EURISOL DS PROJECT

MULTI-MW TARGET DESIGN STUDIES

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on behalf of T2

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Overview

1. Technical Challenges of the EURISOL MMW Target
    - Large Neutron Fluxes and Power Densities
    - Confinement of High-Energy Particles
2. Sensitivity Studies
    - Particle Escapes / Neutron Yields / Power Densities
    - Conclusions: Baseline Parameters
3. Comparison between 1 and 3.5 GeV
    - Primary Particle Flux → Damage and Shielding
    - Neutron Flux and Energy Spectra
    - Fission Densities → Isotopic Yields
    - Energy Deposition → Temperature Increase
4. Conclusions

EURISOL – Multi-MW Target Task

1. The **objective** is to perform technical preparative work and demonstration of principle of a high-power target station for production of Radioactive Ion Beams (RIBs) using a **liquid Hg** proton-to-neutron **converter-target** coupled to a fission target, where the RIBs are generated. This converter is technologically similar to the targets being developed for spallation neutron sources, accelerator-driven systems and neutrino factories.

2. This high-power target will make use of **innovative concepts** that can only be successfully applied in a common effort of several European laboratories within the three communities and their proposed design studies.

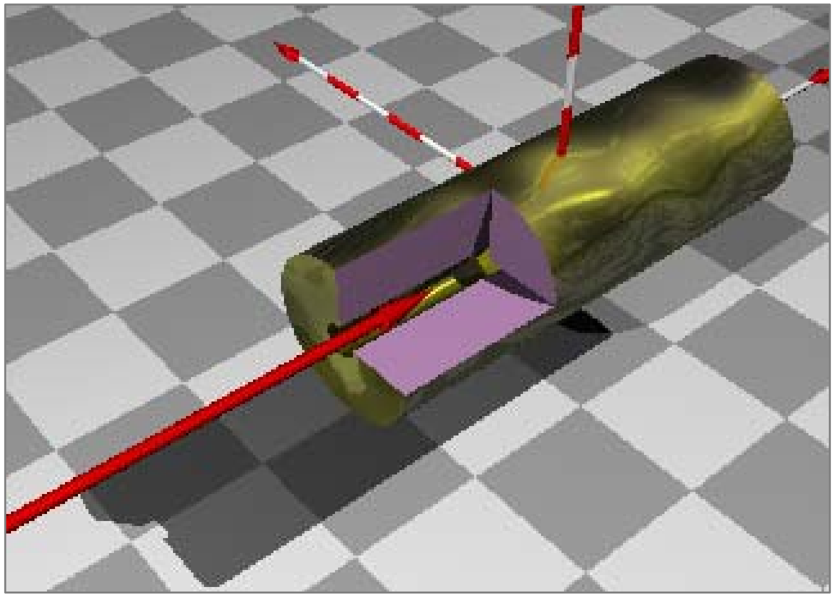
3. In our study, emphasis is put on the most specific item, the **compact window or windowless liquid-metal converter-target** itself, while the design of other aspects of the facility are taken from studies performed by other EURISOL tasks or even from other networks such as ADVICES, IP-EUROTRANS.

Multi-MW Target Challenges

- High-Power Issues
  - Thermal Management
    - Target melting
    - Target vaporization
  - Radiation
    - Radiation protection
    - Radioactivity inventory
    - Remote handling
  - Thermal Shock
    - Beam-induced pressure waves
  - Material Properties

Sensitivity Study

- Projectile Particle: Proton vs. Deuteron
- Beam Shape: Gaussian (1 – 35 mm σ) vs. Parabolic beam
- Energy Range: 1 – 2 – 3 GeV
- Liquid Target Material: Hg vs. LBE
- Target Length: 40 – 60 – 80 – 100 cm
- Target Radius: 20 – 30 – 40 cm
- Spatial and energy particle distribution



- Fission Target Composition: Natural vs. Depleted Uranium

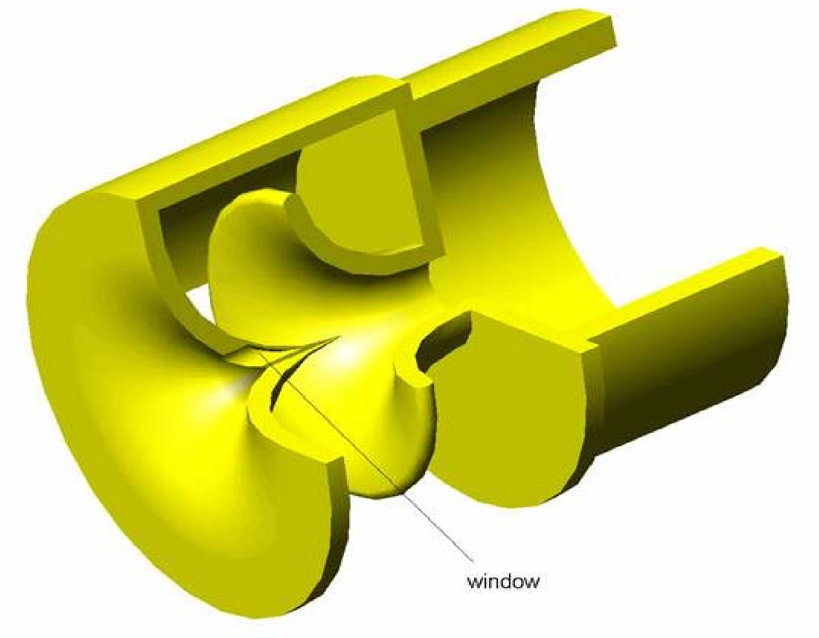
Results of the Sensitivity Study

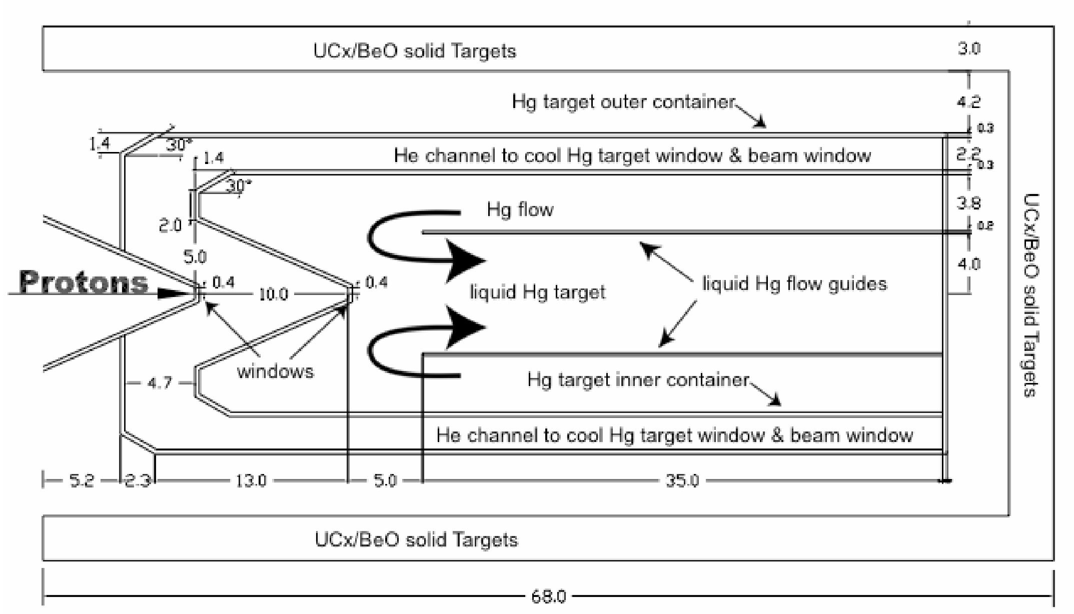
- The use of a **1 or perhaps 2 GeV** proton beam on a compact (~15 cm radius ~50 cm long) Hg target would bring about **important neutron yields** with a reasonable **charged particle confinement**, therefore avoiding the need of a beam dump. The increase in the proton energy up to 2 GeV and use of 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.
- With respect to the use of **deuterons** as projectile, the neutron yield is increased by ~15% but the maximum **power density is increased by ~30%.** This fact and the increasing cost of a deuteron machine may justify the choice of protons.
- Considering these facts, a **baseline design** was proposed, where a 15 cm radius 60 cm long Hg target with a conical void and a cylindrical flow guide was designed, surrounded by a cooling helium tank. Around this converter block, a 3 cm thick ^{nat}UCx fission target was foreseen, together with a beryllium oxide reflector to recuperate the escaping neutrons.

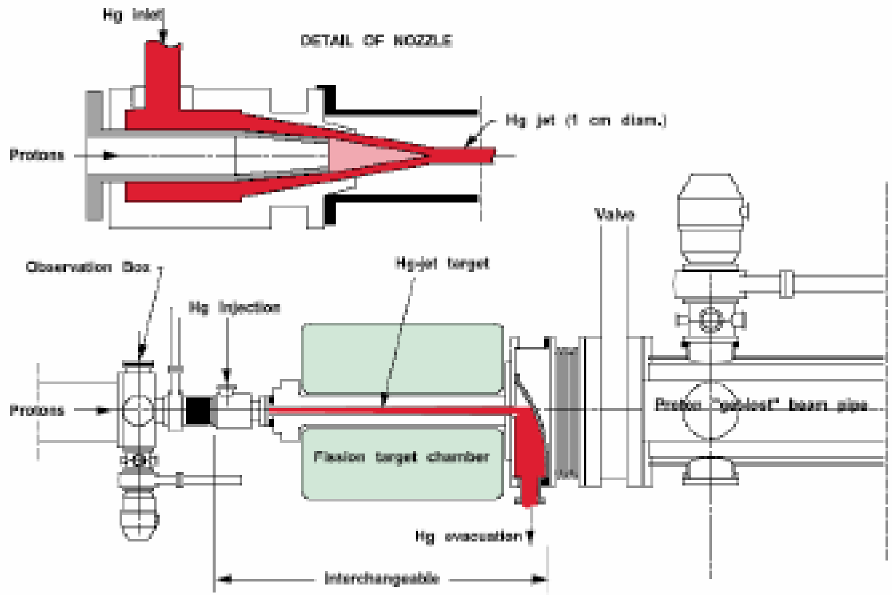
Baseline Parameters of the MMW Hg Target

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**	Deuteron
Beam particle energy	E_{beam}	**GeV**	**1**	≤ 2
Beam current	I_{beam}	mA	4	2 – 5
Beam time structure	-	-	**CW**	Pulsed 50Hz 1ms pulse
Gaussian beam geometry	s_{beam}	mm	15	≤ 25, parabolic
Beam power	P_{beam}	**MW**	**4**	≤ 5
Converter length	l_{conv}	**cm**	**40**	≤ 85
Converter radius (cylinder)	r_{conv}	**cm**	**8**	<15
Hg temperature	T_{conv}	ºC	150 (tbc)	< 357
Hg flow rate	Q_{conv}	kg/s	200 (tbc)	< 3000
Hg speed	V_{conv}	m/s	2 (tbc)	< 30
Hg pressure drop	ΔP_1	bar	tbc	<< 100
Hg overpressure	ΔP_2	bar	tbc	<< 100
UC_x temperature	T_{targ}	ºC	2000	500 – 2500

Alternative 4 MW Target Configurations



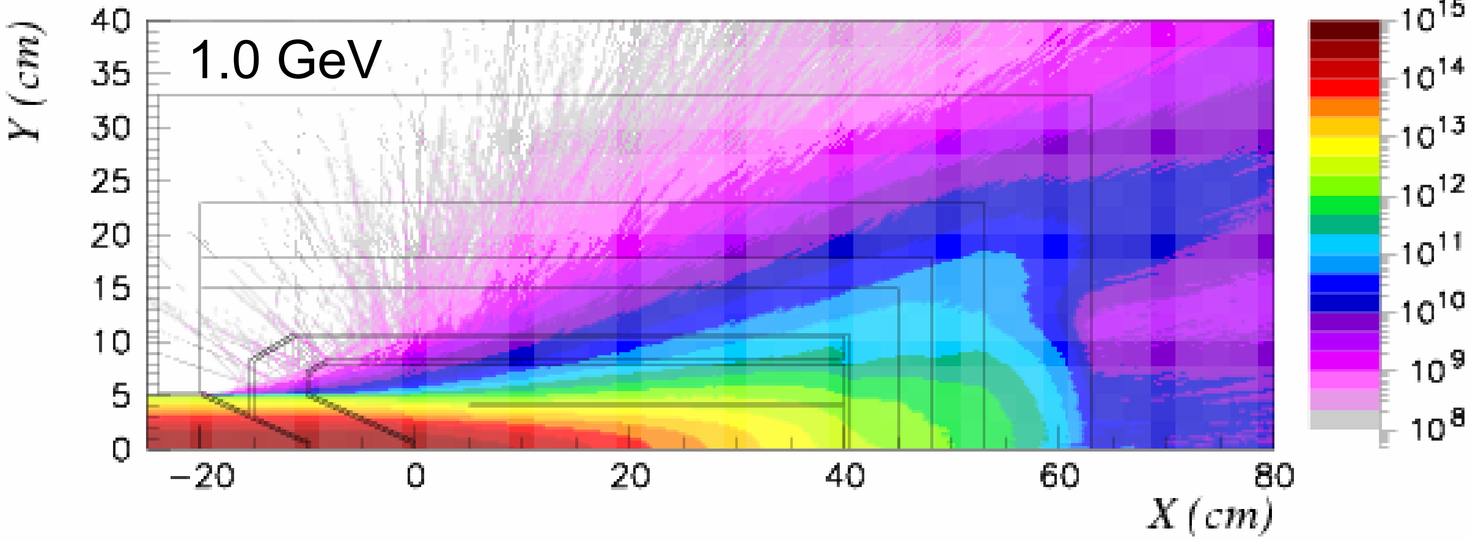


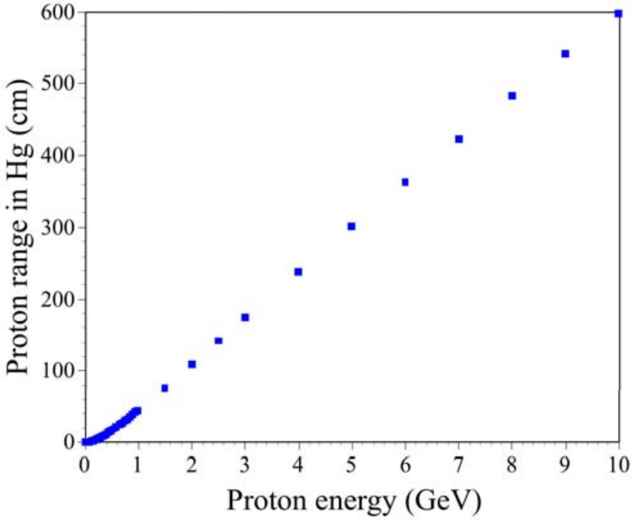


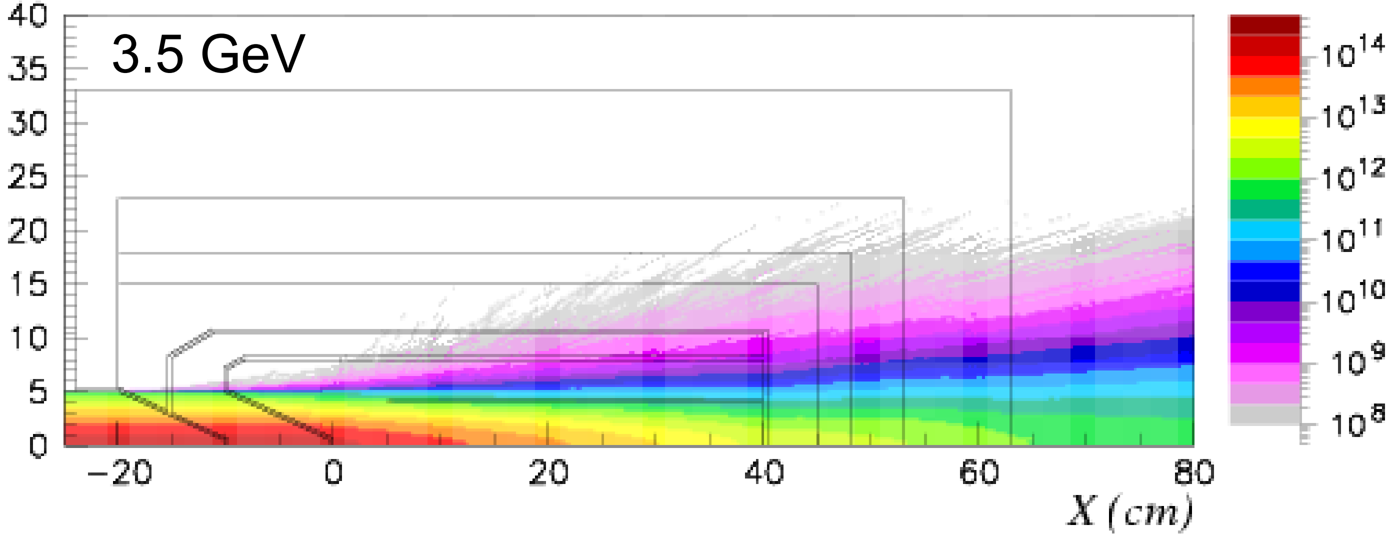
Comparative Study: Primary Flux Distribution

- 1 GeV proton range ~46 cm: acceptable confinement of primary protons inside the target assembly
- 3.5 GeV proton range ~206 cm: Important HE primary escapes (~10^{12} prim/cm^2/s/MW of beam, **~5% of the beam**), very forward peaked. Need for a larger target or a **beam dump**

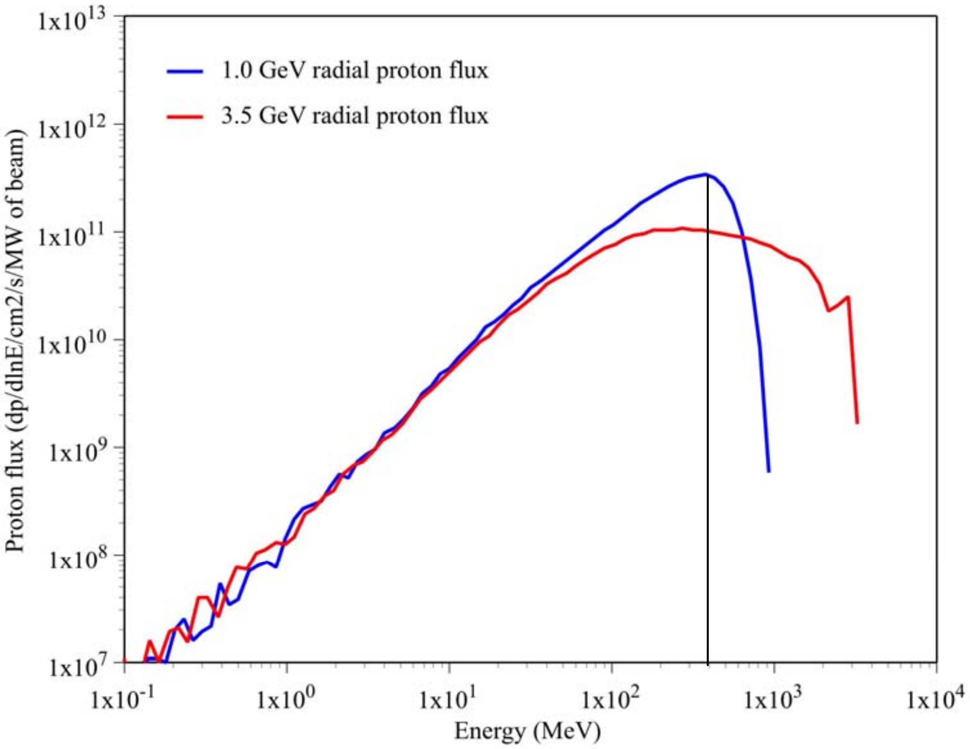
Primary flux (prim/cm^2/s/MW of beam)

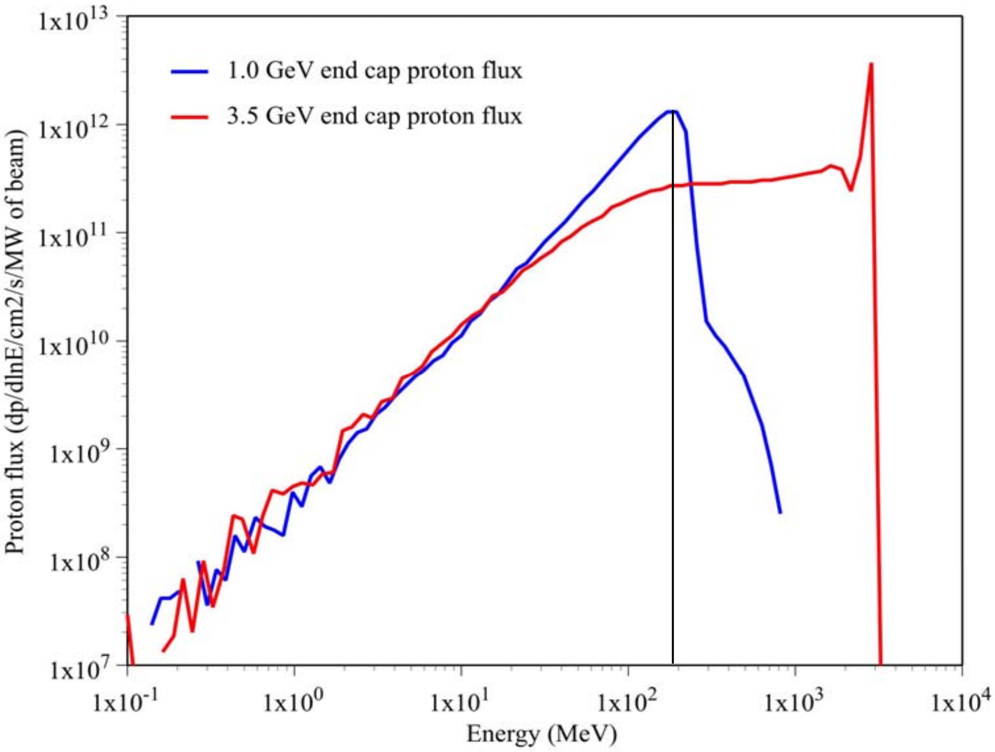






Primary Escapes Energy Spectra



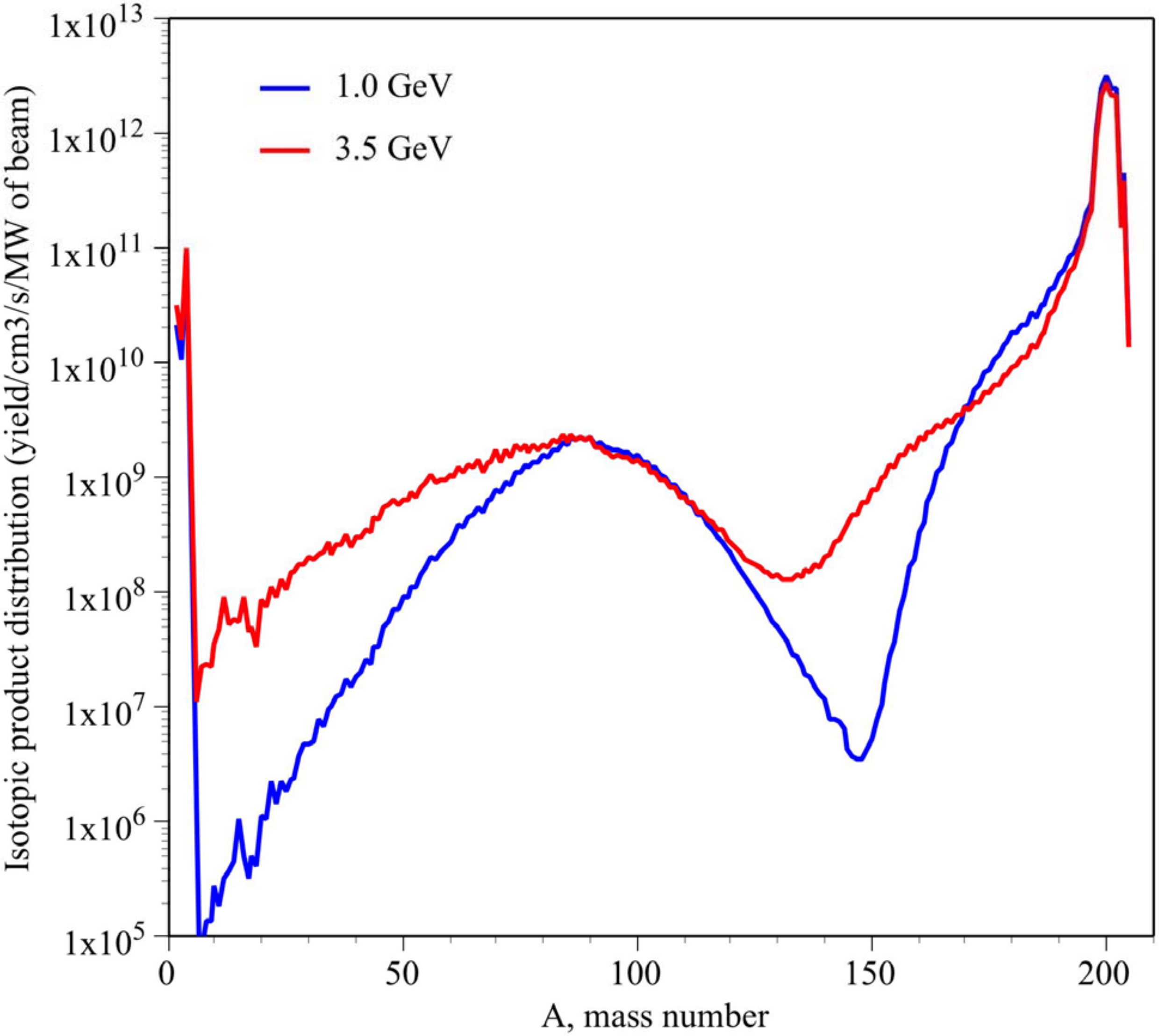


- Average energies of the primary radial escapes: 270 MeV and 480 MeV (for 1 and 3.5 GeV protons, respectively)
- Through the end cap: 140 MeV for 1 GeV and **1.4 GeV (!!)** for 3.5 GeV primaries
- **90%** of the escaping protons are above 100 MeV for a 3.5 GeV beam

Residual Nuclei Distributions in Hg

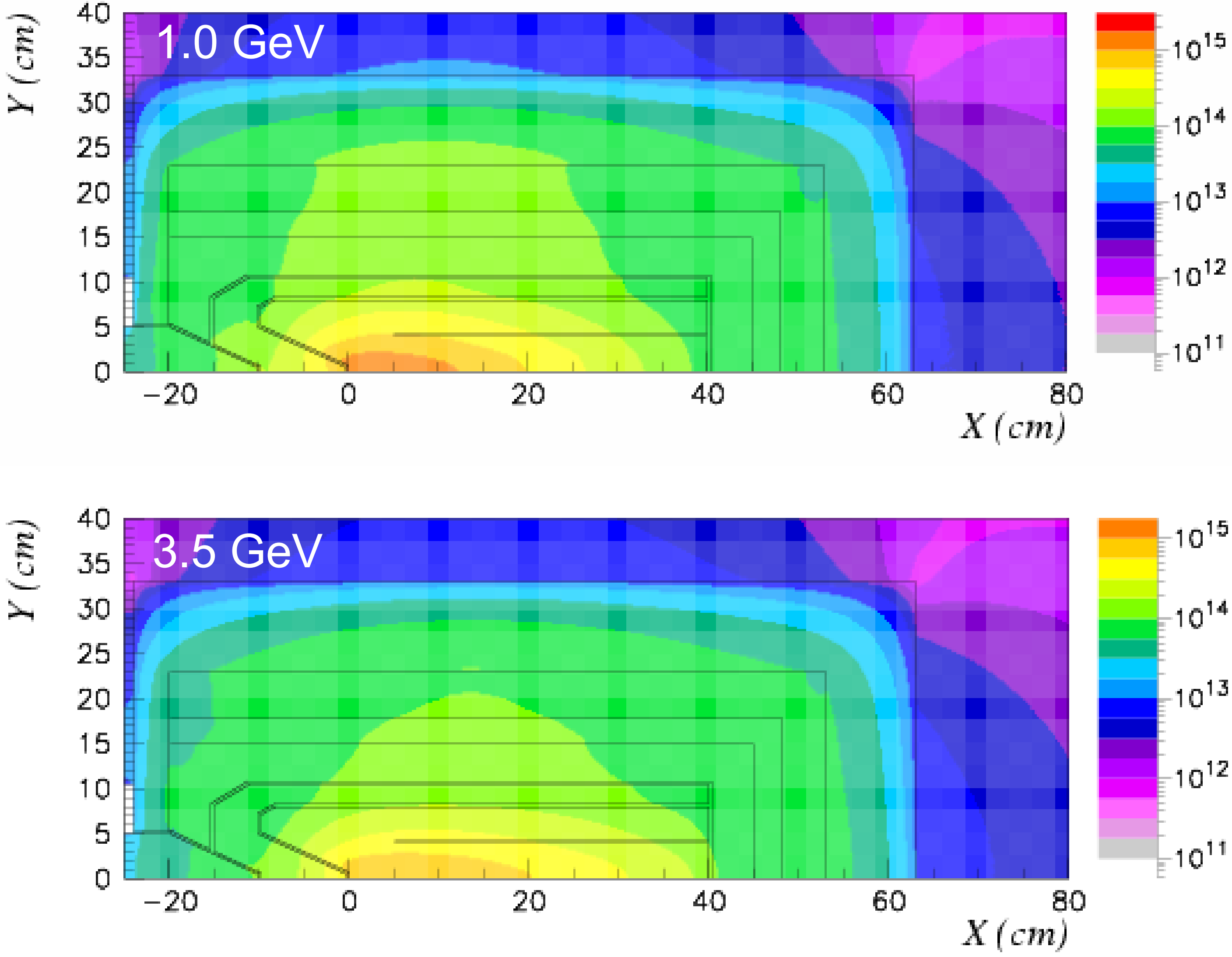
EURISOL Design Study

- 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 activation above (A+1)
- Three very narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, ^{3}He and α)
- An intermediate zone corresponding to nuclei produced by high-energy fissions (symmetric distr.)
- At higher proton energy nuclei from evaporation and multi-fragmentation (light nuclei) are more abundant

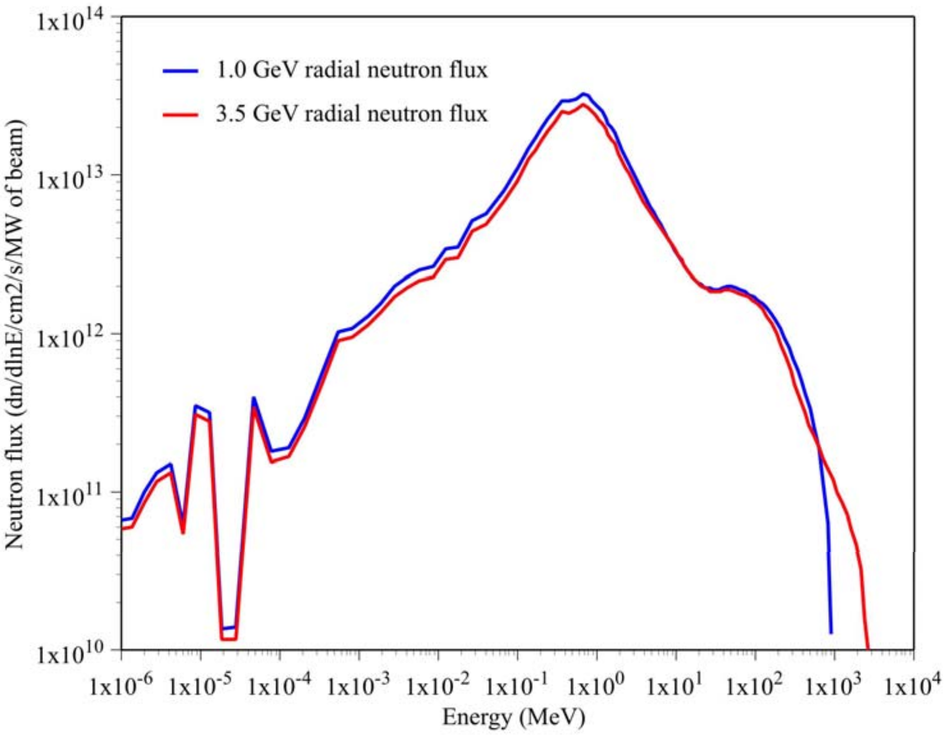


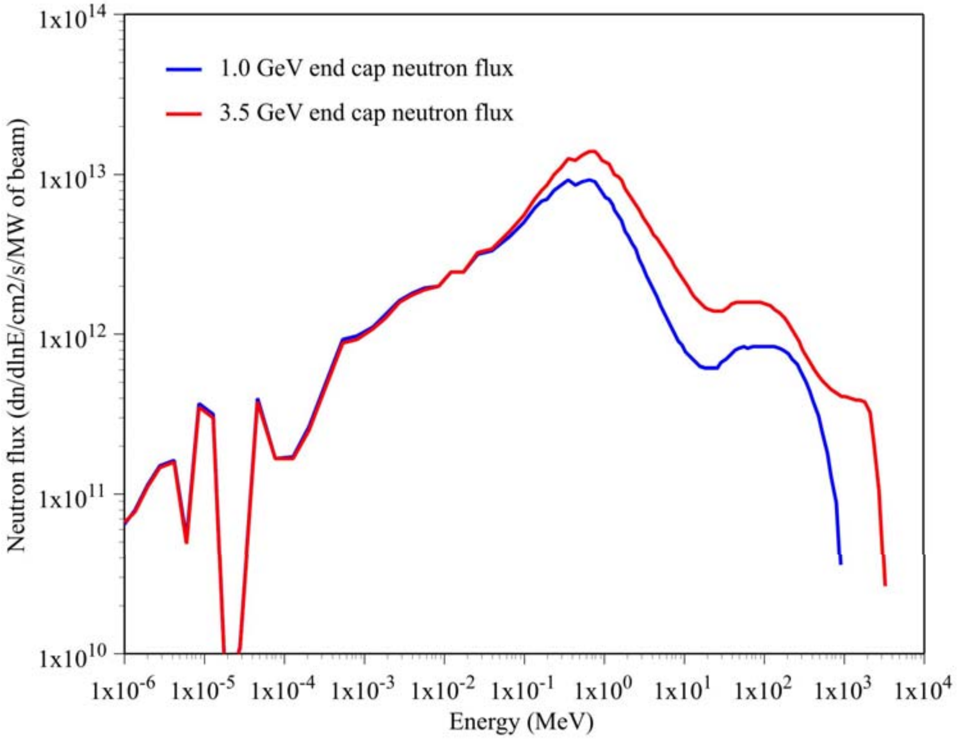
Neutron Flux Distribution

- Neutron fluxes in the fission target ~10^{14} n/cm^2/s/MW of beam
- Spallation neutrons produced over a larger volume
- Neutron flux still dominated by neutrons below 20 MeV


Neutron flux (n/cm^2/s/MW of beam)

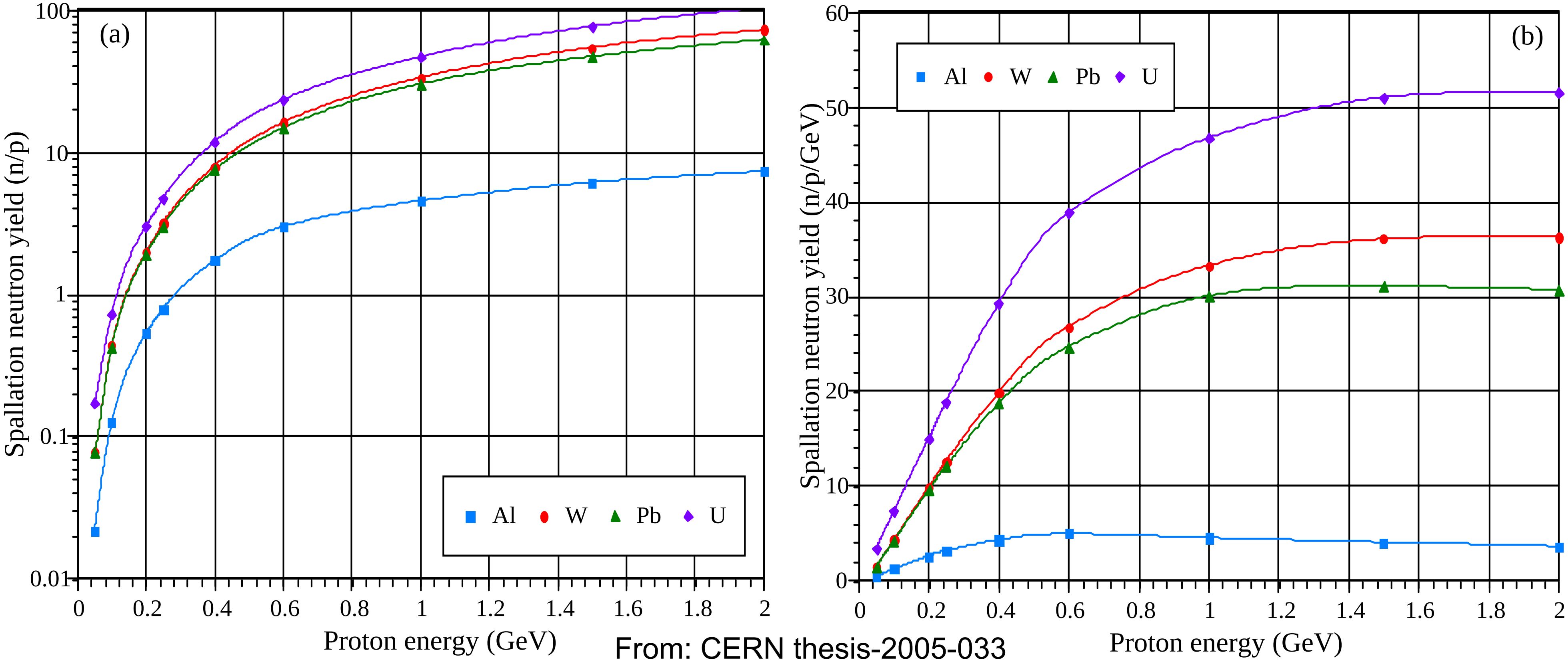
Neutron Energy Spectra





- Small differences in the neutron flux spectrum radially, except for the very high-energy tail from direct nucleon interaction
- Larger HE (10 MeV – 3 GeV) neutron flux exiting the end cap, producing spallation (neutron source displacement) and structural damage (dpa) in the downstream structures (e.g. fission target, reflector…)

Spallation Efficiency



From: CERN thesis-2005-033

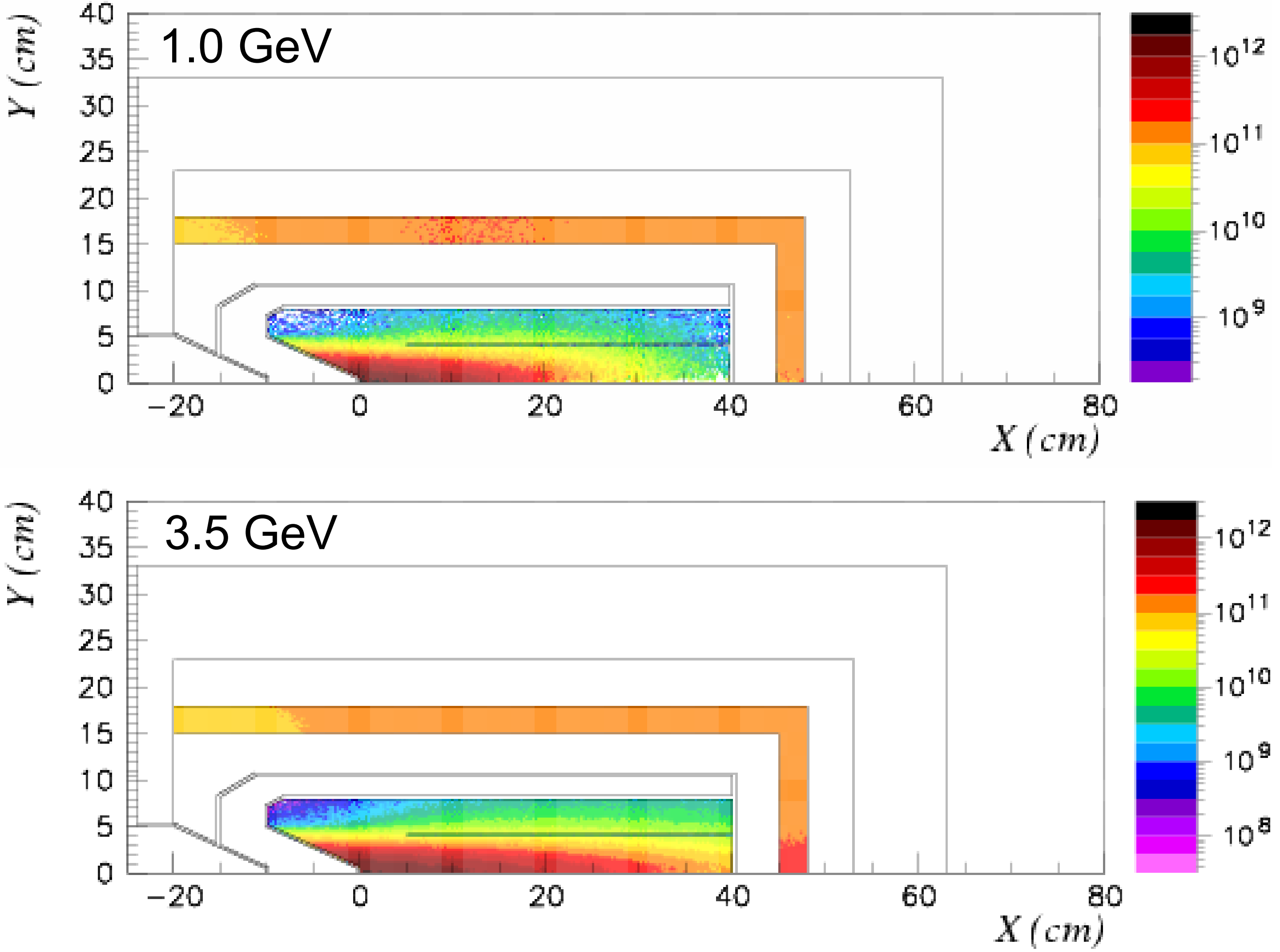
- Spallation neutron yields rapidly increasing with energy up to 600 MeV, slowly increasing above those energies
- Spallation efficiency (Figure b) reaching a maximum between 1 and 2 GeV (depending on the spallation target material), decreasing beyond these energies due to competing reactions (i.e. π-production)

Fission Density Distribution in $U_{nat}C_3$

- Similar fission densities in the radial region (10^{11} fiss/cm^3/s/MW), with slightly more fissions in the 1 GeV case

- In the 3.5 GeV case (possibly HE) fission density peak in the beam axis

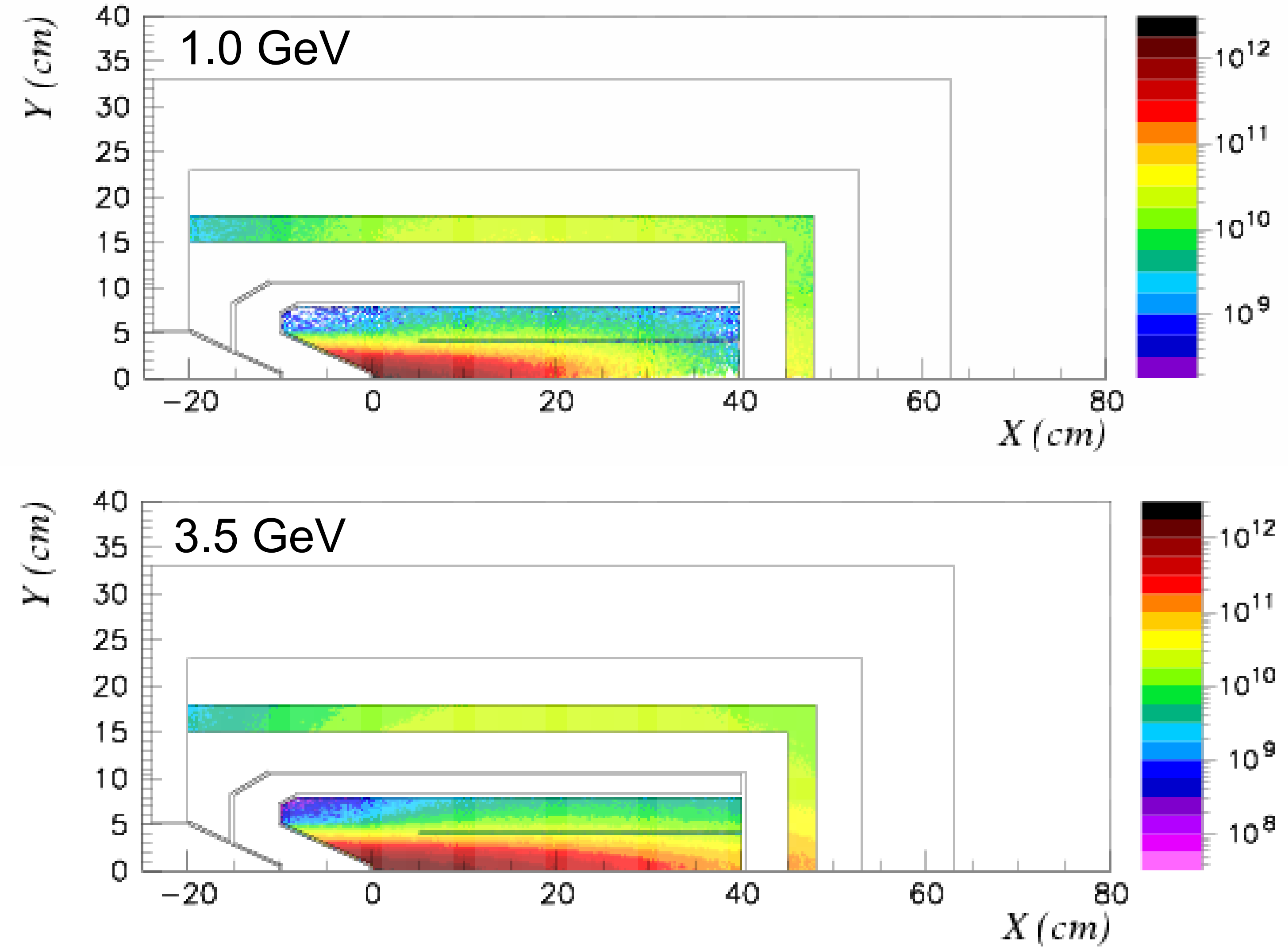
Fission density (fissions/cm^3/s/MW of beam)



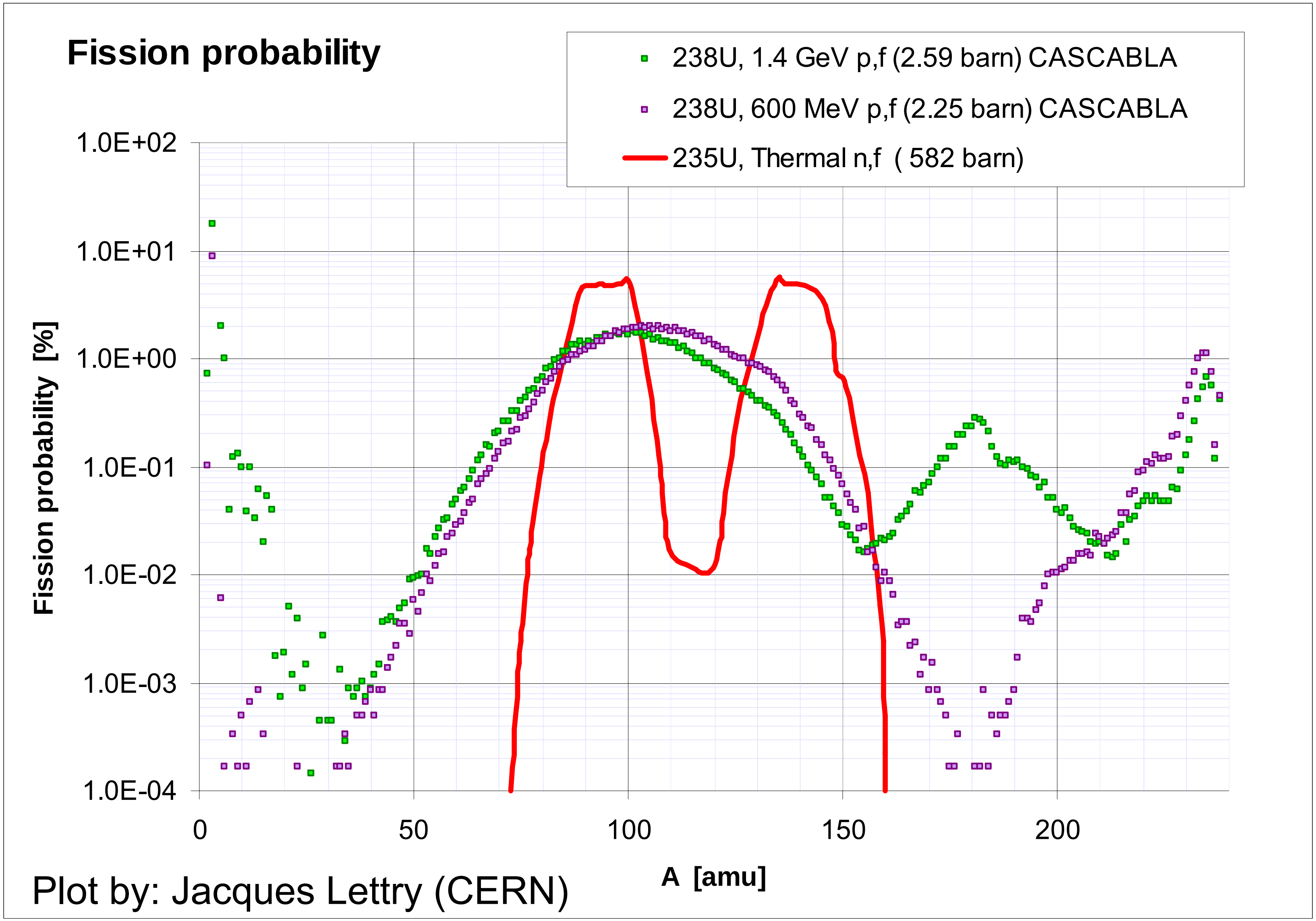
HE Fission Density Distribution in $U_{nat}C_3$

- Non-homogenous HE fissions in both cases
- Similar behaviour radially, but 10 times more HE fissions in the beam axis, with a large gradient
- Impact in terms of ion yields…

HE fission density (fissions[>20 MeV]/cm^3/s/MW of beam)

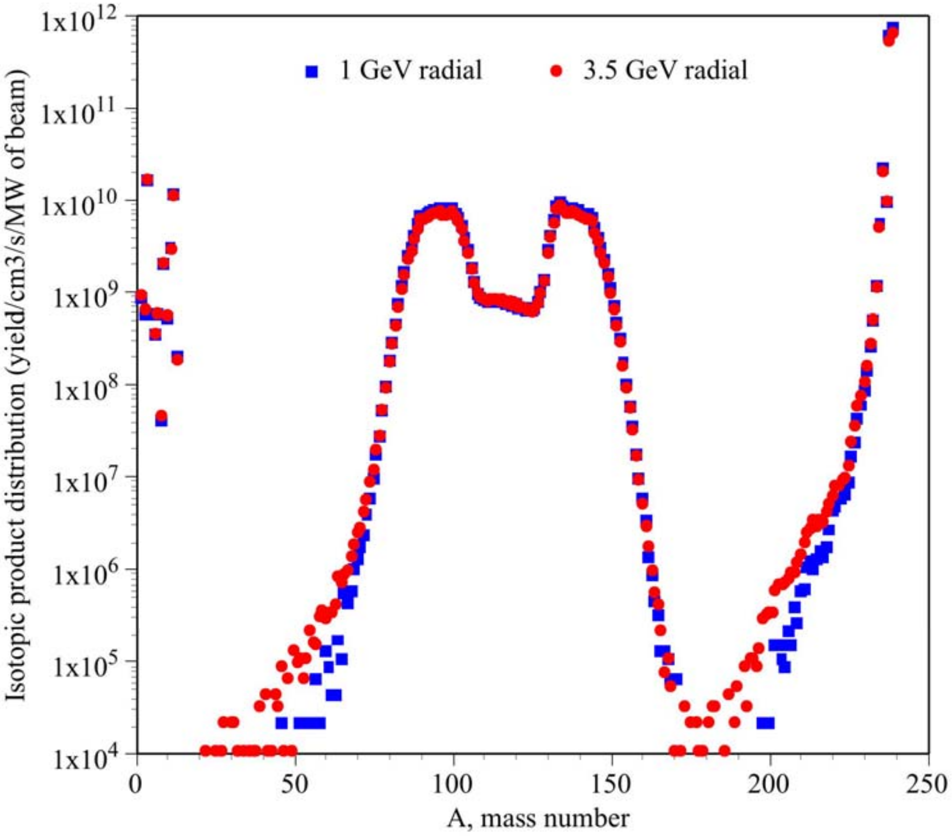


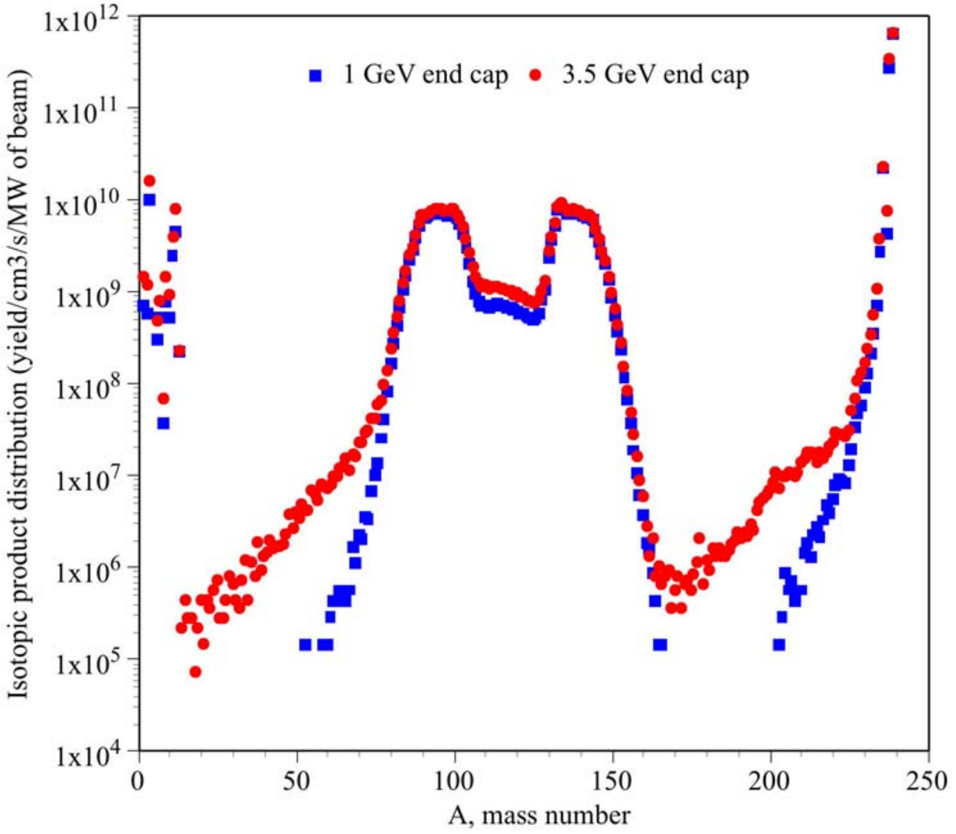
p or n_{fast} vs. n_{th} Induced Fissions



Plot by: Jacques Lettry (CERN)

Radioisotope Yields in $U_{nat}C_3$ Target





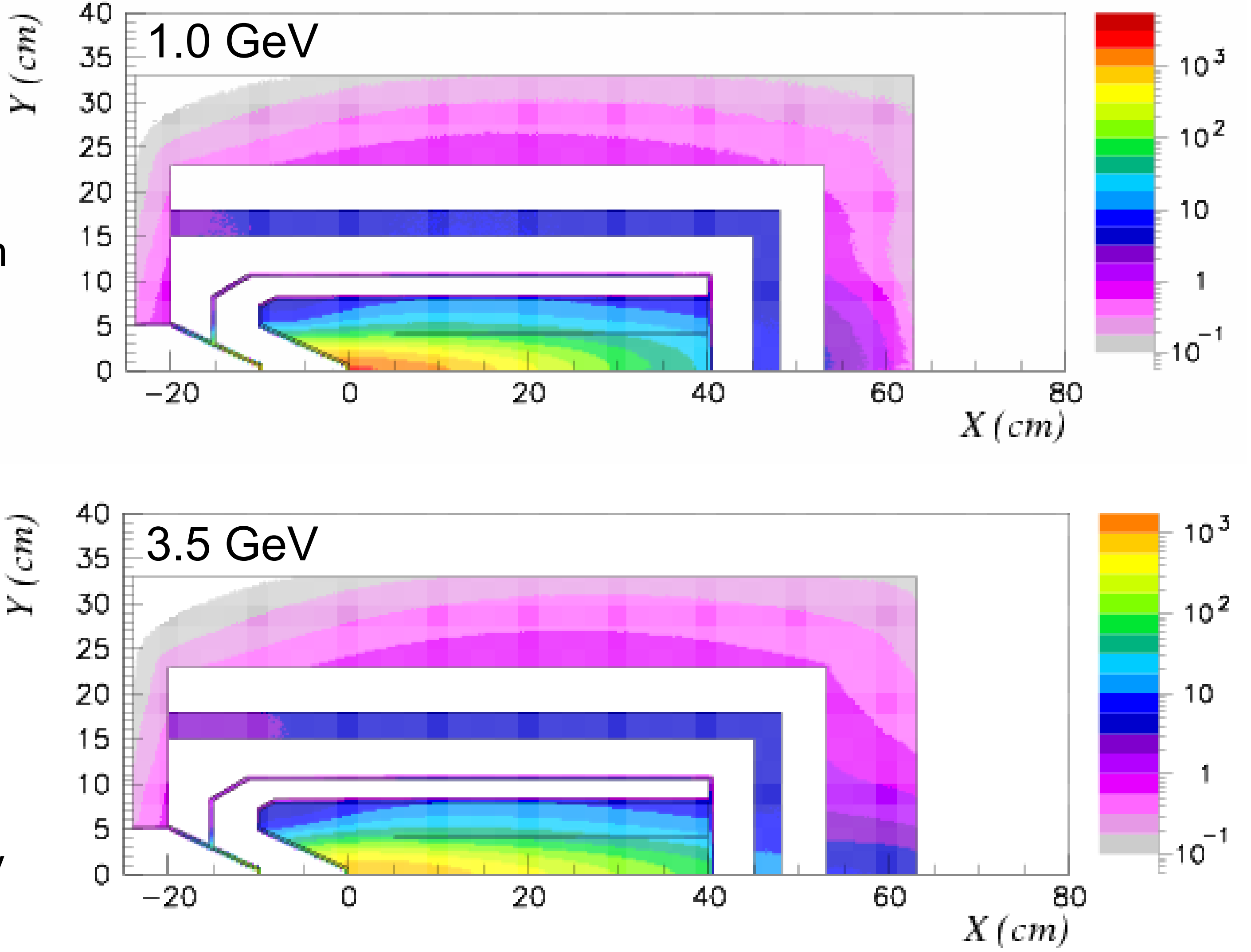
Harder particle (proton and neutron) spectrum in the case 3.5 GeV primaries → more high-energy neutron-induced fissions and spallation → increase in the symmetrical fission products plus spallation products →production of isobars from combined reactions and projectile energies

Small differences in terms of asymmetrical (low-energy) fission fragments

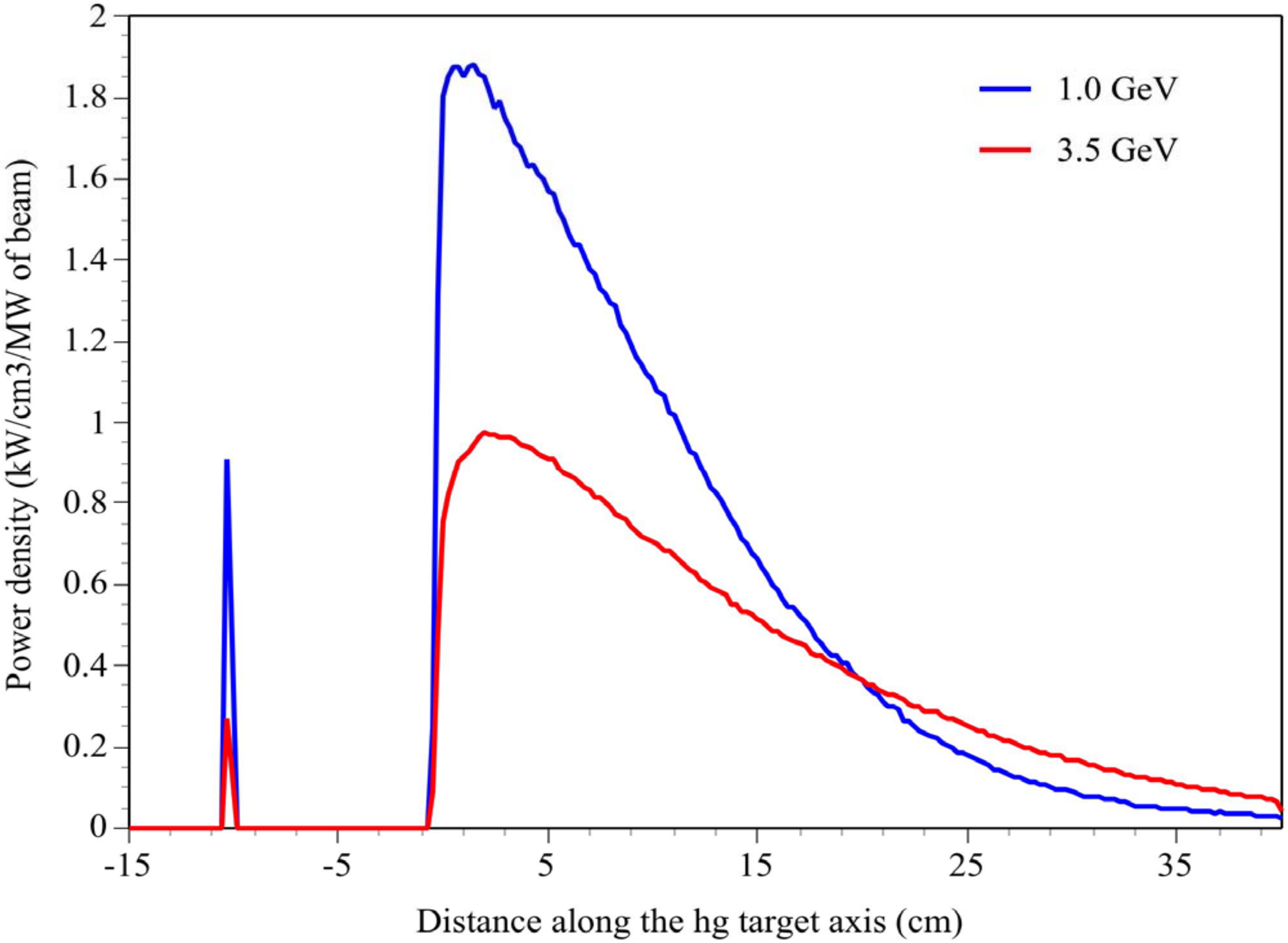
Power Densities (I)

- Maximum energy deposition in the first 10 cm beyond the interaction point, in Hg
- In the 1 GeV case: maximum power density in Hg: ~2 kW/cm^3/MW of beam
- 50% reduction in maximum power density (to ~1 kW/cm^3/MW of beam) if 3.5 GeV protons are used
- Power density in the $U_{nat}C_3$ target: ~5 W/cm^3/MW homogenously distributed in both cases

Power density (W/cm^3/MW of beam)



Power Densities (II)



- Factor of 2 reduction in the maximum power density in Hg, for 3.5 GeV
- **Factor of 3.6 reduction** in the power deposited in the beam window, for 3.5 GeV (28% of the energy deposited in the case of 1 GeV protons)

Conclusions and Synergies

- Increasing difficulties in **confining the incident particle** beam with energy → A 3.5 GeV proton beam on a compact spallation target requires a **beam dump** and special attention to the **displaced neutron source** (structural **damage** and **radioprotection** hazard)

- No increase in the spallation neutron yields or fission densities for 3.5 GeV protons, but a larger **Hg target activation**; power densities of ~1 kW/cm^3/MW of beam for this energies, **~50% lower** than in the case of 1 GeV protons

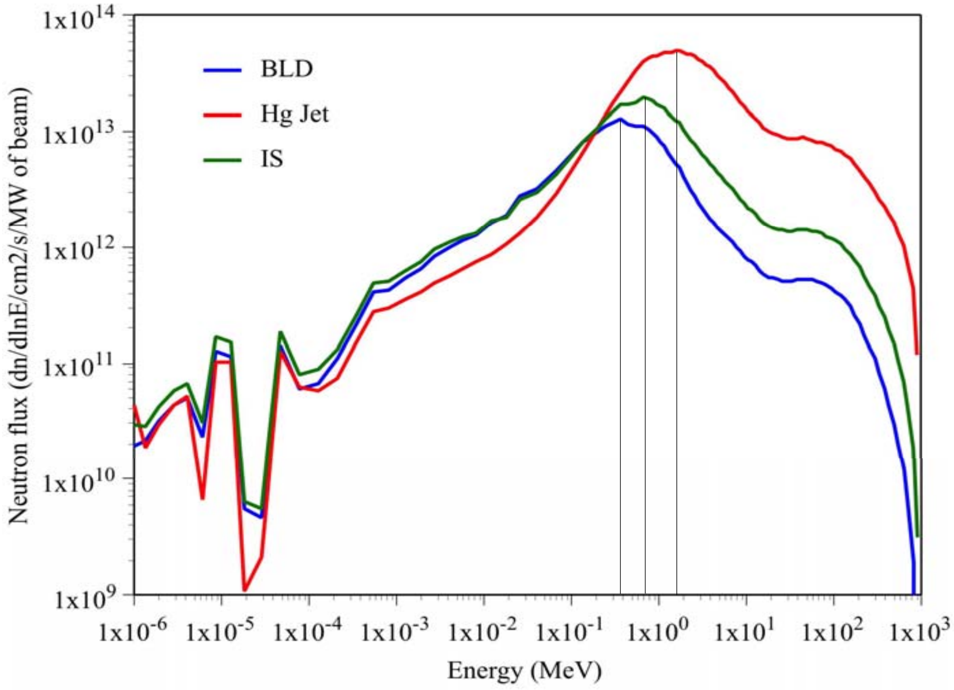
- **Similar isotopic yields** for both proton energies. **Spallation in the fission target** occurring for higher energies, in particular in the end cap

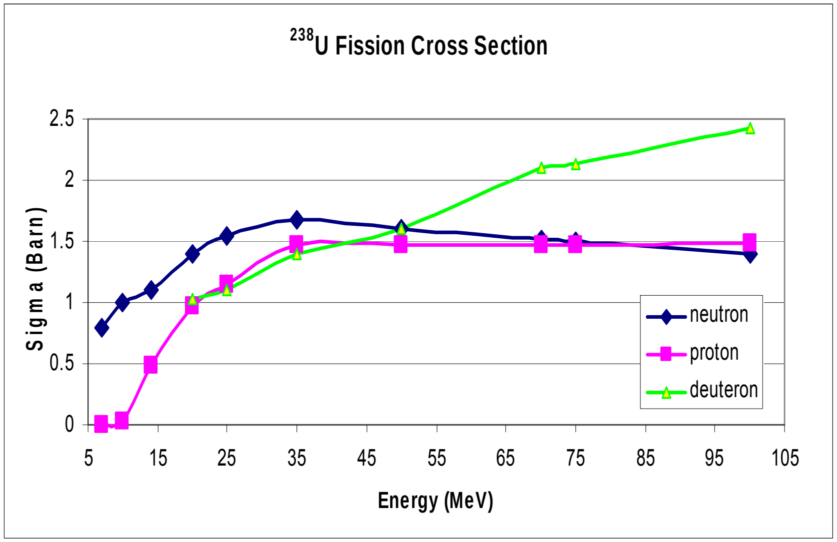
- The nominal time structure of the proton beam is **CW**. A pulsed beam could be studied but important technical problems in terms of **pressure waves** and **cavitation** are foreseen (experience from SNS)

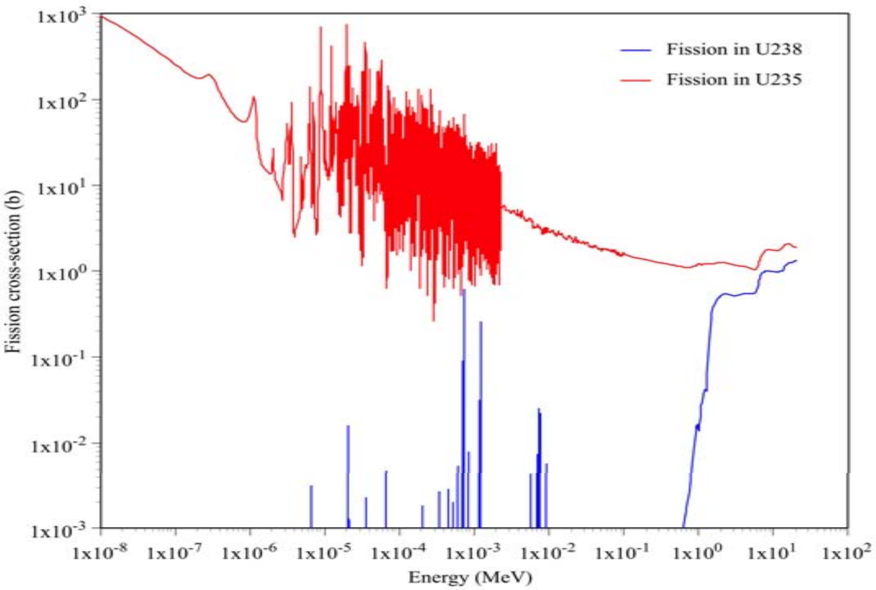
- A synergy between the SPL requirements and the EURISOL design could be found through a 1 GeV extraction line and perhaps(?) a first stage CW beam, being pulsed later for the neutrino factory

Discussion starts...

Neutron Energy Spectrum vs Fission Cross-Section in Uranium



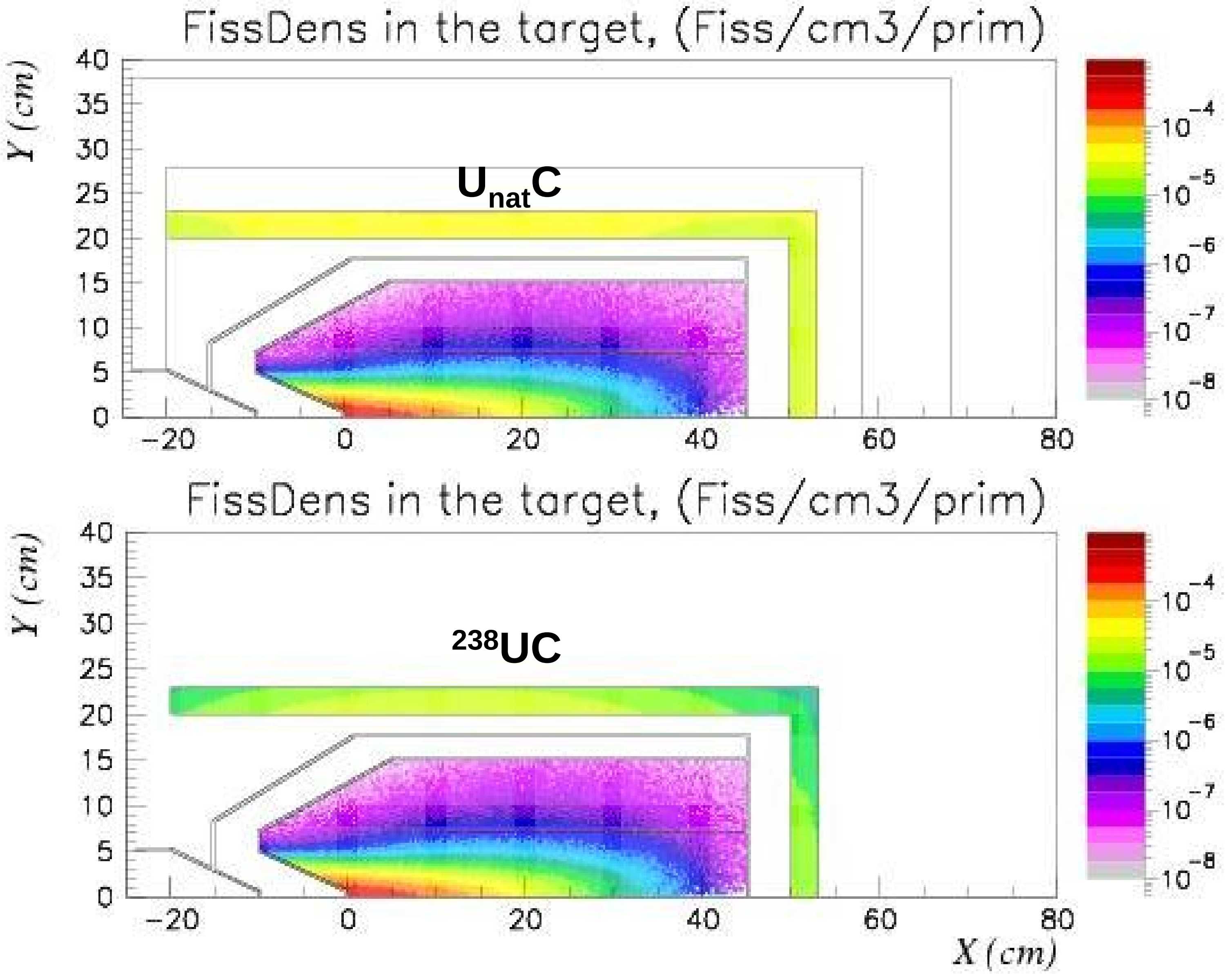




- Significantly harder spectrum for the Hg-J, with a peak neutron energy between 1 − 2 MeV, compared to 300 keV for BLD and 700 keV for IS
- Very low fission cross-section in ^{238}U below 2 MeV (~10^{-4} barns). Optimum energy: 35 MeV
- Use of natural uranium: σ_f in ^{235}U (0.7% wt.): at least 2 barns
- Further gain if neutron flux is reflected (e.g. BeO)

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



Radioisotope yields in UC_x targets

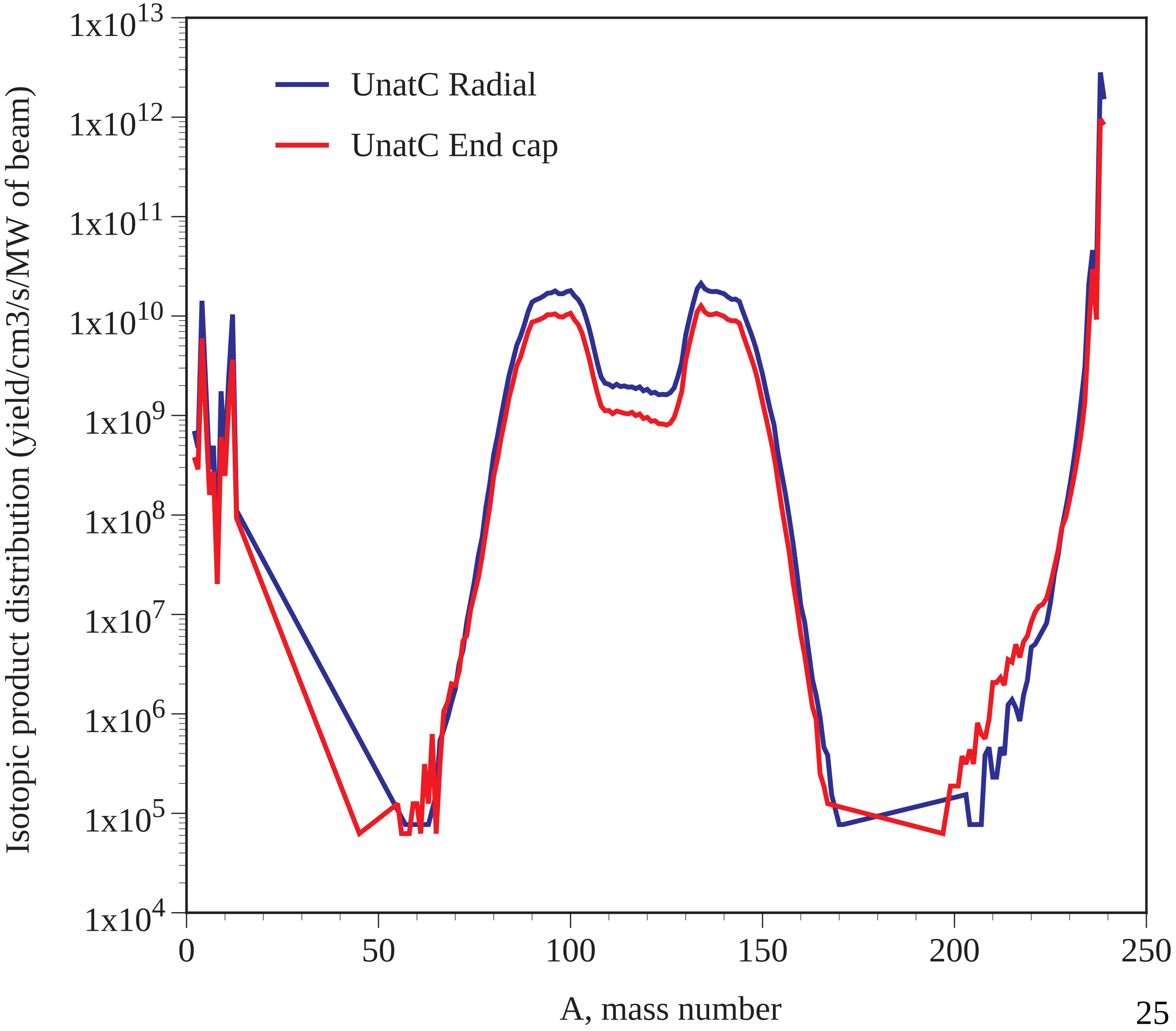
EURISOL Design Study

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

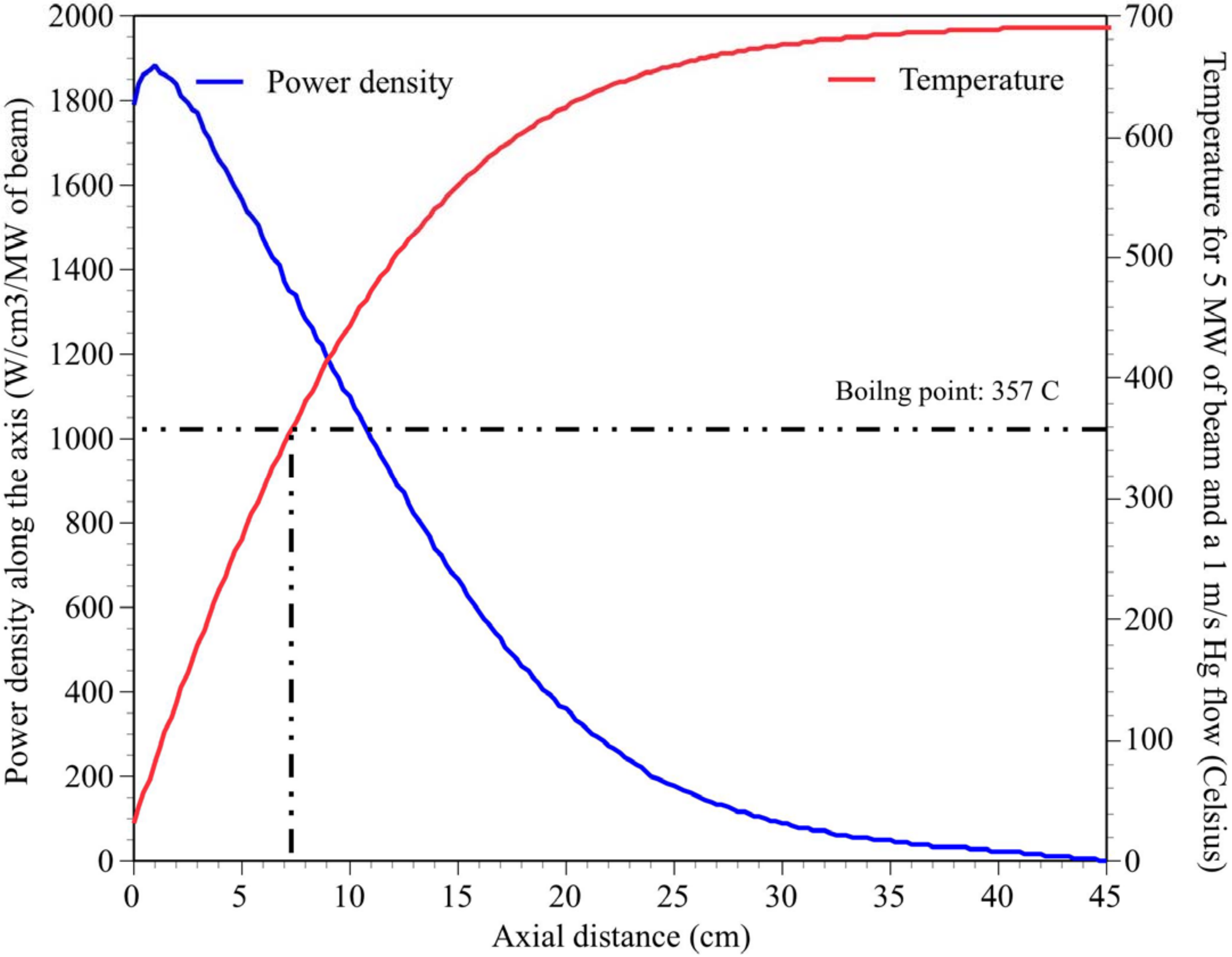
⇦ Three very narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, ^{3}He and α) ==> very few

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

⇦ twice as much fission in radial position



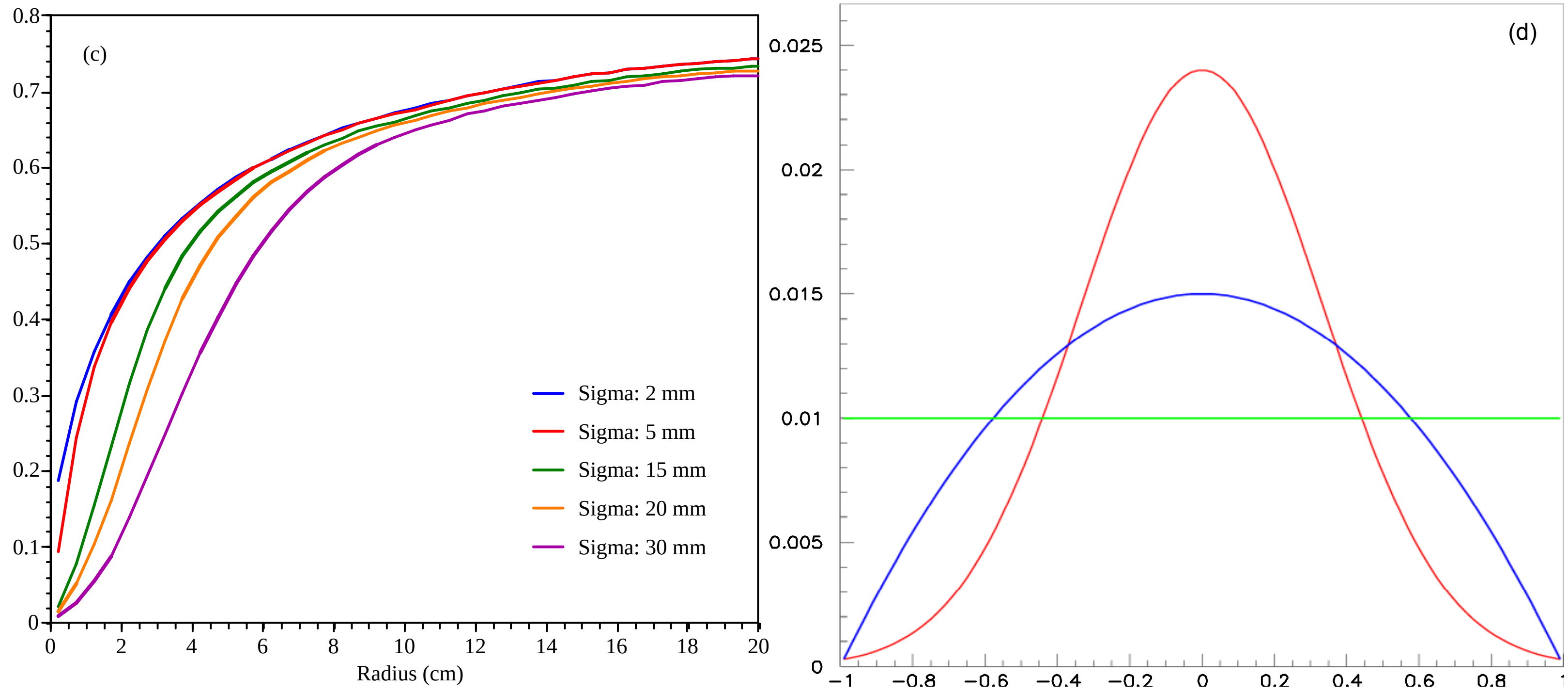
Power Densities (3)



- Increasing σ_{beam} from 15 to 25 mm or taking parabolic beam of at least 45 mm radius → reduce ΔT in Hg by a factor 2 - 2.5
- Doubling the flow rate (~2 m/s) will reduce ΔT by factor 2
- → ΔT ~ 130 - 150 ºC

Impact of the Beam Profile (2)

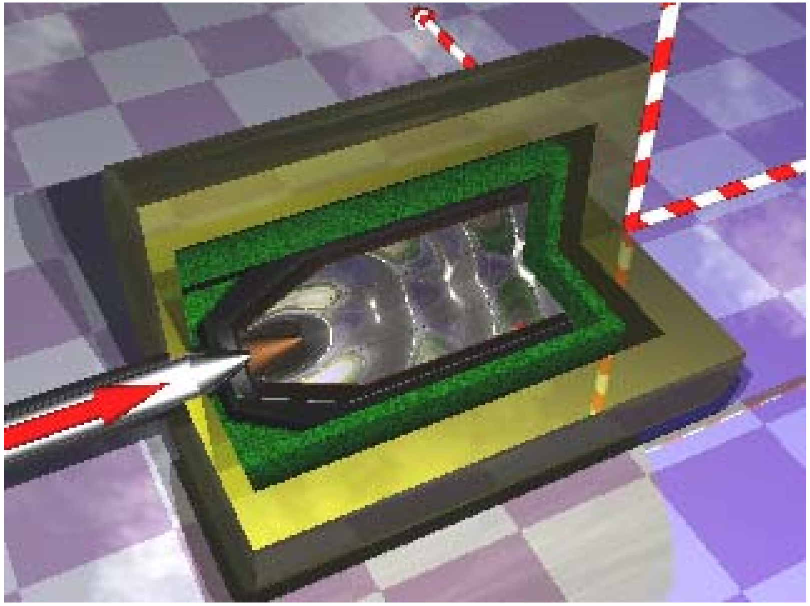
Energy deposition as a function of the beam σ

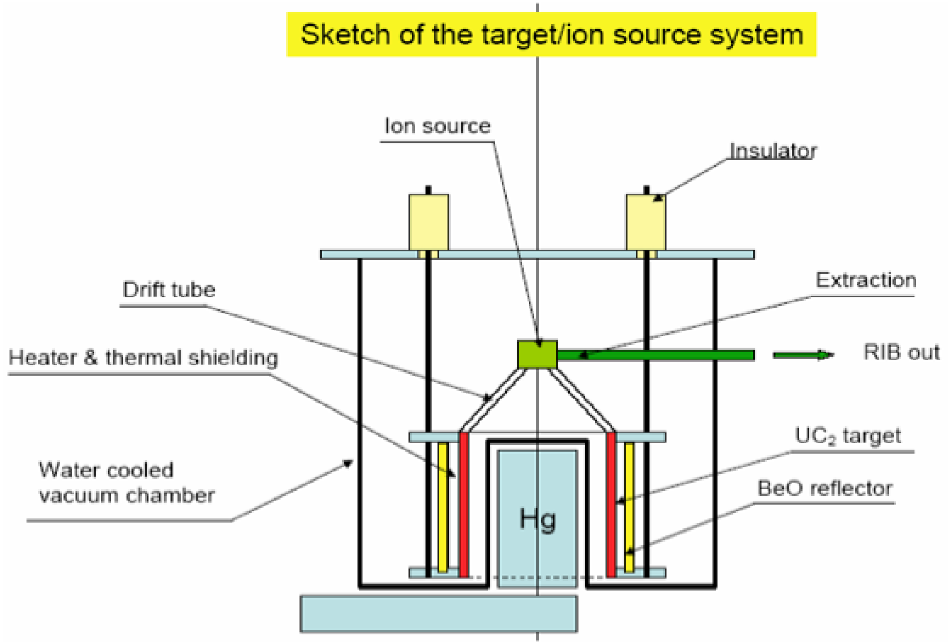


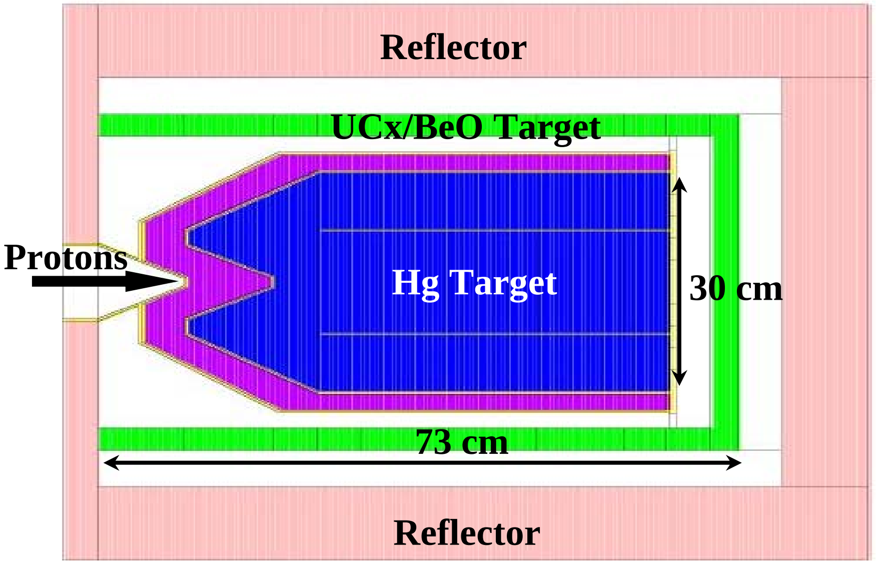
- ~75% of the beam energy is contained inside the target and that σ only has an impact on which radius contains ~50% of the energy (for σ = 2 mm, this occurs at 3 cm, whereas for σ = 30 mm, it happens at 6 cm).

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

Baseline Design

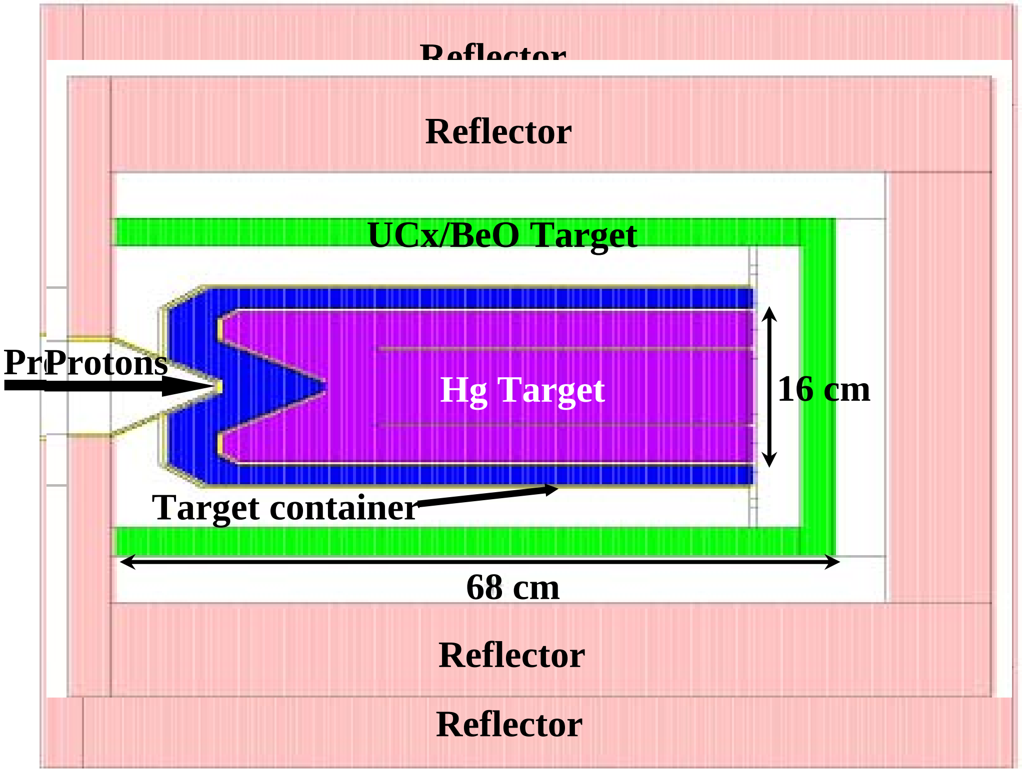


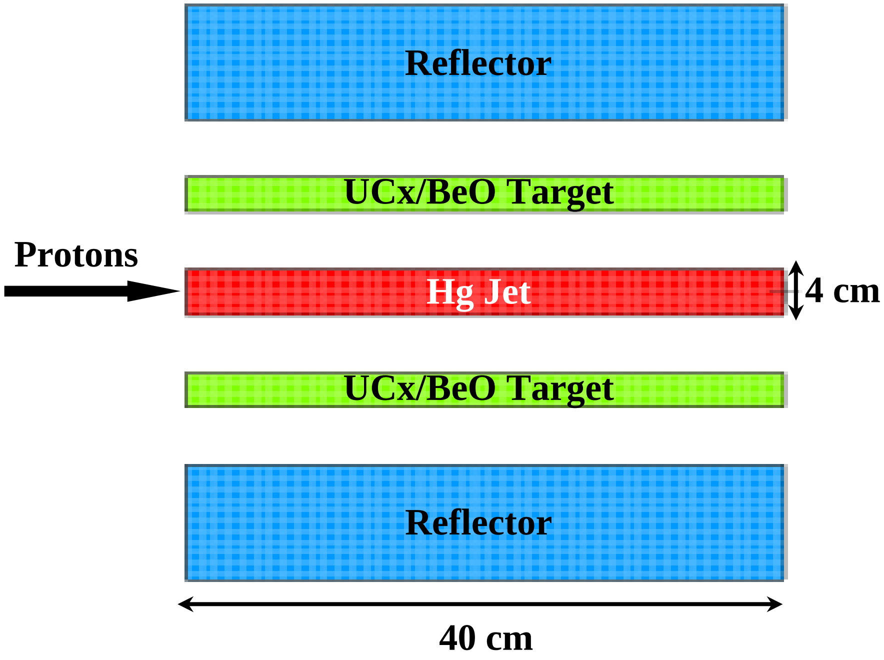




- BLD: Shape of Hg target optimised for neutron production (neutron balance)
- 15 mm sigma proton beam, fully contained in the Hg target
- $U_{nat}C_3$ (3 g/cm^3) fission target, to also induce fission with neutrons below 1 MeV. Higher yields if high-density carbide is used
- Use of BeO reflector to improve neutron economy, to shield HE particles and, possibly, to produce 6He for the beta-beam, through (n,α) reactions in ^{9}Be

Comparative Study





- BLD: Integration problems due to the large weight of the assembly and large volume of fission target
- Possibility of further reduction in Hg target dimensions → Intermediate solution (IS)

- Hg-J: designed for high-energy neutron fluxes in the fission target
- 4 mm sigma proton beam, mostly contained in the 4 cm diameter Hg Jet
- Fission targets closer to the Hg-J and the proton beam

http://eurisol-hg-target.web.cern.ch/eurisol-hg-target/

T2: Multi-MW Proton-to-Neutron Converter

[EURISOL DS] [DIRECT TARGET] [UCx TARGET]

List of Participants

Technical Reports

Preliminary Study of the Liquid Metal Proton-to-Neutron Converter (pdf), EURISOL DS/TASK2/TN-05-01

Neutronic Calculations for the Baseline Multi-MW Mercury Target (pdf), EURISOL DS/TASK2/TN-05-02 (to be released soon)

Baseline Design of a Solid Neutron Converter Driven by 160 MeV Protons (pdf), EURISOL DS/TASK2/TN-05-03

T2 Group Meetings

T2-01 (CERN, 10-11 March 2005)

T2-02 (PSI, 6 July 2005)

Multi-MW Hg Target

Baseline Parameters

Target Layout

FLUKA Models - Baseline Design for 1 GeV Protons:

Configuration I (15 cm radius, input file, output file, 2D view, energy deposition, residual nuclei, MCNPx input file)

Configuration II (8 cm radius, input file, output file, 2D view, energy deposition, residual nuclei, MCNPx input file)

Or just Google: eurisol hg cern