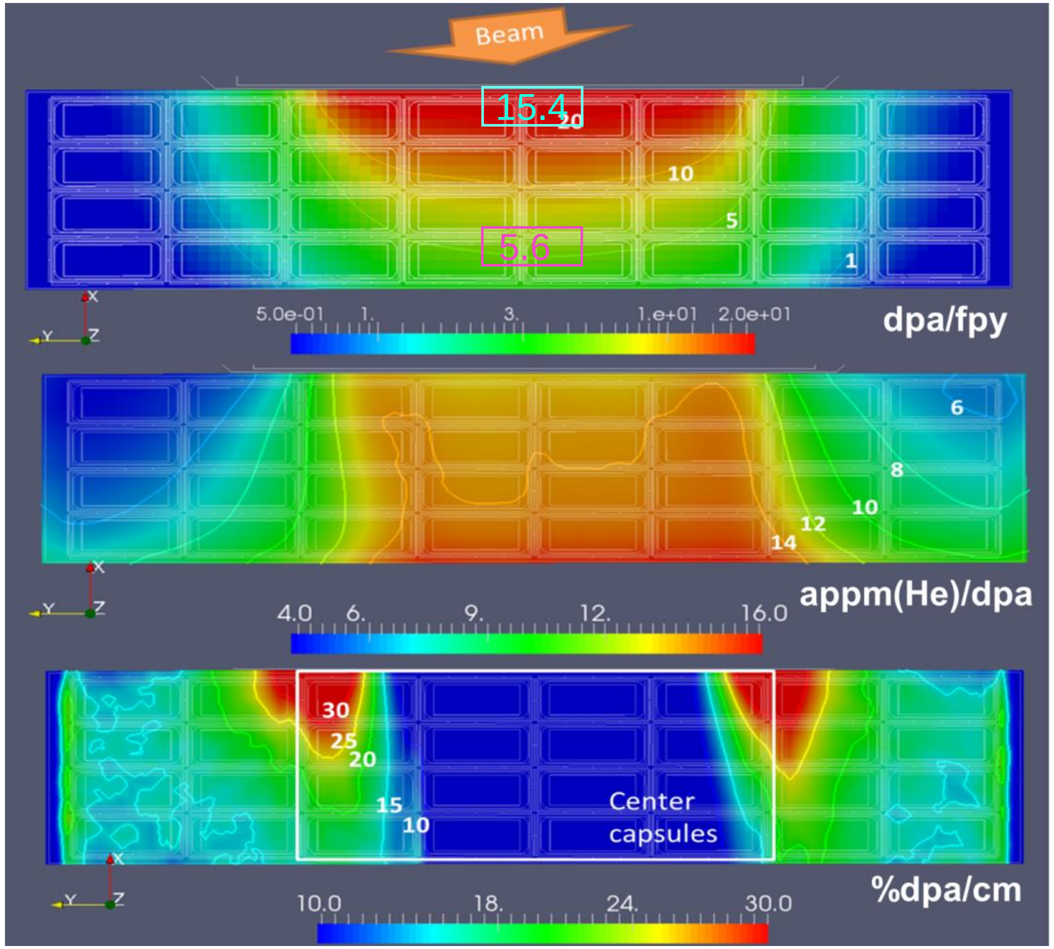
2x125mA
550 °C
Ts=9mm

Allowed spread
Acc. to specifications:

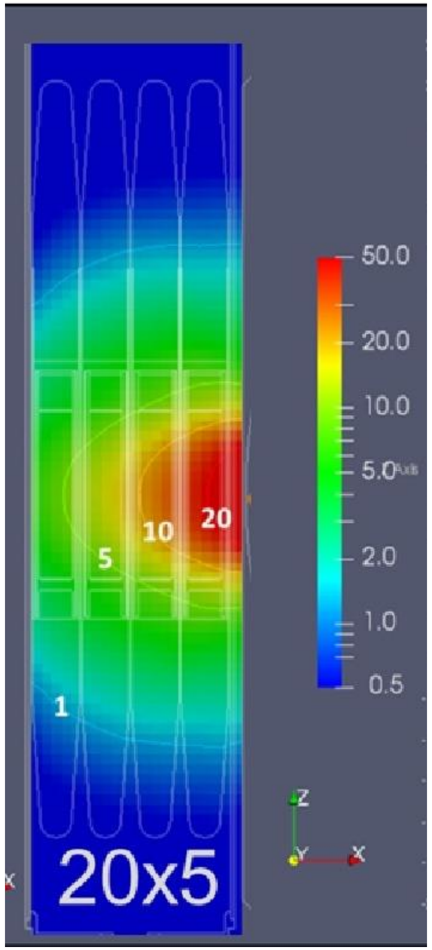
Tref	Tmax-Tmin
250 °C = 523 K	31.4 K
350 °C = 623 K	37.8 K
450 °C = 723 K	43.4 K
550 °C = 823 K	49.4 K

- Temperature spread assessed by CFD considers spatial distribution of heat source Spread is < +/-3% (Example: +/-15K around 627 K)
- The cold spots are in the corners ➔ don‘t affect gauge volumes
- Experiments (with surrogate nuclear heating) established axial temperature spread of Tmax-Tmin = 15K
- Effect of Specimen/gap heat transfer (given Tmax-Tmin)
  - „homogenous Eurofer“ : 24 K
  - „perfect NaK filling“ : 27 K
  - „specimens floating in He“ : 37 K

Neutron irradiation conditions



Nuclear responses in horizontal cut on beam (20x5cm²) level



Vertical cut

- Incident neutron flux: 5×10^{14} n/cm²/s
- 12 – 25 dpa/fpy are reached in a volume of 306 cm³ (~850 specimens)
- 13-15 appm(He)/dpa,
- 50-60 appm(H)/dpa

➔ Good match to DEMO conditions at First Wall

- Significant gradients at beam edges !

Lifetime limiting conditions in high flux irradiation

- Pressure bearing shell “container” made from RCC-MRx X2 CrNiMo 17-12-2 (N) stainless steel
  - Allowed by code up to 53 dpa (fission neutrons!)
  - Temperatures 50 – 160 °C ➔ low swelling regime

- Specimen capsules made from 9%Cr steels (Eurofer97)
  - No irradiated data in code ➔ no safety function
  - Temperatures 250 – 550 °C ➔ embrittlement .. creep

- Capsule heaters are mineral insulated metal sheated (MIMS) wires (NiCr resistive alloy, MgO insulation)
  - Dose rate near O(10^3 Gy/s) , significant RIC expected
  - Dose limit for RIED (10^{10} Gy @ 500°C for Al_2O_3) may limit lifetime

To be reflected by the DONES user commuunity

- Are the current requirements for the HFTM still appropriate to meet the needs for material testing for early DEMO ?

- Specimen payload assumption
- Temperature range (250 – 550 °C)
- Temperature tolerances (+/-3% of Kelvin)
- Limits of flux gradients (10% over gauge volume of each specimen)
- …

Conclusions

- The HFTM is designed for RAFM SSTT irradiation
  - In the high flux region of DONES
  - 250 – 550 °C
  - Nuclear responses matched to DEMO FW

- The design has to balance
  - Lifetime in irradiation
  - Usable specimen payload
  - Thermal requirements

- Input by users to properly set and weight the requirements are welcome!

HFTM system