Activation calculations for the MYRRHA ADS design

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Outline

- A fast look at the FASTEF/MAXSIMA design, in support of MYRRHA
- Motivation of our work: detailed shielding and activation calculations in and around the MYRRHA reactor core
- Our idea: combining two state-of-art Monte Carlo codes to obtain advanced performances
- Source terms and model of the structural materials around the core
- Selected results for activation analysis

A look at the MYRRHA project

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In MYRRHA (Multi-purpose hybrid research reactor for high-tech applications):

- ***A LFR (Lead Fast Reactor) will operate both in critical and subcritical mode.***

  Core power - ***100 MW in critical mode***

  in the FASTEF design: - ***94 MW in subcritical mode***

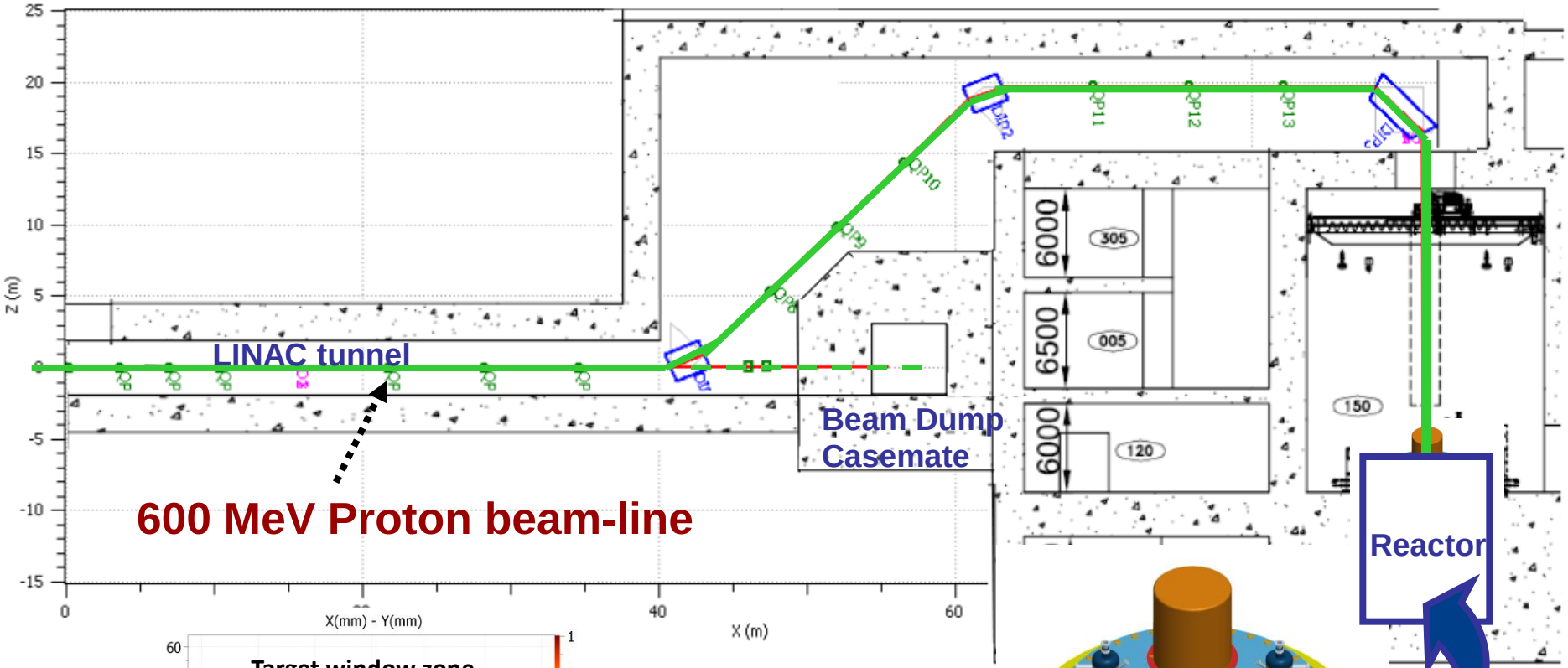
- ***In the ADS mode a 600 MeV proton beam will be provided by a LINAC***
- ***Compact Spallation Target in LBE (Lead Bismuth Eutectic)***

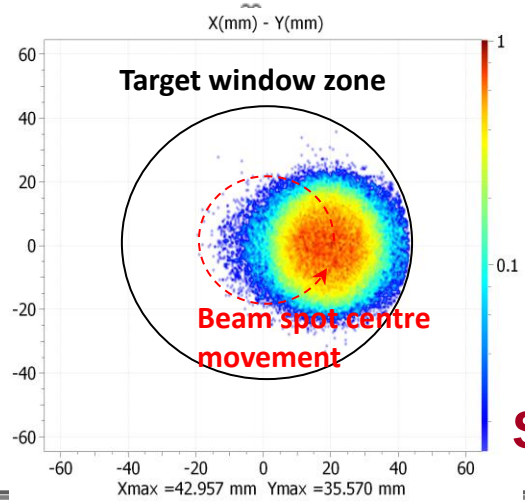
Framework of this work: CDT-FASTEF and MAXSIMA EU FP7 project

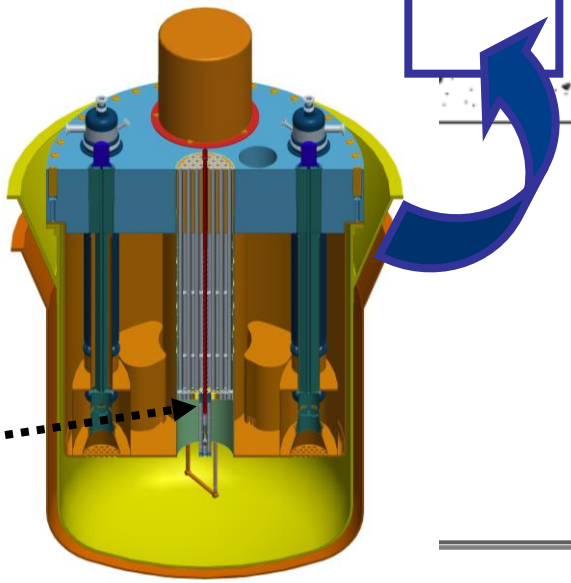
Goal: design a FAst Spectrum Transmutation Experimental Facility, able to demonstrate efficient transmutation of high level waste and associated technology

FASTEF Design → *Heart of the MYRRHA facility at SCK·CEN in Mol*
The MYRRHA construction could start in 2017
(planned to be operational in 2023)

A look at the MYRRHA project







Spallation target

Motivation of our work

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Our goal:

Neutronics, shielding and activation analysis in support of the safety

Key points:

- **Detailed characterization of the shielding and the activation problems around the core in both critical/subcritical modes**

- **Possible optimization of materials/shielding structures**

Our idea: combined use of the two Monte Carlo codes MCNPX and FLUKA.

- **MCNPX is the official tool used to characterize the MYRRHA-FASTEF and the MYRRHA-MAXSIMA cores**
- **FLUKA presents a powerful semi-Monte Carlo method to evaluate the dose rates due to the activated materials**

Result: a powerful tool to cope with shielding and activation problems !

Evaluation and transport of the Residual radiation in FLUKA

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✓ For an arbitrary irradiation pattern, the time evolution of the system (build-up and decay during the irradiation and cooling) can be obtained runtime via the exact analytical solution of the **Bateman equations**:

$$\frac{dN_i}{dt} = -\sum_{j \neq i}\left[\lambda_{ji}^{d} + \bar{\sigma}_{ji}\bar{\varphi}\right]N_i + \sum_{j \neq i}\left[\lambda_{ij}^{d} + \bar{\sigma}_{ij}\bar{\varphi}\right]N_j$$

where $\bar{\varphi} = \int \varphi(E)dE$ and $\bar{\sigma}_{ji} = \frac{1}{\bar{\varphi}}\int \varphi(E)\sigma_{ji}(E)dE$ for each radionuclide in the material

The specific activity of each material at the cooling time t_{cool} is given by: $a(t_{cool}) = N\sigma\phi(1-e^{-\lambda t_{irr}})e^{-\lambda t_{cool}}$

✓ **At the same time FLUKA can perform the generation and transport of the decay radiation** (γ, β^+,β^- X-rays, α and conversion electron emissions).

➡ **In the same run we can obtain production of the residuals, their time evolution and the residual doses due to their decays**

Method

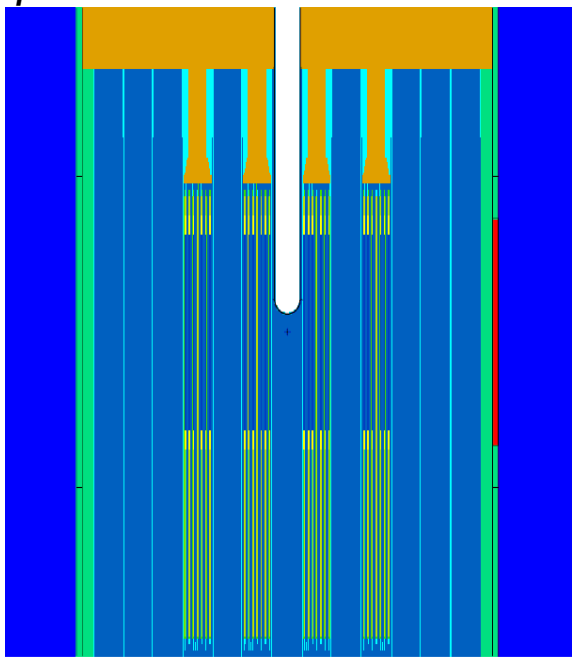
To assess the shielding in the reactor bulding we need source terms for the shielding and activation calculation

Starting point:

MCNPX official SCK·CEN model version 1.4 of the MYRRHA-FASTEF critical and subcritical core

Subcritical core: **72 FA (E_{Pu} = 30%)**, **94 MW** equilibrium core

Composition with fresh fuel are analyzed (conservative case)



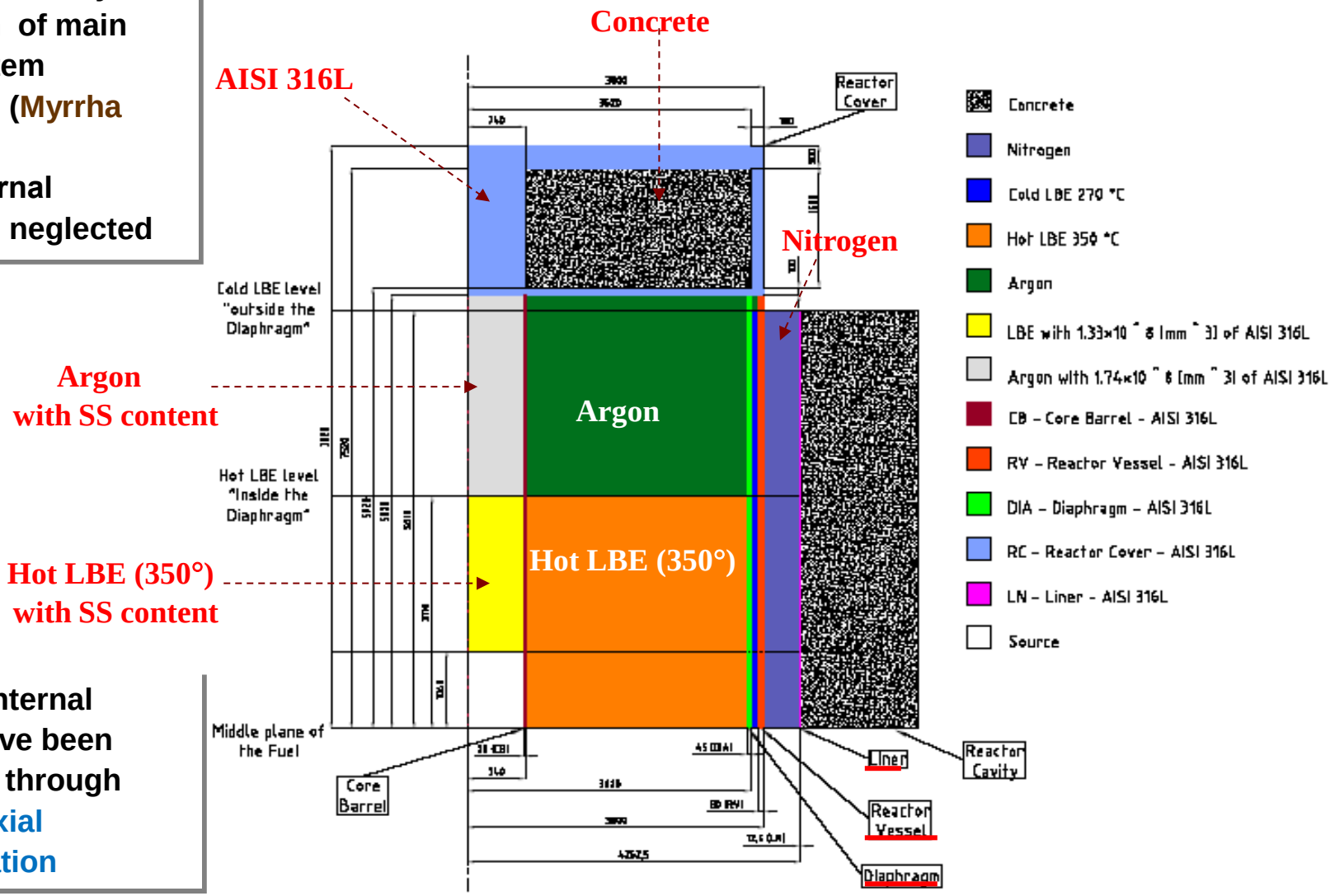
Method: build source terms and use FLUKA to describe the radiation fields in all the structure around the reactor

- ***LATERAL analysis: detailed FLUKA model from the core barrel to the shielding wall***

- ***VERTICAL analysis: detailed FLUKA model from the core to the reactor cover***

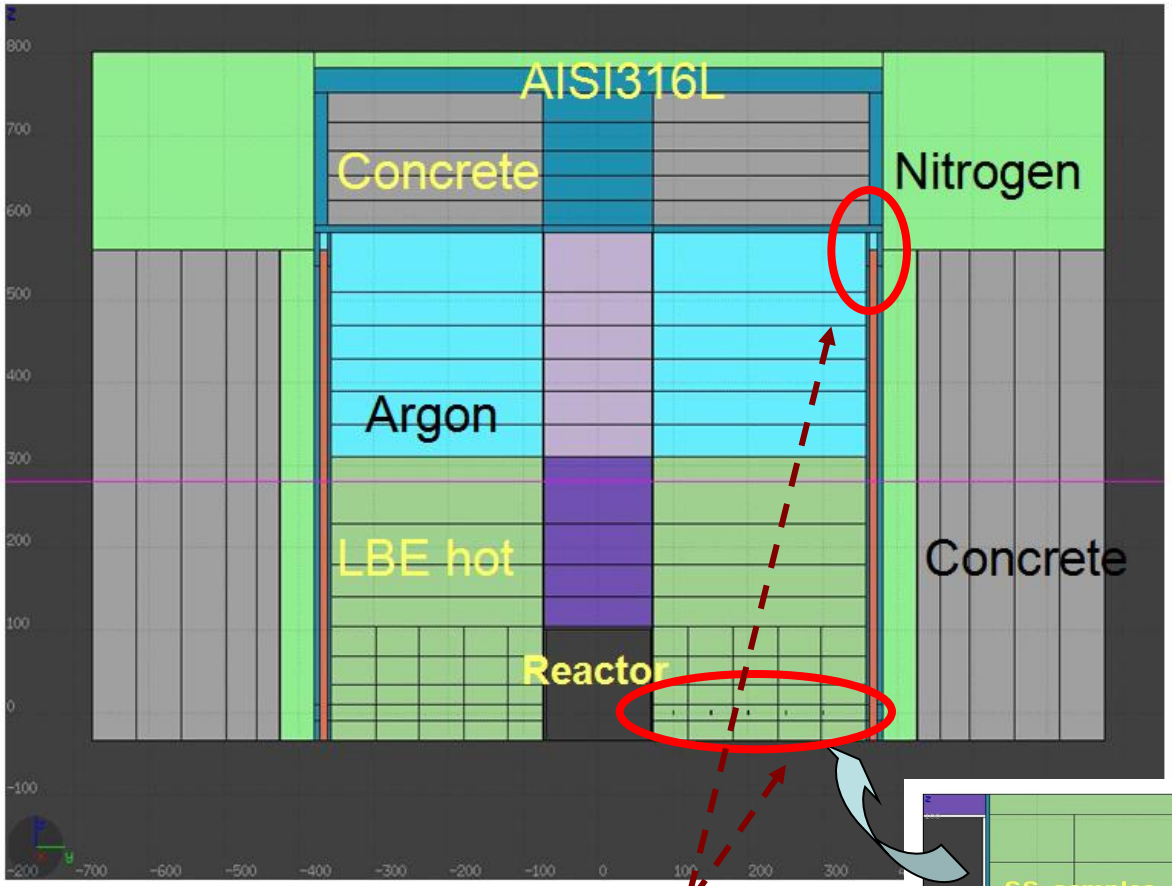
The MYRRHA-FASTEF model of the reactor containment system

- Simplified geometry and composition of main primary system components (Myrrha revision 1.4)
- "Minor" internal components neglected

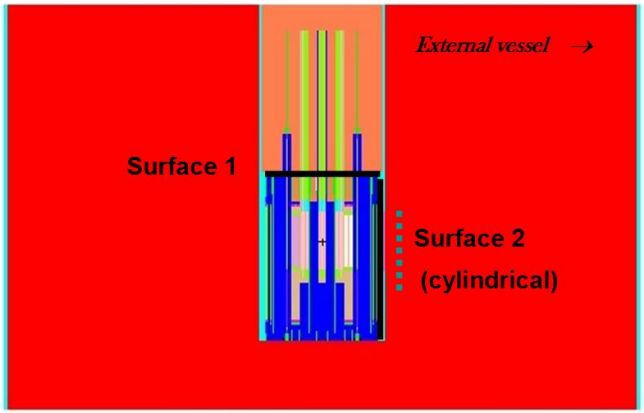


- All reactor internal elements have been represented through radial and axial homogenization

…and the FLUKA model of the reactor containment system



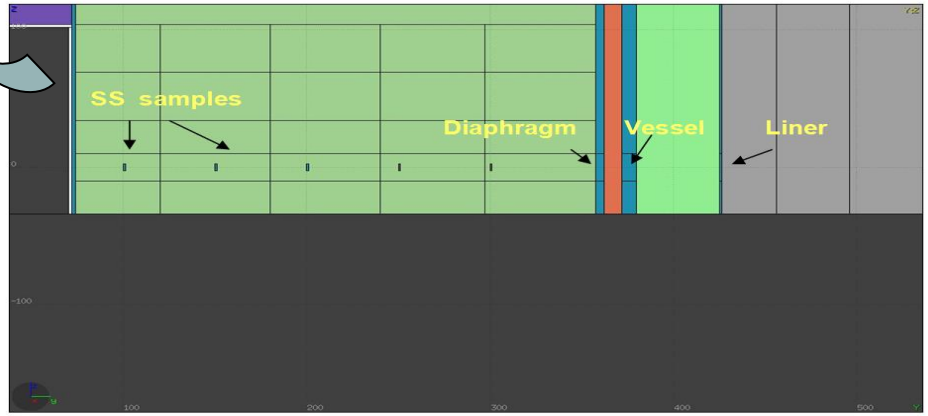
MCNPX surfaces used for the source term calculation:



LBE hot 350 °C

LBE cold 270 °C

Analyzed samples for activation studies



Characterization of a complex neutron source term

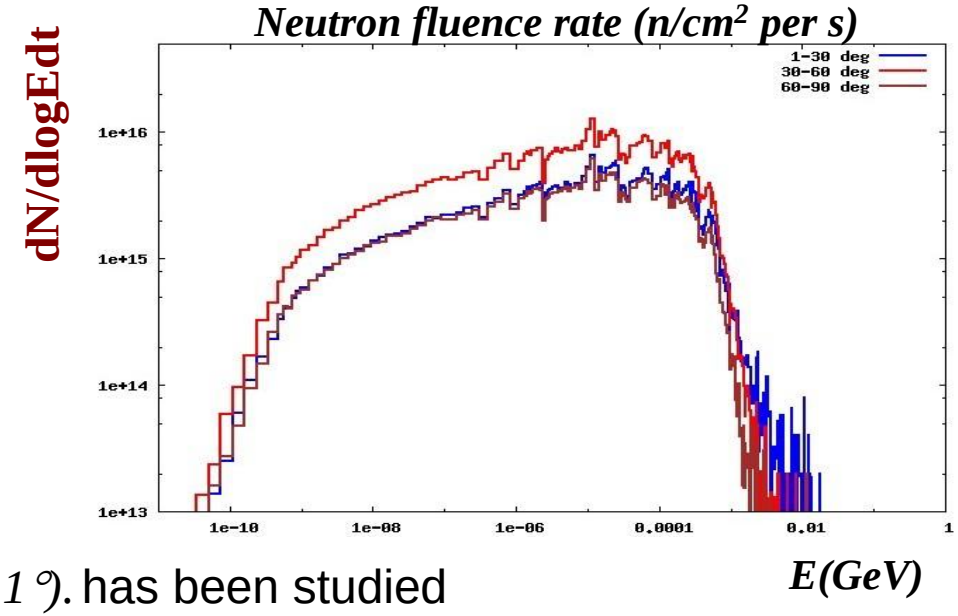
A complex source term has been built looking at the neutrons that come out from the lateral surface of the core vessel and from the top of the core region

- **Lateral emission**: isotropic

- **Vertical emission**: a set of 10 different neutron spectra has been calculated in 3 radial regions and in the angular bins: *(0°, 30°), (30°, 60°), (60°, 90°)*.

Radial regions:

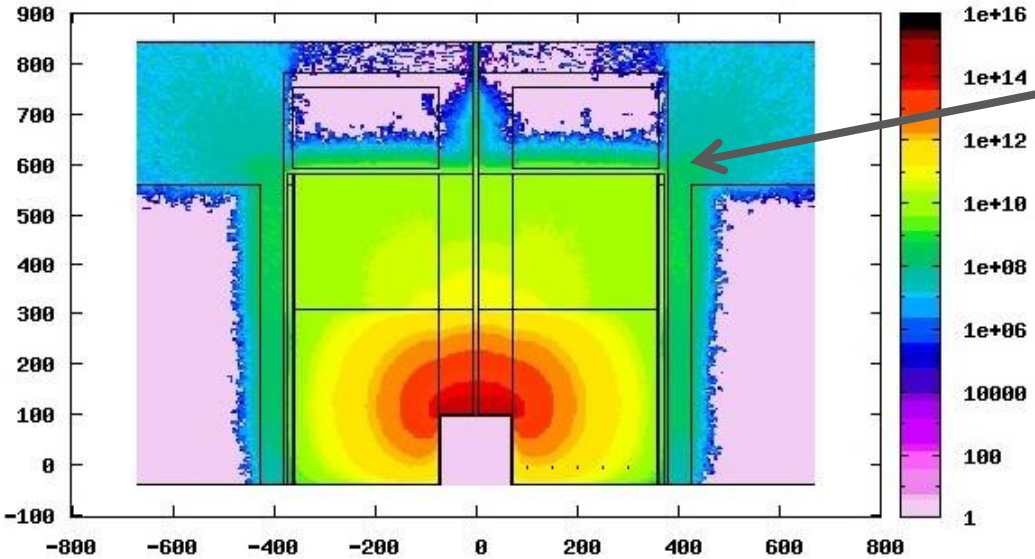
- **R in (0,35 cm)** (first FA ring)
- **R in (34 cm, 65 cm)** (the whole fissile zone)
- **R in (65 cm, 72 cm)** (until the core vessel)



For the inner shell also the interval *(0°, 1°)*. has been studied

Neutron fluence rates and source term validation

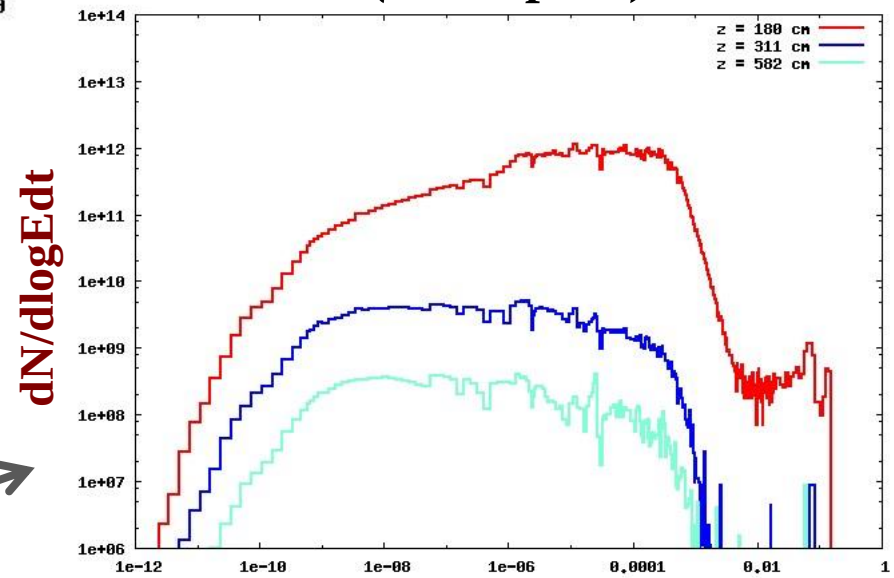
Neutron fluence rate (n/cm^2 per s)



z(cm)

This result caused a new study of the cover design

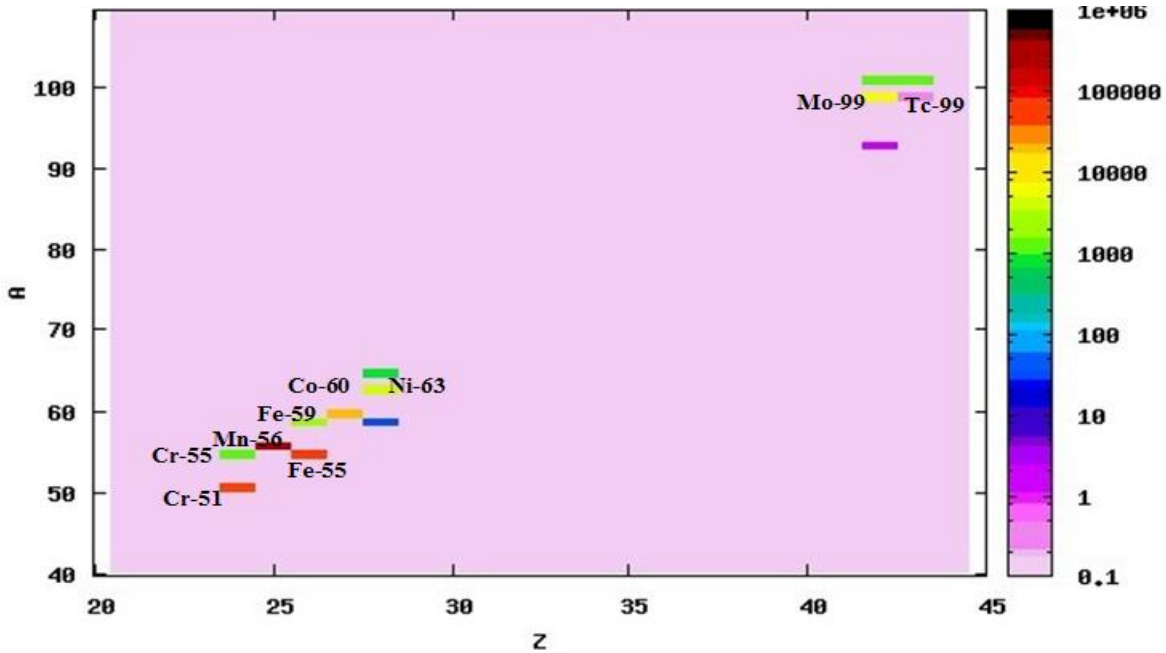
Vertical spectra from the top of the core barrel (n/cm^2 per s)



Very good agreement (few %) with the same spectra evaluated with MCNPX

Activation of the SS samples

RN contribution to the total specific activity [Bq/cm3]- EOI 15 y (diaphragm central)



SS sample	Specific activity [Bq/cm3]			
	Irradiation 90 d, EOI	Irradiation 90 d, cooling = 1 week	Irradiation 15 y, EOI	Irradiation 15 y, cooling = 5 y
Diaphragm s. up	1.00E+6	1.77E+5	1.24E+6	8.76E+4
Vessel s. up	1.84E+5	2.98E+4	2.26E+5	1.58E+4
Liner s. up	5.09E+4	1.15E+4	6.53E+4	5.00E+3
Cover sample	3.75E+5	5.92E+4	4.59E+5	3.20E+4

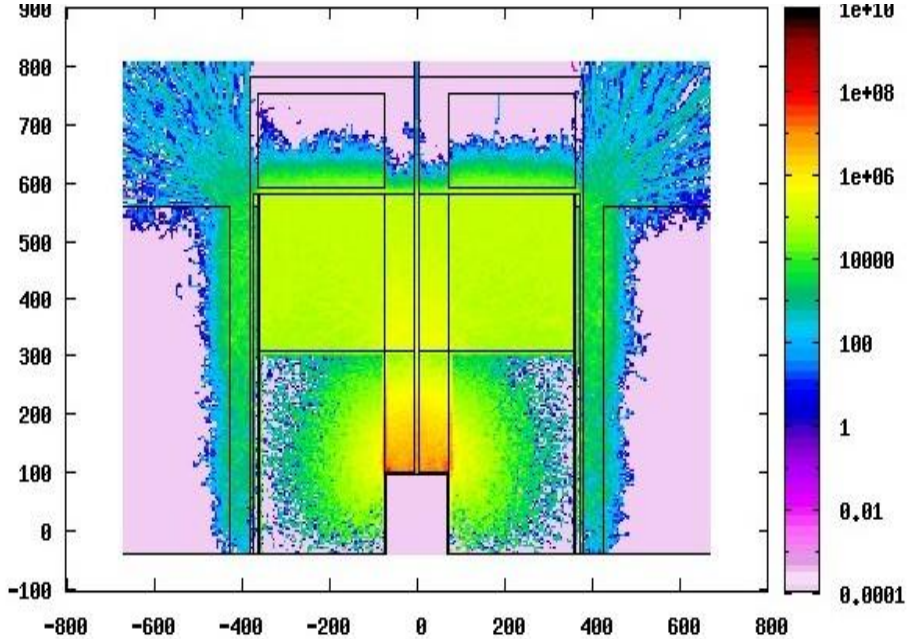
The analysis of the residual radiation

Irradiation patterns:

- **Medium term operation**: 1 cycle 90 d continuous irradiation, cooling until 30 d
- **Long term operation**: 5y continuous irradiation, cooling until 1 y

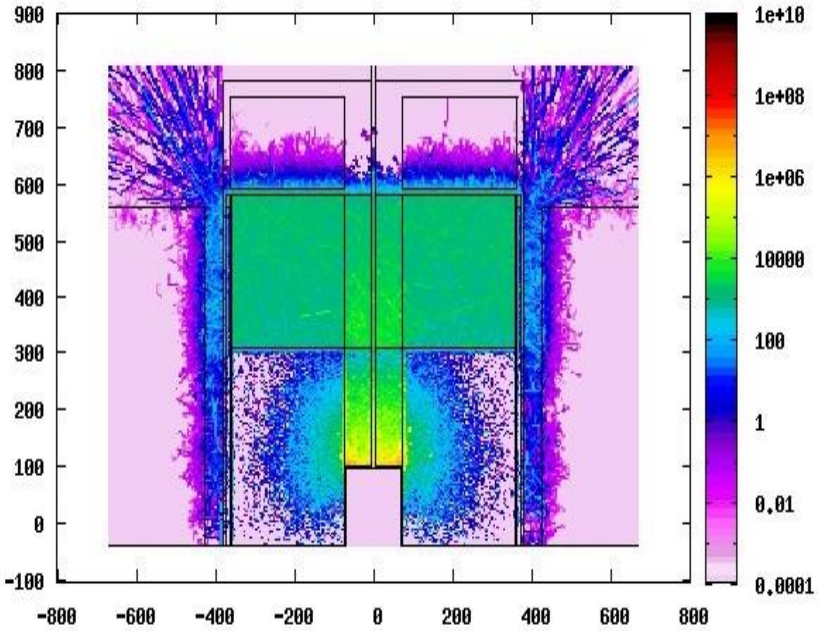
Case 90 d irradiation, EOI

H(10) rate (μSv/h)*



Case 90 d irradiation, 1 w cooling

H(10) rate (μSv/h)*



Production of Ar-37 ($t_{1/2}$= 35 d) by neutron capture from Ar-36

The huge Ar-37 production supported the moving to another gas (nitrogen)

Upgrade of the core model: the MYRRHA-MAXSIMA core

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Main upgrades of the core model (Myrrha revision 1.6):

- **modified fuel composition**
- **larger core (20 cm more in radius), upgraded reflector design**

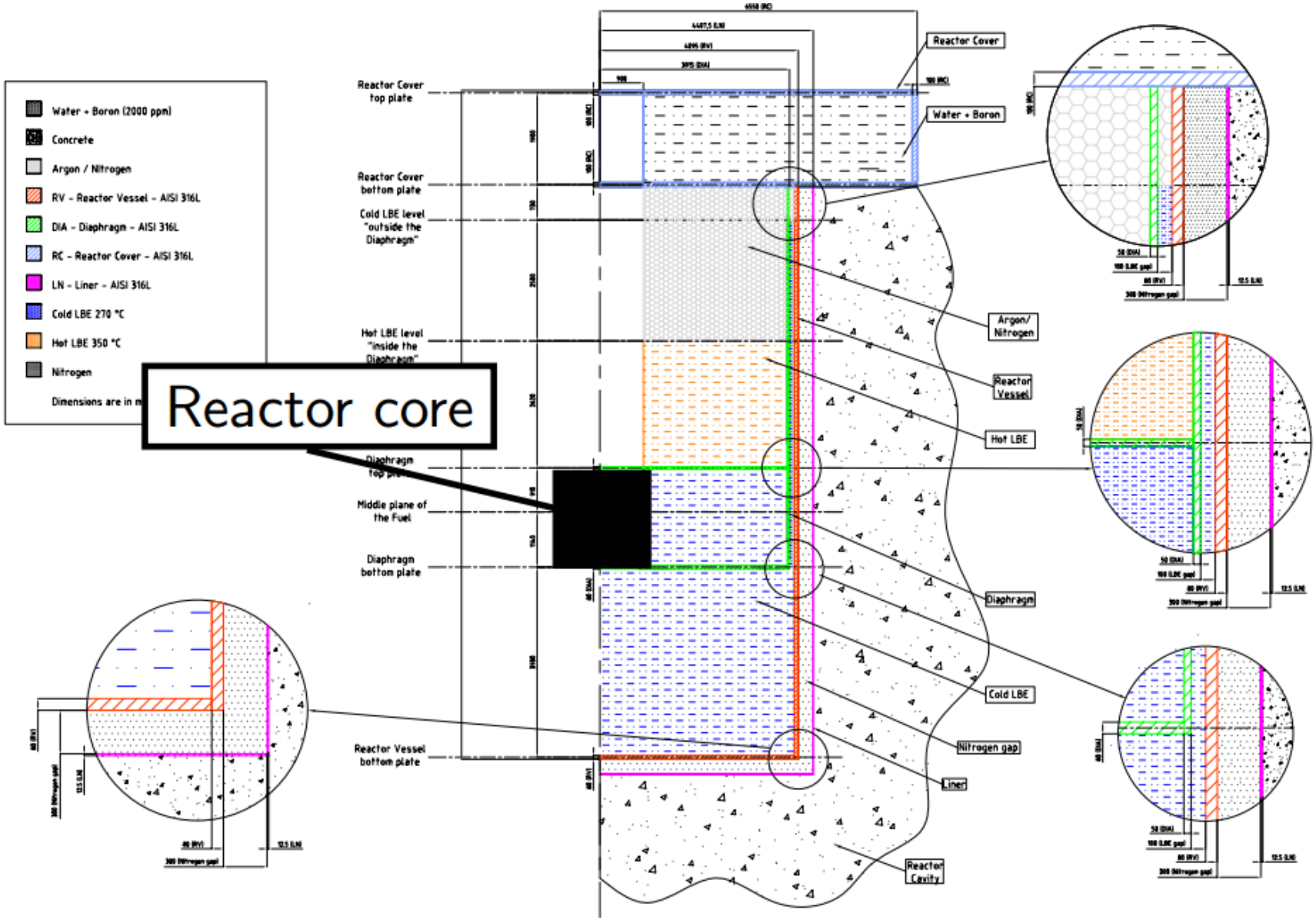
Main upgrades of the containment system:

- **double external vessel**
- **new cover design**

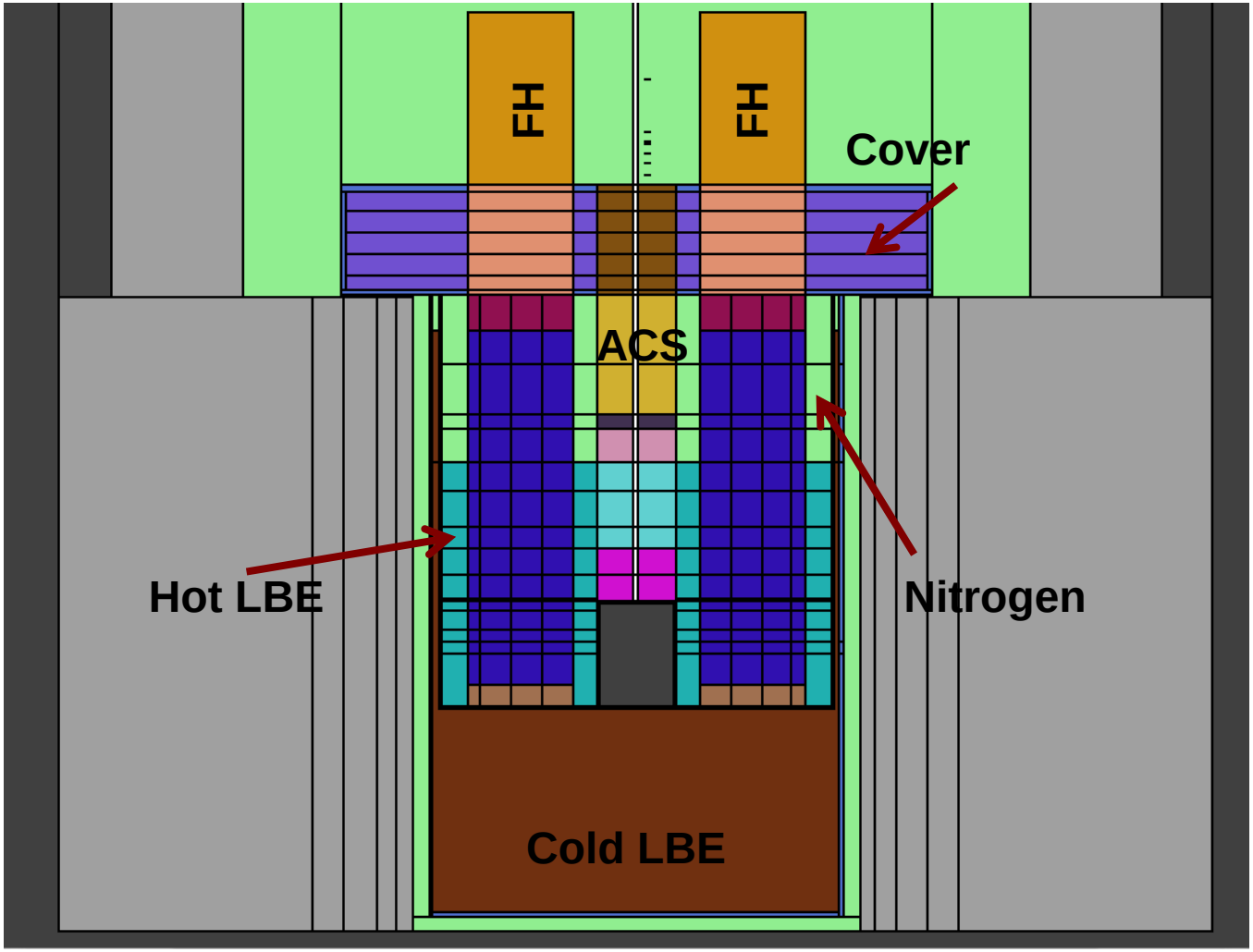
Components included in the MAXSIMA model:

- ✓ reactor vessel
- ✓ reactor diaphragm
- ✓ reactor cover
- ✓ Above Core Structures (ACS)
- ✓ Primary Pumps (PP)
- ✓ Primary Heat Exchangers (PHX)
- ✓ In-Vessel Fuel Handling Machines (IVFHM)
- ✓ Window target
- ✓ Silicium Doping In-Pile Sections (SiDIPS)

The MYRRHA-MAXSIMA model of the reactor containment system

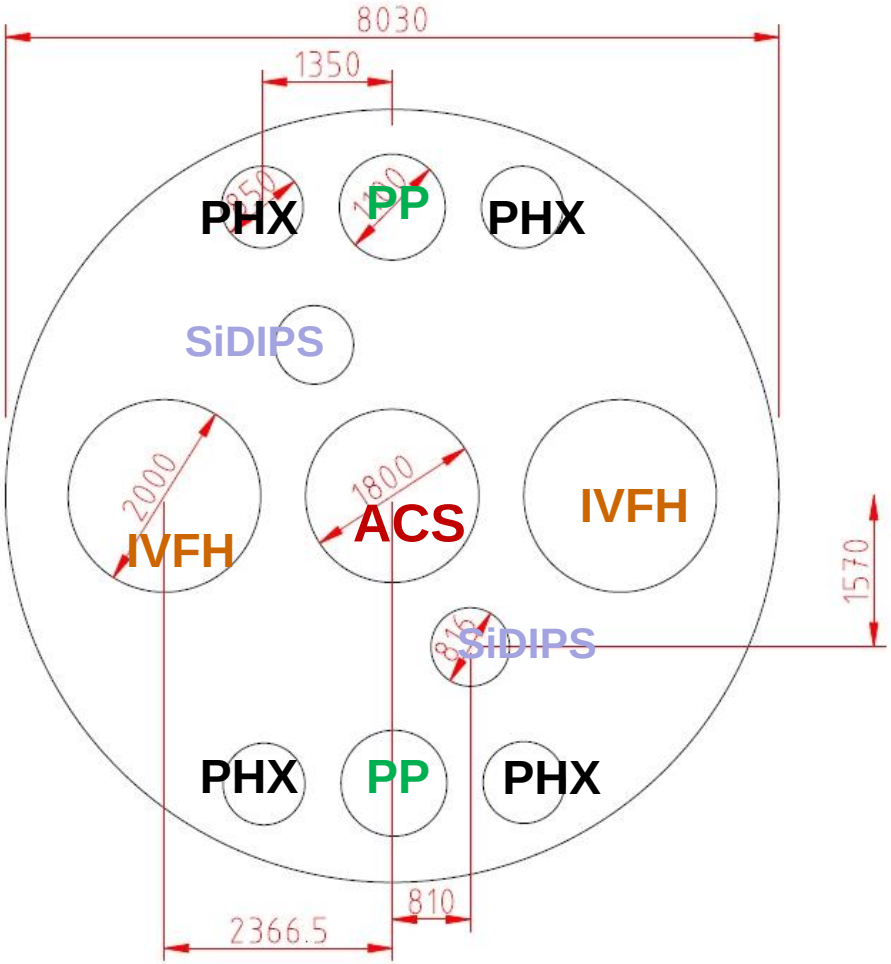


Updated FLUKA Model

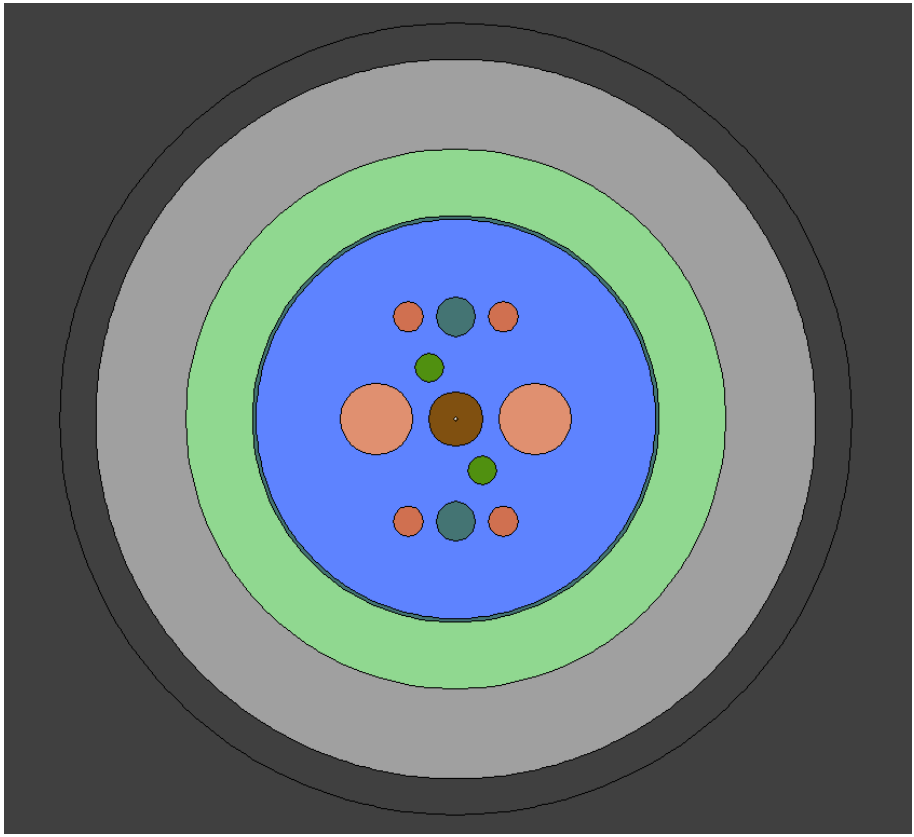


Upgrade of the core model: the MYRRHA-MAXSIMA core

Horizontal section of the reactor vessel:



FLUKA Model



Neutron yields in the ACS

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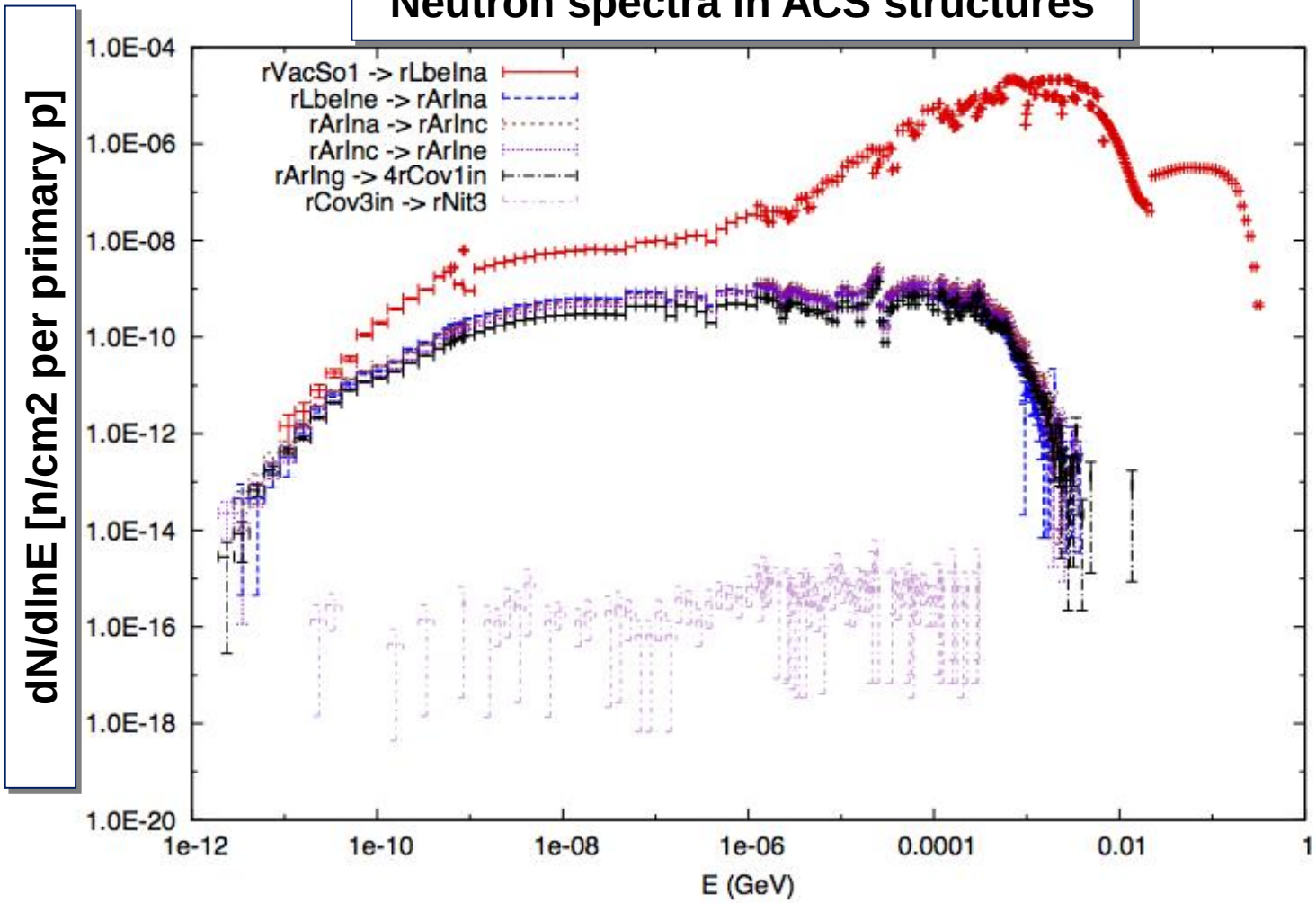
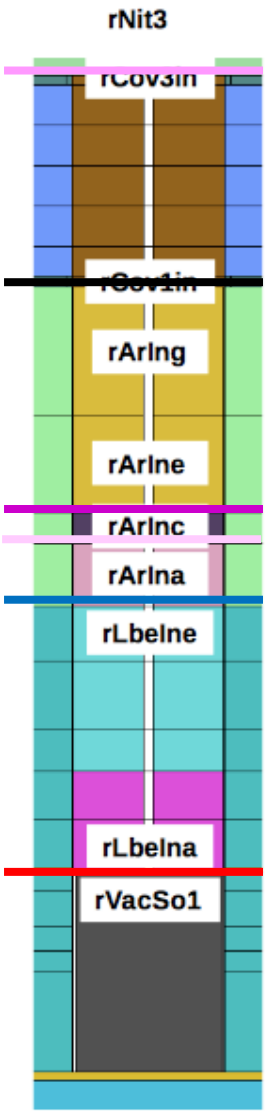
Neutron spectra in ACS structures





Activation samples

61 regions selected for activation studies, each for 16 points in time:

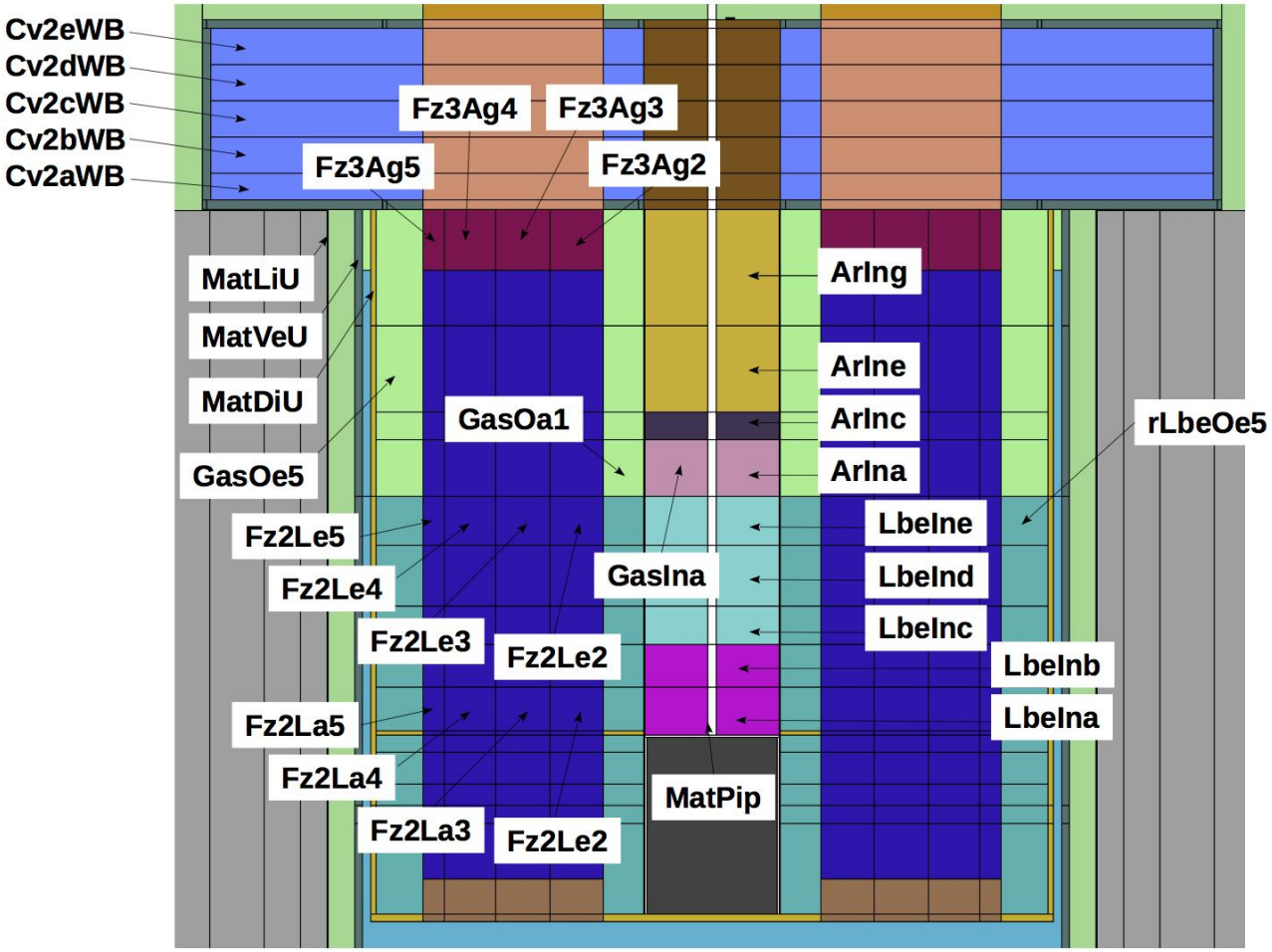
- **EOC (End OF Cycle), 90 d irradiation, EOC + 1 w cooling, EOC + 1 m cooling**

- **End of 11 m Irradiation, EOI + 1 m cooling**
- **End of 9 y + 11 m irradiation, EOI + 1 m cooling**
- **End of 19 y + 11 m Irradiation, EOI + 1 m cooling**

- **End Of Life (EOL): 39 y + 11 m Irradiation**
- **EOL + 1 m cooling, EOL + 1 y cooling**
- **EOL + 10 y , EOL + 100 y, EOL + 1000 y, EOL + 10000 y cooling**

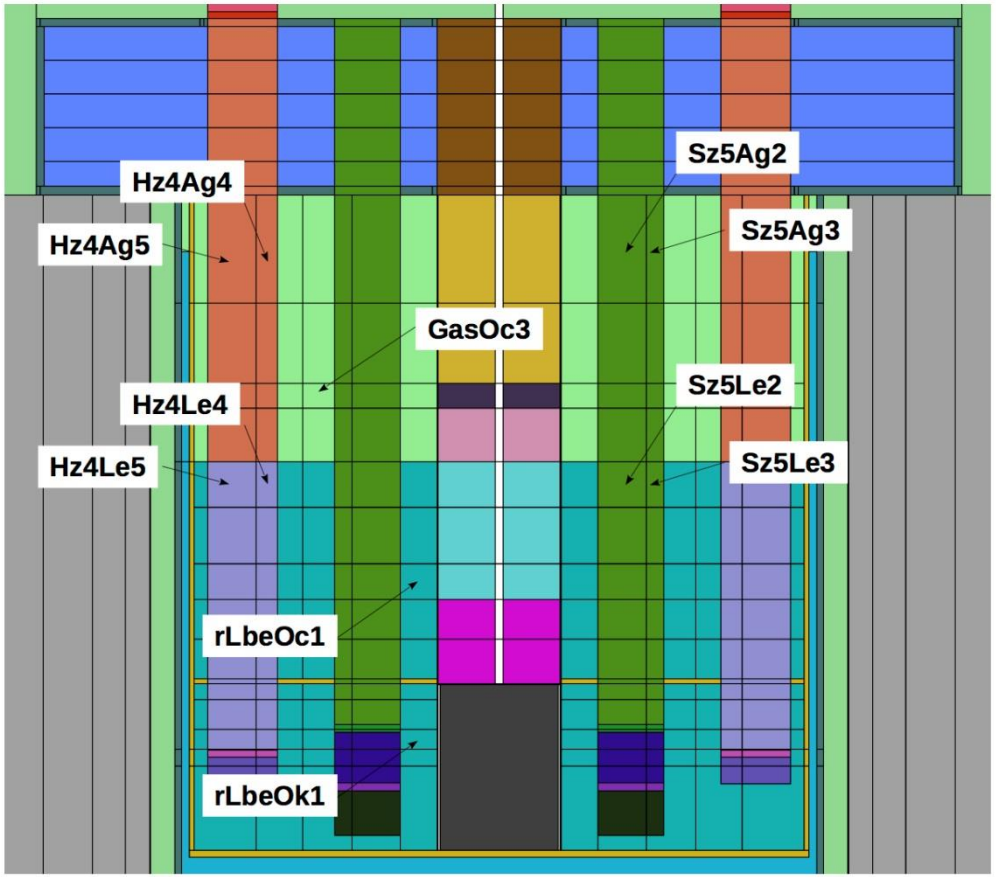
Activation samples

Regions for activation studies in Above Core Structures and Fuel Handling Machinery:



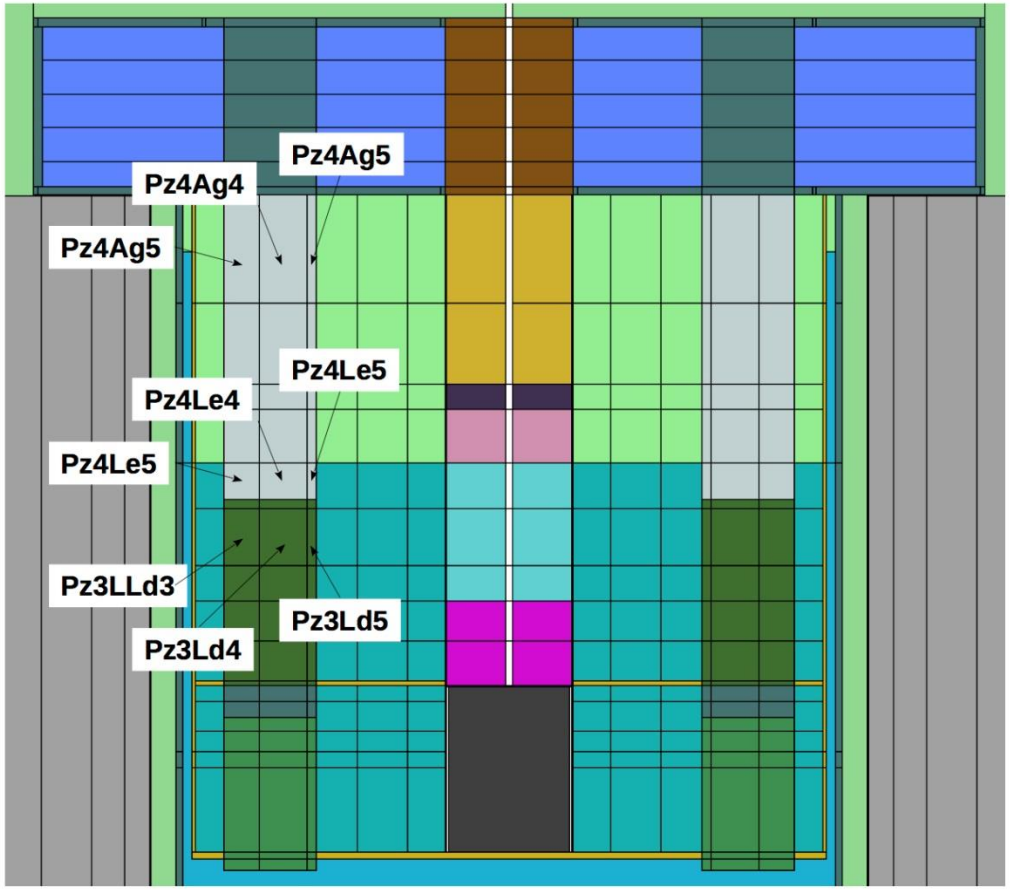
Activation samples

Regions for activation studies in Primary Heat Exchangers and Silicon Doping Devices:



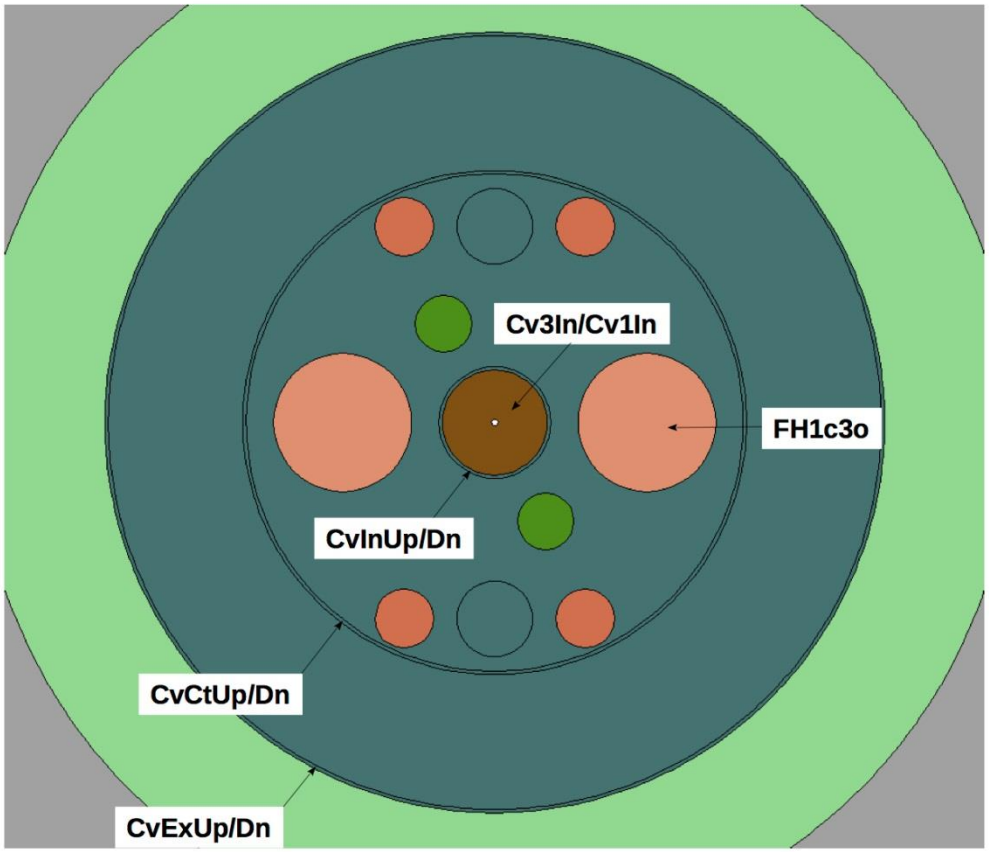
Activation samples

Regions for activation studies in Primary Pumps:



Activation samples

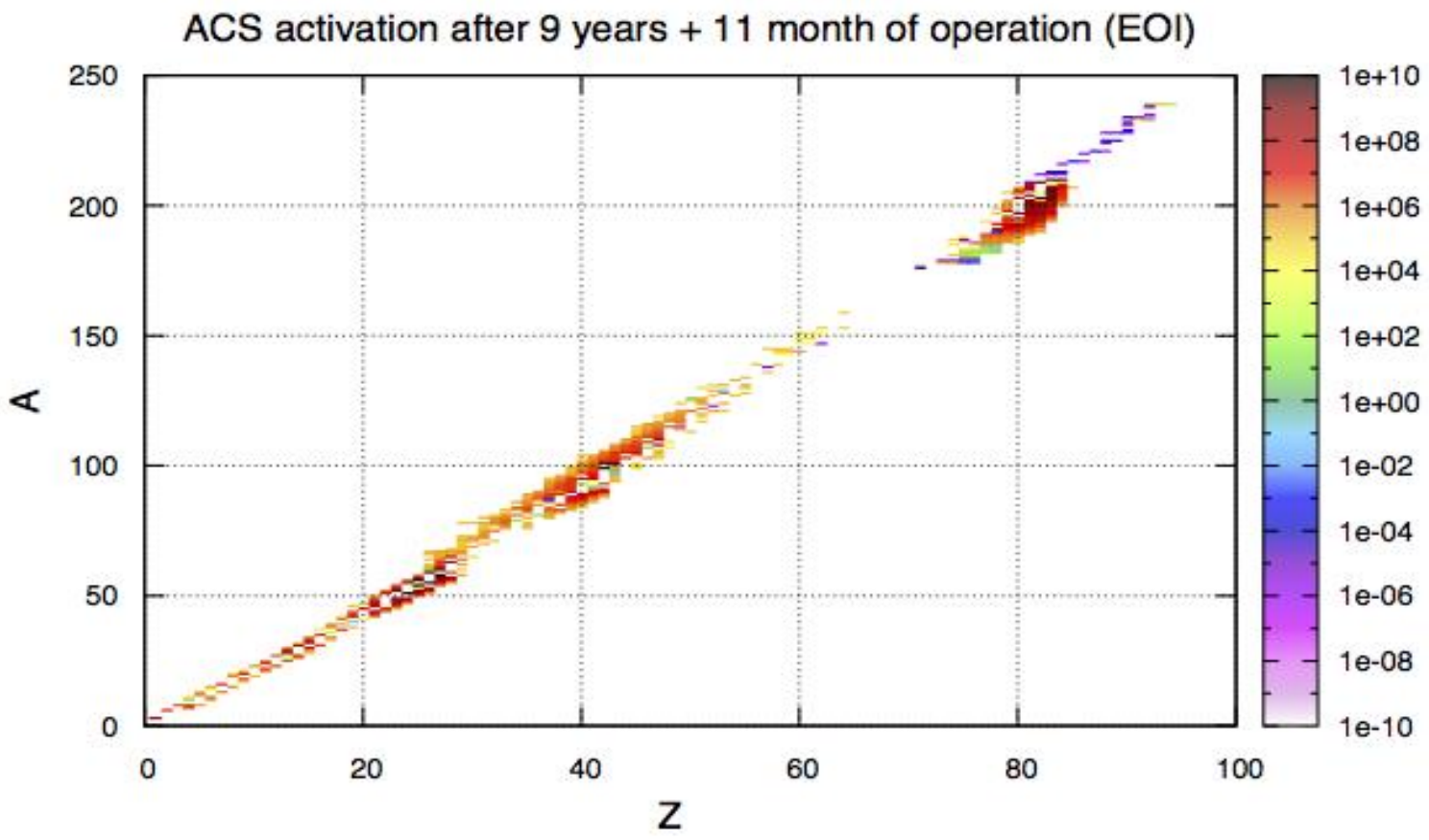
Regions for activation studies in the Reactor Cover:



ACS activation

Activation of the region LBEIna after about 10 y (9 y + 11 m) irradiation

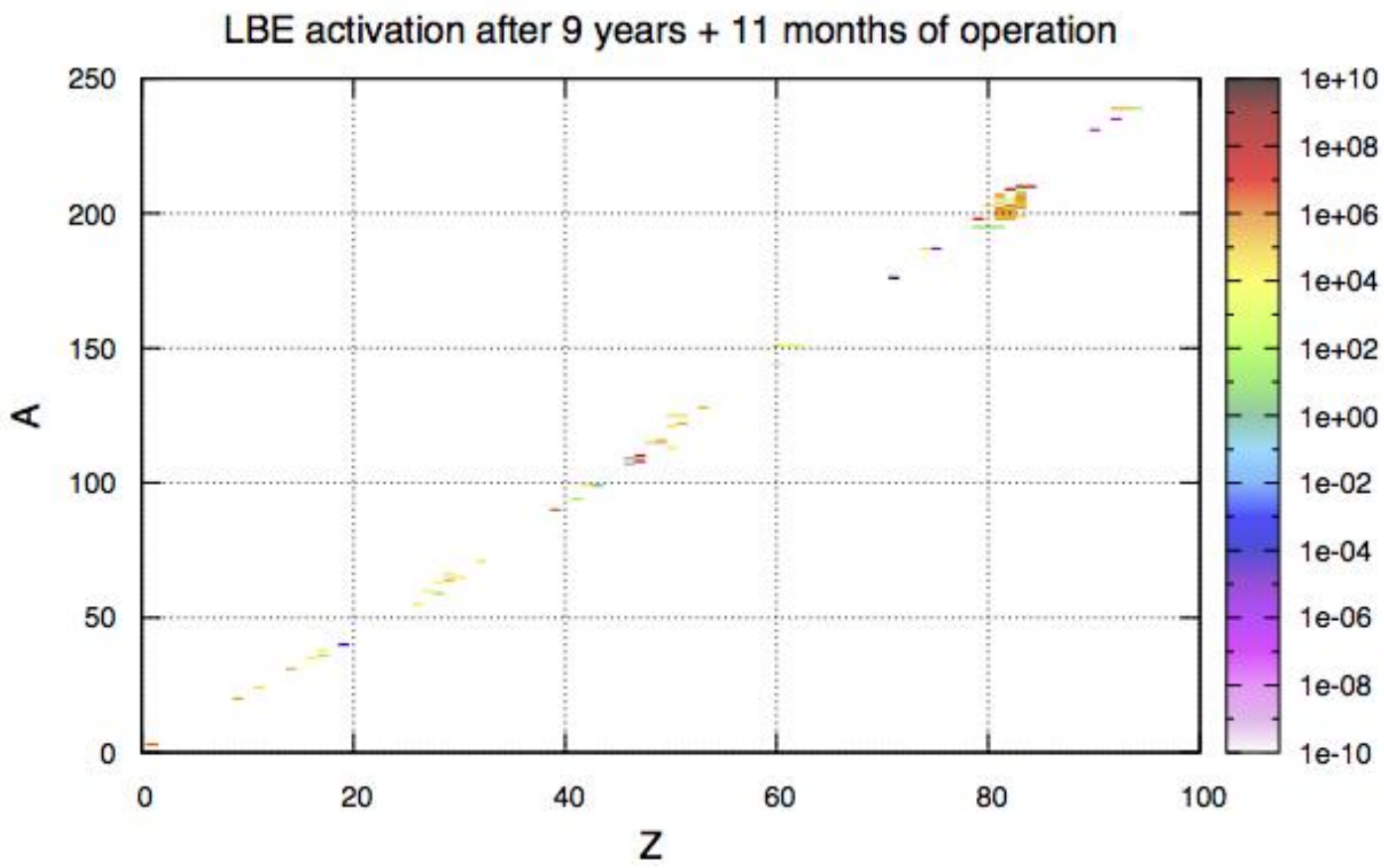
Material: 53% AISI 316L steel at 350 °K + 47% LBE at 350 °K



LBE activation

Activation of the region LBEOk1 after about 10 y (9 y + 11 m) irradiation

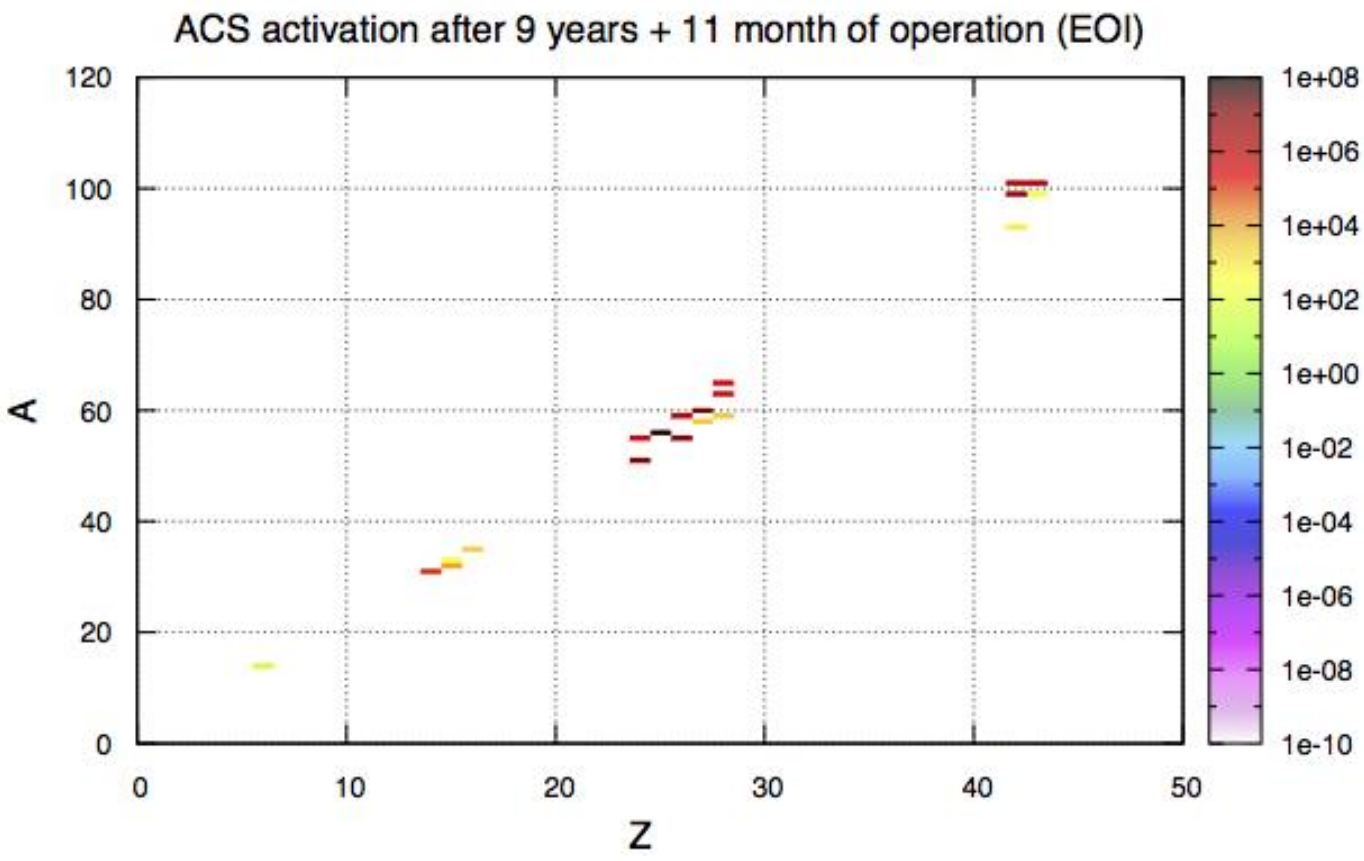
Material: LBE at 350 °K , impurities added



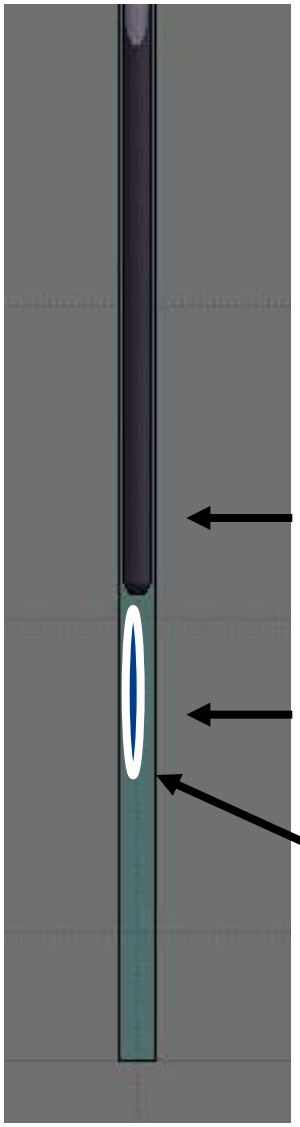
Cover activation

Activation of the region Cov1In after about 10 y (9 y + 11 m) irradiation

Material: 75% AISI 316L Stainless Steel + 25% Nitrogen



Dedicated study around the spallation target



Beam pipe: T91

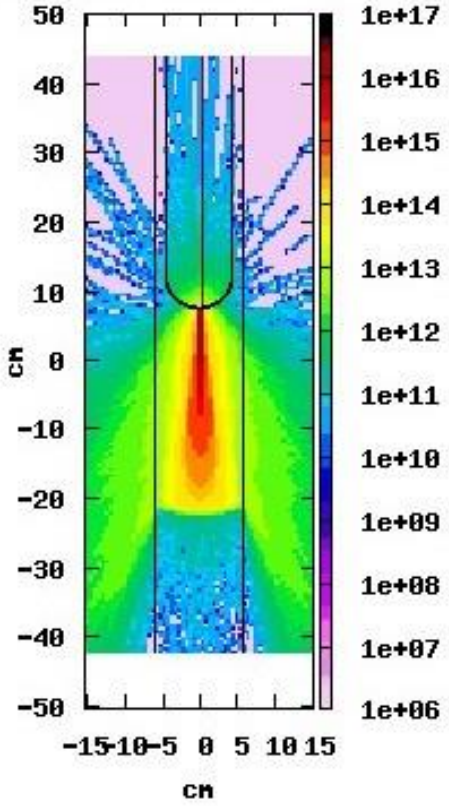
Bulk of the heat deposition

Liquid Lead Bismuth Eutectic Target:
T_{max} = 410 °C

FLUKA and MCNPX Monte Carlo model with <u>only</u> the spallation target (no contribution from the fissions)

Motivation of this work: optimizing the materials around the spallation target via an activation analysis

Proton fluence rate (p/cm^2 per s) (FLUKA)



FLUKA/MCNPX comparison

MCNPX model for the spallation: CEM 03

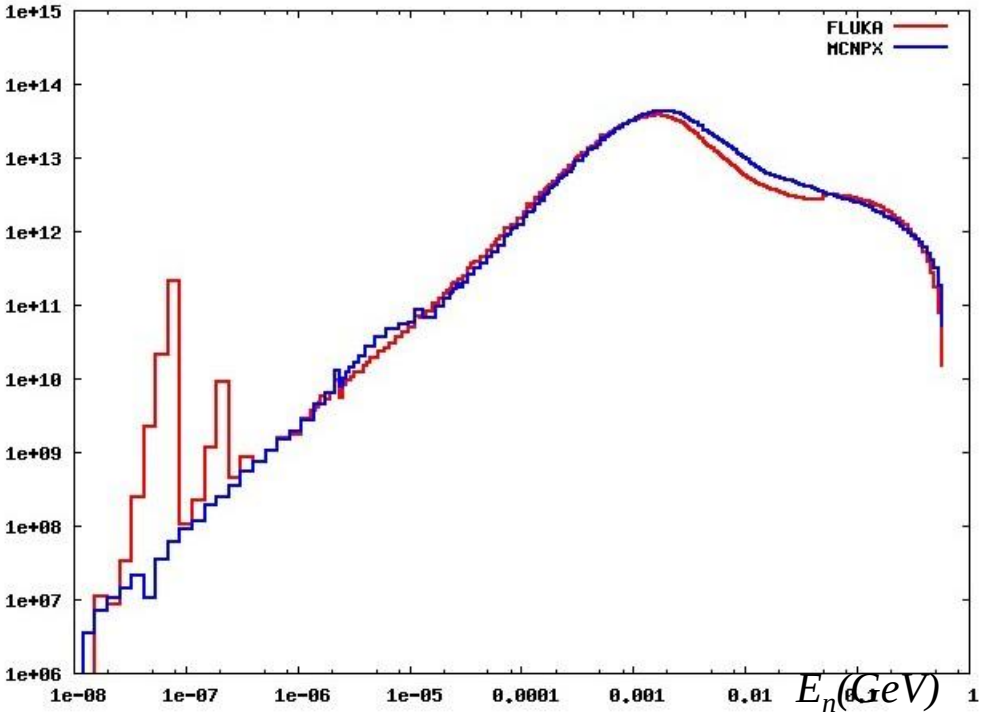
Libraries: JEFF 3.1

Assumed working temperatures and associated libraries:

MOX 1500 K	Jeff3.1-1473
LBE 543,600,643,683 K	Jeff3.1-600
Al 293K	Jeff3.1-293
SS 600K	Jeff3.1-600

Fluence rate of the produced neutrons (n/cm^2 per s):
MCNPX vs FLUKA
(FLUKA: ENDFVII libraries for E_n < 20 MeV)

Neutron fluence rate (n/cm^2 per s)



Fluence rate through the central hot section

Activation of the T91 window (FLUKA simulation)

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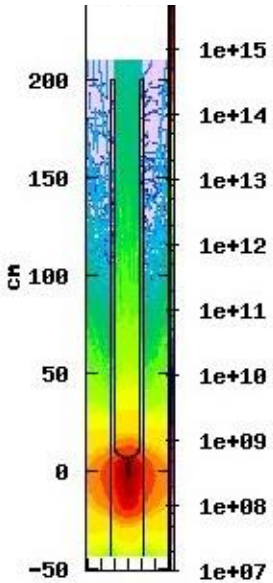
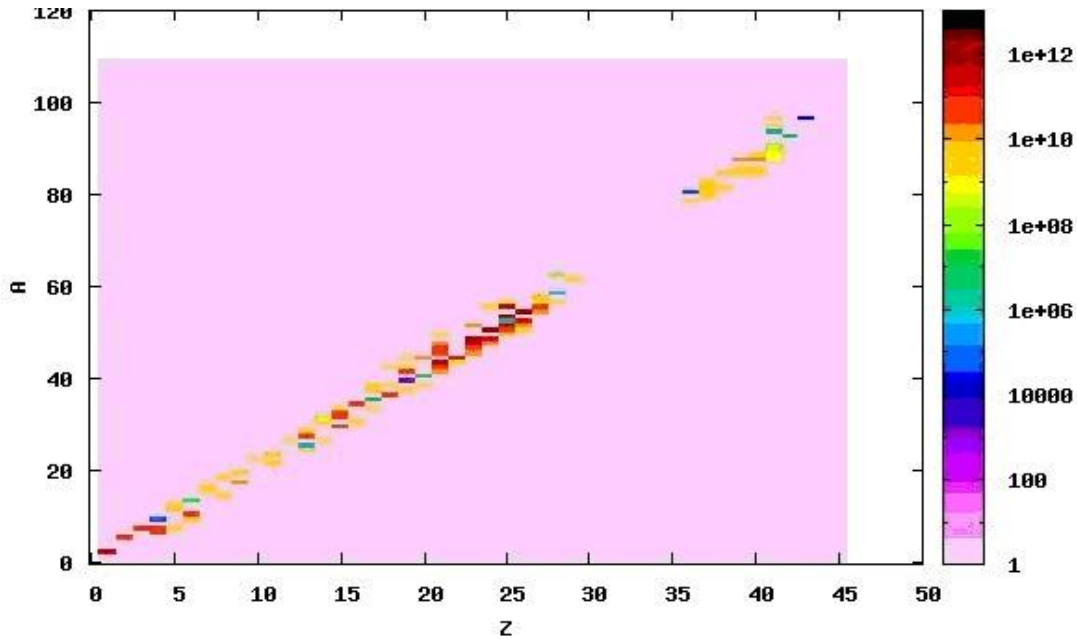
Neutron fluence rate (n/cm^2 per s)



RN contribution to the total specific activity [Bq/cm3]- EOI 15 y



T91 samples	Specific activity [Bq/cm3]					
	EOI 90 days	cooling 1 week	EOI 5 years	cooling 30 days	EOI 15 years	cooling 1 year
Exit window	4.50E+12	1.73E+12	6.95E12	3.28E+12	7.88E+12	2.34E+12
Hexagonal tube (central part)	2.91E+11	1.29E11	5.95E11	3.74E+11	6.70E+11	2.89E+11

These results suggest to investigate other candidate materials in the hot region close to the spallation target

Conclusions

- A two-step method has been developed to assess the core shielding and activation problems at the MYRRHA facility at SCK·CEN in Belgium: starting from the up-to-date models built with the MCNPX Monte Carlo code, suitable source terms have been described to be given in input to a row of FLUKA simulations, to evaluate both the prompt and the residual radiation

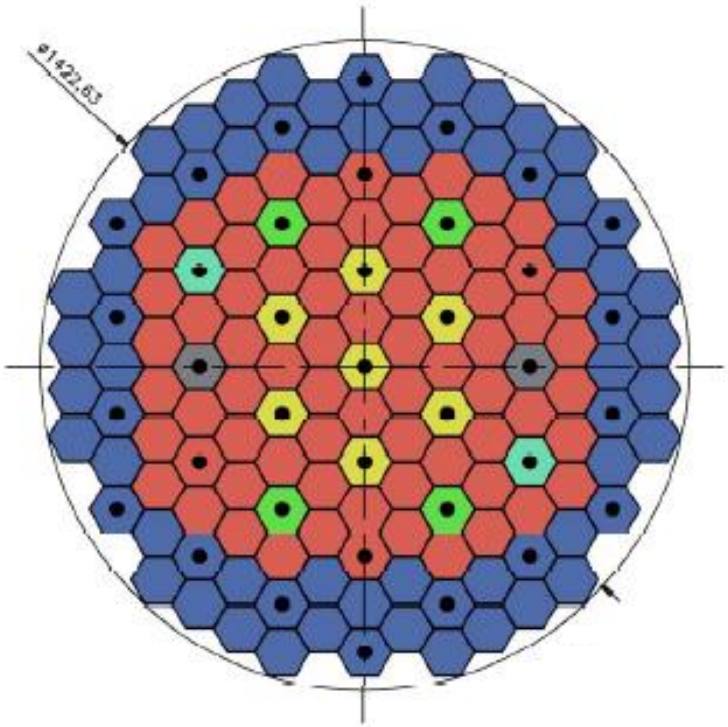
- Calculations with the Myrrha Core model 1.4 and 1.6 have been performed about neutron fluences, doses and activation of key materials around the core in the subcritical configuration.

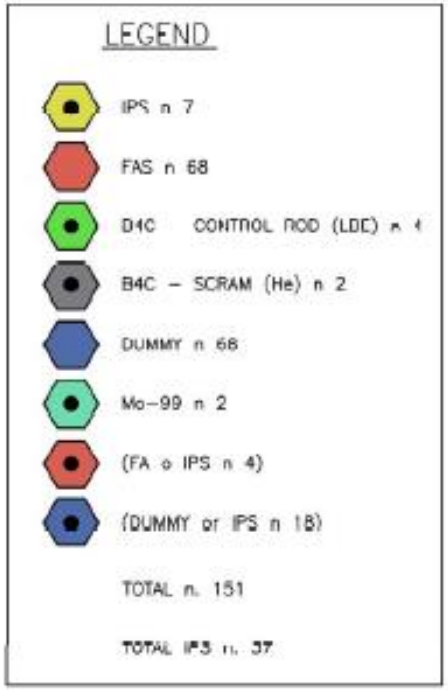
  Results show a general good containment of the radiation. They drove already new technological solutions (ex. Gas choice, Cover design)

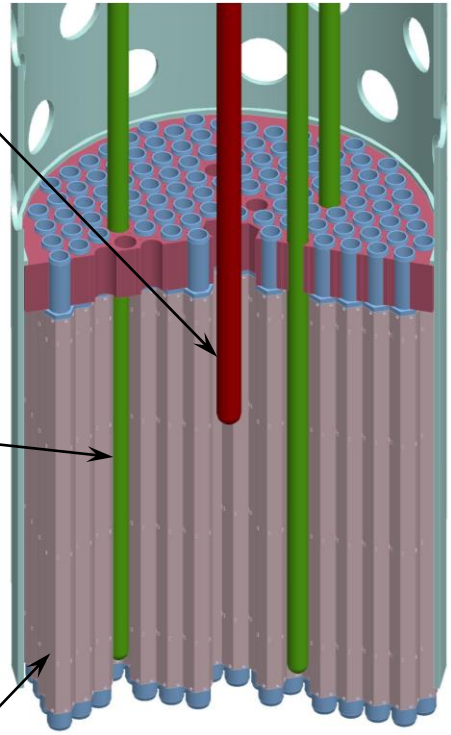
  Activation problems are an issue close to the spallation target.

Reactor layout in the subcritical mode: core

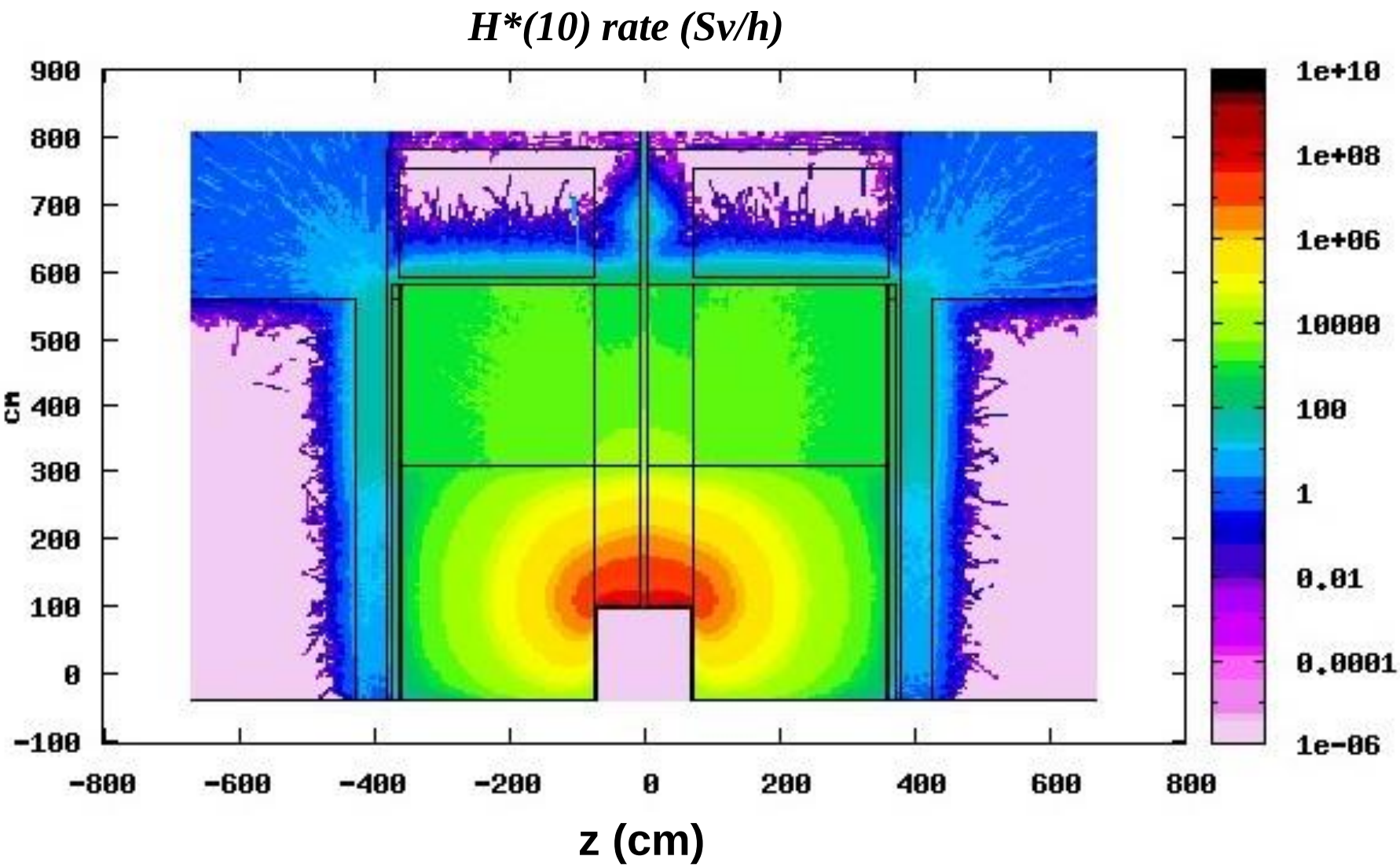
- 151 positions
- Diameter: 1450mm
- **K_{eff} ≈ 0.95** (**ADS mode**)
- **30-35 % MOX fuel**
- 37 multifunctional plugs







Results (III): H*(10) rates



This results caused a new study of the cover design