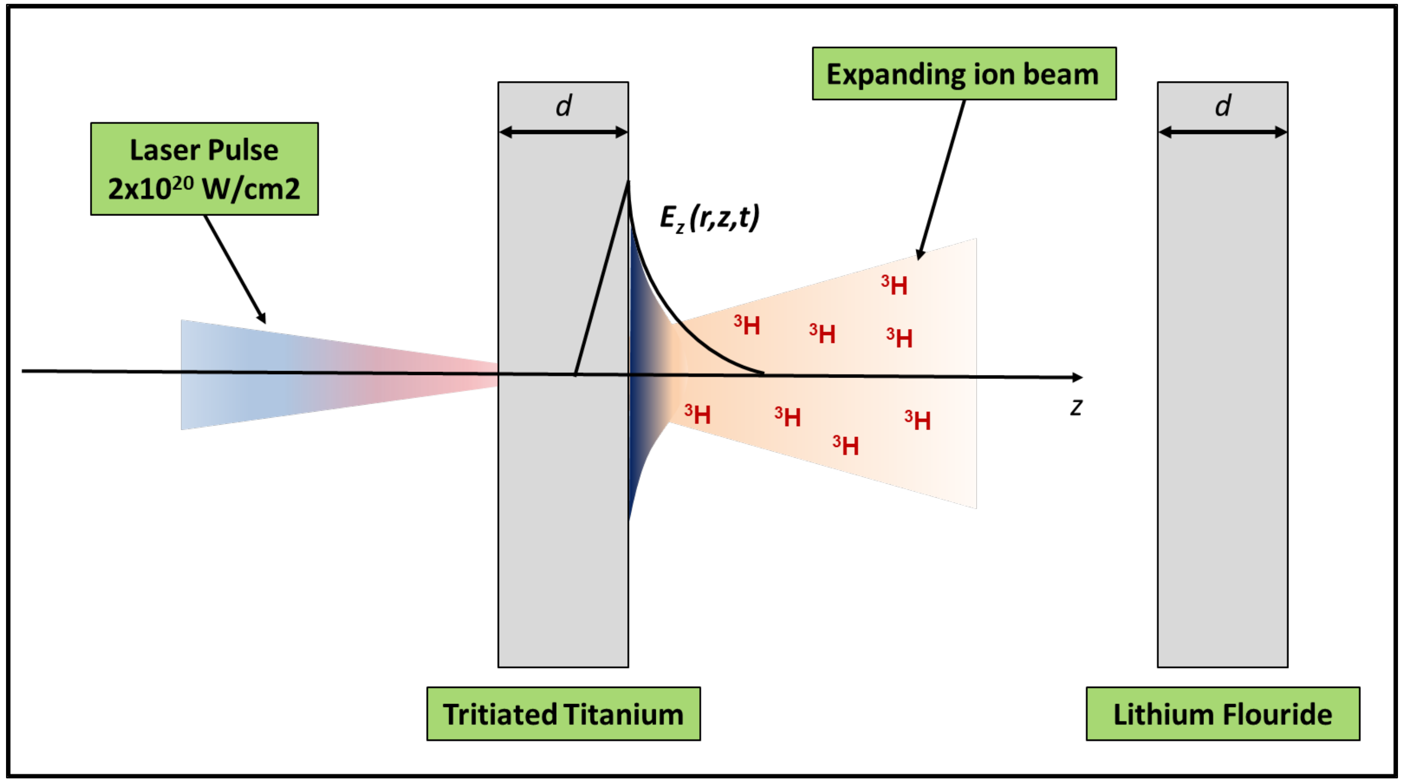
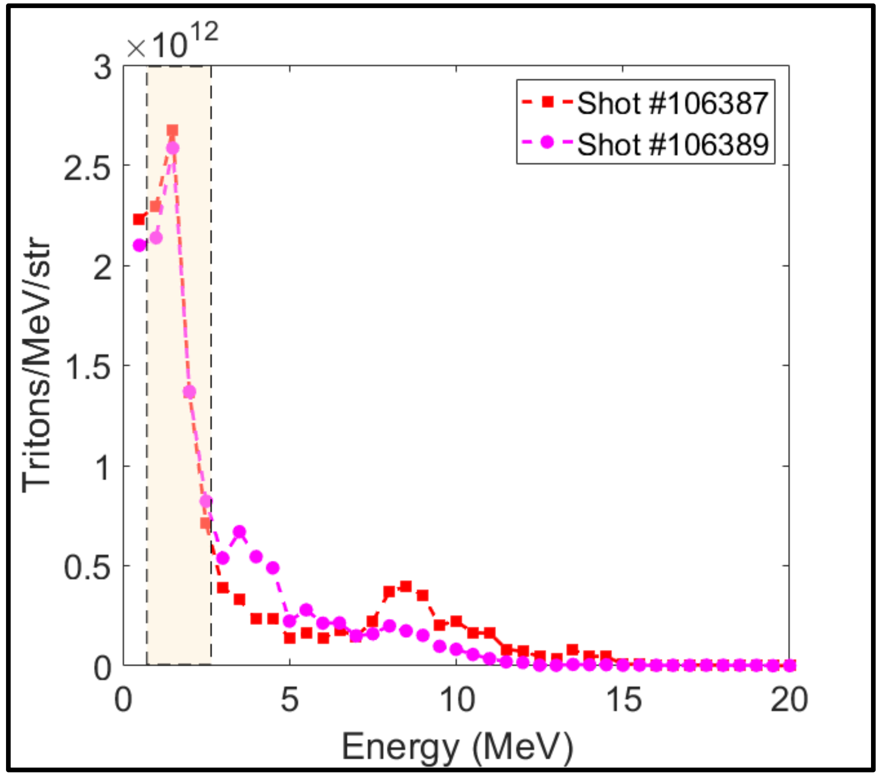
Nuclear Reactions using a Tritium Ion Beam at the University of Rochester's Omega Laser Facility

Target Normal Sheath Acceleration (TNSA)



Triton Energy Spectrum



C. J. Forrest
University of Rochester
Laboratory for Laser Energetics

WANDA
Arlington, VA
11 February 2025

Summary

The Omega Laser Facility has demonstrated that laser-generated tritons can be produced at energies sufficient for nuclear physics experiments

UR LLE

- The development for a controllable triton (^{3}H) beam and experimental platform to study triton-induced reaction is of interest for the broader nuclear scientific community.
- A limited number of tritium-induced reaction cross-sections measurements at low energy (~MeV) exist and are important in several areas of nuclear physics:
  - the neutron energy spectrum from two tritons fusing is relevant for Inertial confinement fusion (ICF) experiments
  - investigate predicted D-T elastic scattering resonances with key implications for laser-induced DT fusion
  - reaction networks in the early r-process (Z < 10) for big bang nucleosynthesis (BBN)[*,**]

[*] A. Aprahamian, Nucleosynthesis with Tritium, to be submitted (2025)
[**] M. Terasawa, The Astrophysical Journal, 562: 470-479 (2001)

Collaborators

A. Aprahamian (Co-PI), M. Wiescher, and J. DeBoer
University of Notre Dame

C.J. Forrest (SP), W.U. Schröder, A. Schwemmlein, and C. Stoeckl
University of Rochester Laboratory for Laser Energetics

G. Hale and M. Paris
Los Alamos National Laboratory

B. Appelbe, A. Crilly, and N. Dover
Imperial College

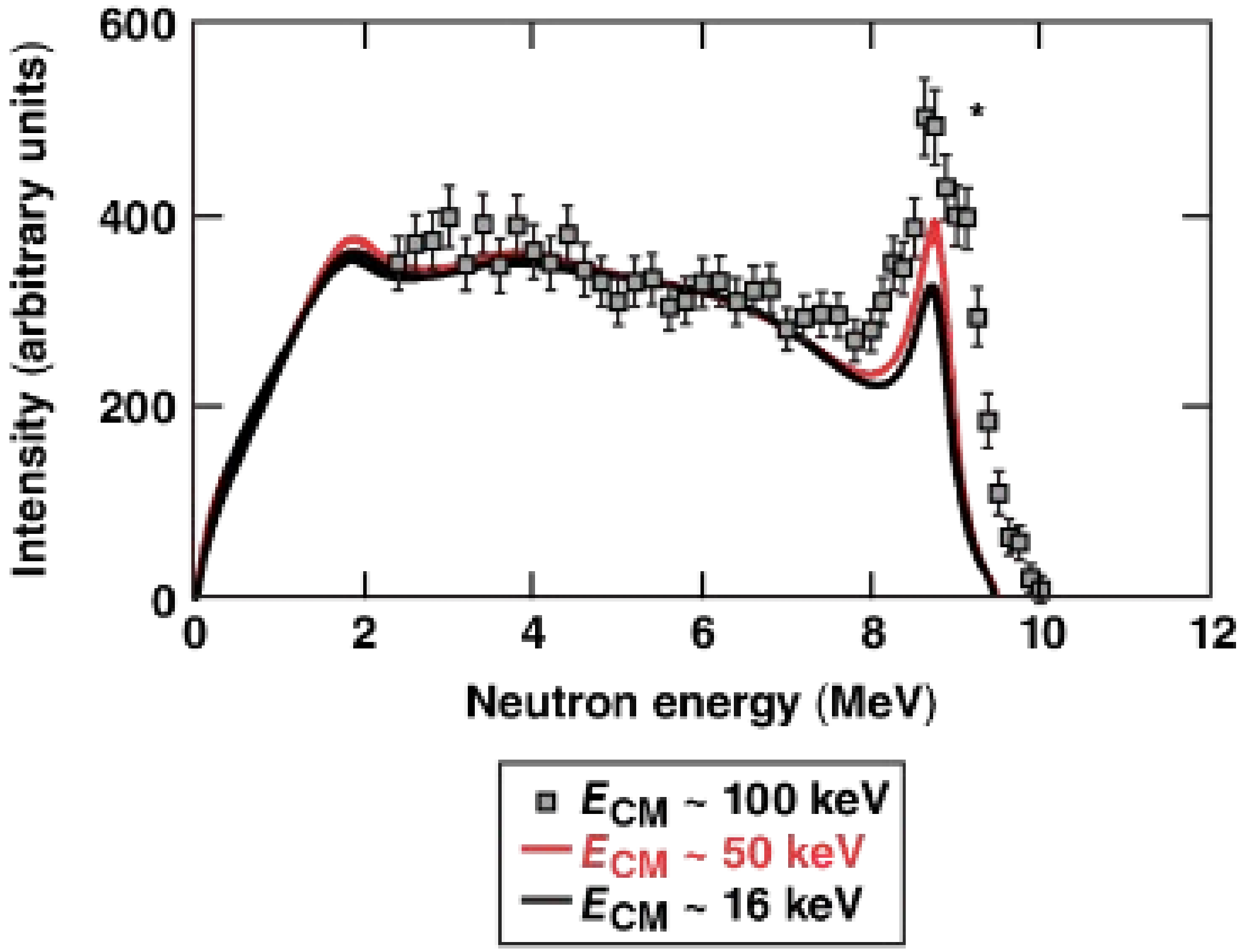
Steve Padalino and Charlie Freeman
SUNY Geneseo

Mark Yuly
Houghton University

Hendrik Schatz
Michigan State University

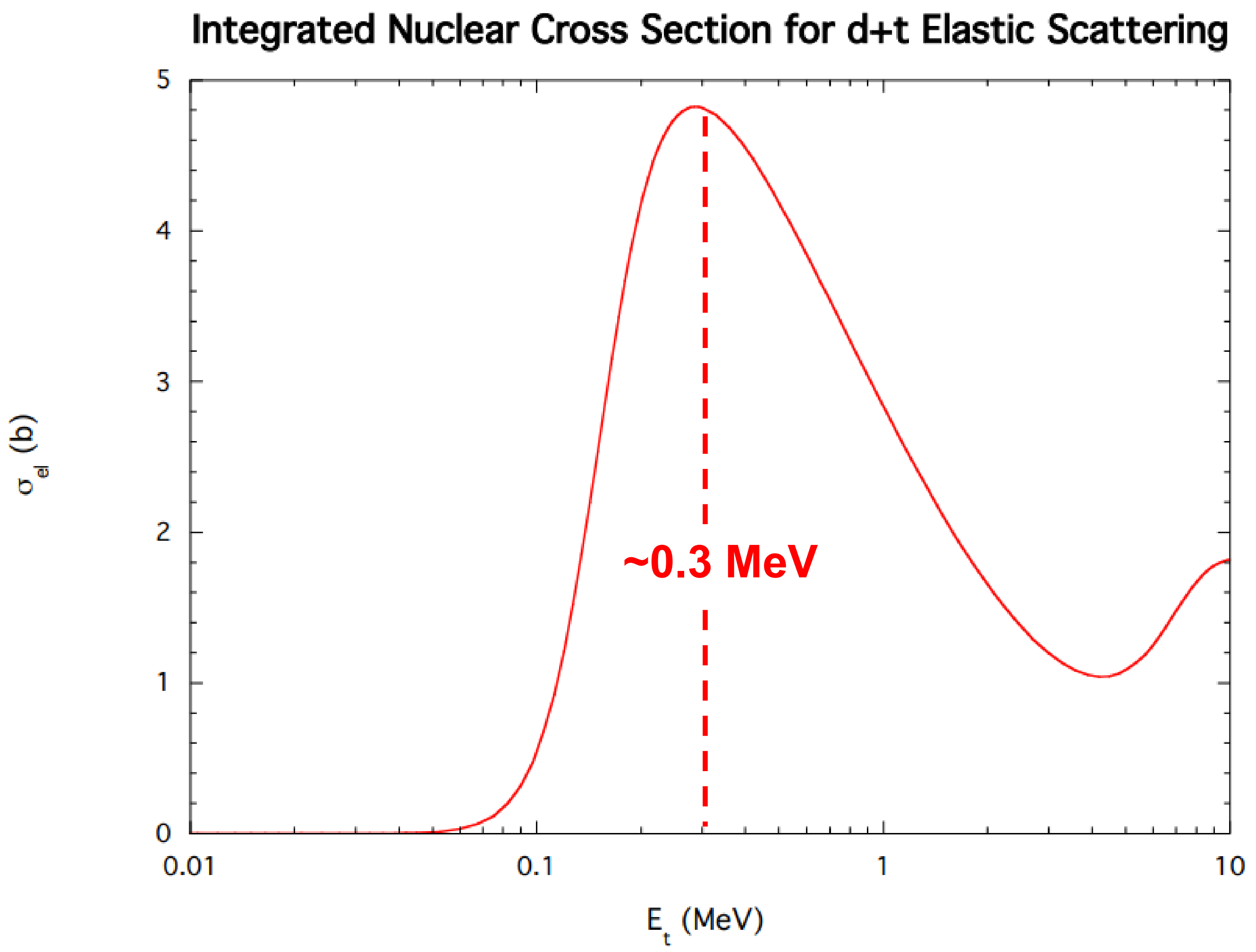
The six-nucleon reaction between two tritons interacting has proven to be an ongoing challenge with current theoretical models

- Recent analysis suggest that the nTOF data below 4 MeV is highly uncertain.
  - earlier experiments were performed on accelerators at COM energies around 100 keV
  - recents experiments on both ICF and MCF facilities were in the 20 keV to 50 keV COM energies
- The observed shape of the distribution as a function of COM energy is unexpected from theory.
  - squares is from an accelerator experiment
  - solid lines is from ICF experiments



Understanding this reaction initiated a new experimental platform to accelerate tritium to ~MeV energies

R-Matrix calculations* show a significant Coulomb-nuclear interference effect with an elastic scattering resonance at ~ 0.3 MeV

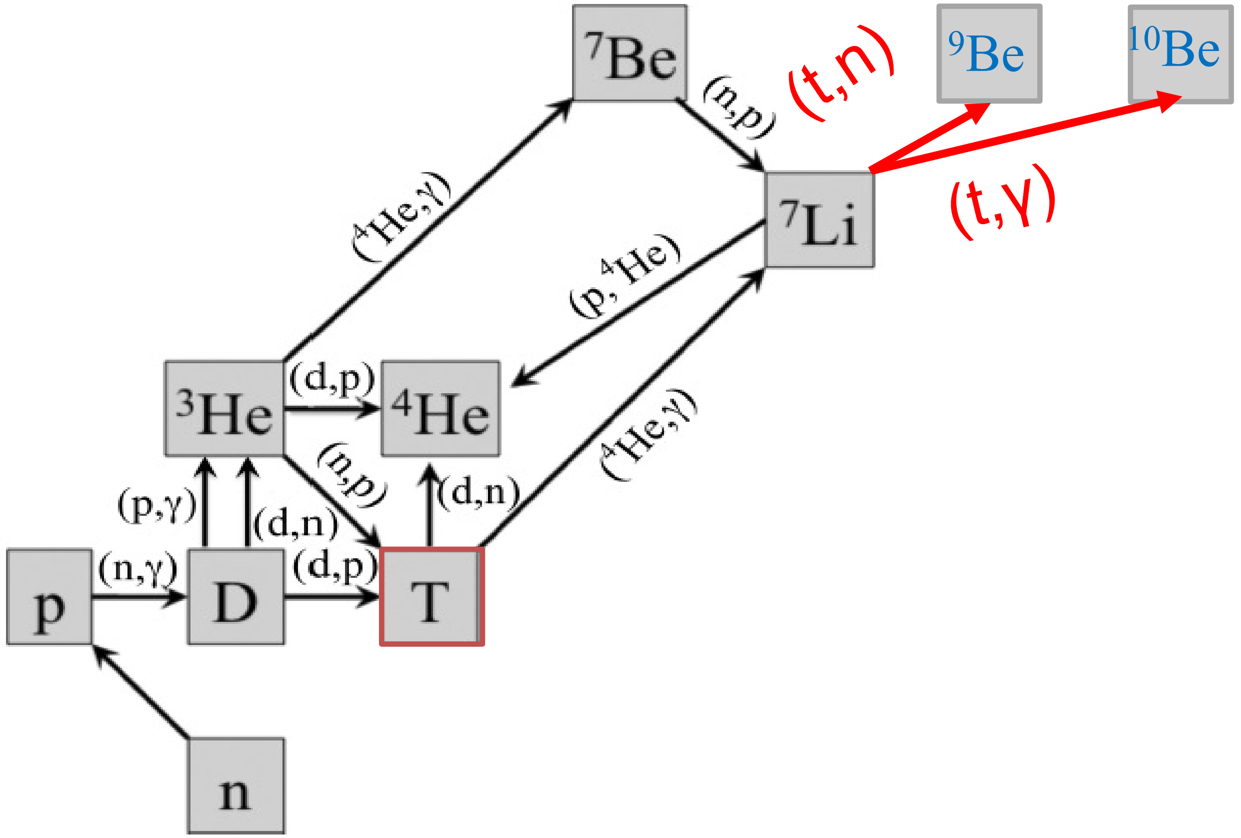


- **R-Matrix calculation performed by LANL indicate a significant Coulomb-nuclear interference effect when the incident deuteron energy is of the order of a few hundred keV.**
  - **however, there are no measurement of deuterium-tritium (D-T) elastic scattering in this energy regime**
- **Confirmation of this resonance would have an implications for the applied work at LANL including laser-induced D-T fusion.**

Simulations to model this reaction are being explored to design an experiment configuration

* G. Hale and M. Paris (LANL), personal communication

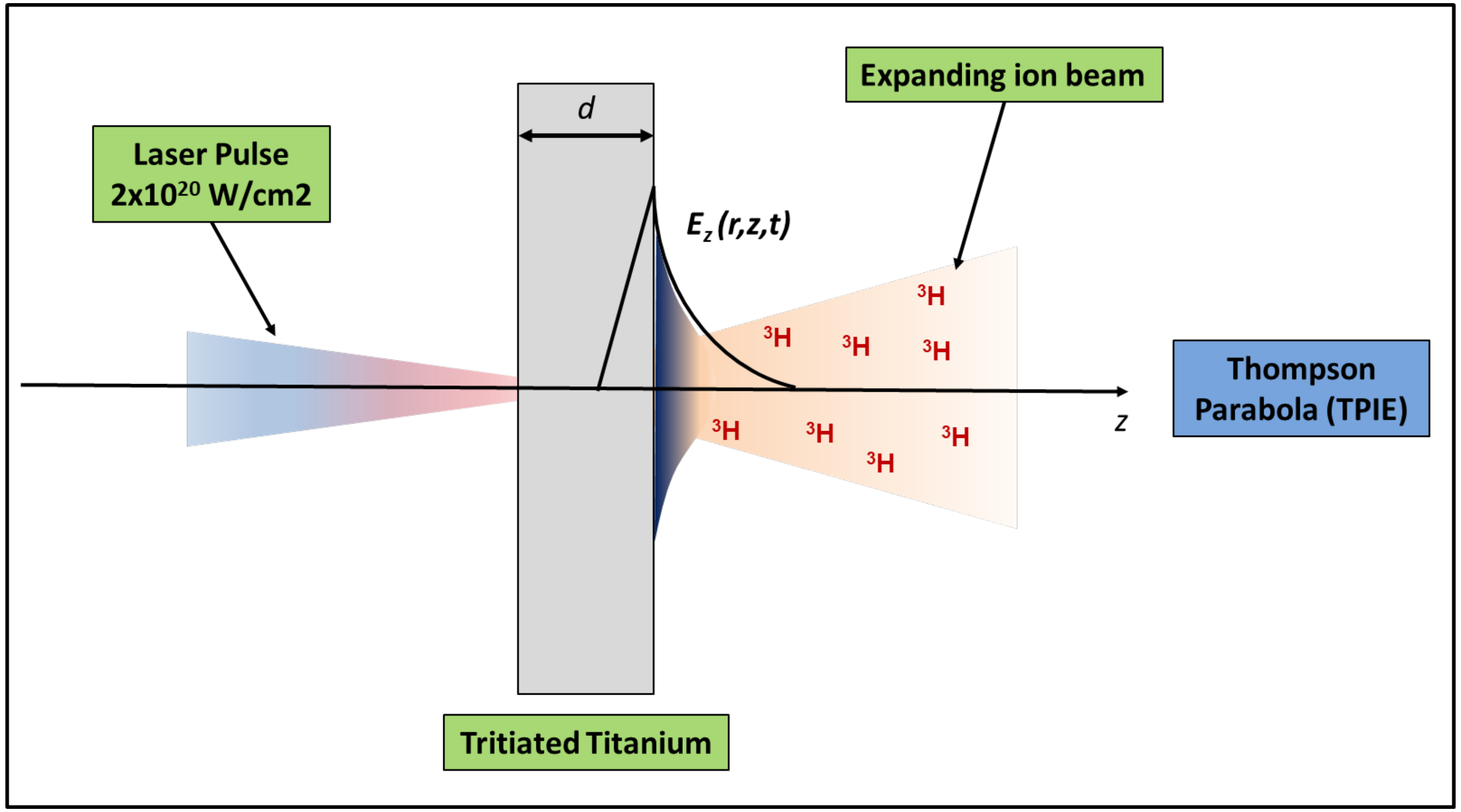
Tritium-induced nuclear reactions are required to fully understand primordial nucleosynthesis and are investigated as a possible solution to the lithium problem

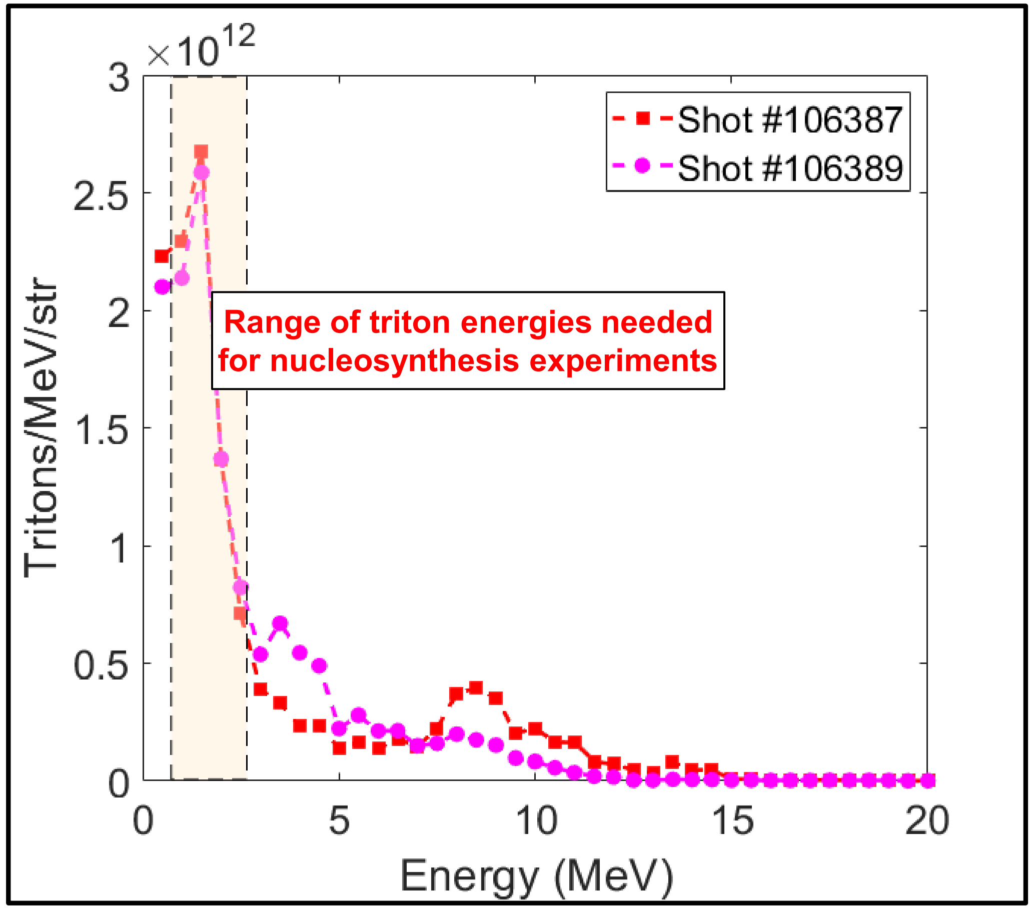


- Current predictions for the abundance of D, ^{3}He, and ^{4}He are consistent with values inferred from astronomical observations.*
  - in opposition, the observed ^{7}Li abundance is three times lower than predicted in current models
- Tritium-induced reactions is one mechanism to explain the depletion of ^{7}Li in the early Universe
  - tritium ^{3}H serves as intermediary storage for neutrons, facilitating the bridge of the mass 5 and mass 8 gaps
  - this feeds the heavier isotopes while generating a high neutron flux if the reaction rates are competitive with inverse ^{7}Li(p,α)^{4}He process*

* A. Aprahamian, Nucleosynthesis with Tritium, to be submitted (2025)

Omega Laser Facility experiments show that laser-generated tritons can be produced in a sufficient energy range for nuclear physics experiments



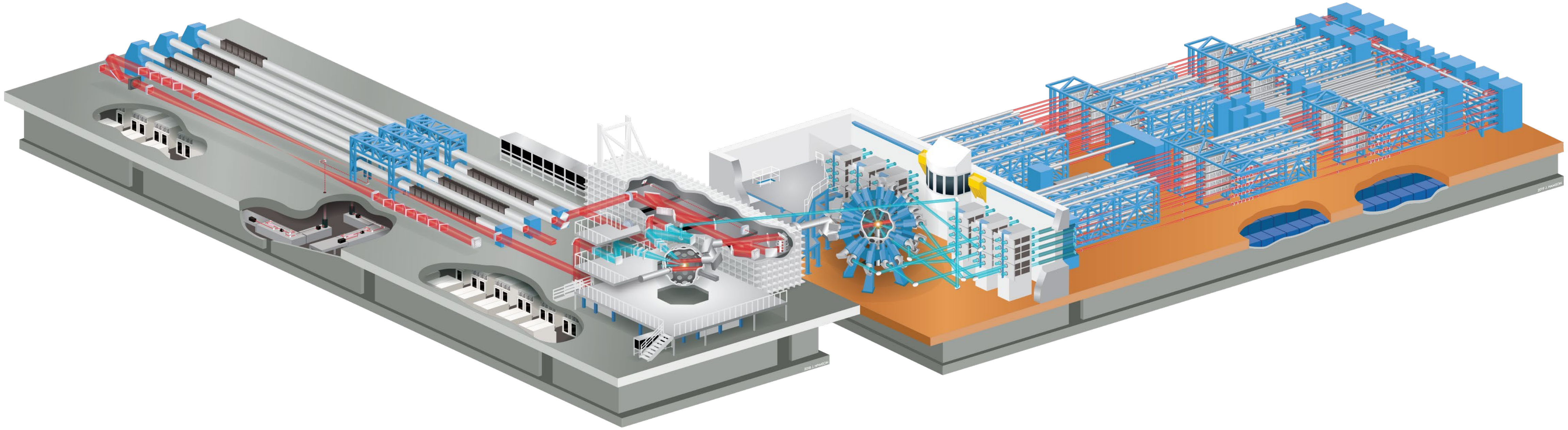


- The triton spectrum obtained from the Thompson Parabola Ion Energy (TPIE) show the exponential shape of the spectrum that has been previously reported for protons and deuterons in literature.
- The TNSA mechanism generated a directed beam of 10^{13} tritons per laser pulse with energies up to 10 MeV.

A nuclear physics platform using laser-generated tritons from target normal sheath acceleration (TNSA) requires both OMEGA and OMEGA-EP (joint shots)

OMEGA EP Laser System
- four NIF*-like beamlines; 6.5-kJ UV (10 ns)
- two beams can be high-energy petawatt (2.6-kJ IR in 10 ps)
- can propagate to the OMEGA or OMEGA EP target chamber

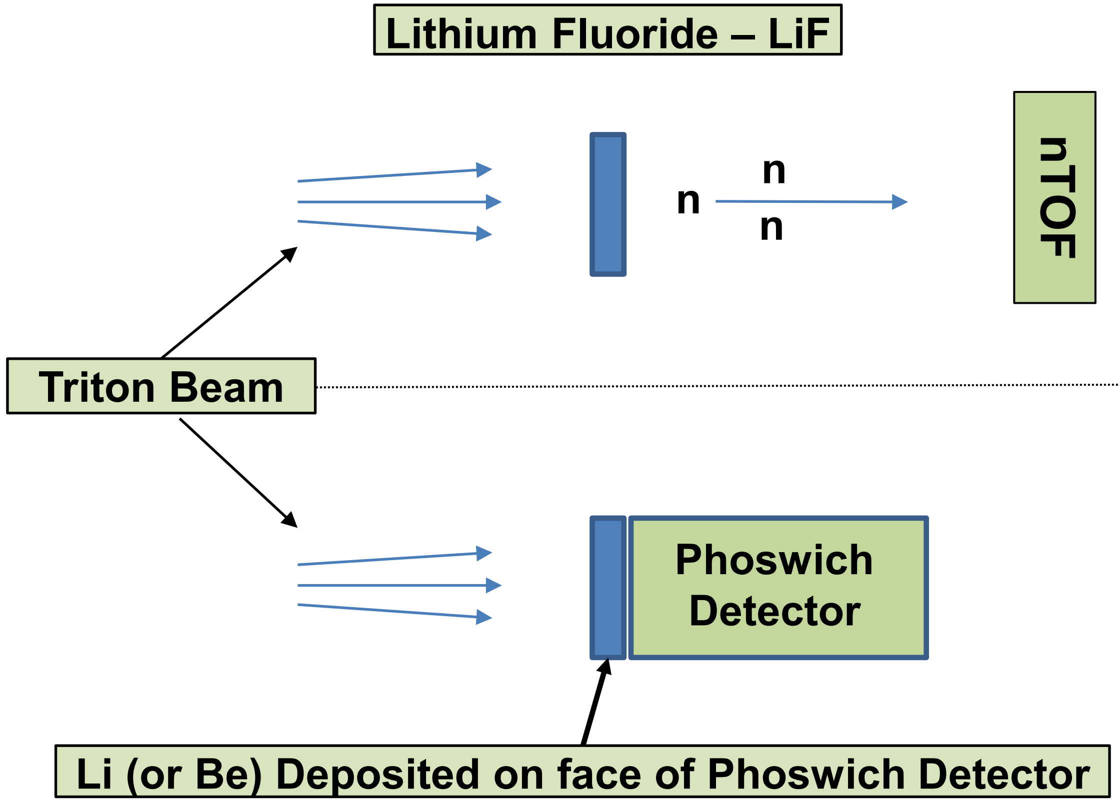
OMEGA Laser System
- tritium handling capabilities



- Experiments using a TNSA* platform has several benefits as compared to traditional methods:
  - background accumulation is minimal following the experiment due to they short time duration (~ns).
  - upcoming petawatt laser facilities will have a high shot rate which will lead to an increase statistics (~ mins).

* TNSA: target normal sheath acceleration

Different physics target configurations will be used to investigate the reactions of interest on the Omega Laser Facility



$^{7}Li + {}^{3}H \rightarrow n + {}^{9}Be$

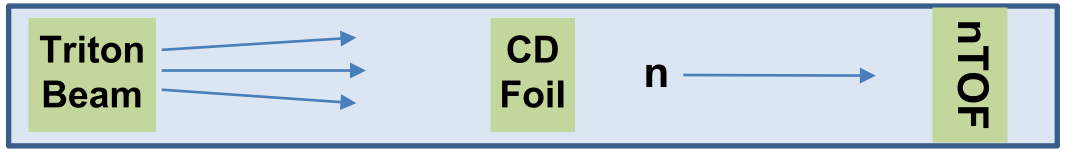
Highly characterized spectrometers will be used to measure the emitted neutrons

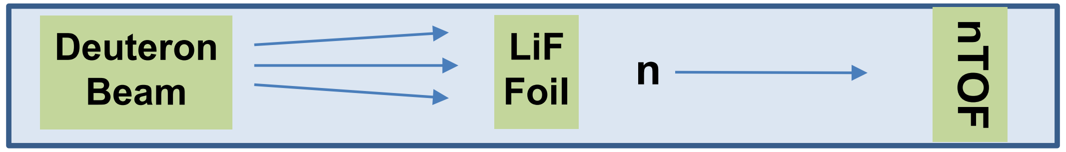
$^{7}Li + {}^{3}H \rightarrow \alpha + {}^{6}He$

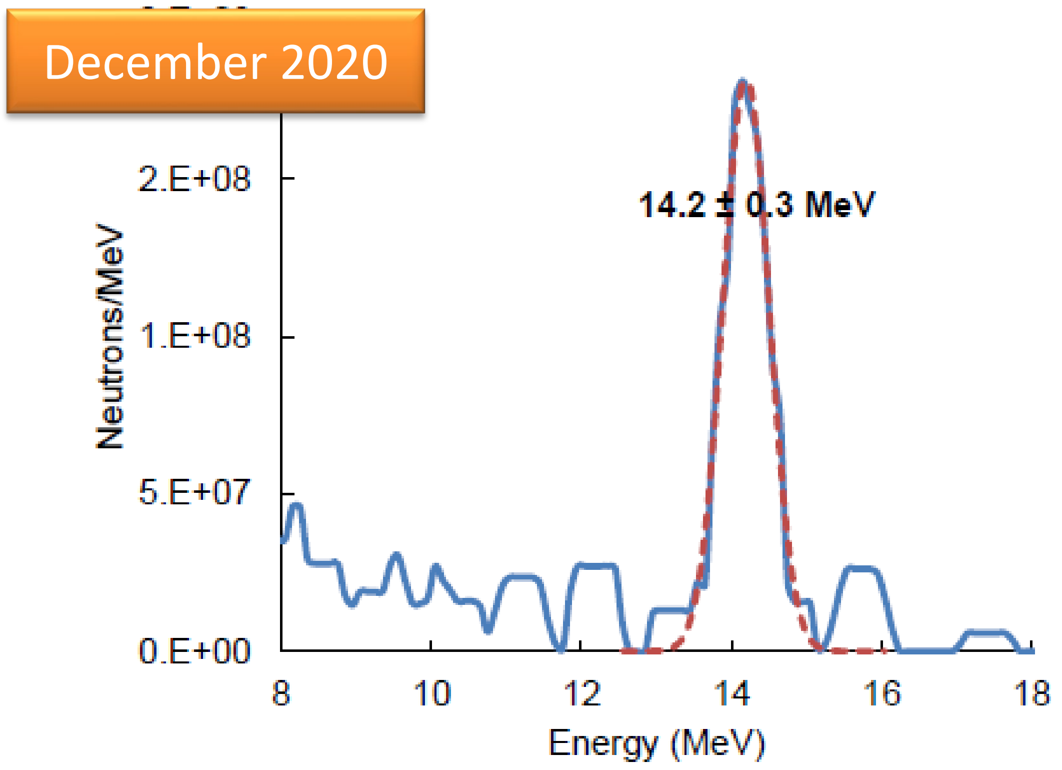
Development of a new diagnostic is underway to measure the beta-decay products – ^{6}He (~800 ms) $\rightarrow {}^{6}Li + \beta^{-}$

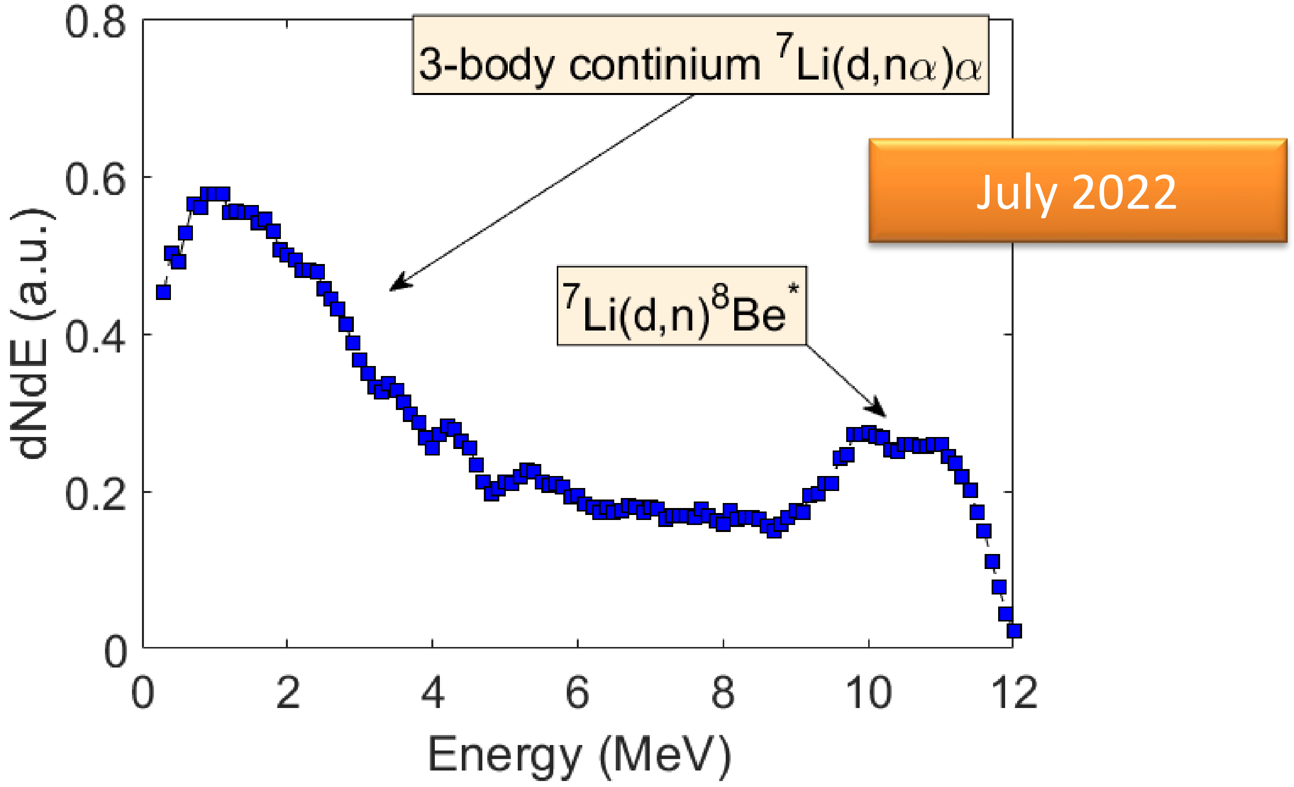
- **Two different physics target configurations will be used for these experiments:**
  - thin lithium-fluoride foils positioned close to the converter target (future experiments will bare lithium and beryllium foils
  - deposited layer of Li and Be directly on the front of a Phoswich detector that measures the beta-decay particles

Initial experiments with this new platform has demonstrated accelerating tritium (deuterium) into CD and LiF foils producing measurable neutron signals*





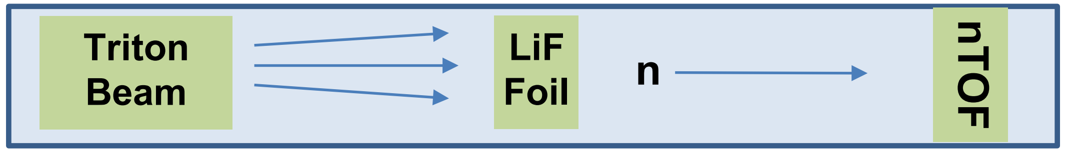


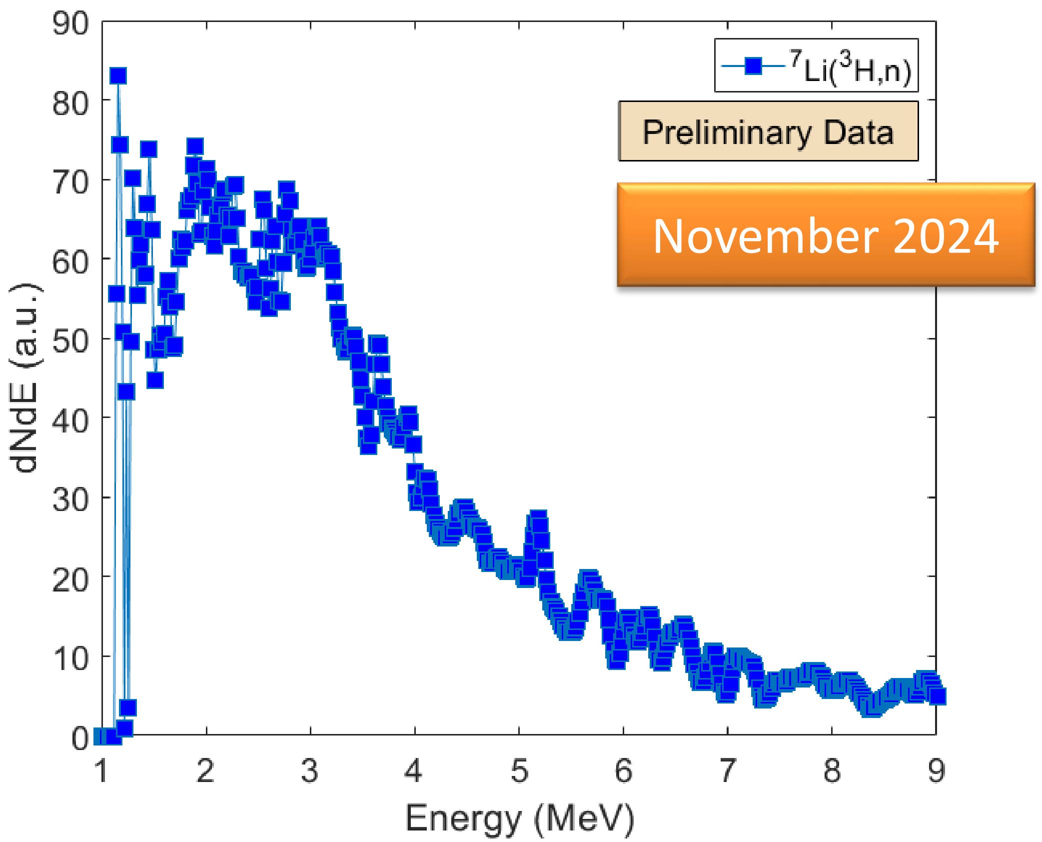


A signal was not observed with a follow up experiment with the triton beam onto a tritiated foil. (Nov 2022)

* A. Schwemmlein et al., Nuclear Instruments and Methods in Physics Research B 522 (2022) 27–31

A neutron signal from a single experiment up to 9 MeV has been observed with the ^{3}H + ^{7}Li reaction on a LiF foil

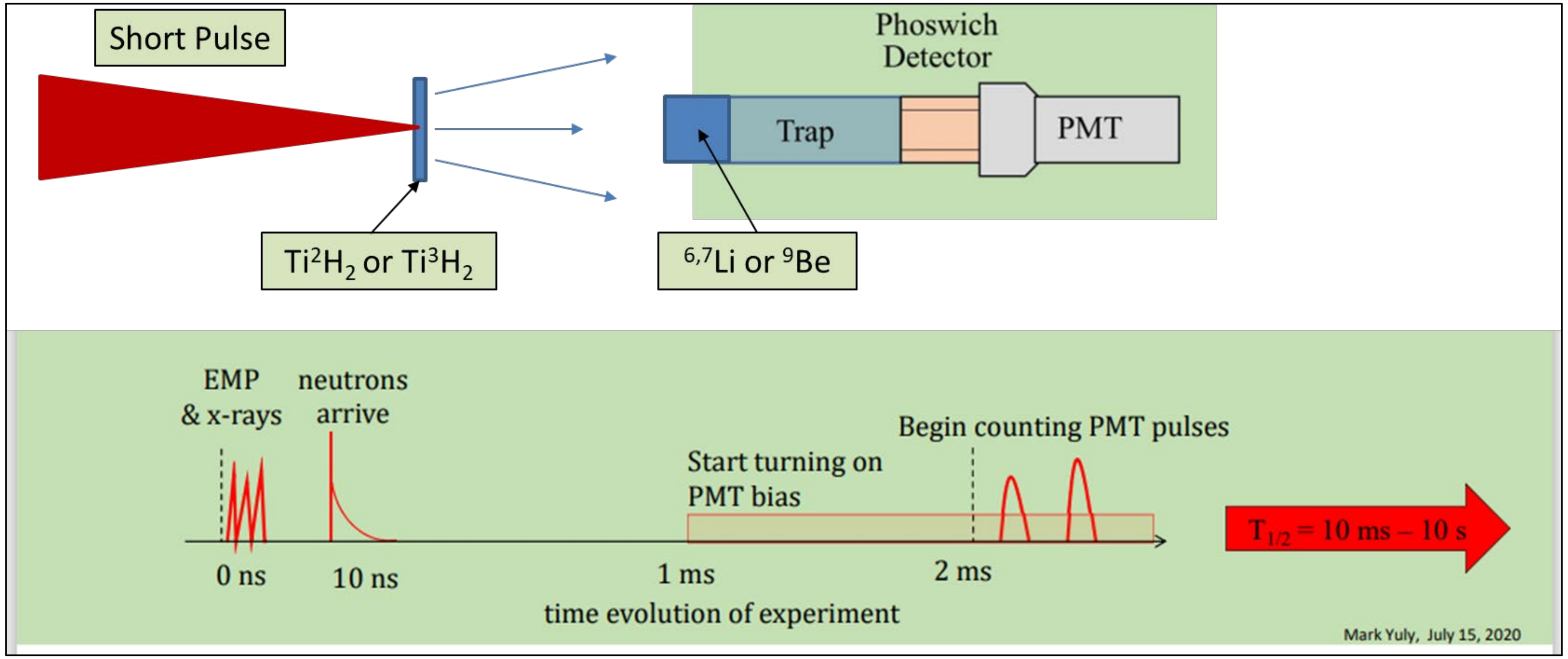




H10 Spectrometer

- **A single TNSA experiments were executed in Nov 2024.**
  - with ^{3}H + LiF foil (neutron signal observed)
  - error analysis is underway
- **Different gate timings were implemented to look just past the scintillator light decay and expected neutron signal. (signal cutoff ~ 9 MeV)**
- **Next steps:**
  - move gate timing to see where neutron signal begins. (look up to 20 MeV)
  - repeat with foil that is not loaded (bare) with tritium.
  - repeat without LiF foil (expect significant p,n) reactions in this scenario
  - use lithium-6 and lithium-7 foils only

A new method to measure low energy nuclear cross sections with beta-emitting products is being developed in collaboration with local universities

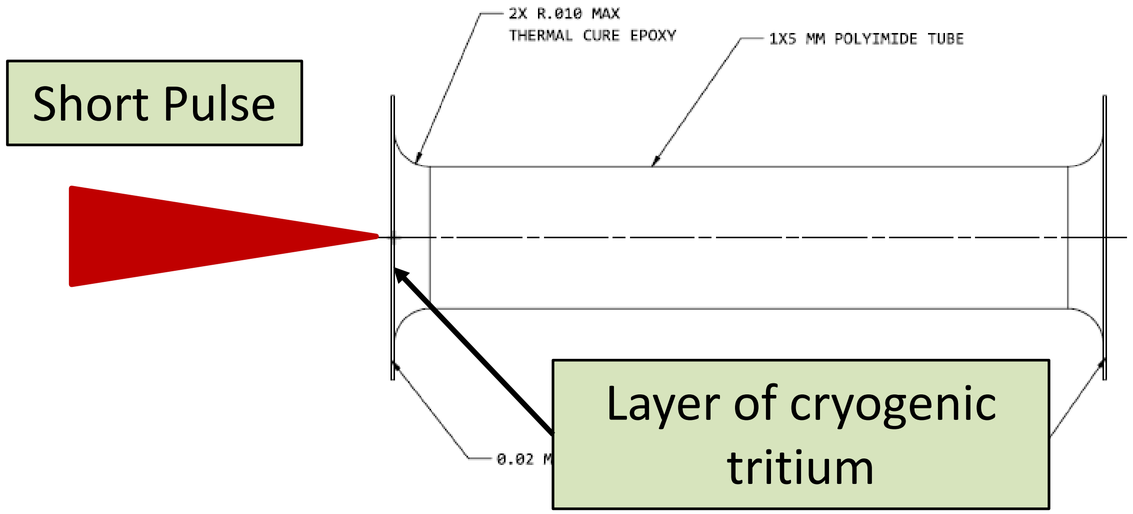


Reaction	Half-life
$^{3}H + {}^{3}H \rightarrow \gamma + {}^{6}He$	*807-ms*
$^{6}Li + {}^{3}H \rightarrow p + {}^{8}Li$	*840-ms*
$^{7}Li + {}^{3}H \rightarrow \alpha + {}^{6}He$	*807-ms*
$^{9}Be + {}^{3}H \rightarrow \alpha + {}^{8}Li$	*840-ms*

Successful demonstration of this Short-Lived Isotope Counting (SLIC) system has been completed with $^{7}Li(d,p)^{8}Li$ on the small Multi-Terawatt (MTW) laser facility at the LLE.

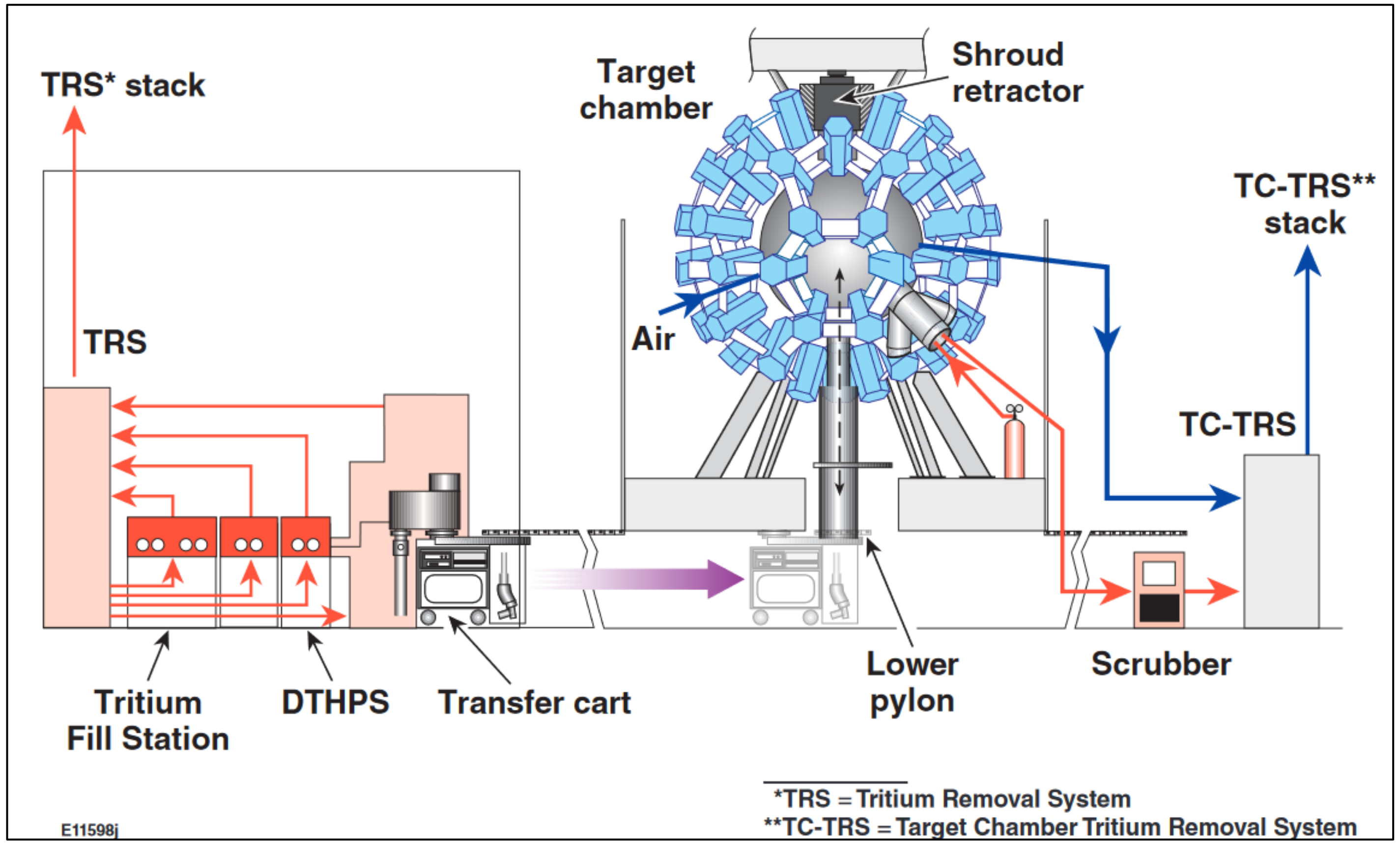
- **diagnostic is currently being designed and built for experiments on OMEGA**
- **first experiments with triton-induced reactions is being planned for FY26**

Novel target development is ongoing with General Atomics (GA) to produce targets for use on the cryogenic system on the OMEGA Laser Facility



- **A permeable cylinder will contain ~1atm of tritium**
- **The fuel will condense of the metal foil to generate a mono-layer of tritons (TFS)**
- **Existing infrastructure allows for the insertion of the target into the target chamber.**

- **Development of thin-layer of solid hydrogen isotope target configuration to allow for the permeation of tritium.**
  - **produce quasi mono-energic ion beam with increased yield and less contaminants**



The Omega Laser Facility has demonstrated that laser-generated tritons can be produced at energies sufficient for nuclear physics experiments

UR LLE

- The development for a controllable triton (^3H) beam and experimental platform to study triton-induced reaction is of interest for the broader nuclear scientific community.

- A limited number of tritium-induced reaction cross-sections measurements at low energy (~MeV) exist and are important in several areas of nuclear physics:
  - the neutron energy spectrum from two tritons fusing is relevant for Inertial confinement fusion (ICF) experiments
  - investigate predicted D-T elastic scattering resonances with key implications for laser-induced DT fusion
  - reaction networks in the early r-process (Z < 10) for big bang nucleosynthesis (BBN)[*,**]

Extra Slides

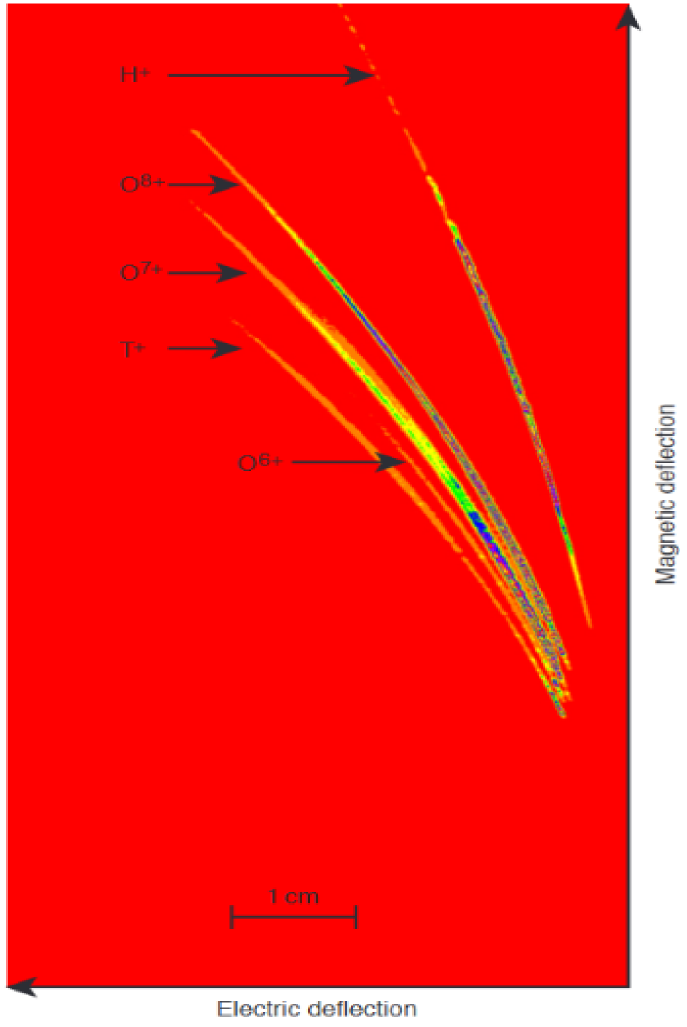
Experimental shot time on the Omega Laser Facility is very competitive with the limited number of options

UR LLE

TNB	Thermonuclear burn and pursuit of High Yield
MAT	Materials
HaP	Hydrodynamic and Properties (Radiation/Plasma/Nuclear)
OaS	Outputs and Survivability

- Every year experimental proposal are submitted to the HED Council.
  - SNL, LANL, LLNL, and LLE
  - proposals for nuclear physics are non-existent
- A laboratory basic science (LBS) allows for proposals outside the NNSA mission.
  - this call is for national labs and the LLE
- A National Laboratory Users' Facility (NLUF)
  - external users are permitted submission to this call
  - LLE personnel are excluded from this option

Surface contaminants is one mechanism known to limit the ion acceleration from the converter target

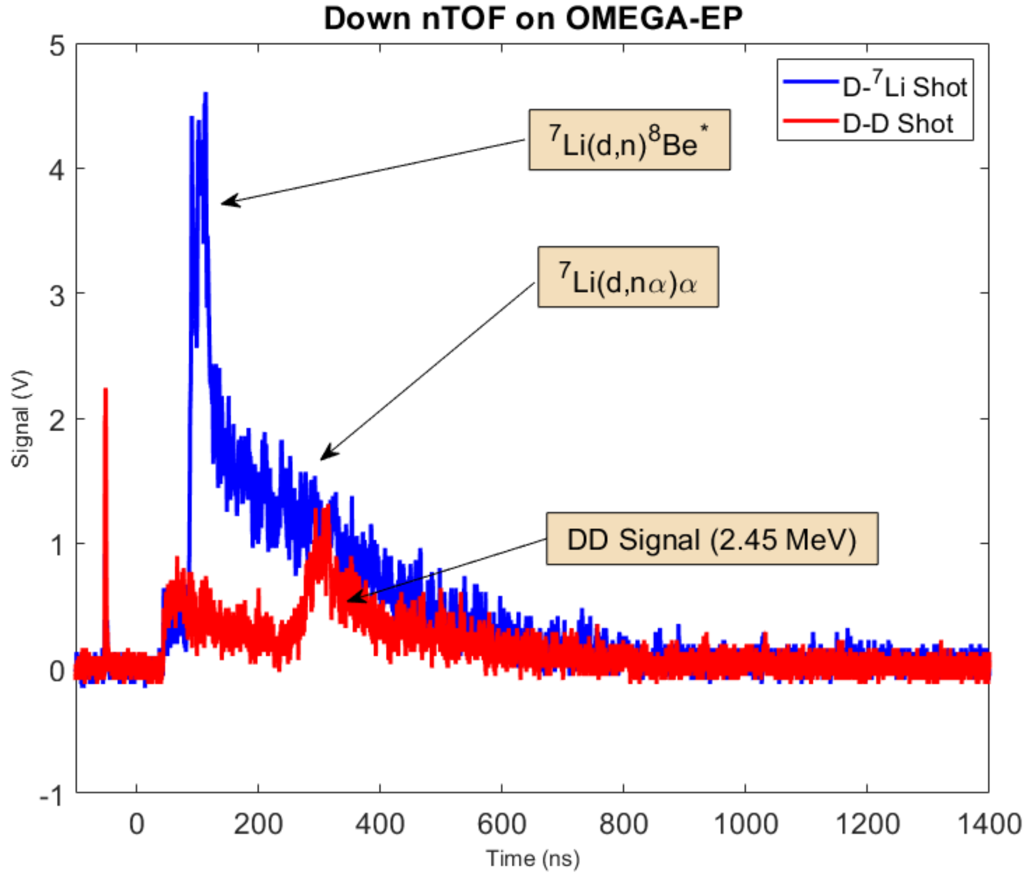


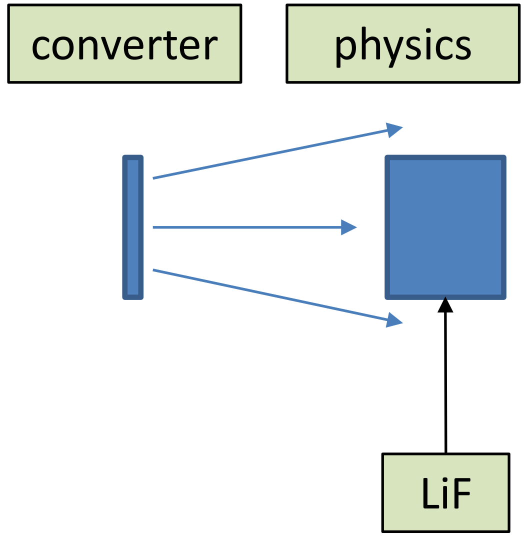
- **Raw data obtained with the Thomson Parabola TPIE shows an appreciable amount of tritium.**
  - **however, the most abundant species are still hydrogen and other elements of hydrocarbon contaminants.**
- **The acceleration, protons accelerate faster, thereby partially shielding the heavier ions from the electrons.**
  - **therefore, most of the tritium in the target remains unused, and using targets with higher tritium content does not significantly improve the beam**

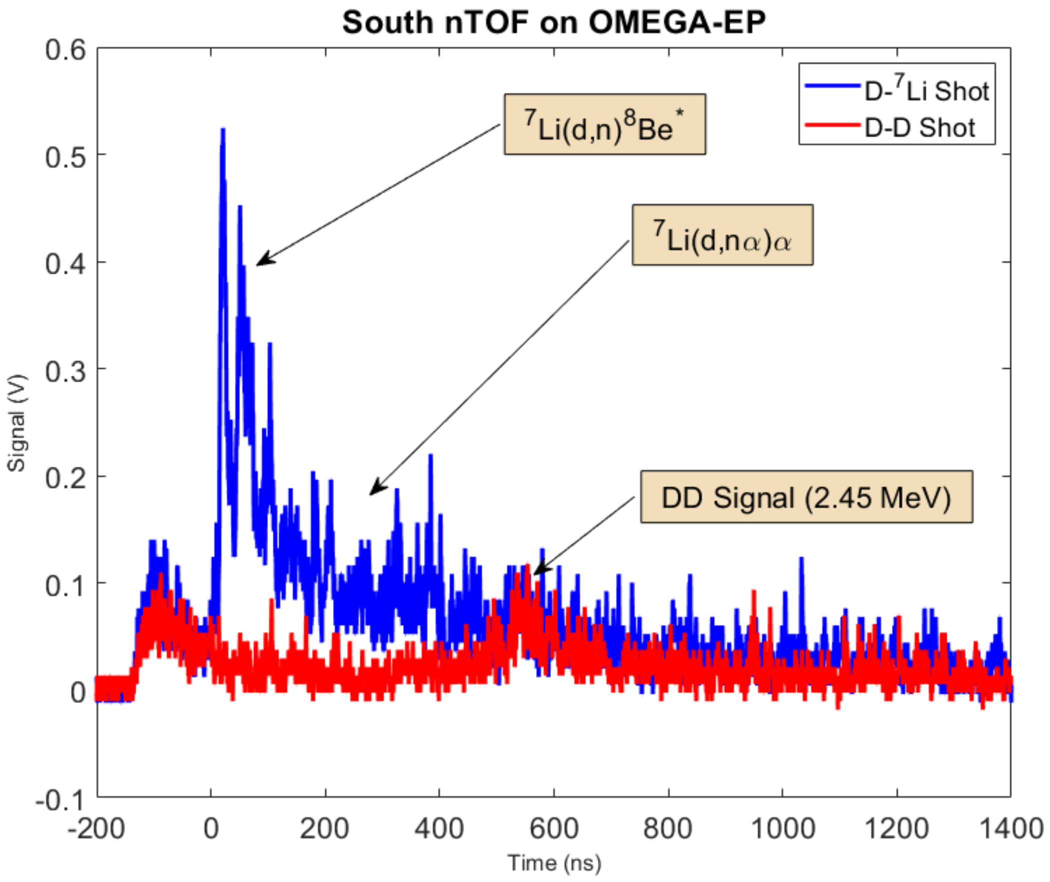
Pre-Shot foil measurements: 1×10^{16} tritium ions	TPIE measurements: 1×10^{13} tritium ions

Different attempts to limit the surface contaminants by keeping the target in an inert environment after loading has had limited success on OMEGA/OMEGA-EP.

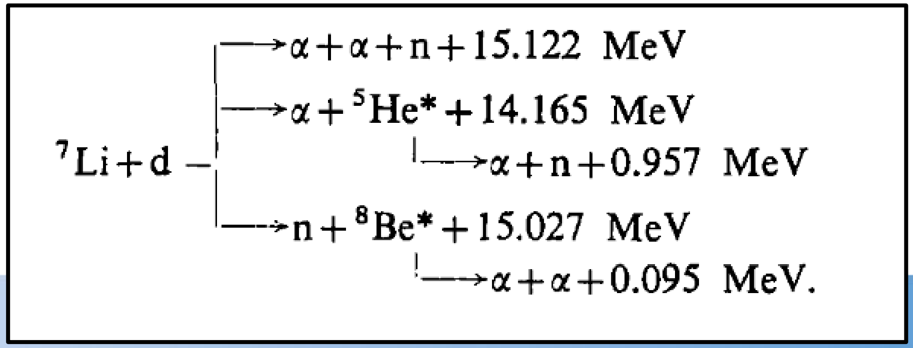
Neutrons with energies up to 15 MeV have been observed with the deuterium-lithium-7 reaction







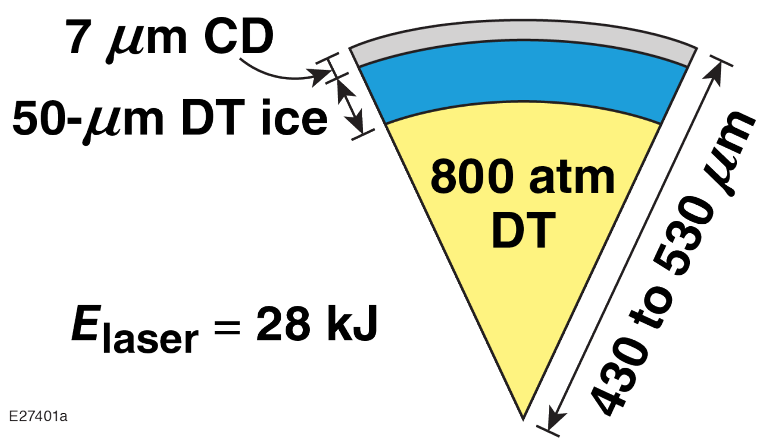
Down nTOF
8.4 meters from TCC

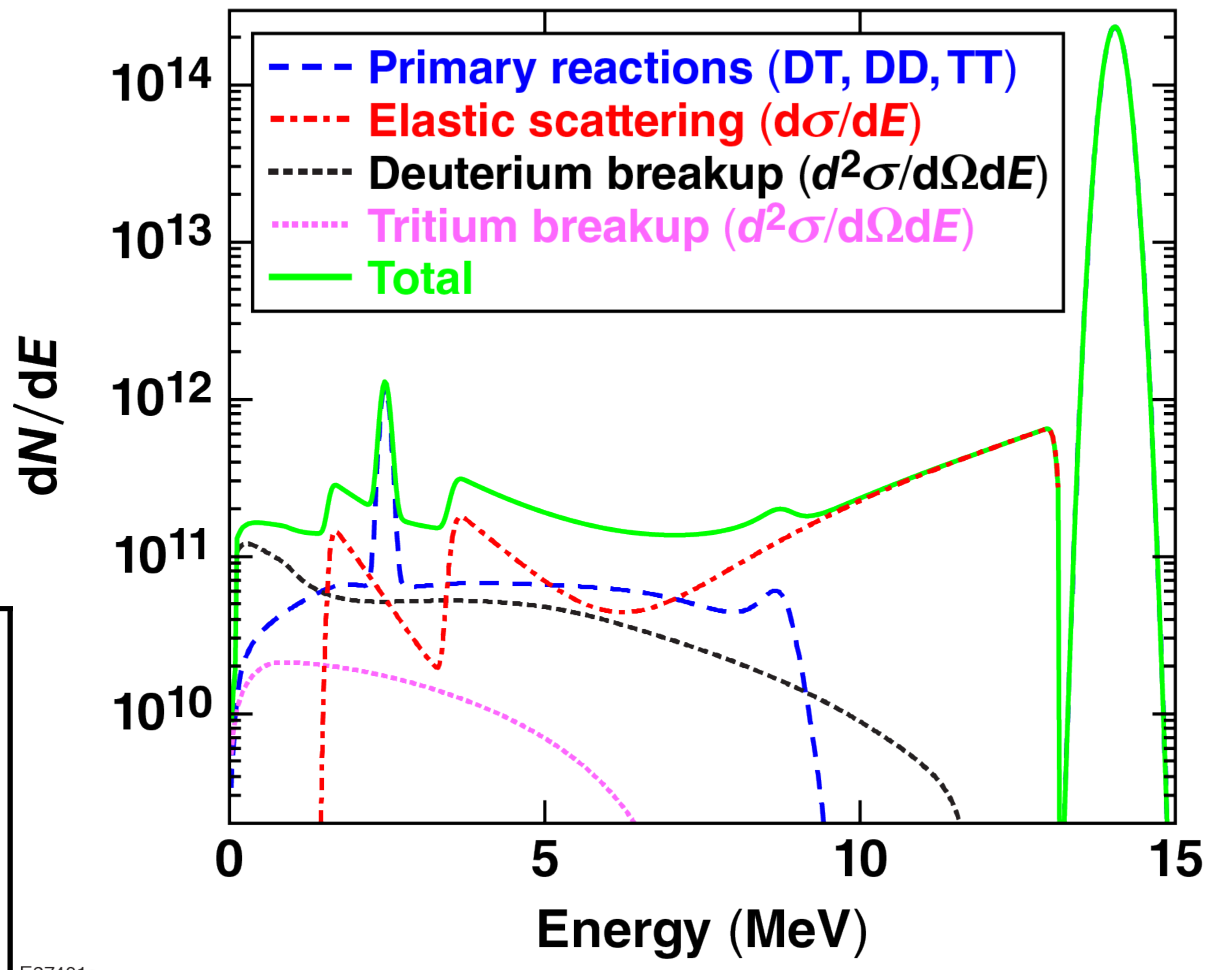


South nTOF
15.1 meters from TCC

Motivation – Inertial Confinement Fusion

An accurate description of the neutron energy spectrum from direct-drive cryogenic DT experiments is crucial to infer the implosion performance

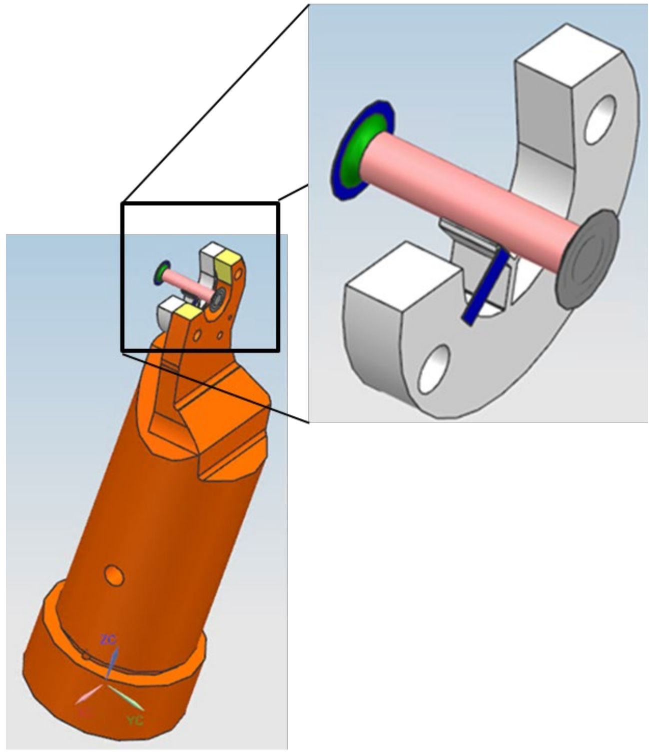




D + T → ^{4}He (3.5 MeV) + n (14 MeV)
D + D → ^{3}He (0.82 MeV) + n (2.45 MeV)
T + T → ^{5}He (1.7 MeV) + n (8.7 MeV)
→ ^{5}He* (~4.4 MeV) + n (~6 MeV)
→ ^{4}He (0 to 3.5 MeV) + 2n (0 to 9.4 MeV)

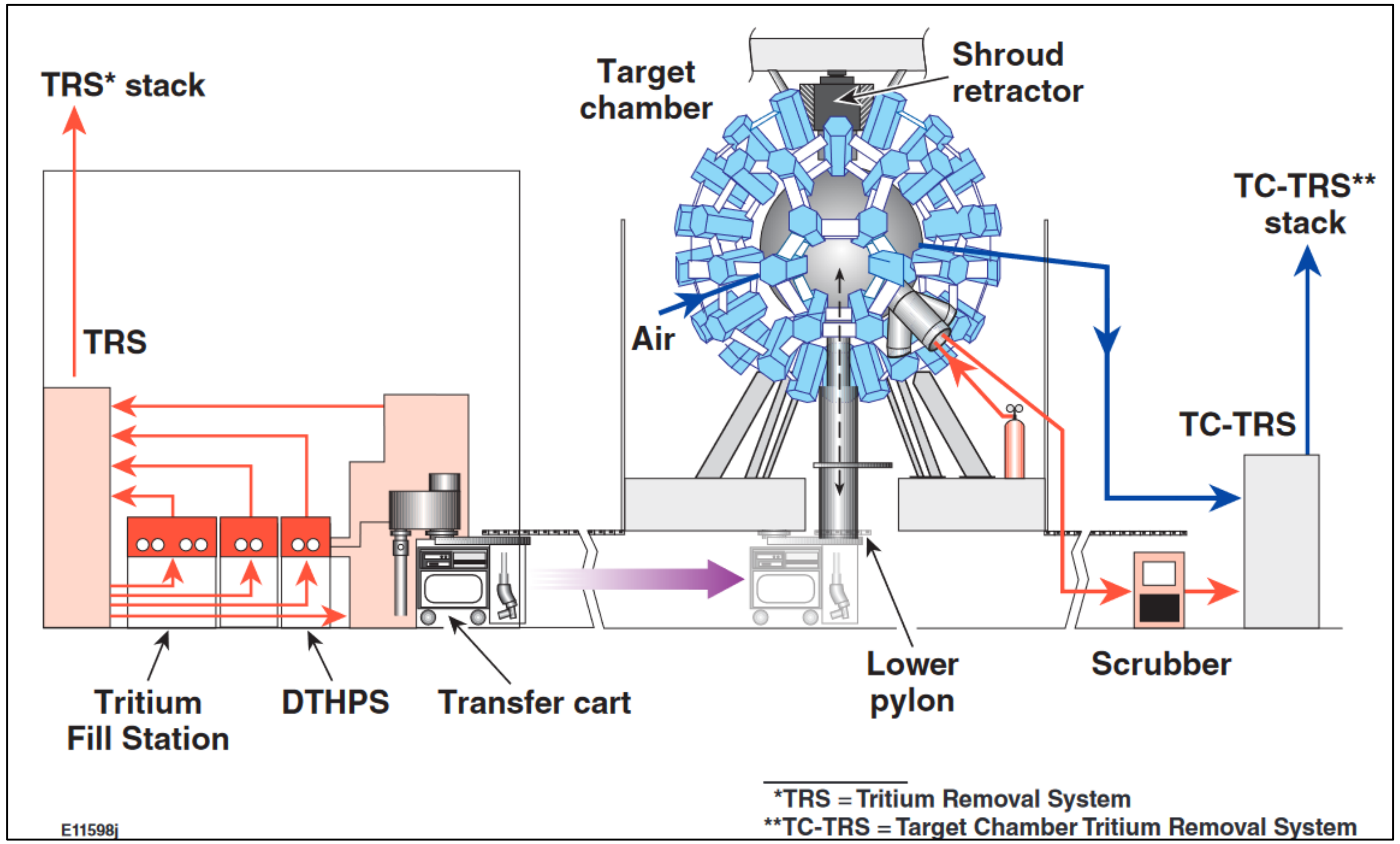
n(14 MeV) + D → n′ (1.6 to 14 MeV) + D′ (<12.5 MeV)
n(14 MeV) + T → n′ (3.5 to 14 MeV) + T′ (<10.6 MeV)
n(14 MeV) + D → 2n (0 to 11.8 MeV) + ^{1}H (0 to 11.8 MeV)
n(14 MeV) + T → 2n (0 to 6 MeV) + ^{2}H (0 to 6 MeV) -- No measurements to date

Novel target development is ongoing with General Atomics (GA) to produce targets for use on the cryogenic system on the OMEGA Laser Facility

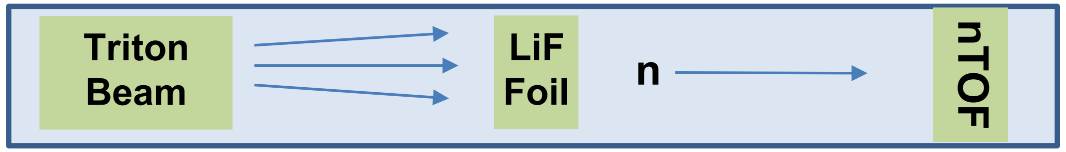


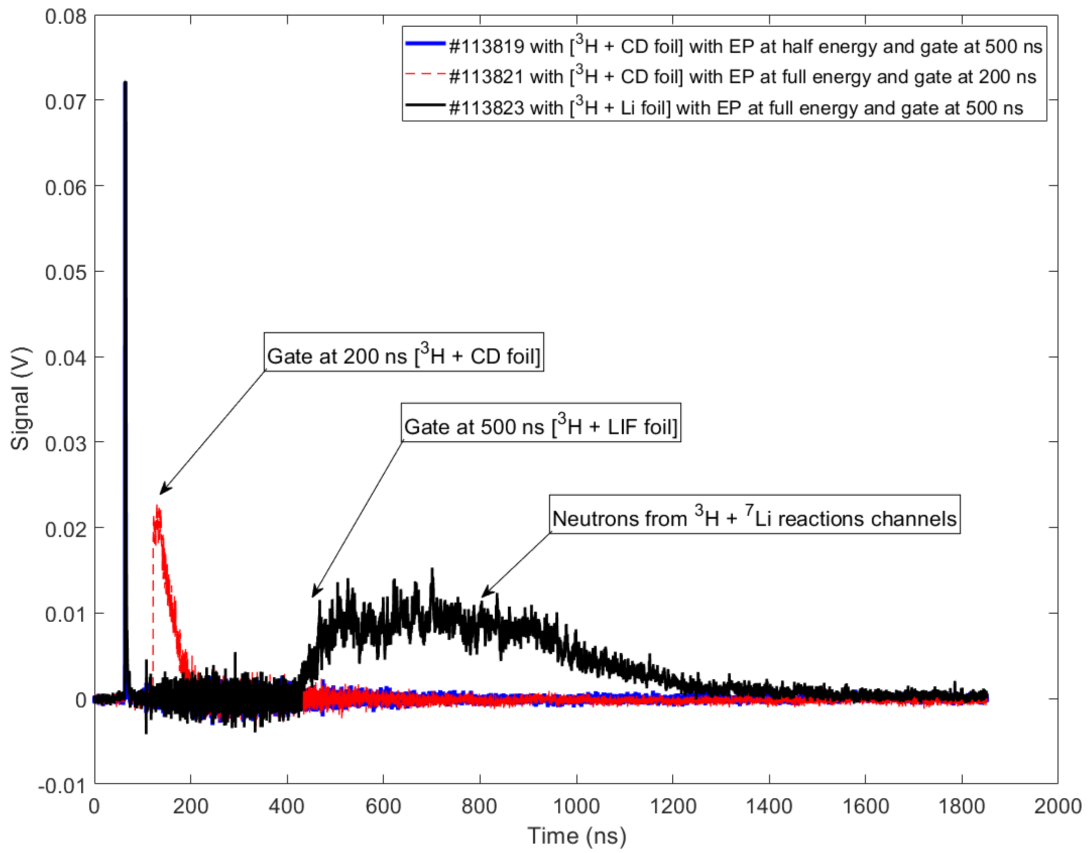
- A permeable cylinder will contain ~1atm of tritium
- The fuel will condense of the metal foil to generate a mono-layer of tritons (TFS)
- Existing infrastructure allows for the insertion of the target into the target chamber.

- Development of thin-layer of solid hydrogen isotope target configuration to allow for the permeation of tritium.
  - produce quasi mono-energic ion beam with increased yield and less contaminants



Preliminary indications are neutrons have been observed with the ^3H + ^7Li reaction [First known example of using TNSA to investigate this reaction]

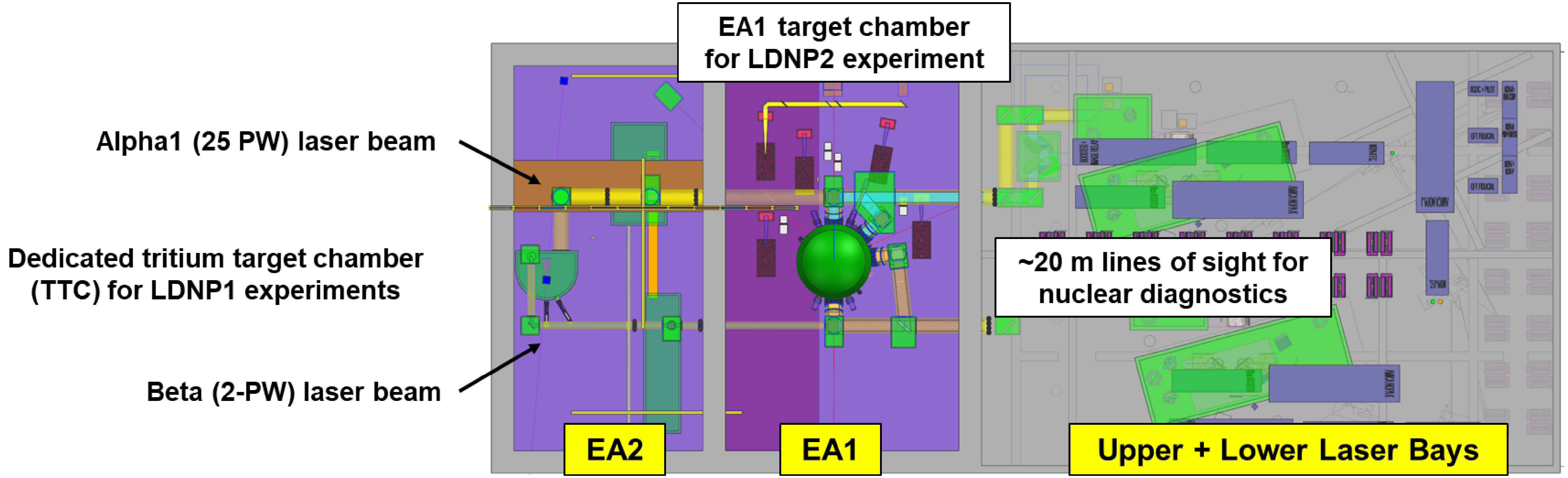




H10 Spectrometer

- **A single TNSA experiments were executed in Nov 2024.**
  - with ^3H + LiF foil (neutron signal observed)
- **Different gate timings were implemented to look just past the scintillator light decay and expected neutron signal.**
- **Next steps:**
  - Move gate to 350 ns and see where neutron signal begins.
  - Repeat with foil that is not loaded (bare) with tritium.
  - Repeat without LiF foil – expect significant p,n reactions in this scenario.

A new high power laser user facility (NSF-OPAL) envisions two new powerful lasers to be located at the University of Rochester (UR/LLE) – Twin 25 PW Lasers



- **The NSF OPAL platform aims to improve the measurement of total reaction cross sections by studying several tritium induced reactions relevant for Big Bang Nucleosynthesis.**
  - **development of a new activation diagnostic that can operate in a short-pulse environment is ongoing (SLIC)**
  - **high shot rate to accumulate good statistics**