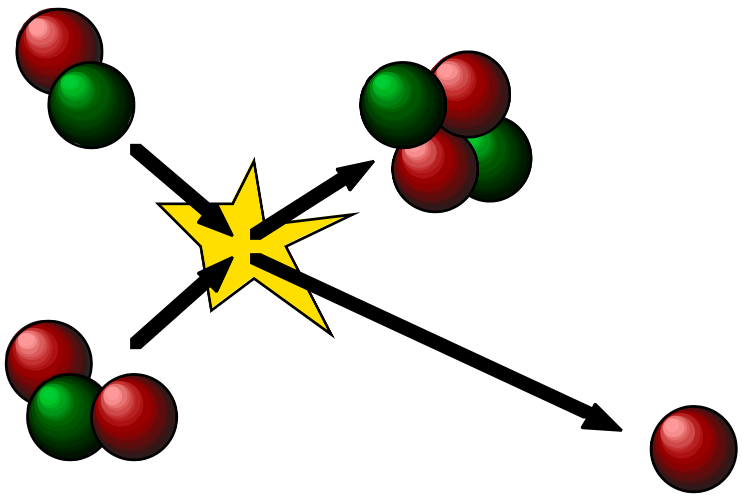
Nuclear Diagnostics for Inertial Confinement Fusion Implosions



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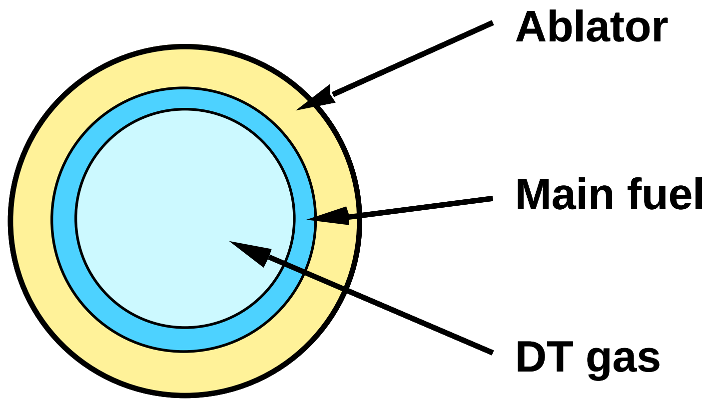
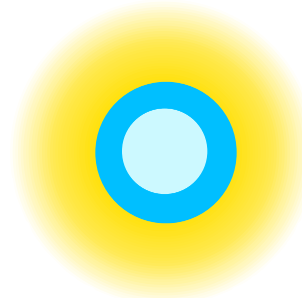
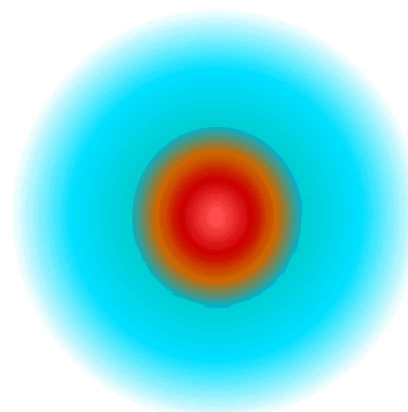
ICF goal: to compress and ignite a capsule of fusion fuel





Compression

Formation of Hot Spot



Thermonuclear Burn

Typical dimensions for ICF implosions

Imploded core size: 20–200 μm

Imploded core fuel temperature: 1–10 keV

Neutron yield: 10^6 – 10^{12} neutrons (DD)

10^8 – 10^{14} neutrons (DT)

Burn duration: ~100 ps

Reactions of interest in ICF

D + D → ^3He + n

D + D → T + p

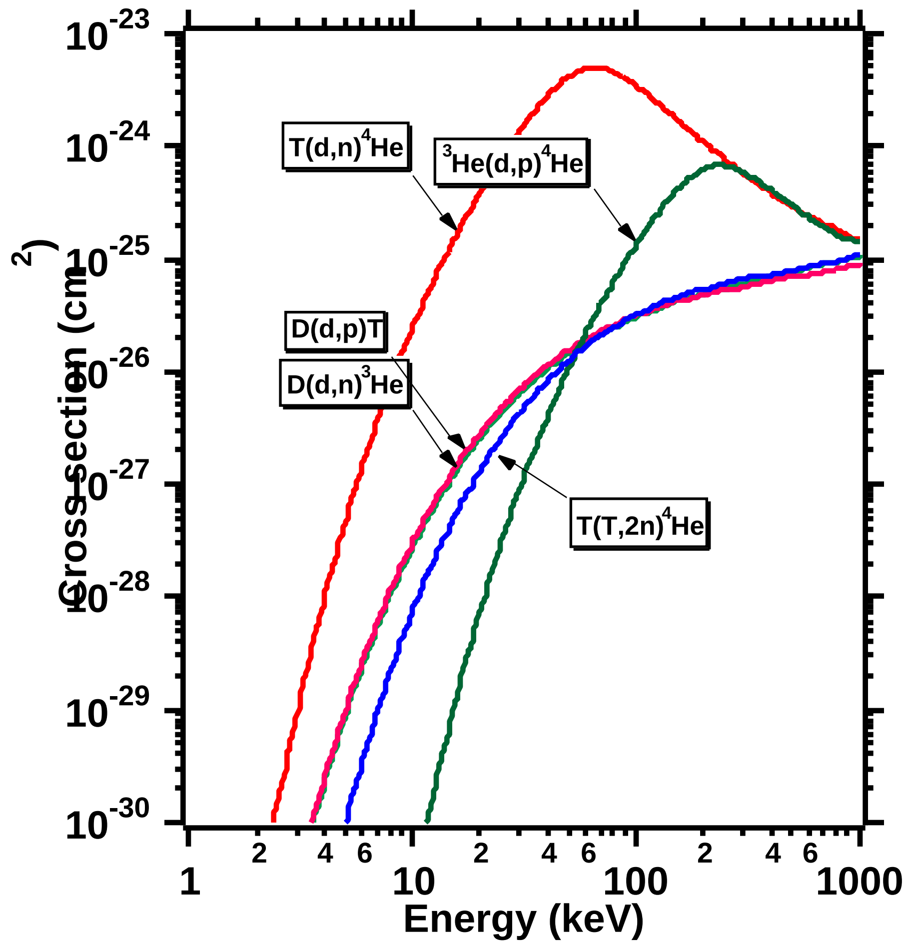
D + T → ^4He + n

D + ^3He → ^4He + p

T + T → ^4He + 2n

Also

D + T → ^5He + γ



Nuclear diagnostics have been used to measure a number of properties of ICF implosions

- Nuclear yield
- Ion temperature
- Implosion time
- Burn width/burn history
- Burn region
- Pusher areal density (ρR)
- Fuel areal density
- Mix

Nuclear diagnostics of ICF implosions have advantages and disadvantages compared to other methods

Advantages:

- **Diagnose deep in the core**
- **Neutrons and gammas can escape easily**

Disadvantages

- **Can only give information about conditions at peak burn**
- **No information about badly failed (no yield) targets**
- **Imaging difficult**

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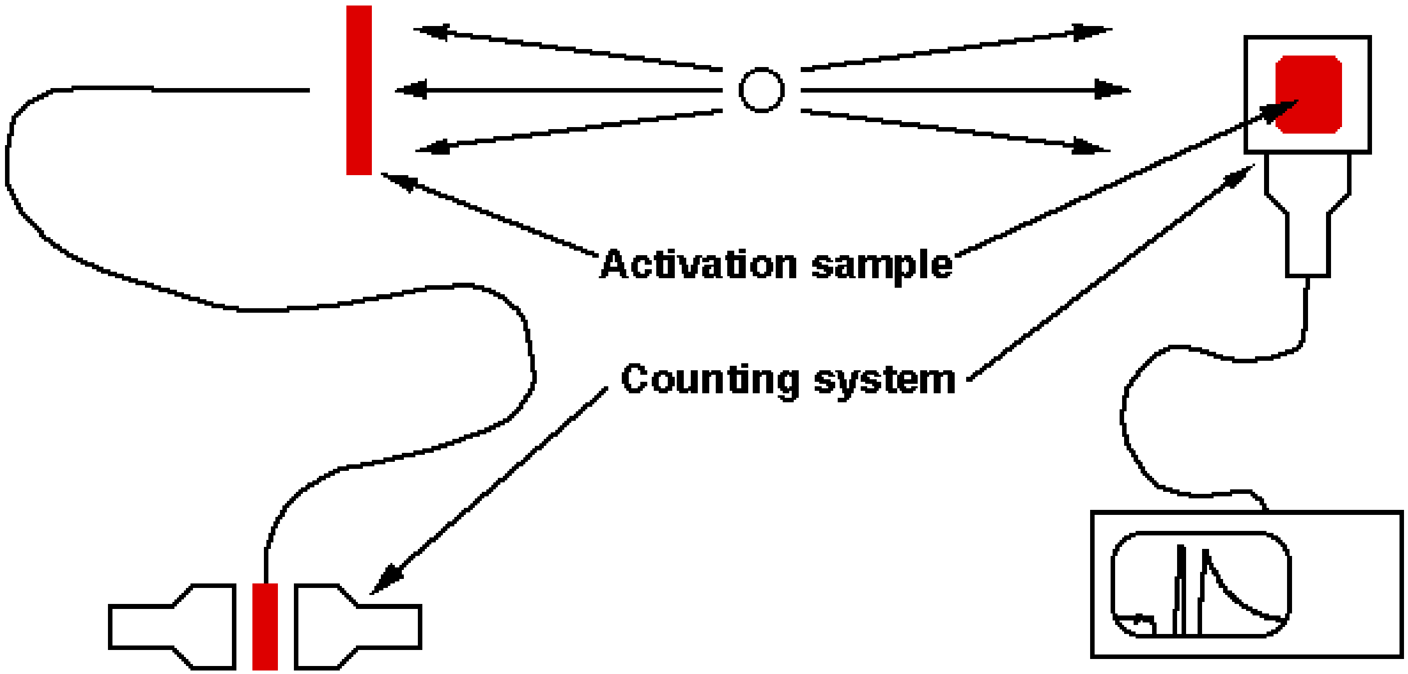
Activation techniques are used for DD and DT neutron measurements in ICF and MFE

Reaction	$\tau_{1/2}$	Threshold	γ/β (MeV)
^{115}In(n,n´)^{115m}In	4.50 h	0.3 MeV	0.336 γ
^{64}Zn(n,p)^{64}Cu	12.7 h	2.0 MeV	β^+
^{9}Be(n,α)^{6}He	800 ms	0.6 MeV	3.51 β^-
^{207}Pb(n,n´)^{207m}Pb	810 ms	1.6 MeV	0.024-0.304 γ
^{63}Cu(n,2n)^{62}Cu	9.8 min	11.9 MeV	β^+
^{16}O(n,p)^{16}N	7.2 s	10.2 MeV	6.13 γ, 4.27-10.4 MeV β
^{19}F(n,α)^{16}N	7.2 s	10.2 MeV	6.13 γ, 4.27-10.4 MeV β
^{27}Al(n,α)^{24}Na	15.0 hr	4.9 MeV	1.368 γ
^{27}Al(n,p)^{27}Mg	9.46 min	3.8 MeV	0.84-1.01 γ
^{28}Si(n,p)^{28}Al	2.24 min	3.8 MeV	1.78 γ
^{58}Ni(n,2n)^{57}Ni	36.0 hr	13.0 MeV	1.37 γ

Activation measurements can be made either remotely or *"in situ"*

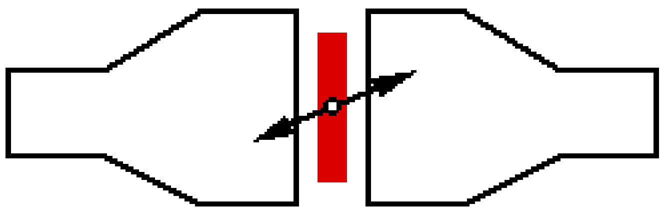


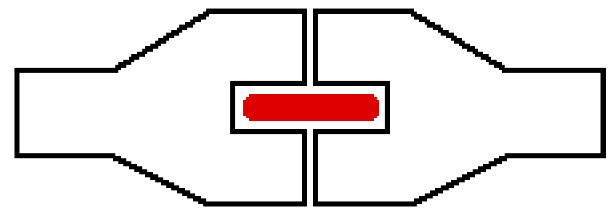
Remote counting
Cu, In, etc. Half-life greater than a few minutes
Background can be controlled

***In situ* counting**
Be, Pb, etc. Half-life too short for sample transport
Must be compatible with machine background

Remote samples can be counted in a manner consistant with the decay scheme and signal level

Low yield





Coincidence methods

Suitable for β^+ emitters or casade decays

Reduces background

Well detectors

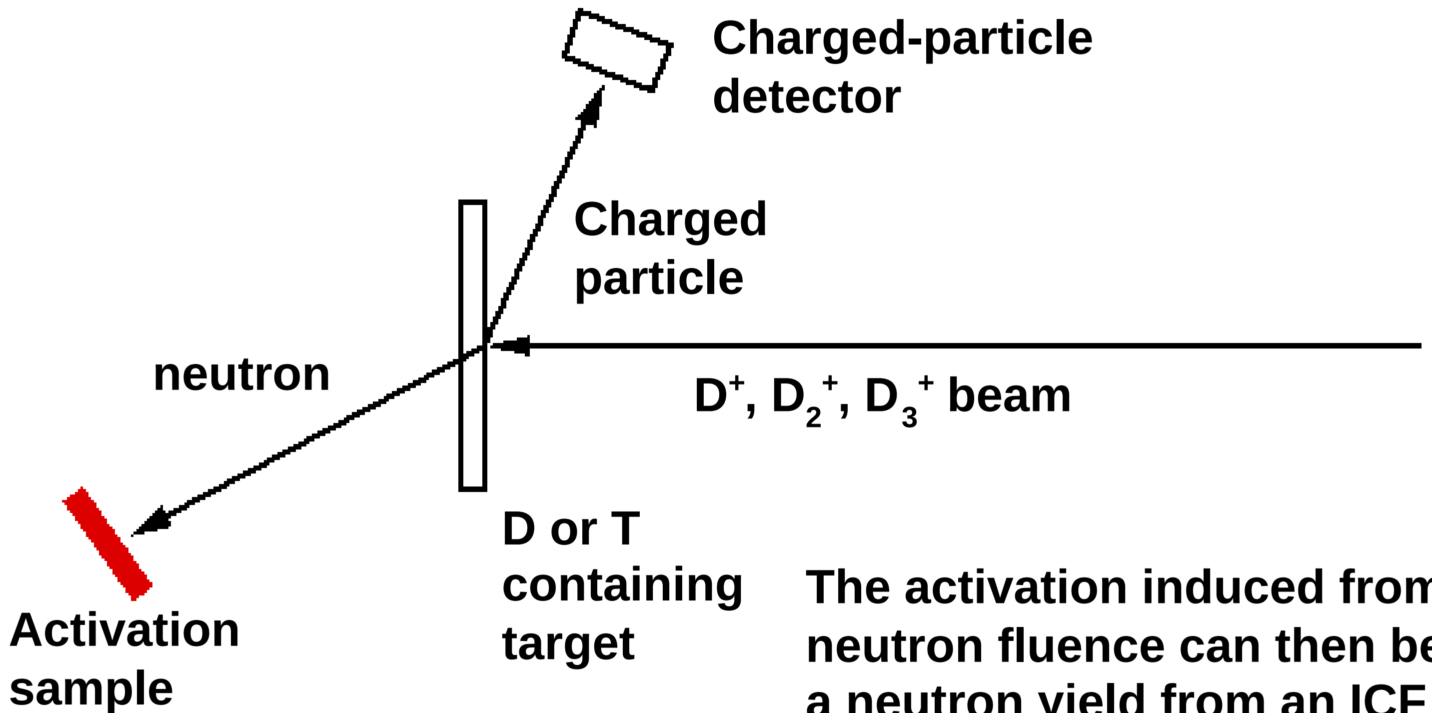
Suitable for decays with single gamma line

High efficiency, good shielding

High yield

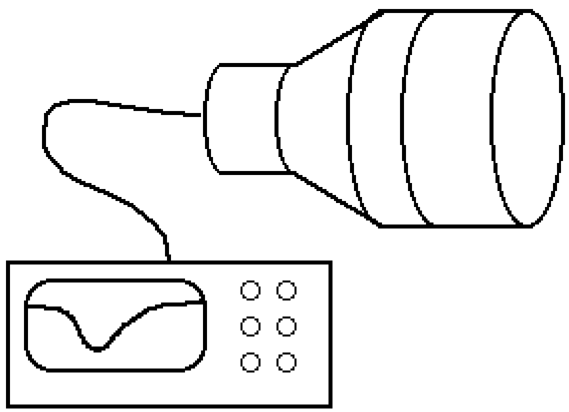
Adjustable distance to prevent pileup in detector

Calibrations are performed on neutron generators using associated particle techniques



The activation induced from a given neutron fluence can then be related to a neutron yield from an ICF target, given the placement of the detector relative to the target

Yields too low for activation techniques can be measured with scintillators



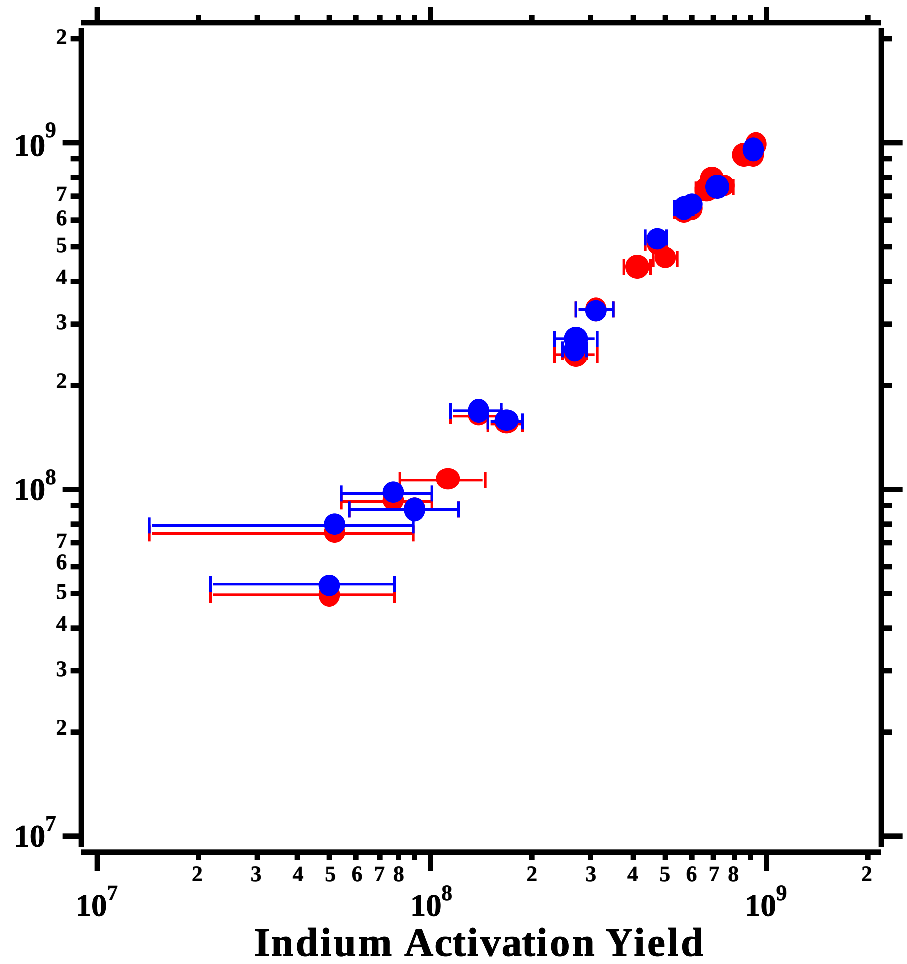
Direct neutrons separated from scattered neutrons by time-of-flight

Detectors are cheap and sensitive

Systems are hard to calibrate directly, but can be cross-calibrated to activation system on higher-yield shots

Nearly all neutron diagnostics can be cross-calibrated to absolutely calibrated systems to allow yield measurements or estimates.

The combination of activation techniques and scintillator-based yield diagnostics has been very successful on Nova

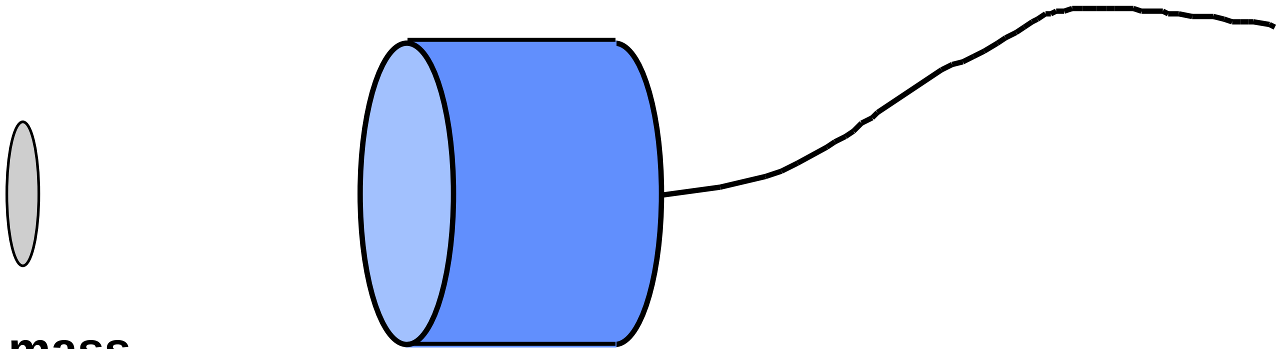


The signal from a scintillator tracks the yield from the Indium Activation system very well over a large portion of the range of interest on Nova.

Scintillator:

- BC-422
- 4.6 cm diam
- 2.4 cm thick
- 3-stage MCP-MPT
- 192 cm from TCC

For large yields, dosemetric neutron cross sections may be used



Low-mass activation foil (negligible self-absorption)

Absolutely-calibrated gamma detector

$$Y_n = \frac{4\pi r^2 N_{\gamma,\infty}}{\sigma f \varepsilon}\,\frac{A}{N_A a m}$$

$$N_{\gamma,\infty} = \frac{N_\gamma}{e^{-\tau_{delay}/\tau}\left(1-e^{-\tau_{count}/\tau}\right)}$$

r = activation foil distance

$N_{\gamma\infty}$ = counts over infinite counting time

σ = cross section

f = branching ratio of decay

ε = detector efficiency

A = atomic mass of activation element

a = abundance of activated isotope

m = mass of foil

N_A = Avagadro' number

Other techniques have also been used

- Plastic track detectors to record charged particle tracks

[see, for example, Phillips et al., Rev. Sci. Instrum. 68, 596 (1997)]

- Recoil proton techniques which measure protons knocked out of plastic foils

[recent work by M. Moran at LLNL]

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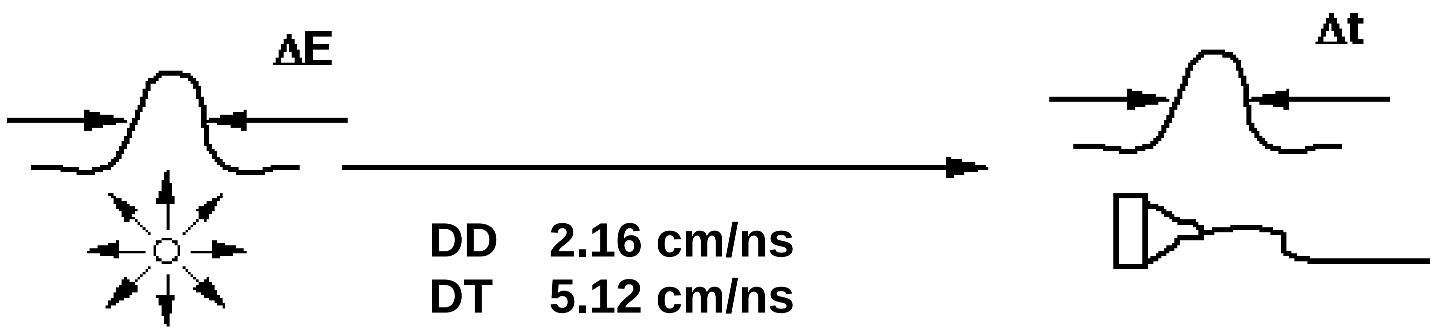
The usual method for measuring neutron energy spectra is through time-of-flight



The neutrons are born in a short time (~100 ps)

$$t = d\sqrt{\frac{m}{2E}}$$

$$\Delta t = \frac{d}{2v_o}\frac{\Delta E}{E_o}$$

Using these relations, at 10 m, 100 ps time resolution corresponds to:

DD	**1.1 keV resolution**
DT	**15 keV resolution**

For a Maxwellian ion distribution, the ion temperature can be determined from the neutron energy spectrum

Neutron energy in the center of mass frame (E_n') can be related to the lab frame (E_n) by:

$$E_n = \frac{1}{2}\left(\mathbf{v_n'} + \mathbf{V}\right)^2$$

$$= E_n' \left[1 + 2\frac{V}{v_n'}\cos\theta + \left(\frac{V}{v_n'}\right)^2\right]$$

so

$$\Delta E \equiv E_n - E_n'$$

$$= E_n' \left(2\frac{V}{v_n'}\cos\theta\right)$$

The width of the neutron energy spectrum is related to the distribution of center-of-mass velocities

$$f(v_1)f(v_2) = C_1 \exp\left[\frac{v_1^2}{2kT/m_1}\right]\exp\left[\frac{v_2^2}{2kT/m_2}\right]$$

$$= C_2 \exp\left[\frac{v^2}{2kT/\mu}\right]\exp\left[\frac{V^2}{2kT/M}\right]$$

From this expression, the FWHM$_{Vz}$ is given by

$$FWHM_{V_z} = \sqrt{\frac{(8\ln 2)kT}{M}}$$

And, therefore, the FWHM$_E$ is given by

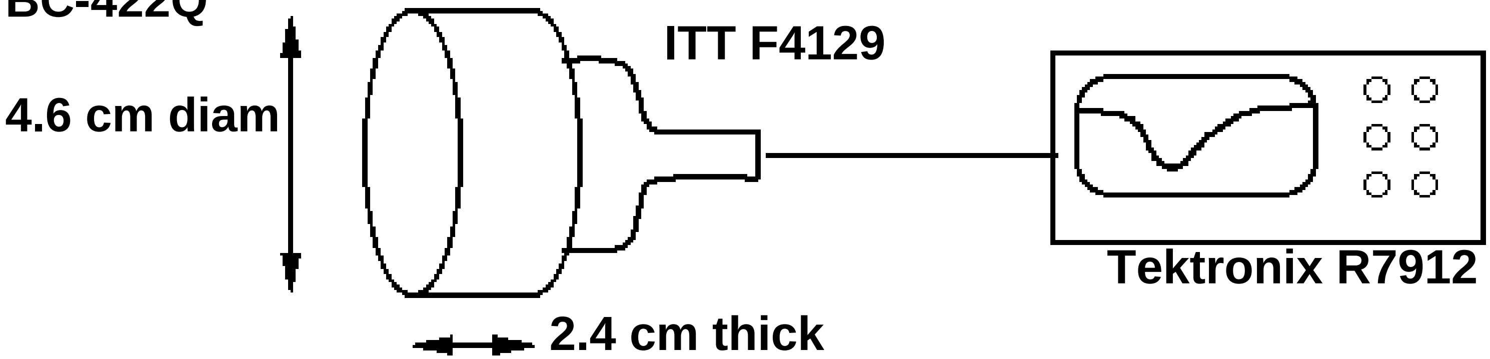
$$FWHM_E = \sqrt{(16\ln 2)\frac{m_n}{M}E'_n\,kT}$$

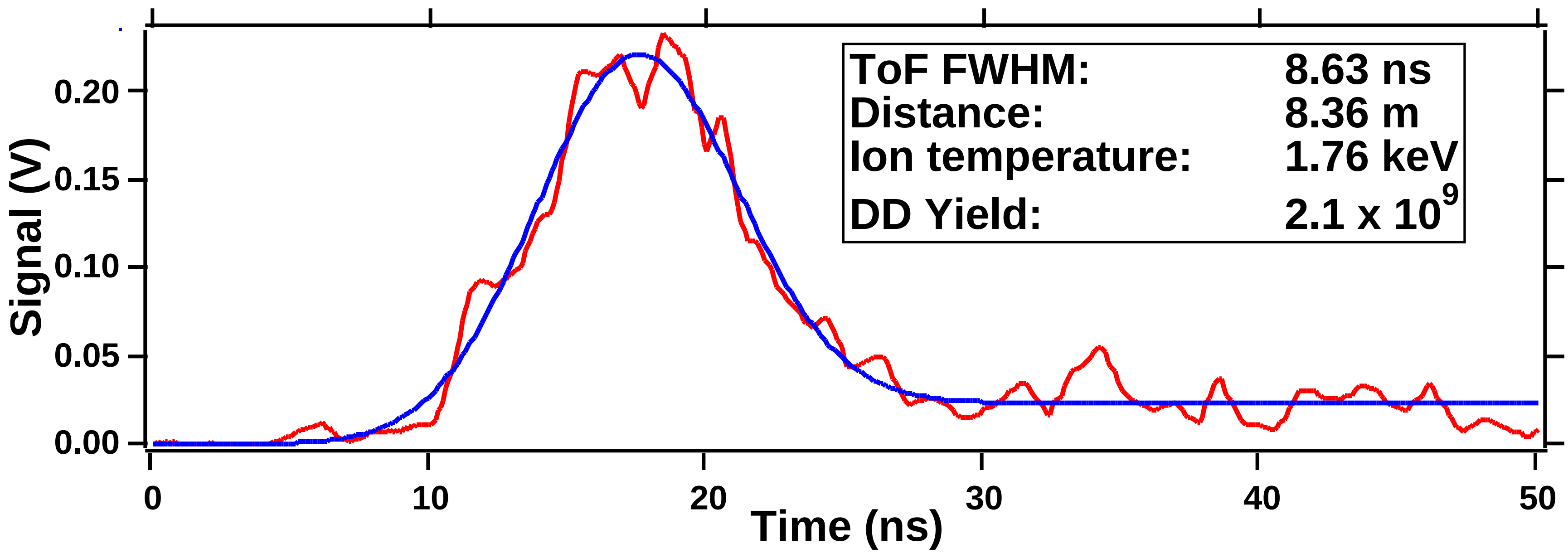
We therefore obtain the familiar expressions relating ion temperature to neutron energy width

$$kT_i = \begin{cases} \left(\dfrac{FWHM_E}{82.5\,\mathrm{keV}^{1/2}}\right)^2 & \text{for DD} \\ \left(\dfrac{FWHM_E}{177\,\mathrm{keV}^{1/2}}\right)^2 & \text{for DT} \end{cases}$$

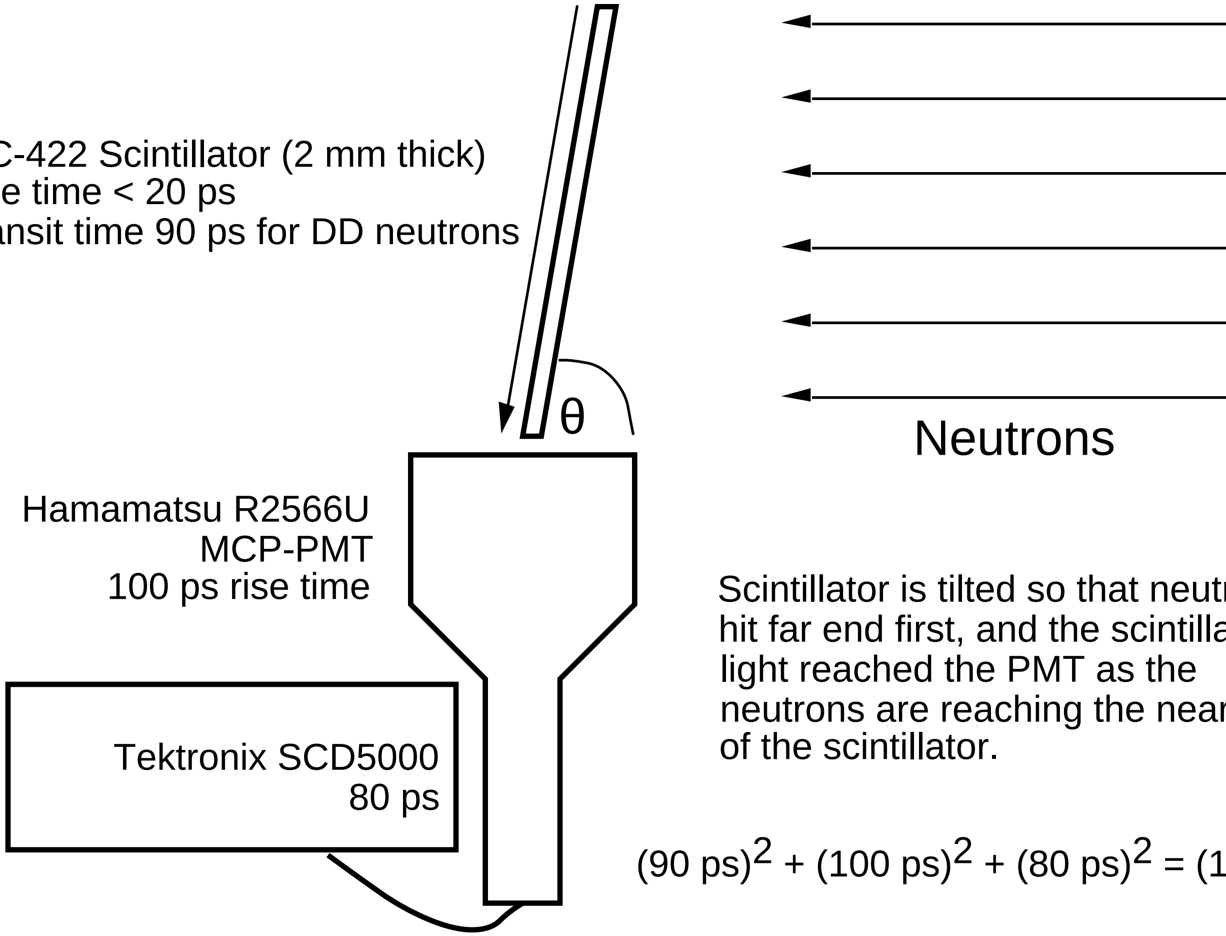
see, for example, H. Brysk, "Fusion neutron energies and spectra," *Plasma Phys.* 15, 611 (1973).

Neutron time-of-flight signals may be obtained with scintillators and fast photomultiplier tubes





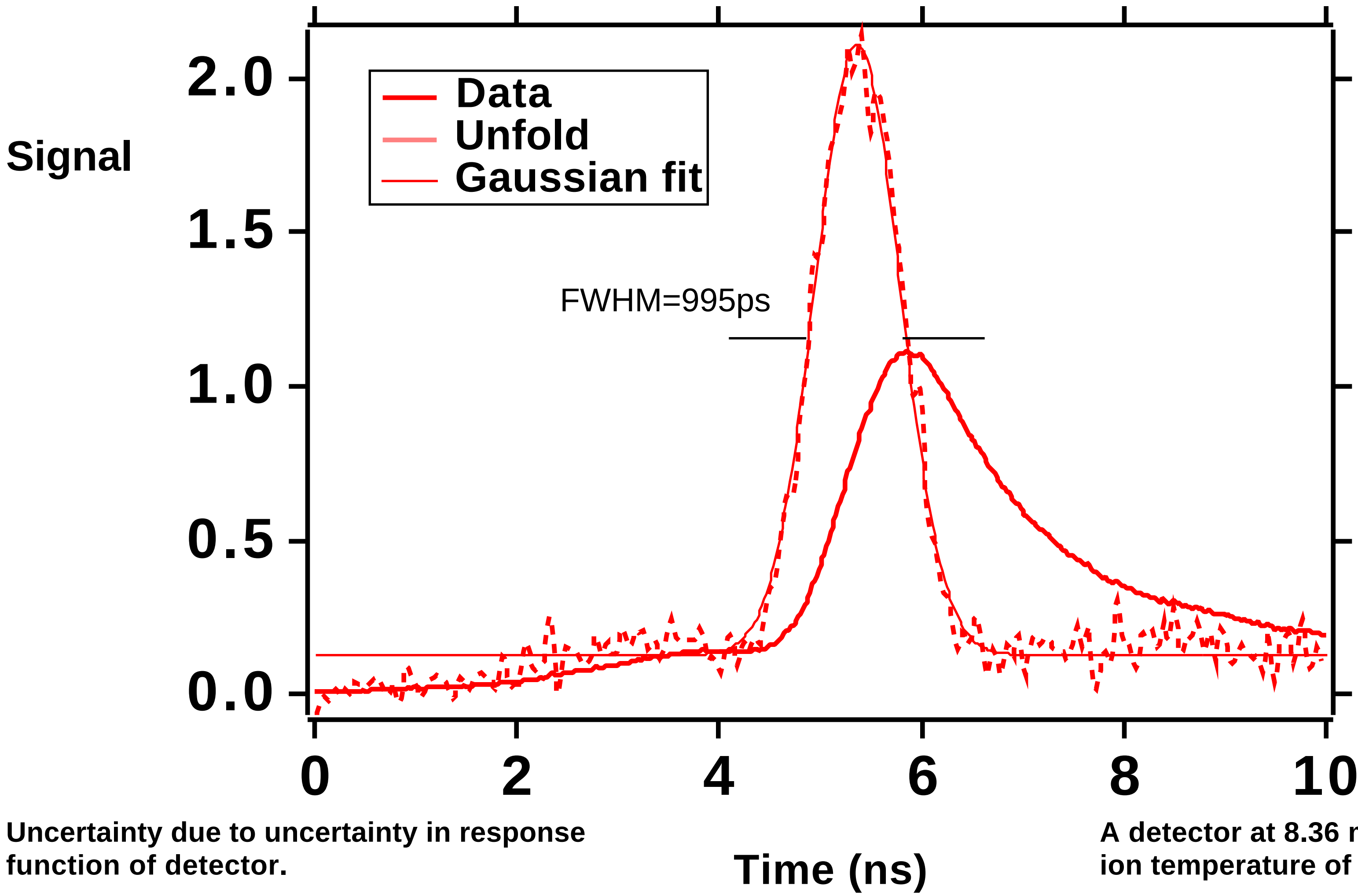
A modification of geometry can yield better time resolution without a loss of efficiency



Scintillator is tilted so that neutrons hit far end first, and the scintillation light reached the PMT as the neutrons are reaching the near end of the scintillator.

$$(90\ \text{ps})^2 + (100\ \text{ps})^2 + (80\ \text{ps})^2 = (160\ \text{ps})^2$$

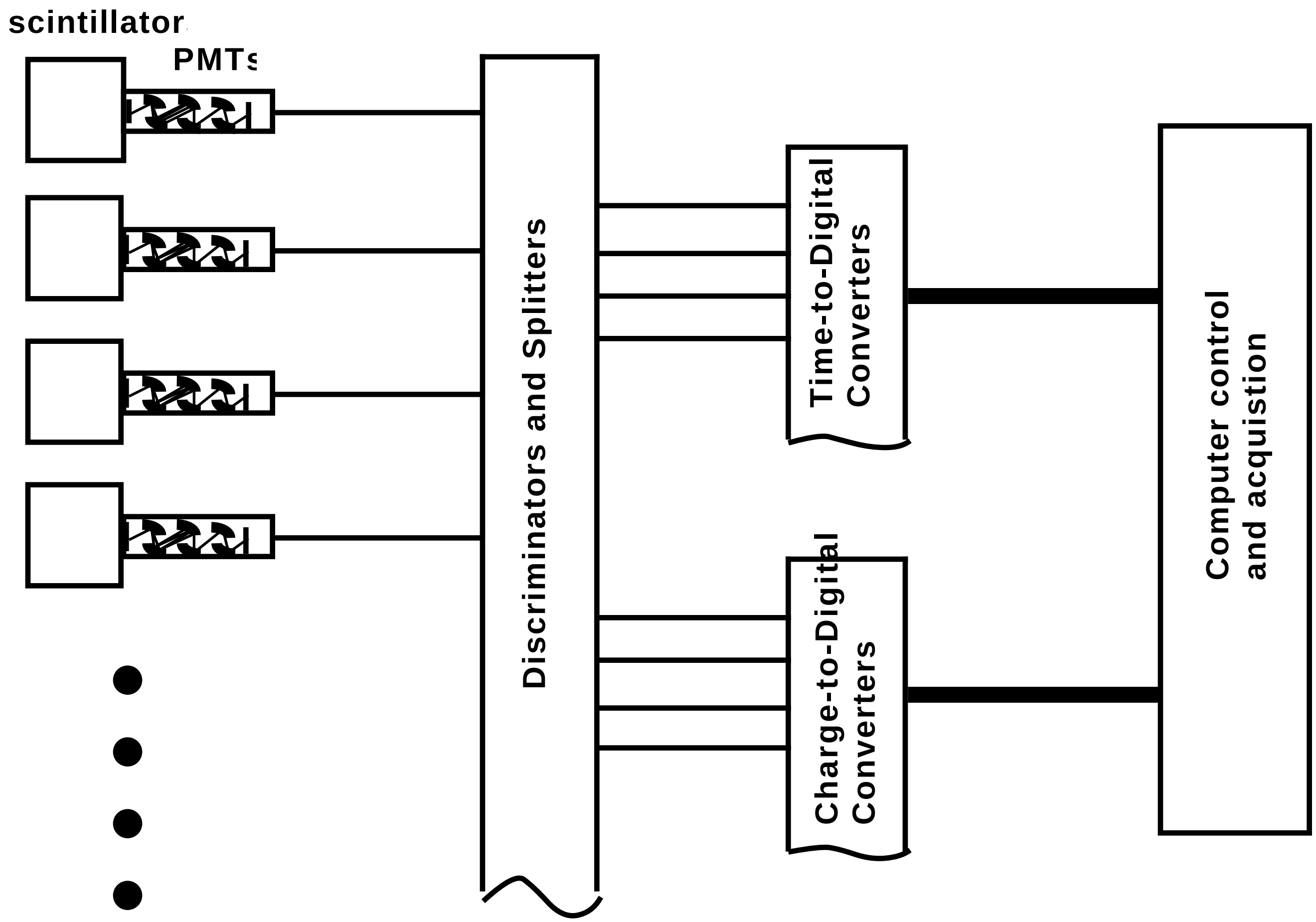
Data from a direct-drive DT shot yielding 1.3 x 10^{13} neutrons implies an ion temperature of 9.1±1.0 keV



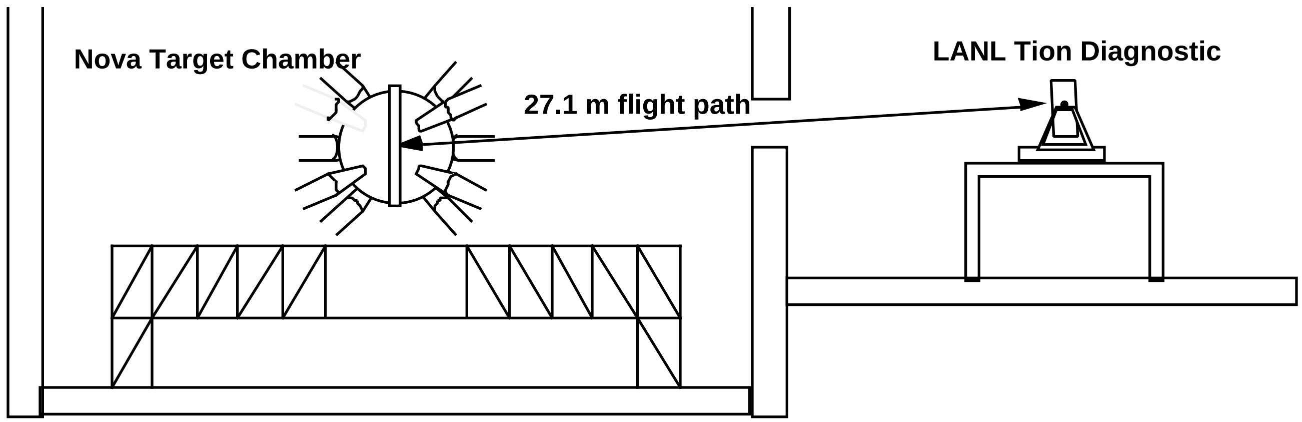
Uncertainty due to uncertainty in response function of detector.

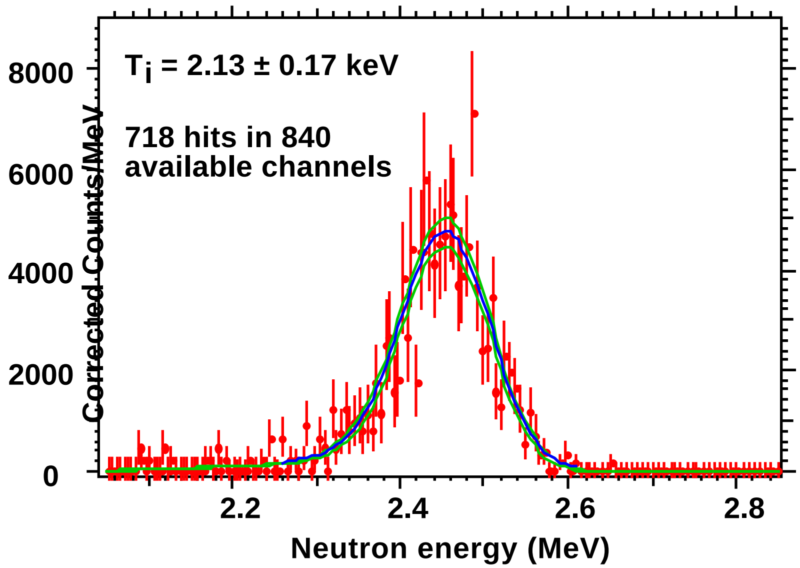
A detector at 8.36 m yielded an ion temperature of 8.3±1.0 keV.

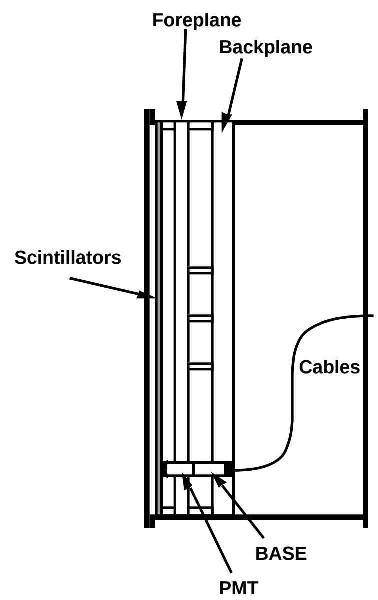
Single-hit neutron time-of-flight arrays have also been used for ion temperature measurements

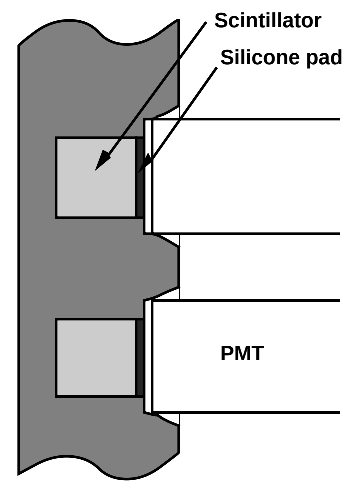


Ion temperatures on Nova are measured with the LANL Tion single-hit neutron detector array





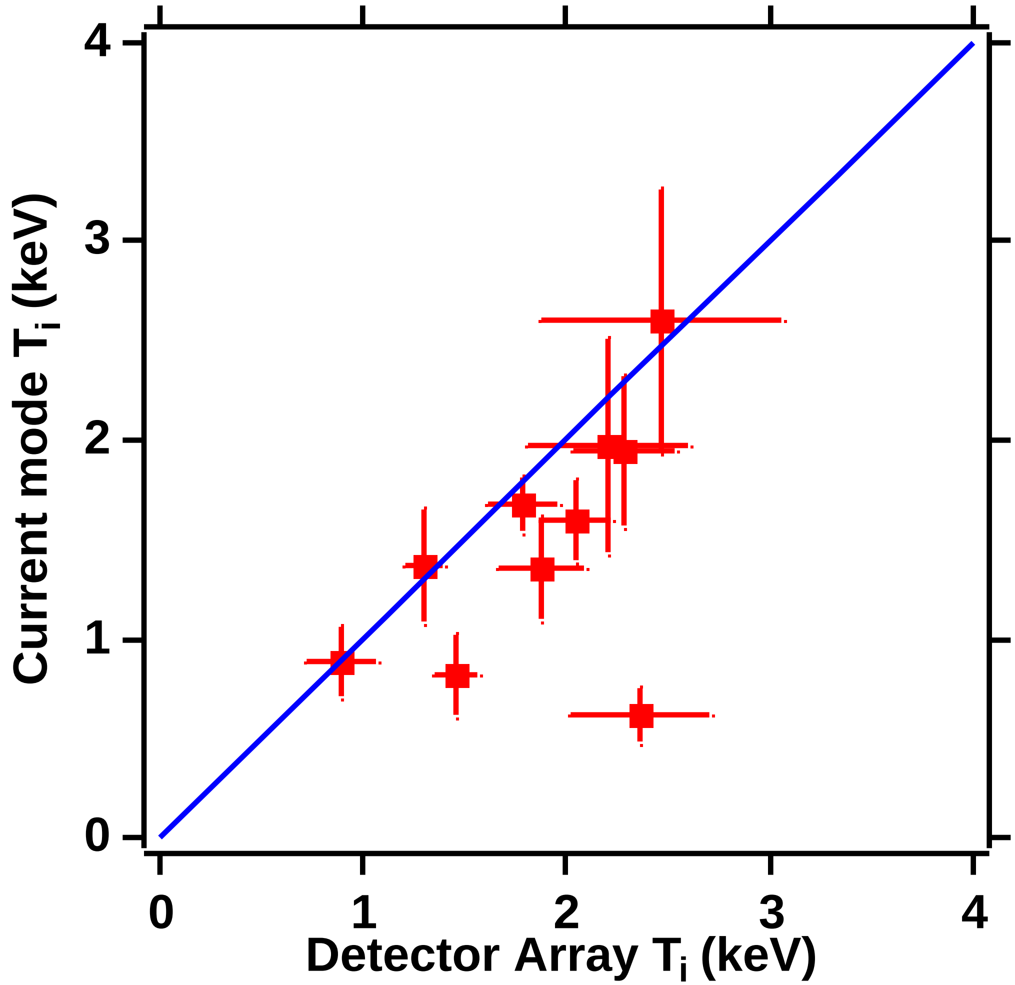




Current-mode and detector array ion temperatures are in good agreement where the yield is appropriate for both

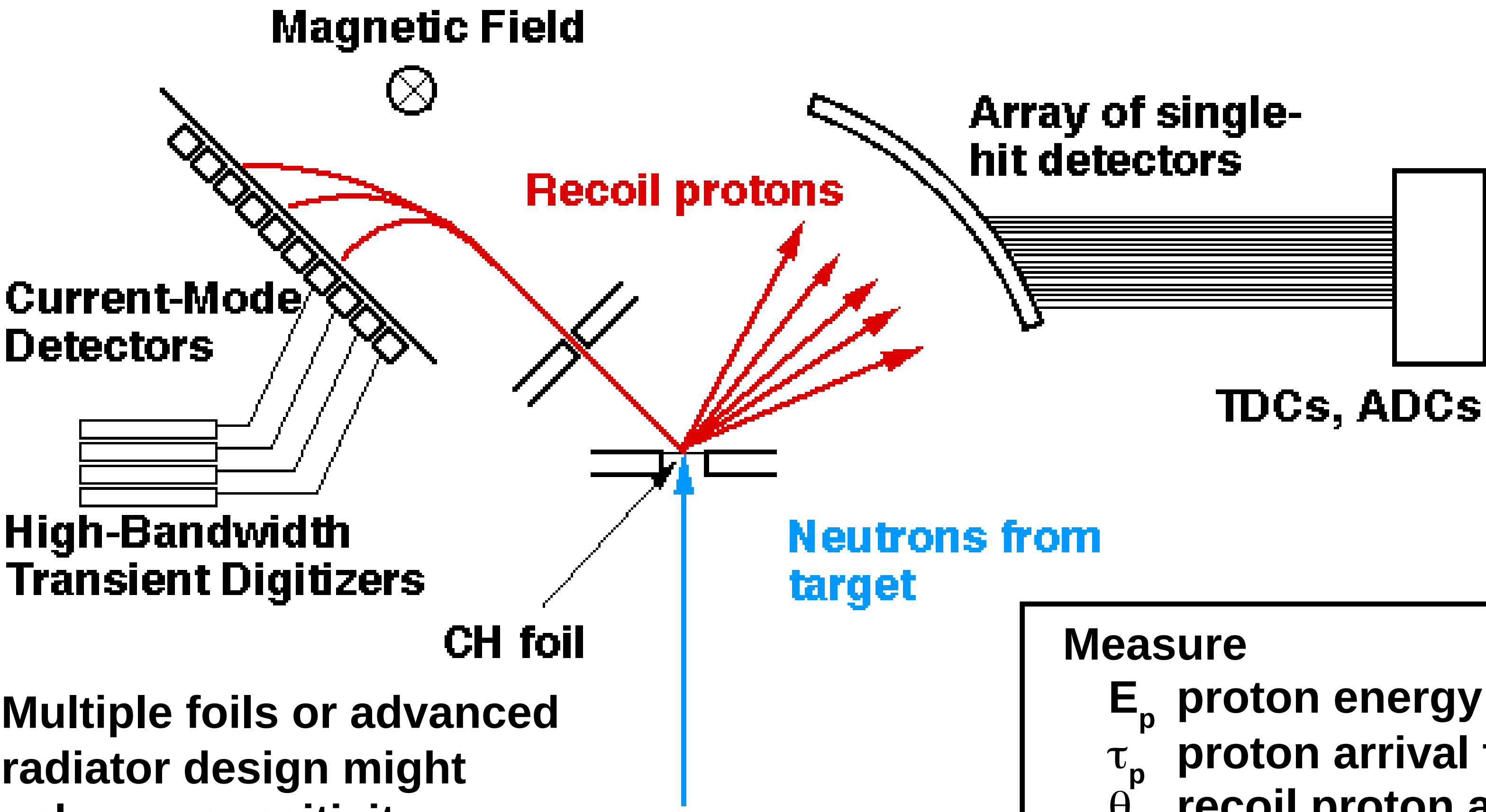
Limited to yields between $2x10^8$ and $2x10^9$

Current mode detector at 6 m



Murphy, Chrien, & Klare,
Rev. Sci. Instrum. 68, 610 (1997).

The higher neutron yields anticipated for NIF will allow innovative techniques such as recoil proton spectroscopy



Multiple foils or advanced radiator design might enhance sensitivity

Measure
- E_p proton energy
- τ_p proton arrival time
- θ recoil proton angle

From these, calculate:
- E_n neutron energy
- τ_n neutron birth time

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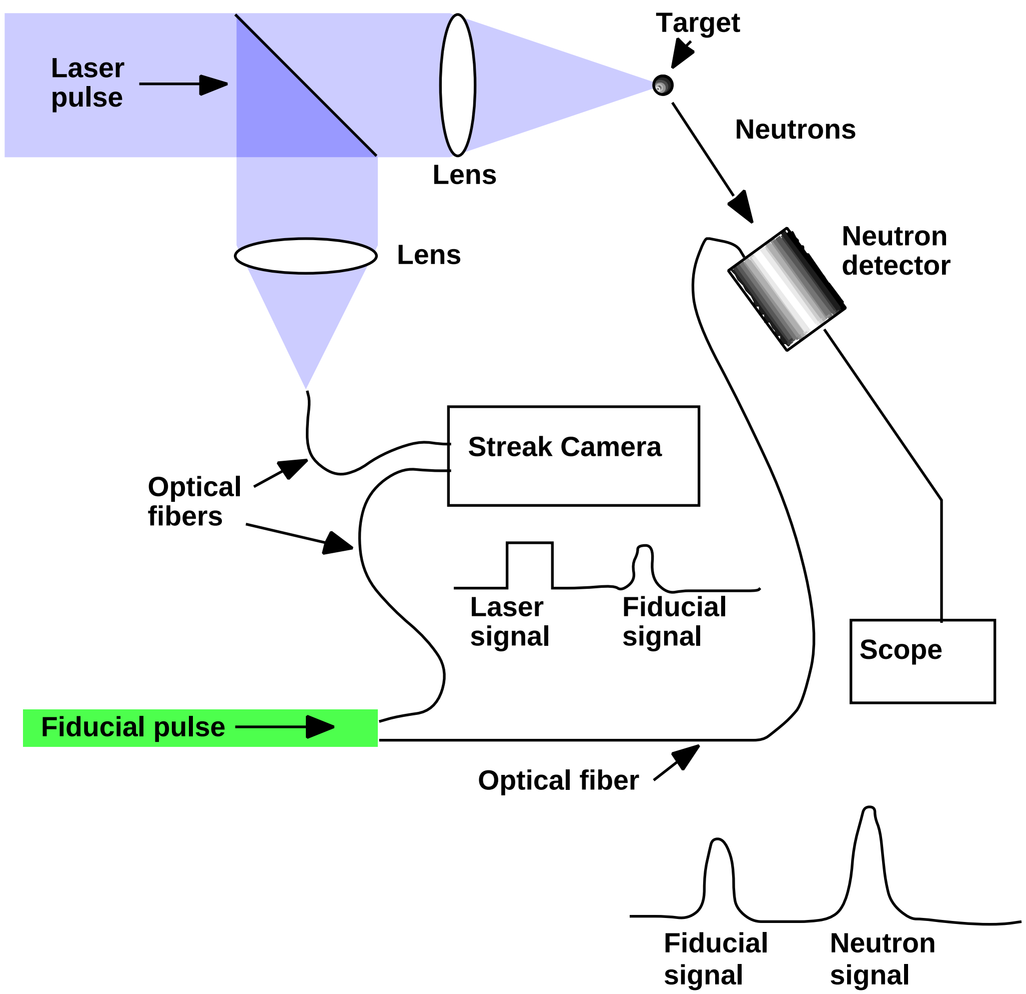
Measuring the implosion time requires relating the time of neutron emission to the laser pulse



$$t_n - t_l = \Delta t_{nf} - \Delta t_{lf} + \Delta t_{cal} - \Delta t_{tof}$$

where:

Δt_{nf} = neutron to fidu time

Δt_{lf} = laser to fidu time

Δt_{cal} = calibration number

Δt_{tof} = radiation time-of-flight

Lerche et al, Rev. Sci. Instrum. 59, 1697 (1988).

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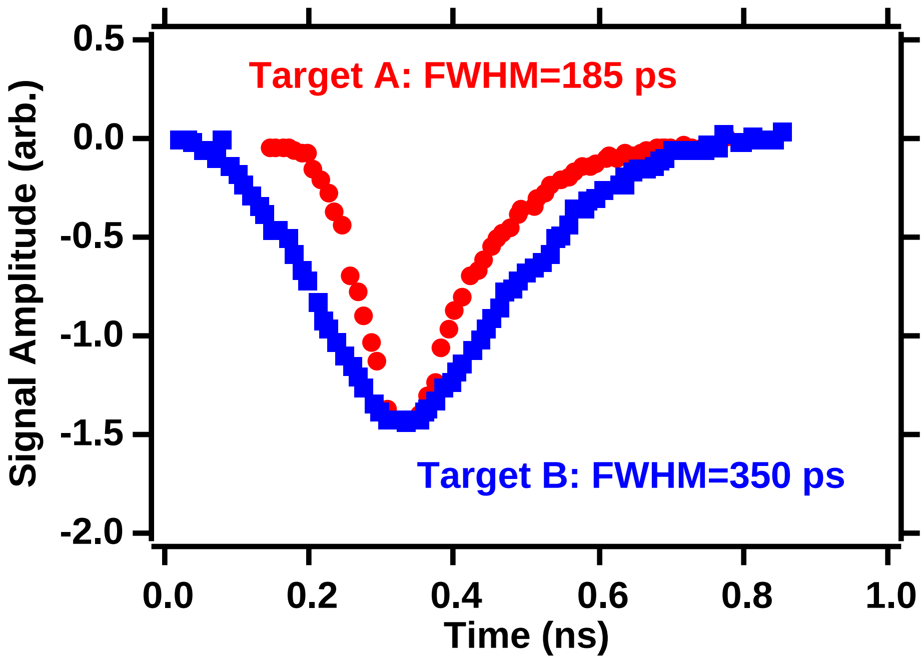
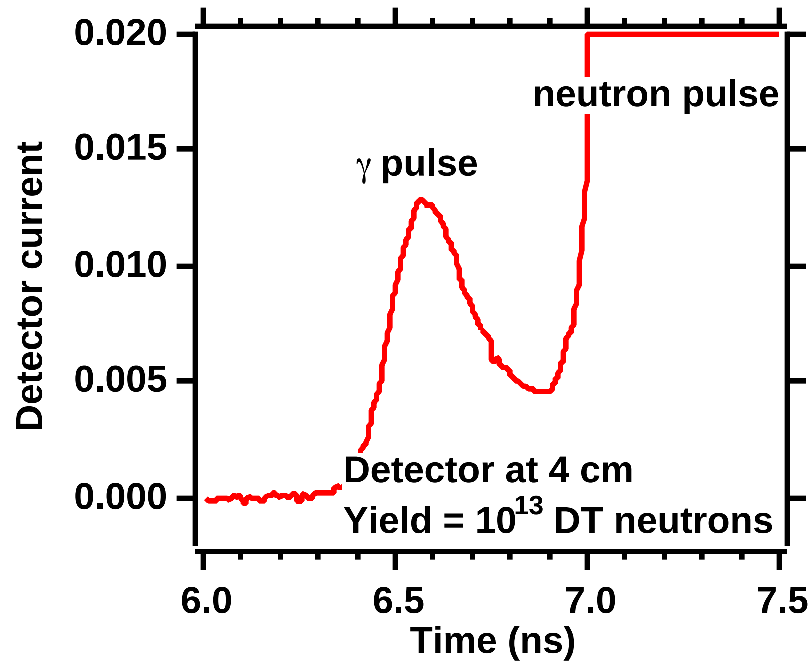
Solid state photoconductive detectors have been used to measure neutrons and gammas

14-MeV neutrons



Kania et al., Appl. Phys. Lett. 53, 1988 (1988).

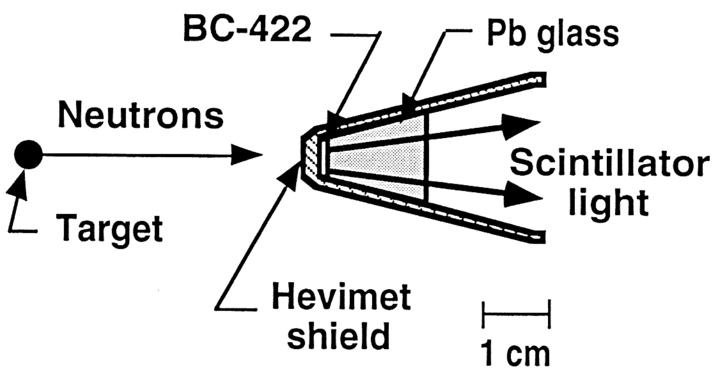
gamma rays



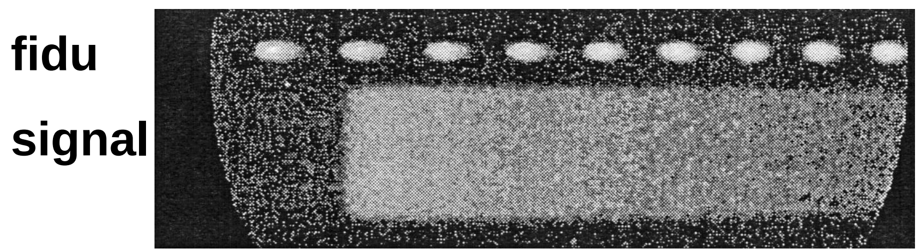
Caldwell et al, Rev. Sci. Instrum. 68, 603 (1997)

Fast plastic scintillators coupled to streak cameras allow time resolution in the 10s of ps

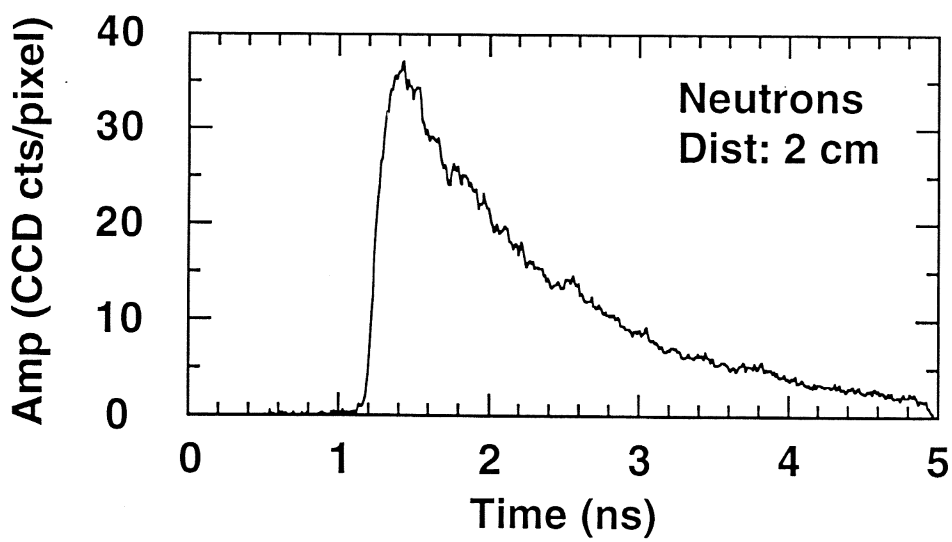
Nose cone



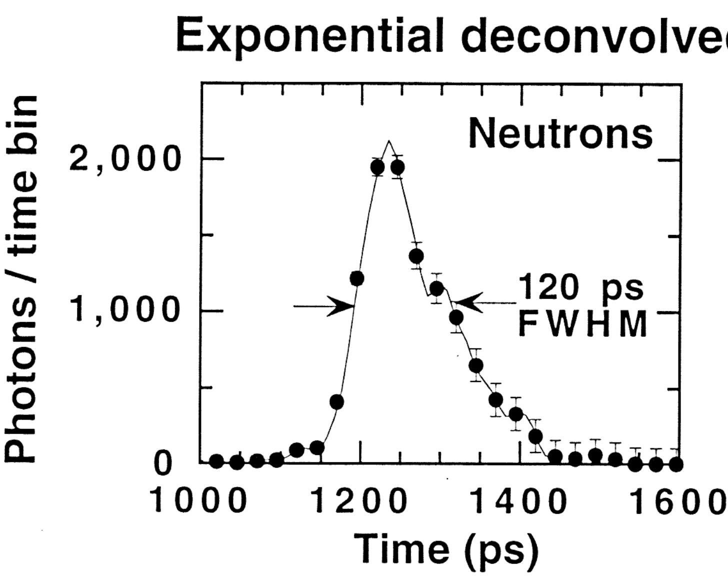
Data



Lineout

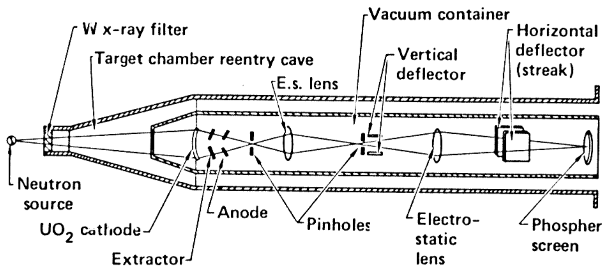


Deconvolved signal



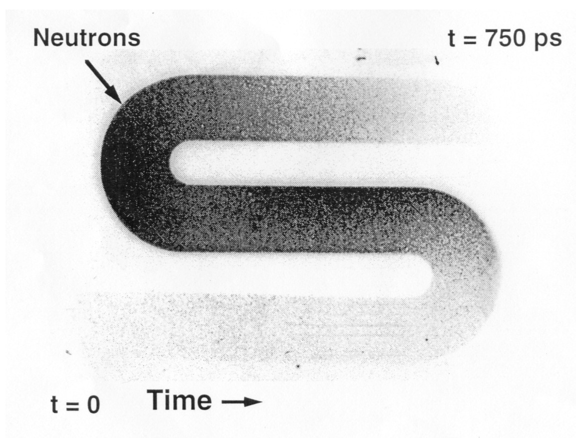
Lerche et at., at 11th LIRPP, 1993.

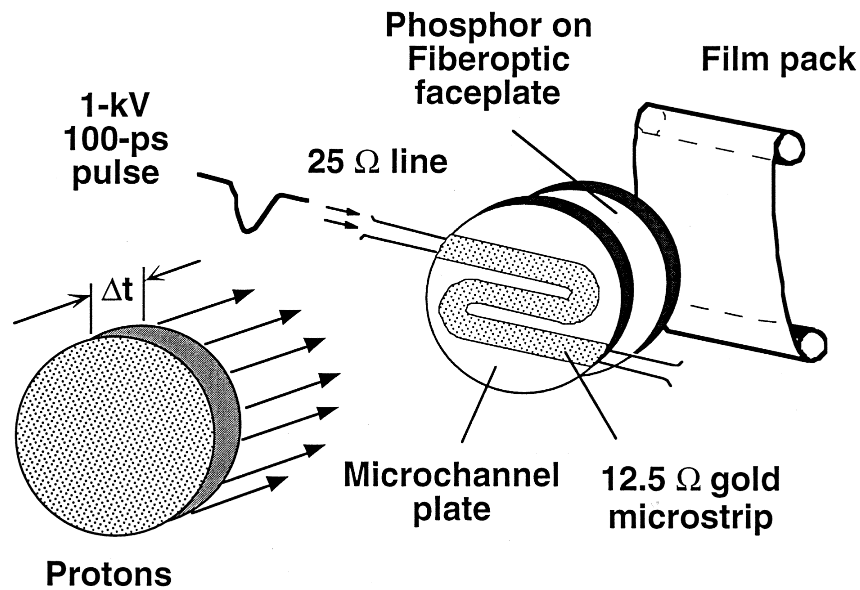
A number of other methods have been proposed or utilized for measuring burn history



Neutron streak camera (proposed)
Wang et al., Rev. Sci. Instrum. 56, 1096 (1985).

Microchannel plate
Lerche et at, 11th LIRPP, 1993





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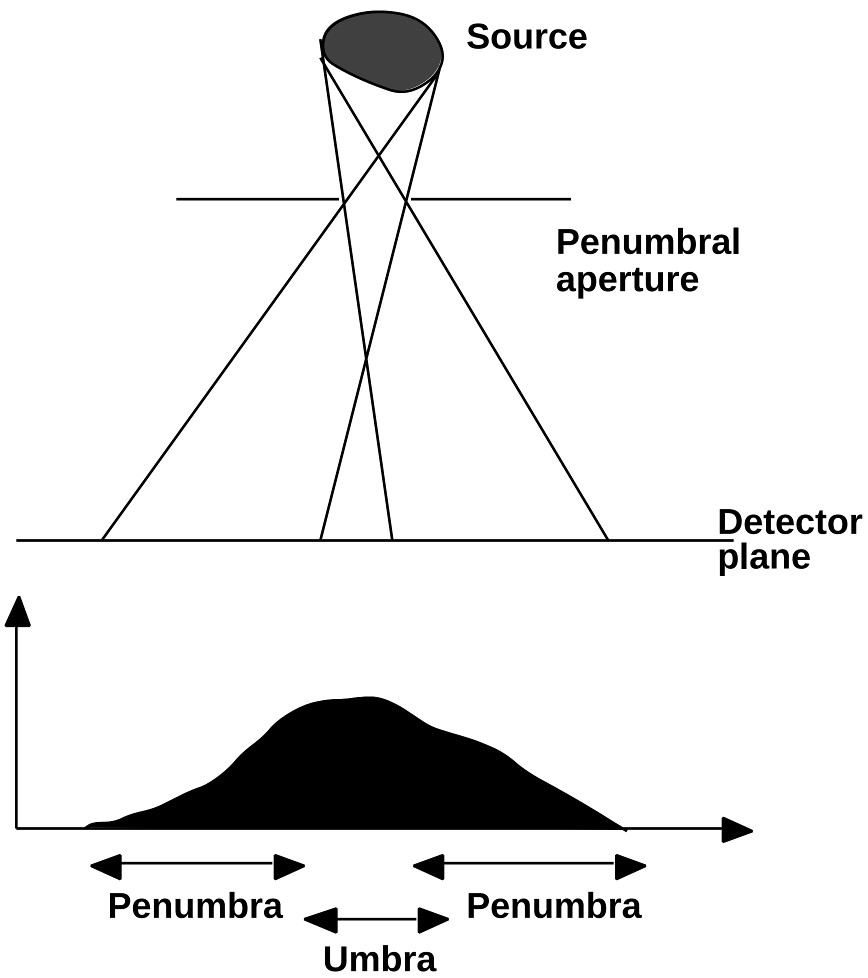
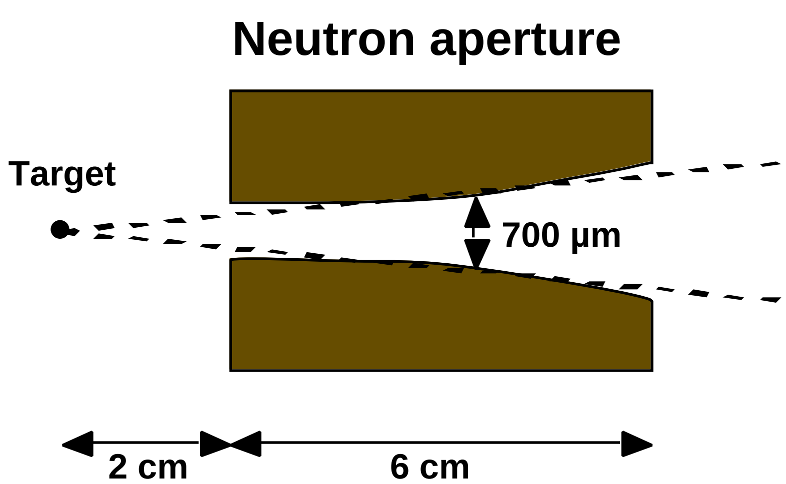
Penumbral imaging has been used to image neutrons from ICF capsules

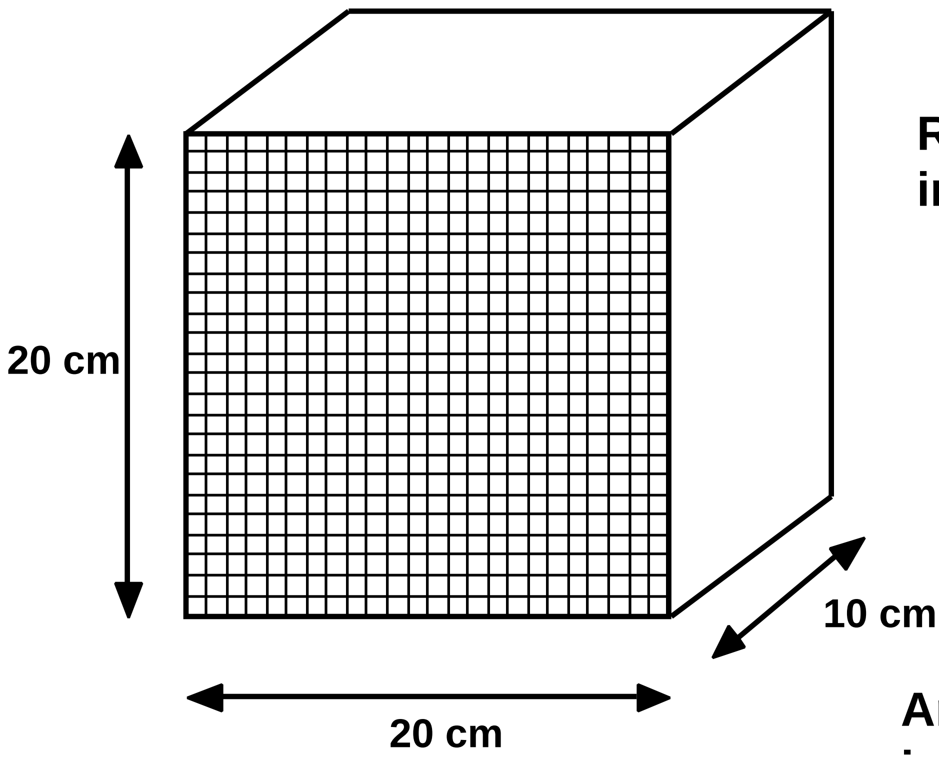




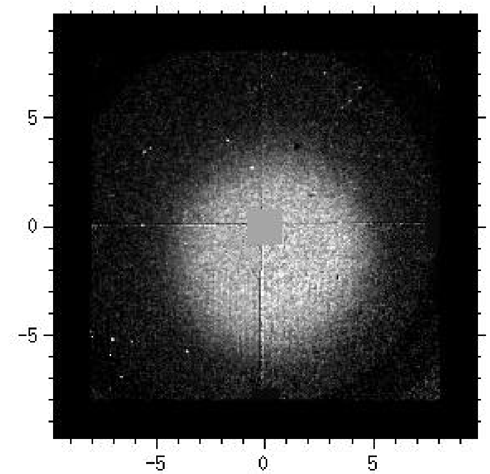
Ress et al., Science 241, 956 (1988);

Ress, UCRL-101179, (1989).

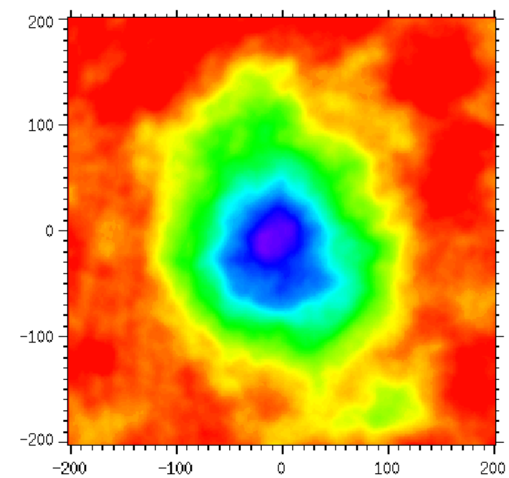
Neutrons are detected in an array of square scintillating fibers and imaged on a CCD camera



Raw image



Analyzed image



Spatial resolution of ~50 μm was demonstrated

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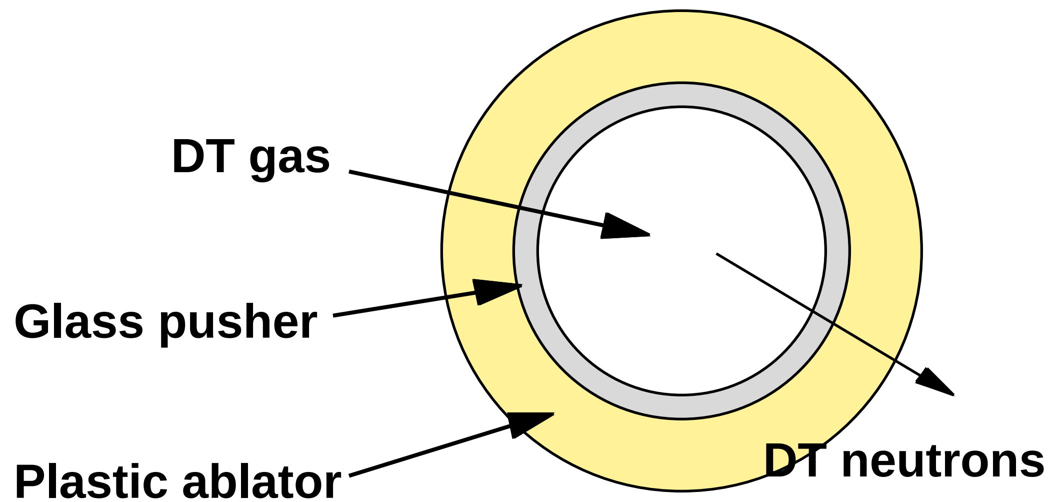
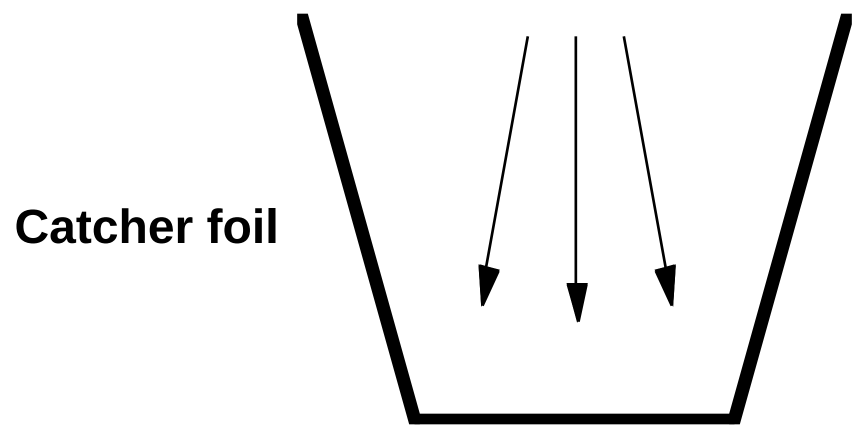
Radiochemical methods can be used to measure pusher areal density

At burn time, the 14 MeV neutrons produced in DT fusion activate dopants in the pusher. A catcher foil collects some fraction of the pusher and is analyzed.



In order to determine the fraction of the pusher collected, the pusher includes a radioactive tracer collected with the activated dopant.



One useful dopant for glass capsules is rubidium

Rb-85 (72.2% natural abundance)

Rb-87 (27.8% natural abundance)

Two reactions involved:

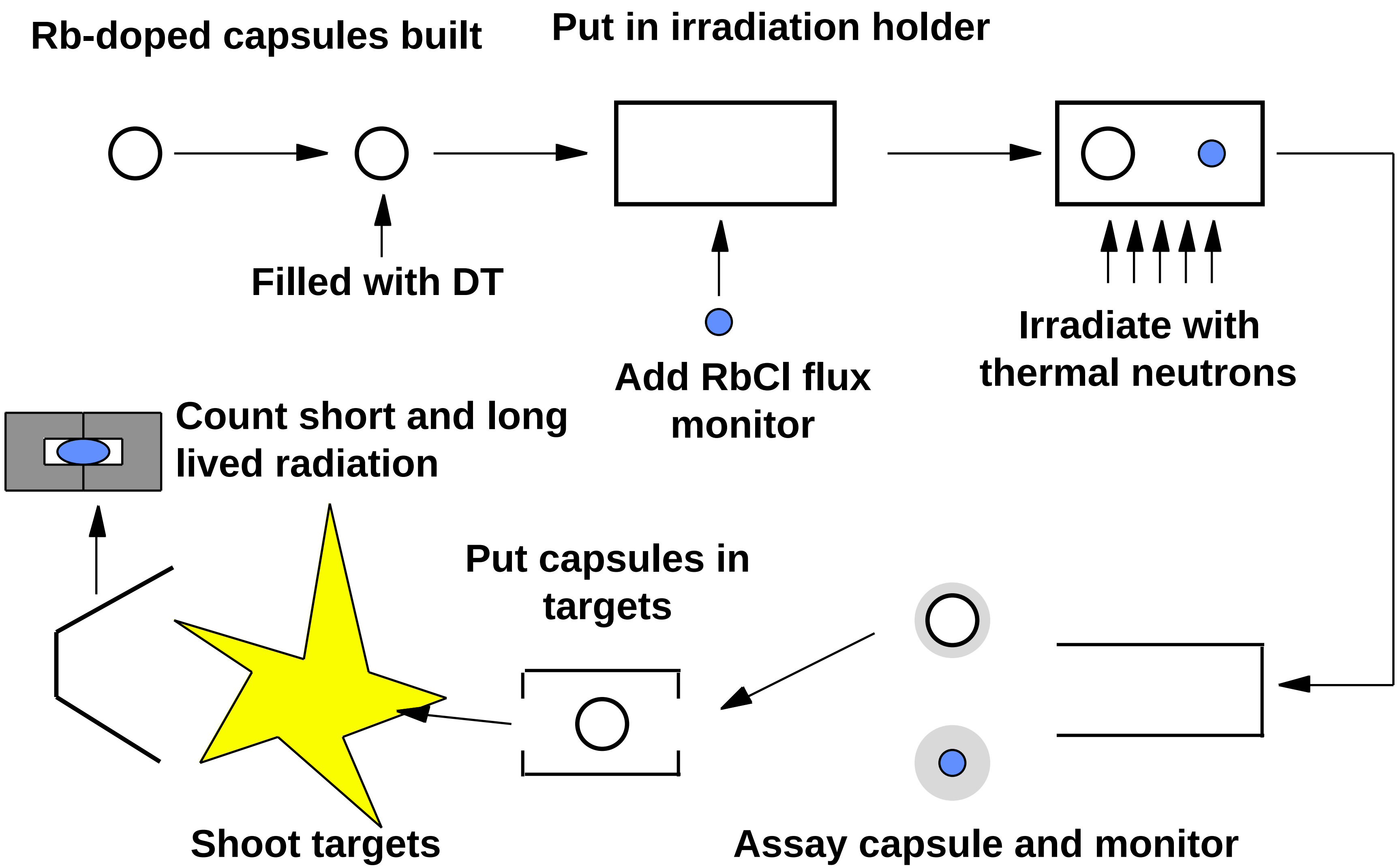
^{85}Rb(n,2n)^{84m}Rb occurs at neutron emission time

^{85}Rb(n,γ)^{86}Rb induced by thermal neutrons at a reactor prior to the experiment

^{84m}Rb decays to its ground state by emission of a gamma ray with a half life of 20.3 min

^{86}Rb decays by beta decay and emission of a gamma ray with a half life of 18.66 days

Use of this technique involved many steps



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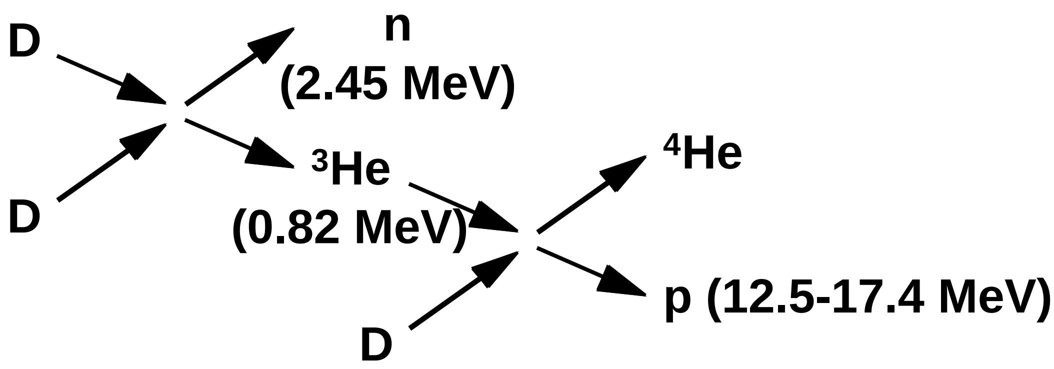
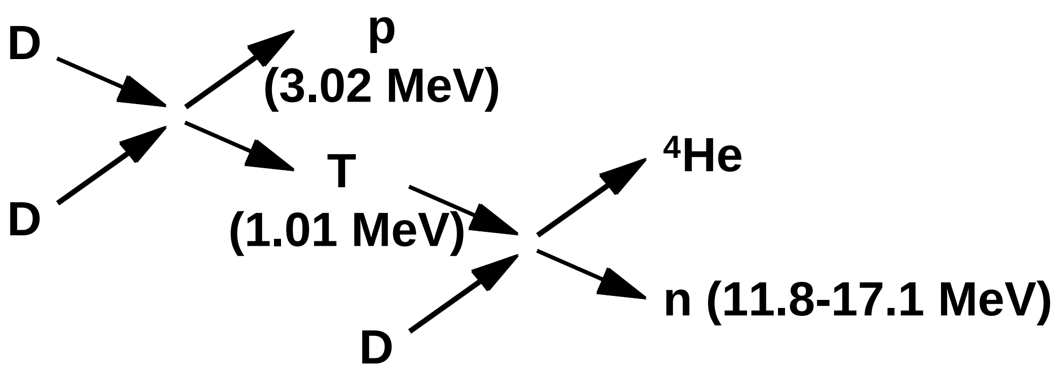
- Mix

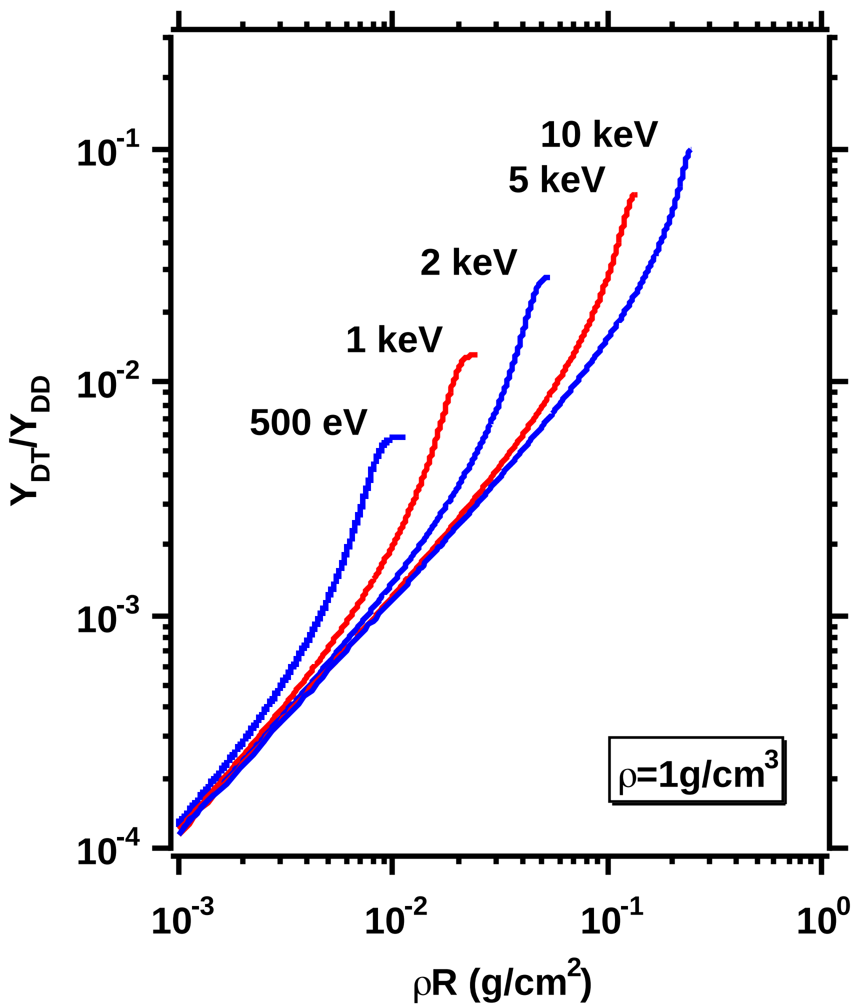
Fuel areal density is inferred from measurements of secondary neutron or proton yield

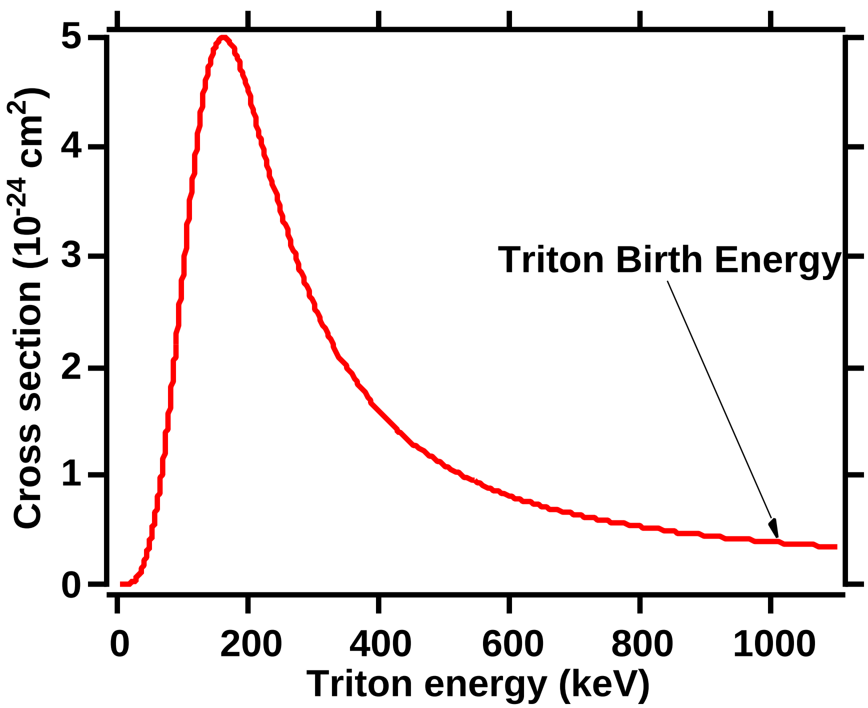




See review by Azechi, Cable, and Stapf, Laser & Part. Beams, 9, 119 (1991).

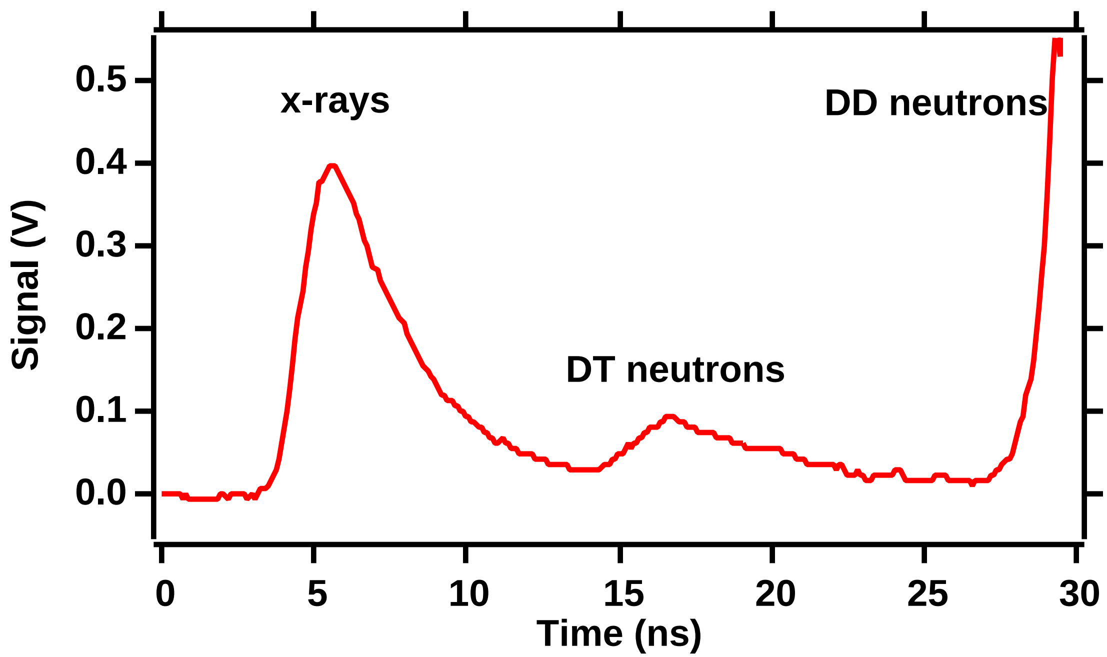
Secondary neutron yield is affected by areal density and temperature



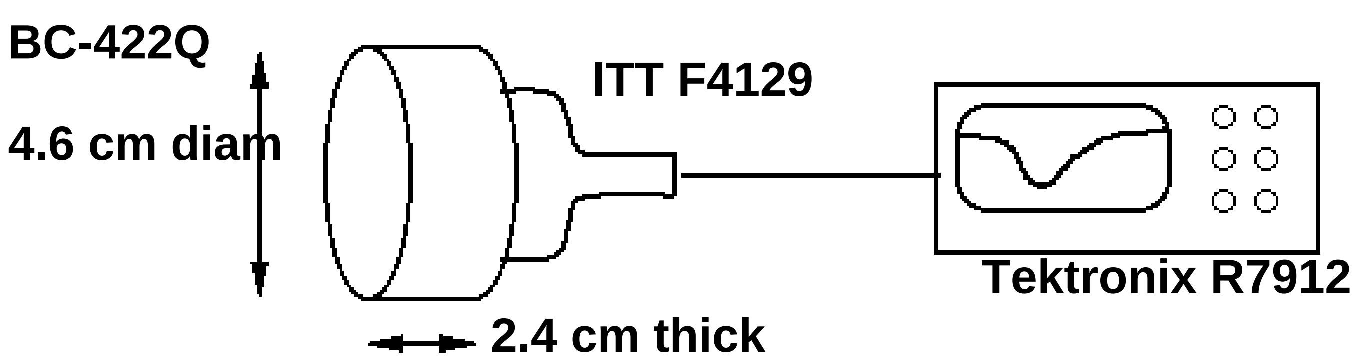


For ρR above ~10 mg/cm^2, modeling must be employed to account for triton slowing

Time-of-flight can be used to separate the primary neutrons from the secondary neutrons

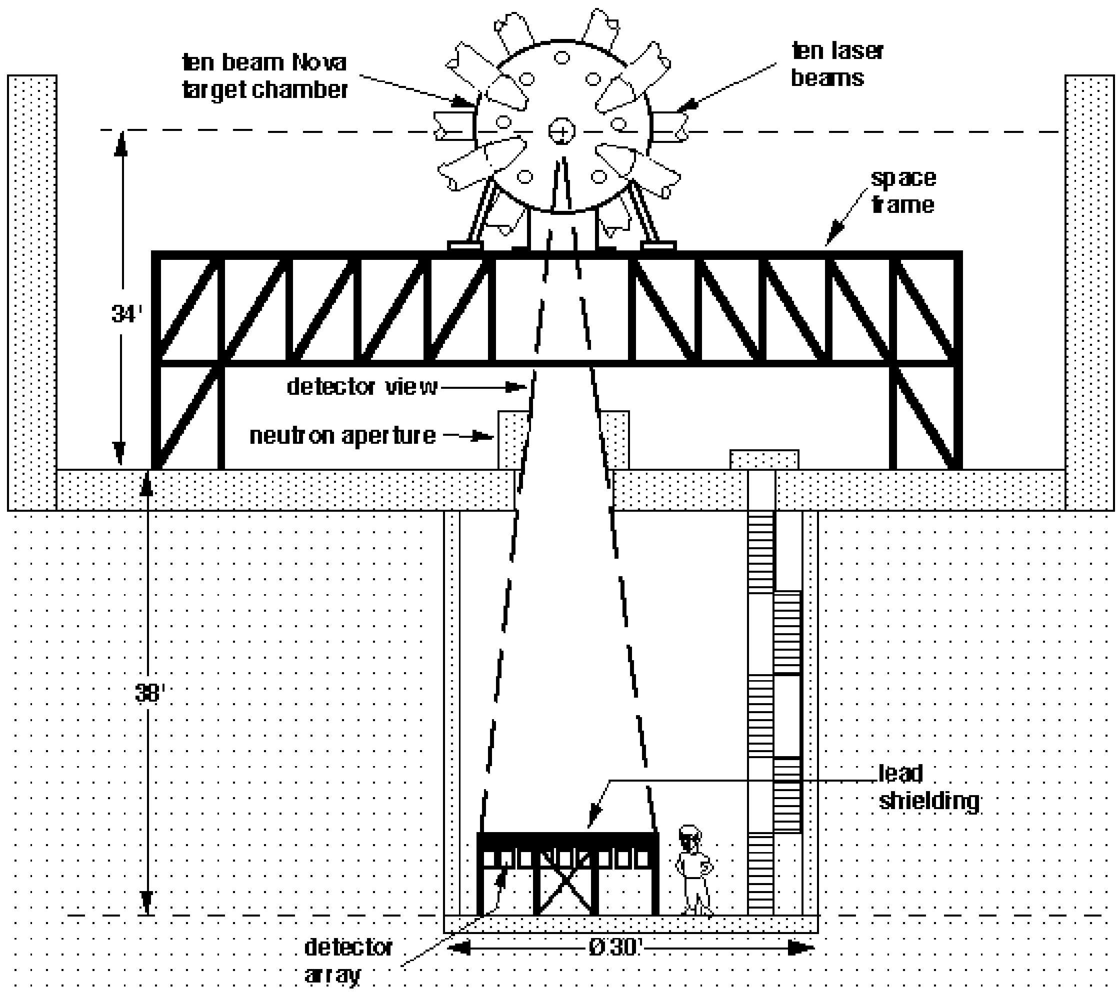


Signal from a current-mode neutron time-of-flight detector at 62 cm from the target



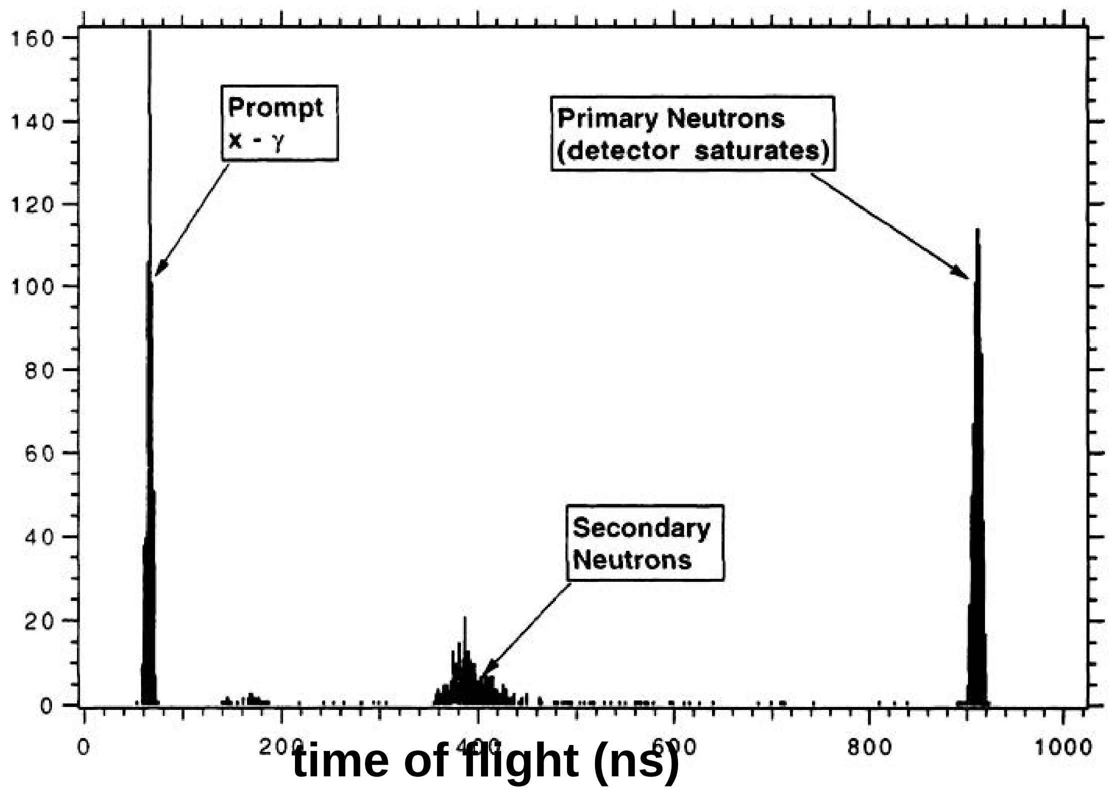
The Large Neutron Scintillator Array (LaNSA) was built to measure secondary yield and spectrum

960 detectors, each ~1000 cc of liquid scintillator, measure neutrons in a single-hit mode



Nelson & Cable, Rev. Sci. Instrum. 63, 4874 (1992).

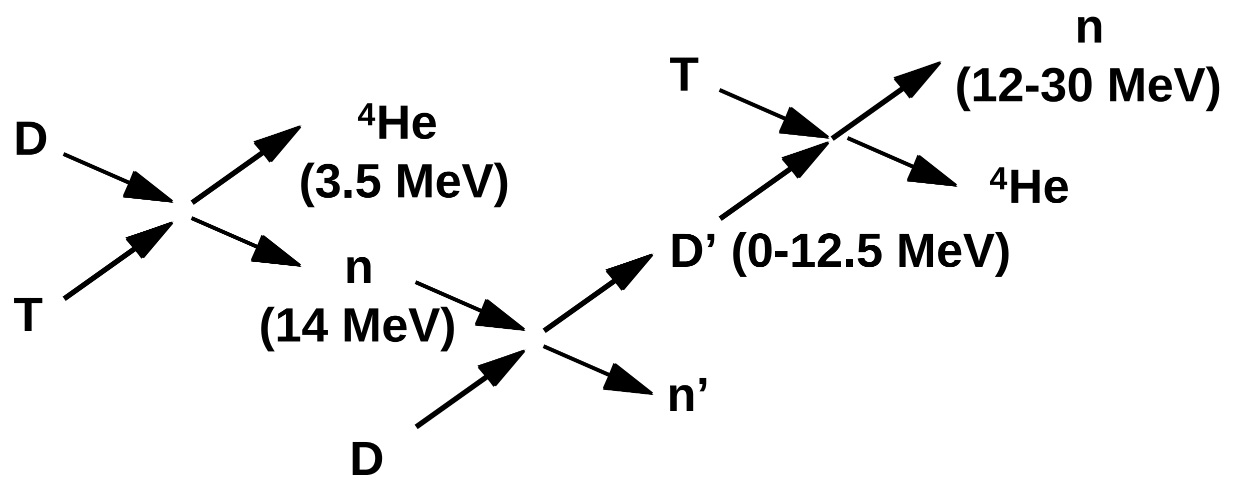
Measuring secondary yield and spectrum constrains models of implosion performance



Secondary yield and spectrum must both be consistent with modeling.

Mix can lead to increased slowing, reduced secondary yield.

For very high ρR, where tritons would be fully stopped, tertiary protons or neutron may be utilized



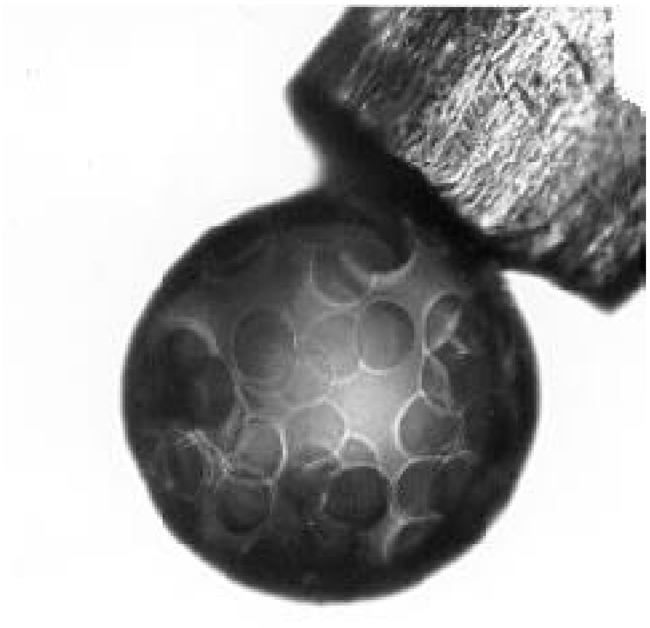
plus an equivalent branch where the 14 MeV neutron collides with a triton.

Petrasso et al., Phys. Rev. Lett 77, 2718 (1996), advocate adding ^3He to the fuel, allowing the production of tertiary protons.

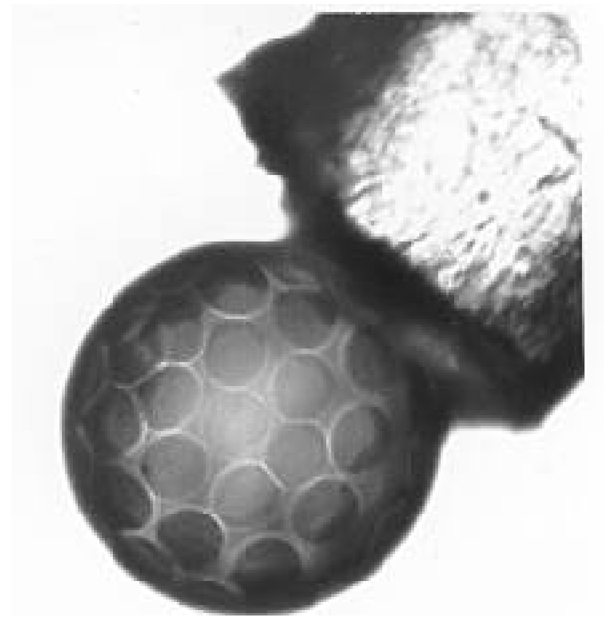
Nuclear diagnostics have been used to measure a number of properties of ICF implosions

- Nuclear yield
- Ion temperature
- Implosion time
- Burn width/burn history
- Burn region
- Pusher areal density (ρR)
- Fuel areal density
- Mix

Capsules with prescribed perturbations were used to test the effects of unstable hydrodynamics



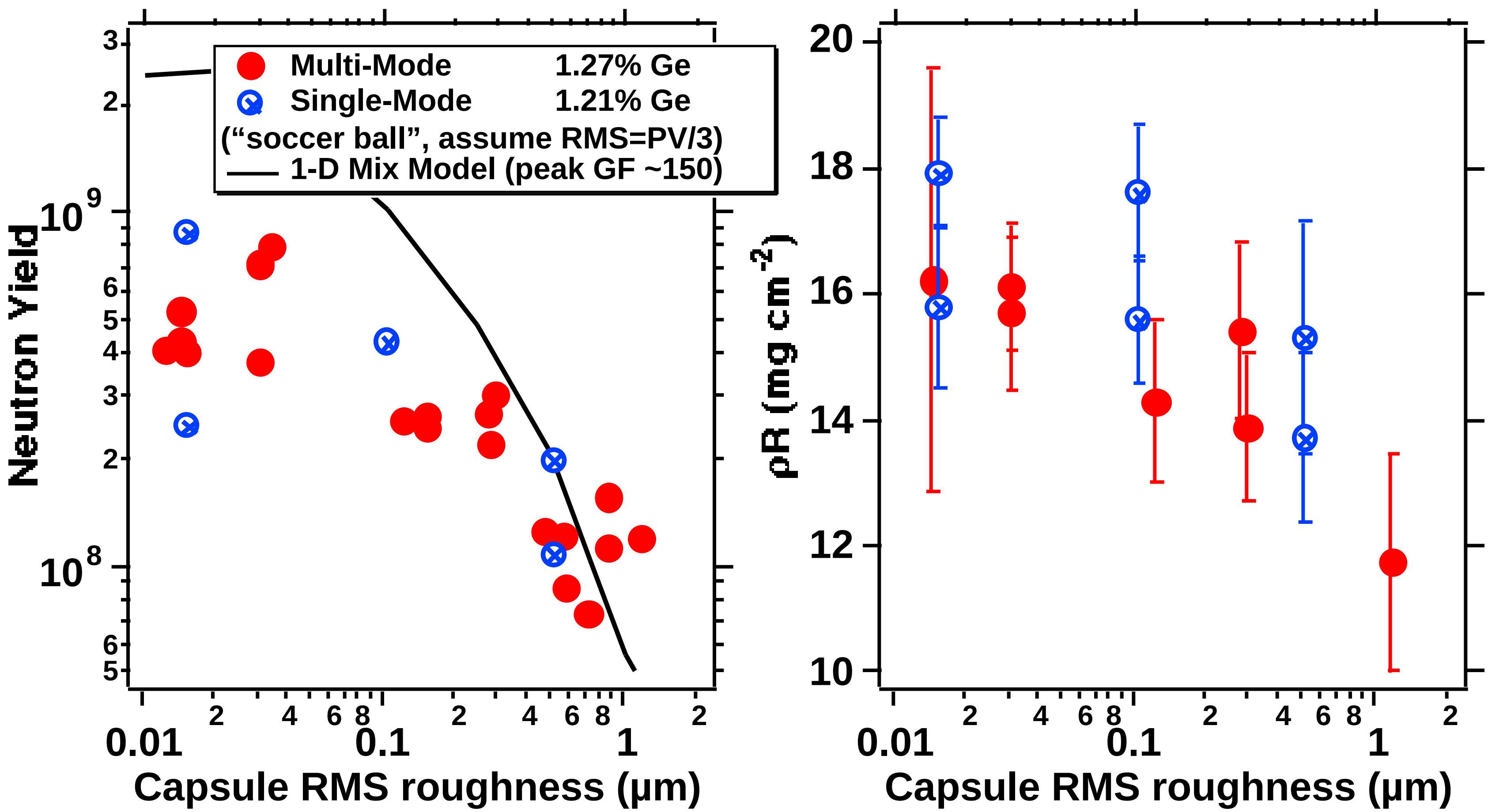
Multi-mode
“Random”



Single Mode
“Soccer Ball”
ℓ~16-18

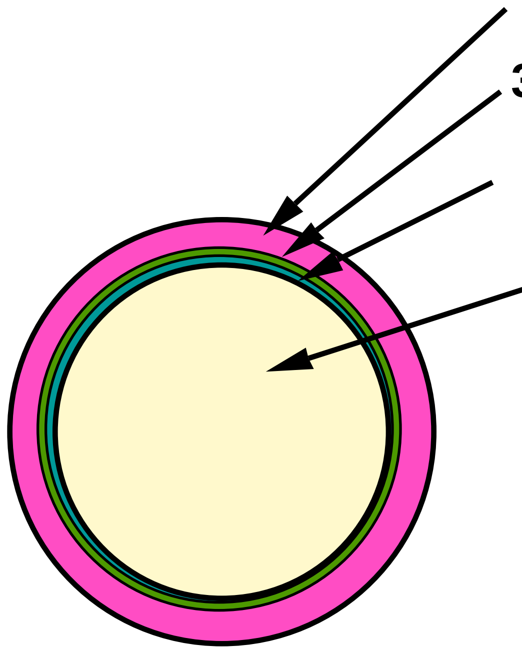
Landen et al, J. Quant. Spect. Radiat. Transfer 54, 245 (1995).

Yield and ρR degradation with increasing surface roughness are measured as an indicator of mix



Deuterated plastic shell capsules were imploded to study pusher-fuel mix through the emission of neutrons

As the deuterated shell mixes with the hot fuel, the increased temperature of the deuterium will lead to neutron emission

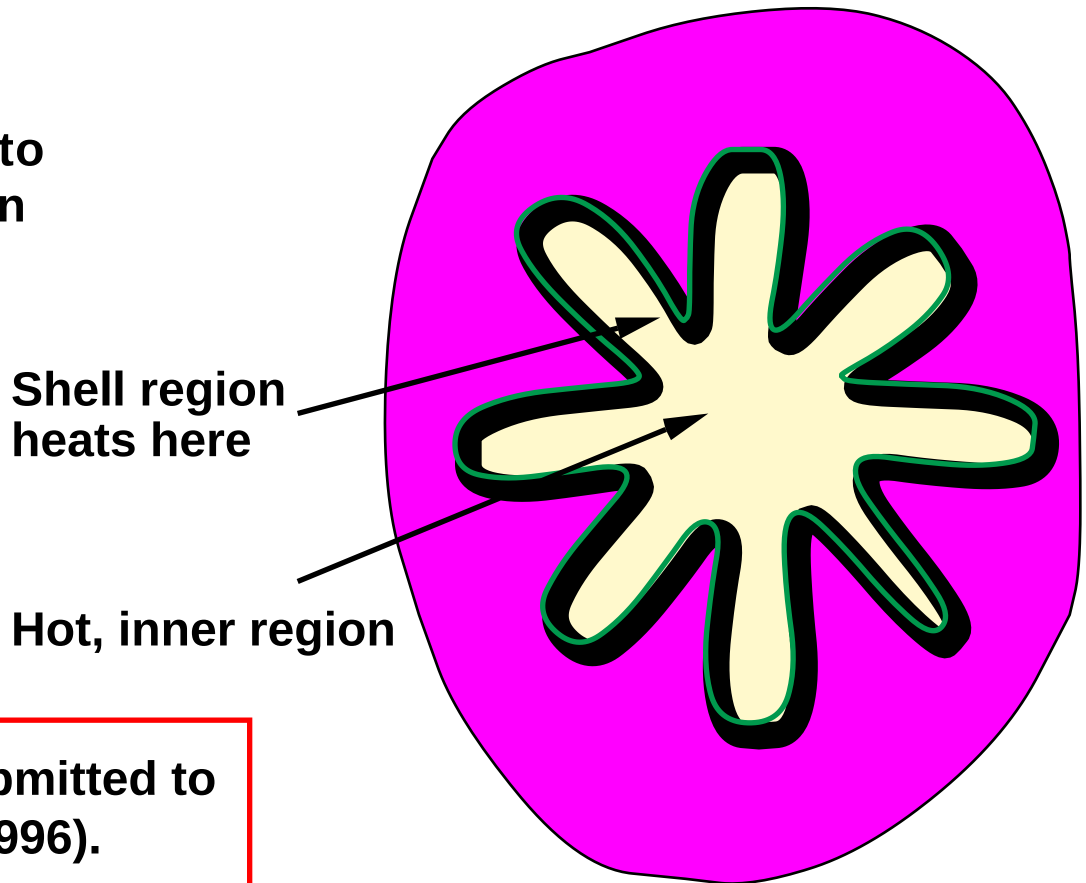


Known perturbations introduced by laser ablating the surface of the capsule increases the mix

Chrien et al, submitted to Phys. Rev. Lett.

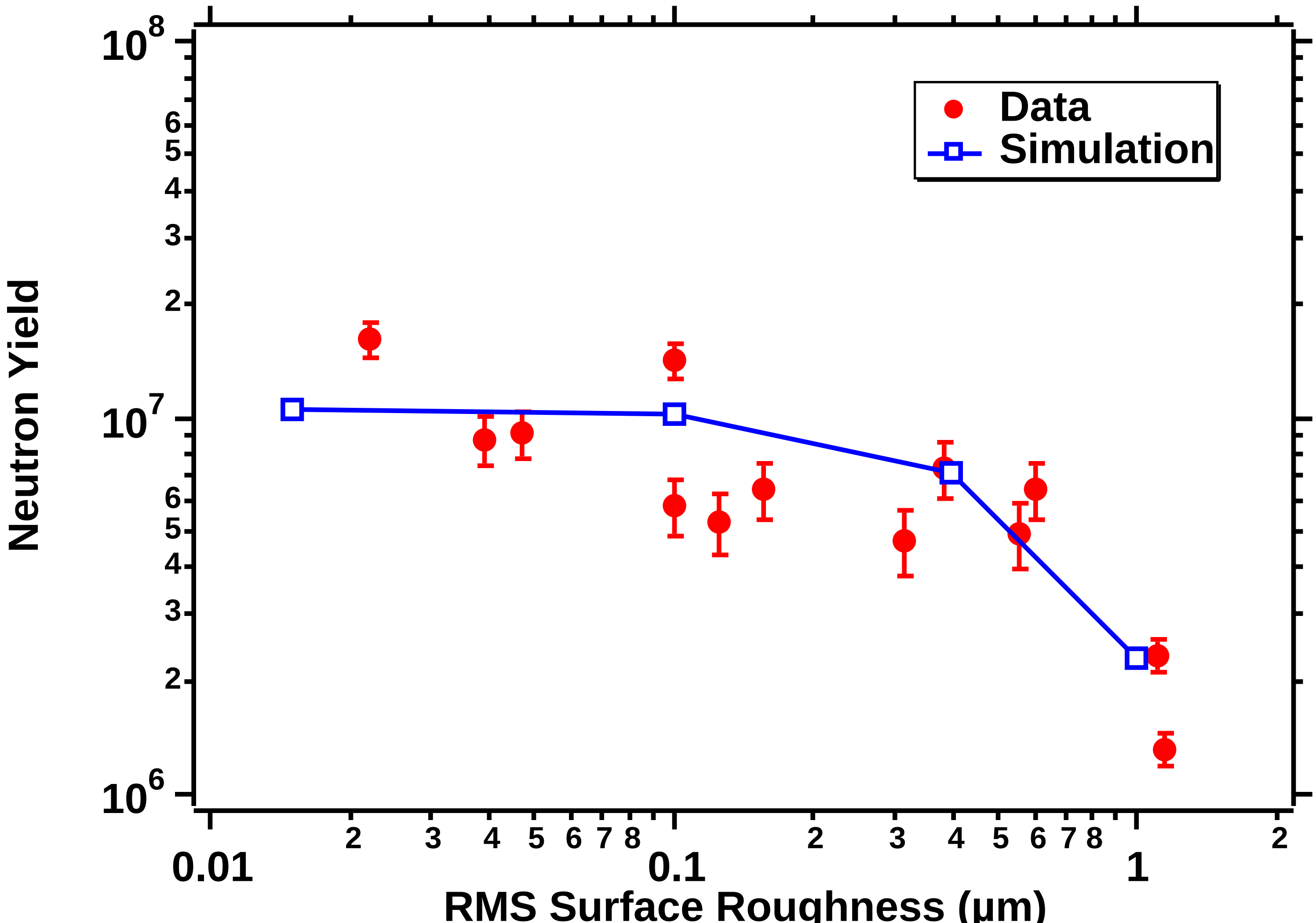
Unstable growth of the initial perturbations leads to “bubbles and spikes” in the interface

Radial motion of the emitting region can lead to broadening of the neutron spectrum



R. E. Chrien *et al.*, submitted to Phys Rev. Lett. (1996).

Yields from the deuterated shell targets are in good agreement with simulations



Nuclear diagnostics on NIF offer new challenges and opportunities

NIF Wish List:

- Nuclear imaging with 10 μm resolution
- Time-resolved nuclear imaging
- Burn history with 10 ps resolution
- Time-resolved ion temperature
- ρR for DT and when alphas are fully stopped