Creation and applications of intense photo-neutrons and gamma-rays > 8 MeV 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]

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

Supported by DOE OFES

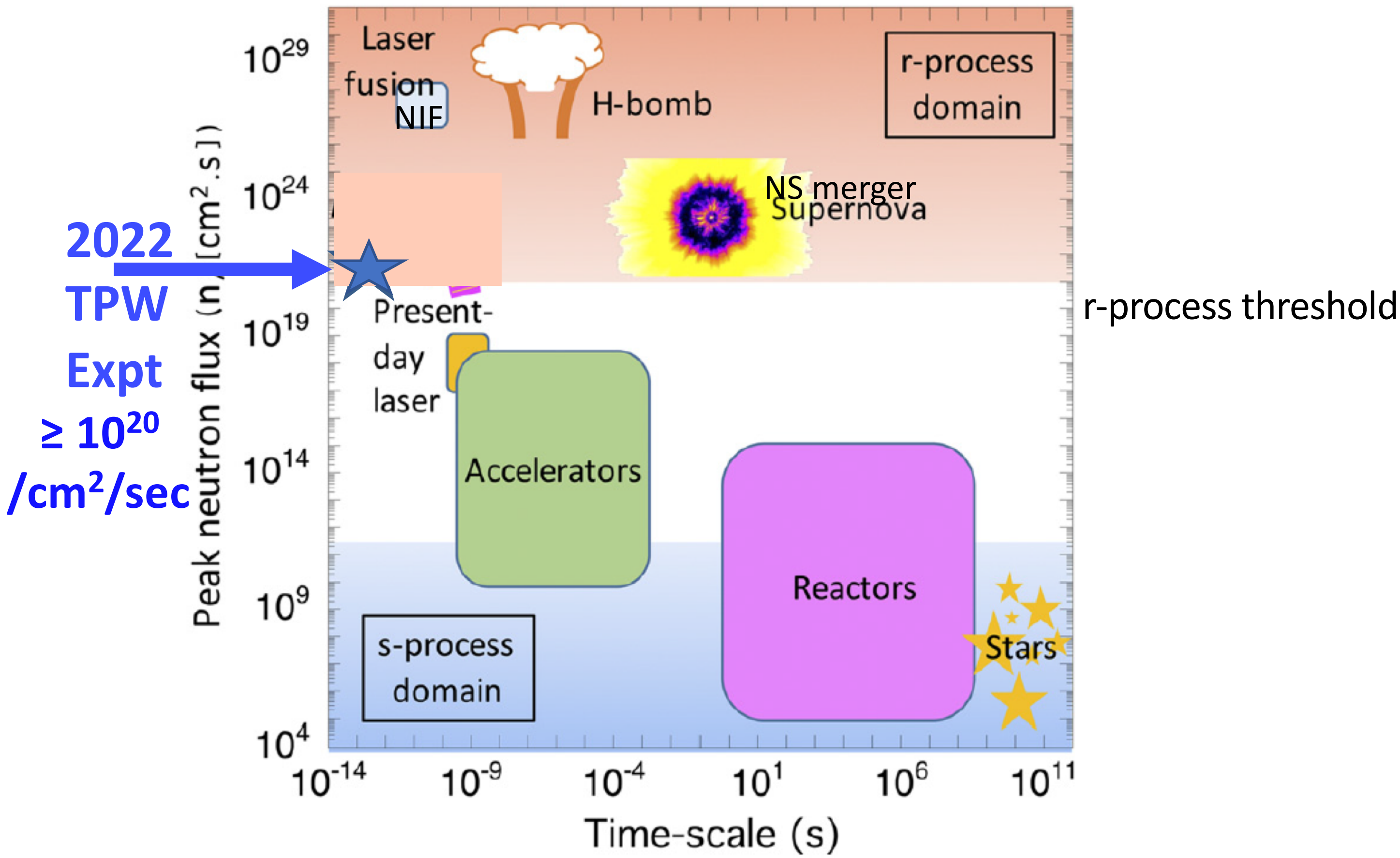
Motivation and History

- In earlier experiments at the Texas Petawatt (TPW) laser to study 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 below ~ 8 MeV, plus (b) a broad high-energy feature > 8 MeV. This discovery was enabled by the newly invented SAS gamma-ray spectrometer.

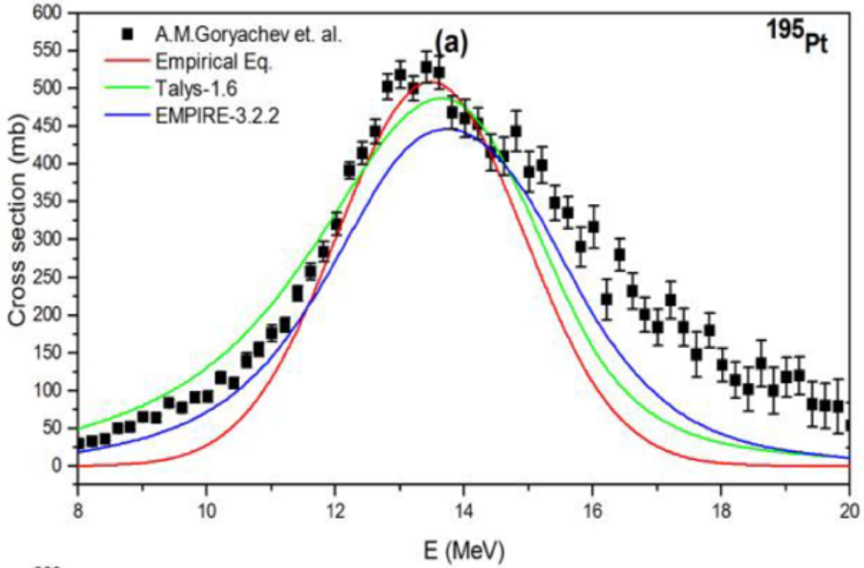
- In 2022 we conducted new experiments at TPW to confirm and characterize the gamma-ray spectrum, and used photo-neutrons and pair production to independently constrain the gamma-ray spectrum > 8 MeV.

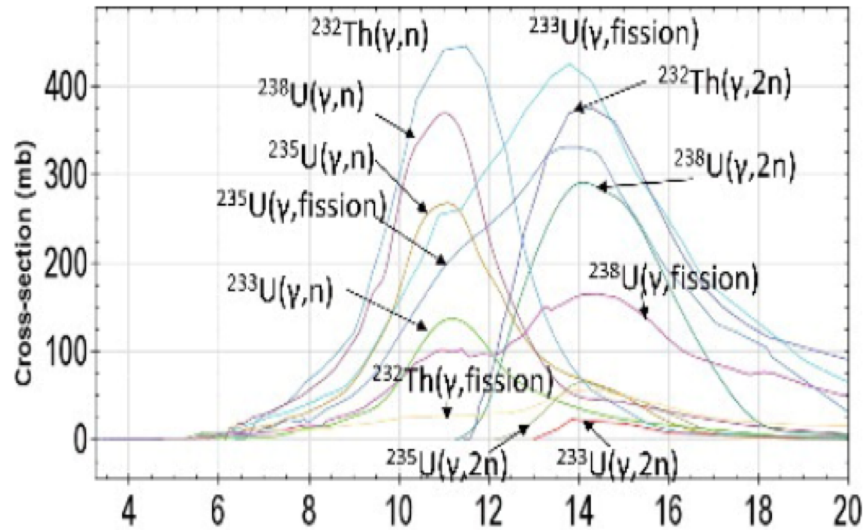
- These experiments (a) confirmed the SAS results, (b) produced up to few x 1012 gamma-ray > 8 MeV (~ 3 % of laser energy), (c) up to ~ 1010 photo-neutrons in most shots.

- 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.



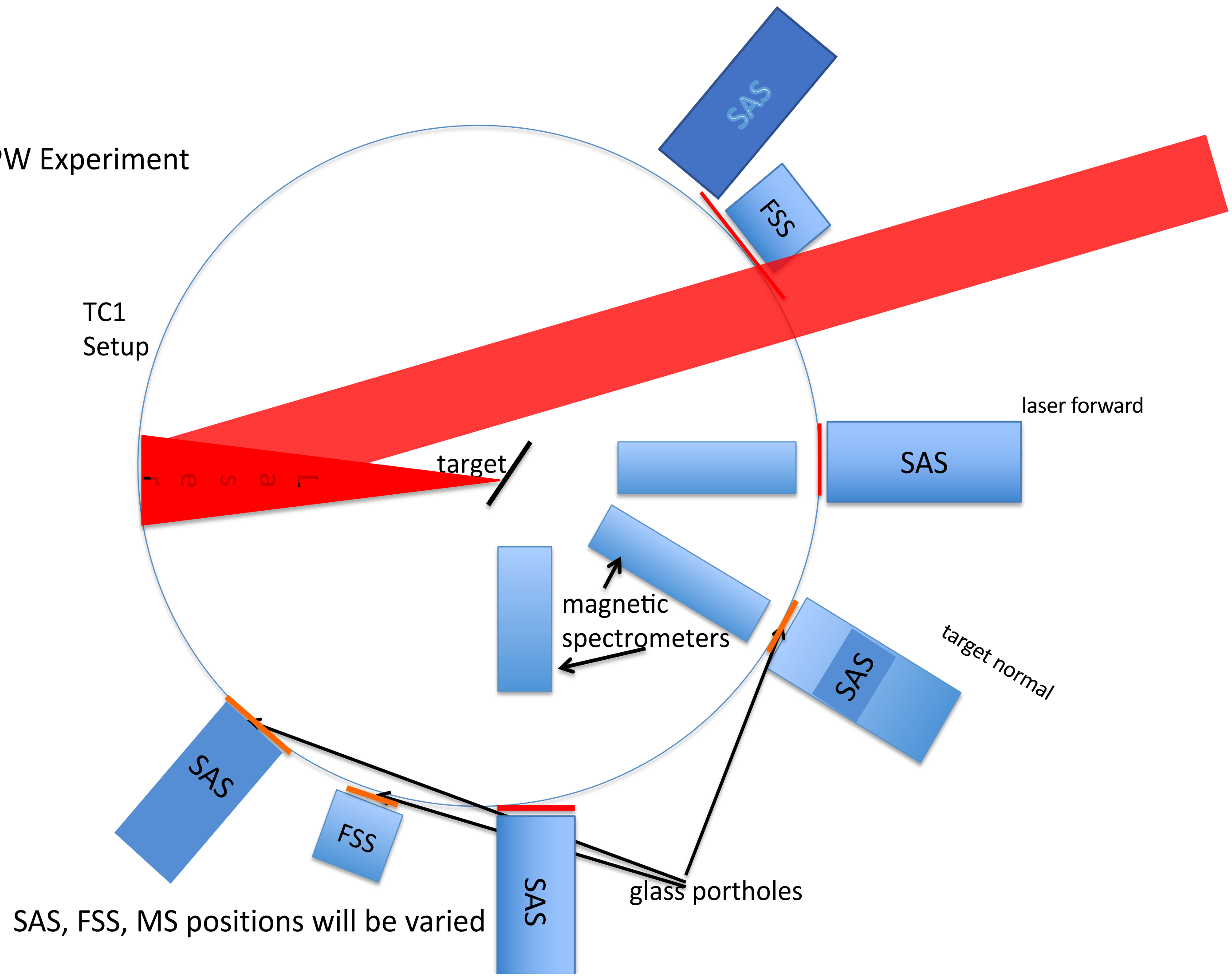
(*Adapted from Chen et al 2019*)



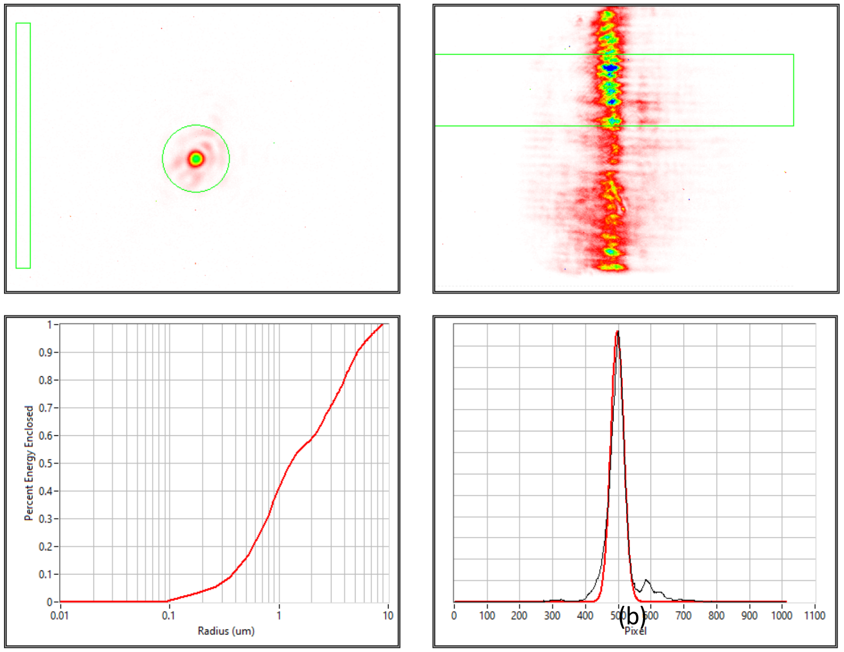


GDR cross-sections for (γ, n), (γ, 2n) and (γ, fission) reactions span 8 – 20 MeV. Hence photo-neutron and photo-fission yields are highly sensitive to the gamma-ray fluence in this energy range.

Setup of TPW Experiment



SHOT# 014897 2022-06-23



Energy
135 J

Pulse Duration
138 fs

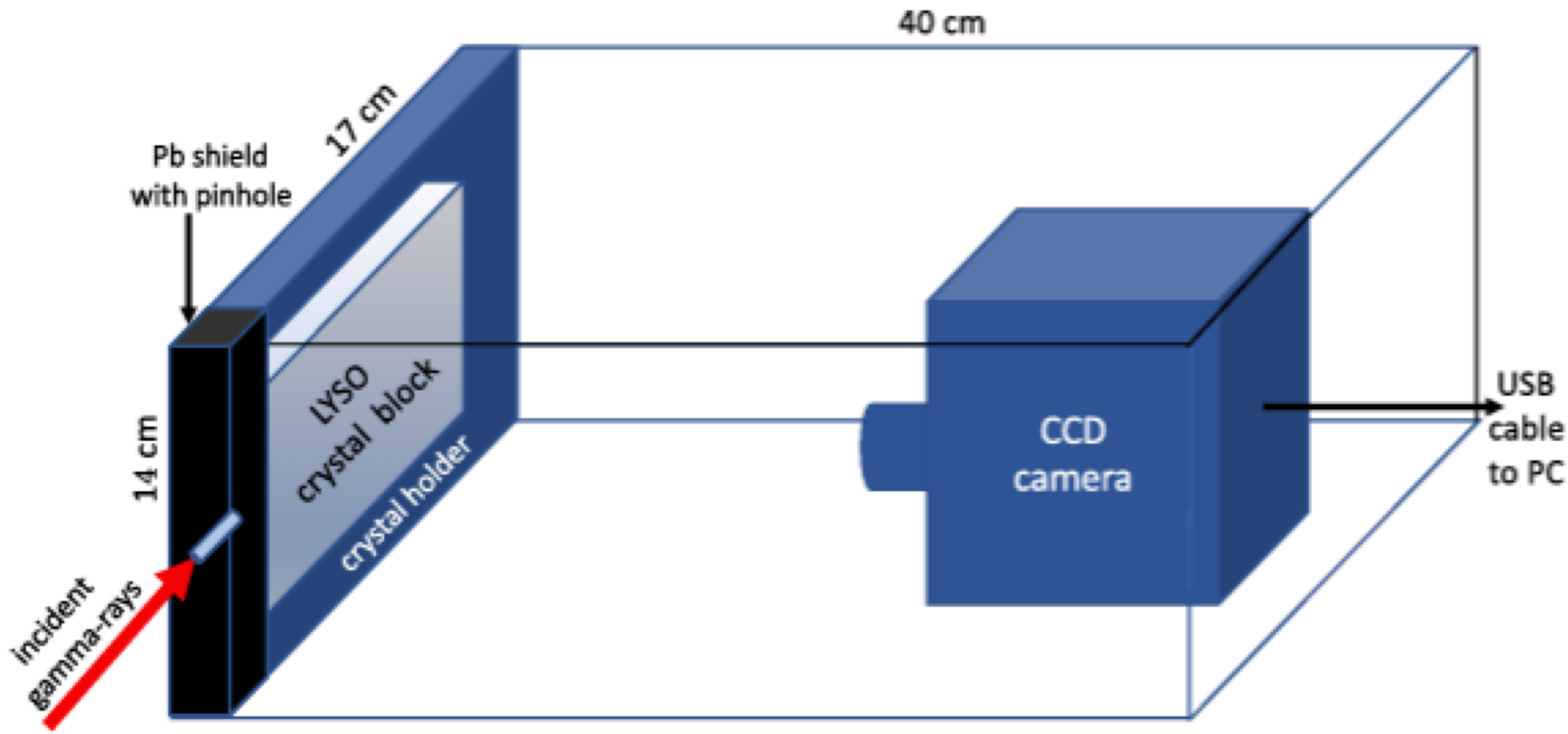
Power
980 TW

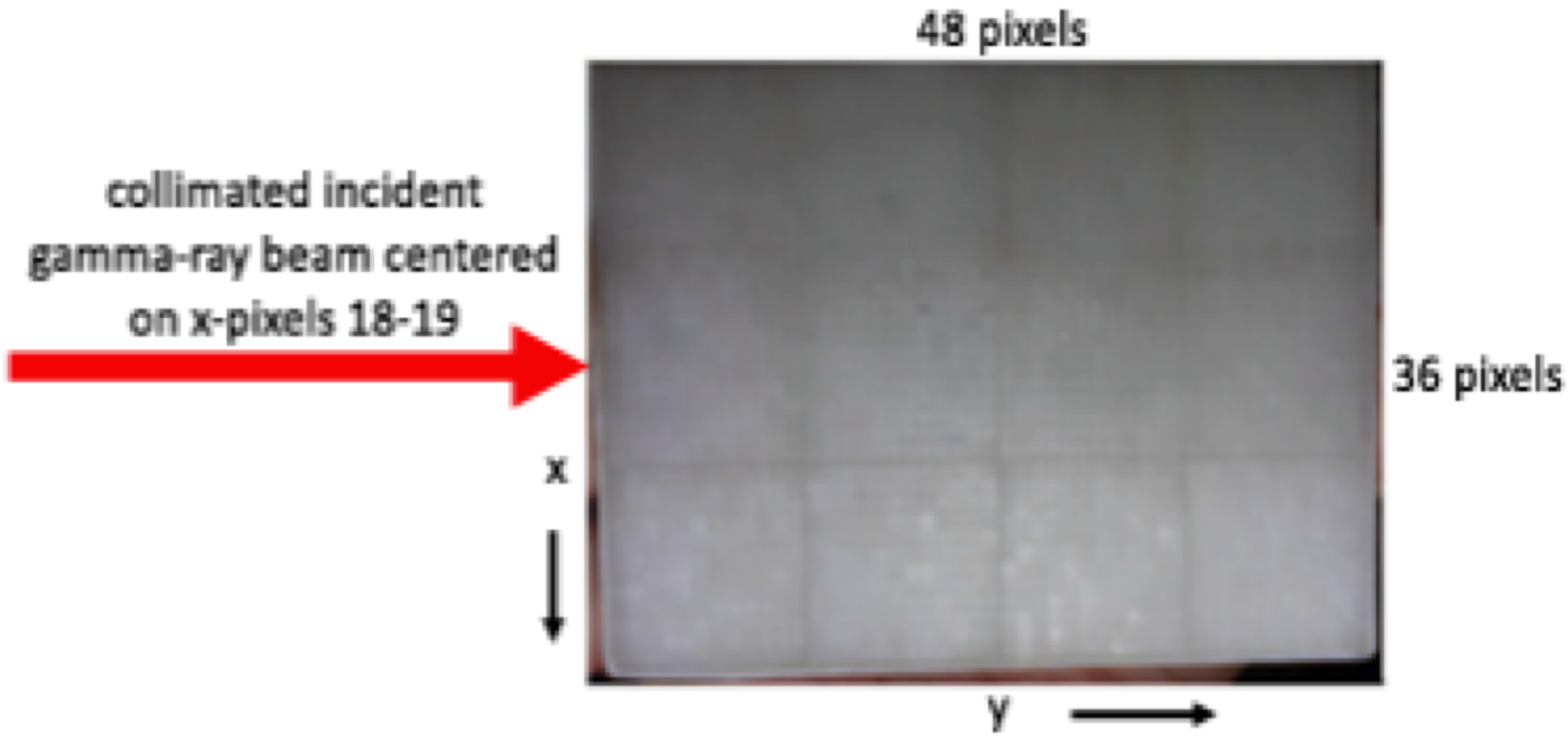
I = 4.7e+21 W/cm2

6/23/2022 4:22:12 PM

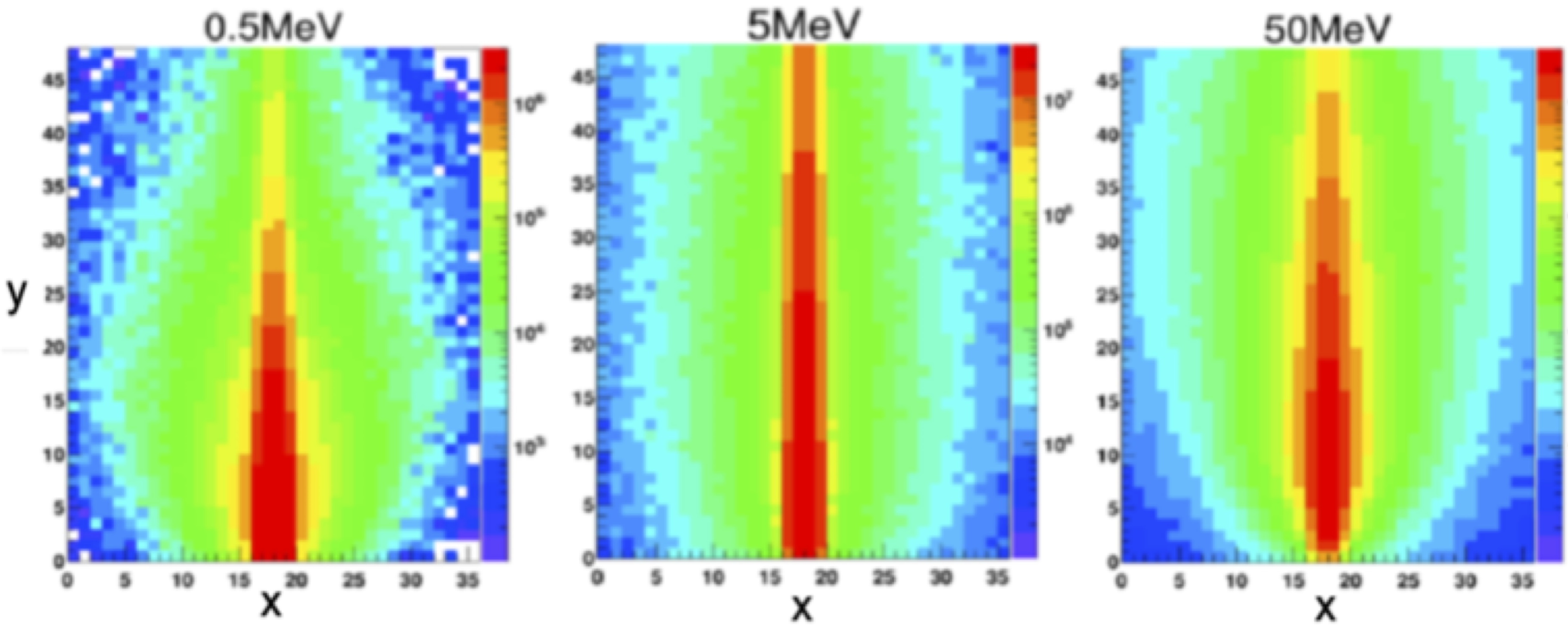
TPW laser parameters of our 2022 60-shot run

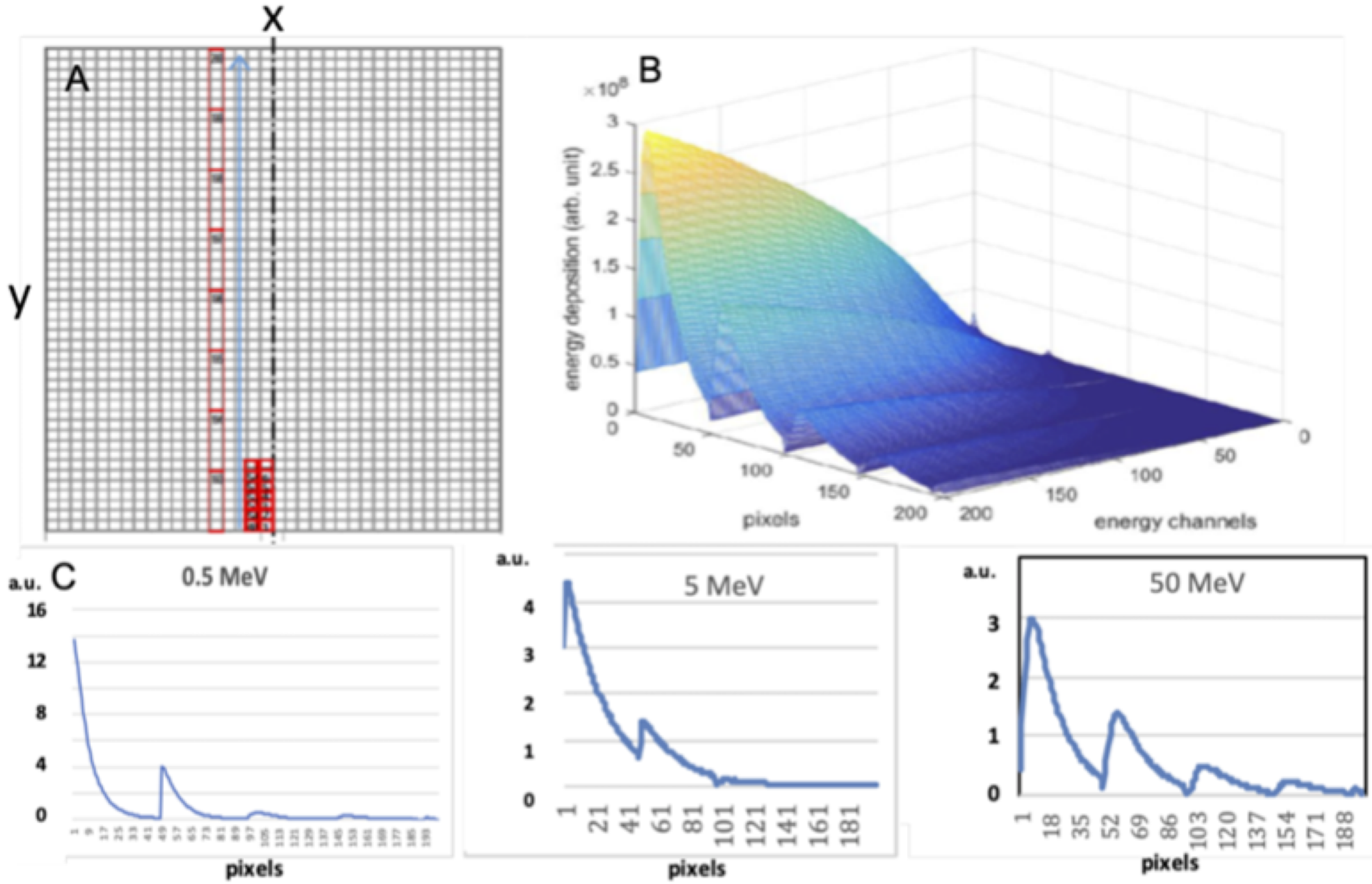
	Energy	Pulse Duration (fs)	Peak Power (TW)	closed Radius with 50% (u	ak Intensity (W/cm	Strehl
AVERAGE	123.25	161.05	781.82	3.8	2.96E+21	0.68
MEDIAN	122.57	158	794.12	3.72	2.89E+21	0.7
MIN	104.2	128	531.29	2.42	1.85E+21	0.46
MAX	139.18	216	1060.68	5.39	4.68E+21	0.82


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

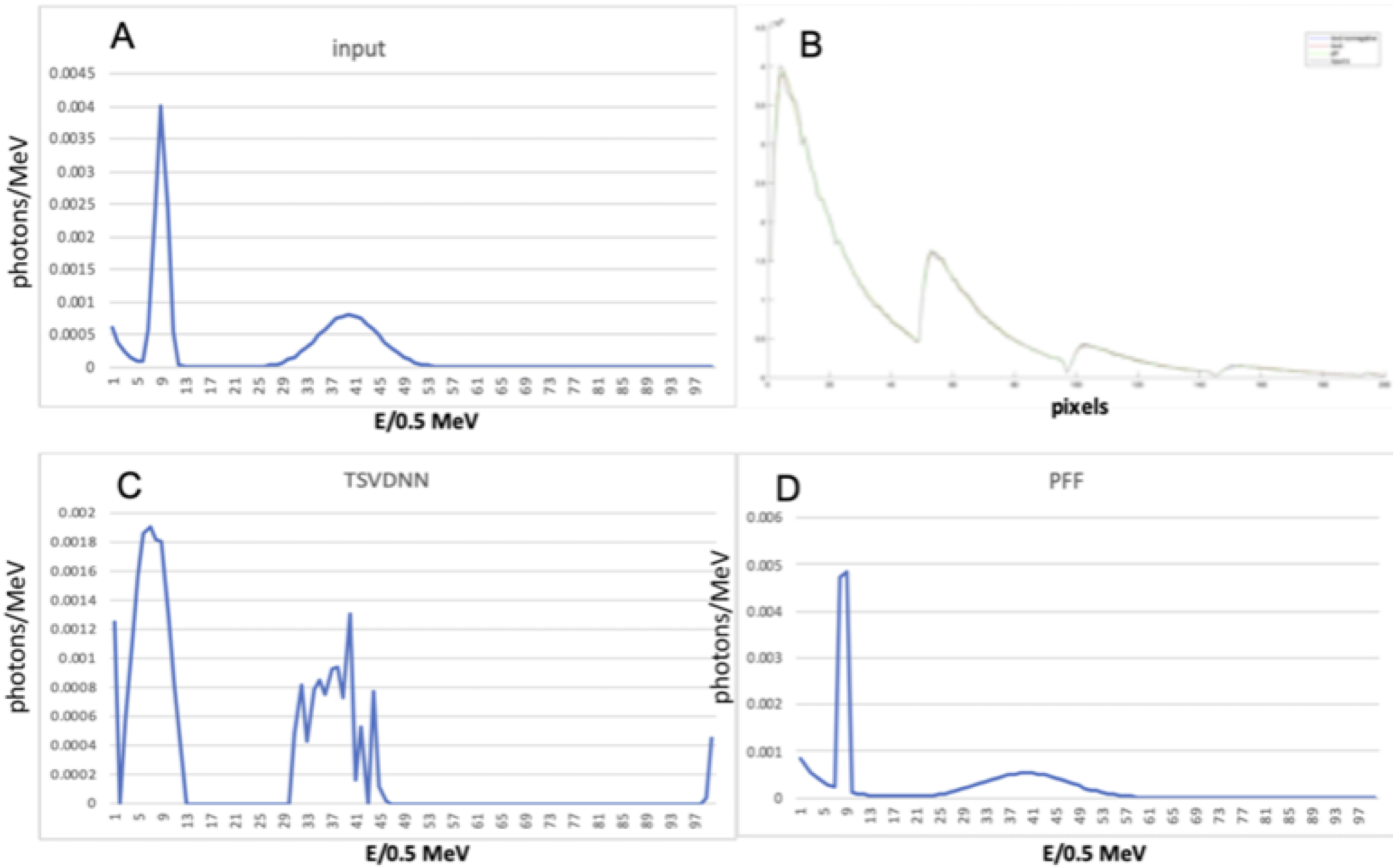

48 pixels
collimated incident
gamma-ray beam centered
on x-pixels 18-19
36 pixels
x
y

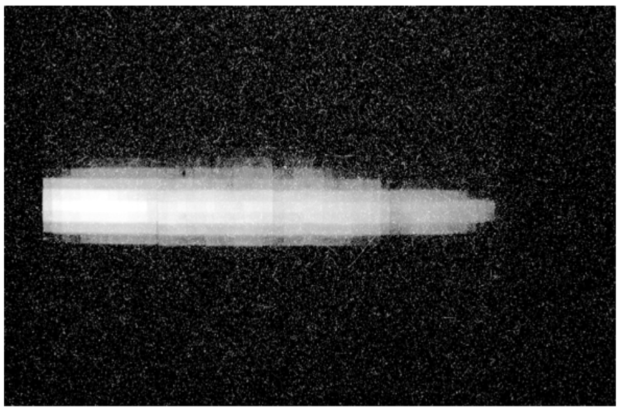
light patterns from different monoenergetic gamma-rays are clearly distinguishable

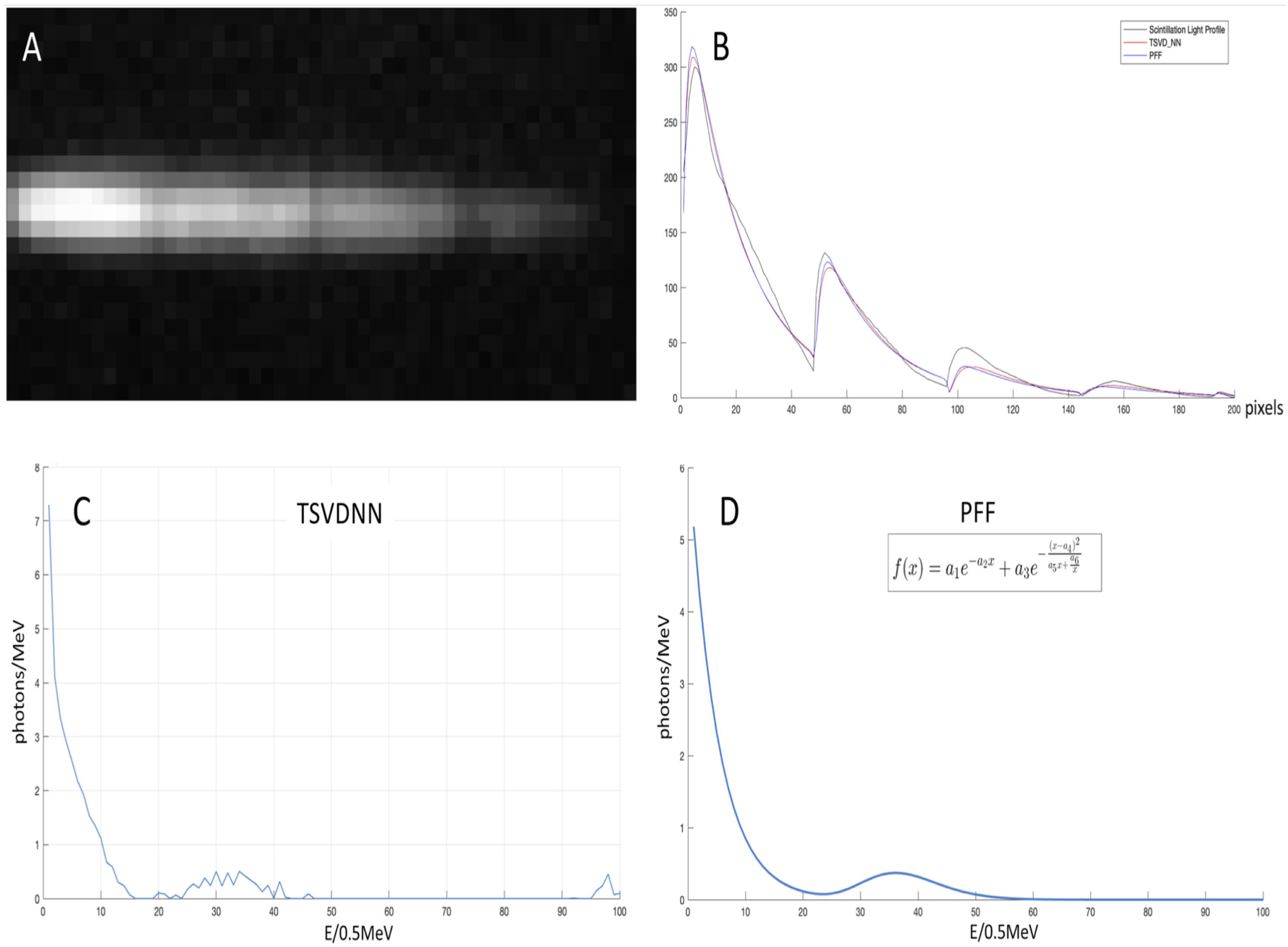




x
A
y
B
$\times 10^8$
energy deposition (arb. unit)
pixels
energy channels
C
a.u.
0.5 MeV
pixels
a.u.
5 MeV
pixels
a.u.
50 MeV
pixels


A
input
photons/MeV
E/0.5 MeV
B
pixels
C
TSVDNN
photons/MeV
E/0.5 MeV
D
PFF
photons/MeV
E/0.5 MeV

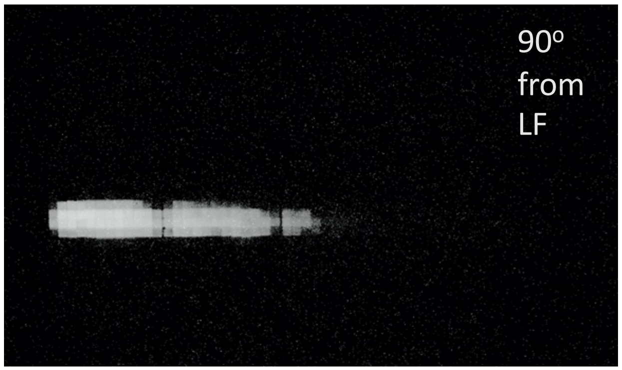




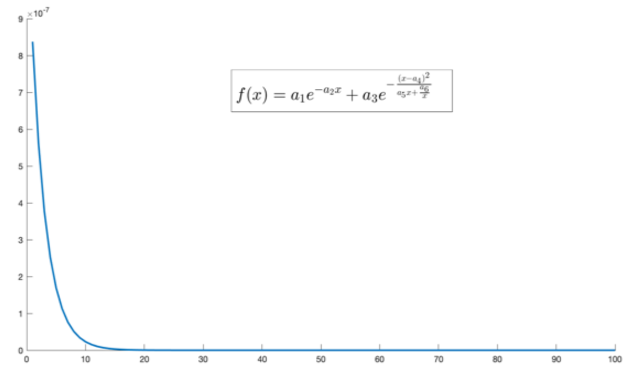
Shot 10084, LF
2016

From RSI June 2022

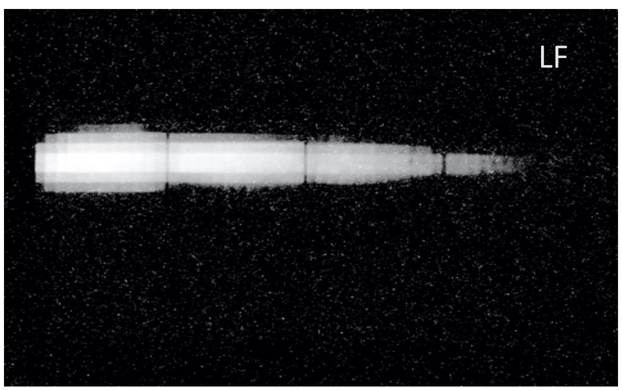
Shot 14833



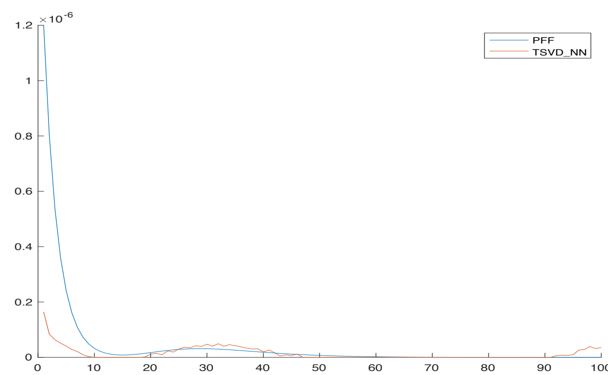
90° from LF



×10^-7
$f(x) = a_1 e^{-a_2 x} + a_3 e^{-\frac{(x-a_4)^2}{a_5 x + \frac{a_6}{x}}}$
0 10 20 30 40 50 60 70 80 90 100

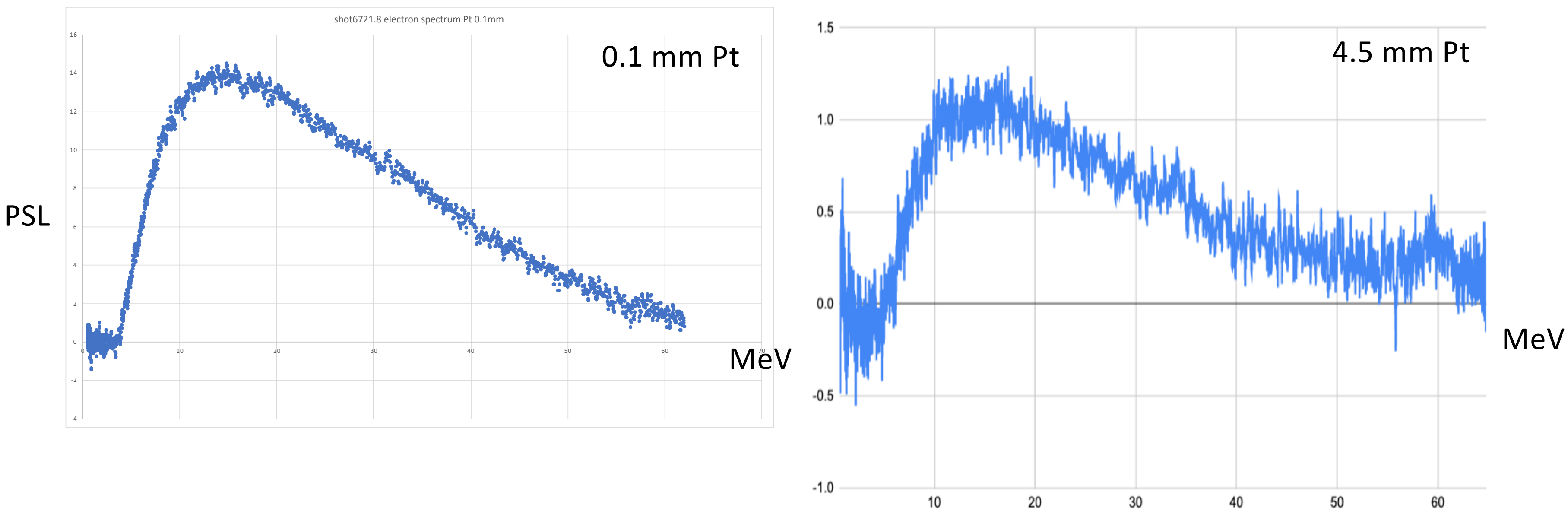


LF

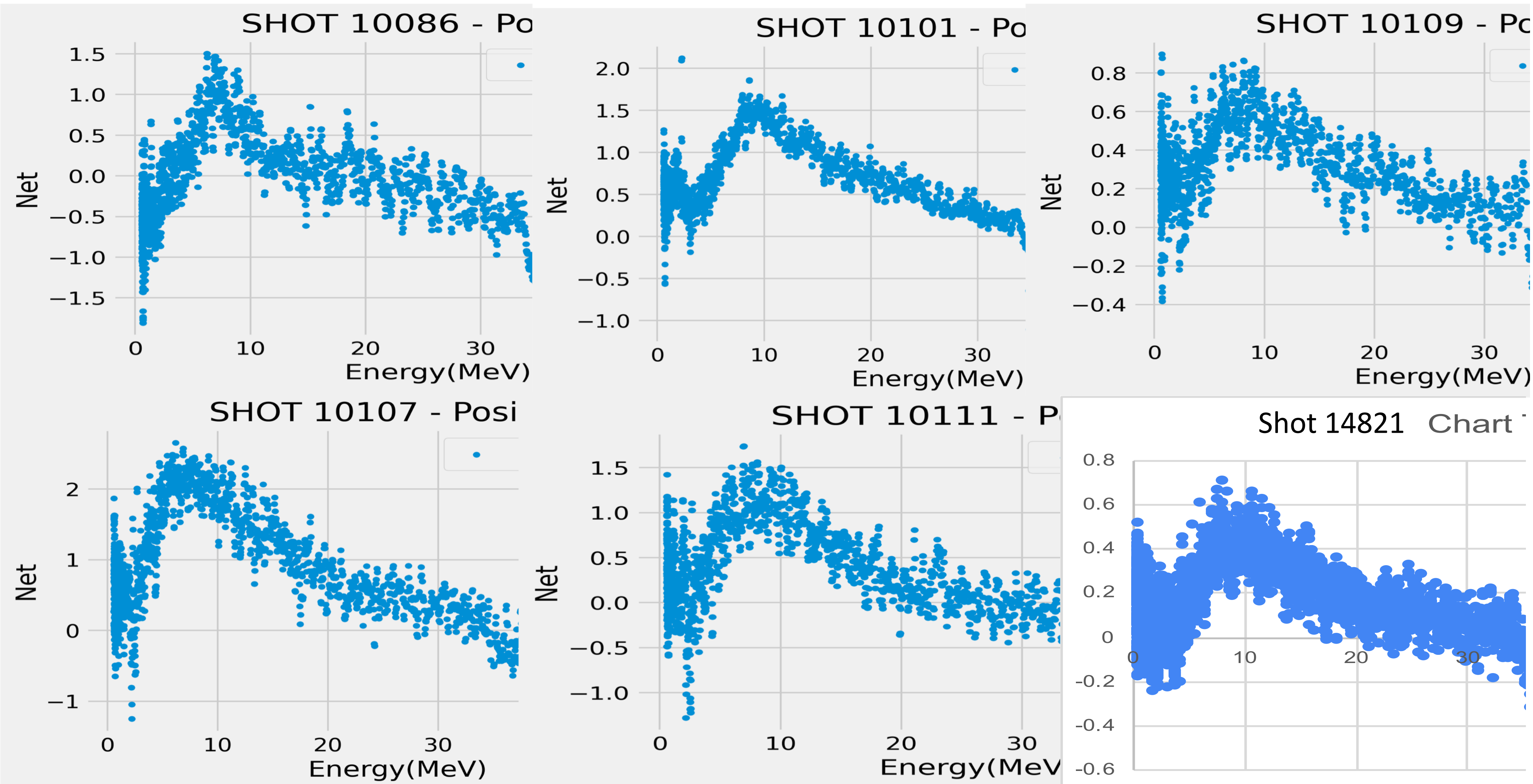


×10^-6
PFF
TSVD_NN
0 10 20 30 40 50 60 70 80 90 100

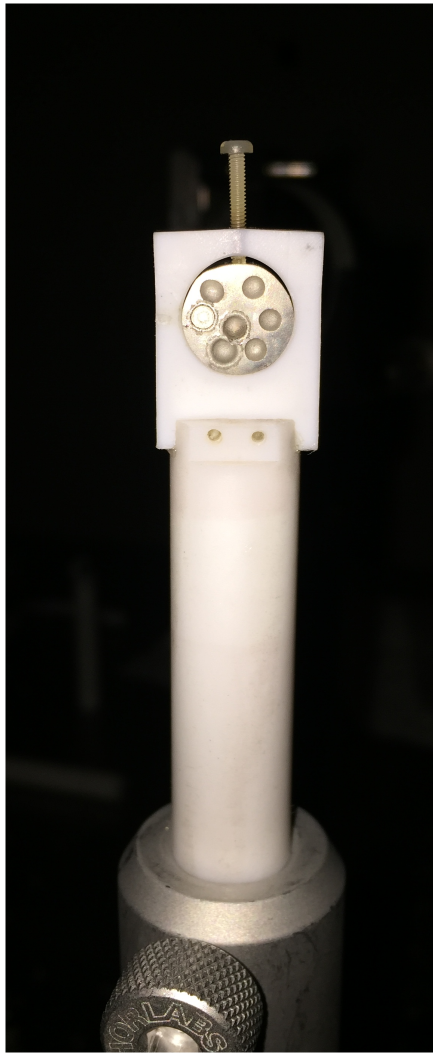
Typical hot electron spectra from TPW shots



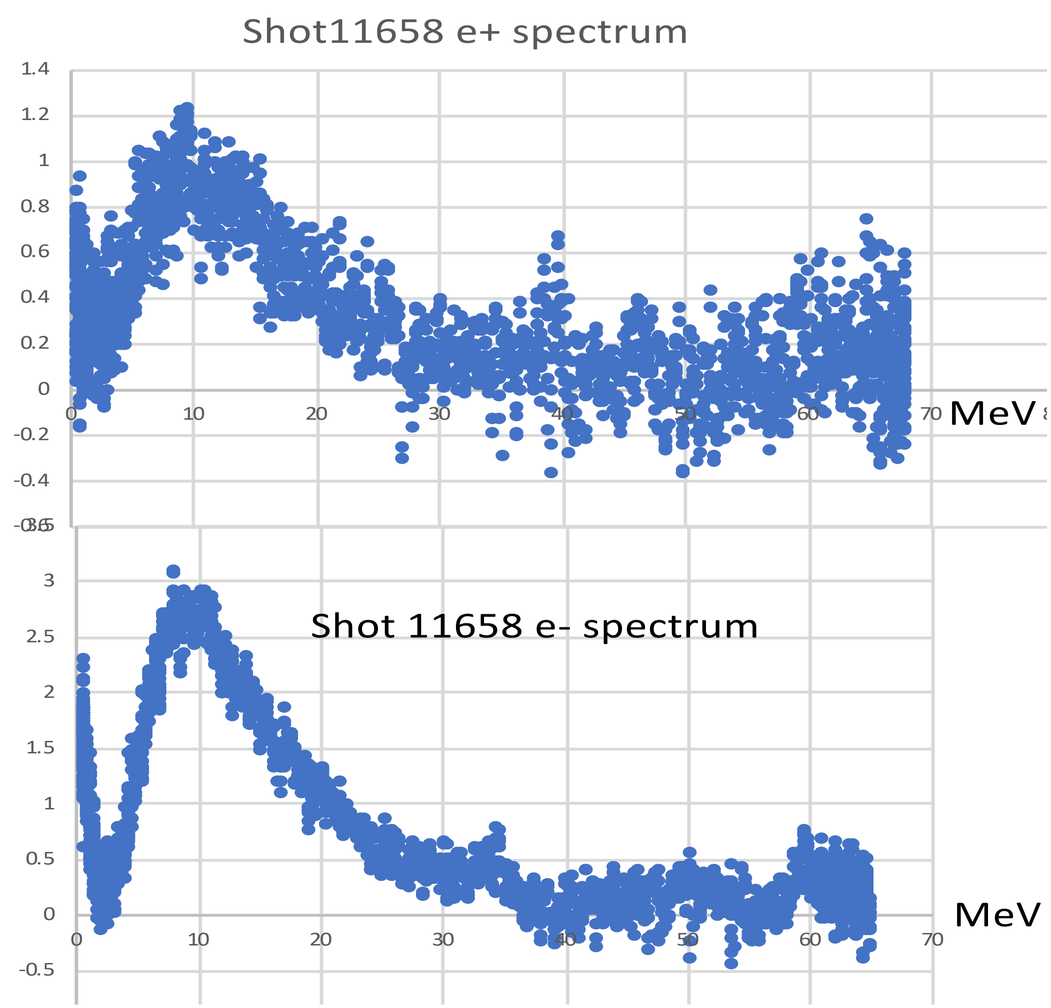
Positron spectra of targets thicker than 5 mm all peak at 7.5 MeV +/- 1.5 MeV

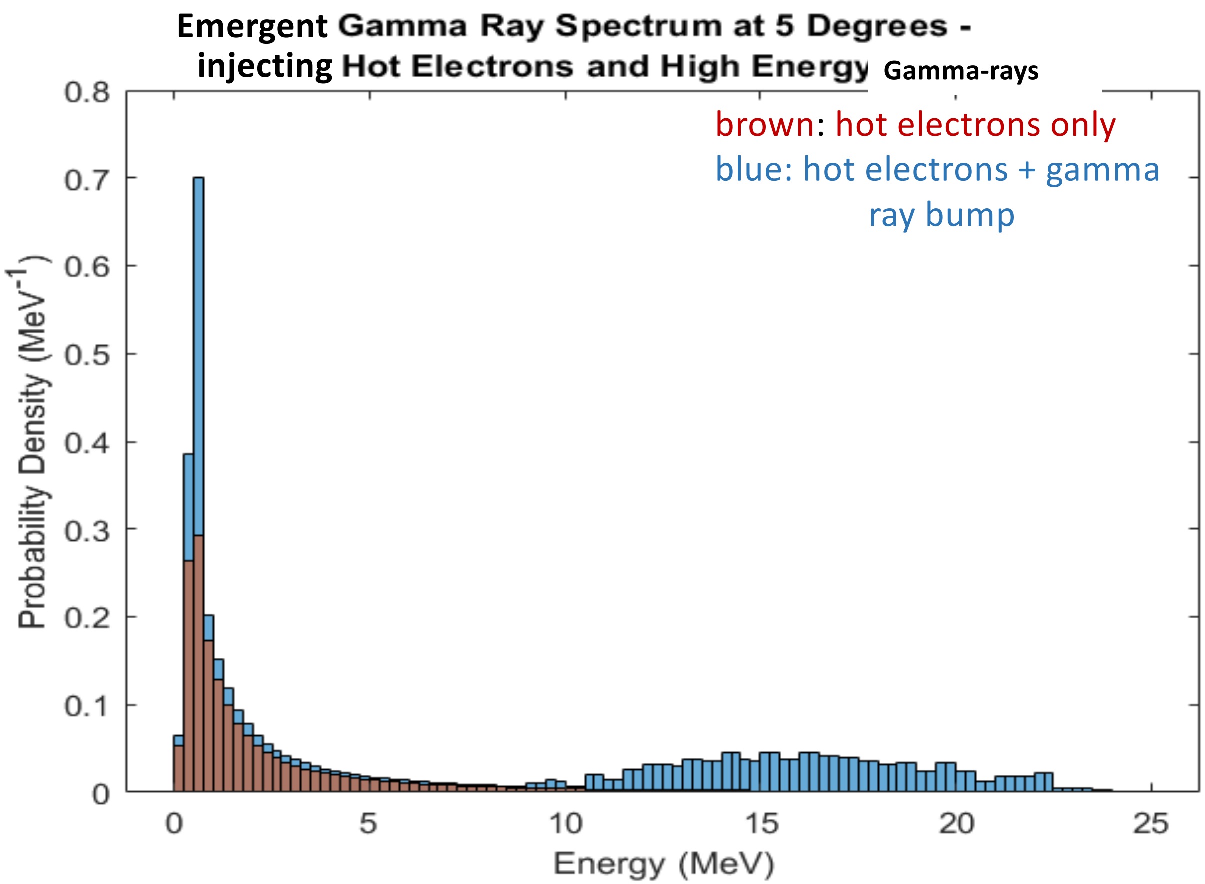


For very thick (~ cm) targets, e+e- spectra almost Identical, dominated by pairs created within ~1 mfp of target back surface. Equal peak energies suggest that sheath fields did not affect the peak energy. Hence Epeak must come from gamma-ray spectrum

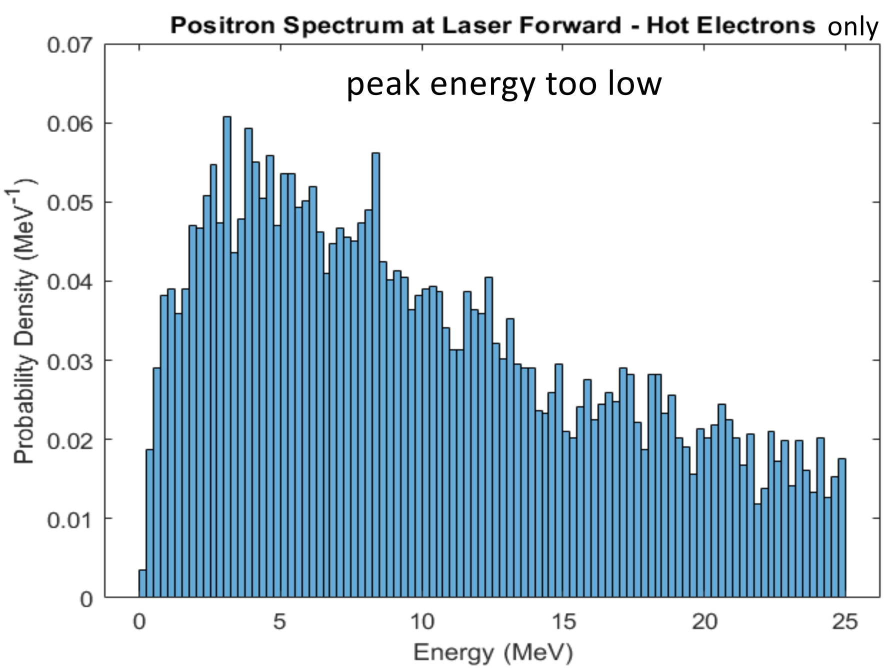


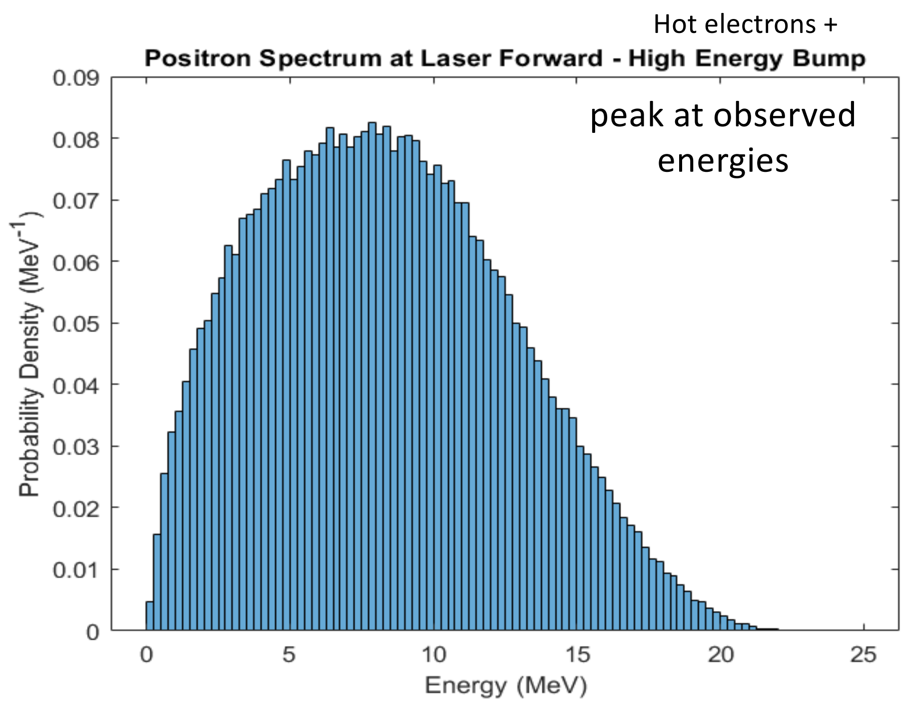
Pt ~ 1 cm thick slug

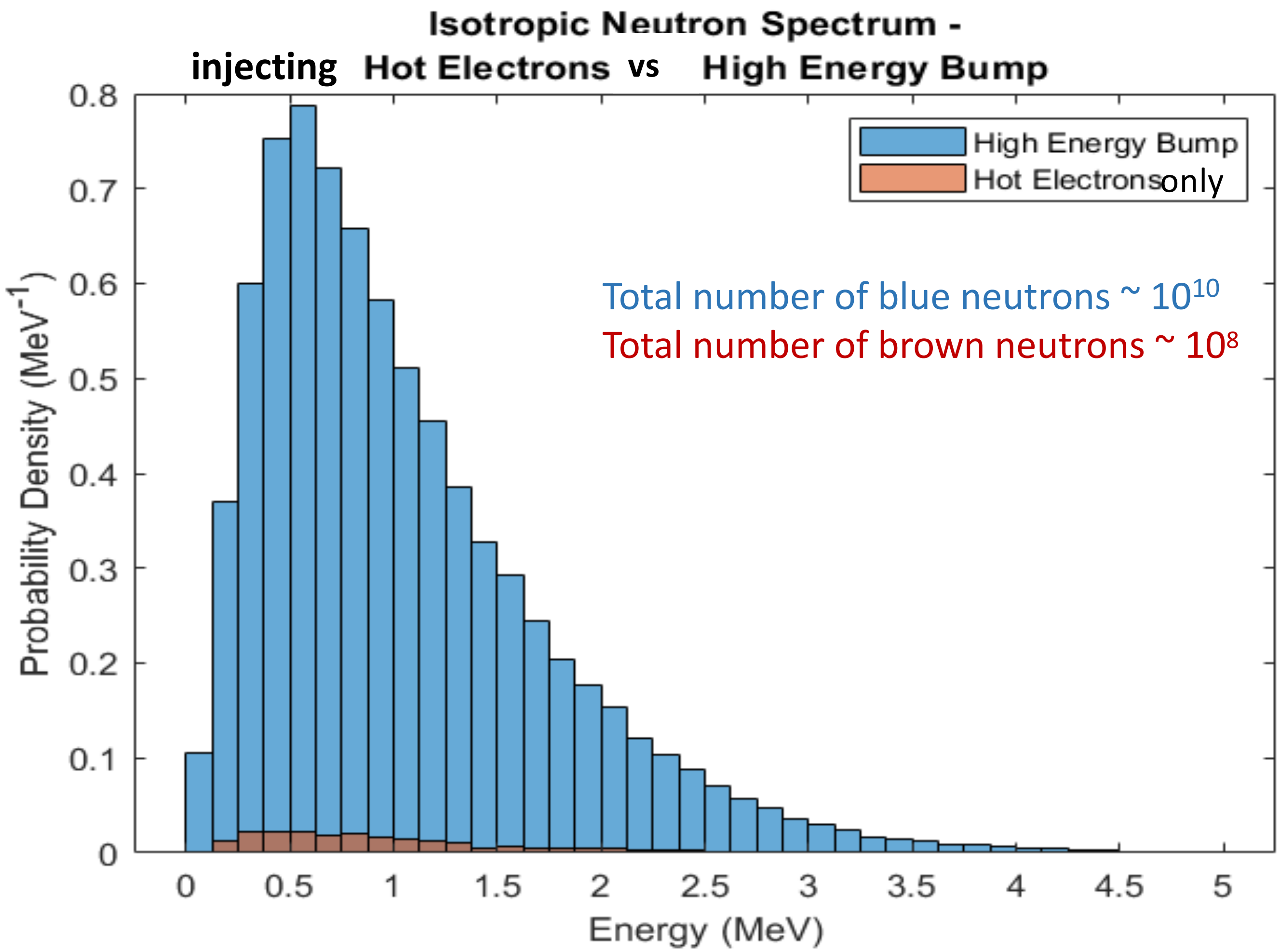




Emergent Gamma Ray Spectrum at 5 Degrees -
injecting Hot Electrons and High Energy Gamma-rays
brown: hot electrons only
blue: hot electrons + gamma ray bump
Probability Density (MeV^{-1})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
5
10
15
20
25
Energy (MeV)


Positron Spectrum at Laser Forward - Hot Electrons only
peak energy too low
Probability Density (MeV^{-1})
Energy (MeV)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0
5
10
15
20
25

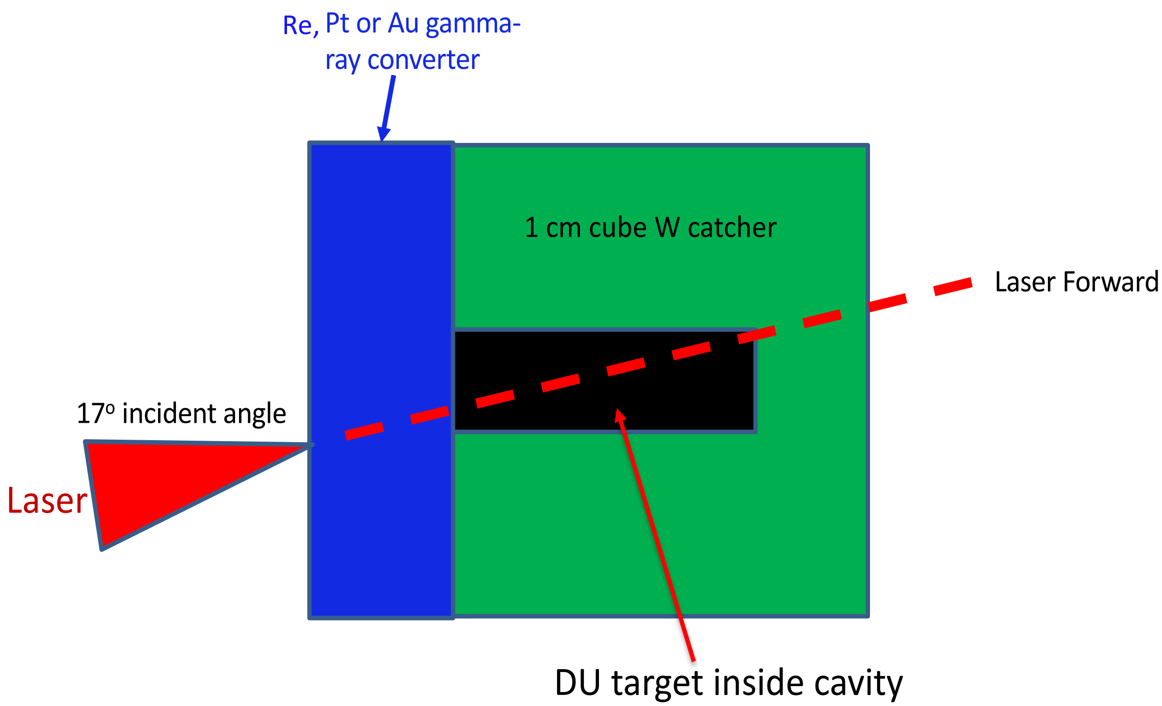

Hot electrons +
Positron Spectrum at Laser Forward - High Energy Bump
peak at observed energies
Probability Density (MeV^{-1})
Energy (MeV)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
5
10
15
20
25

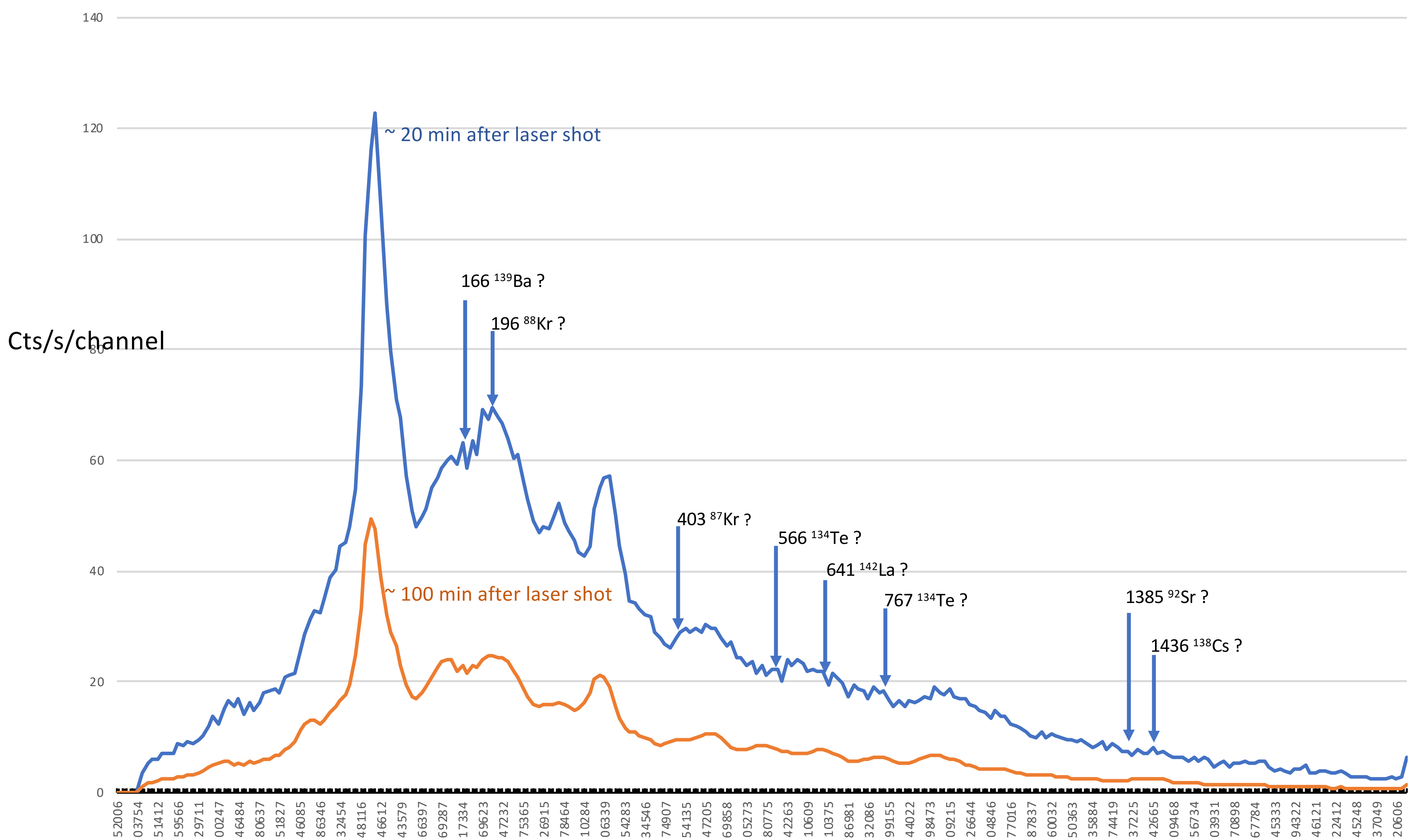


Isotropic Neutron Spectrum -
injecting Hot Electrons vs High Energy Bump
High Energy Bump
Hot Electrons only
Total number of blue neutrons ~ 10^10
Total number of brown neutrons ~ 10^8
Probability Density (MeV^-1)
Energy (MeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

100 bubbles ~ 10^{10} neutrons over 4π

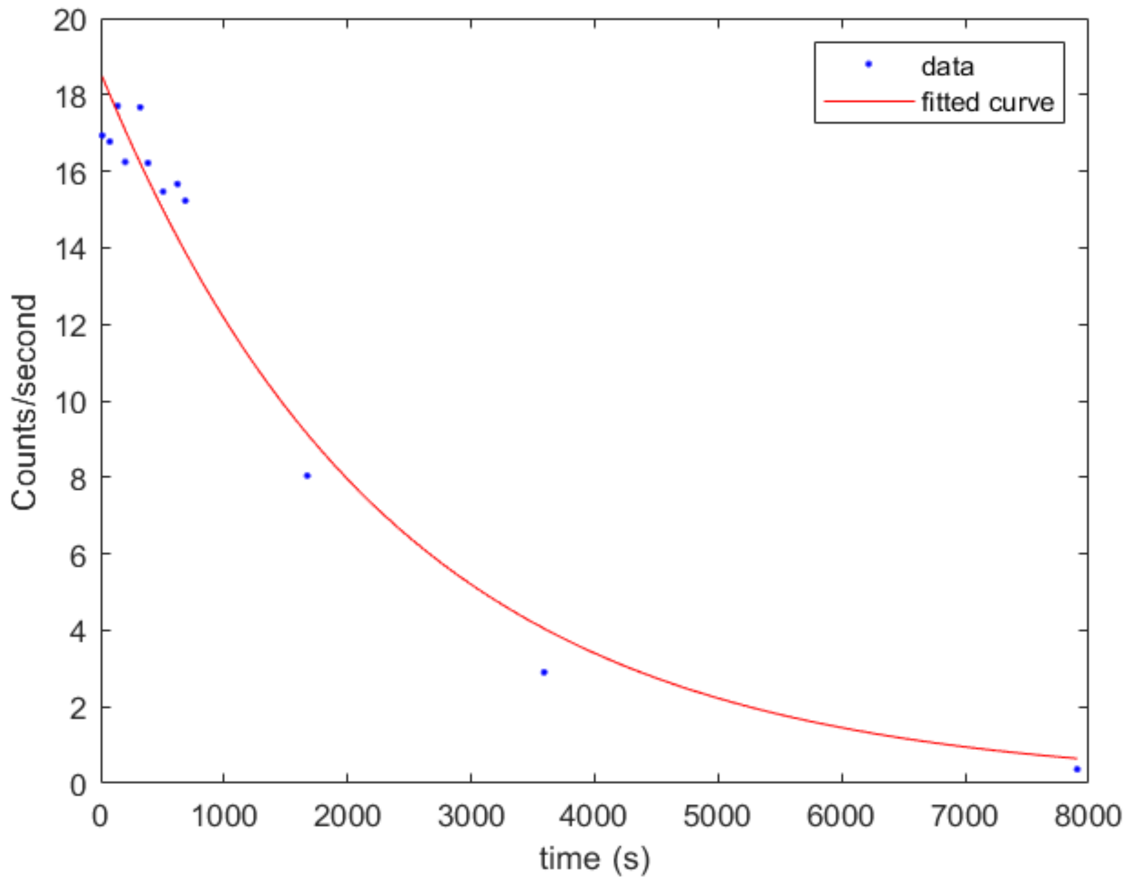
	Bubble Detectors								
#1 Angle	**#1 Bubble Count**		**#2 Angle**	**#2 Bubble Count**		**#3 Angle**	**#3 Bubble Count**		**A**
									(
	forgot to activate bubble detector			forgot to activate bubble detector			forgot to activate bubble detector		
Laser Forward	0°: 201; 90°: 214	194, 179	left side 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	f
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 oppo	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	


Re, Pt or Au gamma-ray converter
1 cm cube W catcher
Laser Forward
17° incident angle
Laser
DU 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 139Ba ?
196 88Kr ?
403 87Kr ?
566 134Te ?
641 142La ?
767 134Te ?
1385 92Sr ?
1436 138Cs ?
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 underlying continuum

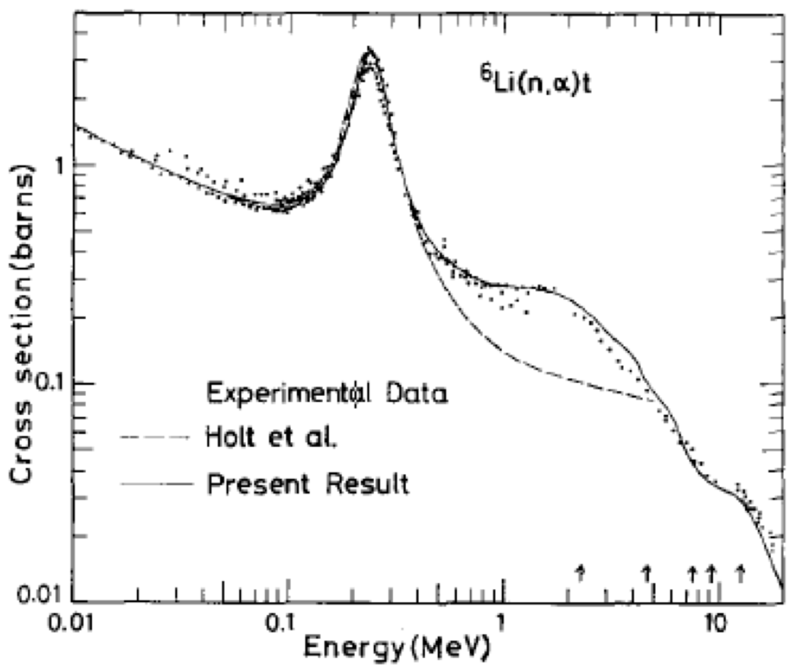


Next Projects

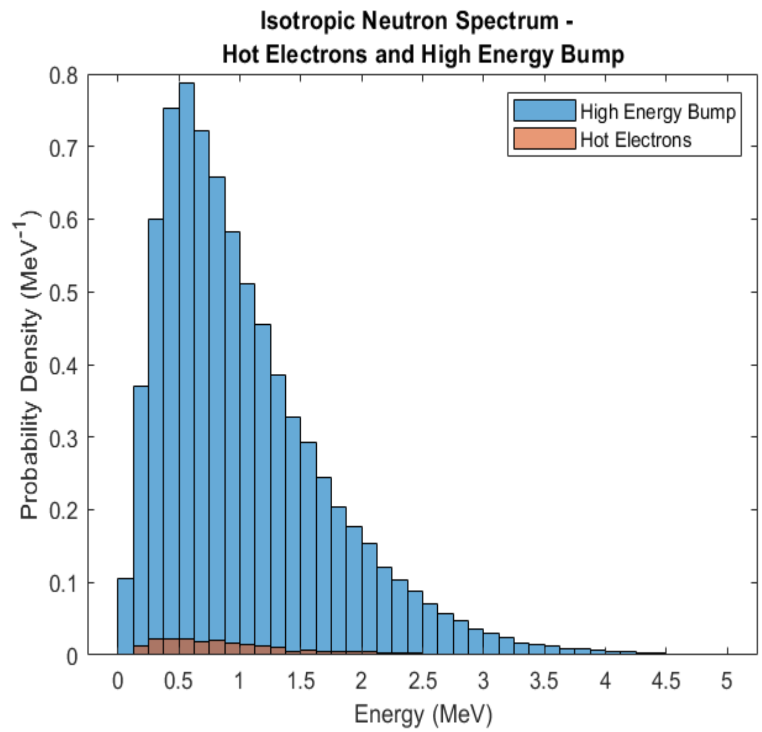
1. Redo DU photo-fission studies using HPGe spectrometer to better identify the primary fission products.

2. Explore r-process element production

3. Explore tritium production using photo-neutrons



$^6Li(n,\alpha)t$
Cross section (barns)
Energy (MeV)
Experimental Data
Holt et al.
Present Result



Isotropic Neutron Spectrum -
Hot Electrons and High Energy Bump
High Energy Bump
Hot Electrons
Probability Density (MeV^{-1})
Energy (MeV)