Investigations of Two-Step ISOL Targets for the Production of Exotic Ion Beams

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We report on work in progress...

- **The majority of the work presented was sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory (ORNL)**

- **ORNL is managed by UT-Battelle, LLC for the U. S. Department of Energy under Contract No. DE-AC05-00OR22725.**

We report on work in progress...

- **Broader R&D effort on the RIA ISOL target area, supported by DOE under contract number DE-FG02-04ER41322 carried out by a multi-institution collaboration involving:**
  - **Michigan State University,**
  - **Oak Ridge National Laboratory,**
  - **Lawrence Livermore National Laboratory,**
  - **Lawrence Berkeley National Laboratory, and**
  - **Los Alamos National Laboratory.**

Outlay

- **Design of 2-Step ISOL targets**
  - **Simulations of interaction of primary beams with the target**
  - **Calculation of fission density and heating in the secondary target**
  - **Cooling (thermo-hydraulic consideration)**
- **Conclusions**

Conceptual Design of ISOL Targets

Challenging requirements for simulations:

- P, n, d, and ion transport and interactions in the targets, beam dumps, magnets, etc.
  - Transport in magnetic fields required
- Calculation of isotope yields, energy deposition, and radiation damage
- Simulation of rare isotopes “extraction” from the target and transport to the experiments
- Determination of the radiation fields, dose levels, and shielding requirements during operation
- Calculation of radioactive inventory build up in the target, post-operation decay heat, and dose rates
- Determination of cooling requirements and stress analysis

ISOL Targets Conceptual Design (Cont.)

The codes we use for simulations

Particle and ion transport

- PHITS (RIST, Japan)
  - Includes heavy-ion transport and interaction
  - Allows magnetic fields
- MCNPX (LANL)
- MARS15 (Fermilab)

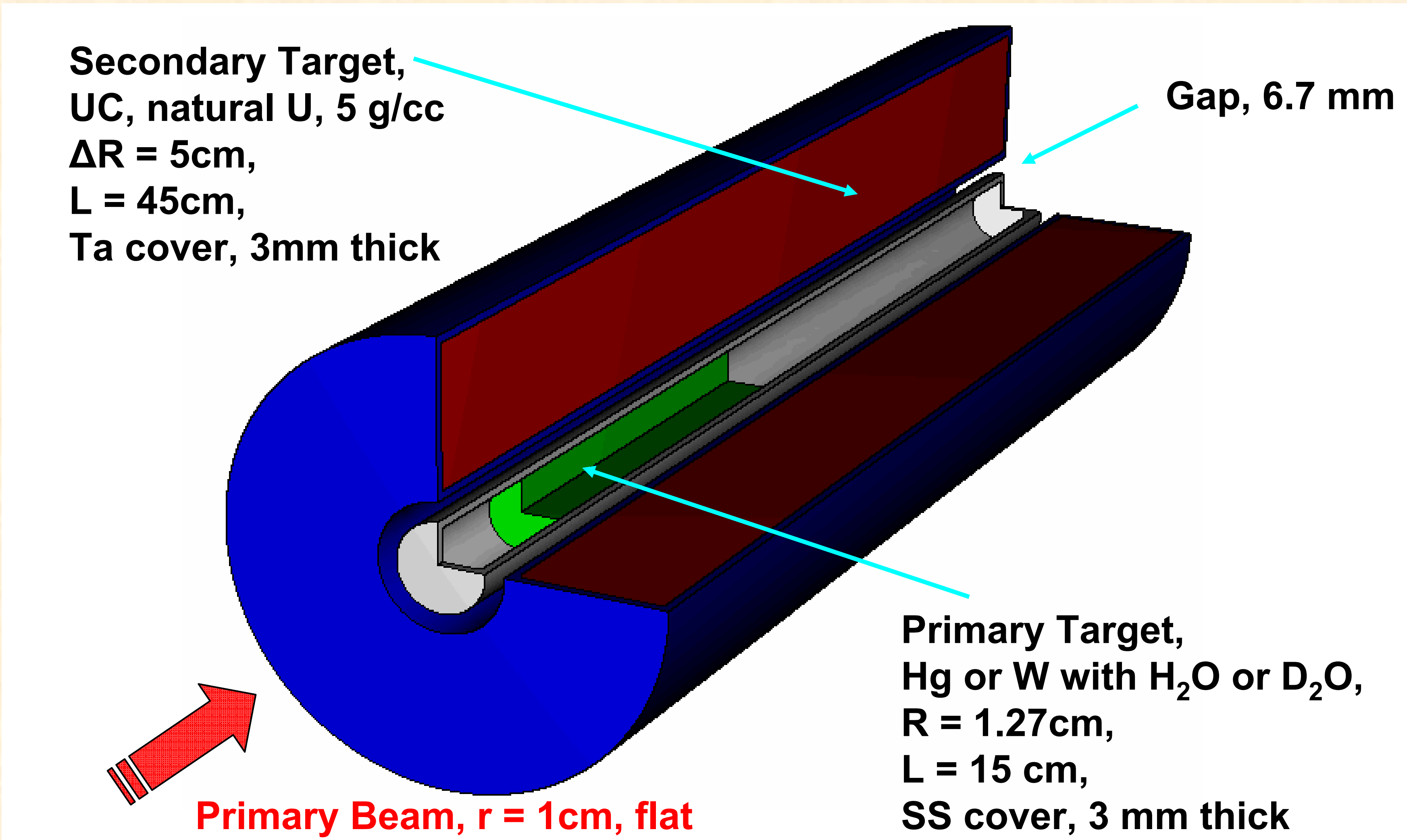
Activation calculations

- Activation Analysis System (AAS) (ORNL, with MCNPX)
- ACAB98 (LLNL)
- DCHAINSP2001 (JAERI, with PHITS)

Work on Conceptual Design of Two-Step ISOL Targets

- **A two-step target was first proposed by J.A. Nolen (ANL)**
  - **Primary beam incident on a neutron-producing high-Z "primary" target**
  - **Neutrons induce fissions in a "secondary" target filled with fissionable material**
- **Advantage:**
  - **Thermally decouples primary beam region and fission region (important at high power beams when cooling is a problem)**
  - **Decouples fission (secondary) and spallation (primary) regions, and therefore reduces isobar contamination in the production of neutron-rich fission products**

Two-Step "Generic" Target



Two-Step "Generic" Target (Cont.)

- **Primary targets considered (to date):**
  - **Hg (serves as target and coolant, can be reused, etc.)**
  - **W with H_2O or D_2O coolant**
    - **10% coolant** } **(by volume)**
    - **20% coolant**
- **Secondary target - UC at 5 $g \cdot cm^{-3}$**
- **Primary beams:**
  - **1-GeV protons**
  - **622-MeV/u deuterons**
  - **777-MeV/u He-3**
- **Primary beam power 400 kW**

Two-Step "Generic" Target (Cont.)

Results for 400-kW beam of 1-GeV protons on Hg primary

- **Produces 1.8 × 10^{15} fissions/s in secondary**
- **Deposits:**
  - **106 kW in primary,**
  - **71 kW in secondary in UC only**
    (84kW including Ta cover)
- **Maximum heating rate in primary ~4.3 kW/cm^3**
- **Dpa rate in steel "beam window" ~5 dpa/month**

Comparison of p, d, and He-3 beams, at Equal Beam Power

	Number of fissions in UC			Energy deposited in primary		
	Hg	0.9 W + 0.1 H_2O	0.9 W + 0.1 D_2O	Hg	0.9 W + 0.1 H_2O	0.9 W + 0.1 D_2O
p, 1 GeV	1.00	1.03 (1.00)*	1.03 (1.00)*	1.00	1.19 (1.32)*	1.19 (1.30)*
d, 622 MeV/u	0.99	1.05	1.05	0.99	1.20	1.20
He-3, 777 MeV/u	0.85	0.86	0.86	1.44	1.72	1.72

*For 0.8 W + 0.2 H_2O or D_2O

Note that results are normalized to p-on-Hg-target results.
1.8×10^{15} fissions/s in secondary, 106 kW in primary.

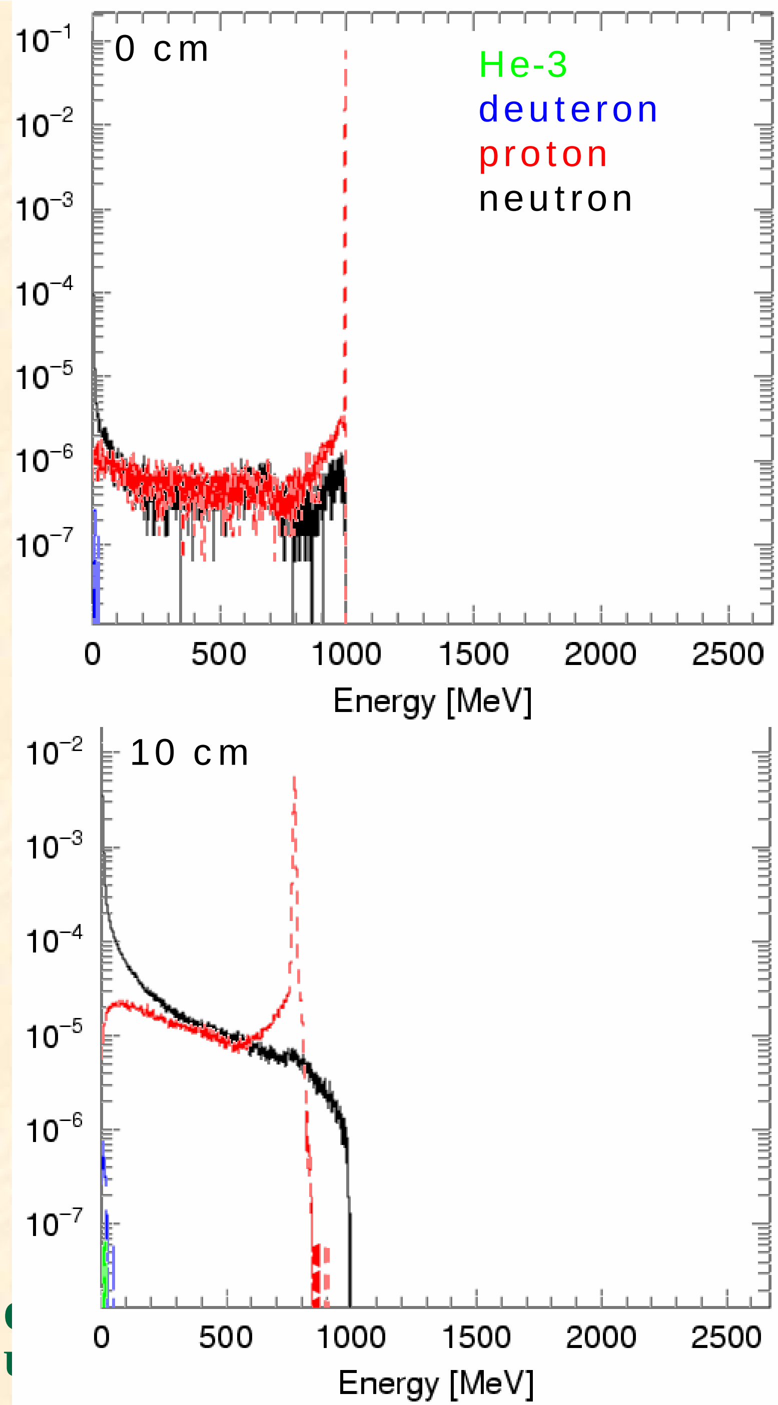
Comparison of p, d, and He-3 beams at Equal Beam Power

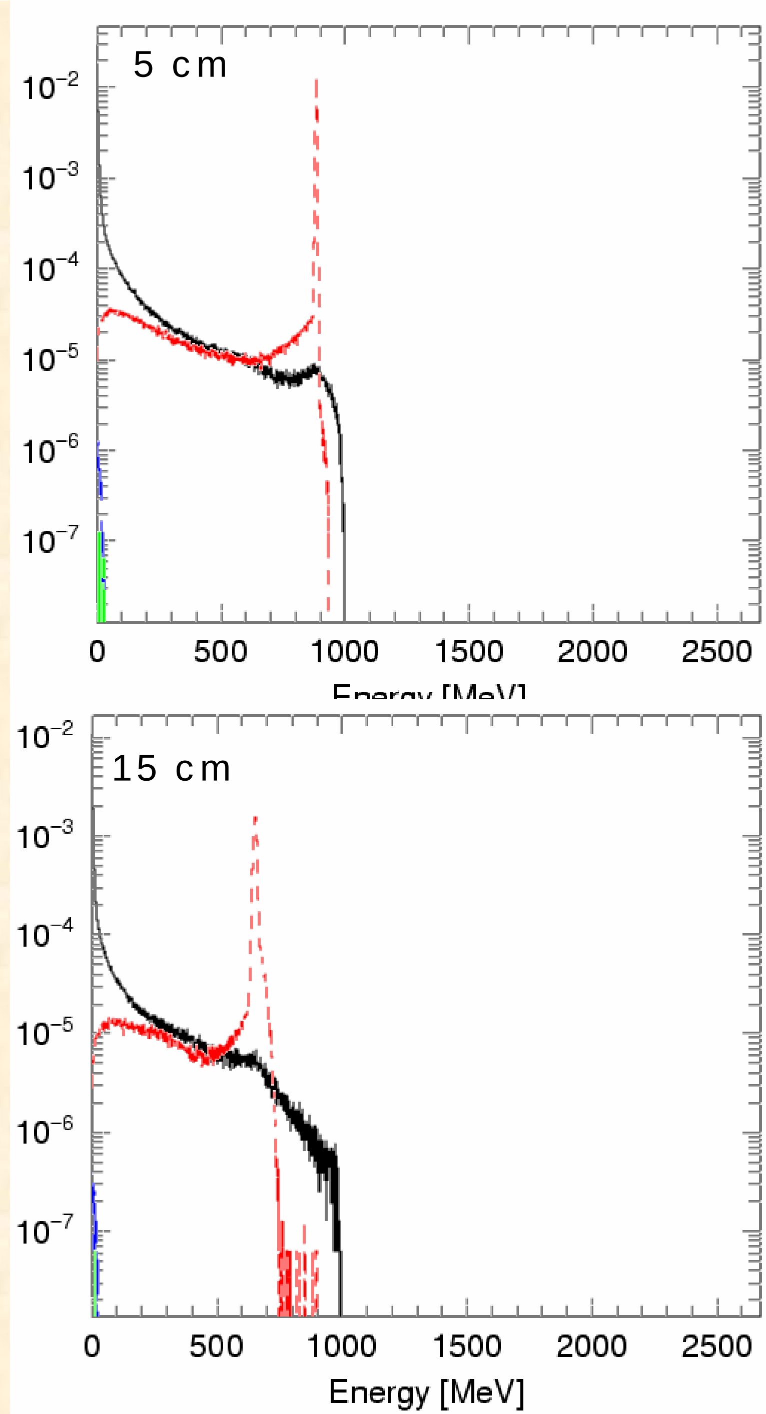
	Number of fissions in UC			Energy deposited in secondary		
	Hg	0.9 W + 0.1 H_2O	0.9 W + 0.1 D_2O	Hg	0.9 W + 0.1 H_2O	0.9 W + 0.1 D_2O
p, 1 GeV	1.00	1.03 (1.00)*	1.03 (1.00)*	1.00	1.02 (1.01)*	1.03 (1.01)*
d, 622 MeV	0.99	1.05	1.05	0.96	1.01	1.01
He-3, 777 MeV	0.85	0.86	0.86	0.87	0.85	0.85

*For 0.8 W + 0.2 H_2O or D_2O

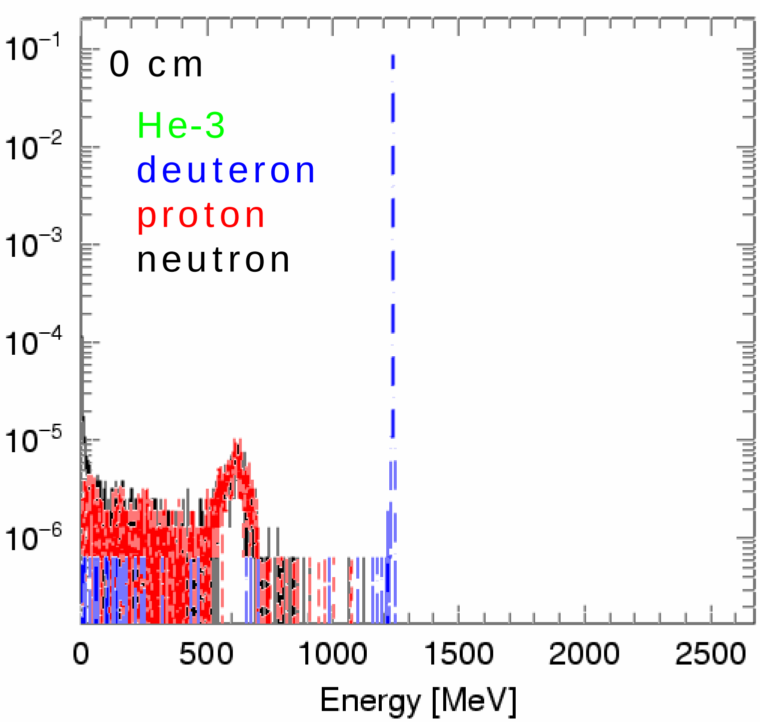
Note that results are normalized to p-on-Hg-target results. 1.8×10^{15} fissions/s in secondary, 71 kW in primary.

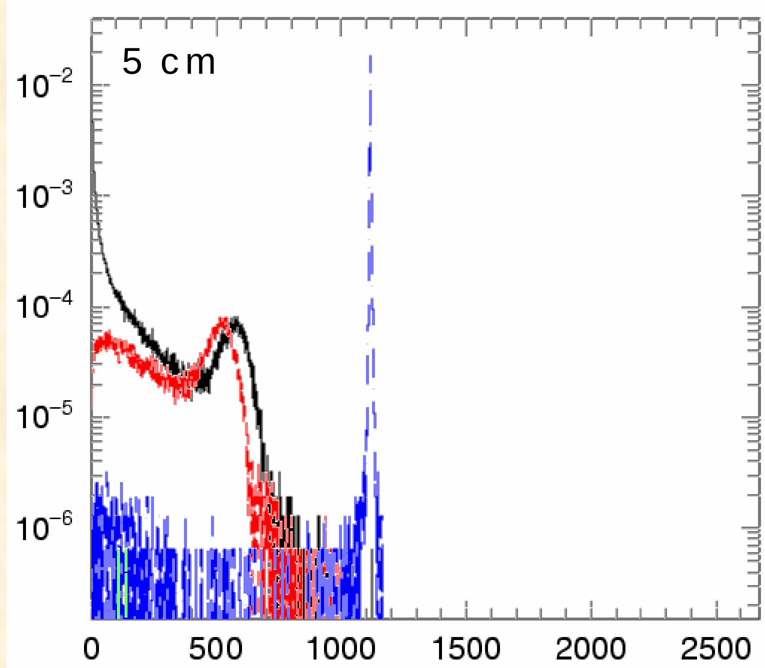
Particle Current Through Primary Target, 1000 MeV p Beam, $W+H_2O$ Target

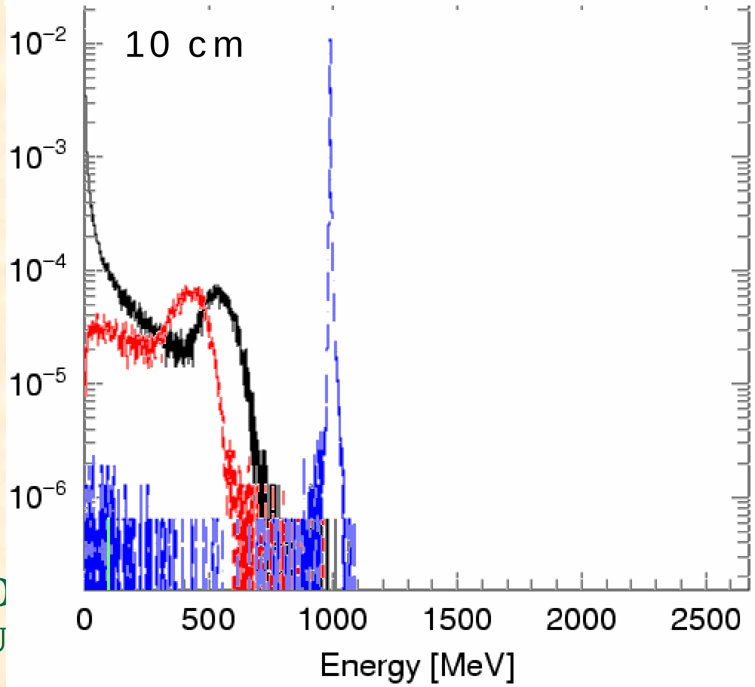


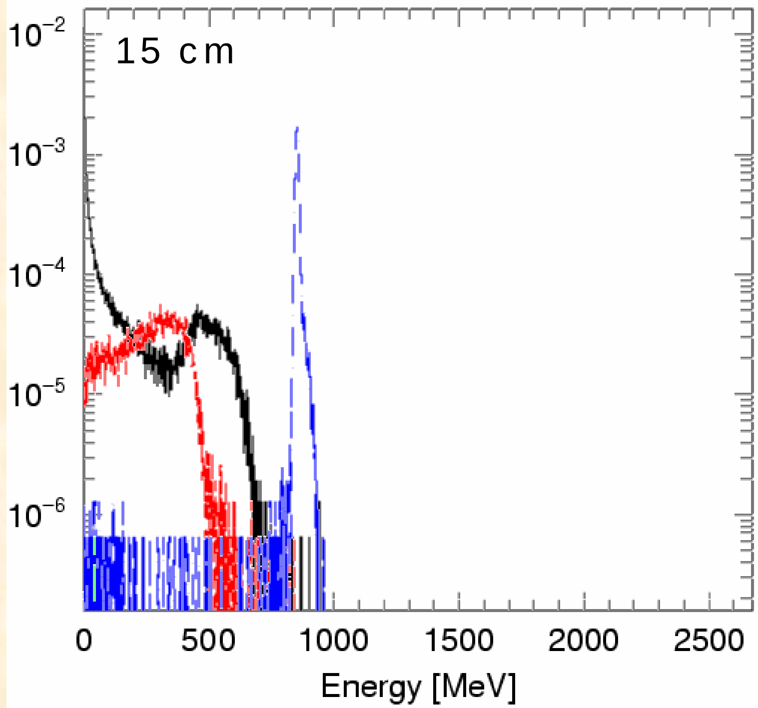


Particle Current Through Primary Target, 622 MeV/u d Beam, W+H_2O Target



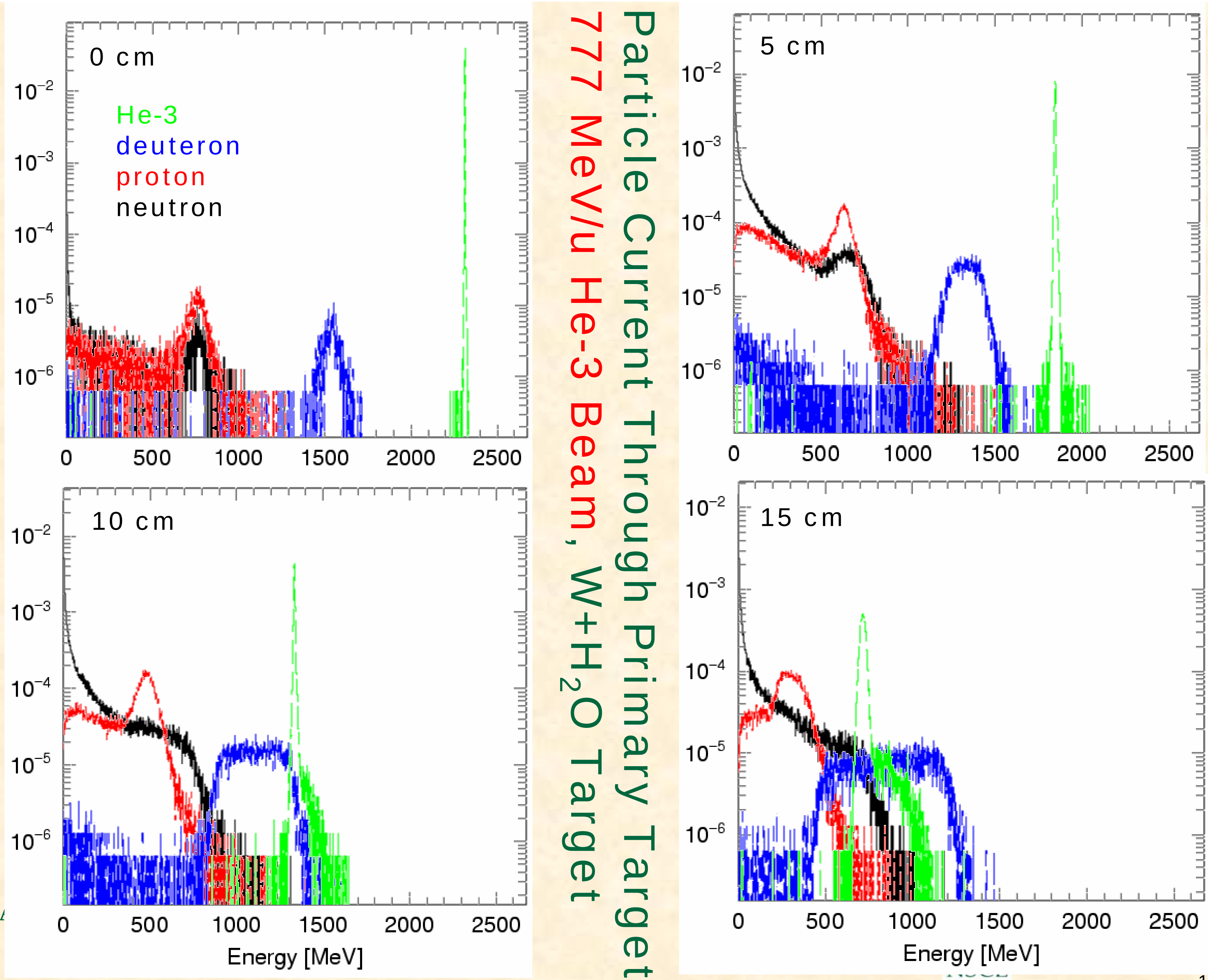






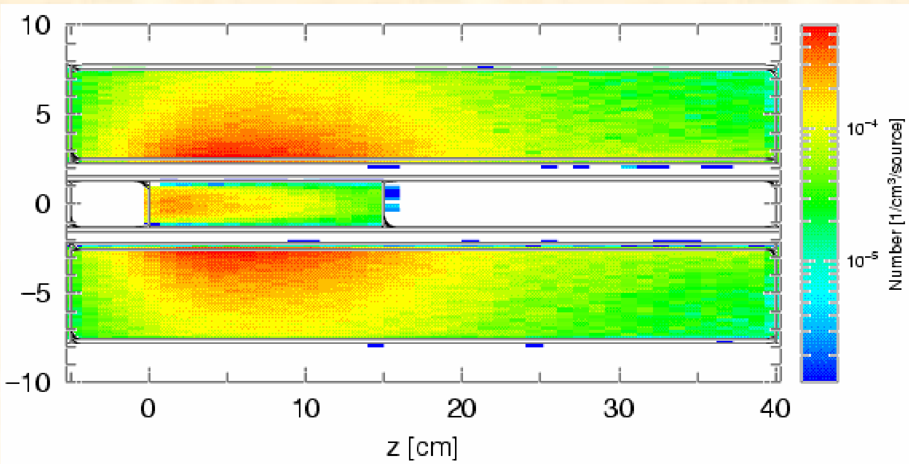
Particle Current Through Primary Target,

777 MeV/u He-3 Beam, W+H_2O Target

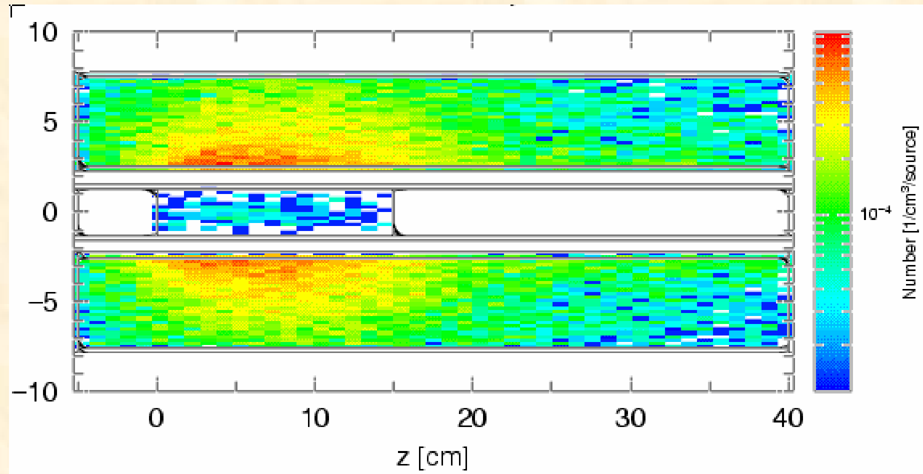


Fission Density Distributions (per Beam Particle)

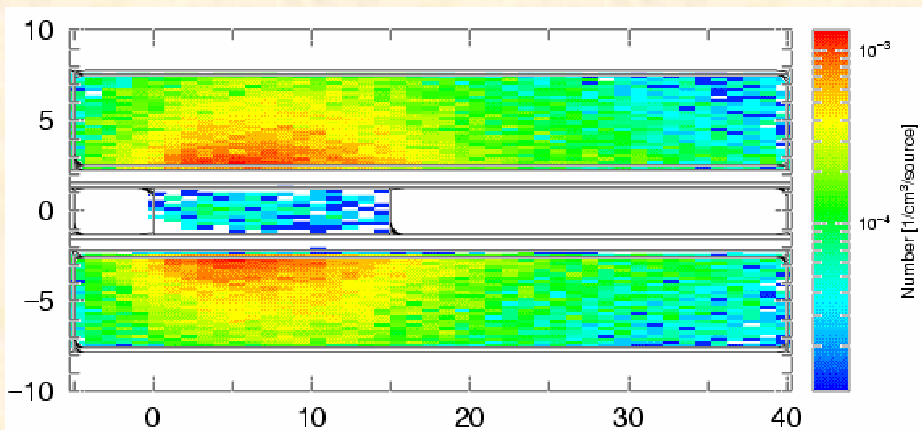
Proton



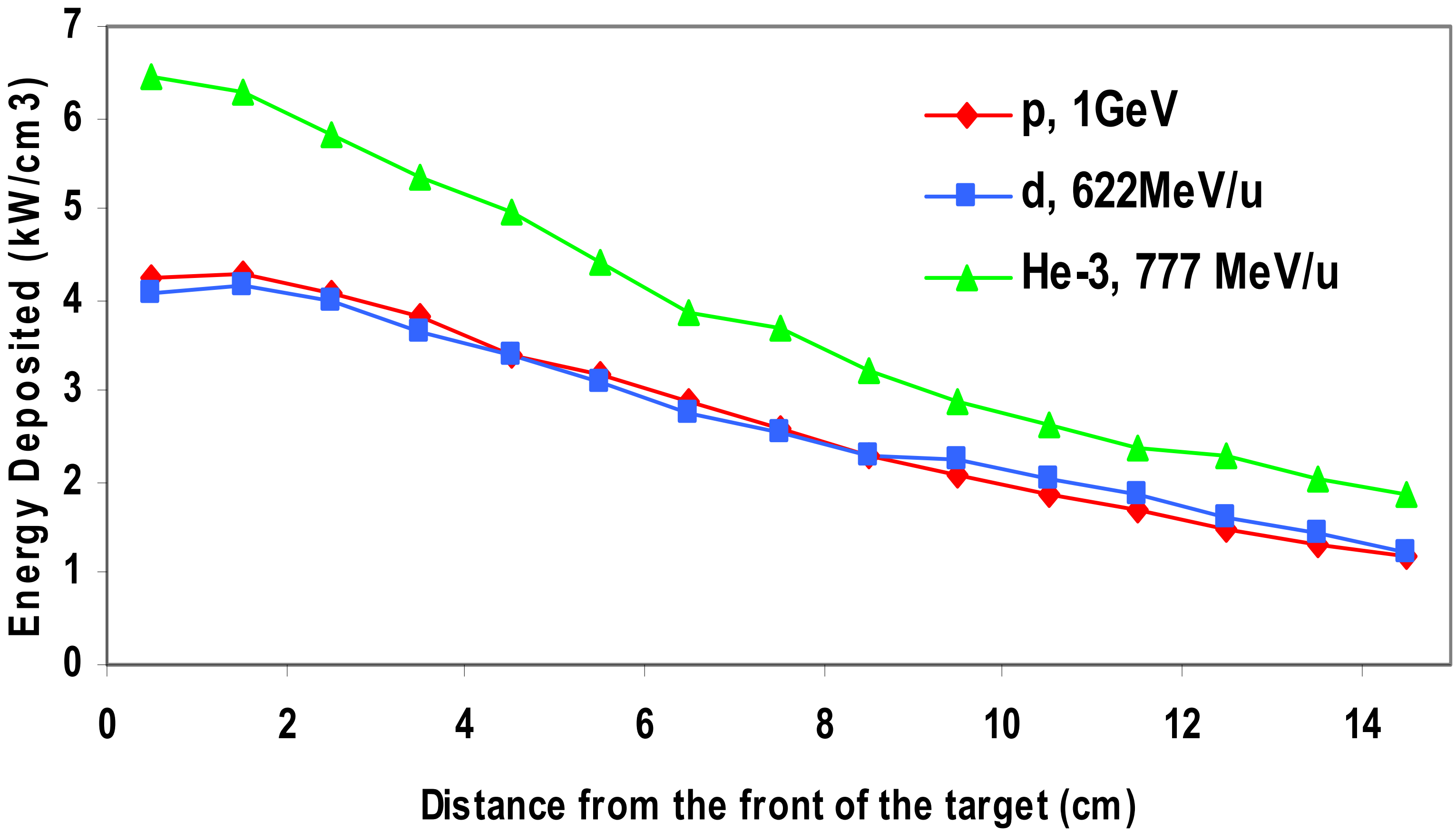
Deuteron



He-3



Heating Profiles in the Primary Target, Along the Axis



Target is W with 10% by volume of heavy water.

Target Cooling

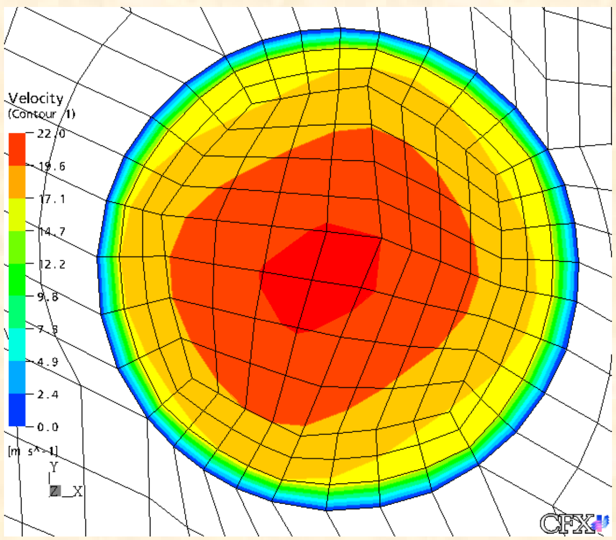
- **Requirements & Limitations**
  - **Primary target:**
    - **Keep T below limit imposed by target material-coolant flow combination**
    - **Uniform T not needed**
    - **Coolant flow through primary target acceptable**
  - **Secondary target:**
    - **Uniform (and high) T desired, but limited to below ~2100ºC for UC_x**
    - **UC_x thermal conductivity is rather low**
    - **"Opened" structure needed for efficient ion effusion**
    - **Coolant channels through secondary "not desirable"**

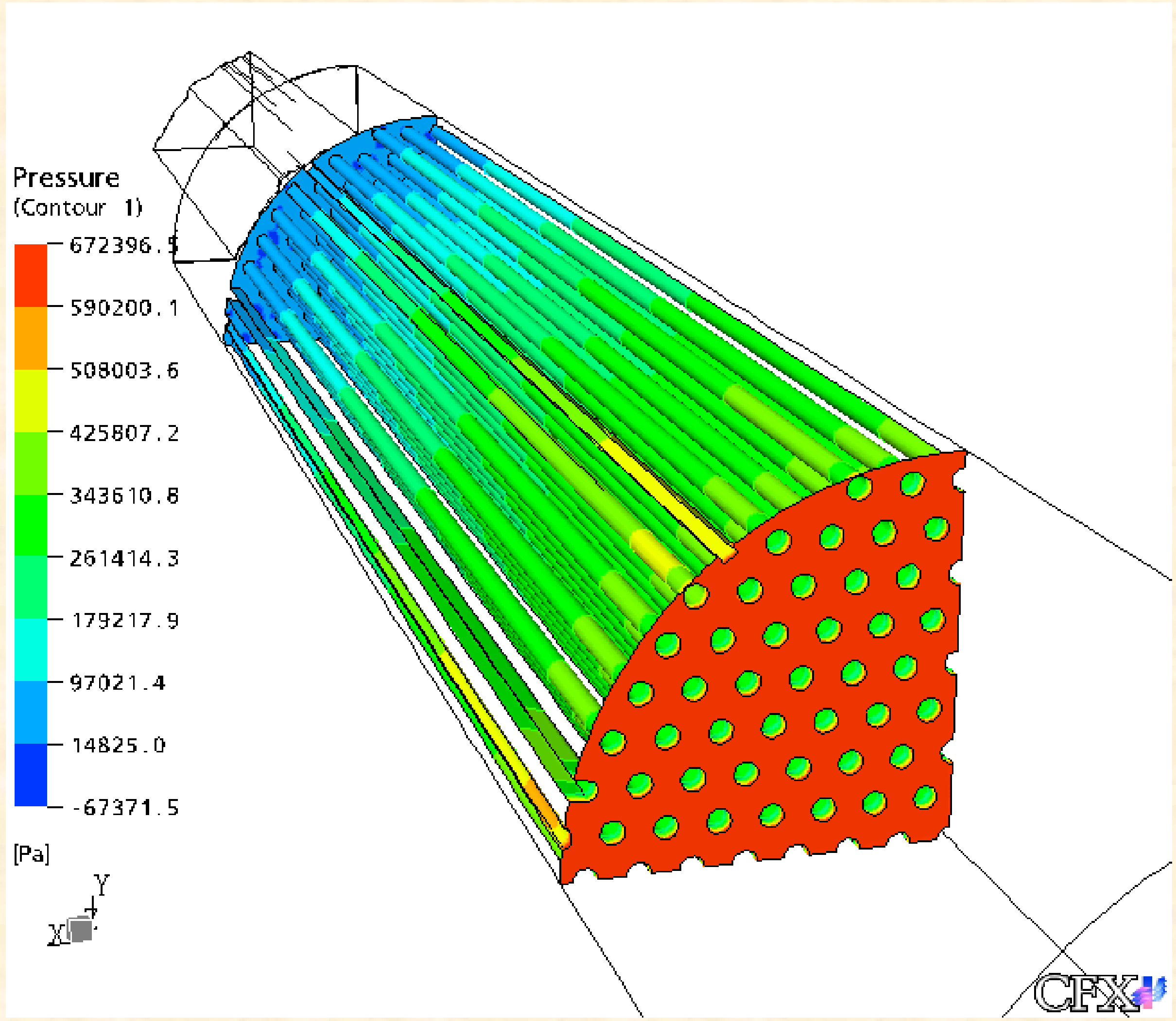
Preliminary Target Cooling Results

For 400-kW beam of p or d the primary target can be cooled with water flow

- **Maximum heat load ~ 5kW/cm^3**
- **Water takes up ~20 % of the primary target volume (coolant channel diameter ~1.6 mm, pitch 3.4 mm)**
- **Temperatures:**
  - **Tungsten < 225^{o}C**
  - **Water < 140^{o}C**
- **Water flow of ~ 2 liters/s**
- **Pressure drop ~ 0.7 MPa,**
- **Water velocity ~ 18 m/s**

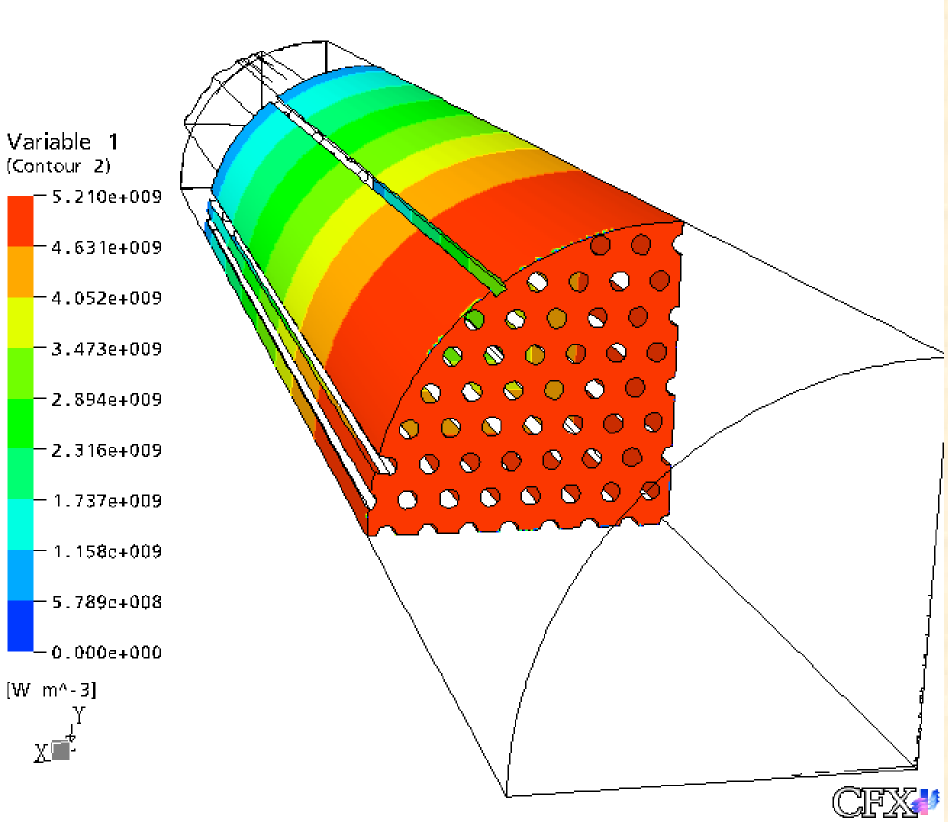
Primary Target Cooling:
Water channels have average velocity of 18.4 m/s



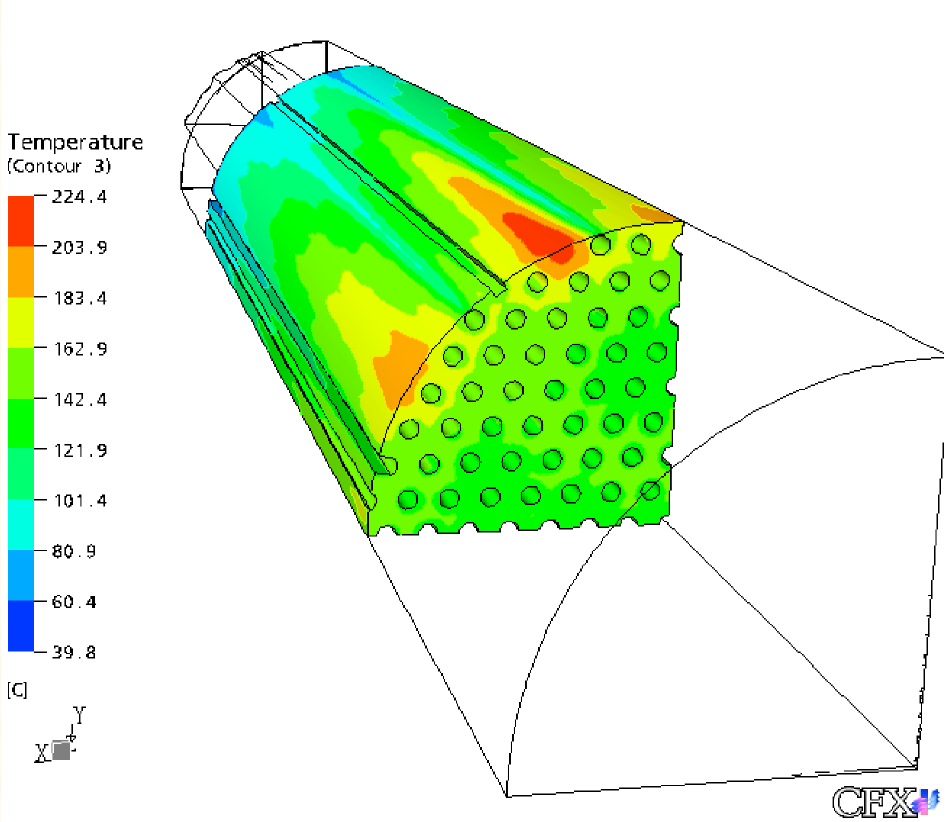


Thermal results with a flat beam profile show acceptable temperatures for axial flow design.

Heat Load



Computed Temperatures



Secondary Target Cooling

Modeling Assumptions

- Radiative cooling to the surrounding
- Thermal radiation from inner and outer radial surfaces to cooled cylindrical surfaces
- 7 mm gap between inner surface and adjacent cooled surface
- 10 mm gap between outer surface and adjacent cooled surface
- Cooled surfaces (not parts of the secondary target; the primary target inside and the shielding outside) are at ~200°C
- All surfaces are gray with emissivity of 0.5
- Front and back of the target assumed adiabatic (not cooled)
- Maximum operating temperature for uranium carbide is 2100°C

Uranium Carbide Thermal Conductivity

“Thermal Conductivity Measurements Of Uranium Carbide by Electron Bombardment”, John P. Greene, et al

“Characterization Studies of Prototype ISOL Targets for the RIA”, John P. Greene, et al

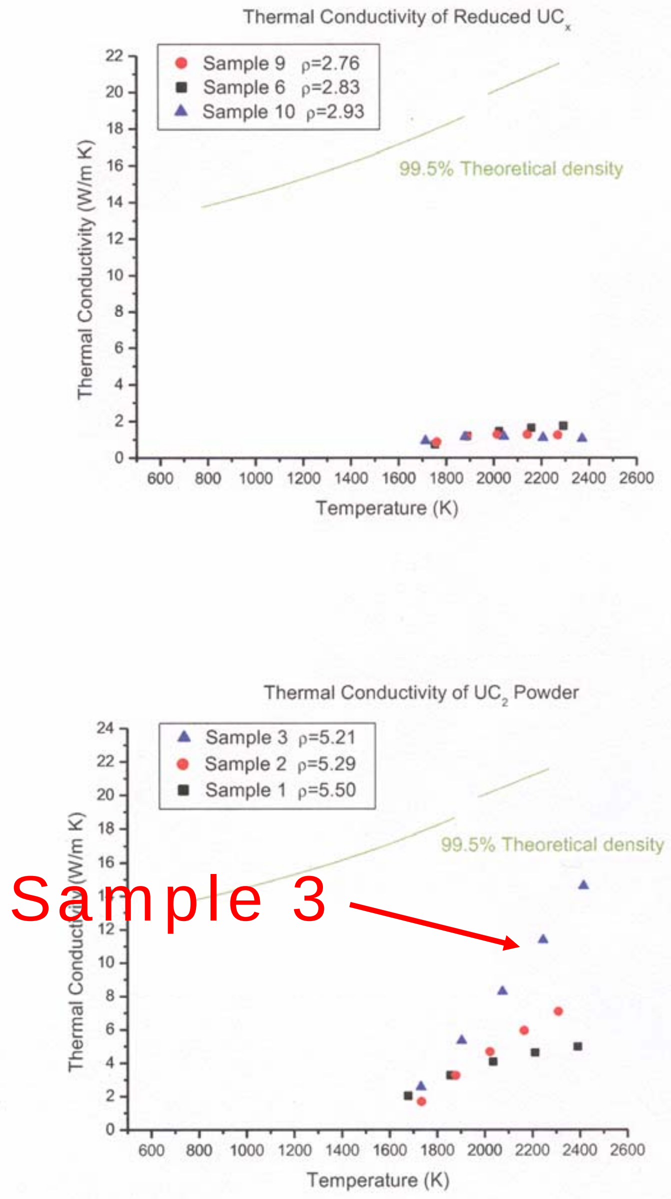


Fig. 5: Initial thermal conductivities obtained for reduced UC_x (top) and UC_2/C (bottom) samples as a function of temperature. Also shown is the thermal conductivity for a “UC_2 Nukem melt”sample (Ref. 3) of 99.5% theoretical density.

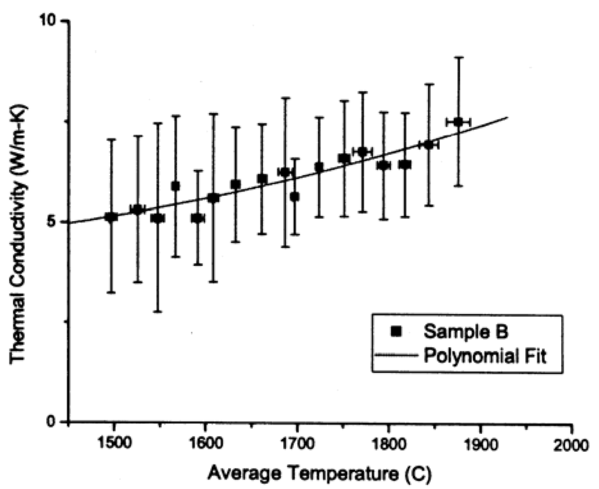
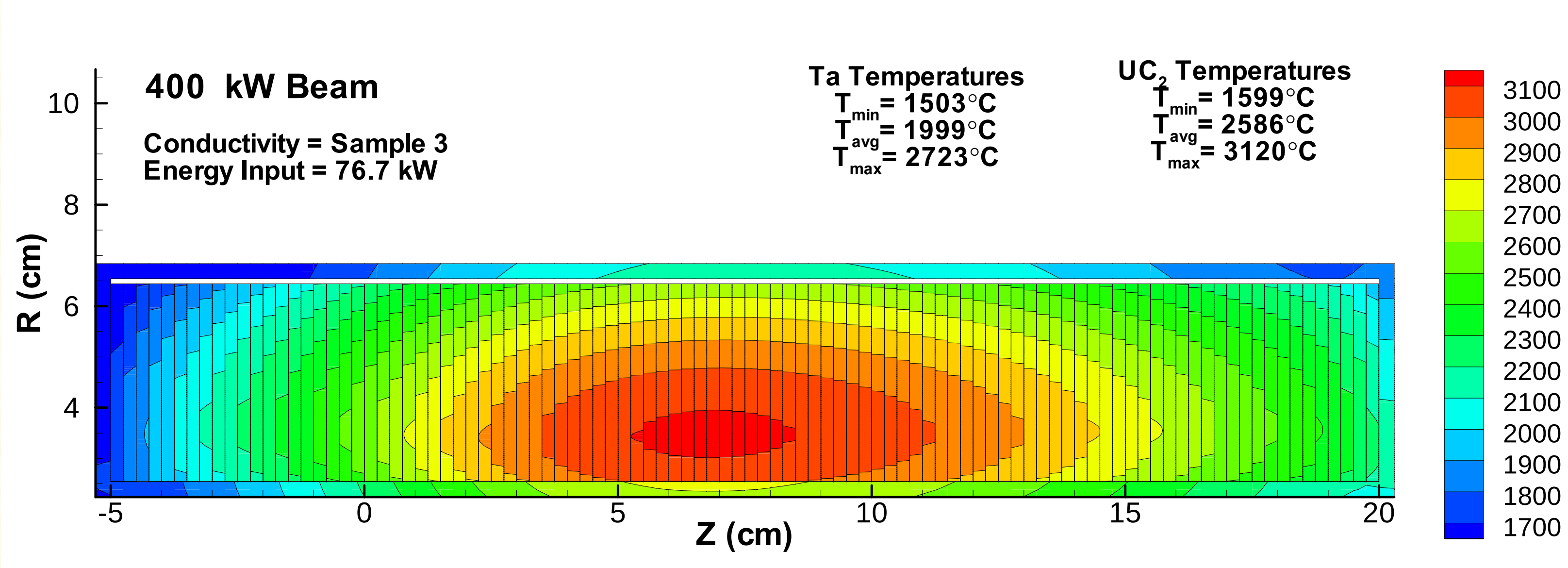


Fig. 2. Plot of thermal conductivity versus temperature for one UC_2 pellet sample.

Temperature Field in Secondary



Target parameters: Temperature too high!

Primary is 15 cm long, 0.8W + 0.2D2O

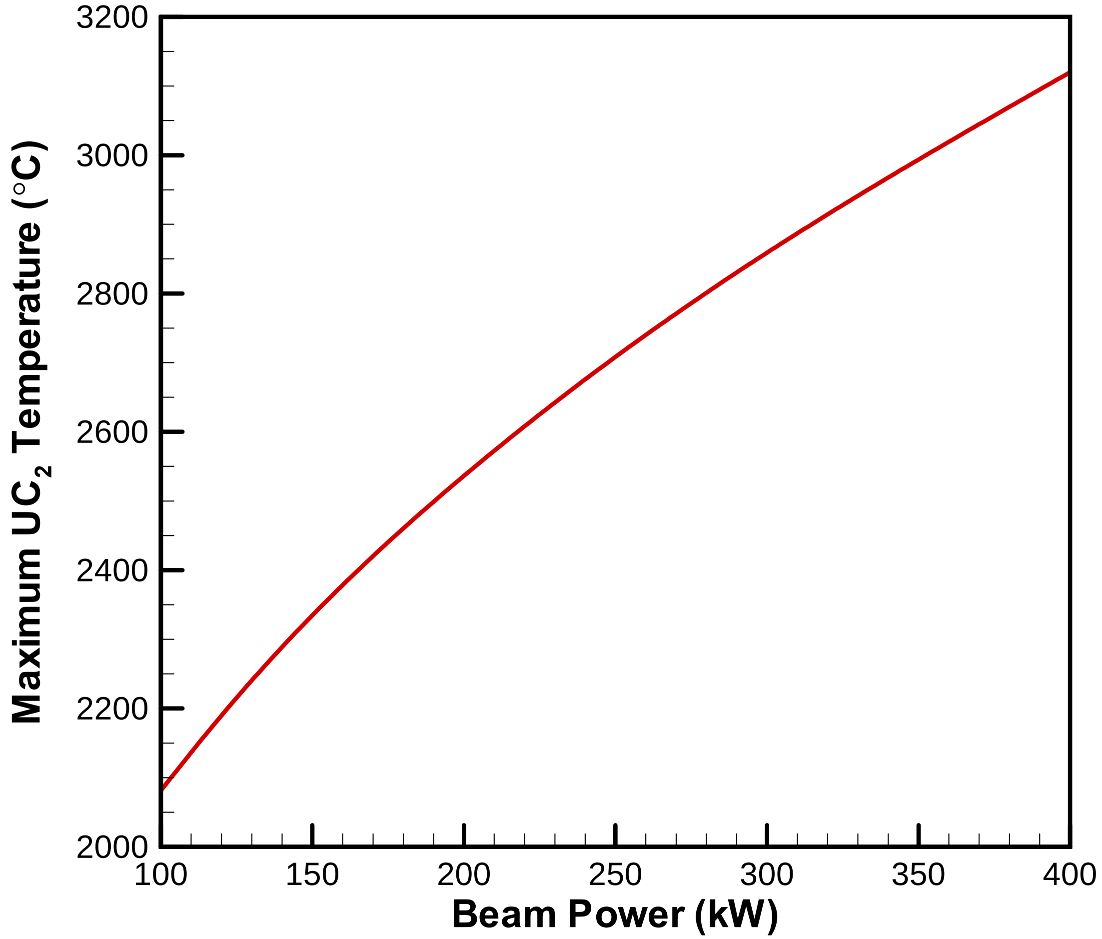
Secondary is UC at 5g/cc, 25 cm long,

4 cm thick (from r=2.54 cm to r=6.54cm)

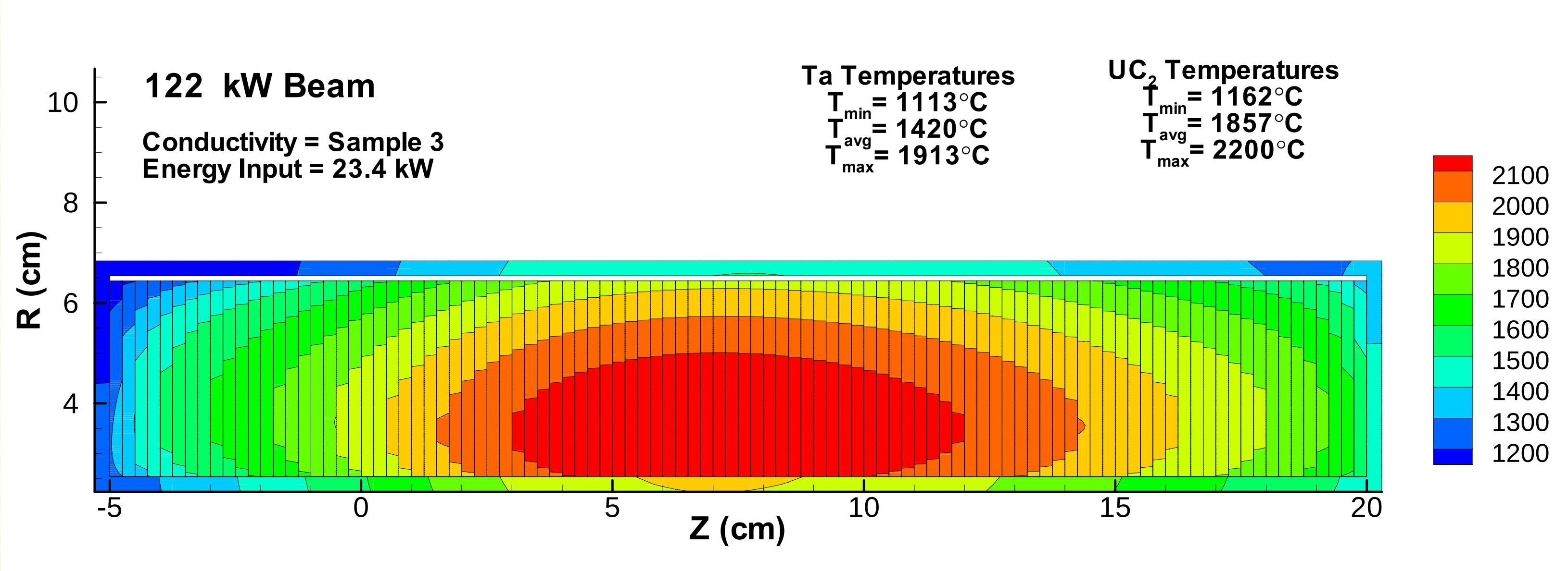
At 400 kW, fission rate is 1.14×10^{15}/s

In temperature calculations UC was in the form of 100 discs, separated by thin gaps.

Max. T in UC versus Beam Power, for the Target in Previous Slide



Temperature Field in Secondary



To keep the UC temperature < 2100ºC, the beam power had to be lowered to 122 kW.

Cooling of the secondary target is the limiting factor for the maximum beam power on the 2-step ISOL target. At ~122 kW beam power the fission rate for this target is ~3.5 E+14 fissions/s.

Conclusions

- **Primary target material:**
  - Hg and W with up to 20% (by volume) of water were found to produce about the same number of fissions in the secondary and heating in the primary and secondary.
  - Using heavy water offers no advantage over ordinary water, probably because of relatively small volume involved.
- **Beam comparisons:**
  - 1-GeV proton and 622-MeV/u deuteron beam are about equivalent in terms of fission rates and heating
  - 777-MeV He-3 beam produces less fissions and higher heating
    - Would probably require > 20% of water (by volume) in the primary for cooling
  - The use of proton beams only appears likely for 2 step ISOL targets

Conclusions (Cont.)

Beam power:

- W primary target can be cooled with water flow for 400-kW beam of p or d
- Cooling of the secondary UC_x target appears to be the limiting factor for the maximum beam power on the 2-step ISOL target
- For the target design considered in this work the maximal beam power appears to be in 100 – 200 kW range and the resulting fission rate is in the range 0.5 – 1 × 10^{15} fissions/s.