



'CARD' – Characterization of Adjoint Response for Ge Detectors

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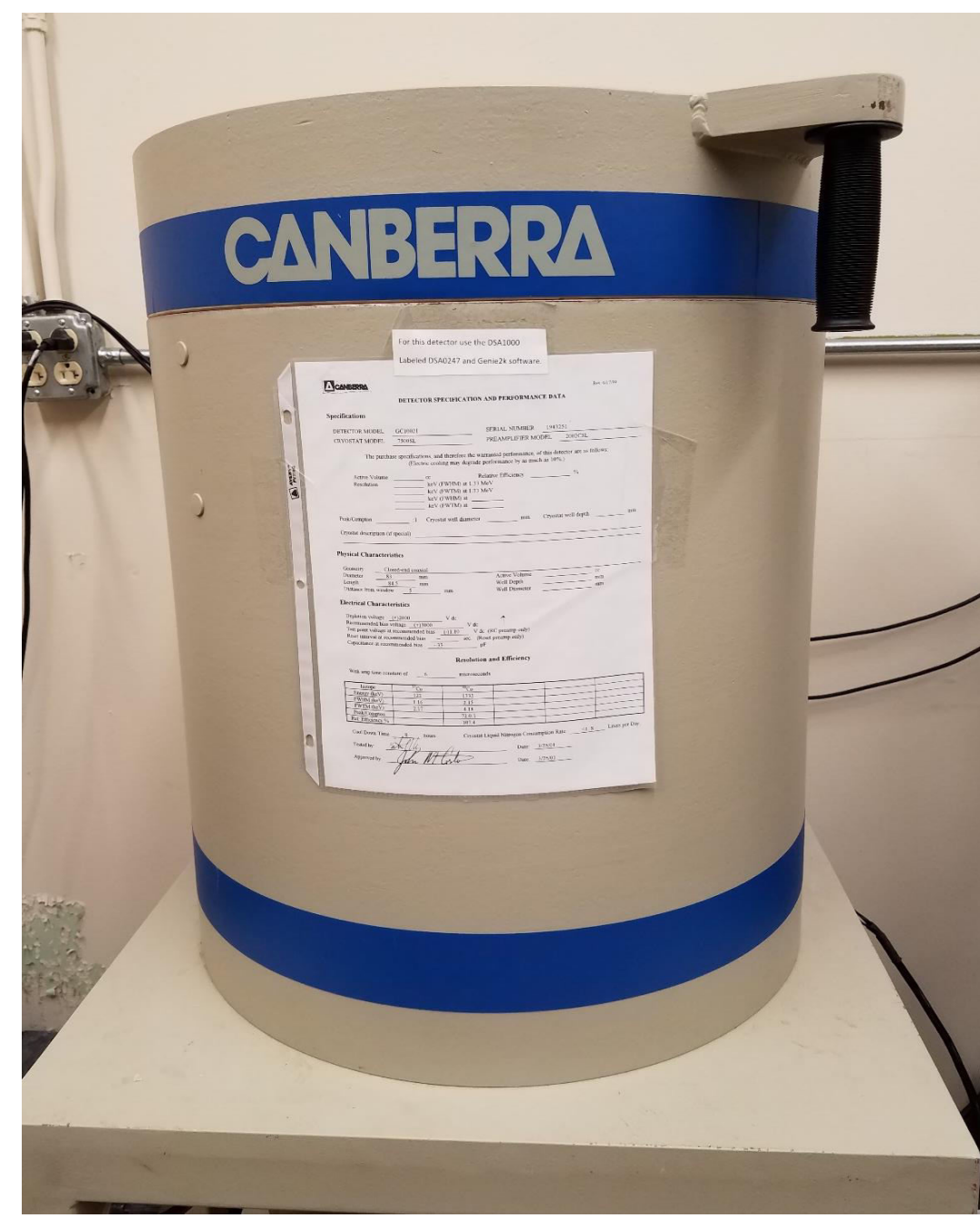
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 Design of Sensor Systems and Advanced Sensor Technologies

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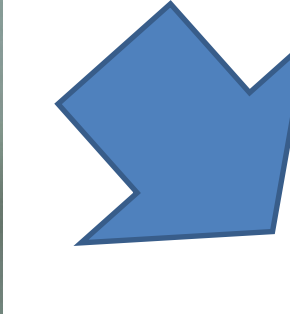
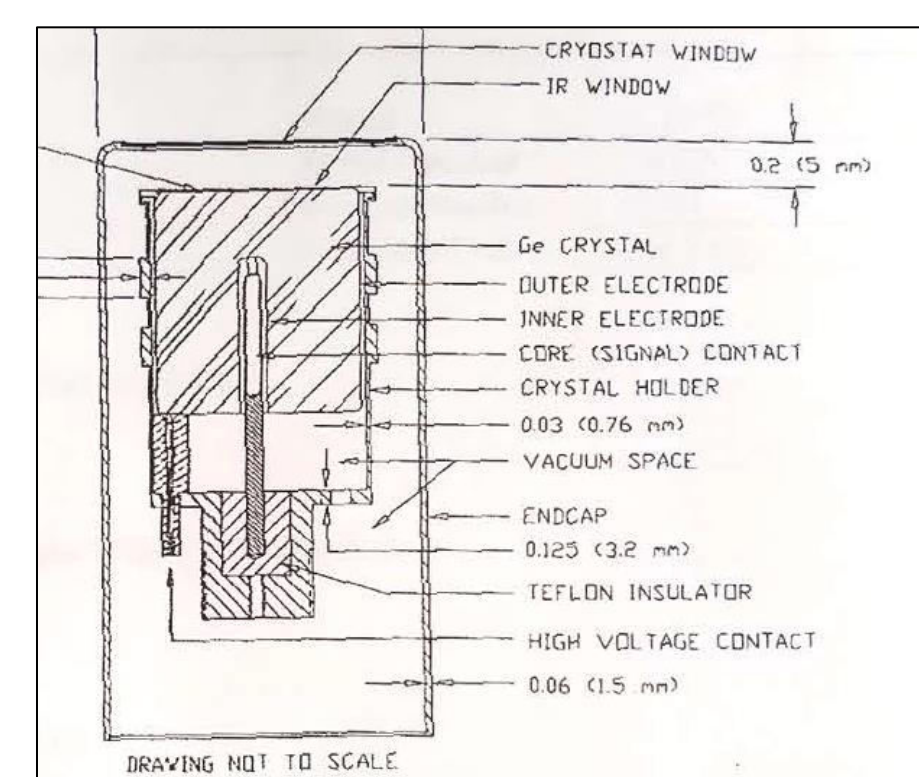
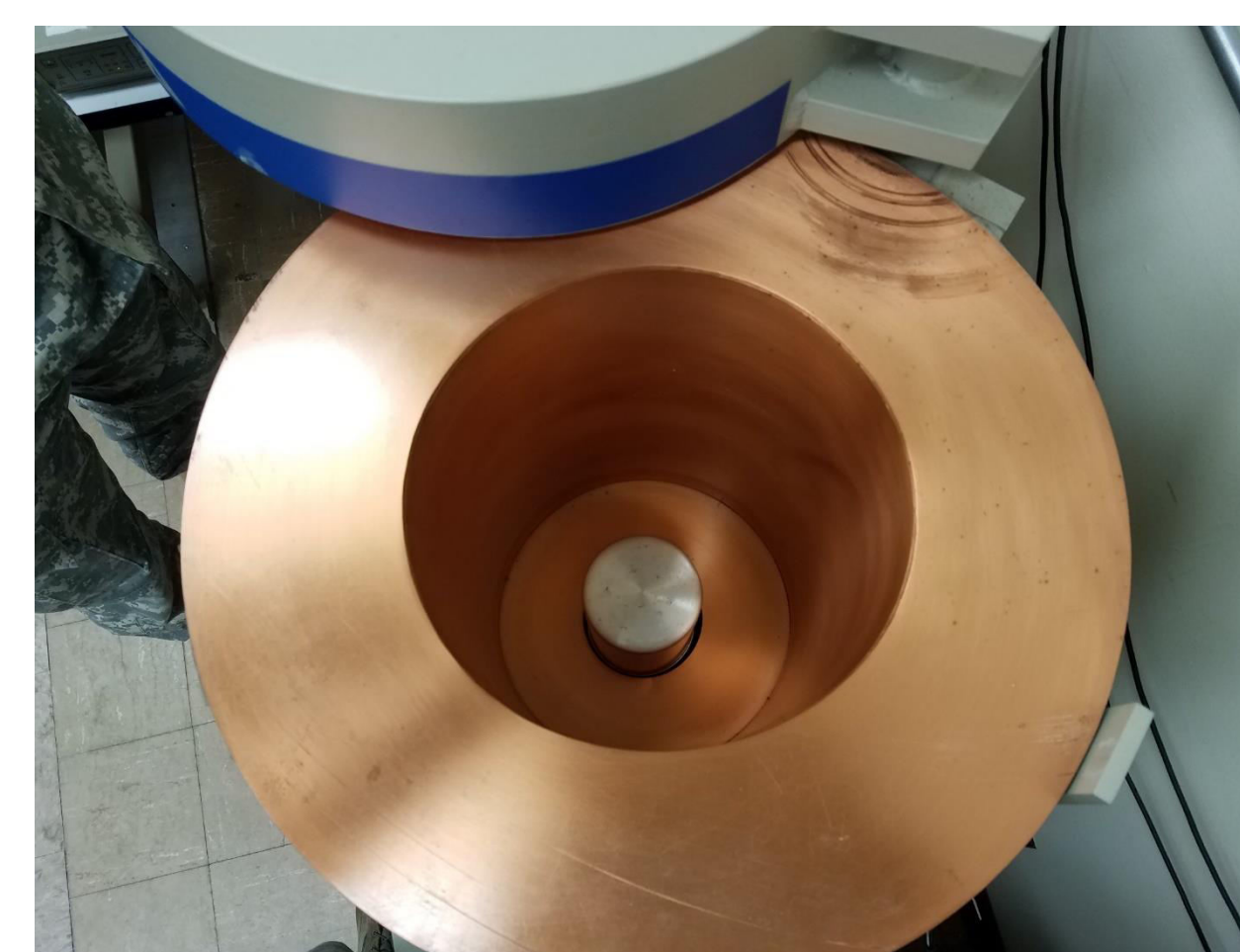
INTRODUCTION

- Gamma ray spectroscopy an important tool in ensuring treaty verification
- Need to understand / characterize HPGe detector efficiency, ϵ
- ϵ calculated via deterministic adjoint radiation transport analysis
- Adjoint transport methodology produces high fidelity map of detector efficiency ϵ for any photon energy
- Adjoint mapping important to reveal subtle effects of source placement & sample geometry on detector ϵ
- Precise ϵ impacts overall sensitivity of detector measurement, detectable quantities being measured, etc.

EXPERIMENT



AFIT HPGe Detector



Test Data for reference source

Eckert & Ziegler
 Isotope Products
 24937 Avenue Tibbitts
 Valencia, California 91355
 Tel: 661-269-1515
 Fax: 661-267-9303

**CERTIFICATE OF CALIBRATION
 MULTINUCLEIDE STANDARD SOURCE**

Customer: AIR FORCE INSTITUTE OF TECHNOLOGY
 P.O. No.: ROBINSON/SEP15/USA
 Catalog No.: GE-86

Source No.: 1909-04-1
 Reference Date: 1-10-16
 Constant Uncertainty: 0.0005 ±0.35%

Physical Description:
 A. Capsule type: D (25.4 mm OD x 6.35 mm maximum THK)
 B. Nature of active deposit: Electroplated metallic salts
 C. Active diameter/volume: 5 mm
 D. Backing: Stony
 E. Cover: Aryle

Gamma Ray Energy (keV)	Nuclide	Half-life	Branching Ratio (%)	Activity per source	Total Source
402	Am-241	432.17 ± 0.05 years	36.0	0.02941	361.7
88	Cs-137	30.17 ± 0.01 years	85.4	0.04255	533.0
122	Co-60	5.27 ± 0.01 years	99.9	0.05951	747.7
159	Tl-203	193.3 ± 0.1 days	84.0	0.04453	556.7
302	Cr-51	27.70 ± 0.07 days	9.99	0.03888	486.0
352	Ba-113	115.0 ± 0.04 days	64.9	0.05109	638.1
814	Bi-208	4.81 ± 0.04 days	56.4	0.05111	638.1
888	Y-88	105.8 ± 0.02 days	84.2	0.06822	852.7
1173	Cs-137	30.17 ± 0.01 years	85.4	0.04255	533.0
1333	Co-60	5.27 ± 0.01 years	99.9	0.05951	747.7
1530	Y-88	105.8 ± 0.02 days	84.2	0.06822	852.7

Method of Calibration:
 This source was assayed using gamma ray spectrometry.

Notes:
 - See reverse side for full NIST certification text.
 - IAEA participates in a NIST measurement assurance program to establish and maintain implicit traceability for a number of radionuclides, based on the third assay (and later NIST certification) of Standard Reference Material (SRM) in NIST Regulatory Guide 4.15.
 - Nuclear data was taken from IAEA TECDOC-615, 1991.
 - Overall uncertainty is calculated at the 95% confidence level.
 - This source has a recommended working life of 1 year.

David B. ...
 Quality Control
 Date: 27-Nov-16
 EZZ Ref No.: 1909-04

ADJOINT TRANSPORT

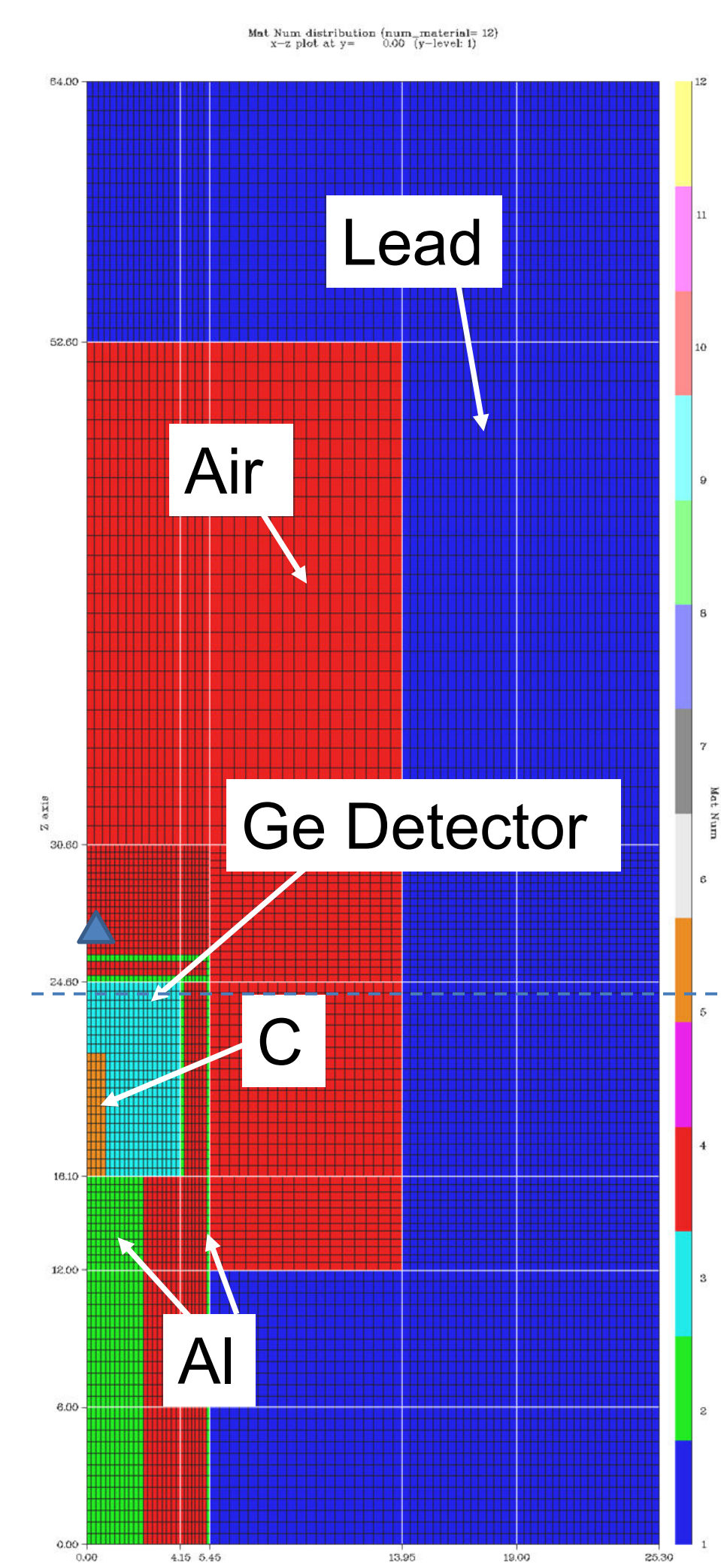
- Forward Boltzmann Transport Eqn:

$$\hat{\Omega} \cdot \nabla \psi(\vec{r}, \hat{\Omega}, E) + \sigma(\vec{r}, E) \psi(\vec{r}, \hat{\Omega}, E) = \int_{0}^{\infty} \int_{4\pi} dE' d\Omega' \sigma_s(\vec{r}, \hat{\Omega}', E' \rightarrow E) \psi(\vec{r}, \hat{\Omega}', E') + q(\vec{r}, \hat{\Omega}, E)$$
- Multigroup approx.: $\psi(\vec{r}, \hat{\Omega}, E) \rightarrow \psi_g(\vec{r}, \hat{\Omega})$
- Forward multi-group transport operator H used to derive adjoint operator H^+ using *adjoint identity* for real functions; $\langle \cdot \rangle$ used for phase space integration:
- Adjoint Identity: $\langle \psi_g^+ H \psi_g \rangle = \langle \psi_g H^+ \psi_g^+ \rangle$
- Leads to adjoint eqn: $H^+ \psi_g^+ = \sigma_{dg}$
- $$H^+ \psi_g^+(\vec{r}, \hat{\Omega}) = -\hat{\Omega} \cdot \nabla \psi_g^+(\vec{r}, \hat{\Omega}) + \sigma_g(\vec{r}) \psi_g^+(\vec{r}, \hat{\Omega}) - \sum_{g'=1}^G \int_{4\pi} d\Omega' \sigma_{s_{g \rightarrow g'}}(\vec{r}, \hat{\Omega} \cdot \hat{\Omega}') \psi_{g'}^+(\vec{r}, \hat{\Omega}')$$
- Adjoint function computed using 'adjoint source' aliased to detector cross section leads to adjoint 'detector efficiency'.
- Response R in detector is computed from either forward: or adjoint:

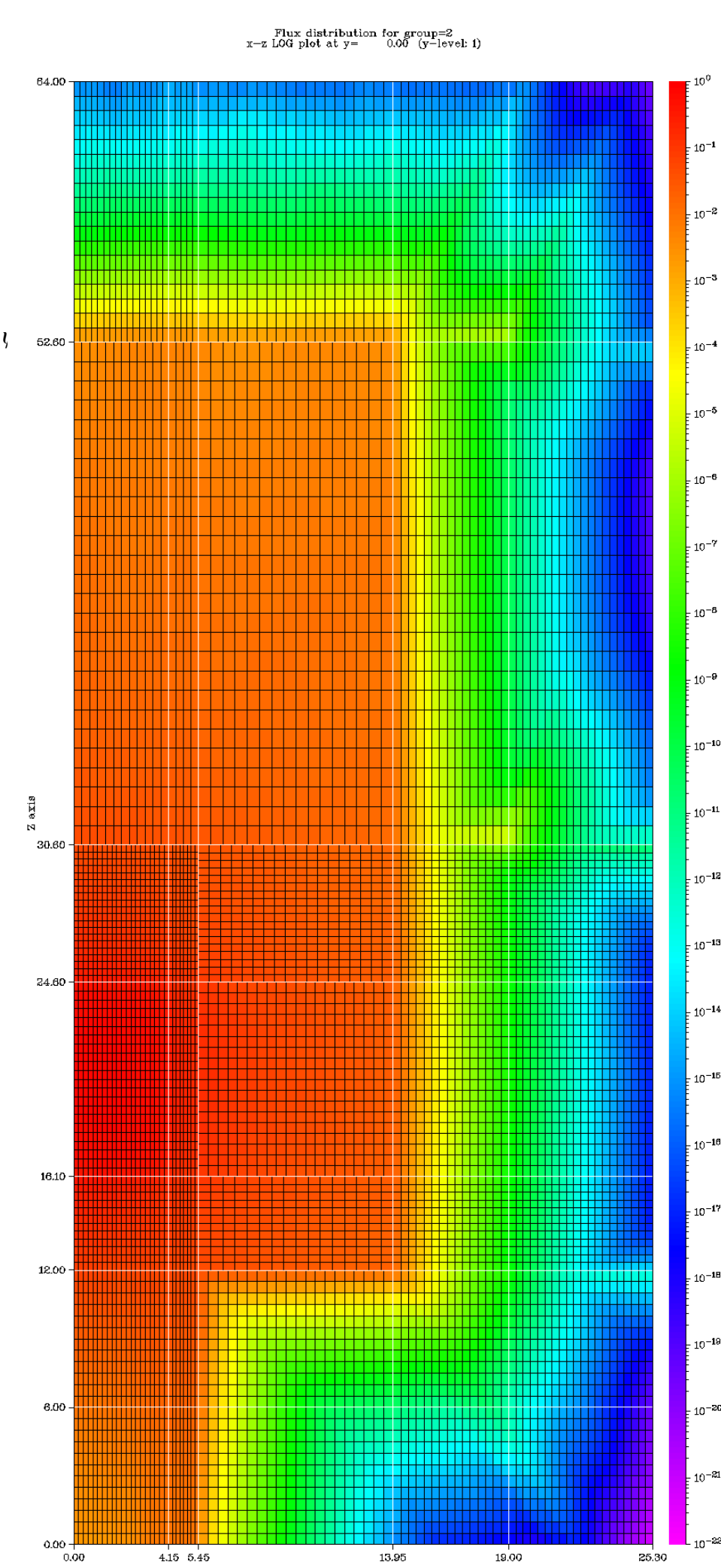
$$R = \langle \psi_g \sigma_{dg} \rangle = \langle \psi_g^+ q_g \rangle$$
- ϵ profiled with either *many* forward models (moving forward source to numerous new source locations, recomputing multigroup transport each time) **OR** run a **SINGLE** adjoint transport computation to map group adjoint ϵ values aliased to detector response cross section as function of position, energy, etc.
- Adjoint transport yields global phase space gamma efficiency ϵ map for detector

ADJOINT EFFICIENCY MODEL

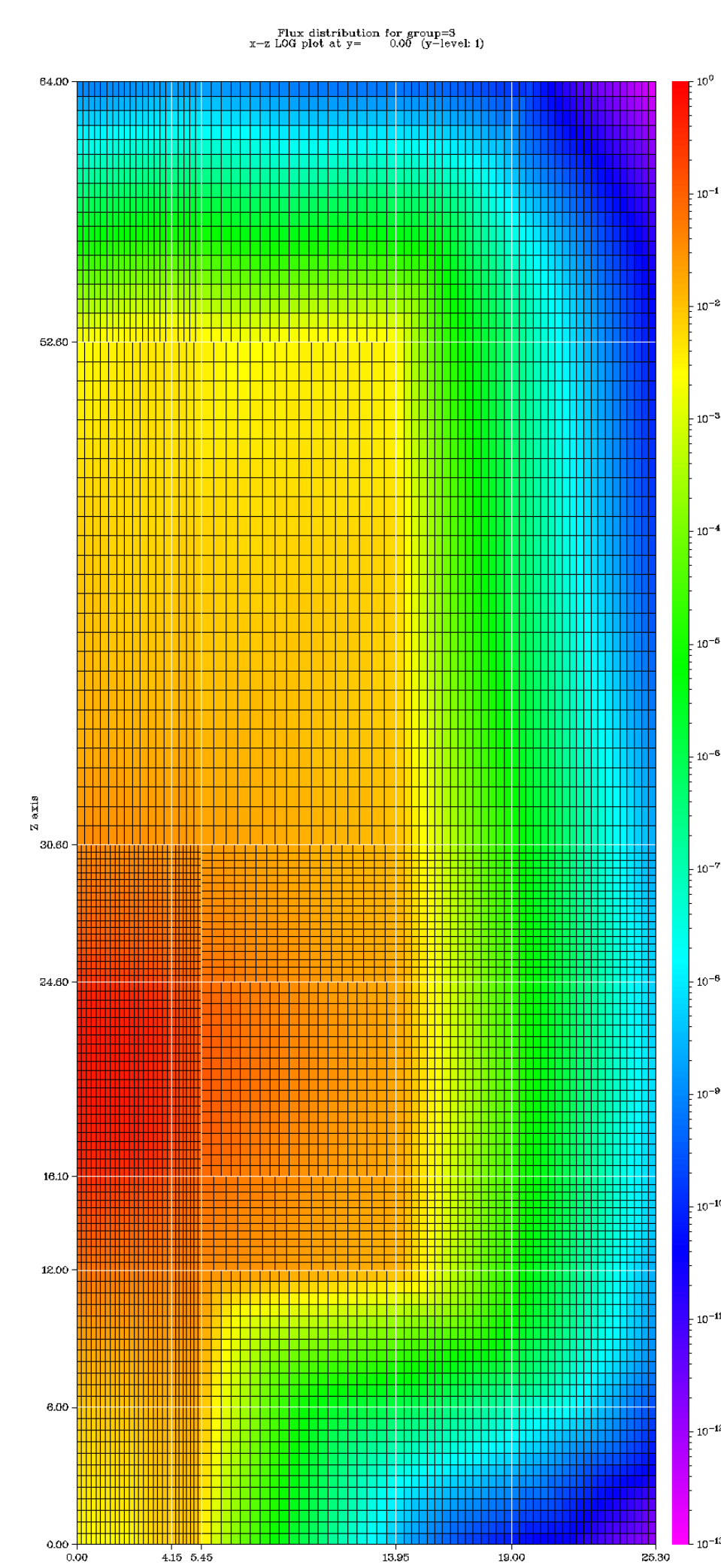
3-D Model x-z Slice



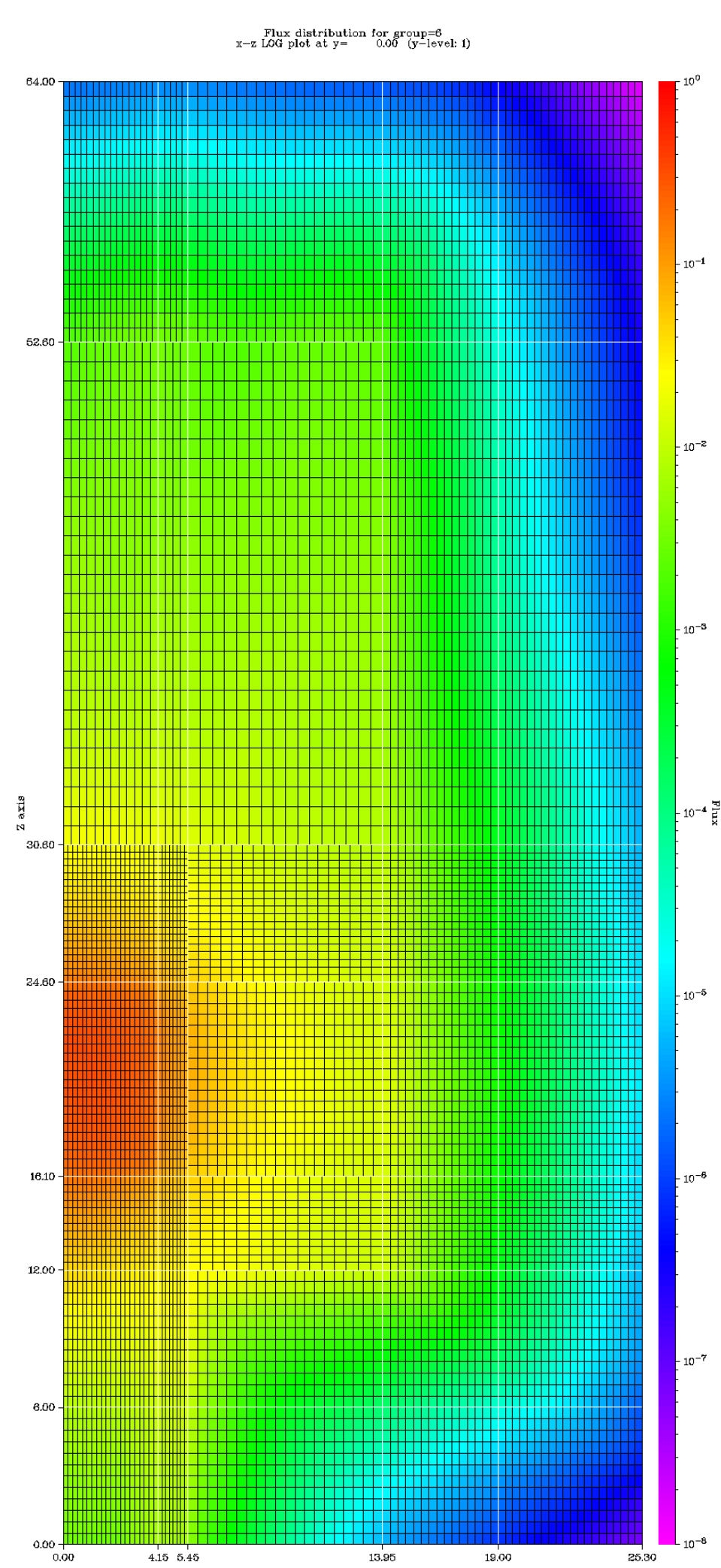
0.375 MeV



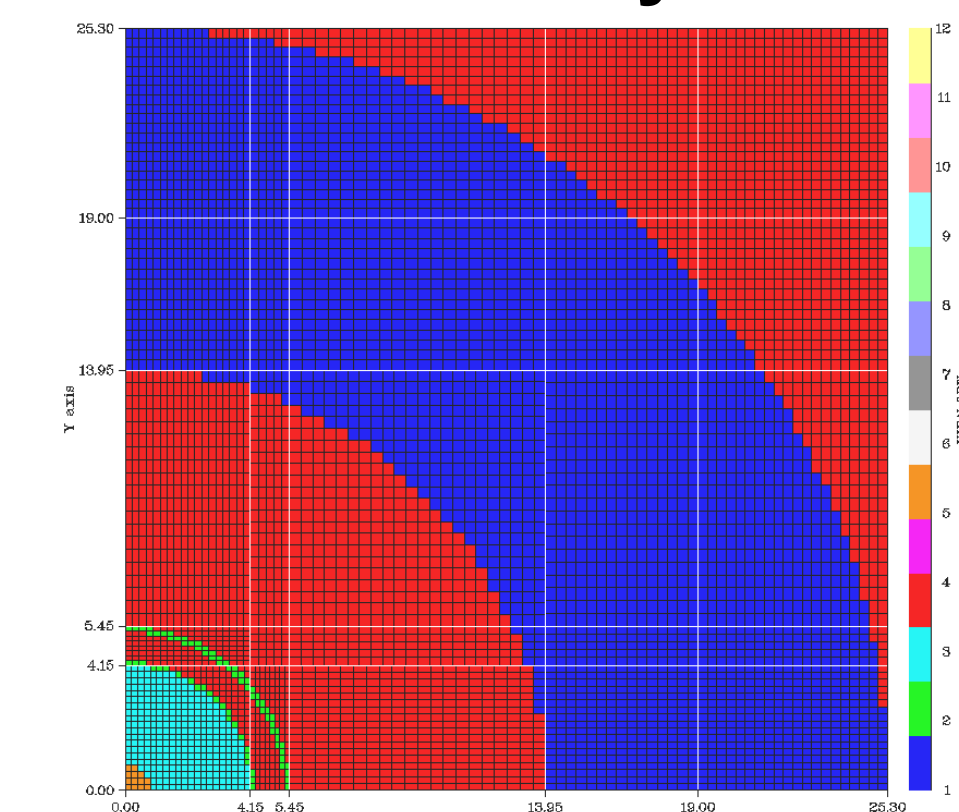
0.625 MeV



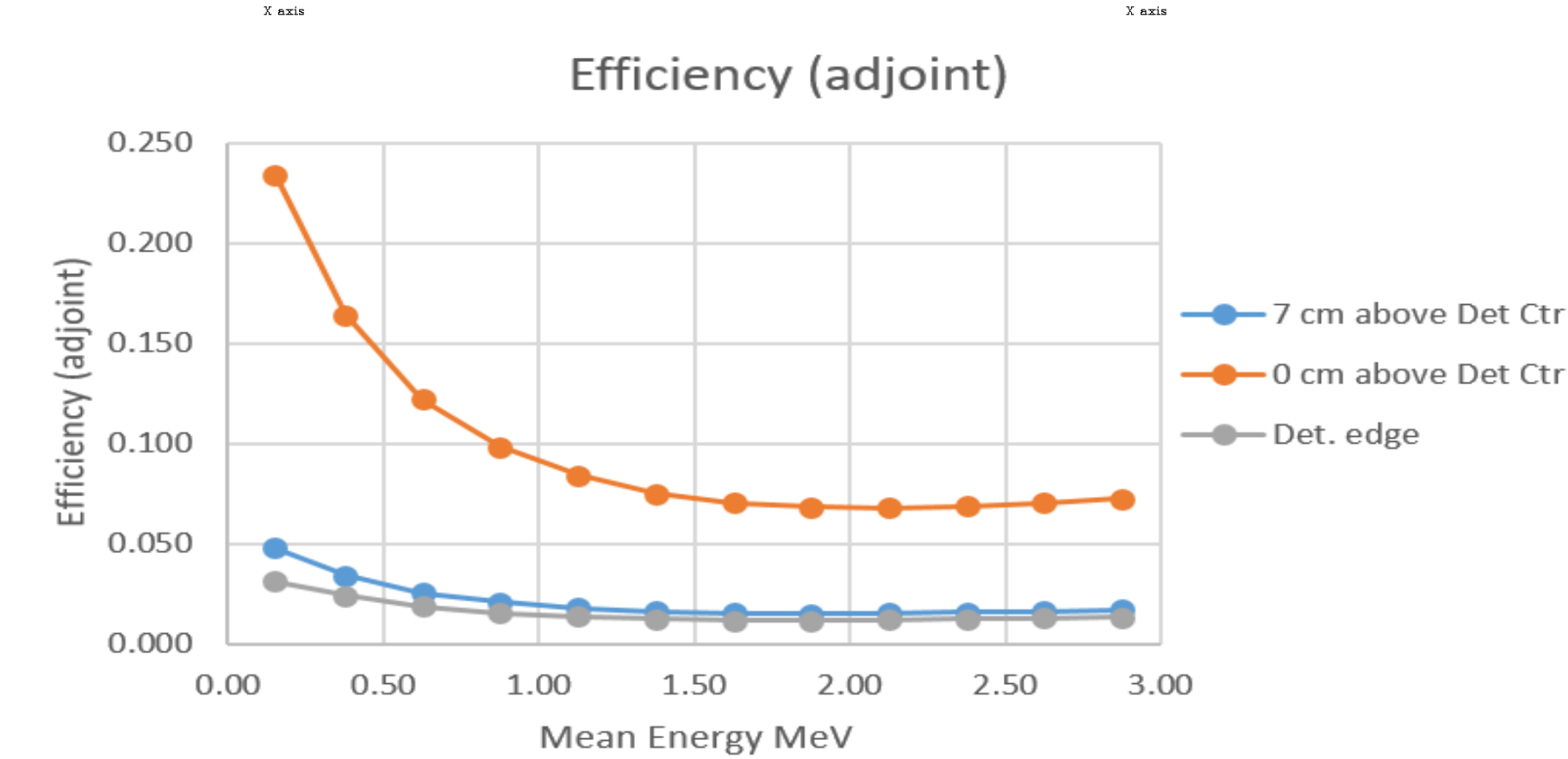
1.375 MeV



3-D Model x-y Slice



Computational (S_{20}/P_1 , >650,000 mesh cells) results depict a dramatic change in efficiency with position and energy, as expected...



C/E RESULTS

Comparisons made for 0 cm on top of detector:

MeV	Experiment	Calculated	Offset Diff	(C-Q*)/E
0.320	0.115	0.182	0.066	1.302
0.392	0.125	0.162	0.036	1.040
0.514	0.108	0.133	0.025	0.946
0.662	0.092	0.119	0.027	0.951
0.898	0.060	0.097	0.037	1.092
1.173	0.050	0.083	0.032	1.022
1.333	0.047	0.077	0.030	0.966
1.836	0.037	0.069	0.032	1.009
		*mean	0.031	1.004
		(grey data only)		

CONCLUSIONS

Detector measurement compared to computed adjoint efficiency data provided consistent results which revealed a ~3% efficiency loss for electronic conversion relative to modeled results ("offset" value). Future work will focus on refining model fidelity (Sn mesh, quadrature refinement), and comparison with additional measurement data for better ϵ corrections.