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STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

The new material irradiation infrastructure at the BR2 reactor

BR 2
@ your service

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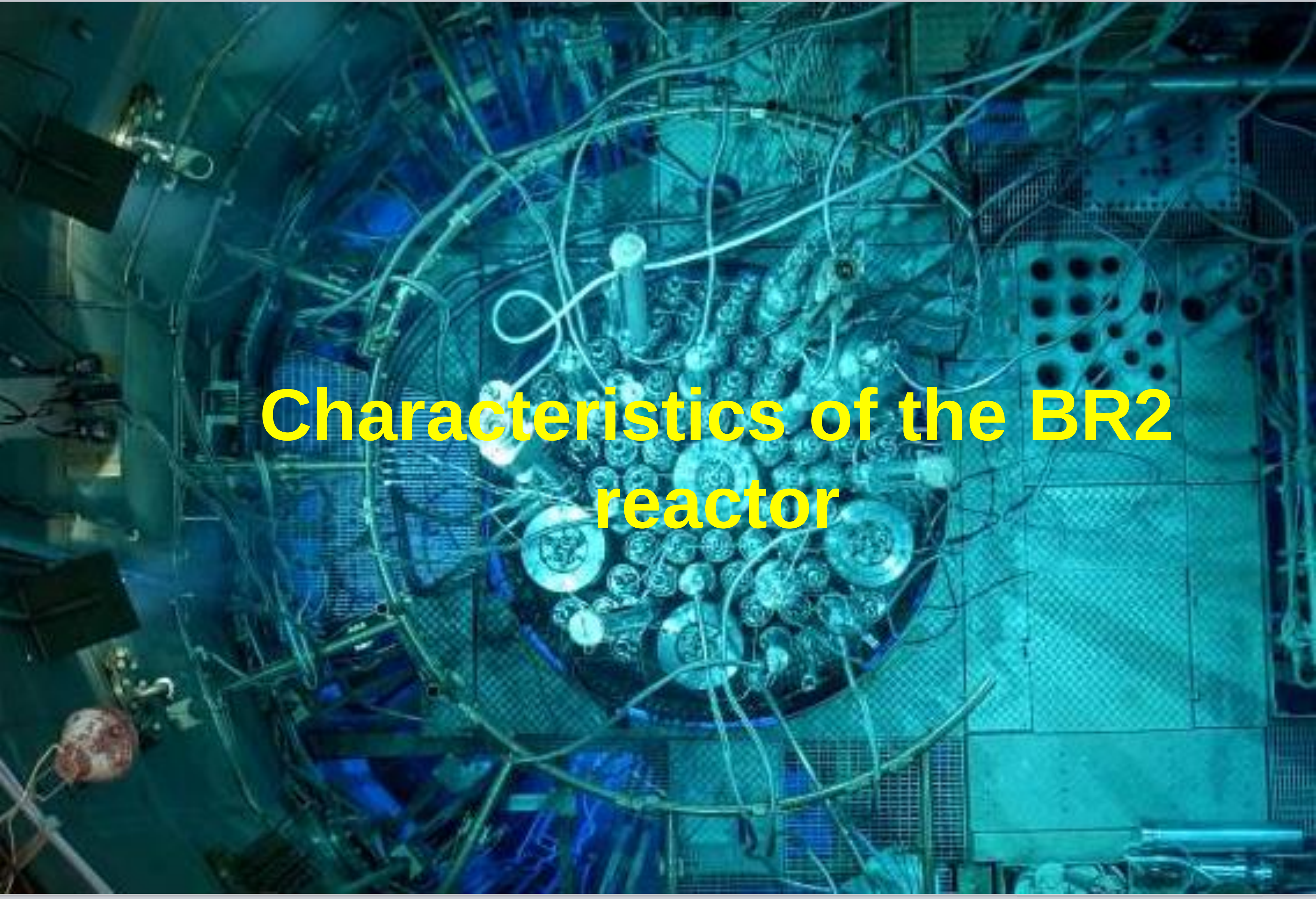
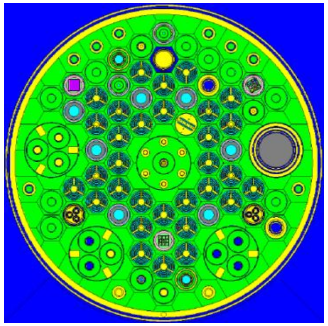
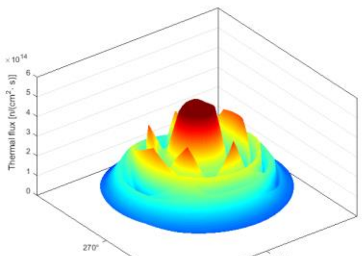


Characteristics of the BR2 reactor

Reactor core performance of BR2

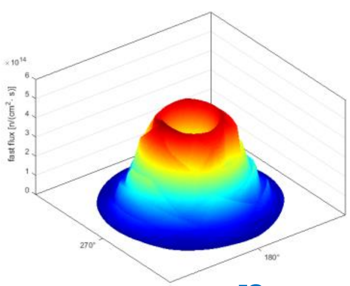


- Design goal: thermal neutron flux up to 10^{15} n/cm^{2}s
  - Achievement by
    - Compact core arrangement with central flux trap
    - Material choice: Be moderator and metallic uranium fuel
    - High overall core power (upgraded from 50 to 100MW in 1968)
      - 25MW additional cooling capacity for experiments



n_{th}

- Achievable flux levels (at mid plane in vessel)
  - Thermal flux: 7 10^{13} n/cm^{2}s to 10^{15} n/cm^{2}s
  - Fast flux (E>0.1MeV): 1 10^{13} n/cm^{2}s to 6 10^{14} n/cm^{2}s

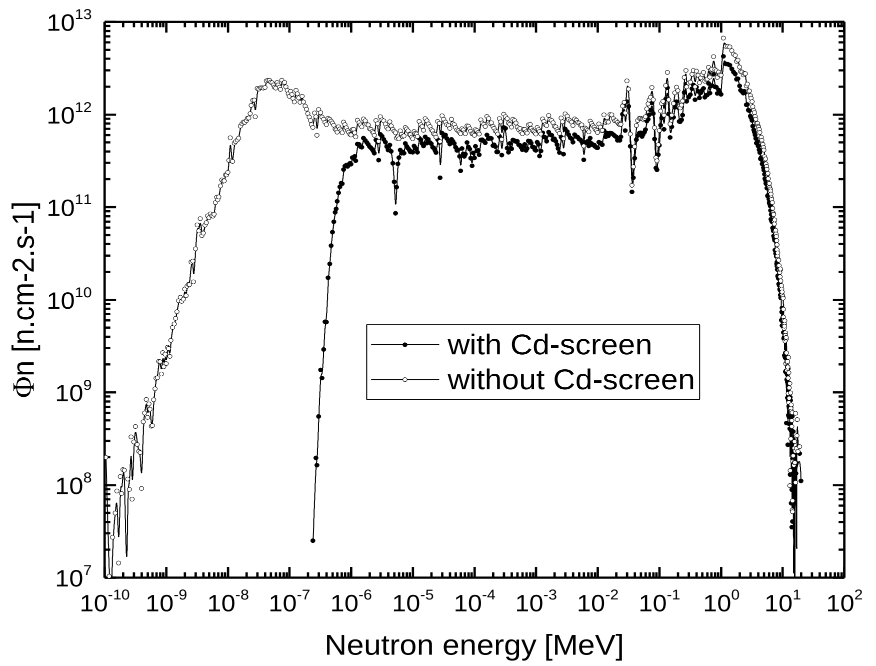


n_f

- Allowable heat flux in primary coolant
  - 470W/cm^2 for the driver fuel plates
    - Demineralised water
    - Pressure to 1.2MPa, temperature 35-50°C
    - 10m/s flow velocity on fuel plate
  - Up to 600W/cm^2 can be allowed in experiments

Spectral tailoring in BR2 experiments

- Objective
  - Simulation of fast reactor conditions
  - Separation between transmutation and lattice damage
- Method
  - Selection of irradiation position in reflector or fuel element
  - Addition of absorbing materials



Reactor core geometry

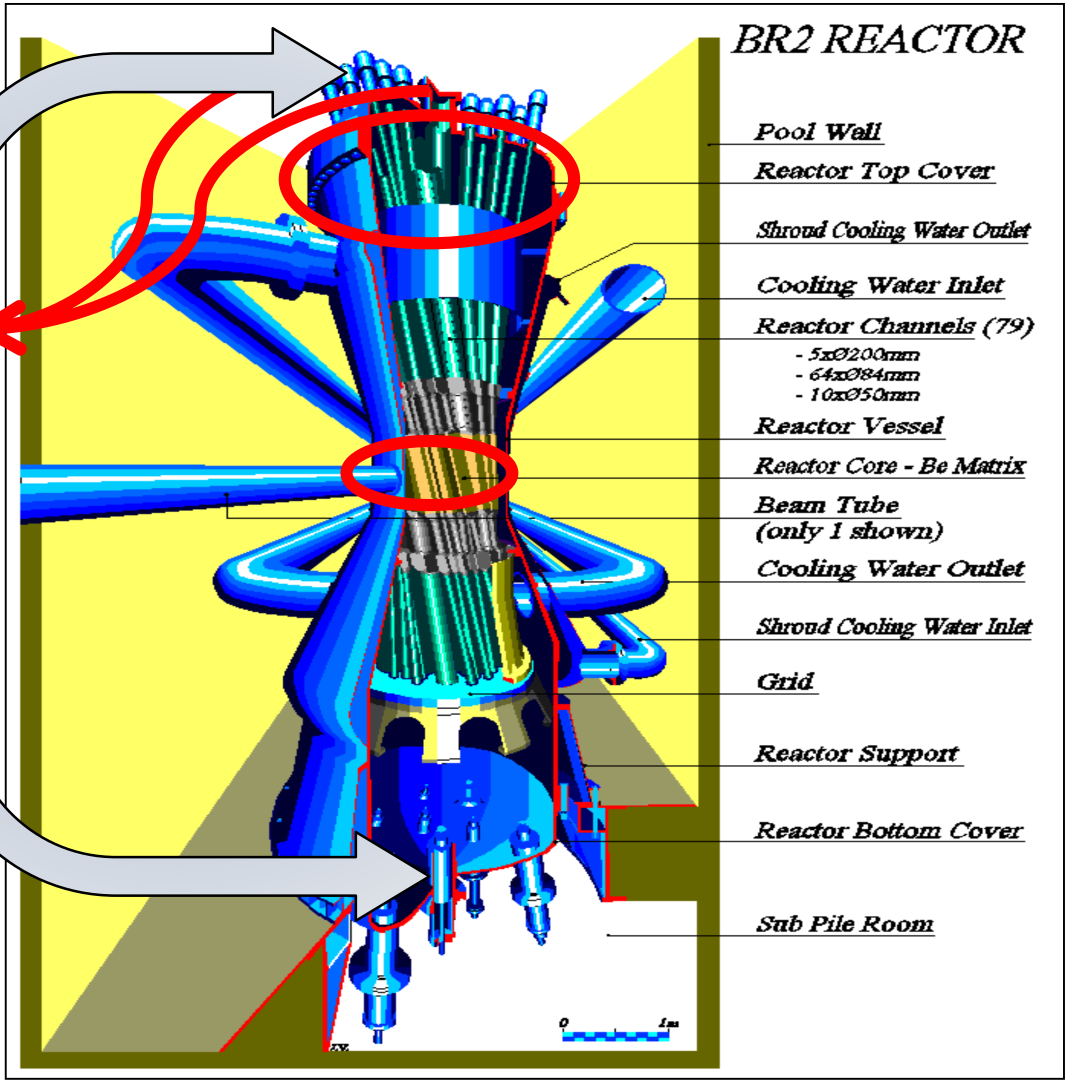
Diverging reactor channels for compact core and good access: core 1m, cover 2m ∅

Angle of channels from 0 to 27°

Reactor channels accessible from top (all) and bottom (17)

Irradiation inside rigs in reactor channel or in axis of fuel element

Loading elements hang on top cover



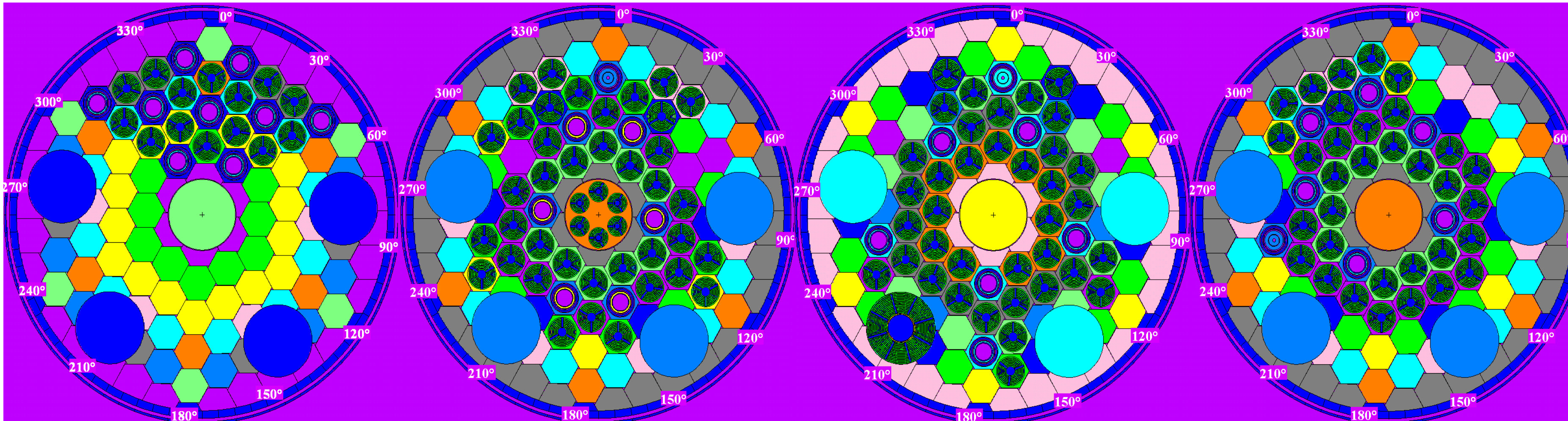
Overview of typical irradiation positions

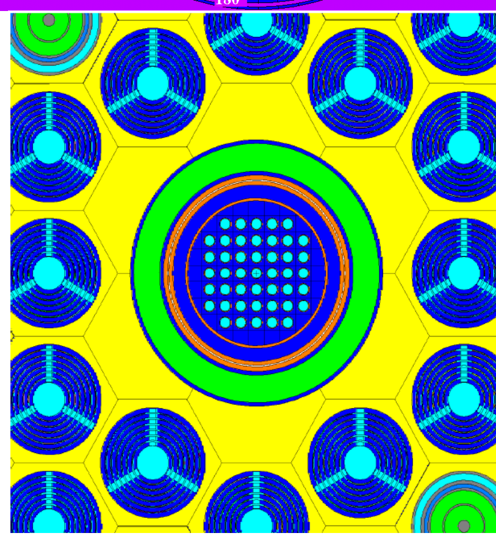
Channel type	thermal flux range ($10^{14} n/cm^2 s$)	fast flux range ($10^{14} n/cm^2 s$) (E>1MeV)	Gamma heating (W/g Al)	diameter (mm)	typical number available
F1	1 to 3.5	0.5 to 2.8	1.7 to 8.8	25.4	30
F2	up to 2.5	up to 2.5	up to 6.8	32	2*
S	1 to 3.5	0.1 to 0.7	0.9 to 2.3	84	24**
Central large channel H1	up to 10	up to 1.8	3	200	1***
Peripheral large channel Hi	3	1.3	0.1	200	4****
Peripheral small channel P	0.7 to 1.5	0.05 to 0.1	0.4 to 1	50	9

Flexible reactor configuration

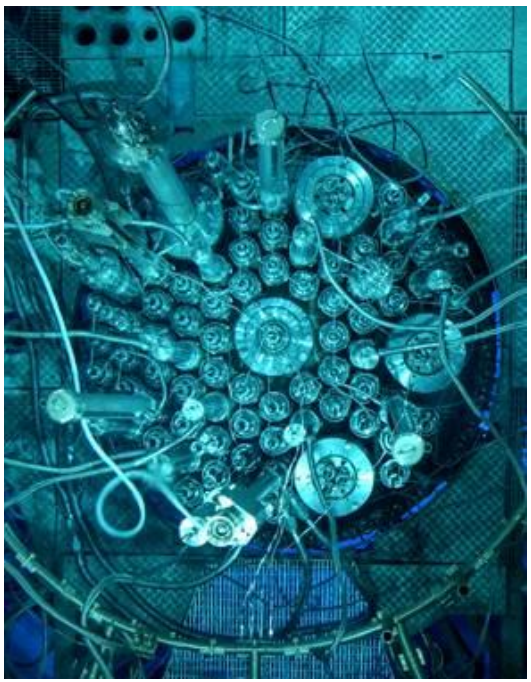
- Combination of multiple experiments in core load
  - Position of fuel, control rods and experiments are optimised
  - Choice of type of fuel elements
  - Adapted reactor power and cycle length
- Reactor load is optimised for each operating cycle
  - 3D MCNP model with burn-up evolution of entire core
  - Detailed model of experiment if required
  - Verification by measurement before start
- BR2 reactor management is ISO 9001 certified (including irradiations)

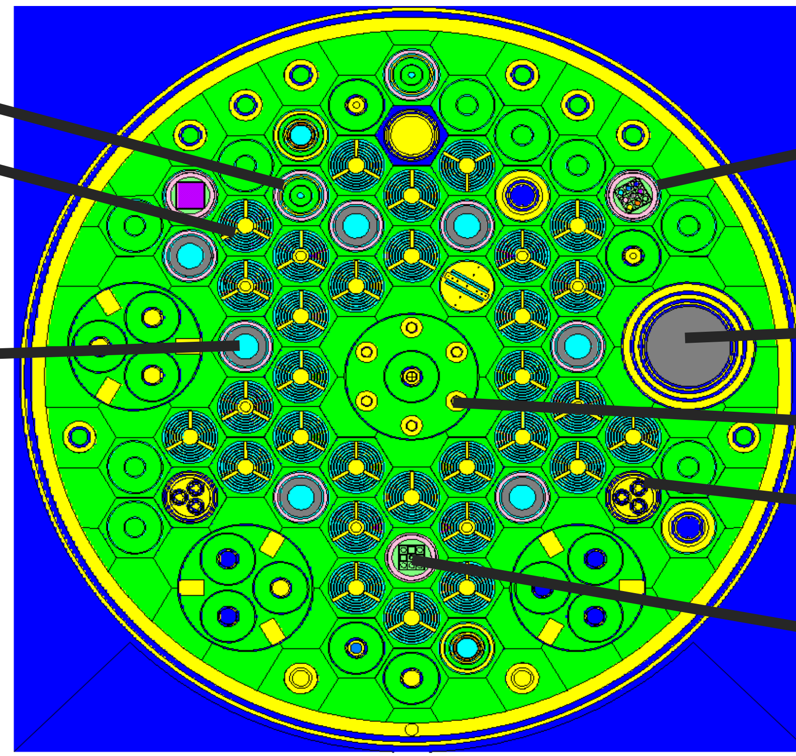
Typical configuration variants in BR2



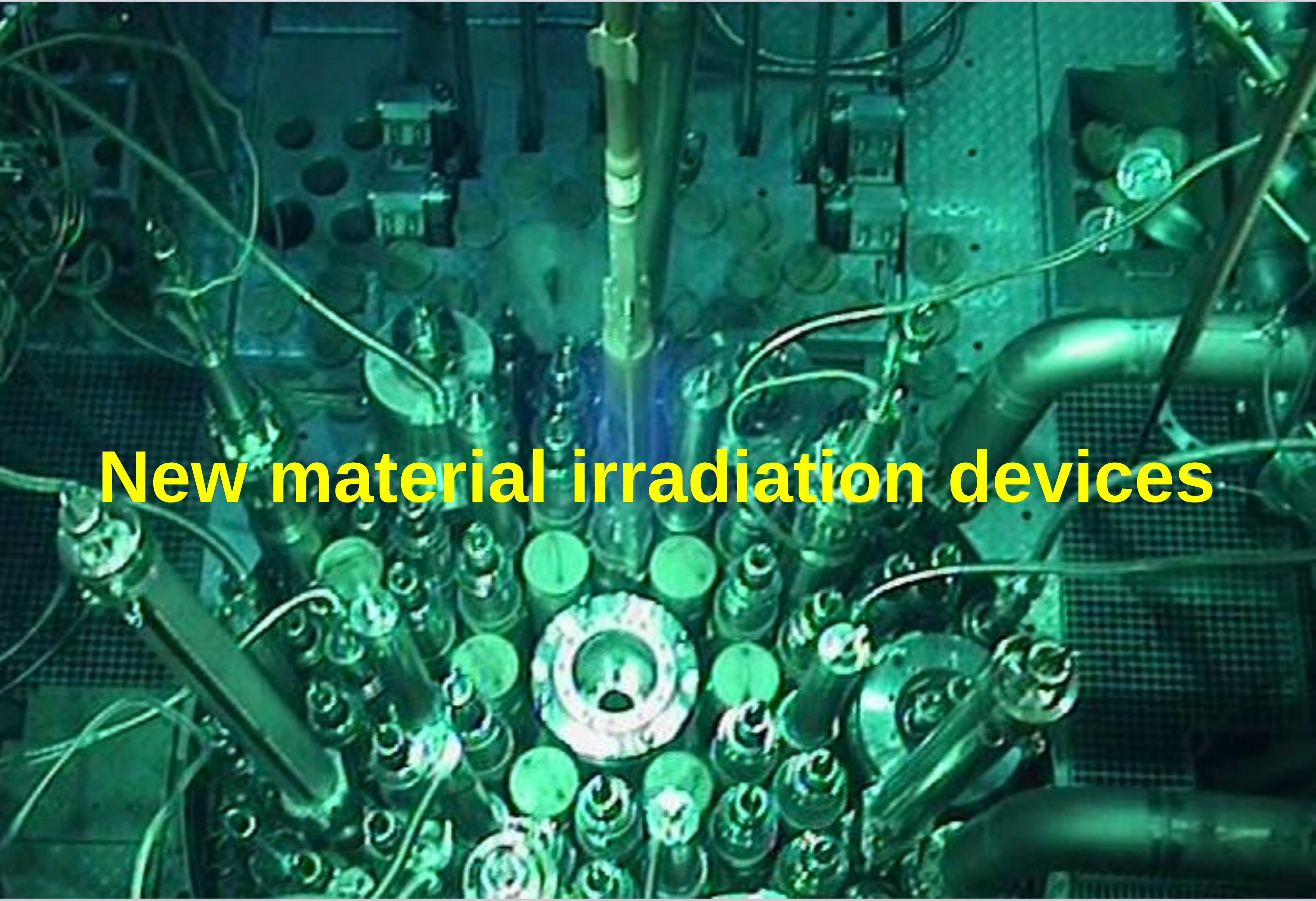


BR2 = Multipurpose Reactor





Mid-plane cross section of a typical BR2 core



New material irradiation devices

Material irradiation for selection and qualification

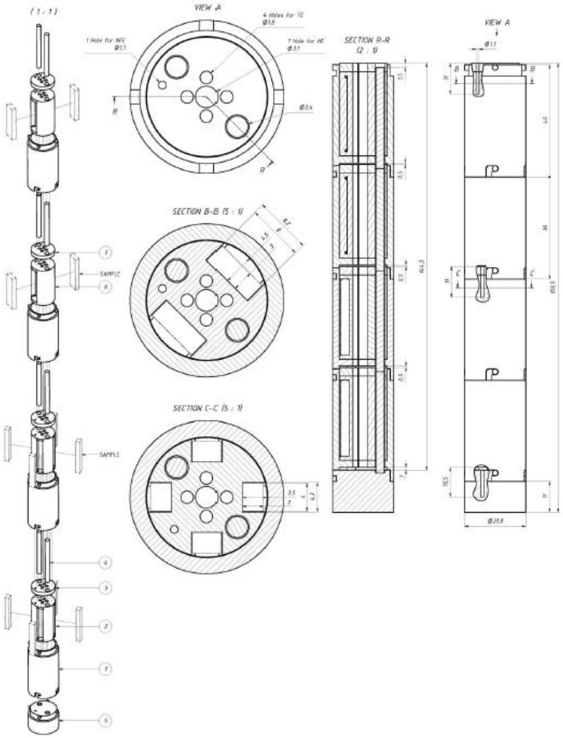
- New applications of nuclear energy
  - Issue: application target is beyond current database
    - Higher temperatures
    - Higher (fast neutron) fluence
    - Different environments
  - Materials: wide variation for screening
    - Stainless & high chromium steels: GEN 3&4
    - Ceramics & cermets: ATF claddings & fusion
    - Copper, tungsten, steel: fusion
  - Solutions
    - Provide rigs with high flexibility in irradiation conditions
    - Select high fast flux positions: ≥0.5 dpa / cycle
    - Provide cost effective solutions for irradiation of many samples

HTHF – High Temperature High Flux

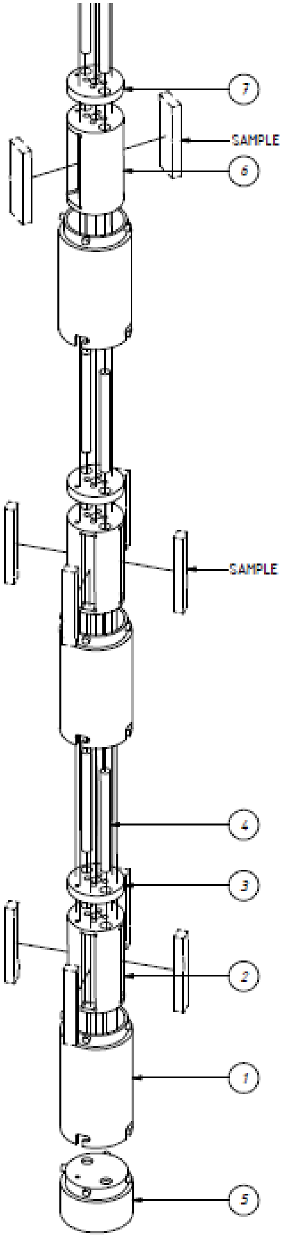
- Purpose of the device
  - Specimens (not fuel) irradiation at
    - High temperature : 300 → 1000 °C (measured and controlled)
    - High flux: in a VIn fuel element (dose up to 10 dpa)
    - Nuclear Heating from 8 up to 14 W/g
  - Specimens:
    - Type: flat tensile, mini-Charpy & simple geometries (like cylinders)
    - Material: High temperature resistant: W, Mo, SiC, … Fe (300 °C)
  - No requirement to preheat specimens at irradiation temperature before the first neutron.
  - Environment: gas (Helium) or vacuum

The High Temperature High Flux device

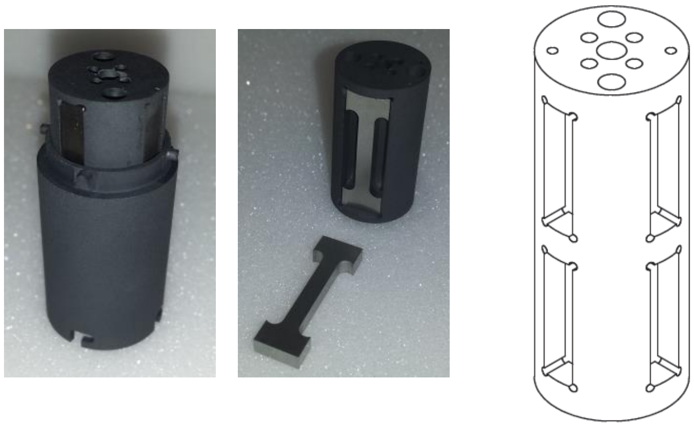
- Material irradiation for GEN 4/fusion conditions
  - High dose rate (>0.5 dpa per reactor cycle)
  - Stable irradiation temperature during irradiation
  - Low cost rig with flexible loading position in reactor
- Solution
  - Gas filled capsule inside 6 plate fuel element and electrical heating
  - Control of temperature by gas gap design and gas pressure
  - Miniature specimens
- Characteristics
  - Temperature 300-1000°C
  - Single use capsule
  - Up to 0.75 dpa per reactor cycle of 3 weeks
    - fluence 4.7 to 5.2E20 n/cm^2 (E>1MeV) in hottest channel

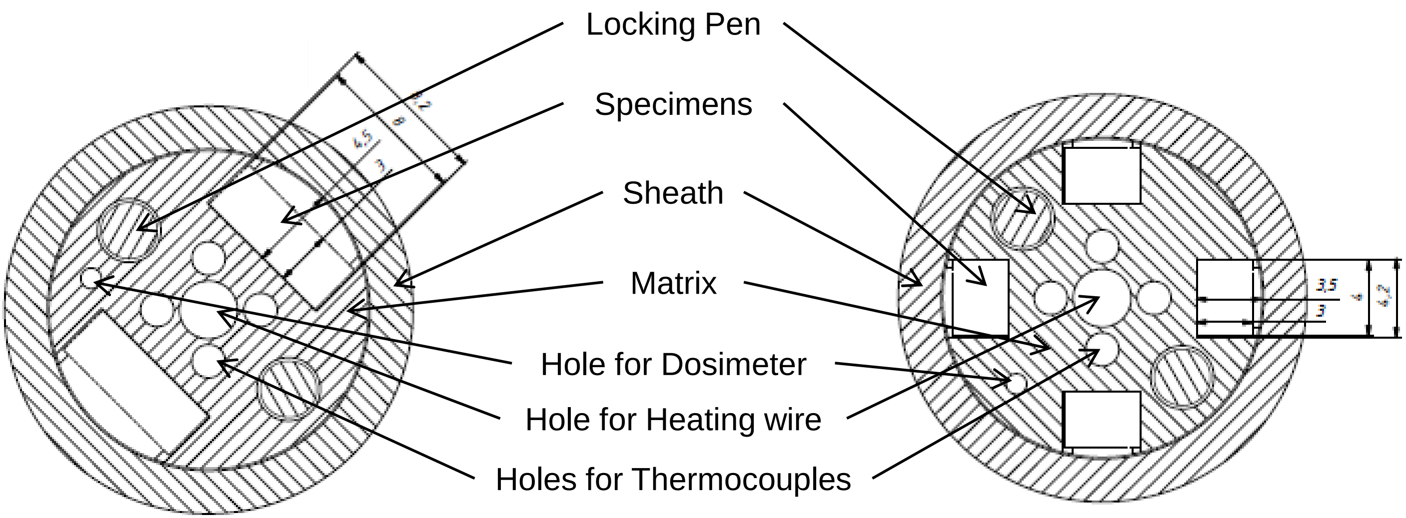


HTHF – Design concept



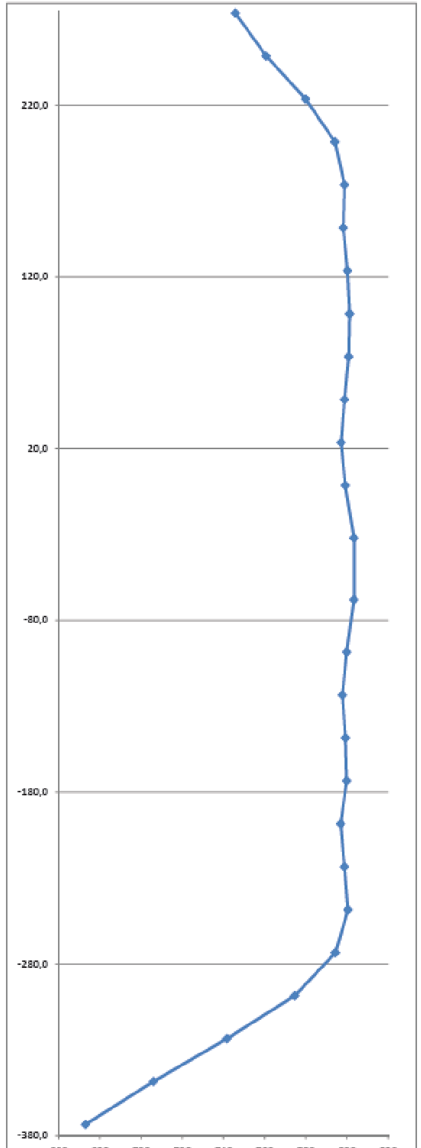
1 - Graphite sheath
2 – Graphite matrix for mini-Charpy
3 – Graphite cover
4 – Graphite pen
5 – Graphite centering plug
6 – Graphite matrix for flat tensile
7 – Graphite cover





HTHF – Calculation results

Pos ---	Diameter mm	Insulation?	Position mm	Flux Shape [%]	Temp °C
1	20,40		273,5	58%	745,7
2	20,40		248,5	63%	760,7
3	20,40		223,5	68%	779,9
4	20,50		198,5	73%	794,1
5	20,80	TK	173,5	78%	798,8
6	21,10		148,5	82%	798,2
7	21,20		123,5	86%	800,2
8	21,30		98,5	90%	801,3
9	21,40		73,5	93%	800,8
10	21,50		48,5	95%	798,8
11	21,60		23,5	97%	797,1
12	21,60		-1,5	99%	799,1
13	21,70	TK	-32,0	100%	803,3
14	21,70	TK	-68,0	100%	803,4
15	21,60		-98,5	99%	799,8
16	21,60		-123,5	98%	797,8
17	21,50		-148,5	96%	799,2
18	21,40		-173,5	93%	799,8
19	21,40		-198,5	90%	796,9
20	21,20		-223,5	86%	798,7
21	20,90	TK + IMR	-248,5	81%	800,5
22	20,60		-273,5	76%	794,3
23	20,40		-298,5	70%	774,6
24	20,40		-323,5	63%	741,7
25	20,40		-348,5	57%	706,0
26	20,40		-373,5	52%	672,9



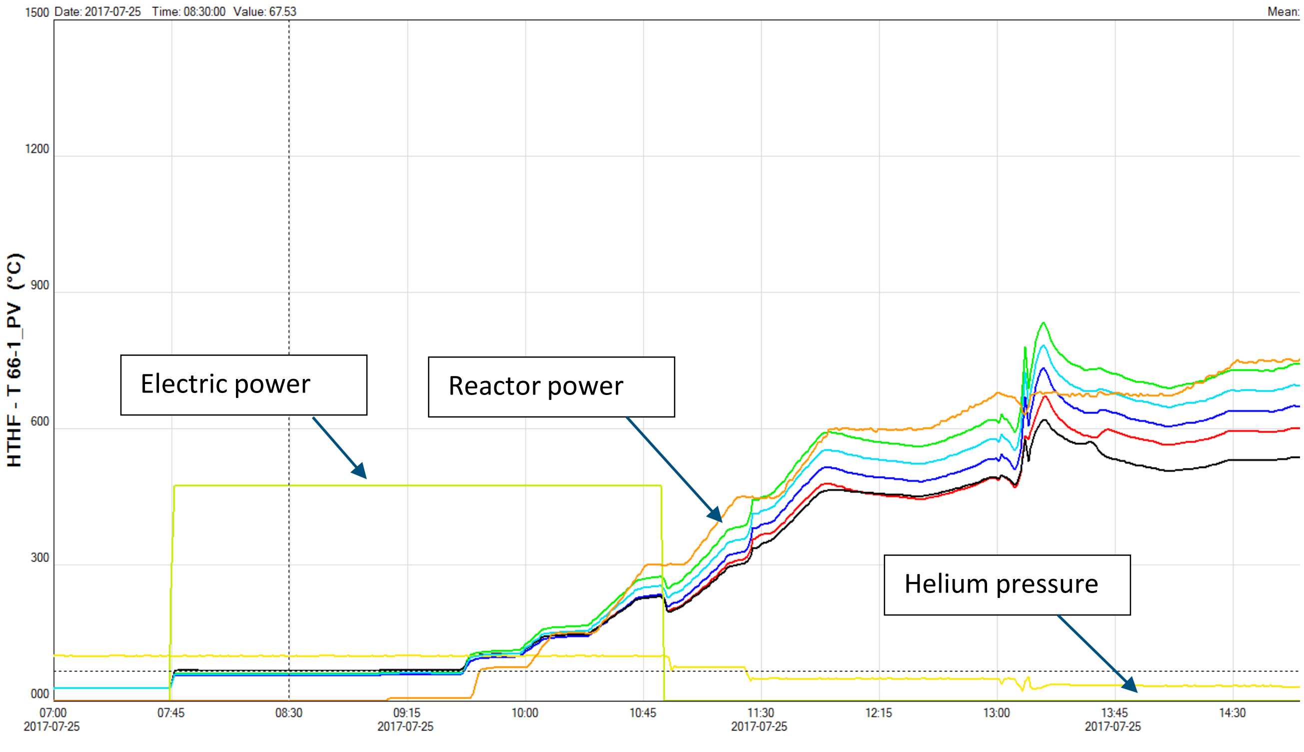
Temperature profile +/- flat over predefined range.

(+/- 1% at calculated pressure)

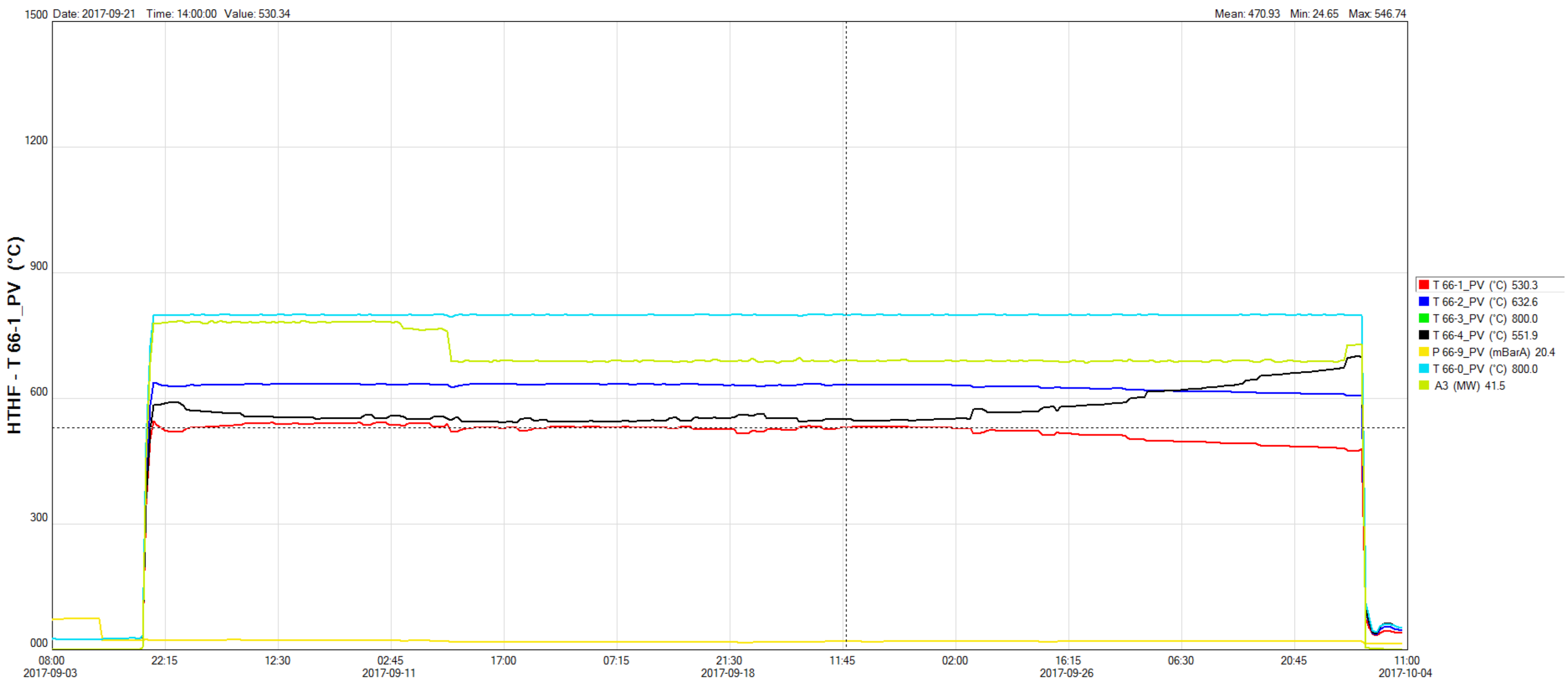
Measurements of temperature at max 4 levels.

Irradiation behavior

- Strong temperature dependence on nuclear heating
- Optimisation of temperature feedback on temperature control
- Strong gradient between W samples and C matrix

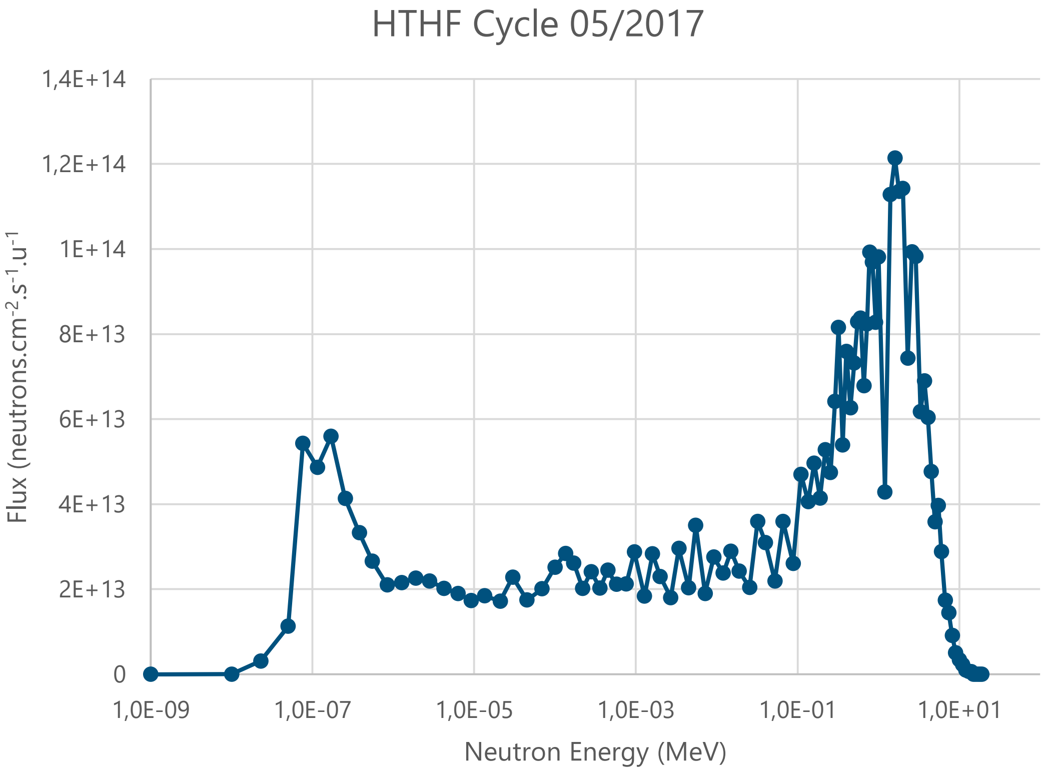


Optimised control: irradiation cycle 2



Irradiation conditions

- Fast flux at mid plane during first 2 cycles
  - 1,7 10^{14}n/cm^{2}s and 1,4 10^{14}n/cm^{2}s
- Accumulated damage after 2 cycles
  - 0,42dpa in W
- Neutron spectrum



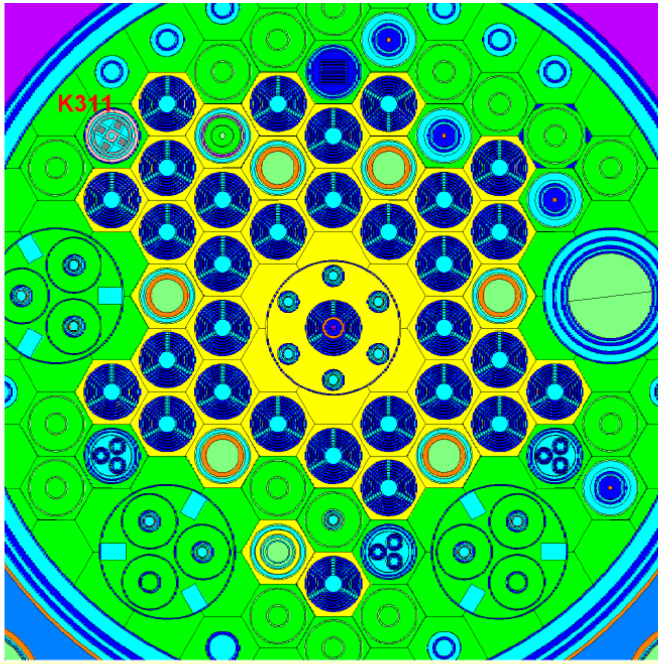
Material irradiation in support of long term operation

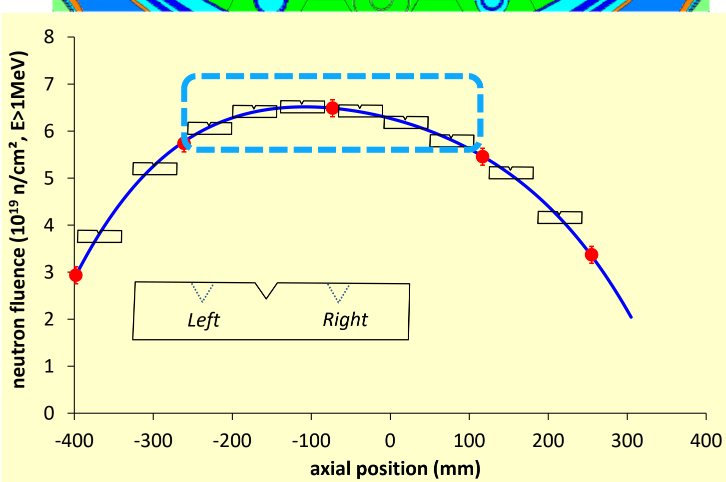
- Irradiation induced ageing of reactor pressure vessel steels
  - Issue: current files from surveillance programmes insufficient for LTO
    - Insufficient material
    - Low lead factor
  - Challenge
    - Provide validated datasets compatible with existing surveillance programmes
      - Relevant dose levels for Long Term Operation
      - Sufficient volume/ numerous specimens
      - Representative and controlled temperature
  - Solution
    - Provide a rig with stable temperature control in low to moderate flux position (0.X dpa in one or 2 reactor cycles)
    - Validate data on standardised specimen type against surveillance data from plant
    - Generate new data beyond database on newly irradiated samples

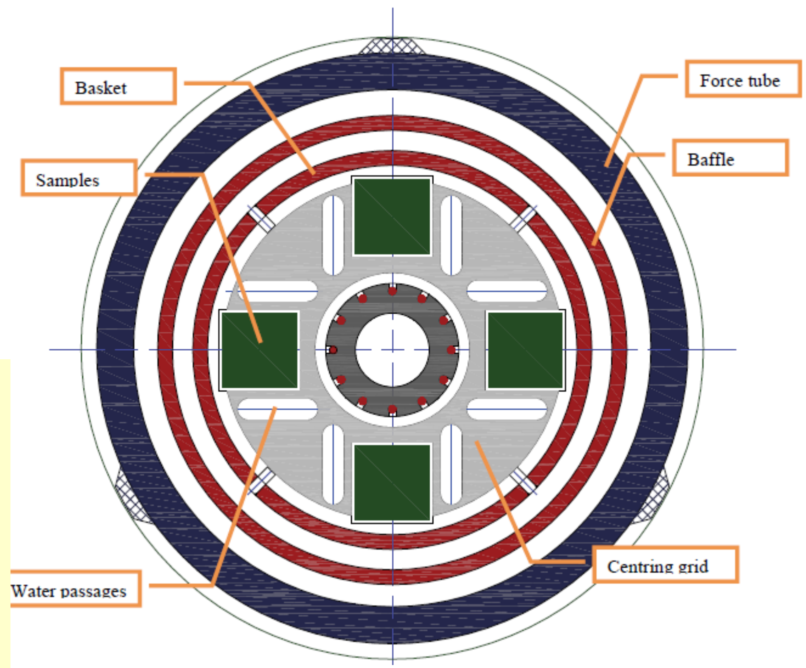
The new RECALL device

- Requirement: material irradiation in typical LWR conditions
  - Loading of full size Charpy specimens (>10)
  - Stable irradiation temperature before, during & after irradiation (250-320°C)
  - Flux levels relevant for LWR plant life management: 0.05 to 0.15 dpa per reactor cycle of 3 weeks
- Solution
  - Reusable rig with flexible loading position in reactor
    - Short lead times
    - Limited impact on other experiments
    - Variable position in reactor yields wider range of dose rates
  - >16 Charpy specimens in flux range >85% maximum

RECALL rig concept

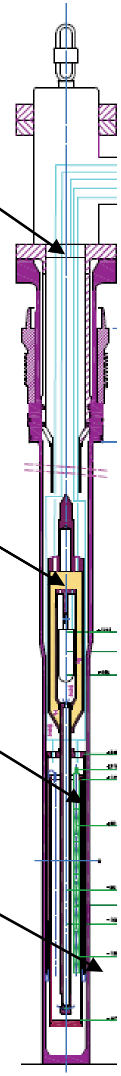




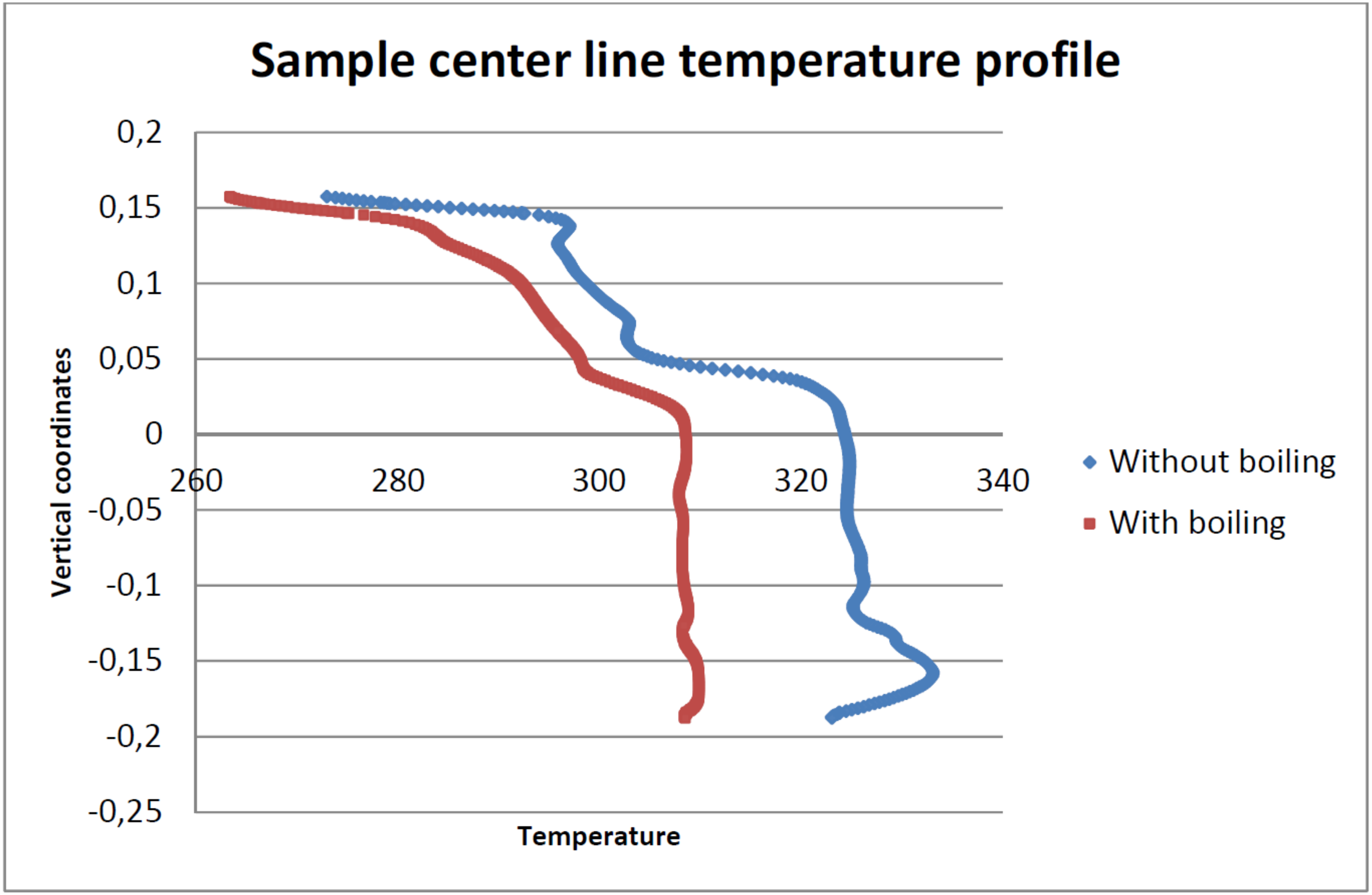


RECALL operation

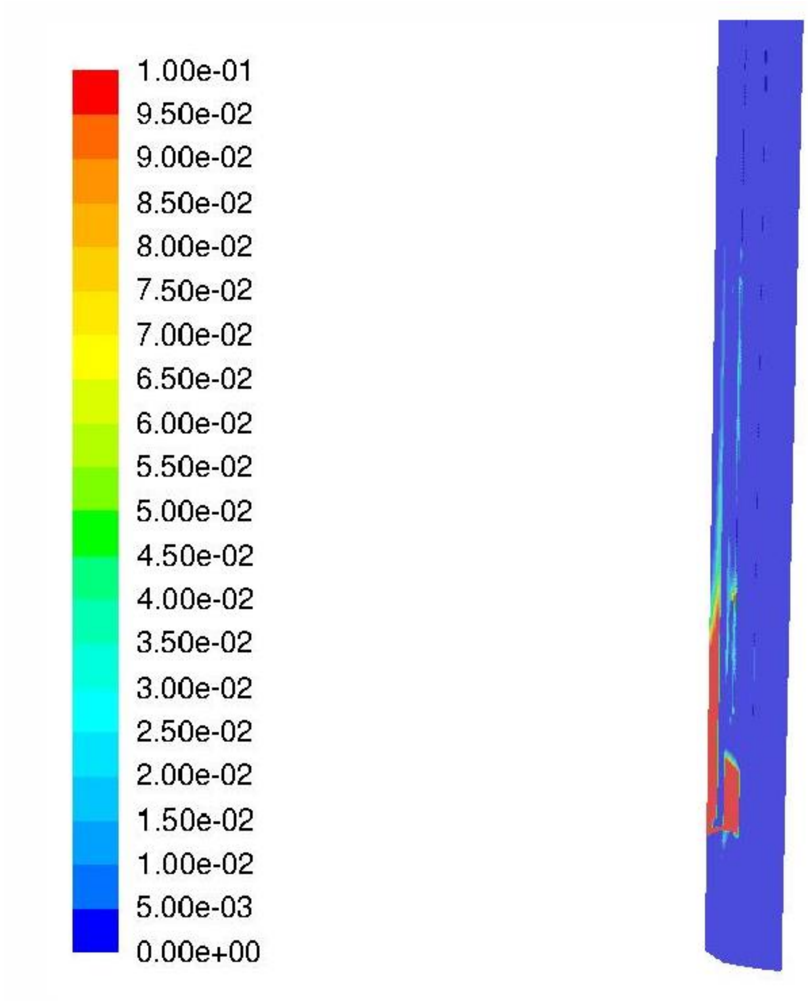
- Pressurised water is injected at low temperature in IPS
  - Saturation pressure set to stabilize irradiation temperature
- Preheating to irradiation temperature
  - Heating of samples before start of irradiation
- Evacuation of nuclear heating by nucleate boiling
  - Stable irradiation temperature independent of heat flux
- Injection of cold water
  - Control of steam fraction and reactivity effect (void factor)

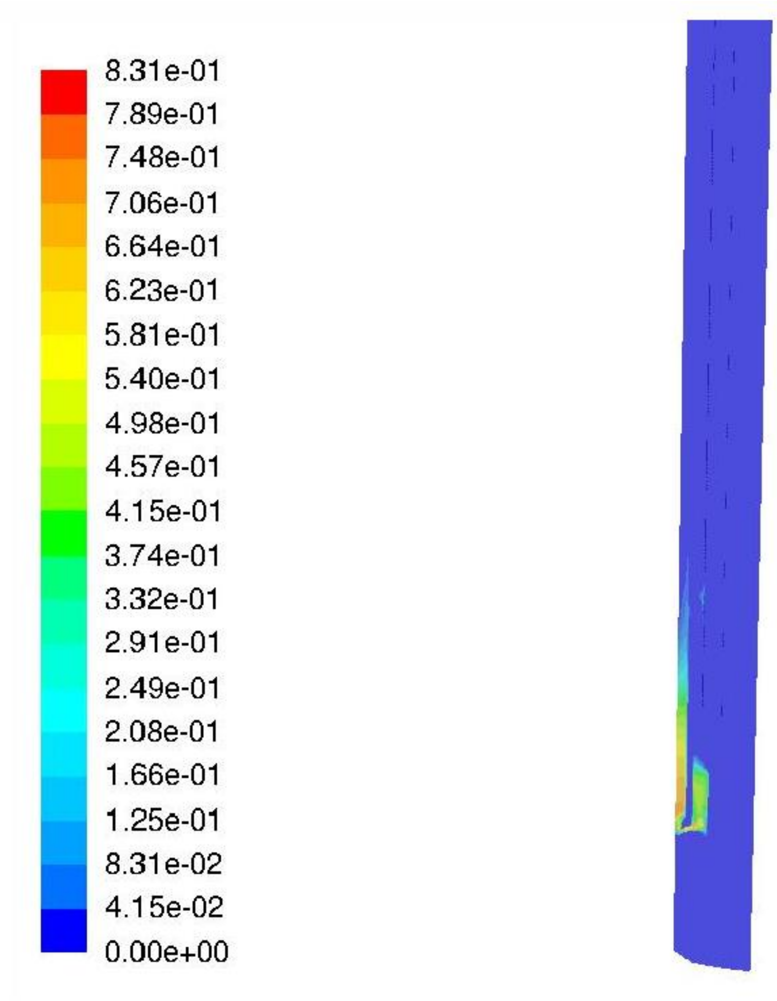


Temperature distribution

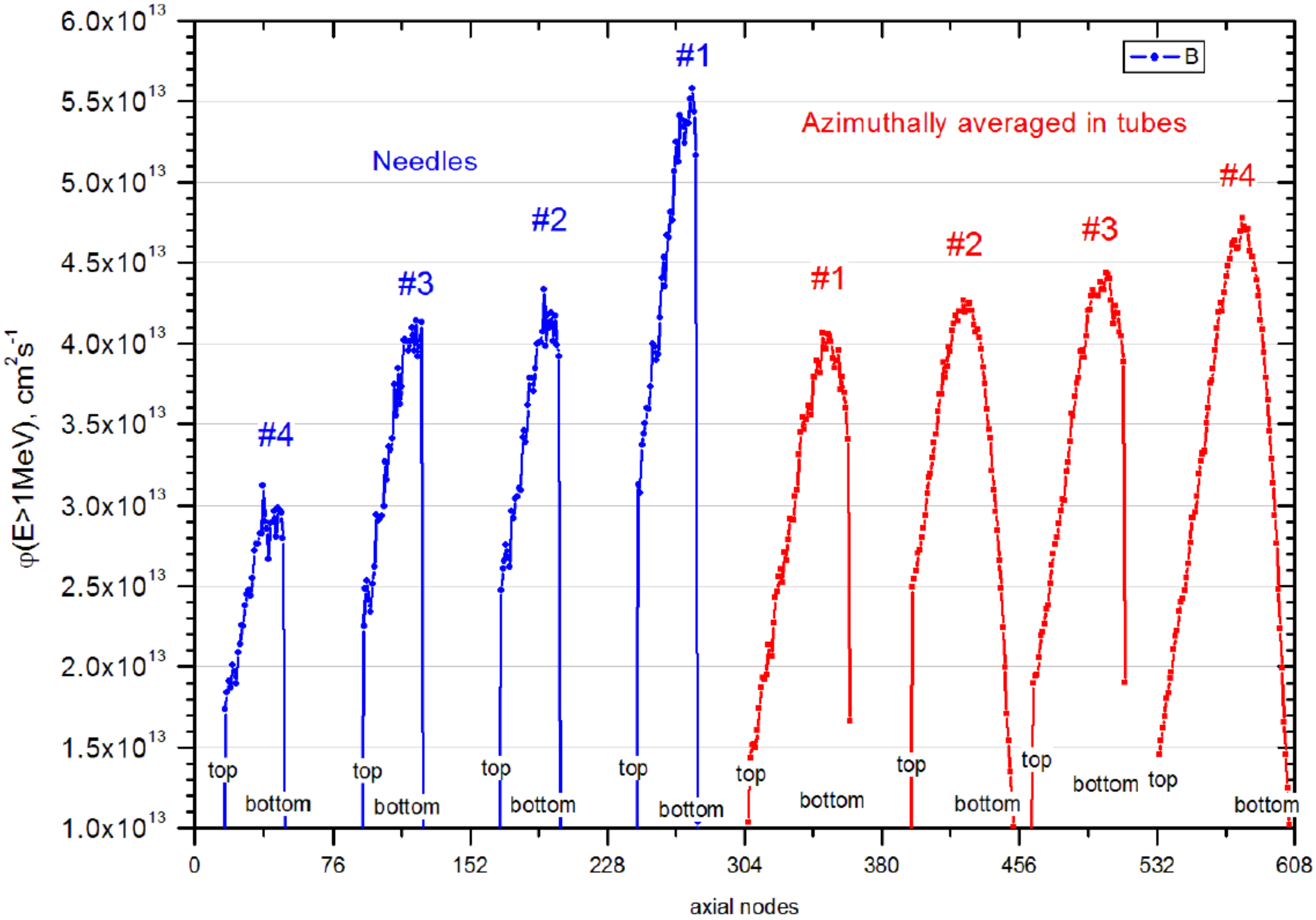


Steam fraction as function of cold water injection





Expected fast flux distribution in needles & structure



Conclusions

- 2 new devices are presented for material irradiation
  - High fast flux device for multi-cycle dpa accumulation: HTHF
  - Low fast flux device for ageing studies with strict temperature control: RECALL
- Utilisation of flexibility of reactor
  - Selection of fuel element with similar heating over cycles: HTHF
  - Creation of reflector position with desired fluence over 2 cycles and rotation at mid experiment: RECALL
- Cost effectiveness and short lead times
  - Generic design method and re-use of OPE: HTHF
  - Reloadable device in reactor pool or hot-cell: RECALL