Positron and photo-neutron creation using a petawatt laser to irradiate high-Z thick targets

Edison Liang, Rice University*

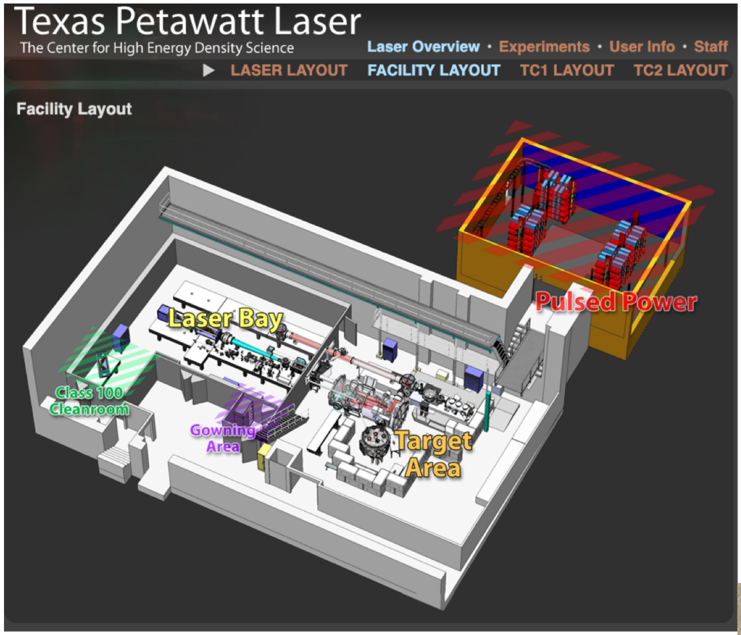
*On behalf of the Rice, UTA and LLNL collaboration:

E.Liang[1], W.Lo[2], B.Cage[1], S.Arora[1], K.Q.Zheng[1], H.Quvedo[2], S.A.Bruce[2], M. Spinks[2], E. Medina[2], A. Helal[2], T. Ditmire[2], S. Libby[3], S. Willks[3], A. Nikroo[3], J. Nguyen[3]

[1] Rice University, [2] University of Texas at Austin, [3] LLNL

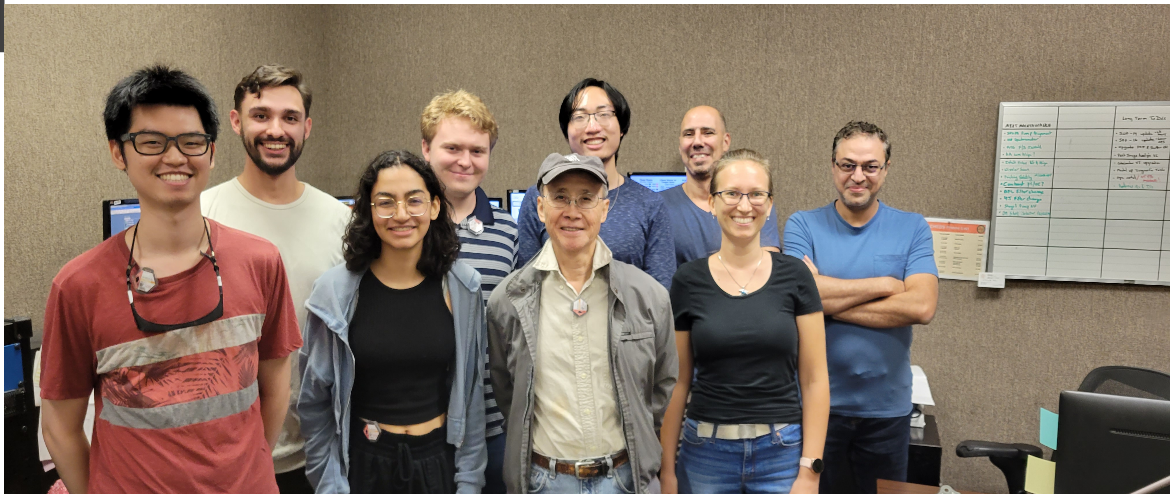
Supported by DOE OFES

Talk presented at the 2023 Nuclear Photonics Conf., Durham NC

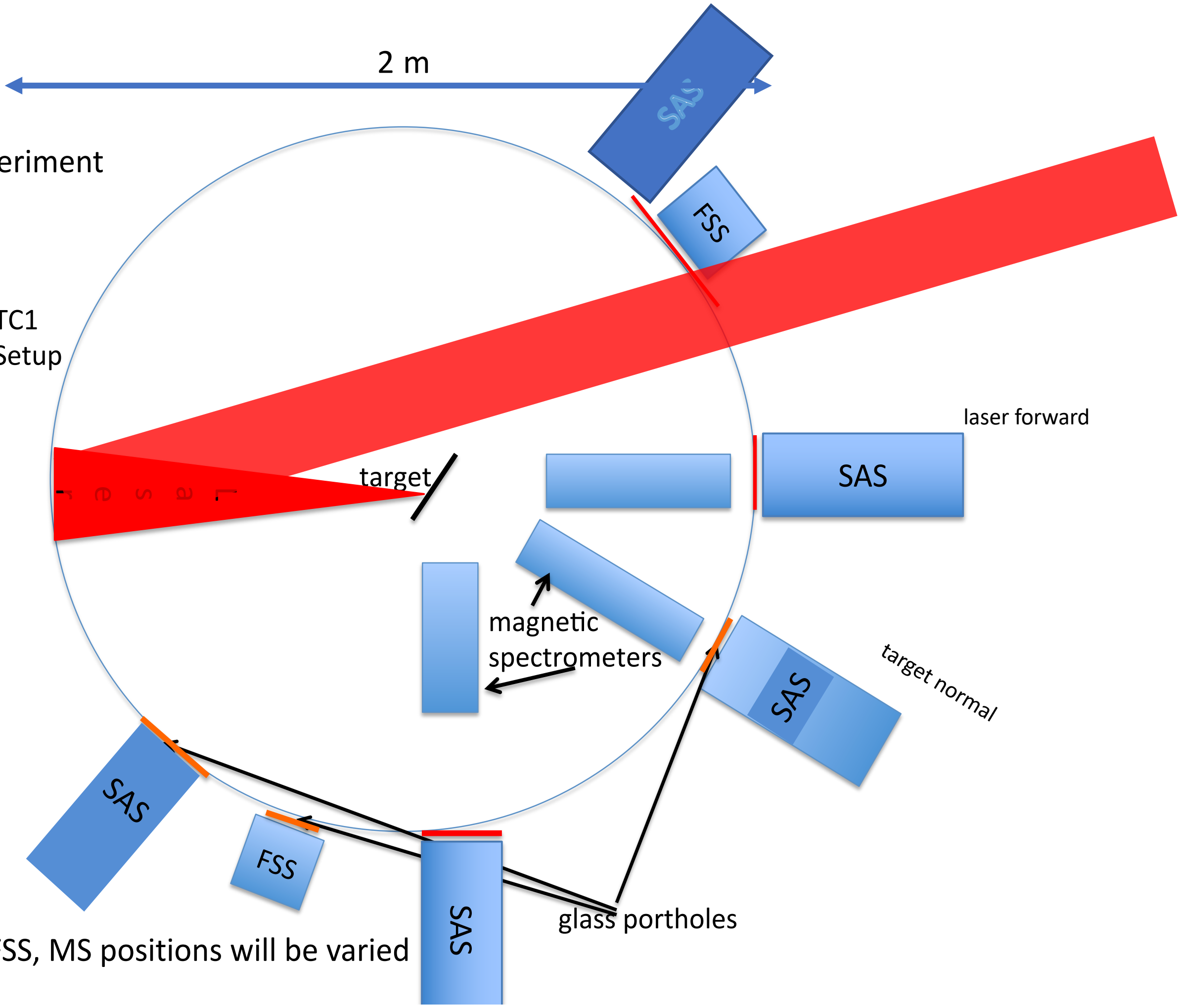


We used the f/3 beam in TC1 of TPW in Austin Texas
~130 J, ~ 130 fs, up to 5x10^{21} W/cm^2

Group Photo 2022

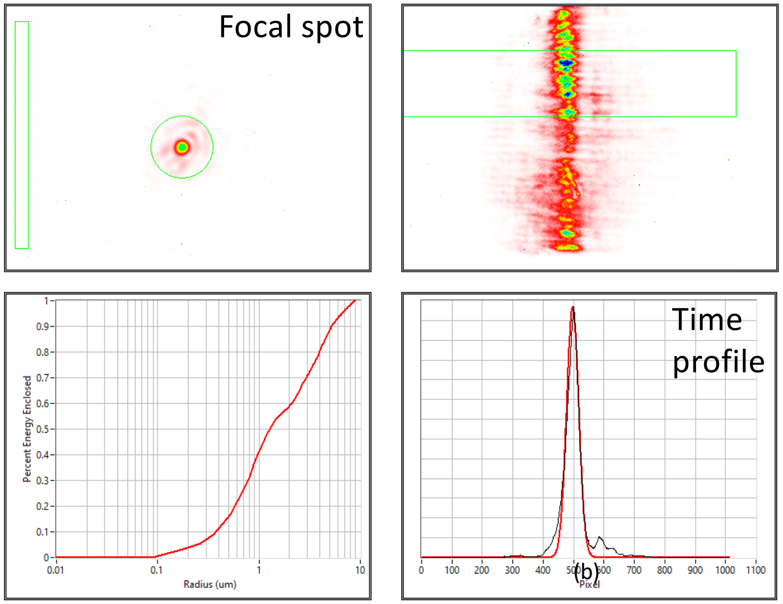


Setup of TPW Experiment



SAS, FSS, MS positions will be varied

SHOT# 014897 2022-06-23



Energy
135 J

Pulse Duration
138 fs

Power
980 TW

I = 4.7e+21 W/cm2

6/23/2022 4:22:12 PM

TPW laser parameters of our 2022 60-shot run

	Energy	Pulse Duration (fs)	Peak Power (TW)	closed Radius with 50% (u	ak Intensity (W/cm	Strehl
AVERAGE	123.25	161.05	781.82	3.8	2.96E+21	0.68
MEDIAN	122.57	158	794.12	3.72	2.89E+21	0.7
MIN	104.2	128	531.29	2.42	1.85E+21	0.46
MAX	139.18	216	1060.68	5.39	4.68E+21	0.82

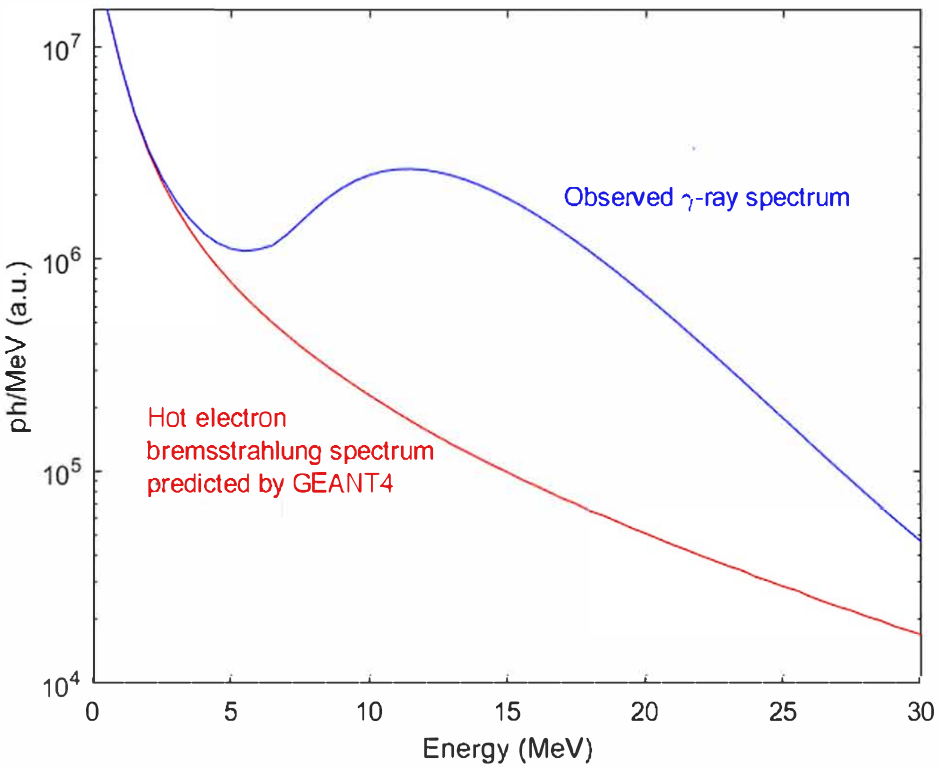
History

- In earlier experiments at the Texas Petawatt (TPW) laser to study e+e- pair creation using high-Z thick targets, we discovered evidence that the gamma-rays consist of two distinct components: (a) hot electron bremsstrahlung emission in the form of an exponential spectrum, plus (b) a broad high-energy bump > 8 MeV. This discovery was first obtained using our SAS gamma-ray spectrometer we developed together with MDACC.

- In 2022 we conducted new experiments at TPW to confirm and characterize the gamma-ray spectrum, using 3 independent techniques in addition to SAS: positron yield and spectrum, photo-neutron yield, and photo-fission yield of actinides, to independently confirm the gamma-ray bump > 8 MeV.

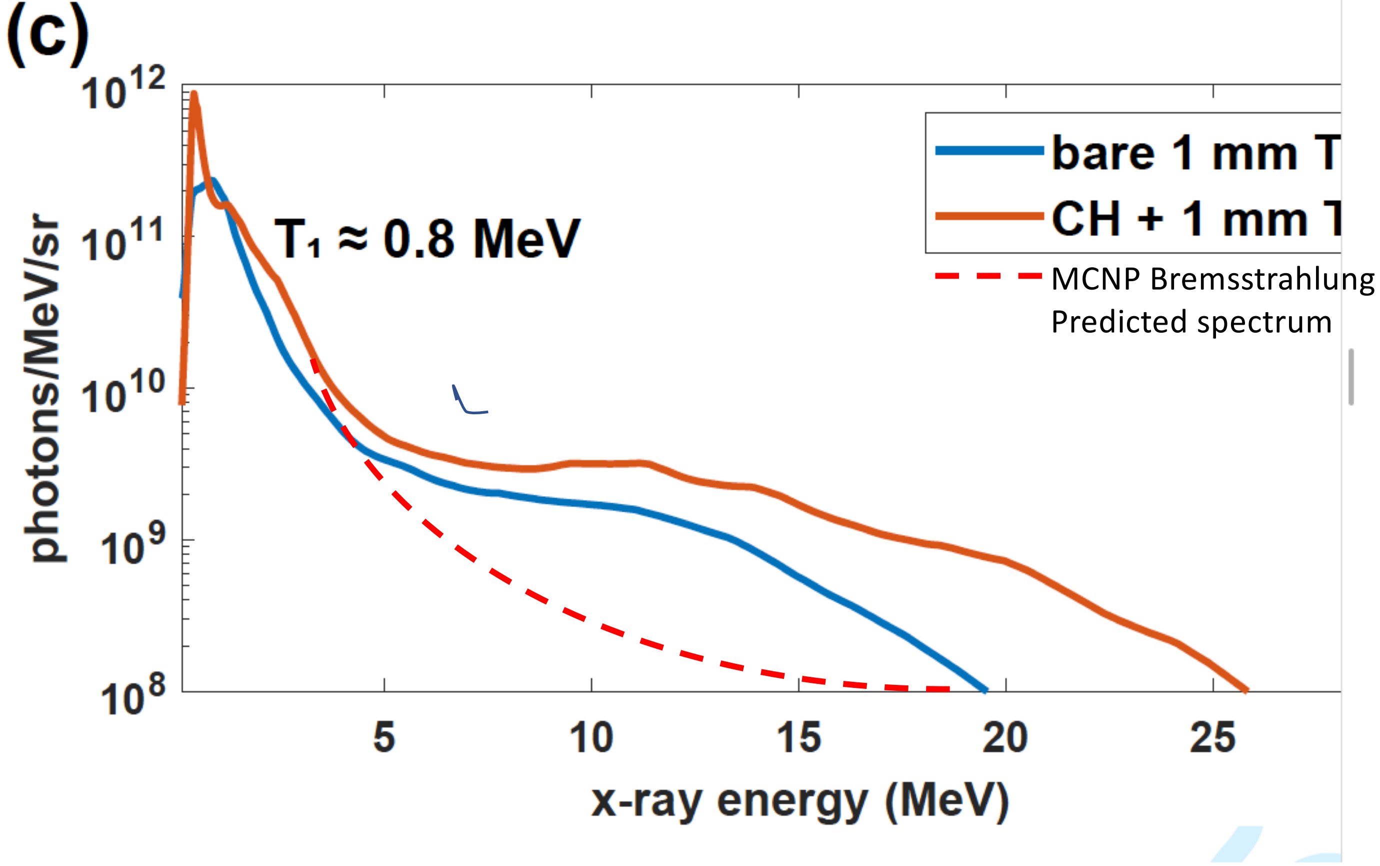
- These results (a) confirmed the SAS results, (b) produced up to few x 10^{12} gamma-ray > 8 MeV (~ 3 % of laser energy), (c) up to ~ 10^{10} photo-neutrons in most shots.

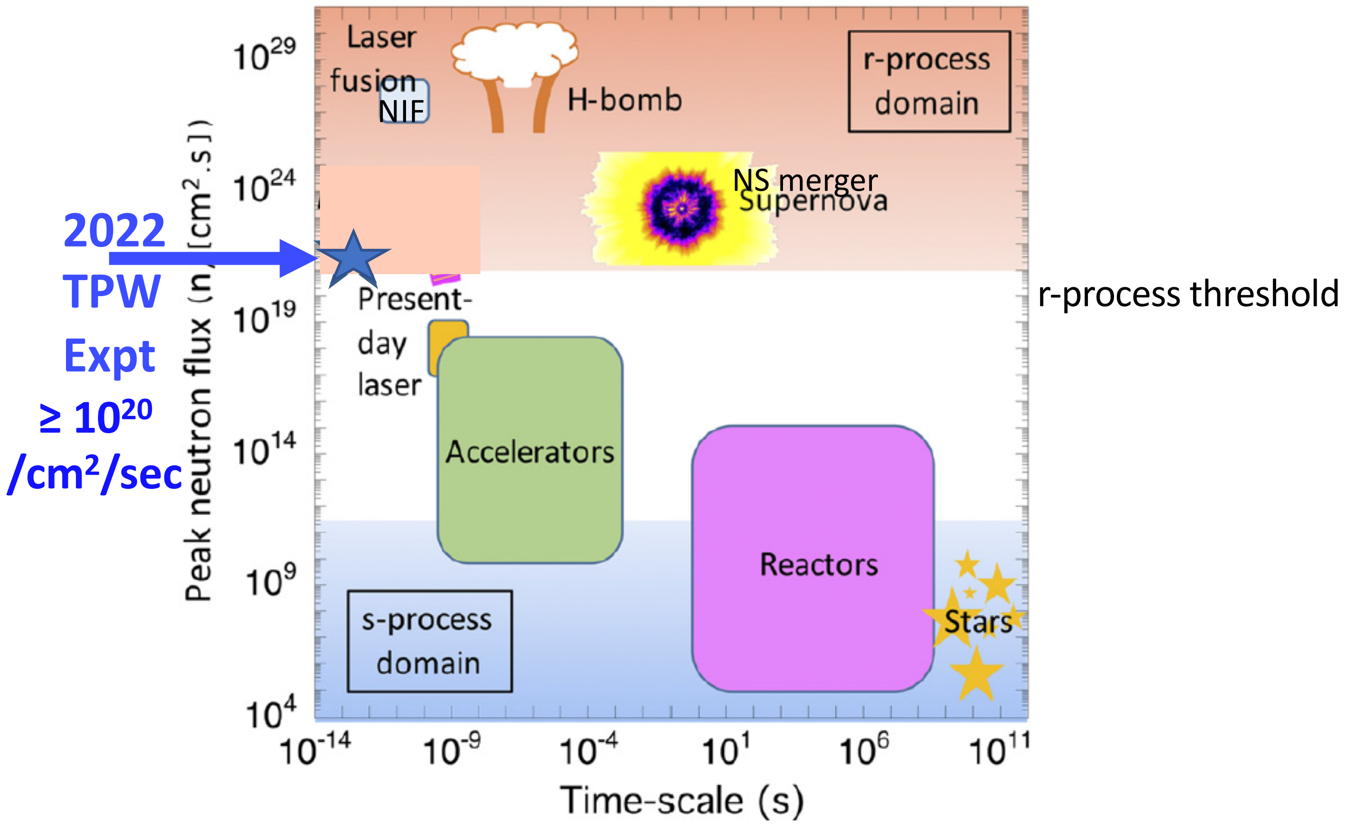
- Due to the short pulse (~140 fs) and narrow gamma-ray cone (~ 17^{o} around laser forward (LF)) the peak emergent gamma-ray flux reach 10^{27} photons/cm^2/sec and the peak photo-neutron flux reached ~ 10^{20} neutrons/cm^2/sec.



Pure hot electron bremsstrahlung would emit ~100 times less gamma rays > 8 MeV than we observed at LF

Similar Broad Gamma-Ray Features > 8 MeV was obtained independently by 2023 LANL experiments at TPW

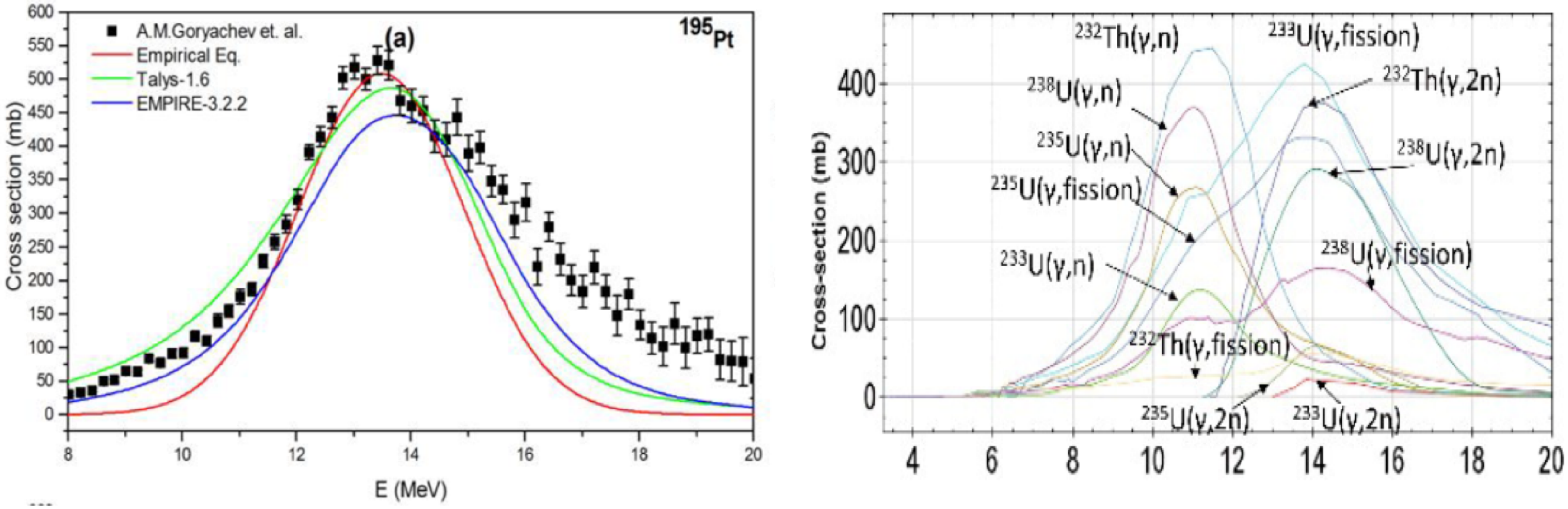




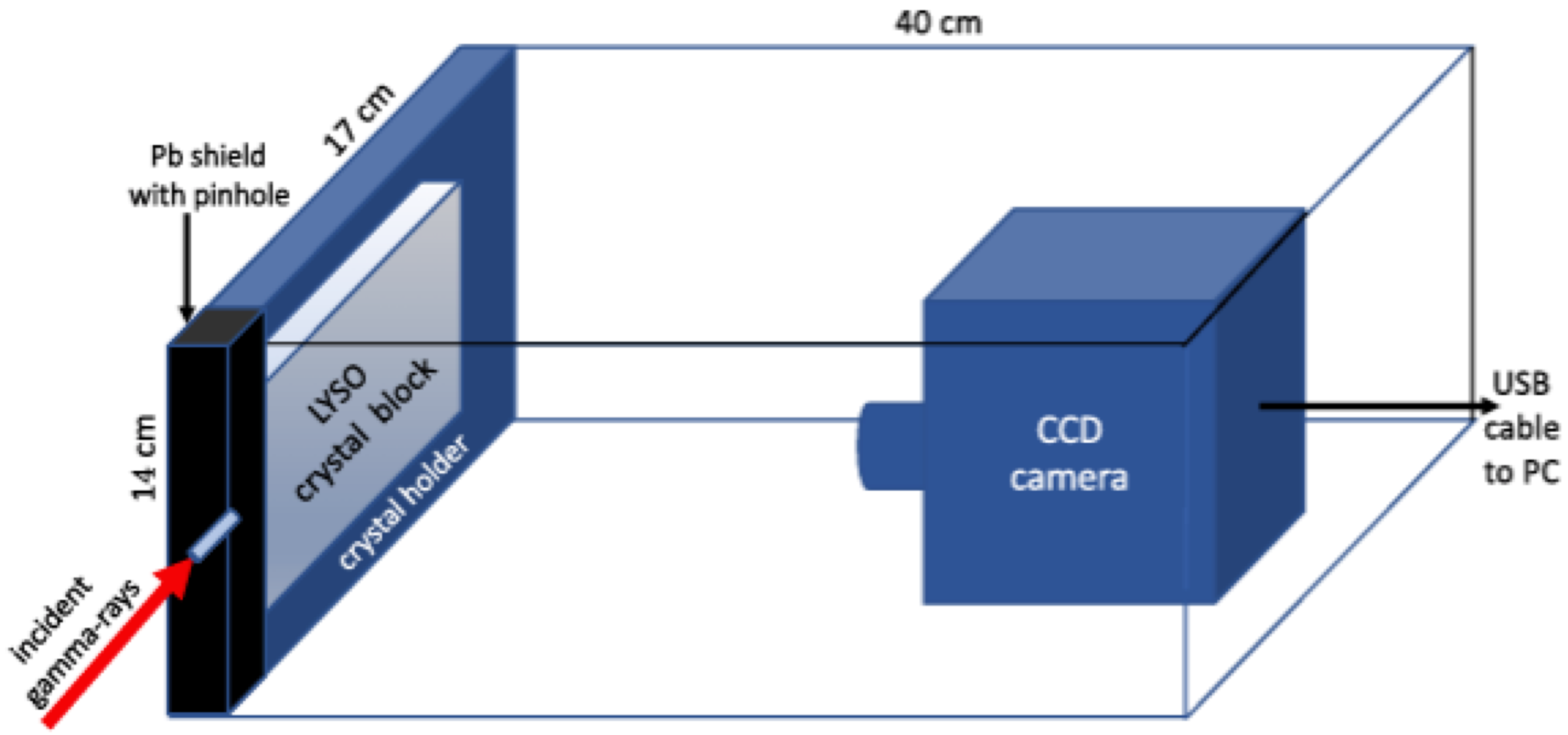
2022 TPW Expt ≥ 10^{20} /cm^2/sec

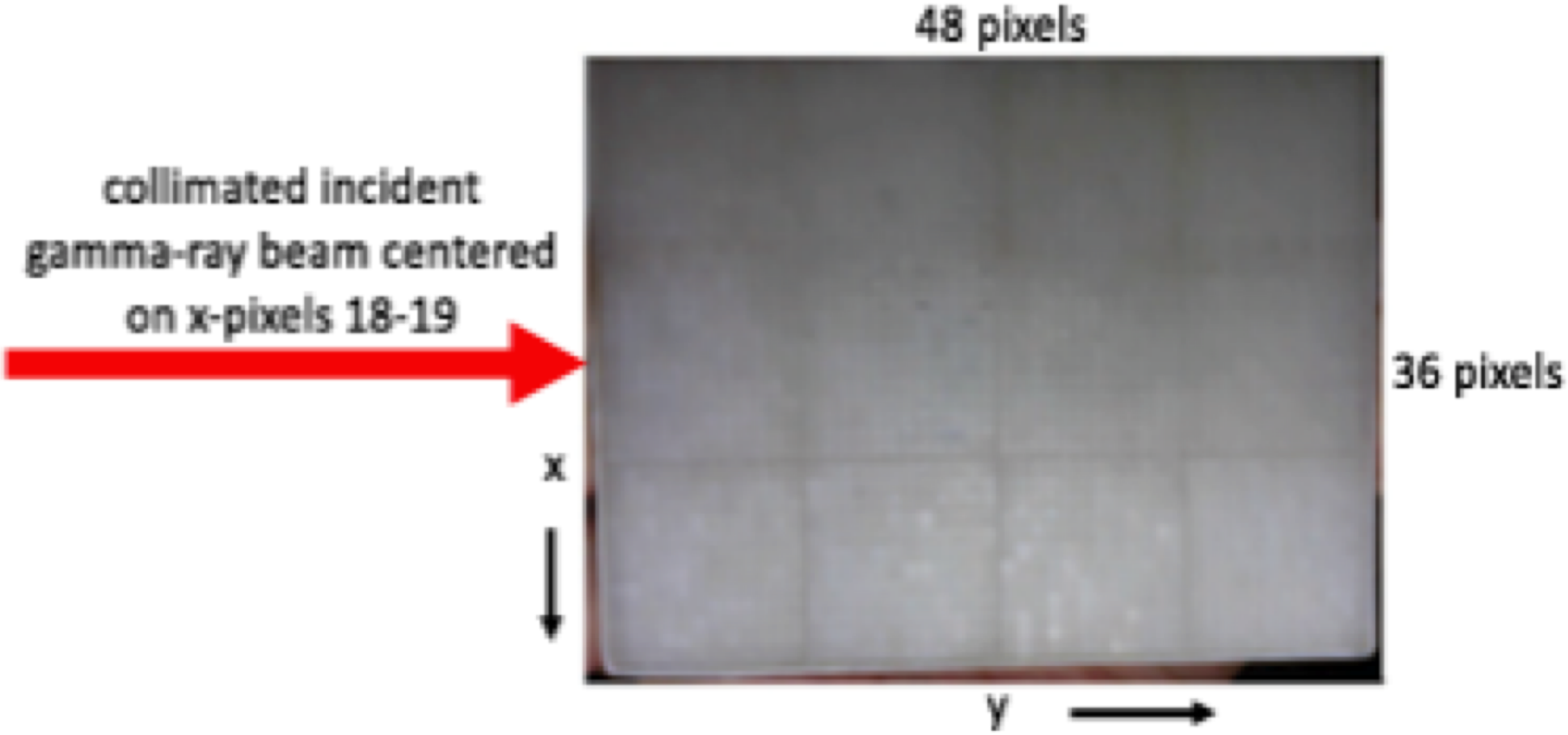
r-process threshold

(*Adapted from Chen et al 2019*)

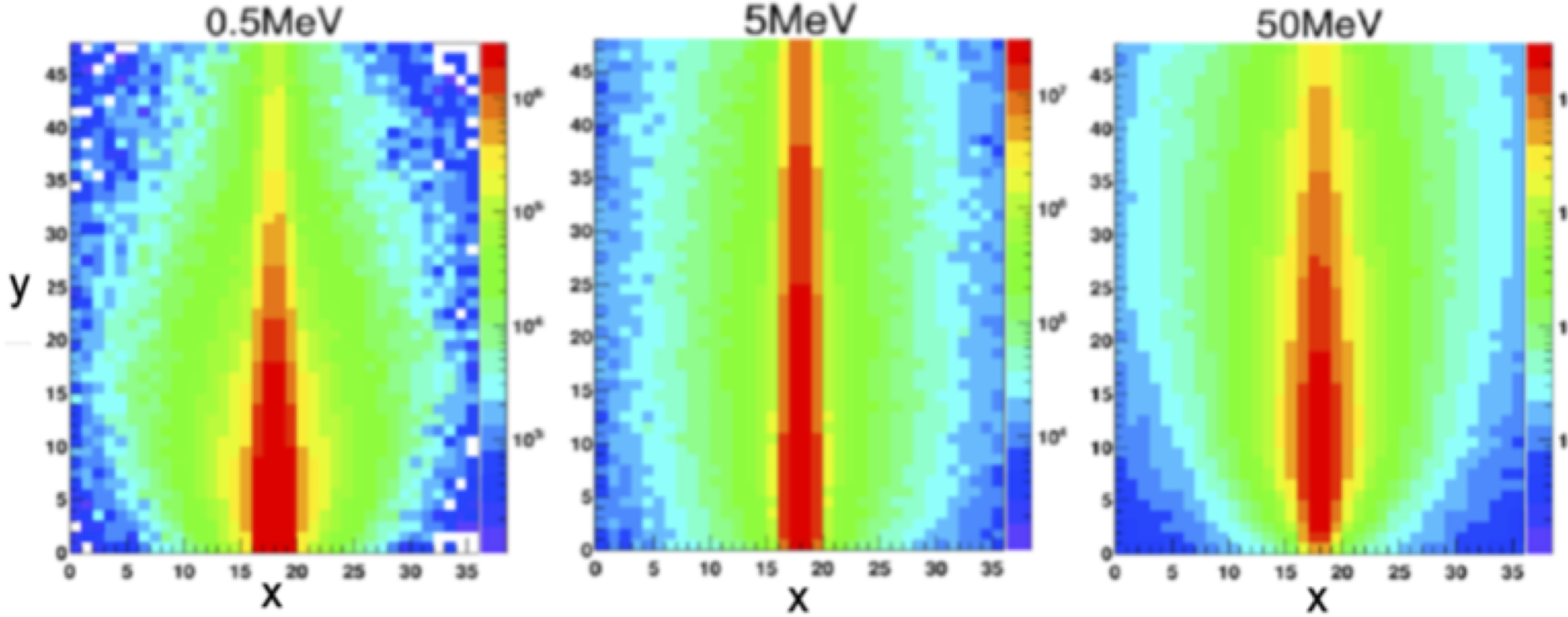


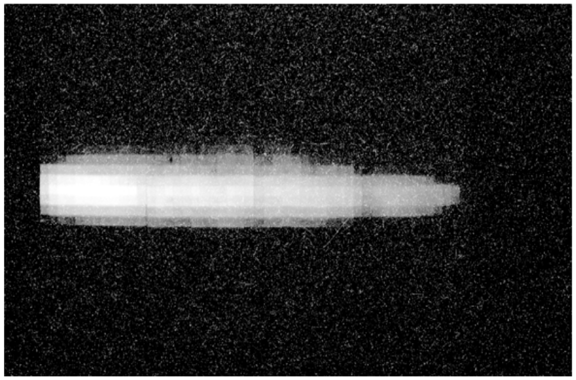
GDR cross-sections for (γ, n), (γ, 2n) and (γ, fission) reactions span 8 – 20 MeV. Hence photo-neutron and photo-fission yields are highly sensitive to the gamma-ray fluence in this energy range.


40 cm
17 cm
Pb shield
with pinhole
14 cm
LYSO
crystal block
crystal holder
incident
gamma-rays
CCD
camera
USB
cable
to PC


48 pixels
collimated incident gamma-ray beam centered on x-pixels 18-19
36 pixels
x
y

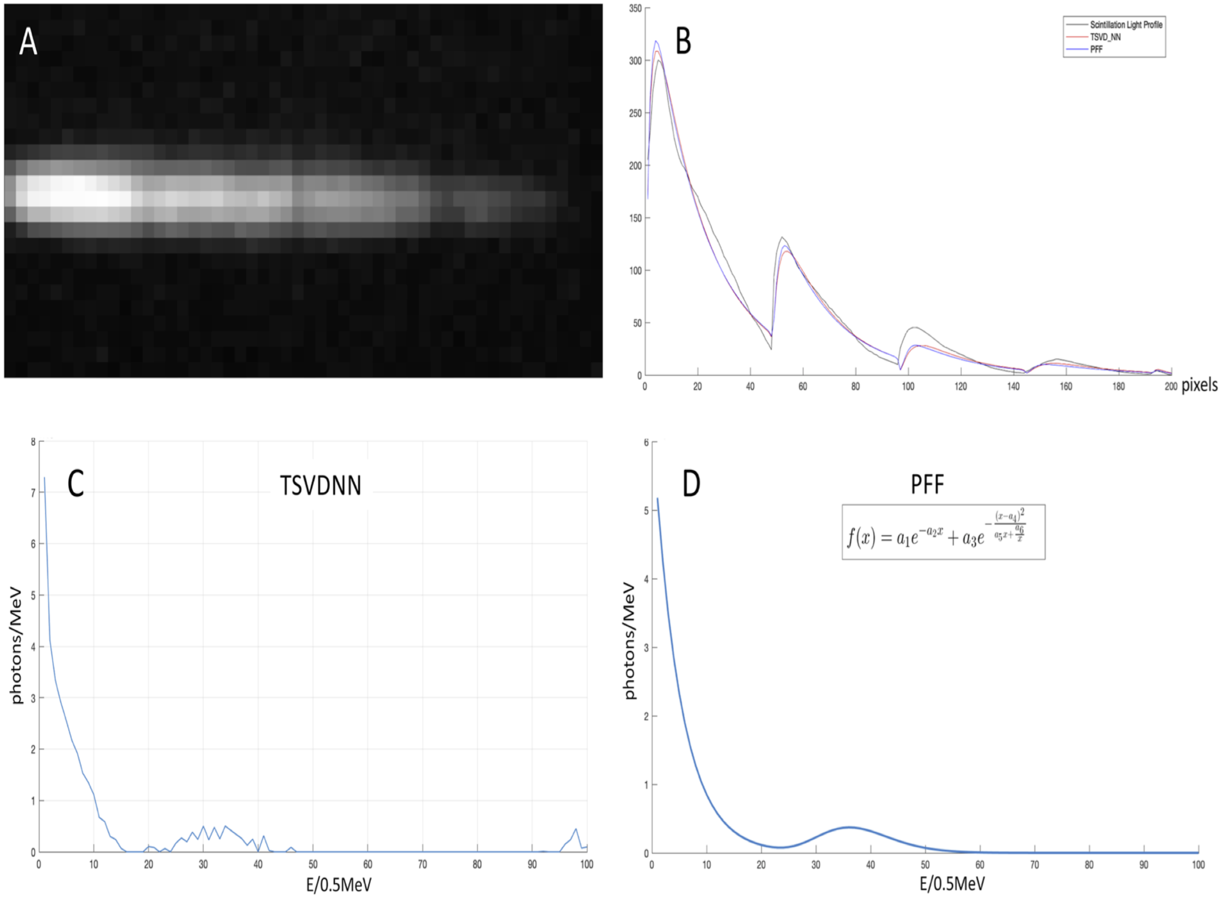
light patterns from different monoenergetic gamma-rays are clearly distinguishable





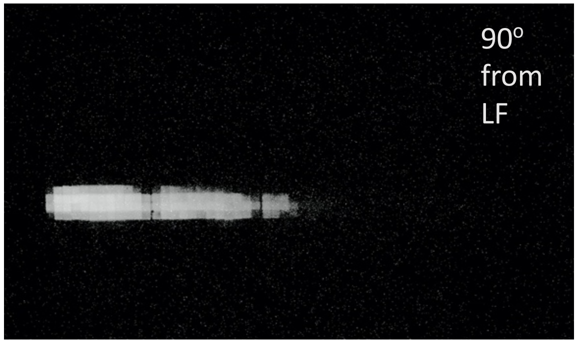
Shot 10084, LF
2016

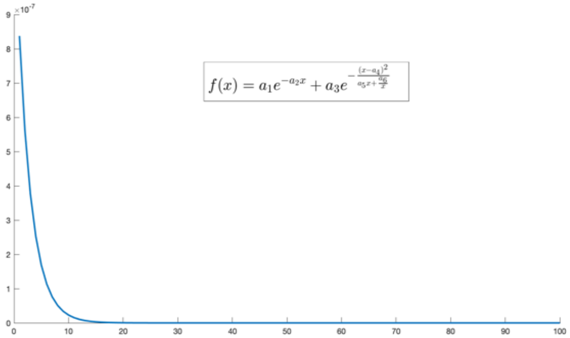
From RSI June 2022

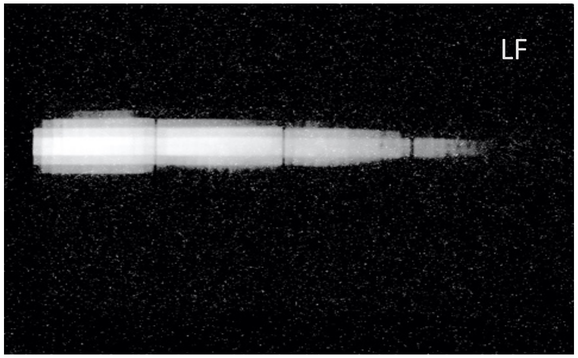


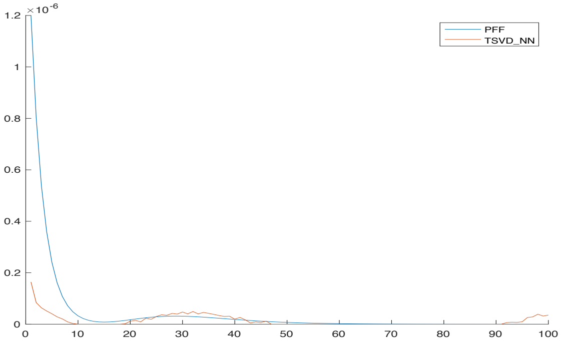
$$f(x) = a_1 e^{-a_2 x} + a_3 e^{-\frac{(x-a_4)^2}{a_5 x + \frac{a_6}{x}}}$$

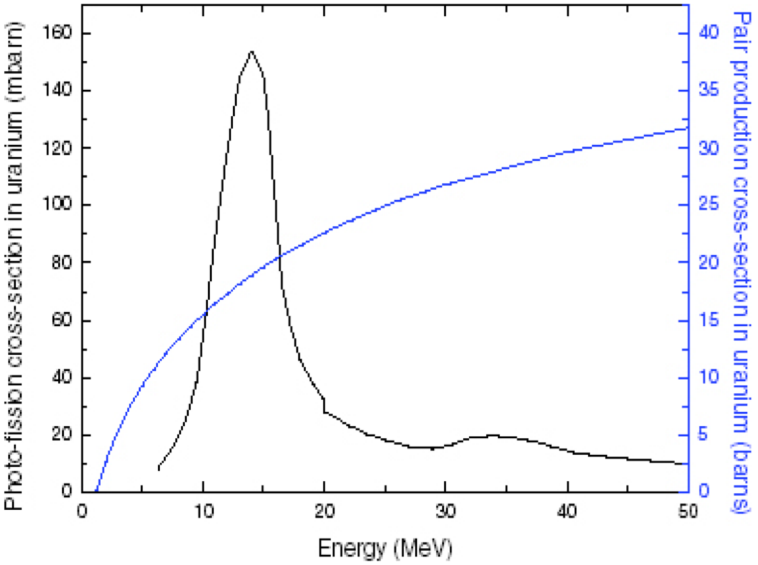
Shot 14833




$$f(x) = a_1 e^{-a_2 x} + a_3 e^{-\frac{(x-a_4)^2}{a_5 x + \frac{a_6}{x}}}$$

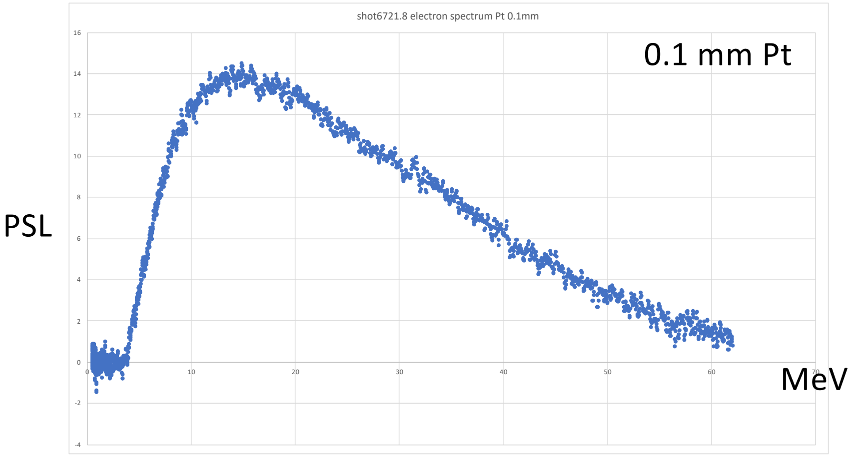


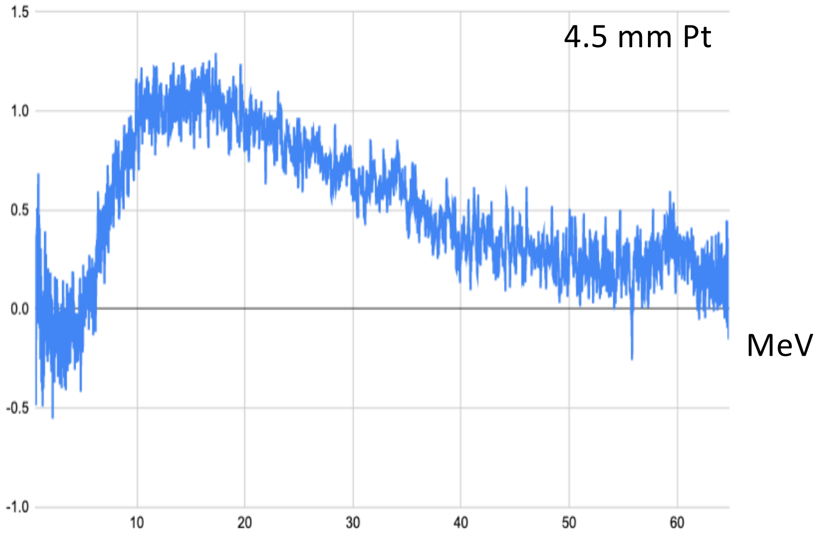




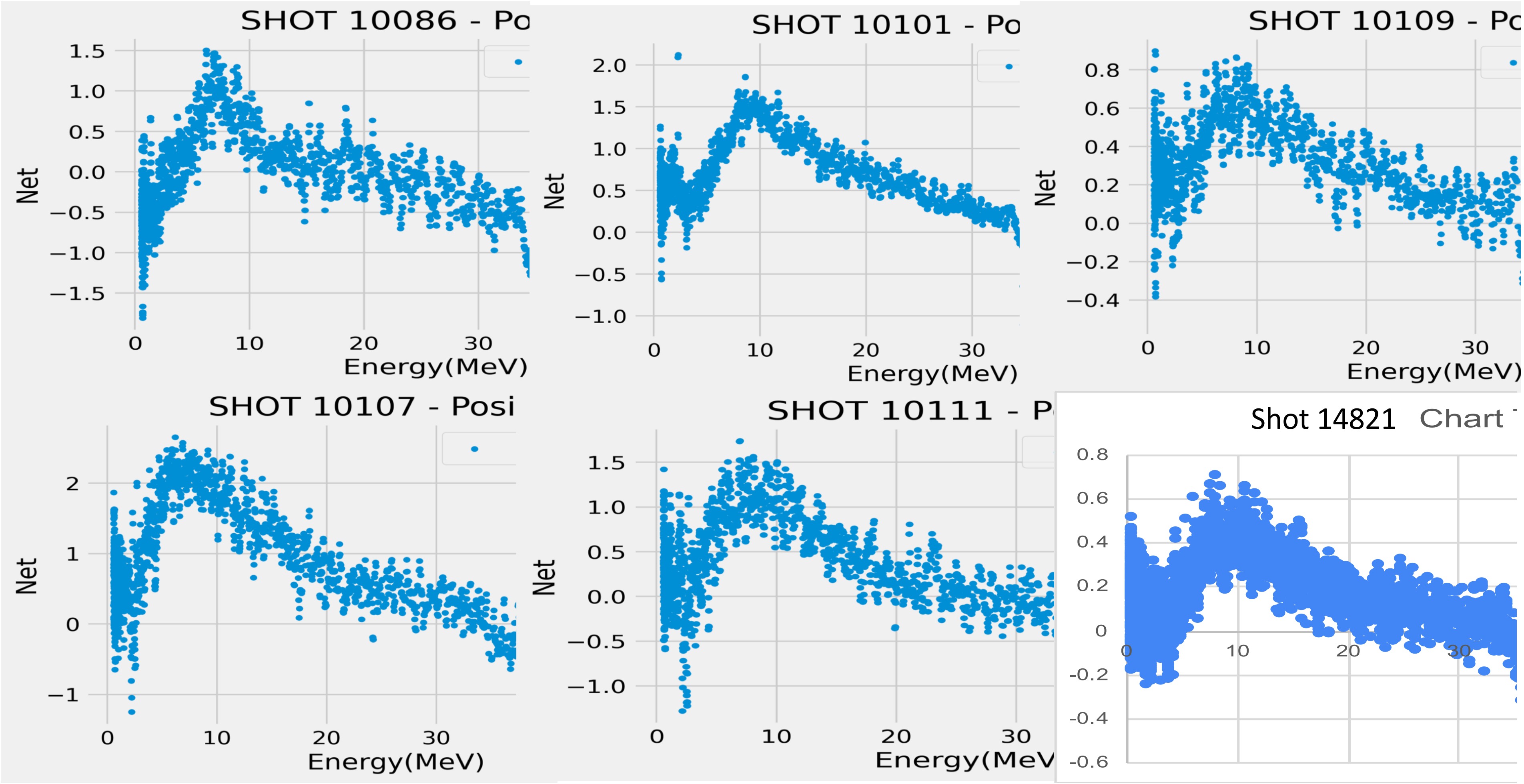
Pair creation and GDR cross sections have very different energy dependence, hence e+/n ratio provides sensitive test of gamma—ray spectrum independent of absolute normalization. Our data was consistent with the presence of excess gamma-rays > 8 MeV and Inconsistent with a pure bremsstrahlung spectrum

Typical hot electron spectra from TPW shots

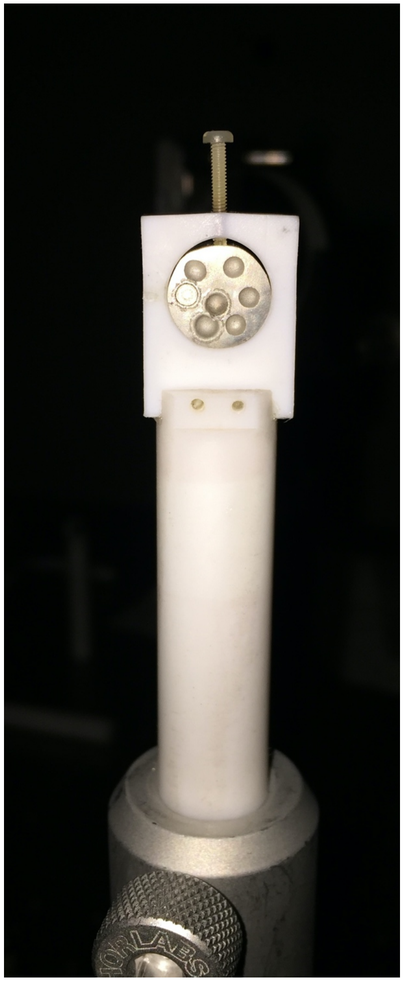




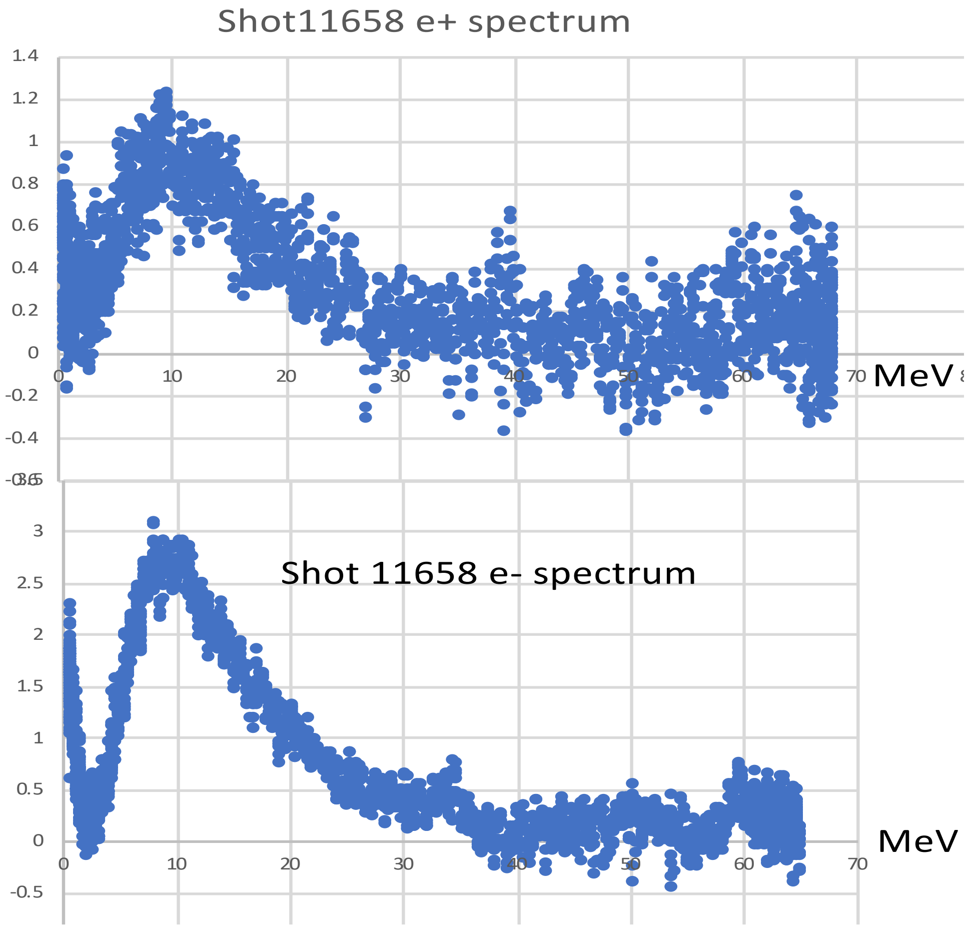
Positron spectra of targets thicker than 6 mm all peak at 7.5 MeV +/- 1.5 MeV

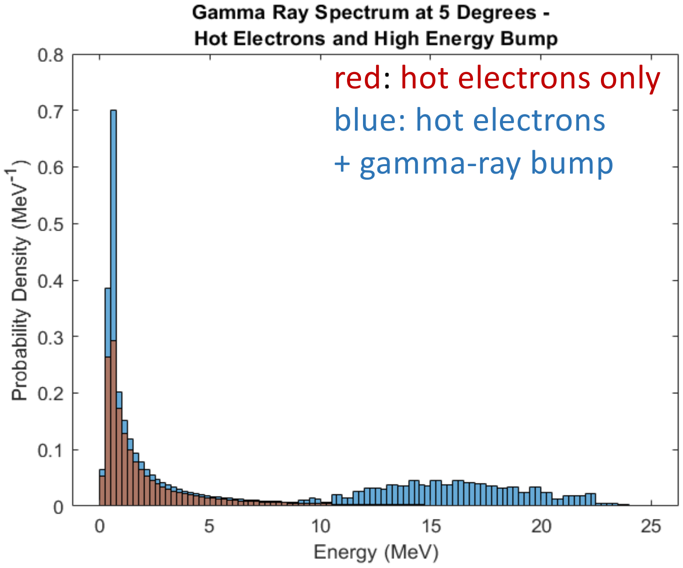


For very thick (~ cm) targets, e+e- spectra almost Identical, dominated by pairs created within ~1 mfp of target back surface. Equal peak energies suggest that sheath fields did not affect the peak energy. Hence Epeak must come from gamma-ray spectrum

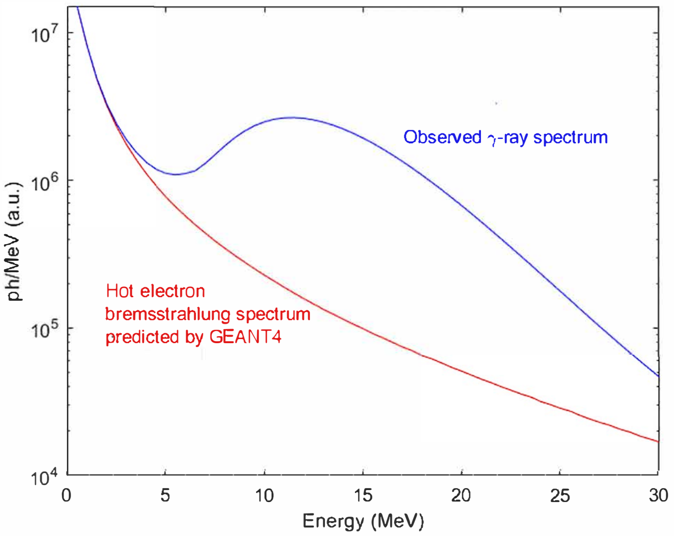


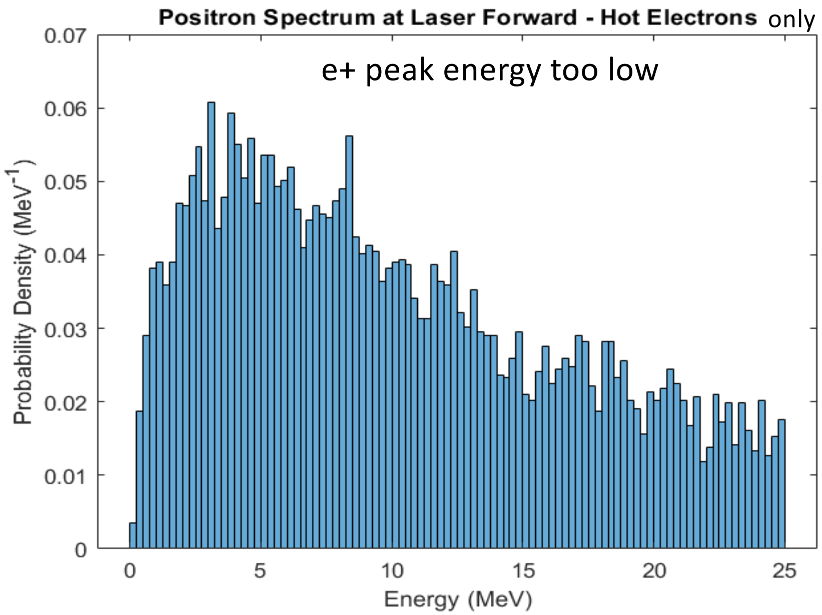
Pt ~ 1 cm thick slug





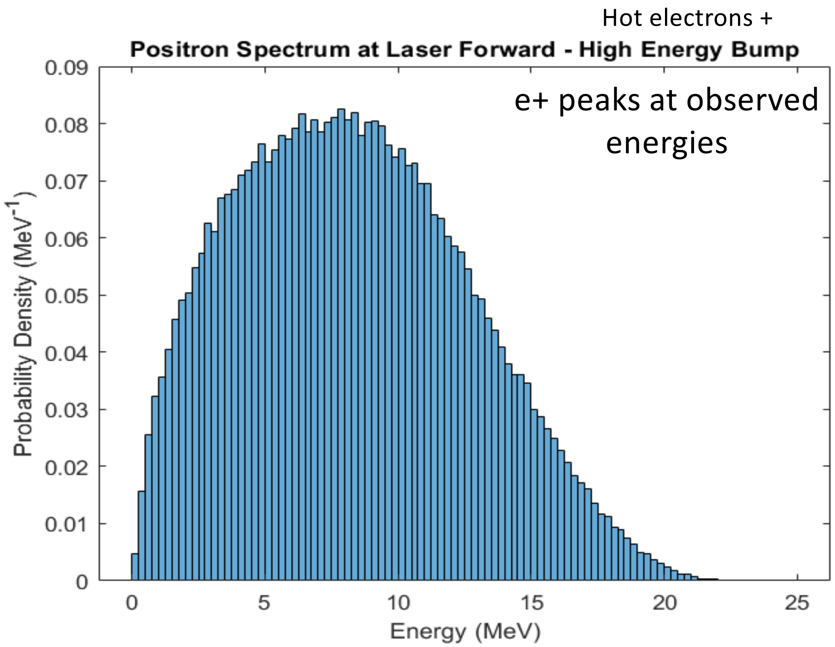
Gamma Ray Spectrum at 5 Degrees - Hot Electrons and High Energy Bump





Positron Spectrum at Laser Forward - Hot Electrons only

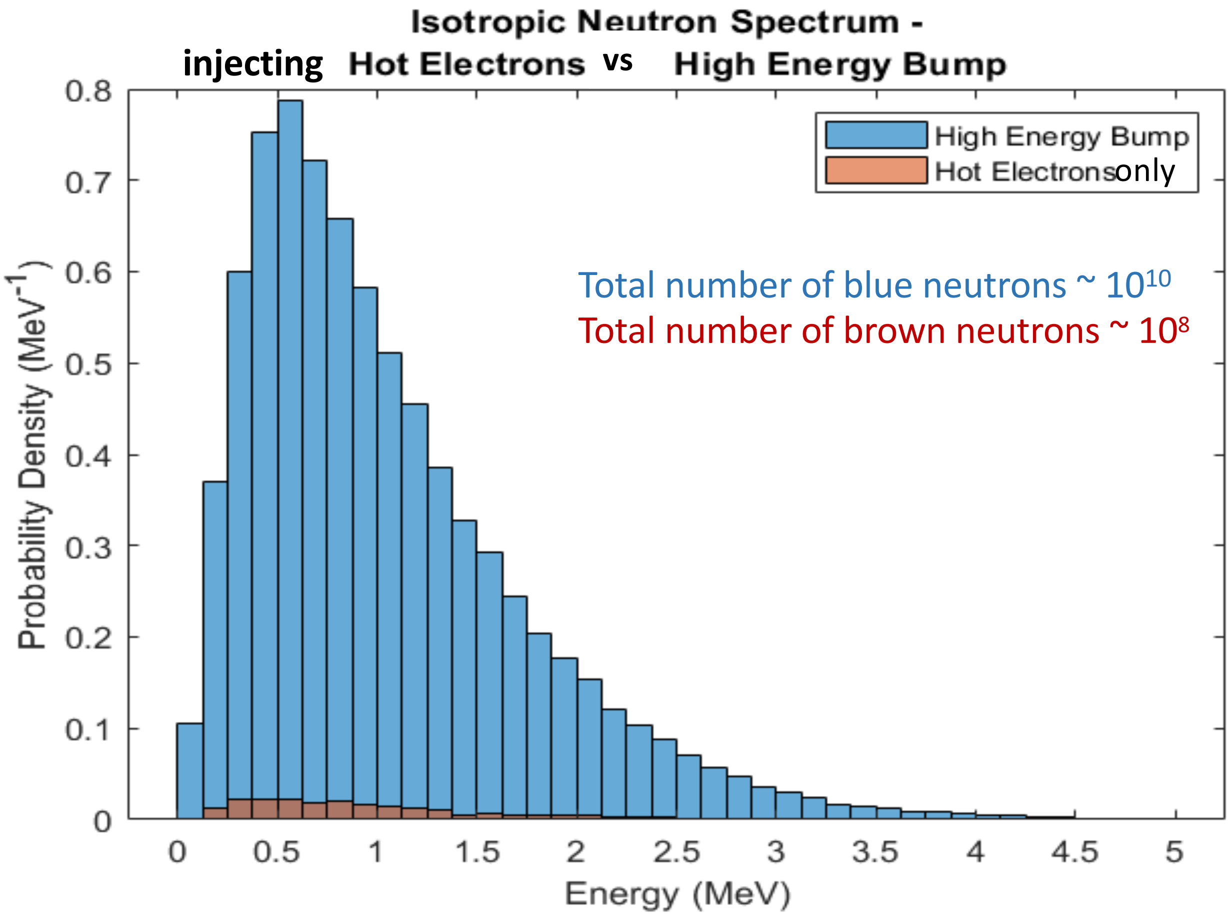
e+ peak energy too low



Hot electrons +

Positron Spectrum at Laser Forward - High Energy Bump

e+ peaks at observed energies

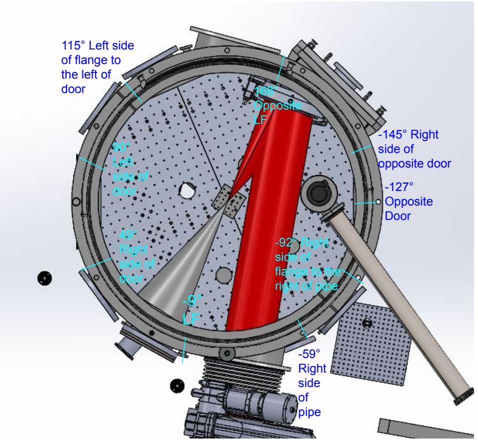


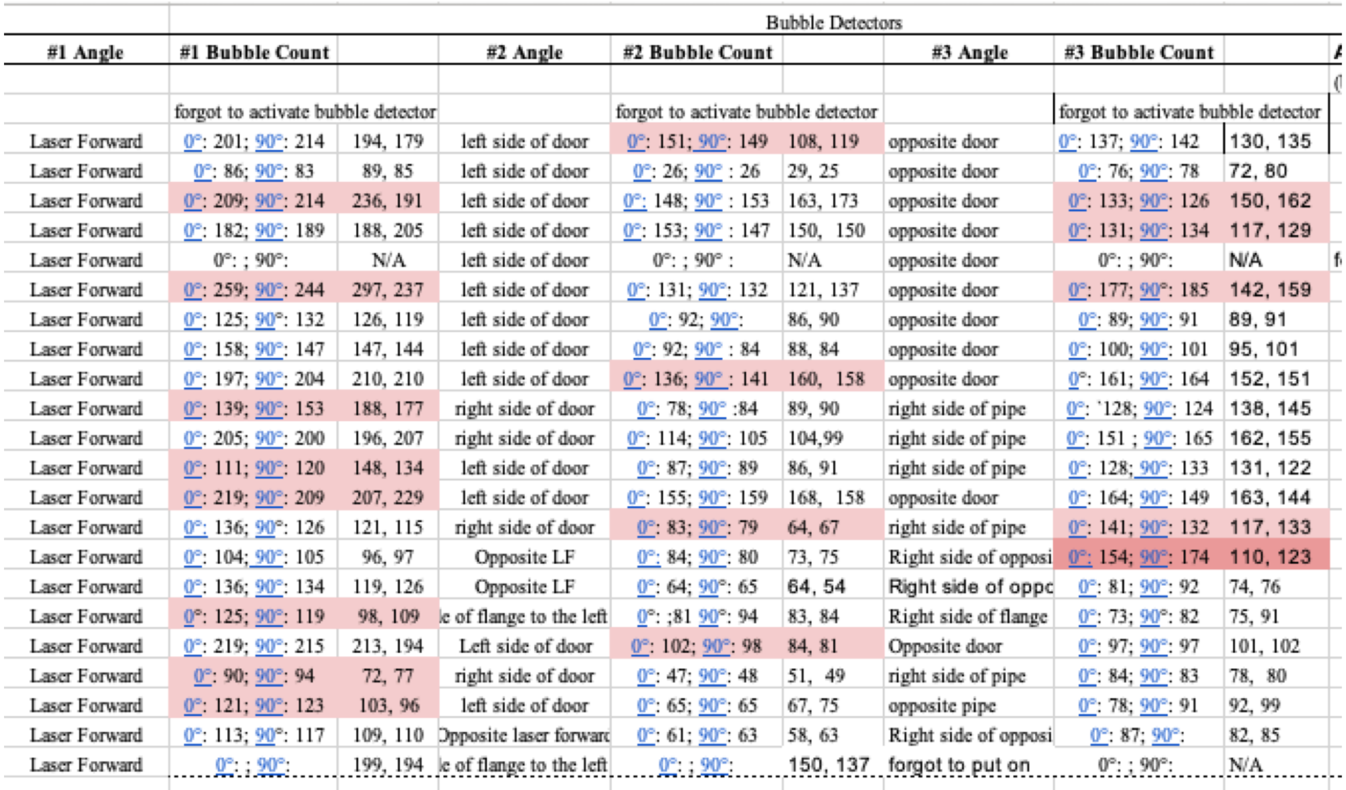
Isotropic Neutron Spectrum - injecting Hot Electrons vs High Energy Bump

Total number of blue neutrons ~ 10^{10}

Total number of brown neutrons ~ 10^{8}

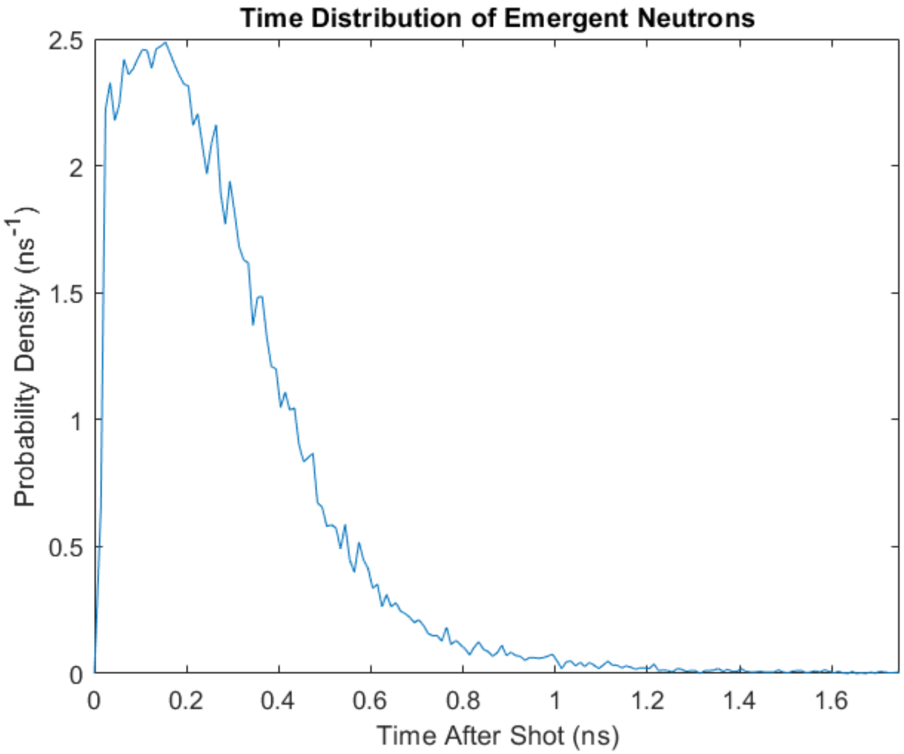
100 bubbles ~ 10^{10} neutrons / 4π



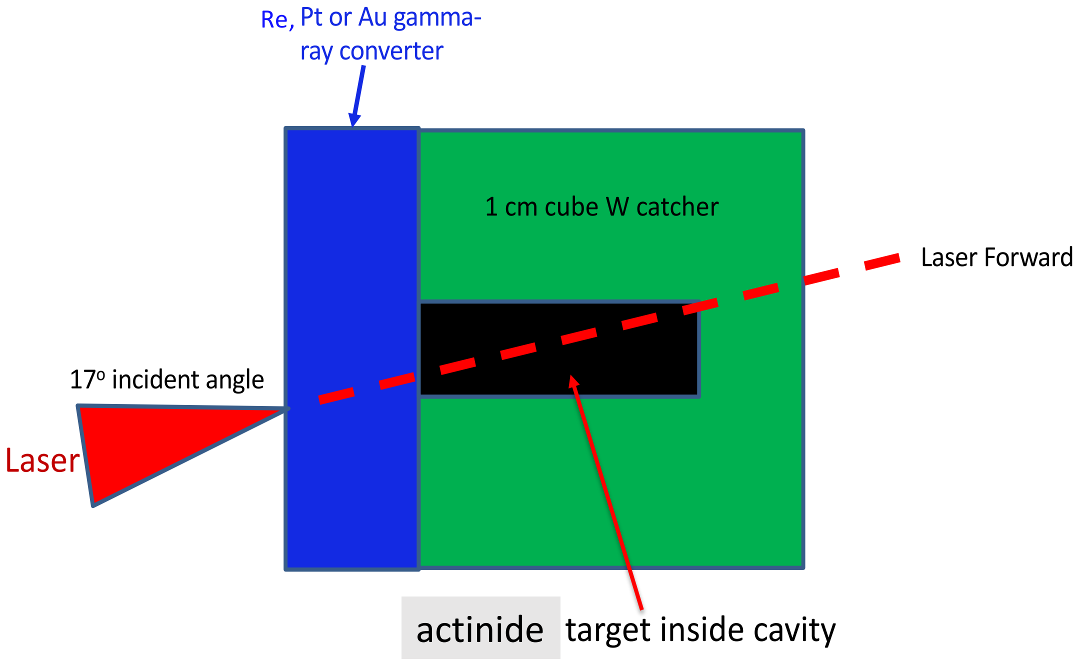


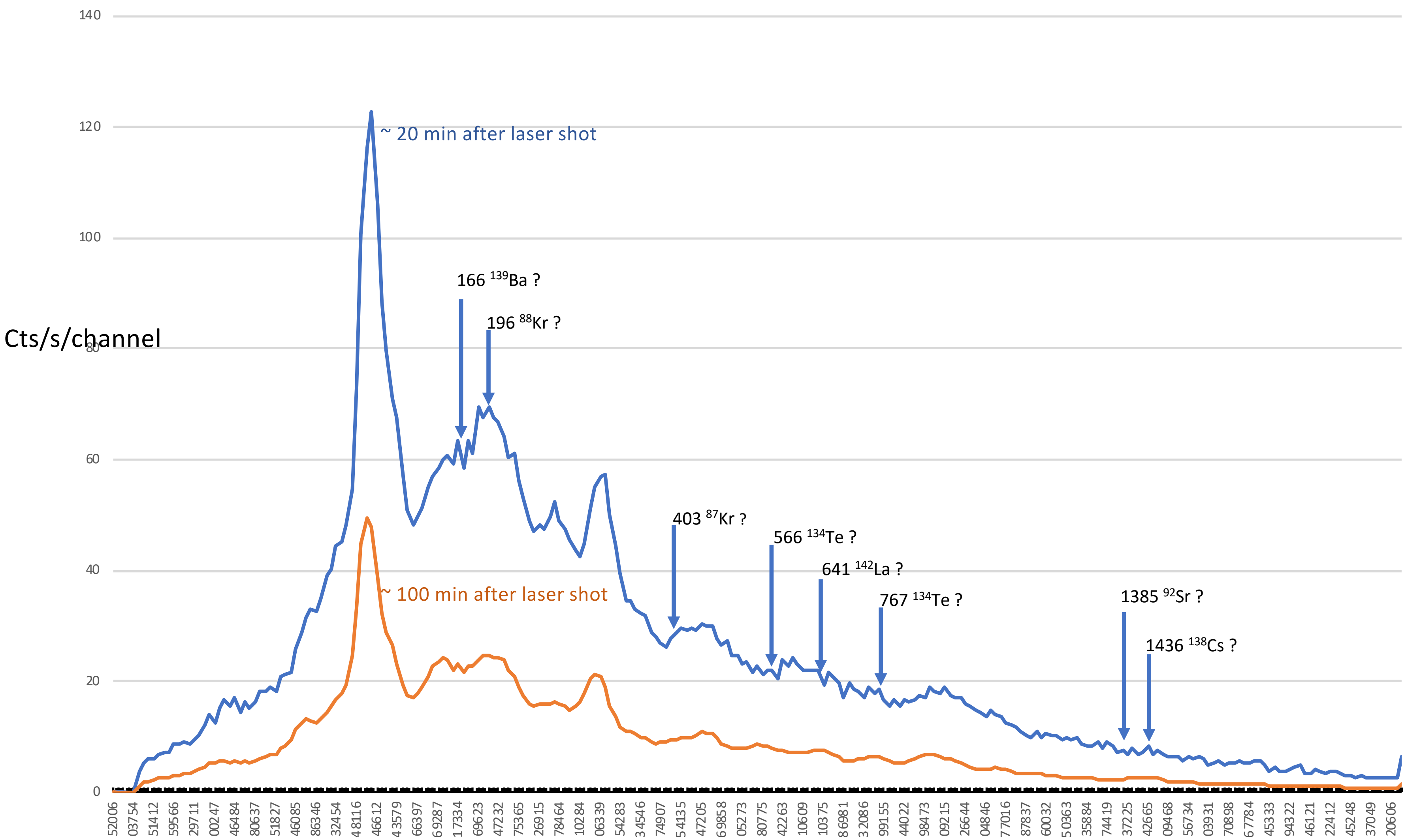
Bubble Detectors

#1 Angle	#1 Bubble Count		#2 Angle	#2 Bubble Count		#3 Angle	#3 Bubble Count	
	forgot to activate bubble detector			forgot to activate bubble detector			forgot to activate bubble detector	
Laser Forward	0°: 201; 90°: 214	194, 179	left side of door	0°: 151; 90°: 149	108, 119	opposite door	0°: 137; 90°: 142	130, 135
Laser Forward	0°: 86; 90°: 83	89, 85	left side of door	0°: 26; 90° : 26	29, 25	opposite door	0°: 76; 90°: 78	72, 80
Laser Forward	0°: 209; 90°: 214	236, 191	left side of door	0°: 148; 90° : 153	163, 173	opposite door	0°: 133; 90°: 126	150, 162
Laser Forward	0°: 182; 90°: 189	188, 205	left side of door	0°: 153; 90° : 147	150, 150	opposite door	0°: 131; 90°: 134	117, 129
Laser Forward	0°: ; 90°:	N/A	left side of door	0°: ; 90° :	N/A	opposite door	0°: ; 90°:	N/A
Laser Forward	0°: 259; 90°: 244	297, 237	left side of door	0°: 131; 90°: 132	121, 137	opposite door	0°: 177; 90°: 185	142, 159
Laser Forward	0°: 125; 90°: 132	126, 119	left side of door	0°: 92; 90°:	86, 90	opposite door	0°: 89; 90°: 91	89, 91
Laser Forward	0°: 158; 90°: 147	147, 144	left side of door	0°: 92; 90° : 84	88, 84	opposite door	0°: 100; 90°: 101	95, 101
Laser Forward	0°: 197; 90°: 204	210, 210	left side of door	0°: 136; 90° : 141	160, 158	opposite door	0°: 161; 90°: 164	152, 151
Laser Forward	0°: 139; 90°: 153	188, 177	right side of door	0°: 78; 90° :84	89, 90	right side of pipe	0°: `128; 90°: 124	138, 145
Laser Forward	0°: 205; 90°: 200	196, 207	right side of door	0°: 114; 90°: 105	104,99	right side of pipe	0°: 151 ; 90°: 165	162, 155
Laser Forward	0°: 111; 90°: 120	148, 134	left side of door	0°: 87; 90°: 89	86, 91	right side of pipe	0°: 128; 90°: 133	131, 122
Laser Forward	0°: 219; 90°: 209	207, 229	left side of door	0°: 155; 90°: 159	168, 158	opposite door	0°: 164; 90°: 149	163, 144
Laser Forward	0°: 136; 90°: 126	121, 115	right side of door	0°: 83; 90°: 79	64, 67	right side of pipe	0°: 141; 90°: 132	117, 133
Laser Forward	0°: 104; 90°: 105	96, 97	Opposite LF	0°: 84; 90°: 80	73, 75	Right side of opposi	0°: 154; 90°: 174	110, 123
Laser Forward	0°: 136; 90°: 134	119, 126	Opposite LF	0°: 64; 90°: 65	64, 54	Right side of oppc	0°: 81; 90°: 92	74, 76
Laser Forward	0°: 125; 90°: 119	98, 109	e of flange to the left	0°: ;81 90°: 94	83, 84	Right side of flange	0°: 73; 90°: 82	75, 91
Laser Forward	0°: 219; 90°: 215	213, 194	Left side of door	0°: 102; 90°: 98	84, 81	Opposite door	0°: 97; 90°: 97	101, 102
Laser Forward	0°: 90; 90°: 94	72, 77	right side of door	0°: 47; 90°: 48	51, 49	right side of pipe	0°: 84; 90°: 83	78, 80
Laser Forward	0°: 121; 90°: 123	103, 96	left side of door	0°: 65; 90°: 65	67, 75	opposite pipe	0°: 78; 90°: 91	92, 99
Laser Forward	0°: 113; 90°: 117	109, 110	Opposite laser forwarc	0°: 61; 90°: 63	58, 63	Right side of opposi	0°: 87; 90°:	82, 85
Laser Forward	0°: ; 90°:	199, 194	e of flange to the left	0°: ; 90°:	150, 137	forgot to put on	0°: ; 90°:	N/A

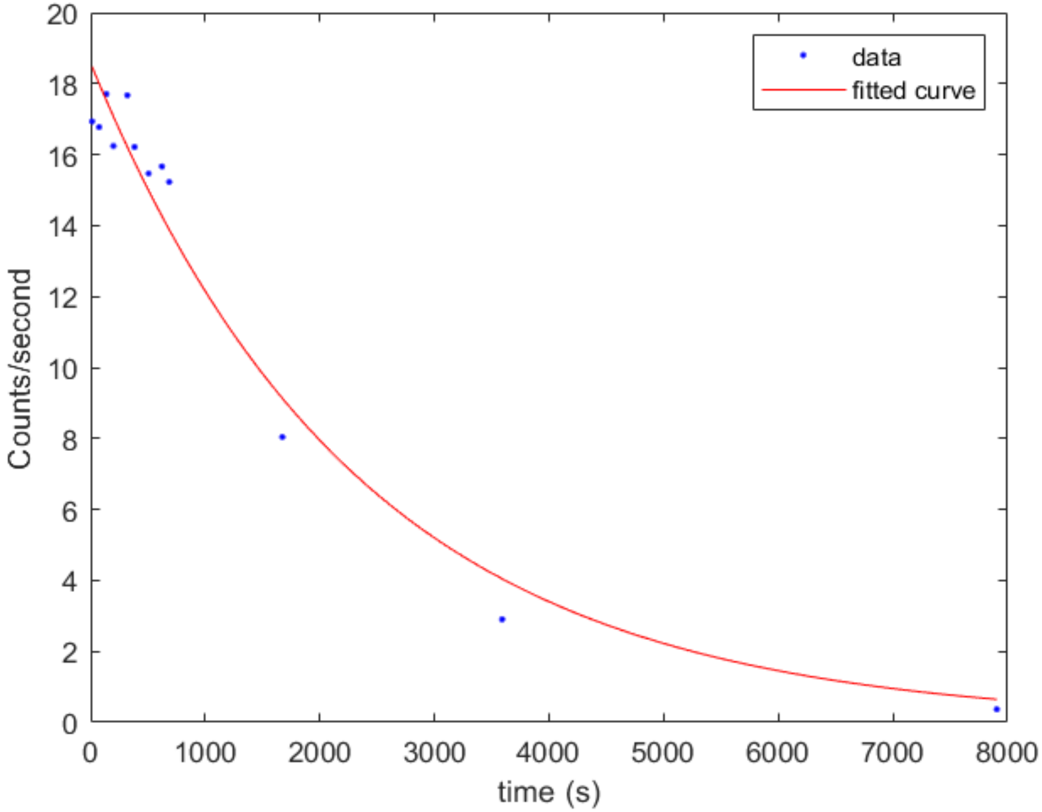


GEANT4 time history of emergent neutrons from target back-surface based on detailed laser time-profile input. We use such time histories and the observed total neutron yield to deduce the maximum neutron flux quoted in the third slide.

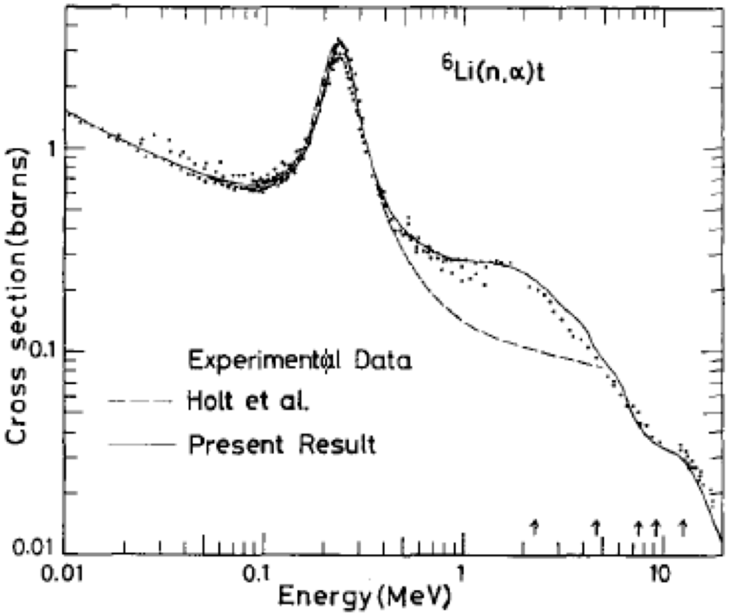

Re, Pt or Au gamma-ray converter
1 cm cube W catcher
Laser Forward
17° incident angle
Laser
actinide target inside cavity

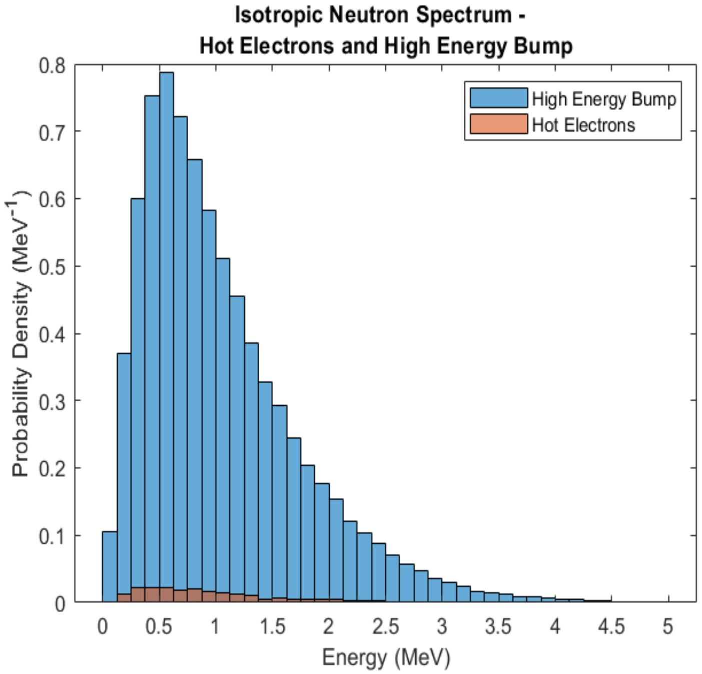

Cts/s/channel
140
120
100
80
60
40
20
0
~ 20 min after laser shot
~ 100 min after laser shot
166 ^{139}Ba ?
196 ^{88}Kr ?
403 ^{87}Kr ?
566 ^{134}Te ?
641 ^{142}La ?
767 ^{134}Te ?
1385 ^{92}Sr ?
1436 ^{138}Cs ?
52006
03754
51412
59566
29711
00247
46484
80637
51827
46085
86346
32454
48116
46612
43579
66397
69287
17334
69623
47232
75365
26915
78464
10284
06339
54283
34546
74907
54135
47205
69858
05273
80775
42263
10609
10375
86981
32086
99155
44022
98473
09215
26644
04846
77016
87837
60032
50363
35884
74419
37225
42665
09468
56734
03931
70898
67784
45333
94322
46121
22412
45248
37049
20606

Decay curve of beta-decay bremsstrahlung continuum is consistent with (γ,n) isotope yield produced by ~10^{12} gamma-rays



With minor moderation, the photo-neutrons can strongly overlap the resonance of ^{6}Li(n, t)^{4}He





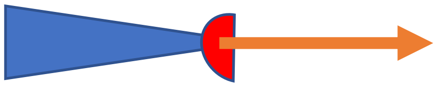
Future Projects

1. To ascertain & explain the physical origin of the gamma-ray bump.

2. Manipulate and optimize the > 8 MeV gamma-ray yield and spectrum

3. Applications of the enhanced emission of gamma-rays , positrons and photo-neutrons.

Inverse Compton Upscattering ?



15 MeV electron

~few keV x-ray

15MeV γ-ray

$\varepsilon_x = \varepsilon_\gamma/(4\gamma^2)$

Under special conditions, inverse Compton upscattering may work

$\varepsilon_o = 15\ \text{MeV}/(4\gamma^2)$
Requires ε_x=few keV

Expt. Data requires P_{scatt} ~0.1.