Neutron diagnostic characterization at the Ion Beam Laboratory for inertial confinement fusion experiments conducted at the Z-accelerator facility

SAND2018-8760C

- University of New Mexico
  - Jed Styron
  - Gary Cooper
  - Jeremy Vaughan
  - Sara Pelka
  - Colin Weaver
- Sandia National Laboratories
  - Carlos Ruiz
  - Kelly Hahn
  - Gordon Chandler
  - Bruce McWatters
  - Jose Torres
  - Brent Jones
  - Clark Highstrete

25th Conference on Application of Accelerators in Research and Industry
August 12 - 17, 2018
Grapevine, TX

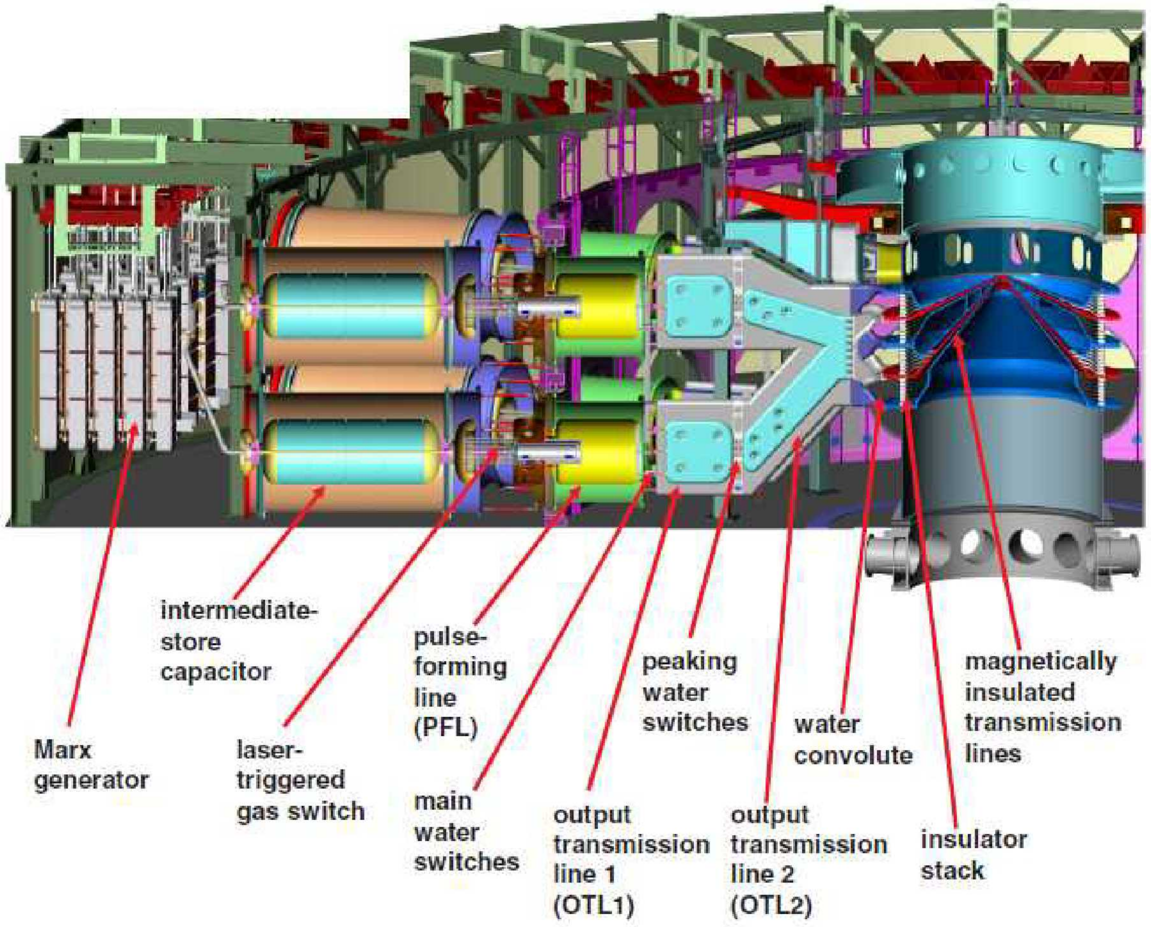
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Summary and Outline

- At Sandia National Laboratories' Z-accelerator facility the MagLIF (Magnetized Liner Inertial Fusion) concept is being studied as a fusion source.
- A variety of neutron diagnostics are fielded on MagLIF experiments to ascertain physical parameters relevant to the performance of the experiment.
- Prior to being fielded on the Z-machine these diagnostics are characterized at Sandia National Laboratories' Ion Beam Laboratory (IBL)
- Neutrons produced at the IBL are known absolutely to < 7% using the Associated Particle Method.

The “Z-Machine” is a pulsed power accelerator and the most powerful x-ray source in the world.

- Z-Machine by the numbers
  - 36 Marx generators
  - ~26 MA of current
  - Nominal pulse width of 100 ns
  - > 300 TW of x-ray power
- User Facility that supports many scientific campaigns
  - Inertial Confinement Fusion
  - High Energy Density Physics
  - Radiation Effects
  - Material Science
  - Fundamental Science



D.V. Rose, Phys. Rev. Accel. and Beams,**17**,(2010)
M.C. Jones et al., Rev. Sci. Instr.,**85**, (2014)

S.A. Slutz et al., Phys. of Plasma,**17**, 056303(2010)
A.B. Sefkow et al., Phys. of Plasma,**21**, 072711 (2014)
M.R. Gomez et al., Phys. Rev. Lett. **113**, 155003 (2014)

The MagLIF (Magnetized Liner Inertial Fusion) concept is being developed as a fusion source at the Z-accelerator.

- Deuterium gas load, 0.7 mg/cm^3 at 60 psi
- External magnetization ~ 10 Tesla
- Laser Pre-heat ~ 2.5 kJ
- Beryllium liner compression ~ 20 MA
- 2-3 keV ion temperatures
- 3E12 D-D neutron yield

Primary Reactions

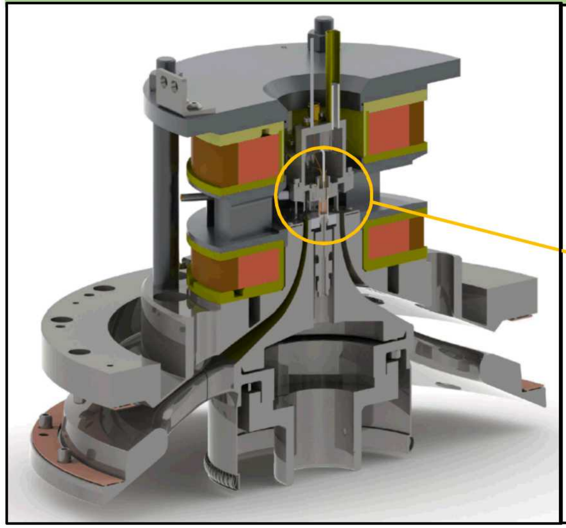
$$D + D \xrightarrow{\sim 50\%} {}^{3}_{2}He(0.82\ MeV) + n(2.45\ MeV)$$

$$D + D \xrightarrow{\sim 50\%} {}^{3}_{1}H(1.01\ MeV) + H(3.02\ MeV)$$

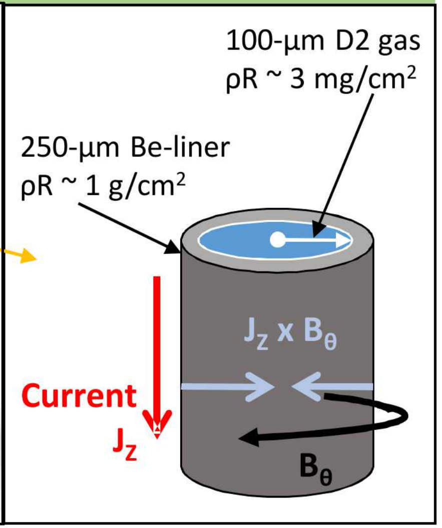
Secondary Reaction

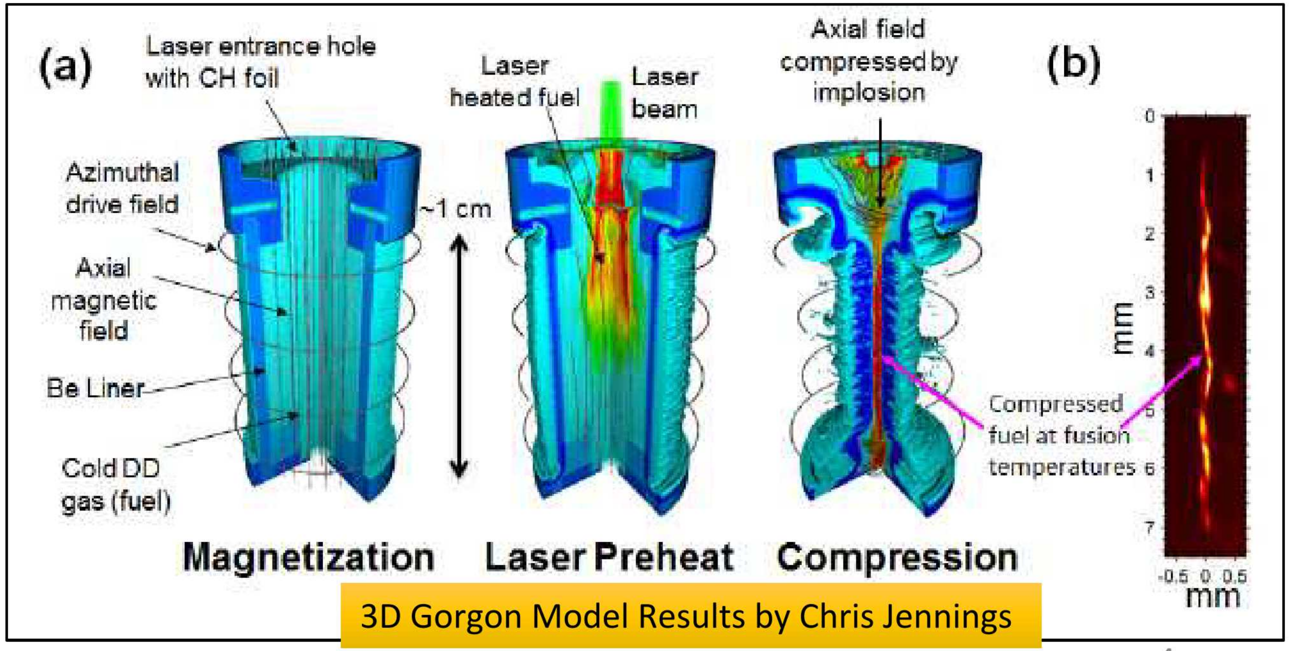
$$D + T \ \rightarrow {}^{4}_{2}He(3.5\ MeV + n(14.1\ MeV)$$

MagLIF Hardware



Liner "z-pinch"

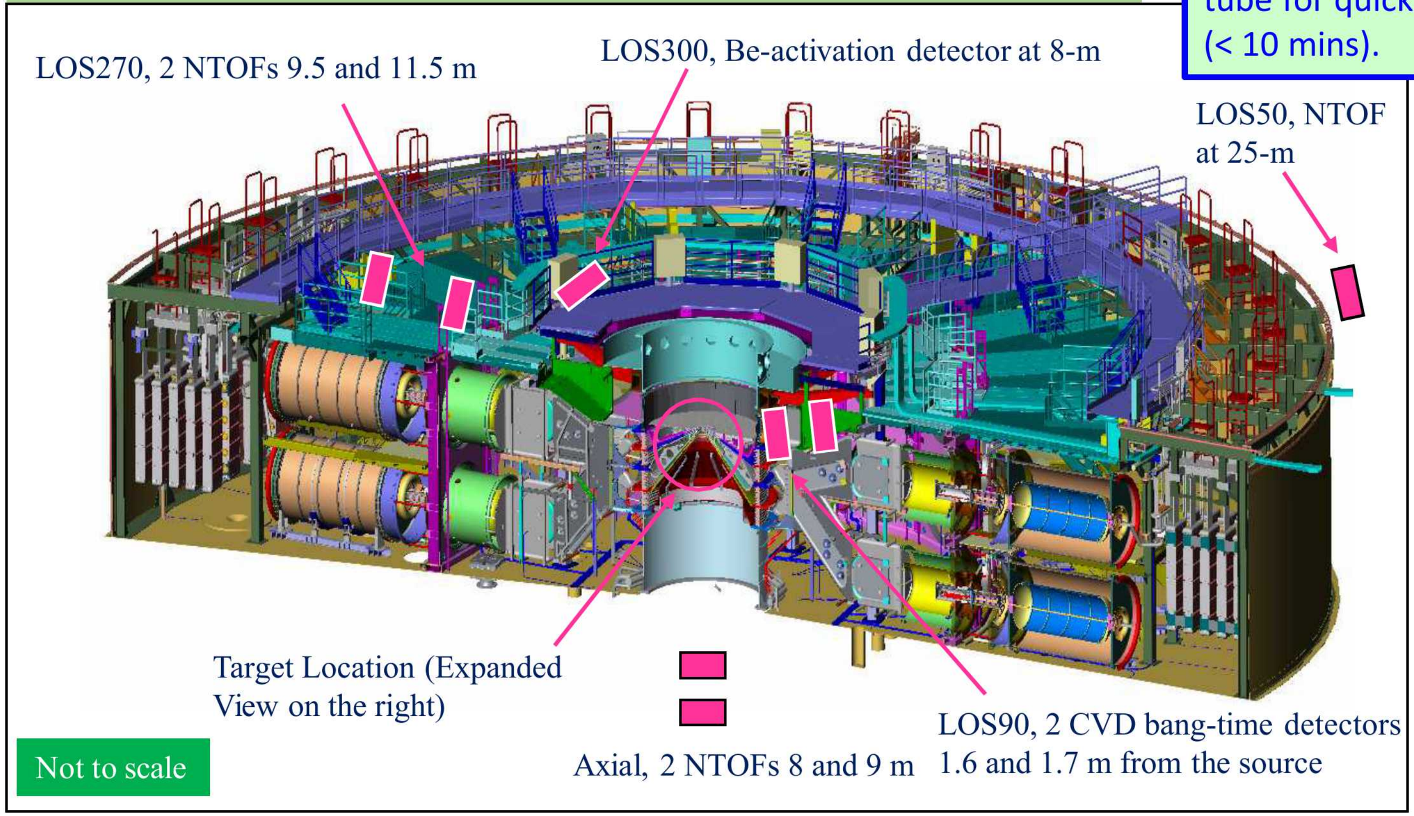




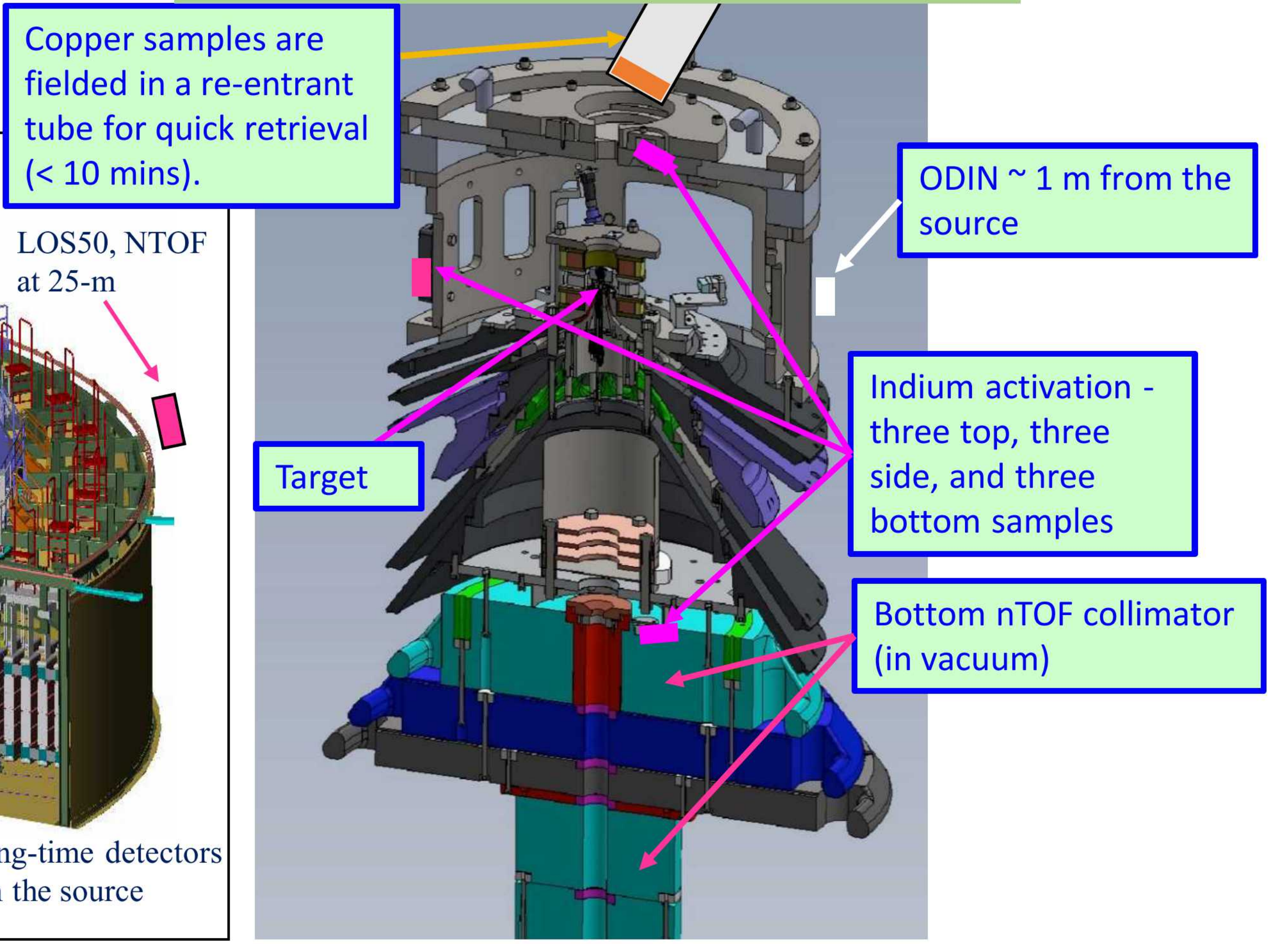
3D Gorgon Model Results by Chris Jennings

There are several diagnostics fielded on MagLIF experiments that view the source through unique geometries.

Cross-section view of the Z-accelerator and diagnostic location



Diagnostics located within the target chamber

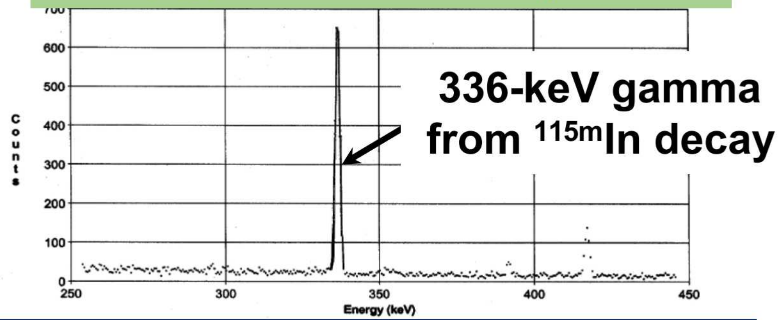


The primary yield (D-D) and secondary yield (D-T) are inferred from activation diagnostics.

C. L. Ruiz et al., Rev. Sci. Instrum., **63**, 4889 (1992)
K. D. Hahn et al., Rev. Sci. Instrum., **83**, 10D914 (2012)
K. D. Hahn et al., Rev. Sci. Instrum., **85**, 043507 (2014)
K.D. Hahn et al., J. Appl. Phys., **717**, 012020 (2016)
C. L. Ruiz et al., submitted to Phys. Rev A (2018)

Indium Activation (D-D)

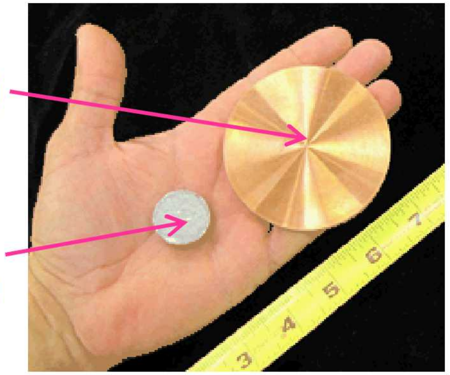
^{115}In(n,γ)^{115m}In → 336 keV γ → ^{115}In



The indium activation spectrum is measured using high-purity germanium detectors.

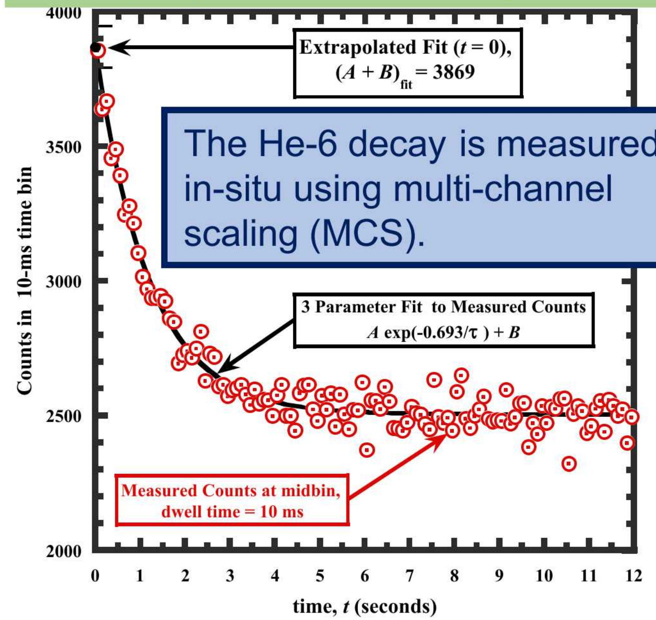
Copper
(0.95 X 7.62 cm)

Indium
(2.54 x 2.54 cm)

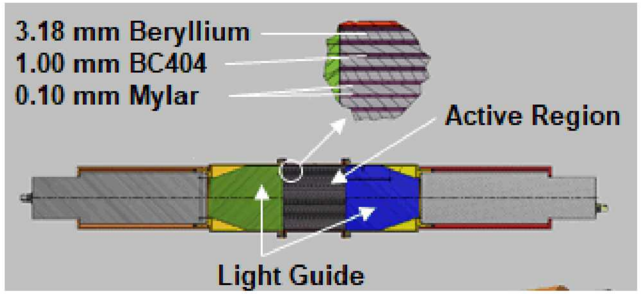


Be-activation detector (D-D)

^{9}Be(n,α)^{6}He→ 3.51 MeV $β^{-}$ → ^{6}Li



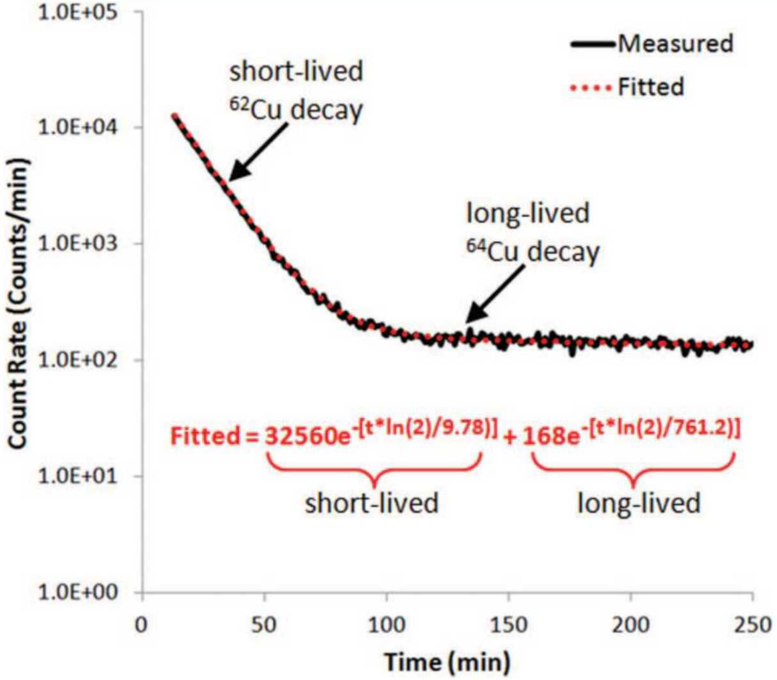
The He-6 decay is measured in-situ using multi-channel scaling (MCS).



Copper Activation (D-T)

^{63}Cu(n,2n)^{62}Cu→1.32 MeV $β^{+}$→ ^{62}Ni (100%)
^{65}Cu(n,2n)^{64}Cu→0.65 MeV $β^{+}$→ ^{64}Ni (61%)

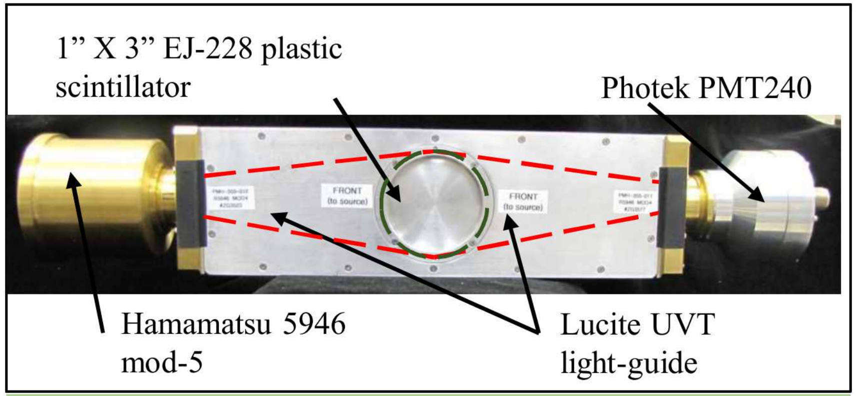
Copper activity is inferred by measuring the 511-keV annihilation gamma's in coincidence.



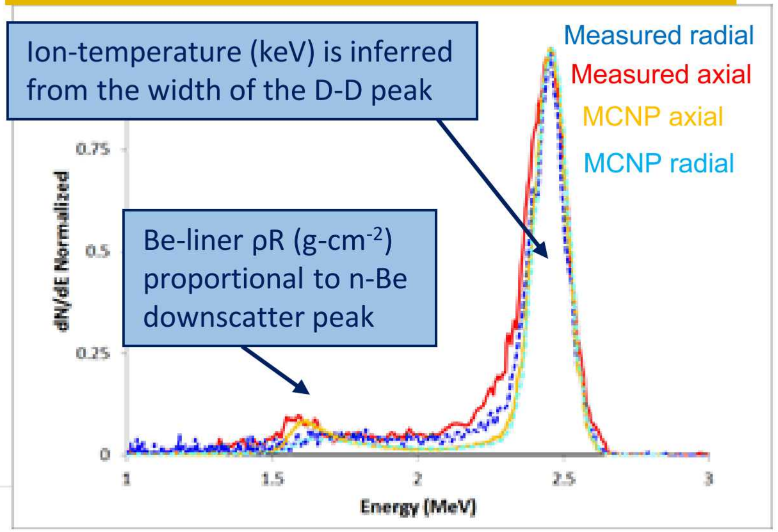
Information about the reaction kinetics and confinement physics can qualitatively be extracted from the neutron time of flight spectra

H. Brysk, Plasma Phys. **15**, 611 (1973)
C. L. Ruiz et al., Phys. Rev. Lett. **93**, 015001 (2004)
P. F. Schmit et al., Phys. Rev. Lett. **113**, 015001 (2014)
S. B. Hansen et al., Phys. Plasmas **22**, 05613 (2015)
M. R. Gomez et al., Phys Plasmas **22**, 056306 (2015)
P. F. Knapp et al., Phys. Plasmas **22**, 056312 (2015)

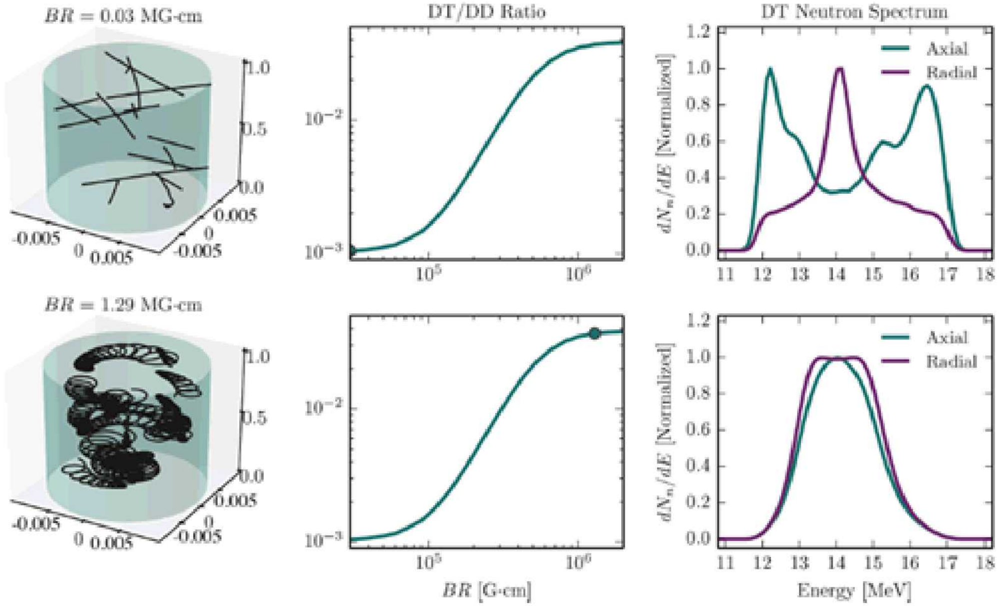
CVD Bang-time detectors

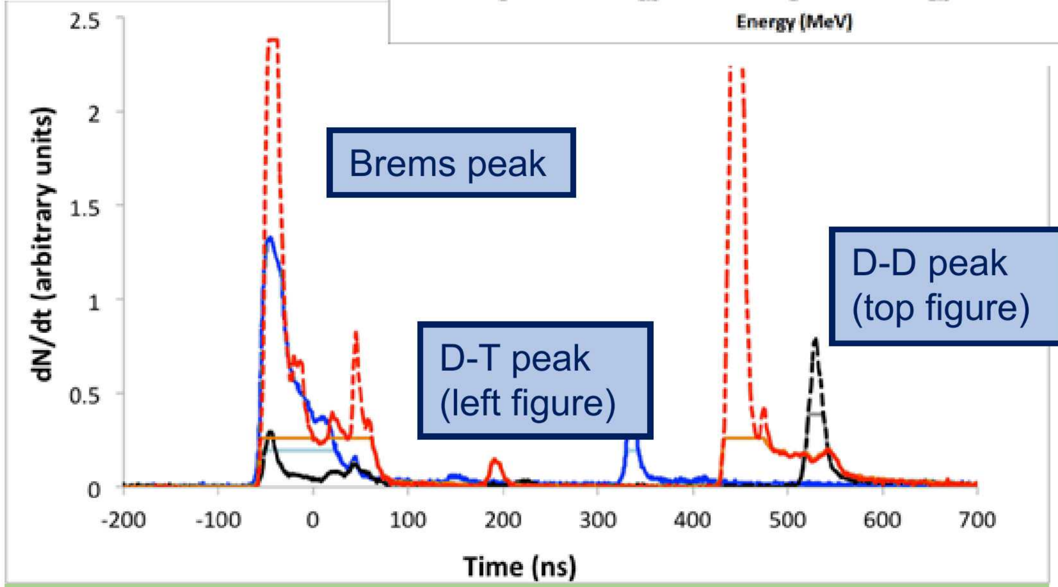


Dual-PMT nToF detector



BR (MG-cm) is the MagLIF confinement parameter inferred from the D-T/D-D yield ratio and the shapes of the D-T axial and radial spectra *Simulated data





Typical MagLIF nToF spectra at various distances

The neutron producing region within the plasma column can be inferred using ODIN (One dimensional imager of neutrons).

D. Ampleford et al. (accepted by Rev. Sci. Instr. **89** (2018)
J. Vaughan et al. (accepted by Rev. Sci. Instr. **89** (2018)

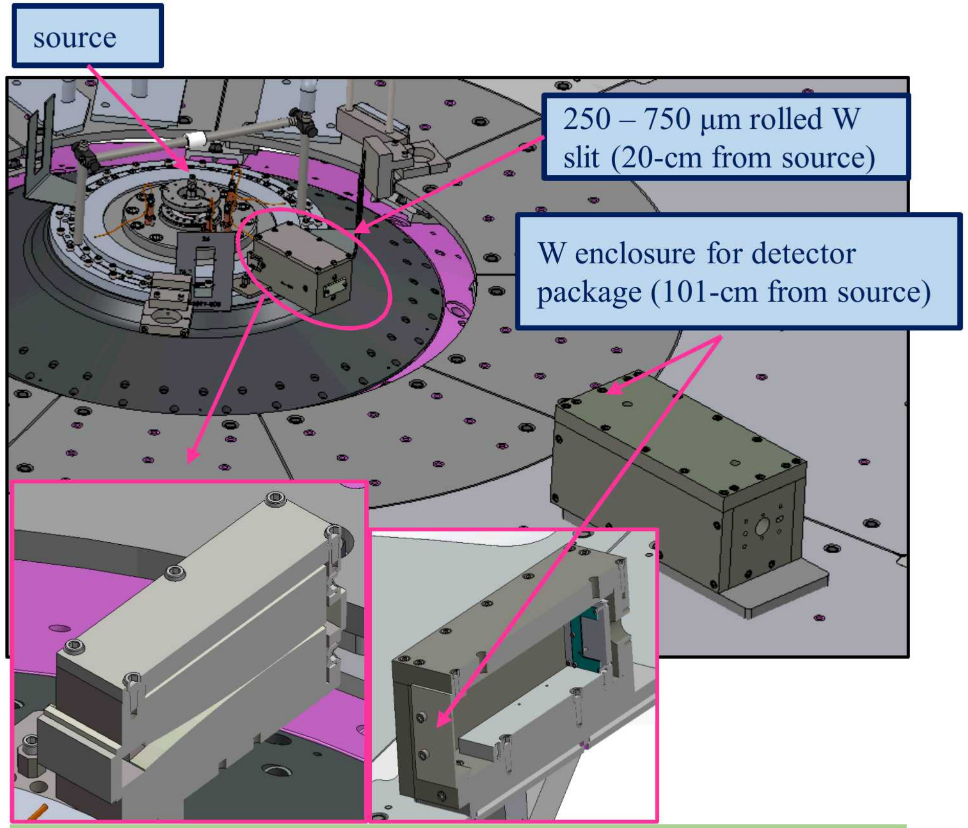
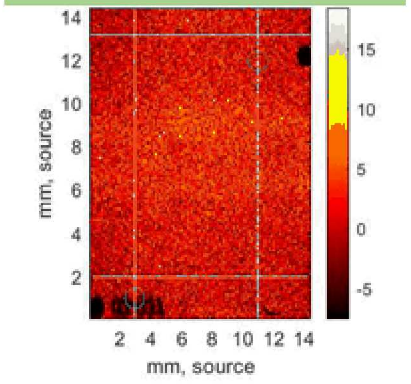
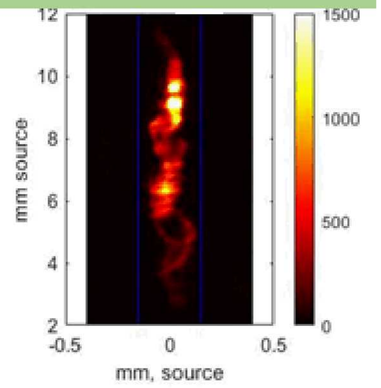


Diagram of ODIN

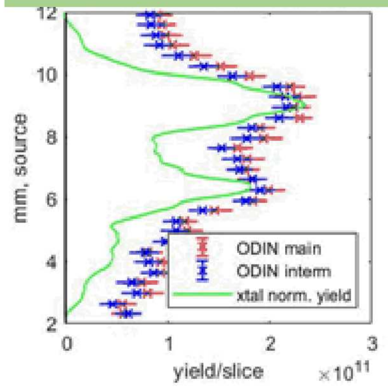
ODIN image de-magnified

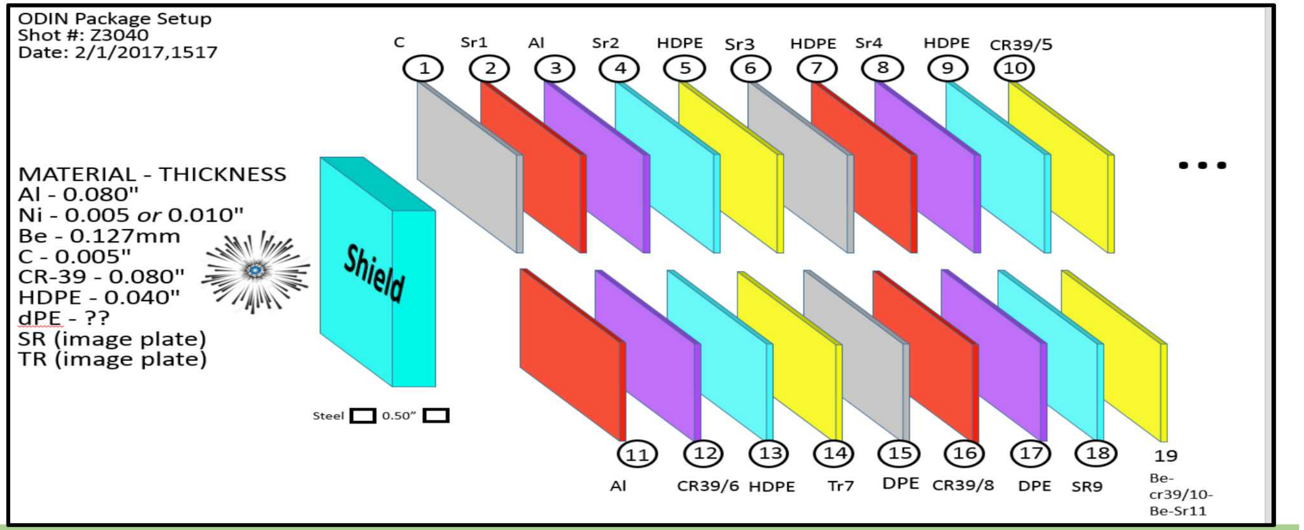


X-ray image of the source



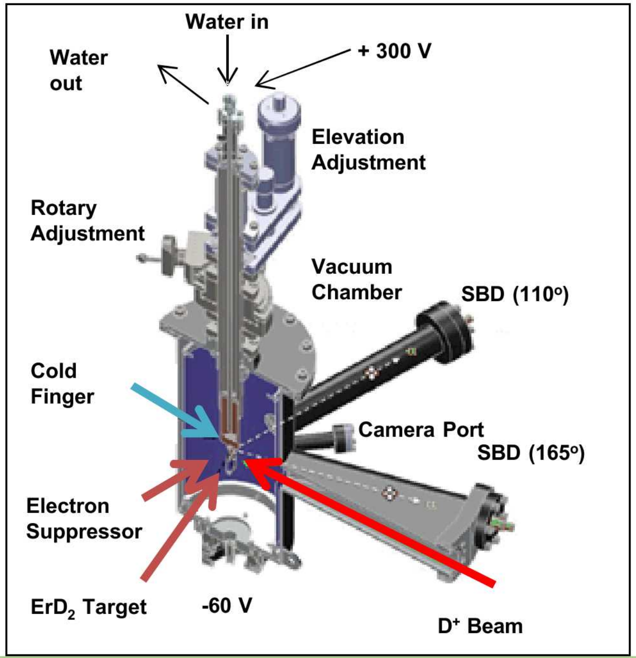
X-ray and ODIN comparison



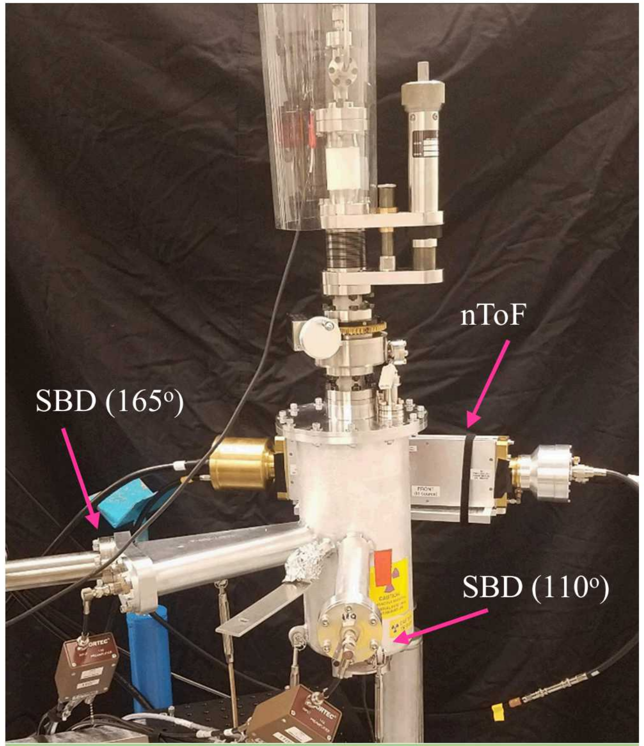


Typical detector package uses image plate and CR-39 detectors with various radiators

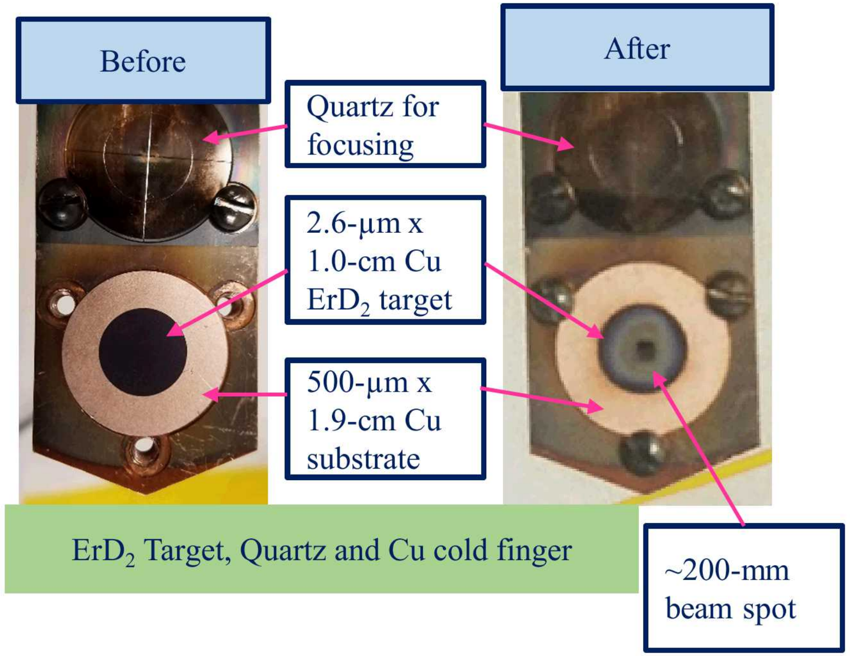
Diagnostics fielded on the Z-accelerator are characterized using a 300-keV Cockroft-Walton generator at the Ion Beam Laboratory.



Schematic of the IBL neutron target chamber



IBL target chamber, shown is a dual PMT nToF under study



ErD_2 Target, Quartz and Cu cold finger

C. L. Ruiz et al., Rev. Sci. Instrum. **83**, 10D913 (2012)

The neutron yield per steradian at any angle is inferred using the Associated Particle Method (APM).

- Associated Particle Method
  - Transformation of differential cross-sections from center-of-mass to the lab frame using relativistic kinematics
  - Accounts for loading ratio and dE/dx ion losses in the target

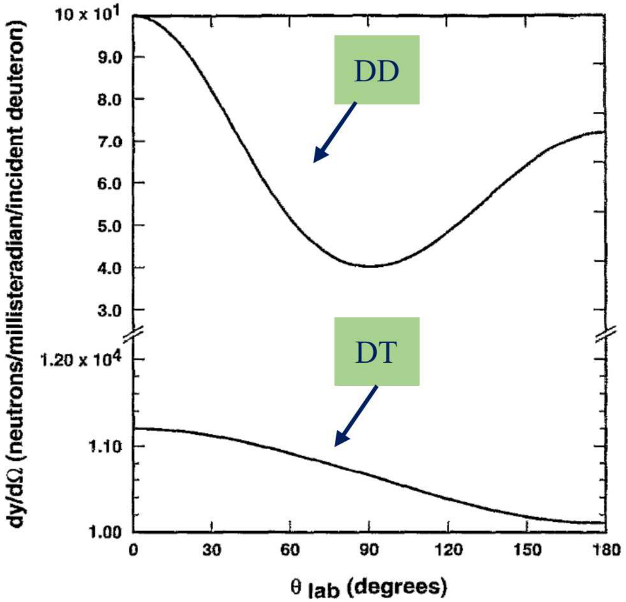
Thick target yield

$$\frac{dy}{d\Omega} = \int_{E_{max}}^{0} \frac{n d\sigma(E)/d\Omega}{dE/dx} dE$$

Incident neutron fluence on a cylindrical sample

$$\phi\left[\frac{n}{cm^2}\right] = (C - B)_\alpha \left(\frac{Y_n}{Y_\alpha}\right)\left(\frac{\Omega_n}{\Omega_\alpha}\right)\left(\frac{t_o}{\pi r_s^2}\right)$$

- ϕ: Neutron flux
- $(C - B)_\alpha$: Net Charged Particle Counts
- Y_n/Y_α: Calculated yield ratio
- Ω_n/Ω_α: Solid angle ratio
- πr_s^2: Sample surface area
- t_o: Irradiation time



Estimated thick target neutron yield for DD and DT reactions as a function of lab angle

C. L. Ruiz et al., Rev. Sci. Instrum., **63**, 4889 (1992)
C. L. Ruiz et al., Rev. Sci. Instrum. **83**, 10D913 (2012)

The calibration factor inferred for the activation diagnostics is known as the F-factor.

- F-factor characterizes the entire detector system
- Examples:
  - Indium sample + HPGe detector
  - Copper sample + NaI coincidence
  - Beryllium detector + CFD (constant fraction discriminator)

C. L. Ruiz et al., Rev. Sci. Instrum., **63**, 4889 (1992)
C. L. Ruiz et al., Rev. Sci. Instrum. **83**, 10D913 (2012)
J. D. Styron et al., Rev. Sci. Instrum. **85**, 11E617 (2014)
C. L. Ruiz et al., submitted to Phys. Rev A (2018)

Expected number of net counts from an exposed cylindrical activation sample

$$(C-B)_n = \frac{\phi\varepsilon_A\varepsilon_D\varepsilon_S\varepsilon_B M N_A \sigma(E)\left[\left(1-\mathrm{e}^{\lambda t_o}\right)\left(e^{-\lambda t_1}-e^{-\lambda t_2}\right)\right]}{\lambda A_w}$$

Calibration F-factor

$$F\left[\left(\frac{cts}{n}\right)\left(\frac{cm^2}{g}\right)\right] = \frac{\phi\varepsilon_A\varepsilon_D\varepsilon_S\varepsilon_B N_A \sigma(E)}{\lambda A_w}$$

F-Factor determined as determined from measurable quantities at IBL

$$F\left[\left(\frac{cts}{n}\right)\left(\frac{cm^2}{g}\right)\right] = \frac{\lambda (C-B)_n}{\phi M\left[\left(1-\mathrm{e}^{\lambda t_o}\right)\left(e^{-\lambda t_1}-e^{-\lambda t_2}\right)\right]}$$

Isotropic neutron yield calculated on MagLIF experiment

$$Y_z = 4\pi d^2\phi(d) = \frac{4\pi d^2 (C-B)_z}{FM\left(e^{-\lambda t_1}-e^{-\lambda t_2}\right)}$$

ODIN is being tested at the IBL to understand the point spread function of the slit and the efficiencies of different radiator materials.

J. Frenje et al., Rev. Sci. Instr. **73,** 2597 (2002)
D. Ampleford et al. (accepted by Rev. Sci. Instr. **89** (2018)
J. Vaughan et al. (accepted by Rev. Sci. Instr. **89** (2018)

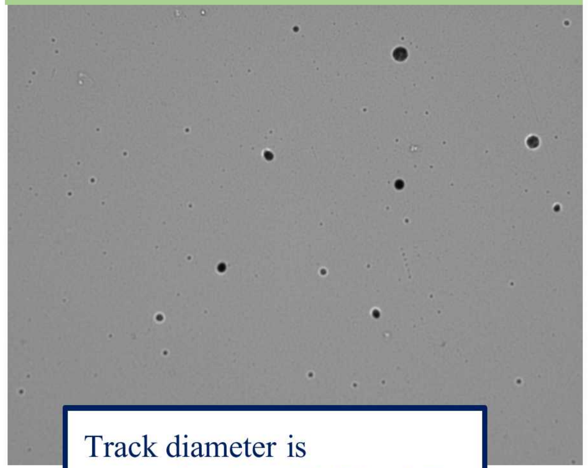
- CR-39 is a plastic substrate used to measure charged particles
- Etched with a 6-mol NaOH solution and viewed under a microscope to view the particle tracks

Experimental Results using the sample shown below at two different distances

	RUN 1		RUN 2	
	0°	95°	0°	95°
CR-39 Etched Label	02-032	03-033	03-035	03-034
Distance to Detector Package (in)	3	3	6	6
Distance to CR-39 Detector (in)	3.55	3.55	6.55	6.55
Active Beam Time (s)	66026	66026	226840	226840
Neutrons incident on CR-39	7.33E9	3.67E9	9.45E9	4.73E9
Neutrons incident per pixel	1.99E5	9.94E4	2.56E5	1.28E5
Neutron tracks per pixel	19.9	9.94	25.6	12.8

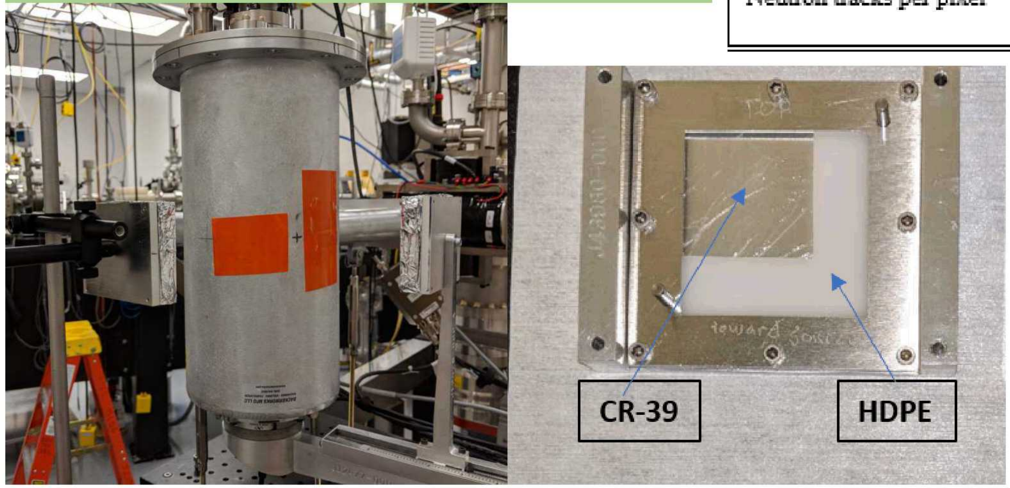
DT neutron efficiency is 1E-4 (tracks/incident neutron)

Typical scan of a CR-39 sample



Track diameter is proportional to dE/dX ~ 1/E

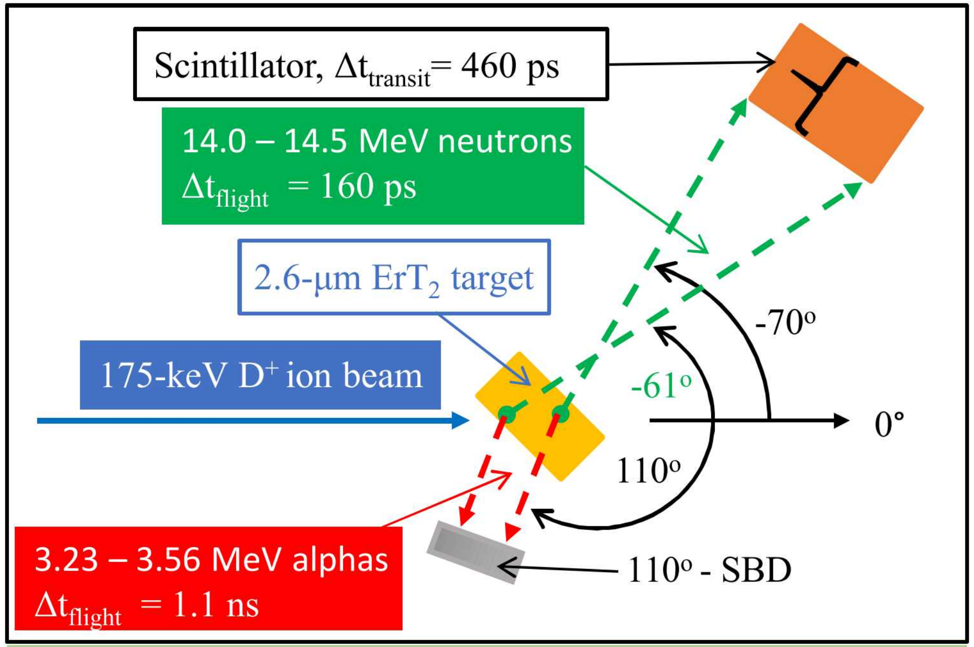
CR-39 samples (shown to the right) fielded at the IBL and exposed to DT neutrons



At the IBL we have developed a novel nToF instrument response function (IRF) measurement that utilizes particle coincidence to infer either DD or DT single neutron interactions.

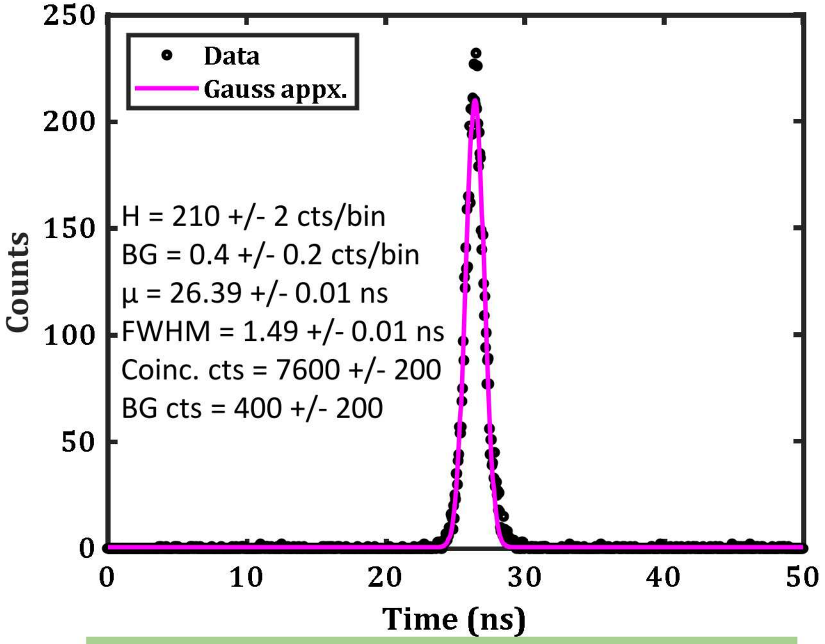
- Instrument Response Function is a measure of the time and energy dependent signal characteristics produced from a neutron time-of-flight detector
  - Scintillator decay
  - Photomultiplier tube
  - Light-guide
  - Does not include throughput delay
  - Historically measured using neutron surrogate sources (bremsstrahlung or x-rays)
- Particle coincidence is derived from the kinematic relationships
  - Related to the Associated Particle Method (APM) used to calculate absolute yields
  - Differences in the kinematics are variable due to dE/dx losses in the target

J. D. Styron et al. (accepted by Rev. Sci. Instr. **89** (2018)



t(d,α)n Kinematics for an incident 175-keV D^+ ion

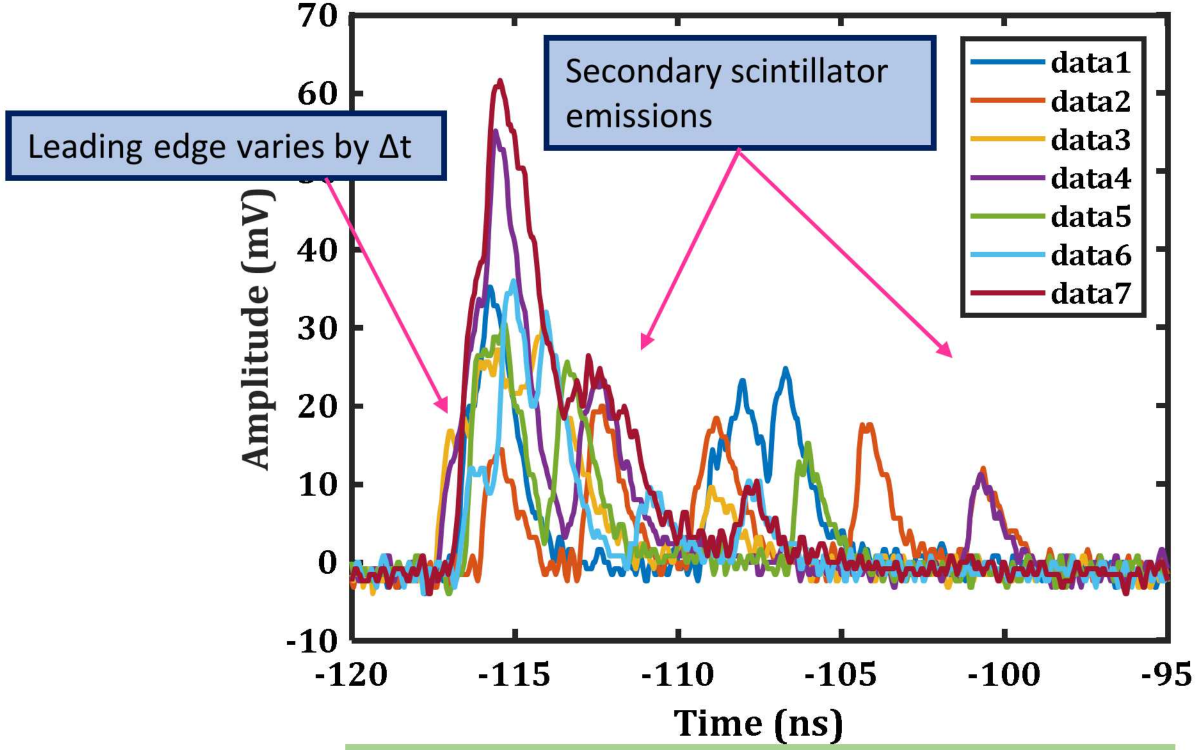
Coincidence is established using a time-to-pulse height converter and then used to trigger data acquisition on a 3.5 GhZ Tektronix DPO7354C Oscilloscope.



n-alpha coincidence curve for NTF22D, Photek at -4.0 kV

Δt for is comparable to expected value (1.49-ns vs. 1.7-ns, kinematics only)

J. D. Styron et al. (accepted by Rev. Sci. Instr. **89** (2018)

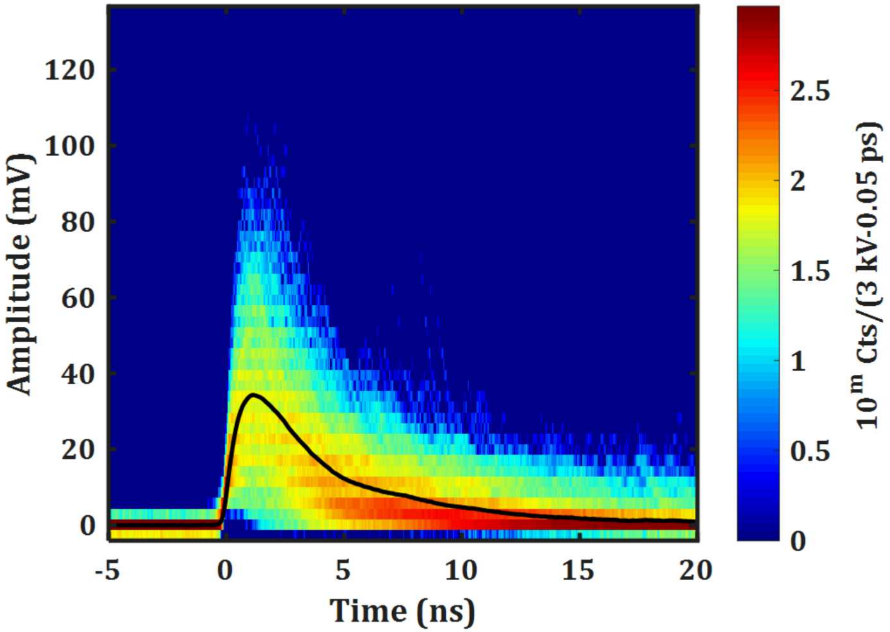


Waveforms as collected on the oscilloscope for NTF22D, Photek at -4.0 kV

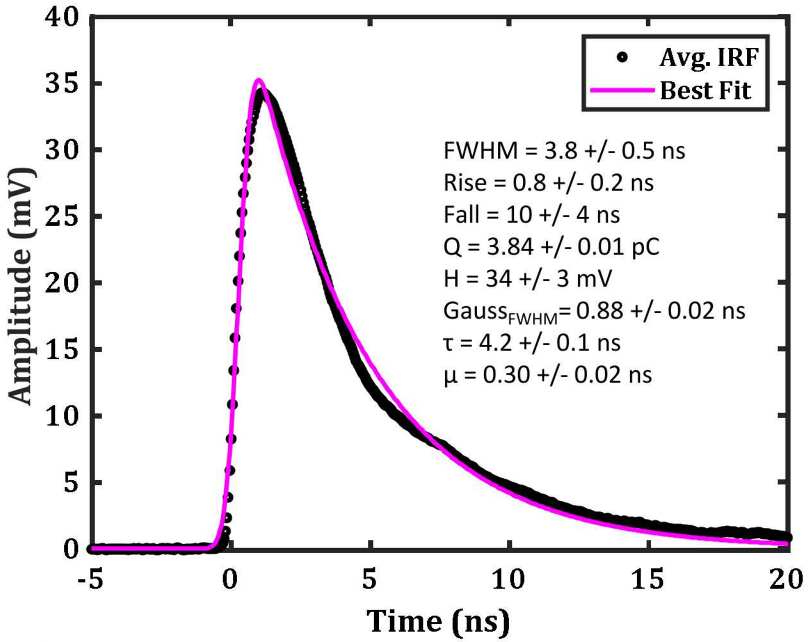
The IRF is an average of the leading-edge normalized data (10% of the max) , which can be described using an exponentially modified Gaussian function.

T. J. Murphy et al., Rev. Sci. Instr. **68**, 610 (1997)
J. D. Styron et al. (accepted by Rev. Sci. Instr. **89** (2018)

$$IRF(t,\mu,\tau,\sigma,A) = A * \exp\left(-\frac{t-\mu}{\tau}\right) * \exp\left(\frac{\sigma^2}{2\tau^2}\right) * \left(1 + \mathrm{erf}\left(\frac{t-\mu-\frac{\sigma^2}{\tau}}{\sqrt{2\sigma^2}}\right)\right)$$



Intensity plot of the normalized data (1000 acquisitions) shown with the average value. Data acquired with NTF22D, Photek at -4.0 kV



Average representation of the IRF. Fit parameters provide a metric to compare data points.

Conclusions

- Neutron diagnostics are a very important tool for diagnosing MagLIF plasmas and thus need to be very well understood (i.e. energy and time response)
- The experimental set-up on the Cockroft-Walton accelerator provides well characterized neutron sources (DD or DT) and experimental flexibility
- Precise quantities (< 7%) can be inferred using the Associated Particle Method