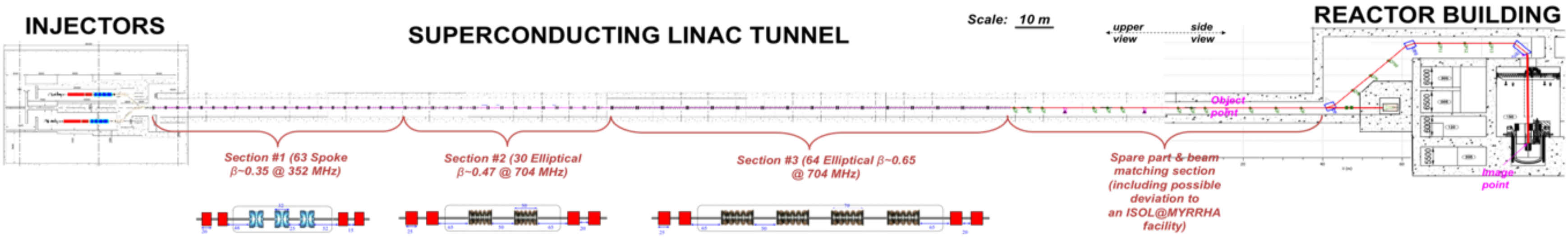
MYRRHA

Multipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications



MYRRHA: a polyvalent research project around an ADS nuclear reactor

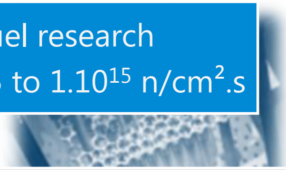
The fast spectrum Pb-Bi cooled nuclear reactor: subcritical and critical configurations

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

Roberto Salemme
ADT - SCK•CEN
Sapienza Università di Roma

Francesco Belloni
NSP - SCK•CEN

MYRRHA: multipurpose irradiation facility



Fuel research
Φ_{tot} = 0.5 to 1.10^{15} n/cm^2.s

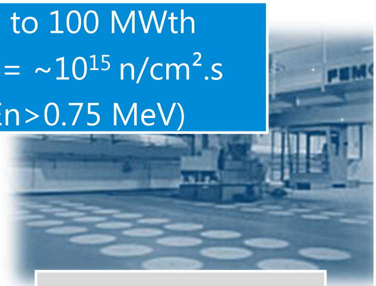
Material research
Φ_{Fast} = 1 to 5.10^{14} n/cm^2.s
(En>1 MeV) in large volumes

Fission GEN IV

Φ = 1 to 5.10^{14} n/cm^2.s
(ppm He/dpa ~ 10)
in medium-large volumes

Fusion

	Challenge	Solution	MYRRHA contribution
Fission	High radiotoxic level waste	Transmutation	ADS demo
Fission GEN IV	Demonstrate concept	Build demonstrators	LFR technology demo Fast spectrum irradiation facility
Fusion	Extreme operating conditions	Material testing & development	Fast spectrum irradiation facility
Fundamental research	Pushing the limits of knowledge	Access to proton beam	Long term experiments with radioactive ion beams (RIB)
Renewable energies	Efficient power electronics	High efficiency transistors (Neutron Transmutation Doped NTD-Si)	Securing NTD-Silicon production
Healthcare	Ageing population	A long term source of medical radioisotopes	Securing radioisotopes production (existing and new ones)



50 to 100 MWth
Φ_{Fast} = ~10^{15} n/cm^2.s
(En>0.75 MeV)

Waste

High energy LINAC
600 MeV – 1 GeV
Long irradiation time

Fundamental research

Φ_{th} = 0.5 to 2.10^{15} n/cm^2.s
(En<0.4 eV)

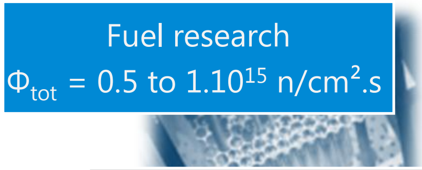
Radioisotopes

Φ_{th} = 0.1 to 1.10^{14} n/cm^2.s
(En<0.4 eV)

Silicon doping

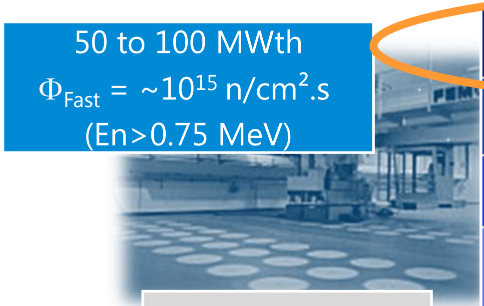
http://myrrha.sckcen.be/en/MYRRHA/Applications

MYRRHA: multipurpose irradiation facility



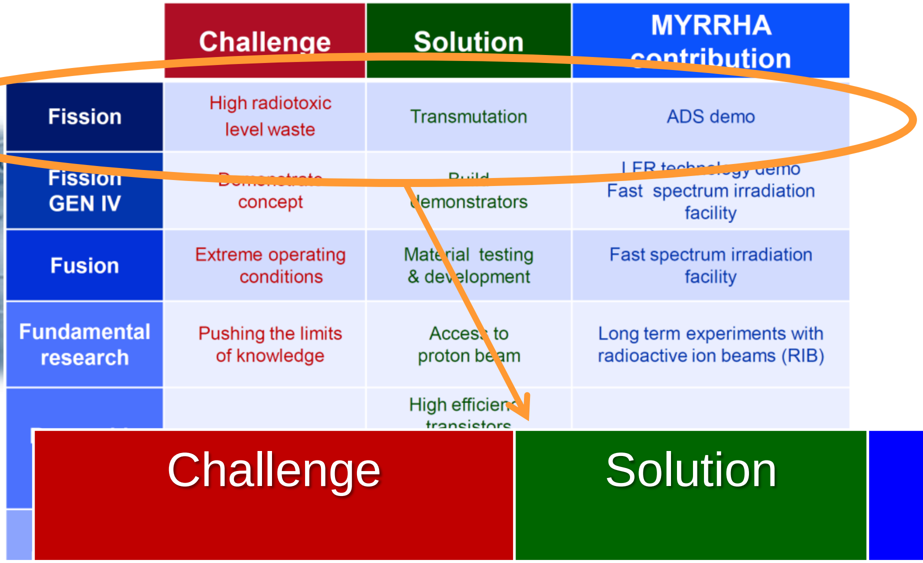
Fuel research
Φ_{tot} = 0.5 to 1.10^{15} n/cm^2.s

Fission GEN IV



50 to 100 MWth
Φ_{Fast} = ~10^{15} n/cm^2.s
(En>0.75 MeV)

Waste



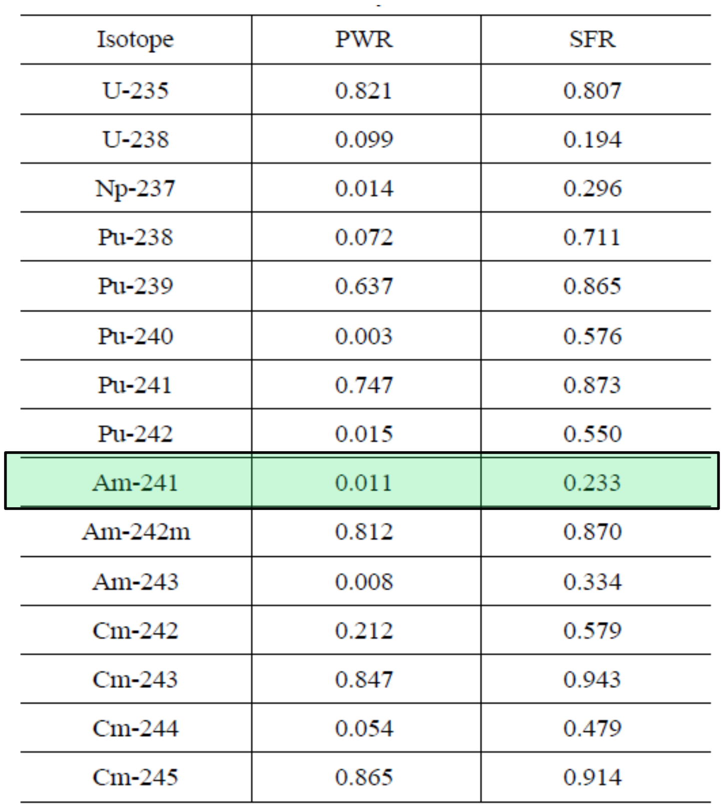
	Challenge	Solution	MYRRHA contribution
Fission	High radiotoxic level waste	Transmutation	ADS demo
Fission GEN IV	Demonstrate concept	Build demonstrators	LFR technology demo Fast spectrum irradiation facility
Fusion	Extreme operating conditions	Material testing & development	Fast spectrum irradiation facility
Fundamental research	Pushing the limits of knowledge	Access to proton beam	Long term experiments with radioactive ion beams (RIB)
		High efficiency transistors	

	Challenge	Solution	MYRRHA contribution
Fission	High radioactive level waste	Transmutation	ADS demo

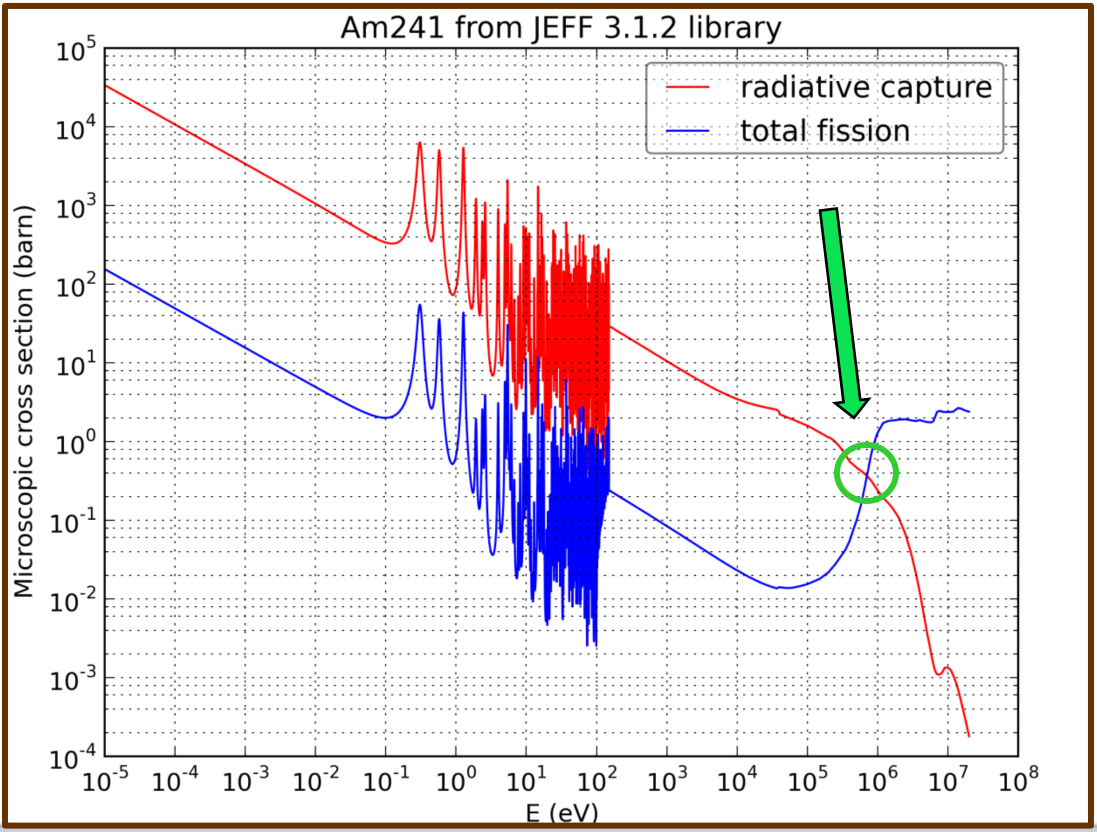
http://myrrha.sckcen.be/en/MYRRHA/Applications

Fast neutrons are fundamental for transmutation

- In order to be transmuted Minor Actinides (MAs) have to be fissioned
- The ratio between fissions and captures is higher at high energy (fast spectrum)
- Increase of fertile fissions: more neutrons available to transmutation



Isotope	PWR	SFR
U-235	0.821	0.807
U-238	0.099	0.194
Np-237	0.014	0.296
Pu-238	0.072	0.711
Pu-239	0.637	0.865
Pu-240	0.003	0.576
Pu-241	0.747	0.873
Pu-242	0.015	0.550
Am-241	0.011	0.233
Am-242m	0.812	0.870
Am-243	0.008	0.334
Cm-242	0.212	0.579
Cm-243	0.847	0.943
Cm-244	0.054	0.479
Cm-245	0.865	0.914



Critical and subcritical configuration

- The fission reaction chain can be obtained either in critical or subcritical configuration:

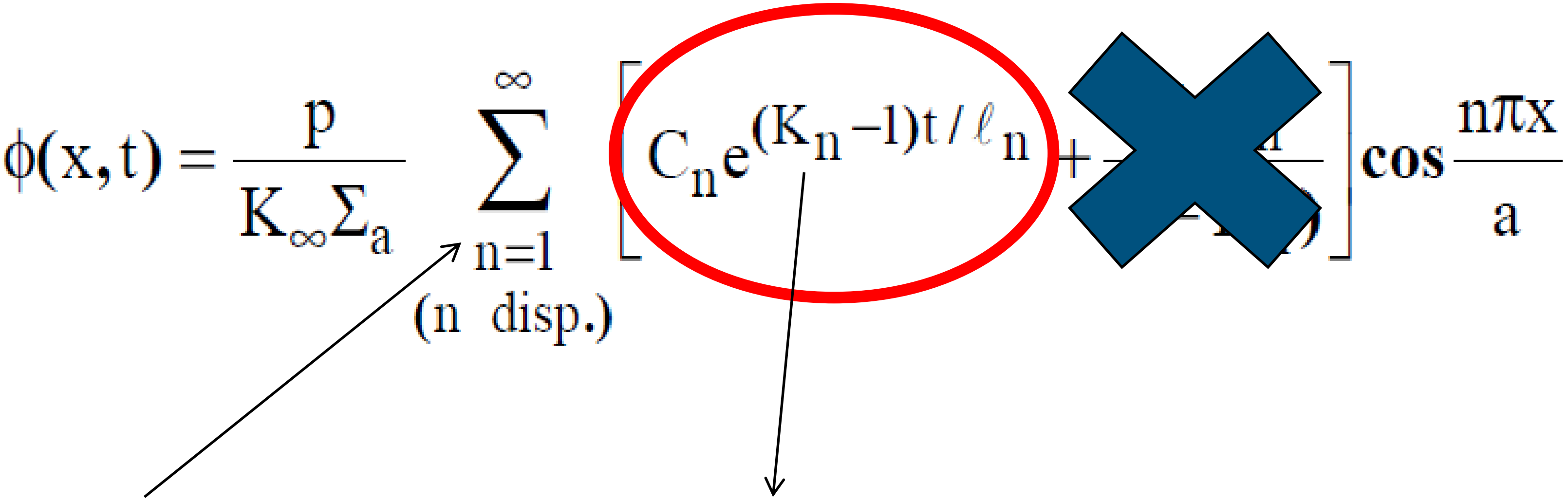
$$\phi(x,t) = \frac{p}{K_\infty \Sigma_a} \sum_{\substack{n=1\\(n\ \text{disp.})}}^{\infty} \left[C_n e^{(K_n-1)t/\ell_n} + \frac{K_n S_n}{(1-K_n)} \right] \cos\frac{n\pi x}{a}$$

Fourier's serie

Example 1: solution for a
thermal neutron flux in an
infinite absorbing slab
(A. Gandini lectures)

Critical and subcritical configuration

- The fission reaction chain can be obtained either in critical or subcritical configuration:



$$\phi(x,t) = \frac{p}{K_\infty \Sigma_a} \sum_{\substack{n=1\\(n\ \text{disp.})}}^{\infty} \left[\boxed{C_n e^{(K_n-1)t/\ell_n}} + \xcancel{\frac{\quad}{\quad}} \right] \cos\frac{n\pi x}{a}$$

Fourier's serie

K_1 = 1
CRITICAL
CONFIGURATION

Example 1: solution for a thermal neutron flux in an infinite absorbing slab (A. Gandini lectures)

Critical and subcritical configuration

- The fission reaction chain can be obtained either in critical or subcritical configuration:

$$\phi(x,t) = \frac{p}{K_\infty \Sigma_a} \sum_{\substack{n=1 \\ (n\ \text{disp.})}}^{\infty} \left[\cancel{C_n e^{\cdots t/\ell_n}} + \boxed{\frac{K_n S_n}{(1-K_n)}} \right] \cos\frac{n\pi x}{a}$$

Fourier's serie

$K_1 < 1, S > 0$

SUBCRITICAL CONFIGURATION

Example 1: solution for a thermal neutron flux in an infinite absorbing slab (A. Gandini lectures)

Intrinsic safety of the ADS

Example 2: Spherical reactor, two energetic groups
of neutrons, static solution
(A. Ottonello, Master thesis)

$$\begin{cases} \Phi_1(r) = \frac{1}{r}\sum_{n=1}^{\infty} \boxed{\frac{s_n}{D_1}} \frac{\left(\frac{n\pi}{R}\right)^2 - \delta}{\left[\left(\left(\frac{n\pi}{R}\right)^2 - \alpha\right)\left(\left(\frac{n\pi}{R}\right)^2 - \delta\right) - \xi\gamma\right]} \sin\frac{n\pi r}{R} \\ \Phi_2(r) = \frac{1}{r}\sum_{n=1}^{\infty} \boxed{\frac{\gamma s_n}{D_1}} \frac{1}{\left[\left(\left(\frac{n\pi}{R}\right)^2 - \alpha\right)\left(\left(\frac{n\pi}{R}\right)^2 - \delta\right) - \xi\gamma\right]} \sin\frac{n\pi r}{R} \end{cases}$$

Φ_1: thermal neutron flux
Φ_2: fast neutron flux

source off → **reactor off !!**

Easy power control

ADS reactor: rather a *necessity* than a *virtue*

- On the contrary a big load of MAs can jeopardize the control of a critical reactor because of:

1) Reduced delayed neutron fractions, β (due also to the reduction of ^{238}U) and reduced margin to prompt criticality ($\rho = \beta$)

$$\psi(\mathbf{r},t) = \psi_o(\mathbf{r}) \sum_{m=0}^{M} A_m e^{\omega_m t}$$

$$\boxed{T} = \frac{1}{\rho}\left[\frac{\ell}{K_{eff}} + \sum_{i=1}^{M} \frac{\boxed{\beta_i}}{\lambda_i}\right]$$

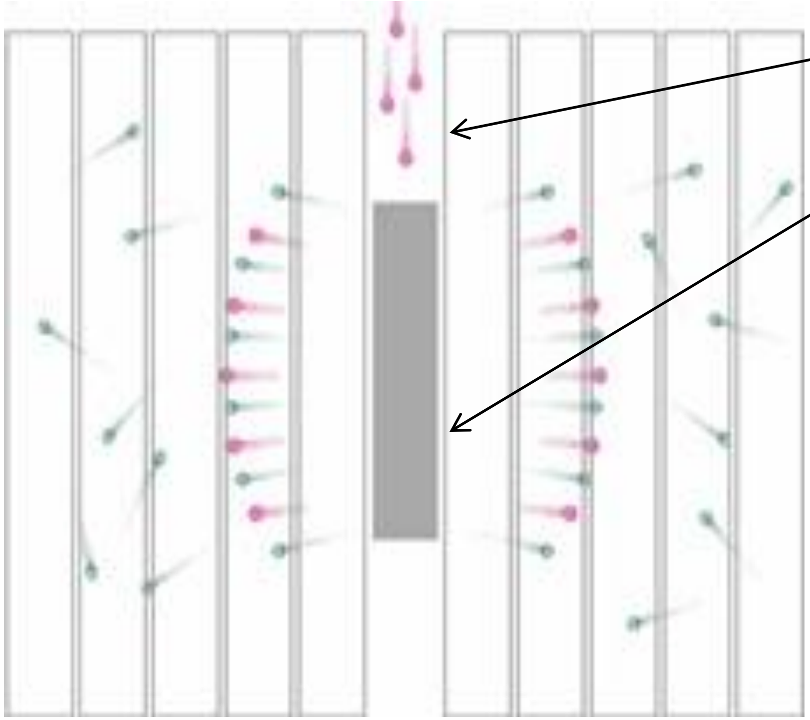
Characteristic period of the reactor

2) Doppler feedback reduced with increasing amount of MAs

The ADS can transmute big loads of MAs without losing safety and this solution is needed for heavily MA loaded core (>10%)

Neutron source by spallation reaction

Spallation

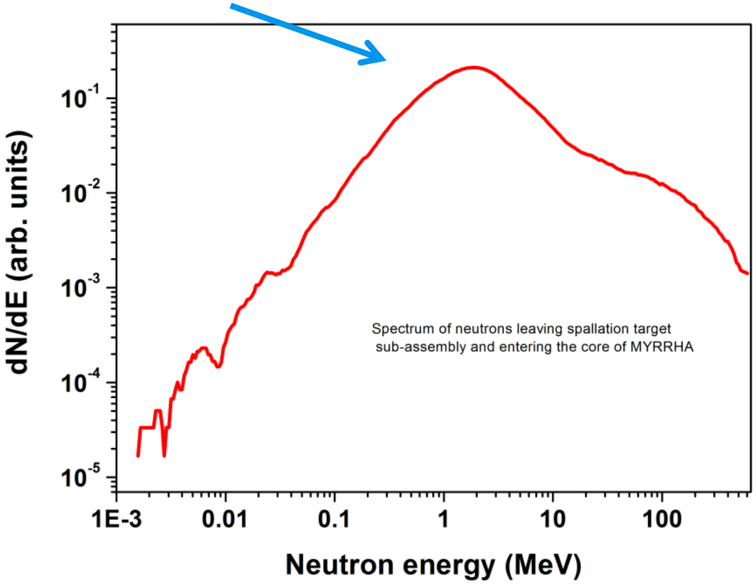


Incoming protons at 600 MeV

Spallation target (HM)

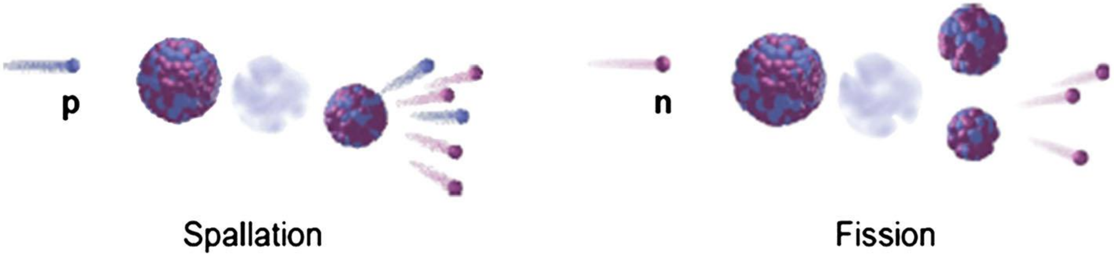
15 neutrons / proton

Spectrum: conventional fast spectrum (Max energy at 2 MeV) + a 3% neutrons tail towards the impinging protons energy



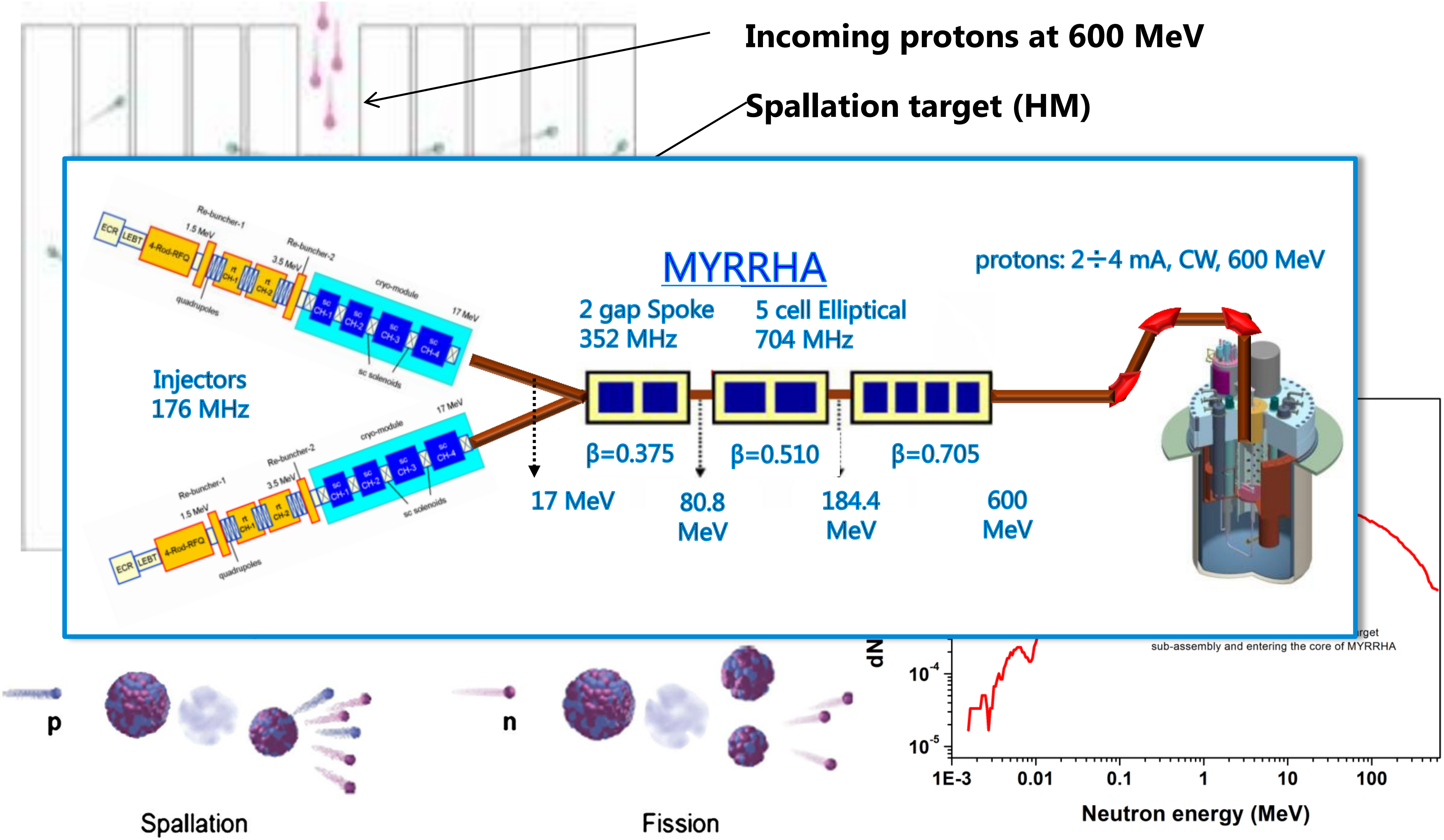
Spectrum of neutrons leaving spallation target sub-assembly and entering the core of MYRRHA

Spallation + Fission



Neutron source by spallation reaction

Spallation



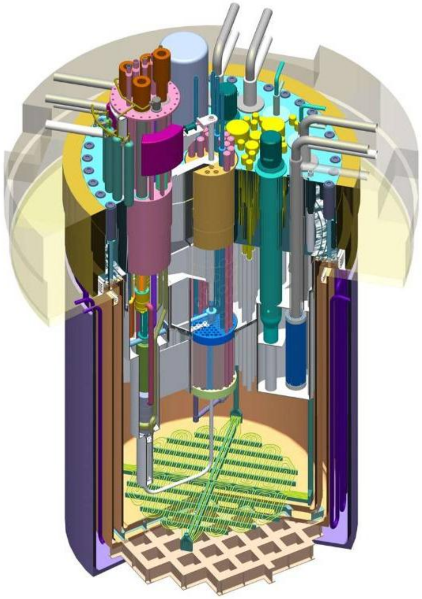
Incoming protons at 600 MeV

Spallation target (HM)

Reactor design rationale

Objectives	**Requirements**	**Choices**
Flexible Fast Spectrum Irradiation facility	•1.10^{15} n/cm^{2}s (>0.75 MeV) in large volumes	• small spallation target • LM cooling
	•availability (65%) •flexibility	• pool-type • in-vessel storage • FA manipulation beneath core • in-vessel inspection & repair • IPS manipulation above core • Replaceability • HLM cooling
	• no high temperatures required	• LBE cooling (T_m = 123 ° C)

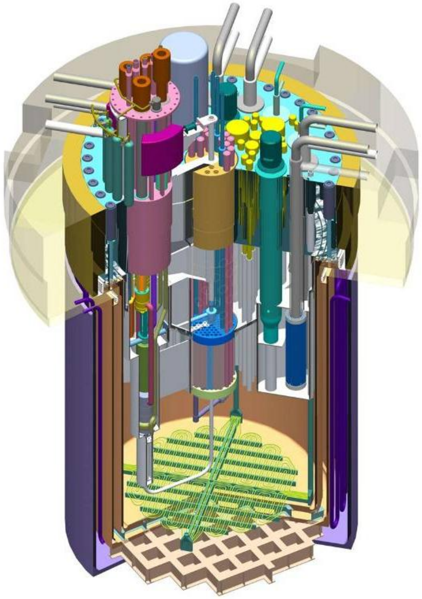
Design History of the MYRRHA reactor



Draft 2

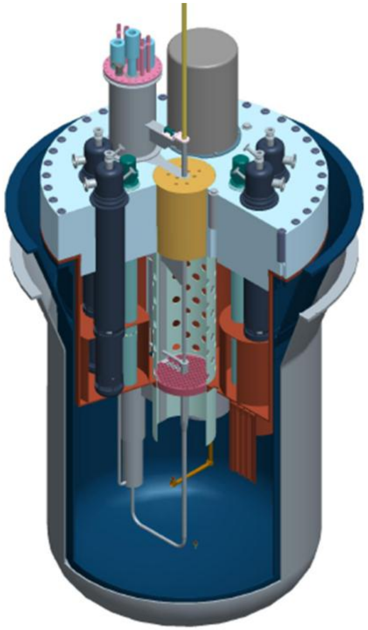
2005

Design History of the MYRRHA reactor



Draft 2

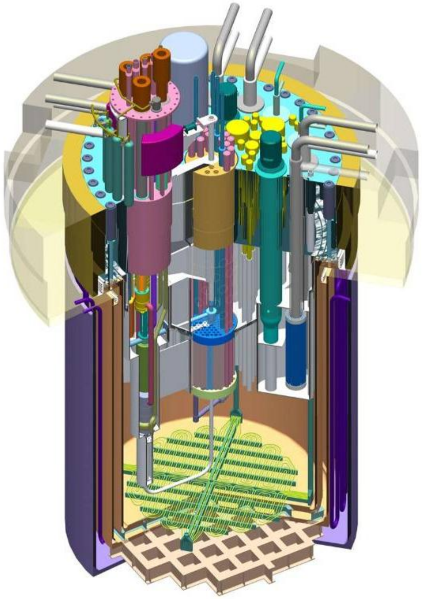
2005



XT-ADS

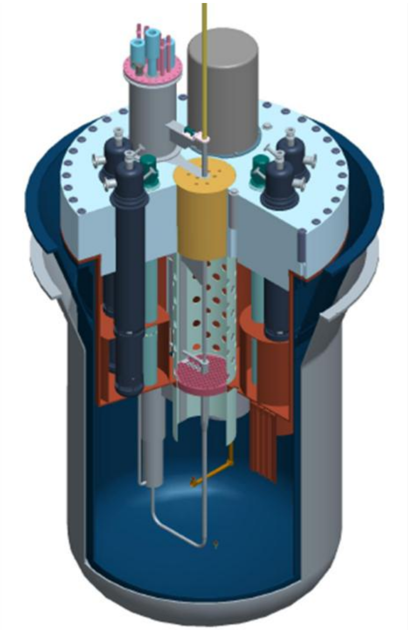
2009

Design History of the MYRRHA reactor



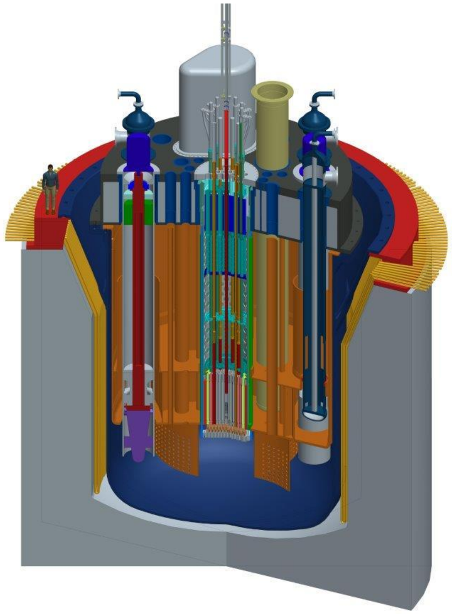
Draft 2

2005



XT-ADS

2009

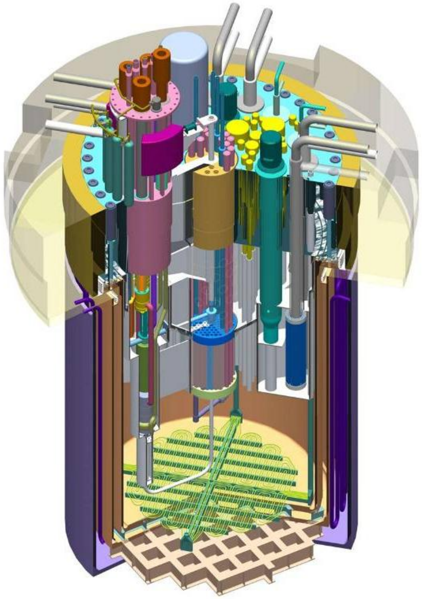


FASTEF

(**CDT Result**)

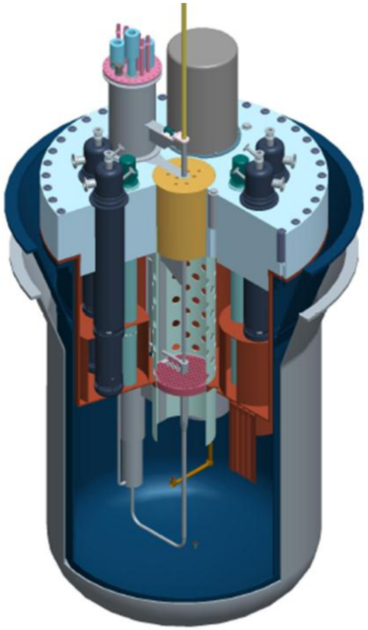
2012

Design History of the MYRRHA reactor



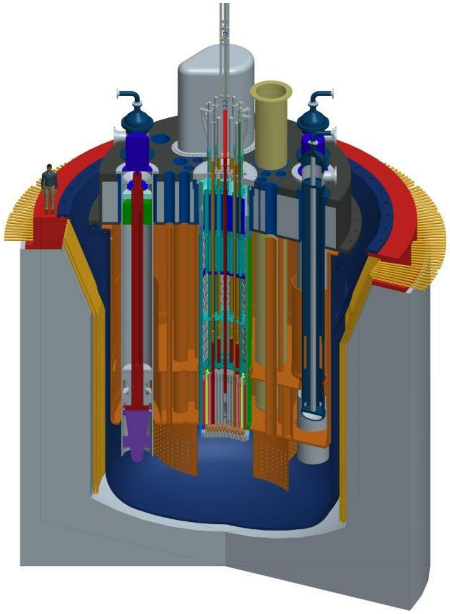
Draft 2

2005



XT-ADS

2009



FASTEF

(**CDT Result**)

2012

Rev. 1.6

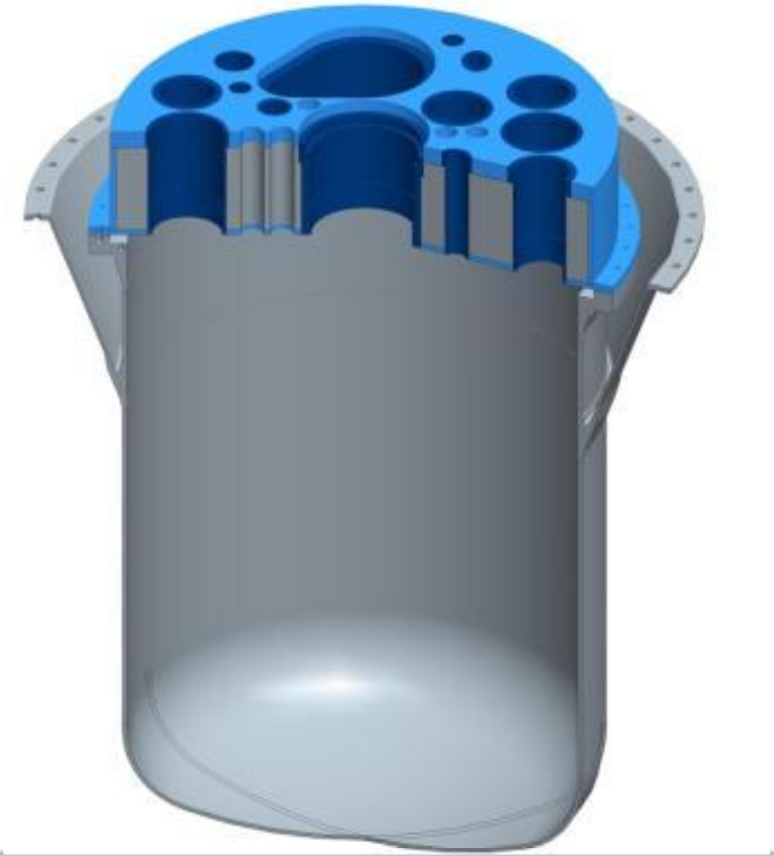
2014

Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM

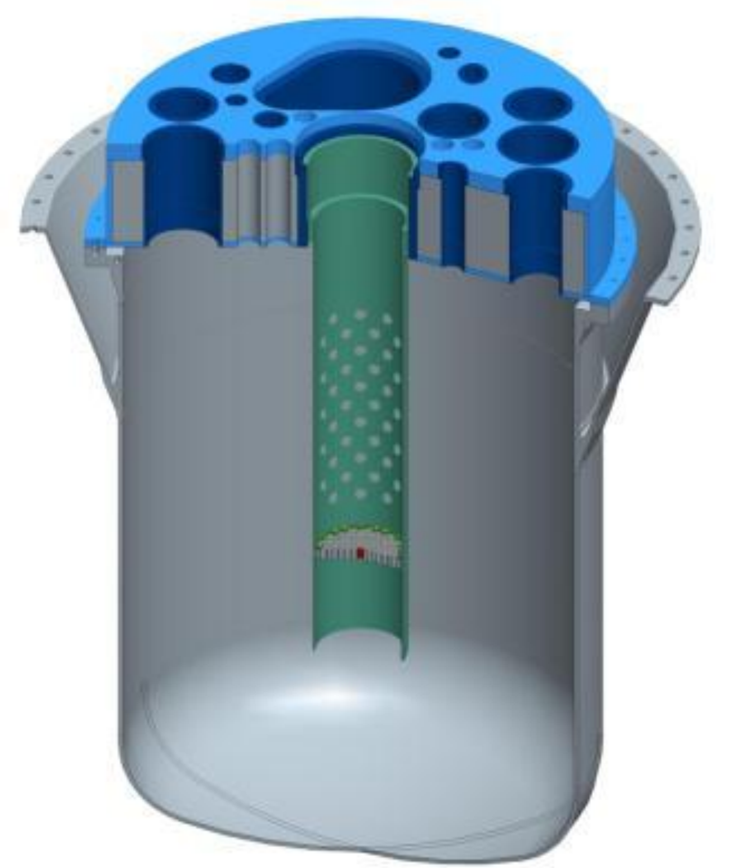
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
    - Core Barrel
    - Core Support Plate
    - Jacket
- Core
    - Reflector Assemblies
    - Dummy Assemblies
    - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
    - Core Plug
    - Multifunctional Channels (CR, SR , Mo-99)
    - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
    - IVFS
    - IVFHM



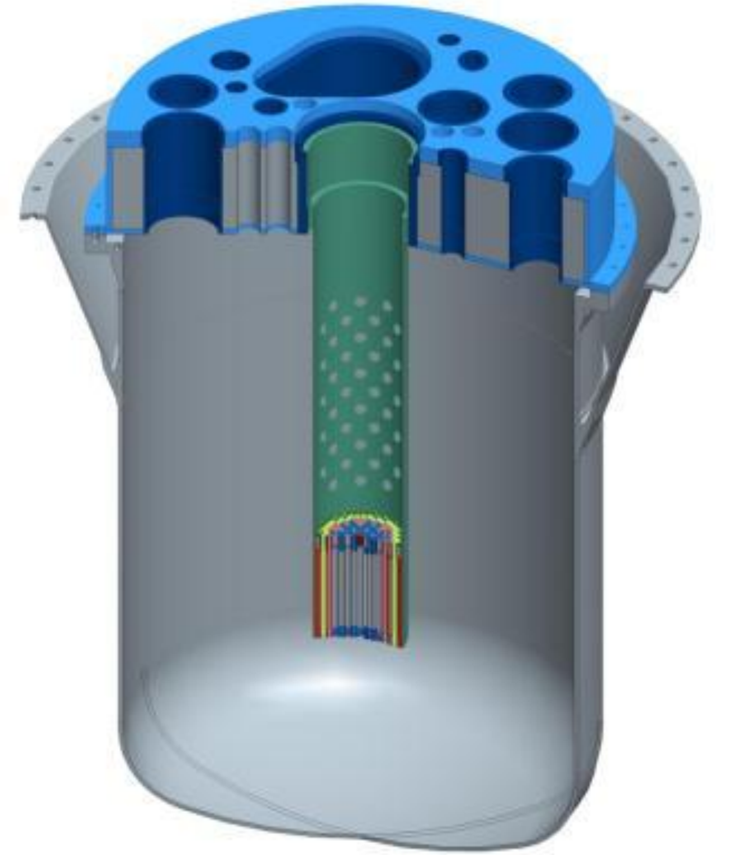
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



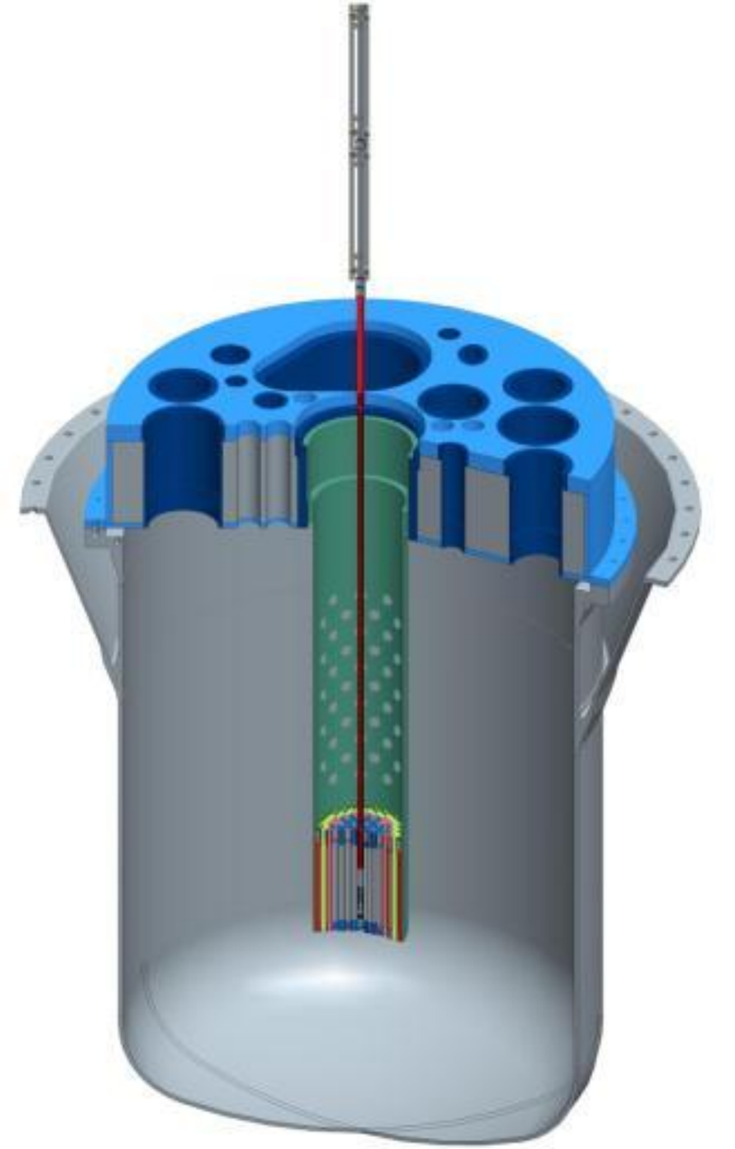
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



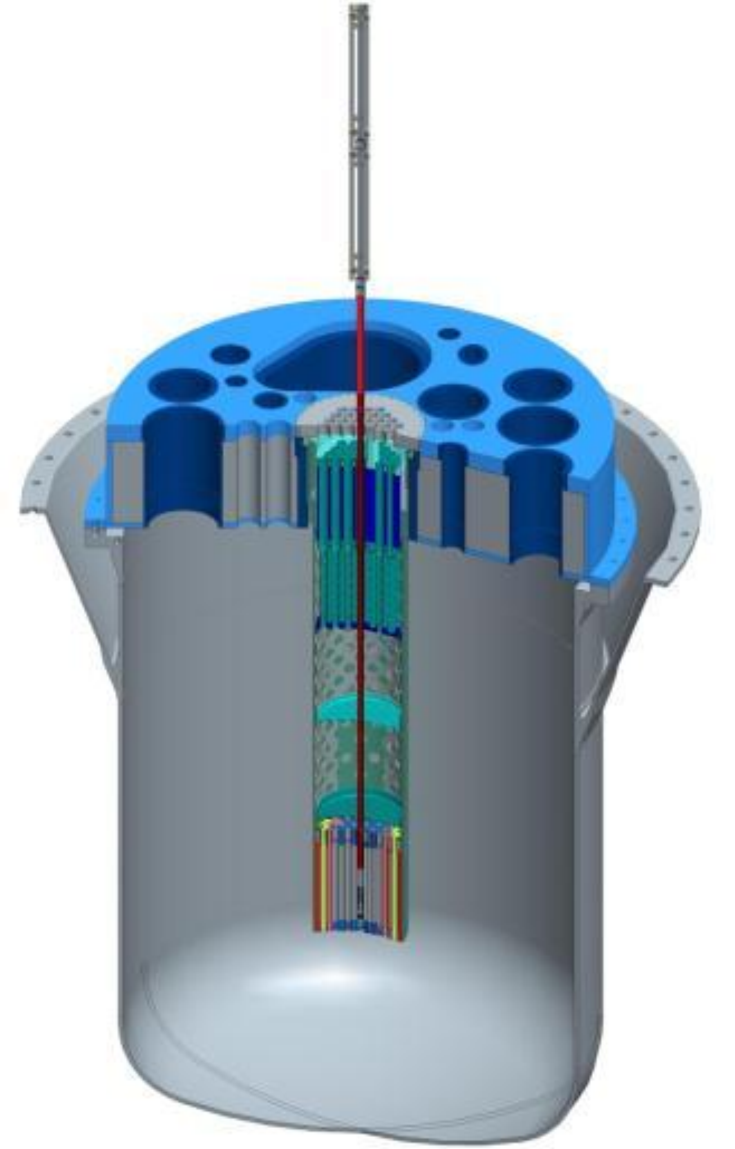
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



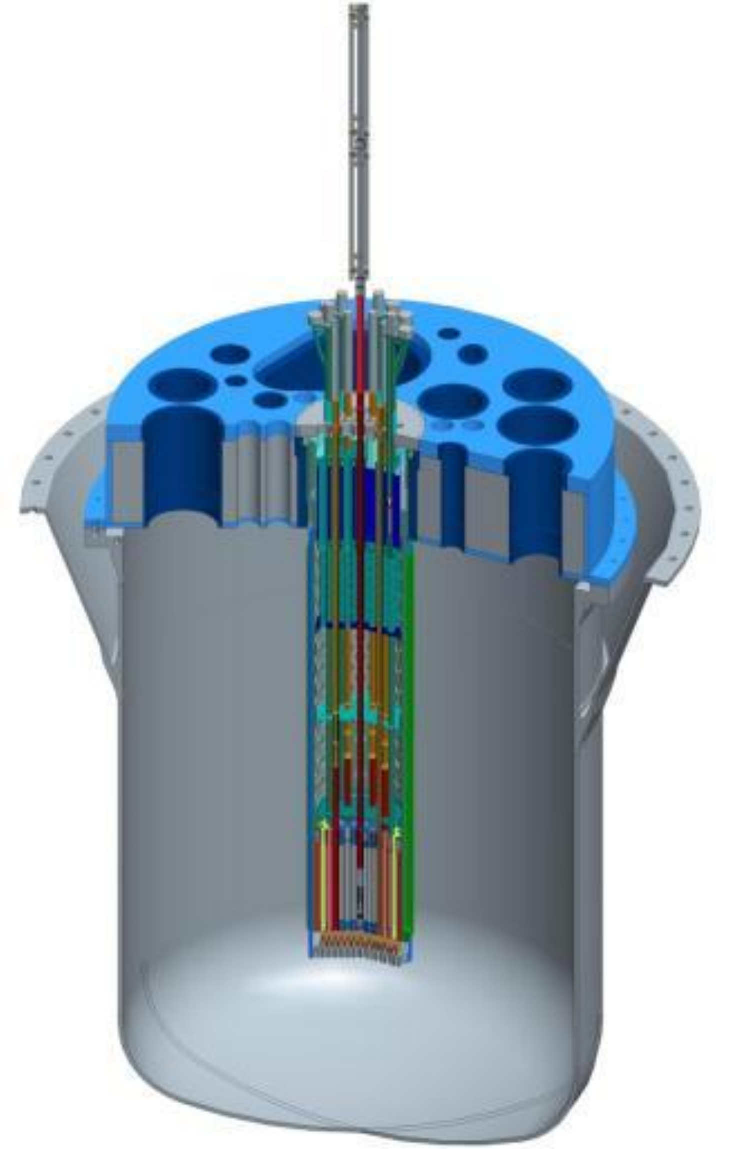
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



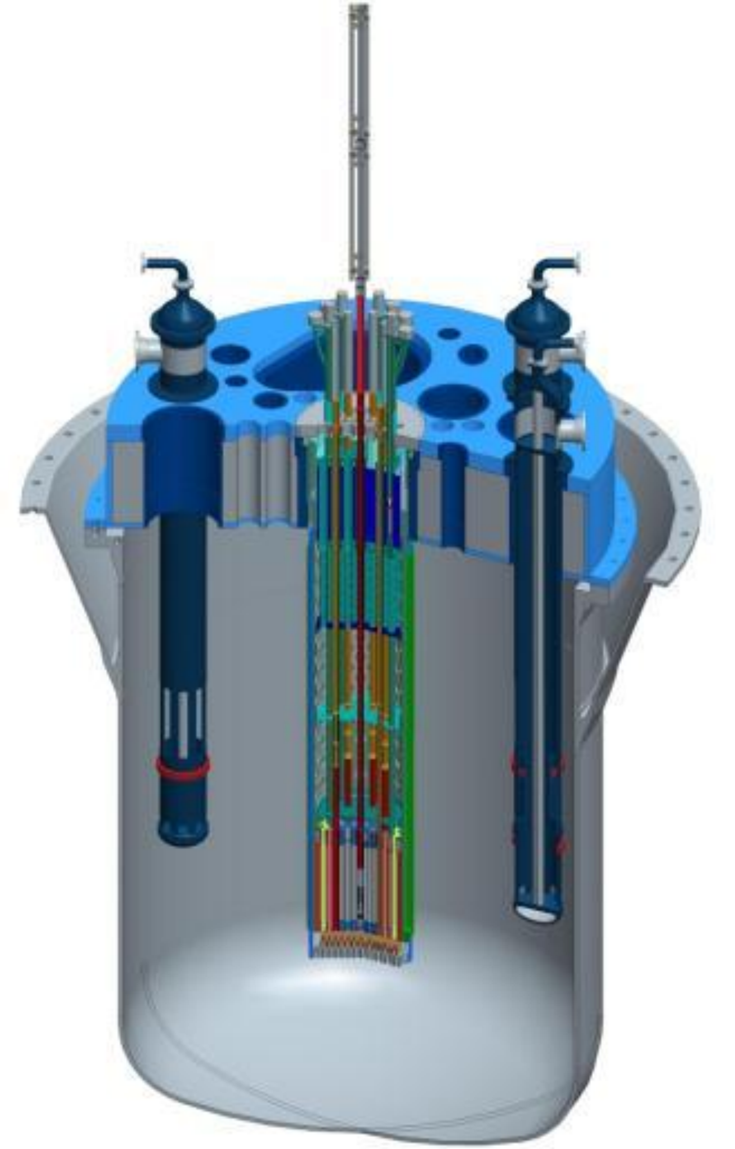
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



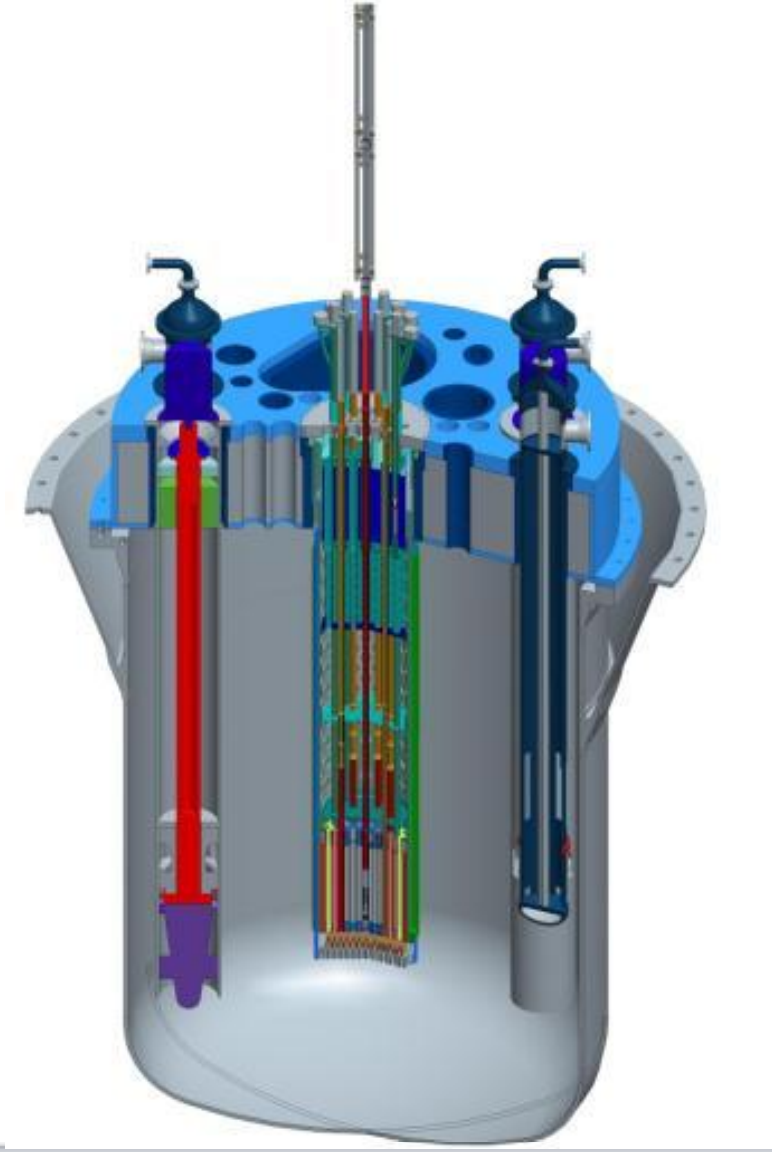
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



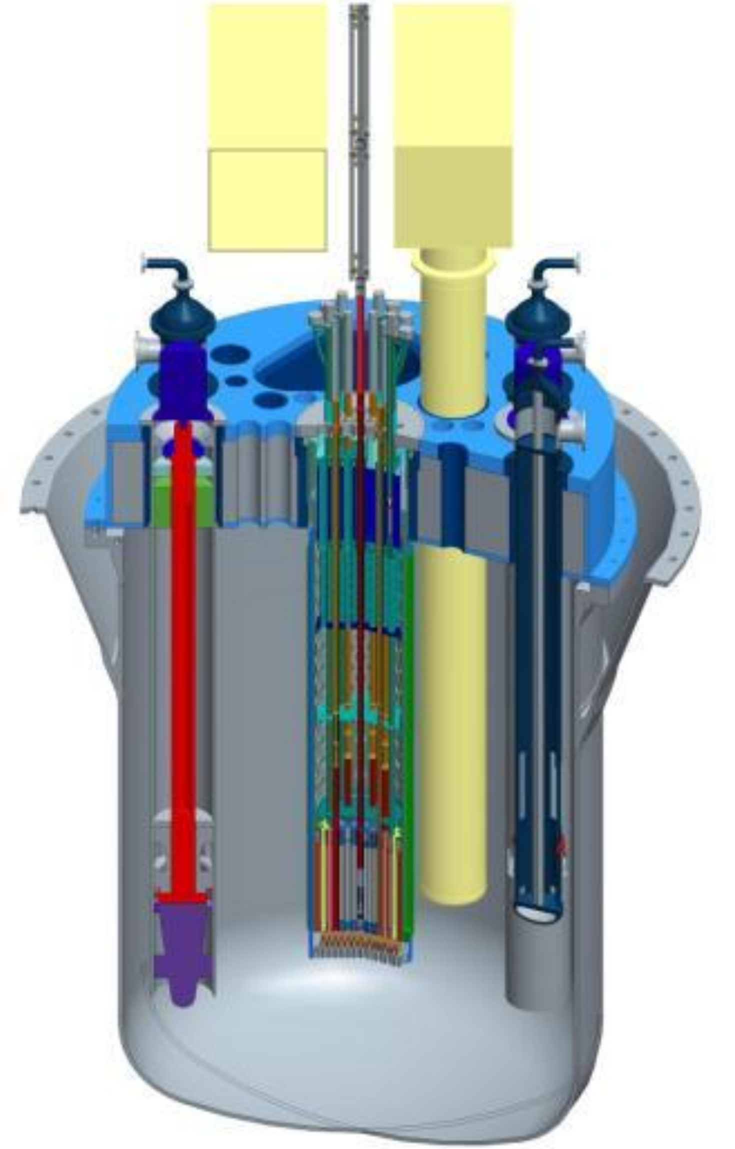
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



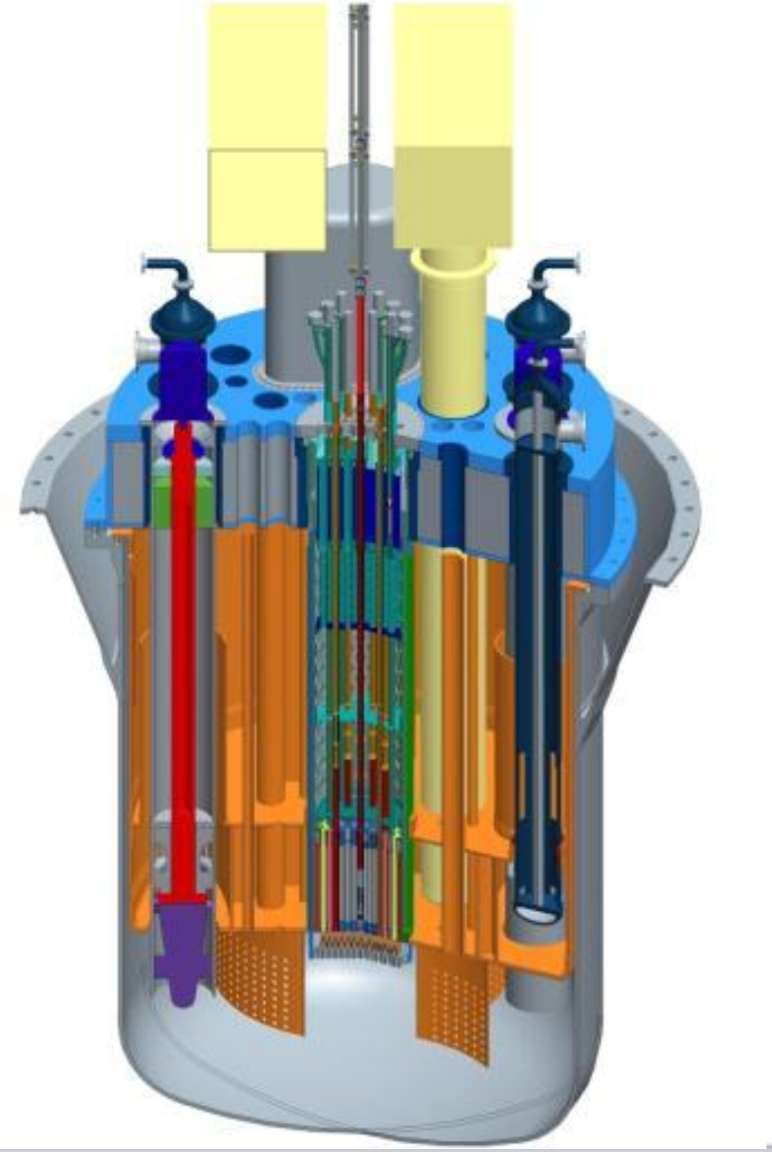
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



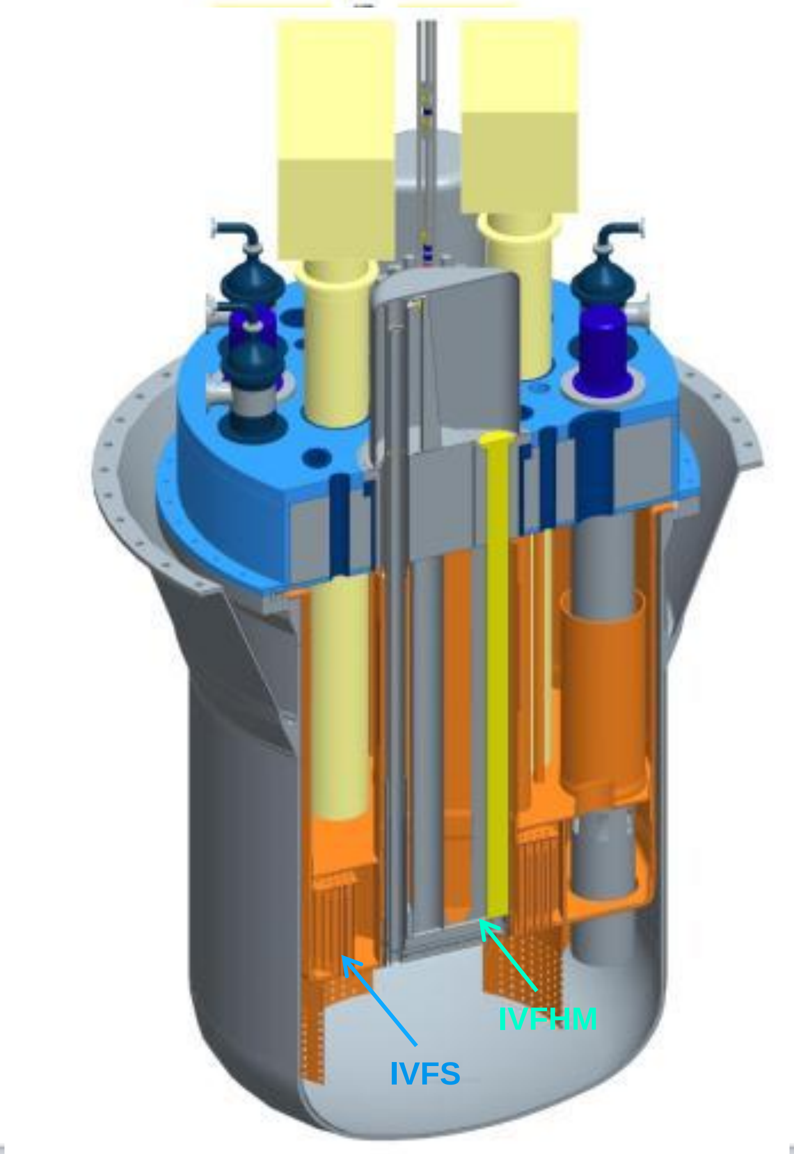
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



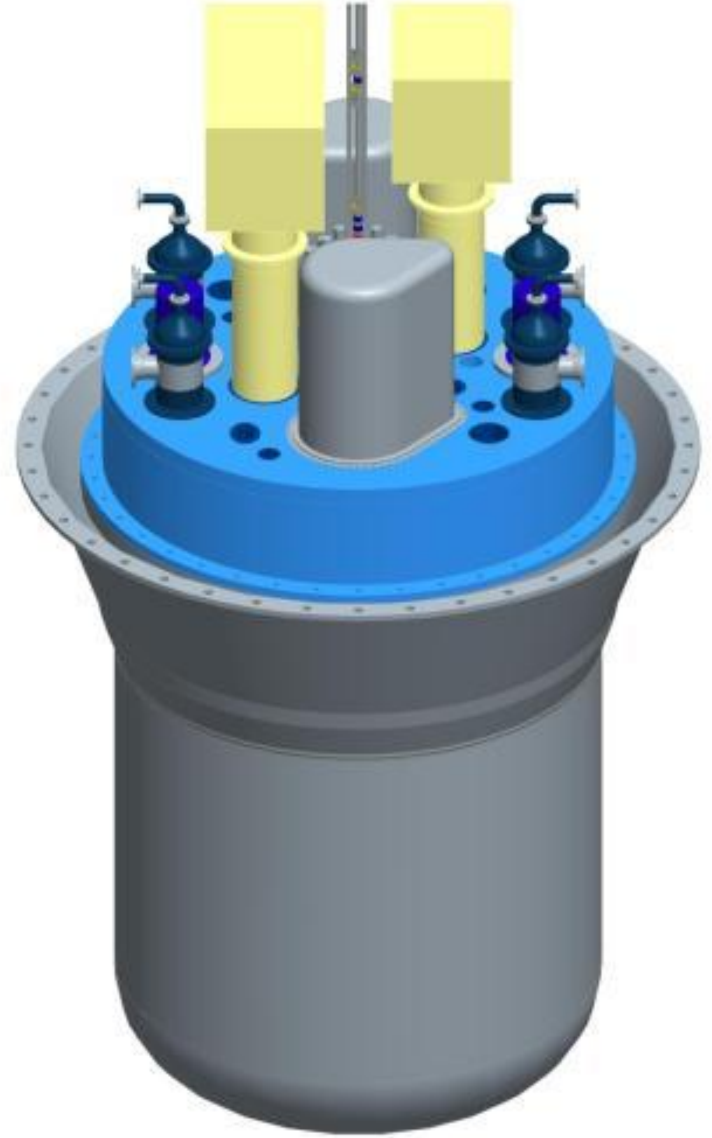
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM

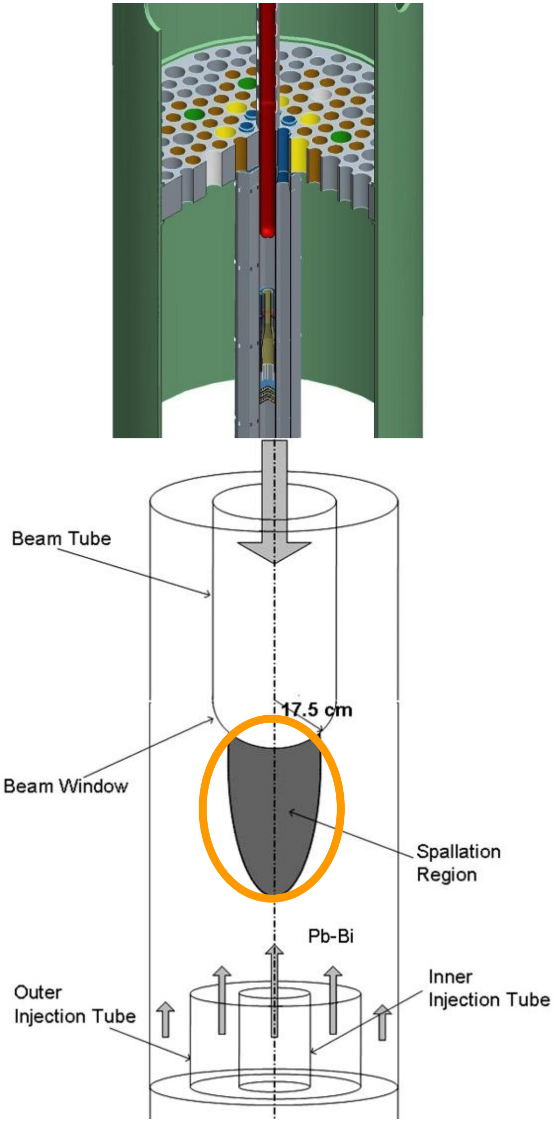


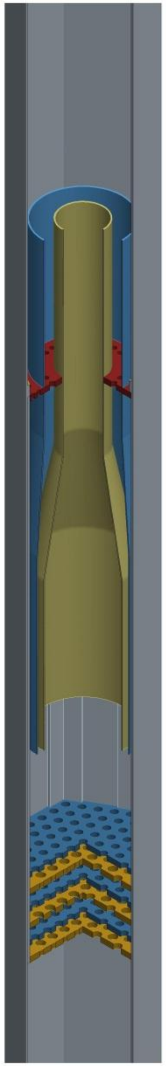
Reactor Design

- Reactor Vessel
- Reactor Cover
- Core Support Structure
  - Core Barrel
  - Core Support Plate
  - Jacket
- Core
  - Reflector Assemblies
  - Dummy Assemblies
  - Fuel Assemblies
- Spallation Target Assembly and Beam Line
- Above Core Structure
  - Core Plug
  - Multifunctional Channels (CR, SR , Mo-99)
  - Core Restraint System
- Primary Heat Exchangers
- Primary Pumps
- Si-doping Facility
- Diaphragm
  - IVFS
  - IVFHM



Spallation target window in the reactor core

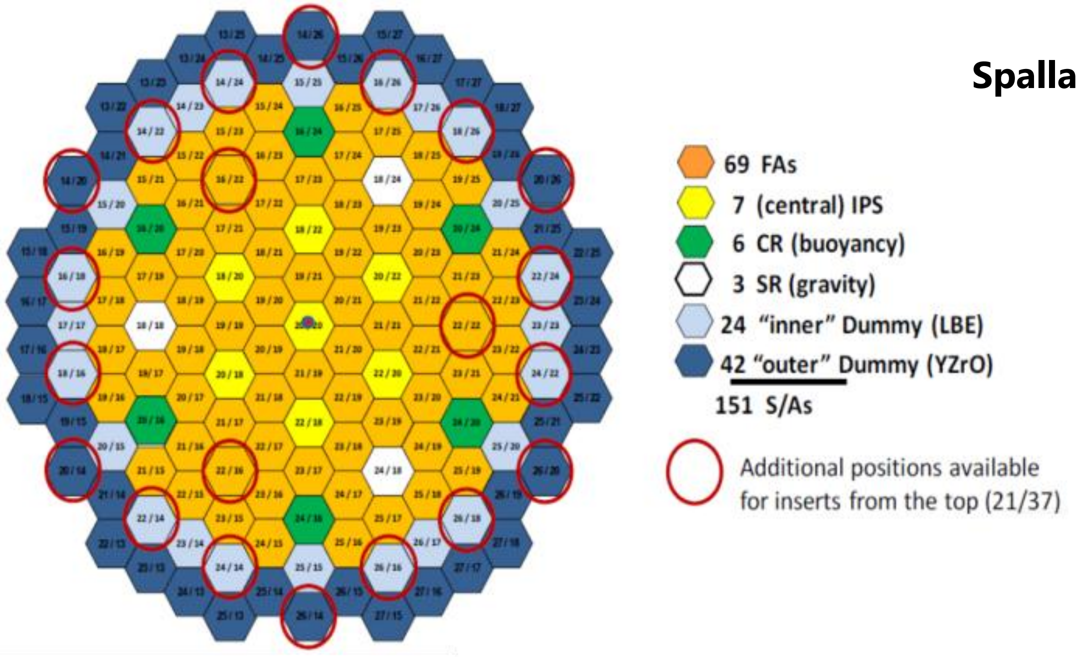




- Produces about 10^{17} neutrons/s at the reactor mid-plane to feed subcritical core
- Fits into a central hole in core
  - Compact target
  - Remove produced heat
- Accepts megawatt proton beam
  - 600 MeV, 3.5 mA → ~2.1 MW heat
  - Cooling of window is feasible
- Material challenges
  - Preferential working temperature: 450 – 500° C
  - Service life of at least 3 full power months (1 cycle) is achievable

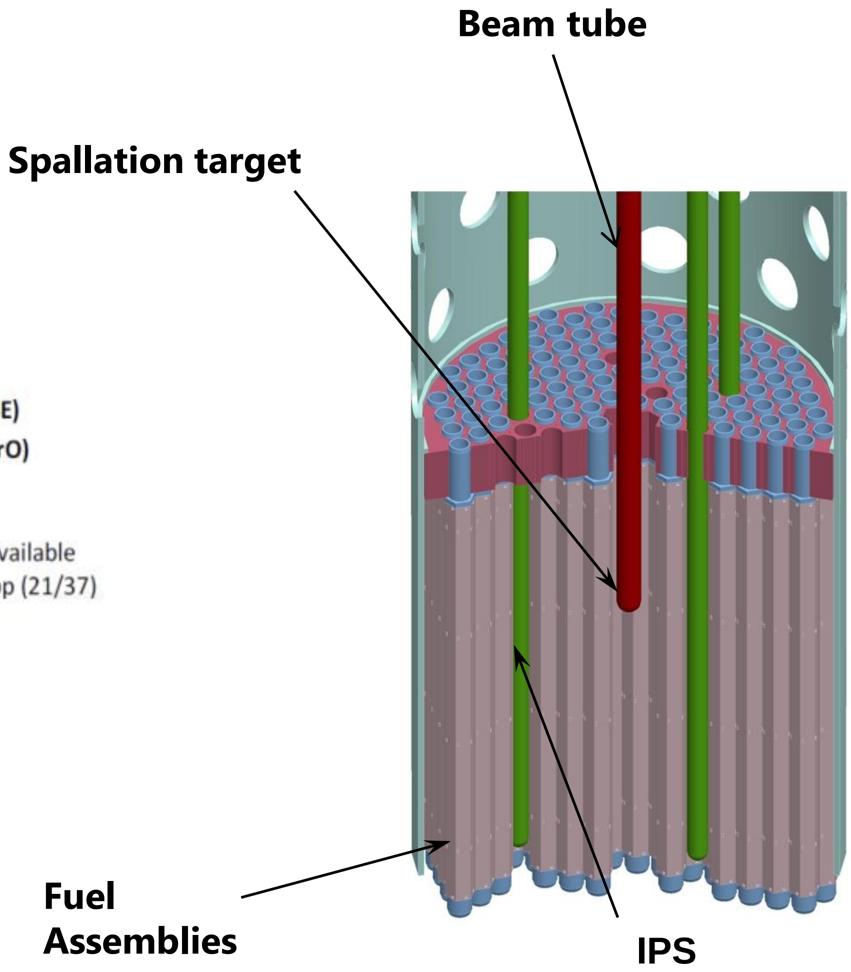
Core and fuel

- 151 positions
- 37 multifunctional plugs



🟧 69 FAs
🟨 7 (central) IPS
🟩 6 CR (buoyancy)
⬡ 3 SR (gravity)
⬢ 24 "inner" Dummy (LBE)
⬢ 42 "outer" Dummy (YZrO)
151 S/As

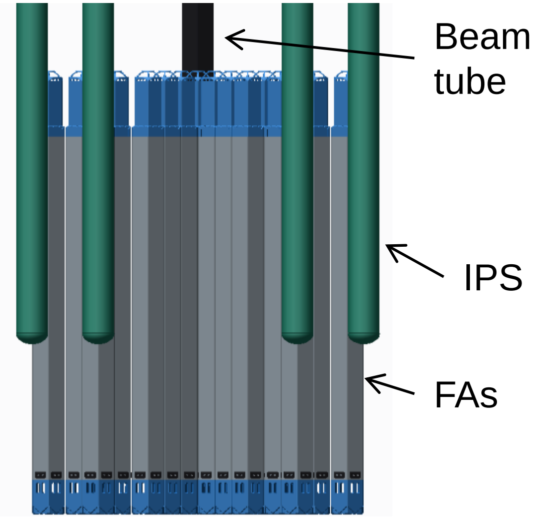
○ Additional positions available for inserts from the top (21/37)



Both critical and subcritical configuration:

- **Critical: 100 MWth**
- **Subcritical 85 MWth (keff ~ 0.96)**

IPS: Material Irradiation Performances for FR Reactors

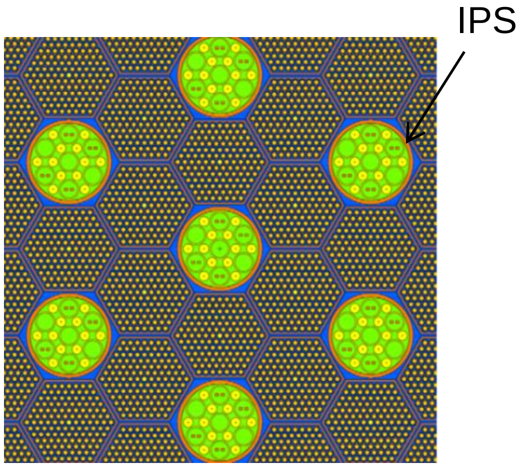


Subcritical

IPS	Total flux, n/(cm^{2}s)	Fast flux (> 0.75MeV), n/(cm^{2}s)	Radiation damage, DPA/FPY
1	2.64×10^{15}	4.20×10^{14}	22.3
2	2.72×10^{15}	4.29×10^{14}	23.0
3	**2.75×10^{15}**	4.29×10^{14}	**23.1**
4	2.72×10^{15}	4.18×10^{14}	22.5
5	2.70×10^{15}	**4.35×10^{14}**	22.7
6	2.68×10^{15}	4.23×10^{14}	22.8

Critical

	IPS in Chan [0 0 0]		IPS in Chan [2 0 0]	
Sample n°	dpa/EFPY	Φ_{tot} (n/cm^{2}s)	dpa/EFPY	Φ_{tot} (n/cm^{2}s)
8	18.1	2.38E+15	16.2	2.12E+15
7	23.0	2.85E+15	20.7	2.54E+15
6	25.9	3.19E+15	23.3	2.85E+15
5	27.5	3.37E+15	24.5	3.02E+15
4	27.2	**3.39E+15**	24.5	**3.03E+15**
3	25.7	3.23E+15	22.9	2.89E+15
2	22.3	2.92E+15	19.9	2.62E+15
1	17.3	2.50E+15	15.5	2.23E+15



MYRRHA-IFMIF for fusion materials

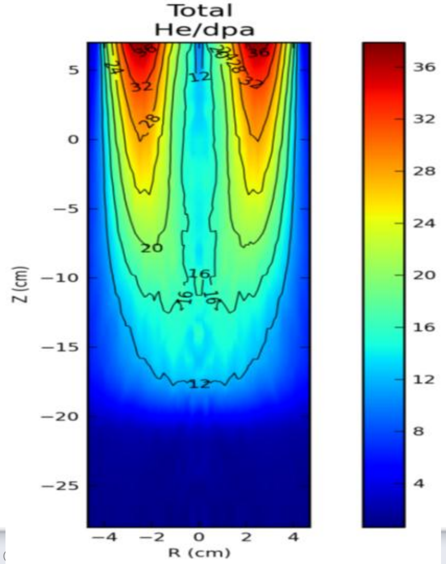
- In sub-critical ADS-mode:

  high appmHe/dpa ratio,
  close to the target window
- Volume of 1 lt with appmHe/dpa (Fe) ~ 12 , close to the spallation target

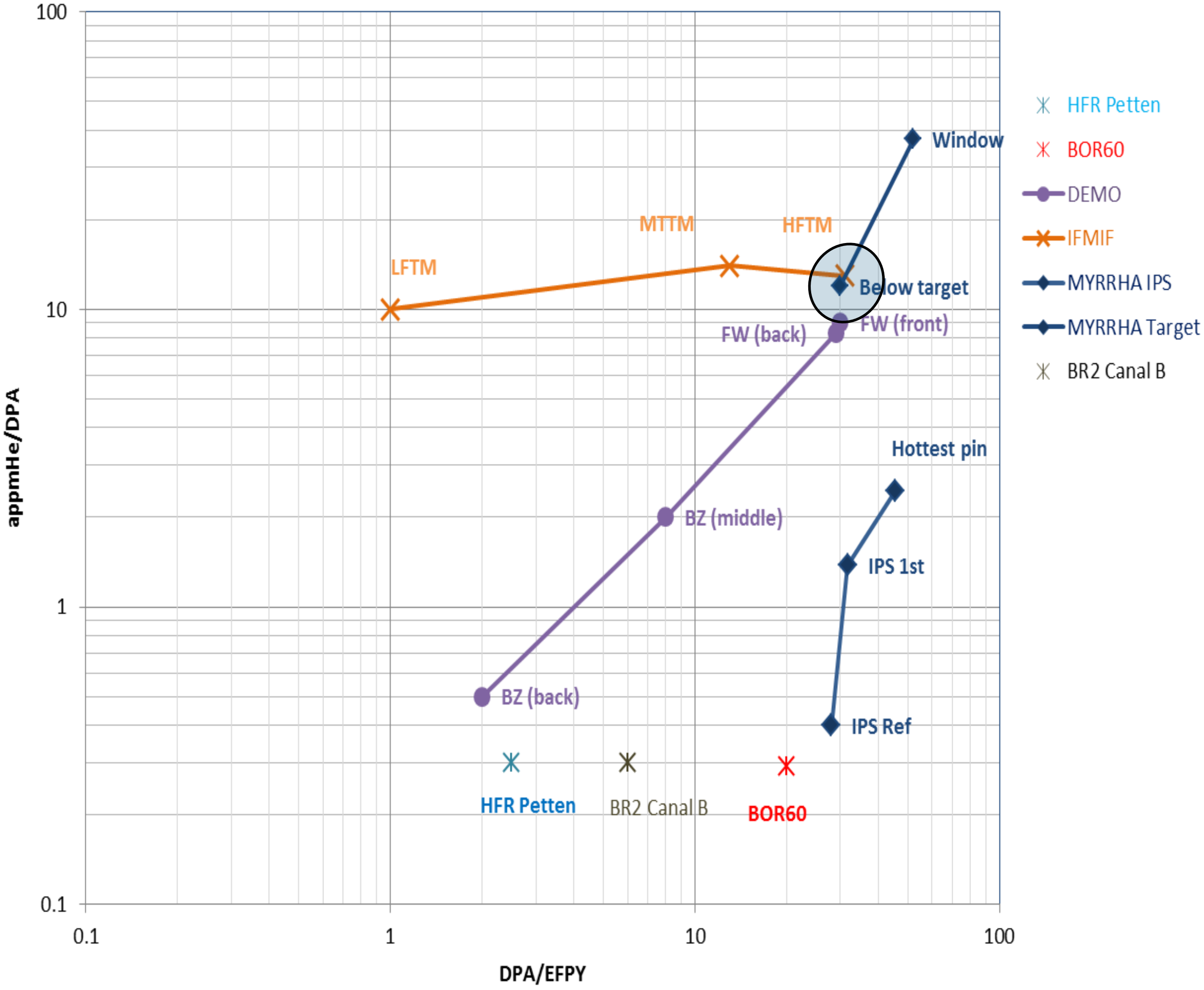
➔ Useful volume

  30 lt with range from 5 to 20 appmHe/dpa

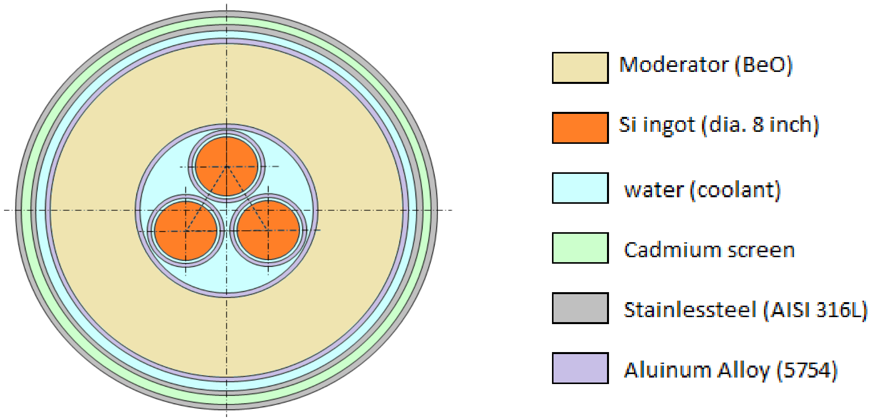
➔ (Pre-)selection of materials for fusion application

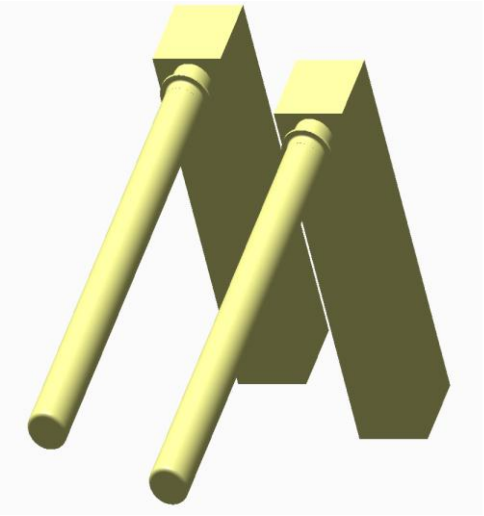


Estimated damage induced in DEMO and proposed irradiation conditions in IFMIF and MYRRHA-IFMIF

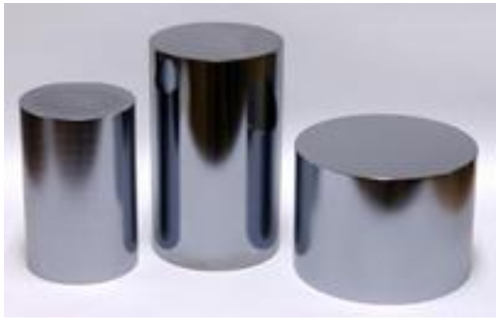


Irradiation at low energy neutron flux: Silicon Doping

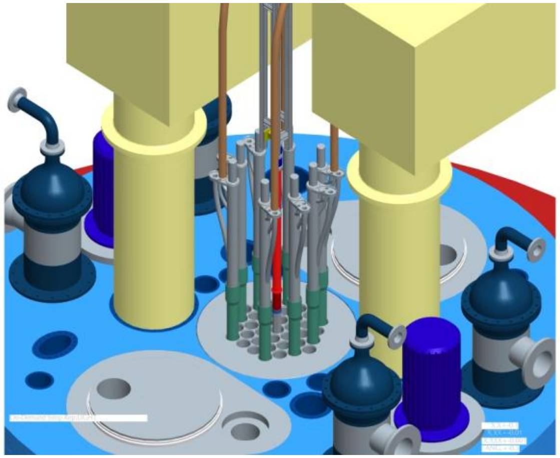


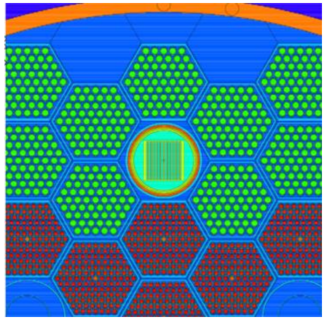


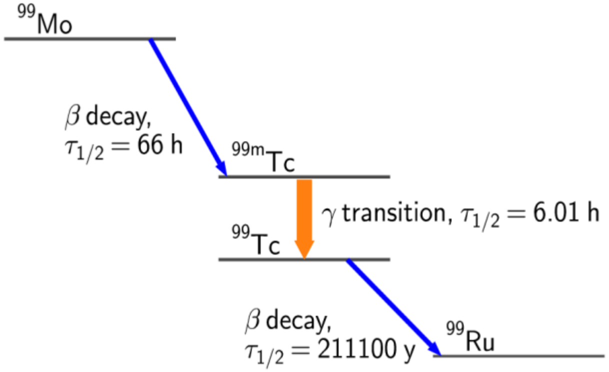
- Production: n (thermal) + Si --> P doped silicon (N-type)
- Silicon ingots are:
  - Huge: 8" in diameter
  - High: 200/250 mm
  - Massive: 10 to 35 Kg per ingot
- Raw material: Si (monocrystalline)

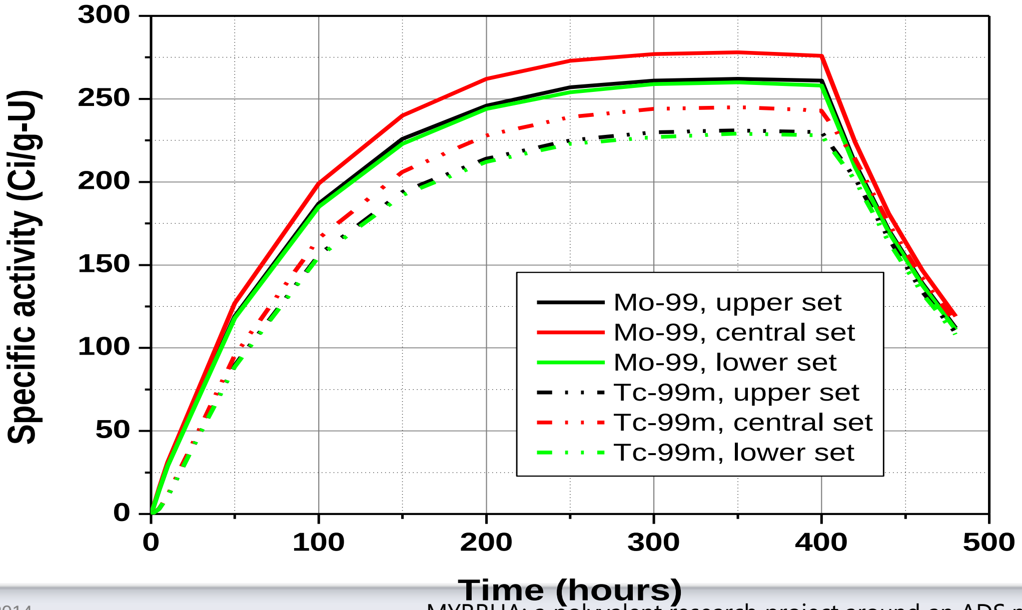


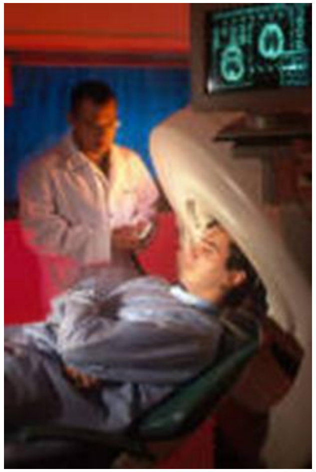
Radioisotope (Mo-99) production capability

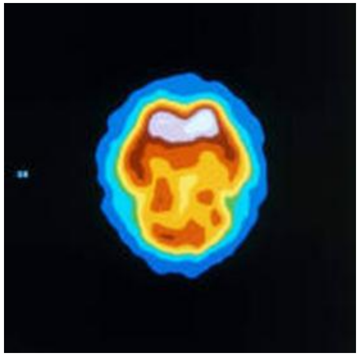












SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

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