# EURISOL DS PROJECT

# Task#2: MULTI-MW TARGET DESIGN

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# Overview

1. Summary of the sensitivity study
2. Baseline parameters of the MMW Hg target
3. Conceptual design of the MMW Hg target
4. Recommendations

# EURISOL Multi-MW Target

## Preliminary Study of the Liquid Metal Proton-to-Neutron Converter

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## Abstract

This technical note summarises the design calculations performed within Task #2 of the EURopean Isotope Separation On-Line Radioactive Ion Beam Facility Design Study (EURISOL DS) [1].

A preliminary study was carried out in order to determine the optimum value of relevant parameters in the target design. Different scenarios were simulated using the Monte Carlo code FLUKA [2]. Namely, sensitivity studies were performed to assess the impact of the projectile particle energy on the neutronics and energy deposition in the spallation target. The optimum target dimension was also studied for every case as well as the proper target material for the liquid metal proton-to-neutron converter, since mercury and lead-bismuth eutectic are reasonable options. The effect of the beam width on the power densities was also evaluated, taking into account the geometrical limitations of the facility. Finally, a comparison between protons and deuterons as primary particles was performed, acknowledging the limitations of using FLUKA for these simulations.

The results of these calculations show the benefit of using protons as primary particles and increasing their energy, in order to reduce the high power densities occurring in the first few centimetres downstream of the interaction point. Particularly, a 2 GeV proton beam with a $\sigma \sim 15$ mm Gaussian distribution on a 15 cm radius 50 cm long target seems a suitable trade between increasing the neutron and fission yields and reducing the power densities in both, the liquid metal and fission targets.

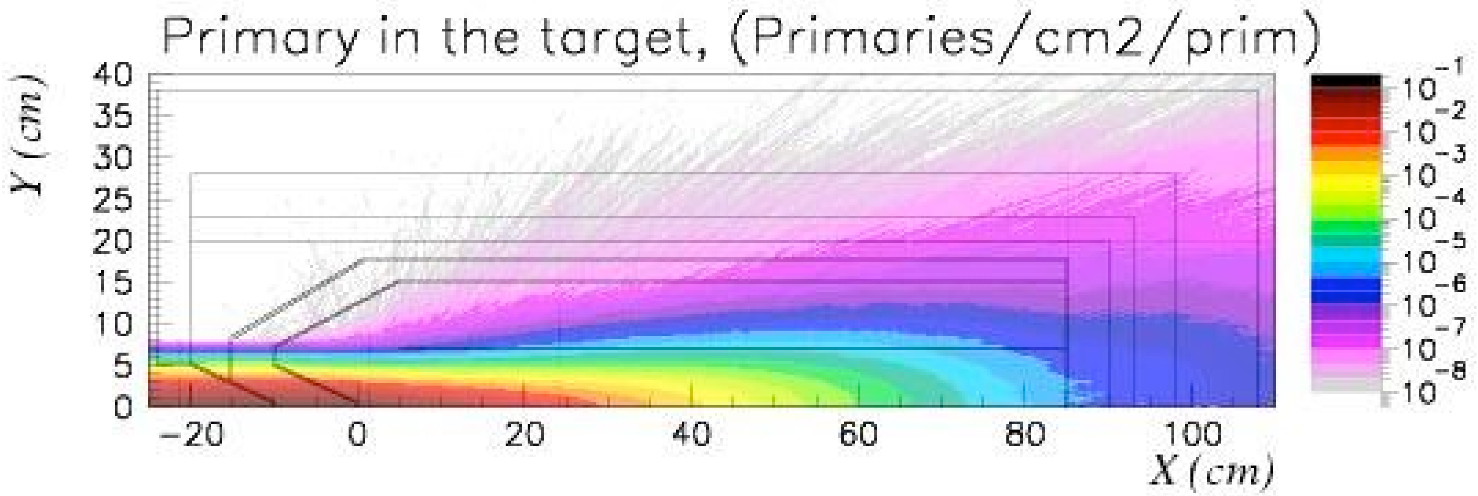
# Sensitivity Study: Content

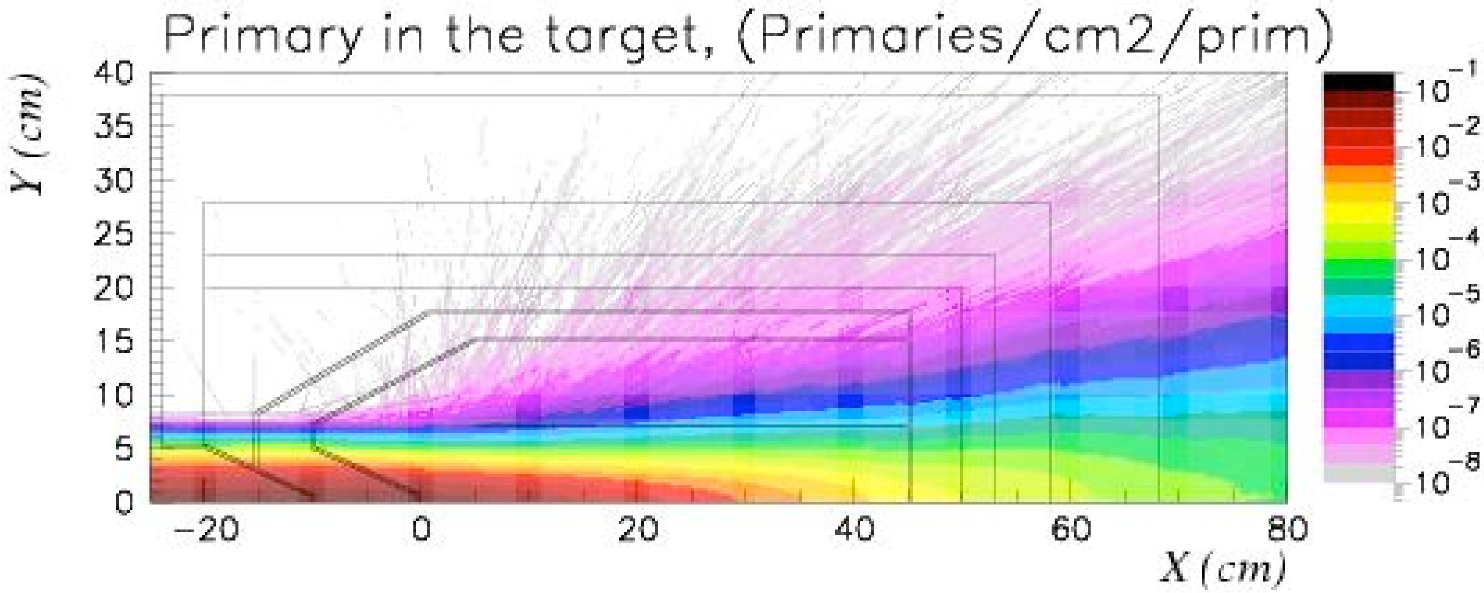
- Projectile Particle: Proton vs deuteron
- Beam Shape: Gaussian, $\sigma$ ~1.7 - 35 mm vs parabolic
- Energy Range: 1–2–3 GeV
- Target Material: Hg / PbBi
- Target Length: 40–60–80–100 cm
- Target Radius: 10–20–30–40 cm
- Spatial and energy particle distribution

# Primary Proton Flux Distribution @ 2 GeV



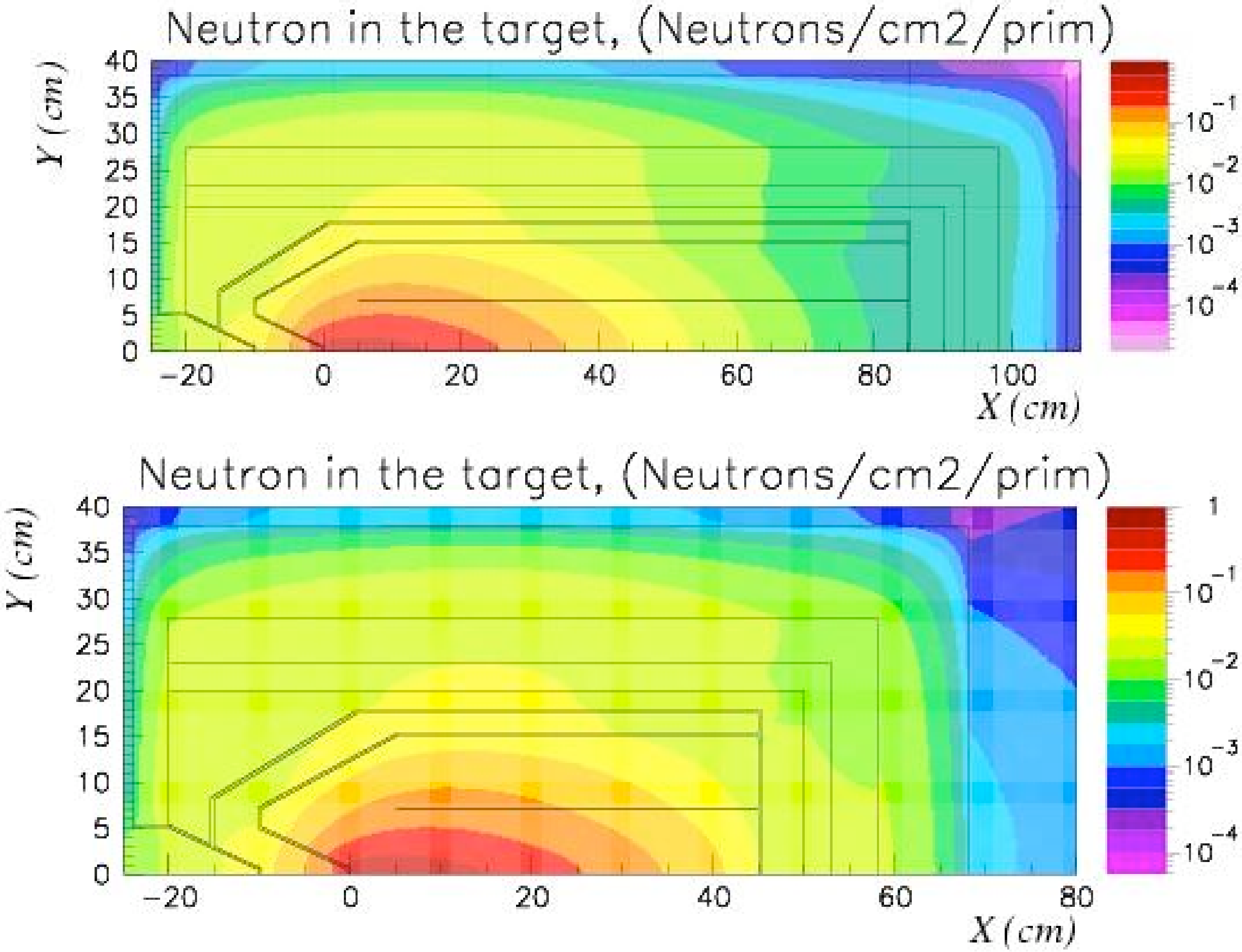
- 2 GeV proton range ~ 110 cm ==> almost stopped inside the target
- Forward peaked primary distribution at ~10 degrees
- $10^{-5}$ escapes per primary with an average energy of 700 MeV
- ==> 100 times more in case of shorter target (same length as for 1 GeV)



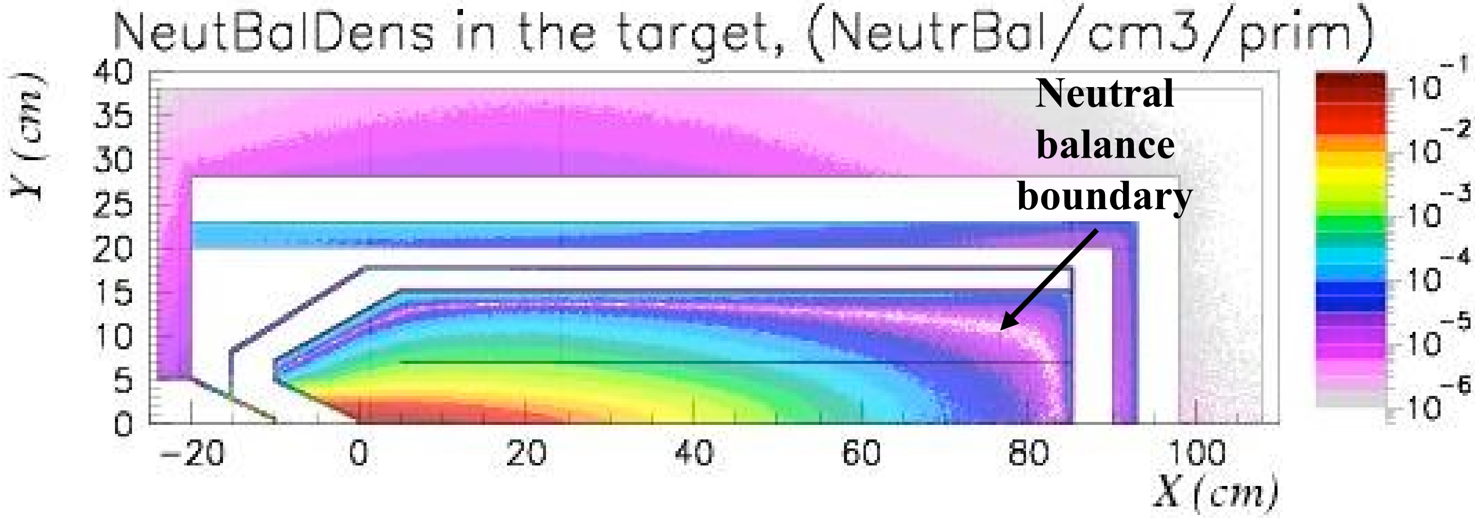



# Neutron Flux Distribution @ 2 GeV

- Neutron flux centered radially around ~15 cm from the impact point, presenting a forward-peaked component
- similar (w.r.t. to 1 GeV) neutron source intensities at the periphery of the Hg target ==> ~$10^{18}$ n/s per MW of beam escaping radially
- $5 \times 10^{-3}$ escapes per primary axially
- ==> 10 times more in case of shorter target

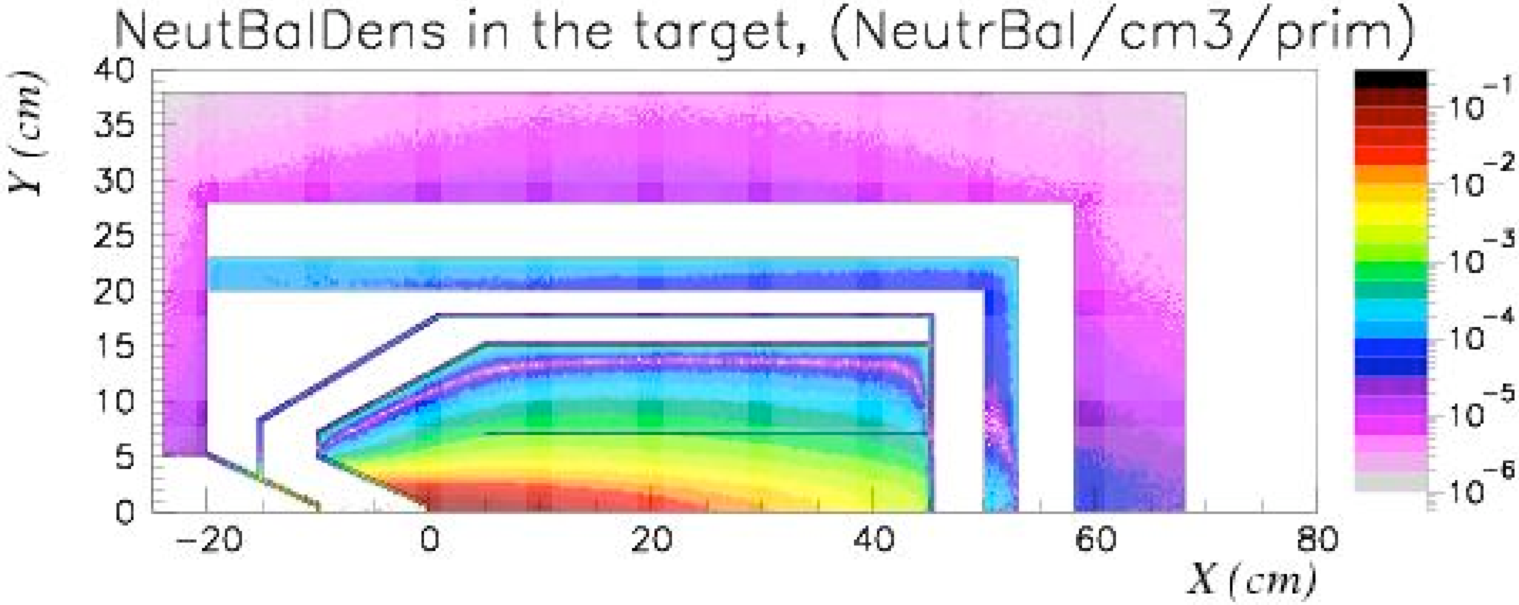


# Neutron Balance Density Distribution @ 2 GeV

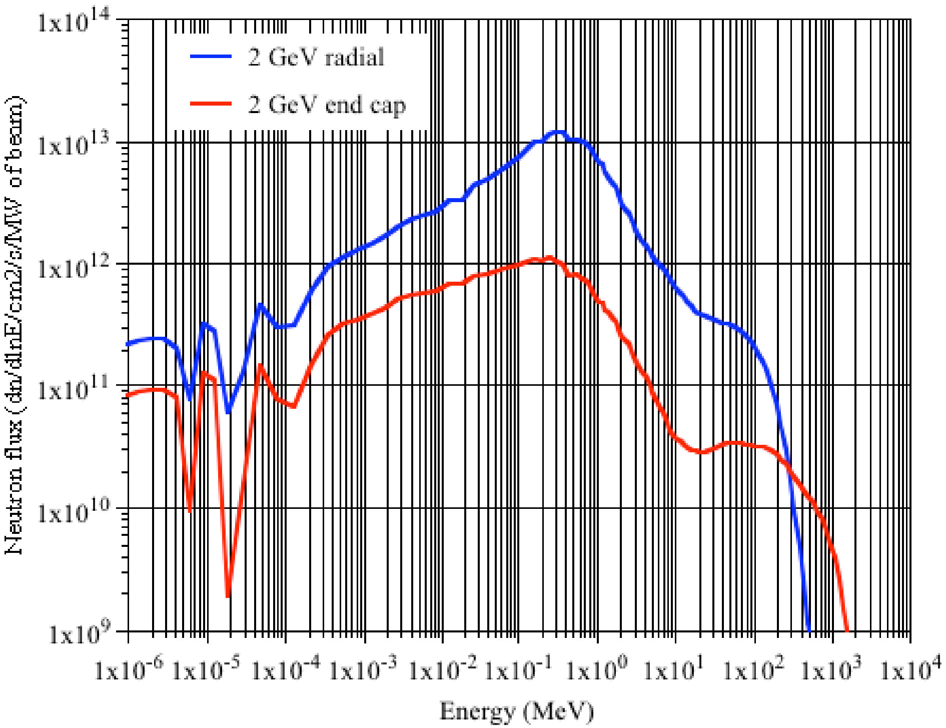


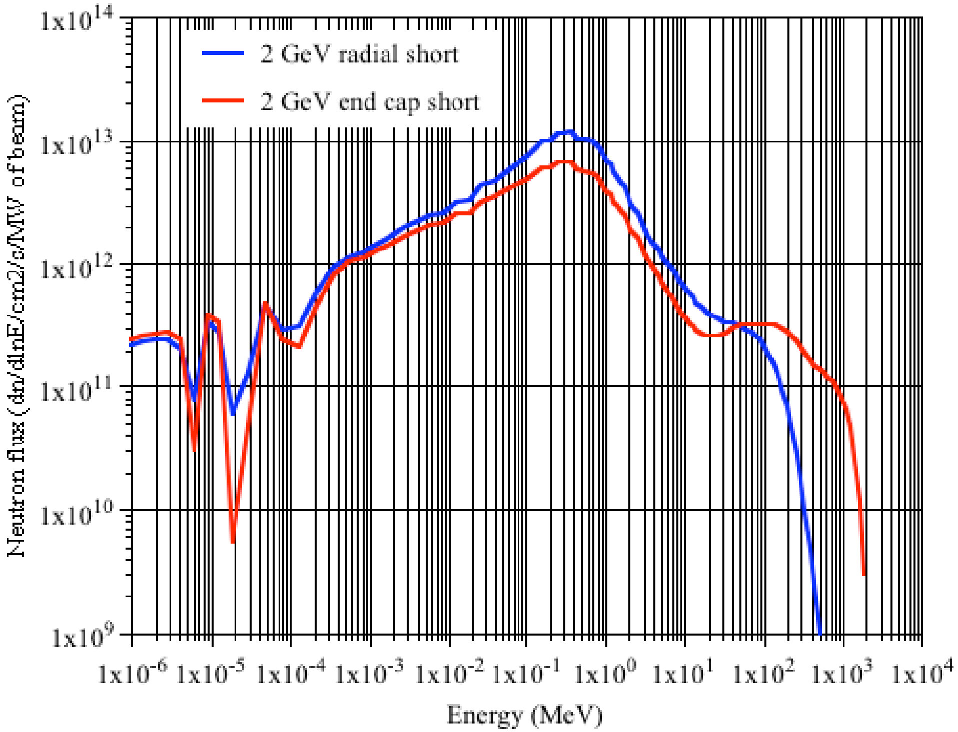

- Neutron producing region extending to the end of the Hg target but also in UCx
- small neutron absorption in the radial periphery
- for shorter target, no difference radially but higher axial leakage

==> more absorption in nearby structures (UCx target and reflector)



# Neutron Energy Spectrum @ 2 GeV

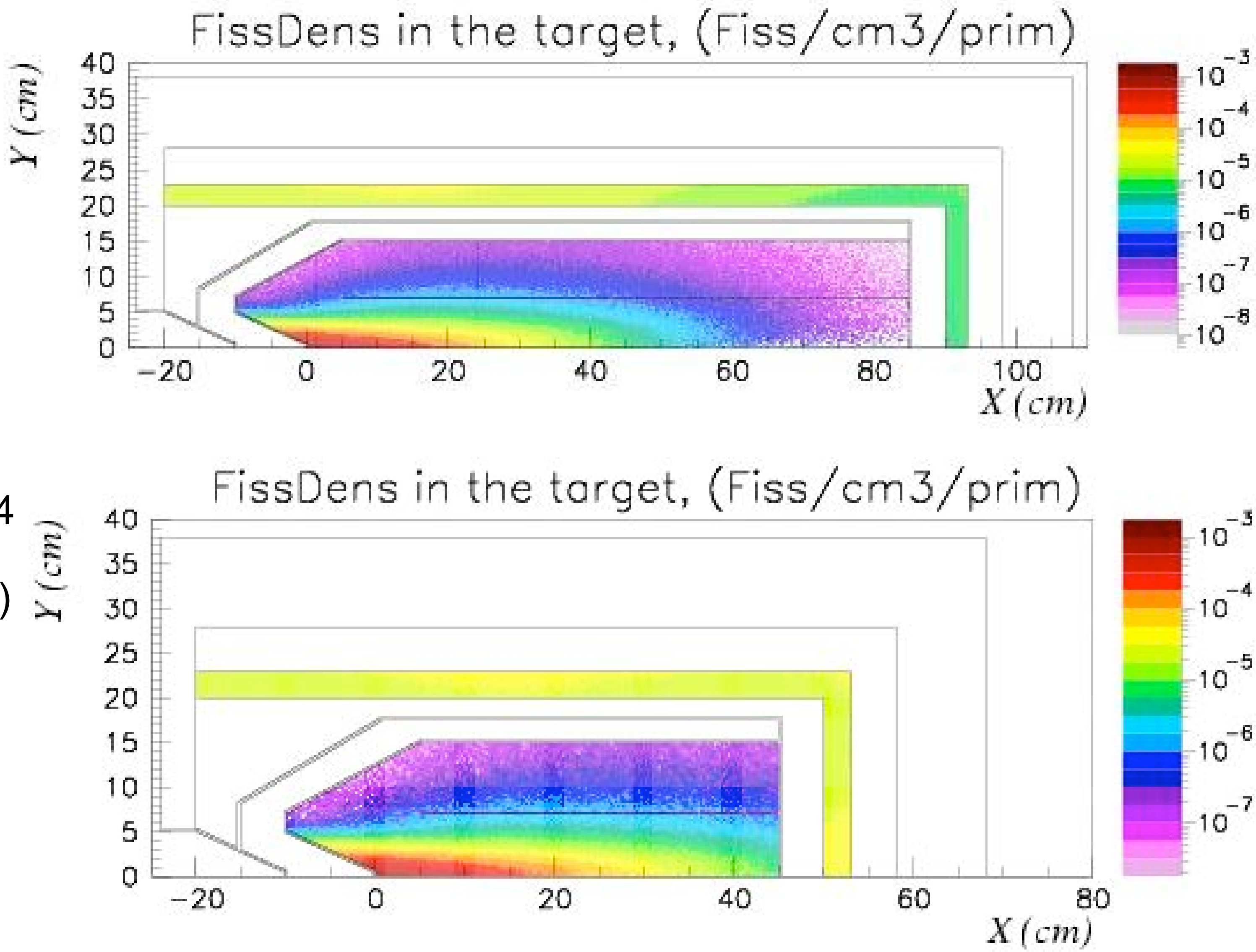


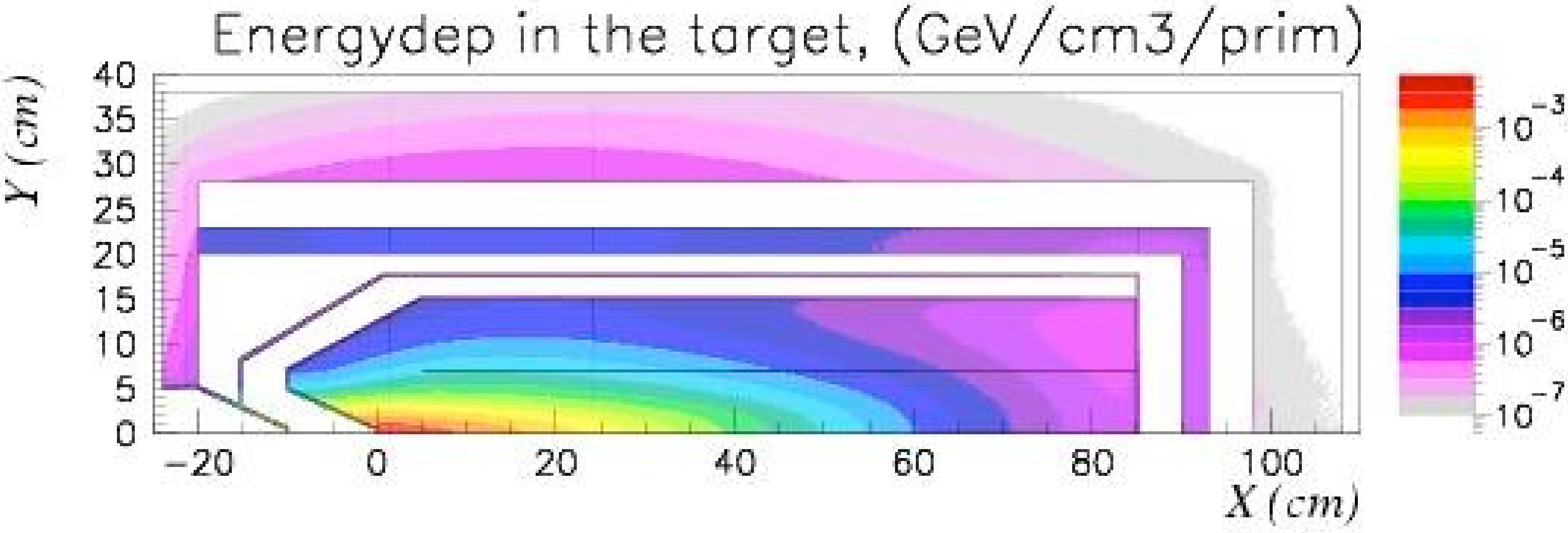

- Escaping neutron flux peaking at ~300 keV (evaporation neutrons), with a 100 MeV component in the forward direction (direct knock-out neutrons) ==> same flux level as for 1 GeV protons
- With shorter target neutron leakage evenly distributed but harder in the axial direction

# Fission Density Distribution in $U_{nat}C_3$ @ 2 GeV

- More homogeneous distribution of fissions in $U_{nat}C_3$ with short target
- independently of the target dimension and proton energy ==> ~$5 \times 10^{14}$ fissions/s for 4 MW of beam and 1 litre of $U_{nat}C_3$ (3 g/cm$^3$)



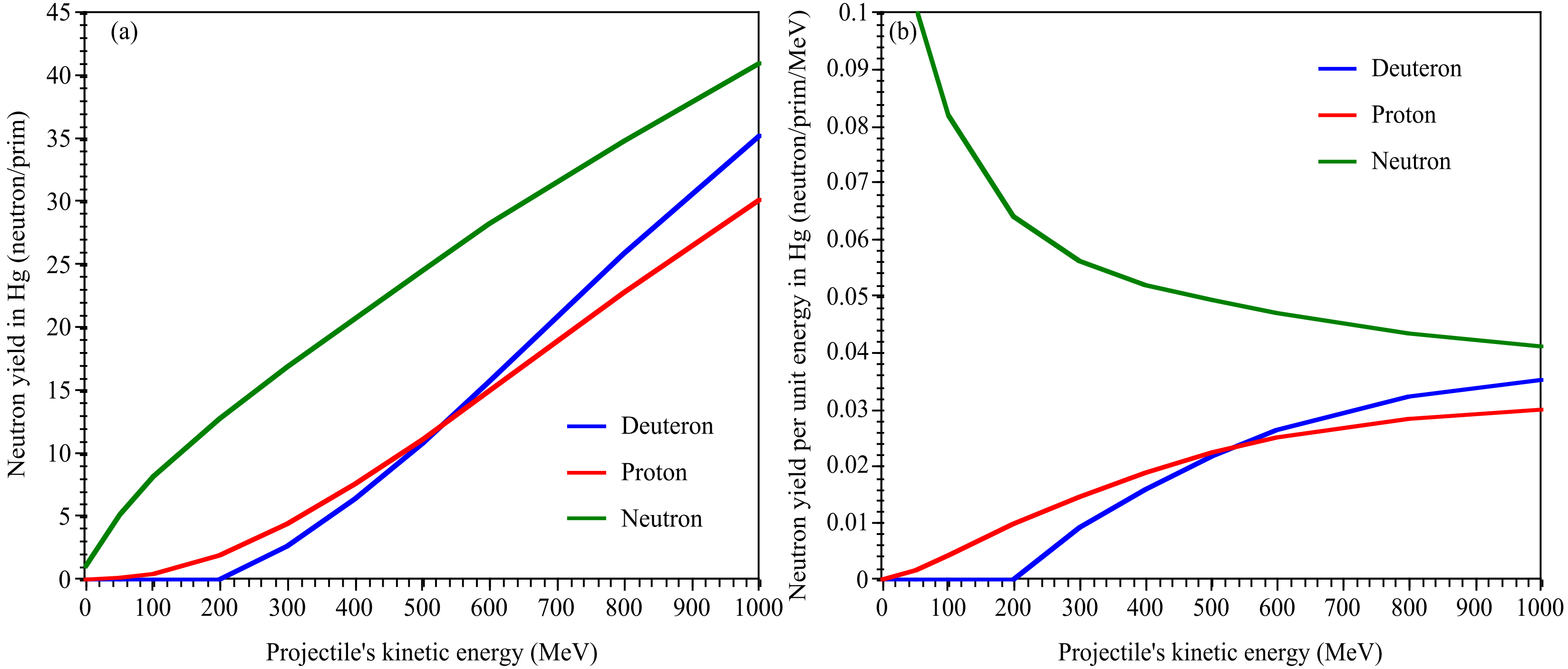
# Energy Deposition @ 2 GeV




- Maximum energy deposition in the first ~10 cm beyond the interaction point, ~1 $kW/cm^3/MW$ of beam ==> 50% lower w.r.t. 1 GeV
- Energy deposition in UCx target: < 1 $W/cm^3/MW$ of beam ==> x10 if target is shorter
- Smaller radial gradients (dE/dr ~5 compared to 15) in the interaction region

# Protons vs Deuterons: Neutron Yields

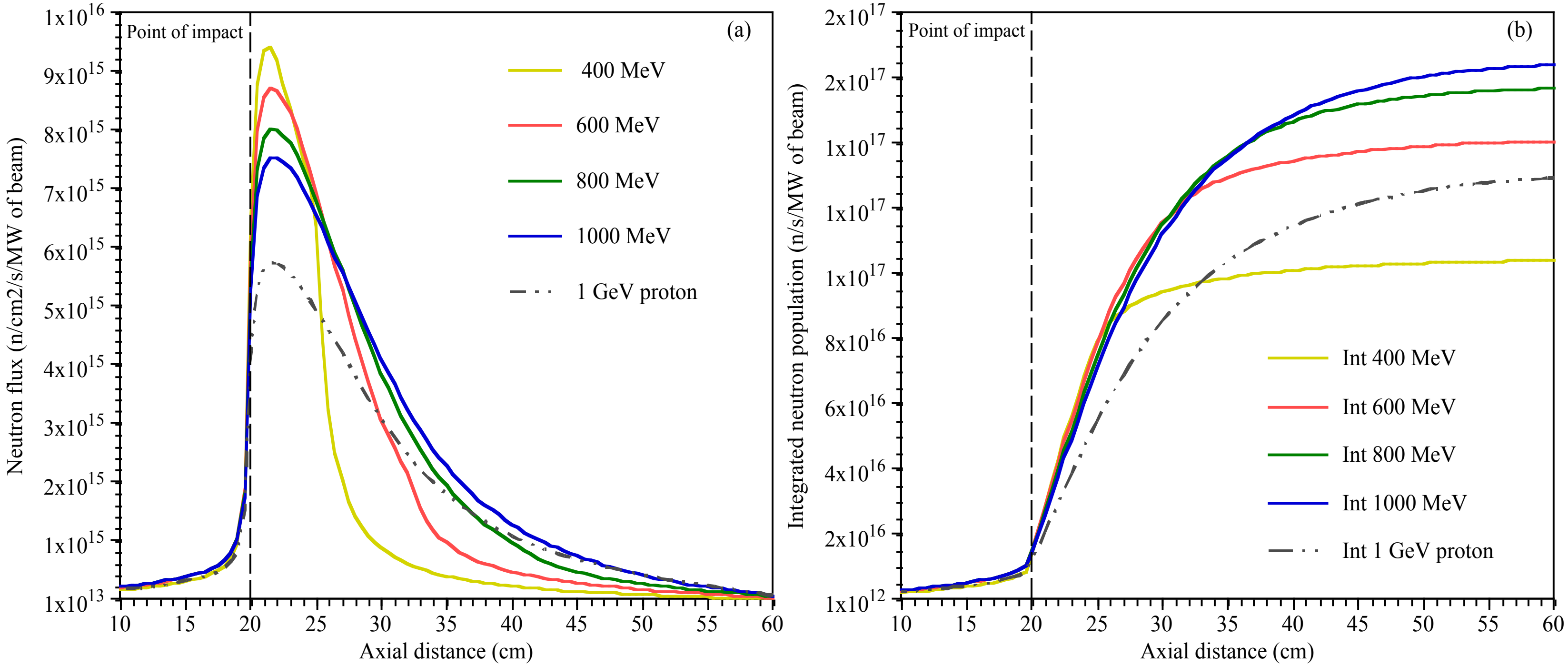
*Neutron yield in Hg for different types of projectile*




- deuterons and protons have similar distribution (yield increases with energy)
- Above 500 MeV Deuterons more effective in producing neutrons
- +15% higher at 1 GeV

# Protons vs Deuterons: Neutron Distribution

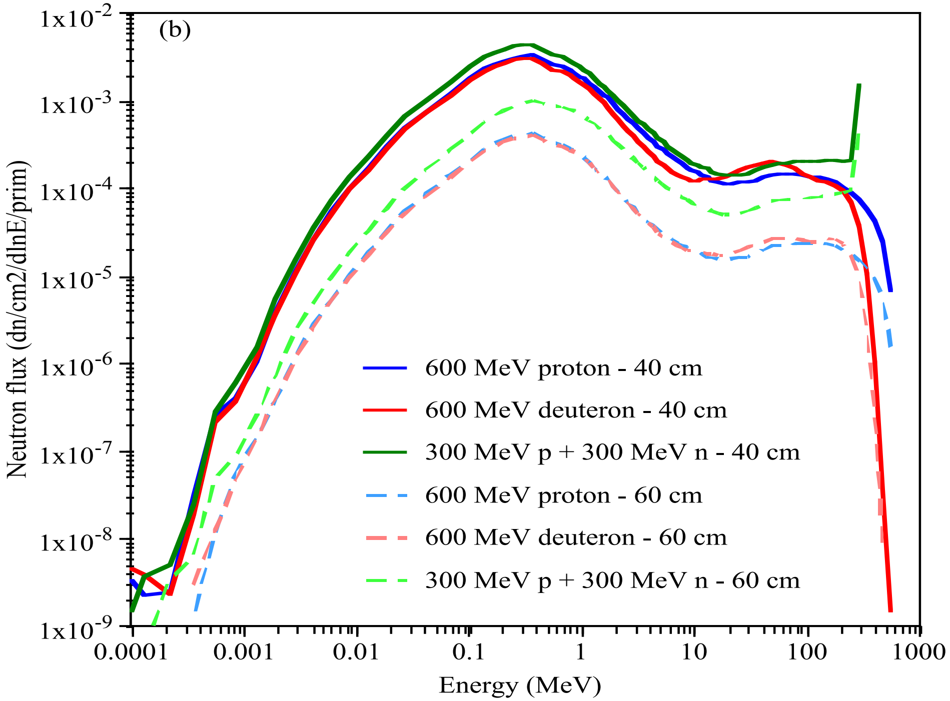
*Neutron distribution along the central axis of the Hg target*

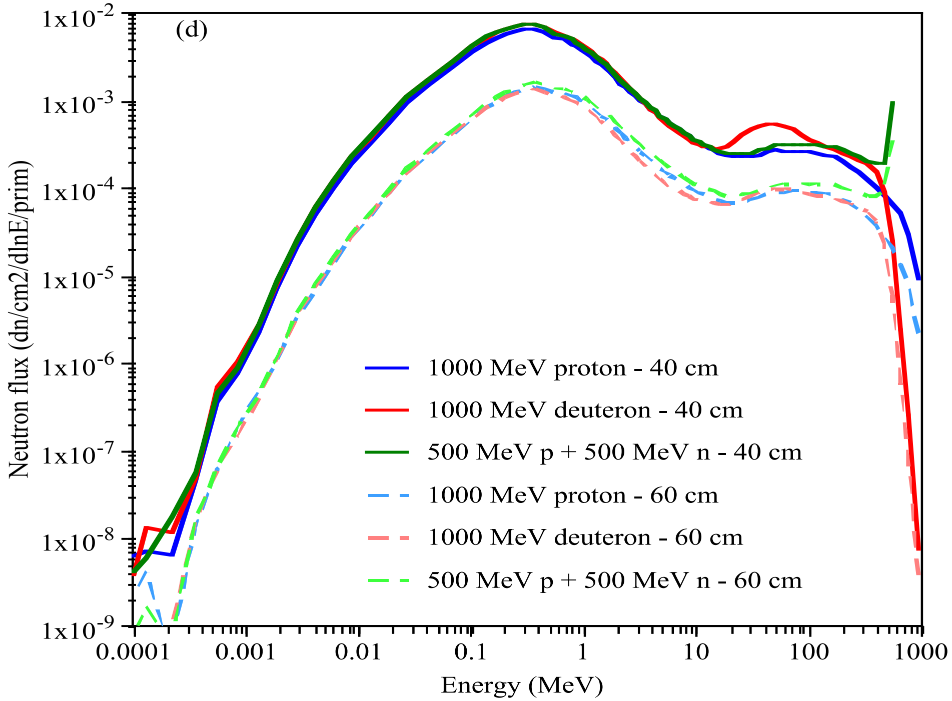



- With deuterons, neutrons are produced in larger quantities over shorter length
- Distribution is more peaked and flattens out with increasing kinetic energy
- ==> shorter target to make use of higher neutron fluxes
- > 600 MeV deuterons more effective

# Protons vs Deuterons: Neutron Spectra

*Neutron energy spectra for deuterons and protons at different target positions*



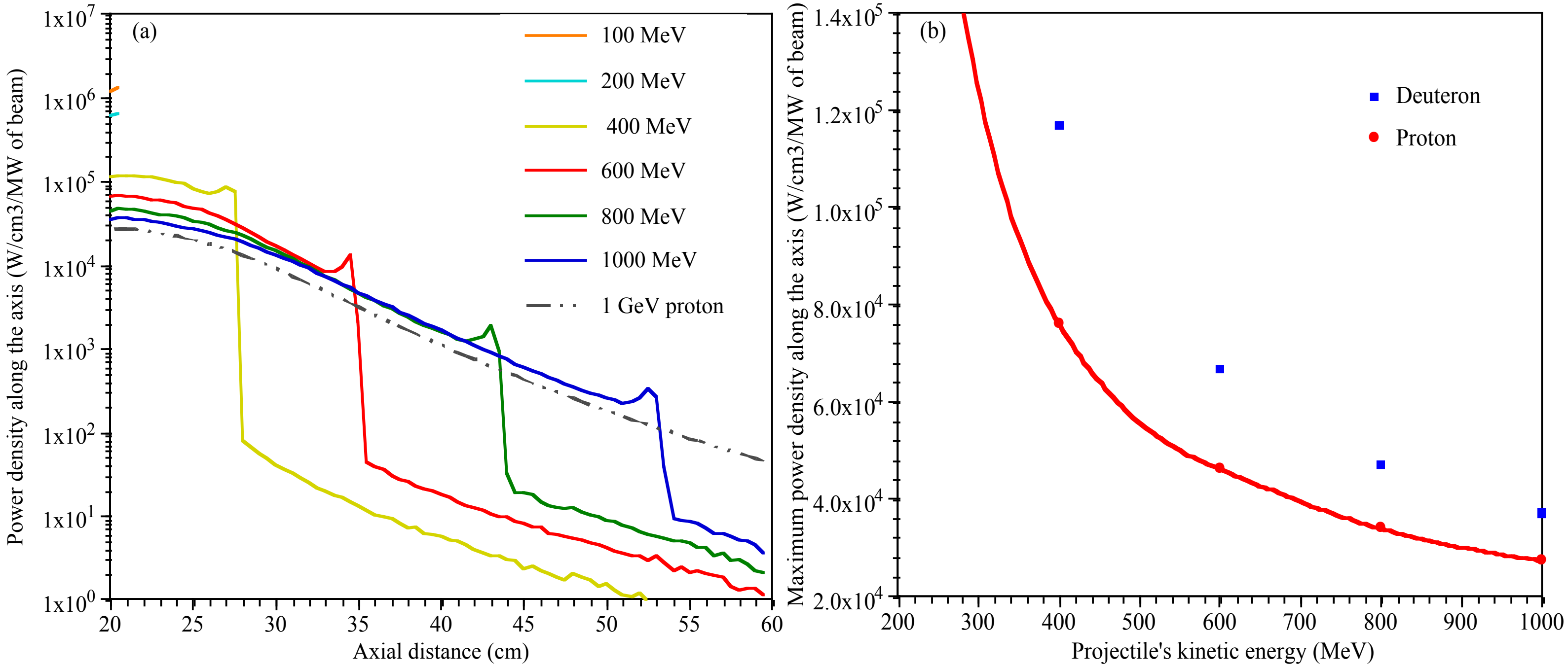

• deuterons & protons present a very similar neutron energy distribution, both, in the middle of the target (in spite of the ~20 MeV flux bump for deuterons) and through the end cap

• at low energies, the use of deuterons may bring about a higher and harder neutron spectrum, in particular through along the beam axis

• at high energies, such as the ones proposed for the Multi-MW target, namely 1000 MeV, the differences are rather small, not evidencing clearly the advantage of using deuterons as projectile instead of protons.

# Protons vs Deuterons: Energy Deposition

*Energy deposition along the central axis of the Hg target*




• the analysis of the power densities shows the difficulties of cooling a Multi-MW target driven by low energy deuterons since, for a σ ~1.7 mm Gaussian beam at 100 MeV, the power **densities** exceed 1 MW/cm$^3$/MW of beam

• protons present lower power densities for all the energies analysed, from 35% lower at 400 MeV to 27% lower at 1 GeV

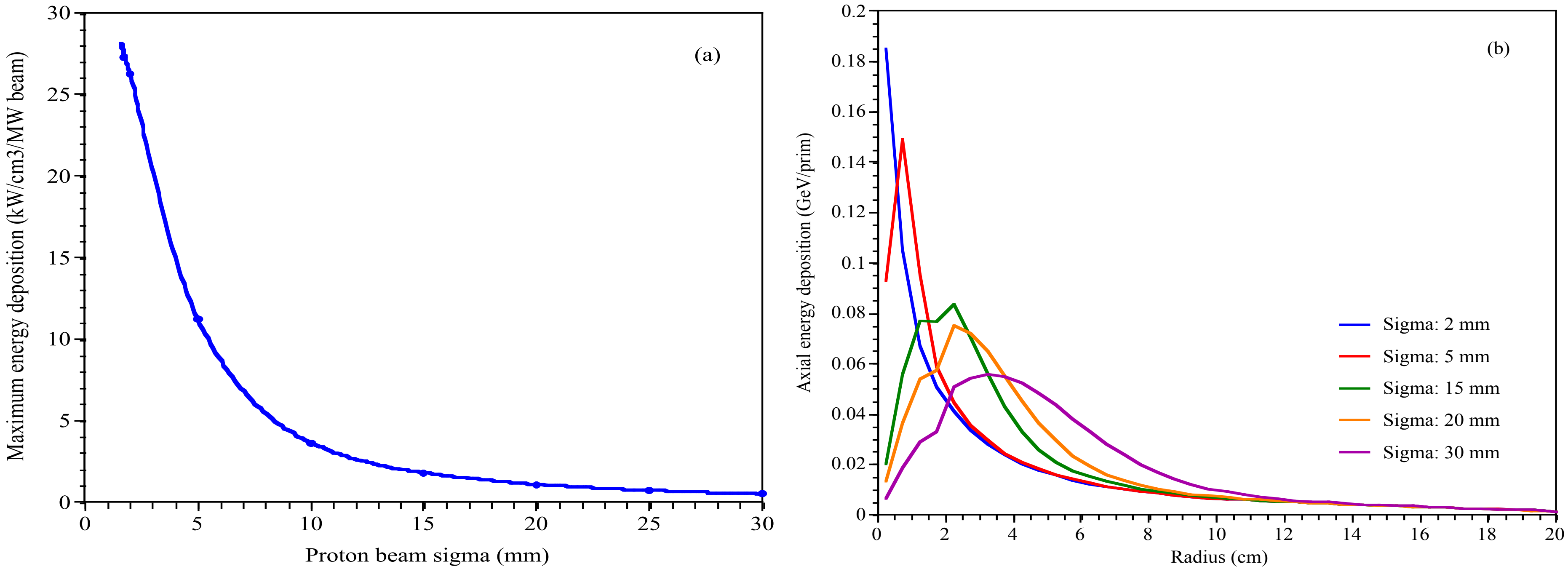
• the choice of a short target driven by a low energy (few hundred MeV) high-intensity deuteron beam would present important difficulties in terms of heat removal

# Protons vs Deuterons: Conclusion

The limited gain in neutron flux through the use of deuterons, especially at high projectile energies, can hardly justifying the increase in technical complexity, thus higher costs, of a deuteron accelerator and worsens the already complex problem of removing the heat around the impact point in the liquid Hg target.

# Impact of the Beam Profile (1)

*Energy deposition as a function of the beam σ*



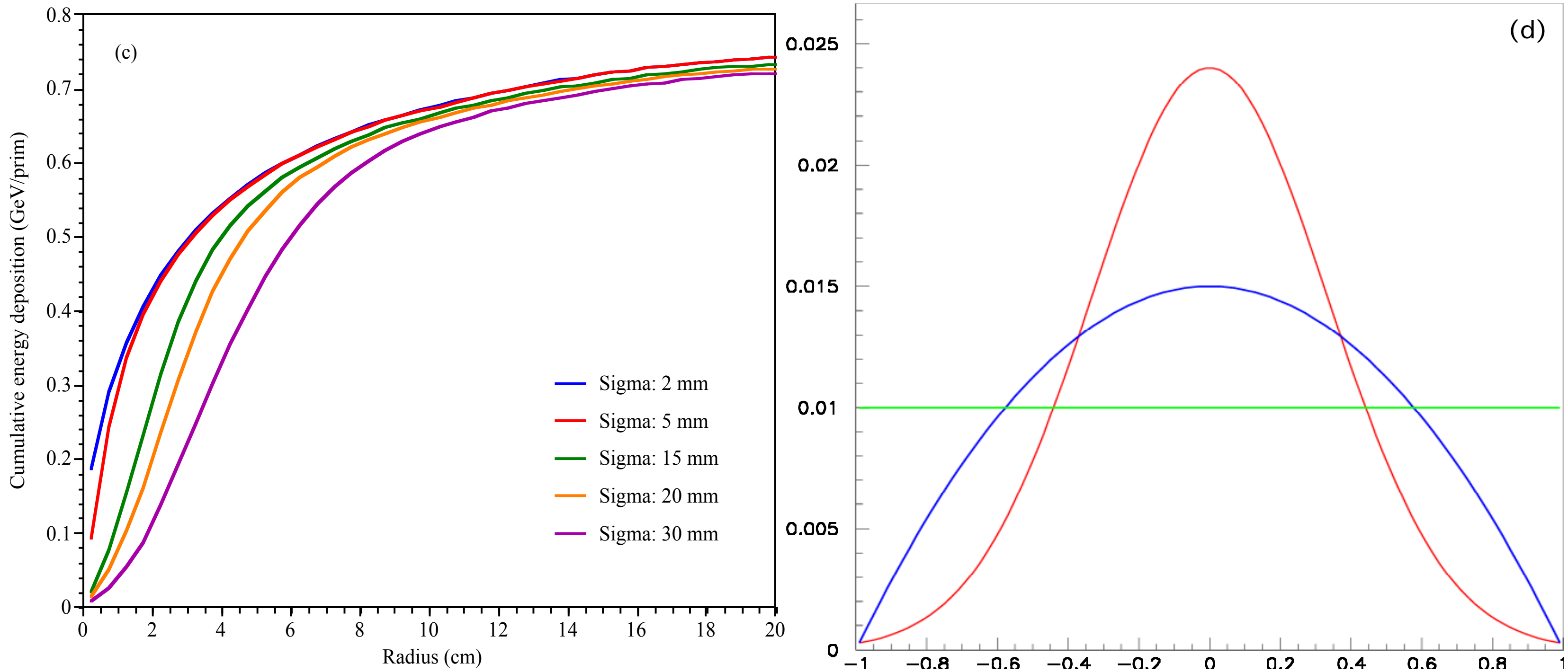

• A beam size of σ ~15 mm seems appropriate to reduce the maximum power density from ~27 kW/cm$^3$/MW of beam to ~1.8 kW/cm$^3$/MW of beam power (15 times less).

• A further increase in the beam size, for example going from σ ~15 mm to 25 mm, reduces the maximum energy deposition by another factor of 2.4.

• For smaller σ, i.e., 2 mm and 5 mm, most of the energy is deposited along the axis or at small radii, whereas for larger σ, i.e. 20 mm or 30 mm, most of the energy is **diluted** on a larger volume at increasing radii (e.g. for σ=30 mm, the maximum value is reached at 3.5 cm from the axis), therefore, reducing the maximum power densities

# Impact of the Beam Profile (2)

*Energy deposition as a function of the beam σ*




• ~75% of the beam energy is contained inside the target and that σ only has an impact on which radius contains ~50% of the energy (for σ = 2 mm, this occurs at 3 cm, whereas for σ = 30 mm, it happens at 6 cm).

• using a parabolic beam of at least 4.5 cm radius , would reduce by 40% the energy density in the Hg target

# Sensitivity Study: Conclusions

1. The use of a 1 or perhaps 2 GeV proton beam on a compact (~15 cm radius ~50 cm long) mercury target would bring about important neutron yields with a reasonable charged particle confinement. The increase in the proton energy up to 2 GeV and use of a wide Gaussian beam profile, or even better, an equivalent parabolic beam, significantly reduces the maximum power densities in the target. Improving the conditions for a proper heat removal, since this issue may be the bottleneck in the design.
2. With respect to the use of deuterons as projectile, the neutron yield is increased in ~15% but the maximum power density is increased in ~30%. This fact and the increase in the costs of a deuteron machine would justify the choice of protons.
3. Considering these facts, a baseline design is proposed, where a 15 cm radius 60 cm long mercury target with a conical void and a cylindrical flow guide has been designed, surrounded by a cooling helium tank. Around this converter block, a 3 cm thick UCx fission target has been foreseen, together with a beryllium oxide reflector to recuperate the escaping neutrons.

# Baseline parameters of the MMW Hg target

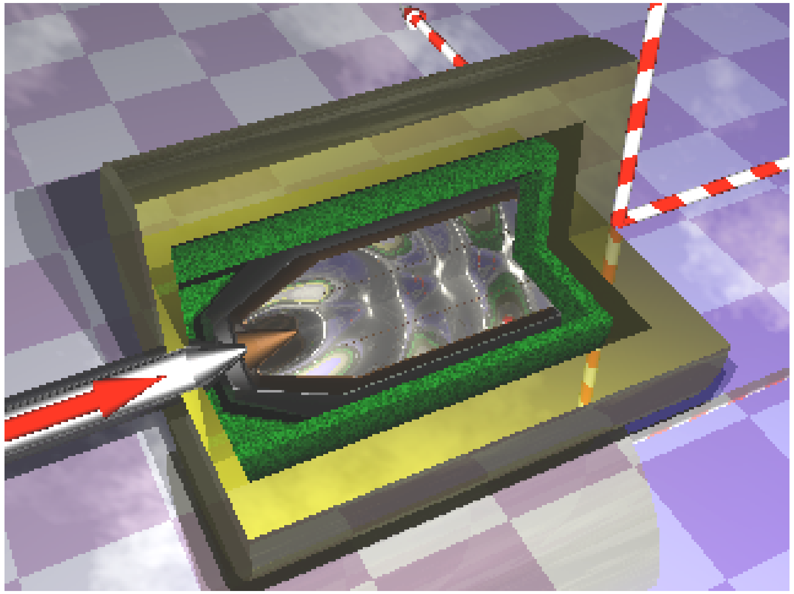
| Parameter | Symbol | Units | Nval | Range |
|---|---|---|---|---|
| Converter Target material | $Z_{conv}$ | - | Hg (liquid) | LBE |
| Secondary Target material | $Z_{targ}$ | - | $UC_x$, BeO | |
| Beam particles | $Z_{beam}$ | - | Proton | |
| Beam particle energy | $E_{beam}$ | GeV | 1 | $\leq 2$ |
| Beam current | $I_{beam}$ | mA | 4 | 2 – 5 |
| Beam time structure | - | - | dc | ac<br>50Hz 1ms pulse |
| Gaussian beam geometry | $\sigma_{beam}$ | mm | 15 | $\leq 25$, parabolic |
| Beam power | $P_{beam}$ | MW | 4 | $\leq 5$ |
| Converter length | $l_{conv}$ | cm | 45 | $\leq 85$ |
| Converter radius (cylinder) | $r_{conv}$ | cm | 15 | 8 – 20 |
| Hg temperature | $T_{conv}$ | °C | 150 (tbc) | $\ll 357$ |
| Hg flow rate | $Q_{conv}$ | ton/s | 1 (tbc) | $\ll 3$ |
| Hg speed | $V_{conv}$ | m/s | 5 (tbc) | $\ll 15$ |
| Hg pressure drop | $\Delta P_1$ | bar | tbc | $\ll 100$ |
| Hg overpressure | $\Delta P_2$ | bar | tbc | $\ll 100$ |
| $UC_x$ temperature | $T_{targ}$ | °C | 2000 | 500-2500 |

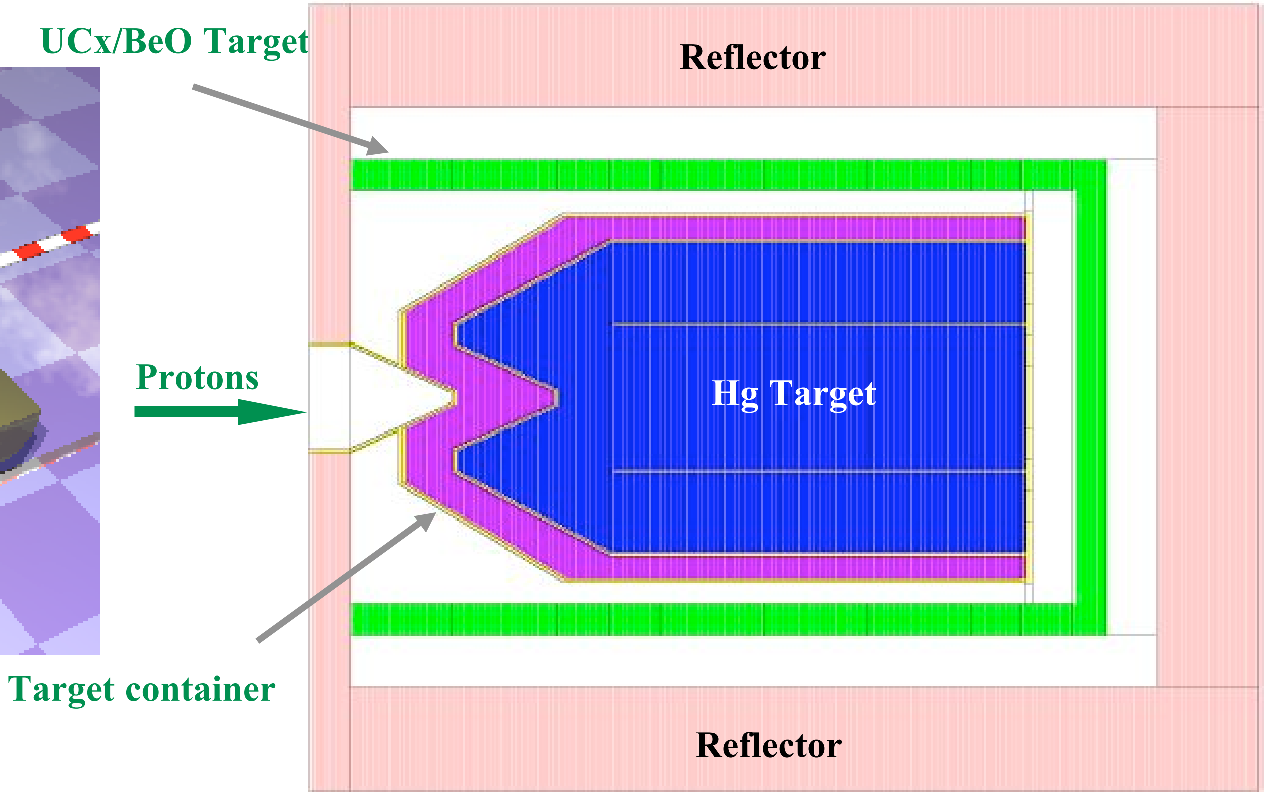
# Conceptual design of the MMW Hg target

1. MMW Hg target configuration
2. Particle flux distributions
3. Energy depositions
4. Residual nuclei distributions in Hg
5. Radio-isotope yields in $UC_x$ and BeO

# MMW Hg target configuration



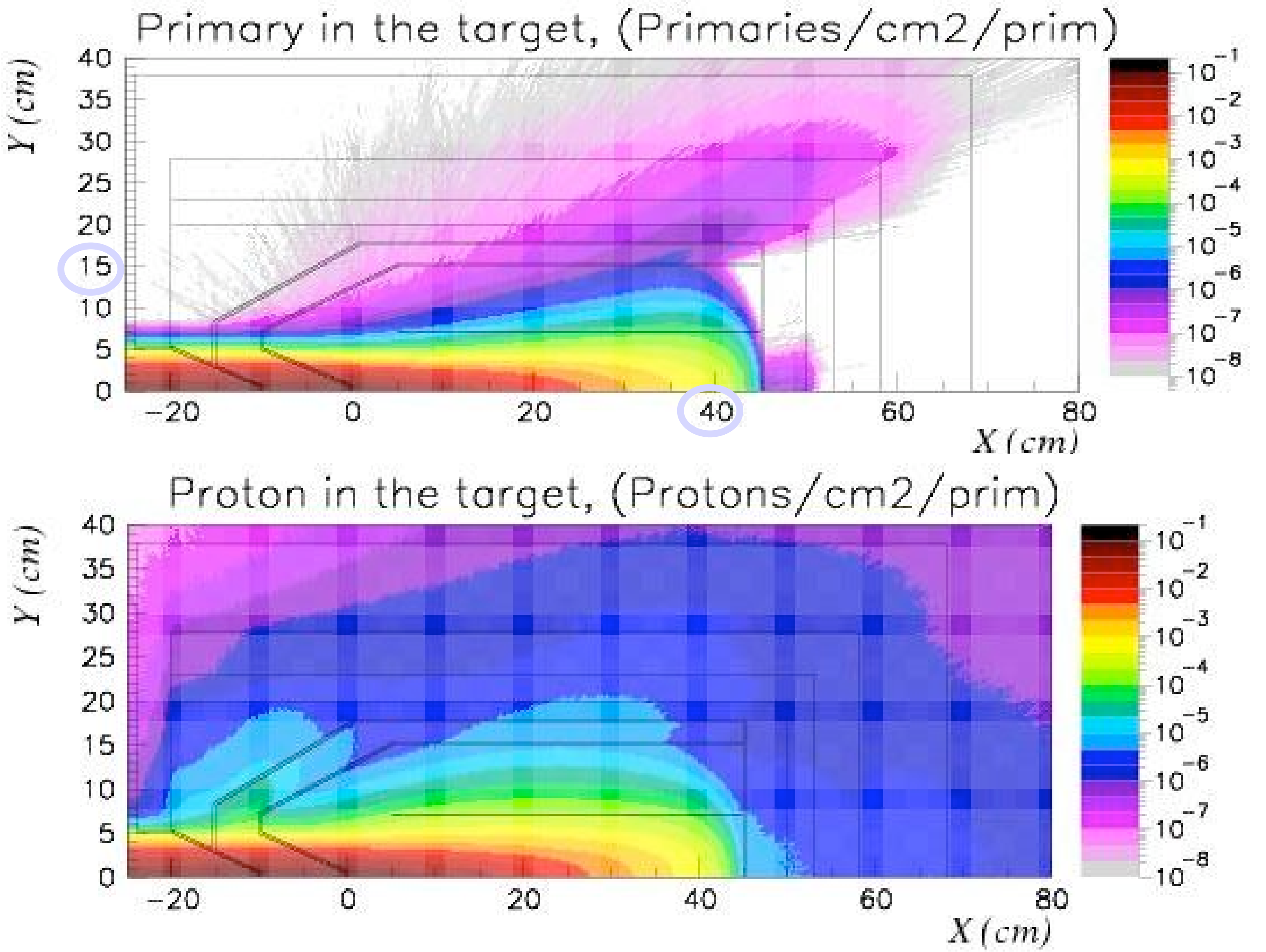





- shape of Hg target optimized for neutron production (neutron balance)
- UCx and BeO target ==> qualitative estimate of yields ==> dimensioning of converter part

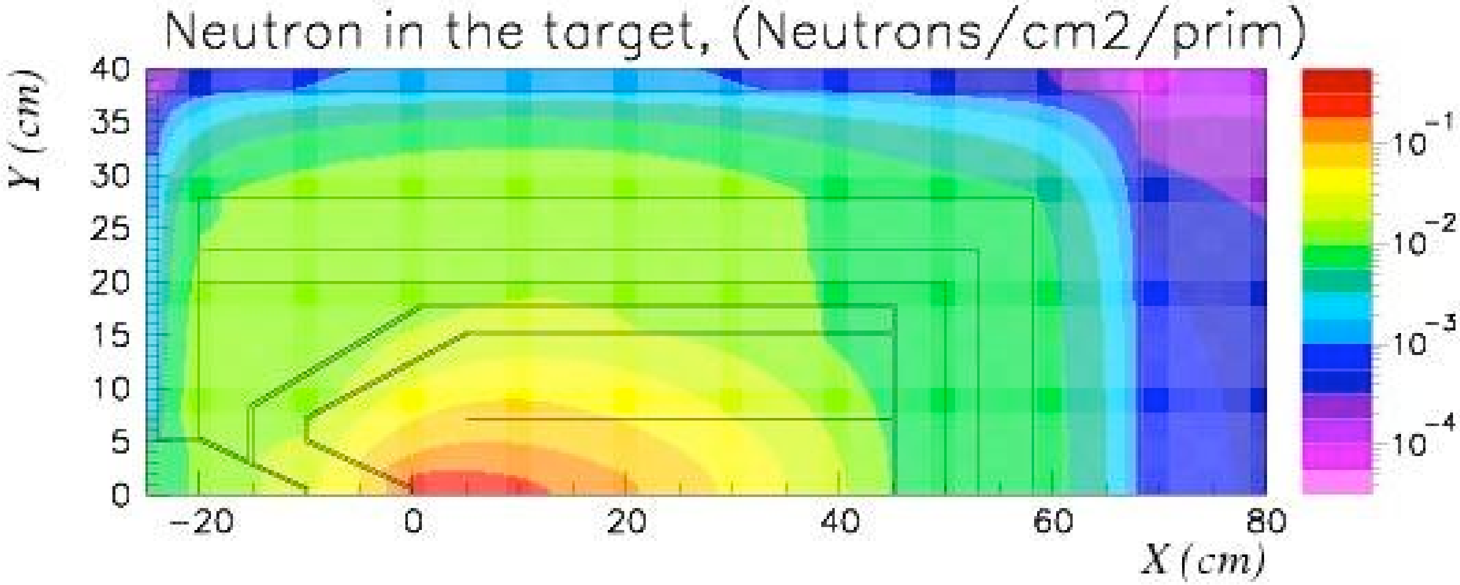
# Primary Proton Flux Distribution

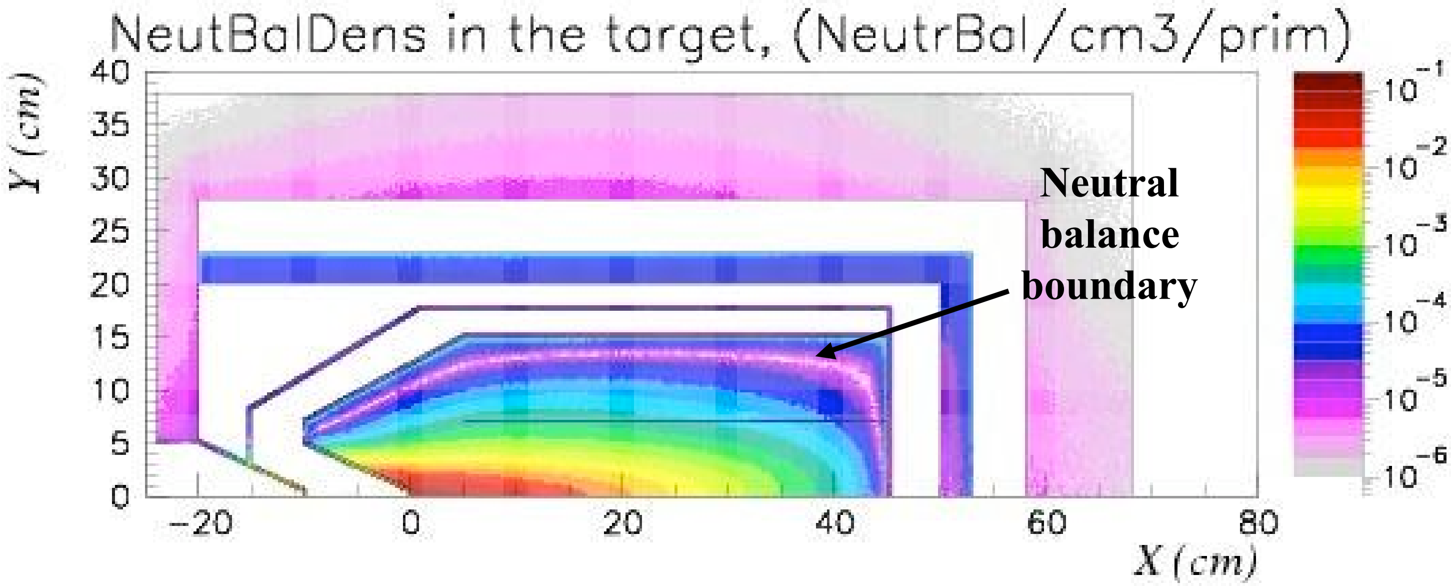
- 1GeV proton range ~ 46 cm ==> stopped inside the target
- protons interacting with target vessel and Hg target ==> few radial escapes $10^{-7}$



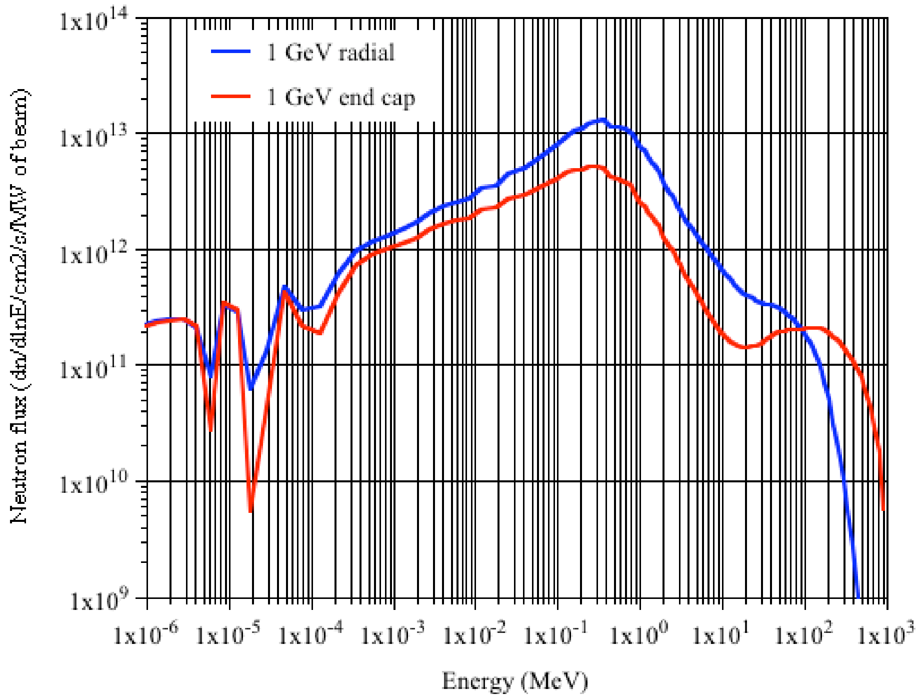
# Neutron Flux Distribution

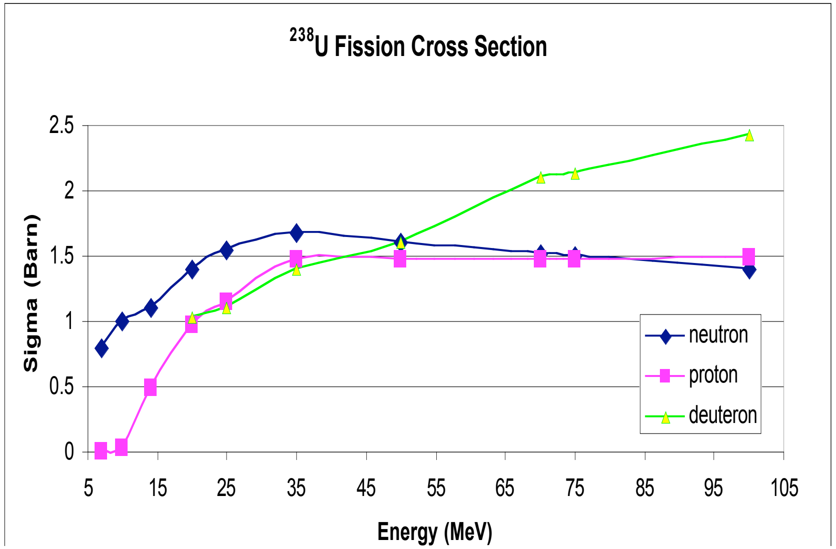
- Neutron flux centered radially around ~10 cm from the impact point
- Isotropic flux after ~15 cm from the center, decreasing with $r^2$
- ==> ~$10^{18}$ n/s per MW of beam escaping the Hg target radially
- Neutron producing region extending to the end of the Hg target but also in UCx
- small neutron absorption in the radial periphery

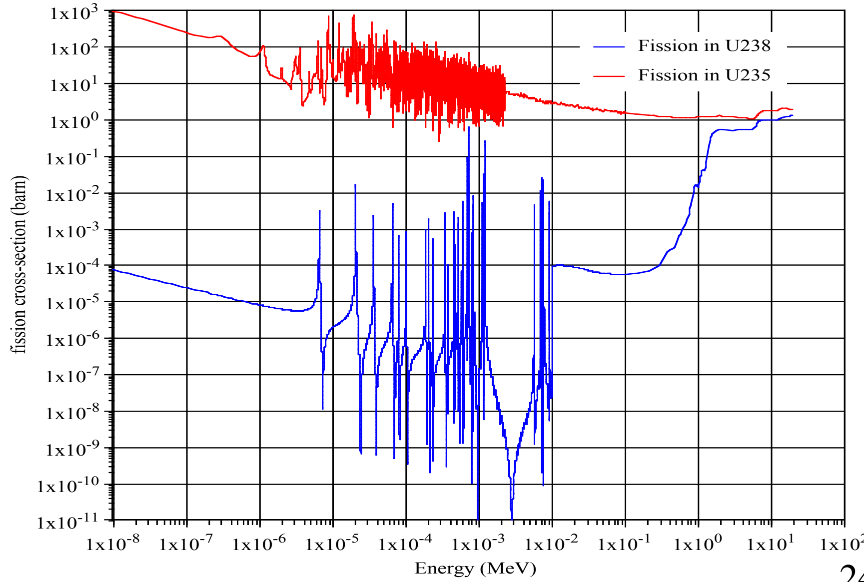


# Neutron Energy Spectrum vs Fission Cross-Section in Uranium



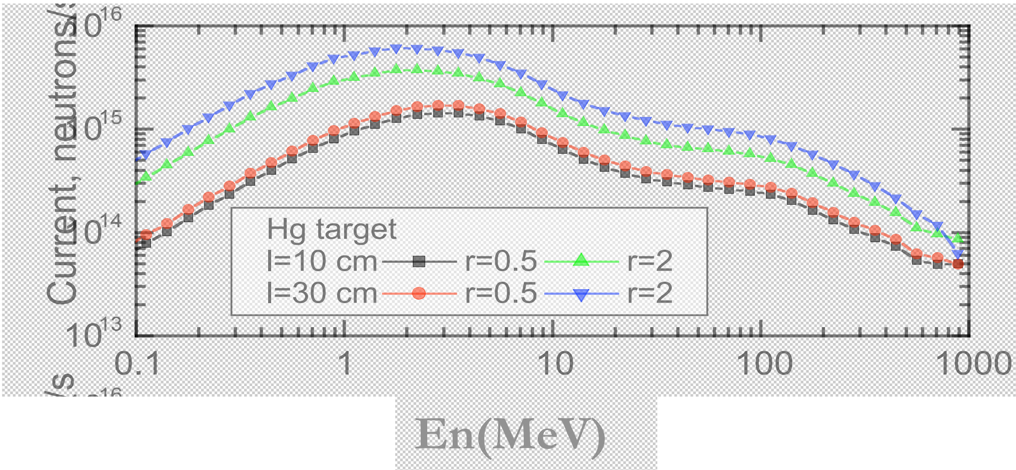



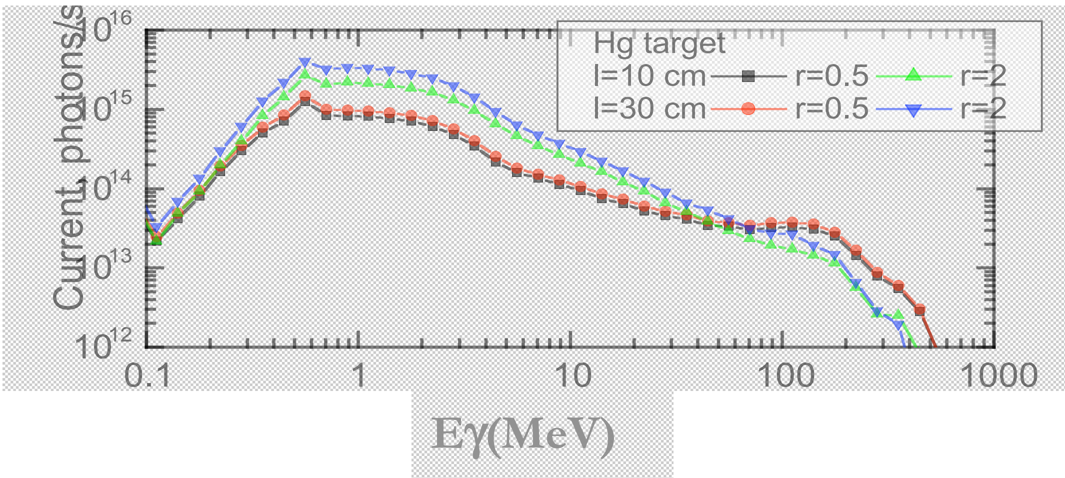




- Escaping neutron flux peaking at ~300 keV (evaporation neutrons), with a 100 MeV component in the forward direction (direct knock-out neutrons)
- Very low fission cross-section in $^{238}U$ below 2 MeV (~$10^{-4}$ barns). Optimum energy: 35 MeV
- Use of natural uranium: $\sigma_f$ in $^{235}U$ (0.7% wt.) for 300 keV neutrons: ~2 barns
- Further gain if neutron flux is moderated (graphite)

# CEA-Saclay Contribution

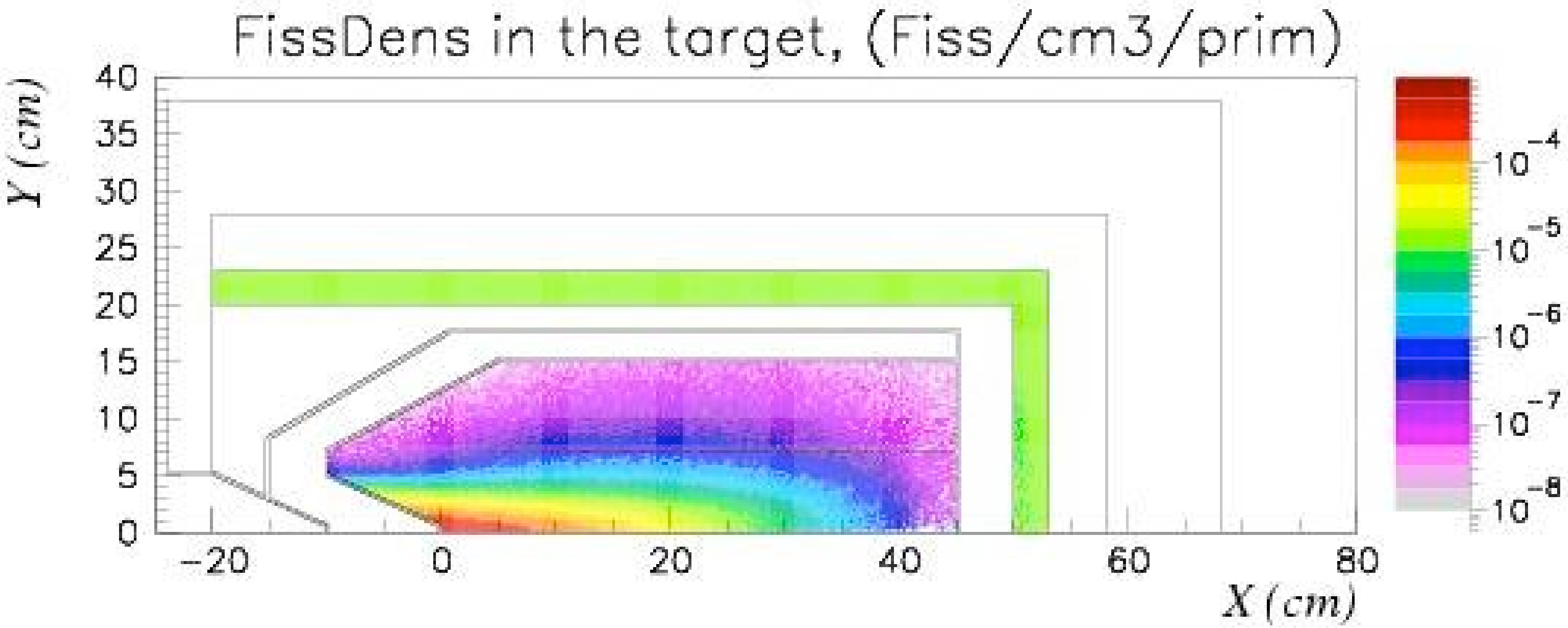
Neutronic calculations done within the EURISOL-RTD project




- Outgoing particles
  - energy spectra
  - (angular distribution)

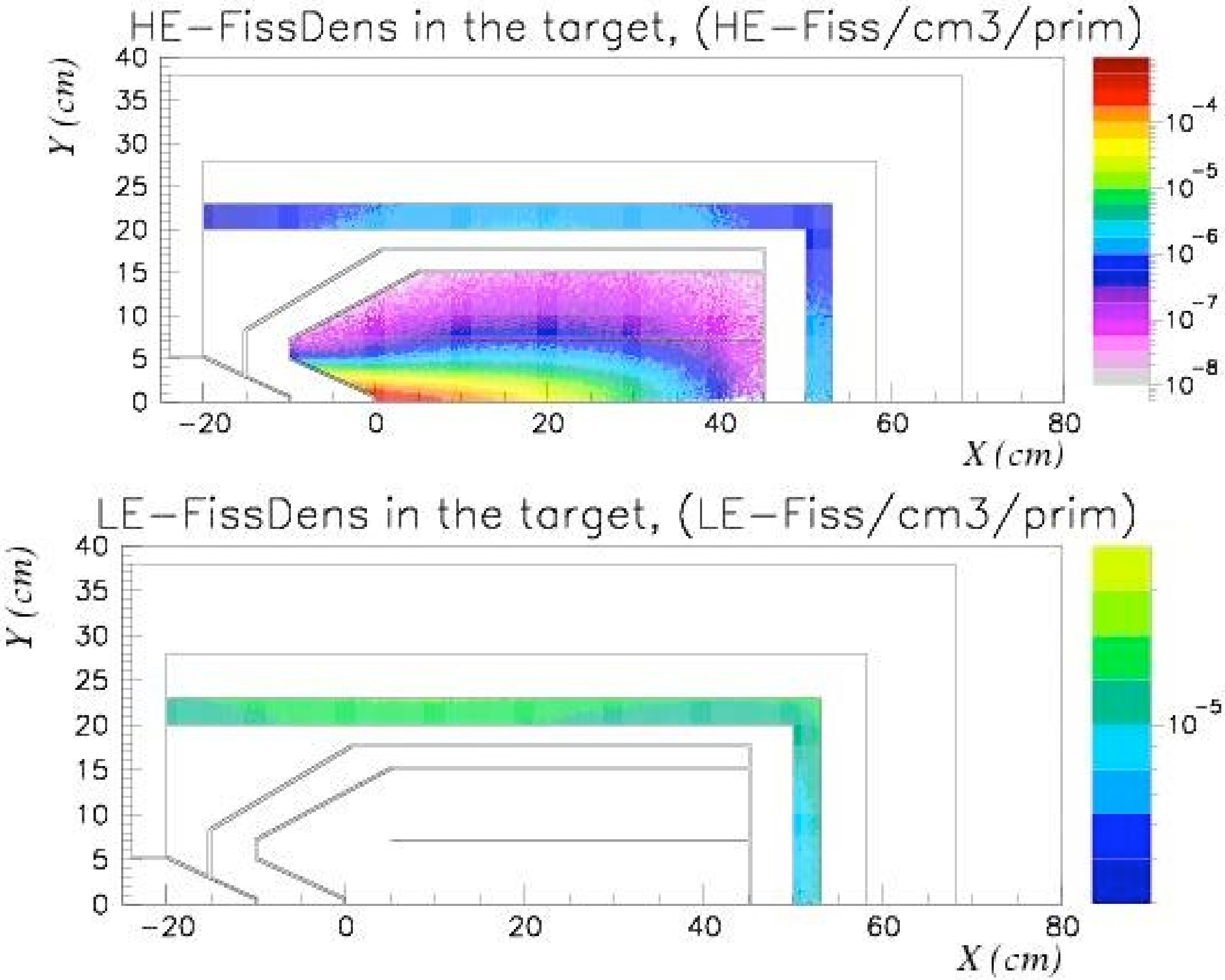
# Fission Density Distribution in $U_{nat}C_3$




- High-energy fissions in Hg !!
- Homogeneous distribution of fissions in $U_{nat}C_3$ independent of position w.r.t. Hg target
- ==> ~$5x10^{14}$ fissions/s for 4 MW of beam and 1 litre of $U_{nat}C_3$ (3 g/$cm^3$)

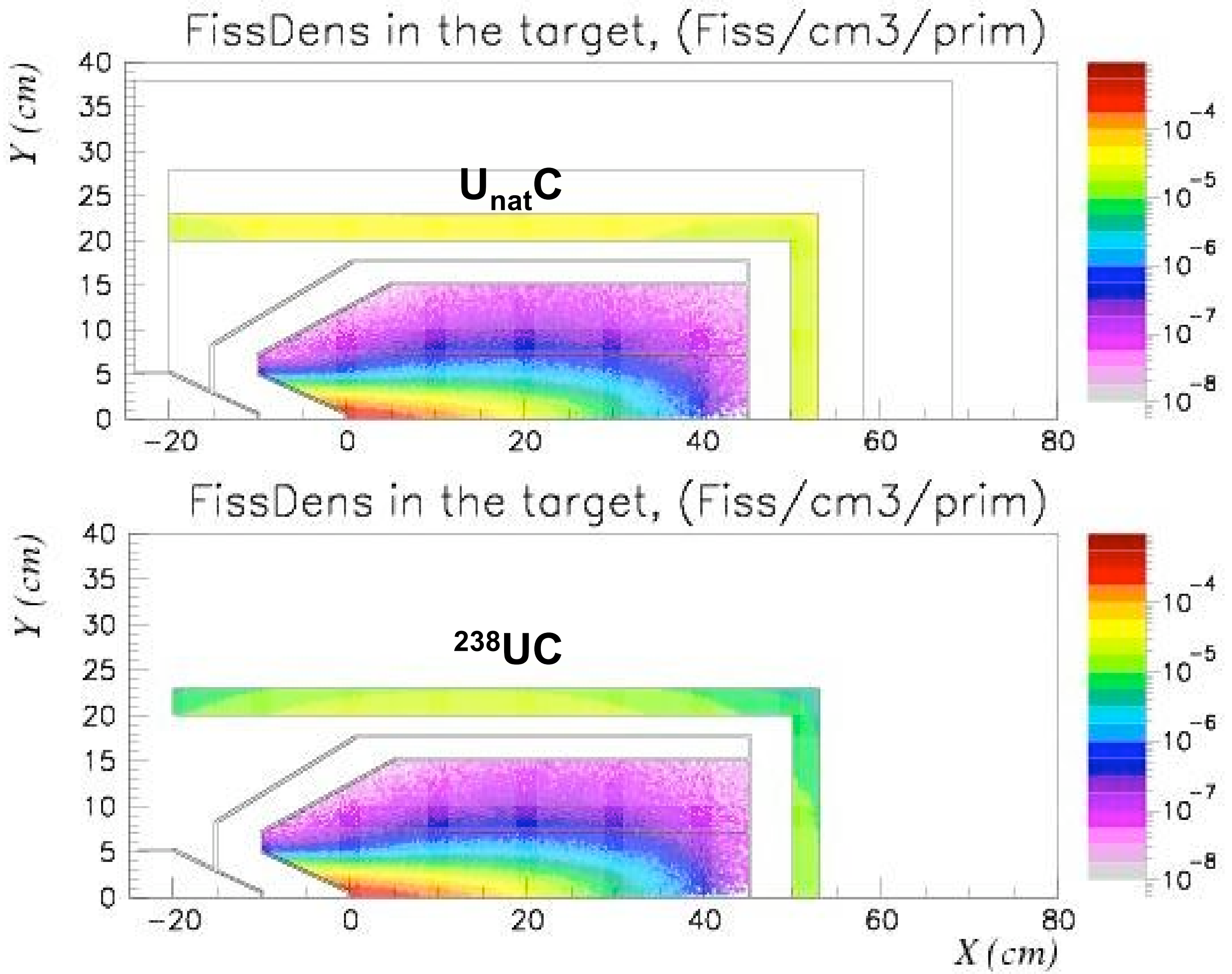
# Fission Density Distribution in $U_{nat}C_3$

- Low-energy fissions (<20MeV) account for 90% of the total fissions in $U_{nat}C_3$ in radial position and only 50% if located downstream of Hg target (harder neutron spectrum)



# Fission Density Distribution: $U_{nat}C$ vs $^{238}UC$

- 3 times more fissions with $U_{nat}C$ compared to $U_{nat}C_3$ (proportional to density)
- With $^{238}UC$ less isotropic distribution and fission yield reduced by factor 3



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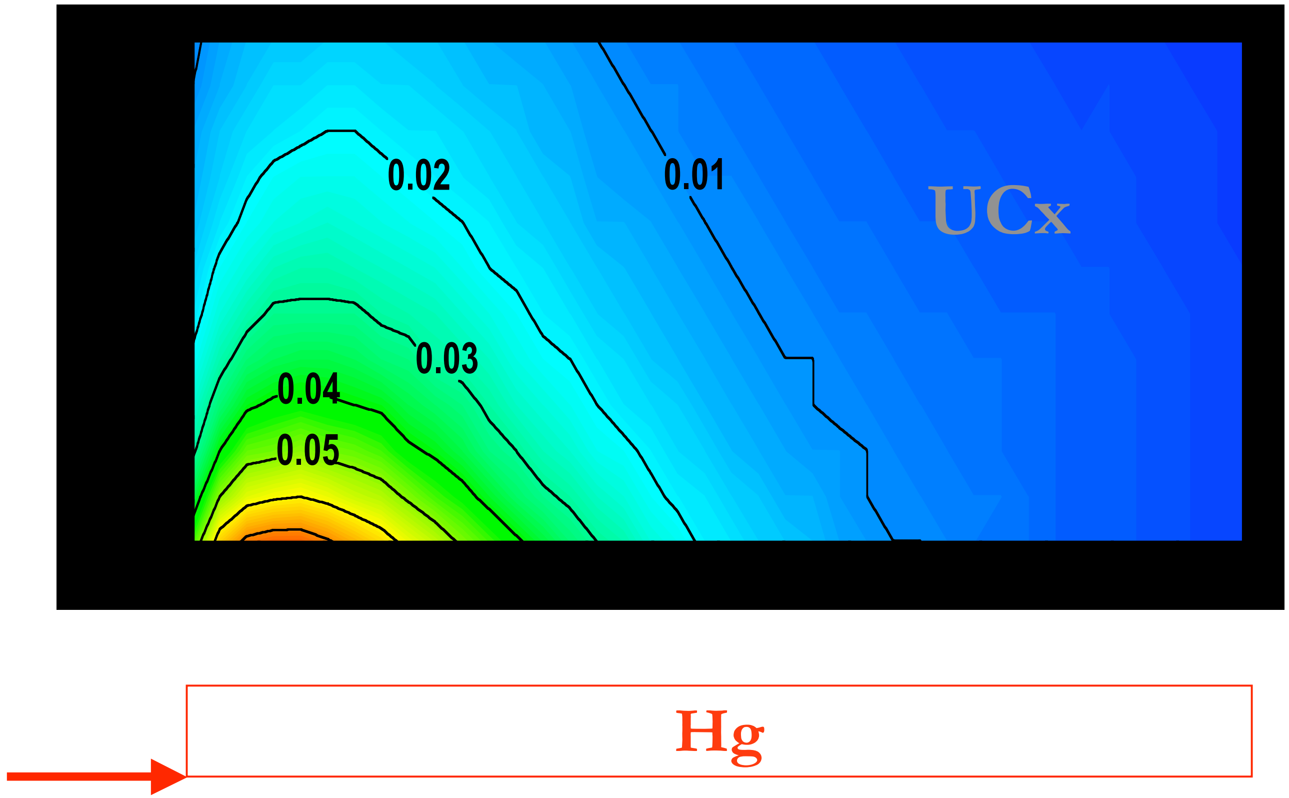
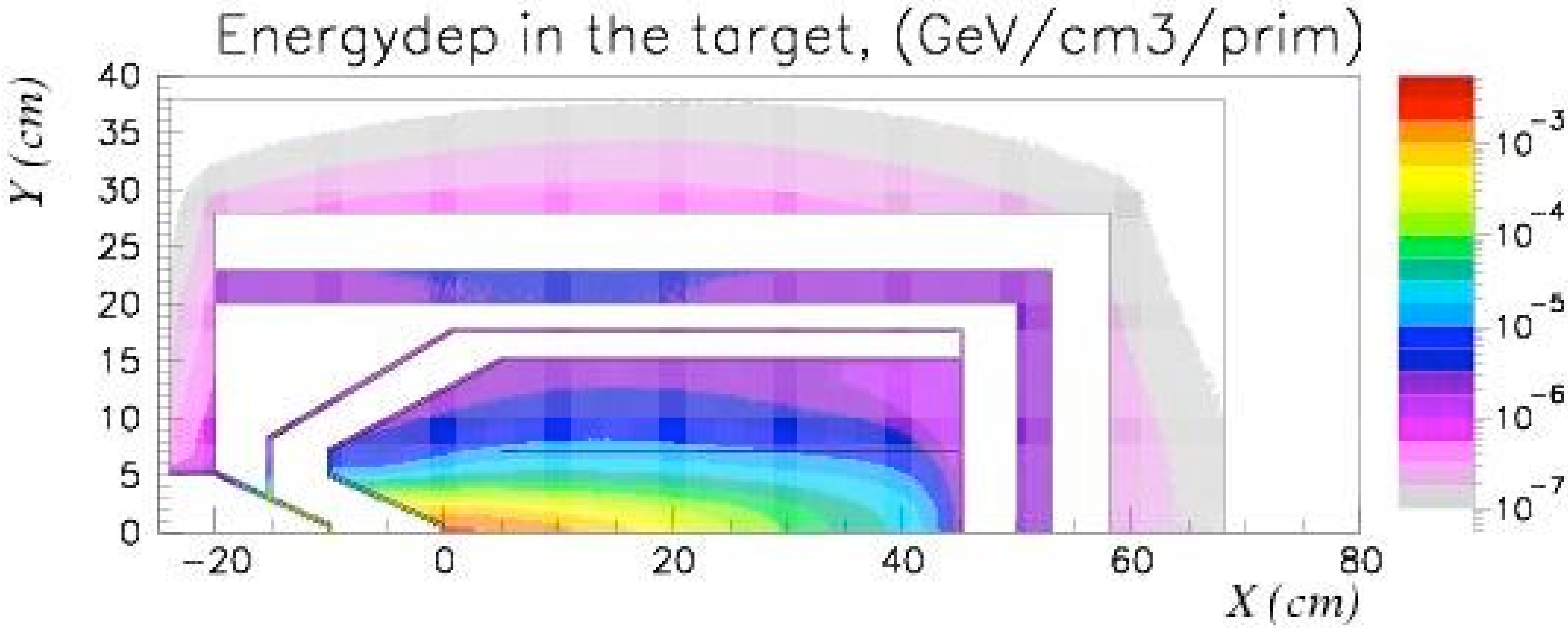



- Fission density (/cm$^3$)

# Energy Deposition (1)



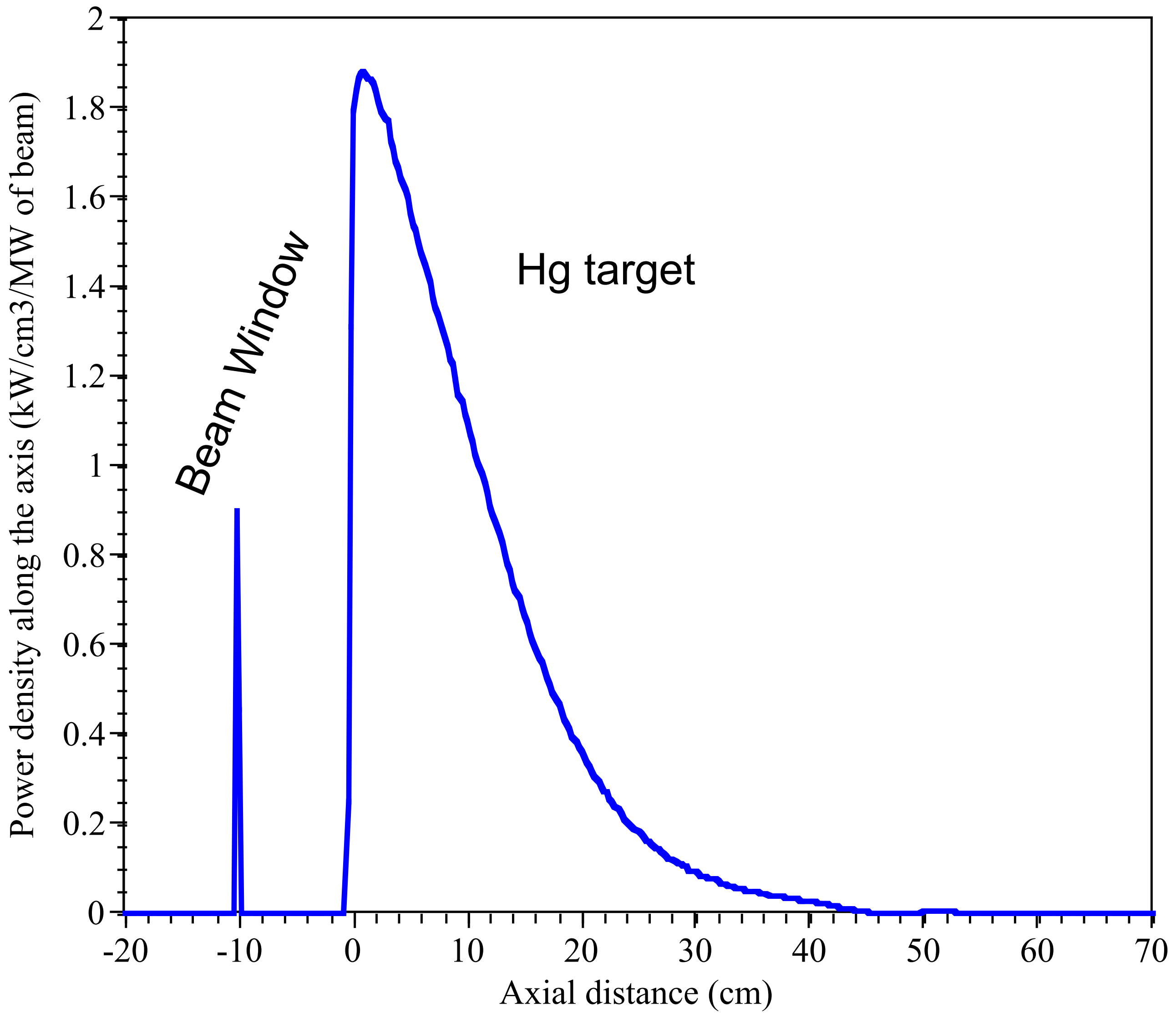

• Maximum energy deposition in the first ~10 cm beyond the interaction point, ~2 kW/cm$^3$/MW of beam

• Energy deposition in UCx target: a few W/cm$^3$/MW of beam

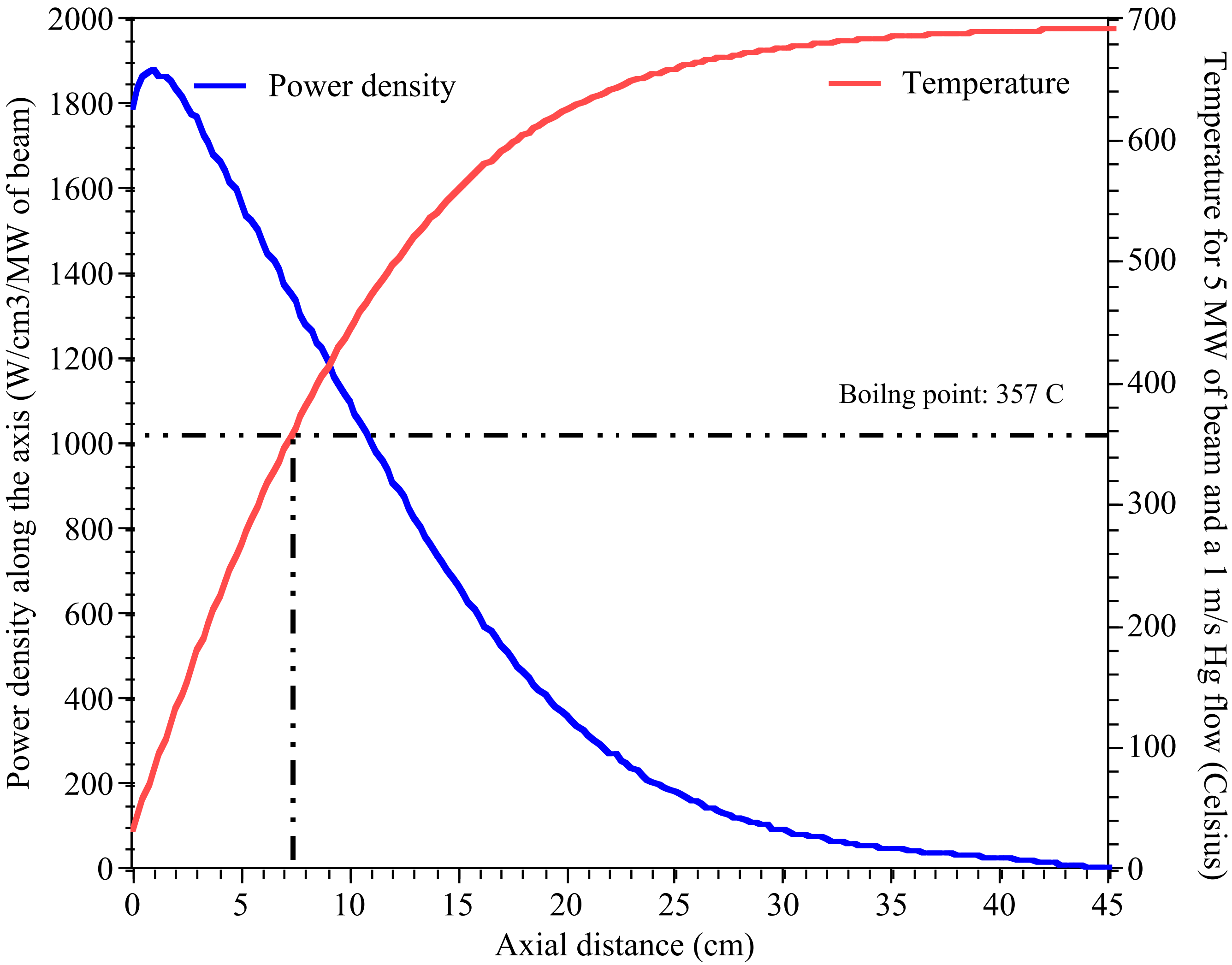
• Energy deposition drops one order of magnitude at the proton range (~46 cm)

• Large radial gradients (dE/dr ~15) in the interaction region

# Energy Deposition (2)



# Energy Deposition (3)




- increasing $\sigma_{beam}$ from 15 to 25 mm or taking parabolic beam of at least 45 mm radius ==> reduce $\Delta T$ in Hg by a factor 2 - 2.5
- doubling the flow rate (~ 2 m/s) will reduce $\Delta T$ by factor 2
- ==> $\Delta T$ ~ 130 - 150 °C

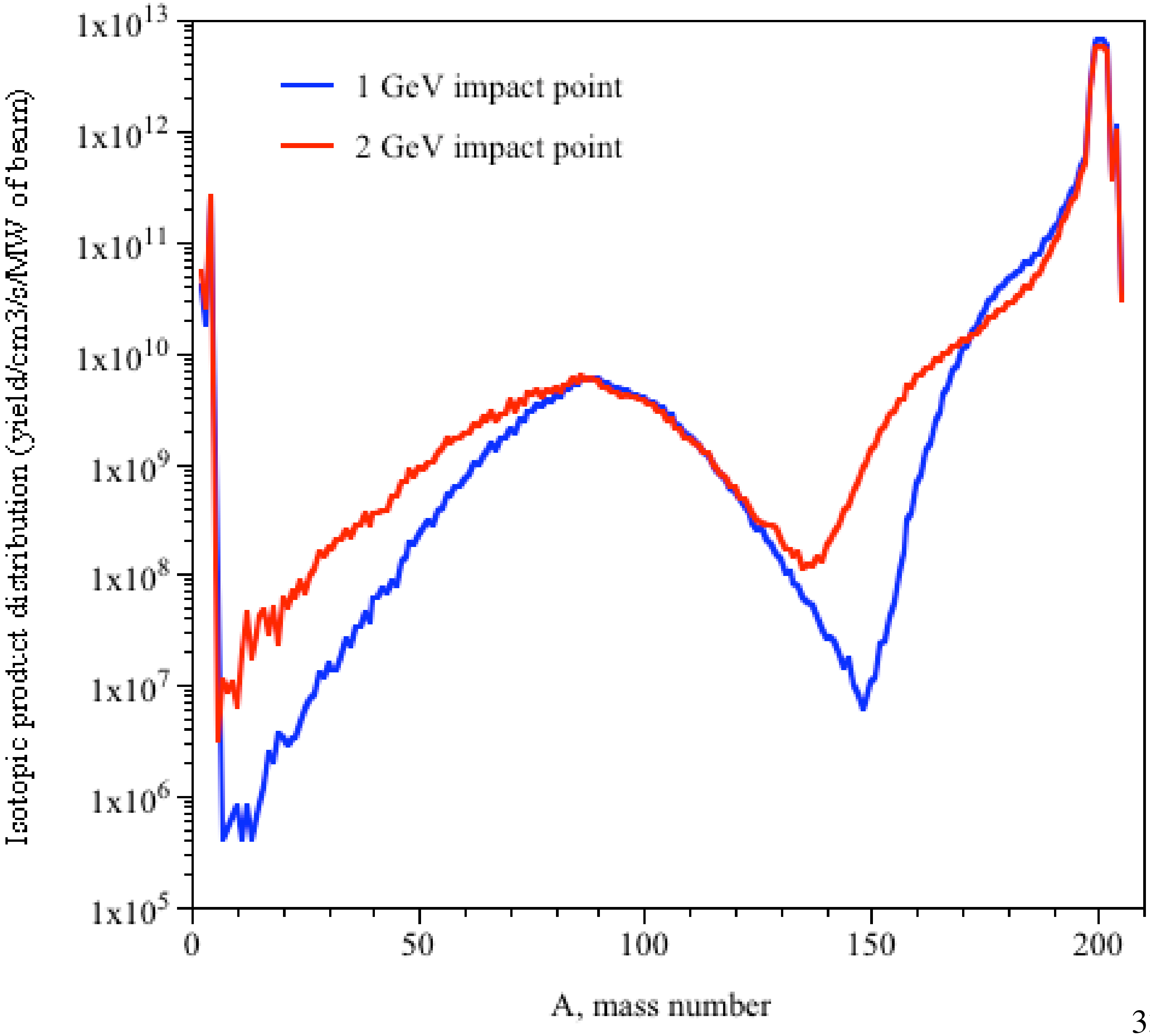
# Residual Nuclei Distributions in Hg

⇨ At high masses it is characterized by the presence of three peaks corresponding to (i) the initial target nuclei, (ii) those obtained after evaporation below and (iii) those obtained after acivation above (A+1)

⇨ Three very narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, $^3$He and a)

⇨An intermediate zone corresponding to nuclei produced by high-energy fissions (symmetric distr.)

⇨ At higher proton energy nuclei from evaporation and multi-fragmentation (ligth nuclei) are more abundant



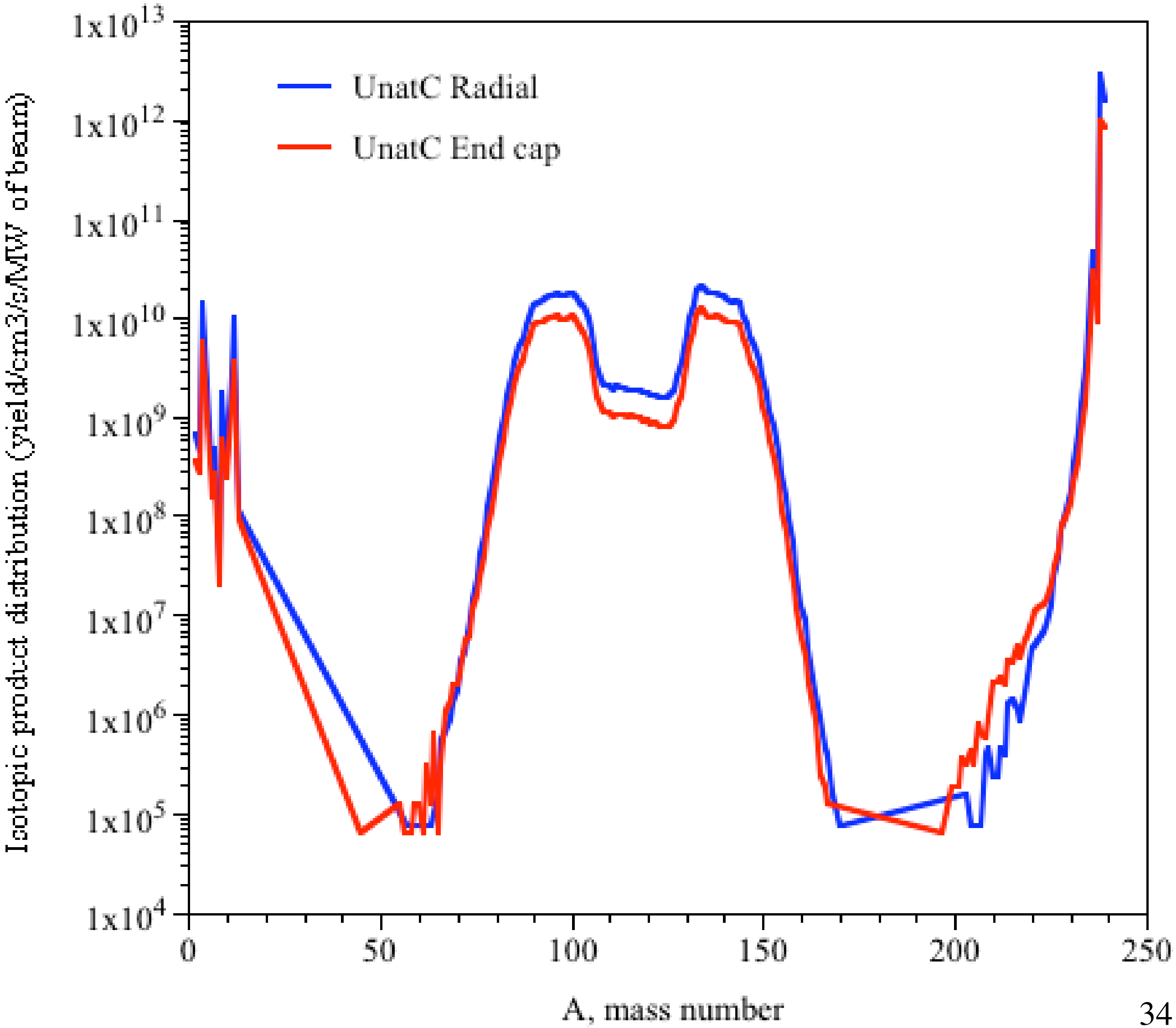
# Radioisotope yields in $UC_x$ targets

⇨ At high masses it is characterized by the presence of acivation products (Pu239 !!) ==> dominates over fission !!

⇨ Three very narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, $^3$He and $\alpha$) ==> very few

⇨An intermediate zone represented double humped distribution corresponding to nuclei produced by low-energy fissions

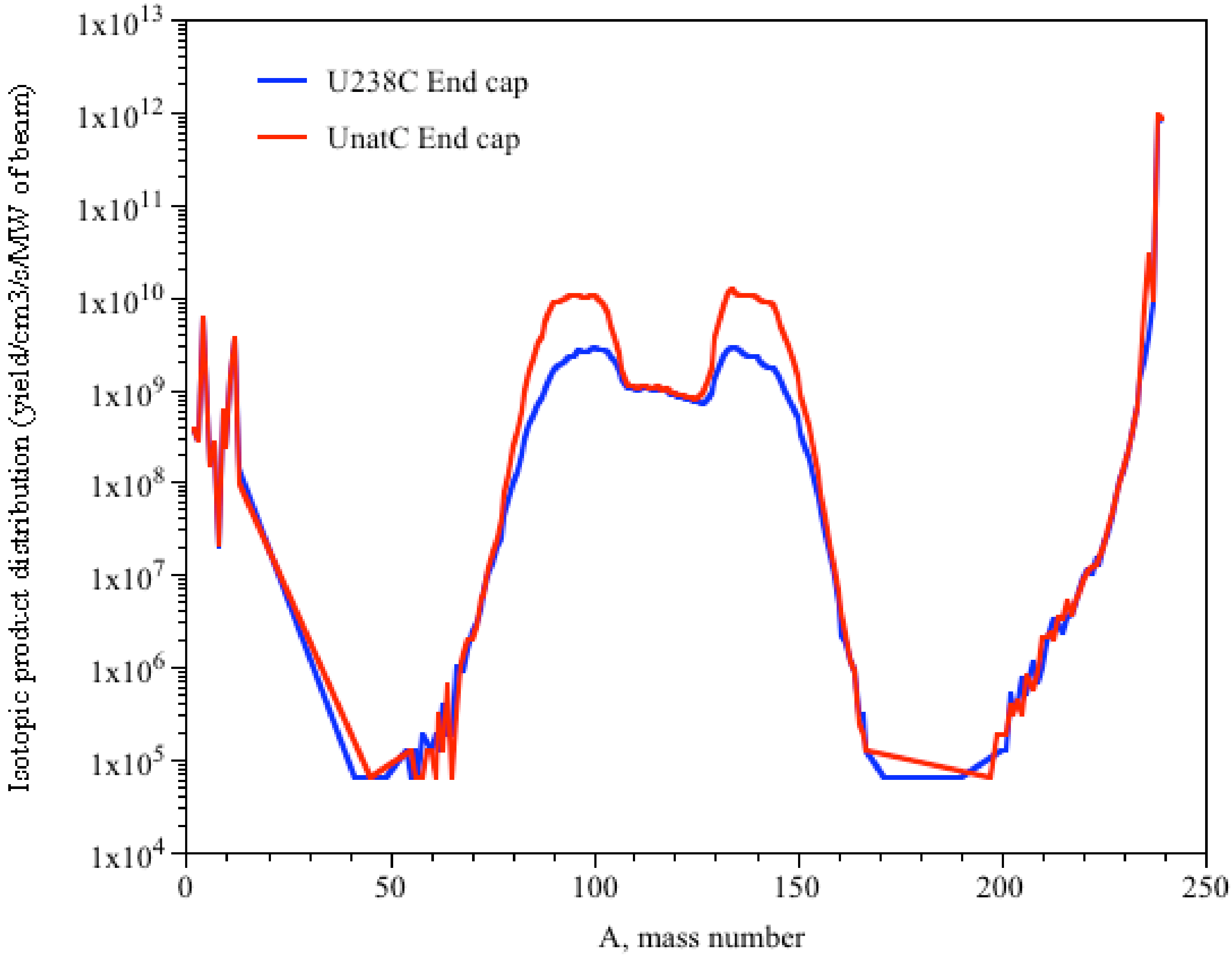
⇨ twice as much fission in radial position



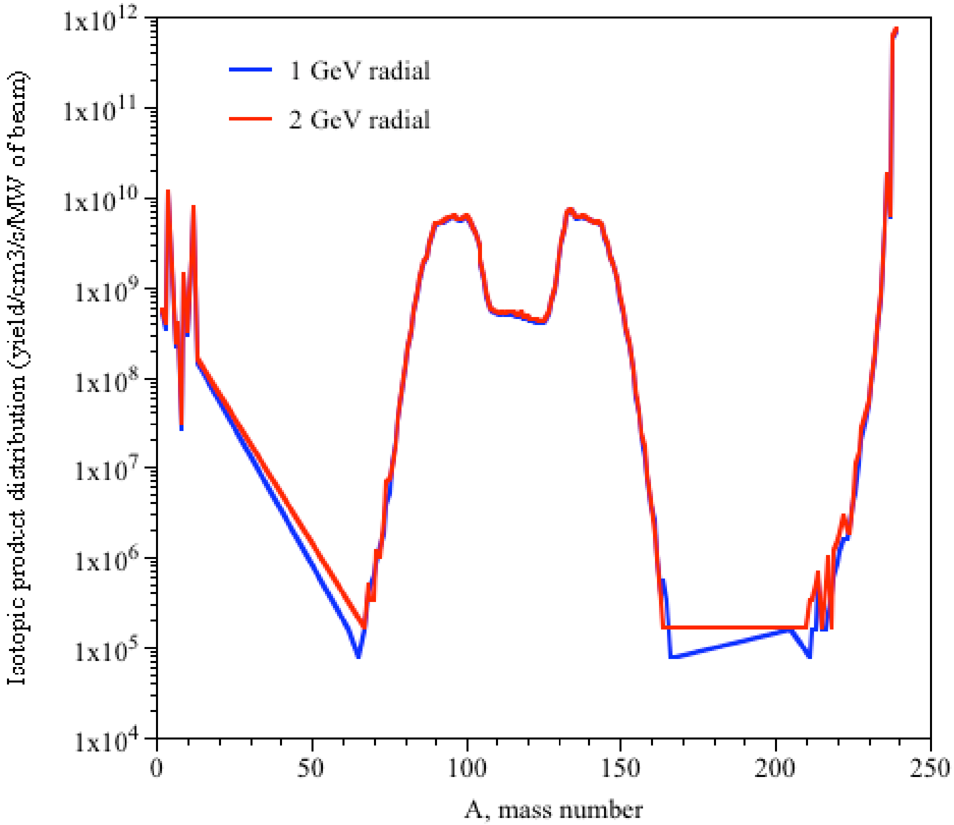
# Radioisotope yields in $UC_x$ targets (2)

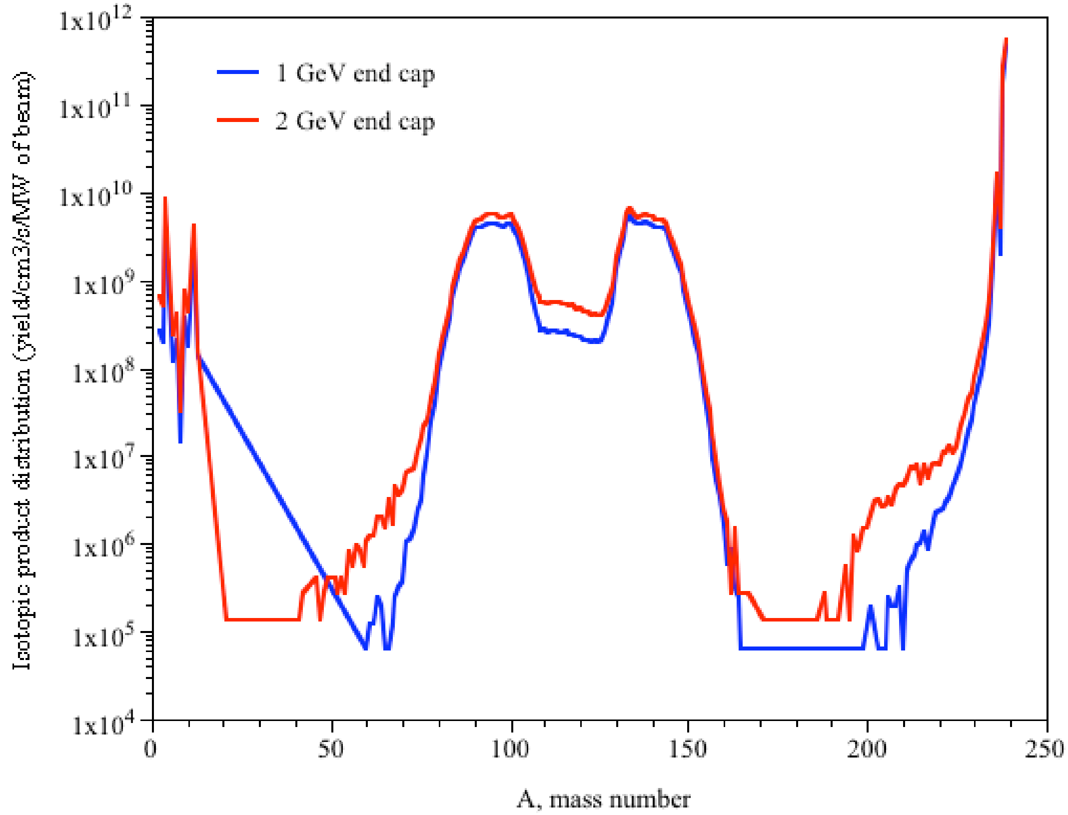
⇨ 5 times less fissions with U238 overall but…

⇨ equal amount of high-energy neutron induced fissions (sym. distribution)



# Radioisotope yields in $UC_x$ targets (3)

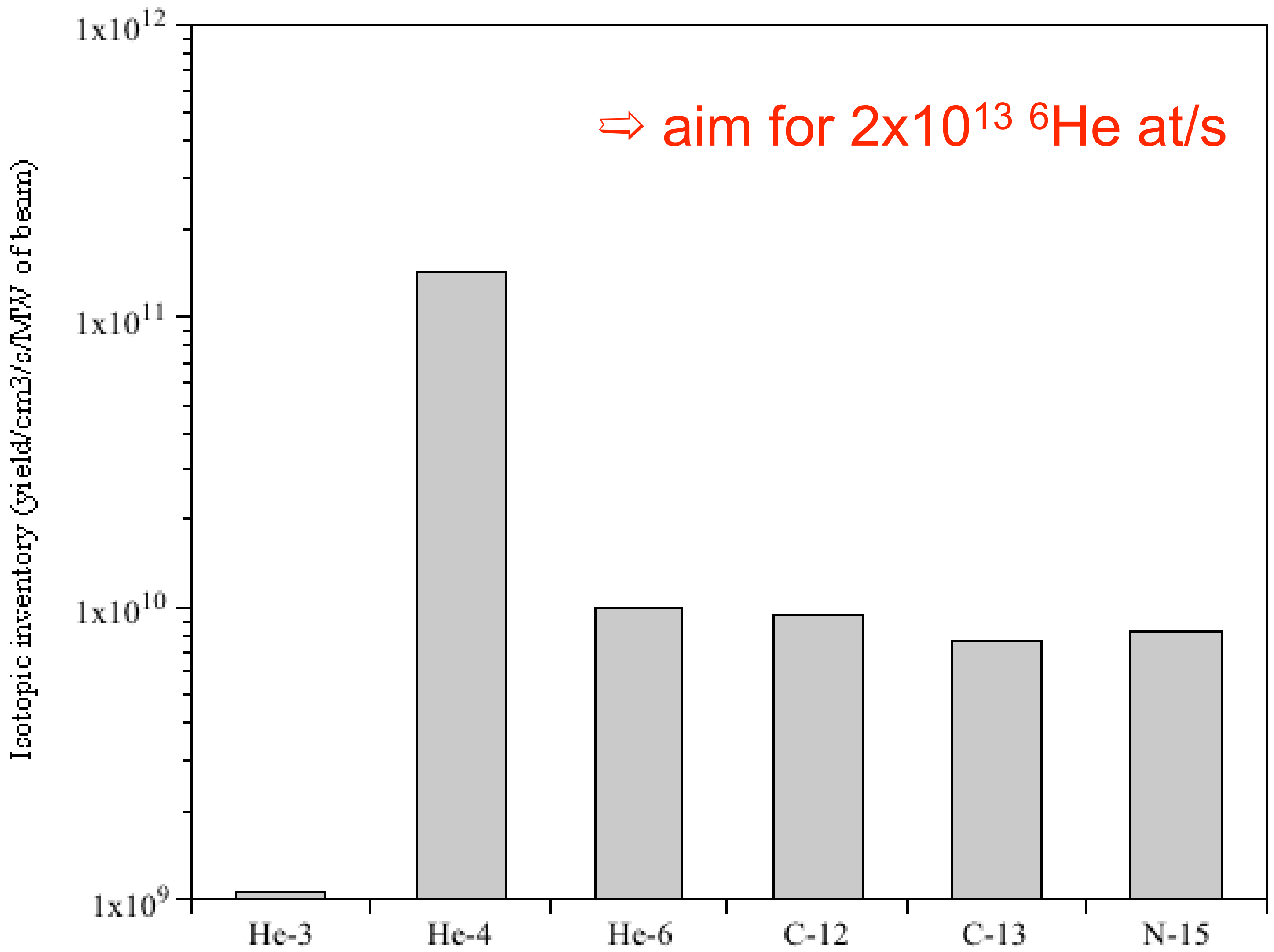



⇨ harder neutron spectrum along the beam axis with 2 GeV protons ==> more high-energy neutron induced fissions and few evaporations

⇨ no differences radially

# Radioisotope yields in BeO target



# Conceptual design of the MMW Hg target

EURISOL
Design Study

## Future Activities

1. Establishment of the operation modes (Hg flow rates, cavitation limits, thermo-mechanical behaviour of the structures under normal operating conditions);
2. Modelisation of transients ==> CW or pulse.
3. preliminary investigation on Hg purification (**Task 2**) and conditioning and disposal (**Task 5**).
4. radioprotection studies related to the MMW target station within **Task 5**.

# The SNS Target Station