The Impact of Radiological Protection and Radiation Safety Requirements in the Next Generation, Emerging and Innovative Nuclear Technology Facilities

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Despite the impressive amount of high-quality design studies and R&D activities during the last 15 years…

Did we overlook
Radiation Protection and Safety
issues and requirements ?

Could Radiation Protection and Safety requirements be *show stoppers* in the operation of such facilities ?

Disclaimer

The intention is <u>NOT</u> to dispute the results and findings of past projects and design studies

But instead

To have a "hard look" at the "(hard) data", from the radiological protection and radiation safety perspective

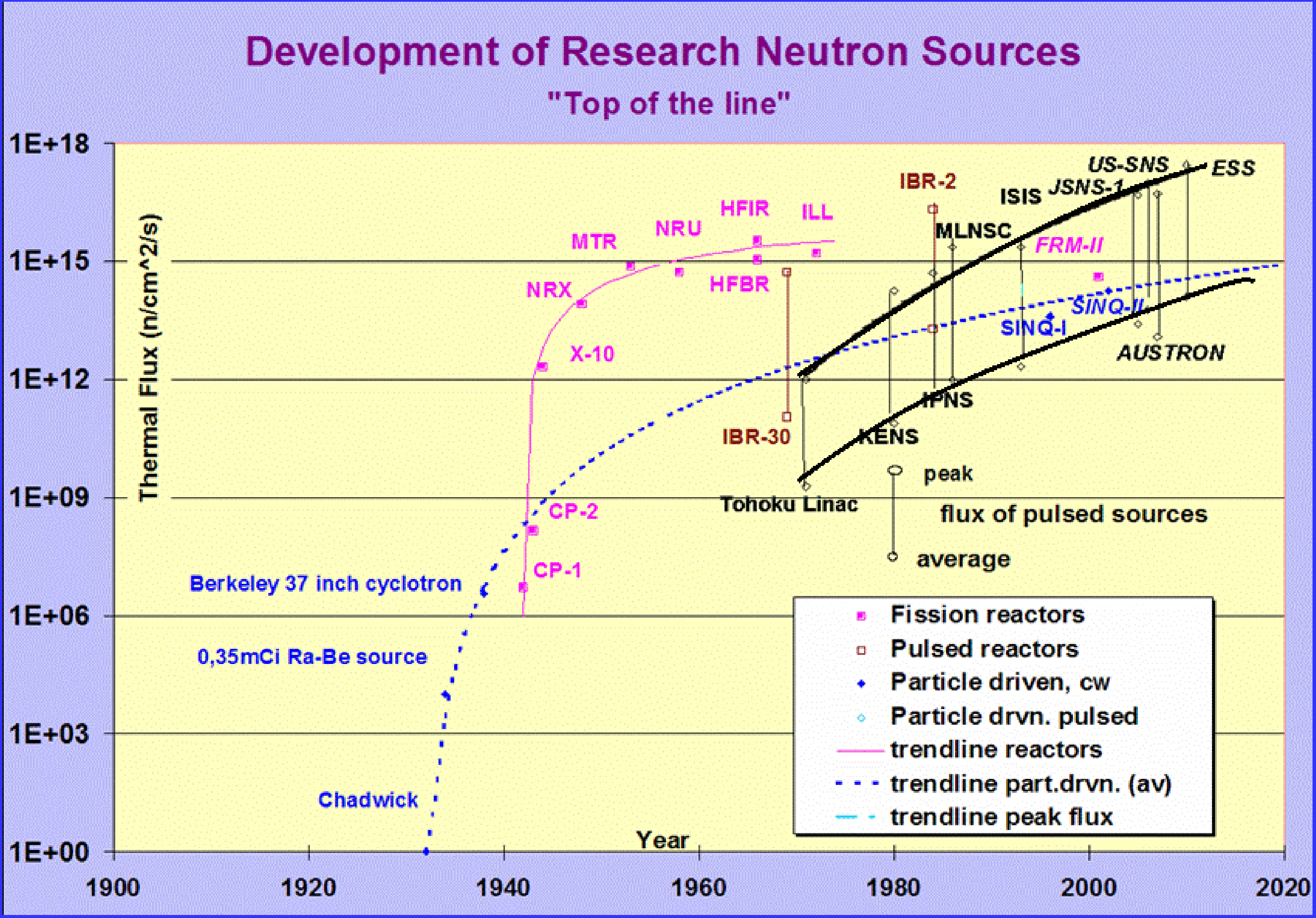
Outline

- Radiological protection and radiation safety issues of next generation emerging and innovative nuclear technology facilities
  - ✓ Radiation damage
  - ✓ Activation of structural components
  - ✓ Dose-rates (n, γ)
  - ✓ Radiotoxicity of targets
  - ✓ Inspection & Repair
  - ✓ Etc.

- 3 "case studies": ADS, EURISOL, Spallation Neutron Sources
  - ✓ Short description, nominal operating parameters
  - ✓ Selected radiological protection and radiation safety issues & requirements

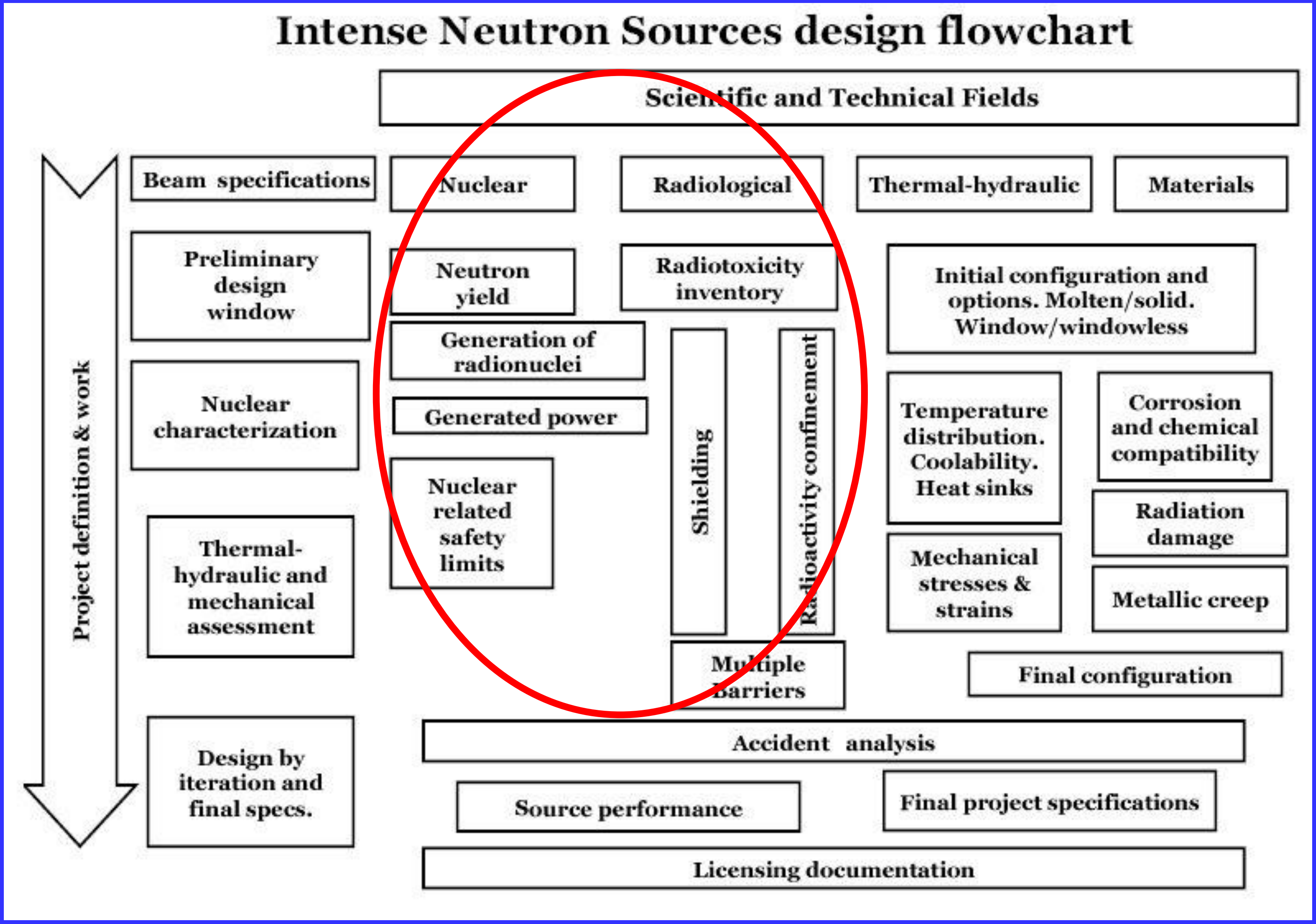
- Summary and Outlook

Quest for intense neutron sources



From G. Bauer (2005)

Emerging and Innovative Nuclear Technology Facilities - Multidisciplinarity



Next Generation, Emerging and Innovative Nuclear Technology Facilities

- "Case studies"
  - ADS – Accelerator Driven Systems (XADS, XT-ADS, MYRRHA)
  - Next-generation Radioactive Ion Beam ISOL facility (EURISOL)
  - Spallation Neutron Sources
    - SNS (Spallation Neutron Source, US, in operation since 2006)
    - ESS (European Spallation Source, currently in design phase)

- Commonalities:
  - High power (Multi-MegaWatt) delivered on target
    - Proton beam:
      - ✓ $E_p \sim 600 - 1500$ MeV
      - ✓ $I_b \sim$ several mA
  - High-density liquid targets (Hg, Pb-Bi, Pb)
  - Unpredented high neutron fluxes: 10^{15}-10^{16} neutrons cm^{-2} s^{-1}
  - Very high dose-rates, activation and radiation damage

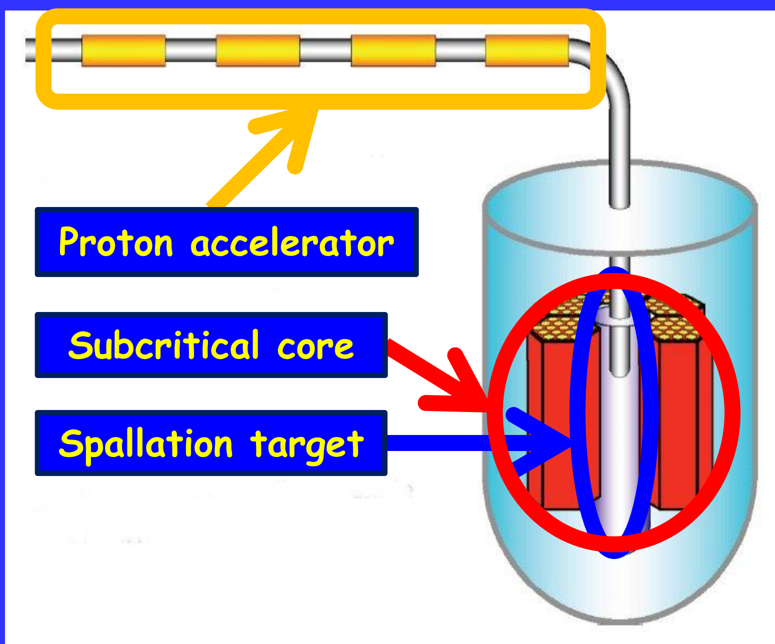
Radiation damage issues

"Case study" - ADS

What is an ADS ?

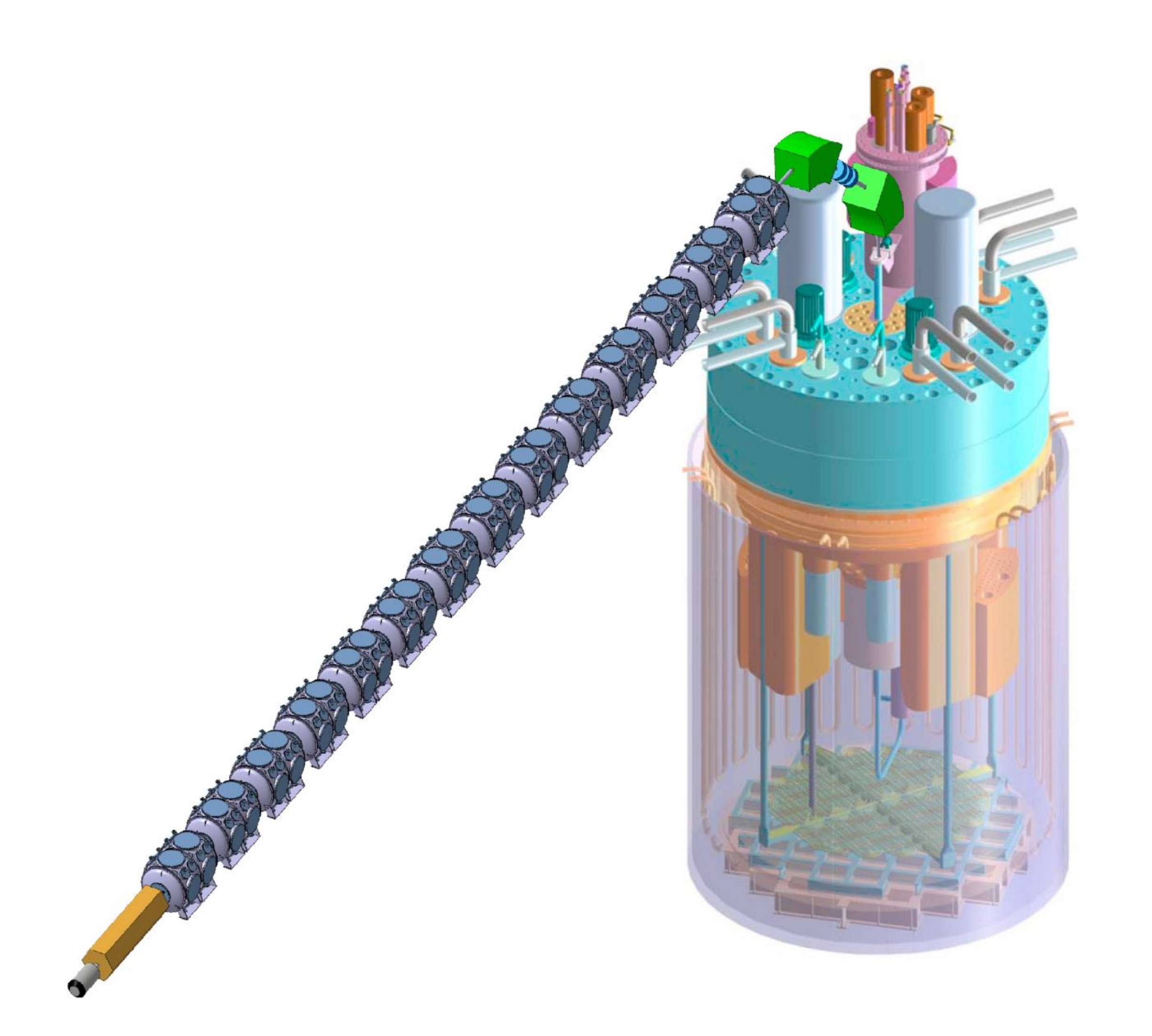
Proton accelerator → *p* → Spallation target (Pb-Bi) → *n* → Sub-critical reactor (k_{eff} ~ 0.95-0.97)

Hybrid system consisting of:



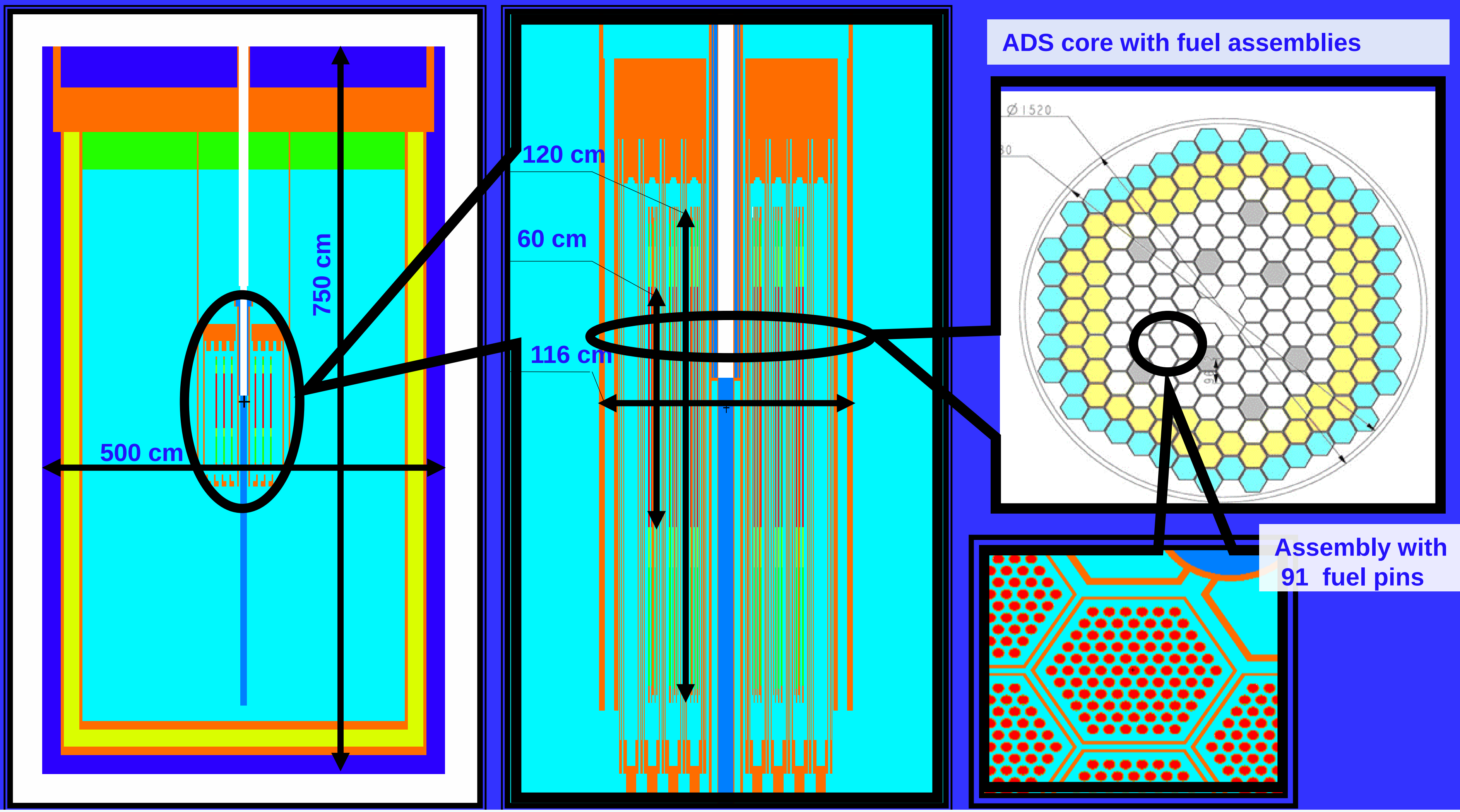
- ✓ A proton beam (E_p ranges from 350 to 800 MeV) of high-intensity (several mA beam current)
- ✓ A liquid high-density target (lead, lead-bismuth)
- ✓ Neutrons are generated by spallation reactions induced by the proton beam in the high-density target ⇒ external neutron source "drives" the core (~15 neutrons per primary proton (E= 600 MeV))
- ✓ A sub-critical core (k_{eff}=0.95-0.97)

XT-ADS
"layout" & design specifications



- E_p = 600 MeV
- I_p = 2.33 mA
- P_{core} = 57 MW_{th}
- $k_{eff} \cong 0.95-0.97$
- $\phi_{fast} \cong 2\text{-}3 \times 10^{15}$ n cm^{-2} s^{-1}
- Highly enriched MOX fuel (> 30% Pu enrichment)

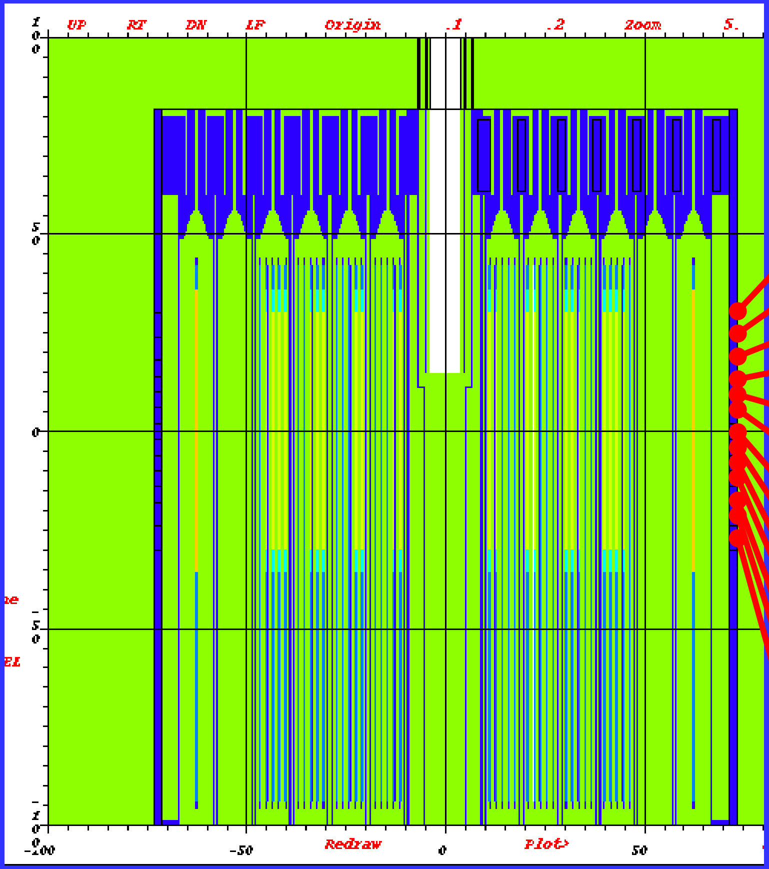
Design of the XT-ADS (EUROTRANS project)



◆ Pb-Bi (coolant) ◆ Air ◆ Concrete ◆ Steel ◆ Fuel pin ◆ Pb-Bi (target)

Vessel
dpa versus core configuration

Y. Romanets - Ph.D. thesis (2012)



z (cm)	*dpa* (year⁻¹mA⁻¹)		*dpa* (year⁻¹mA⁻¹)		*dpa* (year⁻¹mA⁻¹)	
	A1	A2	B1	B2	C1	C2
27	0.84	0.41	0.61	0.41	0.70	0.51
21	0.94	0.45	0.67	0.45	0.76	0.56
16	1.01	0.49	0.71	0.47	0.82	0.61
12	1.05	0.51	0.74	0.50	0.86	0.63
8	1.09	0.52	0.76	0.51	0.88	0.65
4	1.10	0.53	0.77	0.52	0.90	0.67
0	1.11	0.54	0.78	0.52	0.90	0.68
-4	1.11	0.53	0.78	0.52	0.89	0.66
-8	1.09	0.53	0.76	0.51	0.89	0.65
-12	1.06	0.51	0.75	0.50	0.86	0.63
-16	1.02	0.49	0.72	0.48	0.83	0.61
-21	0.96	0.46	0.68	0.45	0.77	0.58
-27	0.87	0.42	0.63	0.41	0.71	0.52
k_{eff}	0.95	0.92	0.96	0.94	0.96	0.94

- Red: Clean core, 72 FA, 31.8% Pu
- Yellow: Clean core, 66 FA, 35% Pu
- Green: IPS loaded core, 78 FA, 35% Pu

ADS - Radiological Protection and Radiation Safety challenges

- Several scientific, technological, engineering and nuclear and radiation safety challenges, namely (not exhaustive list):

✓ Reliability of the proton accelerator

✓ Thermohydraulic behaviour

✓ **Very high radiation damage ⇒ periodic (every 2-5 years ?) replacement of key safety and structural elements (core barrel, top support plates)**

⇒ In view of the currently known material properties

✓ **Po-210 generation**

✓ **Inspection and repair**

⇒ very high residual activity of structural components

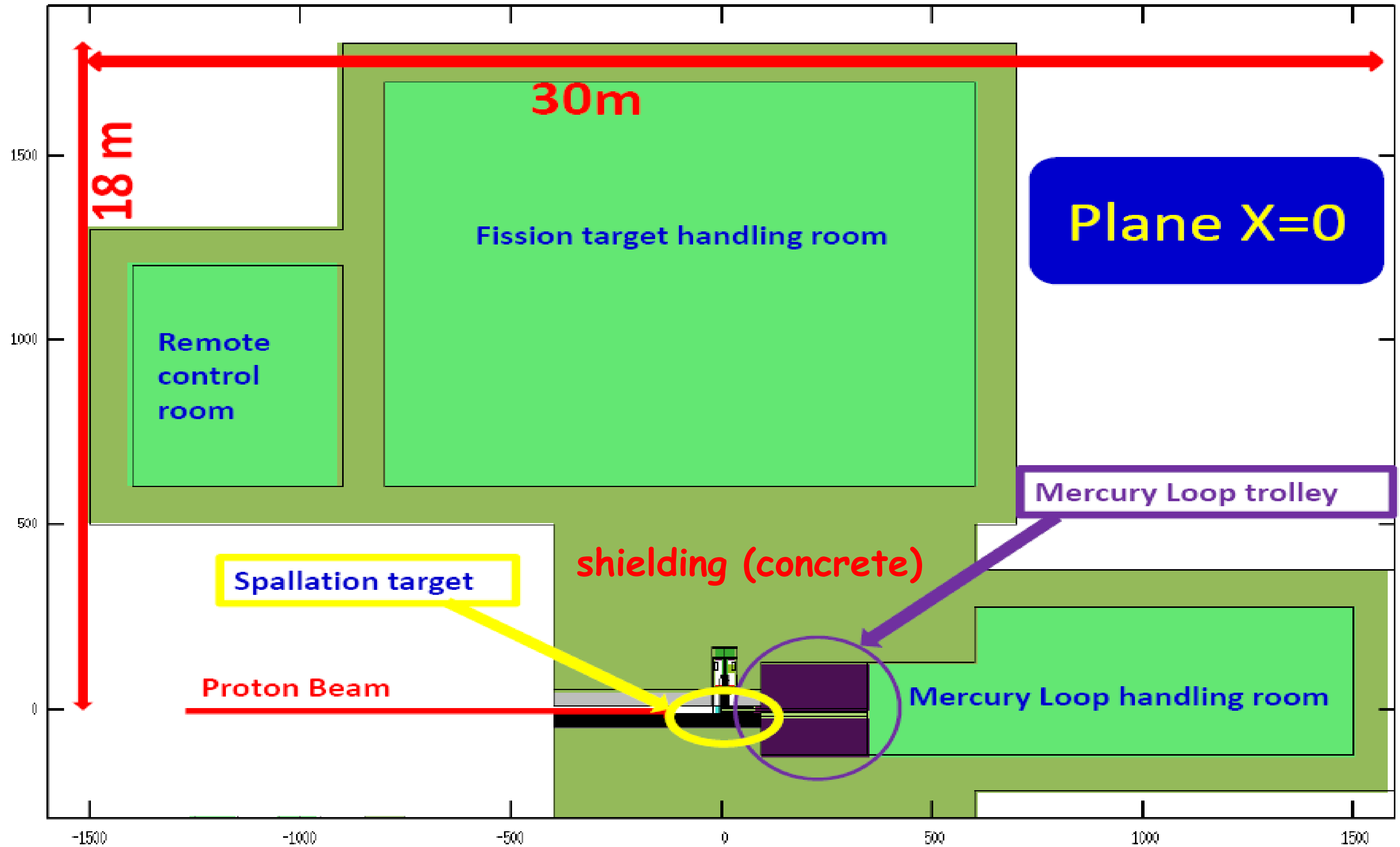
✓ **Radioactive waste management**

⇒ decomissioning, dismantling and disposal

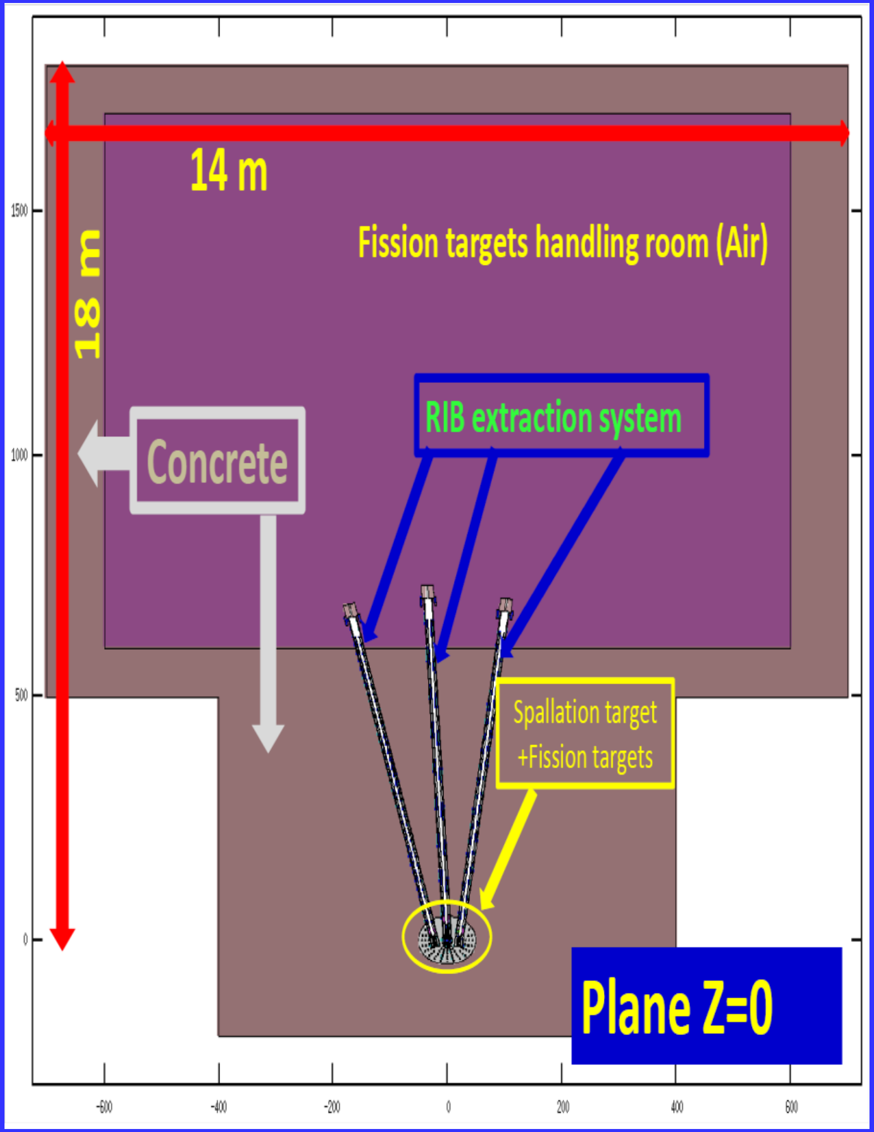
Activation & dose rate issues

"Case study" - EURISOL

EURISOL
Targets and control areas layout (1)

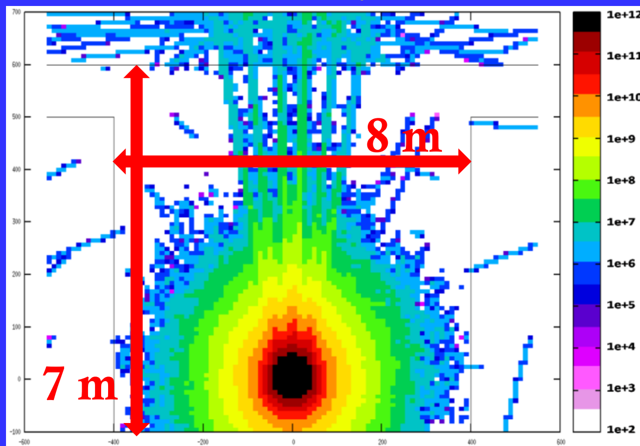


EURISOL
Targets and control areas layout (2)

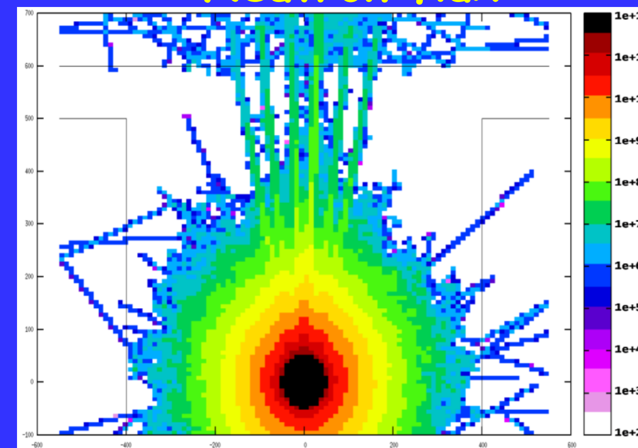


EURISOL - Targets & control areas
Neutron and photon fluxes (cm^{-2} s^{-1})

Photon flux

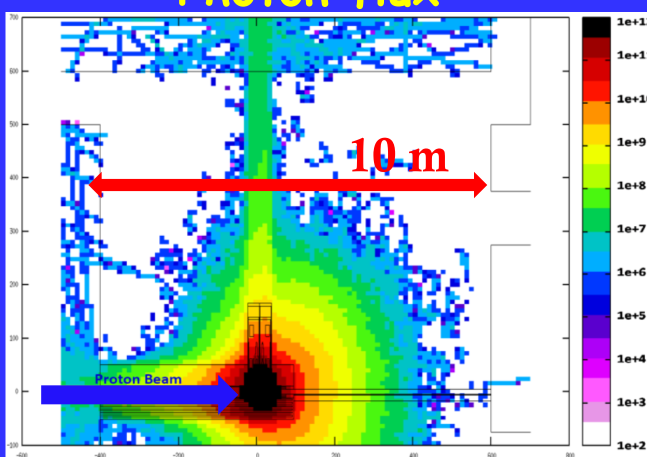


Neutron flux

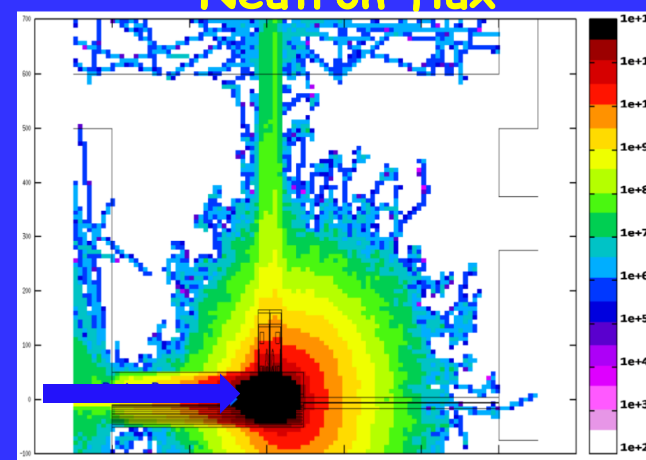


Plane z=0

Photon flux



Neutron flux

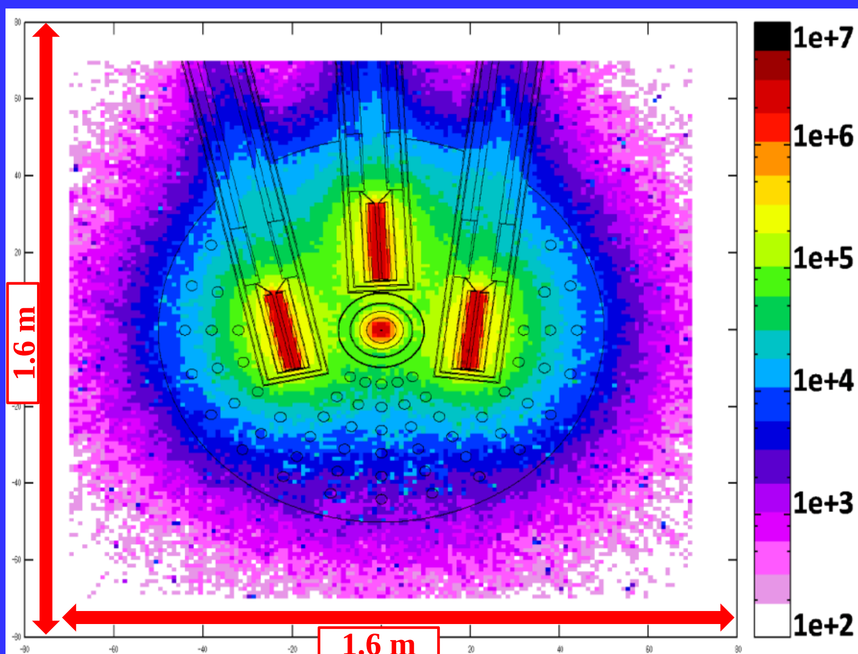


Plane x=0

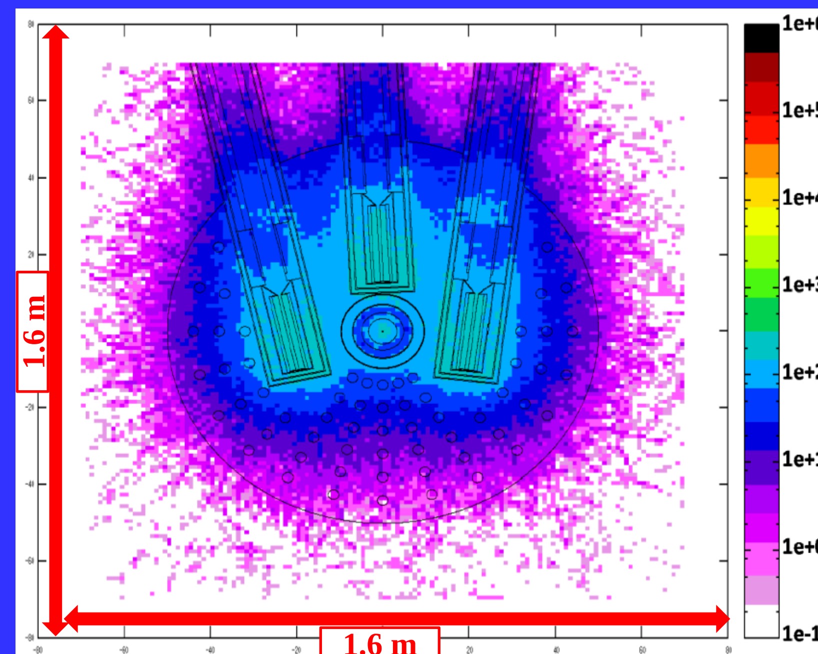
From R. Luís & Y. Romanets – FLUKA MC simulations

EURISOL - Targets
Dose equivalent rate (Sv/h)

beam shutdown (t=0)



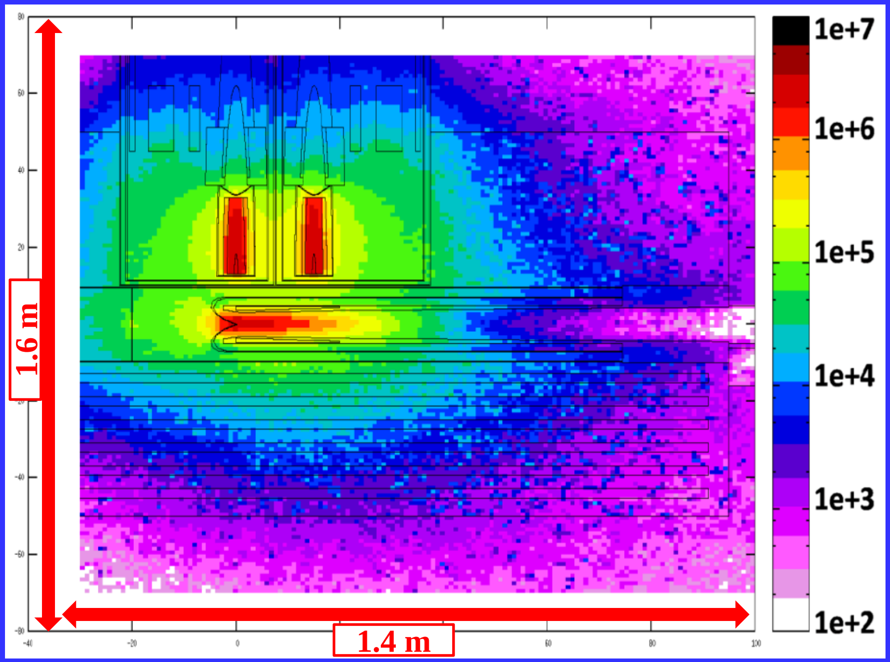
10 years after beam shutdown



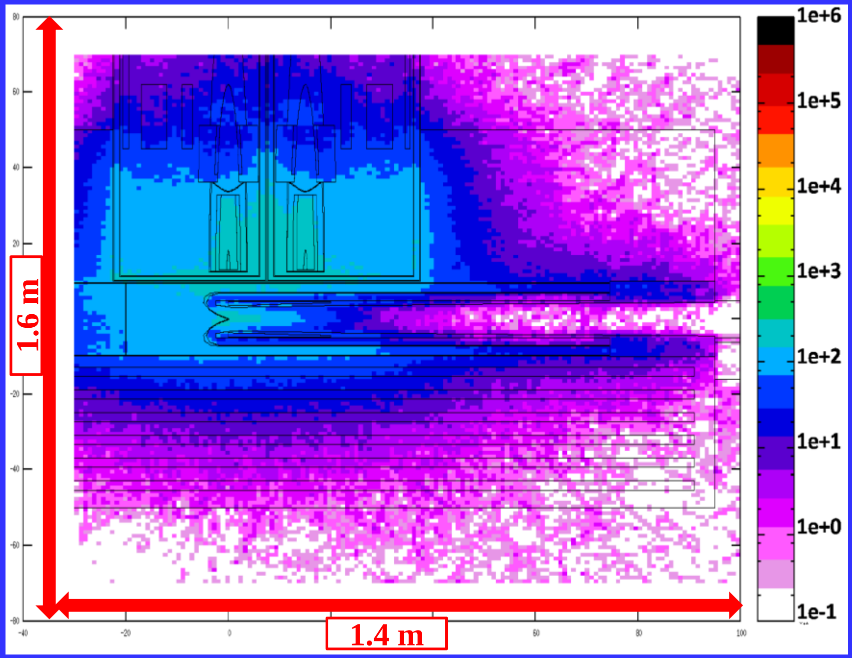
From R. Luís & Y. Romanets – FLUKA MC simulations

EURISOL Design Study
Dose equivalent rate (Sv/h)

beam shutdown (t=0)



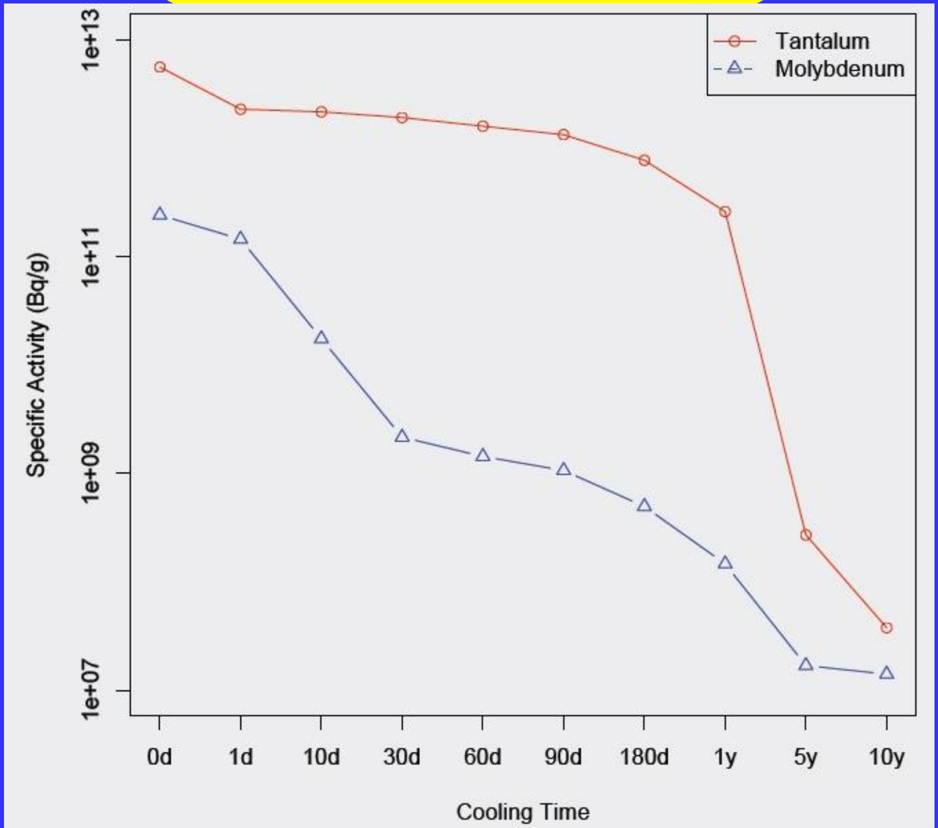
10 years after beam shutdown



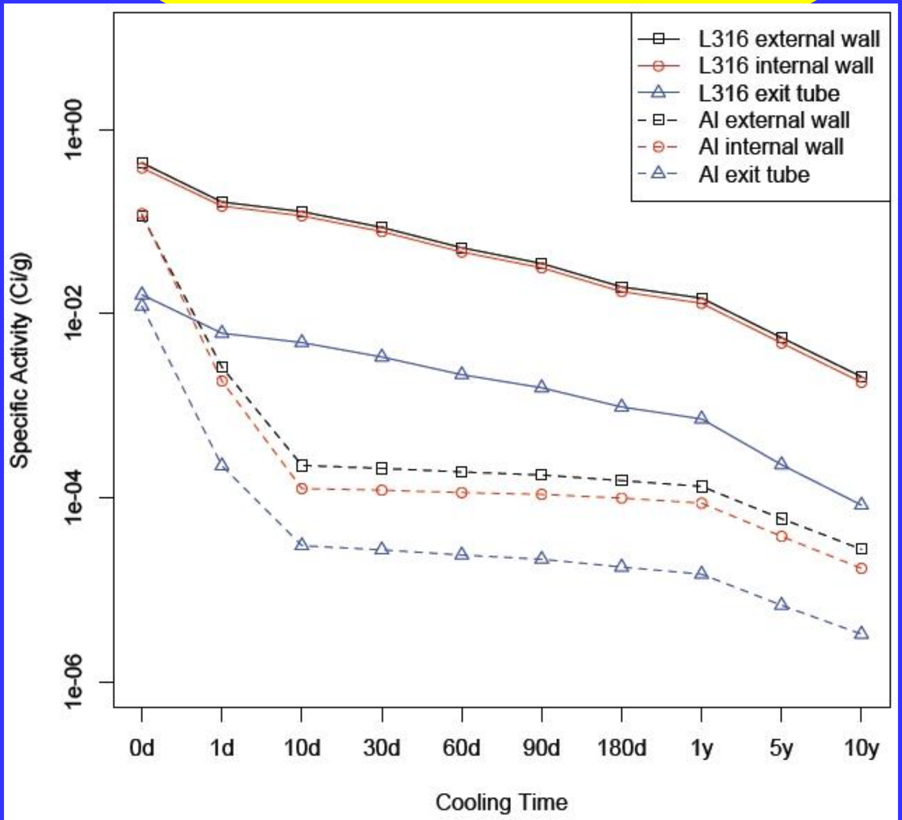
From R. Luís & Y. Romanets – FLUKA MC simulations

EURISOL Design Study
(Residual) activity (after beam shutdown)

fission targets container



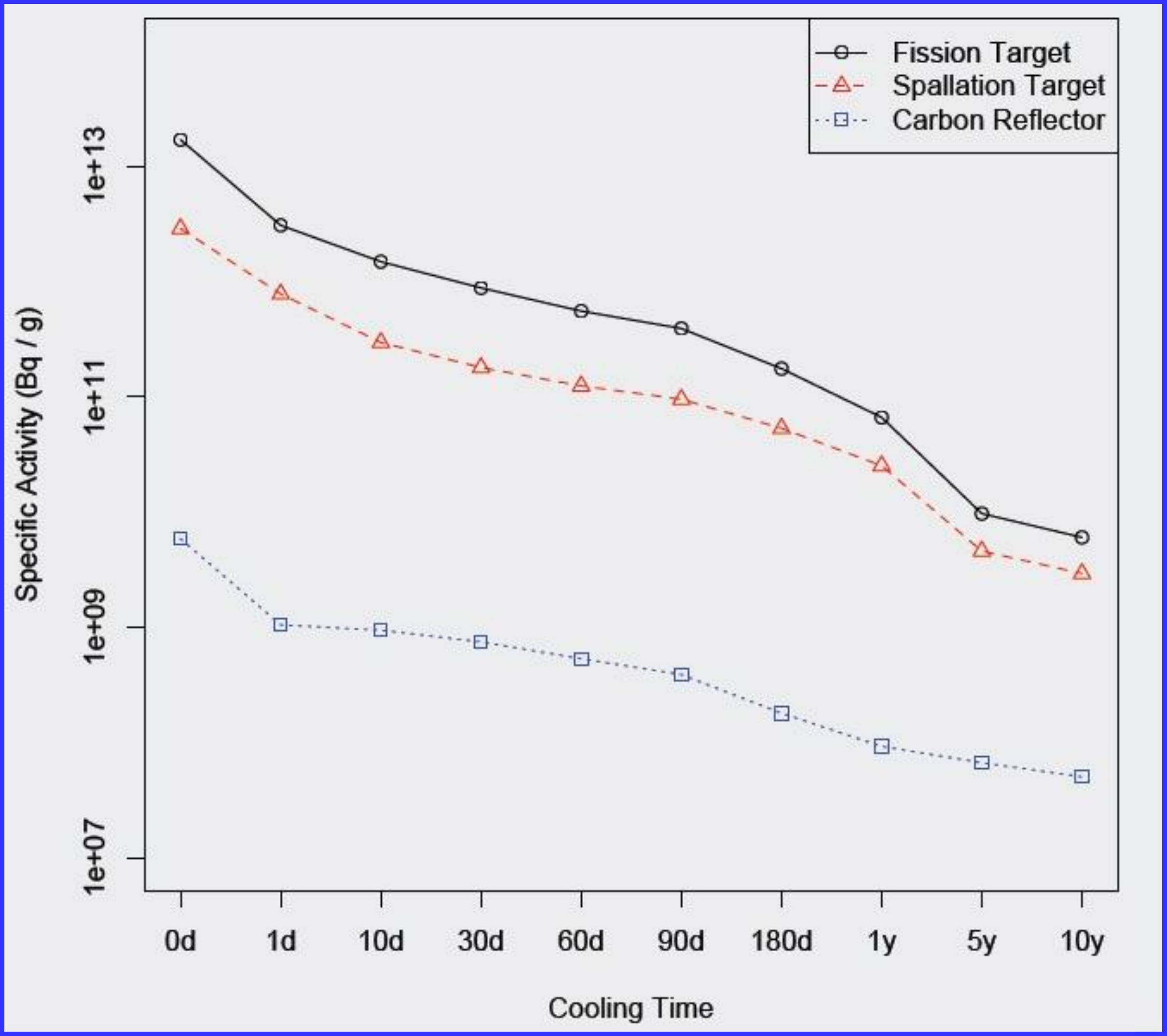
Extraction tubes



From R. Luís & Y. Romanets – FLUKA MC simulations

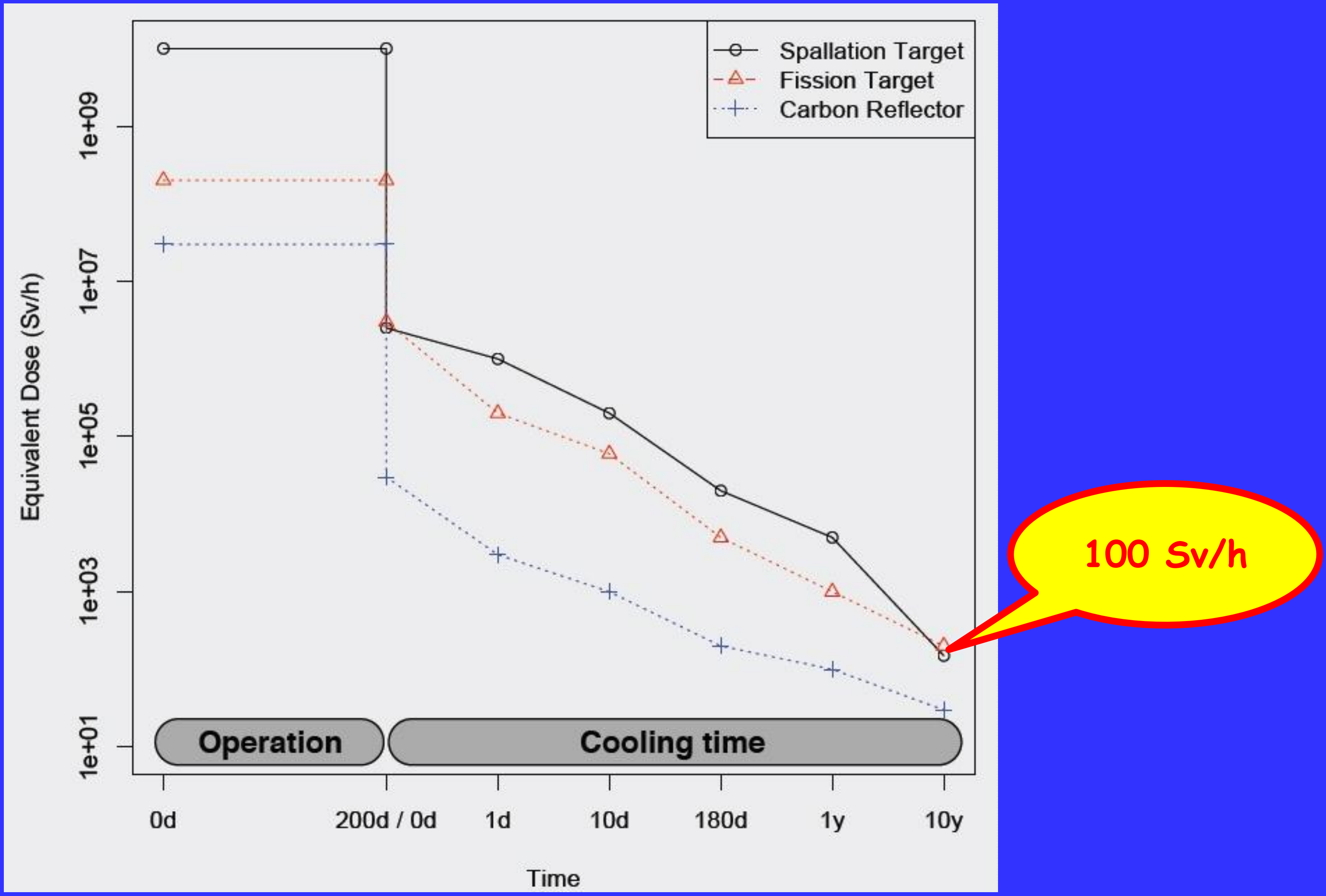
EURISOL Design Study

(Residual) activity - structural components



From R. Luís & Y. Romanets – FLUKA MC simulations

EURISOL Design Study
(Residual) equivalent dose rate



From R. Luís & Y. Romanets – FLUKA MC simulations

EURISOL - Radiological Protection and Radiation Safety challenges

- Several scientific, technological, engineering and nuclear and radiation safety challenges, namely (not exhaustive list):

✓ Mercury target container integrity (dpa assessment, etc.)

✓ Mercury radiotoxicity, volatility, chemistry, etc.

✓ Inspection and repair

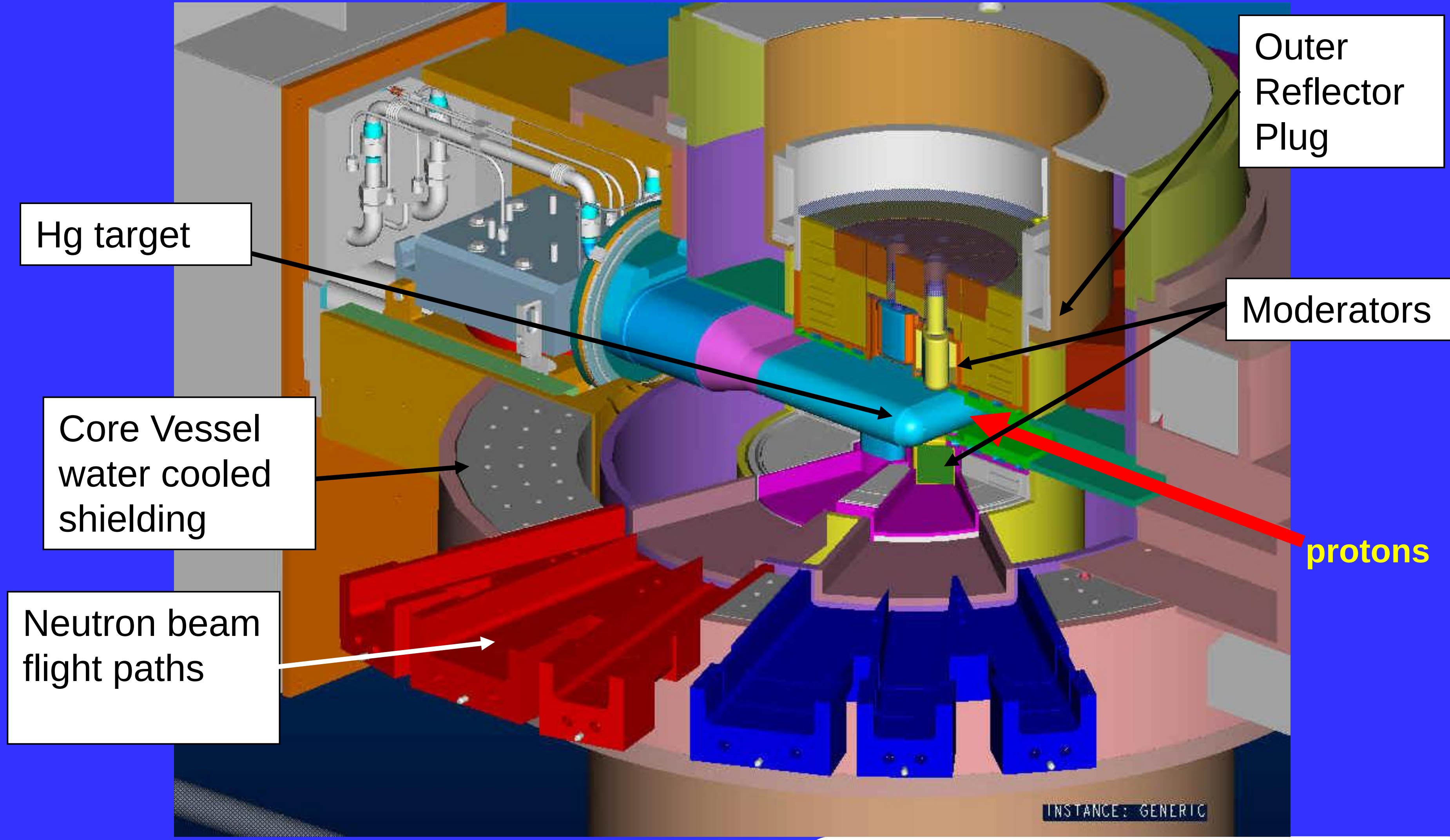
$\Rightarrow$ very high residual activity of structural components

✓ Radioactive waste management and disposal

Radiotoxicity issues

"Case study" – SNS/ESS (Hg) & XADS (Pb-Bi)

Spallation Neutron Sources (SNS)



From P. Ferguson (SNS)

Radiotoxicity issues
Hg targets ("ESS")

Table I: Radiological most relevant nuclides in a 5 MW mercury target (40 y operation, 5000 h/y). Inventories as in [Bongardt 2006]

nuclide	ESS target inventory [GBq]	Half life [d]	boiling point [K]	radia-tion type	dose/emission* [Sv/GBq] ground-shine	cloud-shine (γ)	inhalation	ingestion
H-3/HTO	7.9e5 total	4500	373	weak β	0	0	2.3e-9	4.6e-8
H-3/HT			14		0	0	1.5e-11	3.3e-9
I-124	3100	4.2	387	β,γ	1.9e-6	1.0e-8	3.0e-5	3.4e-3
I-125	14000	60	„	γ	1.2e-6	1.0e-10	1.8e-5	**2.3e-3**
I-126	630	13	„	β,γ	2.6e-6	4.2e-9	6.3e-5	7.6e-3
Hg-193	1.9e6	0.16	629	γ	2.4e-8	1.7e-9	6.5e-9	2.5e-10
Hg-194	1.4e5	1.4e5	„	γ	**5.4e-3**	1.3e-13	1.3e-6	3.7e-7
Hg-195	3.2e6	0.42	„	γ	5.0e-8	1.7e-9	8.1e-9	6.3e-10
Hg-197	2.2e7	2.67	„	γ	7.4e-8	5.2e-10	2.0e-8	3.0e-9
Hg-203	1.5e7	47	„	β, γ	4.9e-6	2.2e-9	1.8e-7	8.1e-9
Sr-90	14000	1.05e4	1653	β	0	0	3.5e-5	**5.2E-3**
Gd-148	3.5e4	2.72e4	3546	α	0	0	**2.2e-3**	3.6e-7
Hf-172	7.3e5	683	4875	γ	1.9e-4	7.7e-10	1.3e-5	1.9e-9
Au-195	4.2e6	186	3081	γ	2.1e-6	6.2e-10	2.2e-8	5.9e-10

From R. Moormann et. al. (@PHYSOR 2008)

Radiotoxicity issues
Pb-Bi targets (XADS) (1)

Mercury produced by spallation

Table 3. Activation of mercury after 20 y

Name	$T_{1/2}$	Mass (g)	Atoms	Activity (Bq)	Radiotoxicity
^{193}Hg	0.146 d	2.209E-05	6.894E+16	3.792E+12	4.172E+03
^{193m}Hg	0.463 d	2.110E-05	6.585E+16	1.142E+12	3.541E+03
^{194}Hg	260 y	1.436E+00	4.459E+21	3.767E+11	1.507E+04
^{195}Hg	0.413 d	1.944E-04	6.006E+17	1.168E+13	1.635E+04
^{195m}Hg	1.73 d	5.516E-05	1.704E+17	7.900E+11	6.478E+03
^{197}Hg	2.67 d	3.846E-03	1.176E+19	3.533E+13	1.554E+05
^{197m}Hg	0.992 d	1.061E-05	3.243E+16	2.624E+11	1.522E+03
^{203}Hg	46.6 d	1.662E-02	4.931E+19	8.489E+12	5.942E+04

From the radioprotection point of view, the analysis of the migration potential of mercury isotopes must be assessed, namely:

^{193}Hg, ^{194}Hg, ^{195}Hg, ^{197}Hg, and ^{203}Hg

From J. Cetznar et. al. (2010)

Radiotoxicity issues
Pb-Bi targets (XADS) (2)

Lead, bismuth and thallium activity

Table 4. Activation of Pb, Tl and Bi after 20 y

Name	$T_{1/2}$	Mass (g)	Activity (Bq)
^{198}Pb	0.100 d	4.31E-05	1.895E+13
^{200}Pb	0.896 d	1.98E-04	8.676E+13
^{201}Pb	0.392 d	3.20E-04	1.407E+14
^{202}Pb	3.00E+05 y	2.81E-08	1.236E+10
^{202m}Pb	0.151 d	2.95E-06	1.297E+12
^{203}Pb	2.17 d	1.23E-03	5.420E+14
^{205}Pb	1.43E+07 y	1.88E-07	8.241E+10
^{209}Pb	0.135 d	1.95E-02	8.551E+15
^{197}Tl	0.118 d	5.22E-05	2.293E+13
^{198}Tl	0.221 d	1.03E-04	4.523E+13
^{199}Tl	0.309 d	1.63E-04	7.138E+13
^{200}Tl	1.09 d	3.10E-04	1.360E+14
^{201}Tl	3.04 d	4.50E-04	1.975E+14
^{202}Tl	12.2 d	1.58E-04	6.960E+13
^{204}Tl	3.78 y	2.10E-04	9.238E+13
^{203}Bi	0.492 d	1.92E-04	8.453E+13
^{204}Bi	0.467 d	4.14E-04	1.819E+14
^{205}Bi	15.3 d	8.22E-04	3.612E+14
^{206}Bi	6.24 d	1.81E-03	7.938E+14
^{207}Bi	38.0 y	2.29E-03	1.006E+15
^{208}Bi	3.68E+05 y	1.02E-06	4.490E+11
^{210}Bi	5.01 d	4.85E-01	2.132E+17
^{210m}Bi	3.00E+06 y	1.65E-06	7.258E+11

From J. Cetznar et. al. (2010)

Radiotoxicity issues
Pb-Bi targets (XADS) (3)

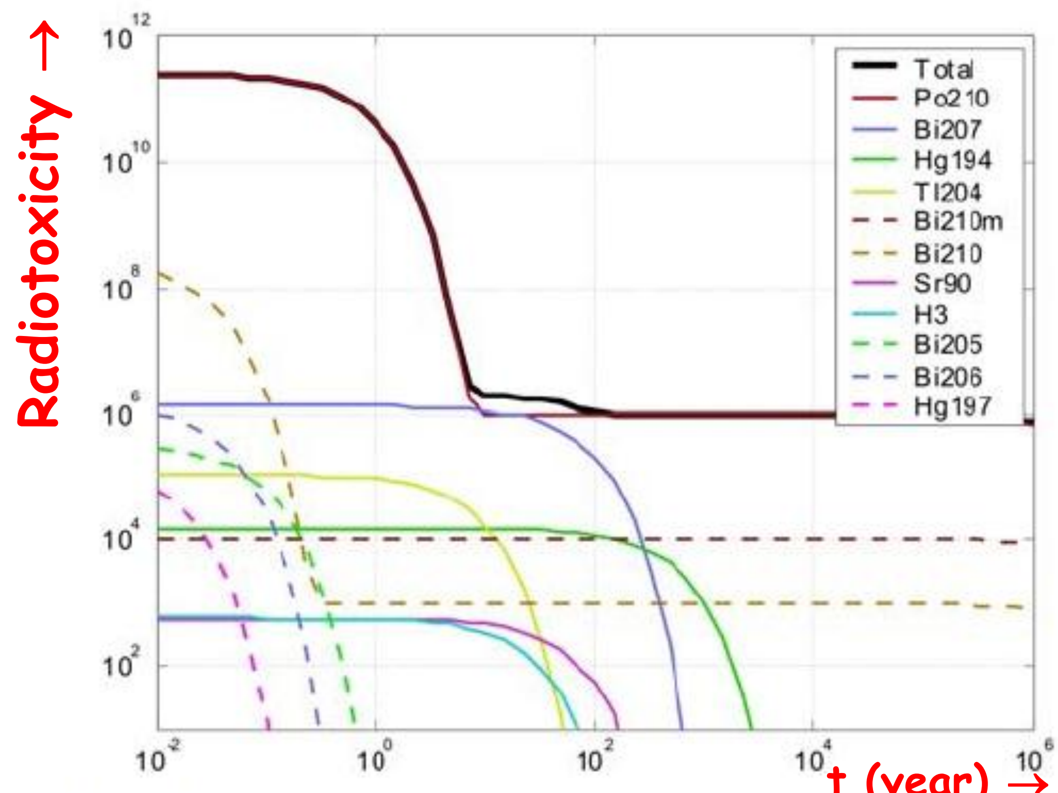


Fig. 7. Radiotoxicity in the primary system coolant of LBE cooled XADS in discharge after 20 y of operation.

From J. Cetznar et. al. (2010)

Activity and associated radiotoxicity of ^{210}Po is reduced by five orders of magnitude after about eight years, but still a high level of radiotoxicity will be maintained over one million years (10^6 Sv !!!)

Radiotoxicity

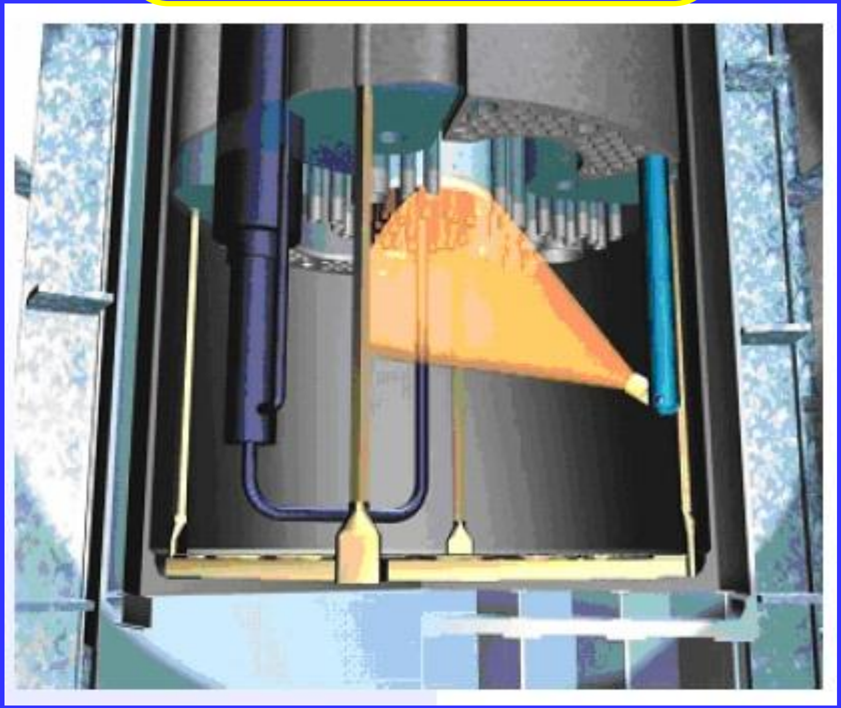
- Nuclides that are predominant for radiotoxicity build-up originating from the interaction with core neutrons are:
  - ^{210}Po, ^{210}Bi, ^{206}Bi, ^{207}Bi, ^{204}Tl.
- The major contributions from the spallation process are given by:
  - ^{194}Hg, ^{197}Hg, ^{204}Tl, ^{207}Tl, ^{203}Pb, ^{203}Bi.

Inspection & Repair issues

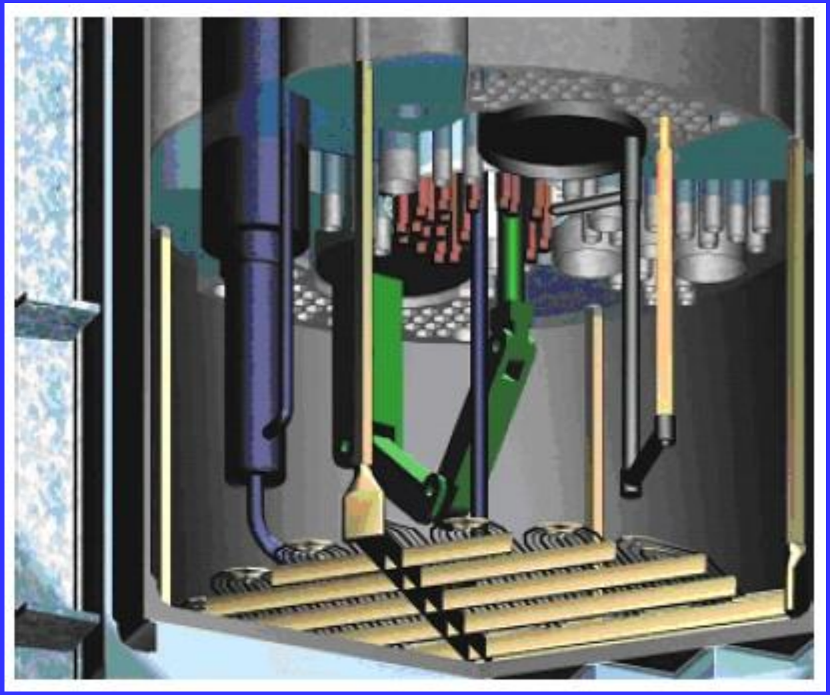
"Case study" – ADS (MYRRHA)

Inspection and Repair (MYRRHA)

Inspection



Repair



Inspection (general overview, detailed analysis of critical components)
Repair (recover of debris, deployment of specialized tools, etc.)
in/through opaque medium
Use of ultrasound technogies
Remote handling

Courtesy of H. Abderrahim & the MYRRHA team (SCK/CEN)

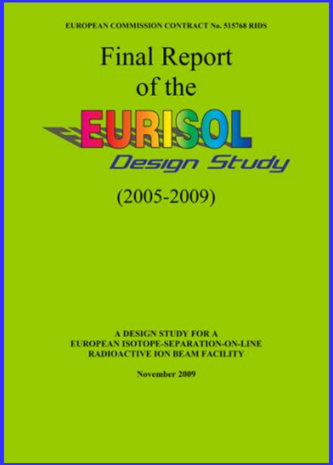
Summary and Outlook
(not Conclusions !)

- Next generation emerging and innovative nucl… gy facilities
  - ✓ Unpredecented radiation environment … ry high:
    - ✓ Radiation damage of struct…
    - ✓ Dose rates
    - ✓ Activation of …
    - ✓ Radiote…
- Ro… ssed:
  - ✓ … s and the whole installation
  - ✓ … ve) solutions
  - ✓ R… agement
  - ✓ Lic…
  - ✓ Dec… ioning, Dismantling and Disposal

Some open question and unresolved issues must be carefully addressed and solutions are still to be found

Annex

EURISOL Design Study
Conclusions on Safety Chapter


EUROPEAN COMMISSION CONTRACT No. 515768 RIDS

Final Report
of the
EURISOL
Design Study
(2005-2009)

A DESIGN STUDY FOR A
EUROPEAN ISOTOPE-SEPARATION-ON-LINE
RADIOACTIVE ION BEAM FACILITY

November 2009

11.7 Conclusion

The envisaged increase by several orders of magnitude of the radioactive ion beam (RIB) intensity within EURISOL means a drastic increase of the radioactive inventory and corresponding radio-protection related issues. The goal of this task within the Design Study was to provide a quantitative evaluation of the major safety and radioprotection issues. Calculations of the expected levels of radiation production and activation have been performed and have shown that the high-power (4 MW) target station should be considered as a research reactor. Methods for shielding against prompt radiation have been given. The containment of activity was also studied, and both cryotrap and aerosol filter devices were developed and tested with very good results. Methods and software (EDAT) were developed to manage activity transport in soil and groundwater and the dispersion of radioactivity. Decommissioning of the facility, and in particular the disposal of spent targets, was analysed and an innovative strategy were developed. Costs related to decommissioning will be high, and should be taken into careful consideration. Finally, when any site is proposed, one should examine whether detailed legal regulations exists in each candidate country, and whether the proposed facility conforms to such legislation.

From the safety point of view the mercury target is a crucial point. Much work has been done to determine how to manage this liquid-metal target and mitigate the risks. Some solutions have been found for the decommissioning, but the studies must be continued. Nevertheless, other options exist. For a liquid-metal target, a Pb-Bi eutectic can be used. This target needs heating to become liquid, and becomes solid again when the heating is removed, so decommissioning should be easier. In fact, such a target has been irradiated for 4 months in 2006 during the MEGAPIE project at PSI, Villigen, using a 575-MeV proton beam current of around 1 mA. This experiment was successful as regards the neutron flux obtained, and the main problem studied concerning safety was gas production and release. A post-irradiation experiment [5] will provide the nuclides produced in the target and not released. This will indicate what decontamination issues could be encountered for the Pb-Bi eutectic target.

Thus, while a mercury target is quite promising, a Pb-Bi target remains an interesting alternative.