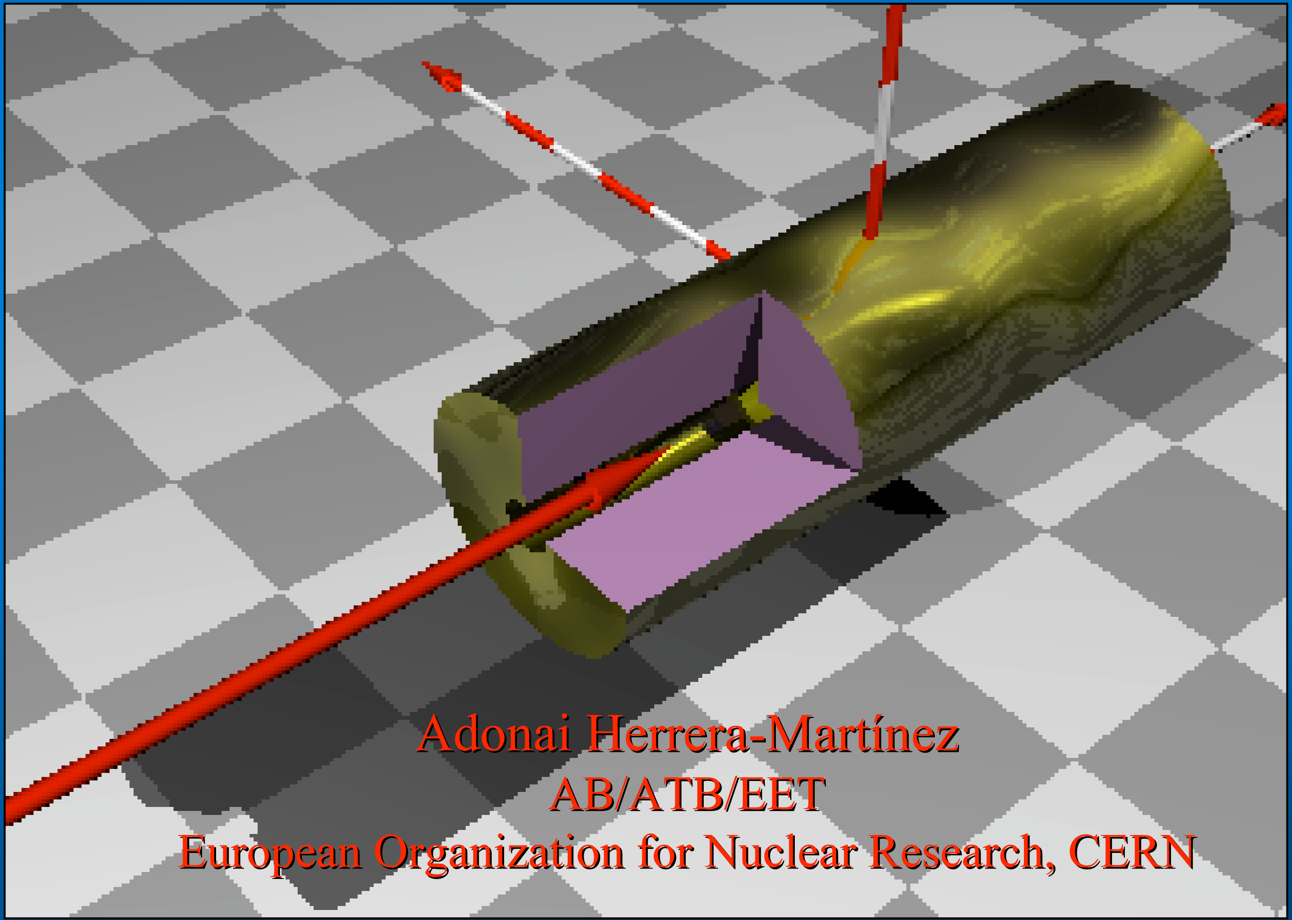
EURISOL Multi-MW Target
Preliminary Study of the Liquid Metal Proton-to-Neutron Converter



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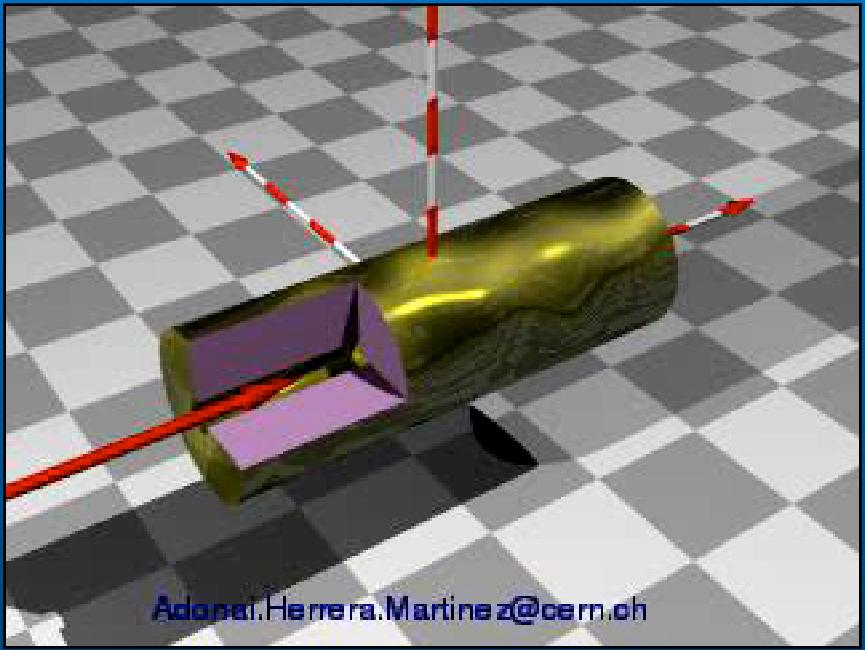
EURISOL Meeting, 10-11 March 2005, CERN

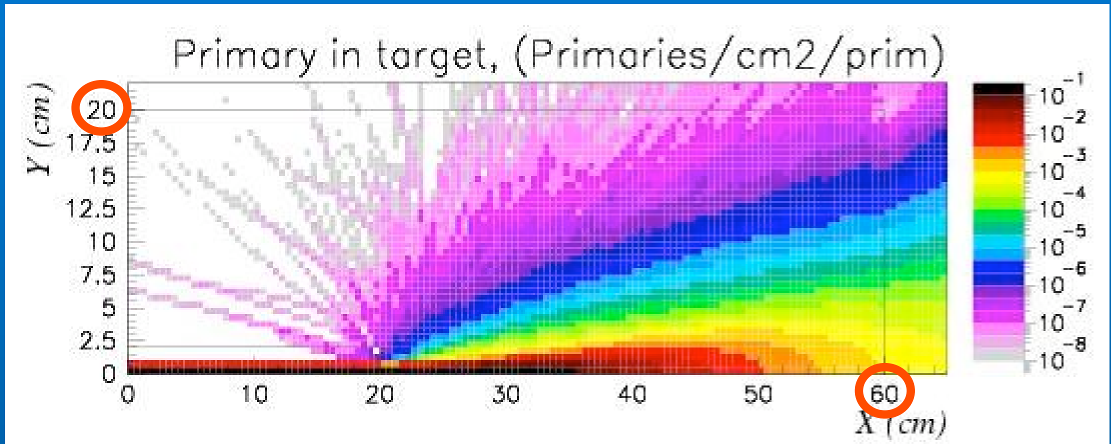
Preliminary Calculations

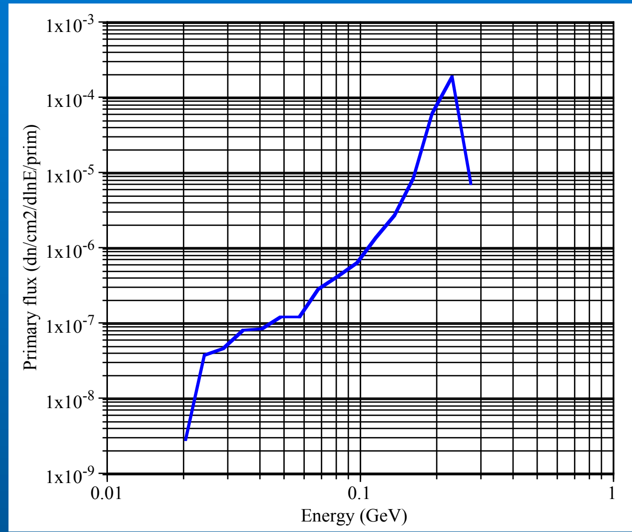
- Projectile Particle: Proton
- Beam Shape: Gaussian, σ ~1.7 mm
- Energy Range: 1–2–3 GeV
- Target Material: Hg / PbBi
- Target Length: 40–60–80–100 cm
- Target Radius: 20–30–40 cm
- Spatial and energy particle distribution

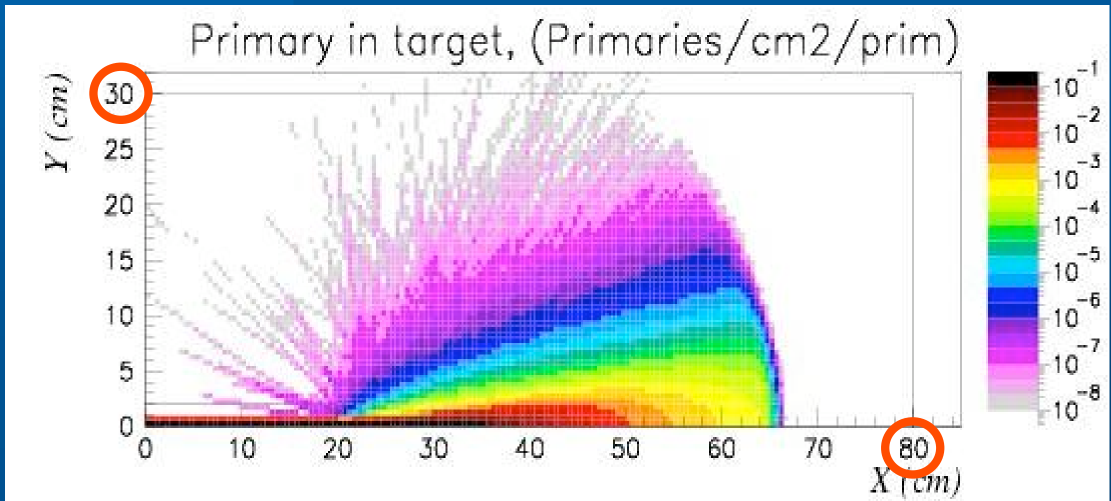


1 GeV Primary Proton Flux

1 GeV Proton range ~46 cm

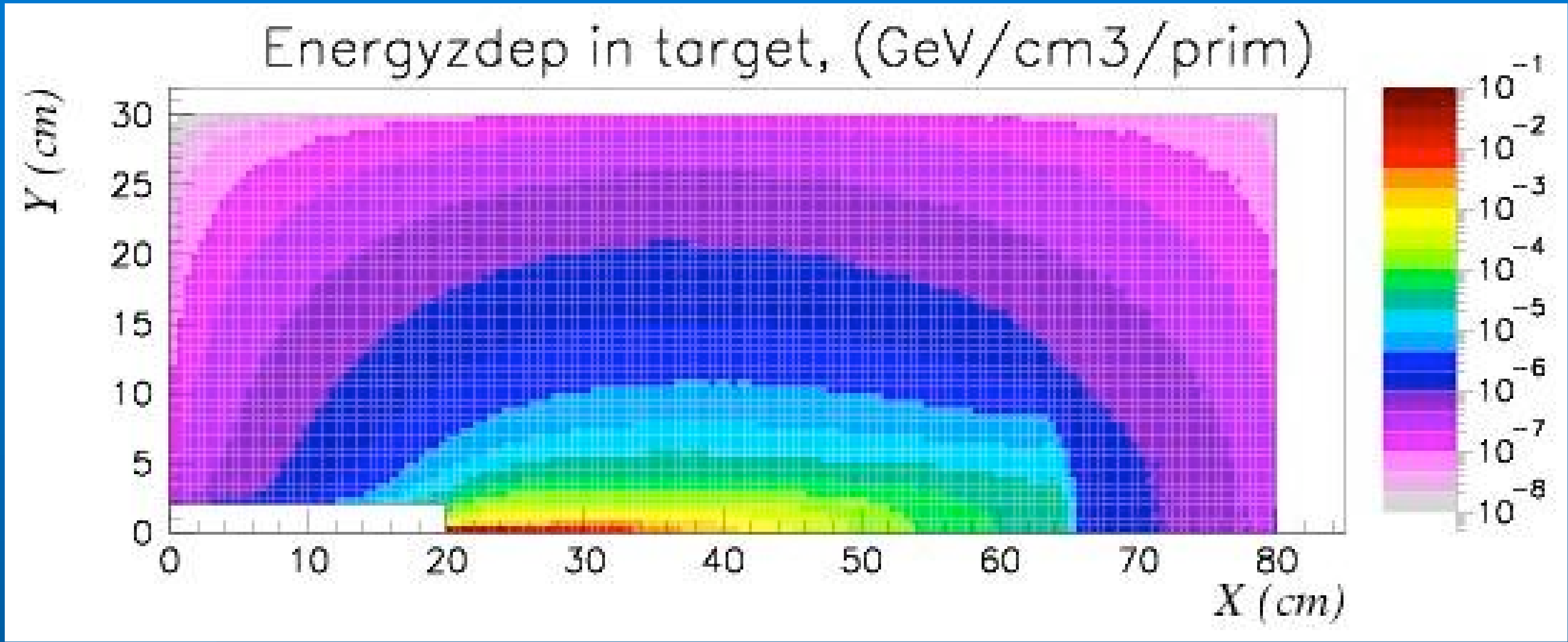






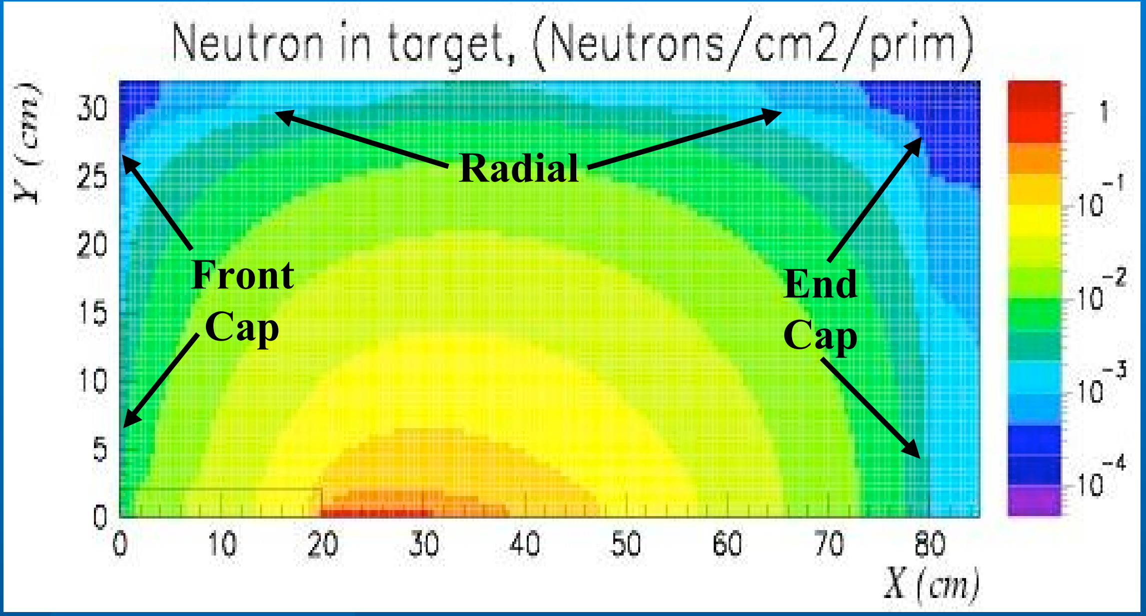
- The beam opens up to ~20 degrees, with some primary back-scattering
- Primaries contained in ~50 cm length and ~30 cm radius

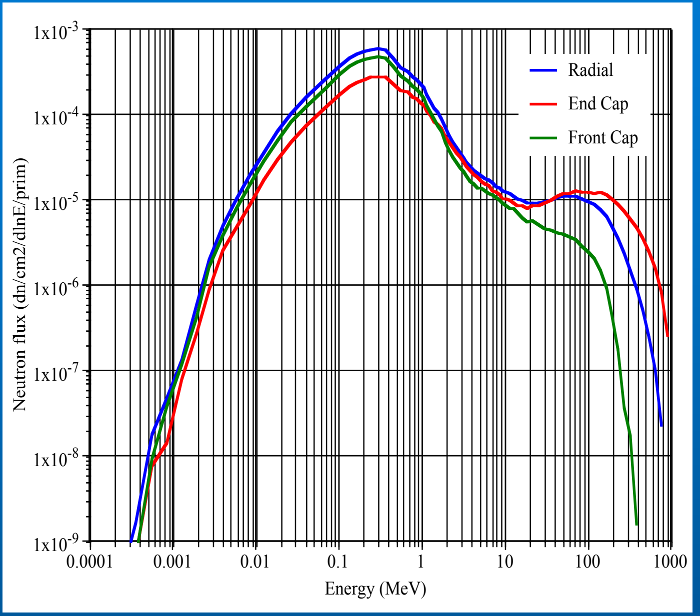
Energy Deposition for 1 GeV protons

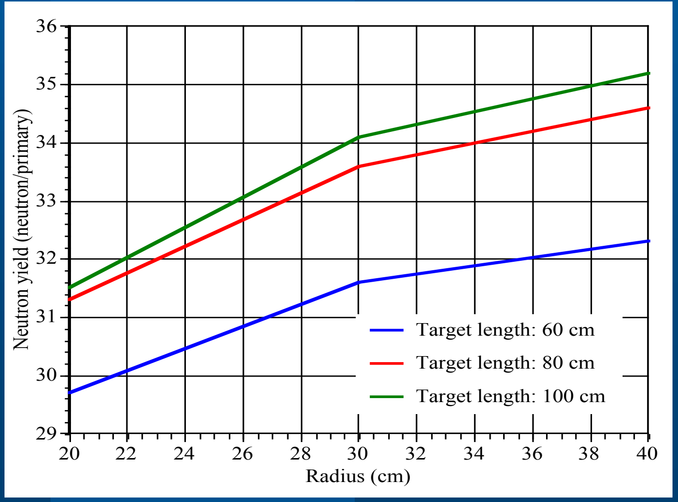


- Maximum energy deposition in the first ~14 cm in the beam axis beyond the interaction point, ~30 kW/cm^3/MW of beam
- Energy deposition drops one order of magnitude at the proton range (~46 cm)
- Large radial gradients (dE/dr ~200) in the interaction region

Neutron Flux Distribution for 1 GeV Protons

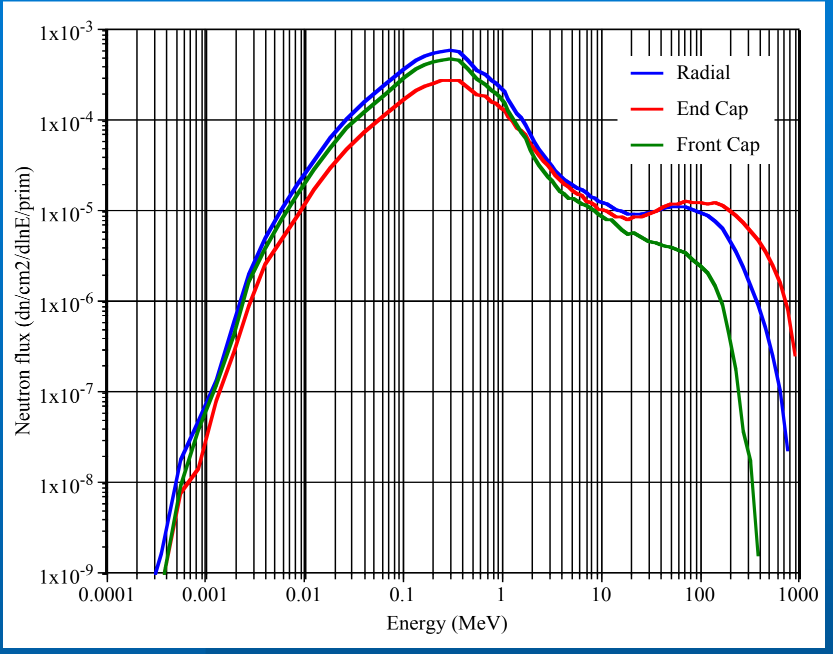


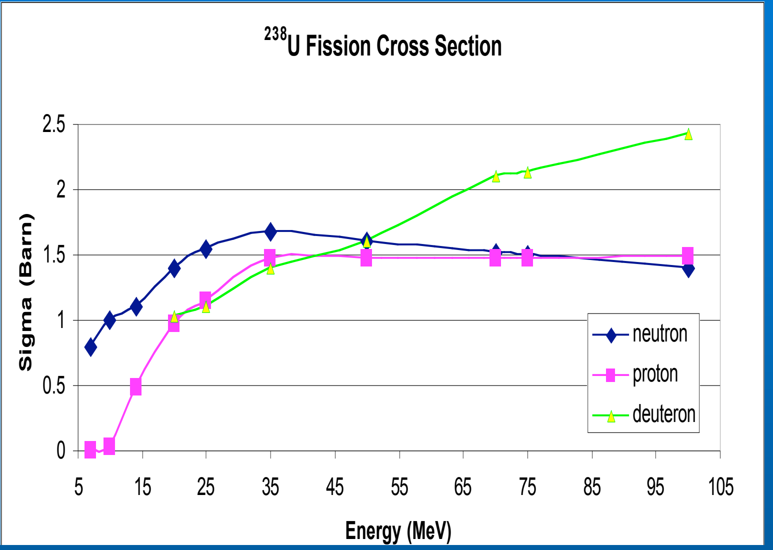


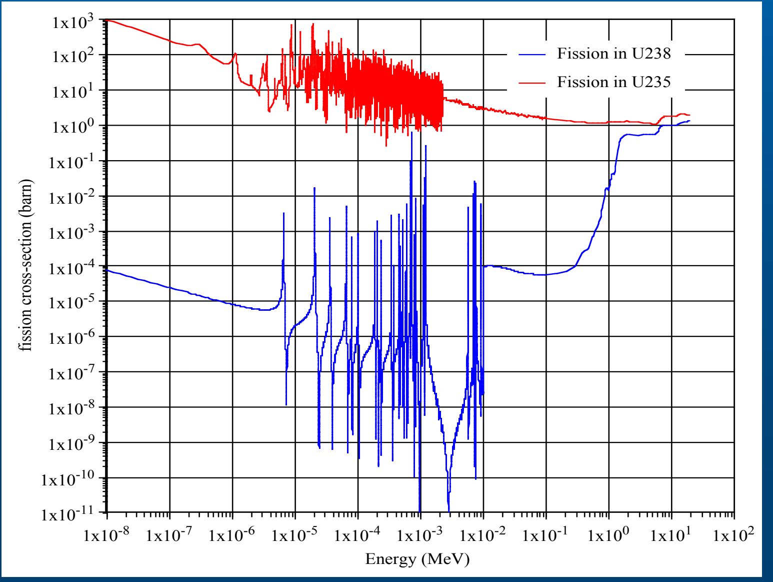


- Neutron flux centered radially around ~10 cm from the impact point
- Isotropic flux after ~15 cm from the center, decreasing with R^2
- Escaping neutron flux peaking at ~300 keV (evaporation neutrons), with a 100 MeV component in the forward direction (direct knock-out neutrons)
- Neutron yield increasing with target volume

Neutron Energy Spectrum vs Fission Cross-Section in Uranium



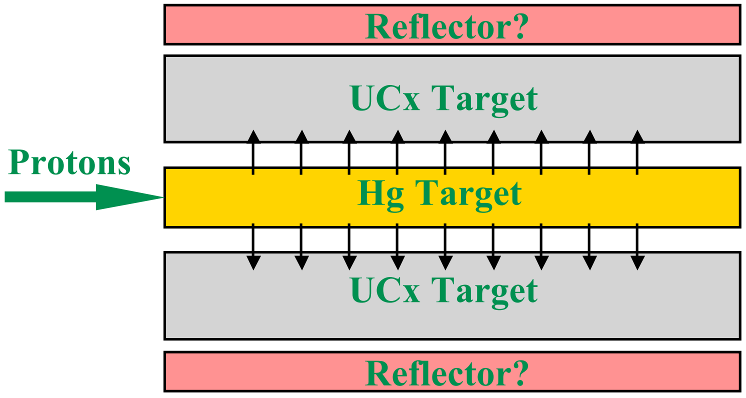




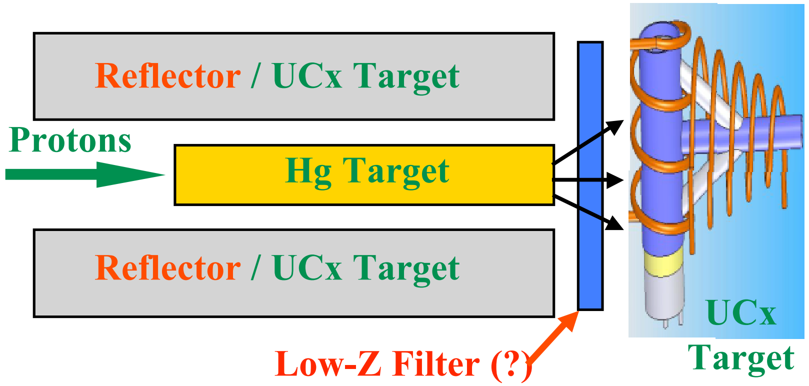
- Very low fission cross-section in ^{238}U below 2 MeV (~10^{-4} barns). Optimum neutron energy: 35 MeV
- Alternatively, use of natural uranium: fission cross-section in ^{235}U (0.7% wt.) for 300 keV neutrons: 1.24 barns
- Further gain if neutron flux is moderated

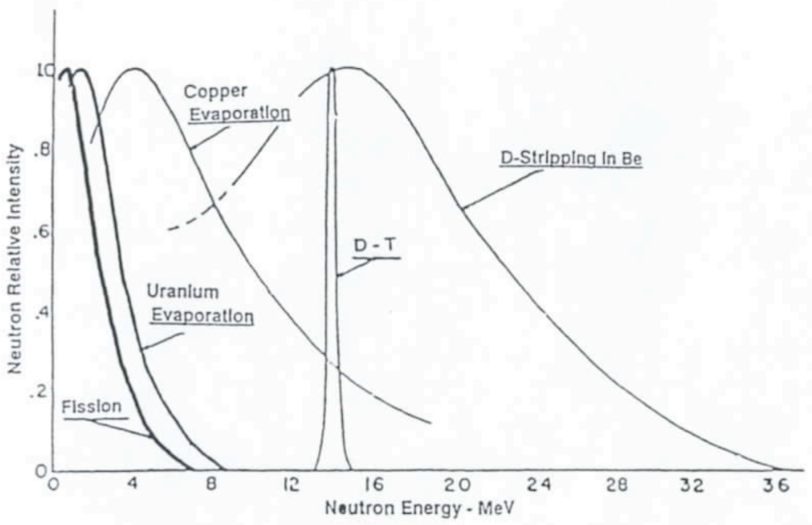
Alternative Target Configurations

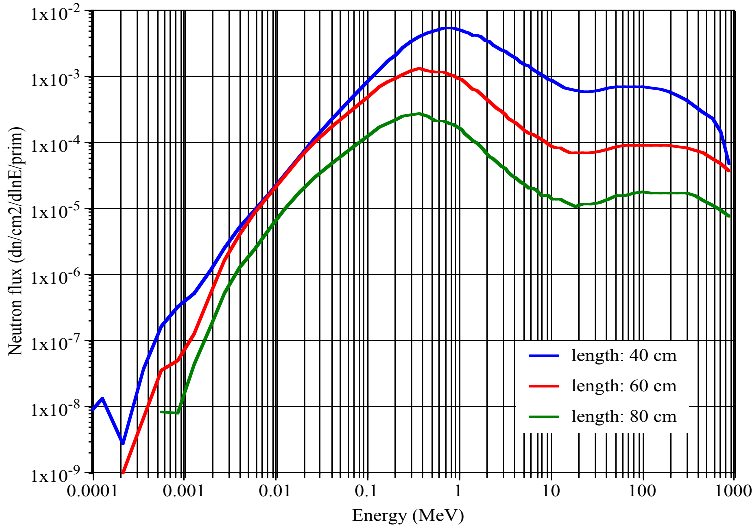
Standard Configuration



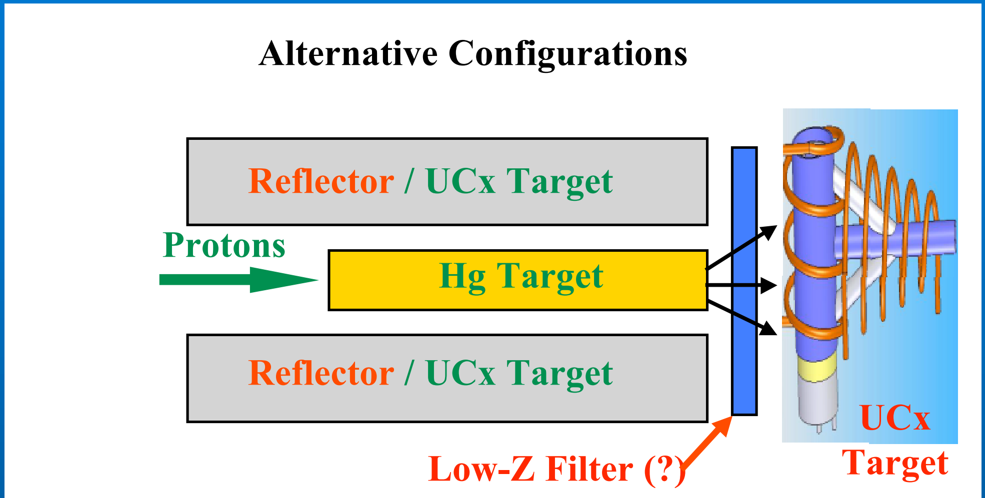
Alternative Configurations

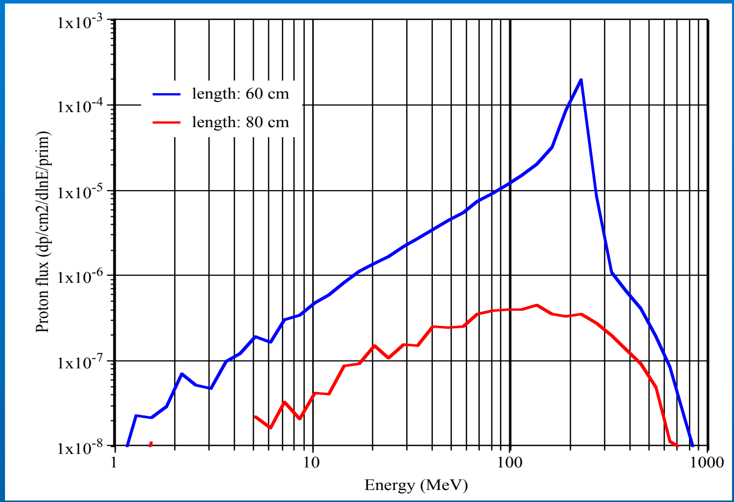


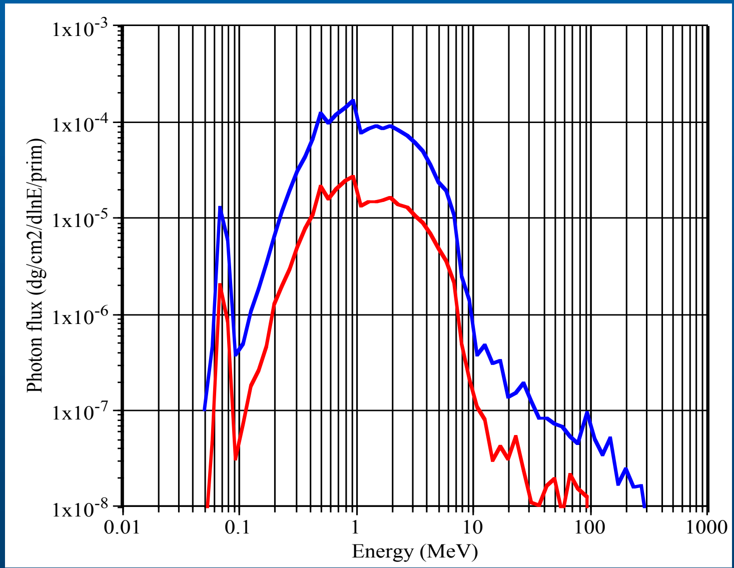




Alternative Target Configurations

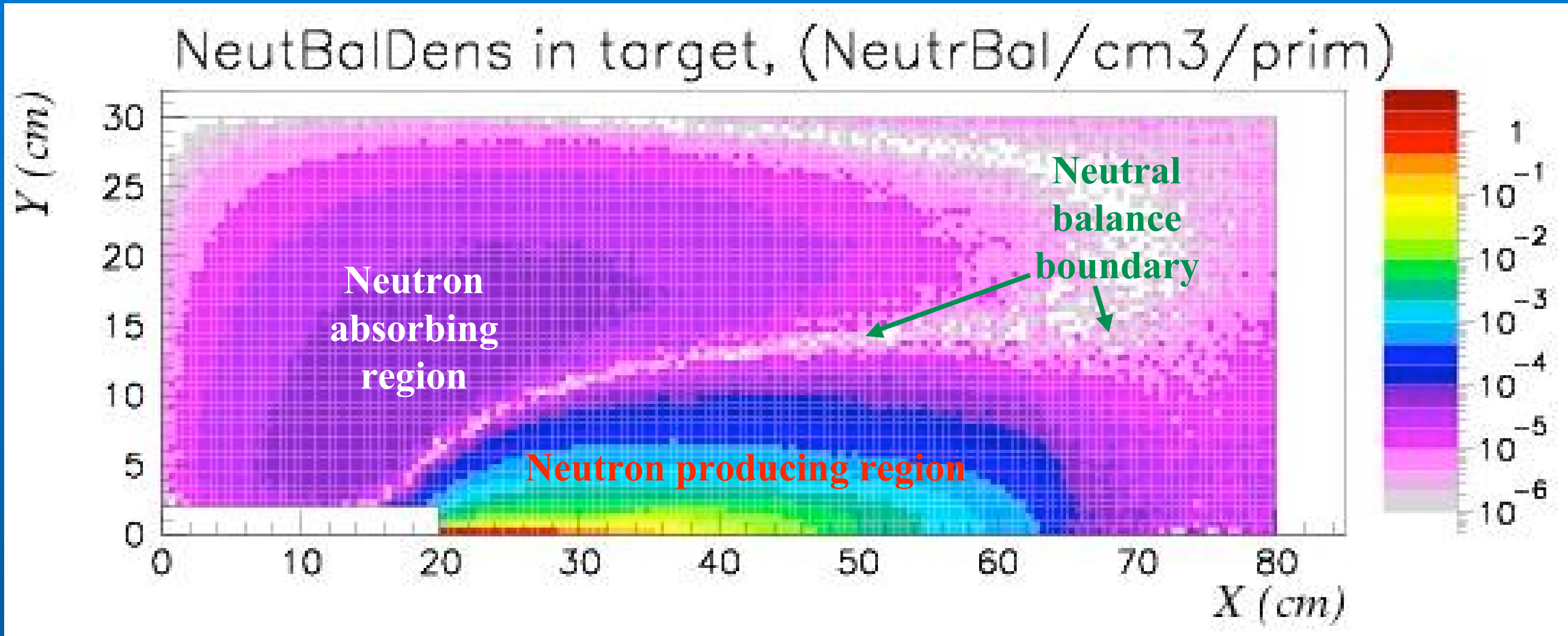






- Increasing HE neutron flux through the End-Cap with decreasing Hg target length
- Increasing charged-particle and photon escapes with with decreasing Hg target length
- Possible use of a low-Z filter to “tune” the average neutron energy to 35 MeV (maximise fission probability in ^{238}U)

Neutron Balance Density for 1 GeV Protons



•Neutron absorbing region ~6 cm behind the interaction region, following the primary particle distribution

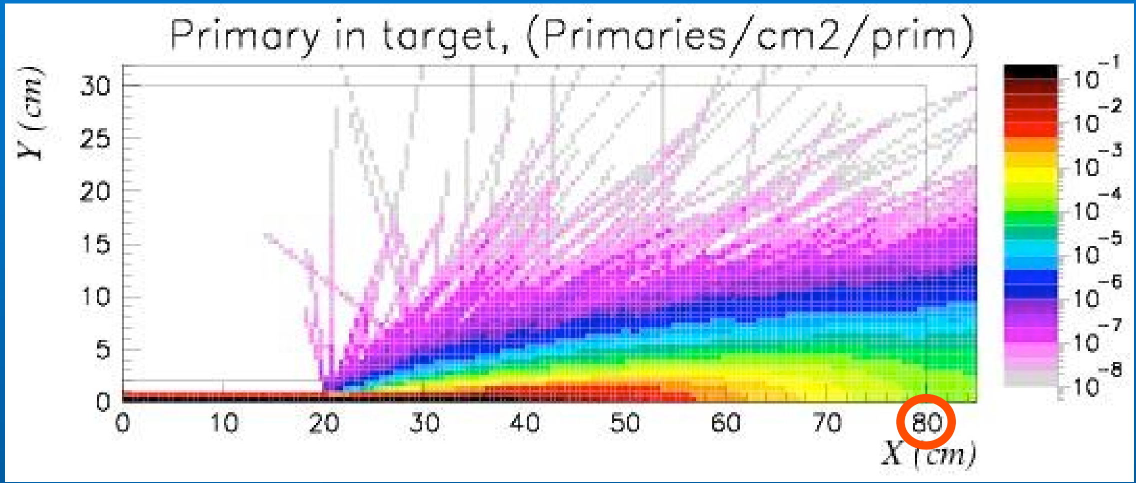
• Neutron producing region extending to the end of the target

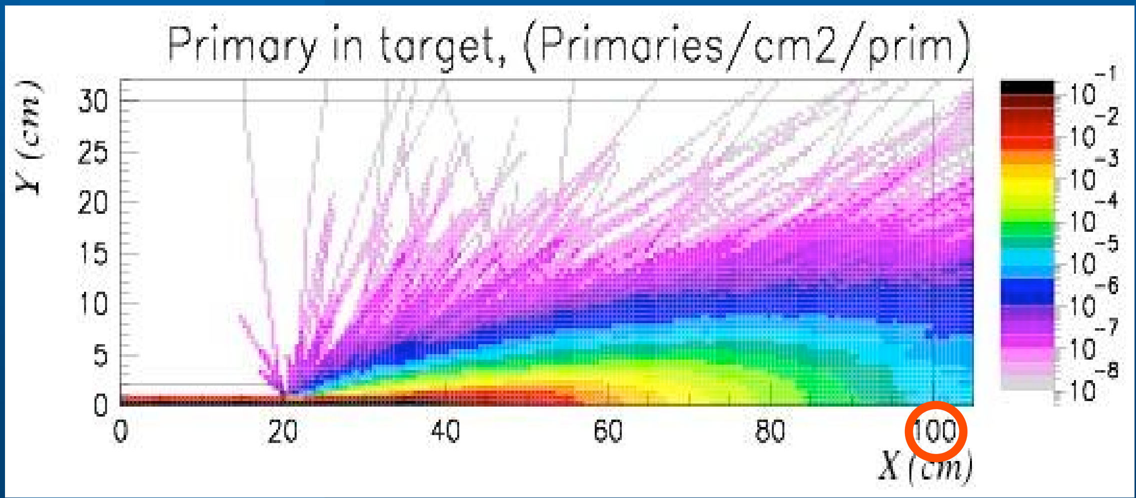
• Small contributions from regions beyond the proton range

• Neutron producing region not extending beyond r =10–13 cm

2 GeV Primary Proton Flux

2 GeV Proton range ~110 cm





- Forward peaked primary distribution at ~10 degrees
- No back-scattering and rare radial escapes
- Few end-cap escapes:

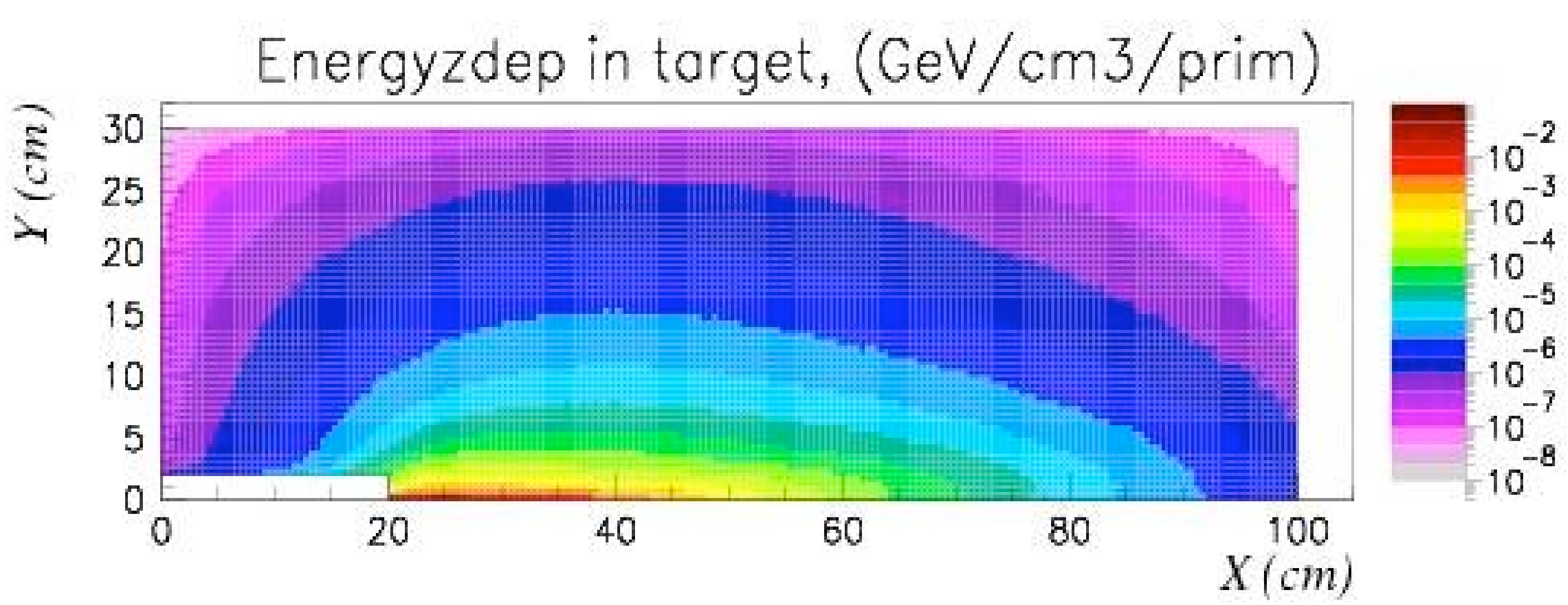
2×10^{-3} escapes/primary

with an average energy of 1 GeV for 80 cm

2×10^{-5} escapes/primary

with an average energy of 0.7 GeV for 100 cm

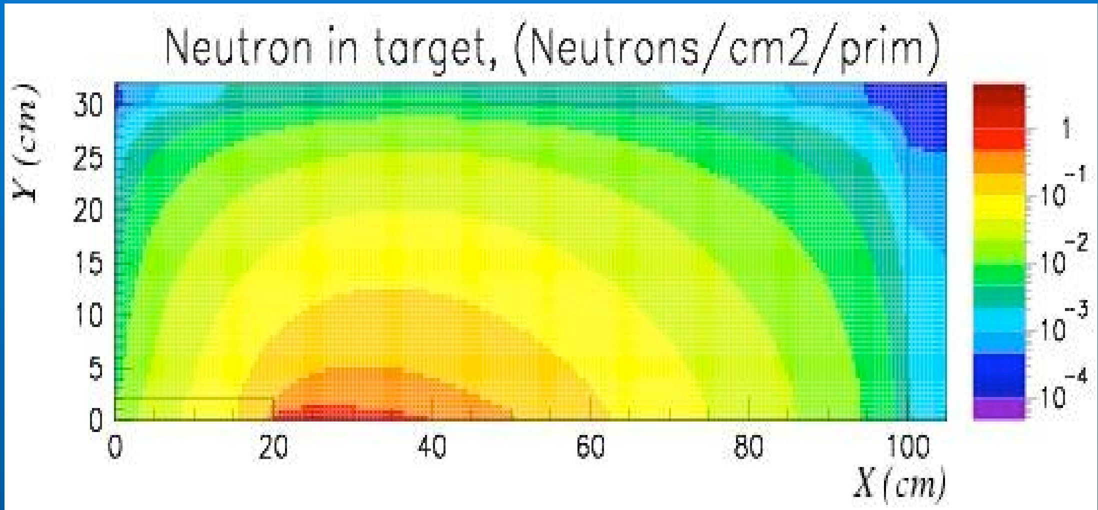
Energy Deposition for 2 GeV protons

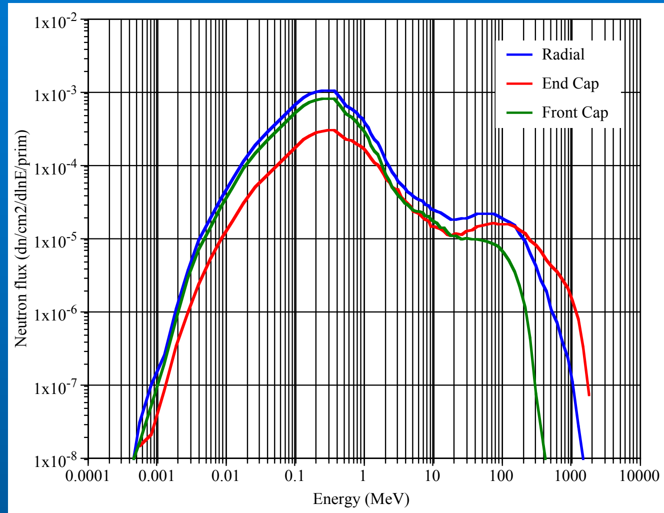


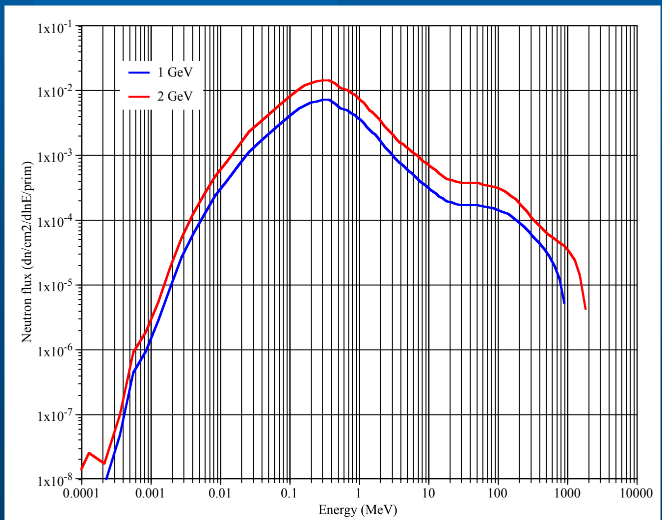
- Largest energy deposition in the first ~18 cm beyond the interaction point, ~16 kW/cm^3/MW of beam (40% lower compared to the use of 1 GeV primary protons)
- Identically, smaller radial gradient in the interaction region (dE/dr ~100)

Neutron Flux Distribution for 2 GeV Protons

Neutron Yield (2 GeV proton) : 57 – 77 n/p

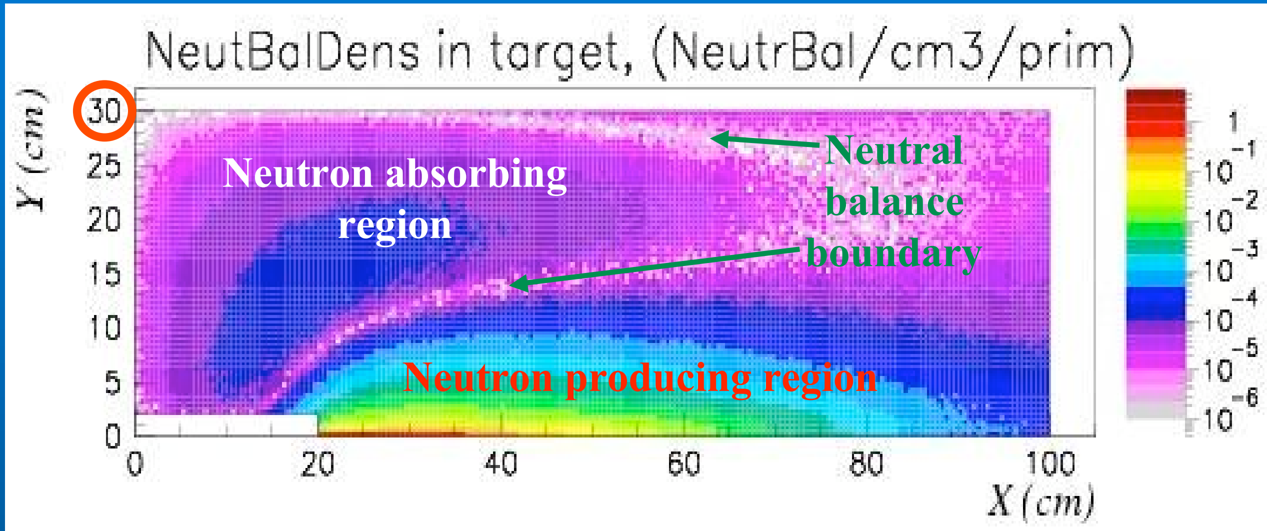


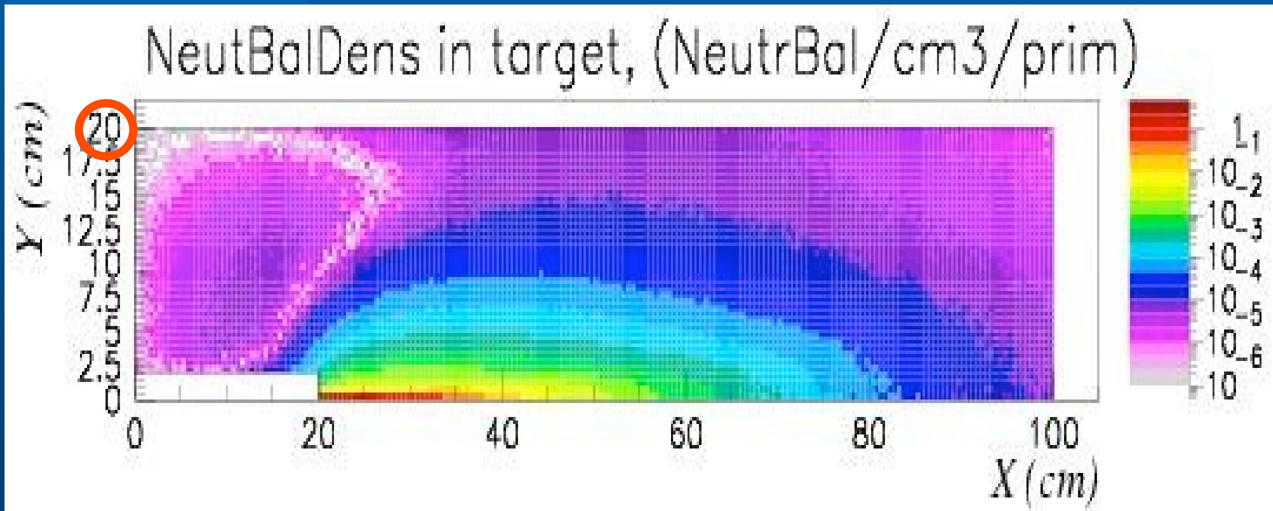




- Neutron flux centered radially around ~15 cm from the impact point, presenting a forward-peaked component
- Escaping neutron flux peaking at ~300 keV, with a 100 MeV component in the forward and radial directions and few 1 GeV neutrons escaping through the end-cap
- Harder neutron energy spectrum and higher flux and in the target compared to the 1 GeV case

Neutron Balance Density for 2 GeV Protons



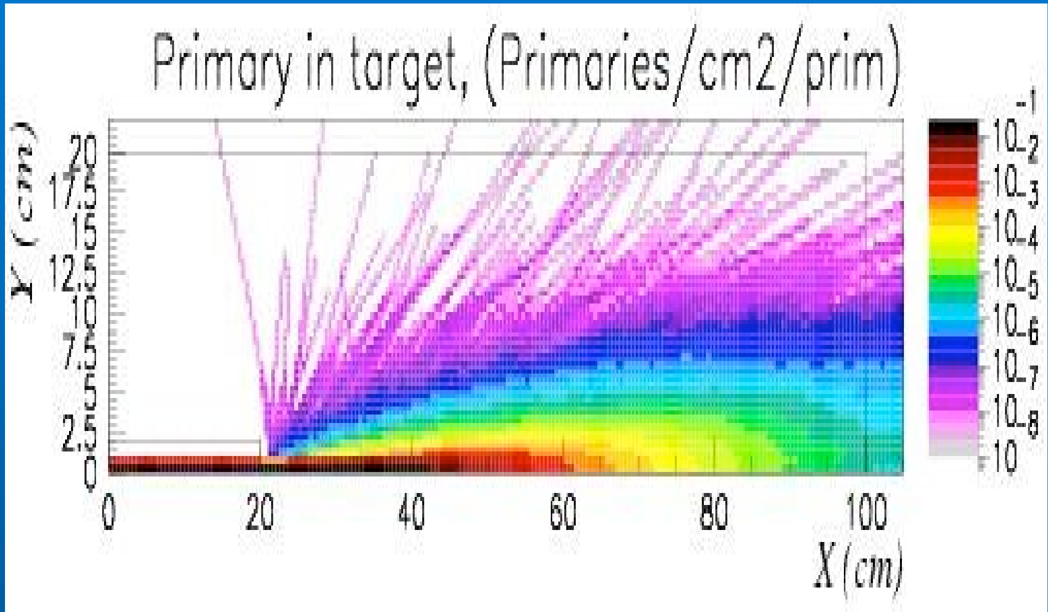


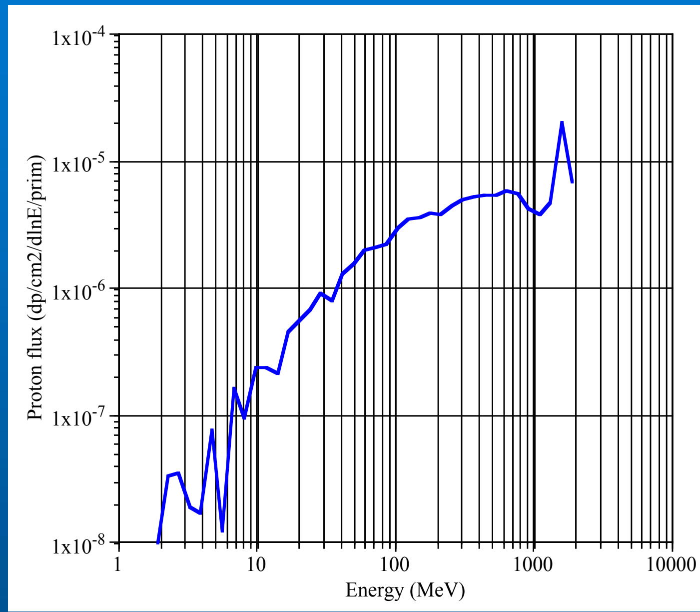
- Increase in the relevance of the axial region in the neutron production
- Neutron producing region still not extending beyond r =10 – 13 cm
- The neutron capturing region gains relevance (-6×10^{-4} bal/cm^3/prim)

  compared to 1 GeV (-6×10^{-5} bal/cm^3/prim)
- Significant reduction in neutron captures (one order of magnitude) by reducing the radius to 20 cm

3 GeV Primary Proton Flux

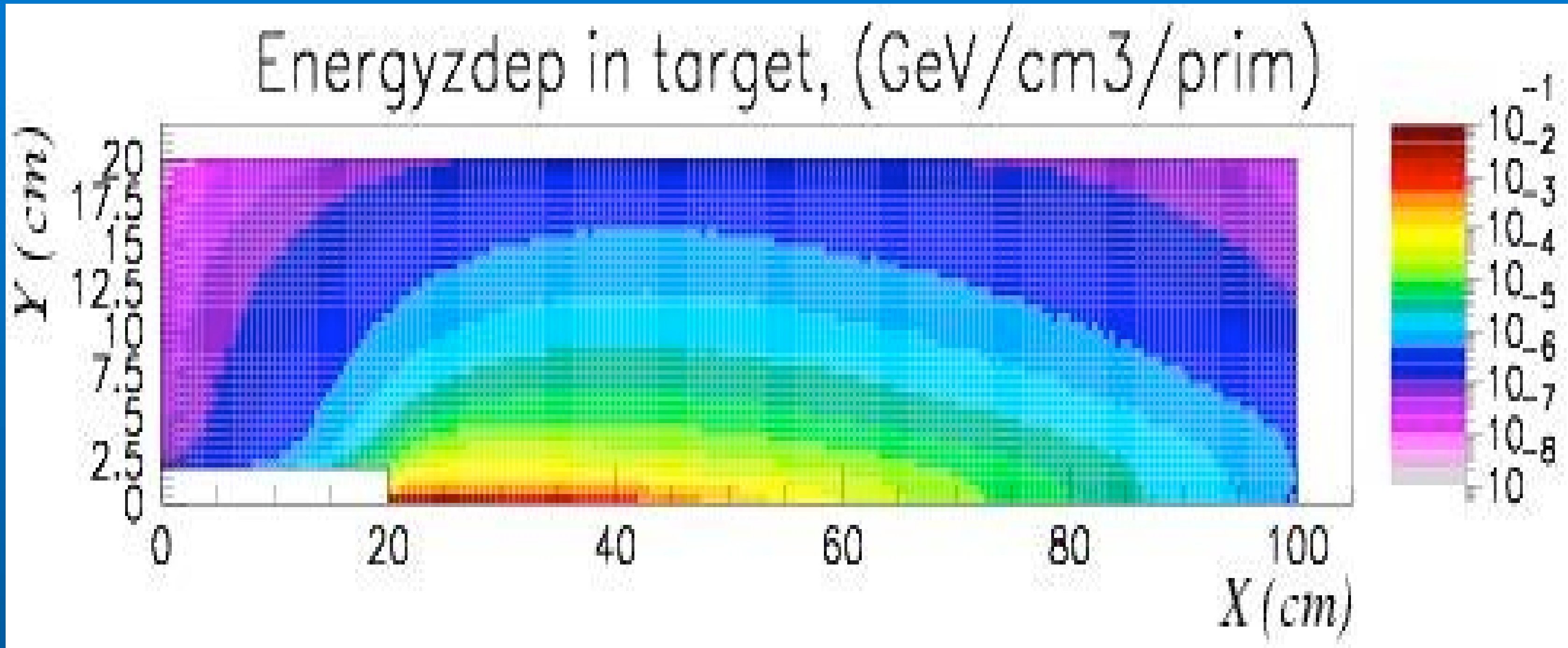
3 GeV Proton range ~175 cm





- The beam opens up to ~8 degrees, no back-scattering and few radial escapes (even for 20 cm radius)
- Some primaries escapes through the end-cap (~ 5×10^{-5} escapes/primary)
- Average energy of the escaping protons ~750 MeV

Energy Deposition for 3 GeV protons

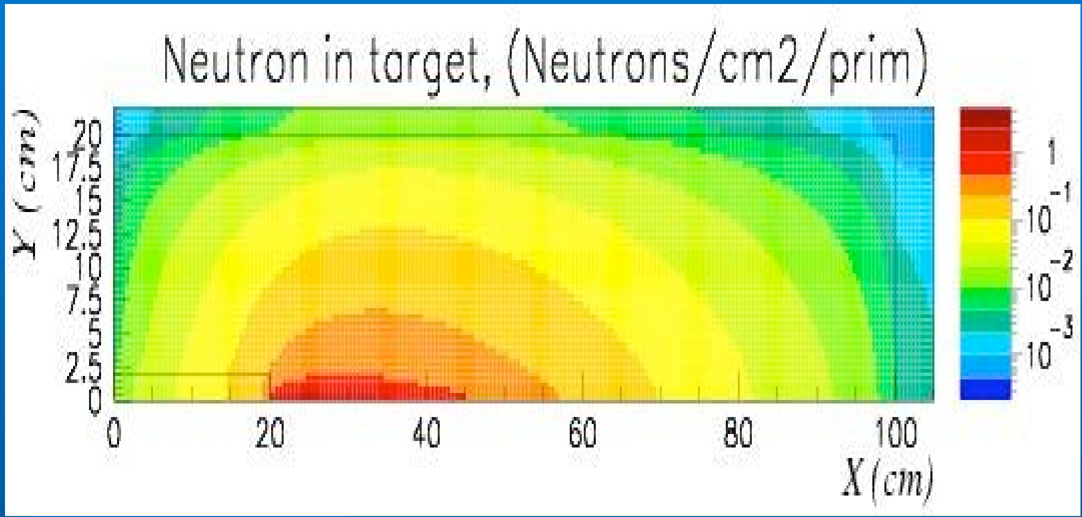


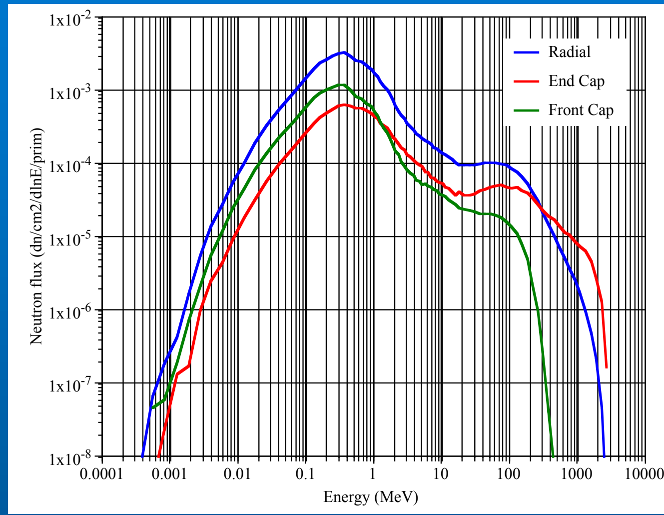
• Largest energy deposition in the first ~22 cm beyond the interaction point, ~12 kW/cm^3/MW of beam (60% lower compared to the use of 1 GeV primary protons)

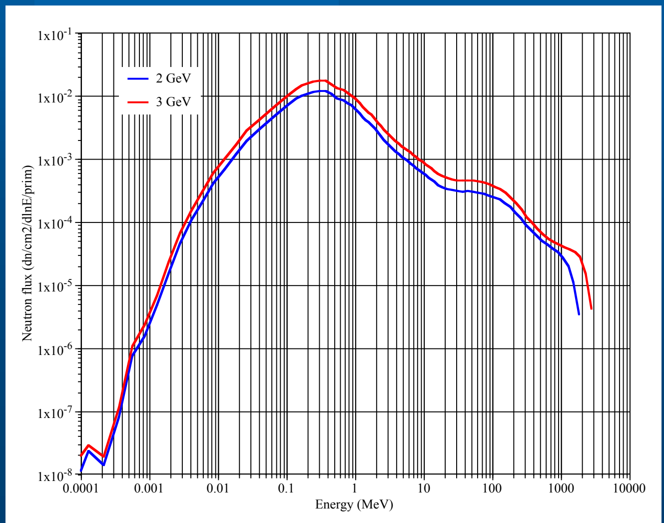
• Smaller radial gradient in the interaction region (dE/dr ~50) compared to the 1 GeV case

Neutron Flux Distribution for 3 GeV Protons

Neutron Yield (3 GeV proton) : 82 – 113 n/p

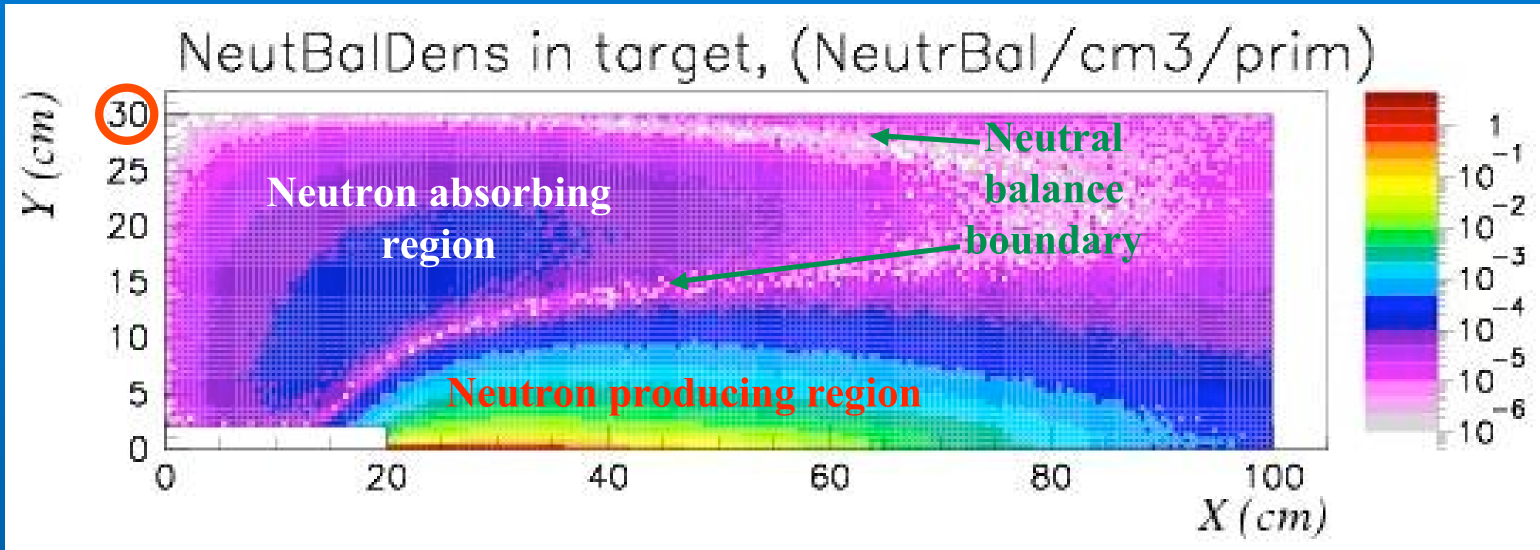


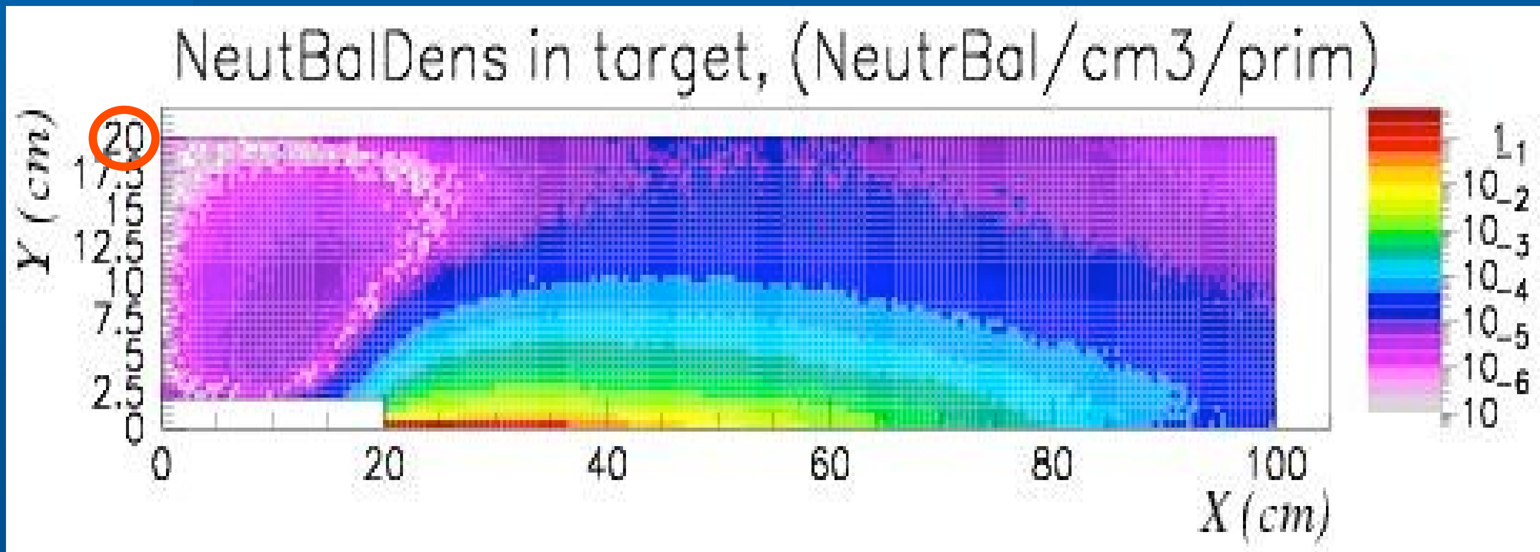




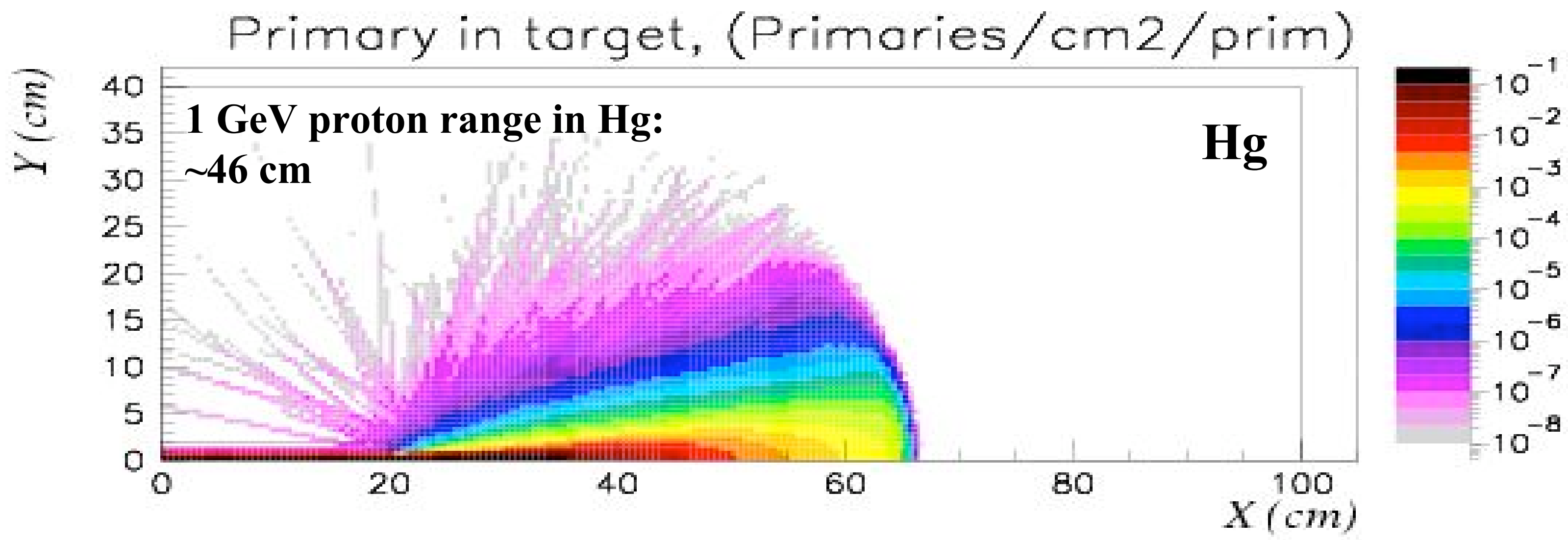
- Neutron flux centered radially around ~20 cm from the impact point, with a larger forward-peaked component
- Escaping neutron flux peaking at ~300 keV, with a 100 MeV component in the forward and radial directions and some 1.5 GeV neutrons escaping through the end-cap
- Slightly higher neutron flux in the target compared to the 2 GeV case

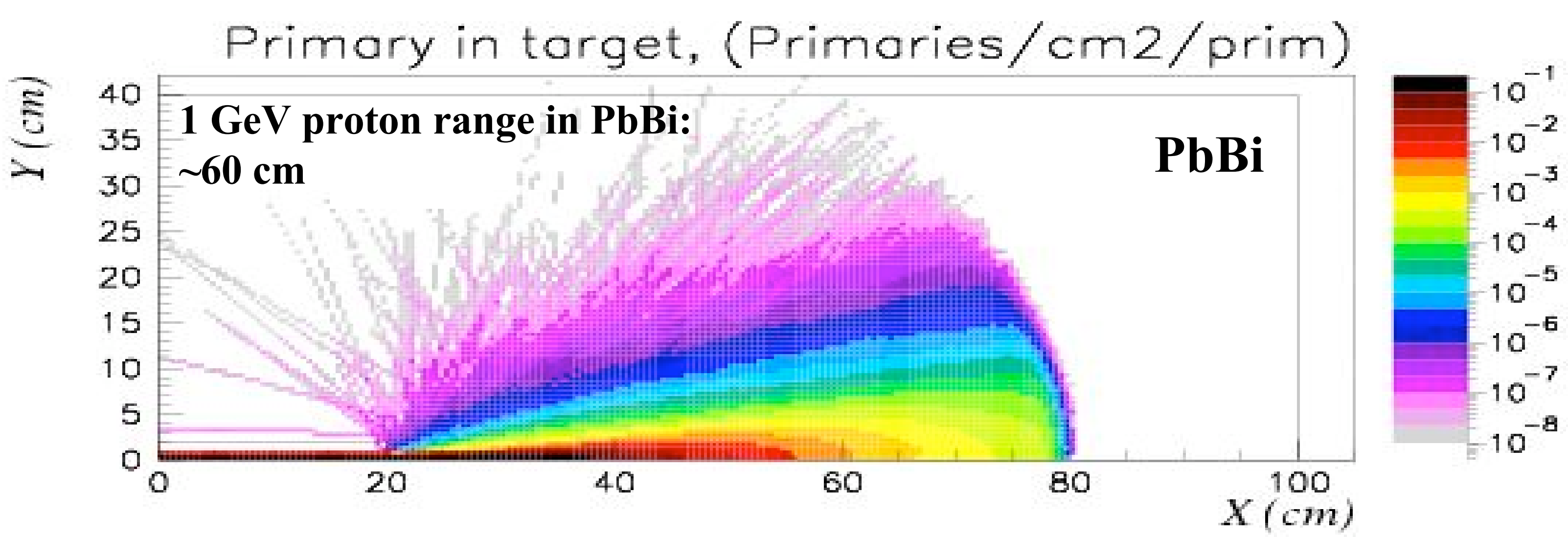
Neutron Balance Density for 3 GeV Protons



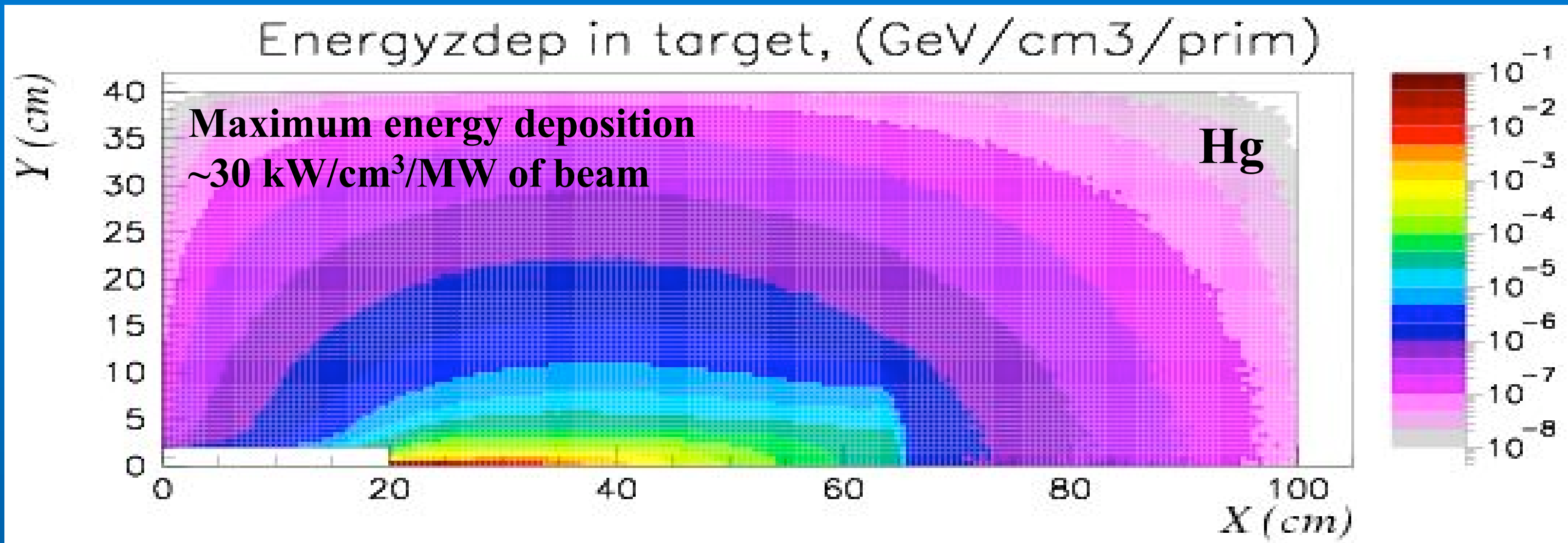


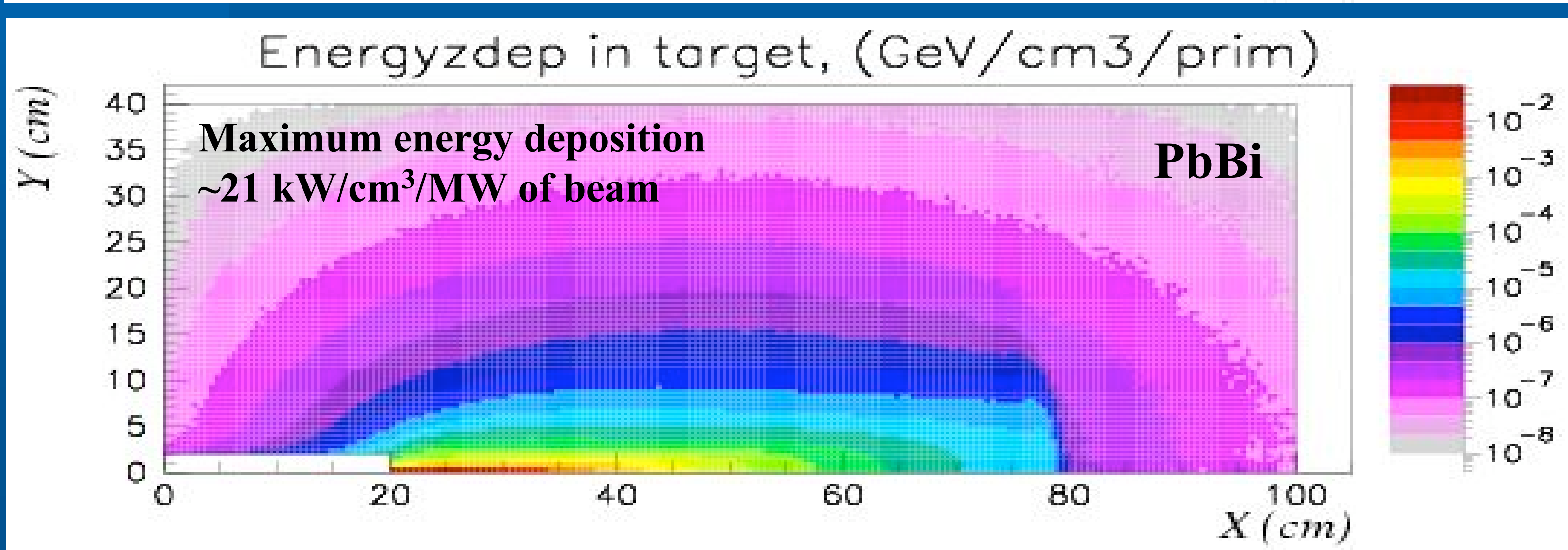
PbBi Alternative – 1 GeV Primary Particles



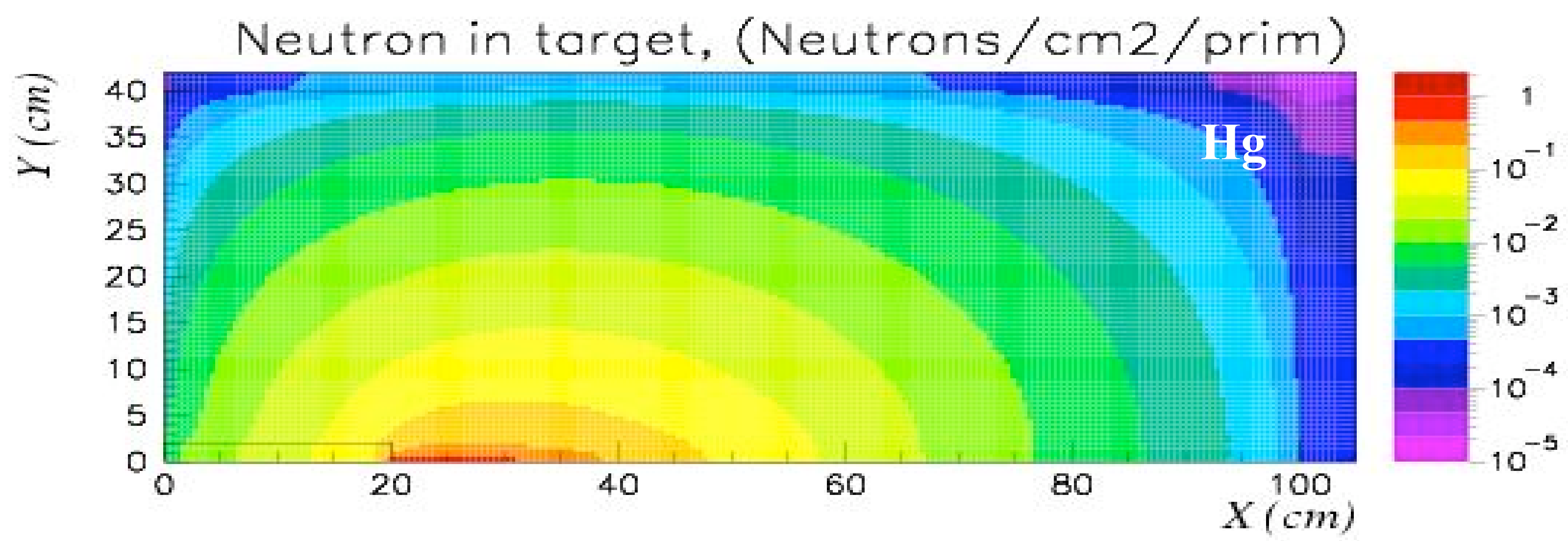


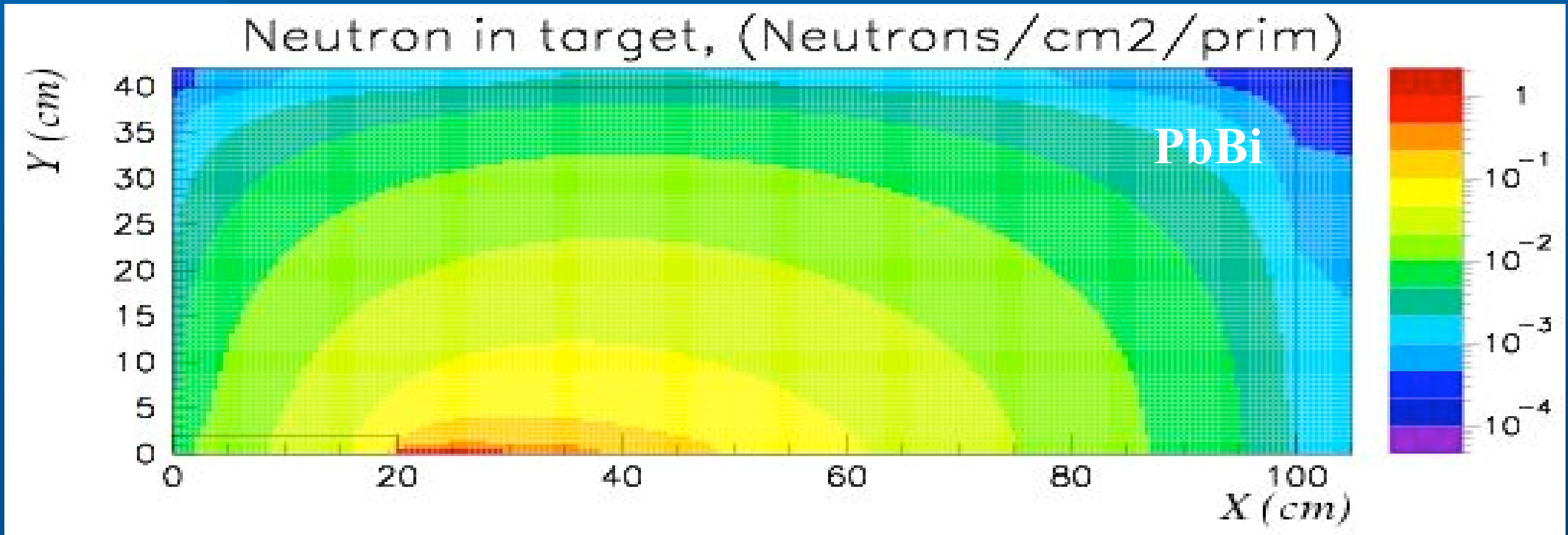
PbBi Alternative – Energy Deposition



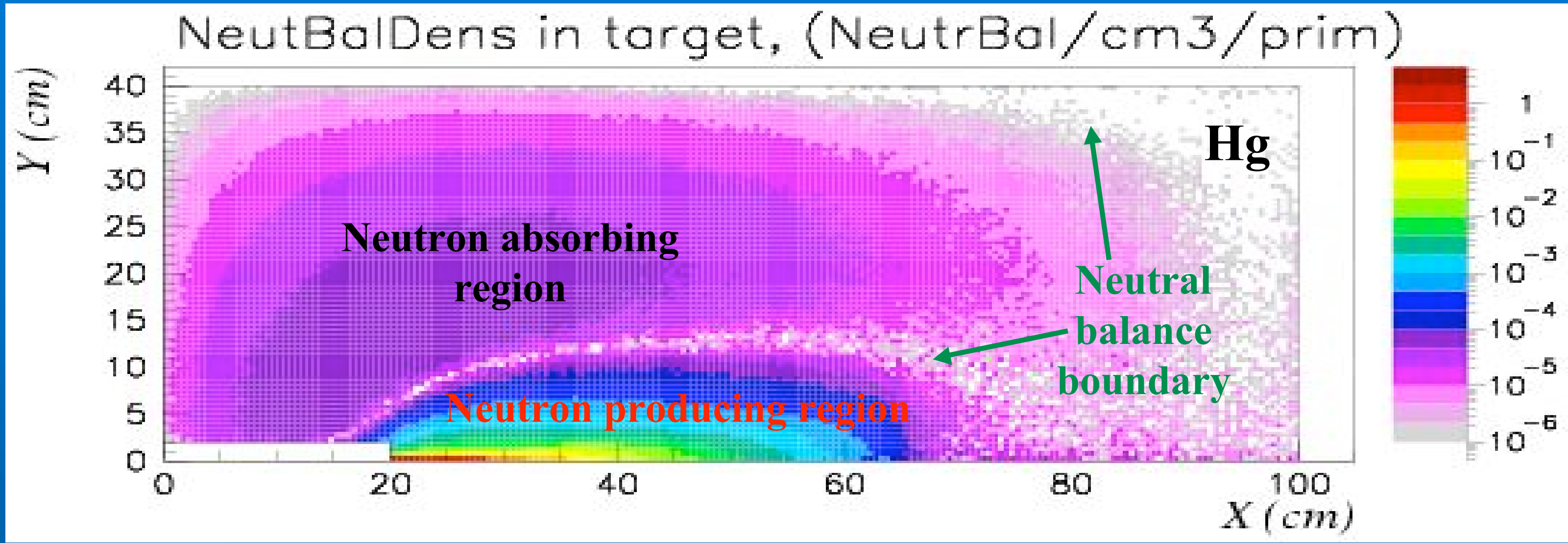


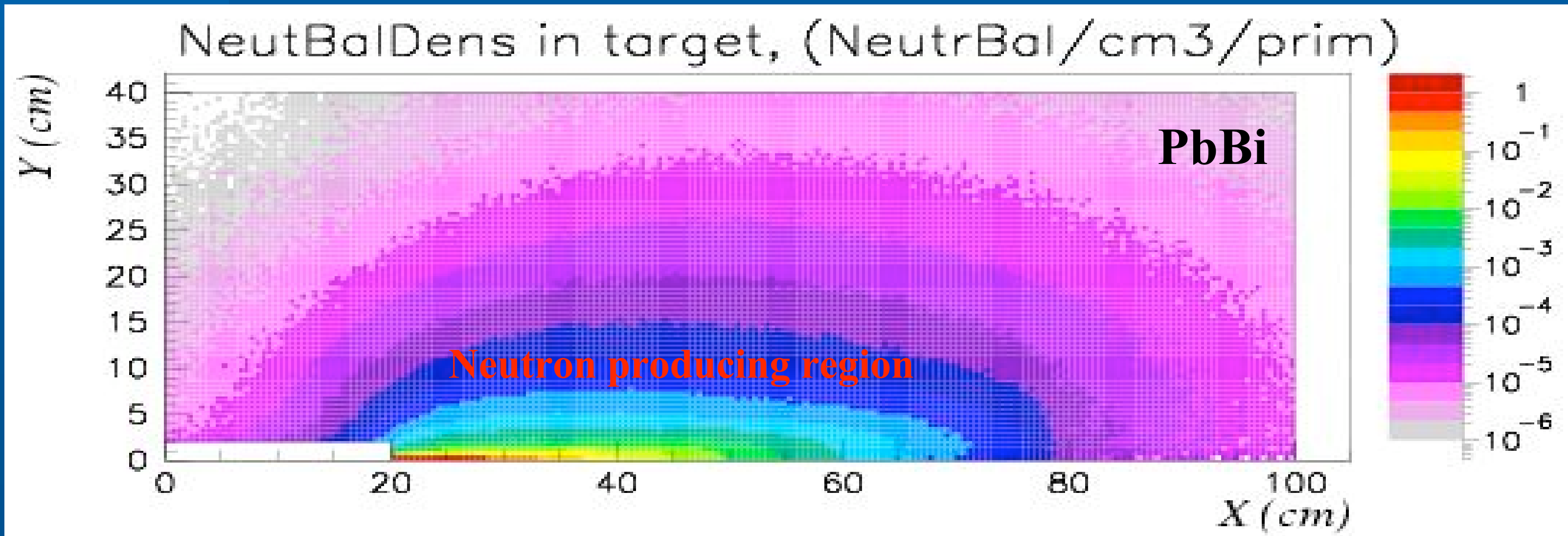
PbBi Alternative – Neutron Flux



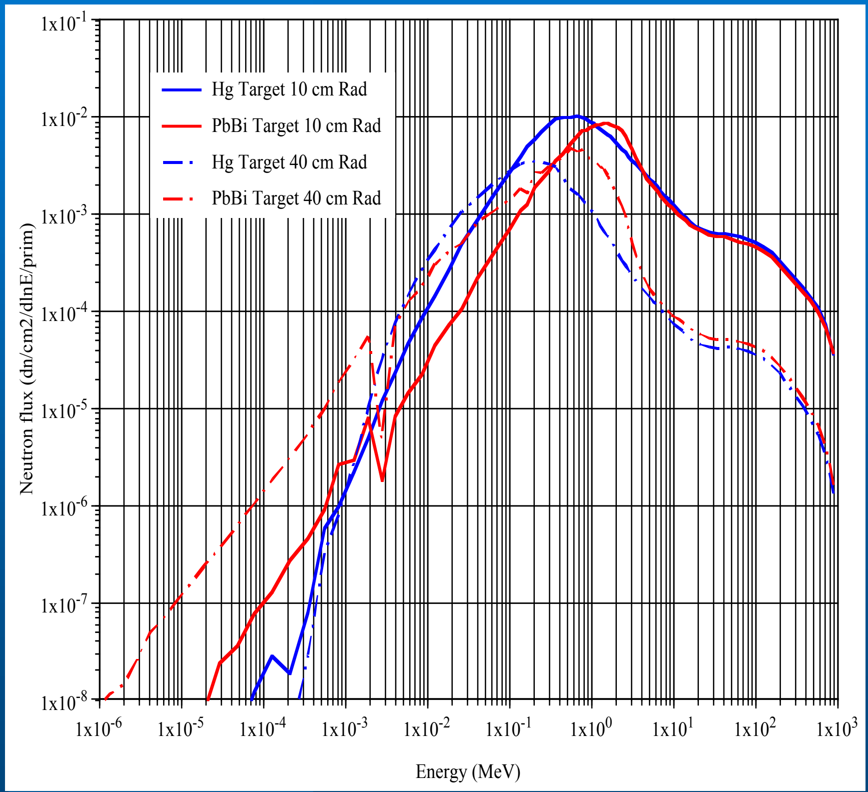


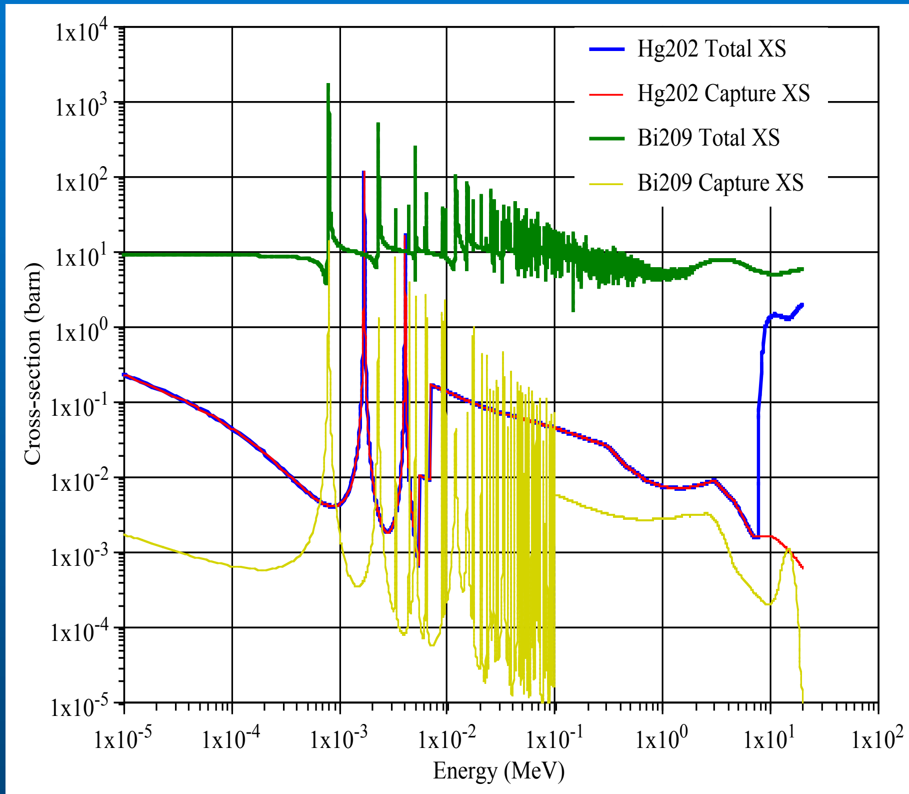
PbBi Alternative – Neutron Balance





PbBi Alternative – Neutron Capture Cross-section





Conclusions

- Optimised for neutron production:
  - Radius: 10 – 15 cm target radius from neutron balance point of view is enough
  - Length: Extend to the proton range to maximise neutron production and avoid charged particles in the UCx
- Energy Spectrum of the neutrons:

  Dominated by the intermediate neutron energy range (20 keV - 2 MeV)

  Harden neutron spectrum by reducing the target size (but reduce yield and increase HE charged particle contamination)

  Use of natural uranium to take advantage of the high fission cross-section of ^{235}U in the resonance region ⇒ Improvement thorough neutron energy moderation

  Alternatively, axial converter-UCx target configuration for depleted uranium target
- Very localised energy deposition, 20 cm from the impact point along the beam axis ~30 kW/cm^3/MW of beam power, reduced with the increasing proton energy
- Possibility of using PbBi eutectic to improve neutron economy and reduce maximum energy deposition

Future Work

- Optimise the energy deposition once the size is fixed

  Study the effect of the shape of the beam (parabolic, annular, variations in the sigma of the Gaussian distribution)

- Activation of the target (calculate the spallation product distribution)
- Model the fission target (including moderator/reflector) and optimise the fission yields
- Analyse alternative target disposition to improve the fission yields
- Study the use of deuterons as projectile particle