# Radiation Safety for High Power Operation

D. Ridikas for Task 5

## List of objectives:

- Shielding against prompt radiation and induced radioactivity
- Containment of radioactivity
- Characterization of nuclear waste and disposal of spent targets
- Conformity of the proposed installation to the legislation

**Major efforts on the 4 MW target station !**



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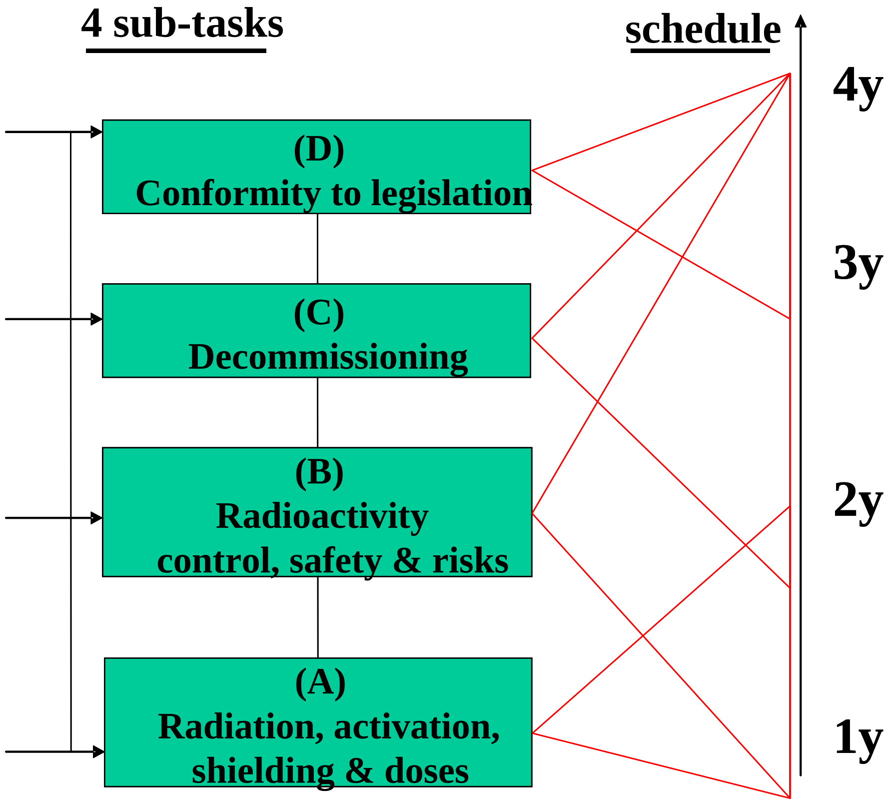
# Task 5: Participants and work plan




| | **Participants:** | **role** |
|---|---|---|
| 1. | GANIL, France | - sub-task D |
| 2. | FZJ, Germany | - sub-task C |
| 3. | LMU, Germany | - sub-task B |
| 4. | CERN, EU | - sub-task A |
| **5.** | CEA, France | - coordination |
| 6. | NIPNE, Romania | - contribution |
| 7. | FI, Lithuania | - contribution |
| 8. | Univ. Warsaw, Poland | - contribution |

**External partners:**

ORNL, ANL, TRIUMF, JAEA, KAERI



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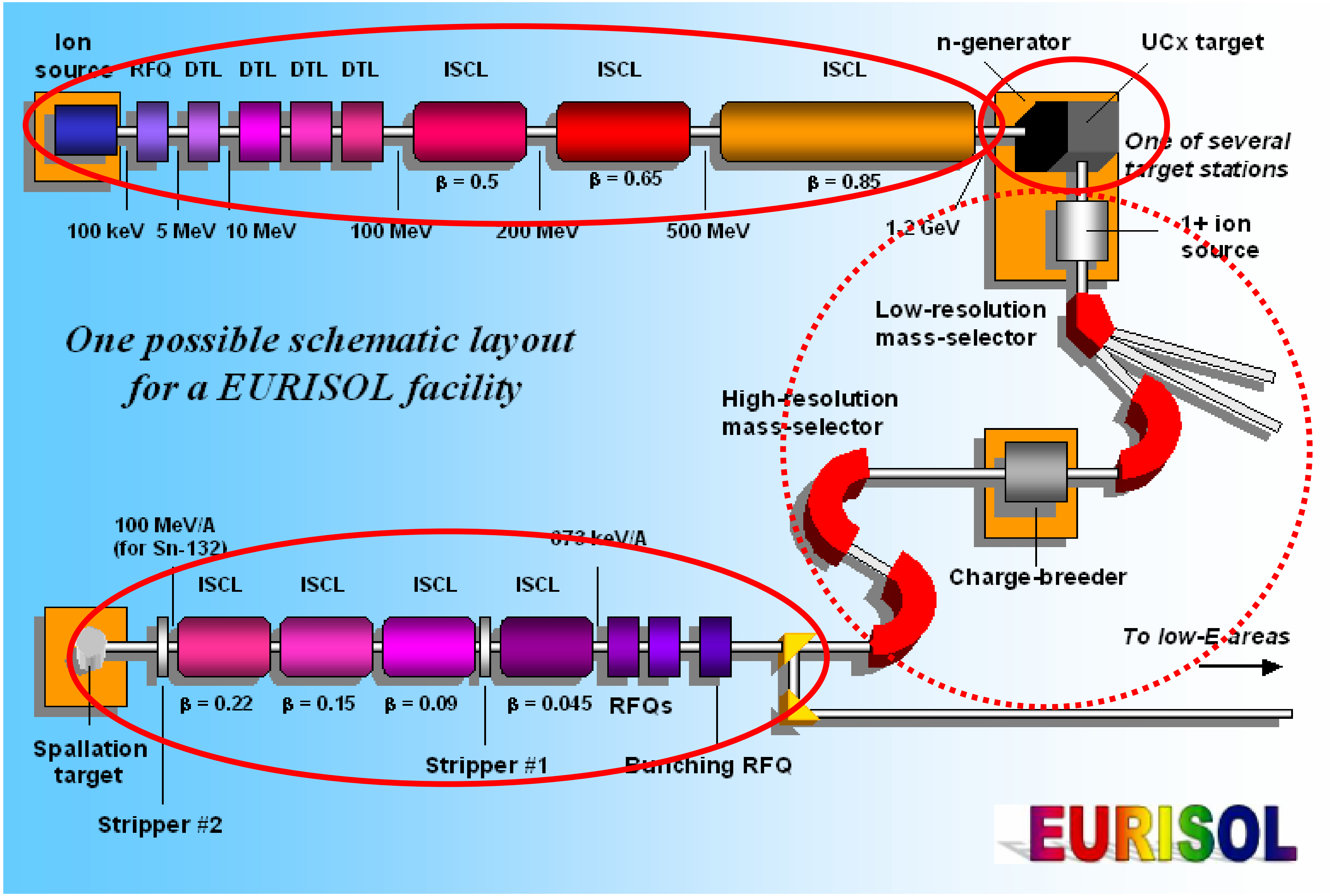
# …compared to other projects…



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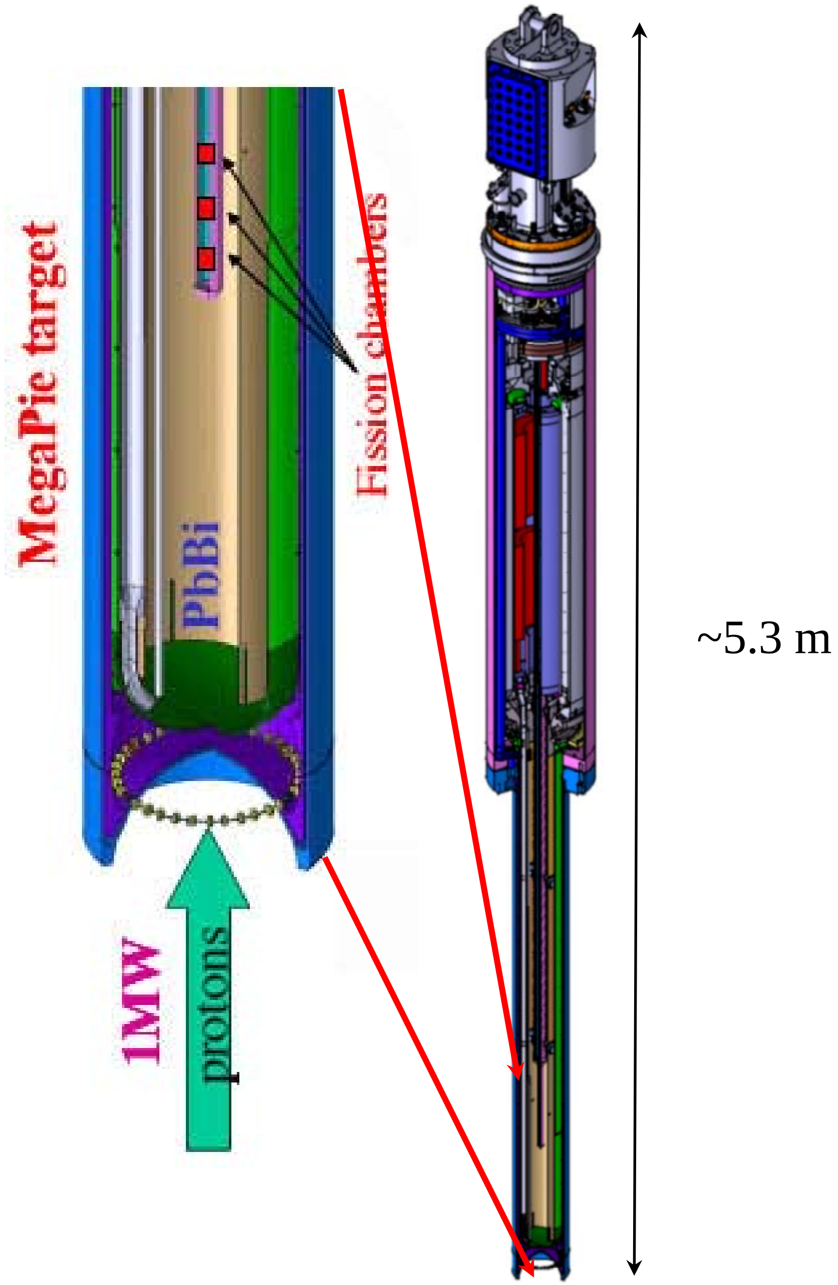
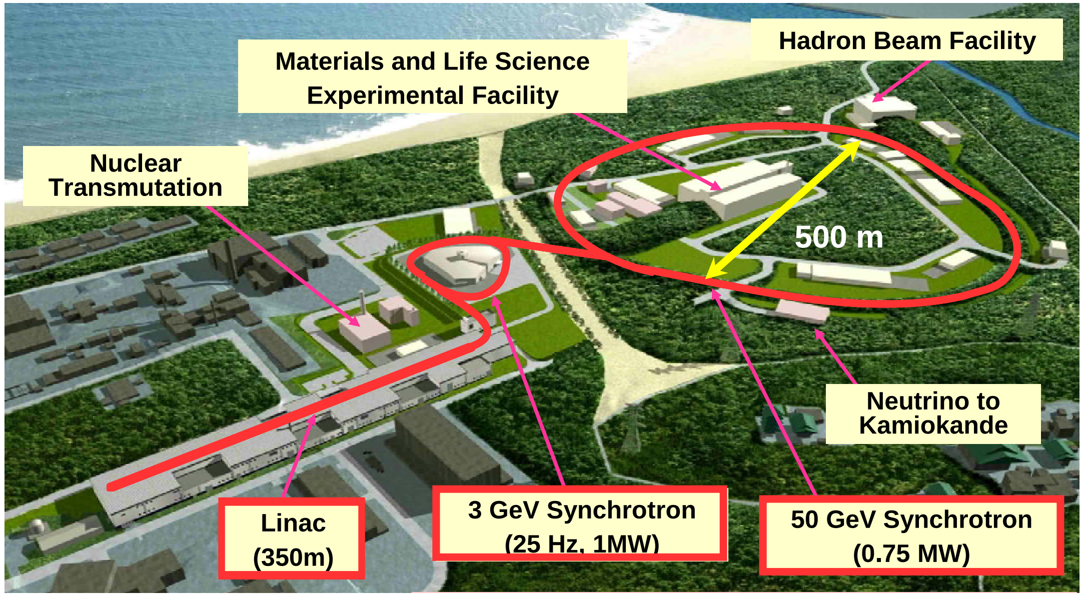
# MegaPie/PSI

| | |
|---|---|
| $E_p$ | 570 MeV |
| $I_p$ | 1.2 mA (1.8) |
| W | 0.7MW (1.0) |
| $V_{PbBi}$ | ~ 82 liters |
| Main pump | ~4.00 l/s |
| $T_{transit}$ | ~20 s |



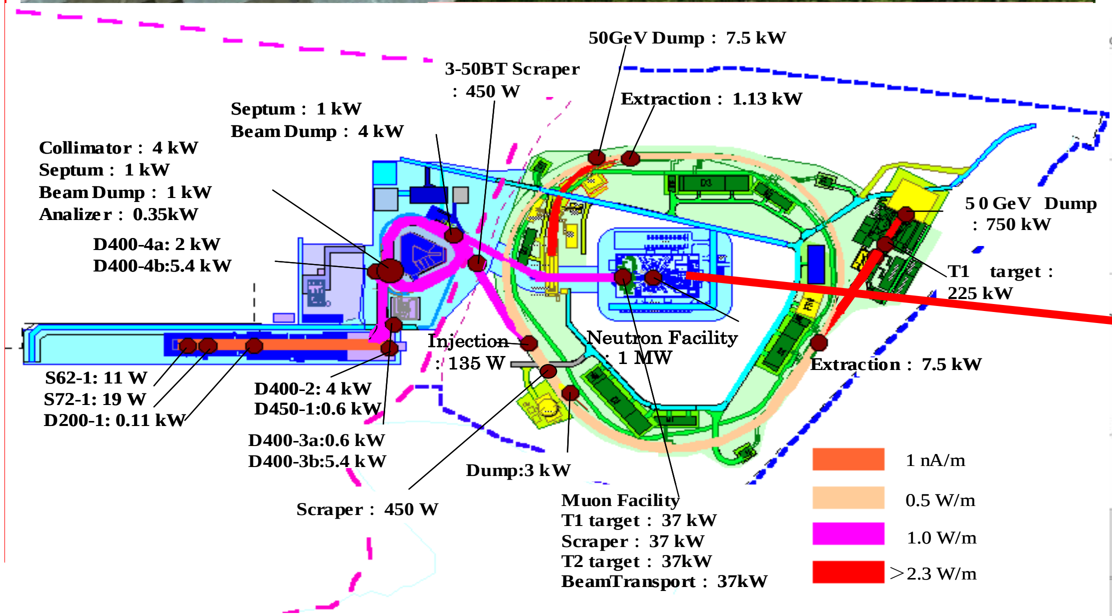

**1st beam on the target since 14 August and still running!**

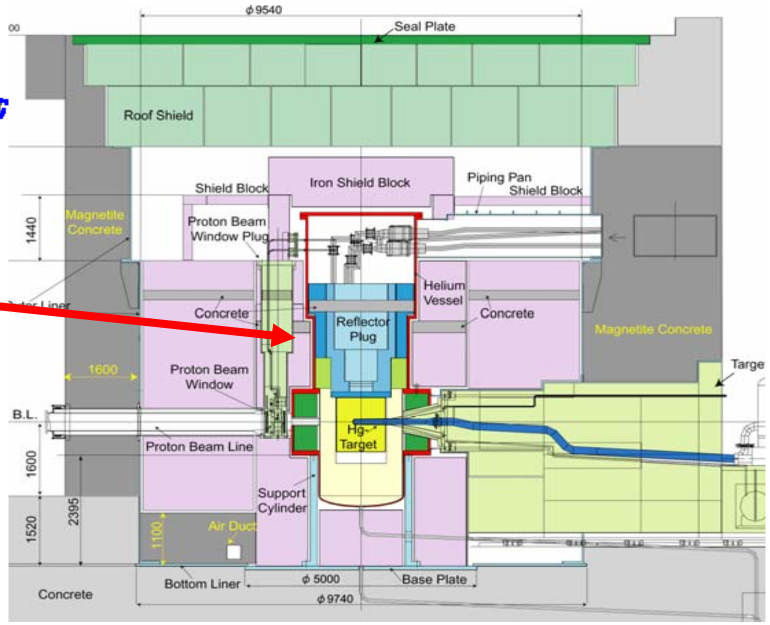
# J-PARK/JAEA - thanks to H. Nakashima



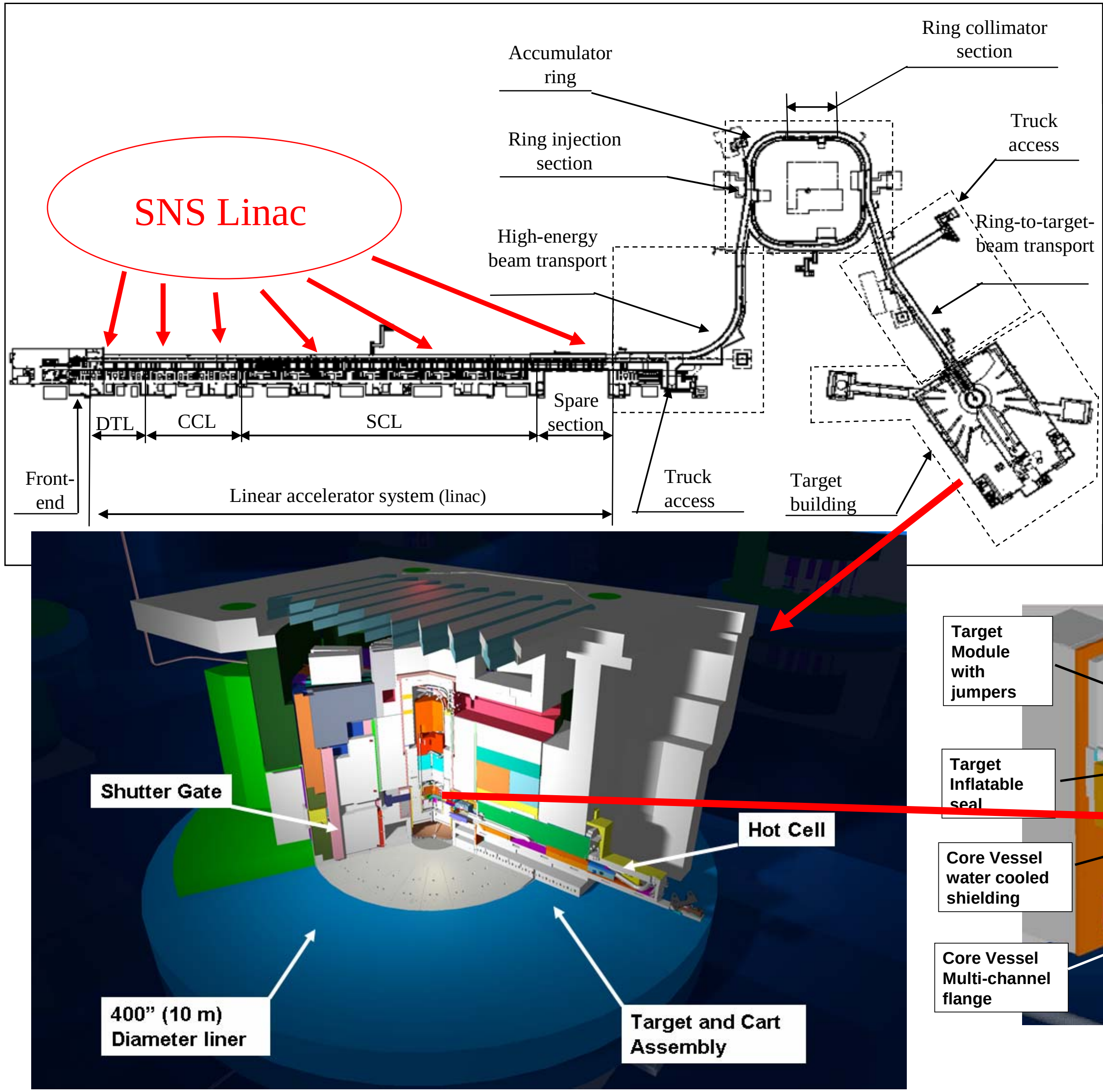

## → Facility Under construction ←

- 3GeV, 1MW, 25Hz, proton beam
- Mercury target of $1.4m^3$
- Moderators with liquid H of 260l
- Shield of about 10,000t and movable target structure

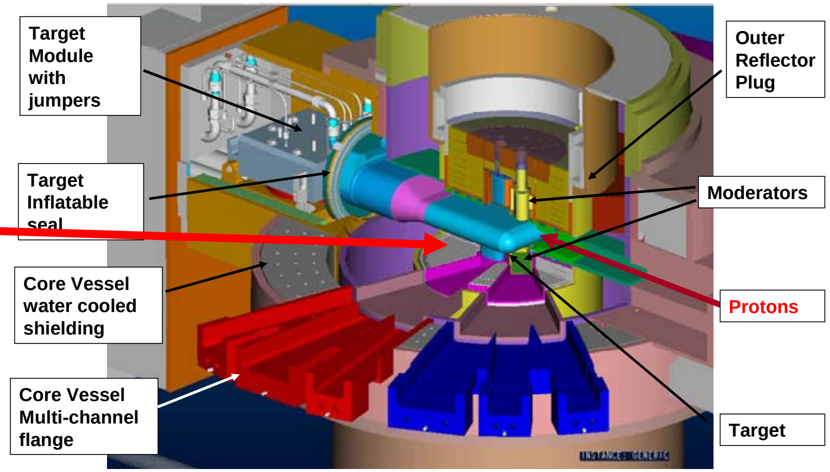


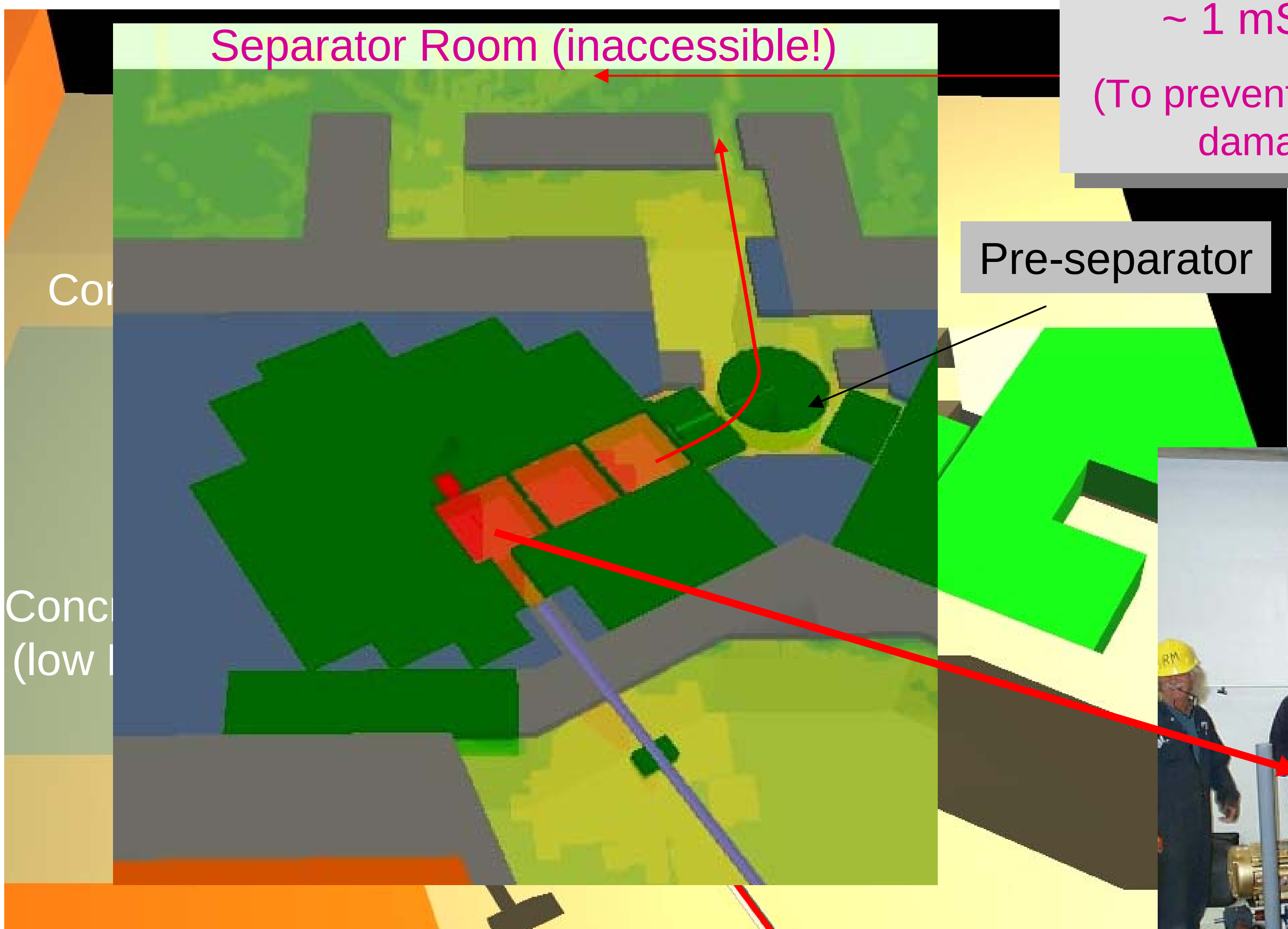
# SNS/ORNL - thanks to F. Gallmeier




- The SNS has started operation in 2006
- 1GeV protons on liquid Hg (1.4 MW)
- The peak neutron flux ~20–100x ILL
- SNS will be the world's leading facility for neutron scattering



# TRIUMF - thanks to L. Moritz




~ 1 mSv $h^{-1}$

(To prevent radiation damage)

Pre-separator

Target: 50 g $cm^{-2}$ $UC_2$
$E_p$ = 500 MeV
$I_p$ = 100 µA

Proton beam

**No license so far!**



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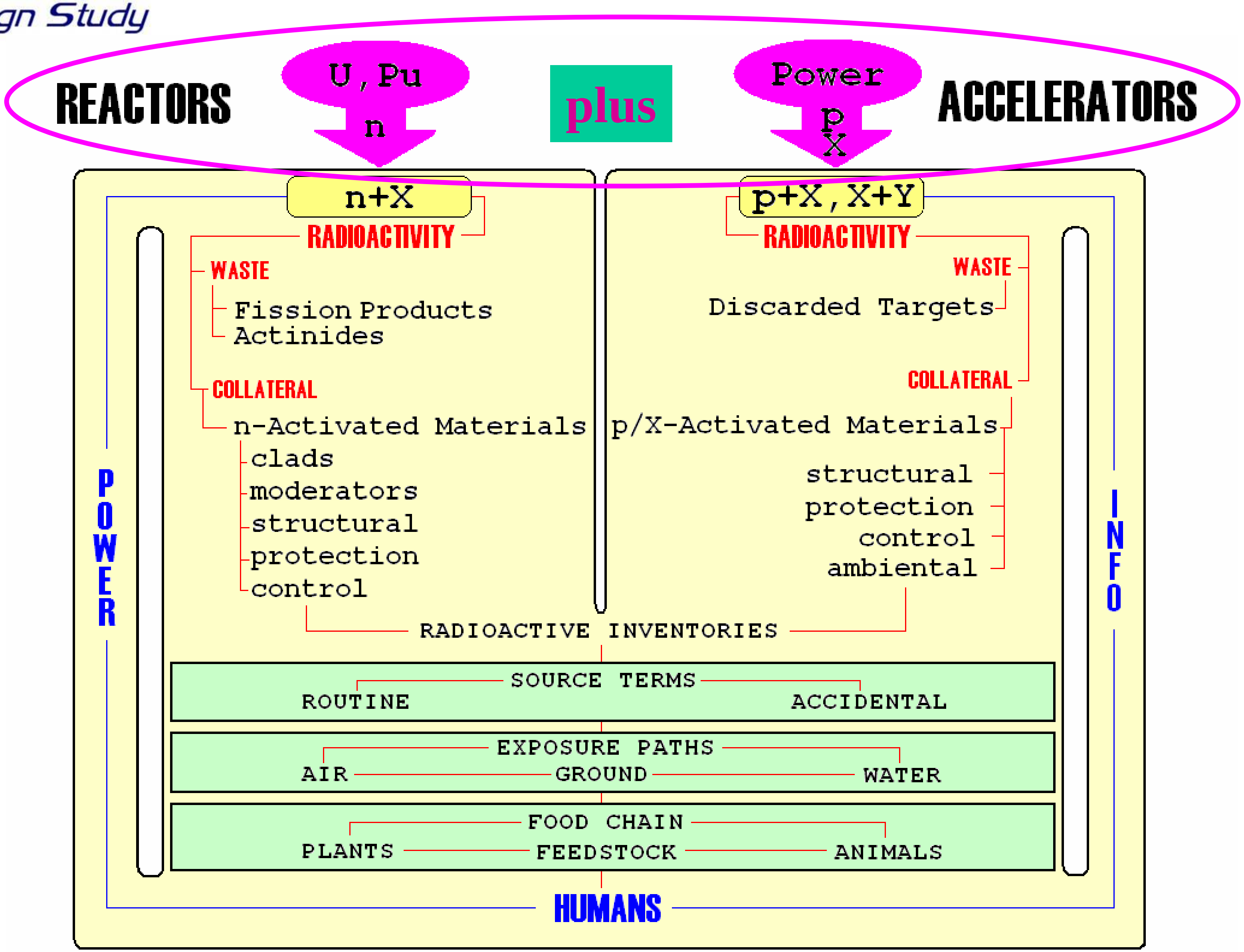


EURISOL → combination of both!



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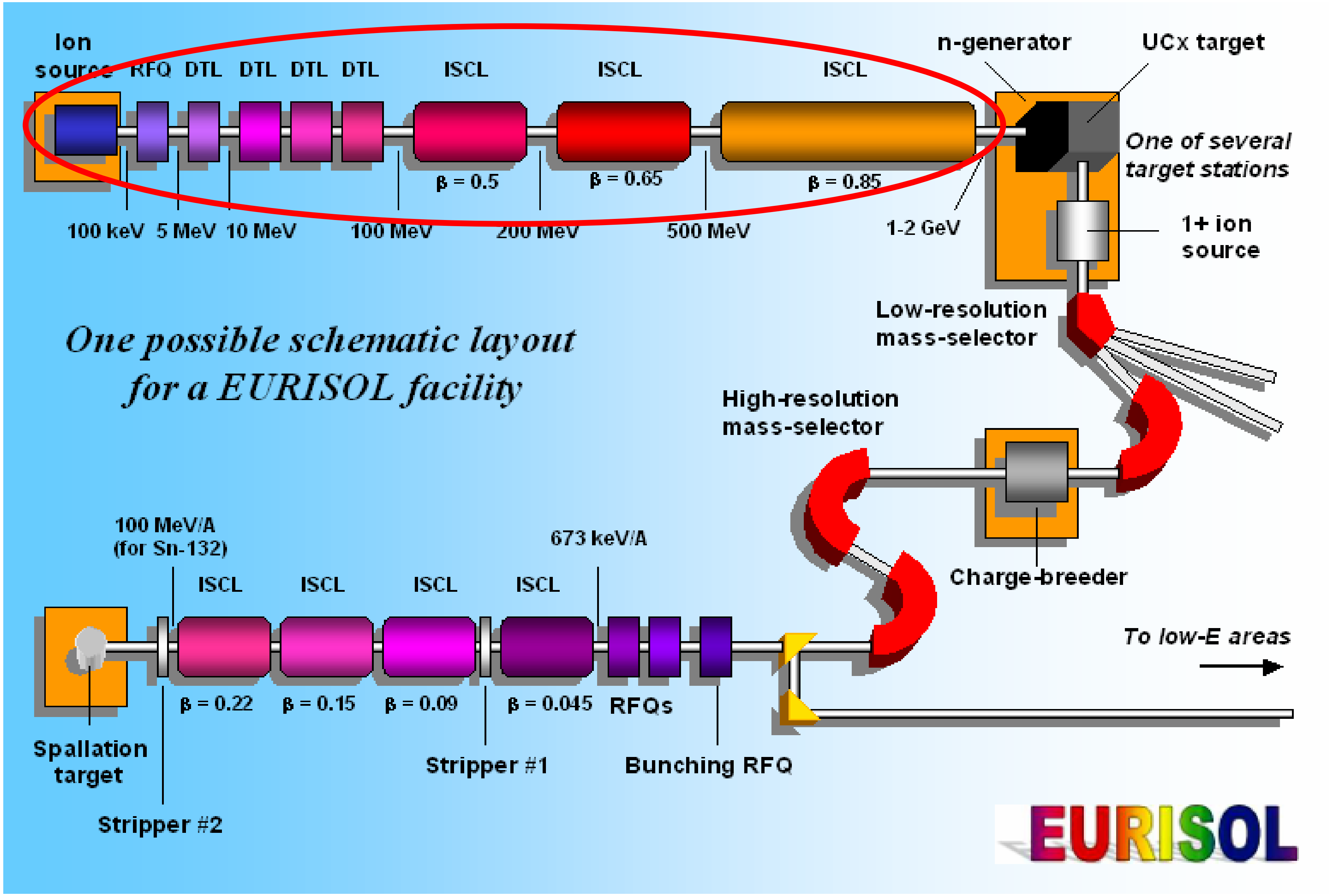
# A) Shielding of the proton driver



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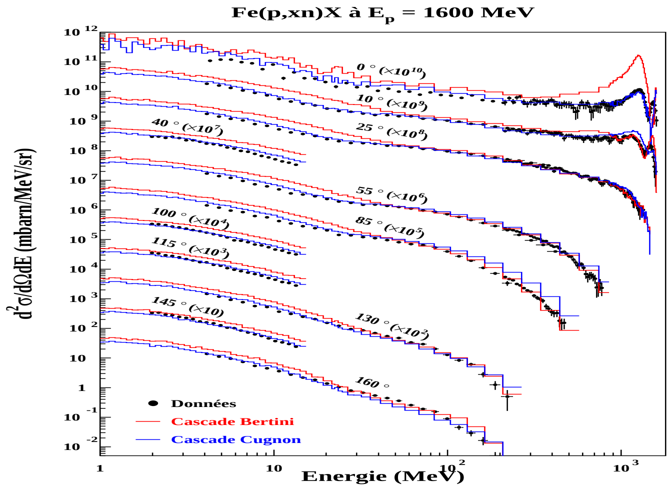
EURISOL Design Study

# A) Shielding benchmarks

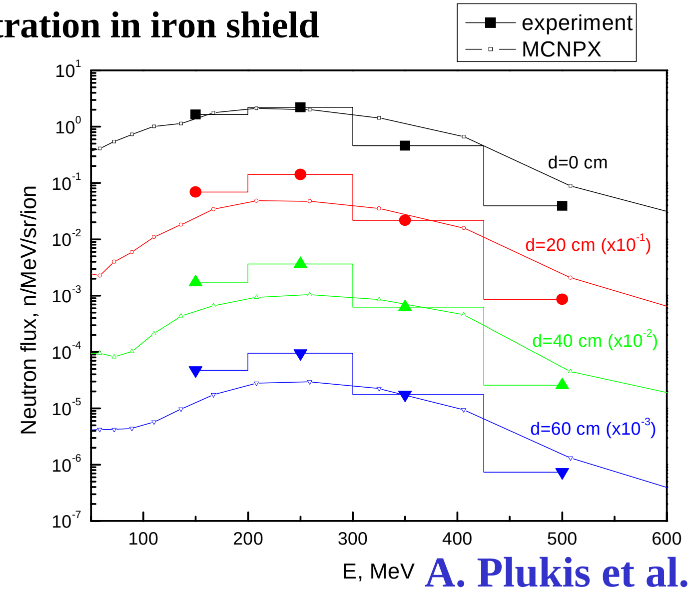
**T5: Safety & Radioprotection**

## p(1.6 GeV) + Fe → neutrons



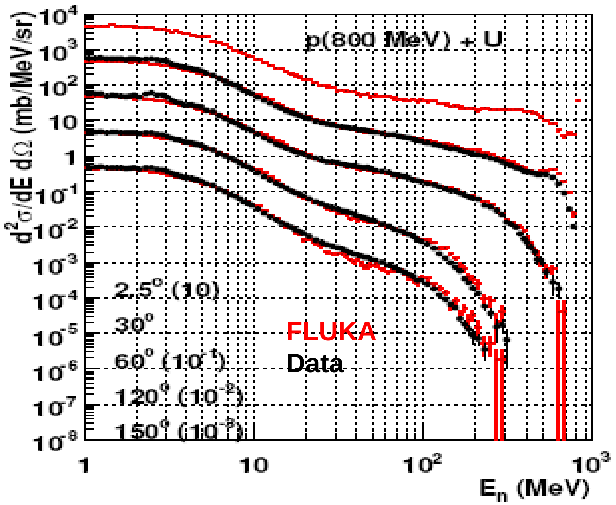

**J.-C. David et al. (CEA)**

## Neutron penetration in iron shield



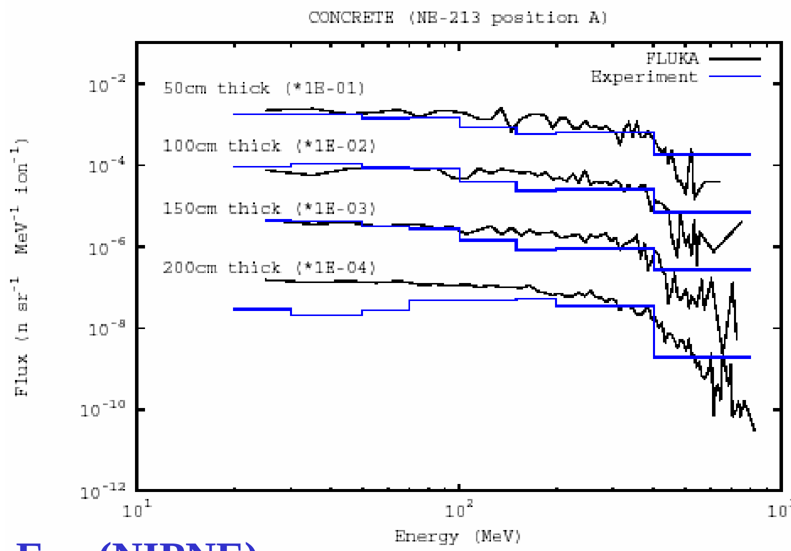

**A. Plukis et al. (FI)**

## p(0.8 GeV) + U → neutrons




**M. Felcini et al. (CERN)**

## Neutron penetration in concrete shield

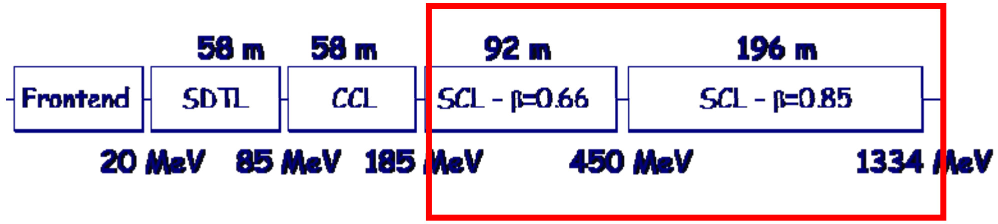



**D. Ene (NIPNE)**

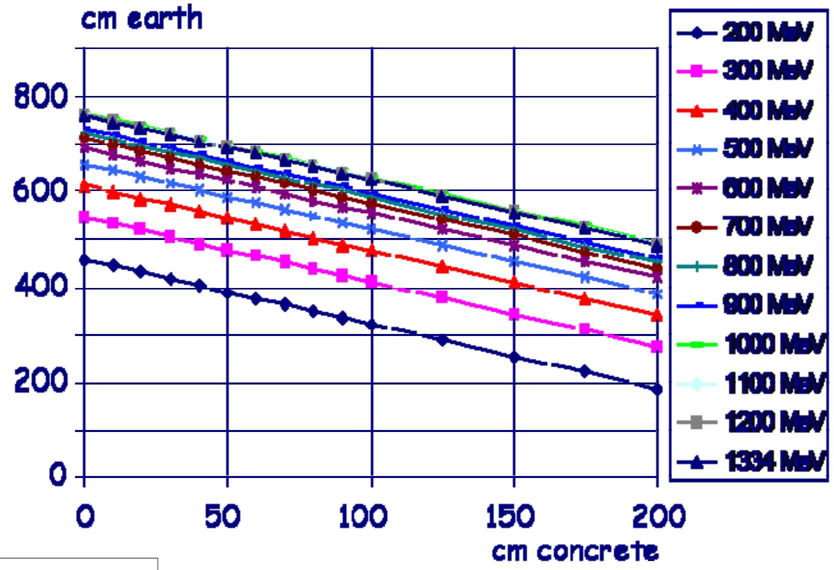
EURISOL Design Study

# A) Shielding of the proton driver





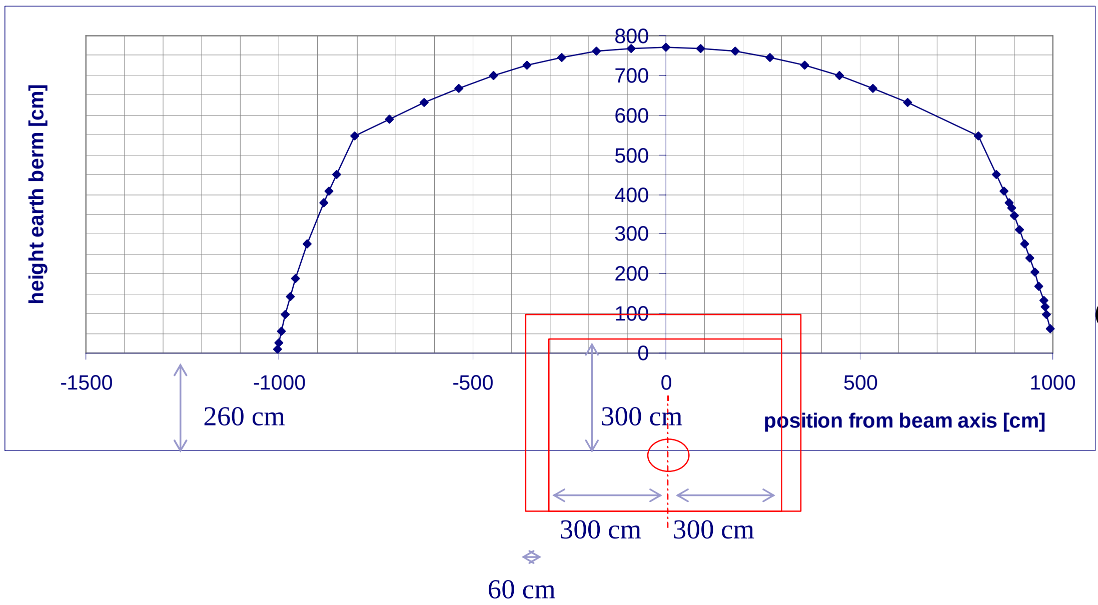

**Guidelines for ESS by P. Berkvens et al. (2006)**




## Shielding criteria:

- Normal losses of 1W/m
- Dose rates < 1.0 μSv/h

Definition of earth shielding for a given concrete thickness




## Cross check: MC versus deterministic

| Shielding thickness | Monte Carlo | Moyer model |
|---|---|---|
| 45 cm concrete + 4.75 m earth | 2.5 μSv/h | 3.8 μSv/h |



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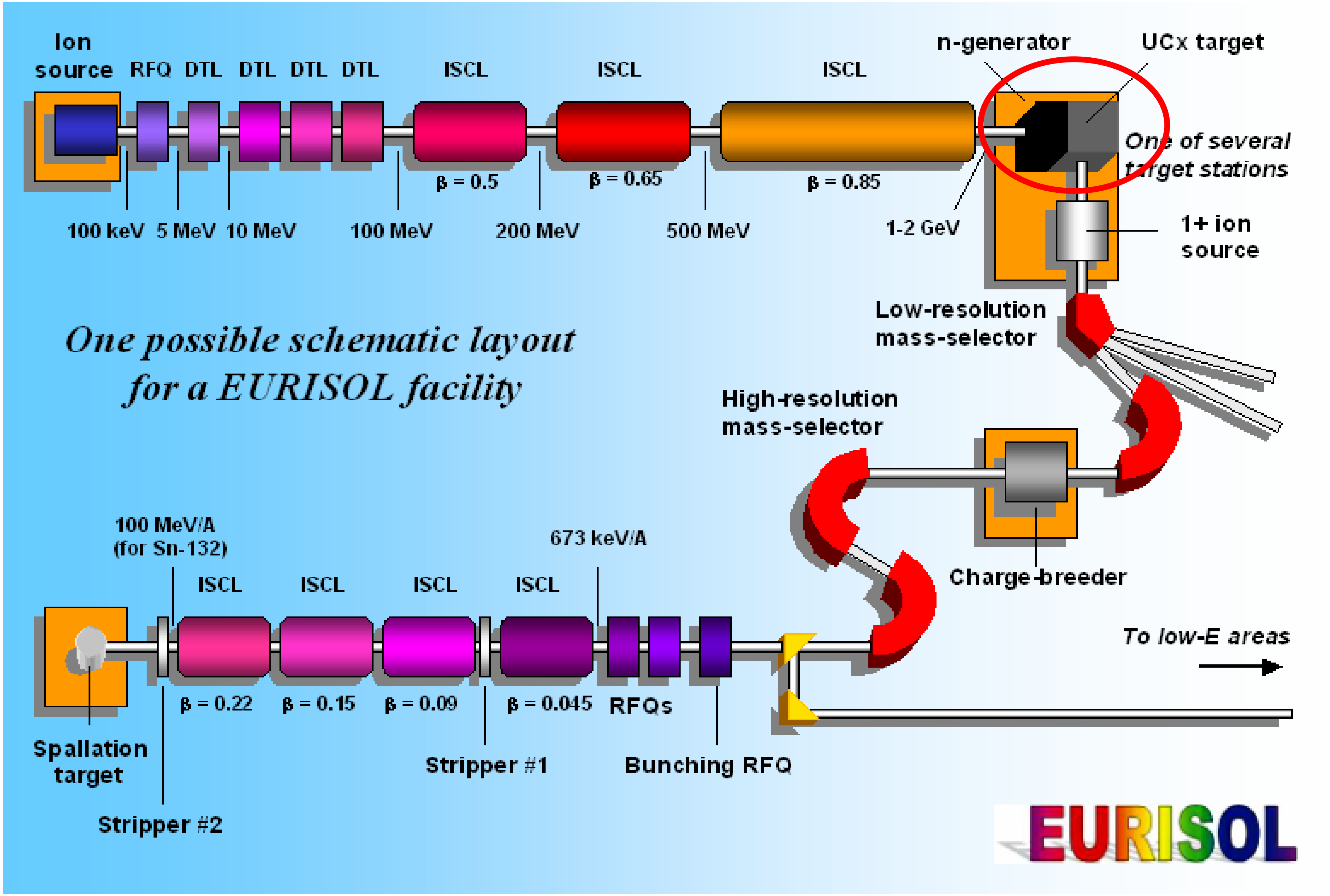
# A) Shielding of the 4 MW target





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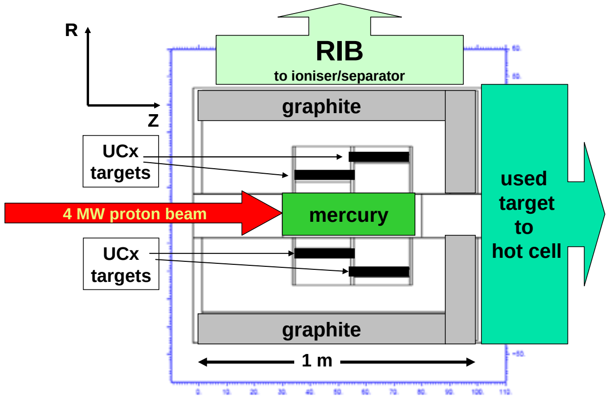
# A) Shielding of the 4 MW target

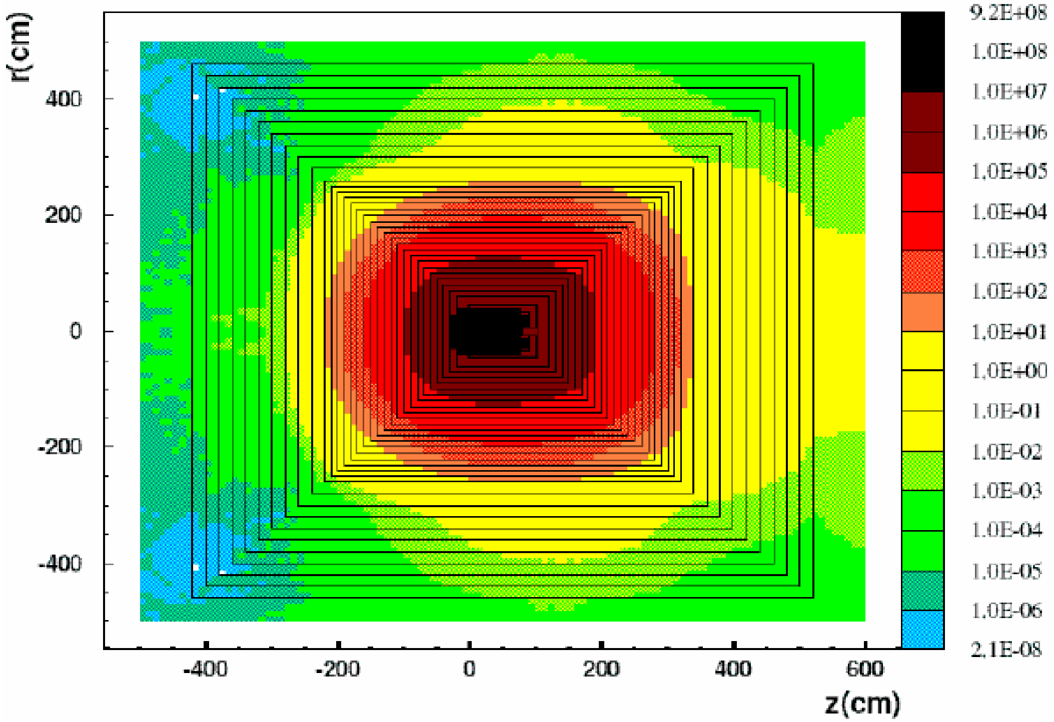


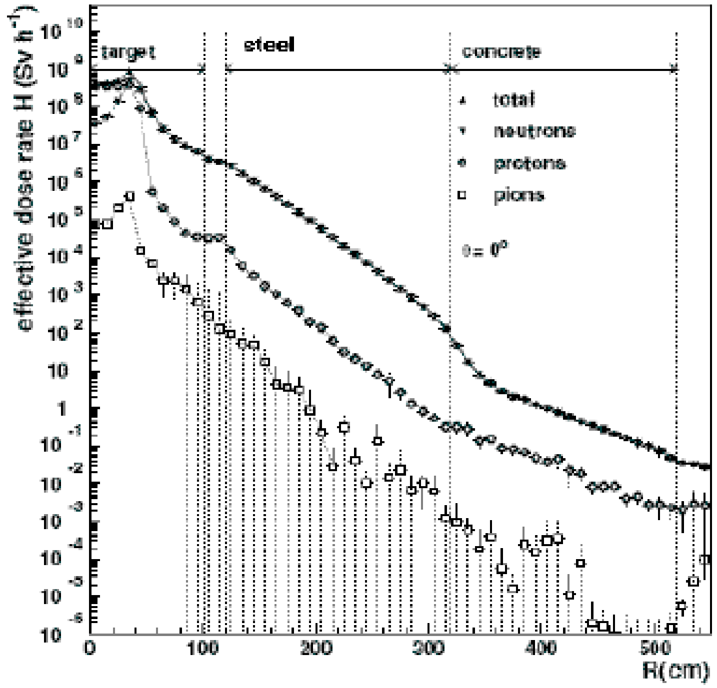
T. Otto & M. Felcini (CERN)




## Condition for dose rates < 1 μSv/h

- 2 m of iron
- For θ = 0, 90 &180º → 9.0, 8.0 & 5.5 m of concrete
- To be complemented with earth

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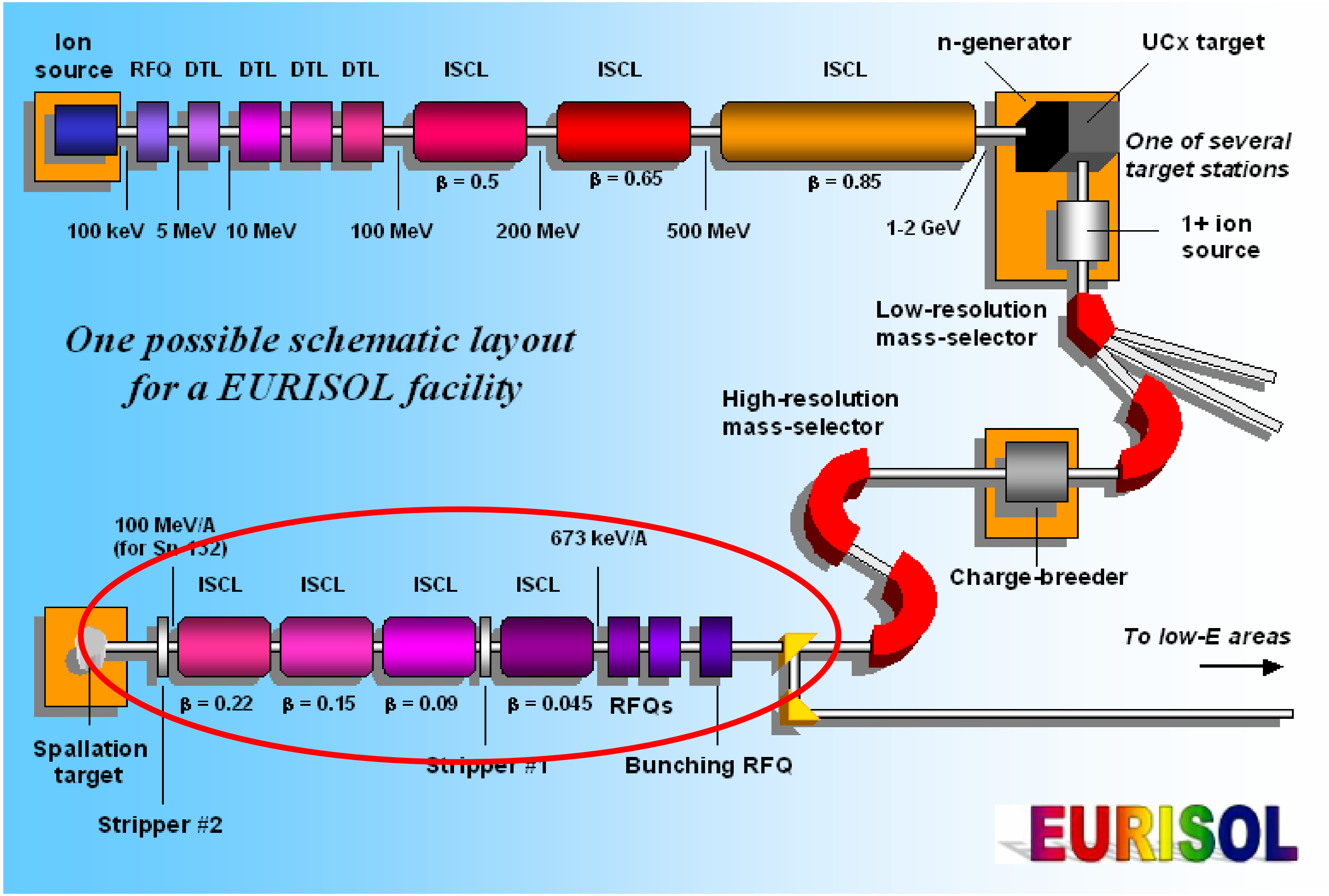
# A) Shielding of the postaccelerator



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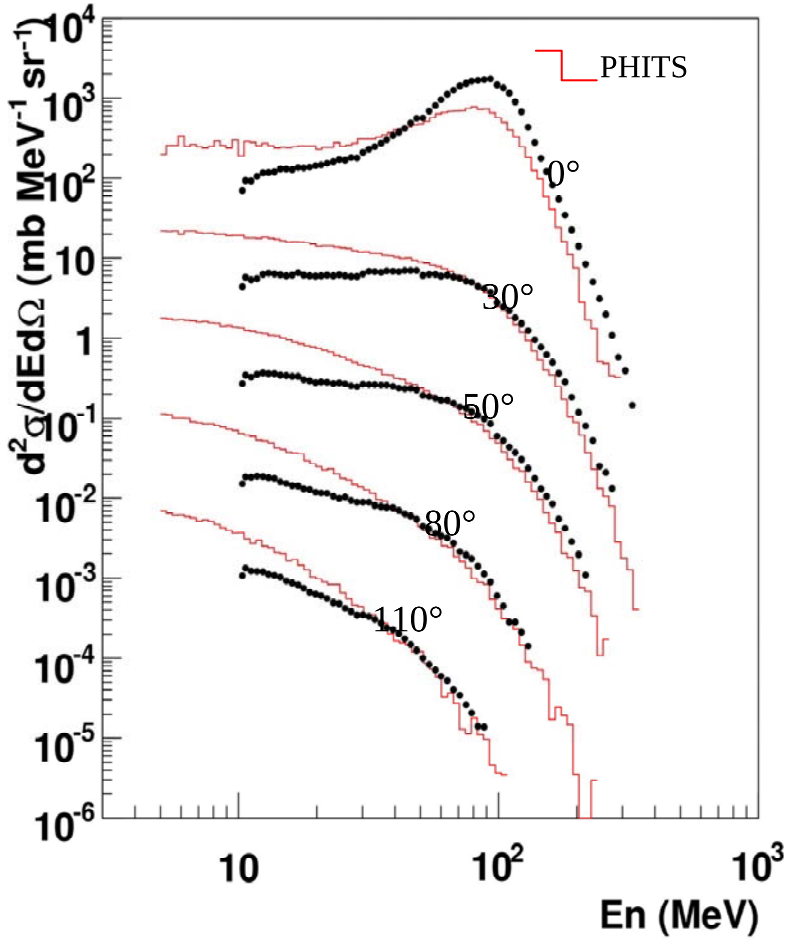
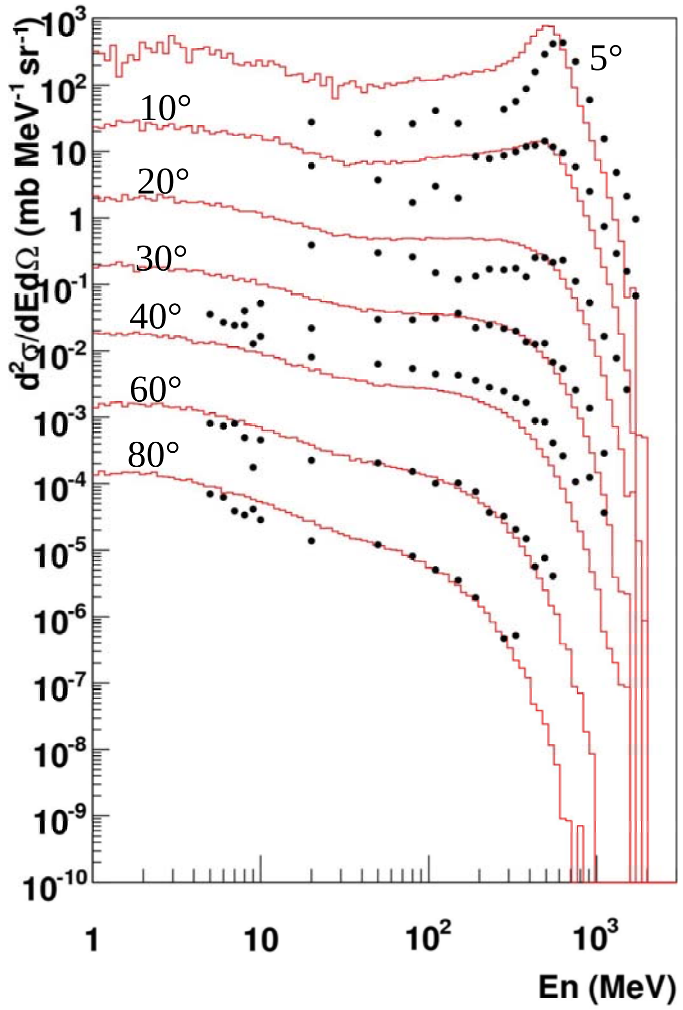
# A) Shielding benchmarks



**Production of neutrons**
**RIKEN data : Ar(95MeV/u)+Cu**




**Production of neutrons**
**HIMAC data : Ar(560MeV/u)+Cu**




**B. Rapp et al. (CEA)**



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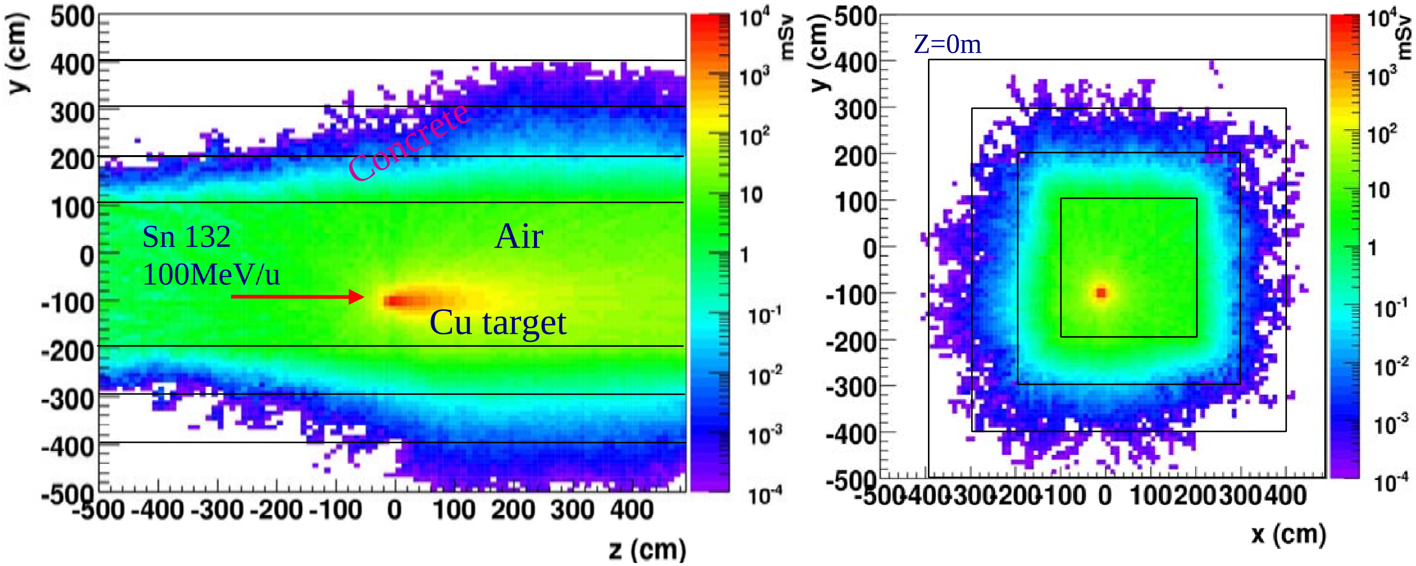
# A) Shielding of the postaccelerator



**Assumption:** 100 MeV/u $^{132}Sn$ + Cu at I = $6 \times 10^{12}$ pps; beam loss of 1 second

**Resulting Dose Map**

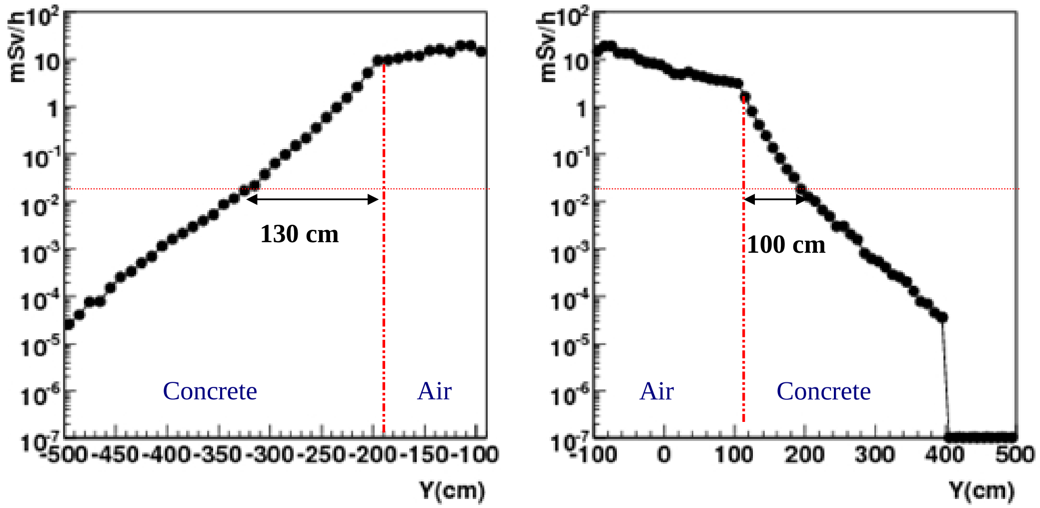



**Condition for dose rates:**

20mSv /2000 h → < 10 μSv/h

**Assumption for losses:**

1 s beam loss once a day with probability of $10^{-5}$/m

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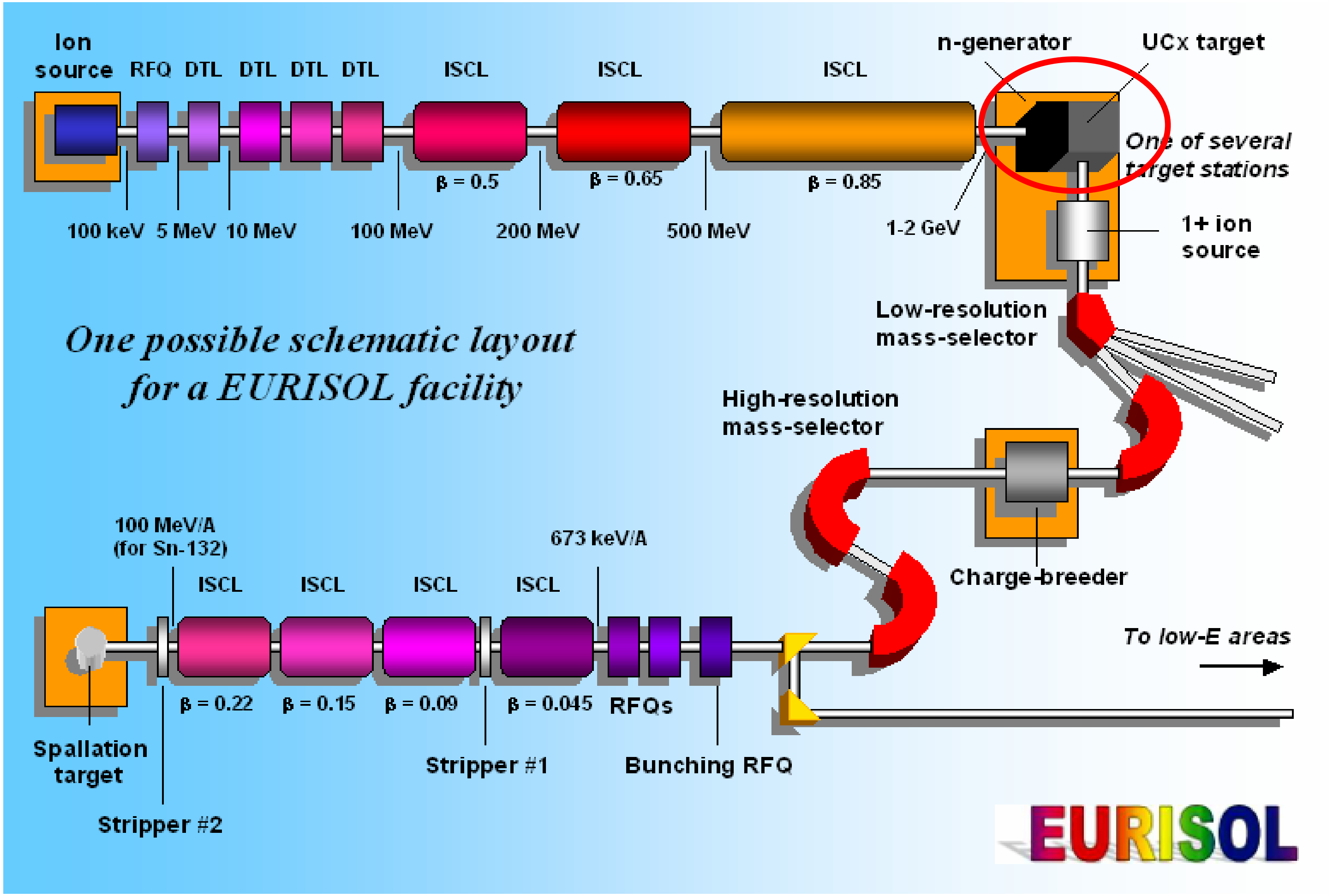
# A) Activation of the 4 MW target





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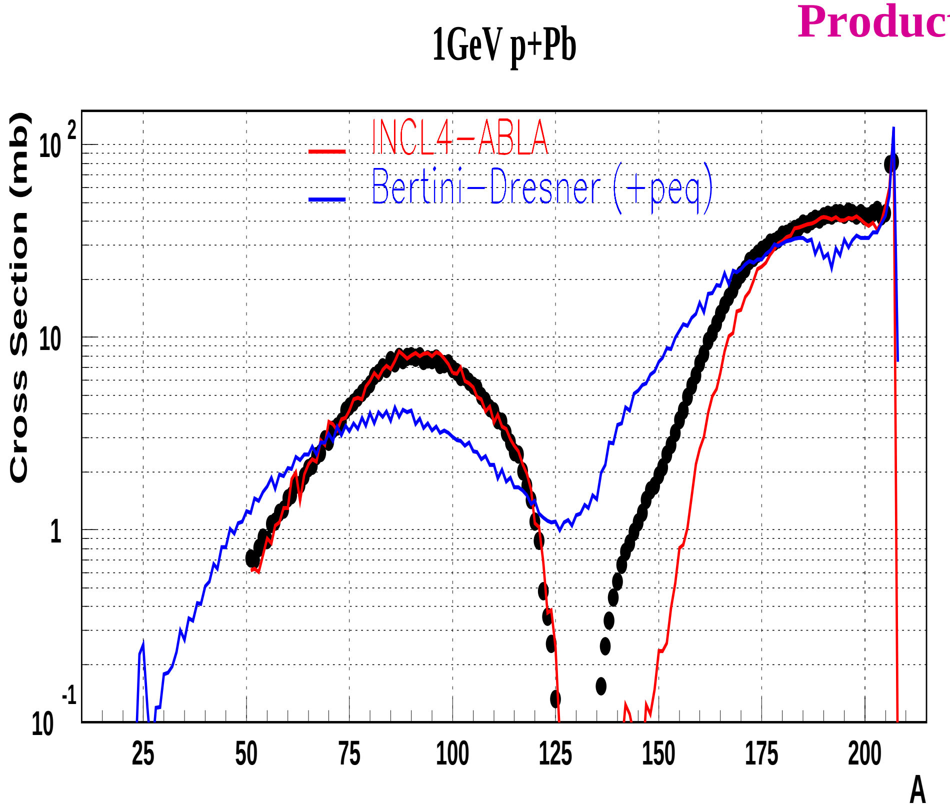
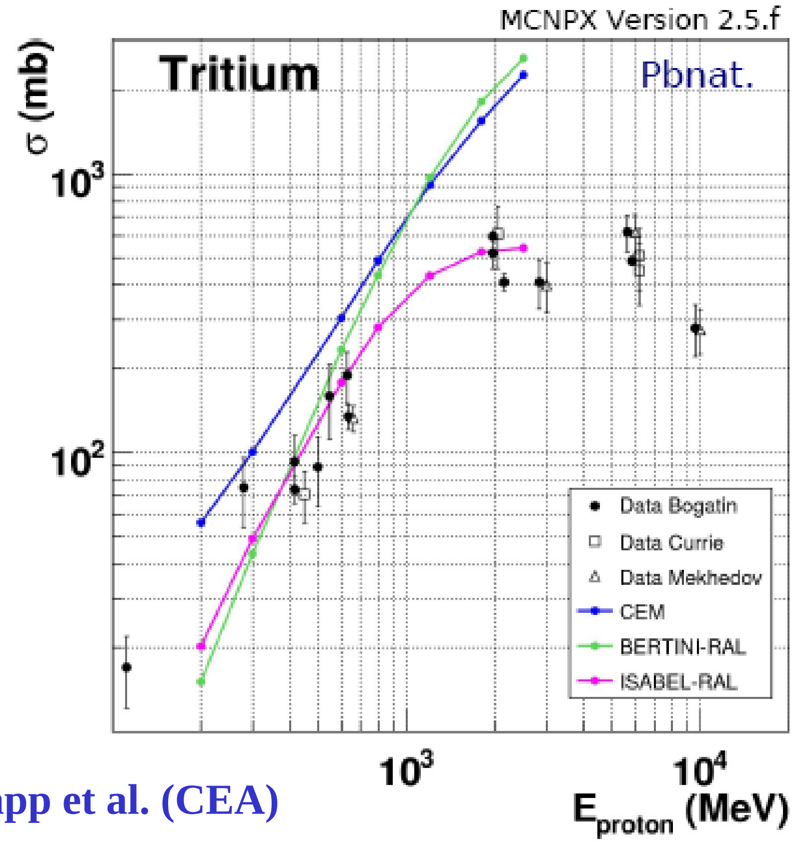
# A) Activation benchmarks

## Production of Residual Nuclei




J.-C. David et al. (CEA)




B. Rapp et al. (CEA)



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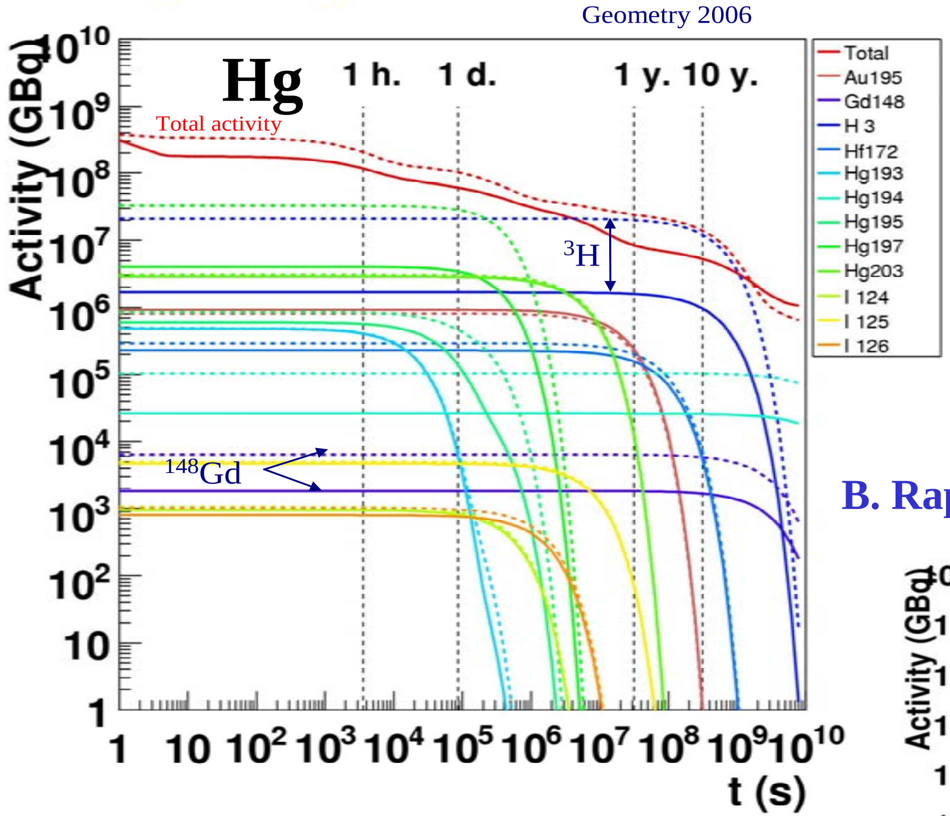
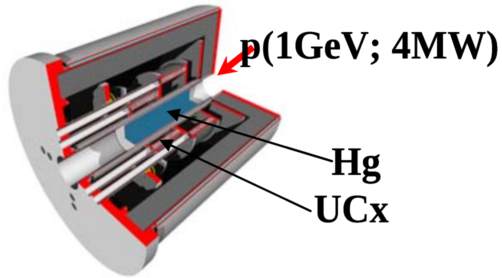
# A) Activation of Hg and UCx

**T5: Safety & Radioprotection**

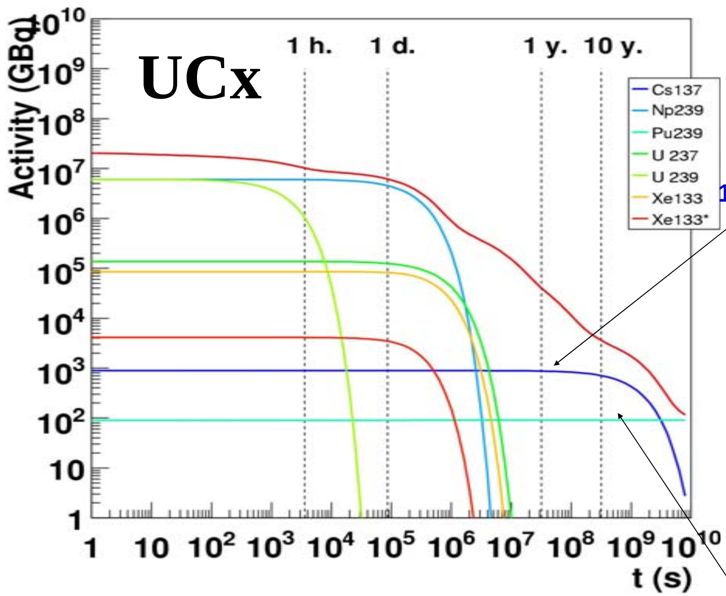



➭ Irradiation : 40 years operation, 5000 h/year, 4MW beam power

➭ Important differences appears in nuclide yield production, and consequently in Hg target activity

**B. Rapp et al. (CEA)**




$^{137}$Cs, $T_{1/2}$=30y

**→ induced activity comparable to the research reactor + $\alpha$ emitters**

**→ production of $^{239}$Pu: ~50 g/year**

$^{239}$Pu, $T_{1/2}$=24110y

**T. Otto et al. (CERN)**

EURISOL Design Study

# A) Activation of MW target shielding

T5: Safety & Radioprotection

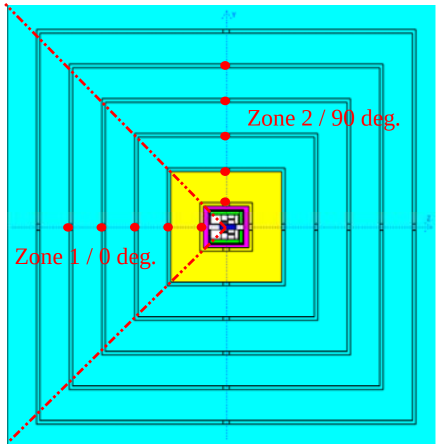
40 years irradiation at 2.28 MW

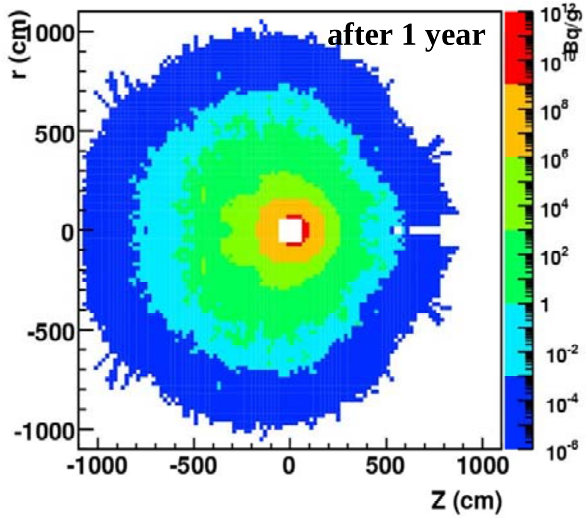
1 MBq/g < A < 1GBq/g

1 kBq/g < A < 1MBq/g

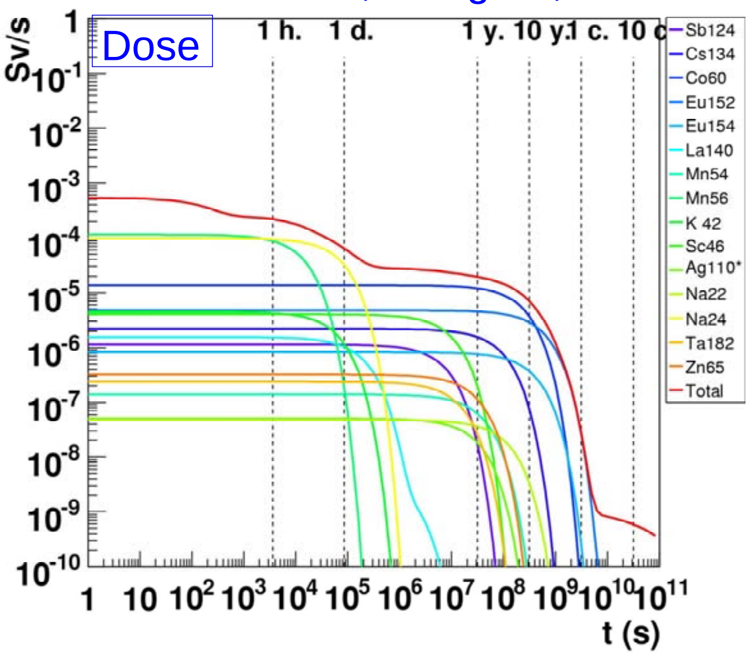
1 Bq/g < A < 1kBq/g

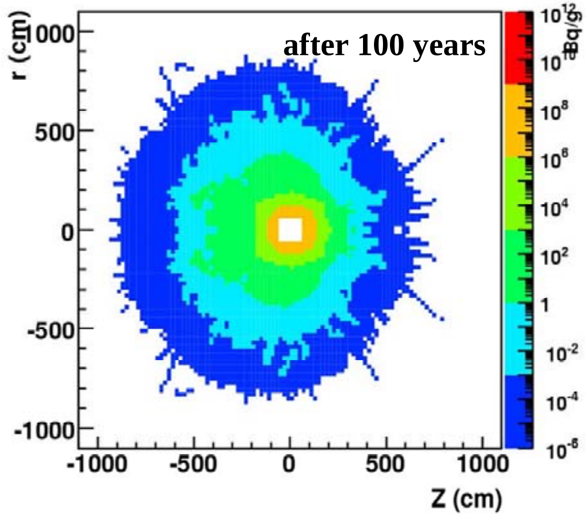
A < 1Bq/g




Concrete, 0 degree, at 1m70

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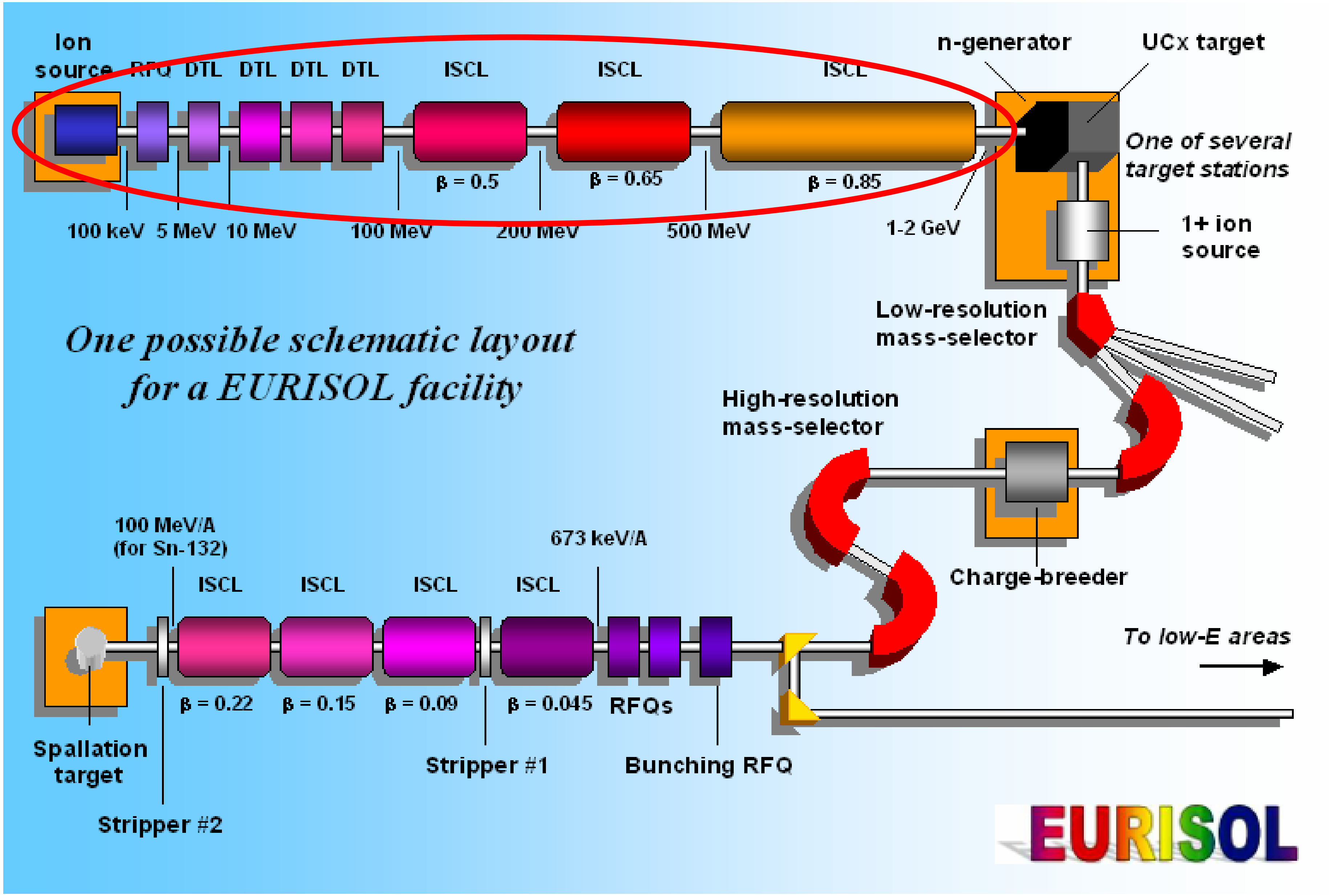
EURISOL Design Study

# B) Activity transport in ground water





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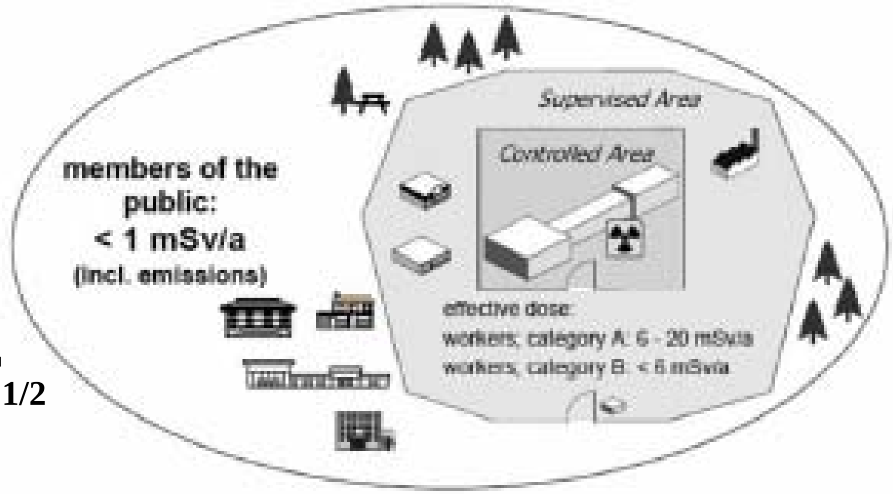
# B) Activity transport in ground water



## Goal: prediction of radioactivity at the boundary of the supervised area

### Conservative assumptions:

- maximum concentration at the source
- saturated water flow
- small partition coefficient $K_d$ & high $T_{1/2}$
- …




### Tools used:

**TRACE**
**water flow simulations needed for**

**PATRACE**
**particle tracking (includes sorption & decay )**

Half-life →, $K_d$ ↓

| | | | |
|---|---|---|---|
| $^{32}P$ 14.26 d 5 cm³/g | $^{45}Ca$ 163 d 5 cm³/g | $^{3}H$ 12.323 a 0 cm³/g | $^{36}Cl$ 300000 a 0 cm³/g |
| $^{55}Co$ 17.54 h 30 cm³/g | $^{35}S$ 87.5 d 14 cm³/g | $^{60}Co$ 5.272 a 30 cm³/g | $^{14}C$ 5730 a 7 cm³/g |
| $^{24}Na$ 14.96 h 76 cm³/g | $^{57}Co$ 271.79 d 30 cm³/g | $^{54}Mn$ 312.2 d 50 cm³/g | $^{32}Si$ 172 a 35 cm³/g |

Prolingheur et al. (FZJ)



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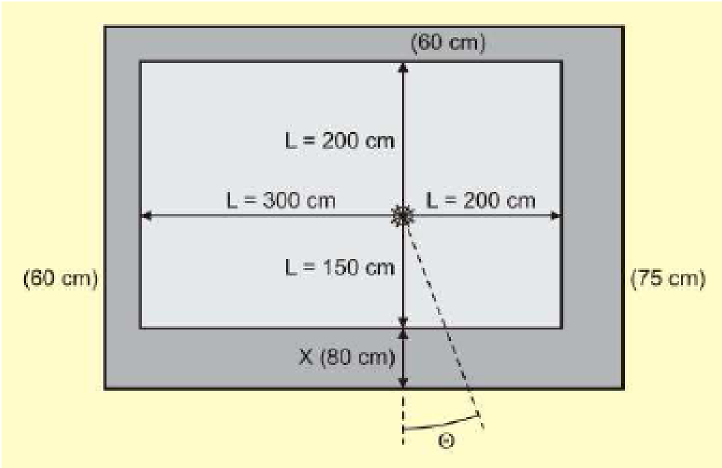
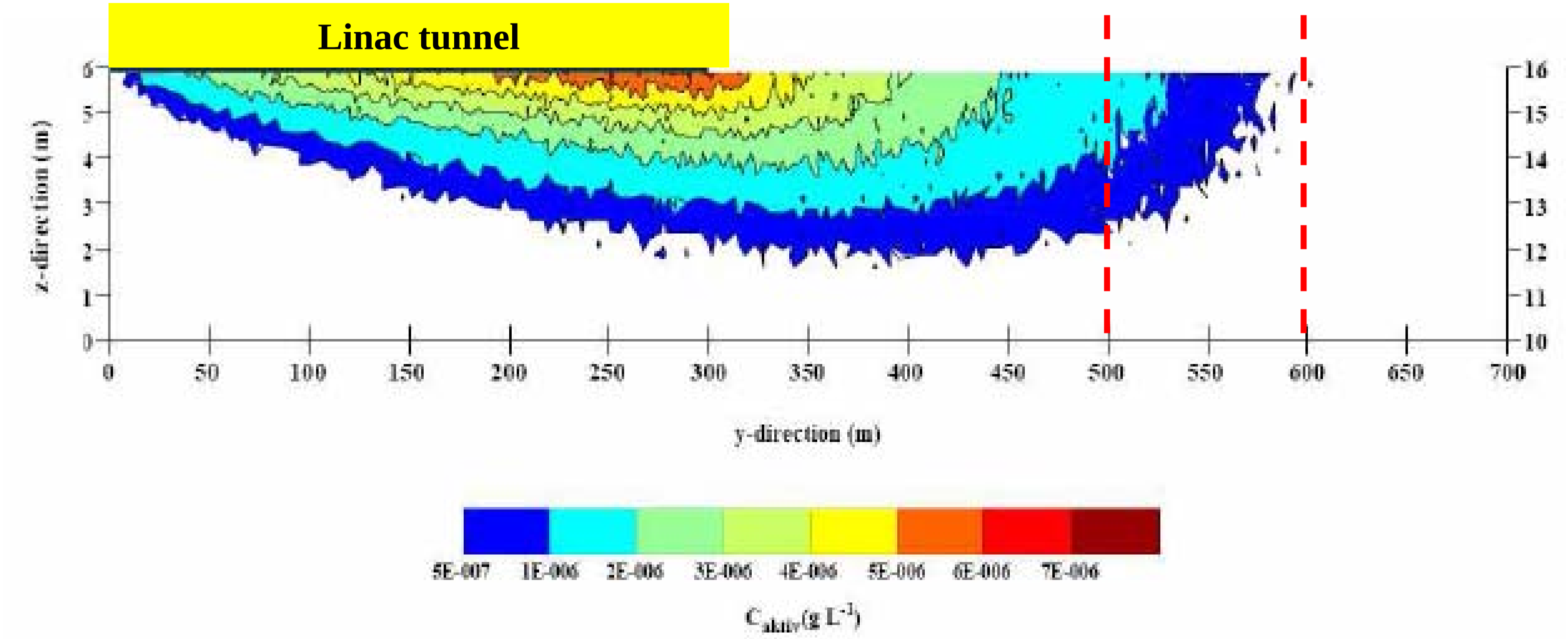
# B) Activity transport in ground water

## Linac tunnel




**Final goal:**

- **Committed effective doses**
- **Effectiveness of the shielding**
- Generalization of the method
- **Extension of the boundary area**




Prolingheur et al. (FZJ)



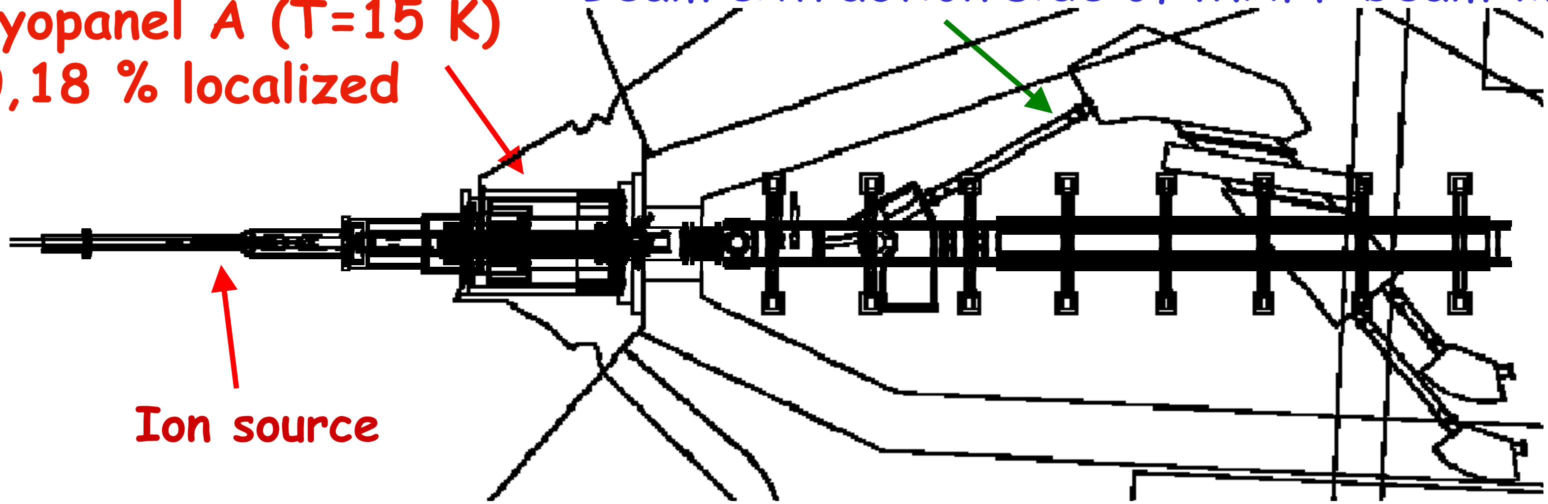
Contact: ridikas@cea.fr

Thirolf et al. (LMU)

# Activity Distribution (MOVAK 3D)

Beam extraction side of MAFF beam-line:

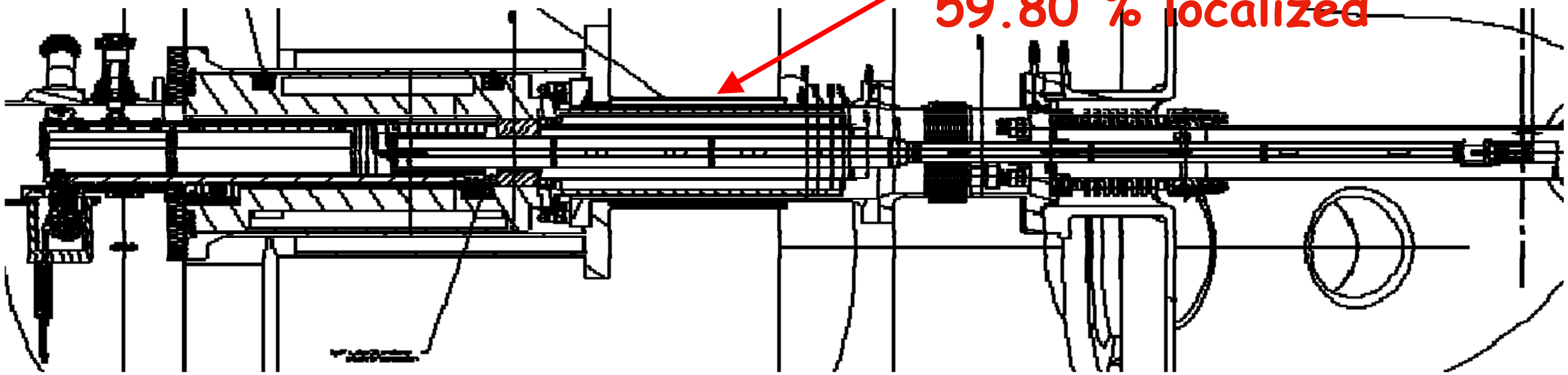
Cryopanel A (T=15 K)
40,18 % localized



Ion source

Source exchange side of MAFF beam-line:

Cryopanel B (T=15 K)
59.80 % localized



**Simulations:** cryopanels will localize 99.98% of volatile radioactivity

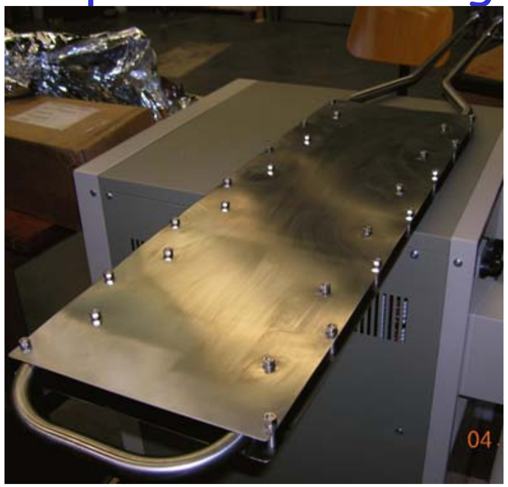
Thirolf et al. (LMU)

# Comparison: 2 cryotrap designs

**'large' panel (GP):**
- double-walled tube
- 6 spiral gas channels
- no passive shield

- turbulent regions of gas flow with compression/expansion -> anisotropic temperature distribution

**'small' panel (SP):**
- only for comparative tests
- 1 bent tube
- 2 passive shielding paddles



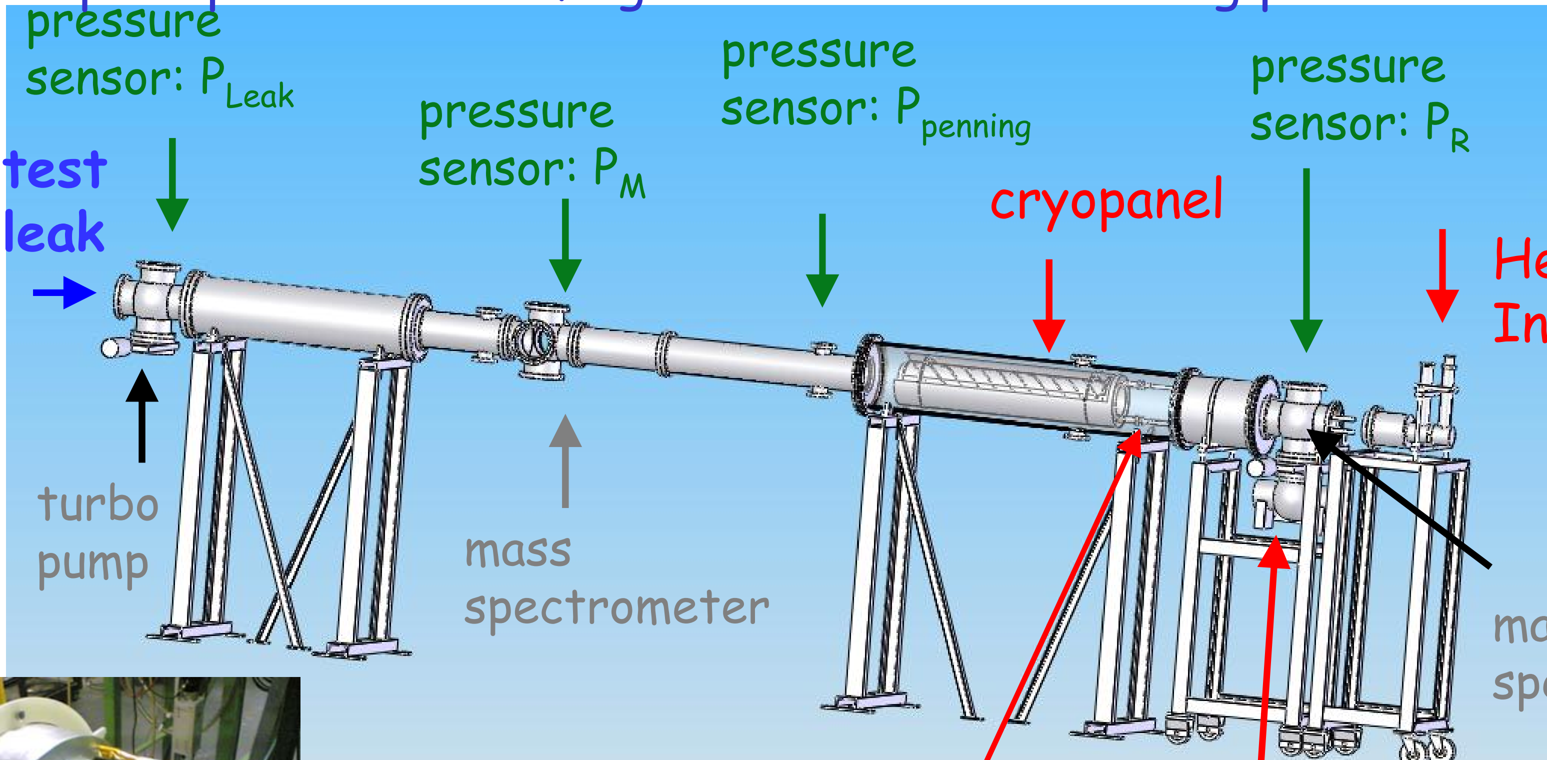
- unambiguous gas flow characteristics
- simple mechanical design, no weldings

Surface ratio: A(GP)/A(SP) ~ 18 (without shield)

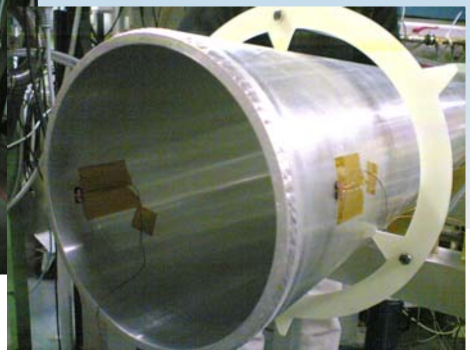
Thirolf et al. (LMU)

# Cryotrap Testbench at MLL/Garching

cryotrap coupled to lHe refrigerator: ~ 600 W cooling power at 12 K




'large' panel (GP)



cryotrap prototype equipped with 6 thermal sensors (Si diodes)

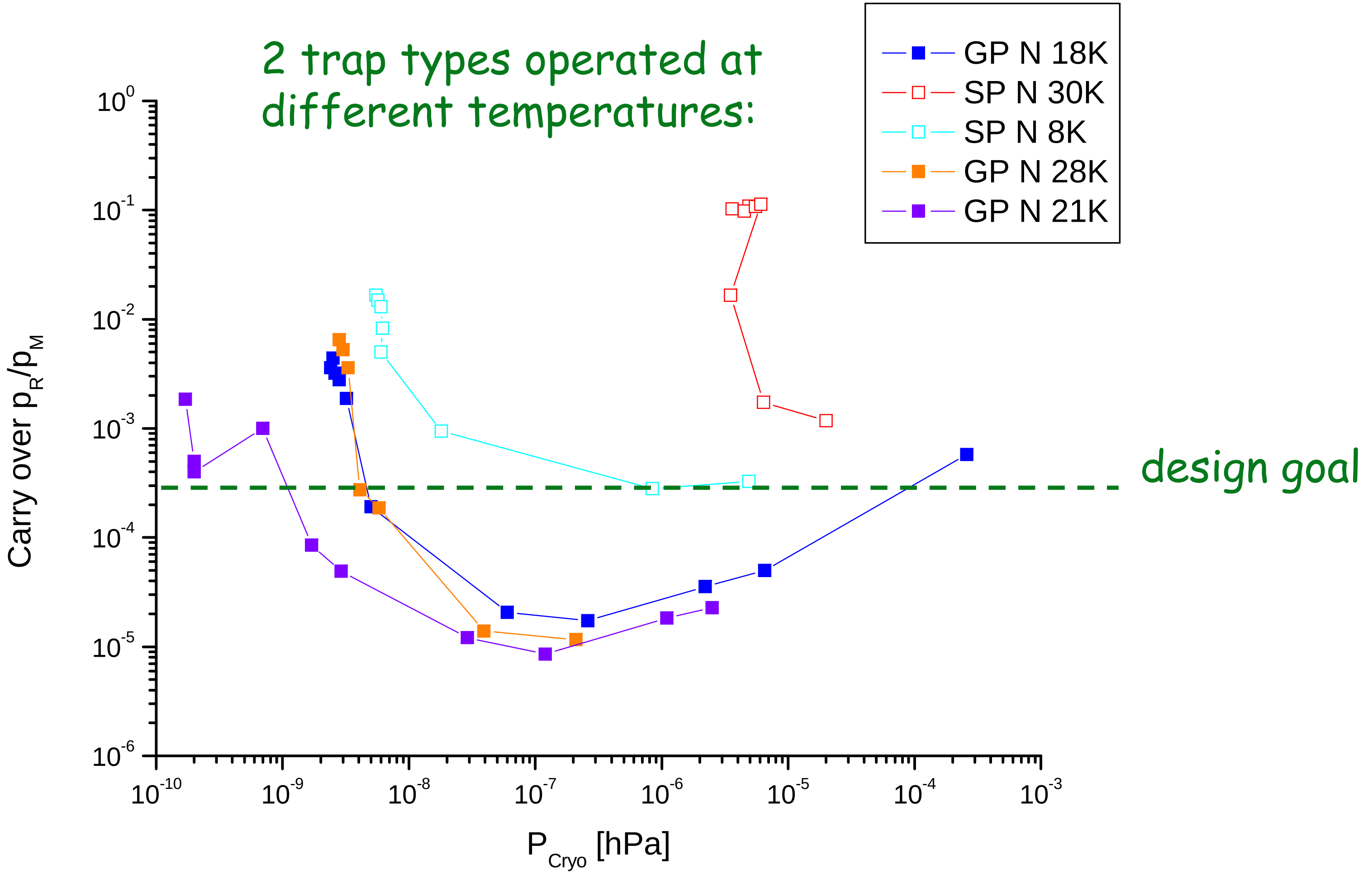
Thirolf et al. (LMU)

# Localization capability of Cryotrap

'carry over': fraction of leaking gas load transported across cryotrap

↳ retention capability (vs. pressure behind cryotrap)

2 trap types operated at different temperatures:




→ cryotrap works within (simulated) expectations!

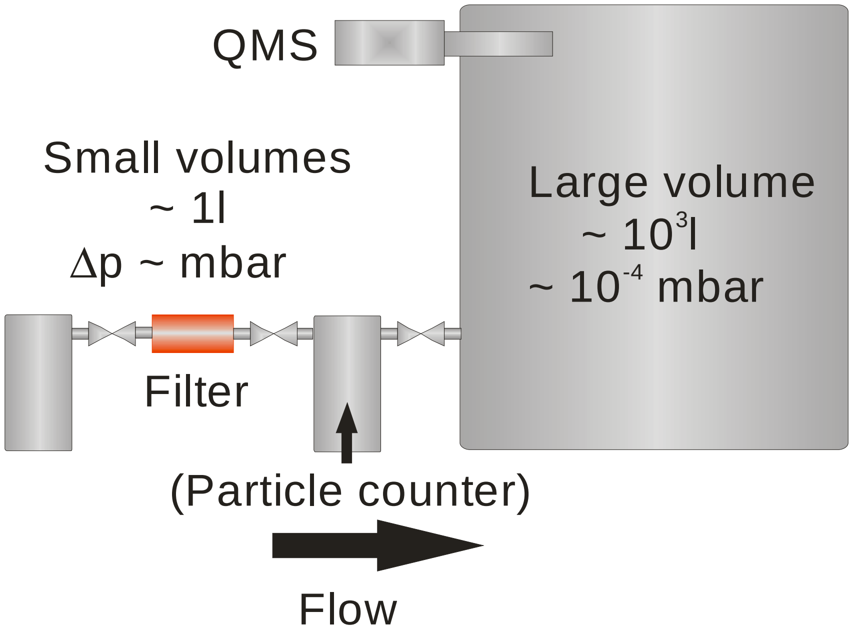
# B) Gas purification system



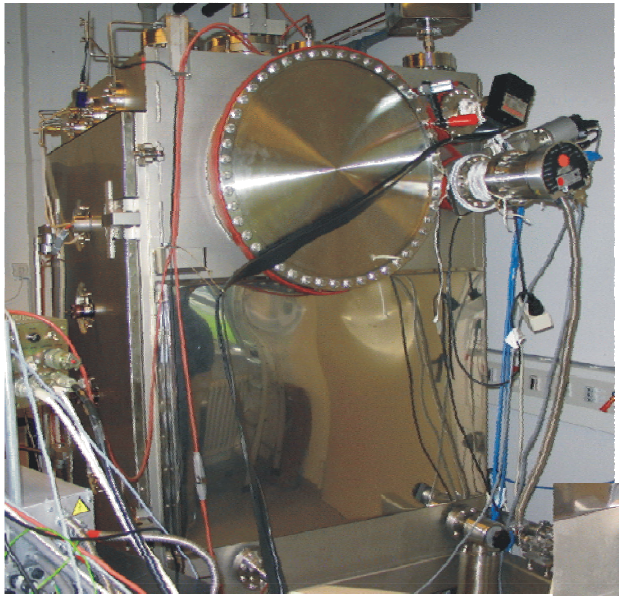
Thirolf et al. (LMU)

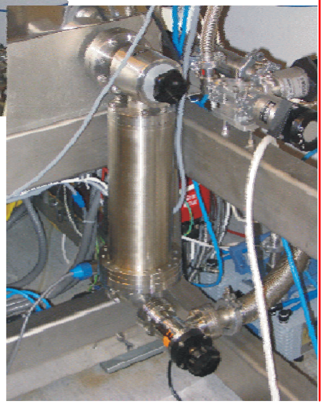
test slow diffusion filter for aerosols (between decay tanks and release stack):

test setup:

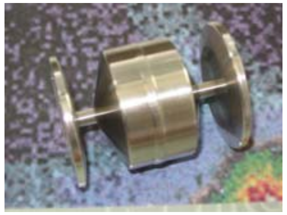



large-volume vacuum chamber (~2 m³, bakeable) with QMS:





- cleanest, most efficient all-metal filter available
- sintered nickel membrane filter
- specification:
  - particle retention: > 99.9999999%
  - < 0.03 particles/liter larger than 0.01μm

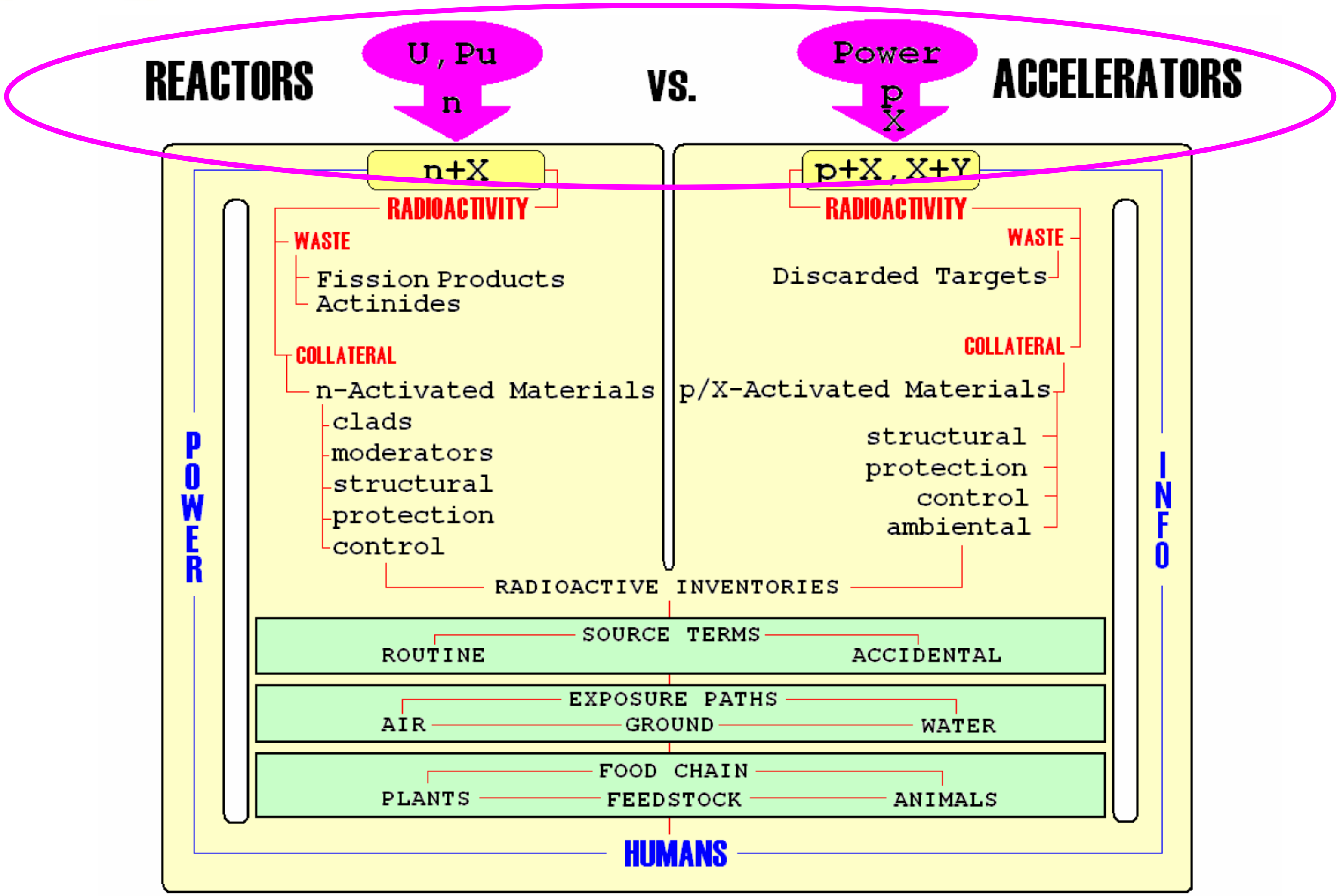




Contact: ridikas@cea.fr

# B) Exposure evaluations

Vamanu et al. (NIPNE)




**Combination of knowledge on accelerator & research reactor based nuclear installations → creation of dedicated toolkit →ADS!**

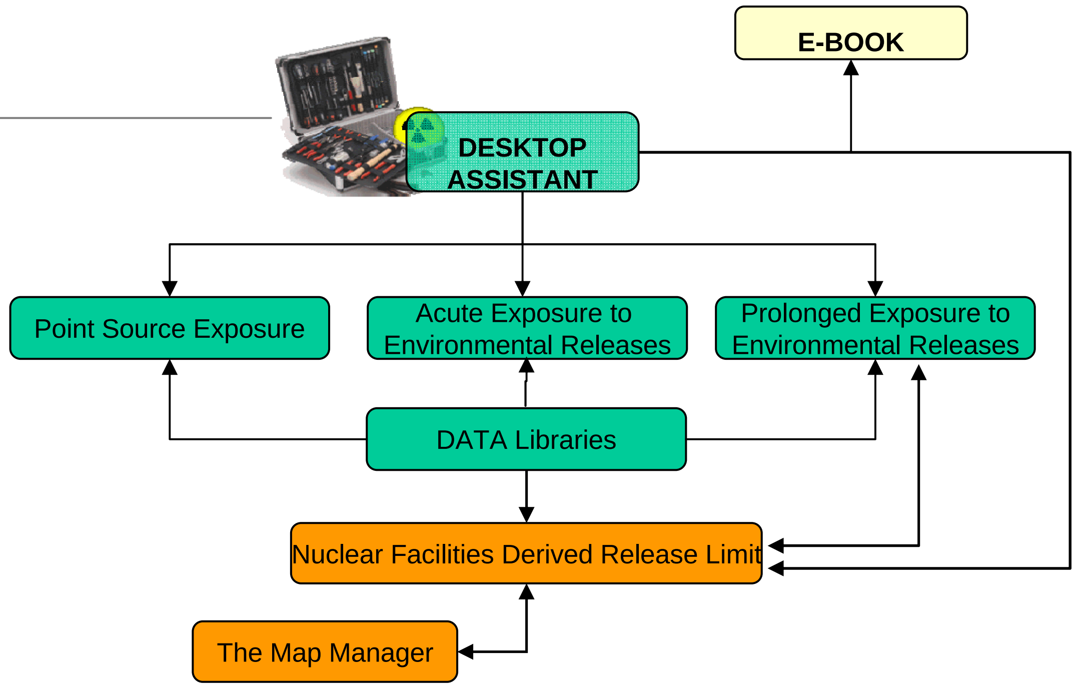
# B) Toolkit Creation for EURISOL: Exposure Evaluations



**Vamanu et al. (NIPNE)**

→ Methodology **validated**, **recommended** & **accepted** by international regulatory bodies

→**Tools**, **data** & **knowledge** to be used in *environmental and health impact*




## Further steps:

- ***Derived Intervention Levels (DIL)***
- ***Exposure from underground water contamination***
- ***Development of a resident GIS platform***
- ***Cadastral Impact Analysis (GIS based)***
- ***…***



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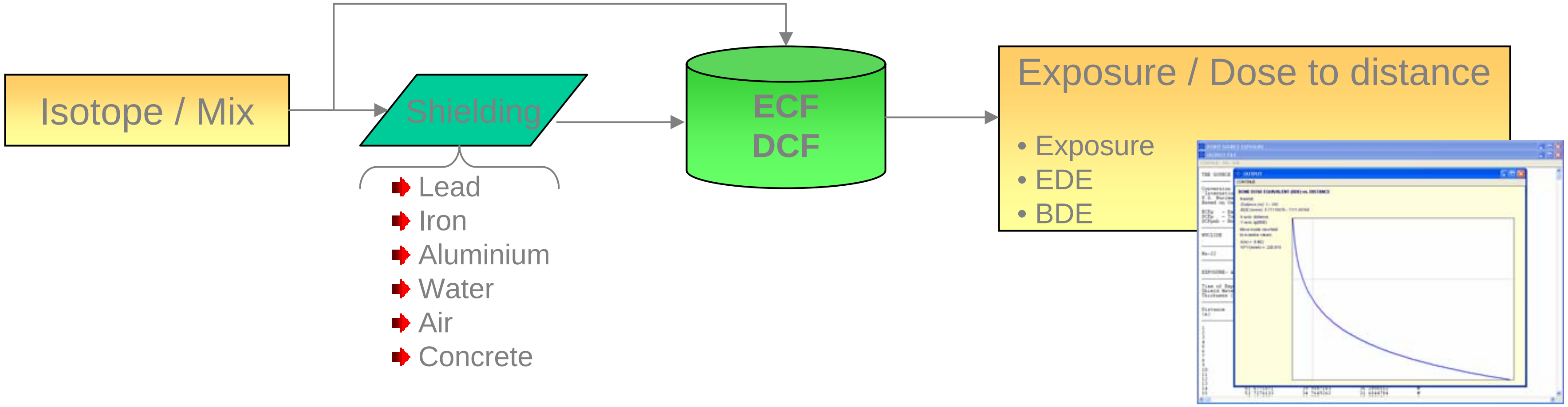
# B) Toolkit Creation for EURISOL

## **Example:** Point Source Exposure




## **Example:** Derived Release Limits

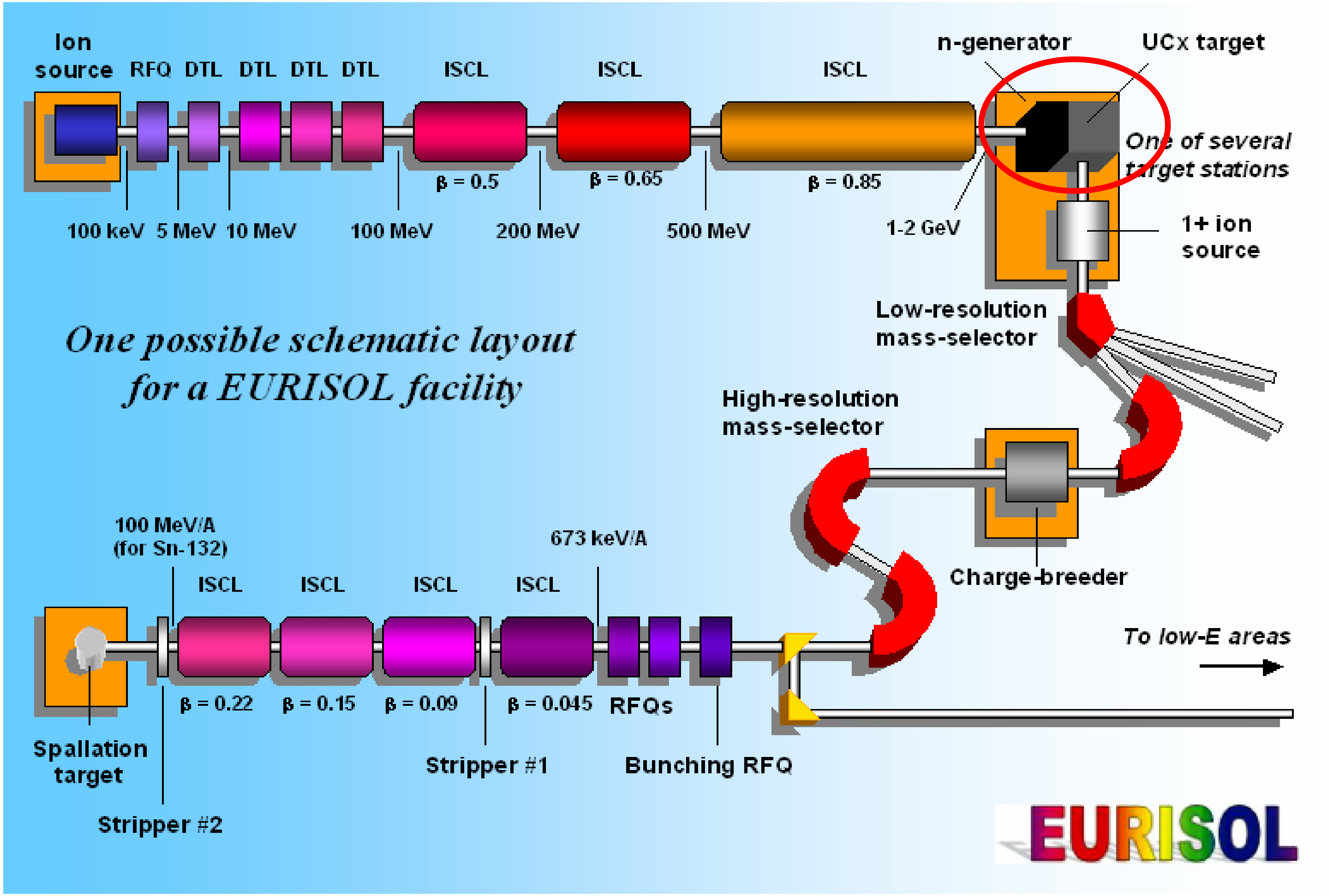
Definition of the Complex Nuclear Compound in terms of

- Emission Sources
- Receptors
- Weather conditions
- …

EURISOL Design Study

# A) DNs in the liquid Hg loop





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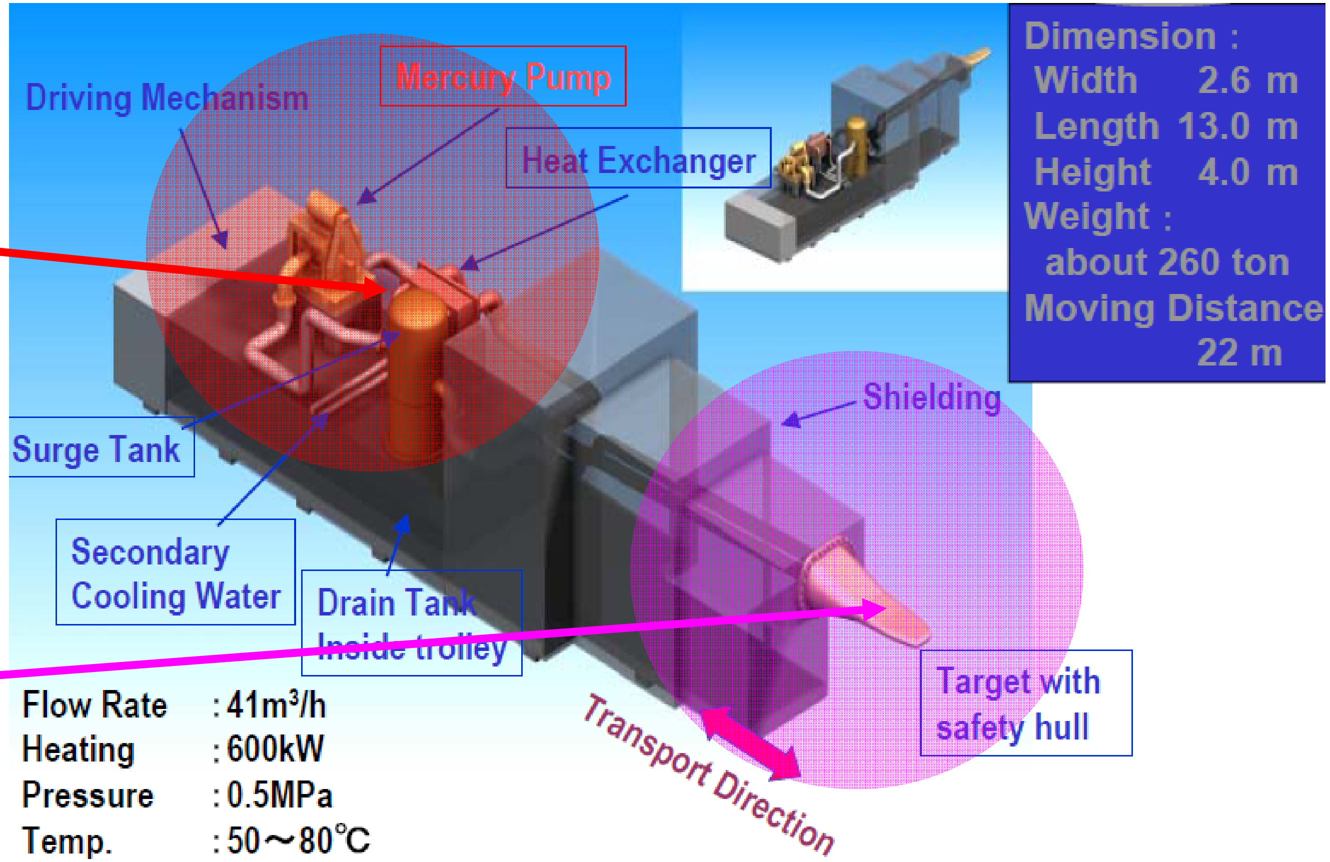
# A) DNs in the liquid Hg loop

J-PARK

**Delayed neutrons**

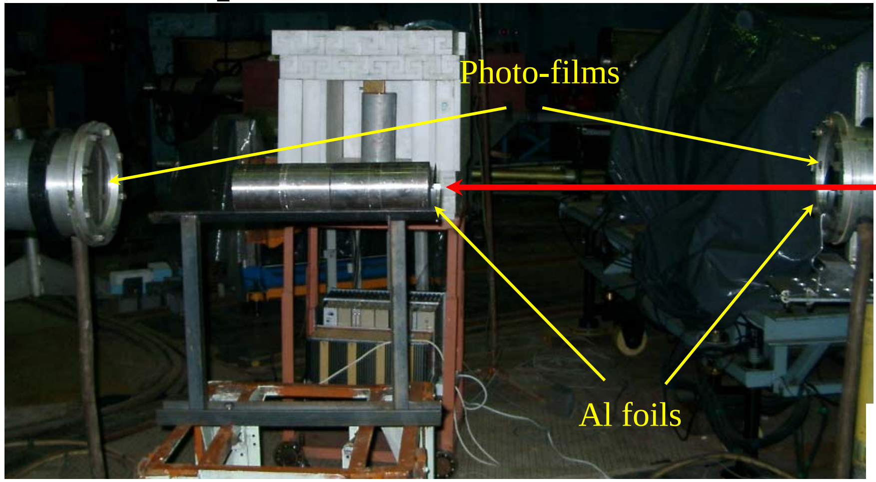
**Prompt neutrons**



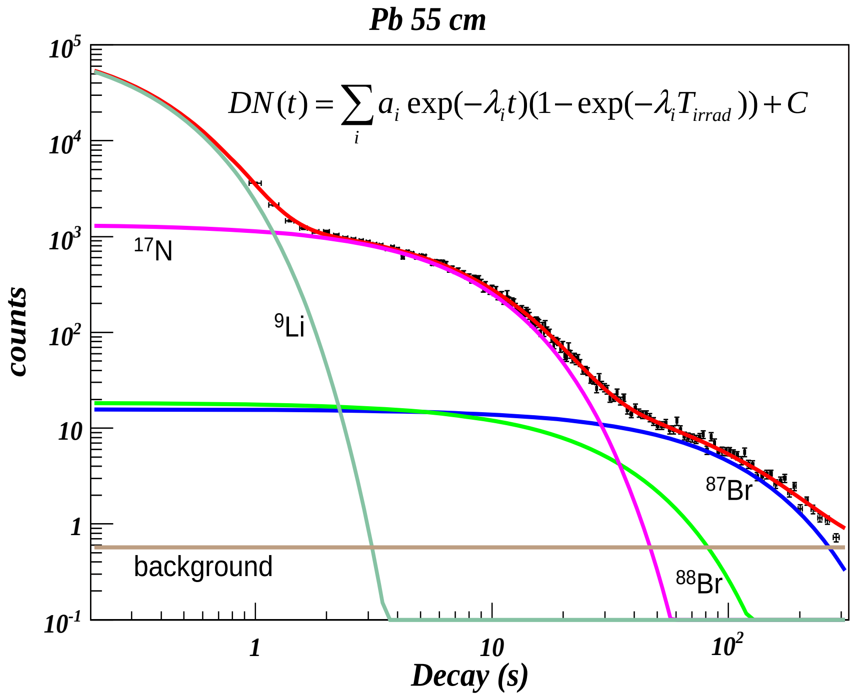

**short Hg transit time →**
**"moving" beta, photon and delayed neutron (DN) radioactivity**

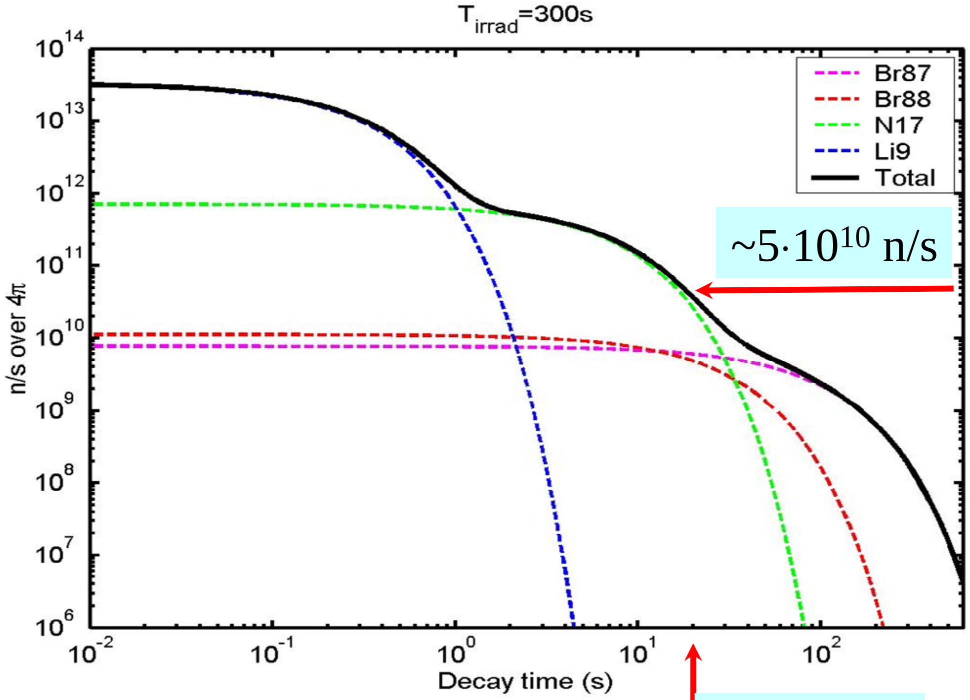
# A) DNs in the liquid targets

## Experimental characterization of DNs from 1GeV p + Pb (55 cm); PNPI-




**p(1GeV) + Pb (55 cm thick; 10 cm ∅) at 1mA (1 MW)**




A. Prevost et al. (CEA)



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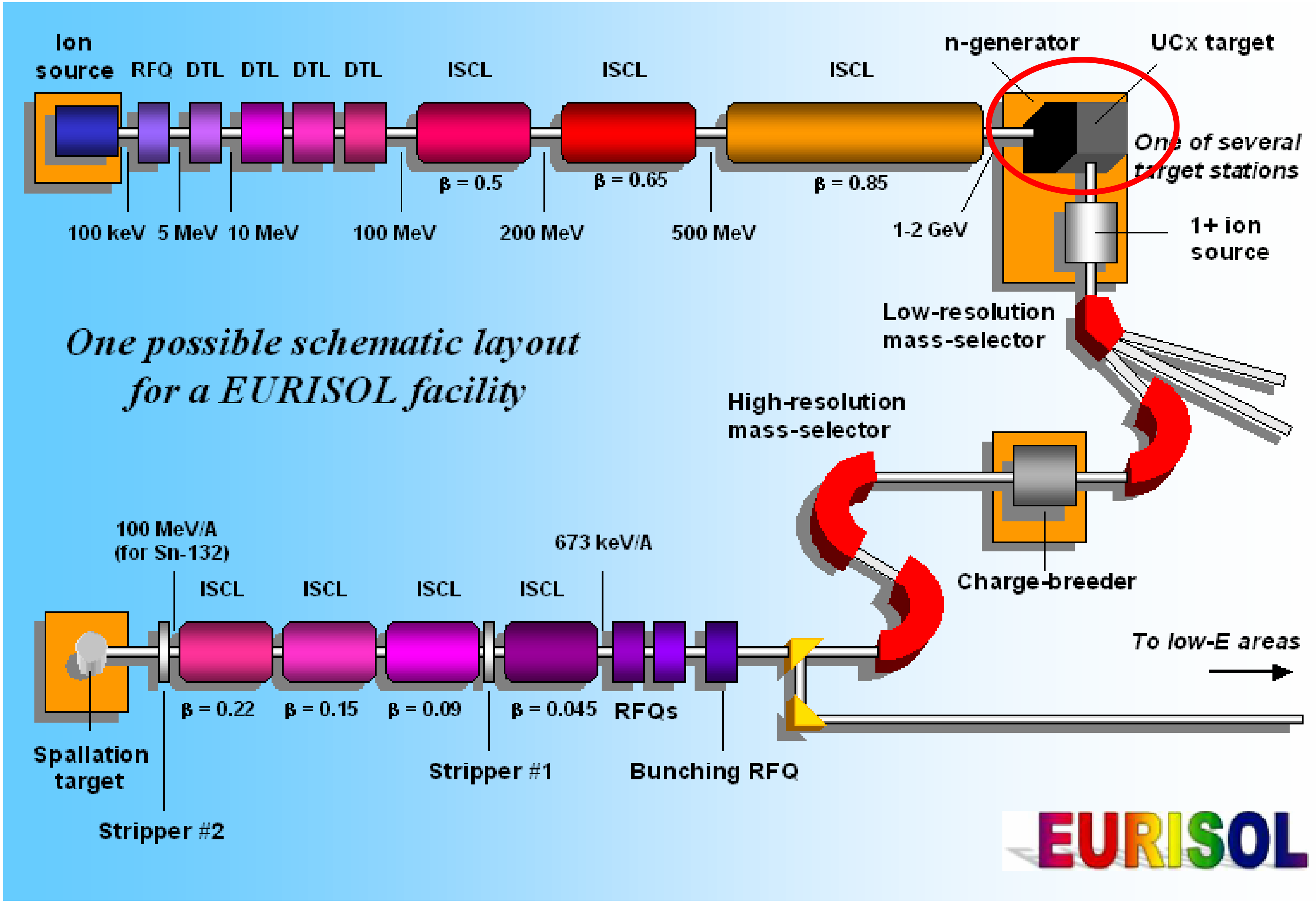
# C) Disposal of liquid Hg



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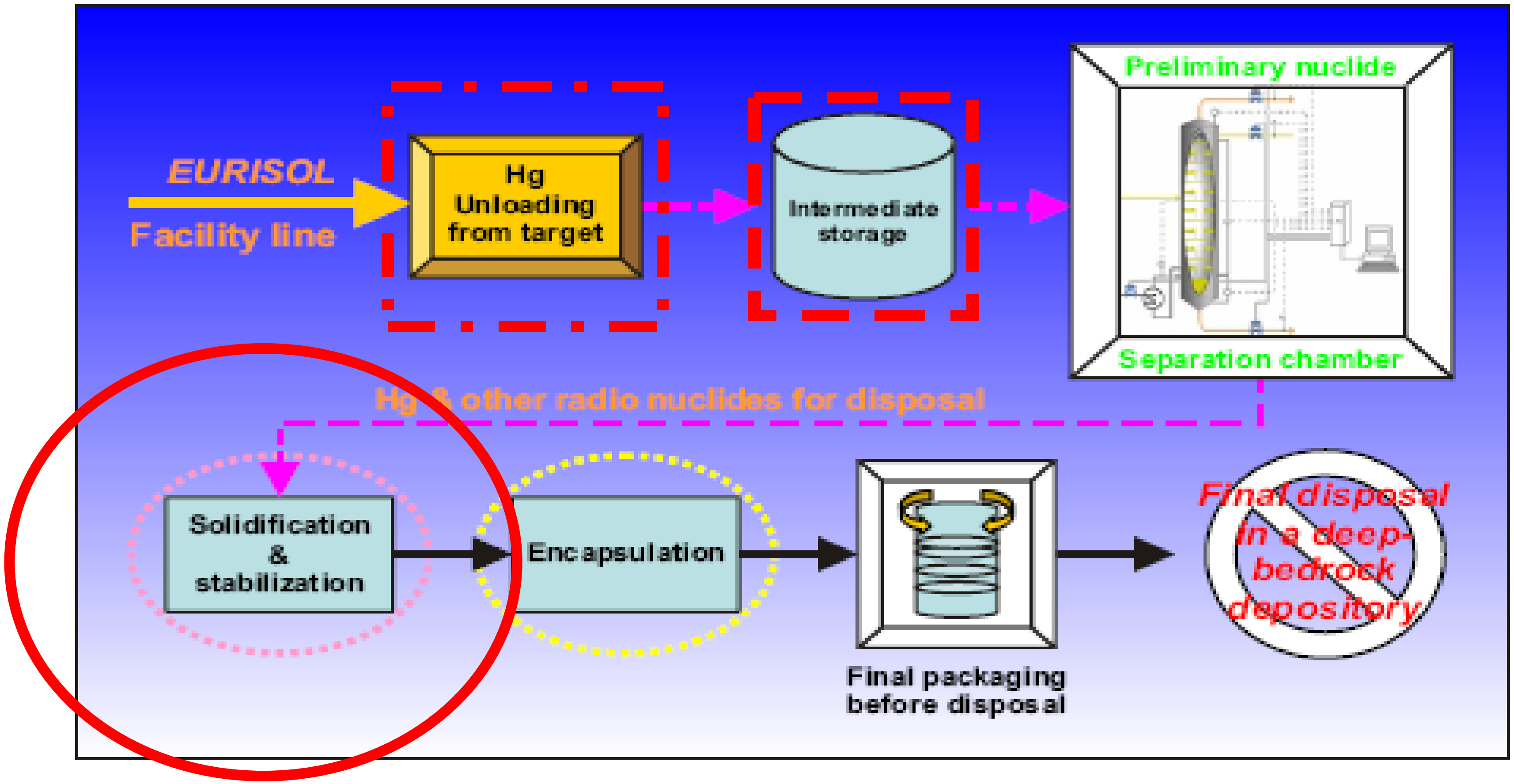
# C) Disposal of liquid Hg

## *A schematic layout for Hg-target disposal strategy*




**Chiriki et al. (FZJ)**

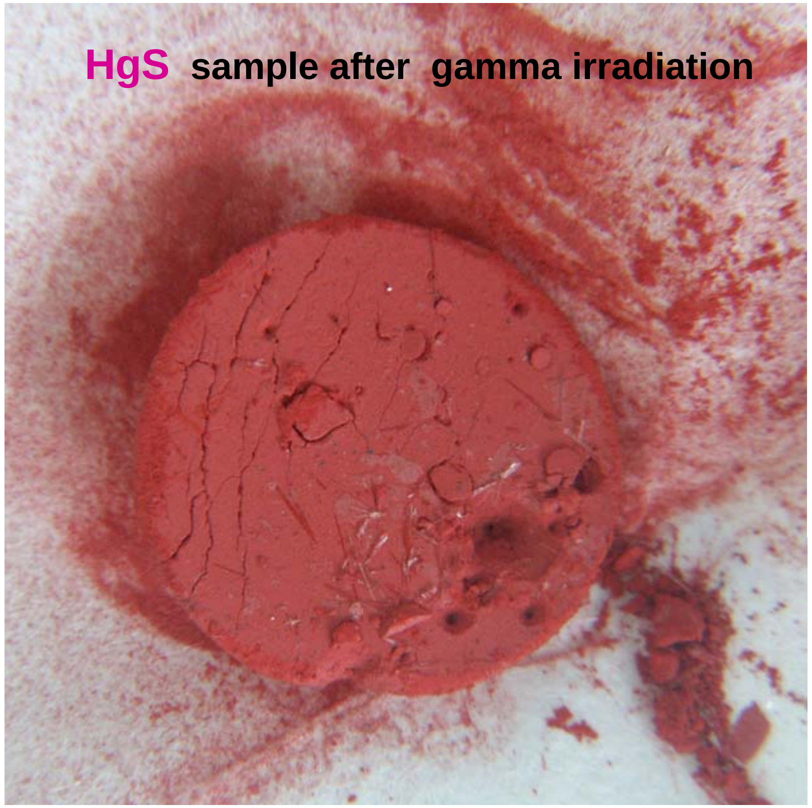
# C) Disposal of liquid Hg → Solidification



**A) Chemical stabilization of Hg as an inorganic compound, e.g. HgS, HgSe, HgO, $Hg_2Cl_2$, $HgCl_2$**

B) Stabilization by dissolution in metals called amalgamation, e.g. Cu, Zn, Sn, Ag, dental amalgam, Alloy powders

- ✓ **HgS is highly insoluble in water, stable solid, and dominating mercury mineral in nature**
- ✓ **HgS is a powder and instead of a paste as amalgams, thus making it is an easier process**
- ✓ **HgS has very high loading compared to transition metal amalgams (Zn amalgam was studied)**
- ✓ **Formation process is a single step reaction**
- ✓ **Elemental sulfur is relatively cheap, and enough process options are available with sulfur**




**Chiriki et al. (FZJ)**



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# Optimistic Summary

**Work is in progress but**

**we are only at the end of the beginning!**



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