ICENES 2007
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(Overview of Selected)

Neutronics and Shielding Issues of ADS

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on behalf of

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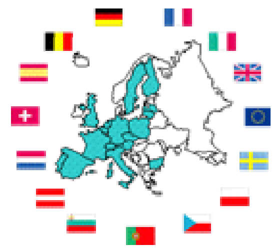
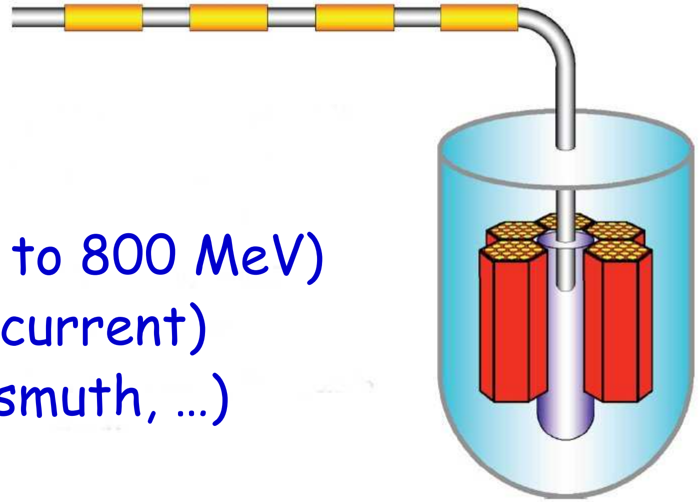
Outline

- Design of ADSs over the last 10 years
  - MYRRHA – SCK/CEN´s project
  - EU´s 5th Framework Programme (2001-2004)
    - XADS - 3 concepts
  - EU´s 6th Framework Programme EURATOM (2005-2009)
    - XT-ADS – irradiation facility and ADS technology demonstrator
    - EFIT – transmutation in ADS at the industrial scale
  - Several international & national R&D projects in support of ADS
- Neutronics Issues (core design)
- Shielding Issues (accelerator and core)
  - Radiation Protection of workers and members of the public
  - Radiation damage of structural components

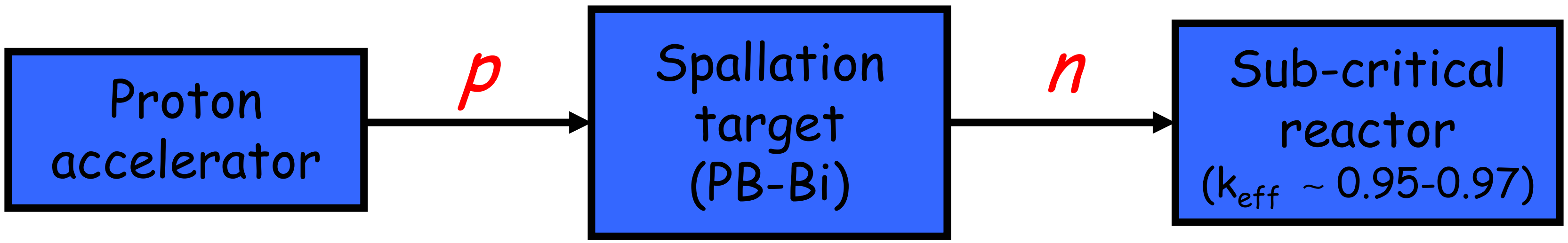
PDS-XADS
5th FWP



What is an ADS ?



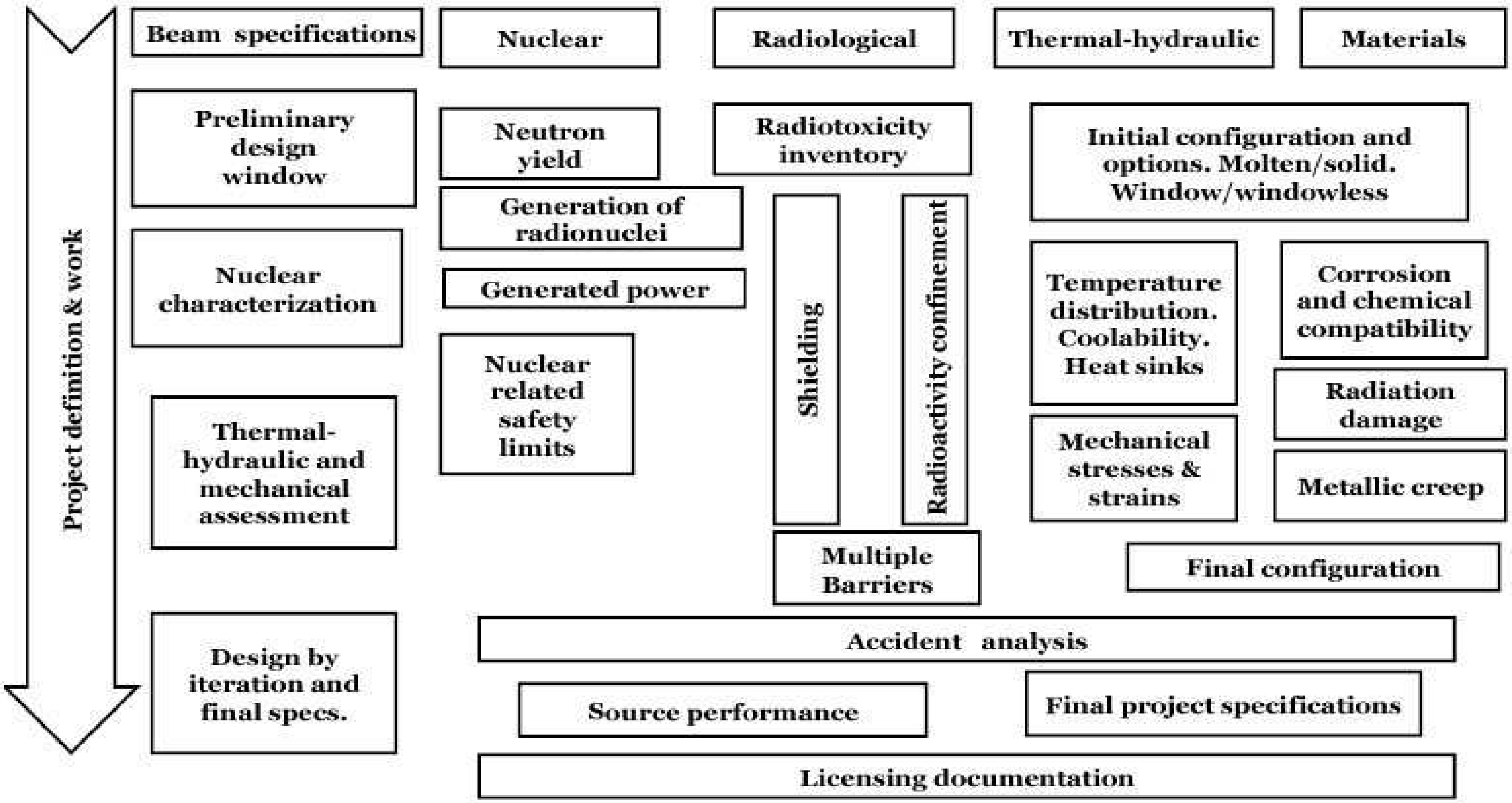
- ADS – Accelerator Driven System
- Hybrid system consisting of:
  - A proton beam (E_p ranges from 350 to 800 MeV) of high-intensity (several mA beam current)
  - A high-density target (lead, lead-bismuth, …)
  - A sub-critical core (k_{eff}=0.95-0.97),
  - Neutrons are generated by spallation reactions induced by the proton beam in the high-density target ⇒ external neutron source "drives" the core



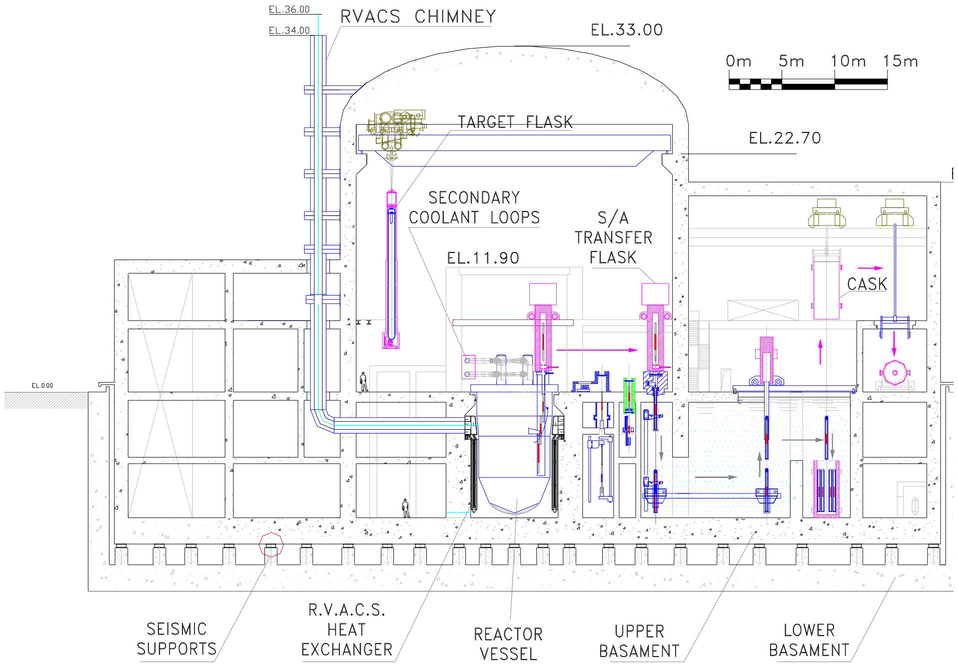
$\frac{n}{p} \simeq 15 \quad \Leftarrow E_p = 600\text{MeV}$

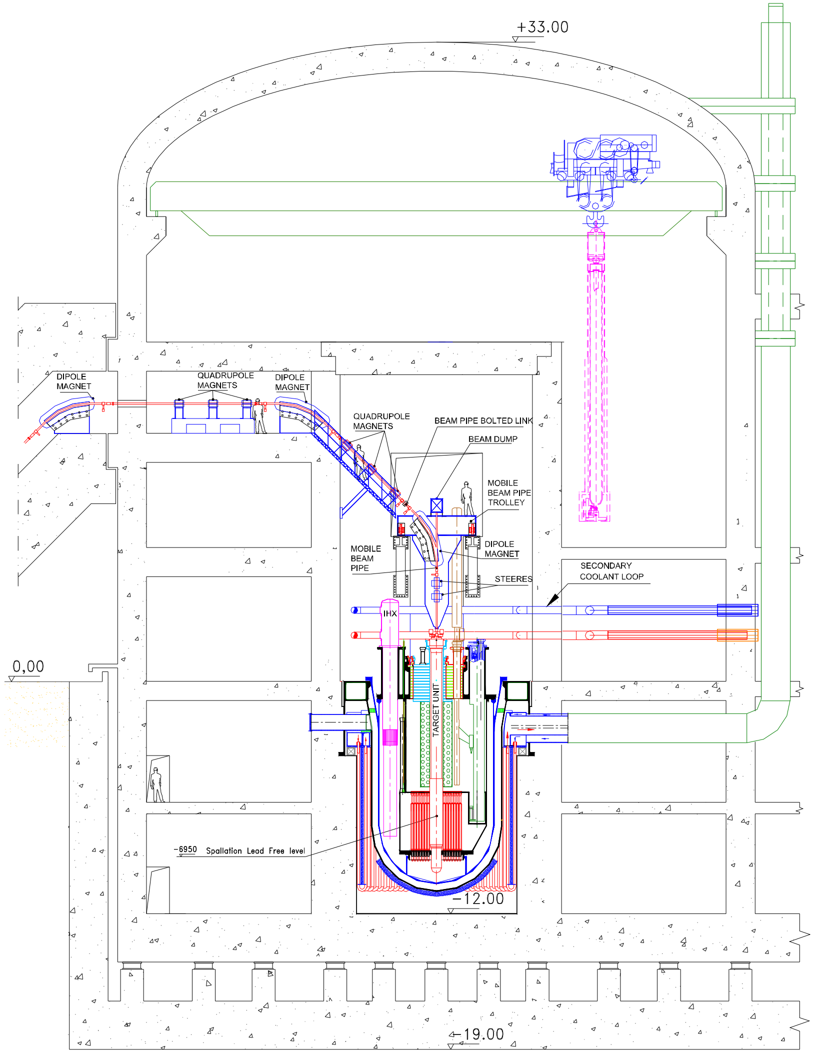
ADS ⇔ Multidisciplinarity

Cutting edge, multidisciplinary scientific, technological and engineering issues



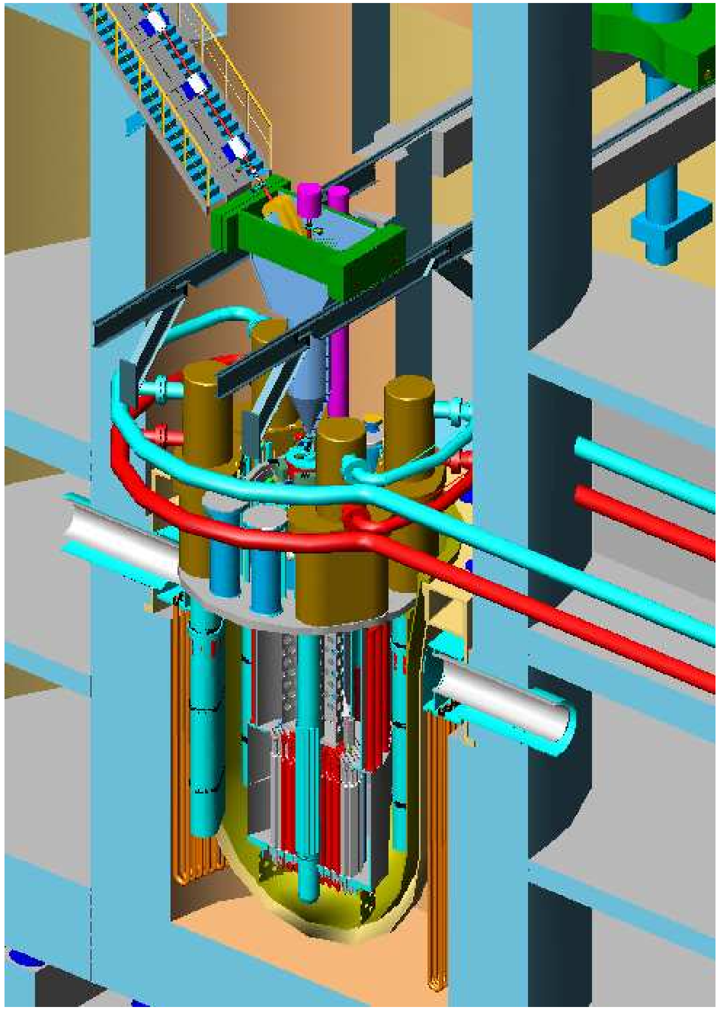
XADS (EU 5th FP)
The reactor building



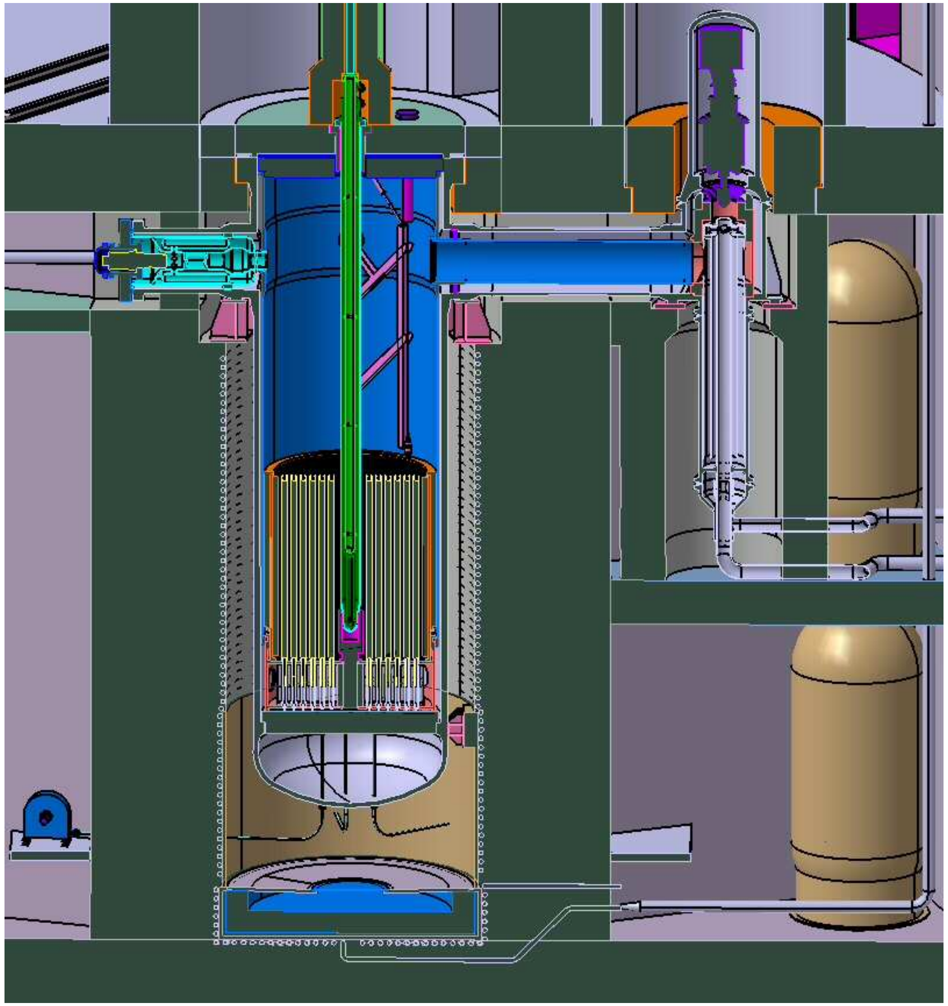


XADS (EU 5th FP)
The sub-critical core

80 MW, Pb-Bi cooled

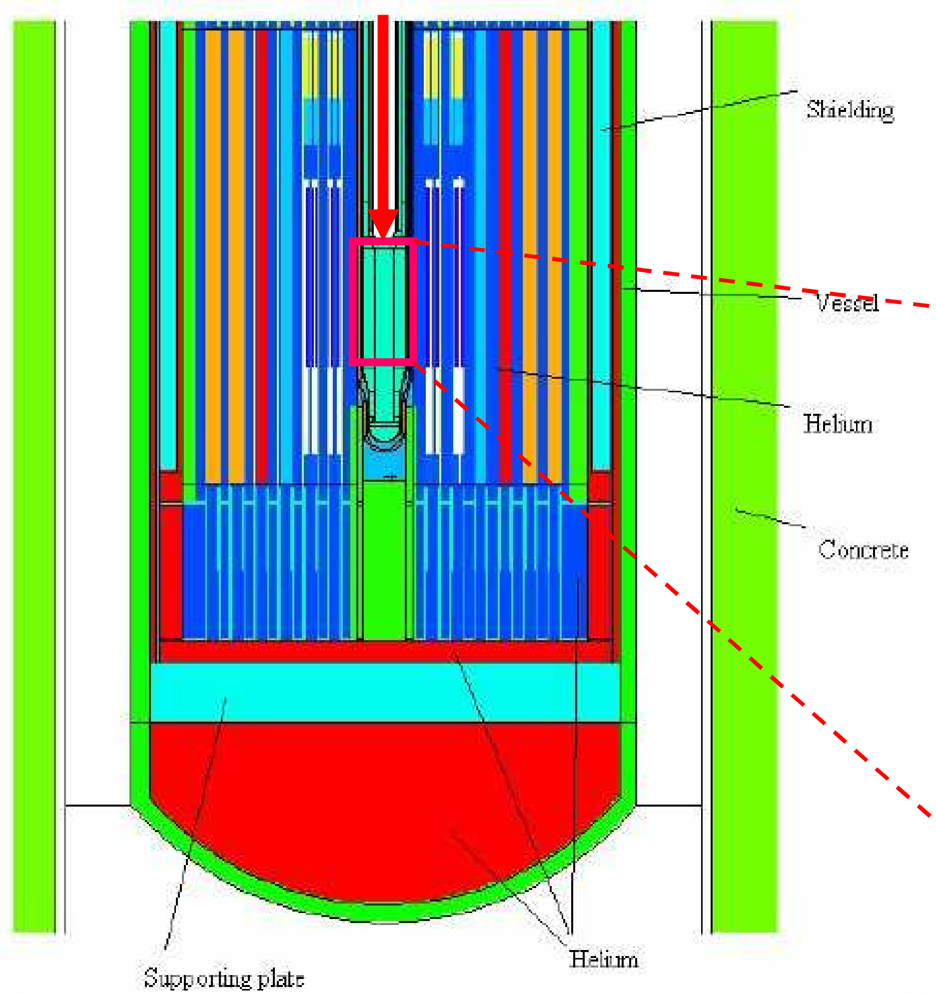


80 MW, Helium cooled

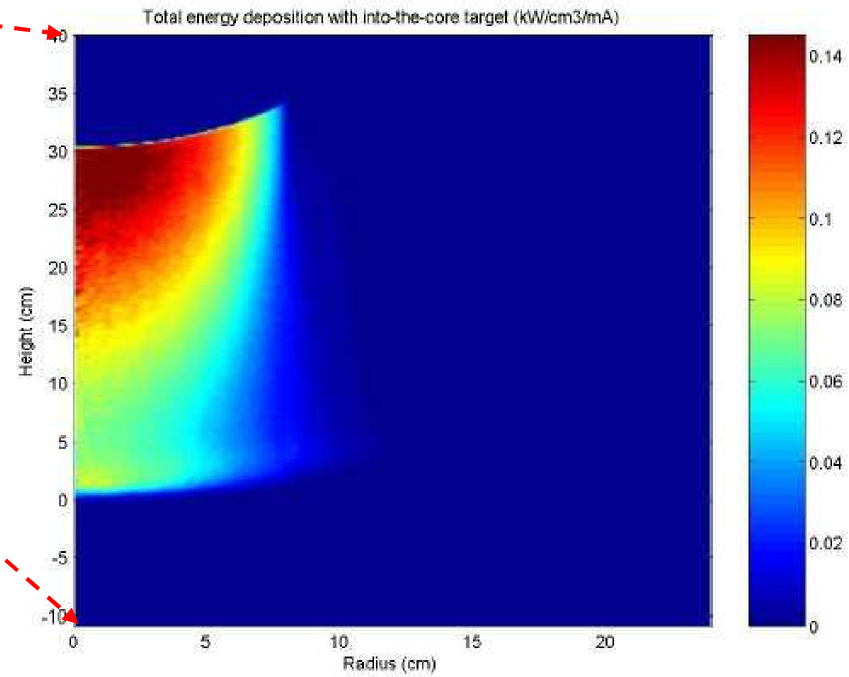


XADS (EU 5th FP)
The target

E_p = 600 MeV, I_p = 6 mA, Target: liquid mixture Pb-Bi
$P_{núcleo}$ = 80 MW, Helium cooled



Monte Carlo simulation
Energy deposition in the target
kW / cm^3 / mA



Neutronics Issues

(core design)

Physics of Transmutation
Fast neutron spectrum

Isotope	PWR spectrum			Fast neutron spectrum		
	$\langle\sigma_f\rangle$	$\langle\sigma_c\rangle$	$\langle\sigma_c\rangle/\langle\sigma_f\rangle$	$\langle\sigma_f\rangle$	$\langle\sigma_c\rangle$	$\langle\sigma_c\rangle/\langle\sigma_f\rangle$
^{237}Np	0.52	33	**63**	0.32	1.7	**5.3**
^{238}Np	134	13.6	**0.1**	3.6	0.2	**0.05**
^{238}Pu	2.4	27.7	**12**	1.1	0.58	**0.53**
^{239}Pu	102	58.7	**0.58**	1.86	0.56	**0.3**
^{240}Pu	0.53	210.2	**396.6**	0.36	0.57	**1.6**
^{241}Pu	102.2	40.9	**0.40**	2.49	0.47	**0.19**
^{242}Pu	0.44	28.8	**65.5**	0.24	0.44	**1.8**
^{241}Am	1.1	110	**100**	0.27	2.0	**7.4**
^{242}Am	159	301	**1.9**	3.2	0.6	**0.19**
^{242m}Am	595	137	**0.23**	3.3	0.6	**0.18**
^{243}Am	0.44	49	**111**	0.21	1.8	**8.6**
^{242}Cm	1.14	4.5	**3.9**	0.58	1.0	**1.7**
^{243}Cm	88	14	**0.16**	7.2	1.0	**0.14**
^{244}Cm	1.0	16	**16**	0.42	0.6	**1.4**
^{245}Cm	116	17	**0.15**	5.1	0.9	**0.18**
^{235}U	38.8	8.7	**0.22**	1.98	0.57	**0.29**
^{238}U	0.103	0.86	**8.3**	0.04	0.30	**7.5**

Feasibility of the transmutation
Neutron economy/balance

⇐ ***Salvatores et. al. (1994)***

- D_J - neutron consumption/fission of isotope J
  Number of neutrons needed to transform the nucleus into fission products
  $D_J > 0$ - net "consumption" $D_J < 0$ - net "production"

- ε_J - fraction of transuranium J present in the fuel, e.g.

$$D_{Pu} = \sum_J \varepsilon_J^{Pu} D_J^{Pu} = \varepsilon_{238}^{Pu} \cdot D_{238}^{Pu} + \varepsilon_{239}^{Pu} \cdot D_{239}^{Pu} + \varepsilon_{240}^{Pu} \cdot D_{240}^{Pu} + \varepsilon_{241}^{Pu} \cdot D_{241}^{Pu} + \varepsilon_{242}^{Pu} \cdot D_{242}^{Pu}$$

$$D_{FUEL} = \sum_i \underbrace{\varepsilon_i}_{\text{fraction of Pu,Am,Cm,Np in the fuel composition}} D_i$$

- G - neutron economy balance parameter

$$G = \underbrace{S_{ext}}_{\text{external neutron source}} - \underbrace{D_{FUEL}}_{\sum \varepsilon_i \cdot D_i} - (\underbrace{L}_{\text{neutron leakage term}} + \underbrace{C_{par}}_{\text{term of capture in structural materials}} + \underbrace{C_{FP}}_{\text{term of capture in fission products}})$$

If $G > 0$, the transmutation is feasible in the ADS system considered

Importance function (φ∗)
Source multiplication factor (k_{src})

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- Spallation-generated versus fission-produced neutrons in the core

$$\varphi^* = \frac{(1-k_{eff})\cdot k_{src}}{(1-k_{src})\cdot k_{eff}}$$

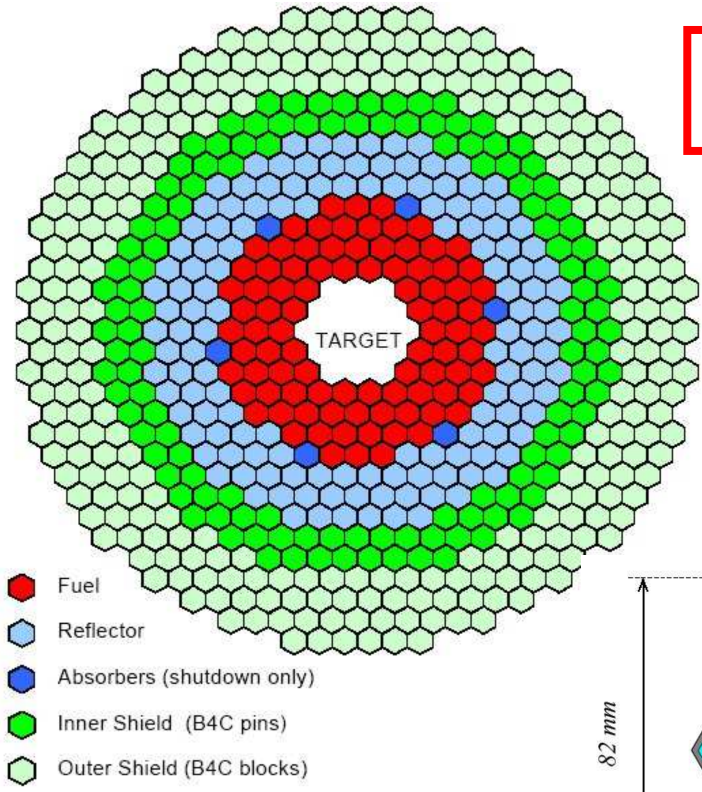
- Interplay between the different parameters of the system:

$$\underbrace{I_p}_{\text{number of protons per second}} = \frac{1-k_{eff}}{k_{eff}} \cdot \frac{P_{core}\cdot\bar{\nu}}{\bar{E}_f\cdot Z\cdot\varphi^*}$$

P_{core} – the core power
k_{eff} – the effective multiplication factor
E_f - the mean energy released per fission in the fuel
ν - the mean number of fission produced neutrons
Z – the average number of neutrons produced per incident proton

XADS (EU 5th FP)
Core and fuel assemblies

Helium cooled
330 cm



P_{core}= 80 MW_{th}

k_{eff}=0.97

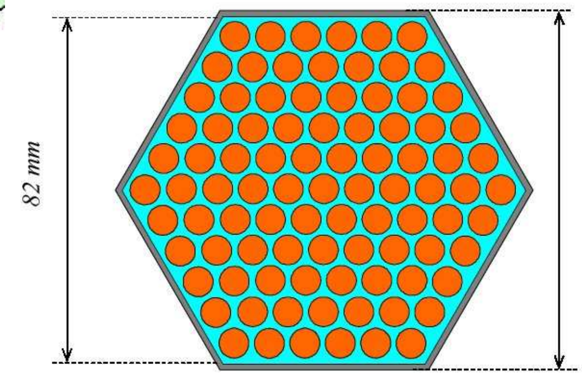
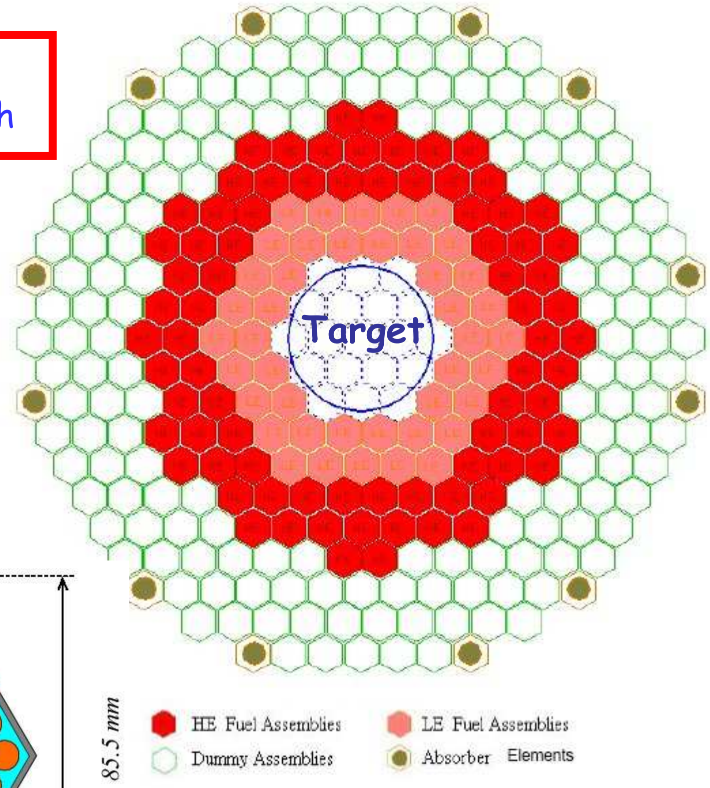


Fig. 4.3.3. Radial cross-section of a fuel assembly at mid-plane

Pb-Bi (LBE) cooled
180 cm



MYRRHA and XT-ADS
Core design and system parameters

	XT-ADS
Design level	Advanced design
Coolant	Pb-Bi
Primary System	Integrated
Power	50 to 100 MWth
Core Inlet Temp	300°C
Core Outlet Temp	400°C
Target Unit interface	Windowless
Target Unit geometry	Off-center / Centered
Fuel	MOX (accept for a few MA Fuel Assemblies)
Fuel Power density	700 W/cm³
Fuel pin spacer	Grid
Fuel Assembly type	Wrapper
Fuel Assembly cross section	Hexagonal
Fuel loading	Top / Bottom TBD
Fuel monitoring	T and FF (per FA)
External fuel handling	RH oriented
Primary coolant circulation in normal operation	Forced with mechanical pumps
Primary coolant circulation for DHR	Natural + Pony motor
Secondary coolant	Low pressure boiling water
Reactor building	Below grade
Seismic design	TBD (site specific)
Structural Material	T91 and A316L
Accelerator	LINAC (power: 2 ~ 5 MW)
Beam Ingress	Top

(†) Normalised to fuel power density of 700 W/cm^3 (‡) 210 MeV/fission

XT-ADS and EFIT (EU 6th FP) Parameters

Identifier	XT-ADS	EFIT
Proton energy	600 MeV x 2.5 mA / 350 MeV x 5 mA	800 MeV x 20 mA
Spallation target concept	Off-centred	Centred
Fuel	MOX, some minor actinide (MA) fuel assemblies accepted	(Pu, AM)O_2 + MgO (or Mo)
Power (MW_{th})	50 – 100	approx 395
Fuel power density (W/cm^3)	700	450 – 650
Presence of absorbers	(yes)	yes
Vessel structural material	T91 and 316L	316L
Vessel type	standing (hanging under consideration)	hanging
Primary coolant	LBE	Pure Lead
Primary system temperature range (°C)	inlet: 300 outlet: 400	inlet: 400 outlet: 480
Secondary coolant	low pressure boiling water	Superheated water cycle
Fuel loading	from bottom (alternative from top was reviewed)	from top
Fuel handling	oriented Remote Handling	Fuel Handling Rotor Lift machine and Transfer machine pantograph type
Seismic design	seismic spectrum specific to the Mol site	Horizontal anti-seismic supports

Shielding of the Accelerator and Core

For Radiation Protection purposes

Shielding of proton accelerators

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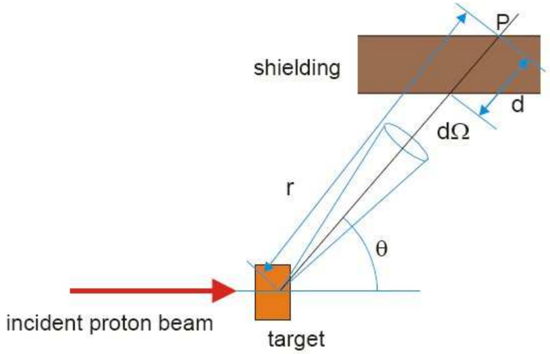
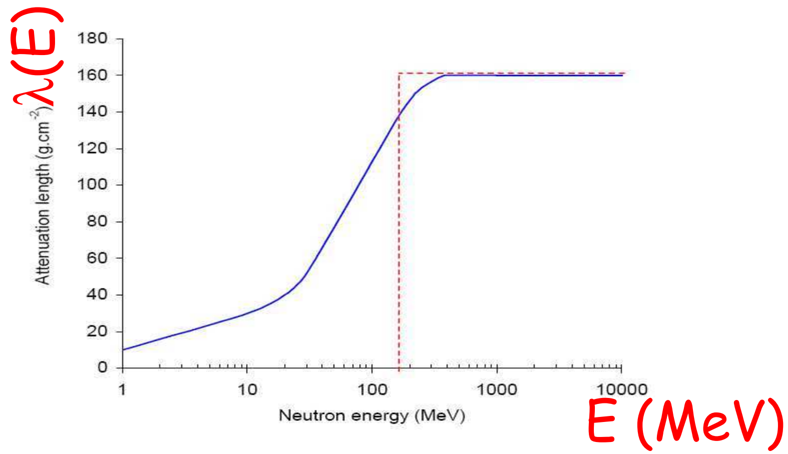
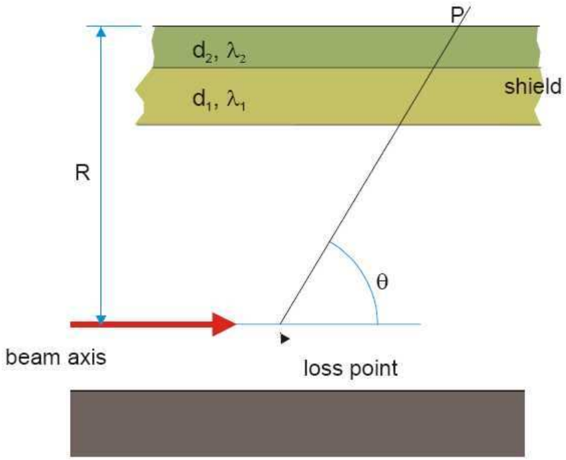
Moyer model – Dose equivalent behind a shield



$$\underbrace{\dot{H}(\theta)}_{\text{Dose equivalent rate}} = \frac{1}{r^2}\cdot\int \underbrace{F(E)}_{\text{Fluence-to-dose conversion factor}} \cdot \underbrace{B(E,\theta)}_{\text{Buildup factor}} \cdot \underbrace{\exp\left(-\frac{d(\theta)}{\lambda(E)}\right)}_{\text{attenuation}} \cdot \underbrace{\frac{d^2n(E,\theta)}{dE\,d\Omega}}_{\text{neutron differential yield}} \cdot dE$$





$$H(\theta) = \frac{N\cdot\Psi(E_P)\cdot\exp(-\beta\theta)\cdot\exp\left(-D/\sin\theta\right)}{R^2/\sin^2\theta}$$

$\Psi(E_p)=2.8\times10^{-13}\,(E_P)^{0.8}$ Sv m^2, $\beta=2.3$ rad^{-1} , $D=\Sigma d_i/\lambda_i$

Shielding of the proton accelerator XADS

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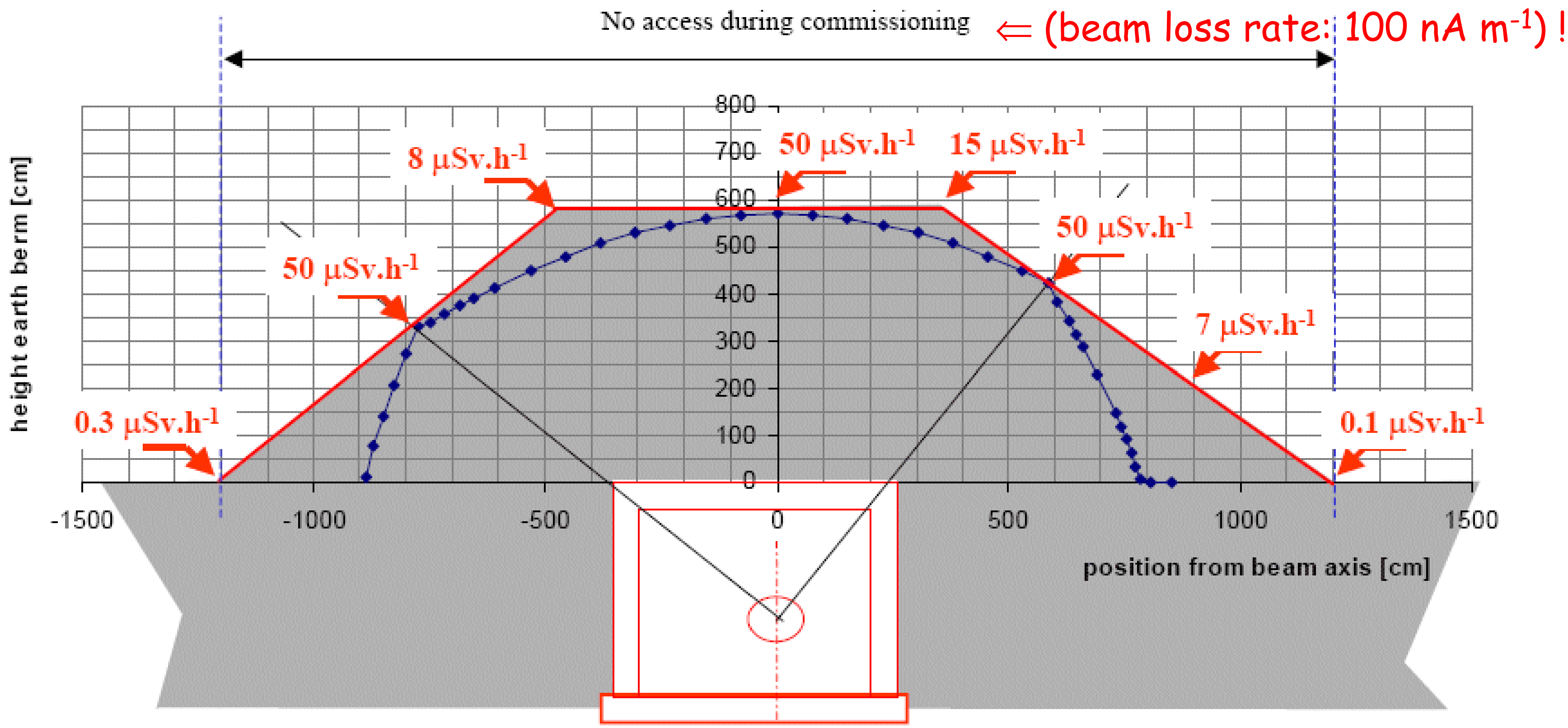
E_P=600 MeV, normal beam loss rate = 1 nA m^{-1}
Shielding: 60 cm concrete tunnel + earth



Residual dose 0.5 µSv h^{-1}

Realistic earth profile

P. Berkvens *et. al.*

Shielding of MYRRHA
Radial Dose assessment

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Top shielding

- 1 m Heavy Concrete (3.4 g cm^{-3})
- 1 m Fe

Lateral shielding

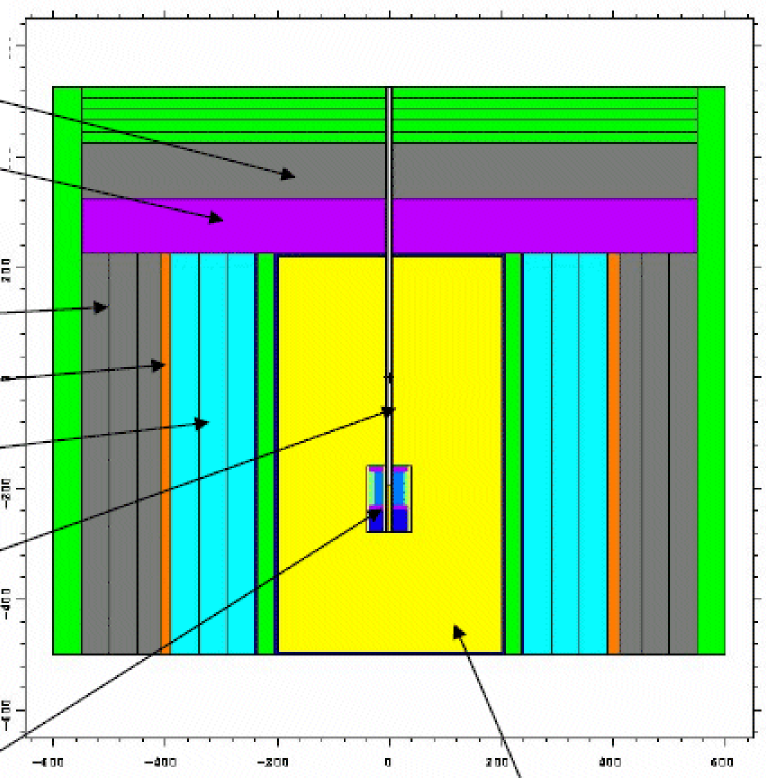
- 1.5 m Heavy Concrete (3.4 g cm^{-3})
- 0.2 m Pb
- 1.5 m Water

Protons beam

(350 MeV ; 5 mA)

Sub-critical core

Pb-Bi pool



Shielding of the structural components (core vessel and support plate…)

To reduce the fast neutron induced radiation damage

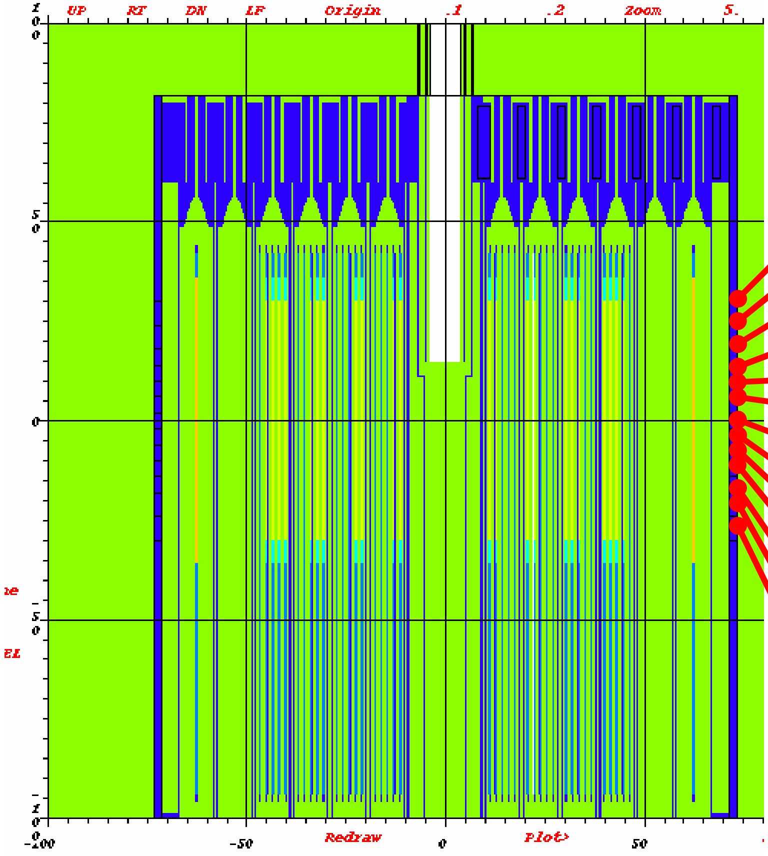
Radiation damage (dpa) calculations (XT-ADS)

- Constrains:
  - $K_{eff} = 0.95$
  - $\phi_{fast} \sim 2\text{-}3 \times 10^{15}$ n cm^{-2} s^{-1}
  - $P_{core} = 57$ MW$_{th}$
  - $E_p = 600$ MeV
  - $I_p = 2.33$ mA
  - Highly enriched MOX fuel (up to 35% Pu enrichment)

- Objective
  - dpa (core vessel and grid plate): 0.1 dpa/year up to an cumulative value of 2 dpa !

- Solution (?): shield vessel with
  - B_4C assemblies
  - Steel+LBE filled assemblies

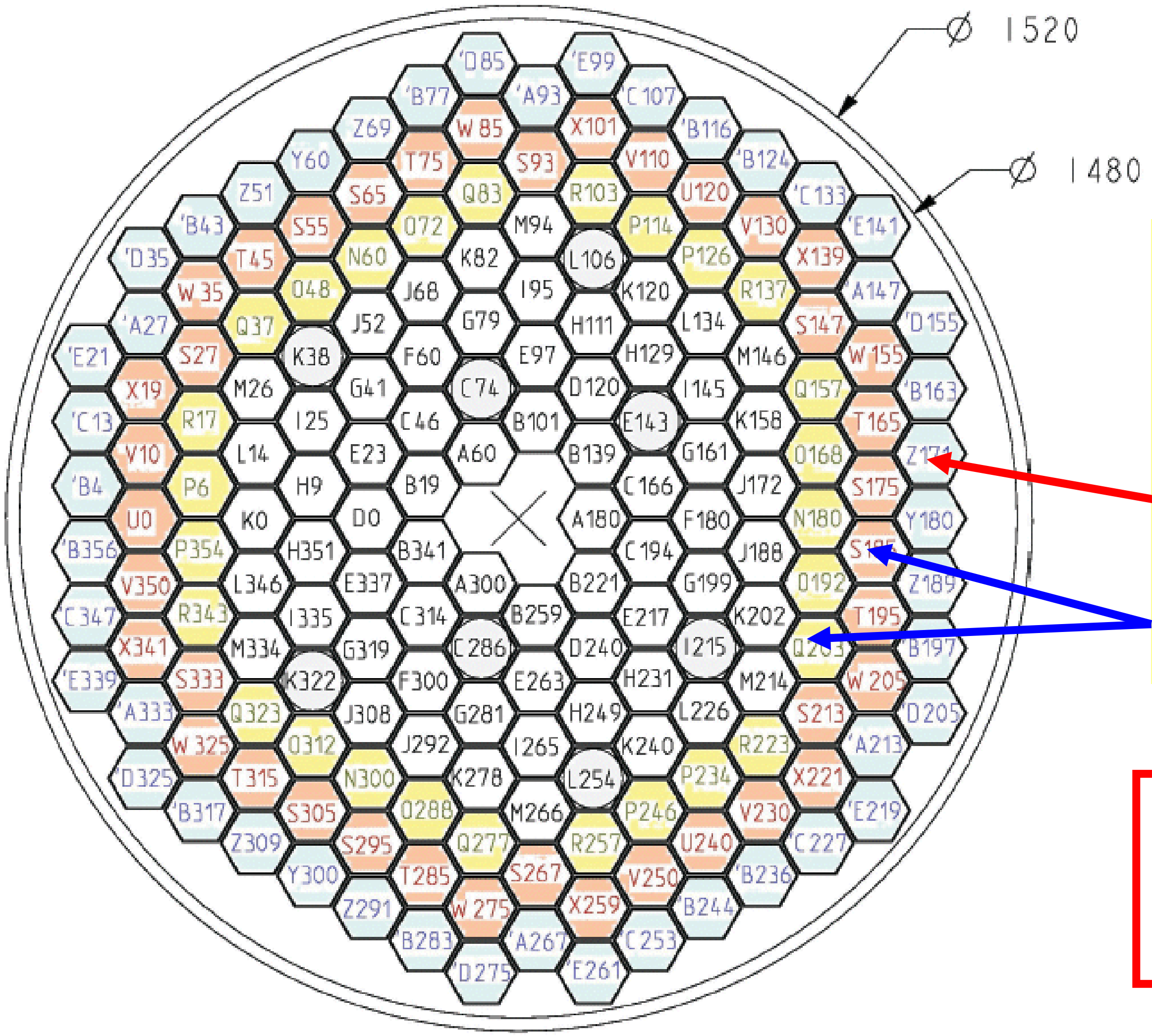
Computational results (XT-ADS, core barrel)



Preliminary results

z (cm)	DPA (year^{-1} mA^{-1})		Flux (cm^{-2} s^{-1} mA^{-1})	
	With B4C	Without B4C	With B4C	Without B4C
27	0.4	0.8	1.04E+14	2.50E+14
21	0.5	0.9	1.10E+14	2.68E+14
16	0.5	1.0	1.15E+14	2.80E+14
12	0.5	1.1	1.18E+14	2.88E+14
8	0.5	1.1	1.20E+14	2.94E+14
4	0.5	1.1	1.22E+14	2.98E+14
0	0.5	1.1	1.23E+14	2.99E+14
-4	0.5	1.1	1.23E+14	2.99E+14
-8	0.5	1.1	1.21E+14	2.96E+14
-12	0.5	1.1	1.19E+14	2.92E+14
-16	0.5	1.0	1.16E+14	2.85E+14
-21	0.5	1.0	1.12E+14	2.75E+14
-27	0.4	0.9	1.07E+14	2.59E+14

XT-ADS
Core Design (Option B)



Core Design (Option B)

99 "fuel positions"

45 "outer" assemblies: B_4C

39 assemblies filled with LBE

Goal: (core vessel)

Dpa/year ~ 0.1

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Summary and Outlook

- ADS are a promising solution to perform the transmutation of long-lived and highly radiotoxic nuclear waste

- They can contribute to a reduction of the burden (volume and heat load) on the deep geological repositories, therefore contributing to the solution of the problem of the sustainability of nuclear energy

- Different ADS concepts have been studied and designed in recent years in the context of the EU 5th & 6th Framework Programmes

- Neutronics and shielding issues have been carefully investigated, radiation damage of structural materials emerging as one of the key issues to which particular attention has to be devoted

- No show-stoppers have been identified in the different design studies ⇒ time to start the construction and deployment of a prototype (XT-ADS) ?

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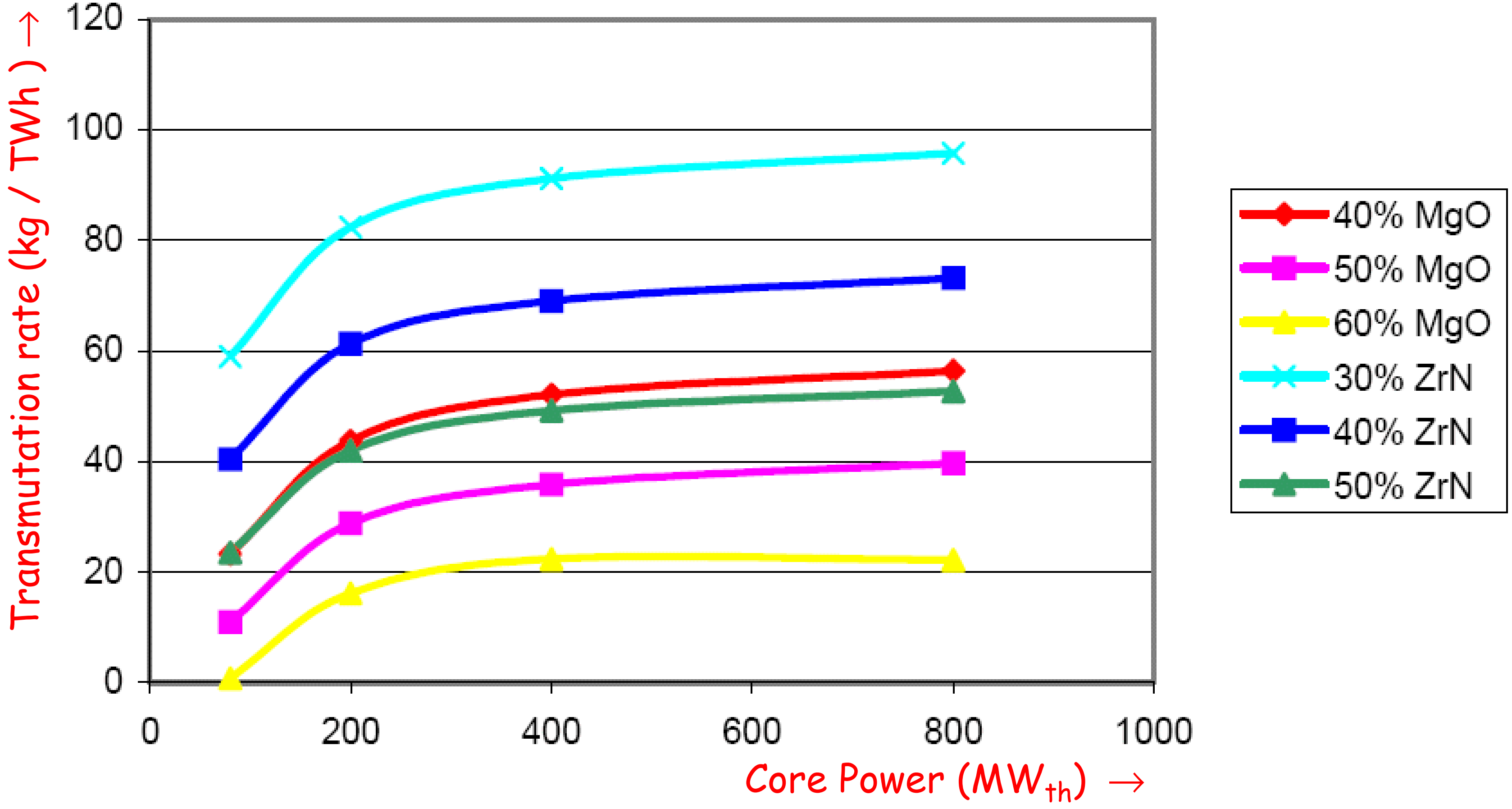
The end

Thank you for your attention!

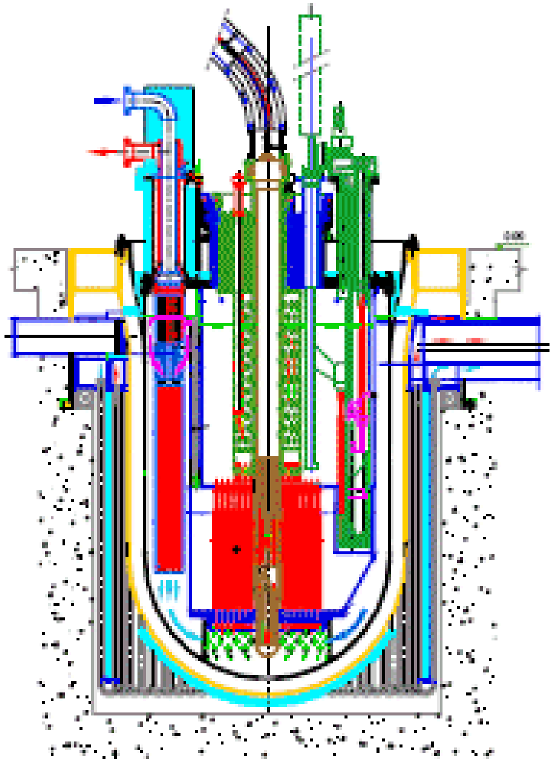
Transmutation rate
Minor Actinides



Typical value: 45 kg / TWh_{th}

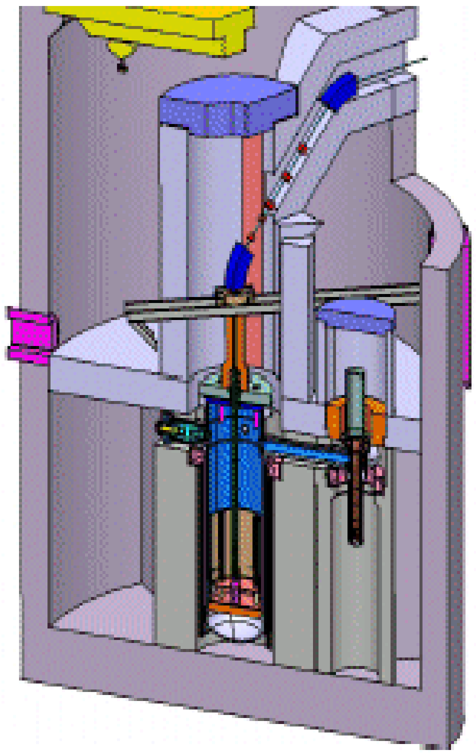
Design Concepts of PDS-XADS

80MWth
Pb-Bi cooled XADS



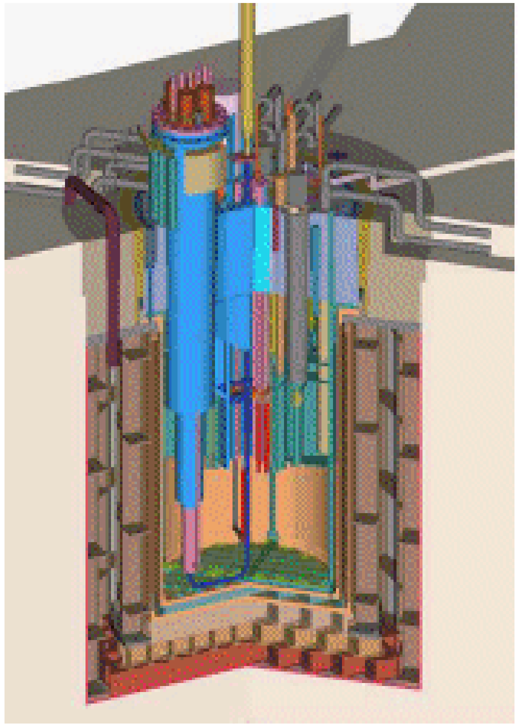
Ansaldo

80MWth
Gas-cooled XADS



Framatome ANP

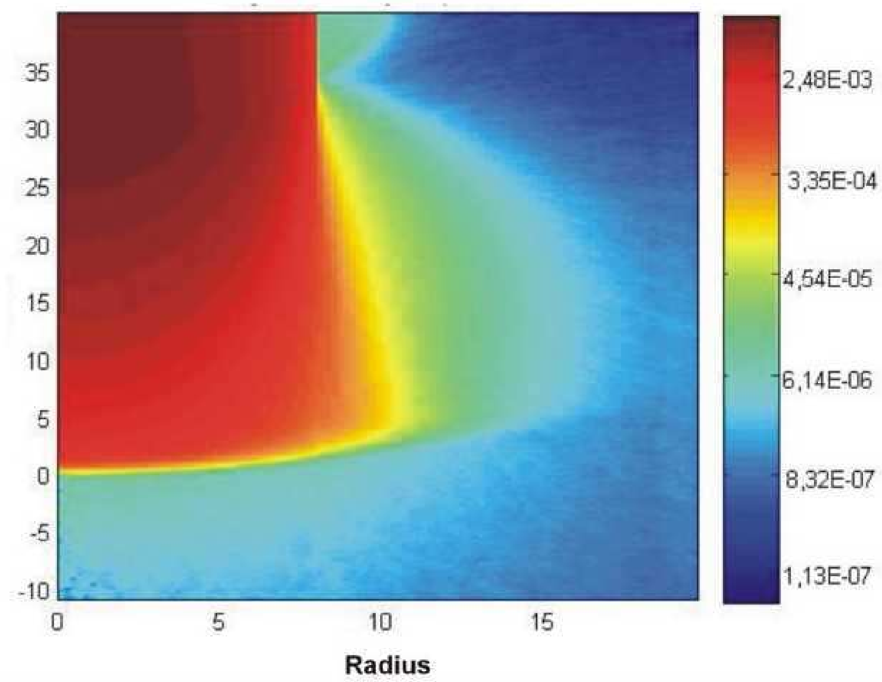
50MWth
Pb-Bi cooled MYRRHA



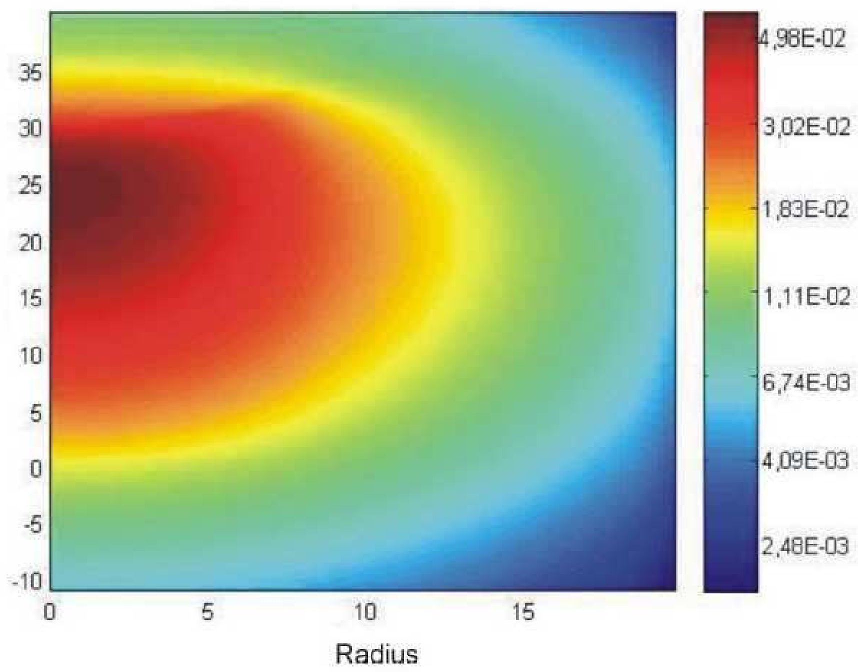
SCK·CEN

XADS (EU 5^{th} FP)
The target

Monte Carlo simulation
Proton (p) flux on target
p / cm^2 / incident proton



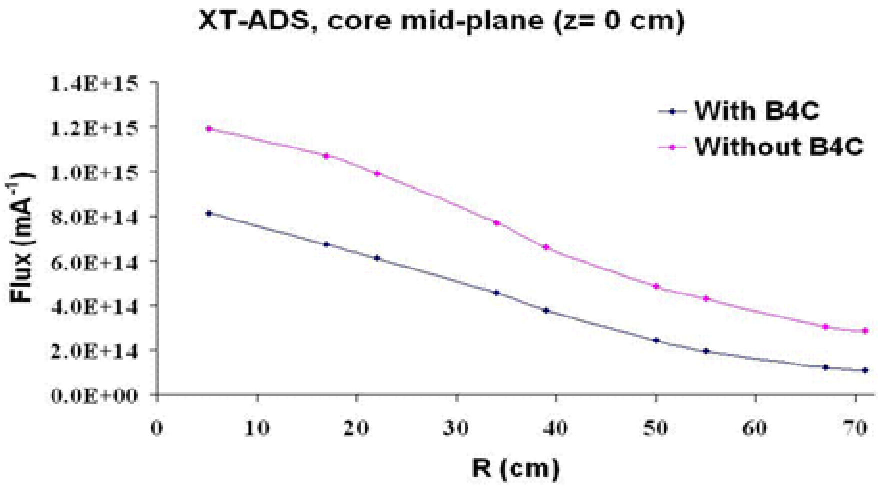
Monte Carlo simulation
Neutron (n) flux on target
n / cm^2 / incident neutron

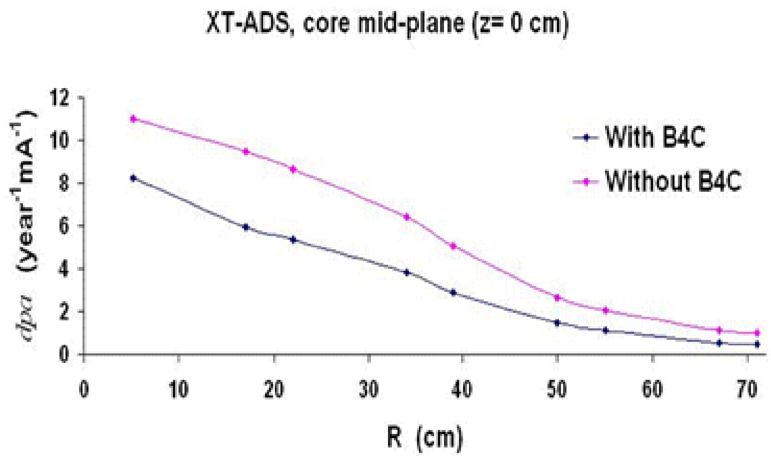


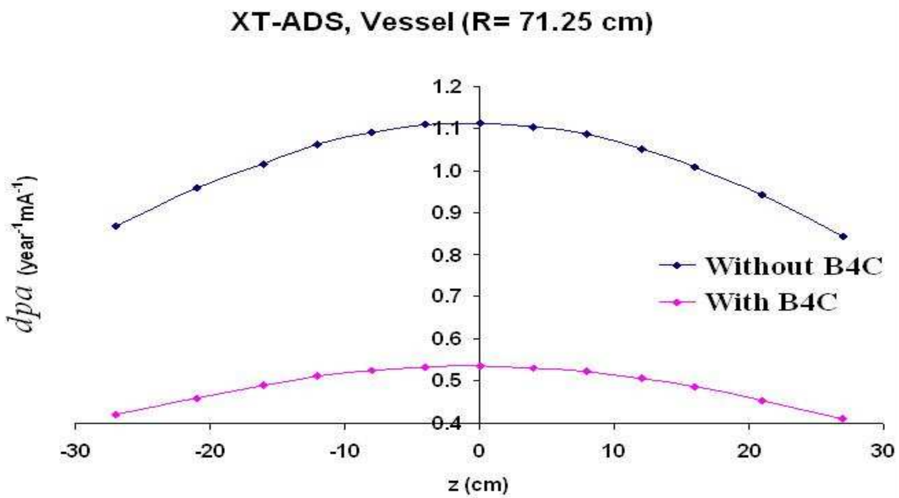
Power incident on target: $P_{accelerator} = E_p \, I_P$ = 600 MeV x 6 mA = 3.6 MW
Power deposited in the target (MC) ≡ 2.323 MW (p) + 0.049 MW (n)

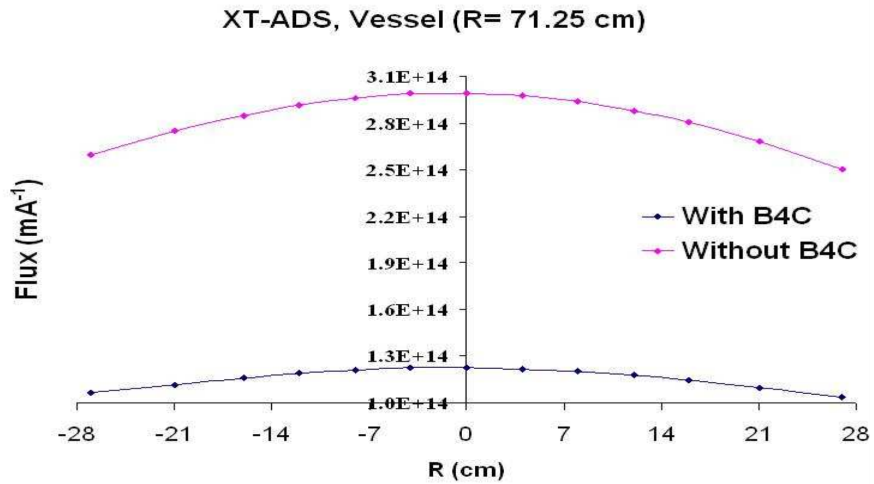
Computational results (XT-ADS, core mid-plane and vessel)

Preliminary results









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