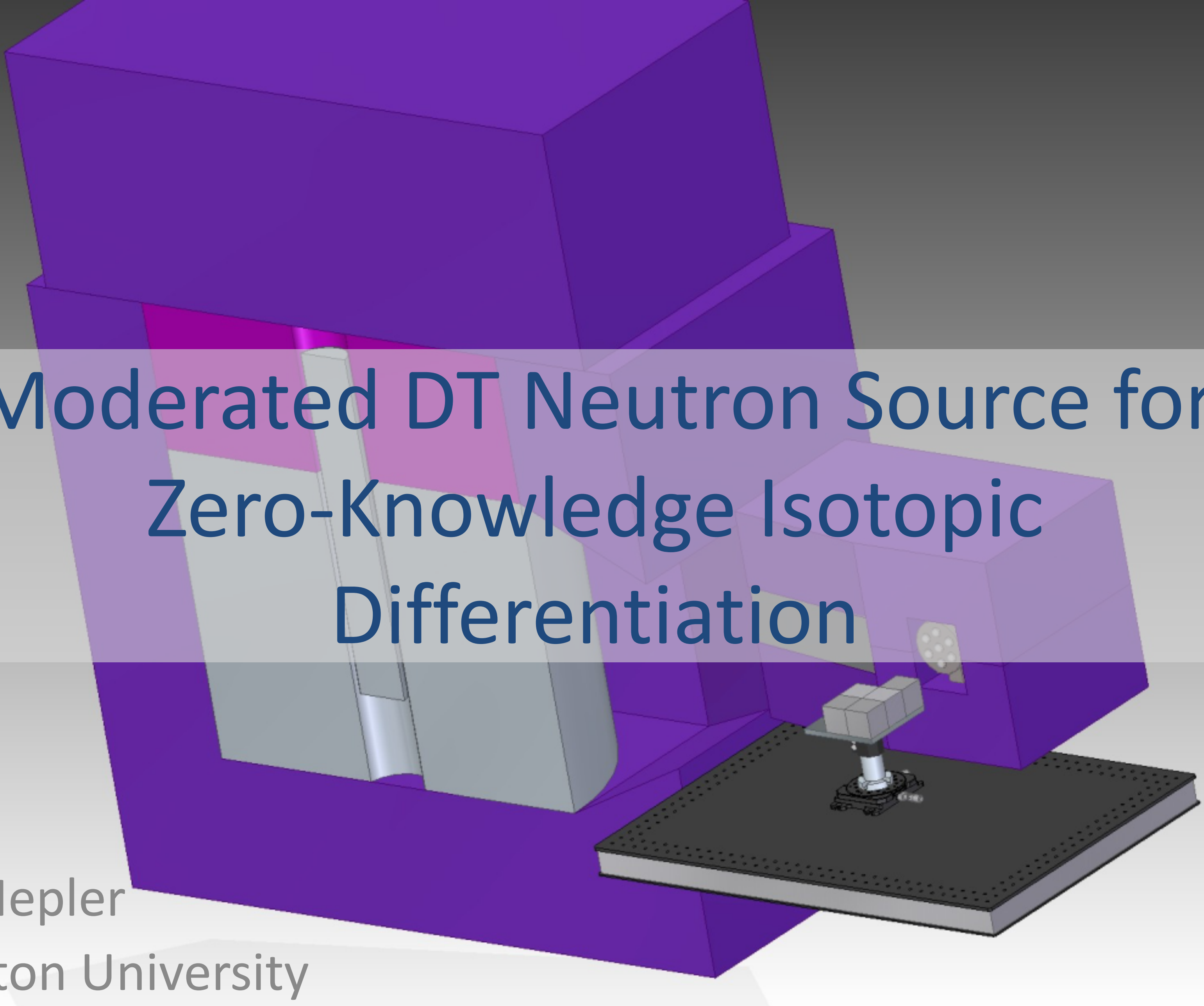
V 02



Moderated DT Neutron Source for Zero-Knowledge Isotopic Differentiation

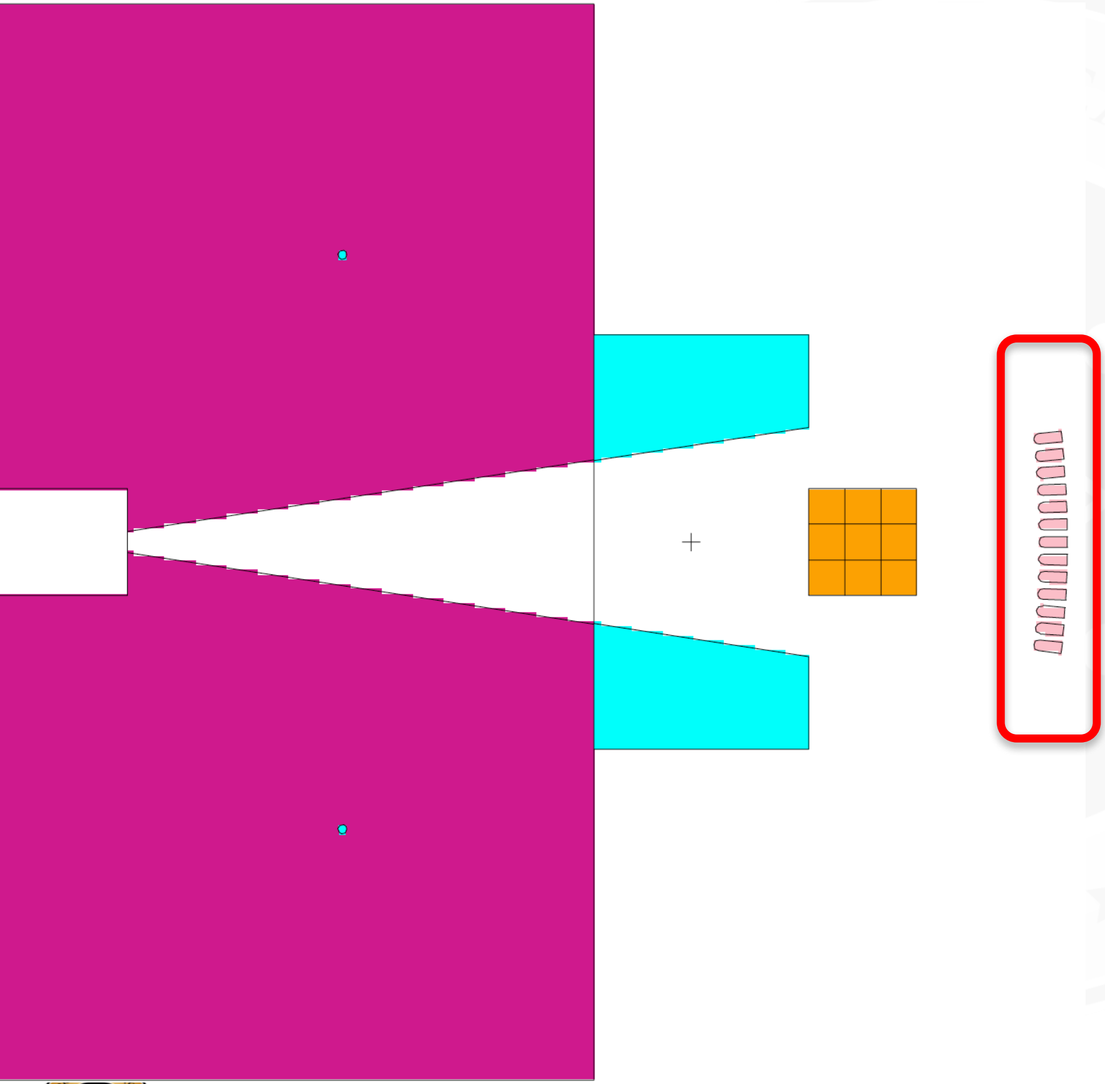
Mike Hepler

Princeton University

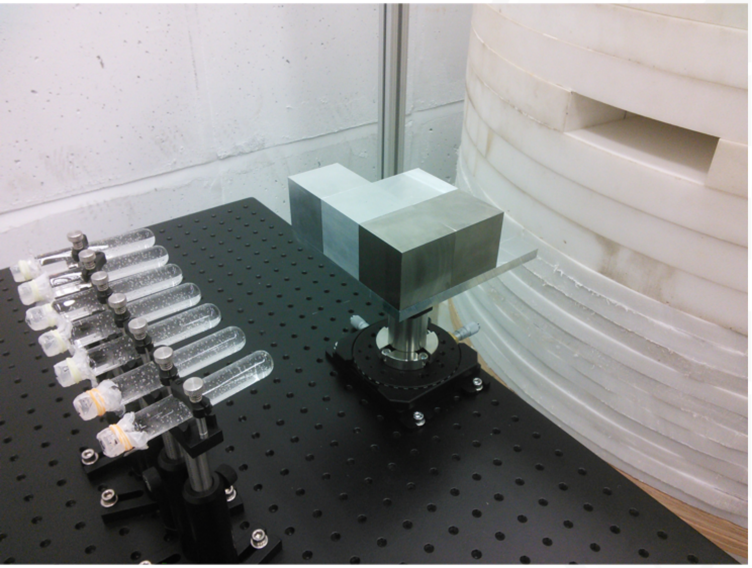
Organization

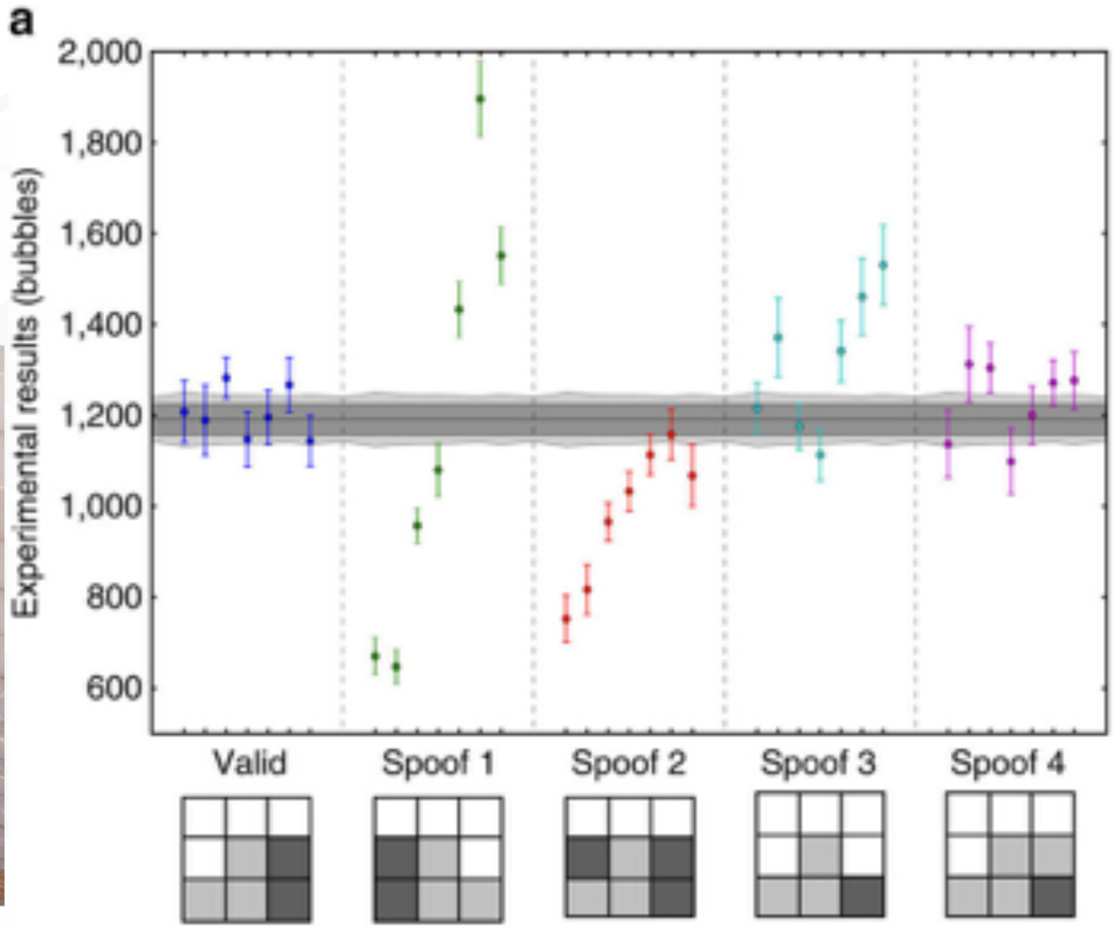
- State of Zero-Knowledge Experiment
- Moderated DT Collimator Source
- Moderator Integration and Optimization
- Simulation Test Results

State of ZKP: Princeton



State of ZKP





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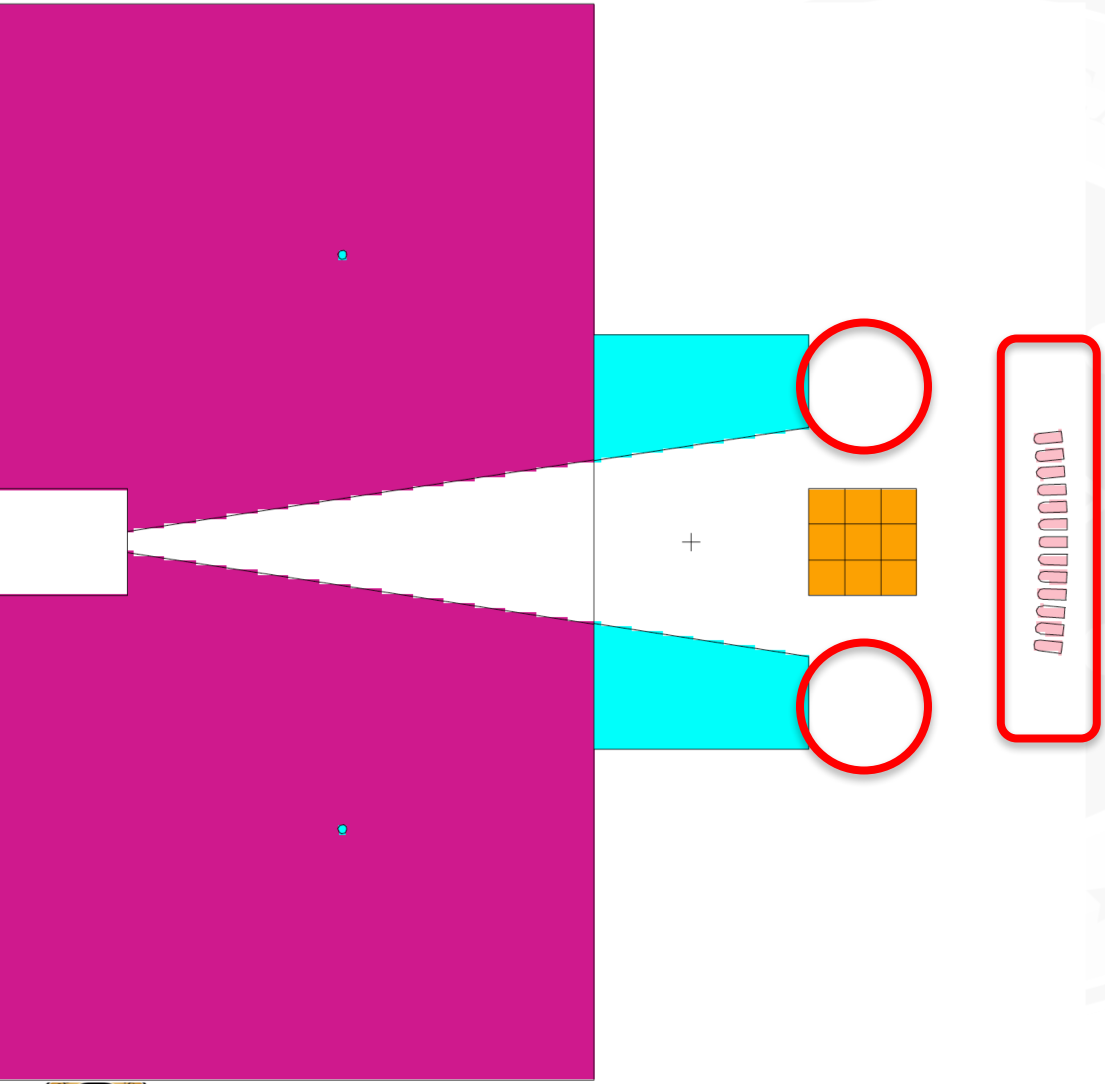
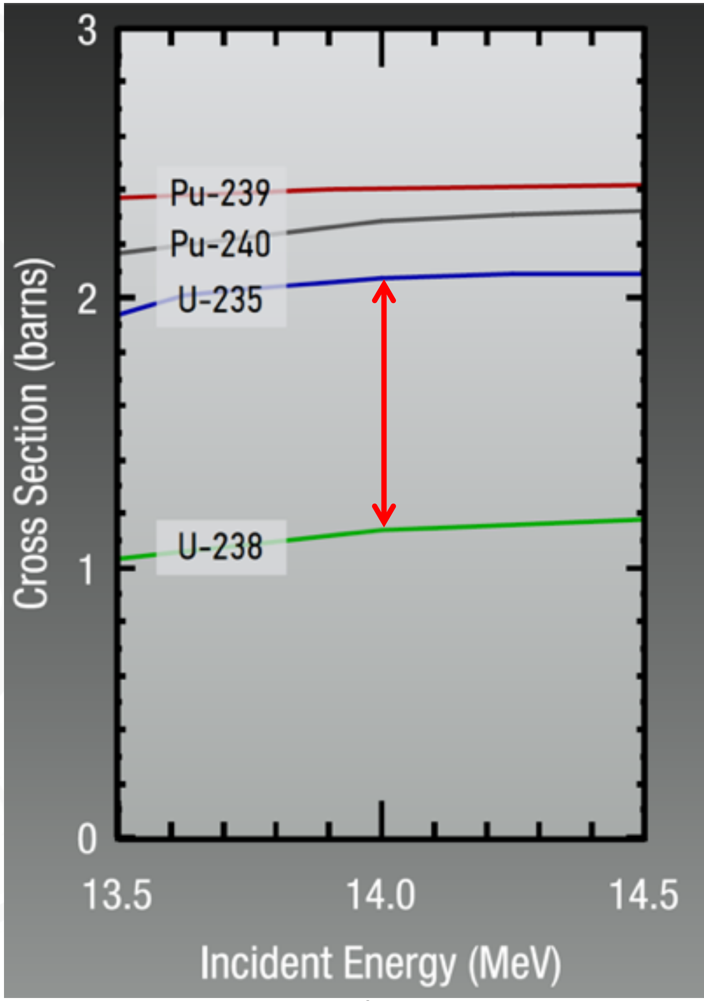
* *"A physical zero-knowledge object-comparison system for nuclear warhead verification,"* Nature Communications, 2016

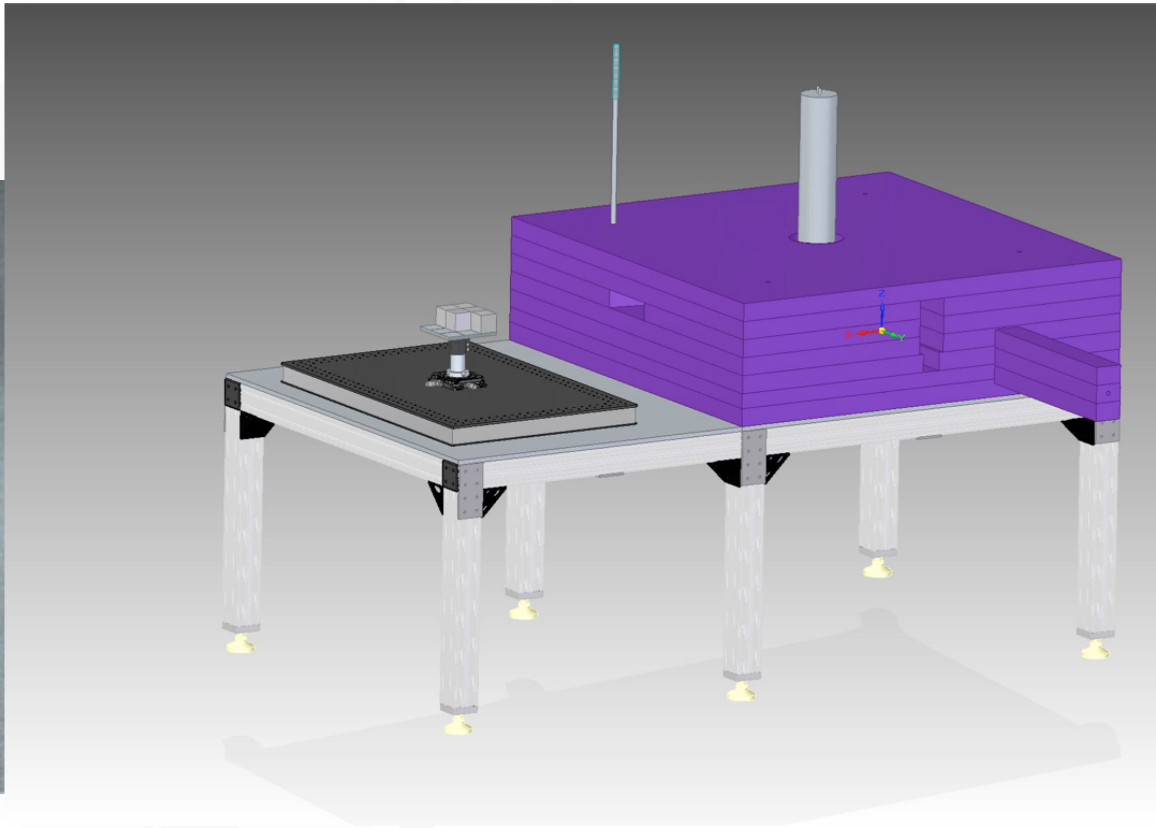
State of ZKP: Princeton





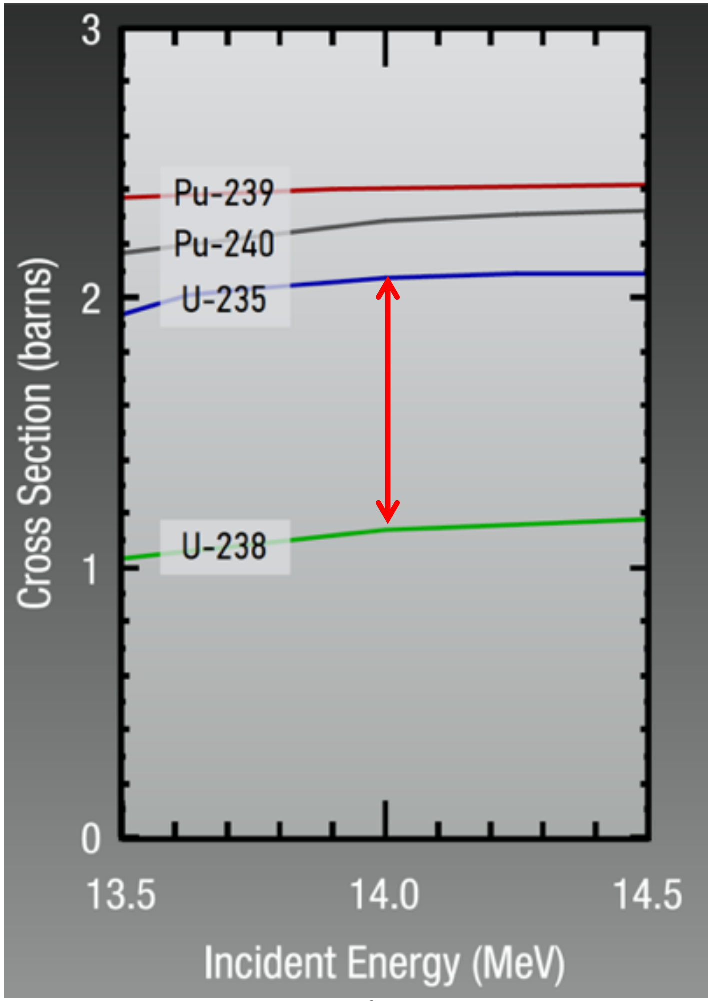
* Yan and Glaser

DT Neutron Generator



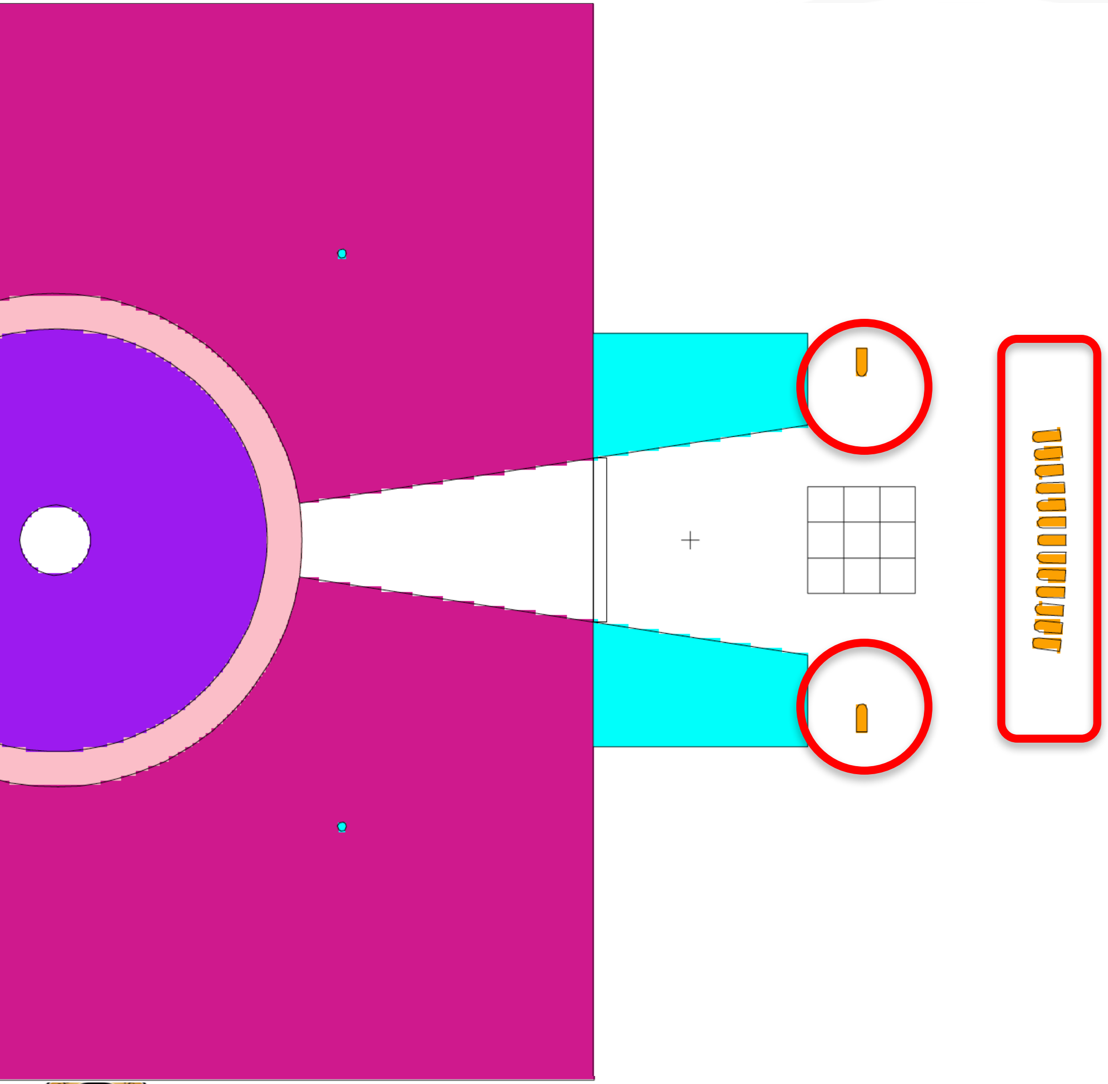
Above: Thermofisher

Isotopic Differentiation



* Yan and Glaser

Isotopic Differentiation



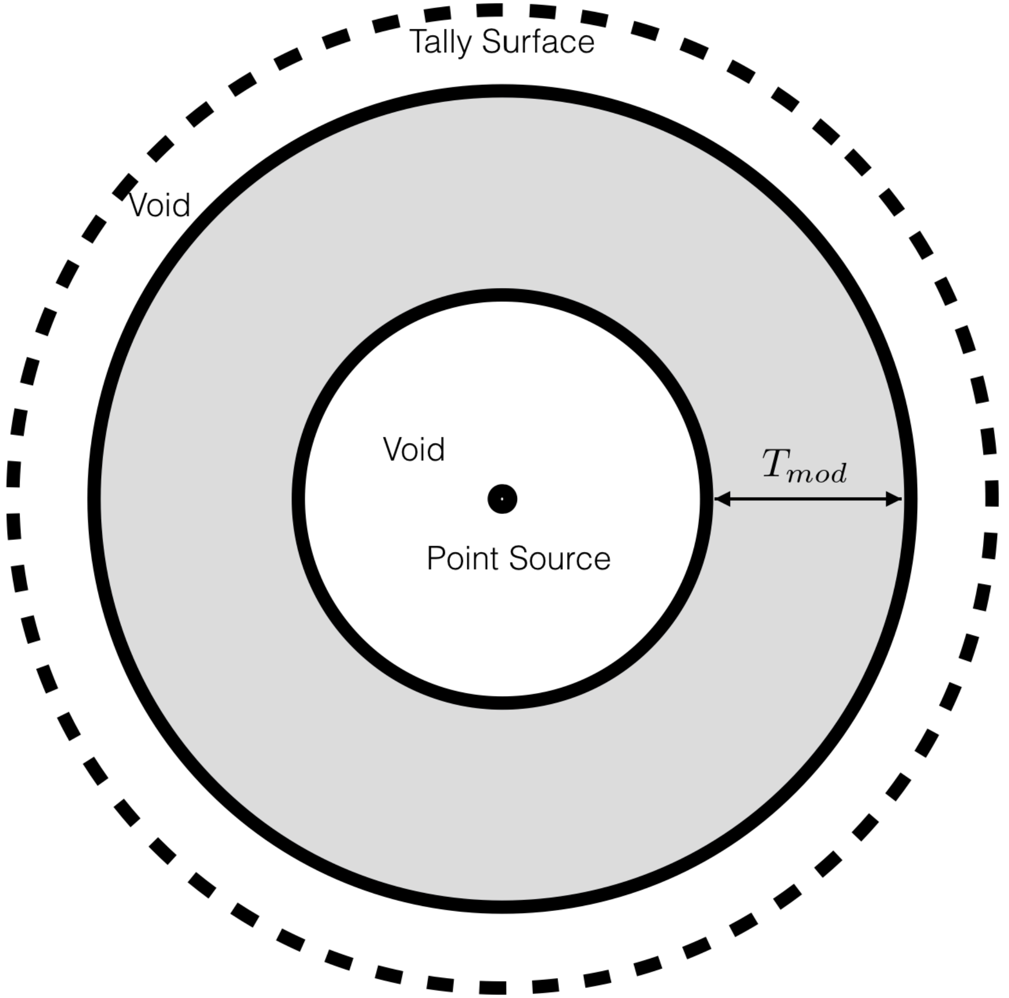
Moderator Material

Material	Activated	Accountable	Hazardous	Cost
Iron	**X**	-	-	-
Copper	**X**	-	-	-
Tungsten	-	-	-	**X**
Lead	-	-	**X**	-
Carbon	-	-	-	-
Poly	-	-	-	-

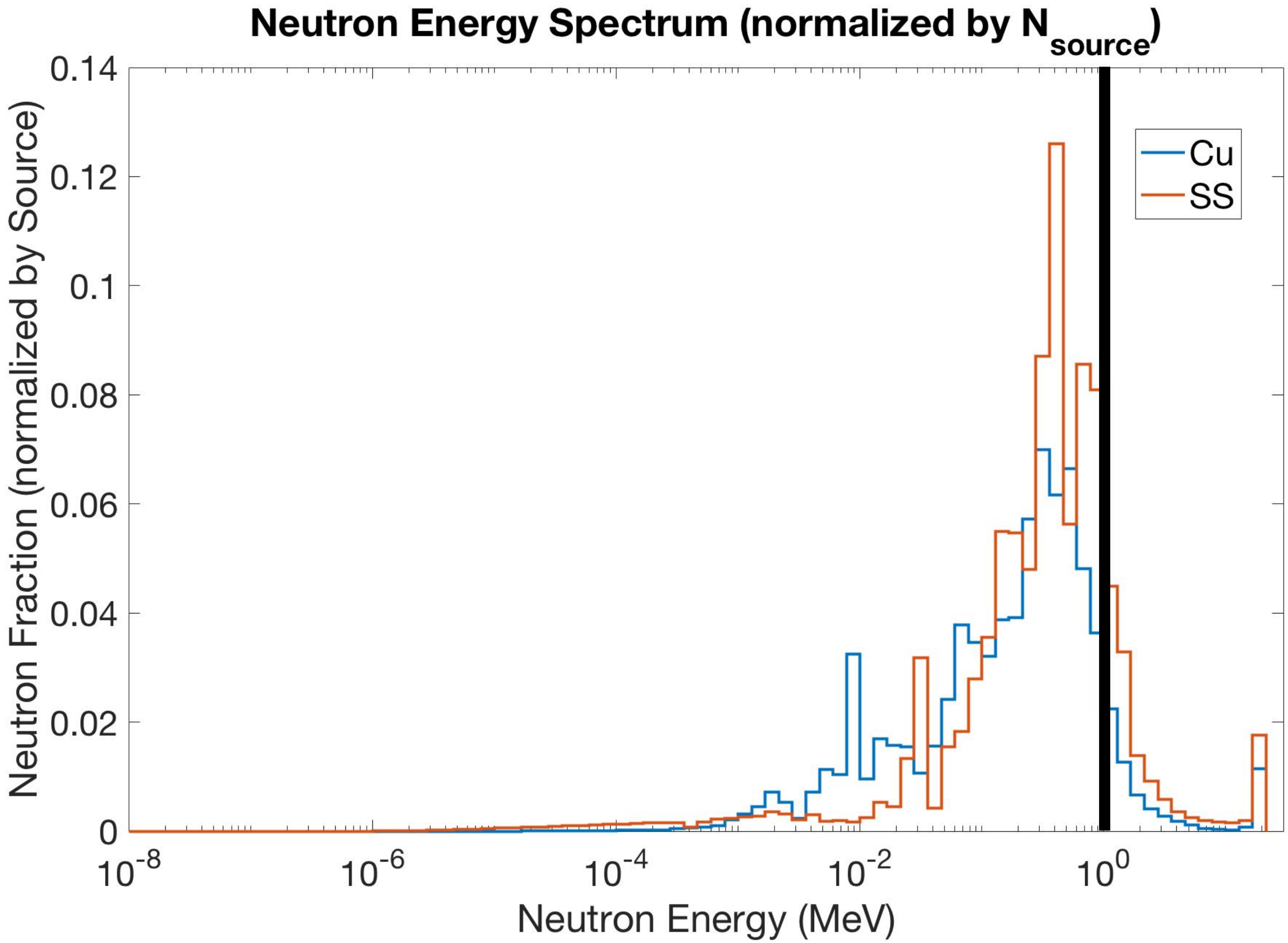
*

* Mozhayev, Piper, Rathbone, McDonald, 2016

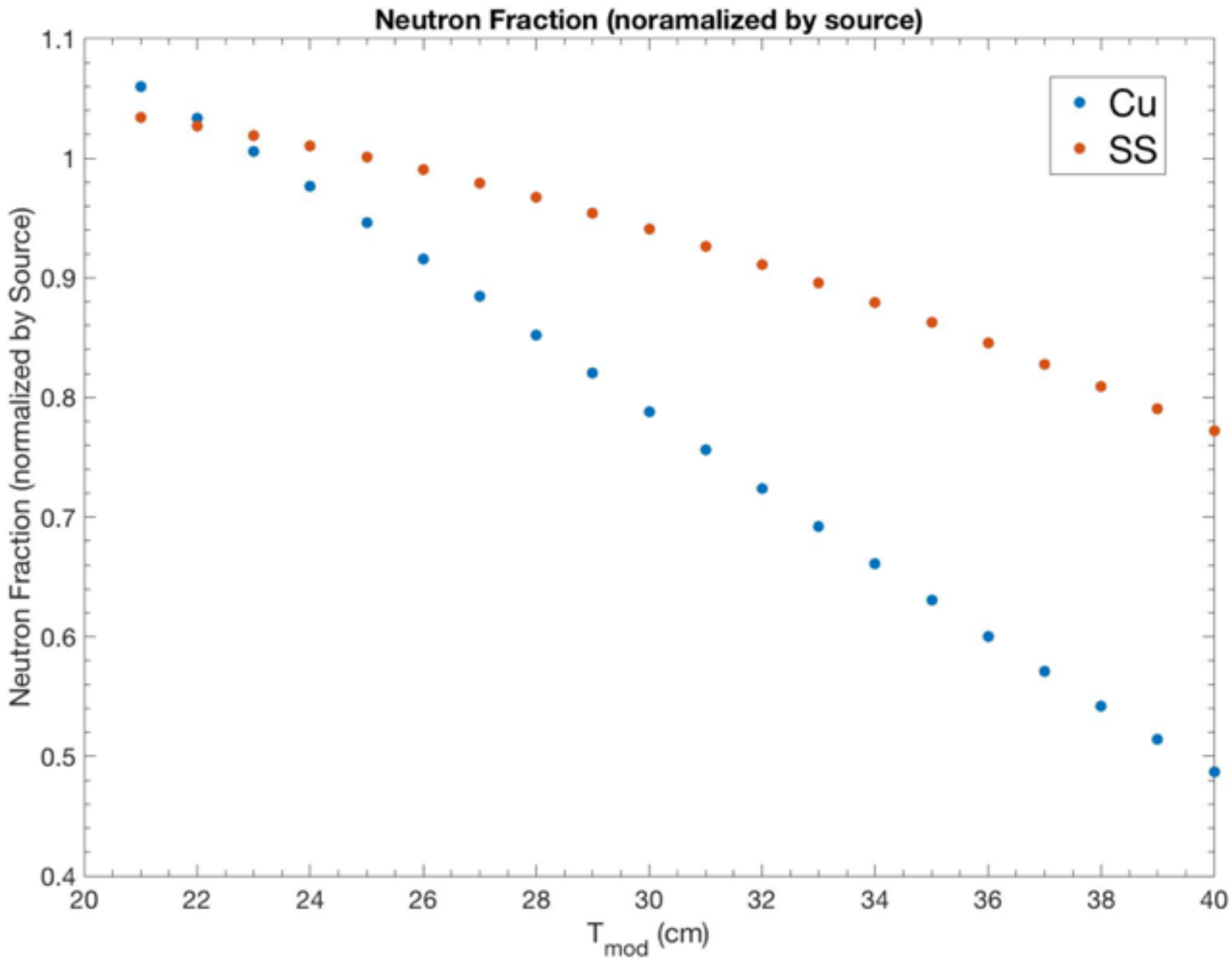
Moderator Material: Spherical Tally



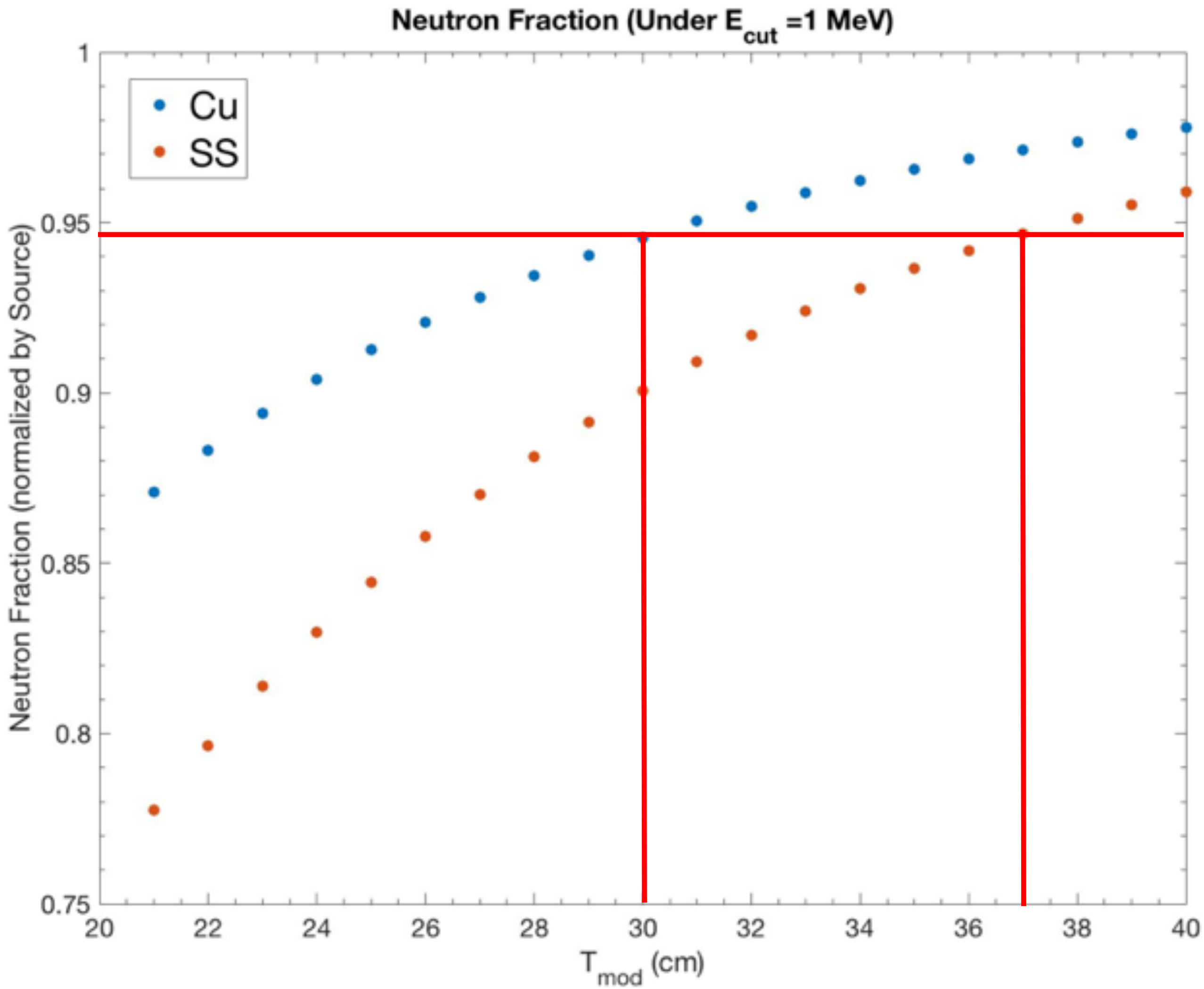
Moderator Material



Moderator Material



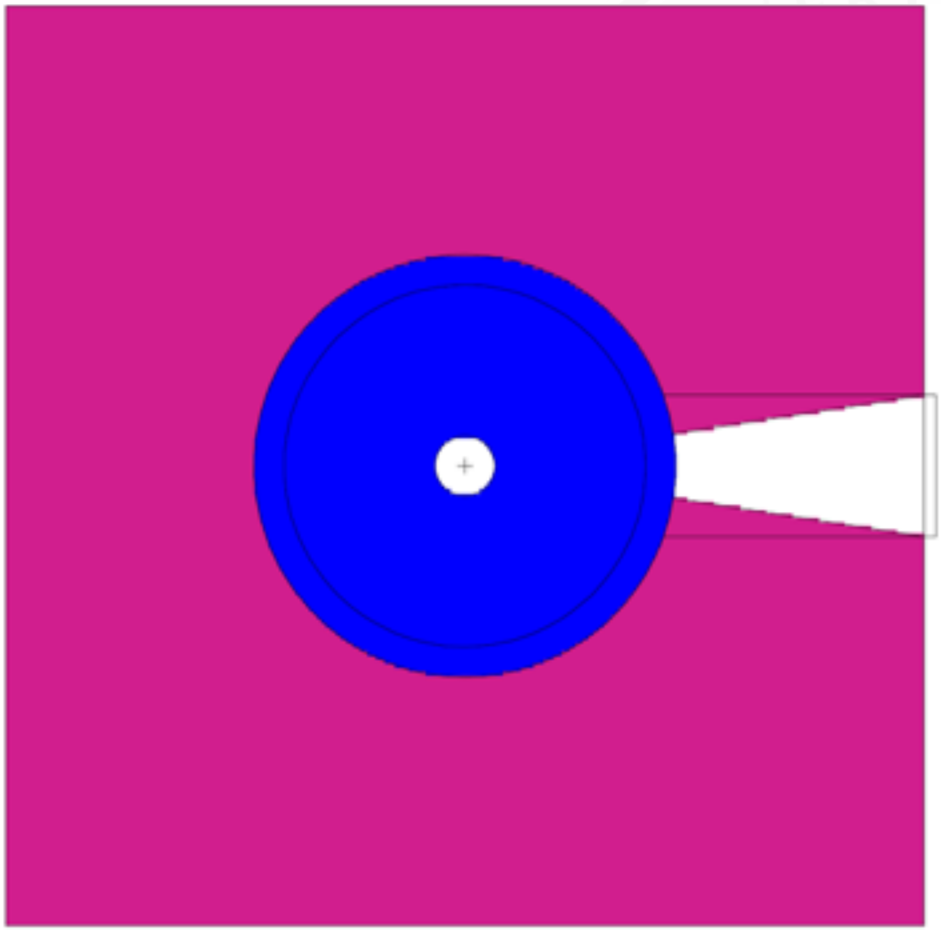
Moderator Material

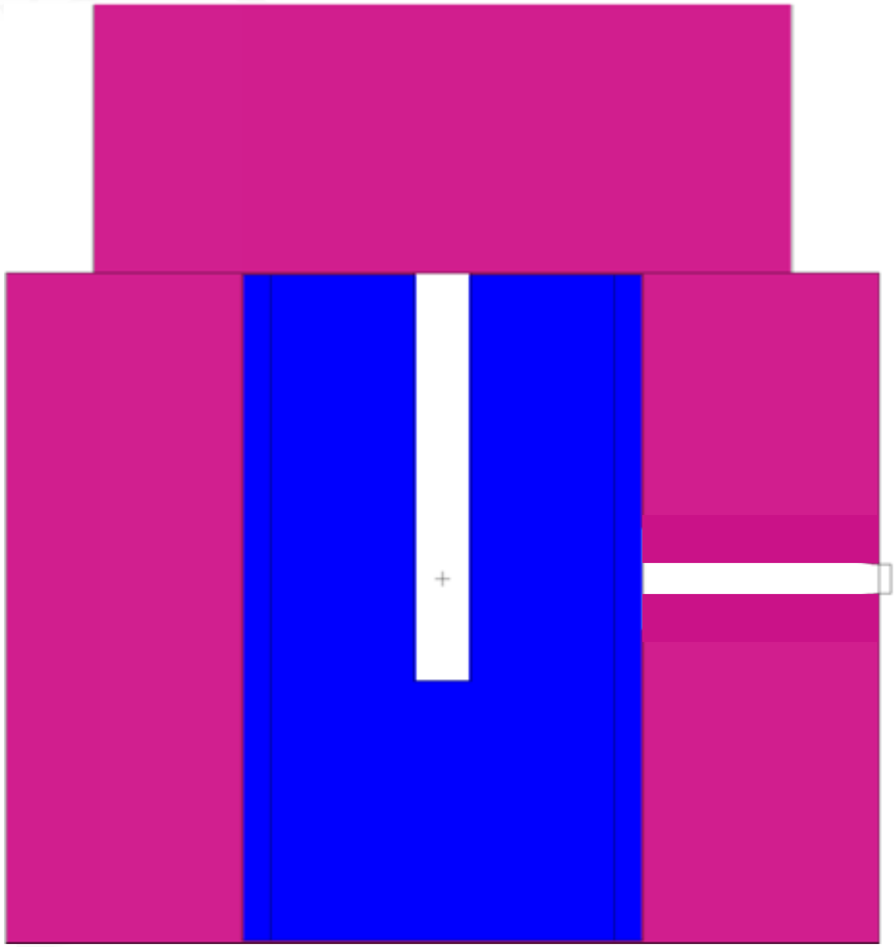


Moderator Material: Take-away

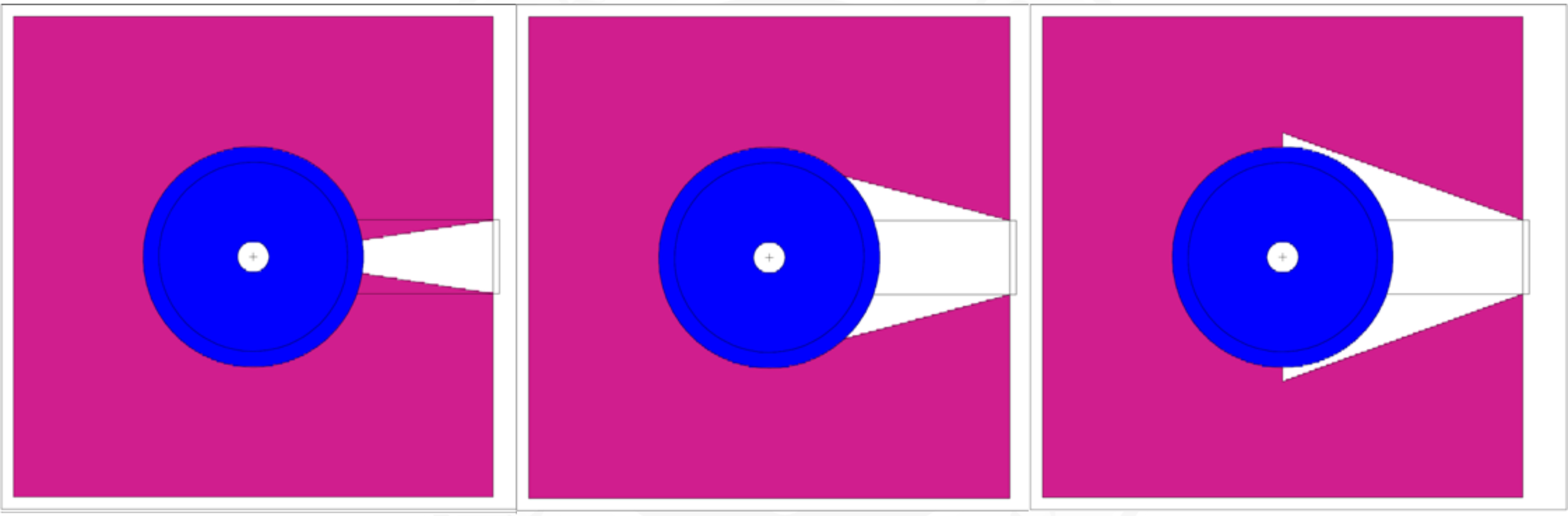
- Copper and Stainless Steel considered
  - Non-hazardous
  - Machinable
  - Easily procured
- Stainless Steel:
  - Less attenuation in total neutron fraction than Cu
  - Cheaper by factor of ~1/2
  - Requires greater thickness to achieve same spectrum fraction below 1 MeV

Collimator Integration



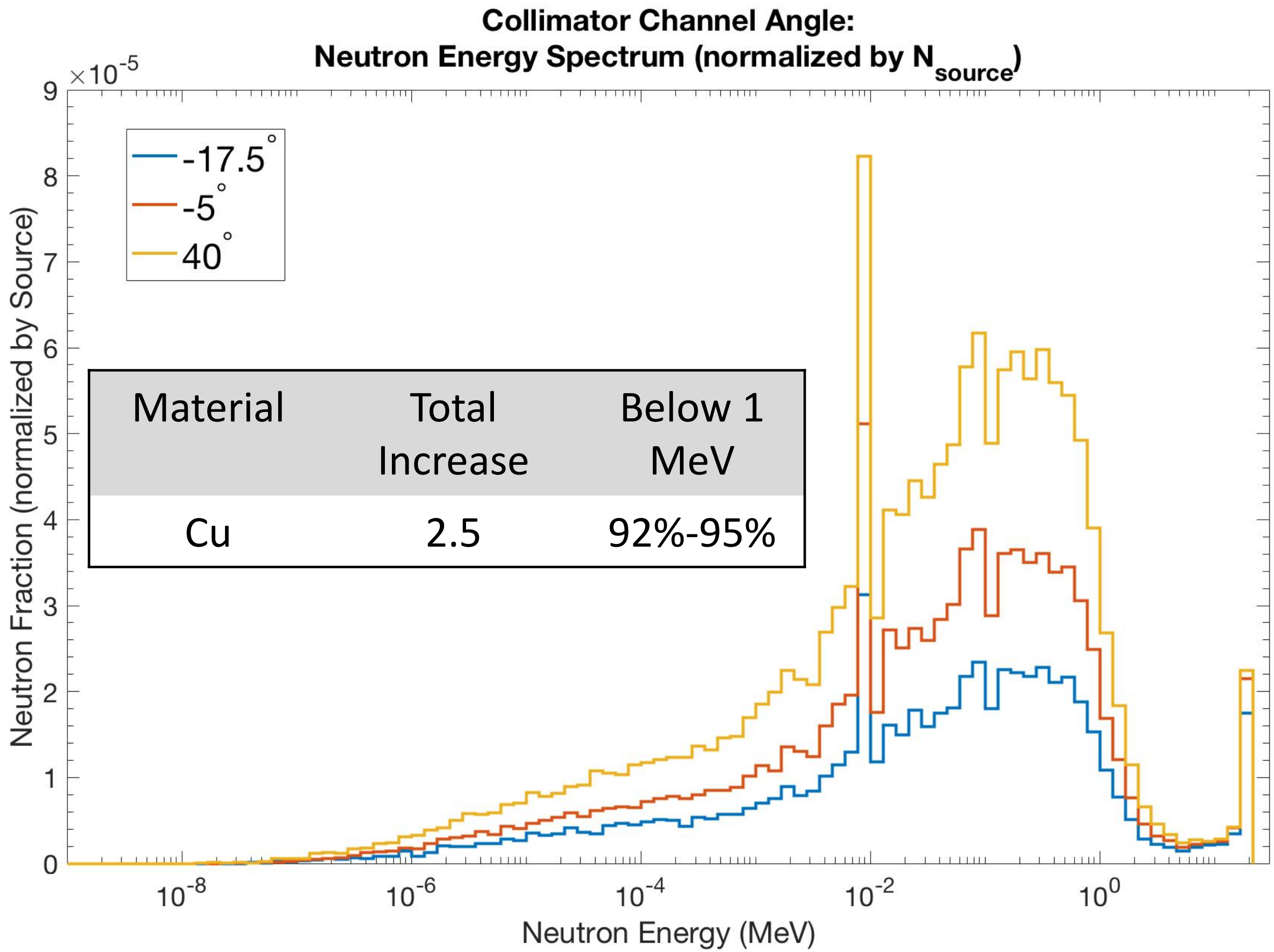


Channel Angle



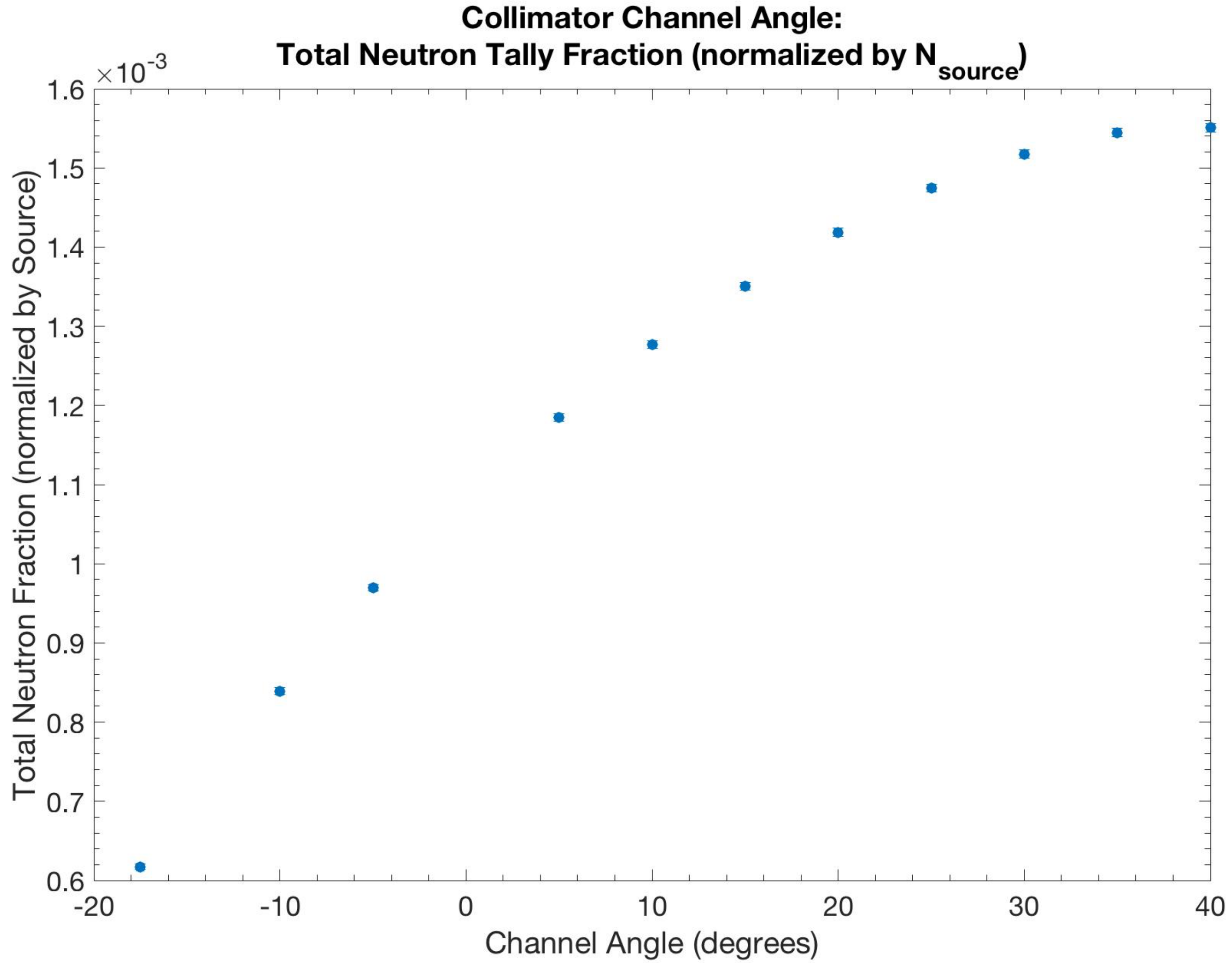
$-17.5^\circ \longrightarrow 40^\circ$

Channel Angle: Cu

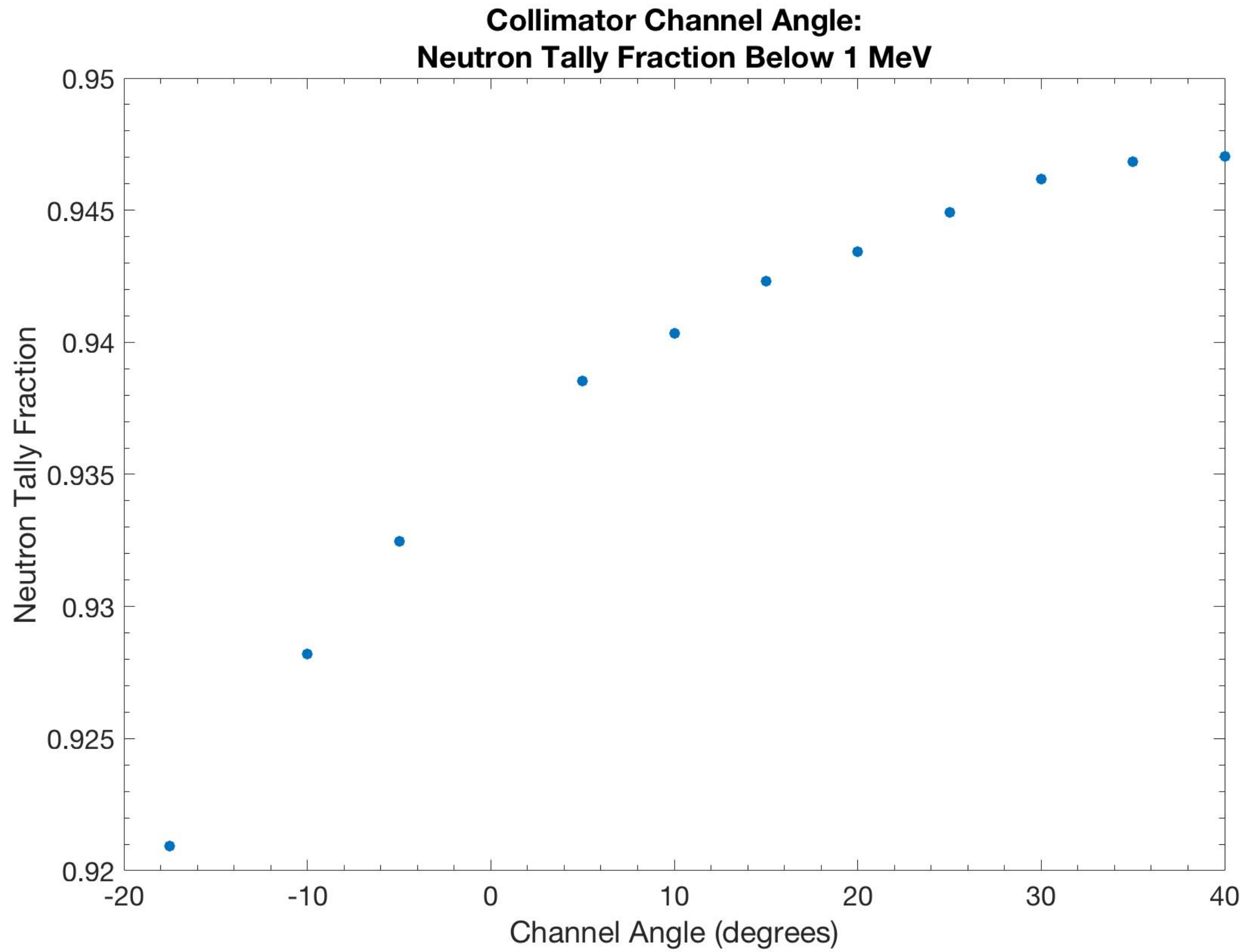


Material	Total Increase	Below 1 MeV
Cu	2.5	92%-95%

Channel Angle: Cu 30 cm

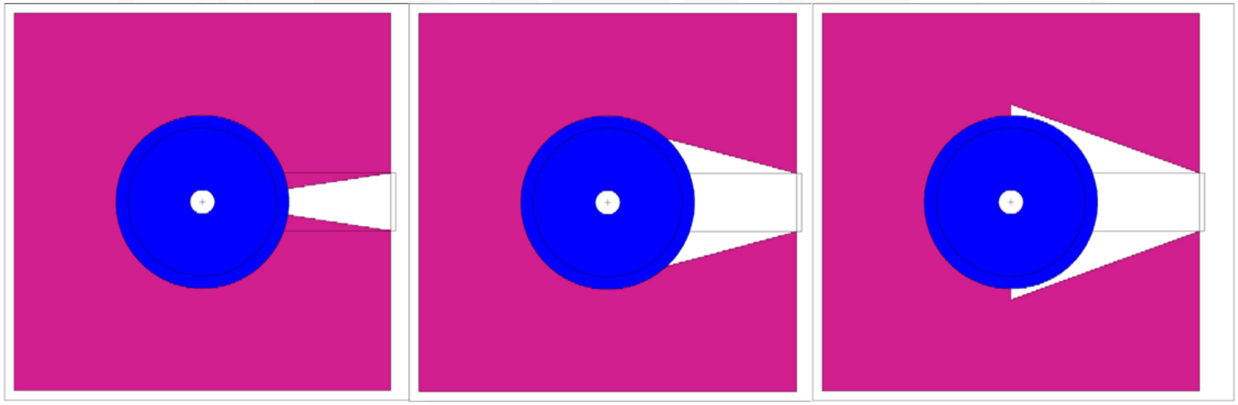


Channel Angle: Cu 30 cm

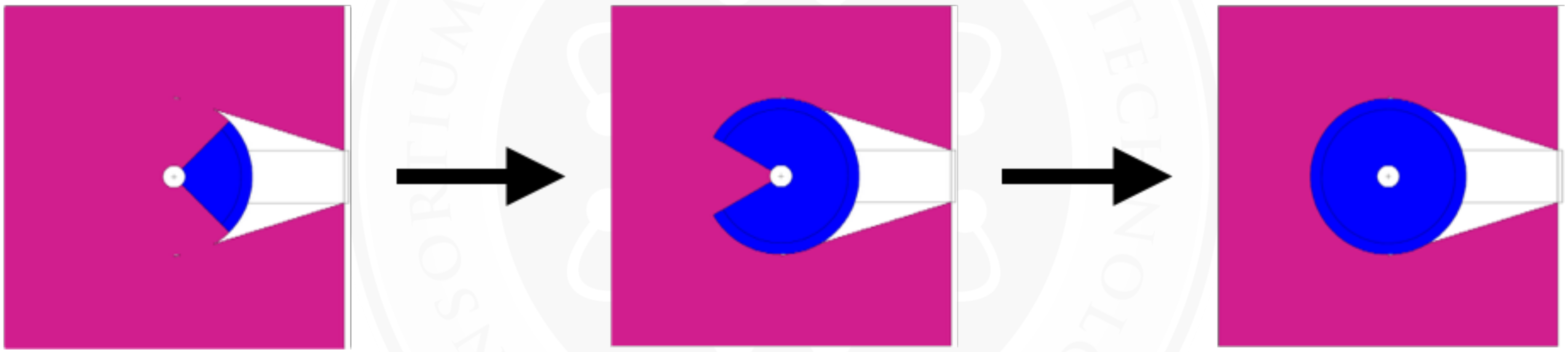


Channel Angle: Take-away

- Narrow-angle channel:
  - Unscattered 14 MeV neutrons preferentially
- Wide-angle channel:
  - Increase total fraction of neutrons at aperture exit
  - Increase spectrum fraction below 1 MeV
  - “Inverted” design allows for full width of moderator to be exposed

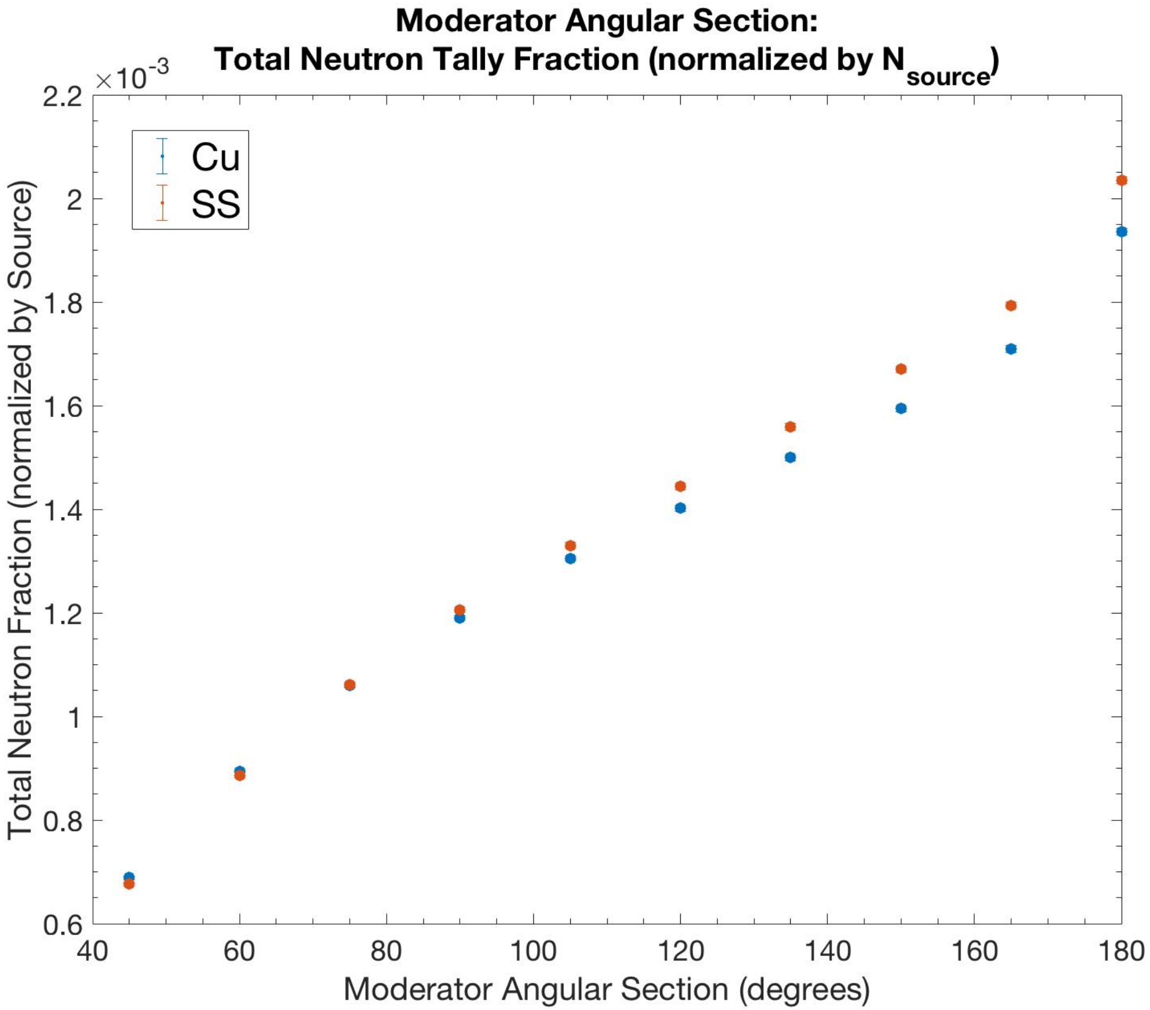


Moderator Angular Sections

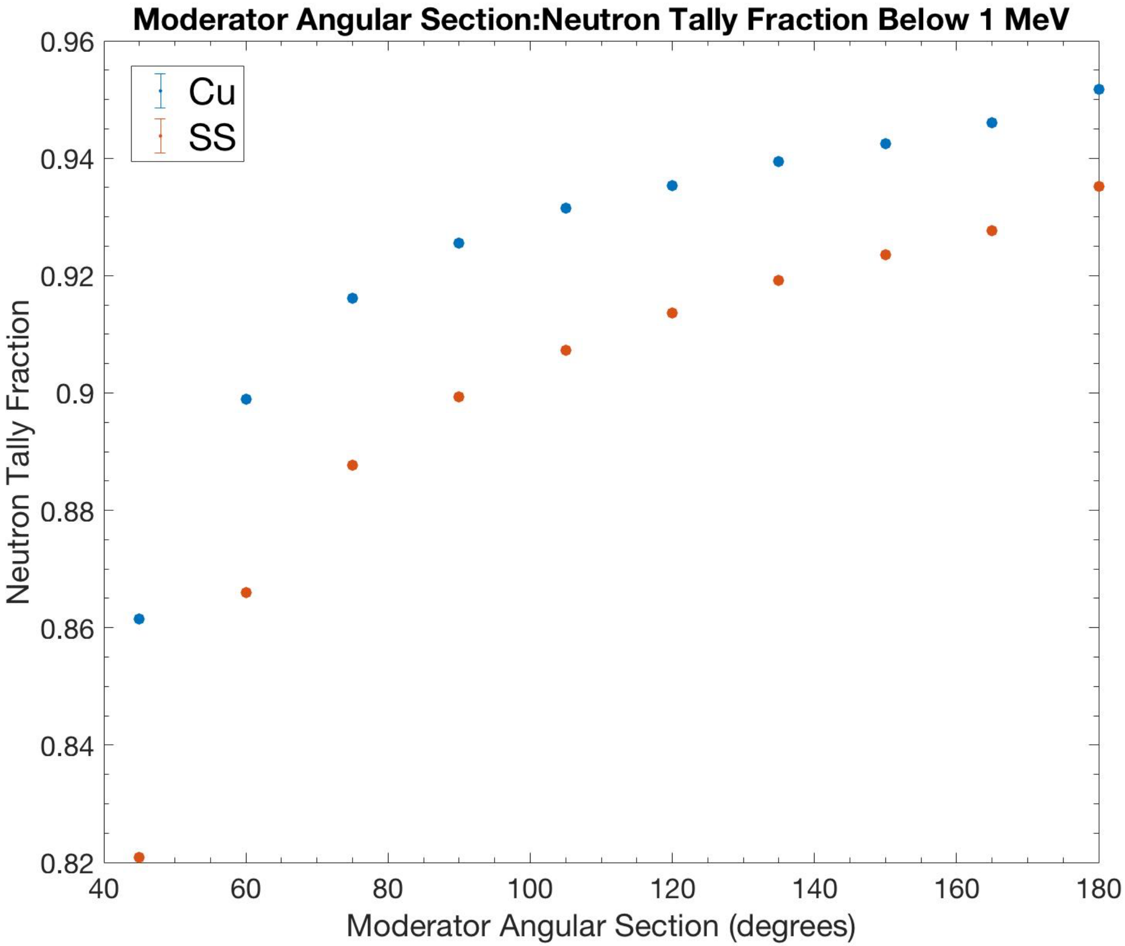


Material	Total Increase	Below 1 MeV
Cu	2.7	86% -> 95%
SS	2.8	82% -> 94%

Moderator Angular Sections

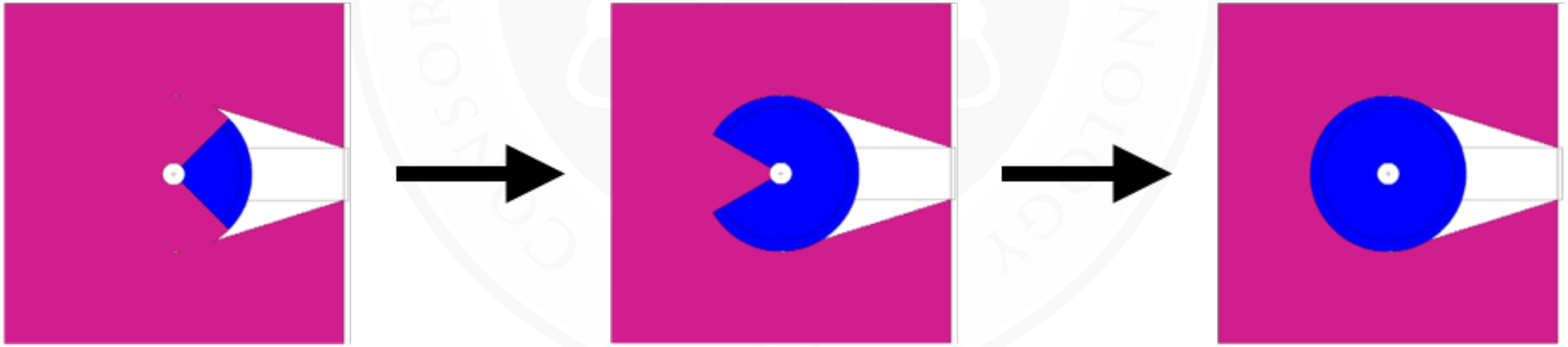


Moderator Angular Sections

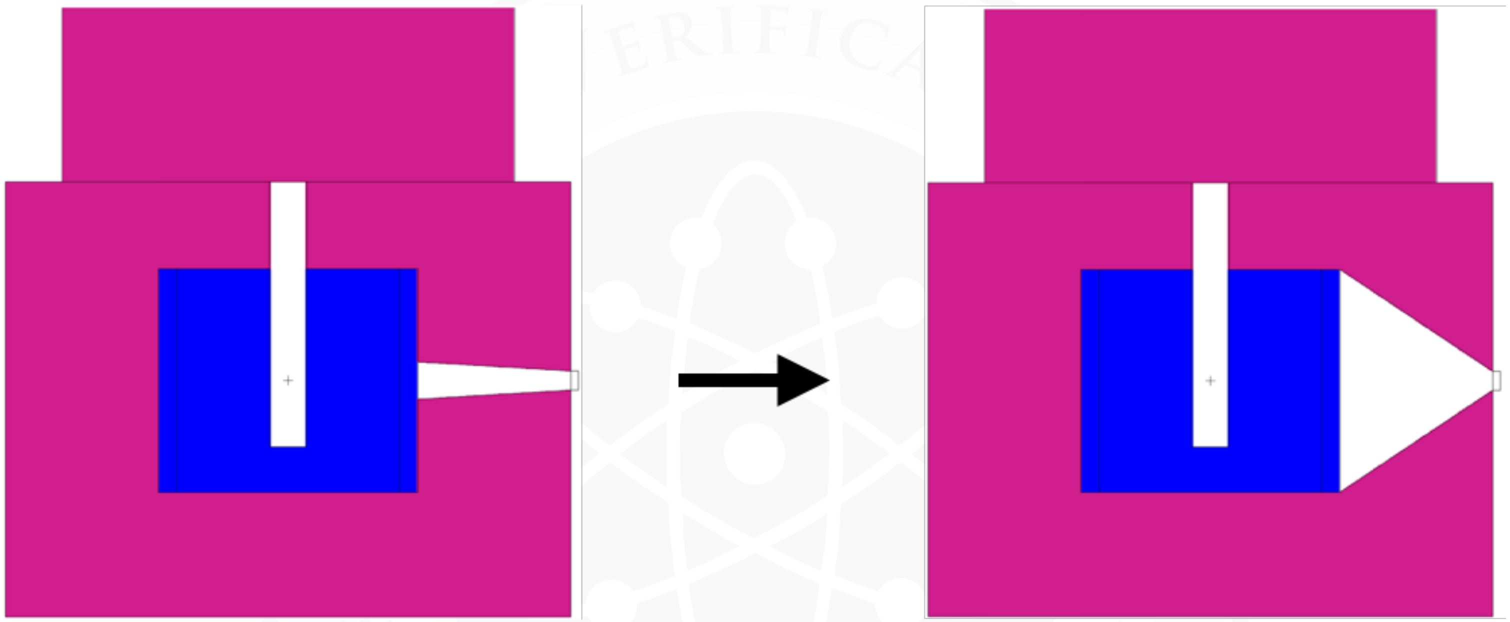


Moderator Angle: Take-away

- Full Circular Moderator is Preferable
  - Significant contribution in total flux from wide angles and behind
  - Contributions to below 1 MeV fraction from wide angles and behind



Moderator Height and Exposure

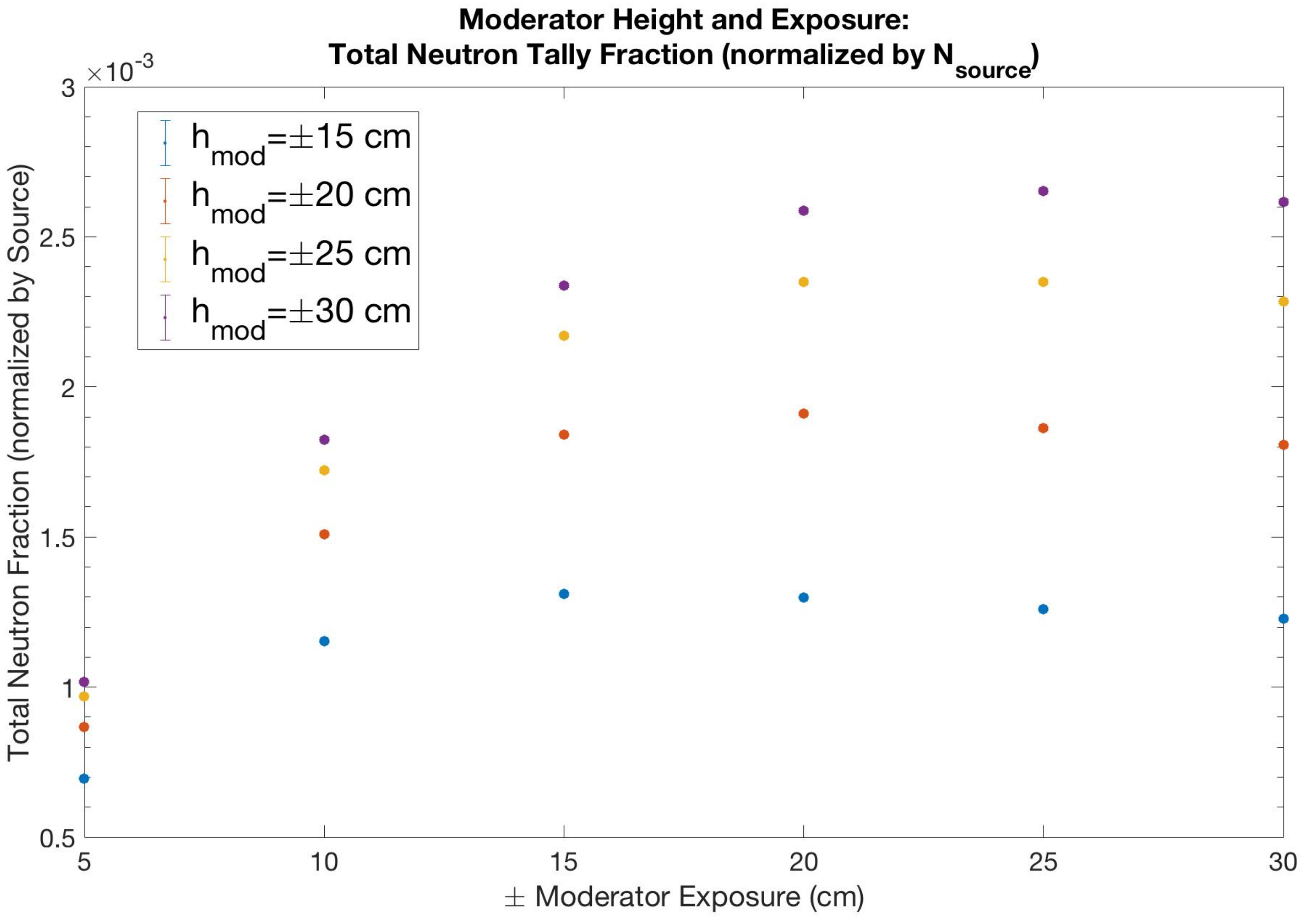


$h_{mod} = \pm 15\ c$ … $_d = \pm 30\ cm$

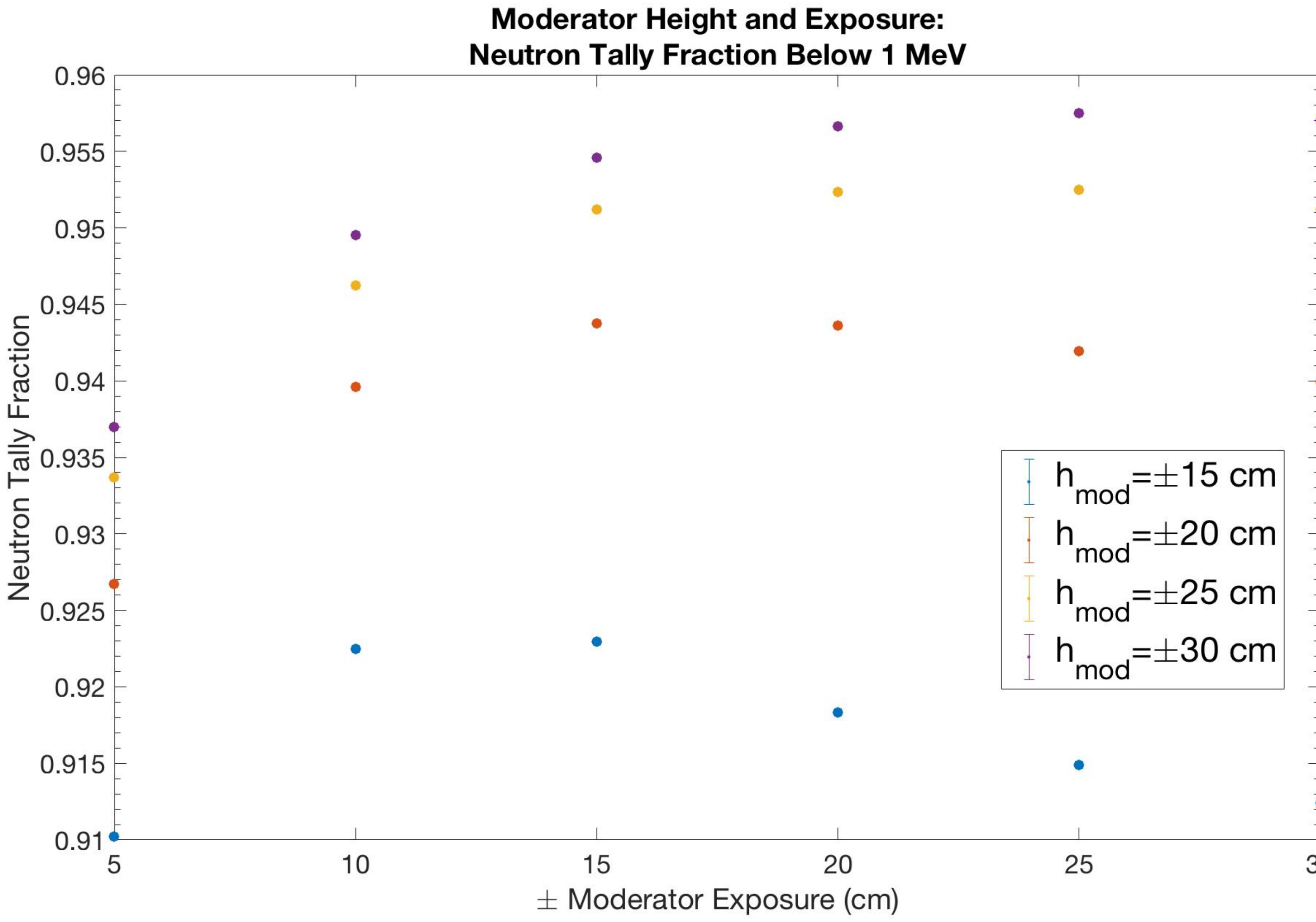
$h_{exp} = \pm 5\ c$ … $_p = \pm 30\ cm$

Material	Total Increase	Below 1 MeV
Cu	2.7	86% -> 95%
SS	2.8	82% -> 94%

Moderator Height and Exposure: Cu

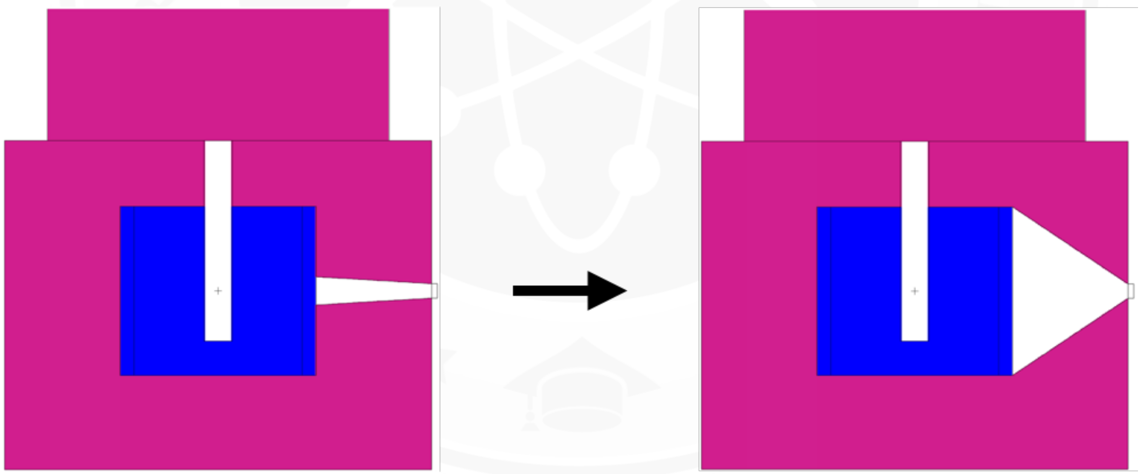


Moderator Height and Exposure: Cu

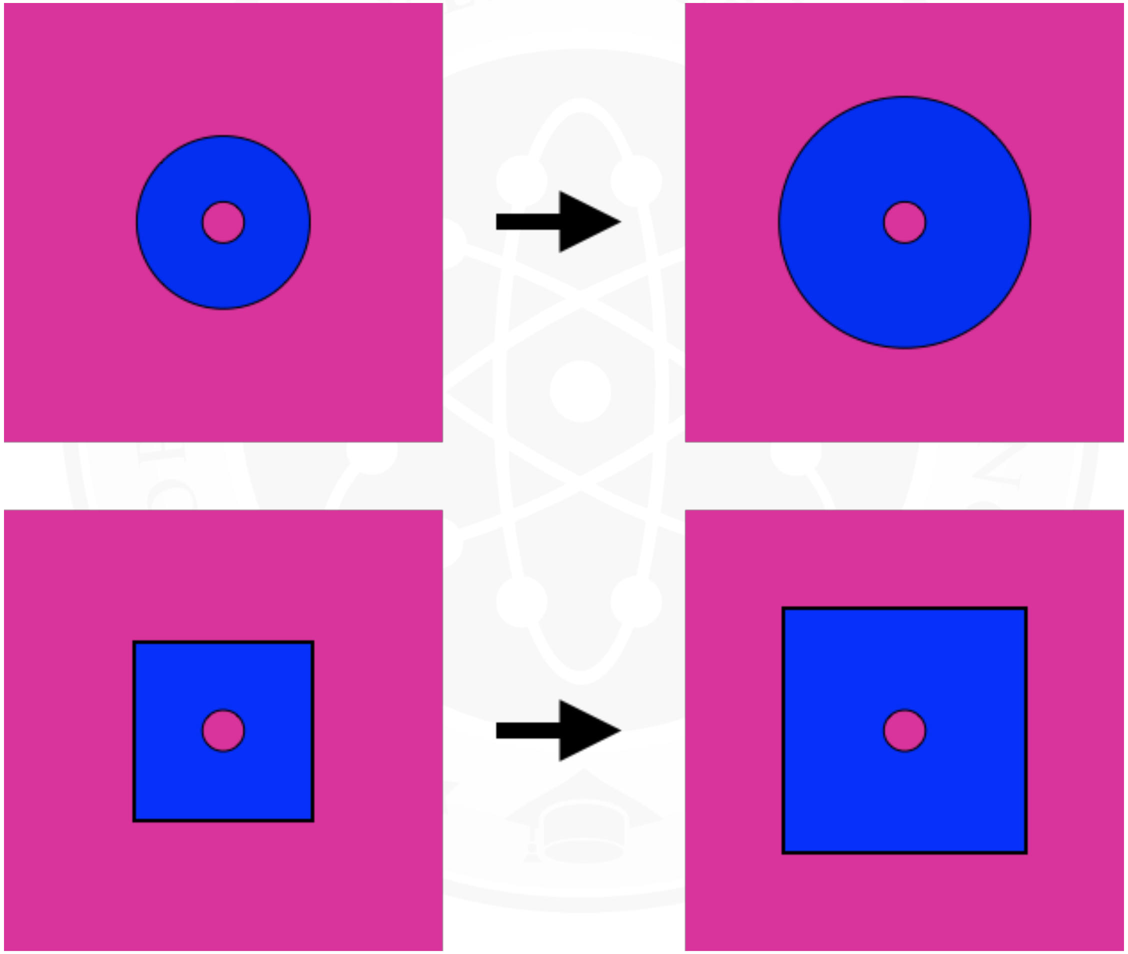


Moderator Height and Exposure:Take-away

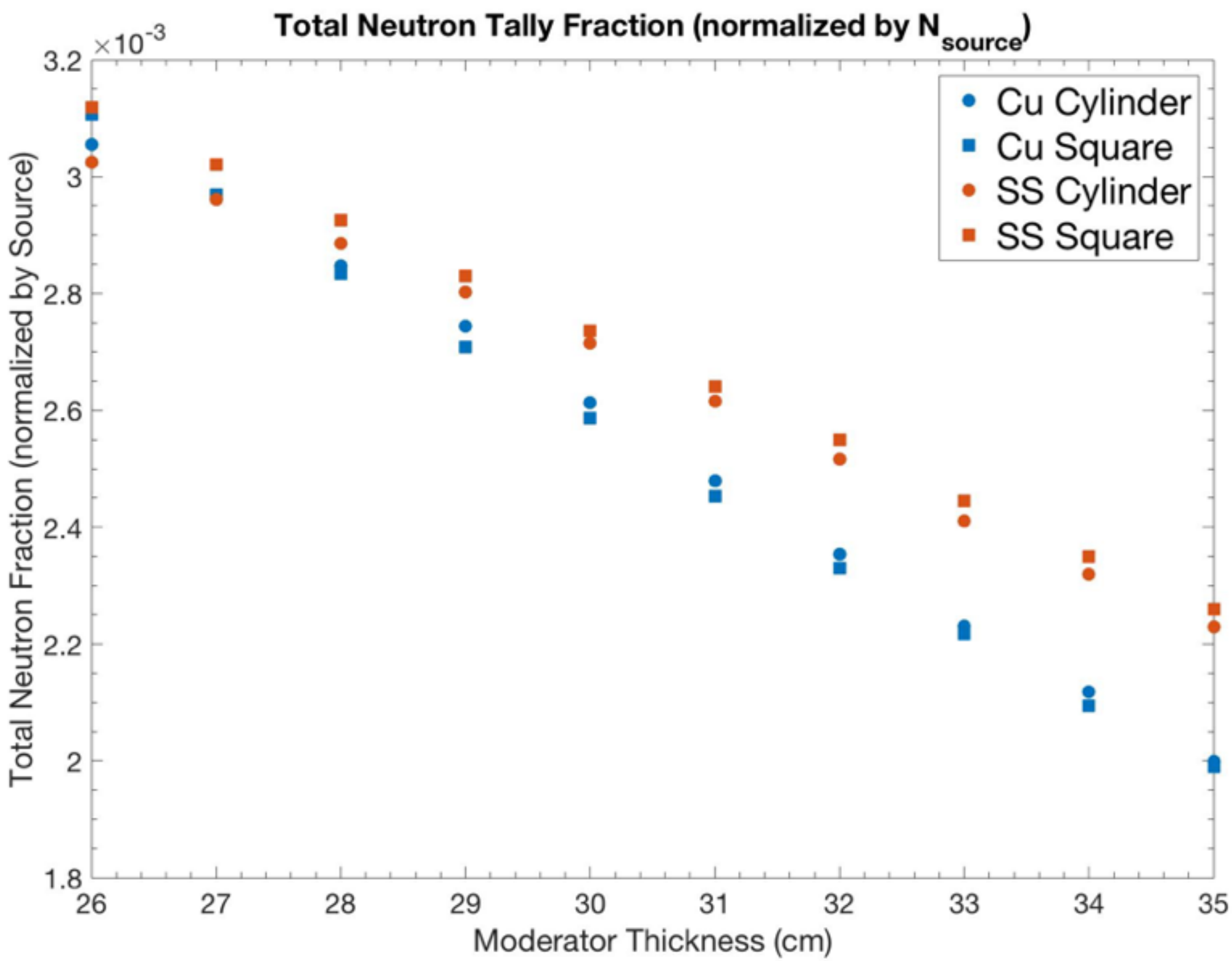
- Exposure:
  - Full height of the moderator should be exposed
- Moderator Height
  - Increasing height over 30 cm above the target plane give diminishing returns.



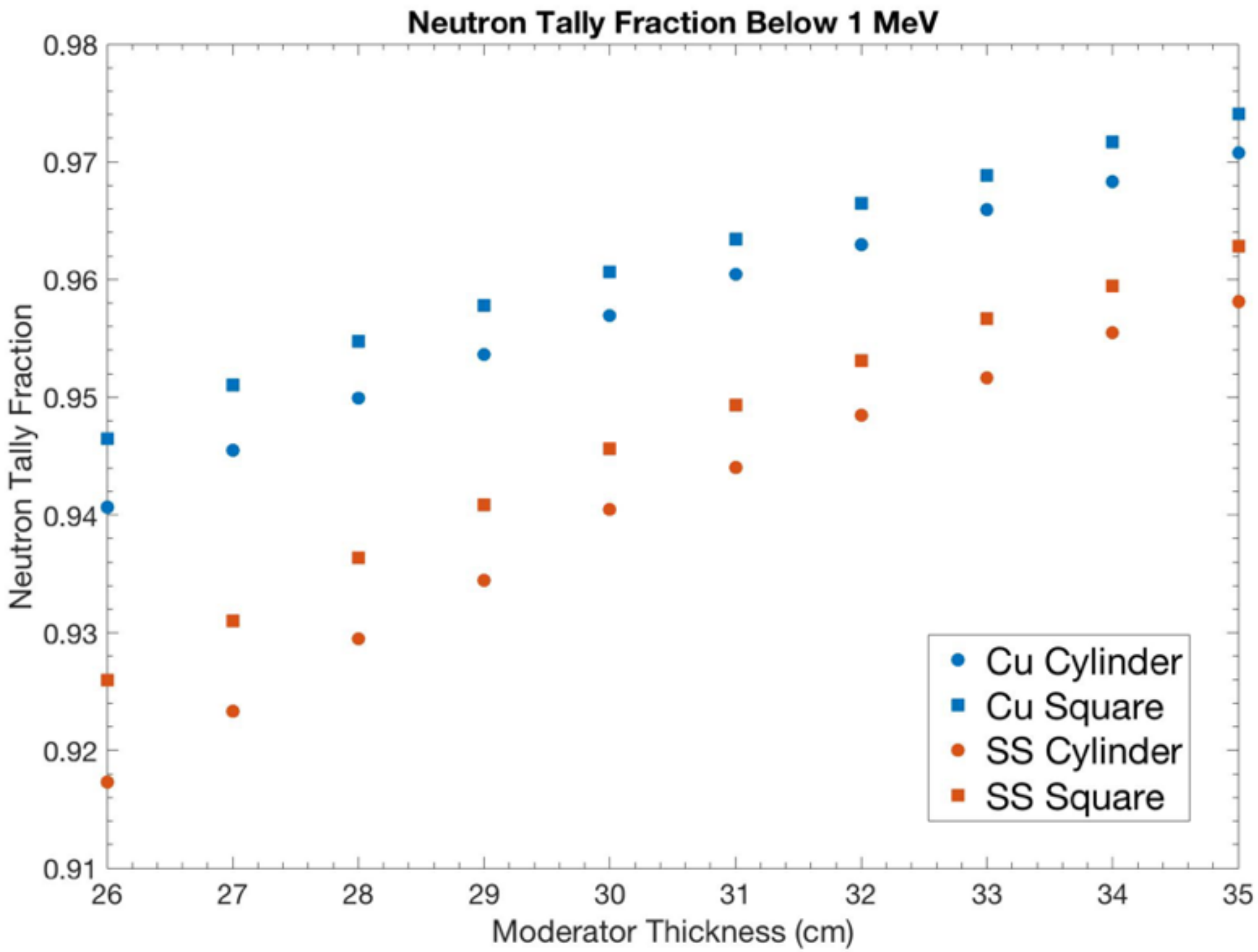
Moderator Thickness: Cu vs SS.



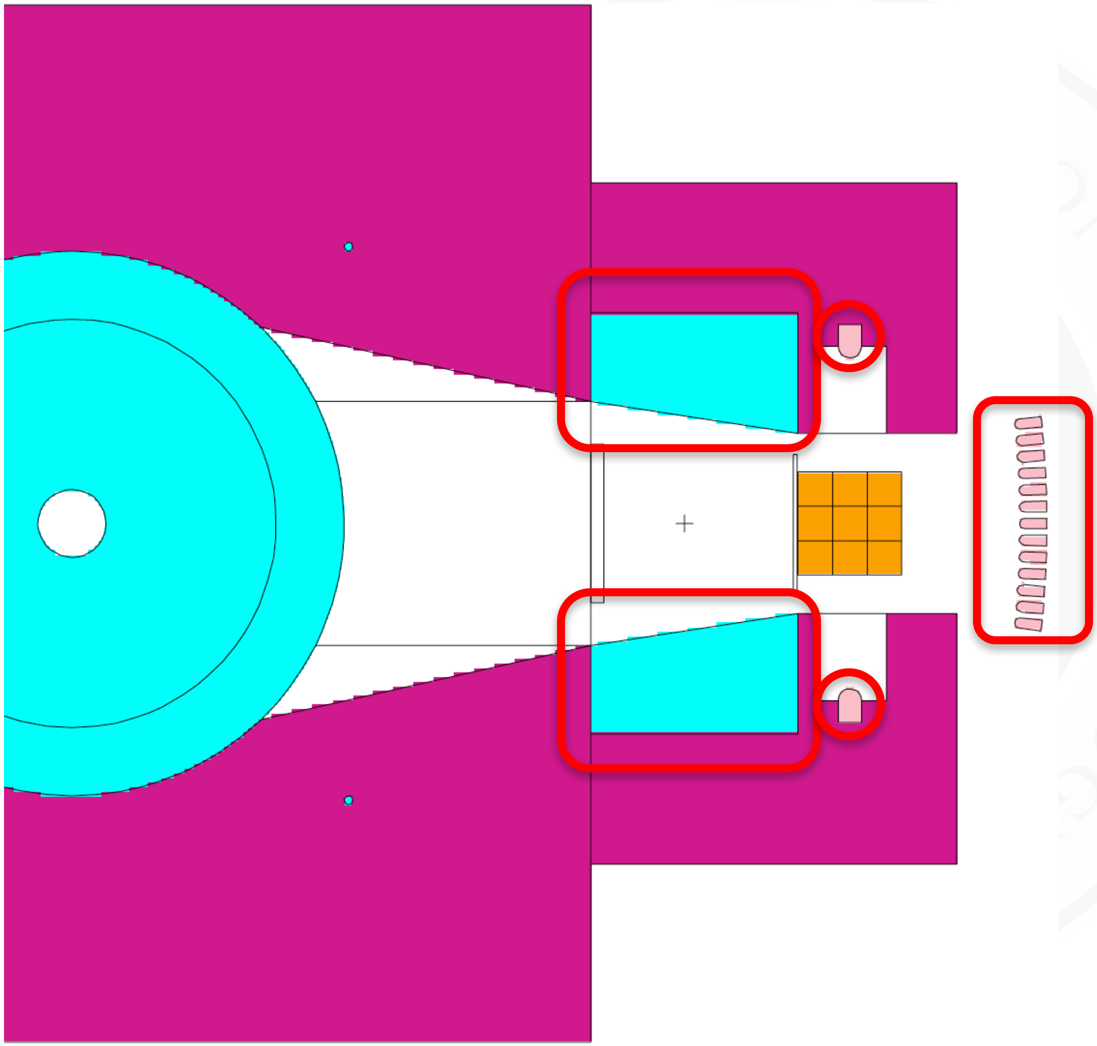
Moderator Thickness: Cu vs SS.



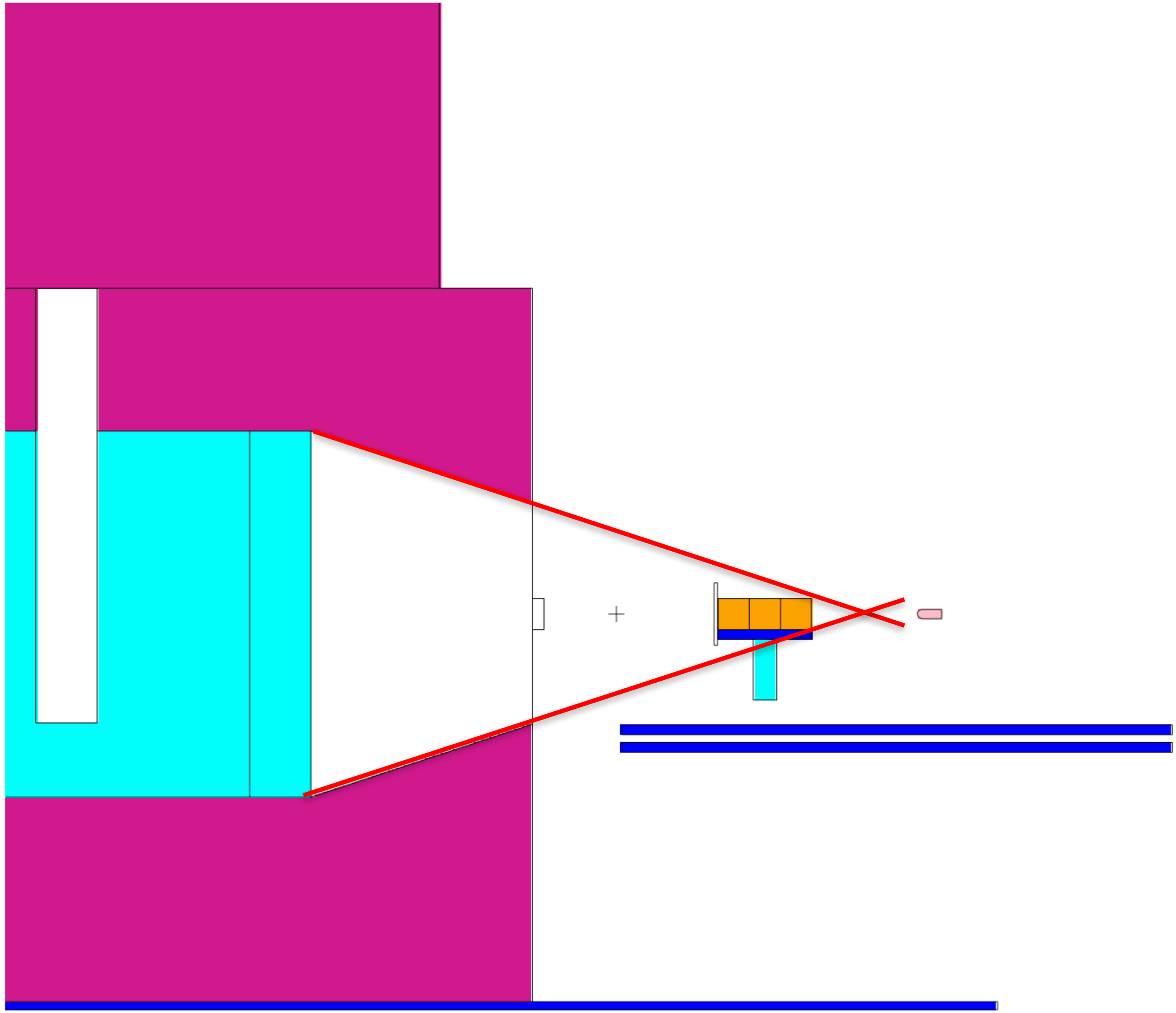
Moderator Thickness: Cu vs SS.

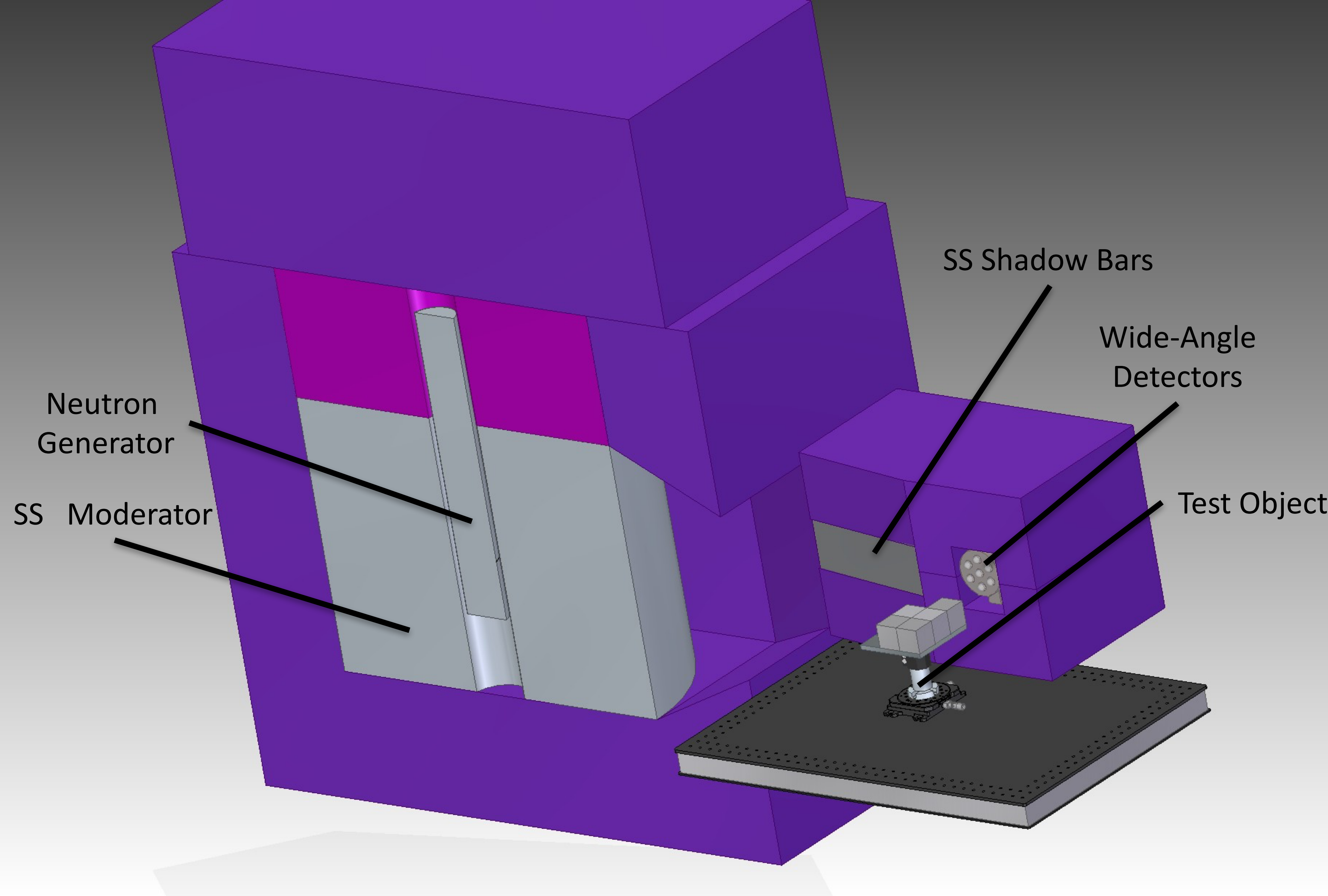


Full Experiment: Bubble Detectors

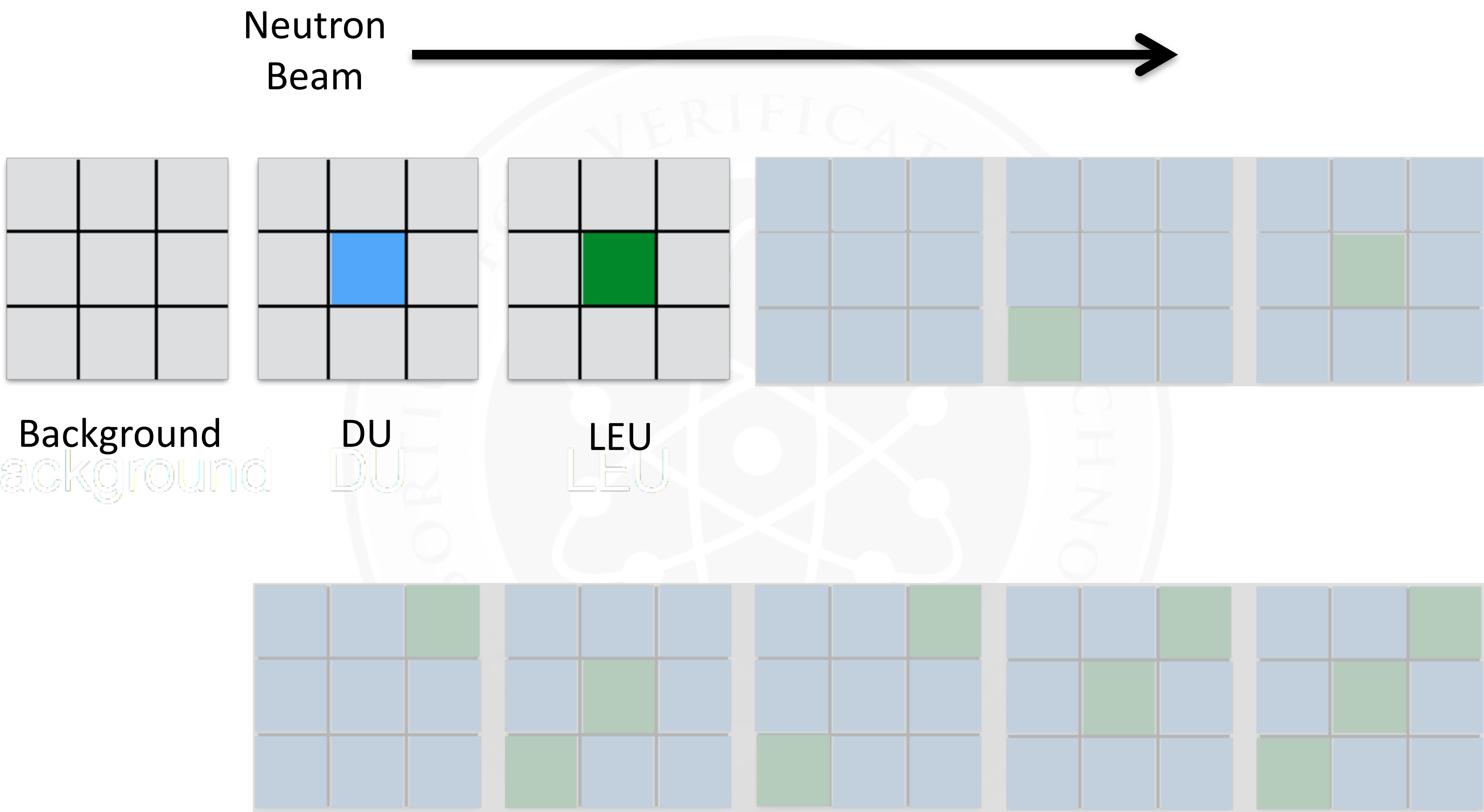


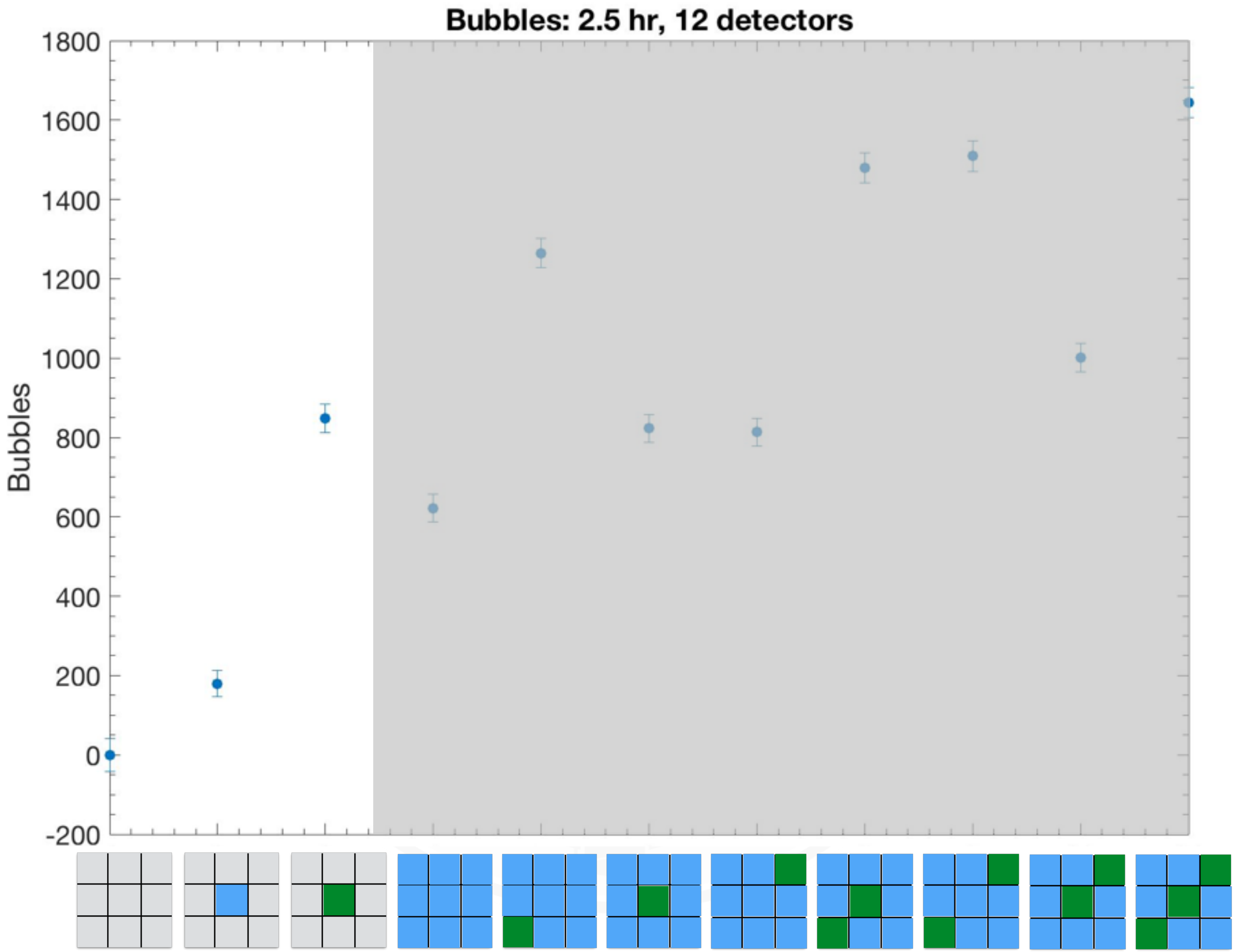
$$\mathit{Stainless\ Steel}$$
$$T_{mod} = 35\ cm$$

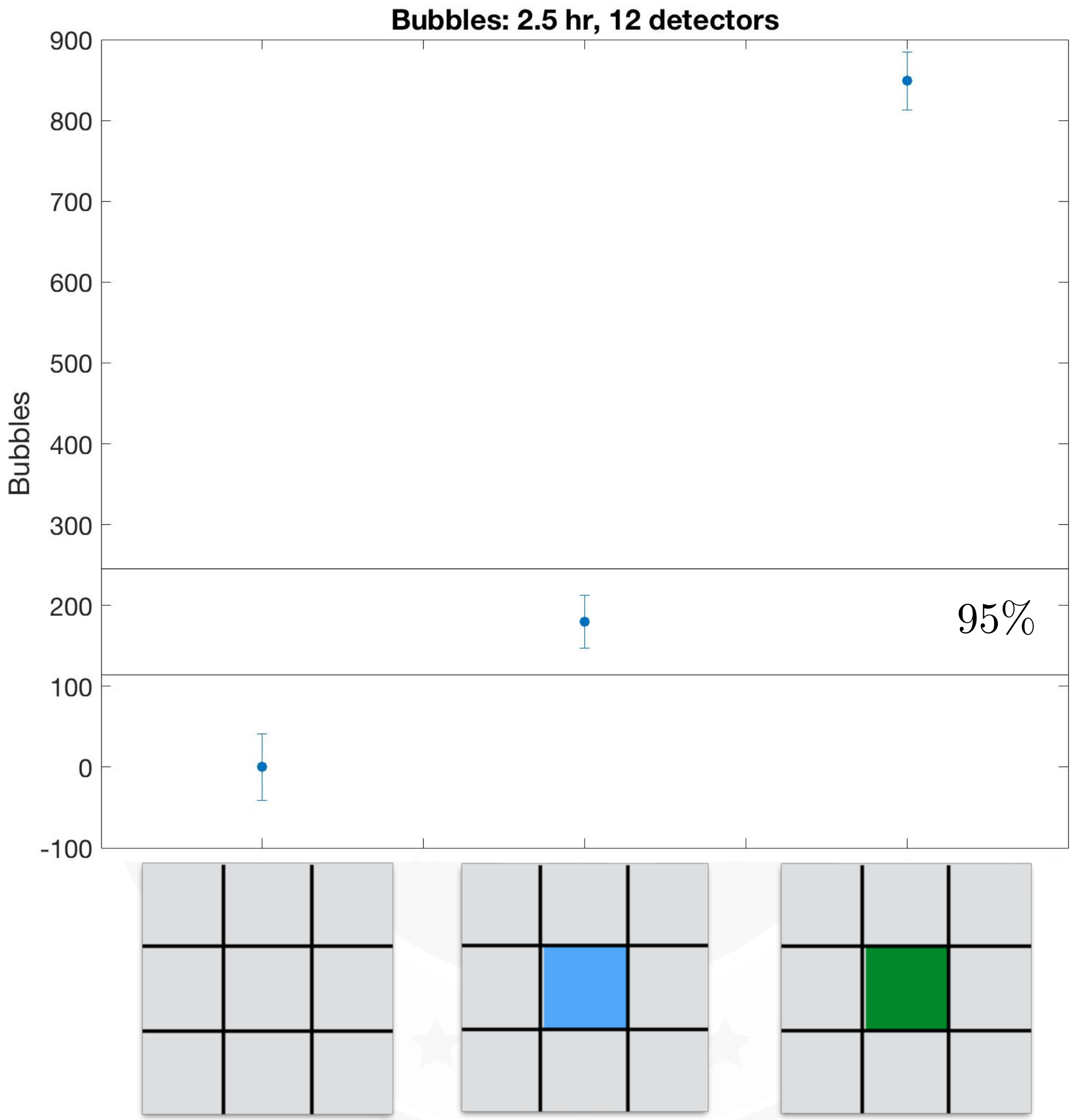


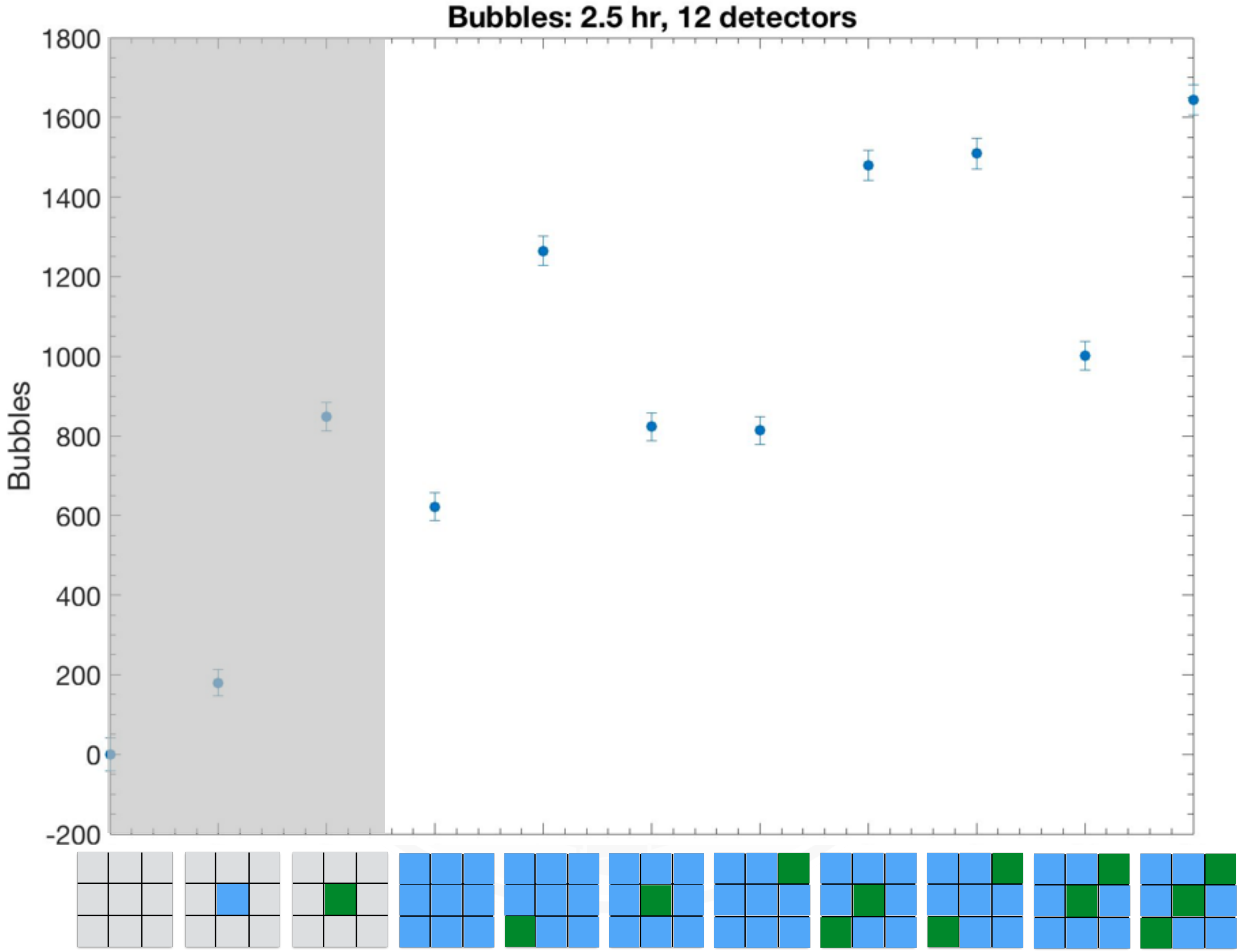

SS Shadow Bars
Wide-Angle
Detectors
Neutron
Generator
Test Object
SS Moderator

Test Object Differentiation




Bubbles: 2.5 hr, 12 detectors
Bubbles
1800
1600
1400
1200
1000
800
600
400
200
0
-200

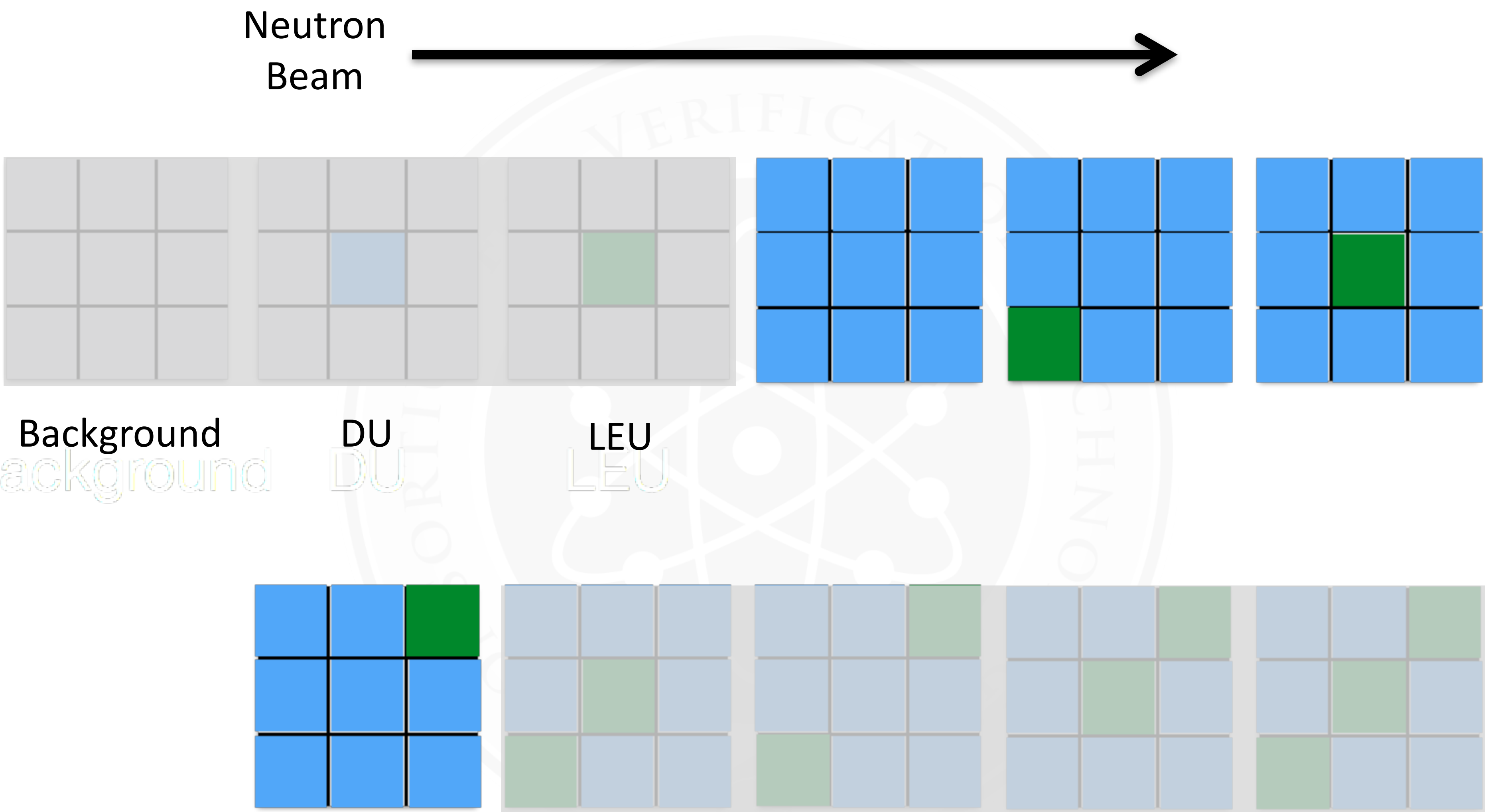

Bubbles: 2.5 hr, 12 detectors
Bubbles
900
800
700
600
500
400
300
200
100
0
-100
95%

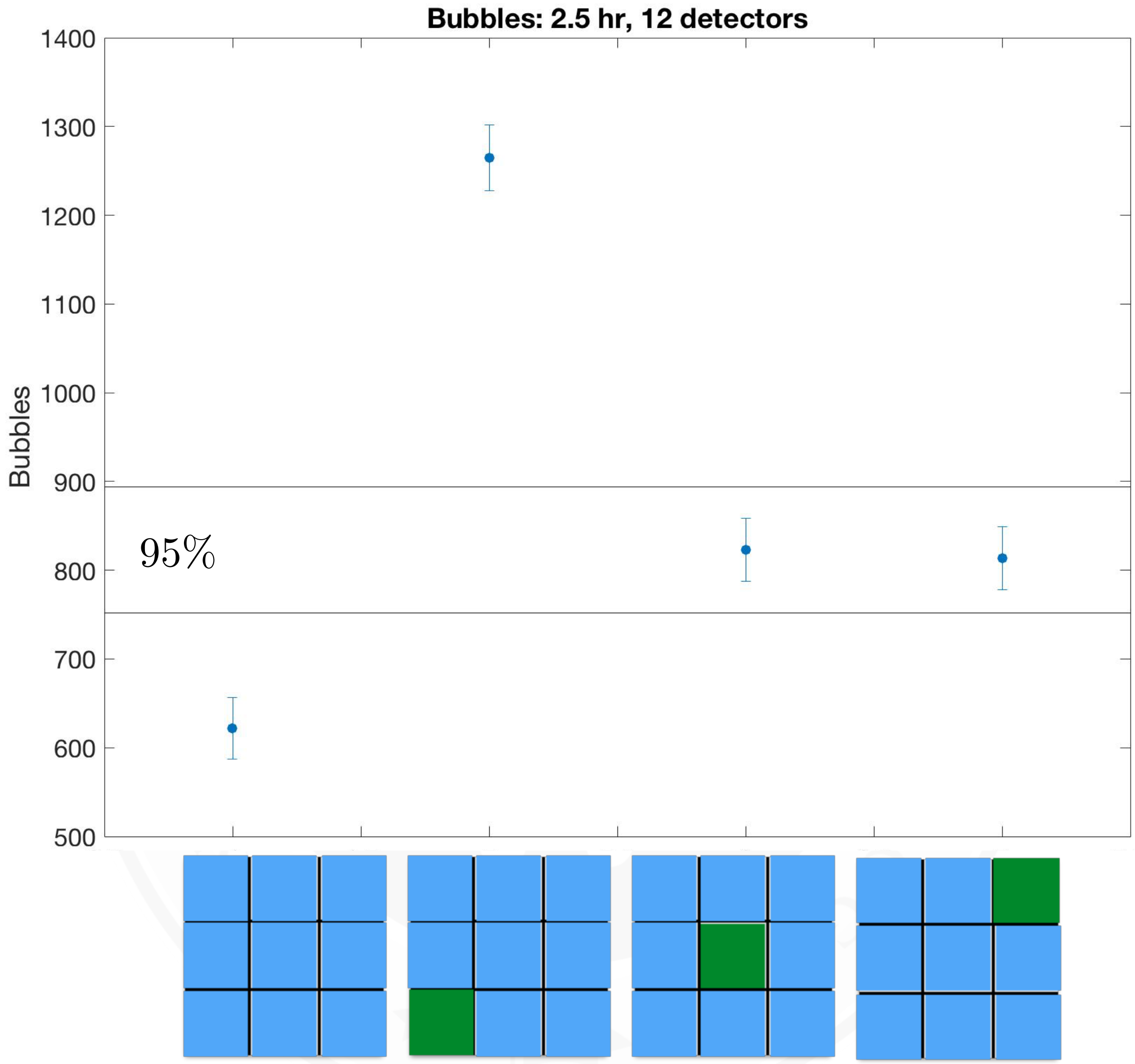


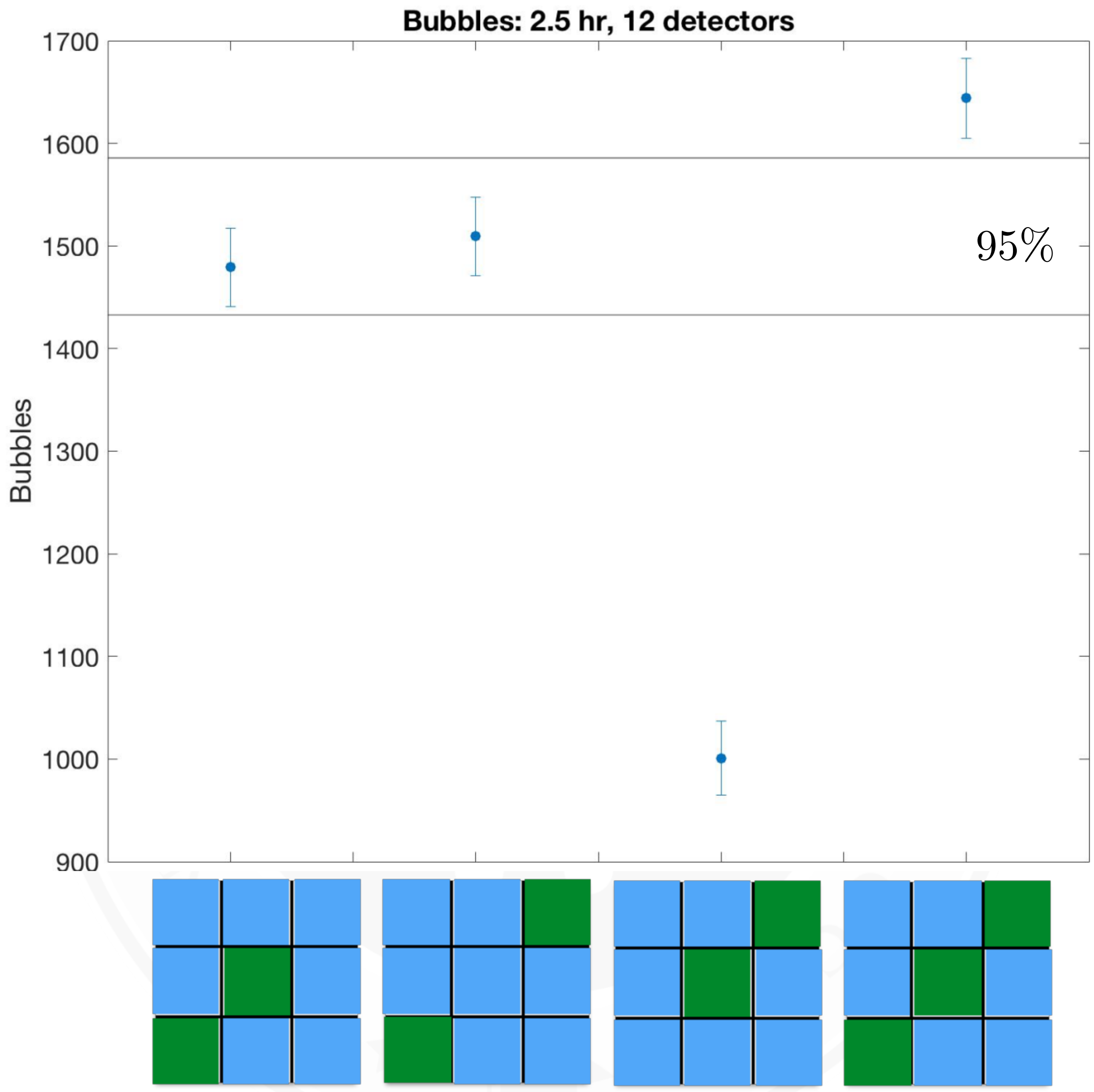
Consortium for Verification Technology

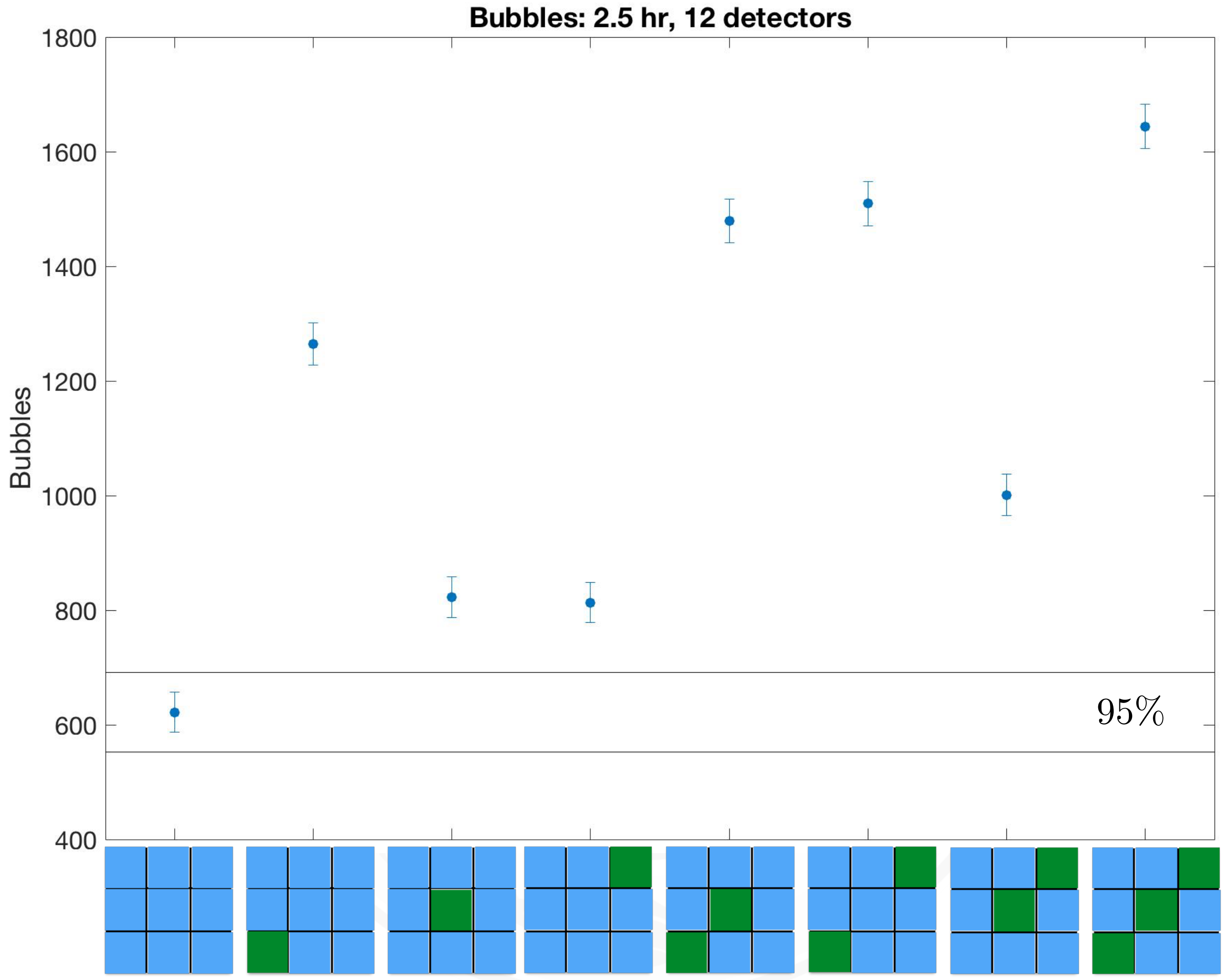
National Nuclear Security Administration

Test Object Differentiation




Bubbles: 2.5 hr, 12 detectors
Bubbles
1400
1300
1200
1100
1000
900
800
700
600
500
95%


Bubbles: 2.5 hr, 12 detectors
Bubbles
1700
1600
1500
1400
1300
1200
1100
1000
900
95%


Bubbles: 2.5 hr, 12 detectors
1800
1600
1400
1200
1000
800
600
400
Bubbles
95%

Conclusions

- Established SS as a suitable moderator to soften the 14 MeV DT source
- Redesigned and tuned collimator geometry
  - Maximize fraction < 1 MeV
  - Maximize neutron flux
  - Minimize background counts to detector arrays and facility
- Showed differentiation between DU and LEU configurations
  - Single cube of DU vs LEU
  - With additional measurements at multiple orientations, can distinguish between multi-LEU cube configurations

- Future work:
  - Use in conjunction with differential transmission radiography
  - Explore more spoof scenarios with more materials
  - Explore ways to move beyond an experimental test-bed toward a fieldable setup