Marvel Fusion

Investigation of proton-beam-driven fusion reactions generated by an ultra-short petawatt-scale laser pulse

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Marvel Fusion

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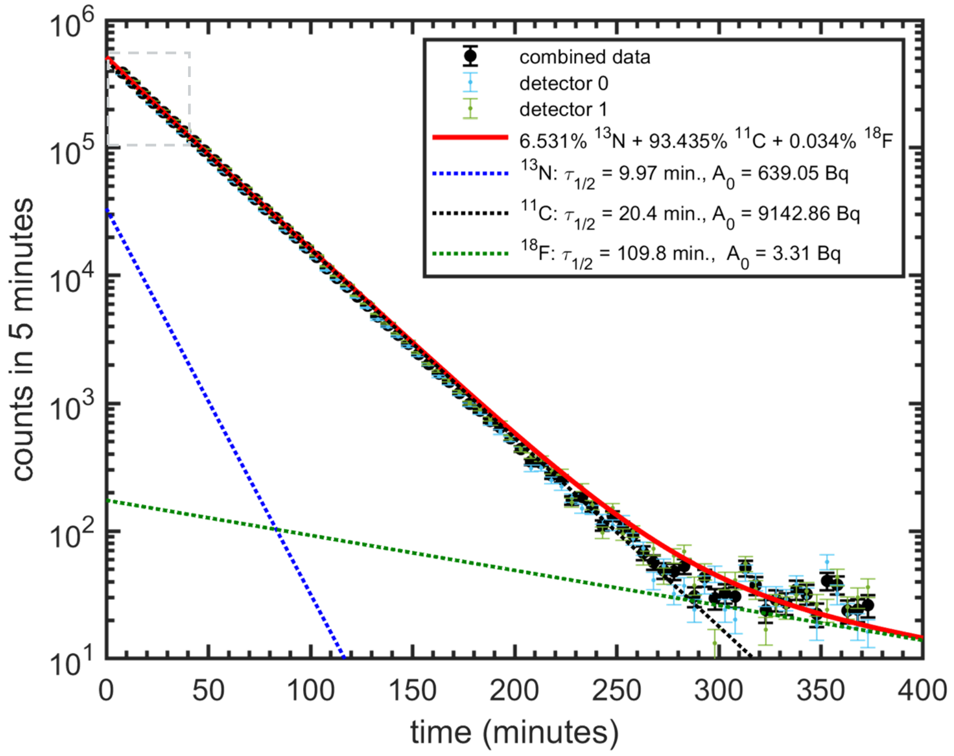

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Measuring fusion reaction rates & ion energy distributions inside the target may become feasible via nuclear reactions

Short-pulse laser-driven $p^{11}B(N)$ fusion

- Primary reactions produce alpha particles:
  $p + {}^{11}B \rightarrow \alpha_0 + {}^{8}Be \rightarrow \alpha_0 + \alpha_{01} + \alpha_{02} + 8.59$ MeV
  $p + {}^{11}B \rightarrow \alpha_1 + {}^{8}Be^{*} \rightarrow \alpha_1 + \alpha_{11} + \alpha_{12} + 5.65$ MeV
  $p + {}^{11}B \rightarrow 3\alpha + 8.68$ MeV

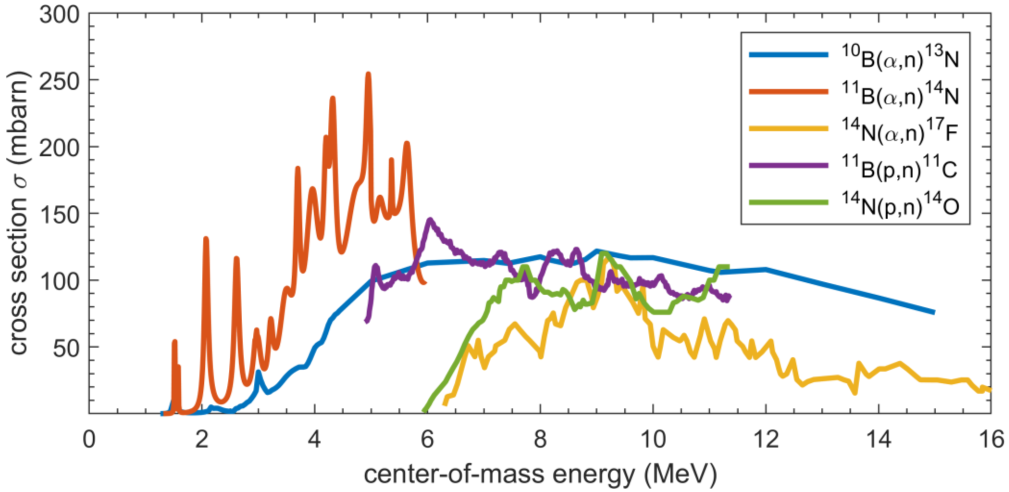
- Alpha particle detection is challenging:
  - Emission of protons, borons, etc., with identical energies and charge-to-mass ratios
  - Alphas are subject to electromagnetic fields

- Alpha particle emission alone may not be sufficient to gain physics insights

- Additional diagnostic methodologies are needed to increase confidence in data interpretation, e.g., nuclear diagnostics

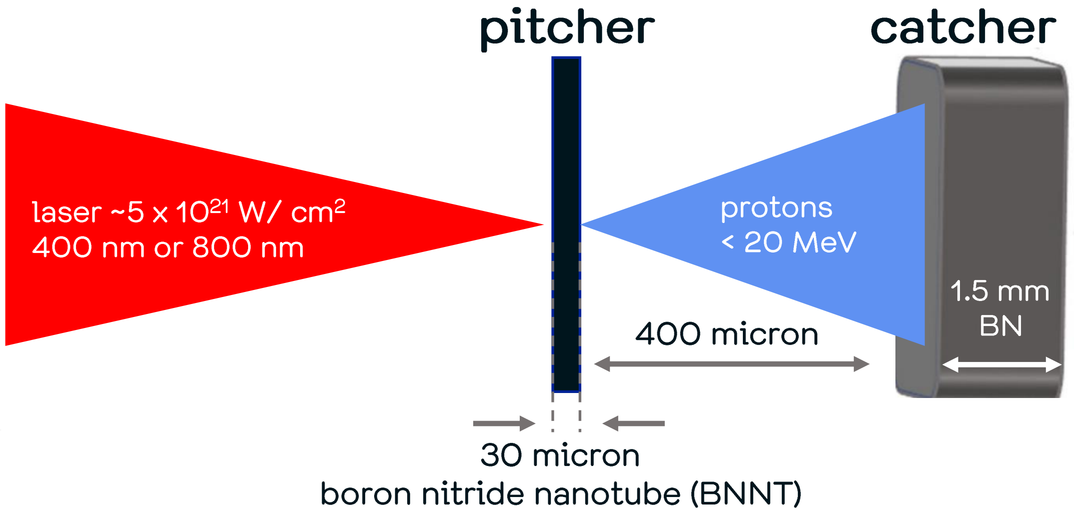
Neutronic primary & secondary reactions in p-BN

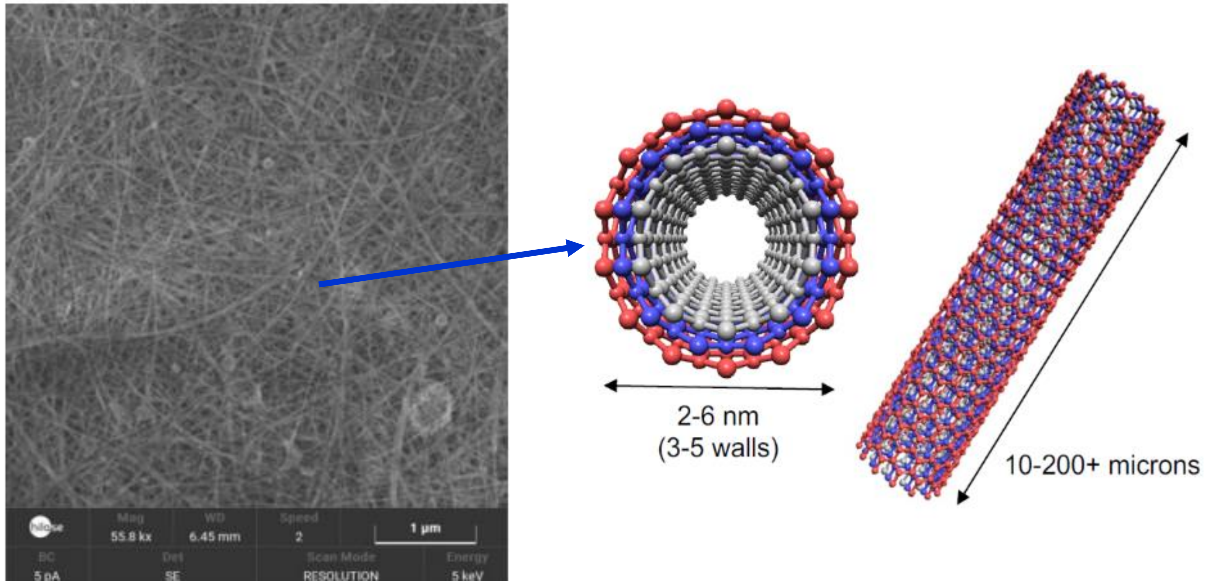
	Max. cross sec. [mb]	Half life
Boron:		
$\alpha + {}^{10}B \rightarrow {}^{13}N^{*} + n + 1.06$ MeV	130	9.97 min.
$p + {}^{10}B \rightarrow {}^{11}C^{*} + \gamma + 8.69$ MeV	~µb	20.4 min.
$\alpha + {}^{11}B \rightarrow {}^{14}N + n + 0.158$ MeV	250	stable
$p + {}^{11}B \rightarrow {}^{11}C^{*} + n - 2.765$ MeV	150	20.4 min.
Nitrogen:		
$\alpha + {}^{14}N \rightarrow {}^{18}F^{*} + \gamma + 4.415$ MeV	5	109.8 min.
$p + {}^{14}N \rightarrow {}^{14}O^{*} + n - 5.93$ MeV	130	70 s
$p + {}^{14}N \rightarrow {}^{11}C^{*} + \alpha - 2.92$ MeV	200	20.4 min.
$\alpha + {}^{14}N \rightarrow {}^{17}F^{*} + n - 4.73$ MeV	130	64.3 s

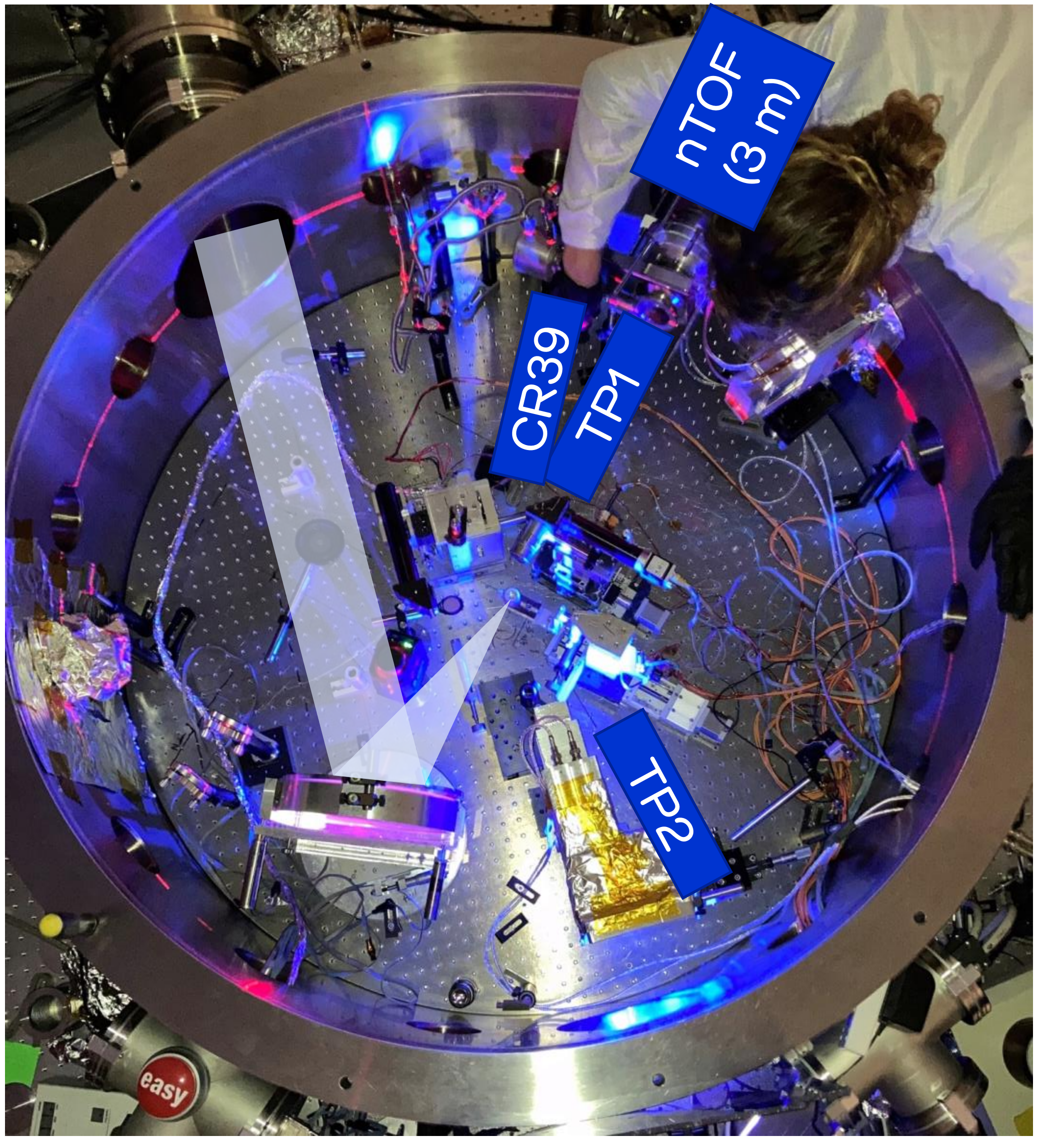


C. Labaune *et al.*, Sci. Rep. 6, 21202 (2016) & own work

We performed pitcher-catcher shots to investigate secondary reactions in BN

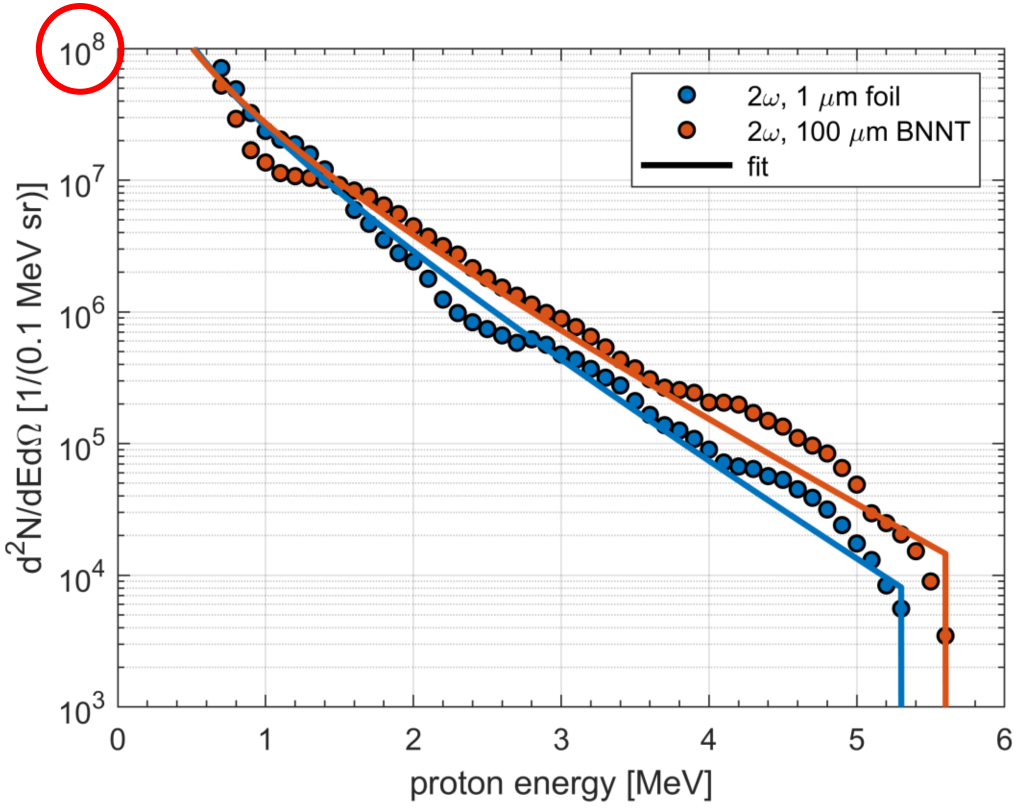




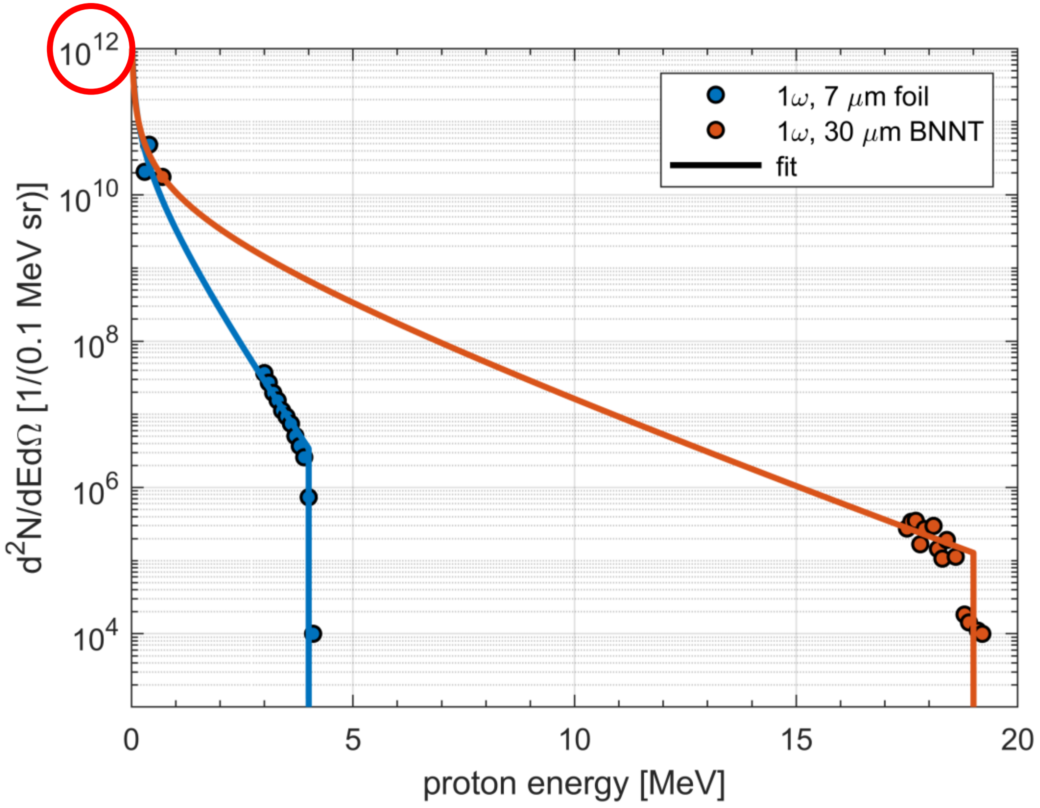


Rear-side TP ion spectra (TNSA protons) show 10^4 times more particles for 1ω vs. 2ω

2ω, 400 nm



1ω, 800 nm



~4×10^9 protons/J for the Al foil
~4×10^{10} protons/J for the BNNT

Single-shot spectra, per 1 J of laser energy

Calculation of fusion yields per incoming particle shows alphas can escape from the bulk, and results in measurable neutron & nuclear activation signals

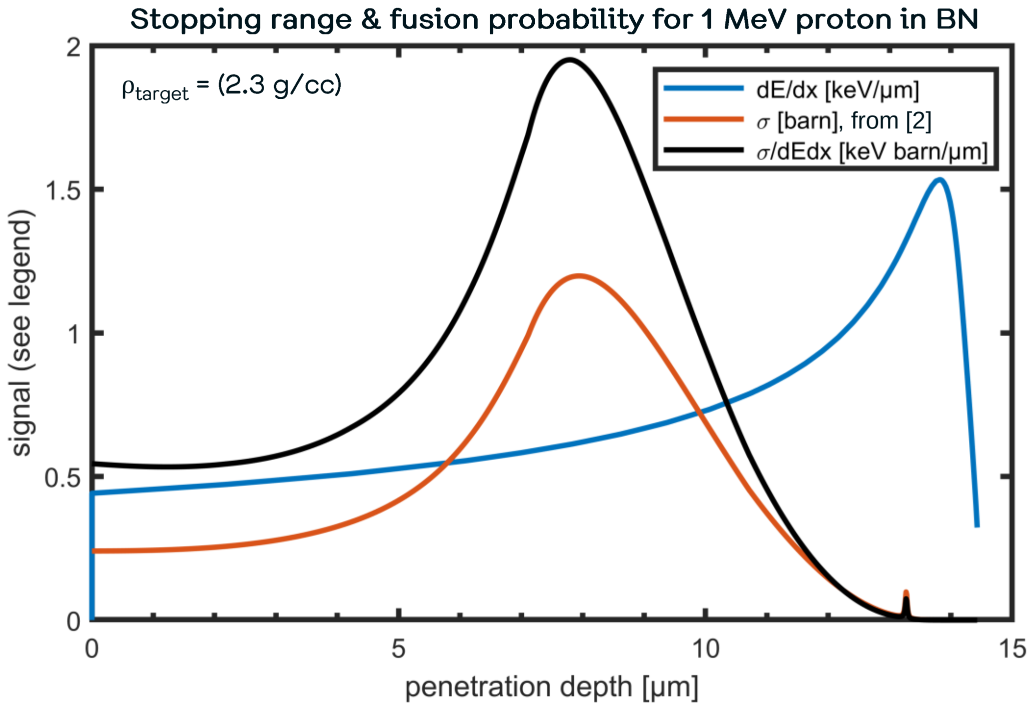
- Reaction yield: $N_2 = N_{projectile} \times \rho_{target} \times \sigma \times R$
- Replace σR by integration over stopping range (Giuffrida *et al.* [1]):

$$N_2 = N_{\text{projectile}}\, n_{\text{target}} \int_0^{E_0} \sigma(E) \left(\frac{dE}{dx}\right)^{-1} dE$$

- Then integrate N_2 over proton spectrum to get the total yield:

$$\text{Yield} = \int_0^{E_{\max}} \frac{dN_2}{dE}\, dE'$$

- 3 MeV alpha range: ~10 μm



$p + {}^{11}B \rightarrow 3\alpha + 8.7$ MeV:

- 1 MeV protons, R = 14.45 μm
- $N_2 = 4.4 \times 10^{-5}$ per proton
- Yield = 6.6×10^{6} per J

$p + {}^{11}B \rightarrow {}^{11}C^{*} + n - 2.765$ MeV:

- 6 MeV protons, R = 275.4 μm
- $N_2 = 5.7 \times 10^{-5}$ per proton
- Yield = 6.6×10^{4} per J

[1]: L. Giuffrida *et al.*, Phys. Rev. E 101, 013204 (2020)
[2]: Nevins & Swain, Nuclear Fusion 40, 865 (2000)

Post-shot gamma spectroscopy indicates production of ^{11}C, ^{13}N and ^{18}F isotopes

Reactions:

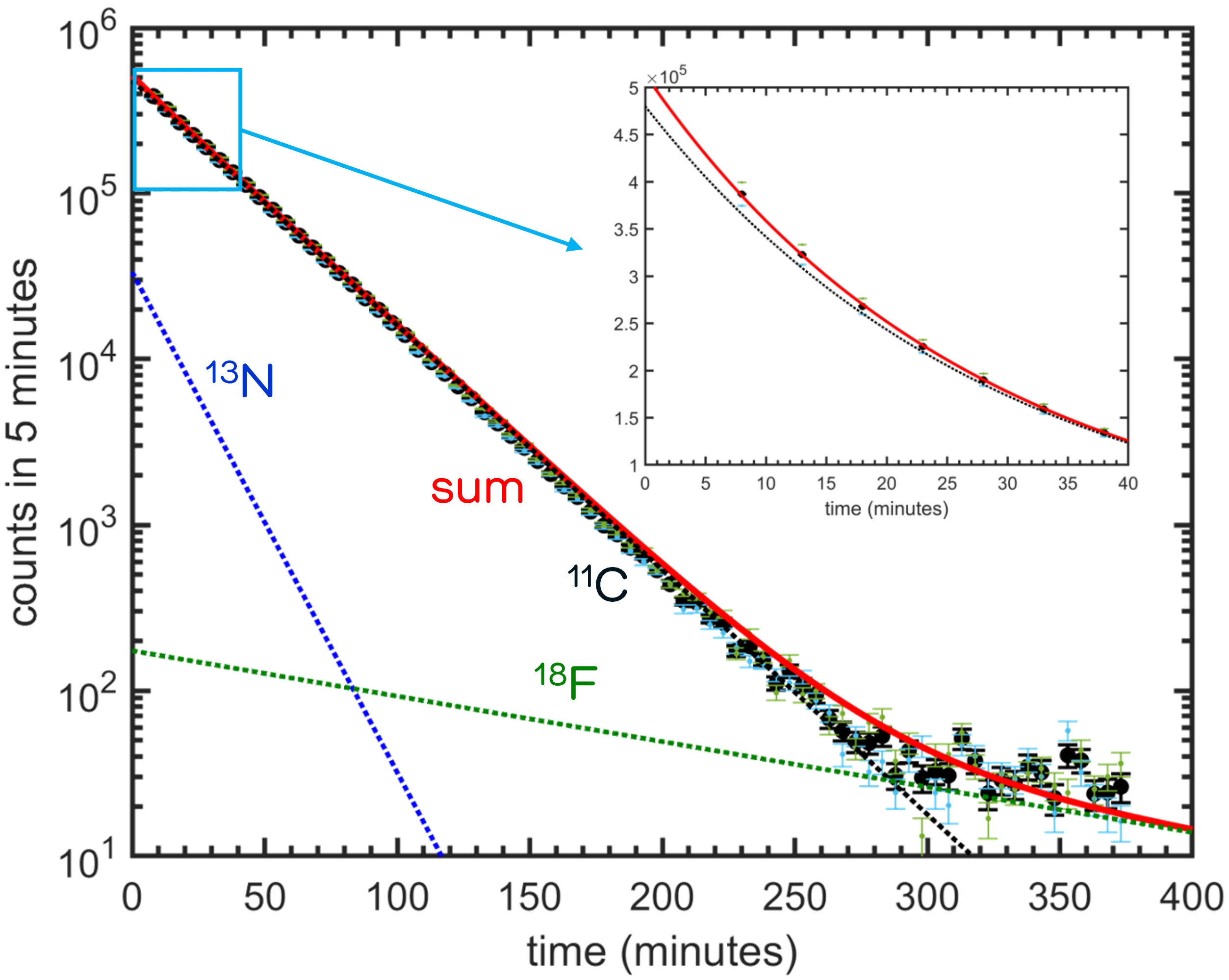
$\alpha + {}^{10}B \rightarrow {}^{13}N + n + 1.06$ MeV

$p + {}^{10}B \rightarrow {}^{11}C + \gamma + 8.69$ MeV
$p + {}^{11}B \rightarrow {}^{11}C + n - 2.765$ MeV
$p + {}^{14}N \rightarrow {}^{11}C + \alpha - 2.92$ MeV

$\alpha + {}^{14}N \rightarrow {}^{18}F + \gamma + 4.415$ MeV

Results:

	^{11}C	^{13}N	^{18}F
Half life [min]	20.4	9.94	109.8
Relative contrib. [%]	93.435	6.531	0.034
Activity at t = 0 [Bq]	9143	639	3.3
Number of nuclei N_2	1.6×10^7	5.5×10^5	3.2×10^4
N_2 per shot per J	37,000	1,300	75



Comparison of measured and calculated activation suggests large contribution from oxygen impurities to the measured activation

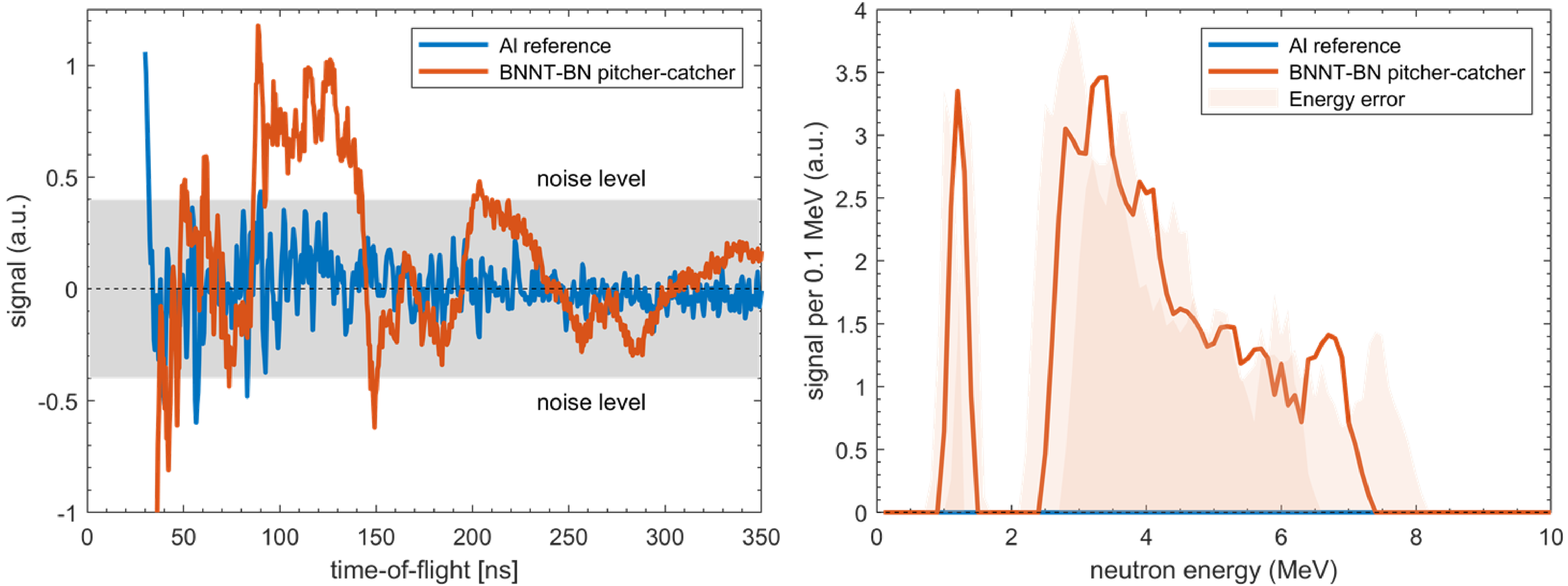
- Calculated alpha yields per shot per J:
  - From p^+ : 6×10^6
  - From ^{13}N: 2×10^{10}
  - From ^{18}F: 4×10^8

- Post-shot BN plate composition analysis:
  - 95 % boron nitride
  - 5 % boron trioxide (0.2% ^{18}O):
    - $p + {}^{16}O \rightarrow {}^{13}N + \alpha - 5.22$ MeV
    - $p + {}^{18}O \rightarrow {}^{18}F + n - 2.44$ MeV

→ most of the measured radioactive isotopes are the result of protons interacting with ^{11}B or the O contamination

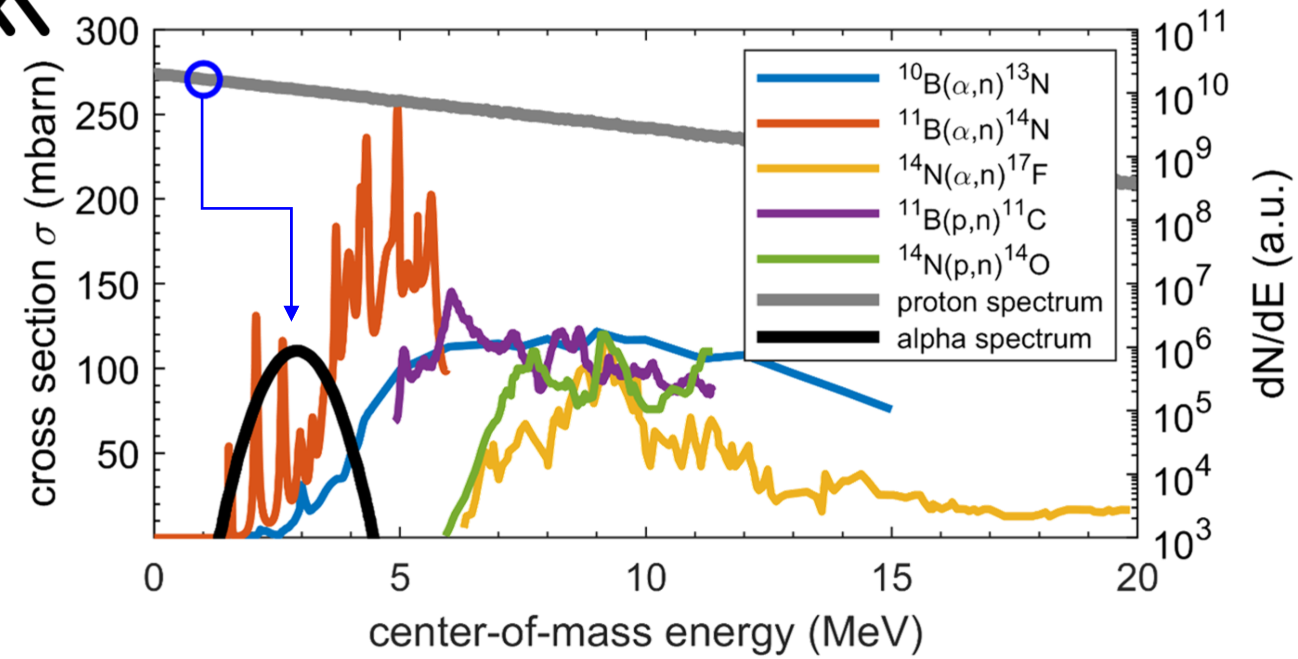
	3α	^{11}C	^{13}N		^{18}F	
	$^{11}B(p,\alpha)2\alpha$	$^{11}B(p,n)^{11}C$	$^{10}B(\alpha,n)^{13}N$	$^{16}O(p,\alpha)^{13}N$	$^{14}N(\alpha,\gamma)^{18}F$	$^{18}O(p,n)^{18}F$
Calc.	6×10^6	66,000	0.5	800	1	80
Meas.	n/a	37,000	1,300	1,300	75	75

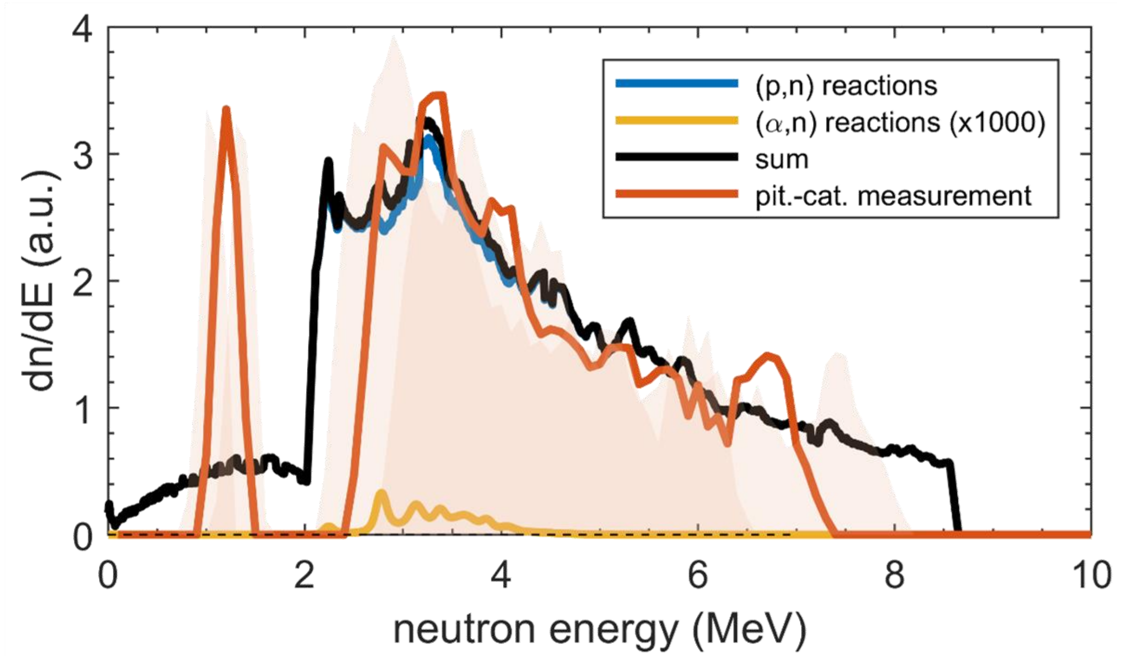
A low-particle-number neutron spectrum with energies between 1 and 8 MeV was measured with BNNT-BN pitcher-catcher shots



The measured & calculated neutron spectra are quite similar, demonstrating the diagnostic potential for the proton & alpha populations

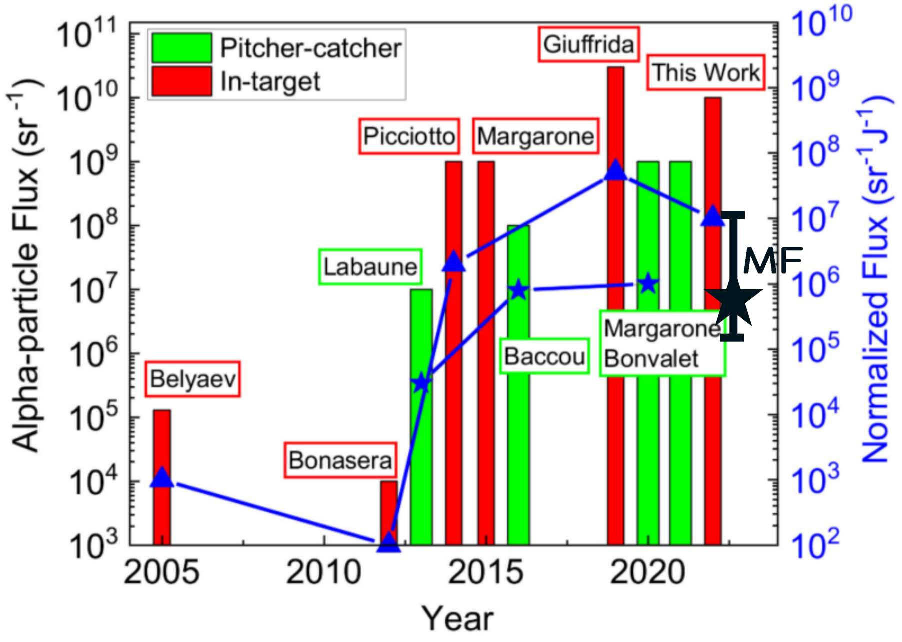
- Use cross sections and input proton spectrum to produce neutron energy distribution via kinematic reaction calculations
- (a,n) reactions in same spectral range as (p,n) reactions → may lead to alpha diagnostic in the future





Summary & Conclusions

- BNNTs are efficient proton sources creating ~4 x 10^{10} protons/J
- Post-shot gamma spectroscopy:
  - Can be used to infer primary proton numbers
  - Has the potential to infer alpha particle yield but requires oxygen-free samples
- When >6 MeV protons or alphas are present:
  - high likelihood of neutron generation
  - Neutron spectrum shows diagnostic potential for proton & alpha particle populations
- Pitcher-catcher alpha yields:
  - Calculated from proton spectrum: 5e5/sr/J
  - Measured:
    - From activation: Dwarfed by protons interacting with O contamination
    - From neutrons: Yields too low for now
    - From CR39 analysis: ~6x10^5-10^7/sr/J (large error bar; data not shown in this presentation)



D. Margarone et al., Appl. Sci. 12, 1444 (2022)

BACKUP

Ion spectra, 2w, Mylar vs. BNNT – pitcher only

Mylar, 1 µm:

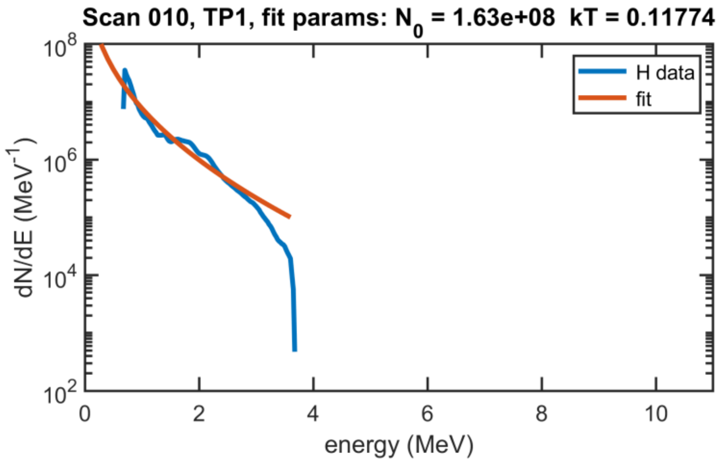
- Nearly identical particle spectra front and back
- Well-collimated proton beams
- No heavy ions

⇒ Double-sided TNSA due to the high contrast

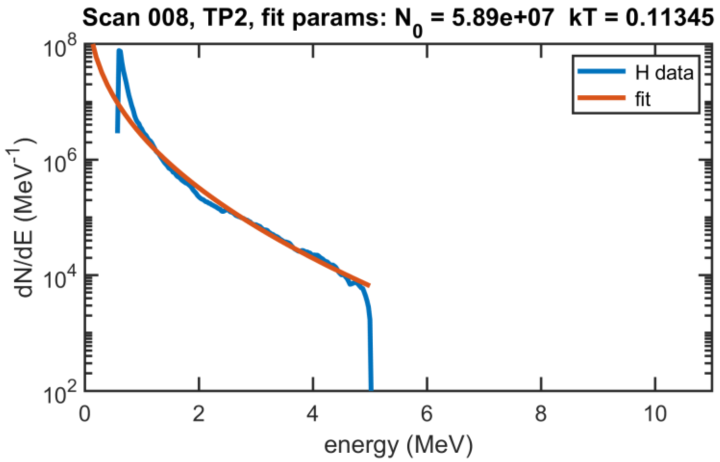
BNNT, 100 µm, 0.55 g/cm³:

- Wide angle emission
- Front: high proton energies
- Back: same as Mylar, despite the 100x larger thickness

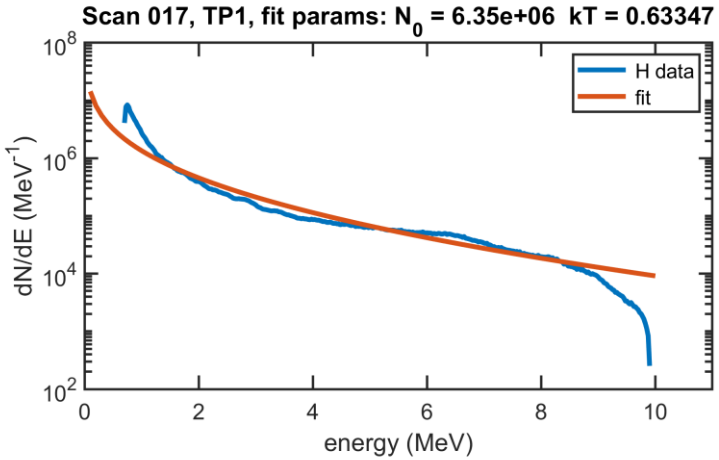
Mylar front



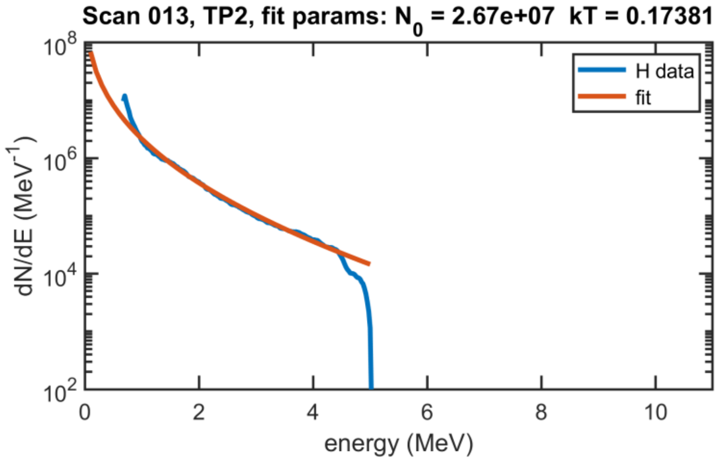
Mylar back



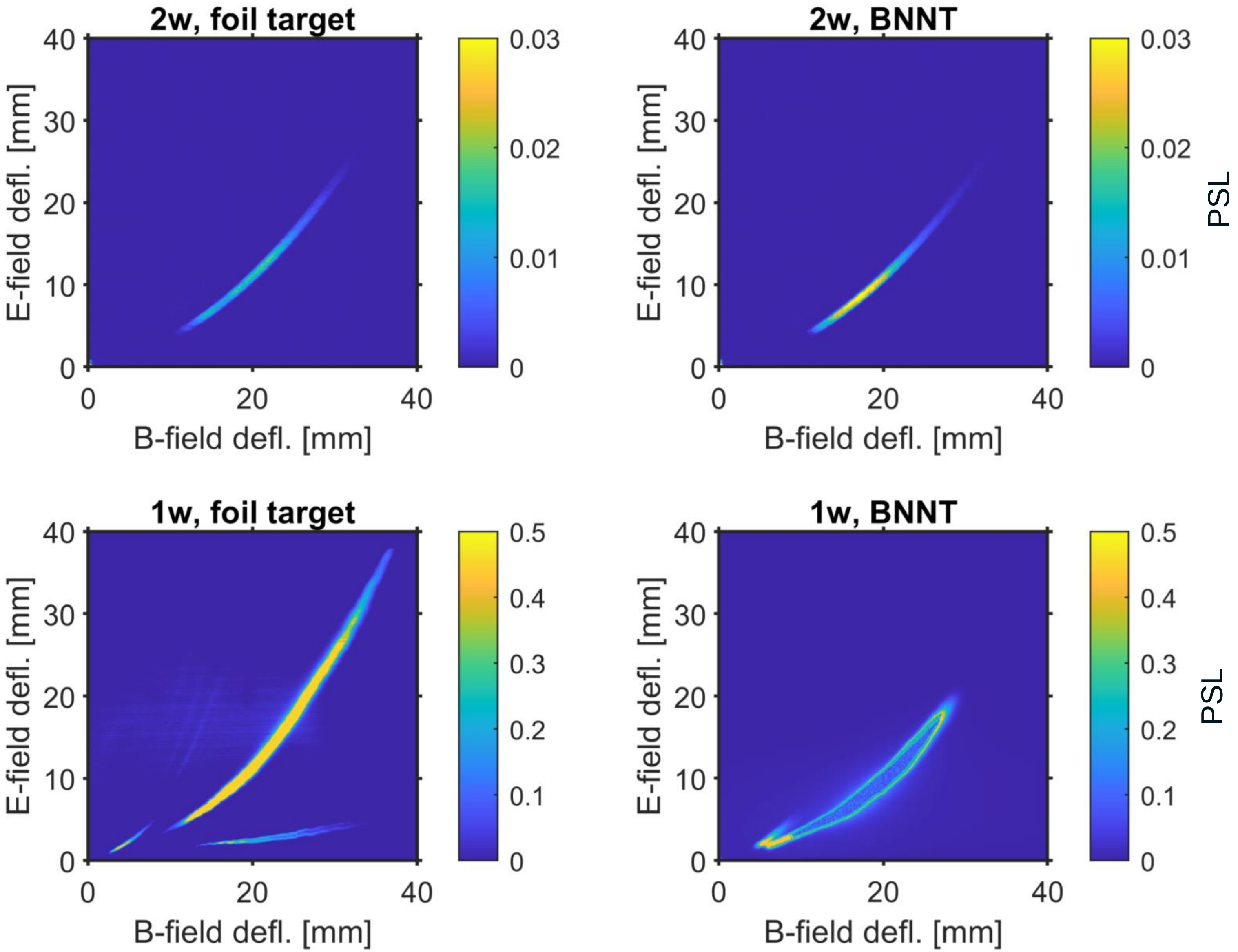
BNNT front



BNNT back



800 nm irradiation of BNNT targets resulted in the strongest proton pitcher signal with the highest maximum energy



Single-shot spectra, per 1 J of laser energy

Activation measurements