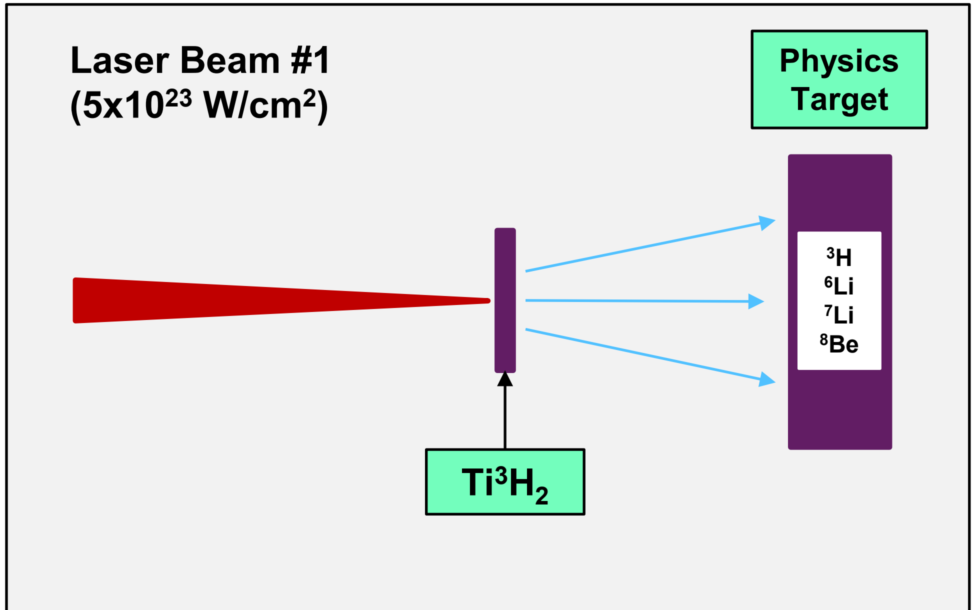
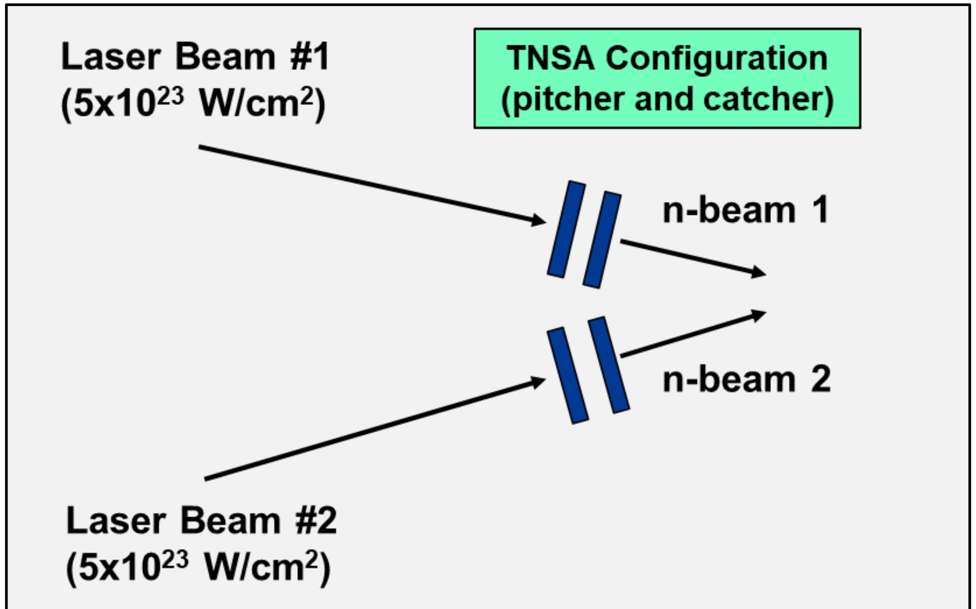
Two Laser-Driven Nuclear Physics (LDNP) flagship experiments have been identified for the NSF OPAL Laser Facility



Flagship #1: Tritium-Induced Nuclear Experiment Platform

- investigate nuclear structure of light nuclei
- measurements of cross-sections at low energy (MeV)



Flagship #2: Neutron-Neutron Elastic Scattering Platform

- directly test nuclear charge symmetry
- essential to understand the dynamics of neutron stars

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

Nuclear Physics with High Power Lasers (Opportunities and Challenges)
Trento, Italy
1-5 July 2024

Summary

Studying fundamental nuclear physics using an advanced laser driven ion-acceleration platform will complement current experiments on OMEGA/OMEGA-EP

Flagship #1 – Tritium Induced Nuclear Experiments

- A controllable, high-yield triton beam is an invaluable tool for nuclear physics in studying the properties of light nuclei.
  - Investigate the A=5 mass gap that impeded the production of lithium and beryllium whereas the mass A=8 gap impedes the production of heavier elements such as boron and carbon
  - study the six-nucleon (A=6) system which is of interest for *ab-initio* nuclear structure calculations
  - studying reactions of ^{7}Li(t,γ)^{10}Be and ^{7}Li(t,n)^{9}Be reactions which may explain why the ^{7}Li abundance is three times lower than predicted from current big-bang nucleosynthesis (BBN) models

Flagship #2 – Neutron-Neutron Elastic Scattering

- The newly proposed NSF-OPAL will utilize advanced ion-acceleration to generate neutrons emitted in a very short pulse to induce neutron-neutron elastic scattering.
  - nucleon-nucleon scattering remains important as one of only a few methods to access strong interactions in the absence of the Coulomb force
  - the neutron-neutron scattering (a_{nn}) length is a direct check on charge symmetry and charge independence of the nuclear force

Collaborators

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B. Appelbe, A. Crilly, and N. Dover
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G. Hale and M. Paris
Los Alamos National Laboratory

S. Padalino and C. Freeman
SUNY Geneseo

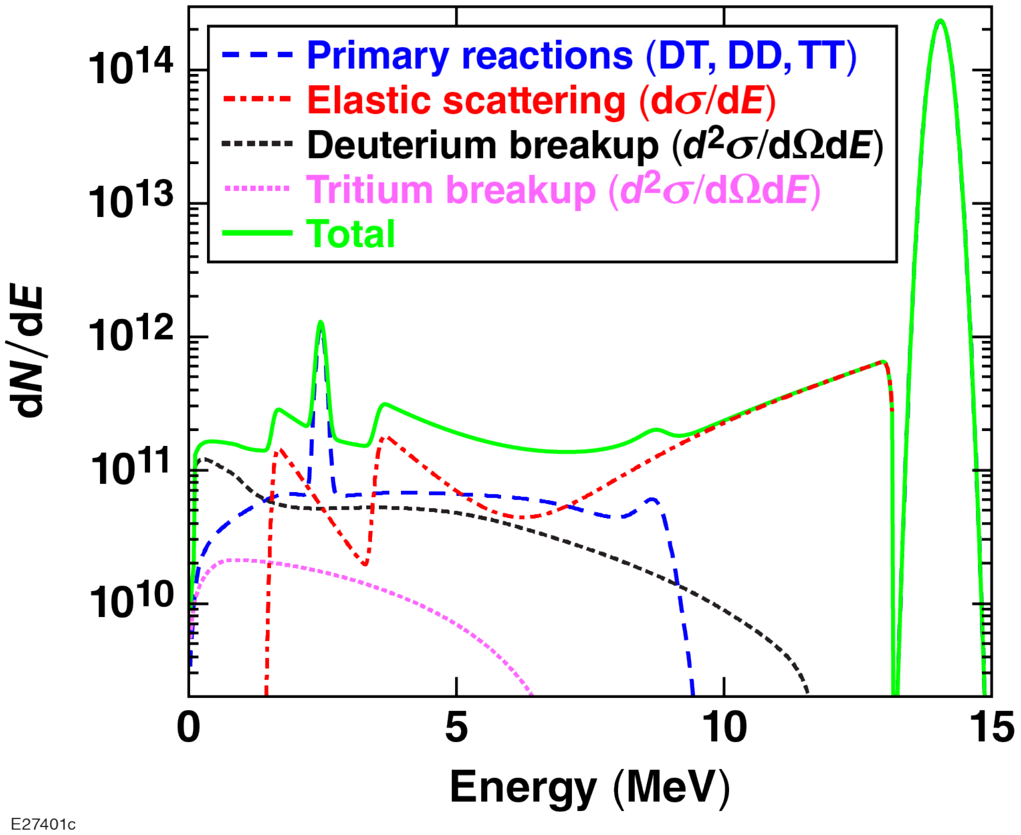
M. Yuly
Houghton University

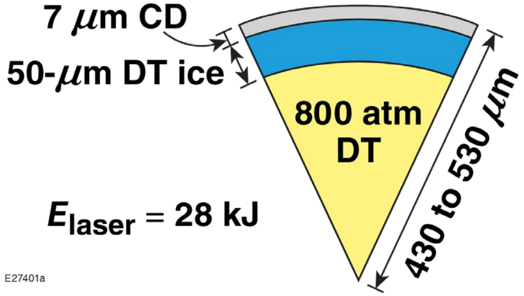
H. Schatz
Michigan State University

Outline

- Introduction
  - nuclear physics experiments on OMEGA that initiated the development of a triton beam
  - planned experiments for the NSF-OPAL Laser Facility
- Flagship #1 – <u>Tritium Induced Nuclear Experiments</u>
  - scientific motivation
  - laser-accelerated ions (deuterons, tritons)
  - nuclear experiments to date
  - proposed experiments
- Flagship #2 – <u>Neutron-Neutron Elastic Scattering</u>
  - scientific motivation
  - laser-driven neutron source requirements
  - proposed proof-of-principle experiments

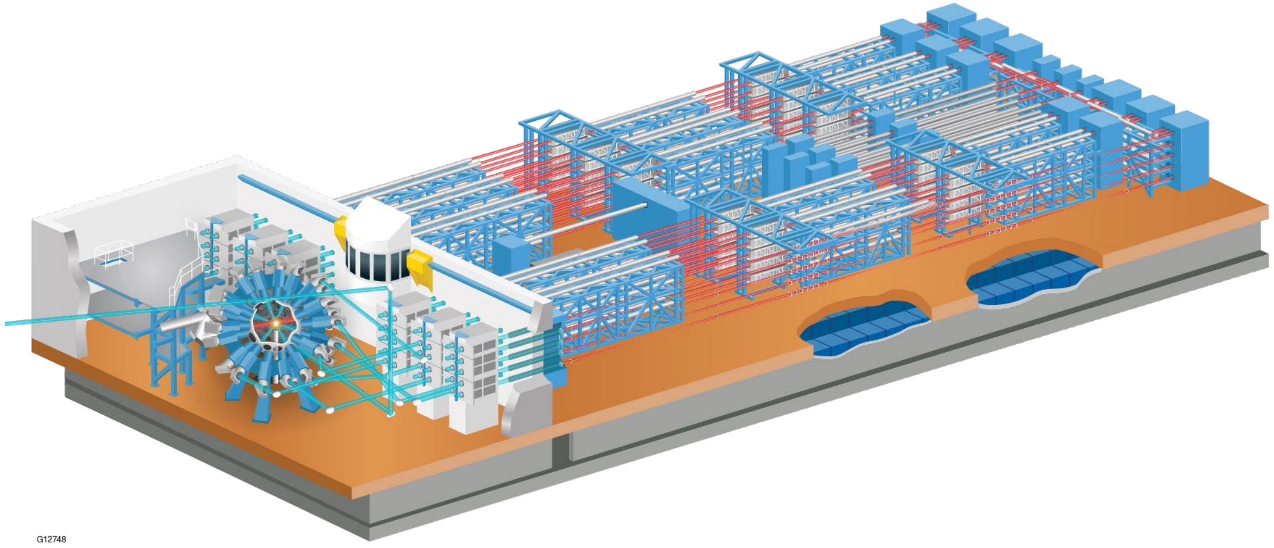
The primary focus of the OMEGA Laser Facility is to perform inertial confinement fusion (ICF) experiments and study high-energy density physics (HEDP)



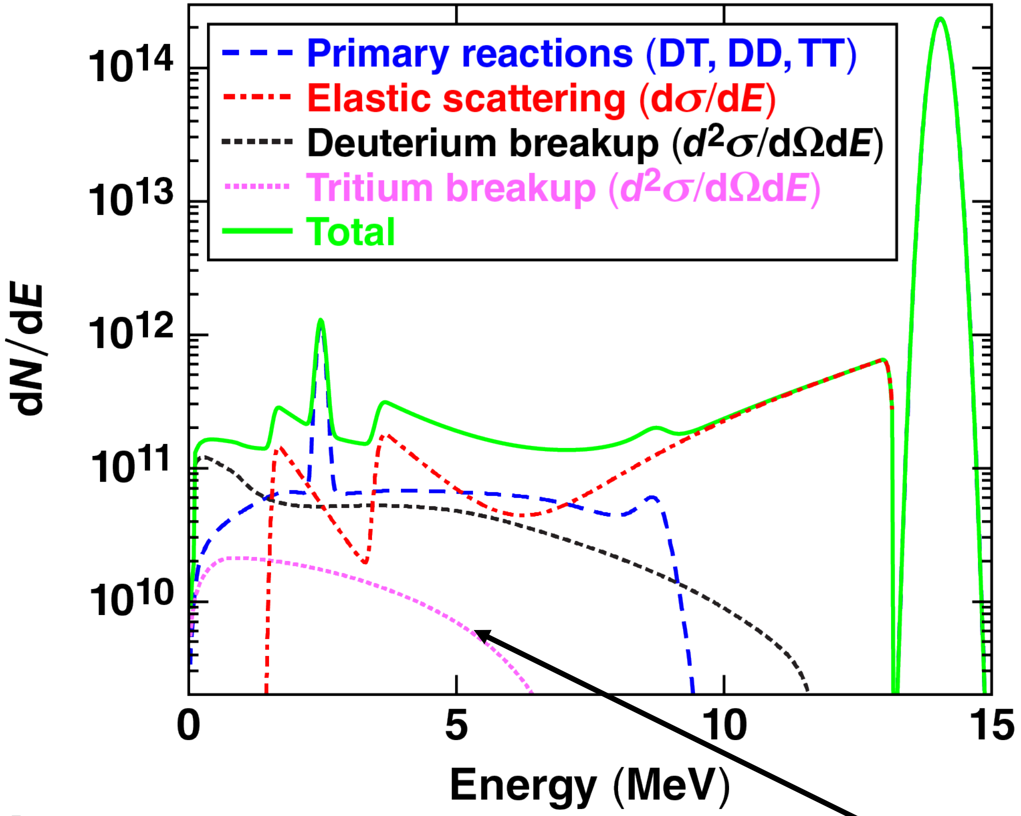


OMEGA Laser System

- 60 beams symmetric configuration
- maximum 30 kJUV on target
- up to 16 shots/day (1600/yr)
- 3.2-m target chamber
- DT fusion Y_n up to 3×10^{14}
- < 40-μm-diam hot spot
- < 100-ps burn duration



This HEDP experimental platform has motivated additional experiments to study fundamental nuclear physics over the past decade



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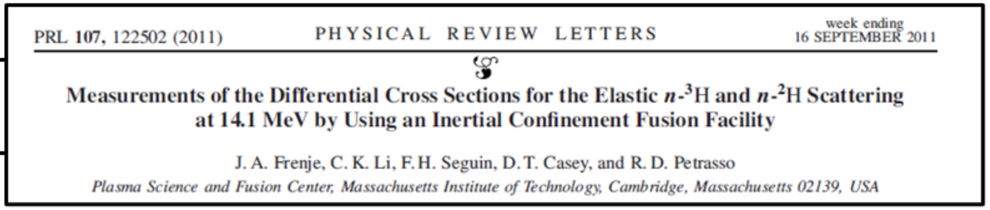
Tritium Breakup (20??)

nD and nT elastic scattering (2011)

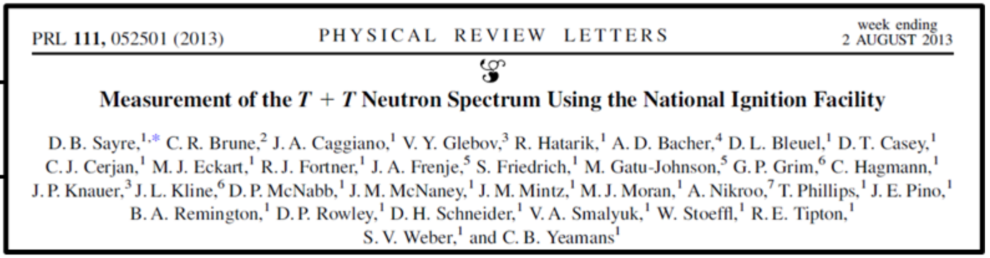

PRL **107**, 122502 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Measurements of the Differential Cross Sections for the Elastic n-^{3}H and n-^{2}H Scattering at 14.1 MeV by Using an Inertial Confinement Fusion Facility

J. A. Frenje, C. K. Li, F. H. Seguin, D. T. Casey, and R. D. Petrasso

Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

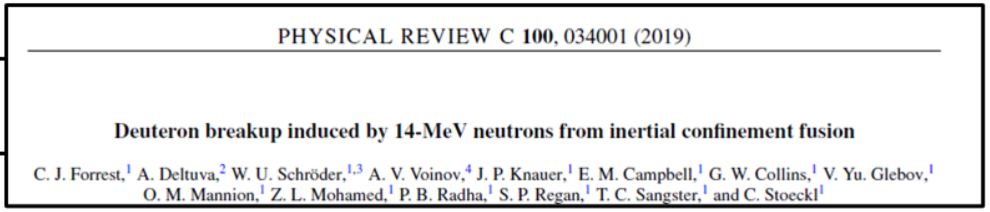
T+T Reaction (~2013)


PRL **111**, 052501 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

Measurement of the $T + T$ Neutron Spectrum Using the National Ignition Facility

D. B. Sayre,[1,*] C. R. Brune,[2] J. A. Caggiano,[1] V. Y. Glebov,[3] R. Hatarik,[1] A. D. Bacher,[4] D. L. Bleuel,[1] D. T. Casey,[1] C. J. Cerjan,[1] M. J. Eckart,[1] R. J. Fortner,[1] J. A. Frenje,[5] S. Friedrich,[1] M. Gatu-Johnson,[5] G. P. Grim,[6] C. Hagmann,[1] J. P. Knauer,[3] J. L. Kline,[6] D. P. McNabb,[1] J. M. McNaney,[1] J. M. Mintz,[1] M. J. Moran,[1] A. Nikroo,[7] T. Phillips,[1] J. E. Pino,[1] B. A. Remington,[1] D. P. Rowley,[1] D. H. Schneider,[1] V. A. Smalyuk,[1] W. Stoeffl,[1] R. E. Tipton,[1] S. V. Weber,[1] and C. B. Yeamans[1]

Deuterium Breakup (2019)


PHYSICAL REVIEW C **100**, 034001 (2019)

Deuteron breakup induced by 14-MeV neutrons from inertial confinement fusion

C. J. Forrest,[1] A. Deltuva,[2] W. U. Schröder,[1,3] A. V. Voinov,[4] J. P. Knauer,[1] E. M. Campbell,[1] G. W. Collins,[1] V. Yu. Glebov,[1] O. M. Mannion,[1] Z. L. Mohamed,[1] P. B. Radha,[1] S. P. Regan,[1] T. C. Sangster,[1] and C. Stoeckl[1]

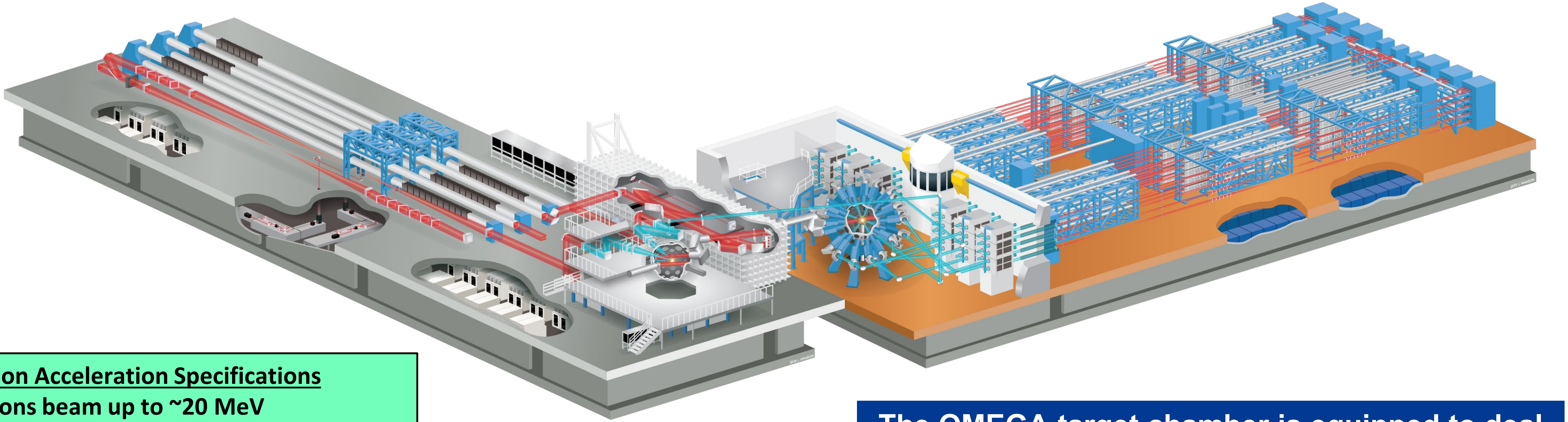
The current model of the ^{3}H + T energy spectrum is based on a R-matrix analysis that assumes the formation of the ^{6}He nucleus.

- **understanding this reaction initiated a new experimental platform to accelerate tritons to ~ MeV energies at the UR/LLE.**

A nuclear physics platform* using laser-generated triton from target normal sheath acceleration (TNSA) has been developed on the Omega Laser Facility

OMEGA EP Laser System

- operating since 2008
- 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



Ion Acceleration Specifications

- protons beam up to ~20 MeV
- deuteron beam up to ~20 MeV
- triton beam up to 10 MeV (OMEGA only)

The OMEGA target chamber is equipped to deal with tritium handling required for triton beam.

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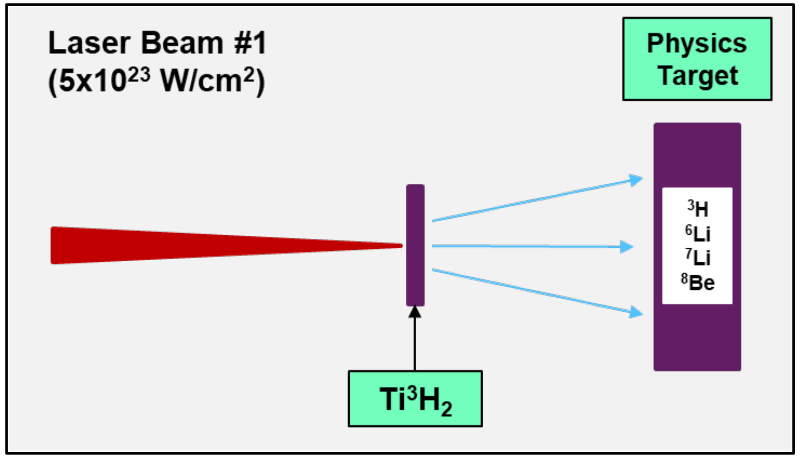
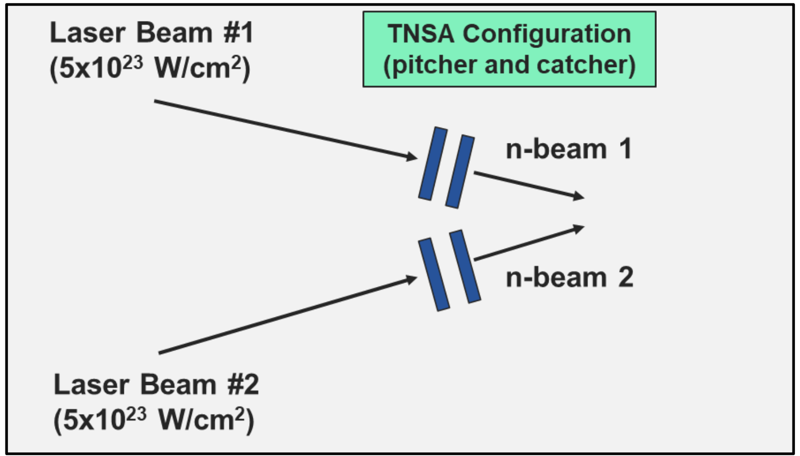
* T-LIANS: tritium laser ion acceleration for nuclear science.

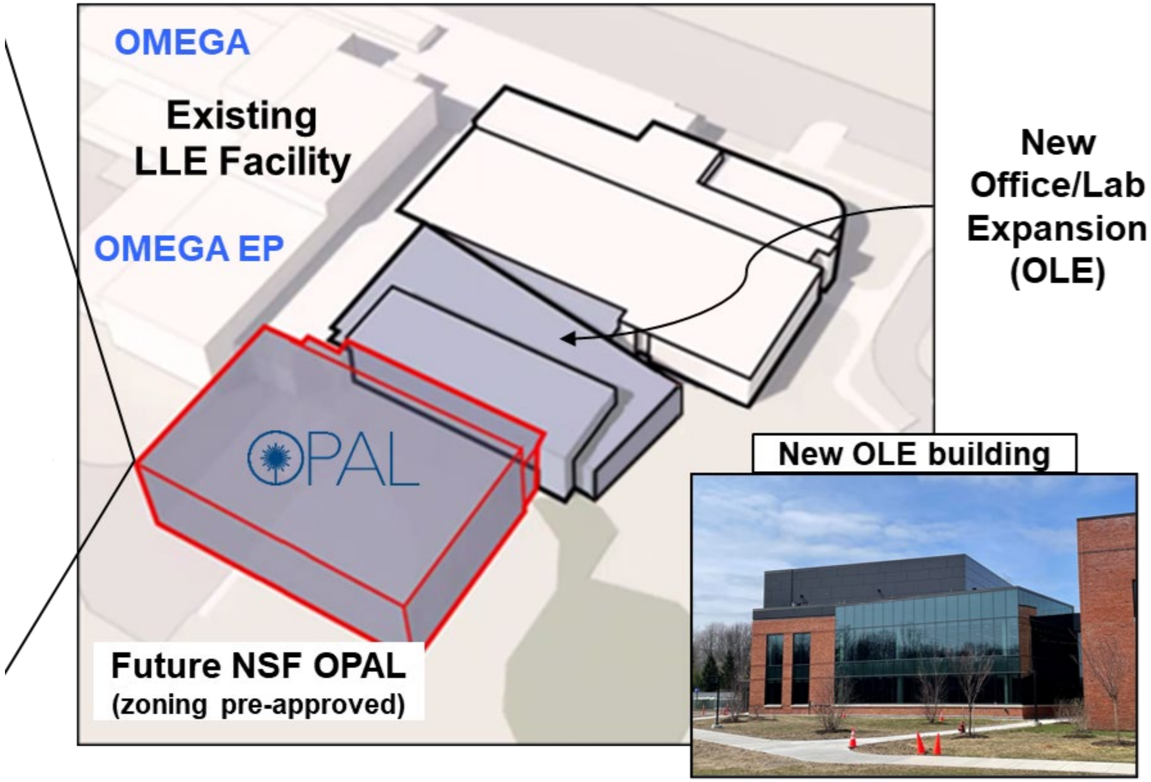
Focused experiment on laser-driven nuclear physics (LDNP) outlined in the UR/LLE mission for FY24-FY28 will be integral to the development of NSF-OPAL ~ FY30

Tritium Induced Nuclear Experiments



Nucleon-Nucleon Scattering





Two buildings constructed in phases would house NSF OPAL, plus labs and offices for new research

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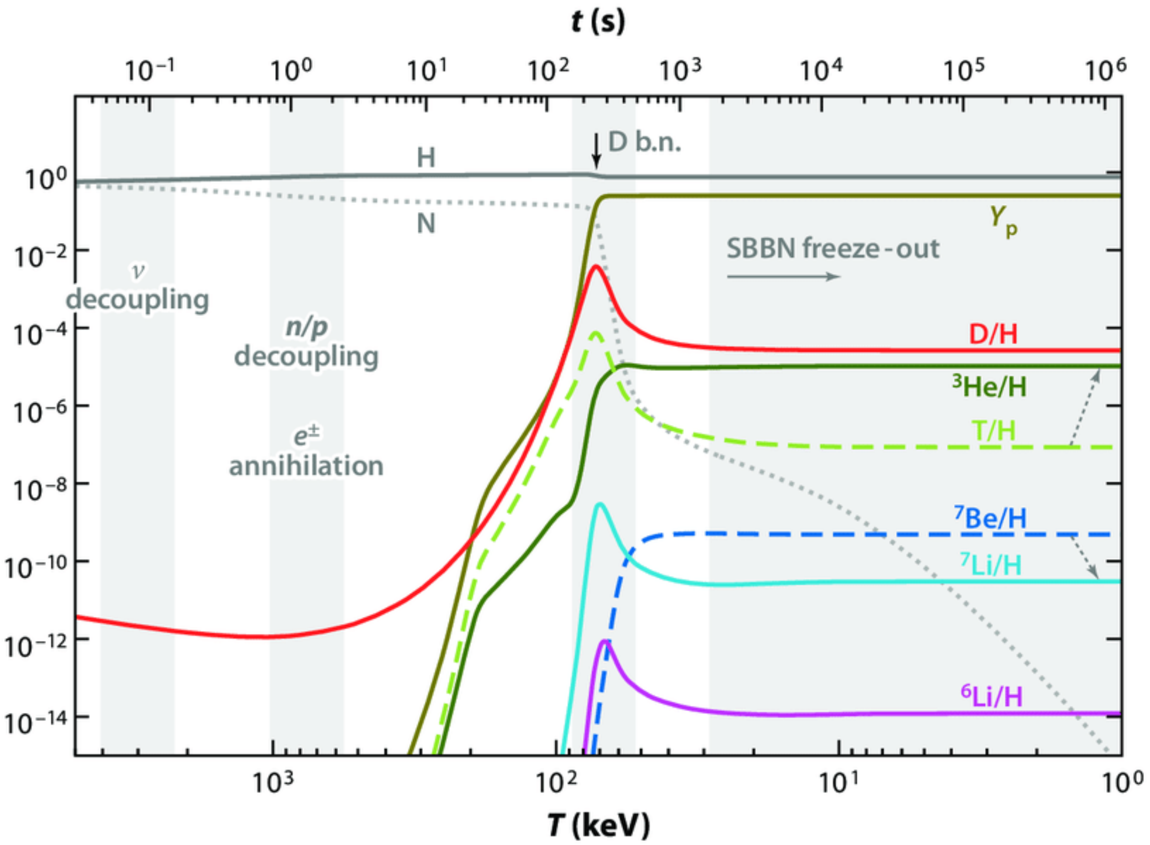
Most elements (A<7) in the Universe were created just a few minutes after the Big Bang through a process commonly referred to as Big Bang Nucleosynthesis* (BBN)



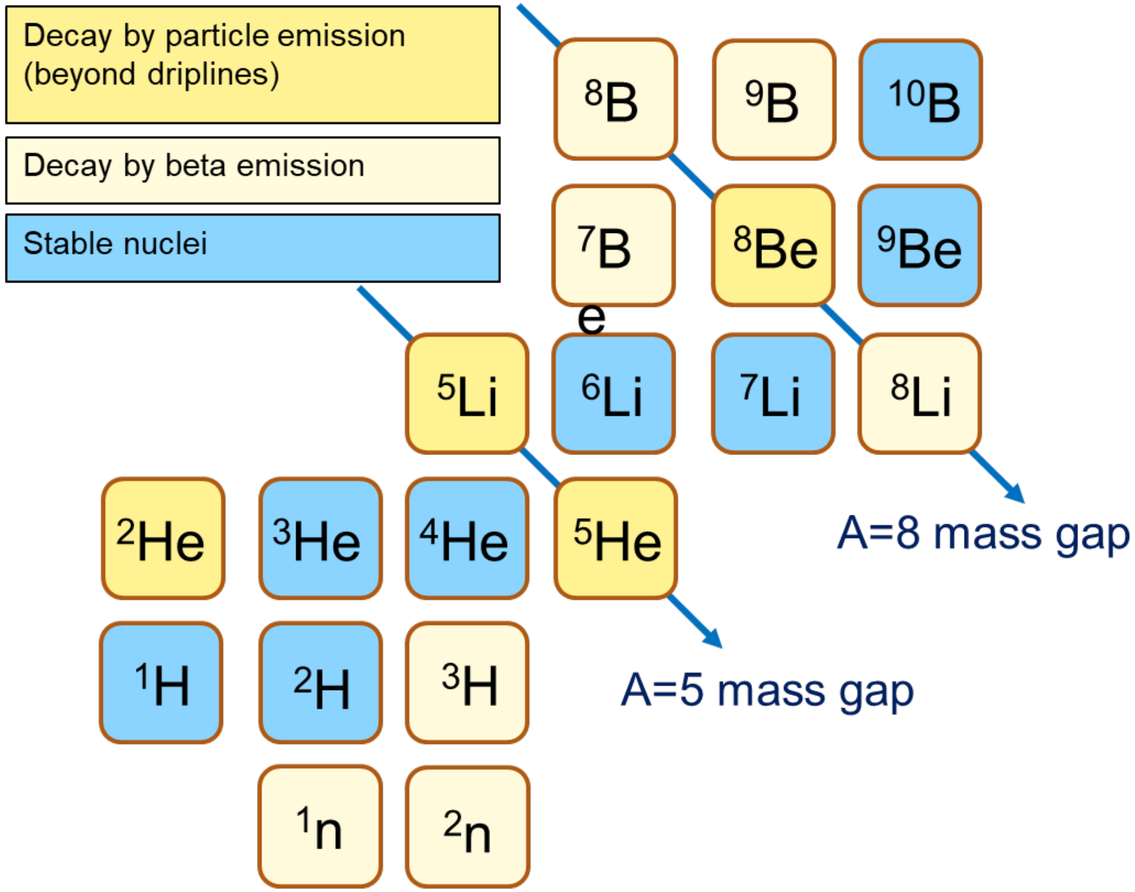
- **Once deuteron formation has occurred, further reactions proceed to make helium nuclei.**
  - **nearly all of the neutrons remained unbound and decayed away (880 second half-life)**

- **Smaller amounts of D, ^{3}He, and ^{7}Li were synthesized following the formation of helium.**
  - **low density and increasing Coulomb barriers with the A=5 and A=8 stability gaps worked against the formation of larger nuclei**

- **The elemental composition (A>7) of the Universe subsequently remained unchanged until the formation of the first stars several billion years later.**

*** M. Pospelov and J. Pradler. Big Bang Nucleosynthesis as a Probe of New Physics. Annual Review of Nuclear and Particle Science, 60:539–568, 2010.**

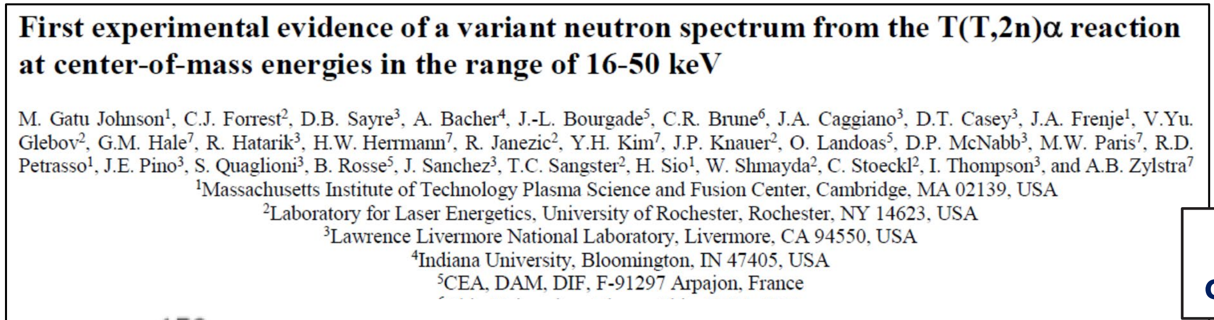
Several important reactions are of great interest to understand primordial nucleosynthesis and the formation of nuclei beyond the A=5 and A=8 mass gaps



- **Subsequent studies for the fusion reaction of $^{3}H(\alpha,\gamma)^{7}Li$ have shown significant discrepancies.***
  - **this reaction is essential to calculate the primordial ^{7}Li abundance in the universe**
  - **bridges the A=5 mass gap**
- **Given the high abundances of tritium in the early Big Bang environment, the strength of the subsequent $^{7}Li(t,\gamma)^{10}Be$ and $^{7}Li(t,n)^{9}Be$ reactions are not well understood.**
  - **better measurements of these reactions may help resolve of ^{7}Li abundance problem**
  - **bridges the A=8 mass gap**

*** J. Dohet-Eraly, *et. al.*, Physics Letters B 757, 430(2016).**

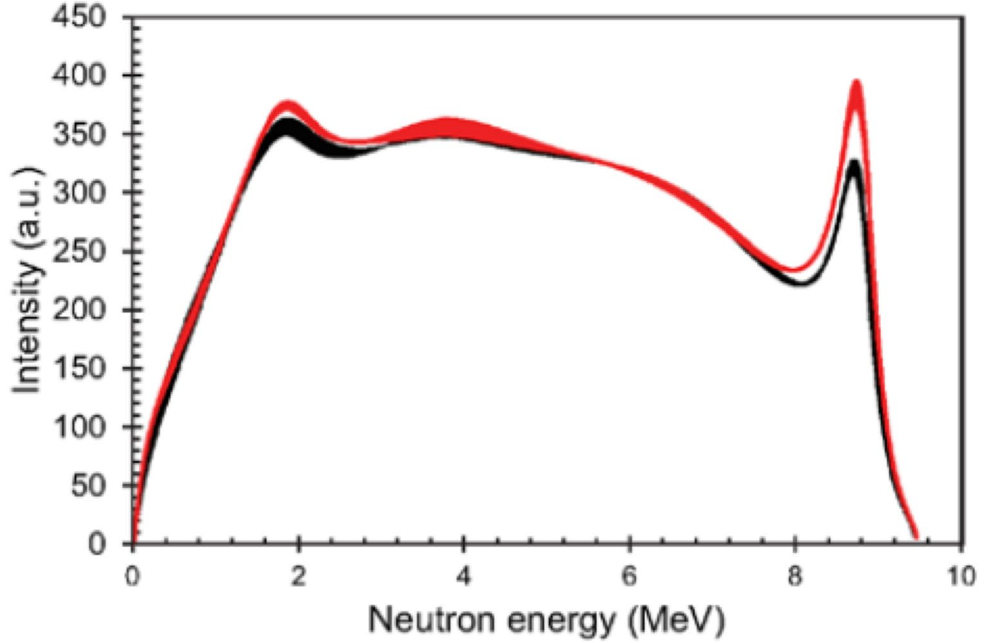
The nuclear science community has an increased interest in the structure of light nuclei (A=6) and their interactions at energies approaching an MeV

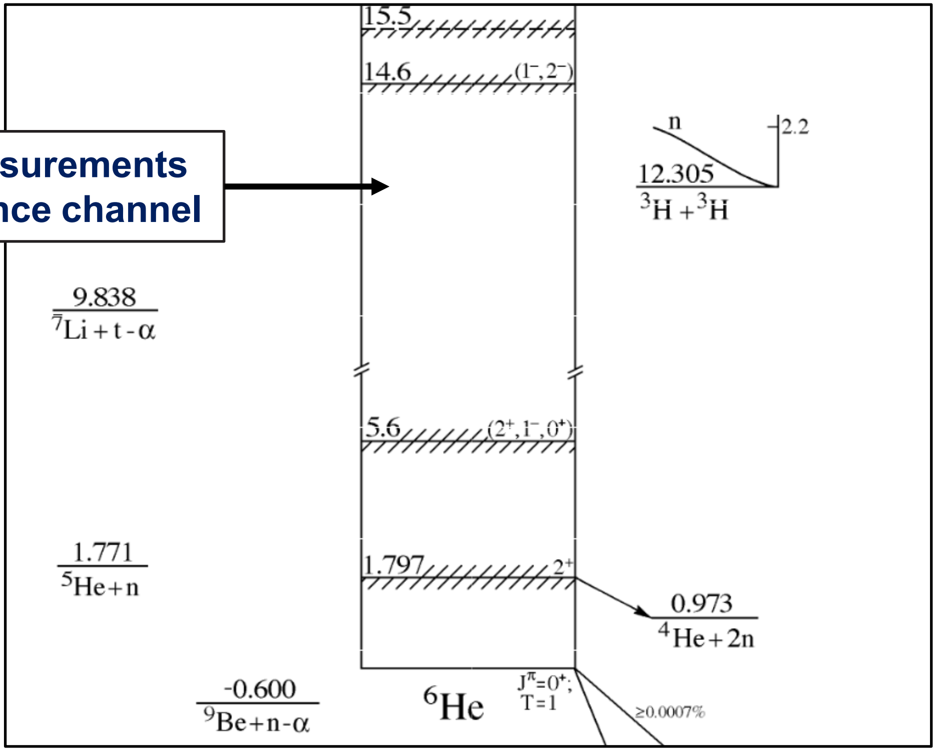


First experimental evidence of a variant neutron spectrum from the T(T,2n)α reaction at center-of-mass energies in the range of 16-50 keV

M. Gatu Johnson[1], C.J. Forrest[2], D.B. Sayre[3], A. Bacher[4], J.-L. Bourgade[5], C.R. Brune[6], J.A. Caggiano[3], D.T. Casey[3], J.A. Frenje[1], V.Yu. Glebov[2], G.M. Hale[7], R. Hatarik[3], H.W. Herrmann[7], R. Janezic[2], Y.H. Kim[7], J.P. Knauer[2], O. Landoas[5], D.P. McNabb[3], M.W. Paris[7], R.D. Petrasso[1], J.E. Pino[3], S. Quaglioni[3], B. Rosse[5], J. Sanchez[3], T.C. Sangster[2], H. Sio[1], W. Shmayda[2], C. Stoeckl[2], I. Thompson[3], and A.B. Zylstra[7]

[1]Massachusetts Institute of Technology Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[2]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA
[3]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[4]Indiana University, Bloomington, IN 47405, USA
[5]CEA, DAM, DIF, F-91297 Arpajon, France



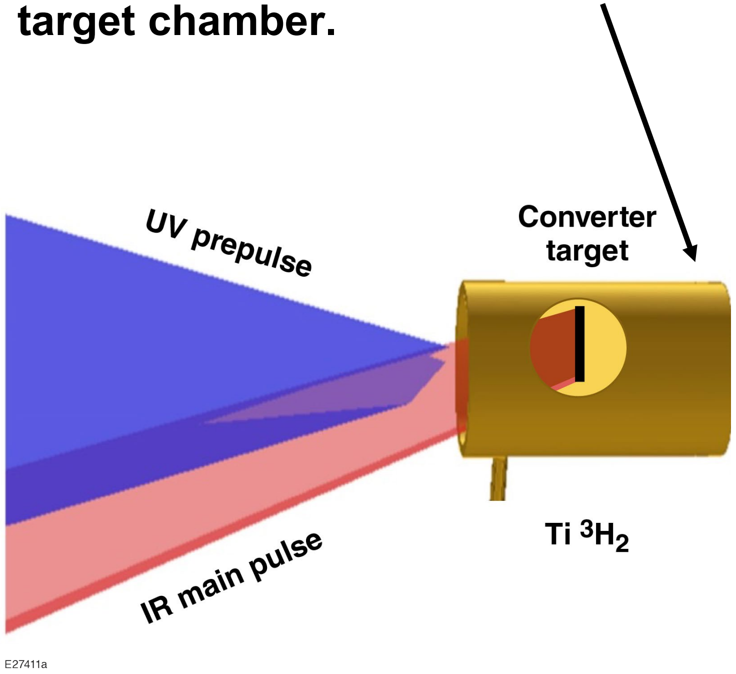


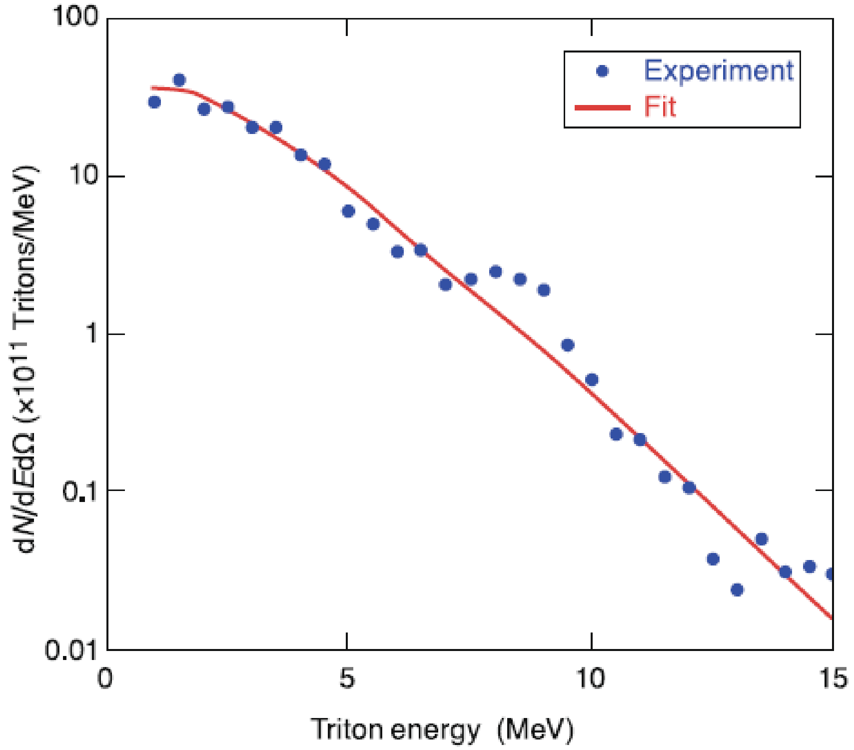
No measurements of entrance channel

No ultrashort-pulse laser facility, presently existing or planned, can handle tritiated targets for nuclear experiments.

A triton beam with an energy from 1-10 MeV has been successfully fielded on OMEGA in December 2020 (Thesis project for Arnold Schwemmlein -- UR)

The introduction of the CH tube significantly reduces a background contributed from (p,n) reactions off the target chamber.

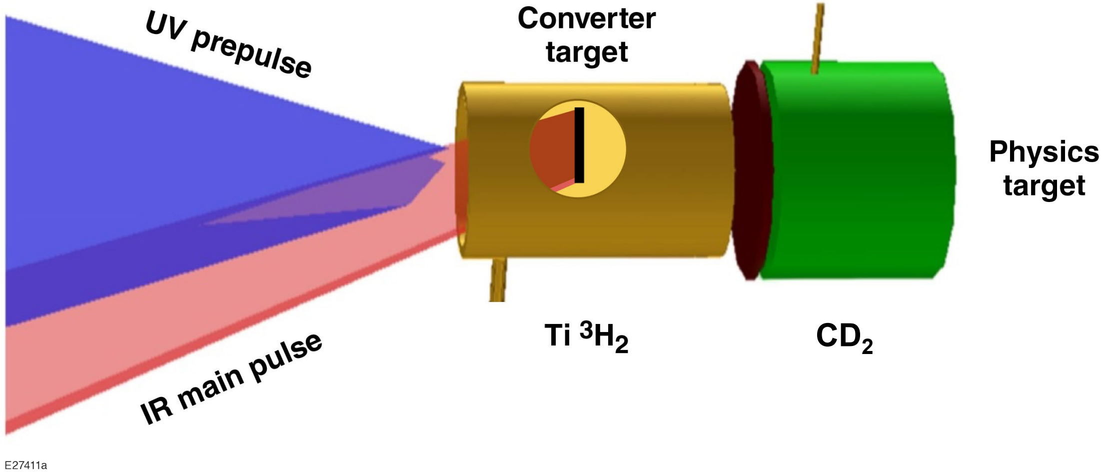


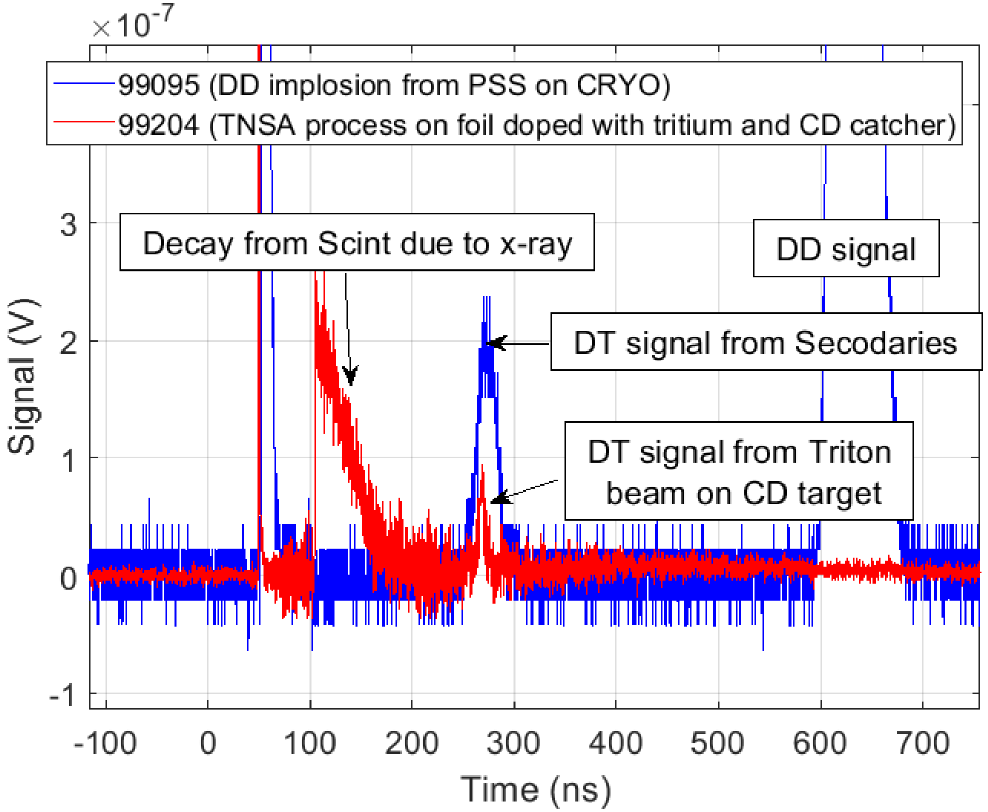


- The triton spectrum obtained from the Thompson Parabola Ion Energy (TPIE) show the exponential shape of the spectrum that has been previously reported for protons and deuterons in literature.
- The TNSA mechanism generated a directed beam of 10^{12} tritons per laser pulse with energies up to 10 MeV.

The new platform produced the first demonstration of accelerating tritium into a CD foil and producing DT neutrons* (Thesis project for Arnold Schwemmlein -- UR)

$^{2}H + D$	→	^{3}He (0.82 MeV) + n (2.45 MeV)
		^{3}H (1.01 MeV) + p (3.02 MeV)





- The DT peak from secondary DT reactions was used as a fiducial for the DT neutrons from the tritons stopping and fusing in the CD foil.

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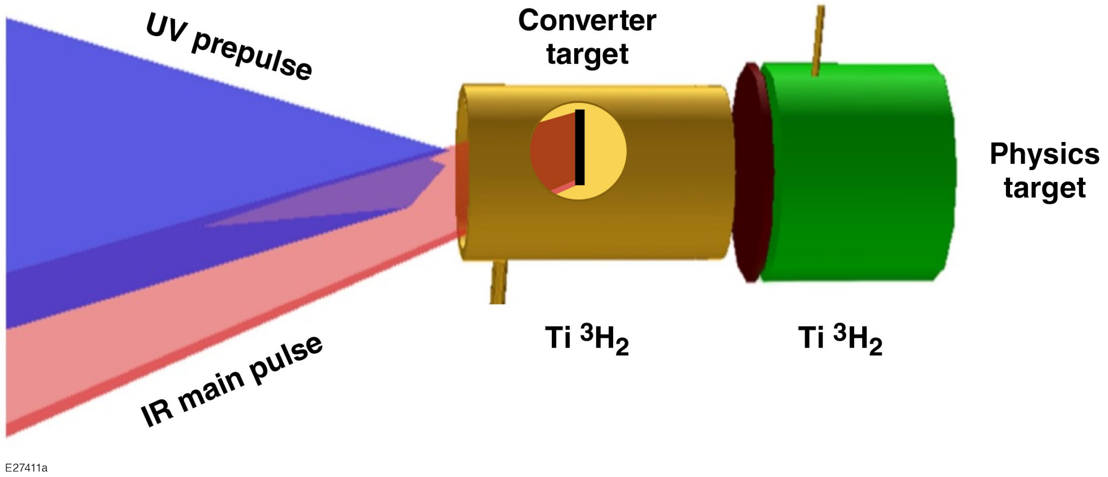
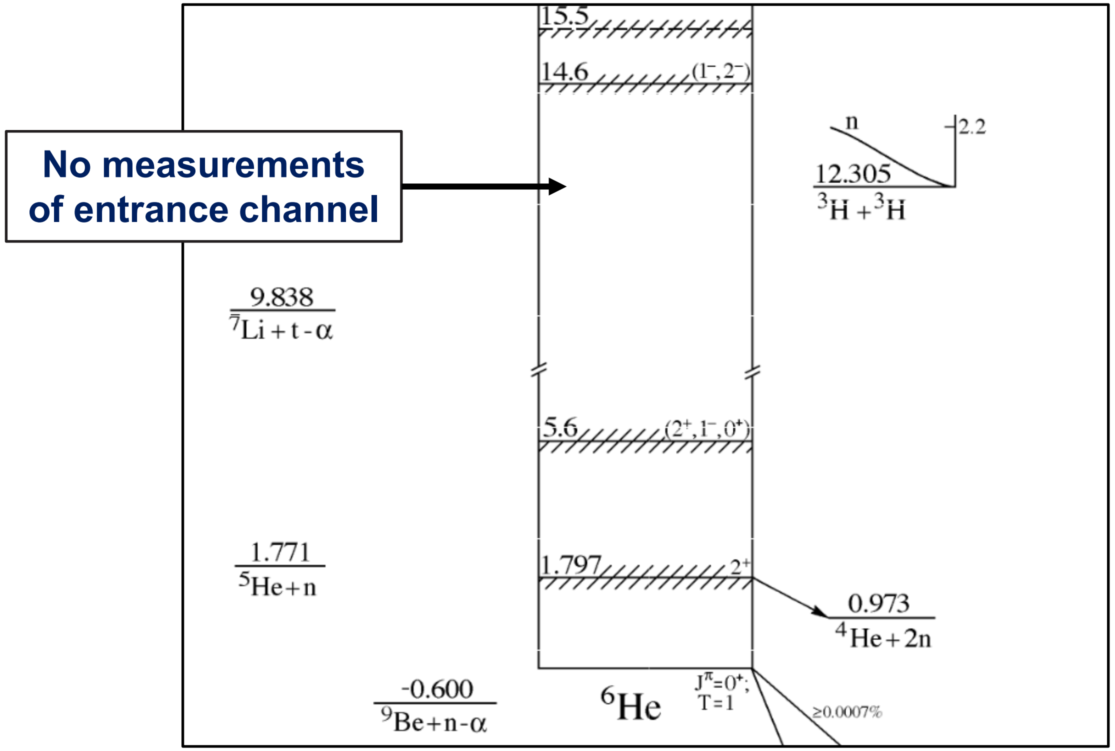
* A. Schwemmlein et al., Nuclear Instruments and Methods in Physics Research B 522 (2022) 27–31

An experiment in 2022 with laser-driven tritons upward of 10 MeV incident on a tritiated foil was demonstrated for the first time

^{3}H + 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)
→ ^{4}He + (nn)

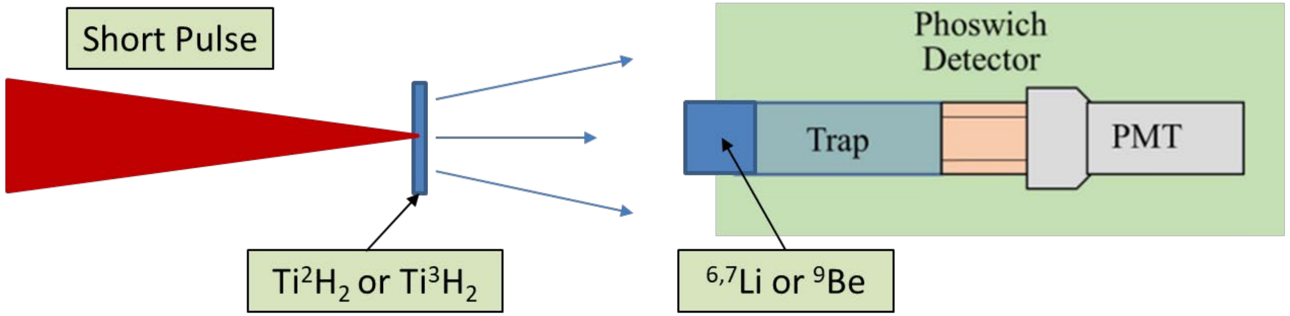


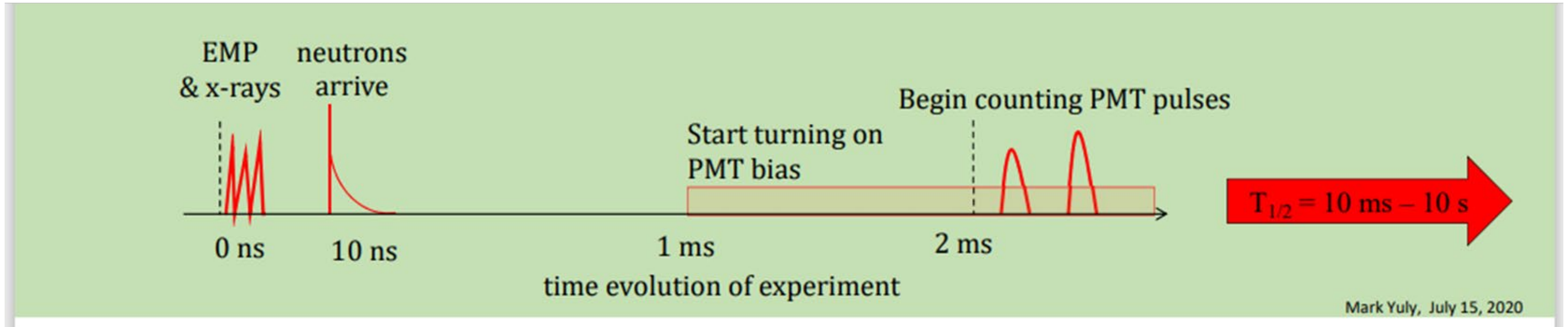

No measurements of entrance channel

Preliminary indication is that this is a direct reaction (stripping reaction) since no enhancement at ~2 MeV about the threshold was observed.

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

Reaction	Product Half-life
$^{3}H(t,\gamma)^{6}He$	807 ms
$^{6}Li(t,p)^{8}Li$	840 ms
$^{7}Li(t,\alpha)^{6}He$	807 ms
$^{9}Be(t,\alpha)^{8}Li$	840 ms
$^{9}Be(t,\gamma)^{12}B$	20.2 ms
$^{10}B(t,p)^{12}B$	20.2 ms
$^{11}B(d,p)^{12}B$	20.2 ms
$^{13}C(t,\gamma)^{16}N$	7.1 s
$^{13}C(t,\alpha)^{12}B$	20.2 ms
$^{13}C(t,p)^{15}C$	2.45 s
$^{14}N(t,p)^{16}N$	7.1 s
$^{15}N(d,p)^{16}N$	7.1 s





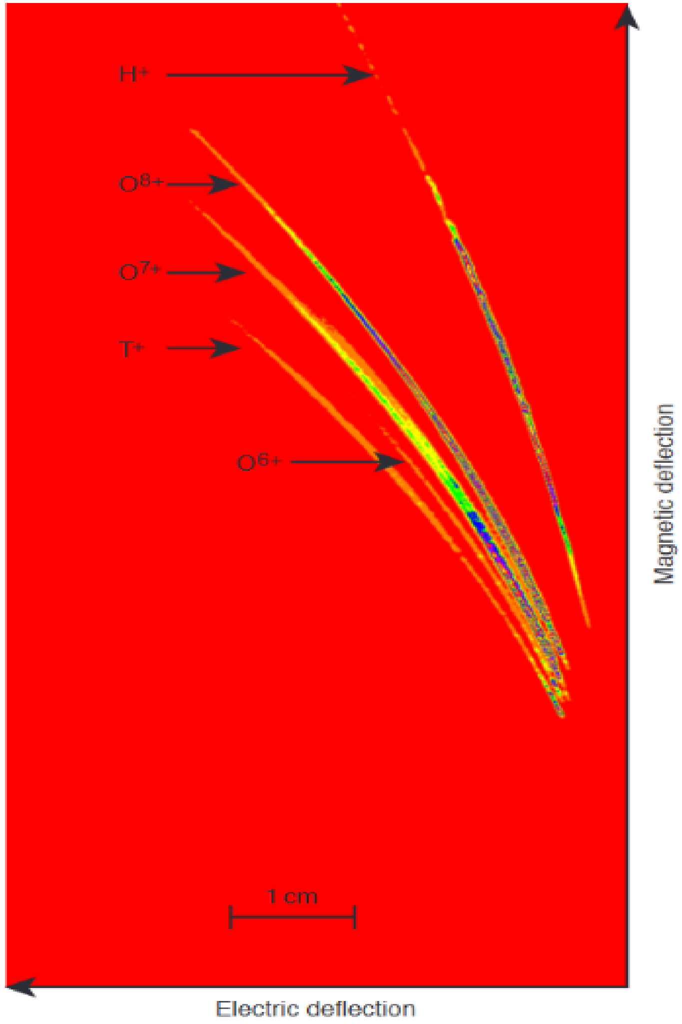
Successful demonstration of this Short-Lived Isotope Counting (SLIC) system has been completed with $^{7}Li(d,p)^{8}Li$ on a small Mulit -Terra Watt (MTW) laser facility at the LLE.

- currently this diagnostic is being designed and built for experiments on OMEGA
- first experiments with incident tritons for (t,p) reactions are being planned for in FY26

Work is ongoing to optimize the acceleration of the tritons for a monoenergetic, higher yield source for future experiments on NSF-OPAL

- **Current view on unsolved/open problems for this experimental platform.**
  - **advanced laser techniques to remove contaminates on converter foils to increase ion yield**
  - **cryogenic layer of tritium could produce a more mono-energetic ion beam**

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.

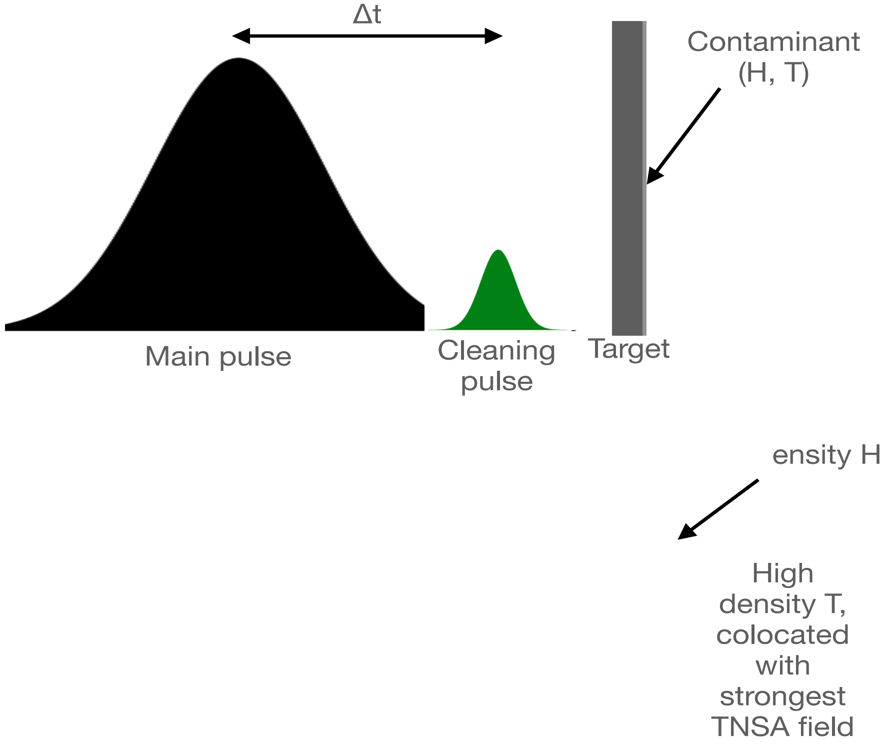
- The acceleration, protons accelerate faster, thereby partially shielding the heavier ions from the electrons.
  - therefore, most of the tritium in the target remains unused, and using targets with higher tritium content does not significantly improve the beam

Pre-Shot foil measurements:
$1x10^{16}$ tritium ions

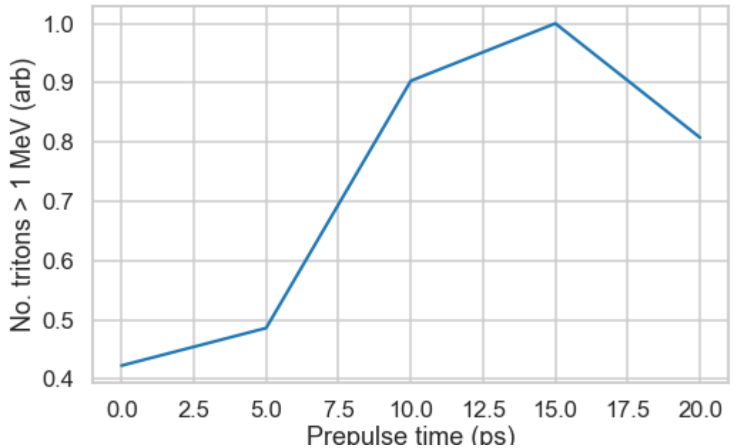
TPIE measurements:
$1x10^{12}$ tritium ions

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.

Experiments are underway to increase the success of this platform with advanced laser techniques specified laser pulses to “clean” the surface of these contaminants



- **Increasing the ion yield and controlling the energy spectrum of TNSA accelerated ions using laser pre-pulses techniques.**
  - **A high intensity cleaning laser pulse is used to set up a weak plasma sheath on the target surface ~10 picoseconds before the arrival of the ion accelerating drive pulse**

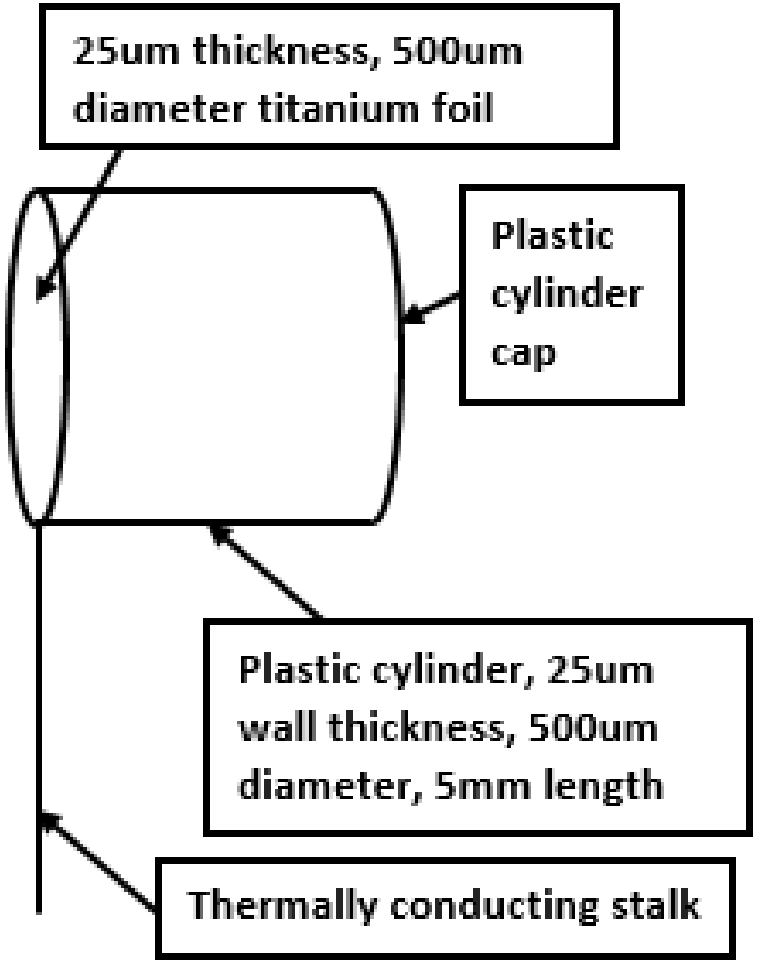


Pre-Shot foil measurements: 1×10^{16} tritium ions

TPIE measurements: 1×10^{12} tritium ions

A recent experimental campaign in May 2024 showed that the system could reach a 30-ps separation but incremental moves of 10 ps and 20 ps closer in time were not achieved.

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



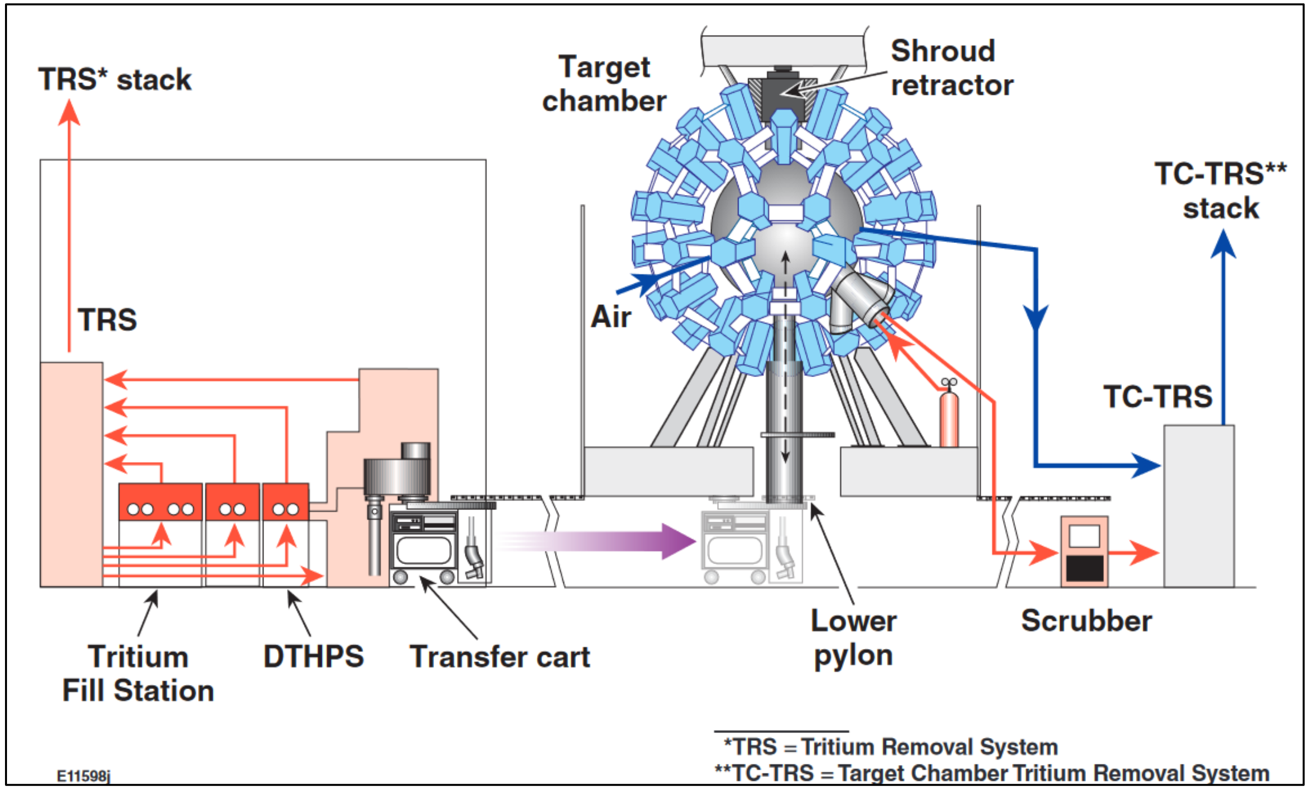
25um thickness, 500um diameter titanium foil

Plastic cylinder cap

Plastic cylinder, 25um wall thickness, 500um diameter, 5mm length

Thermally conducting stalk

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



*TRS = Tritium Removal System

**TC-TRS = Target Chamber Tritium Removal System

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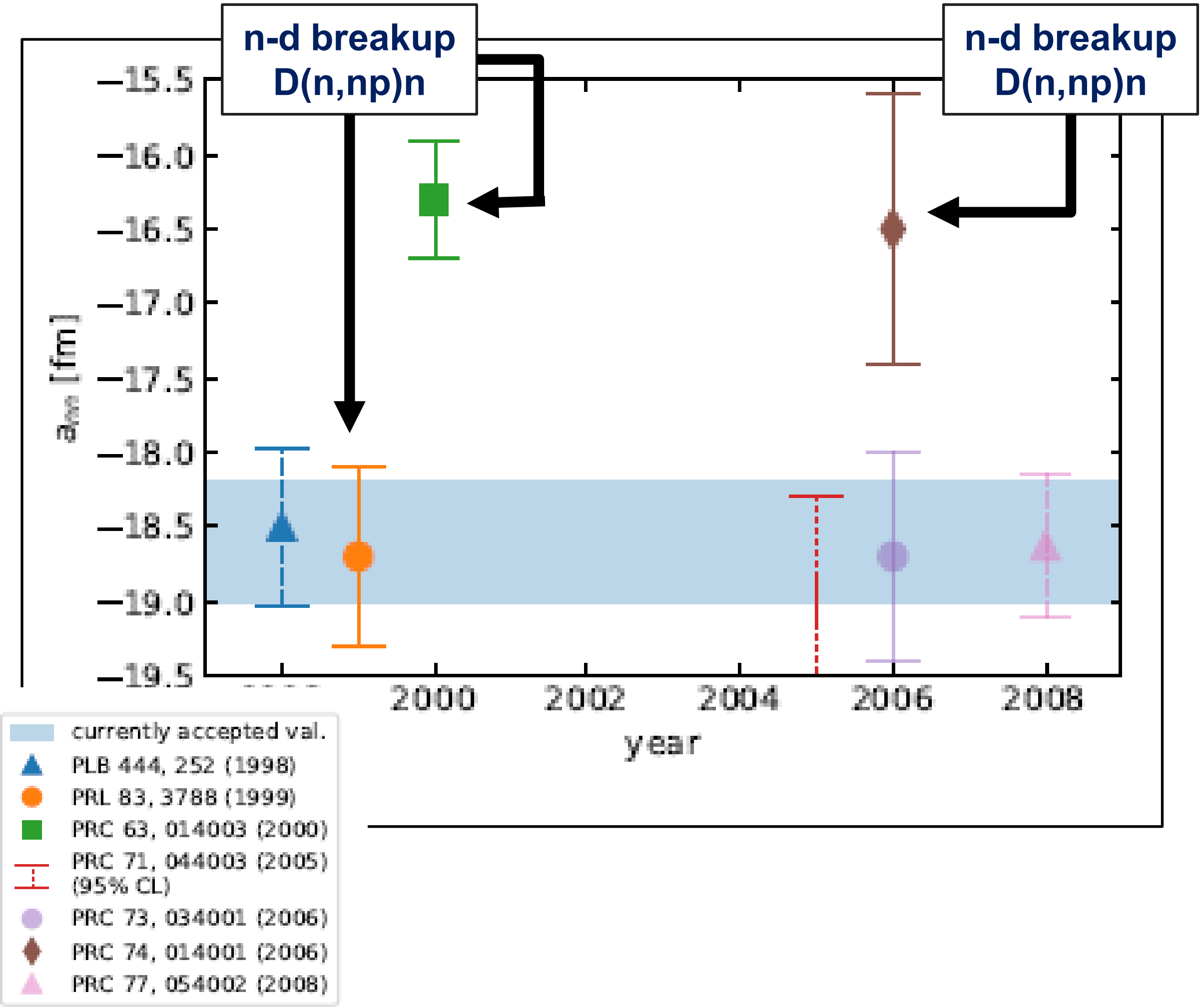
The neutron-neutron elastic scattering length is a quantity of fundamental importance in nuclear and particle physics that has not been directly measured



n-d breakup
D(n,np)n

n-d breakup
D(n,np)n

- The difference in the $^1S_0$ neutron-neutron and proton-proton scattering lengths is a conclusive measure of charge-symmetry breaking (CSB) of the nuclear force.*
  - p-p and n-n forces in a singlet state, suggests that the a_{pp} scattering length should be smaller than the a_{nn} scattering length
- Discrepancies between the extracted values of a_{nn} from neutron-induced deuteron breakup reactions measured by two different collaborations is still not resolved.
  - $a_{pp} = (-17.3 \pm 0.8)$ fm
  - $a_{nn} = (-18.5 \pm 0.3)$ fm (π – d capture, n-d breakup)
  - $a_{nn} = (-16.3 \pm 0.4)$ fm (n-d breakup)

$$\Delta a_{CSB} = (a_{pp} - a_{nn})$$

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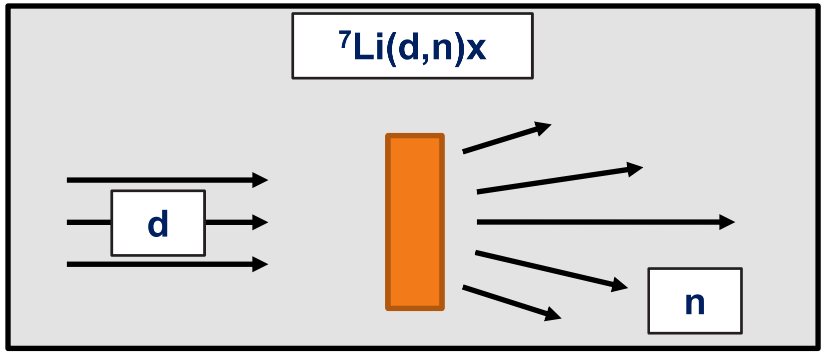
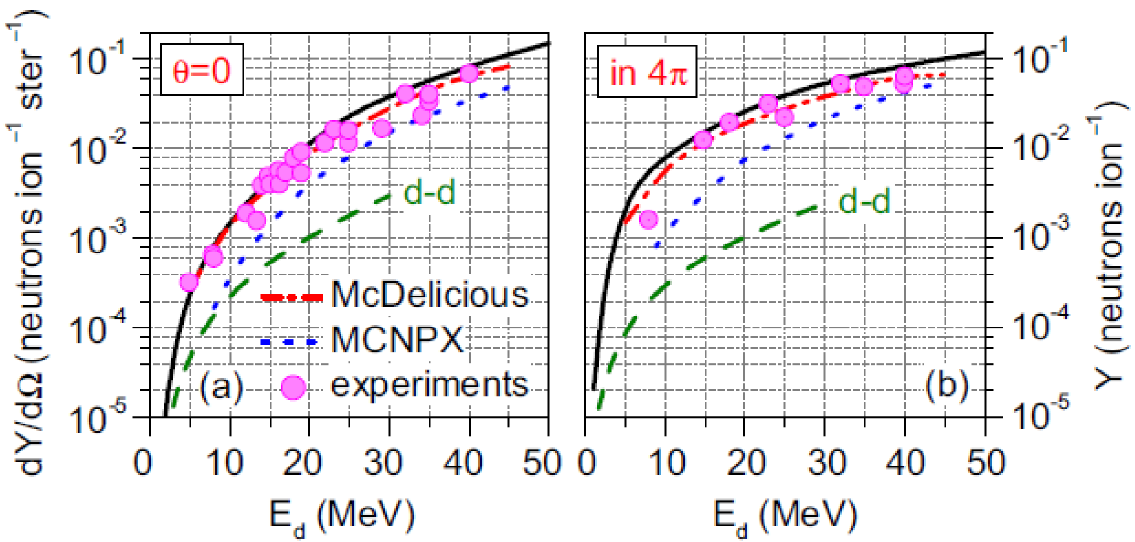
* D. E. Gonzalez Trotter et al., Phys. Rev. Lett. 83, 3788 (1999)

Numerical simulations and experimental data* in the literature indicate that the required neutron flux might be achieved with laser-target accelerations interactions





- **The acceleration of energetic deuterons (~40 MeV) focused on a LiF target yields a sharply forward-focused beam of neutrons.**
  - **the neutron yield dY/dΩ (E_d,θ = 0) depends very strongly on the incident deuteron energy**
- **The neutron yield is sensitive to the incident deuteron energy and increases by ~3 orders of magnitude with the deuteron energy increased from 5 to 50MeV.**
- **The proposed laser systems is capable of accelerating deuterons to kinetic energies of up to about 60 MeV.**
  - **expected to generate a very high neutron flux in the forward direction, reaching ~0.1 neutrons sr^{-1} per incident deuteron**
  - **recall, we can load up to 1x10^{16} ions into a metal foil**

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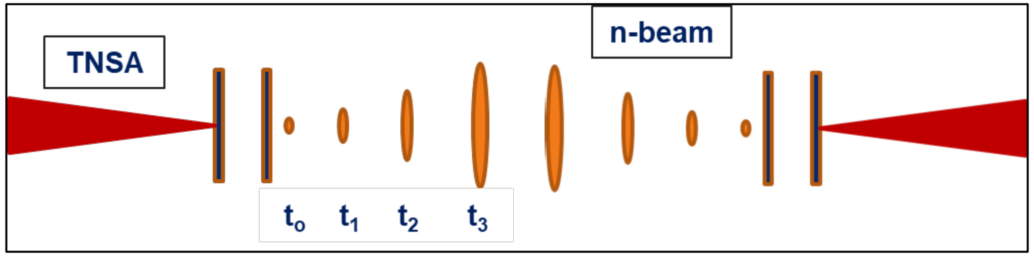
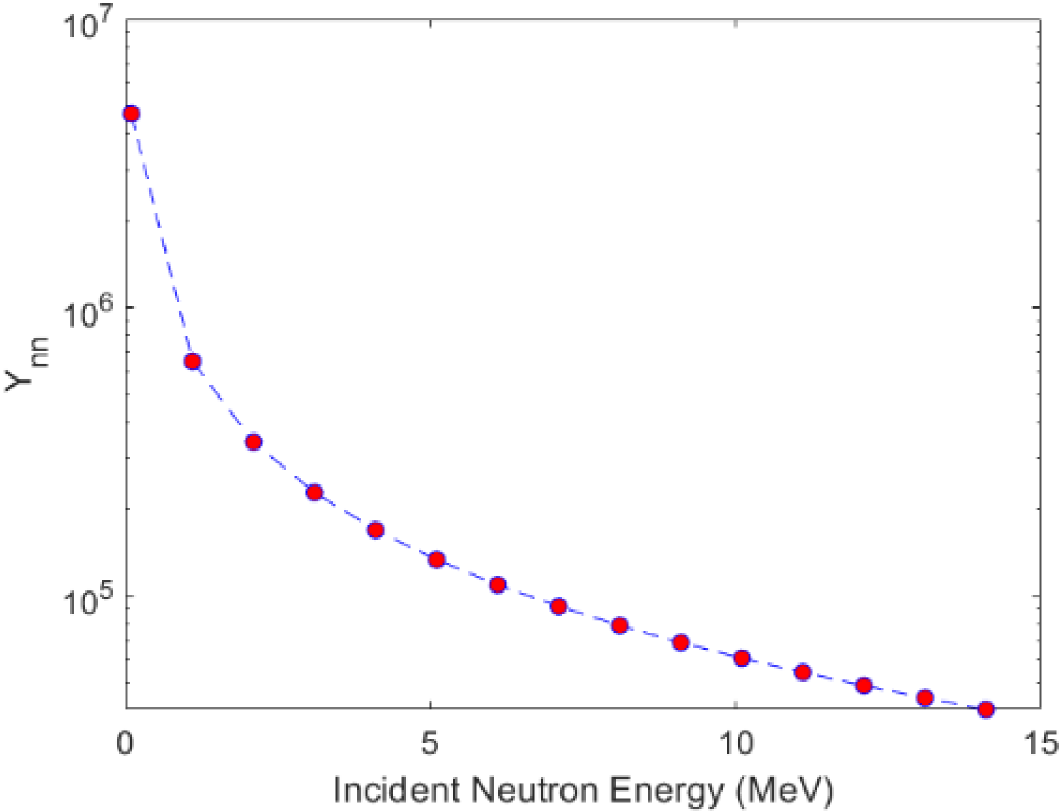
* J. Davis *et al.*, Plasma Phys. Control. Fusion 52 (2010) 045015

High neutrons flux directed in a narrowly focused cone from two well timed beams is a crucial requirement for this experiment to be successful





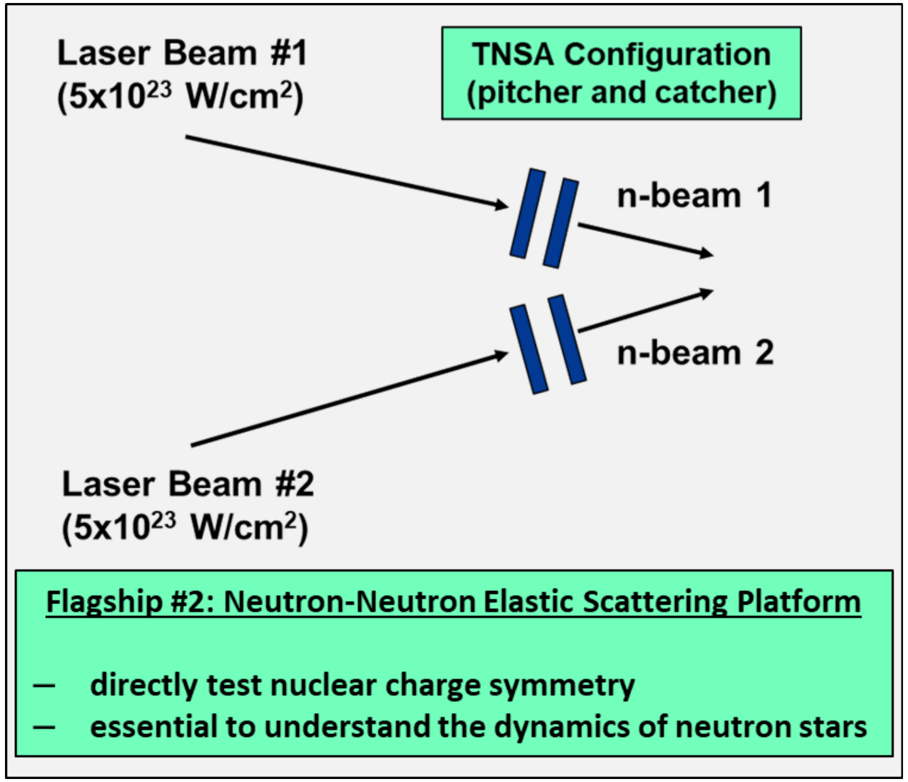
- **An estimate of the neutron-neutron elastic scattering yield can be calculated from the following expression,**

$$Y_{nn} = \frac{\sigma_{nn} {Y_n}^2 l_p}{A_b v_n t_i}$$

- **This example with $Y_n = 10^{14}$ suggests that the experiment requires lower energy neutrons where the cross-section is significantly higher in the ~1 MeV region.**
- **There are effectively two approaches to achieve lower energy neutrons:**
  - **focus on d-d reactions at ~2.45 MeV as compared to d-^{7}Li that results in ~15 MeV neutrons**
  - **the neutron beams to overlap as small of an angle as achievable where the elastic scattering will take place at low center-of-mass energies**

Work is ongoing to increase the neutrons emission into a tightly focused beam and model neutron-neutron elastic scattering required for NSF-OPAL

- **Current view on unsolved/open problems for this experimental platform.**
  - no available code can currently model neutron-neutron scattering
  - novel target designs to focus the high-yield neutrons into a smaller solid angle



Laser Beam #1
(5x10^{23} W/cm^2)

TNSA Configuration
(pitcher and catcher)

n-beam 1

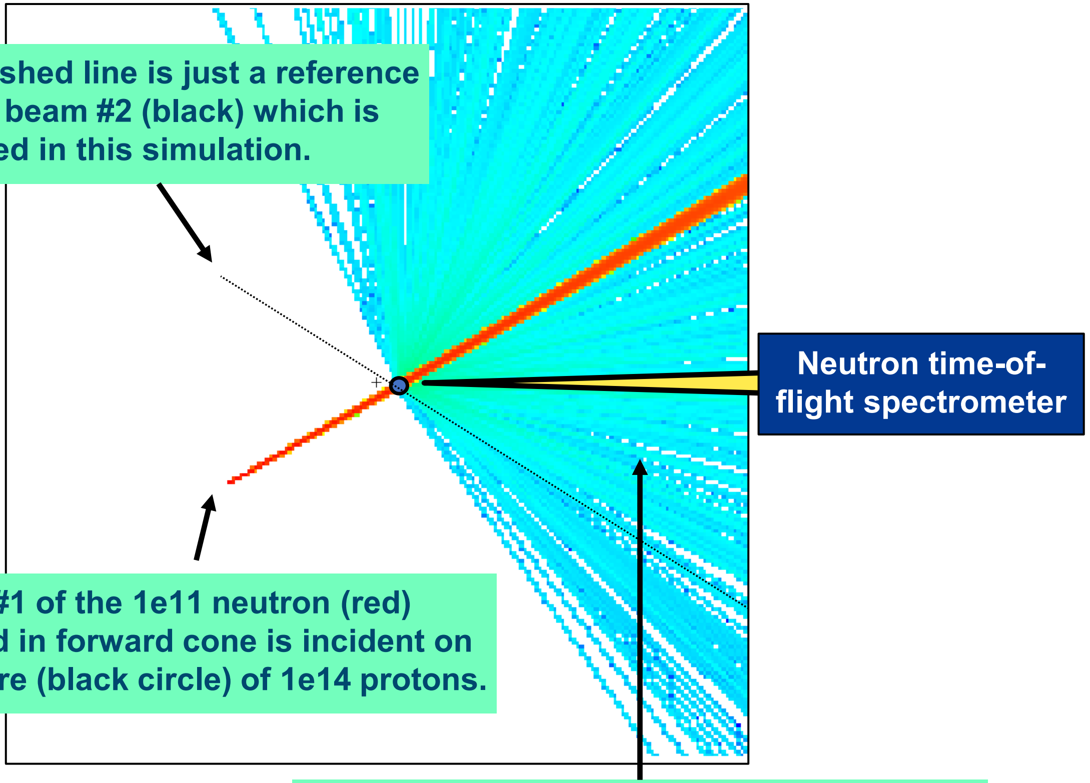
n-beam 2

Laser Beam #2
(5x10^{23} W/cm^2)

Flagship #2: Neutron-Neutron Elastic Scattering Platform

- directly test nuclear charge symmetry
- essential to understand the dynamics of neutron stars

A simulation to investigate the neutron beams is essential to optimize signal-to-noise from the surrounding environment when planning for future diagnostics



The dashed line is just a reference for the beam #2 (black) which is not used in this simulation.

Neutron time-of-flight spectrometer

Beam #1 of the 1e11 neutron (red) emitted in forward cone is incident on a sphere (black circle) of 1e14 protons.

It was calculated that ~5e2 neutrons (green-blue) scattered from the proton sphere.

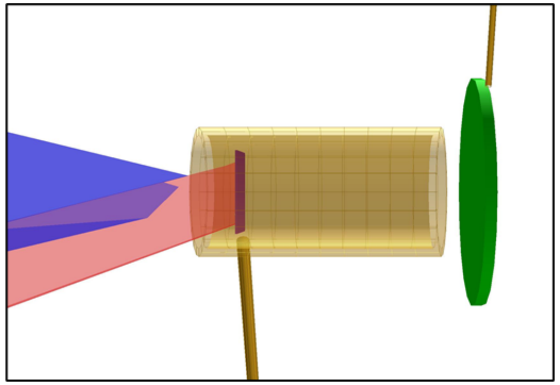
Simulations to optimize the diagnostics will take place once target chamber and surrounding structure models are available.

- **In the transport code a 1-mm sphere of 1x10^{14} protons was positioned in the interaction region with 1x10^{11} neutrons incident on the volume.**
  - recent evaluations show that the neutron-proton and neutron-neutron scattering lengths as a function of energy are similar

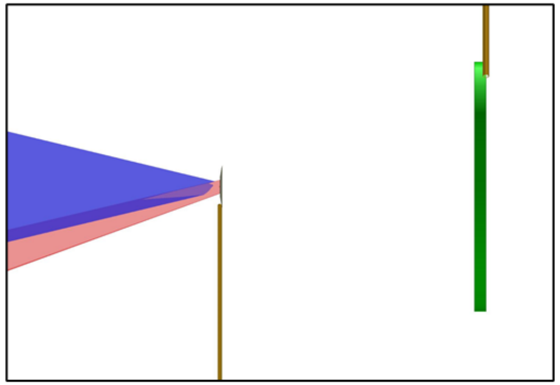
- **We are in the process of proposing this experimental setup (proof-of-principle) on the Zeus Laser Facility.**
- **These experiments on Zeus will:**
  - investigate different PW laser parameters to optimize neutron emission yields
  - develop targets that tightly focus the neutron beam to increase the density in the interaction region

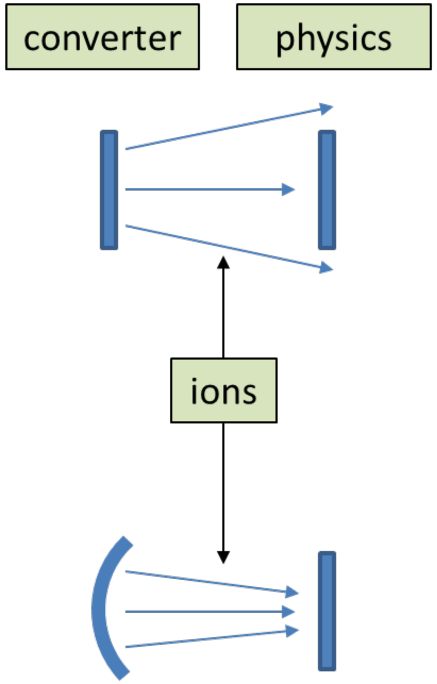
Experimental data from a recent campaign does not appear to show an enhancement in the nuclear yield between a flat and a curved converter target

1000x1000x20um flat foil



1000um radius hemispherical foil

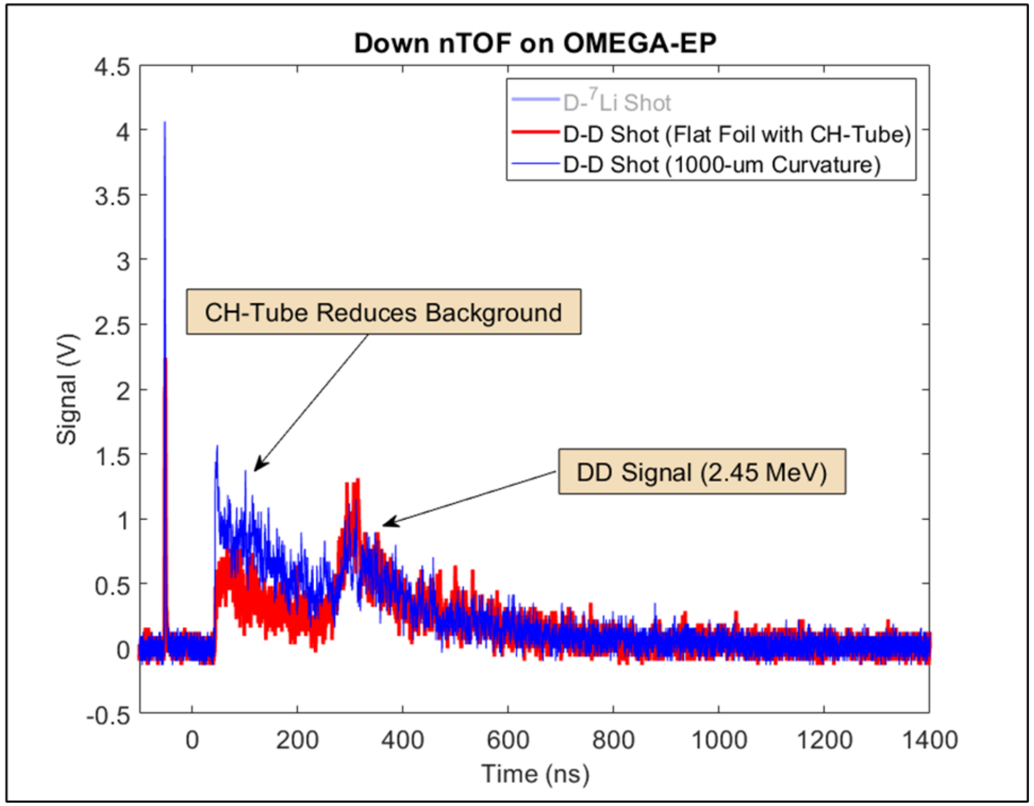




converter

physics

ions



For completeness, the flat foil had a CH-tube around the foil whereas the hemispherical foil did not which does appear to reduce the background.

Proof-of-principle experiments for the proposed flagship experiments are underway that will lead to transformational science on NSF OPAL

Laser Pre-Pulse Testing (FY24-25)

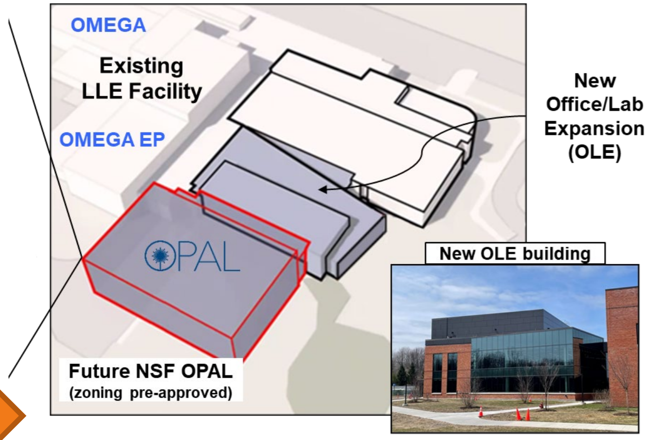
Novel Target Design Testing (FY25-26)

Phoswich Detector Development (FY26)

Cryogenic Target Design Testing (FY27-28)

<u>Planned experiment for subset of outstanding goals in LDNP</u>

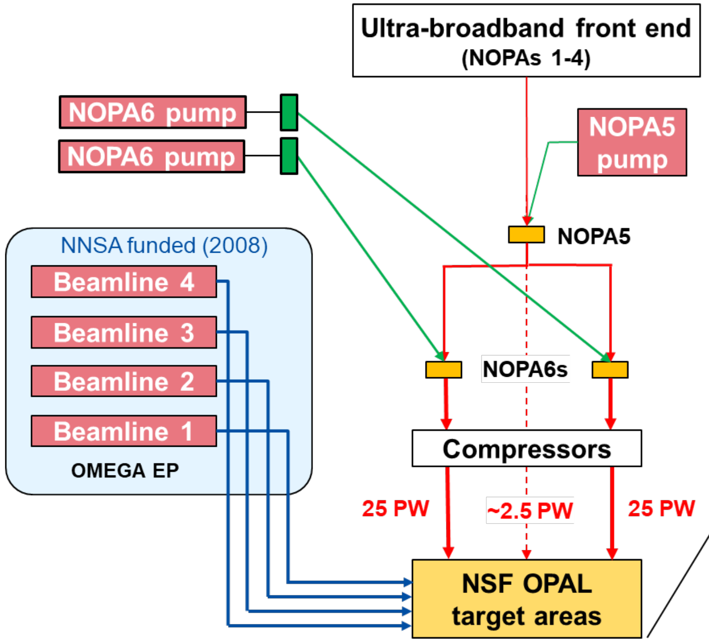
- Monoenergetic ion energy spectrum testing on ZEUS
- Optimization of ion acceleration from metal foils on ZEUS
- Detector development for new cross-section measurements at UR
- Development of cryogenic hydrogen isotope targets at UR
- Test neutron-proton scattering at ZEUS (in proposal stage)

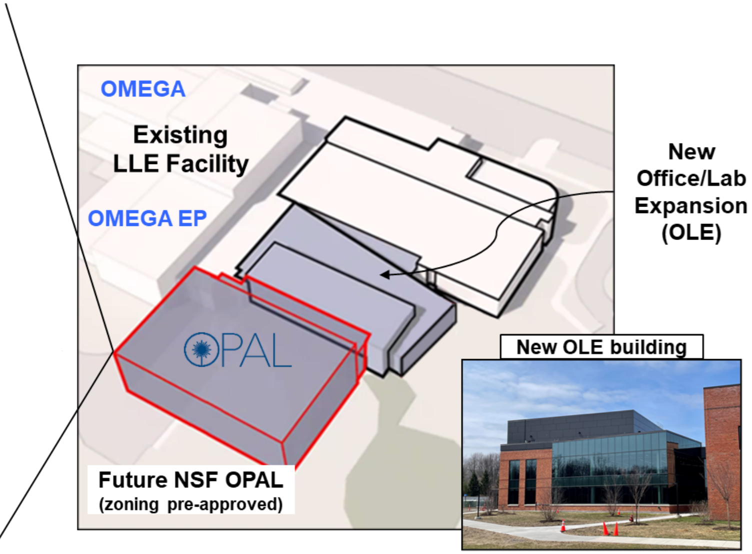


Two buildings constructed in phases would house NSF OPAL, plus labs and offices for new research

Summary/Conclusion

A new, world-leading, high power laser user facility (NSF-OPAL) envisions two new powerful lasers to be located at the University of Rochester (UR/LLE)





Two buildings constructed in phases would house NSF OPAL, plus labs and offices for new research

- 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
- Utilize advanced ion-acceleration to generate neutrons emitted in a very short pulse to induce neutron-neutron elastic scattering which remains important as one of only a few methods to access strong interactions.
  - high shot rate to accumulate good statistics

Summary/Conclusion

Studying fundamental nuclear physics using an advanced laser driven ion-acceleration platform will complement current experiments on OMEGA/OMEGA-EP

Flagship #1 – Tritium Induced Nuclear Experiments

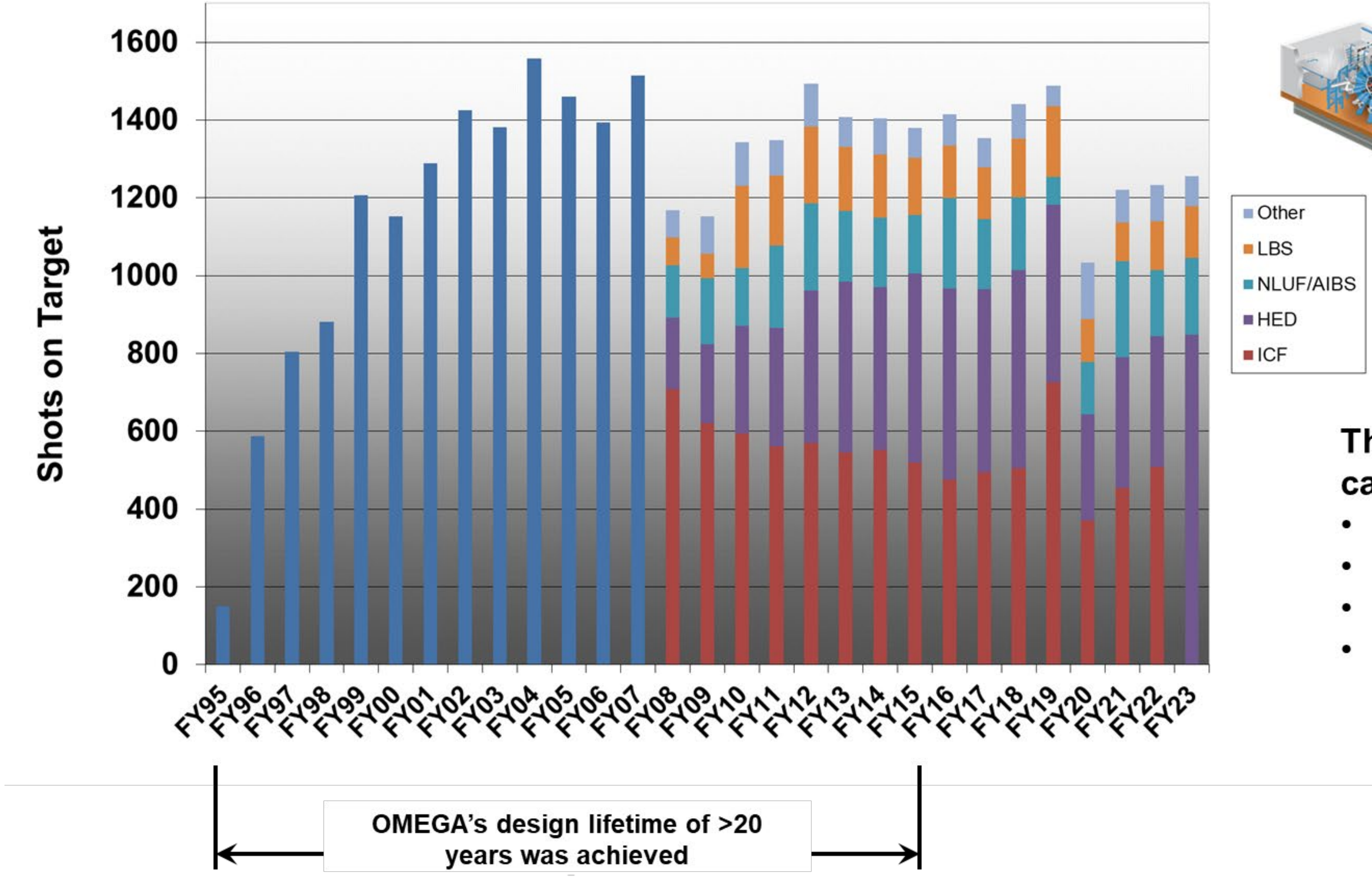
- A controllable, high-yield triton beam is an invaluable tool for nuclear physics in studying the properties of light nuclei.
  - Investigate the A=5 mass gap that impedes the production of lithium and beryllium whereas the mass A=8 gap impedes the production of heavier elements such as boron and carbon
  - study the six-nucleon (A=6) system which is of interest for *ab-initio* nuclear structure calculations
  - studying reactions of ^{7}Li(t,γ)^{10}Be and ^{7}Li(t,n)^{9}Be reactions which may explain why the ^{7}Li abundance is three times lower than predicted from current big-bang nucleosynthesis (BBN) models

Flagship #2 – Neutron-Neutron Elastic Scattering

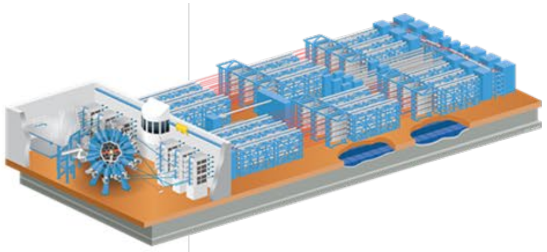
- The newly proposed NSF-OPAL will utilize advanced ion-acceleration to generate neutrons emitted in a very short pulse to induce neutron-neutron elastic scattering.
  - nucleon-nucleon scattering remains important as one of only a few methods to access strong interactions in the absence of the Coulomb force
  - the neutron-neutron scattering (a_{nn}) length is a direct check on charge symmetry and charge independence of the nuclear force

Backup Slides

OMEGA has shot 35,388 target shots through May 2024



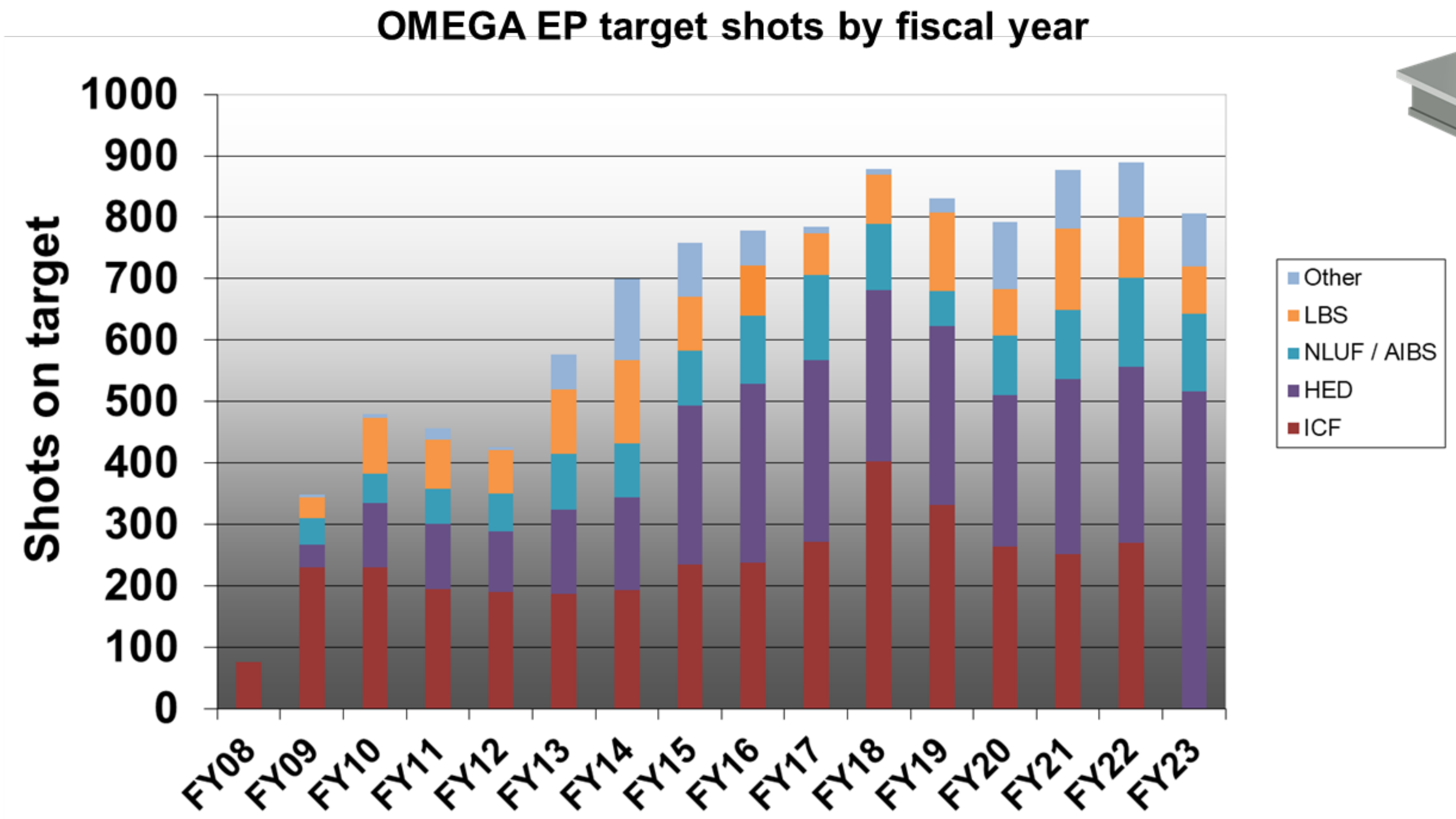
OMEGA's design lifetime of >20 years was achieved

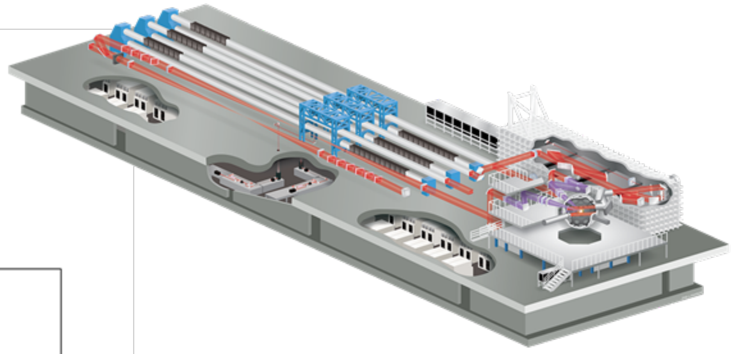


The HED Council selects campaigns for OMEGA

- **Hydro and Properties**
- **Thermonuclear Burn**
- **Materials**
- **Outputs and Survivability**

OMEGA EP has performed 11,110 shots through May 2024





OMEGA EP has operated for 15 full FY's