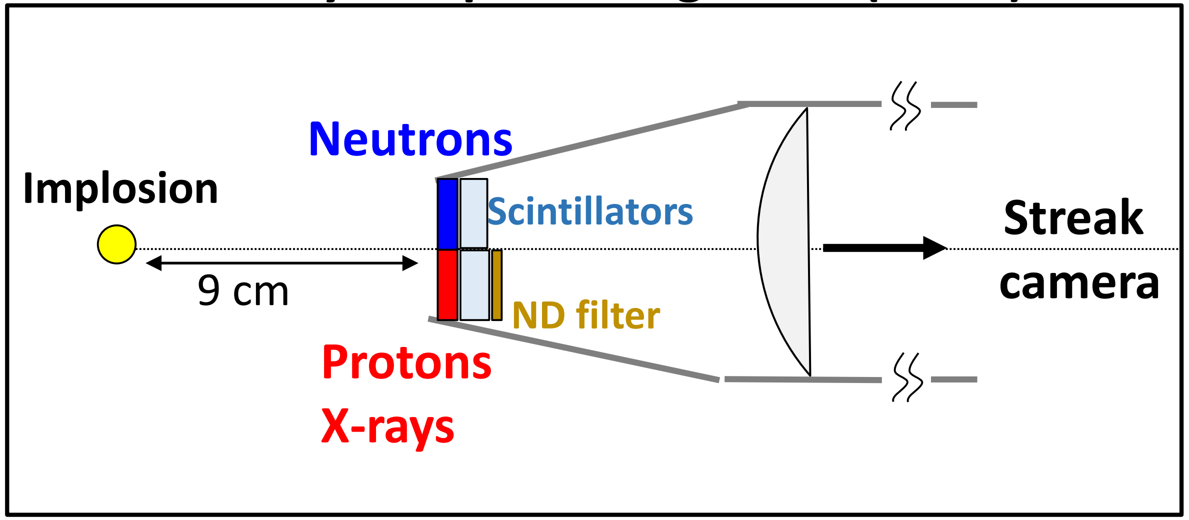
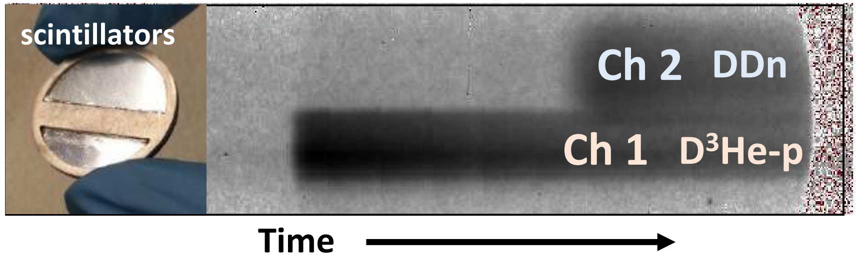
Time-resolved nuclear diagnostics for probing implosion dynamics and kinetic & multi-ion effects on OMEGA and the NIF

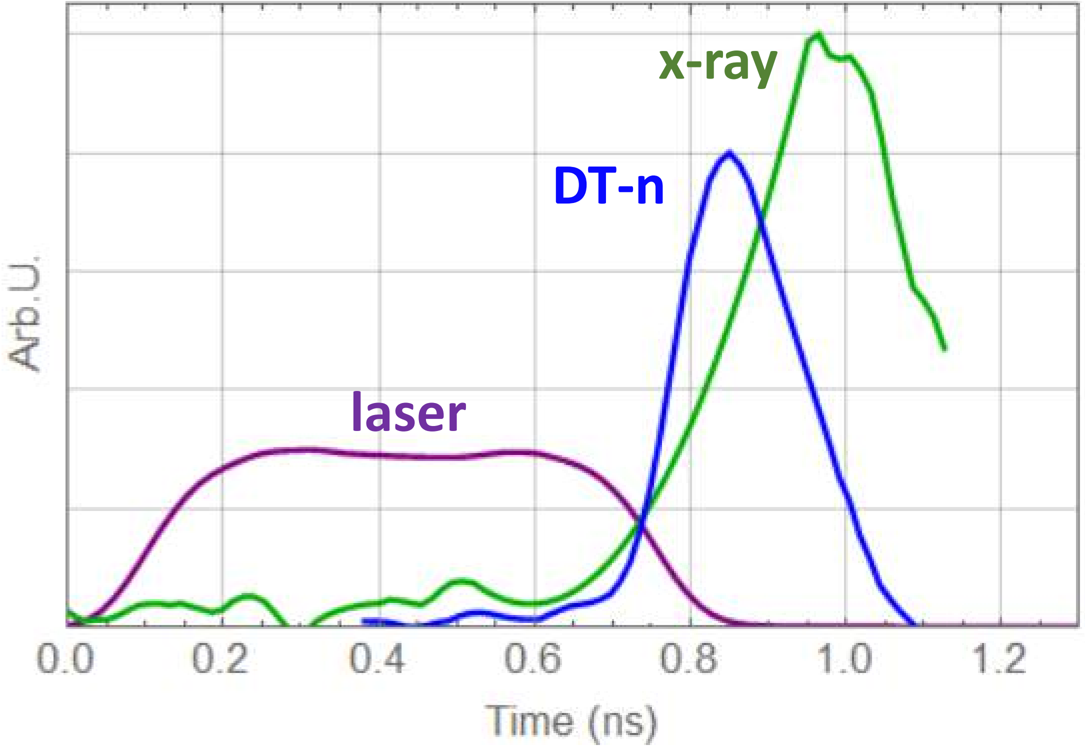
Particle X-ray Temporal diagnostic (PXTD)



Shot 75694 Streak of D3He protons and DD neutrons



Emission histories



Hong Sio, MIT
June 28th, 2016, Las Vegas, NV
SSGF Annual Review

Time-resolved nuclear diagnostics for probing implosion dynamics and kinetic & multi-ion effects on OMEGA and the NIF

- **Platform development, diagnostic work, and physics studies on the OMEGA laser facility**
  1. Kinetic and multiple-ion-fluid effects in ICF implosions using time-resolved data on several nuclear reactions, as well as the core x-ray continuum
  2. Design and implementation of the Particle Xray Temporal Diagnostic (PXTD)

- **Diagnostic development, and physics studies on the National Ignition Facility (NIF)**
  1. Implosion dynamics from measurements of the shock and compression bang-times
  2. Design and implementation of the magnetic Particle-Time-of-Flight (magPTOF) diagnostic

Collaborators

OMEGA

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Laboratory for Laser Energetics, University of Rochester

H. Rinderknecht, P. Amendt, S. Wilks, L. Berzak-Hopkins, …

Lawrence Livermore National Laboratory

T. Kwan, A. Le, G. Kagan, W. Taitano, A. Simakov, L. Chacon, B. Keenan, R. Shah, A. Zylstra, N. Hoffman, K. Molvig,

Los Alamos National Laboratory

S. Atzeni

Universita di Roma

R. Mancini

University of Nevada, Reno

Collaborators

NIF

<u>MIT/PSFC</u>

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M. Shoup
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Sangster
T. Buczek
R. Betti
D. Edgell
P. McKenty
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H. Rinderknecht
J.R. Rygg
J. Kimbrough
A. MacPhee
G.W. Collins
D. Hicks
A. Mackinnon
T. Döppner
H.S. Park
S. LePape
O. Landen
N. Meezan

H. Robey
R. Zacharias
J. Eggert
J. Moody
D. Callahan
J. Edwards
S. Friedrich
S. Haan
S. Hatchett
R. Prasad
S. Weber
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<u>SNL</u>

R. Olson
G. Chandler
R. Leeper
....

<u>LANL</u>

A. Zylstra
J. Kline
D. Wilson
....

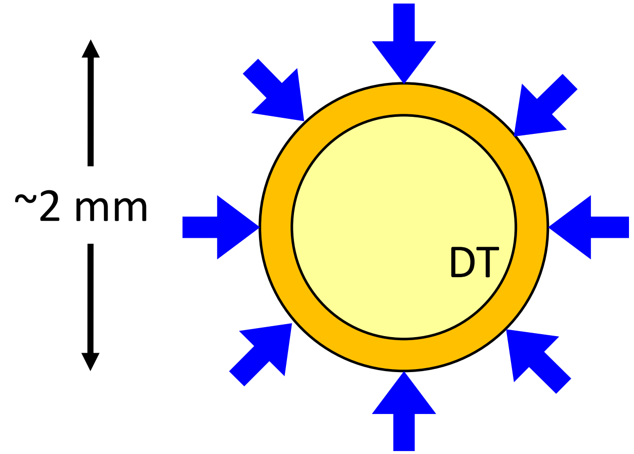
<u>GA</u>

J. Kilkenny
A. Nikroo
....

*: Graduate student
†: Ph.D. advisor

This work was supported in part by the U.S. DoE, LLNL, LLE, FSC, and NLUF.

In ICF, the fusion fuel is compressed to achieve high density and temperature, then contained by its own inertia long enough for ignition and burn to occur



1. Laser or x-ray irradiates and heats the surface, increasing the pressure

~20ns

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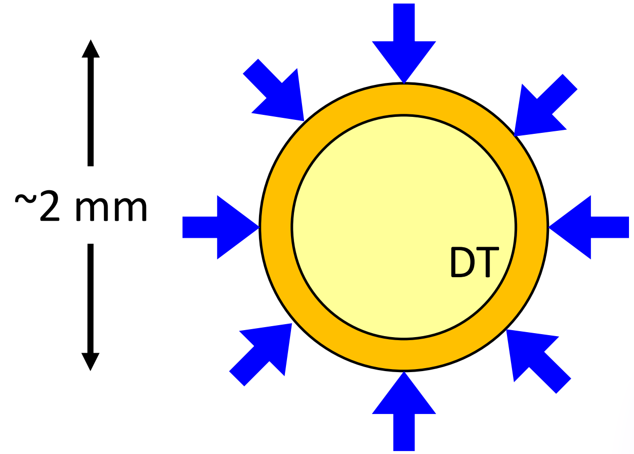

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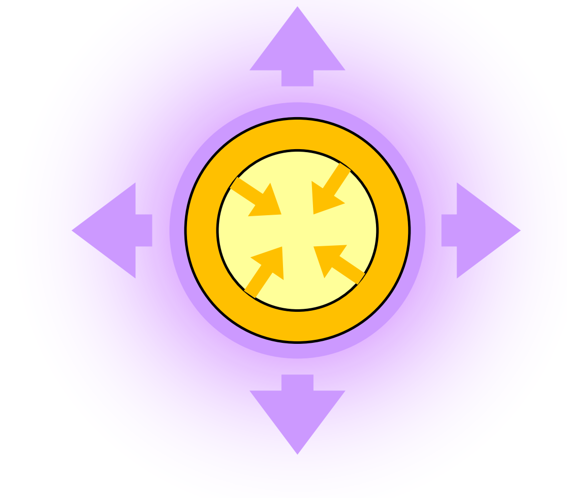

2. Ablation of the surface material accelerates the capsule inwards

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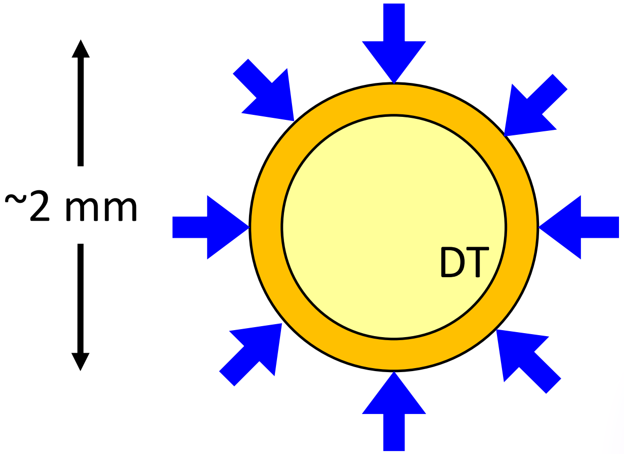

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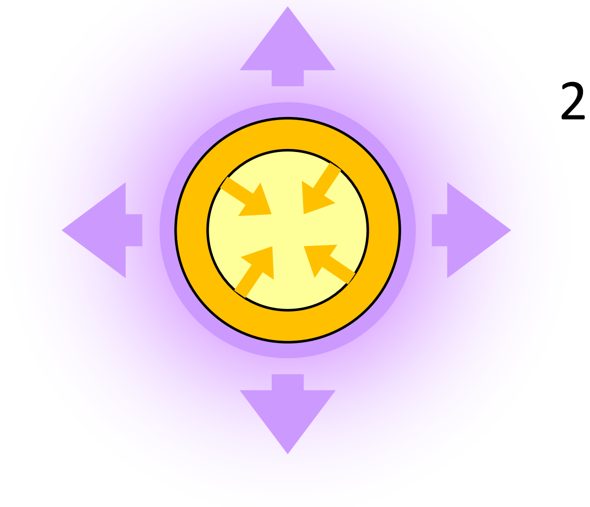
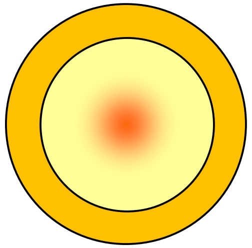


2. Ablation of the surface material accelerates the capsule inwards

3. Temperature and density increase as fuel compresses



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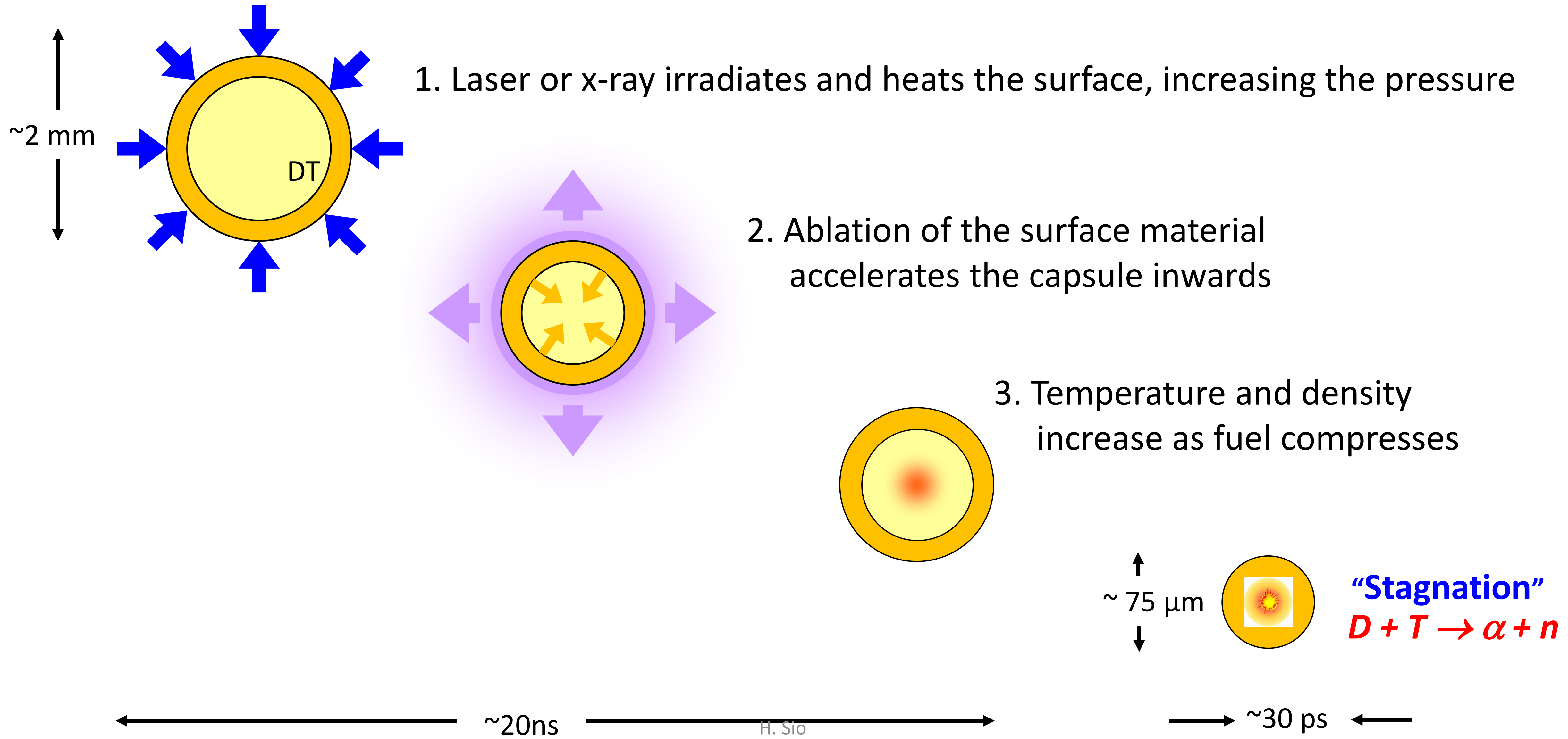

Time-resolved nuclear diagnostics for probing implosion dynamics and kinetic & multi-ion effects on OMEGA and the NIF

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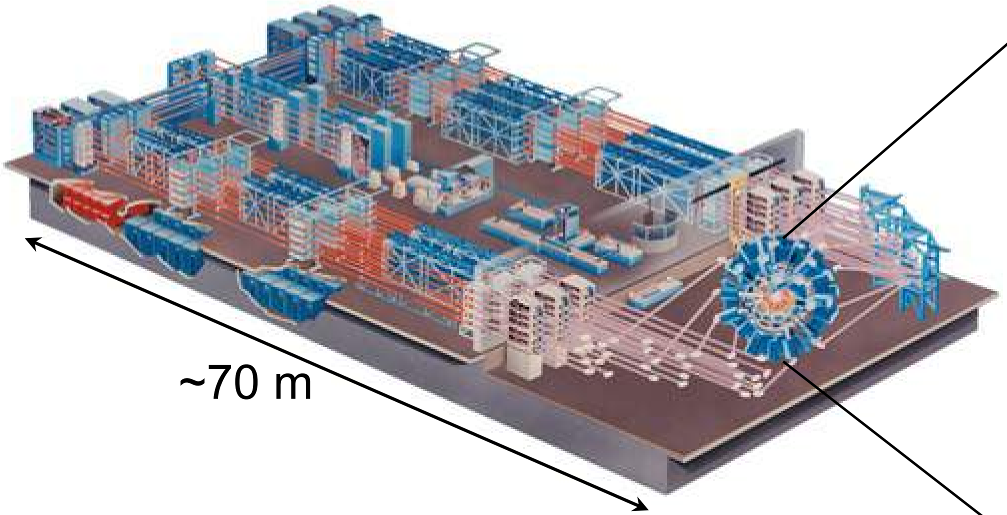
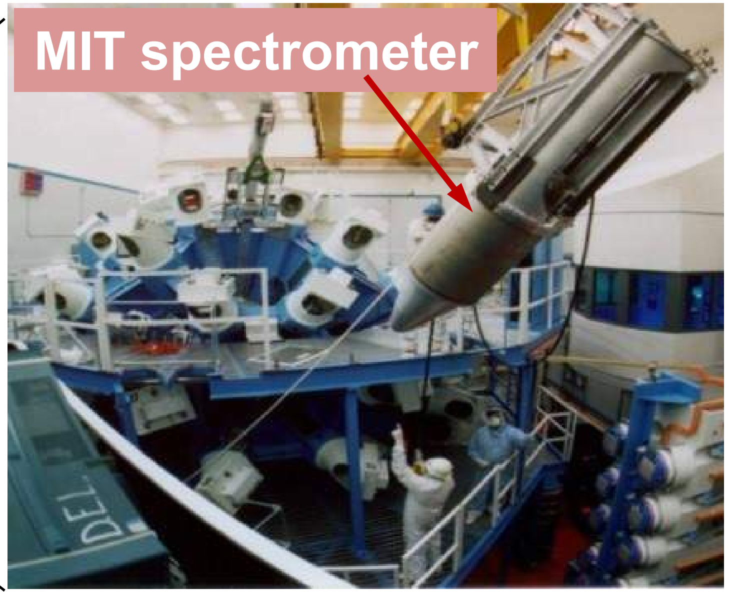
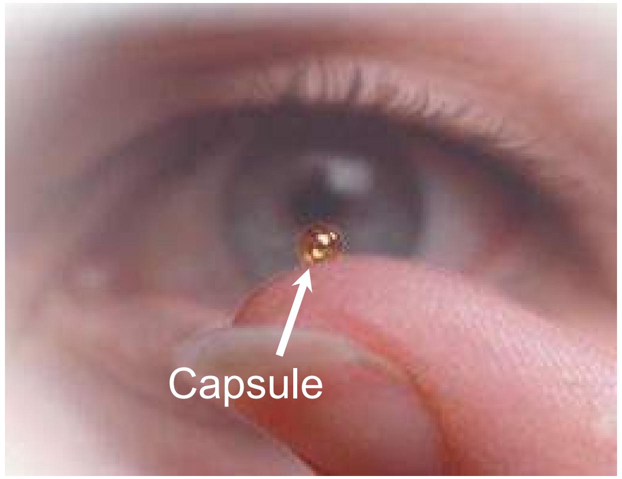
The OMEGA laser facility is a versatile Inertial Confinement Fusion laser facility for studying implosions and high-energy-density systems

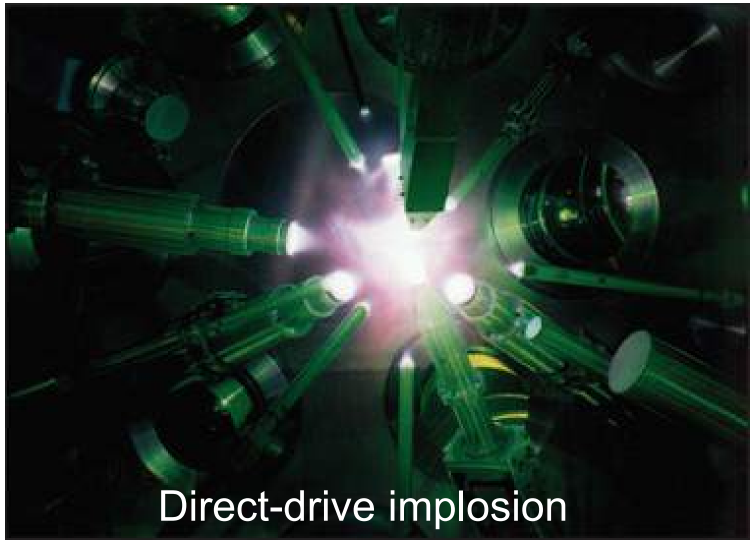
OMEGA





60 beams
30 kJ over ~ 1 ns
Shots per day: ~ 12

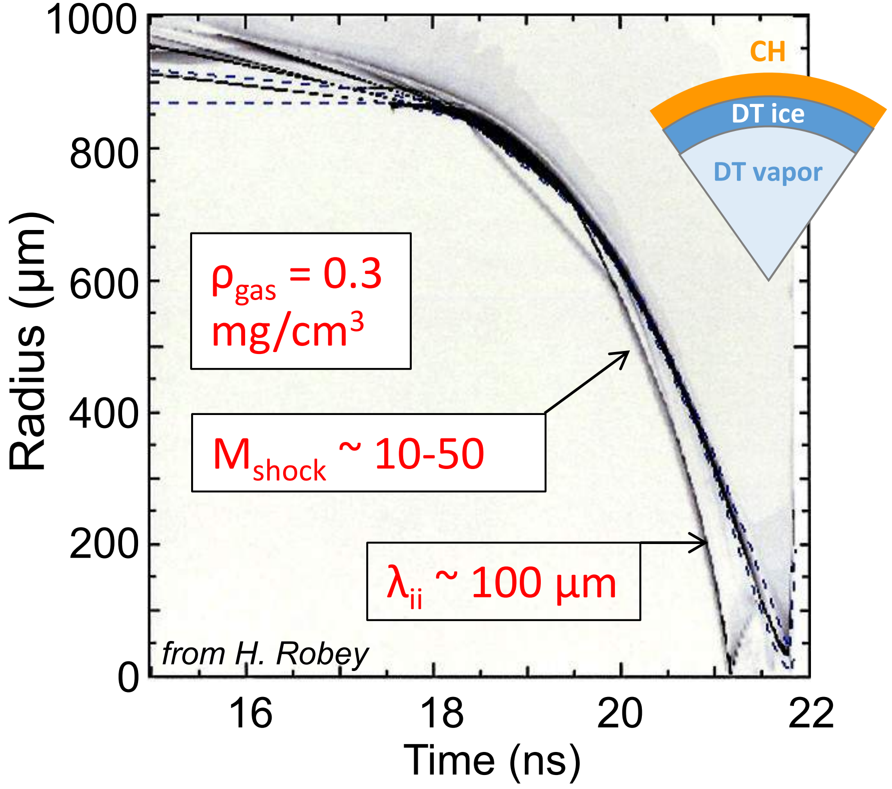




During the shock propagation phase of an ICF implosion, ion-ion mean free path (λ_{ii}) in the fuel is on the order of the implosion radius due to high temperature and low density

OMEGA

Simulation of Hot-spot ignition



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OMEGA

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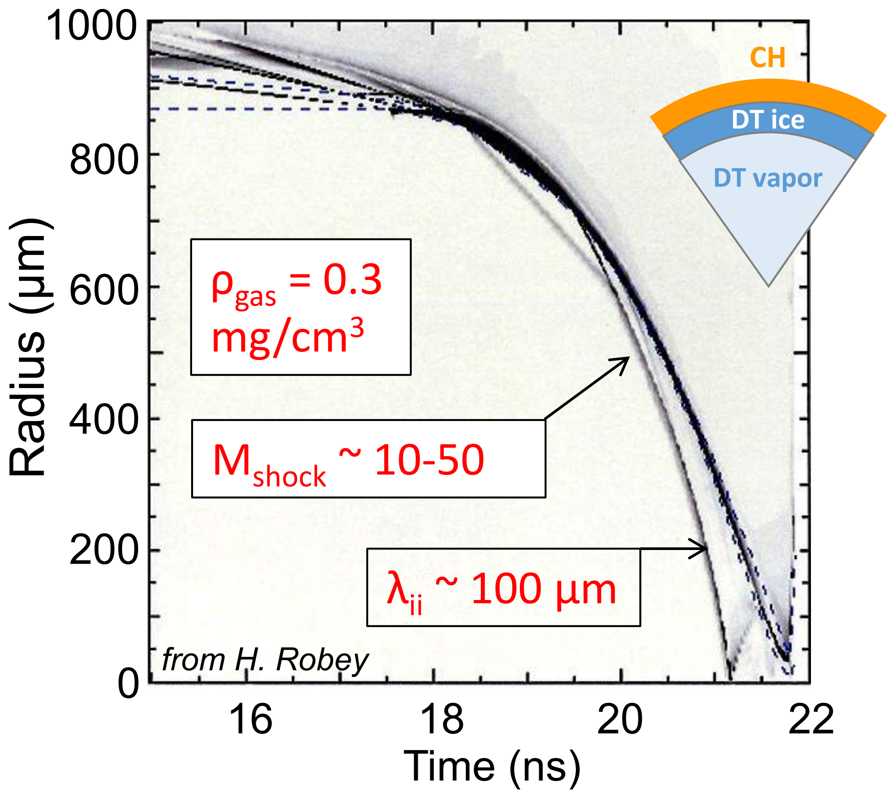
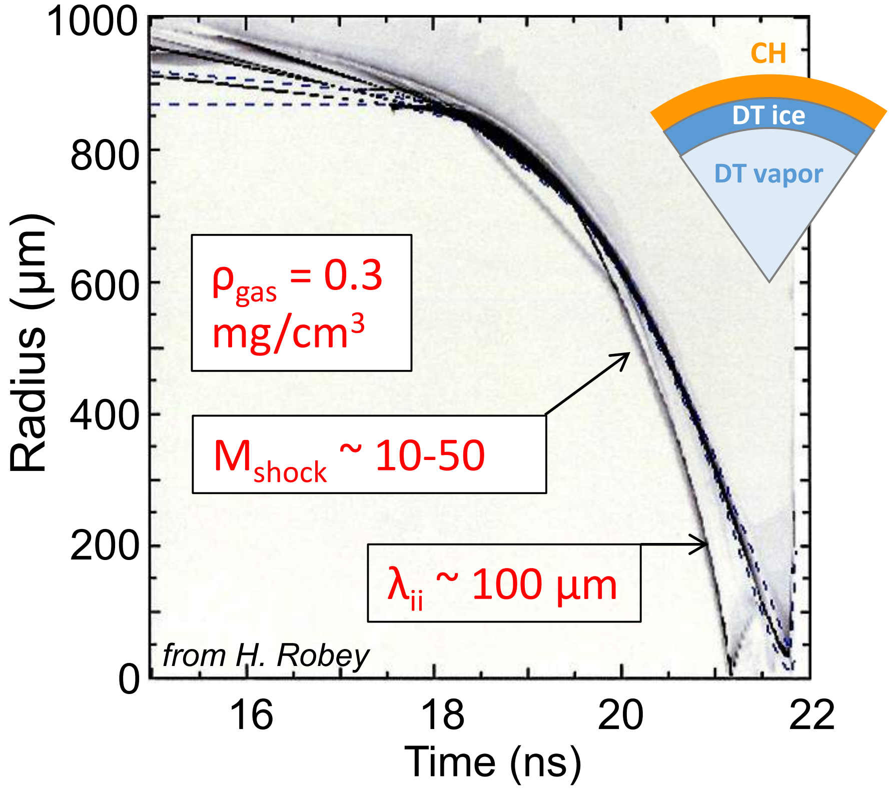


- Kinetic physics refers to phenomena that occurred at the time- or length-scale of particle collisions (λ_{ii})
- Hydrodynamic codes assume that these collisional scales (λ_{ii}) are much smaller than the scale of interest (i.e. radius)
- **Kinetic effects** refers to observed phenomena that results from kinetic physics not captured in hydrodynamic codes

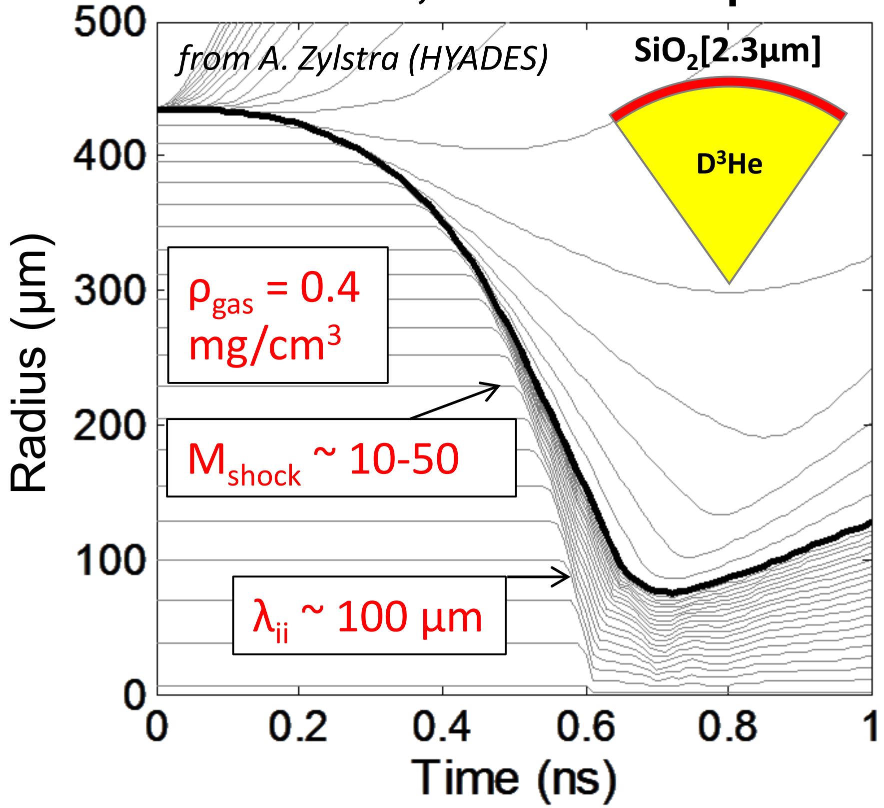
Kinetic conditions in shock-driven, thin-shell implosions are similar to the shock propagation phase of hot-spot ignition experiments

OMEGA

Simulation of Hot-spot ignition



Simulation of shock-driven, thin-shell implosion

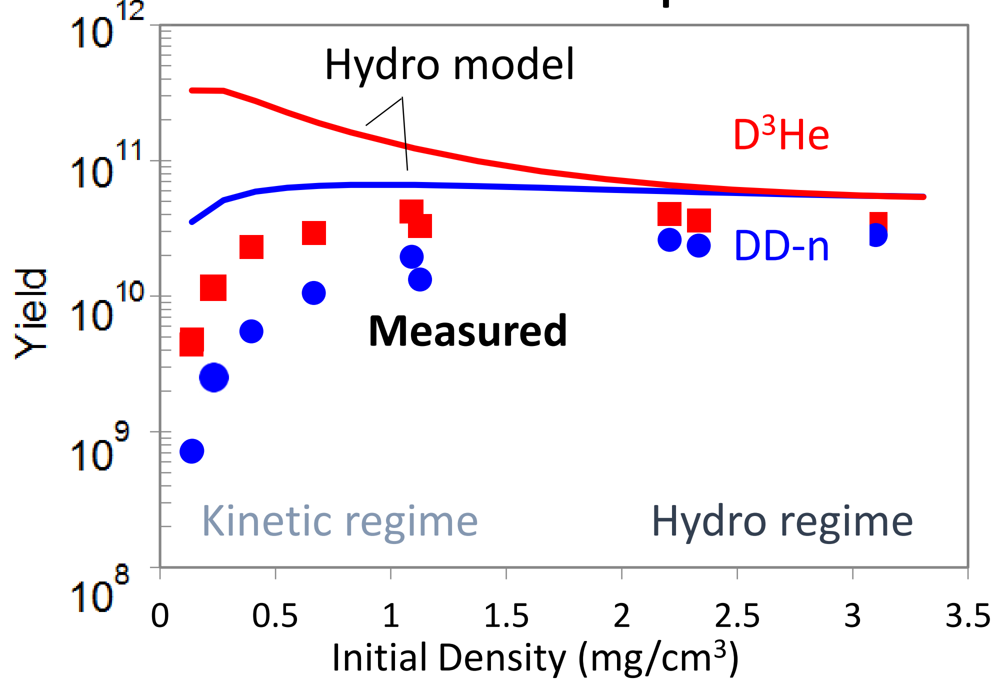


These shock-driven, thin-shell implosions are excellent surrogates to study kinetic effects in the shock phase of ICF implosions

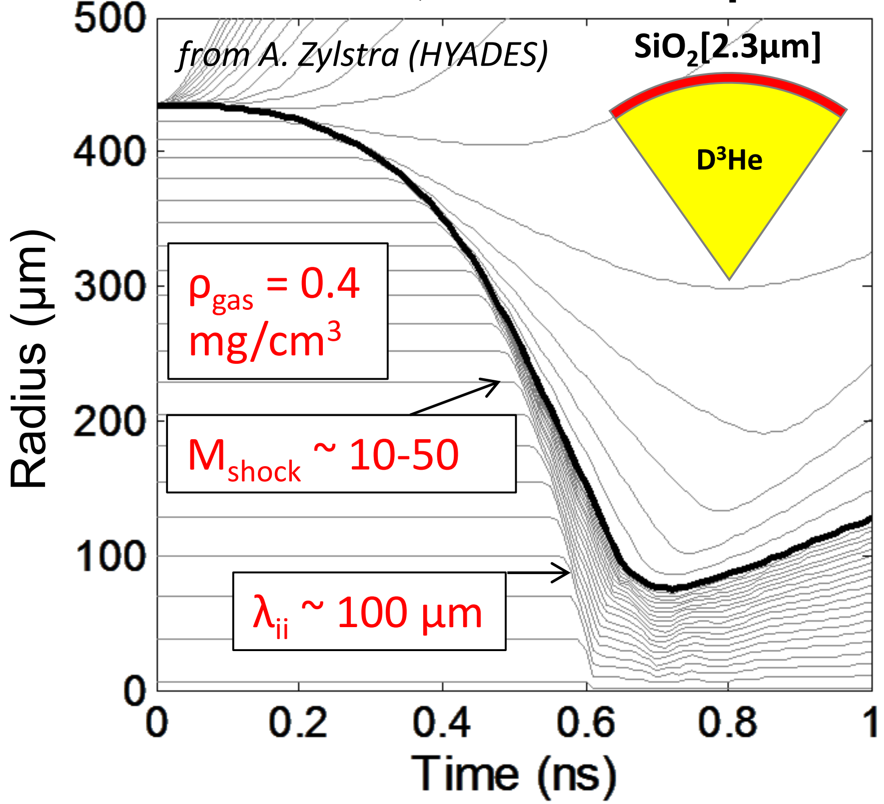
time-averaged quantities (yields, ion temperatures) have been used to study transition from the hydrodynamic to kinetic regime in shock-driven implosions

OMEGA

DD, D^3He-p yields in D^3He thin-shell implosions



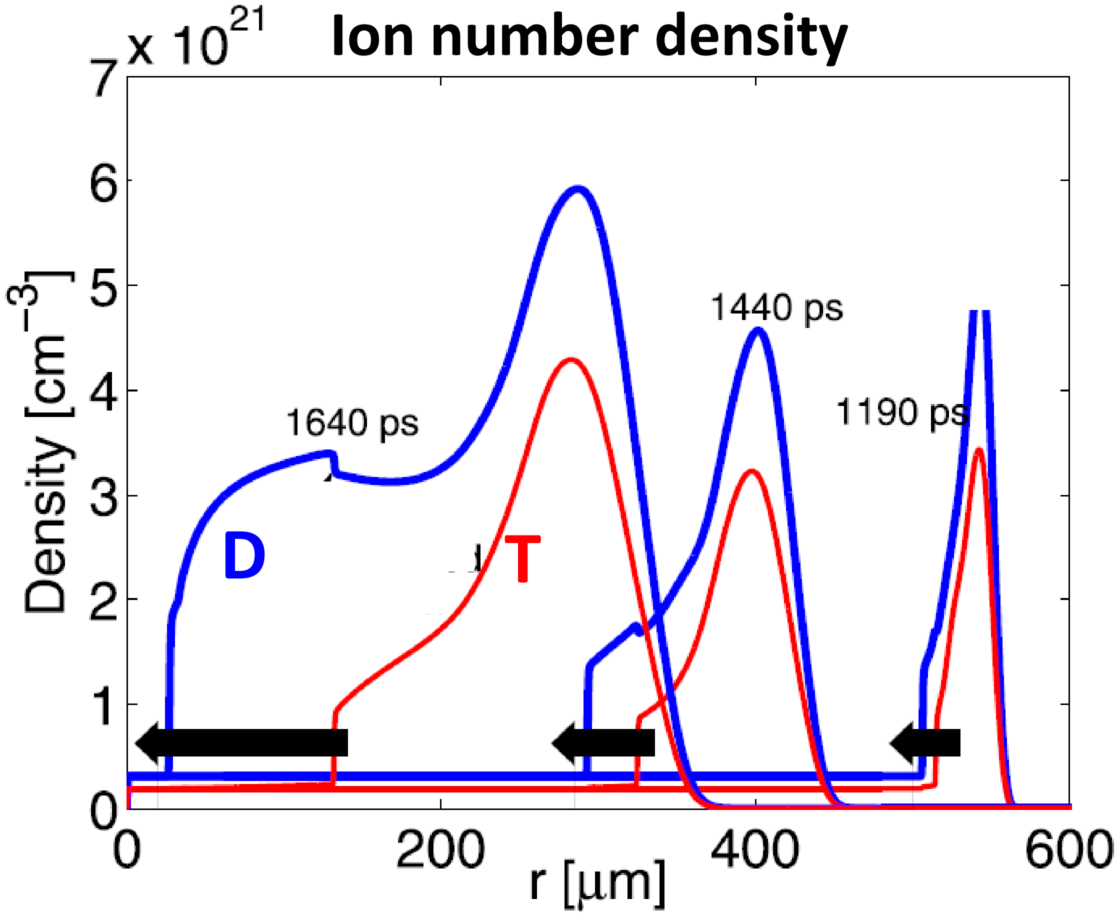
Simulation of shock-driven, thin-shell implosion

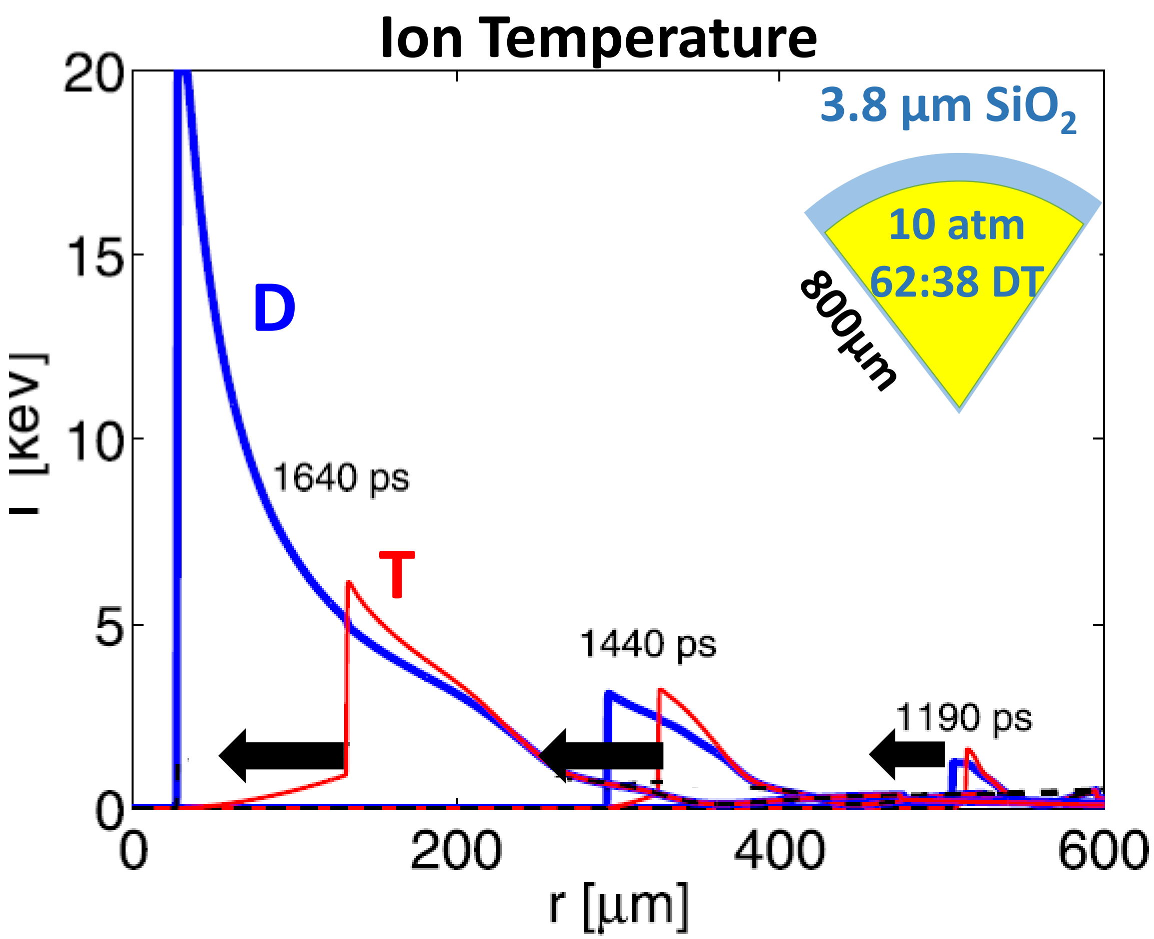


Goal of the PXTD is to understand impact of kinetic effects in ICF plasmas **using time-resolved data**

Multi-ion-fluid simulation of ICF implosion using LSP also shows species separation and thermal decoupling in a D + T plasma during shock propagation and rebound

OMEGA

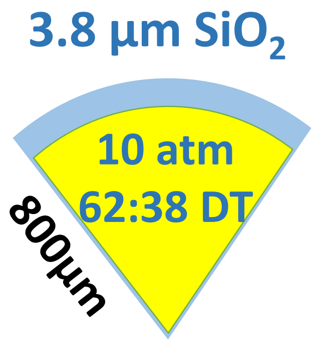




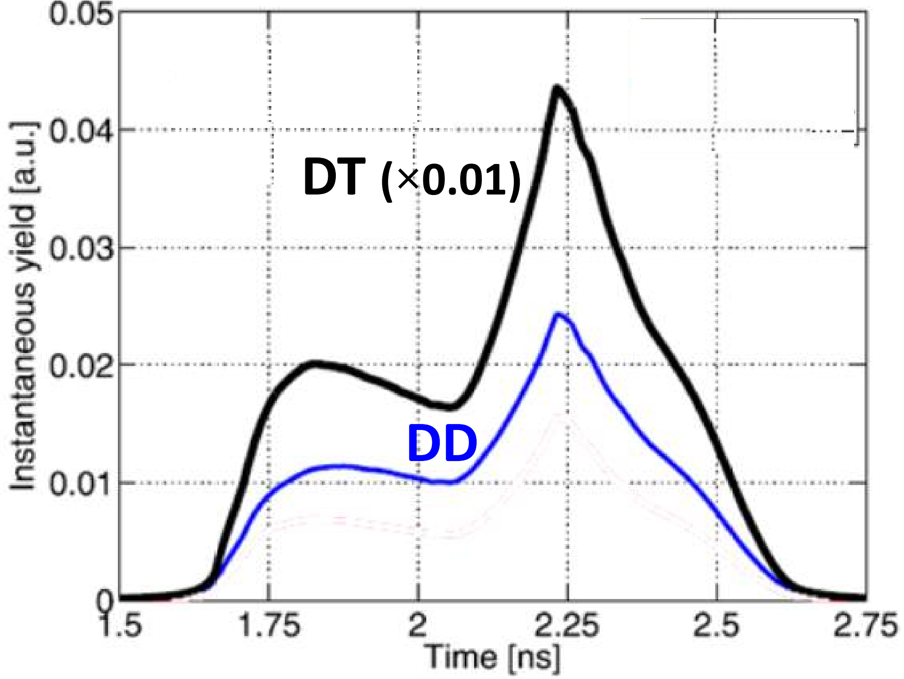
Bellei, PoP 2013

These multi-ion-fluid effects translate into quantitative changes in the reaction histories that can be measured (bang-time, burn onset, burnwidth)

OMEGA



Average-ion-fluid LSP reaction histories



Bellei et al., PoP 2013

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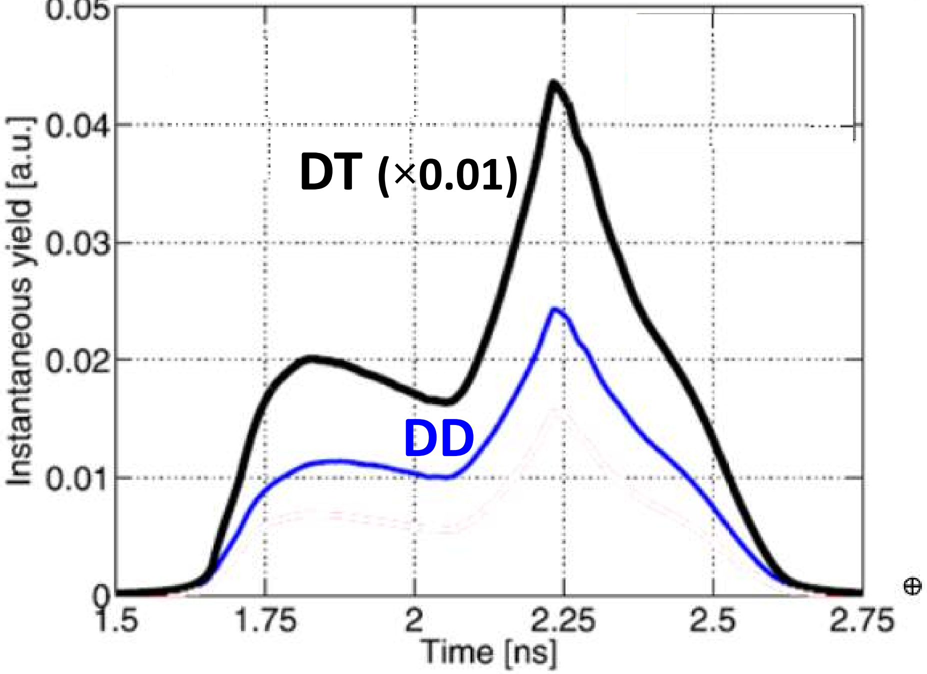
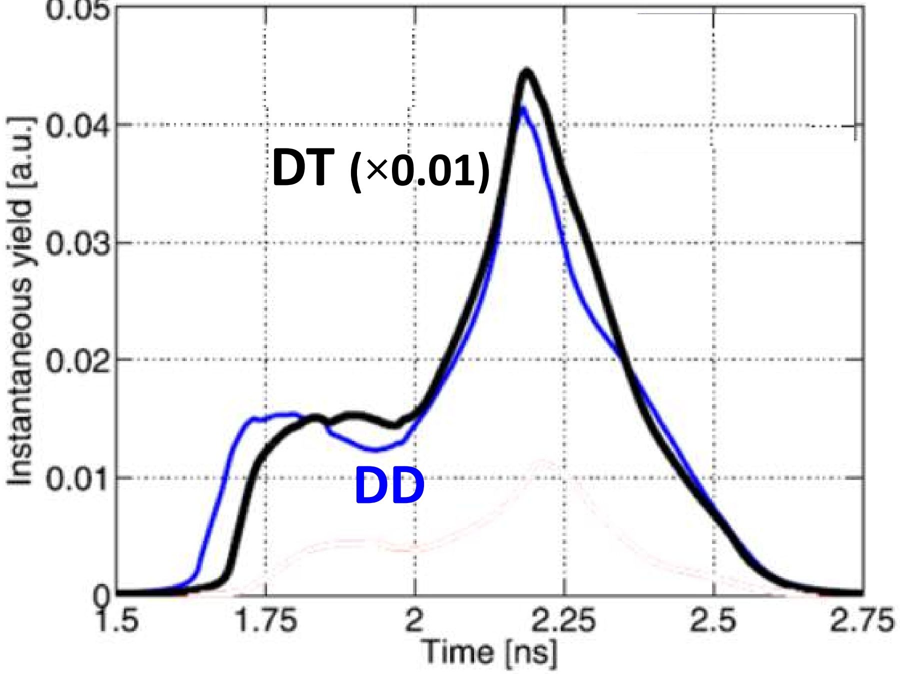
OMEGA

3.8 µm SiO_2

Average-ion-fluid LSP reaction histories



Two-ion-fluids LSP reaction histories



Bellei et al., PoP 2013

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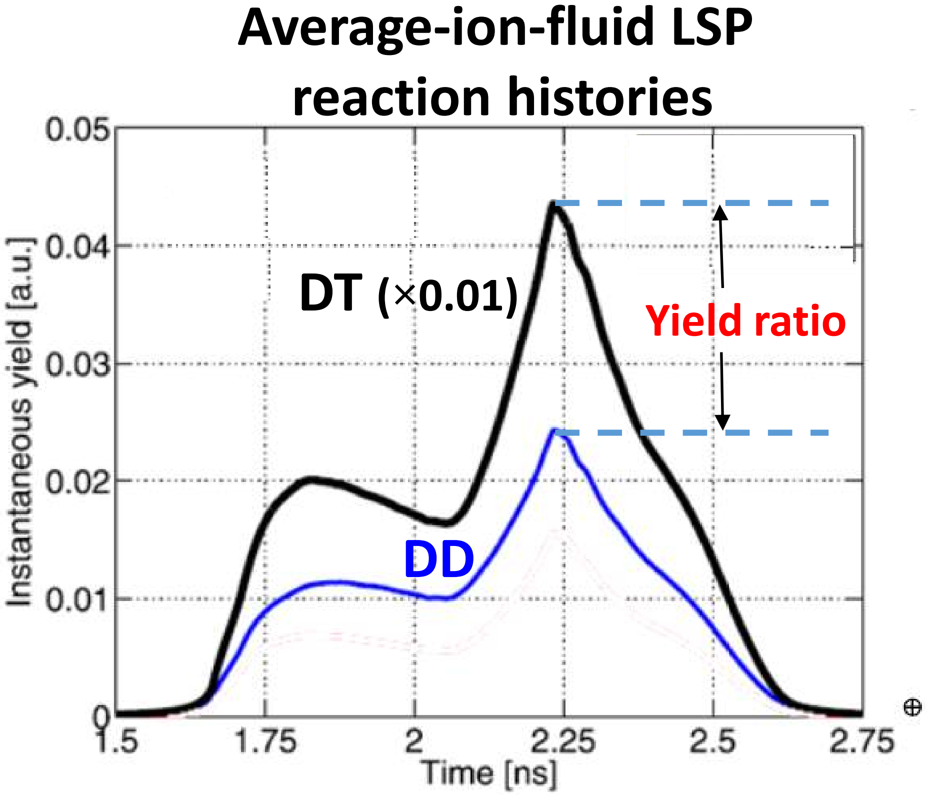
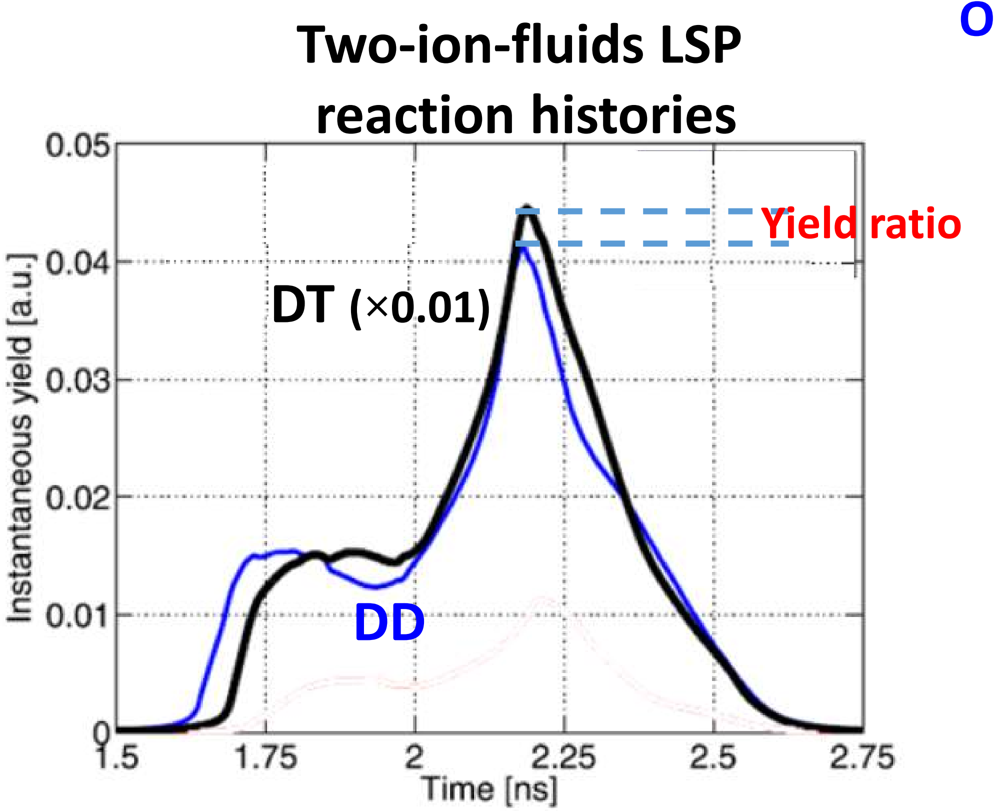


OMEGA



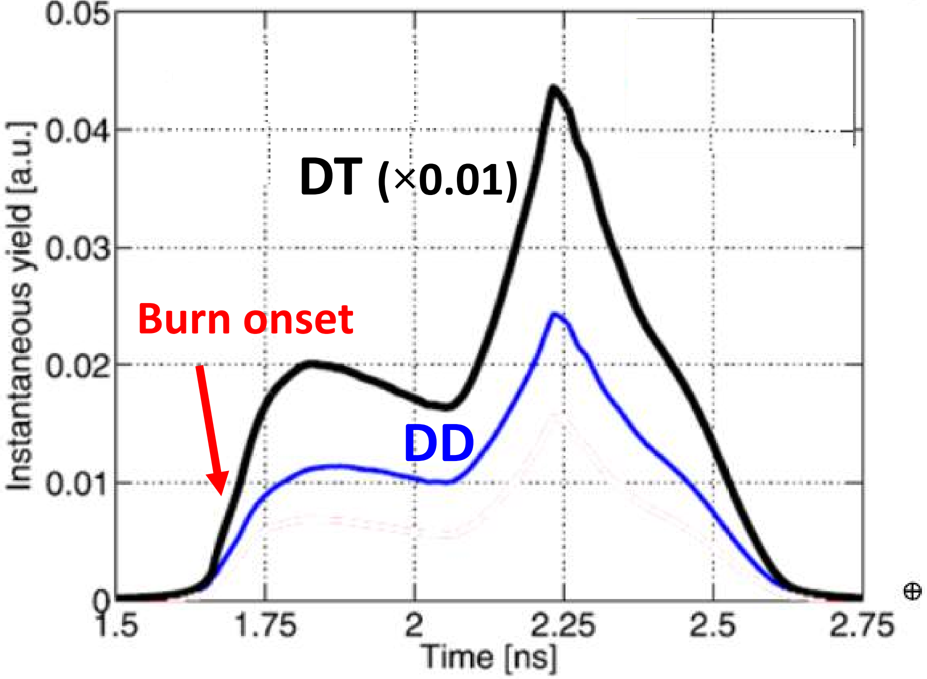
When comparing average-ion-fluid to multi-ion-fluid simulations, we observe:
~ 40% higher DD burn rate (relative to DT rate)

Bellei et al., PoP 2013

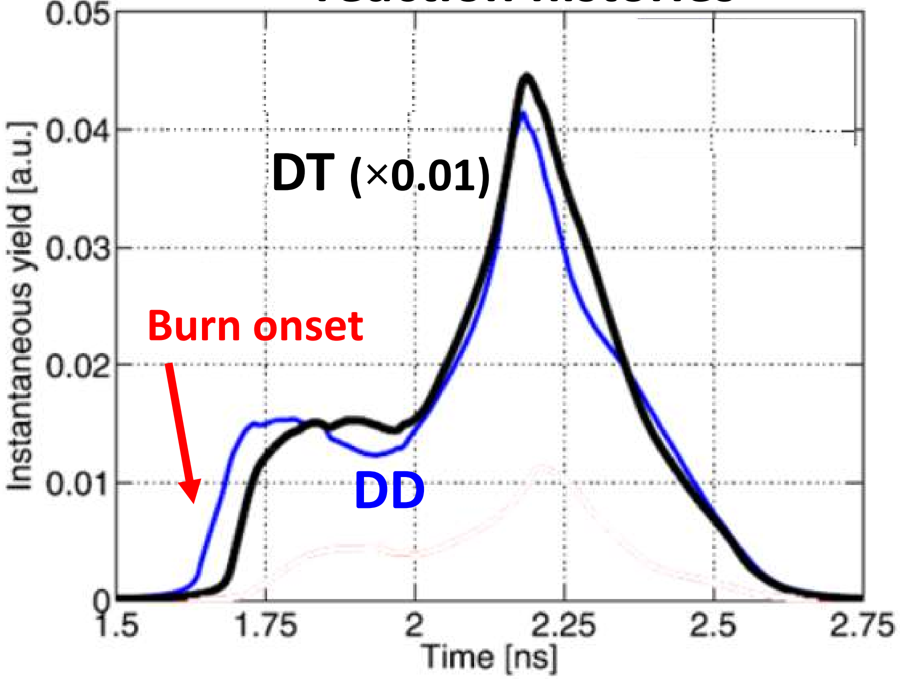
These multi-ion-fluid effects translate into quantitative changes in the reaction histories that can be measured (bang-time, burn onset, burnwidth)

OMEGA

Average-ion-fluid LSP reaction histories



Two-ion-fluids LSP reaction histories



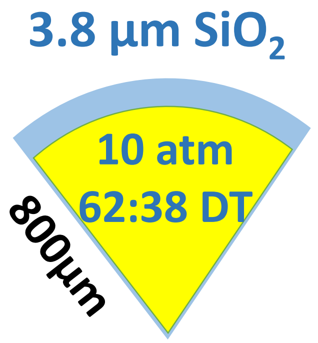
When comparing average-ion-fluid to multi-ion-fluid simulations, we observe:

~ 50 ps earlier DD burn onset (relative to DT burn onset)

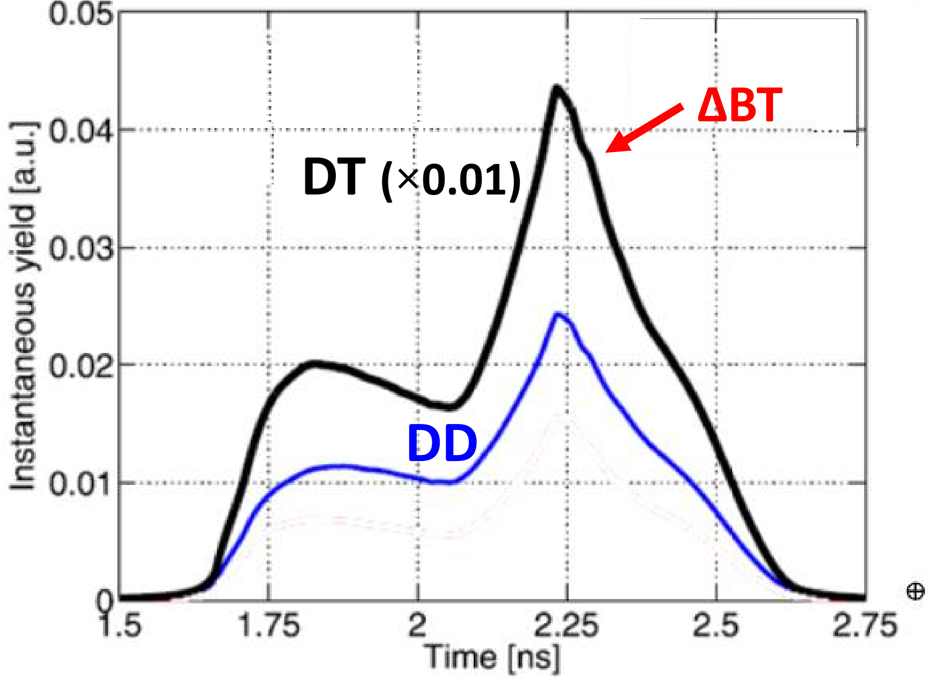
Bellei et al., PoP 2013

These multi-ion-fluid effects translate into quantitative changes in the reaction histories that can be measured (bang-time, burn onset, burnwidth)

OMEGA



Average-ion-fluid LSP reaction histories



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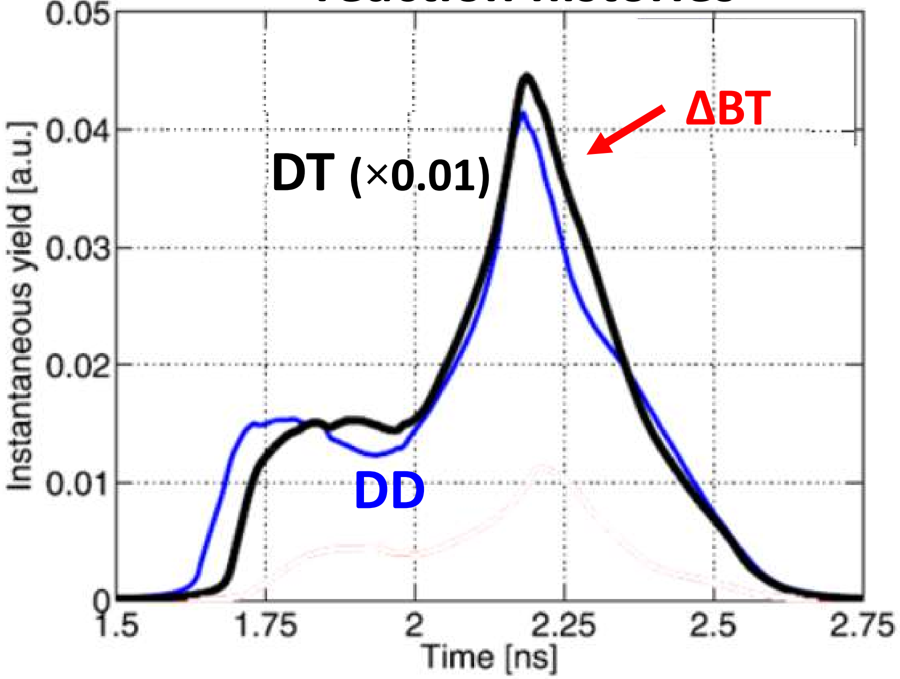
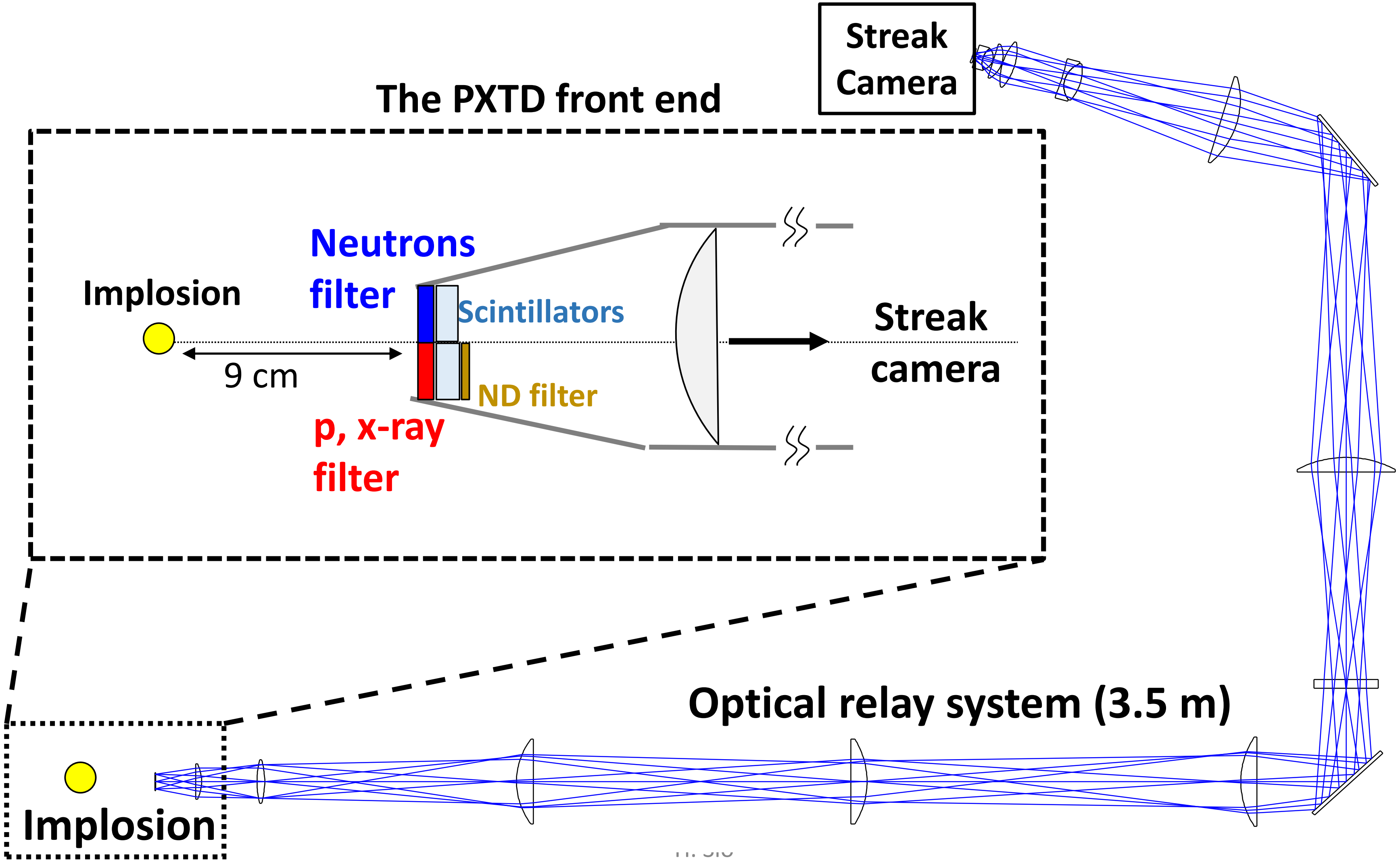


When comparing average-ion-fluid to multi-ion-fluid simulations, we observe:
~ 30 ps earlier DD bang-time (relative to DT bang-time)

Bellei et al., PoP 2013

The Particle X-ray Temporal Diagnostic (PXTD) is a multi-channel, streaked emission history diagnostic sensitive to charged particles, neutrons and x-rays

OMEGA



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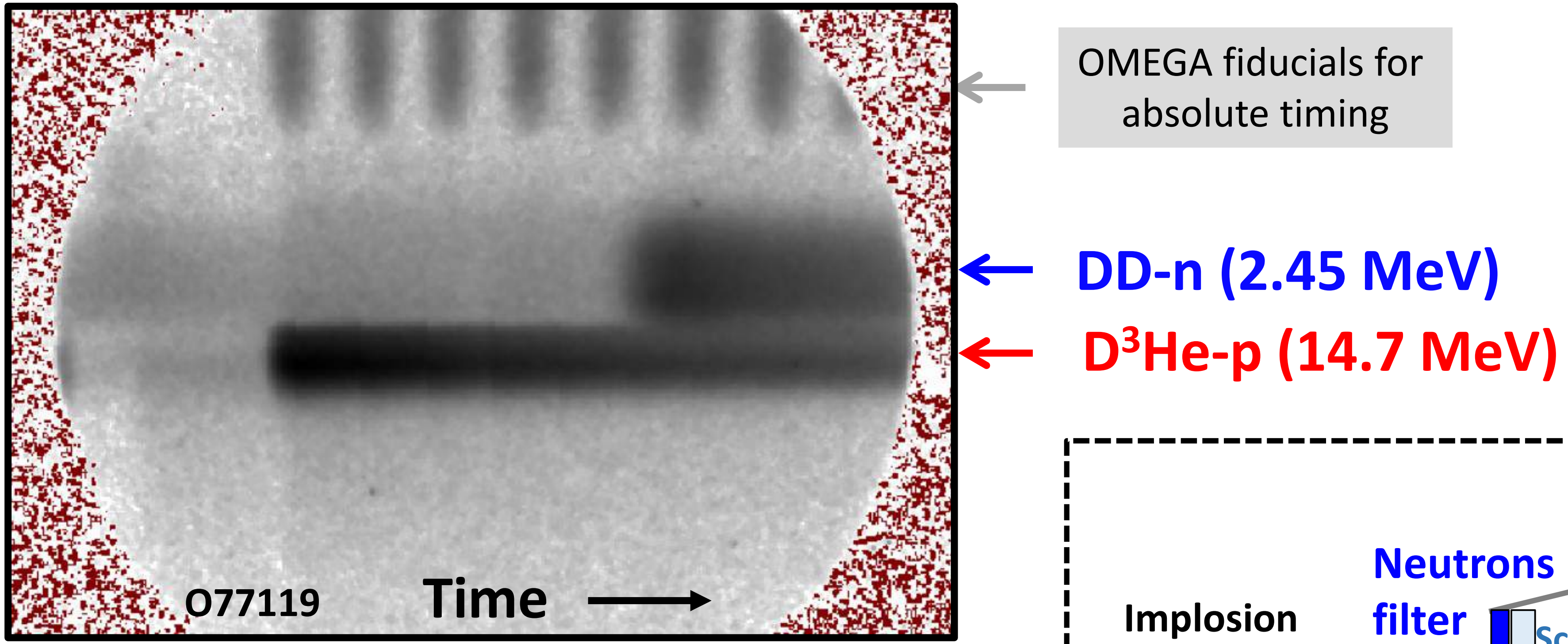

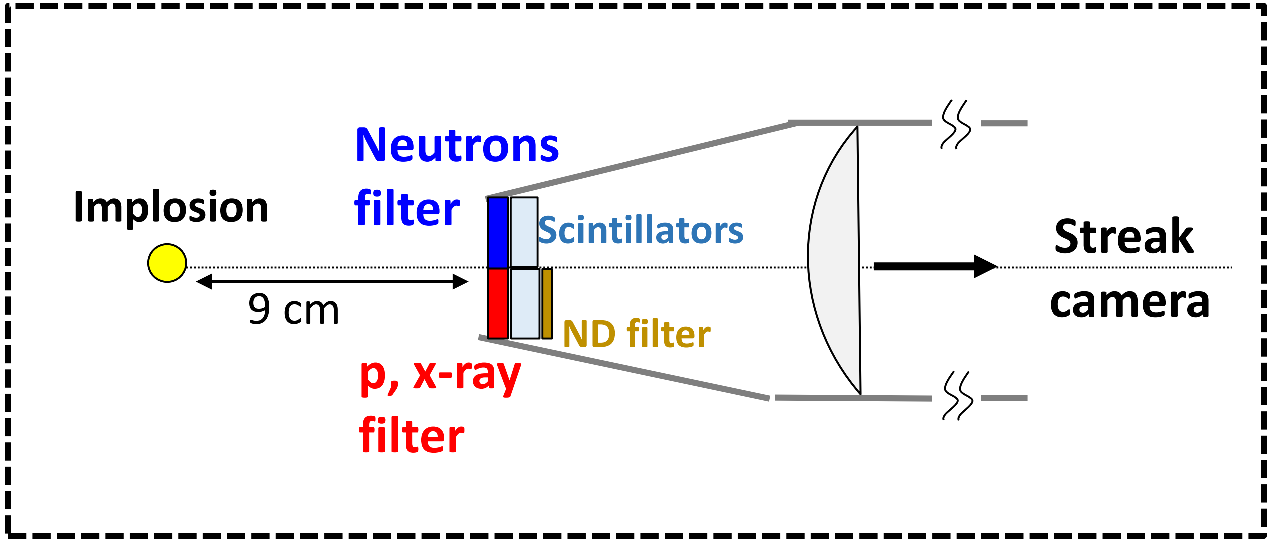

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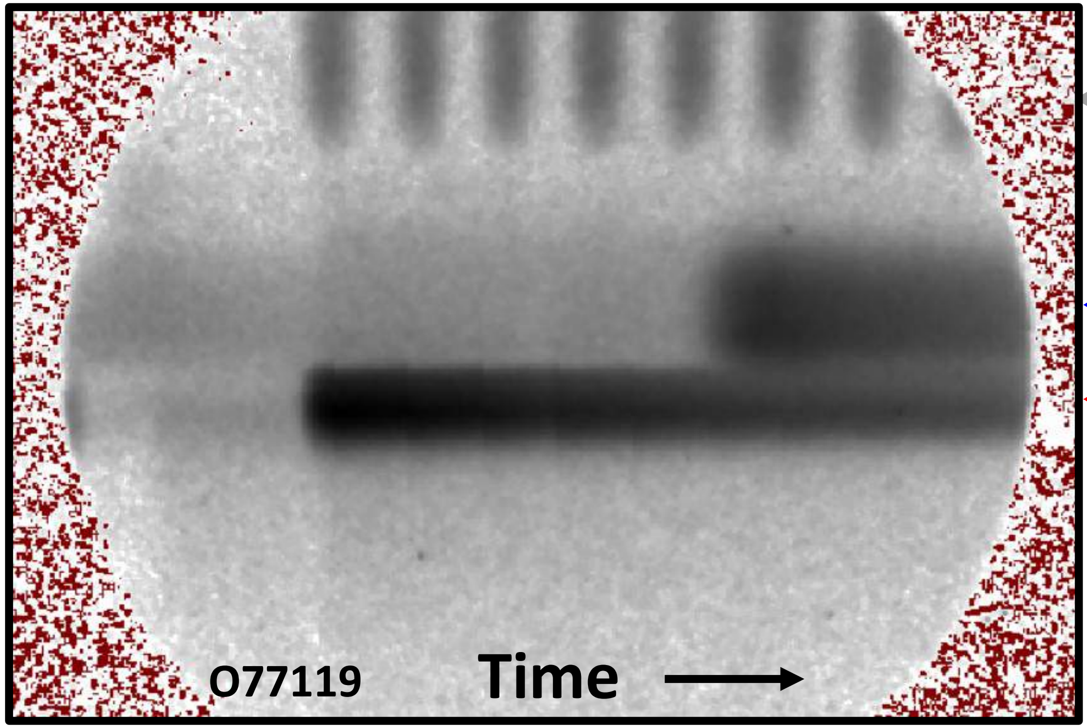
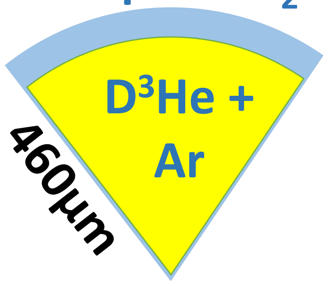
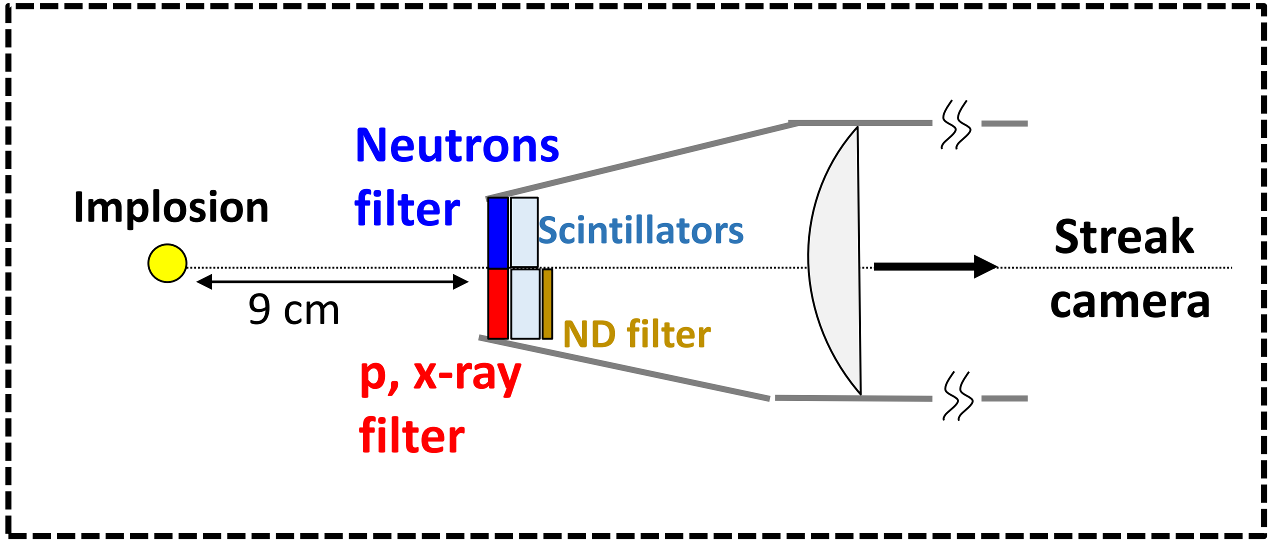


OMEGA fiducials for absolute timing

DD-n (2.45 MeV)

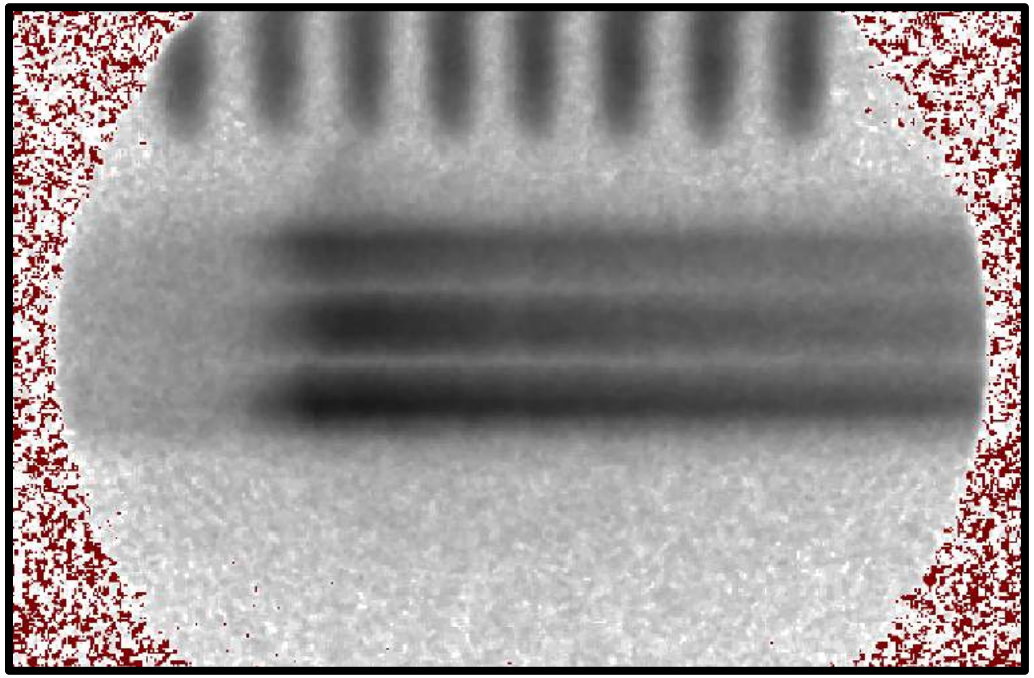
D^3He-p (14.7 MeV)





different signals on PXTD can be relative timed to ~ 15 ps because measurements are made on a single diagnostic

Three channels, each individually filtered, enable simultaneous measurements of multiple nuclear reaction and x-ray emission histories



OMEGA 80705 **Time** ⟶

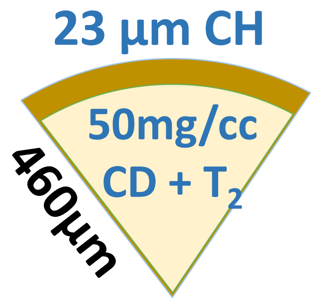
OMEGA fiducials for absolute timing

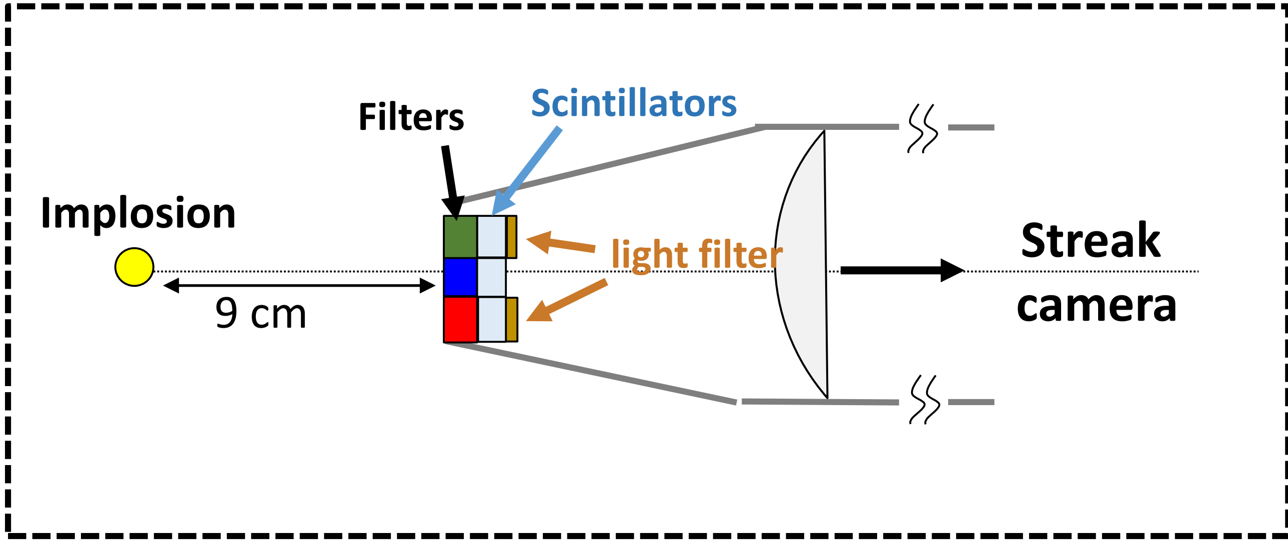
x-ray > 12 keV

x-ray > 20 keV

x-ray > 6 keV

OMEGA

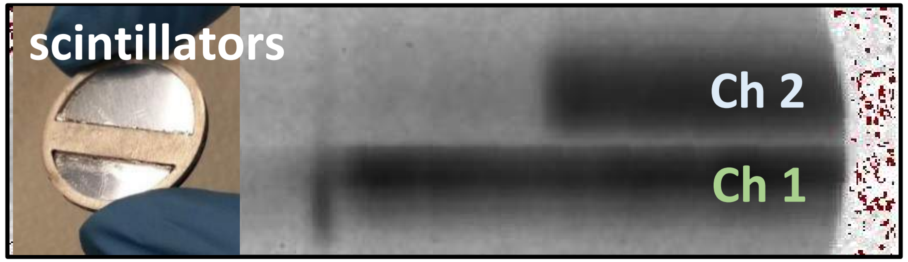




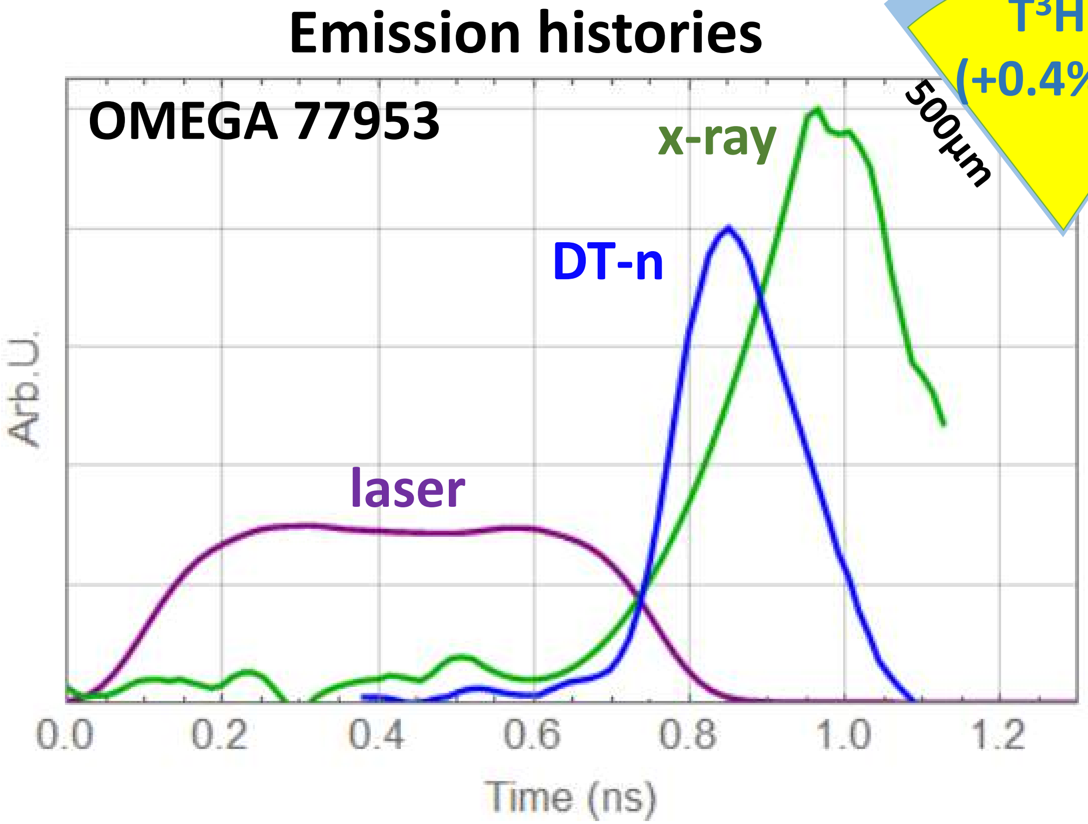
For a T_e = 3 keV plasma, x-ray signal magnitude varies by three order of magnitude for these three energy bands

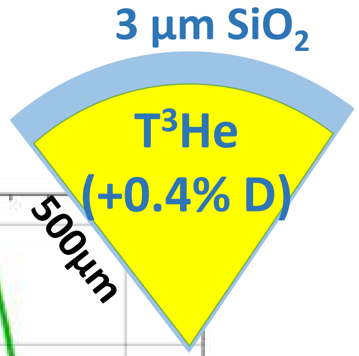
Multiple nuclear-reaction and x-ray-emission histories are also being measured simultaneously

OMEGA



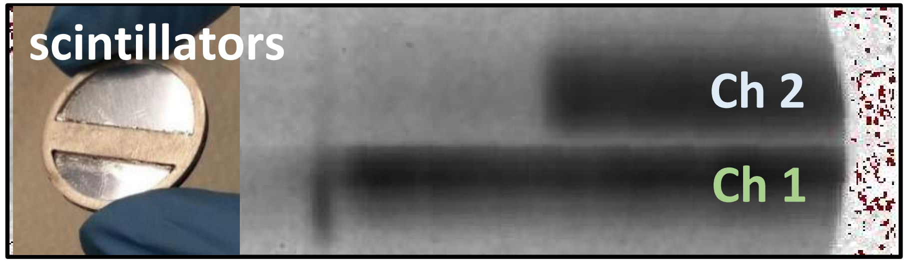
Relative x-ray, DT-n timing uncertainty ~ 10 ps





This has enabled measurements of x-ray bang-time, nuclear bang-time and their time differences with high relative precision

OMEGA



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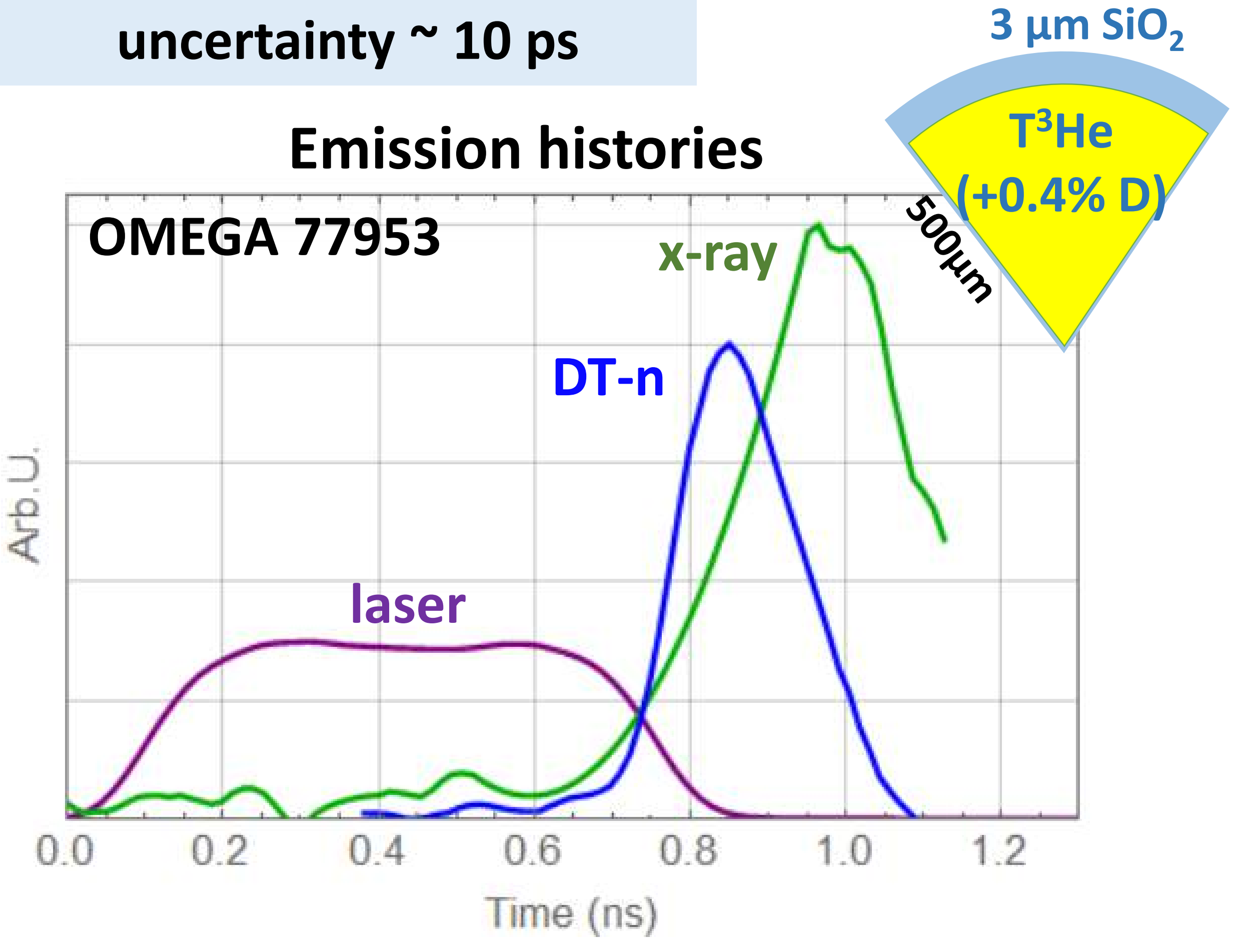

Precise measurements of the x-ray and nuclear histories, and their time difference, are being used to study kinetic and multi-ion effects during the shock phase of ICF implosions

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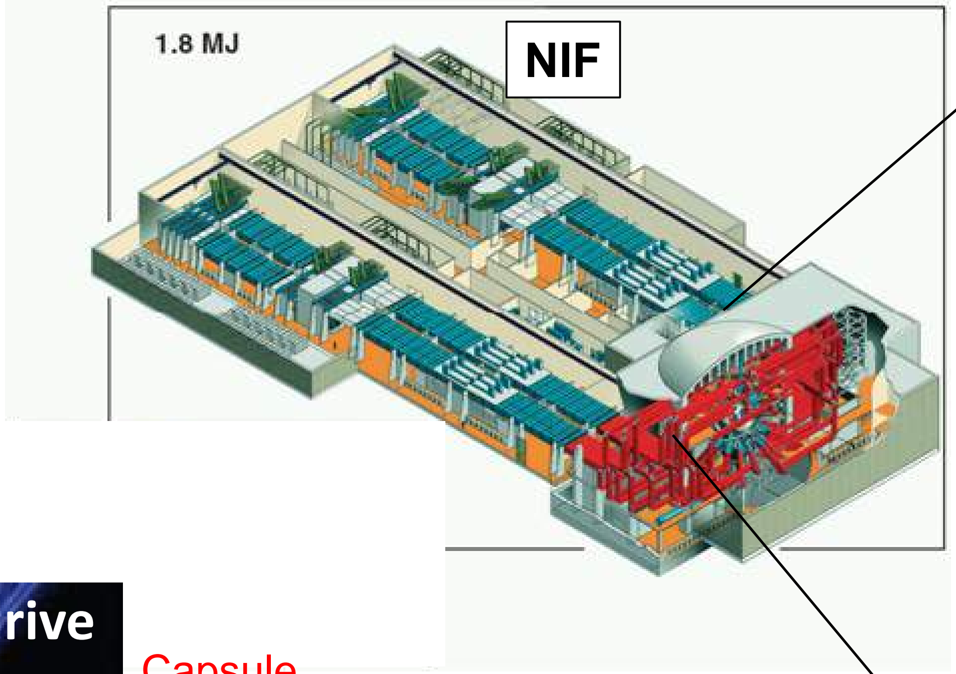
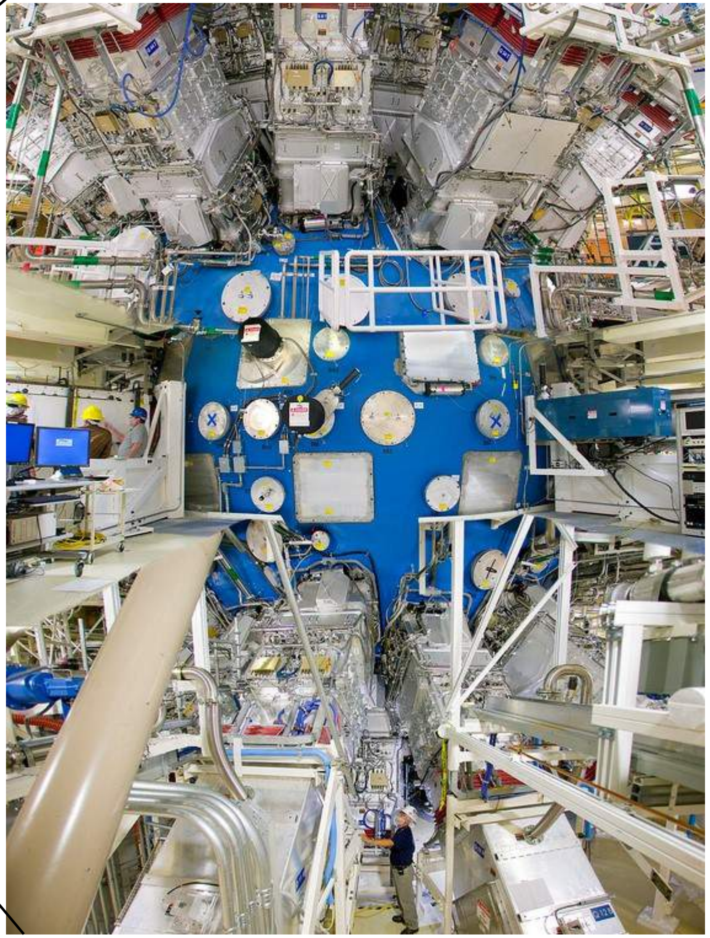
The National Ignition Facility (NIF) is the most energetic laser facility in the world

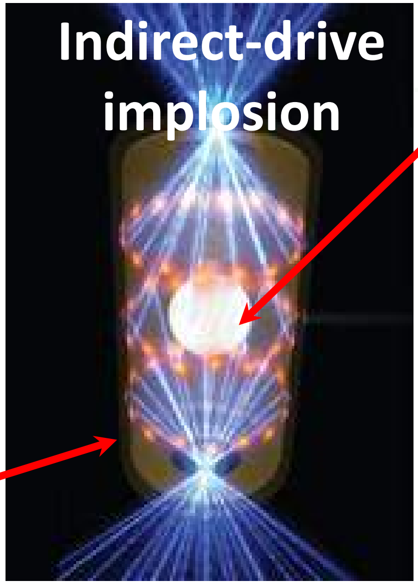
NIF

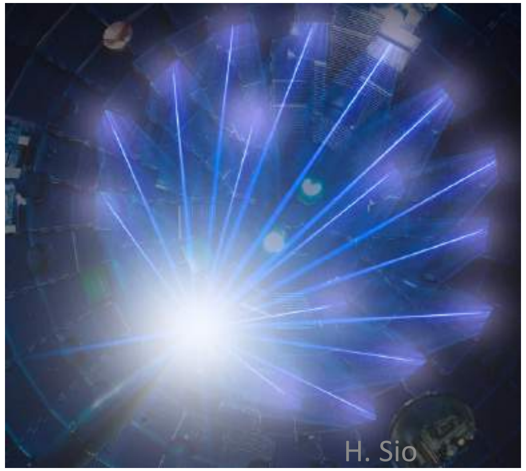
192 beams
1.8 MJ over ~ 20 ns
Shots per day: ~ 2-3





The NIF target chamber

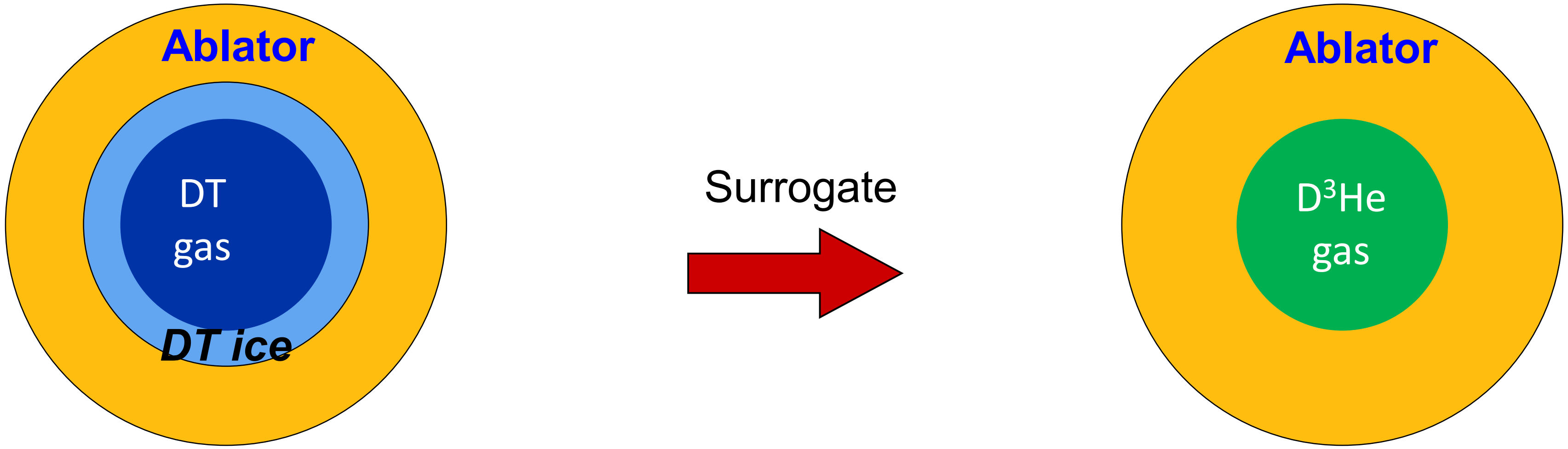




While integrated ignition experiments at NIF use DT fuel, surrogate implosions filled with D^3He fuel are used to study basic implosion physics

NIF

Cryogenic implosion | **Surrogate implosion**



DT-n (14.7 MeV)

DD-n (2.45 MeV)

D^3He-p (14.7 MeV)

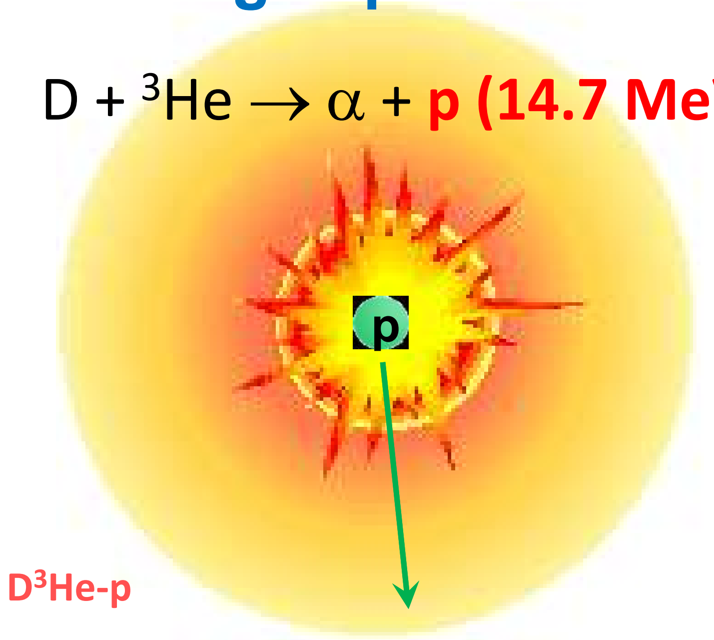
The ‘surrogate’ implosions are easier to field (allowing more physics experiments) and enable novel diagnostic techniques.

Confinement and burn properties can be probed by studying the nuclear fusion reactions products

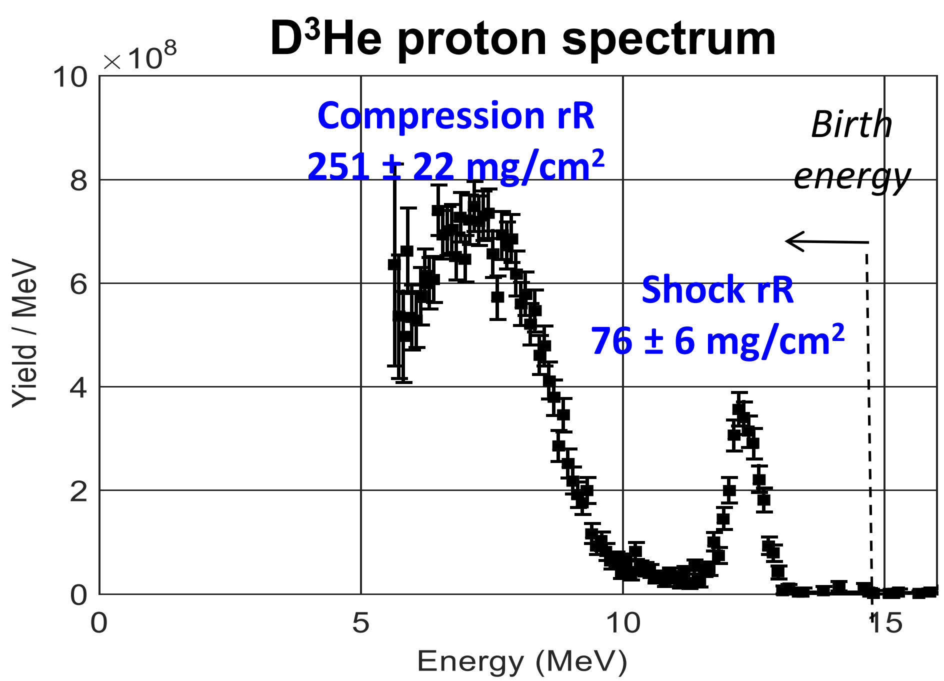
NIF

1. Charged particles

$D + {}^3He \rightarrow \alpha + p\ (14.7\ MeV)$



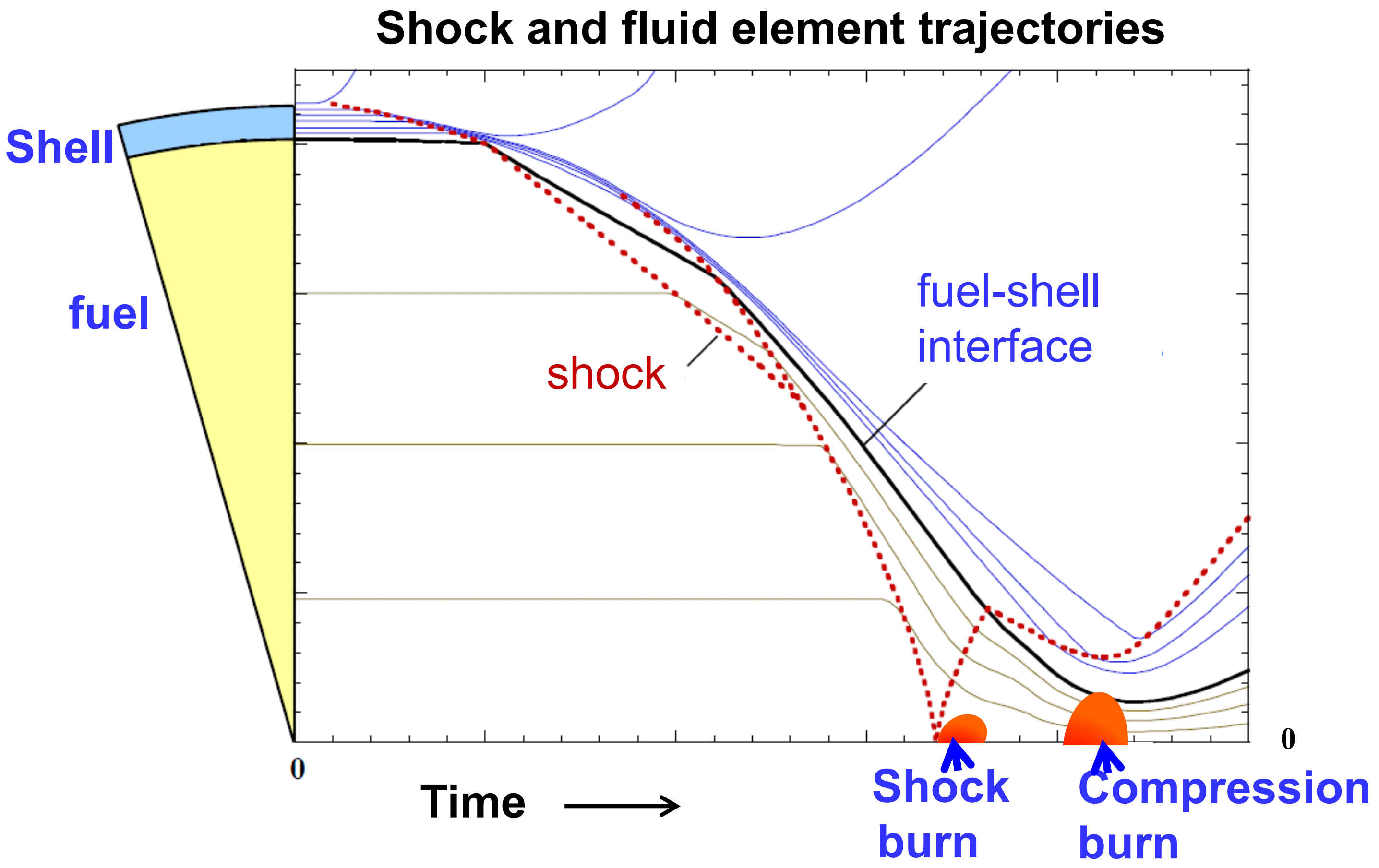
All charged fusion products lose energy due to ranging in the shell



The MIT-led wedge-range-filter (WRF) proton spectrometer measures evolution of areal density (ρR) from shock to compression

In ICF implosions, nuclear burn occurs at two different times: (1) Shock burn, and then (2) Compression burn

NIF

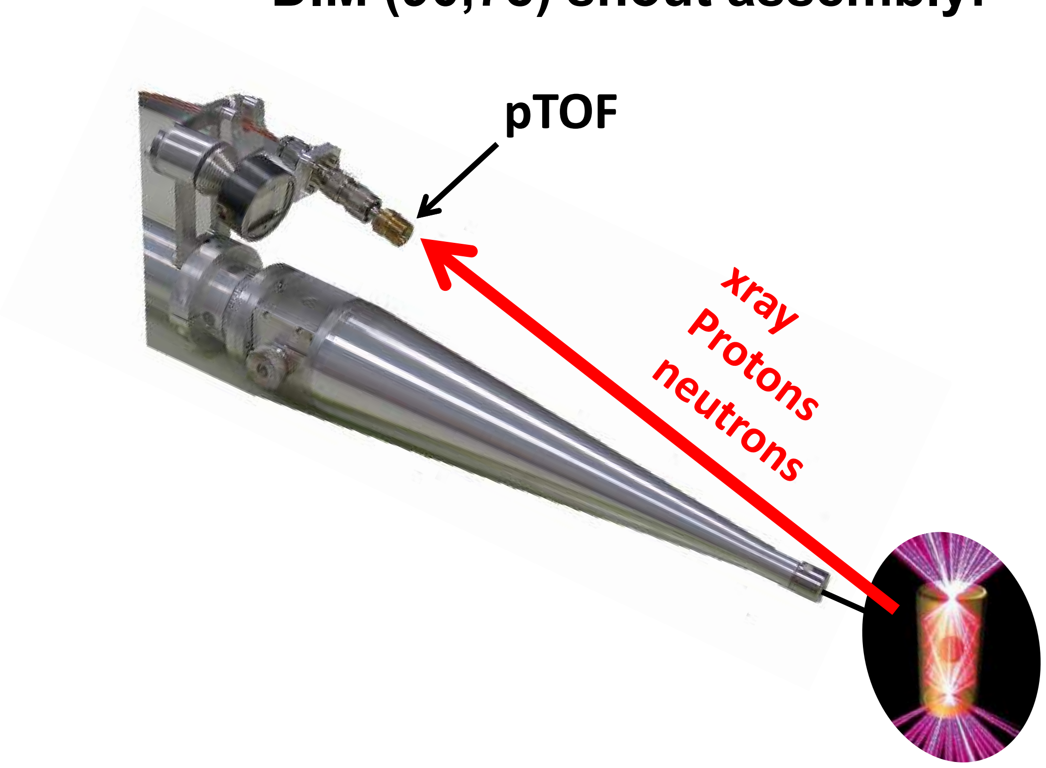


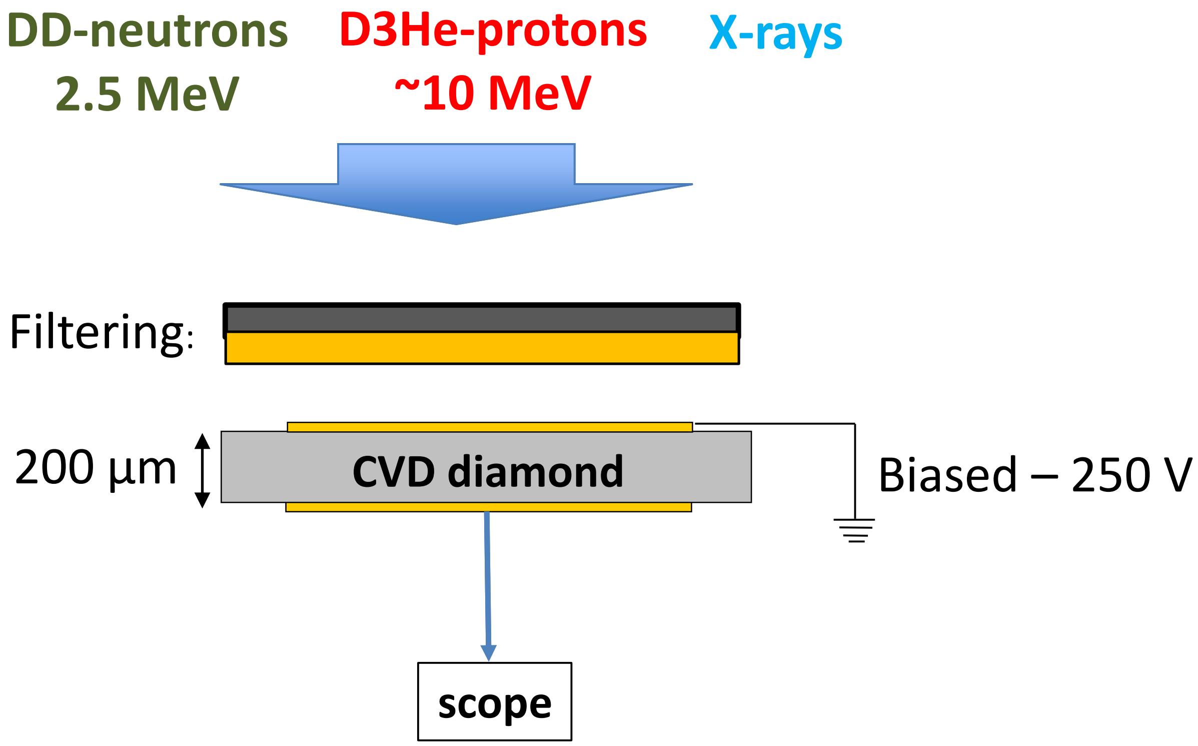
The MIT-led magnetic-particle-time-of-flight (magPTOF) diagnostic measure both shock and compression bang-time on the same diagnostic

The particle Time-of-Flight (pTOF) is a nuclear bang-time diagnostic sensitive to xray, protons, and neutrons

NIF

DIM (90,78) snout assembly:



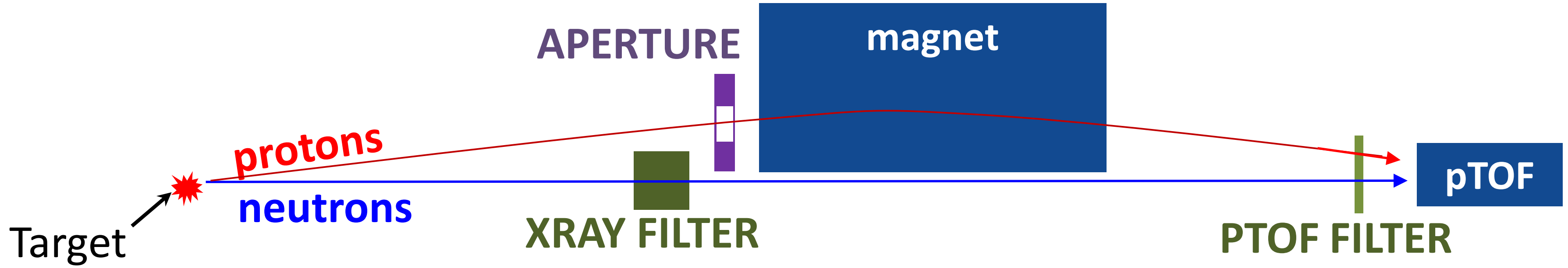


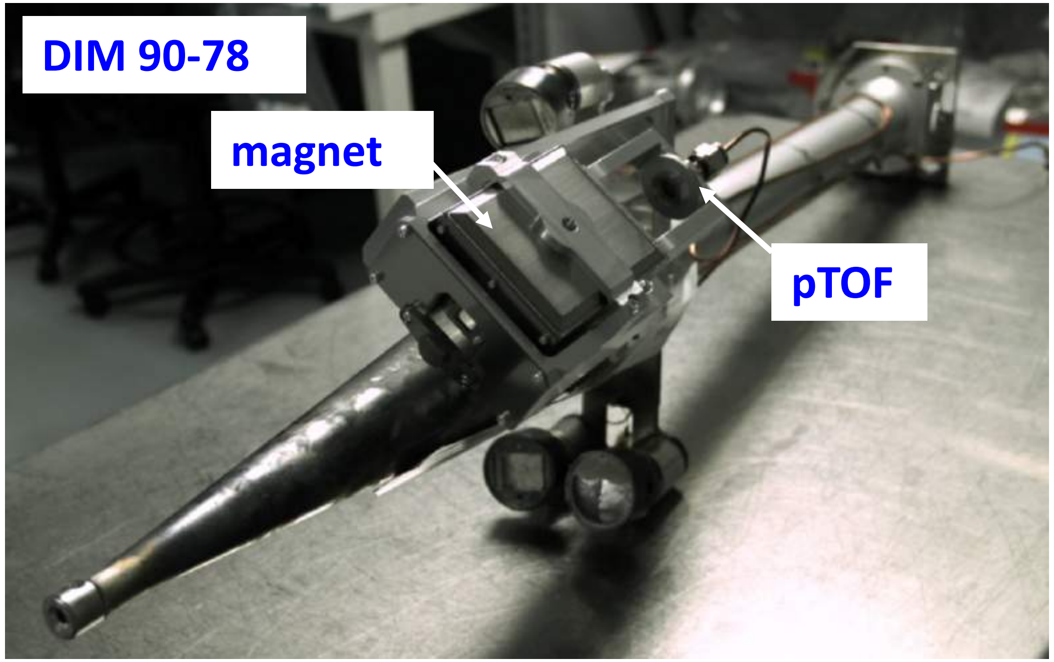
pTOF has been fielded on low x-ray background shots at the NIF for the past 4 years, and is the only diagnostic capable of measuring nuclear bang-time for yield < 1e13

H.G. Rinderknecht, et al. Rev. Sci. Instrum. 83, 10D902 (2012)

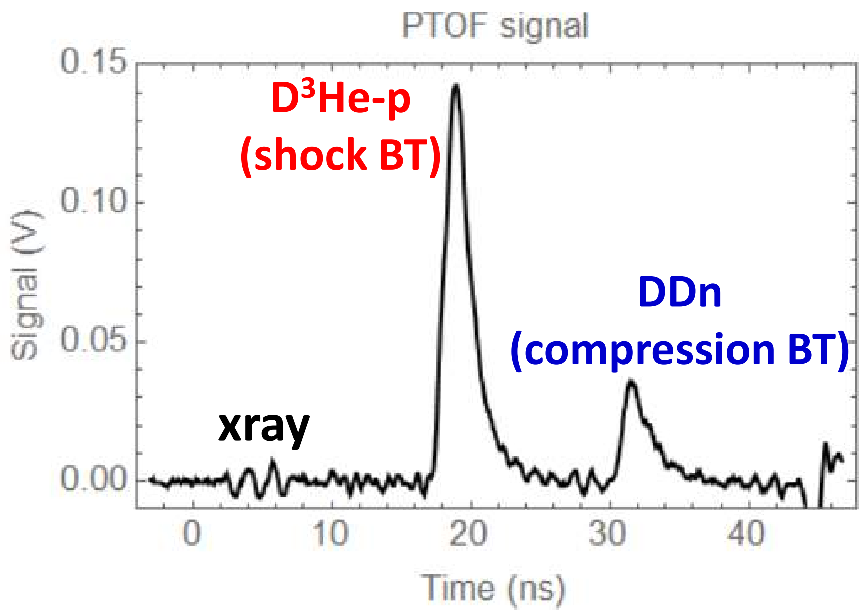
In the magPTOF upgrade, magnet and x-ray shielding allow x-ray, proton and neutron signals to be measured with similar amplitudes

NIF



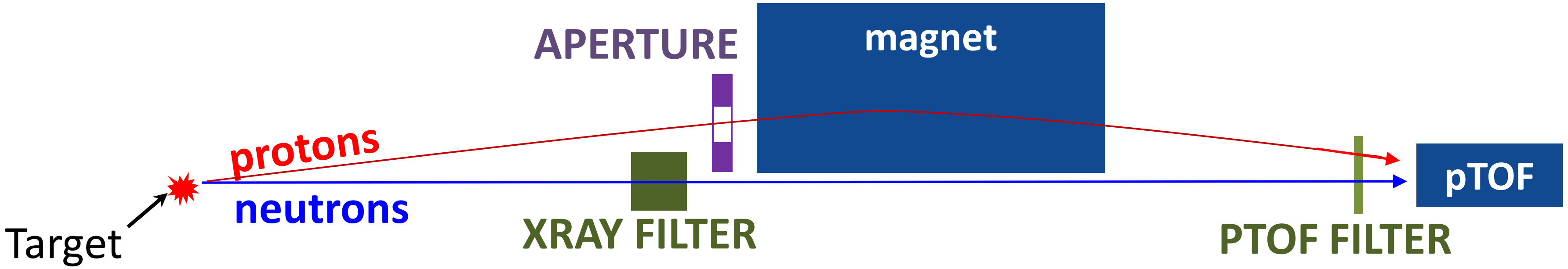


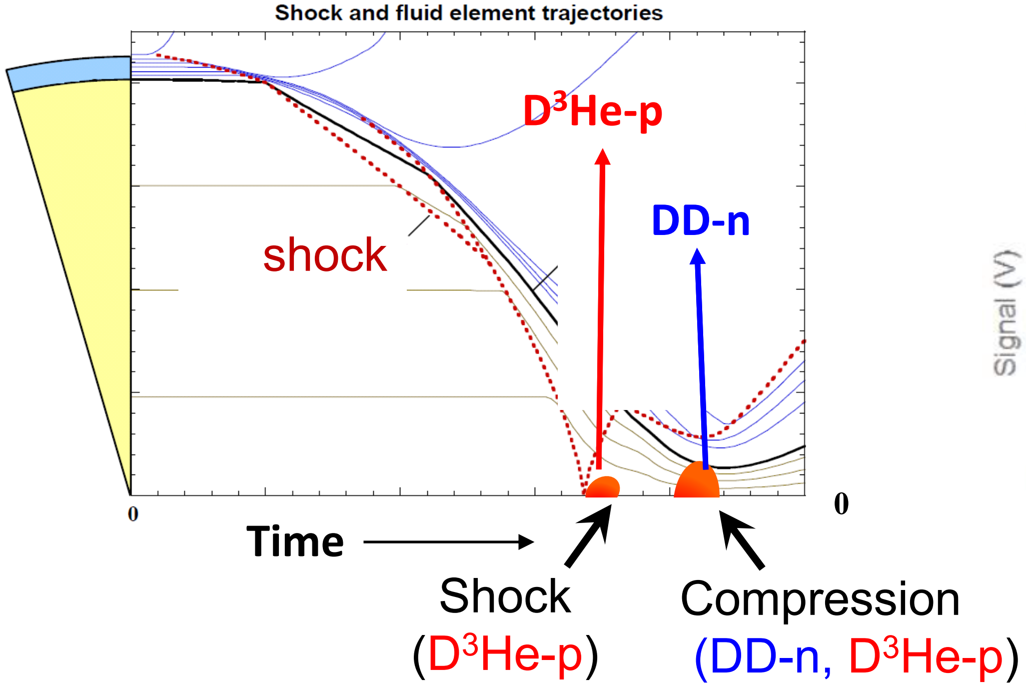
NIF surrogate shot N151221



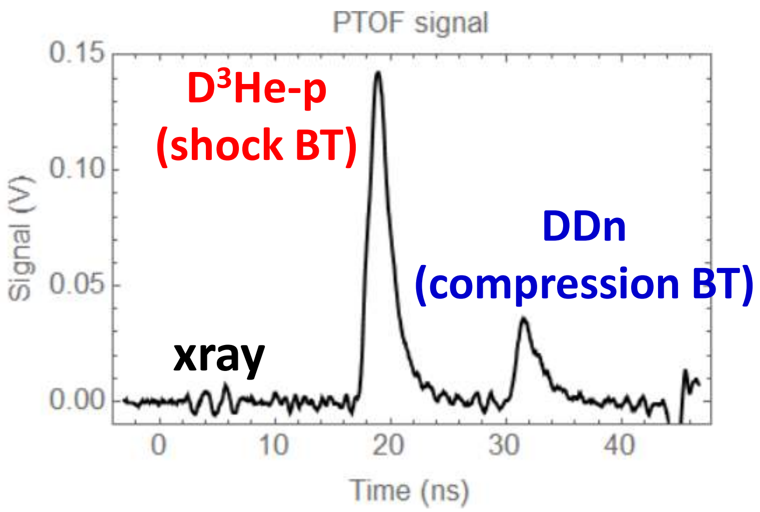
In the magPTOF upgrade, magnet and x-ray shielding allow x-ray, proton and neutron signals to be measured with similar amplitudes

NIF





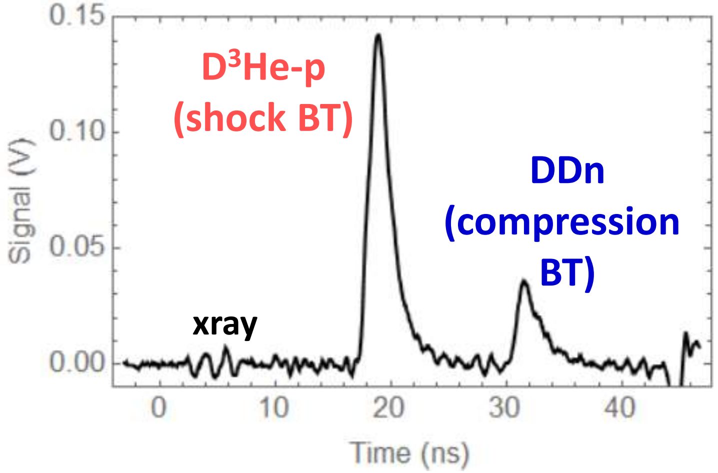
NIF surrogate shot N151221



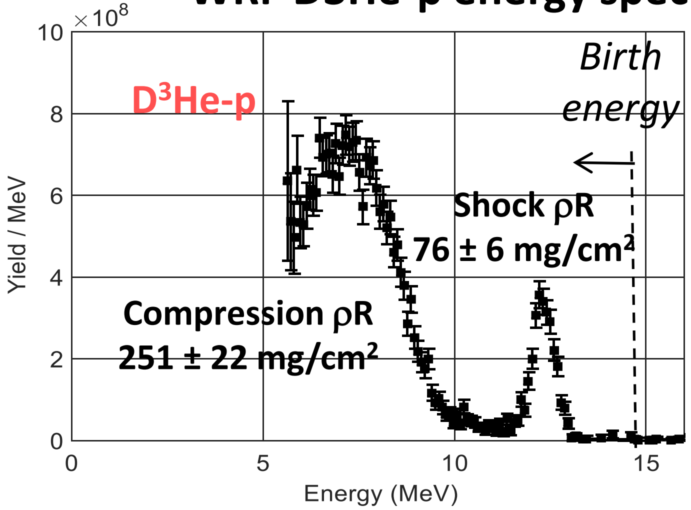
At the NIF, magPTOF and WRF spectrometers precisely measure bang times and areal densities at shock & compression

NIF

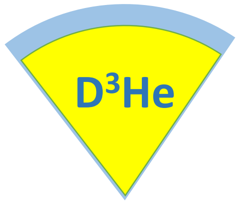
magPTOF bang-time signals



WRF D3He-p energy spectrum



NIF surrogate shot N151221



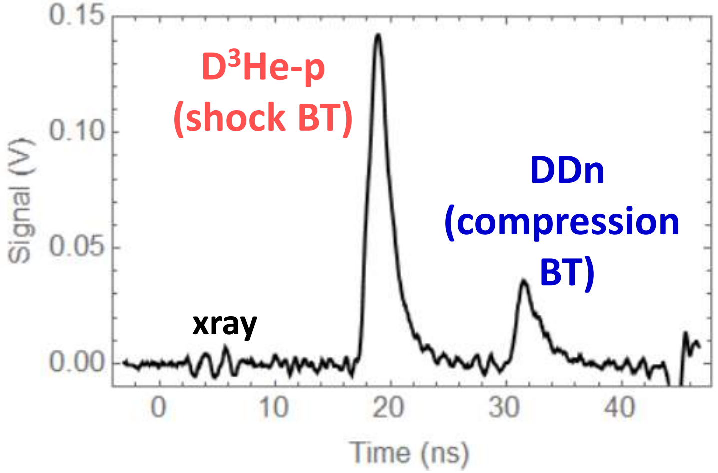
$D + {}^3He \rightarrow$ p (14.7 MeV) $+ \alpha$

$D + D \rightarrow$ n (2.5 MeV) $+ T$

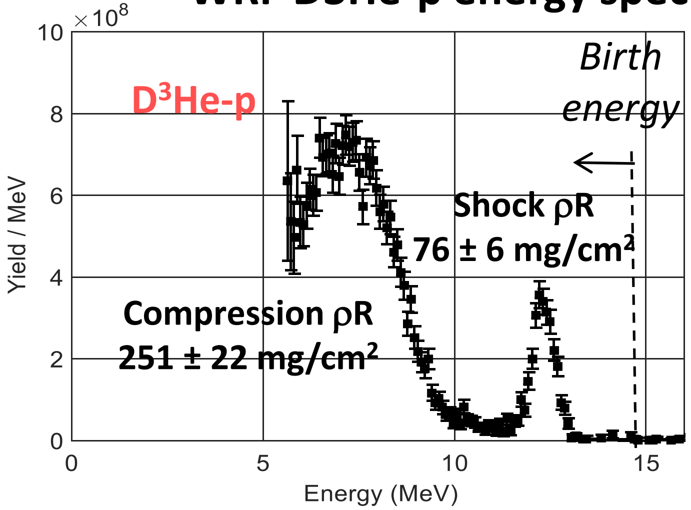
At the NIF, magPTOF and WRF spectrometers precisely measure bang times and areal densities at shock & compression

NIF

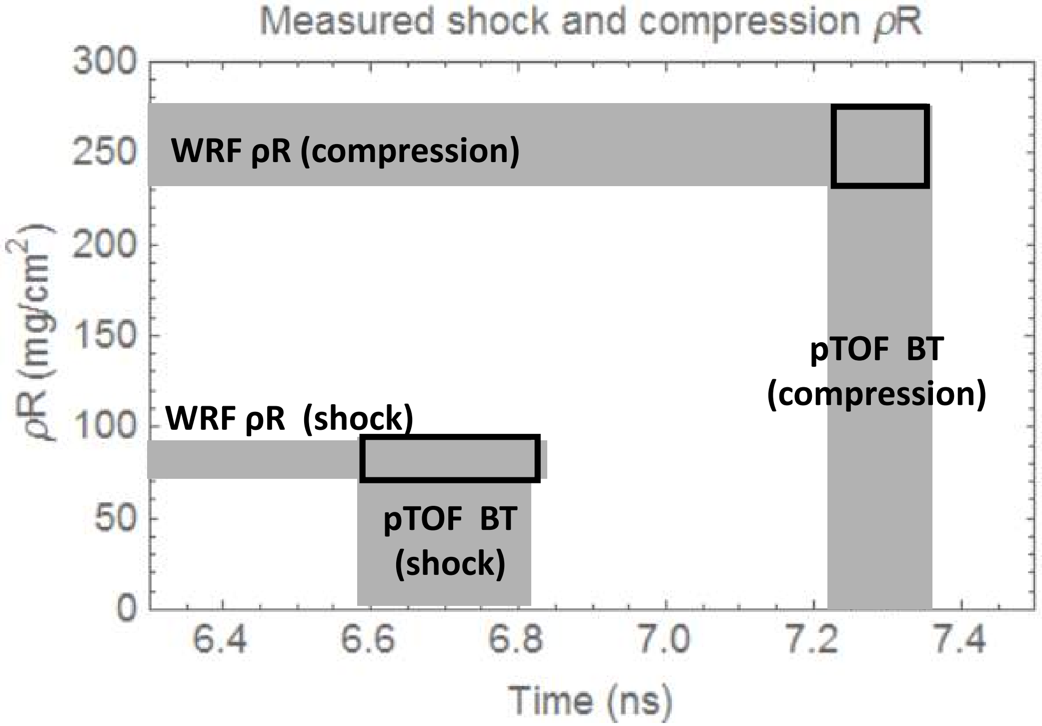
magPTOF bang-time signals



WRF D3He-p energy spectrum



NIF surrogate shot N151221

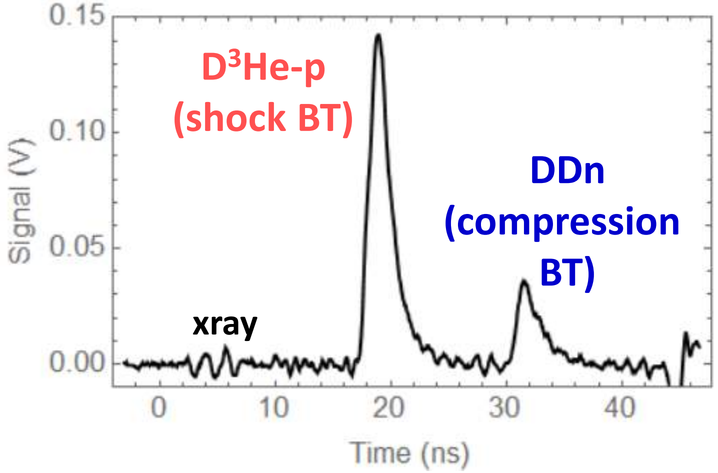


grey bars denote measurement uncertainty

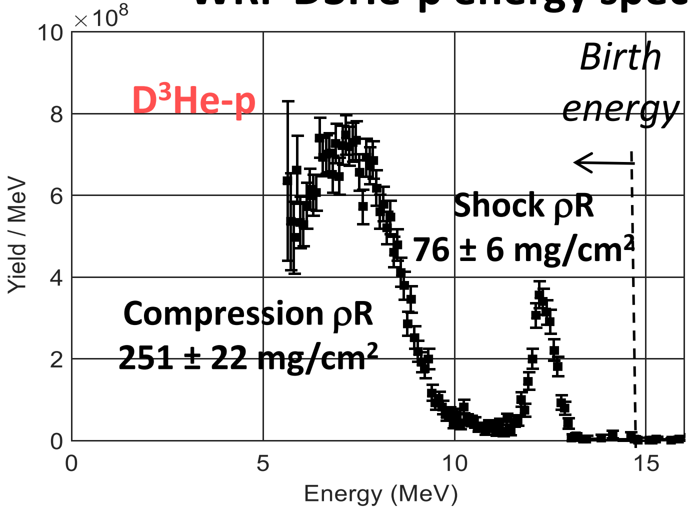
Measured bang times and areal densities at shock & compression are being used to infer ρR evolution from shock to compression

NIF

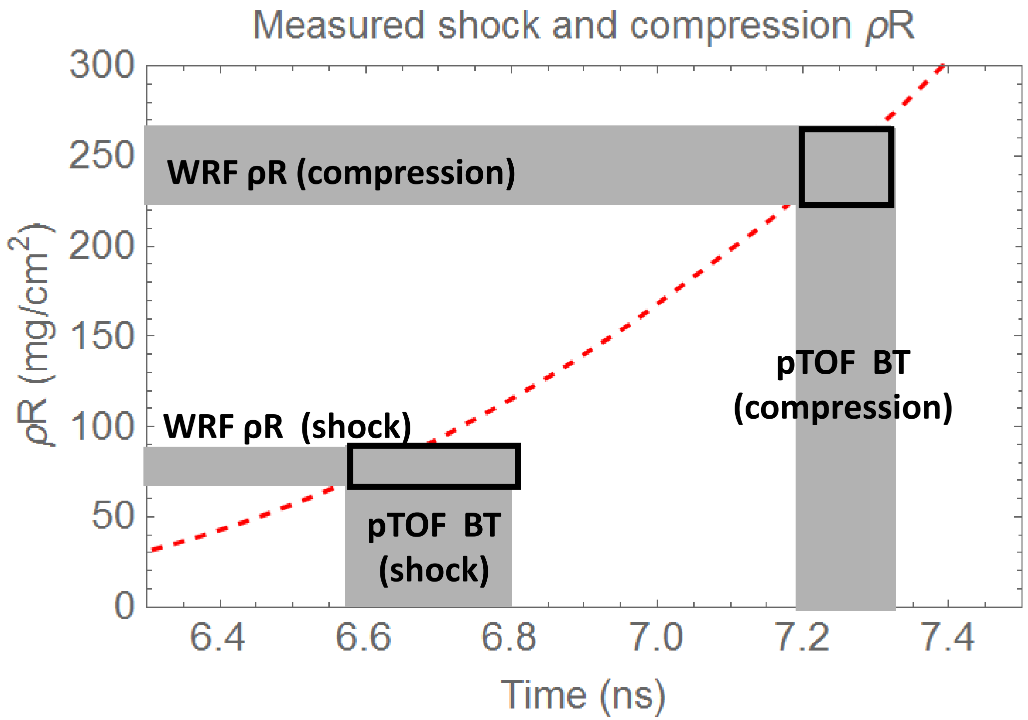
magPTOF bang-time signals



WRF D3He-p energy spectrum

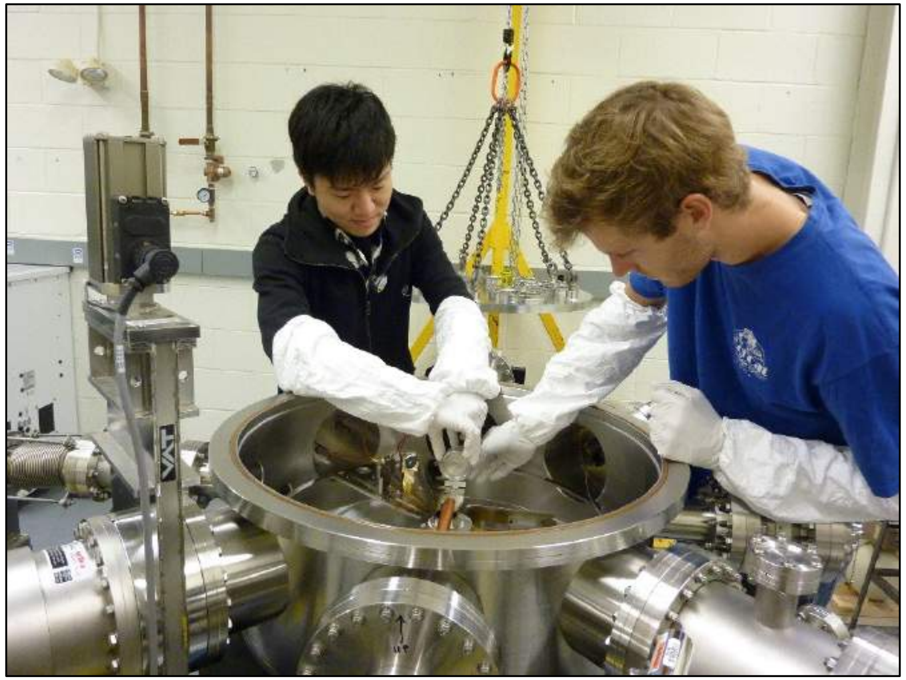


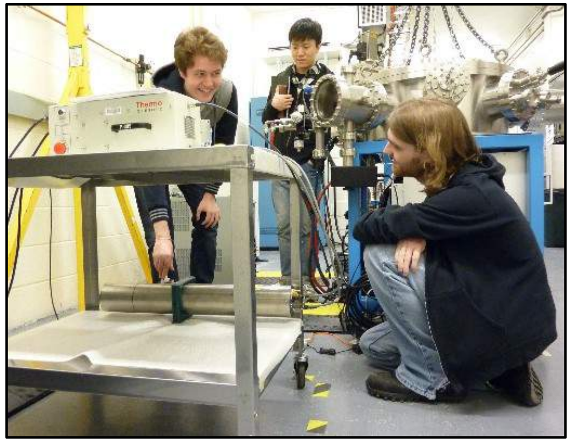
NIF surrogate shot N151221



grey bars denote measurement uncertainty

Students develop and test MIT diagnostics at the MIT HEDP Accelerator Facility before fielding at NIF, OMEGA & Z





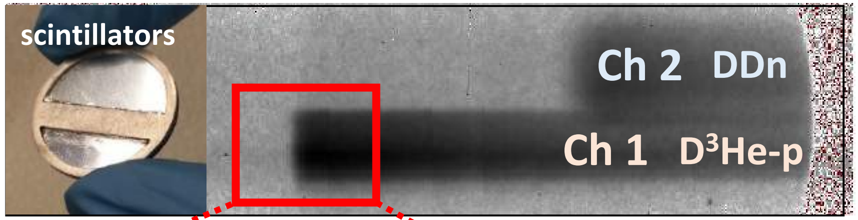
Time-resolved nuclear diagnostics for probing implosion dynamics and kinetic & multi-ion effects on OMEGA and the NIF

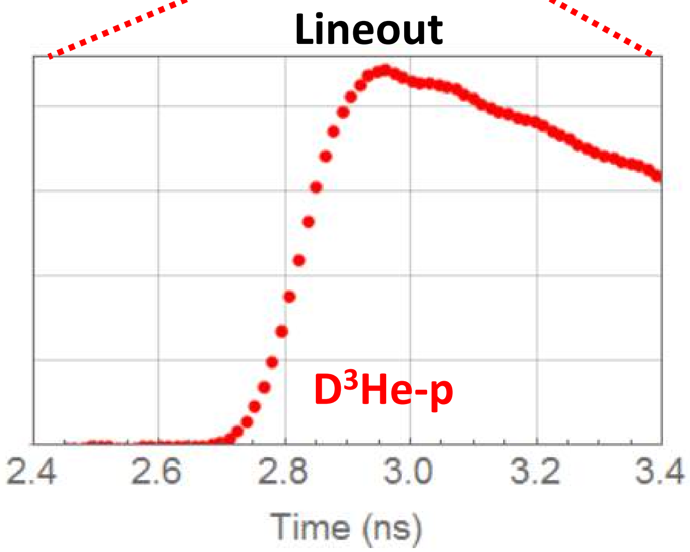
- **Platform development, diagnostic work, and physics studies on the OMEGA laser facility**
  1. Kinetic and multiple-ion-fluid effects in ICF implosions using time-resolved data on several nuclear reactions, as well as the core x-ray continuum
  2. Design and implementation of the Particle Xray Temporal Diagnostic (PXTD)

- **Diagnostic development, and physics studies on the National Ignition Facility (NIF)**
  1. Implosion dynamics from measurements of the shock and compression bang-times
  2. Implementation and improvement of the magnetic Particle-Time-of-Flight (magPTOF) diagnostic

The reaction history is determined from the leading edge of the streak signal using a forward fit approach

Shot 75694 Streak of D3He protons and DD neutrons





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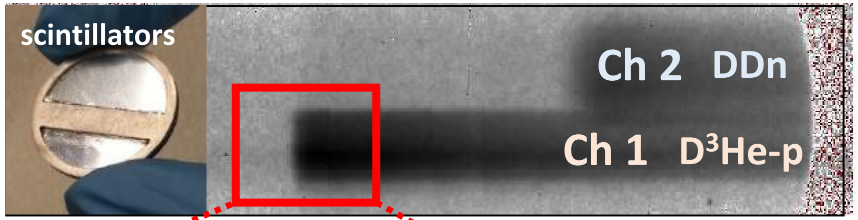
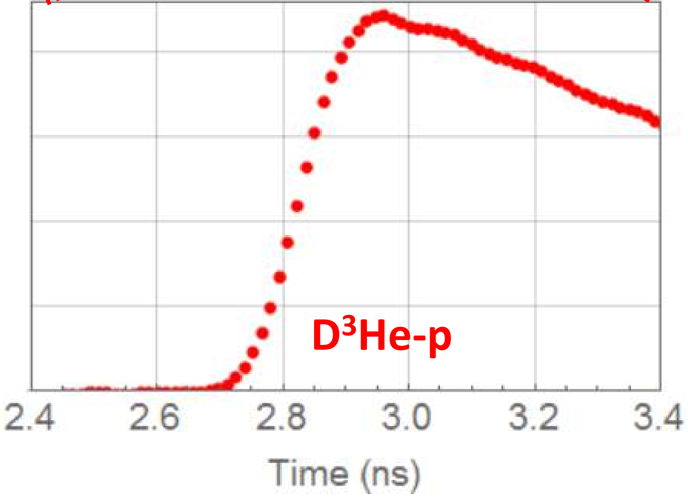
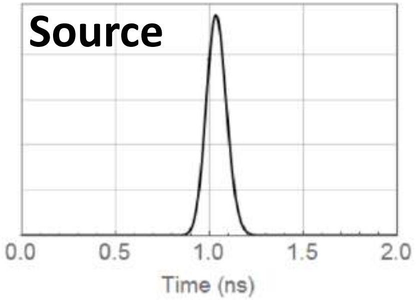
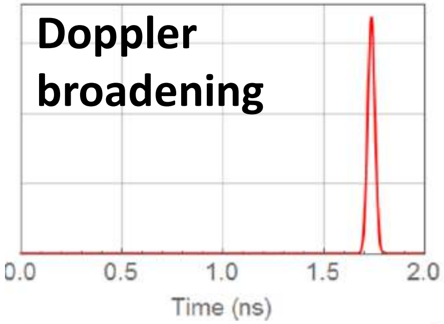


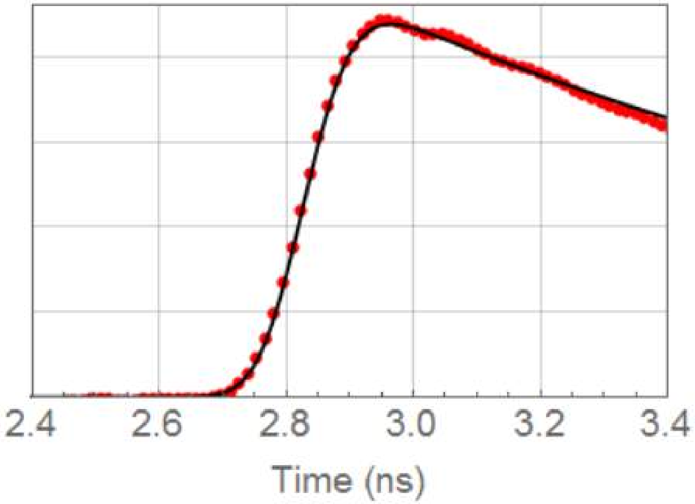
Lineout







Lineout + Forward Fit

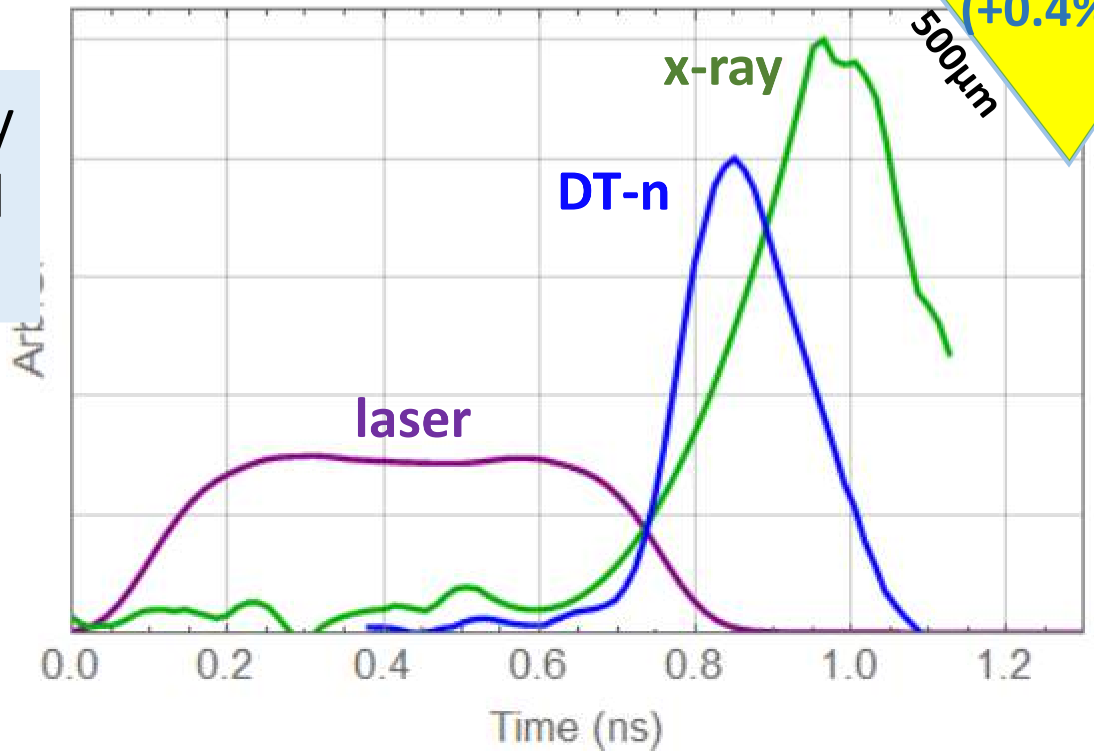


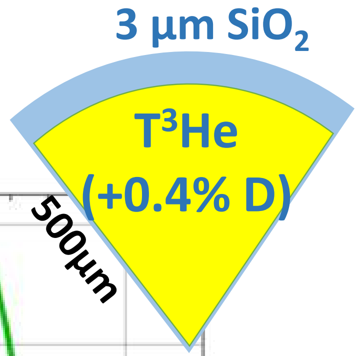
Deconvolution provides the same answers in terms of inferred bang time, burn duration, and burn onset

Measured nuclear-reaction and x-ray emission histories will be compared to different hydrodynamic and kinetic simulations

Goal is to infer Ti(t) and Te(t) in ICF plasmas by measuring **two** nuclear-reaction histories and **three** x-ray emission histories simultaneously

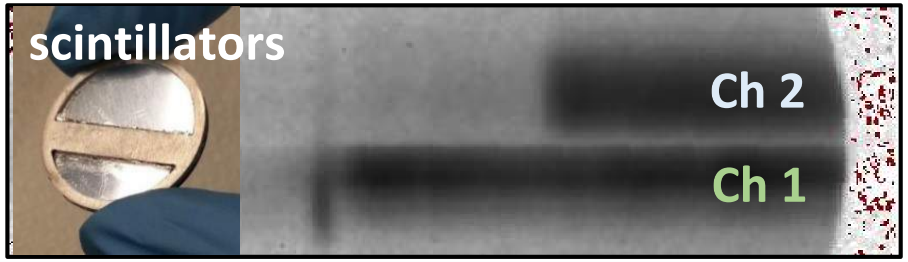
Emission histories

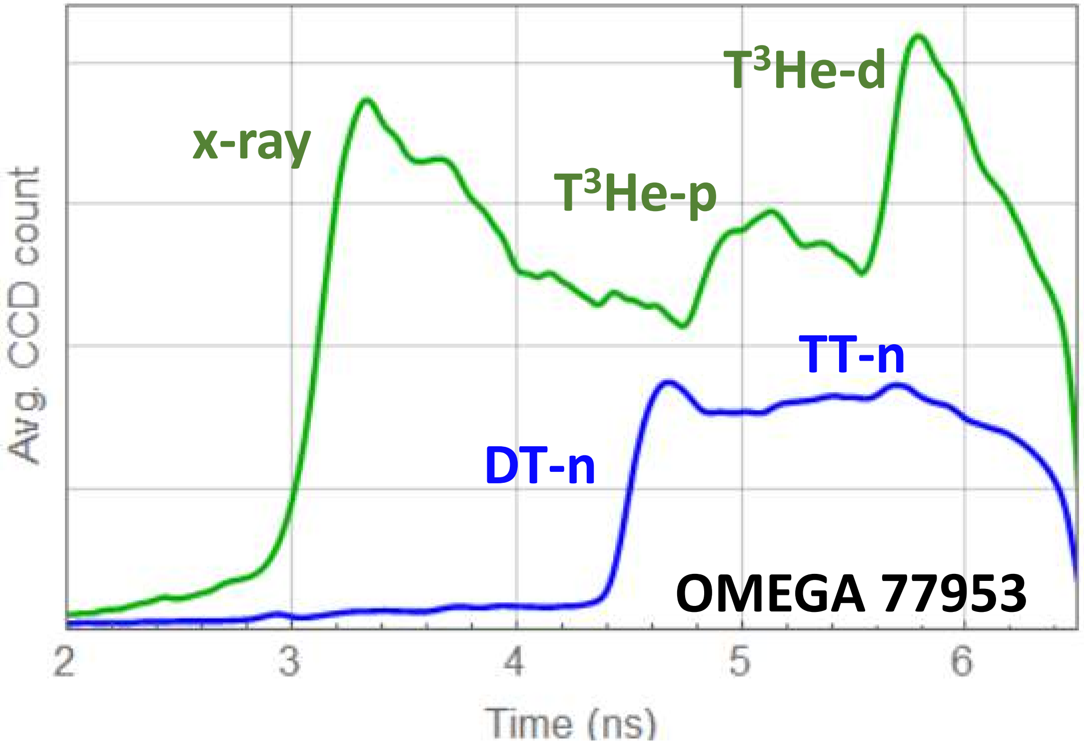




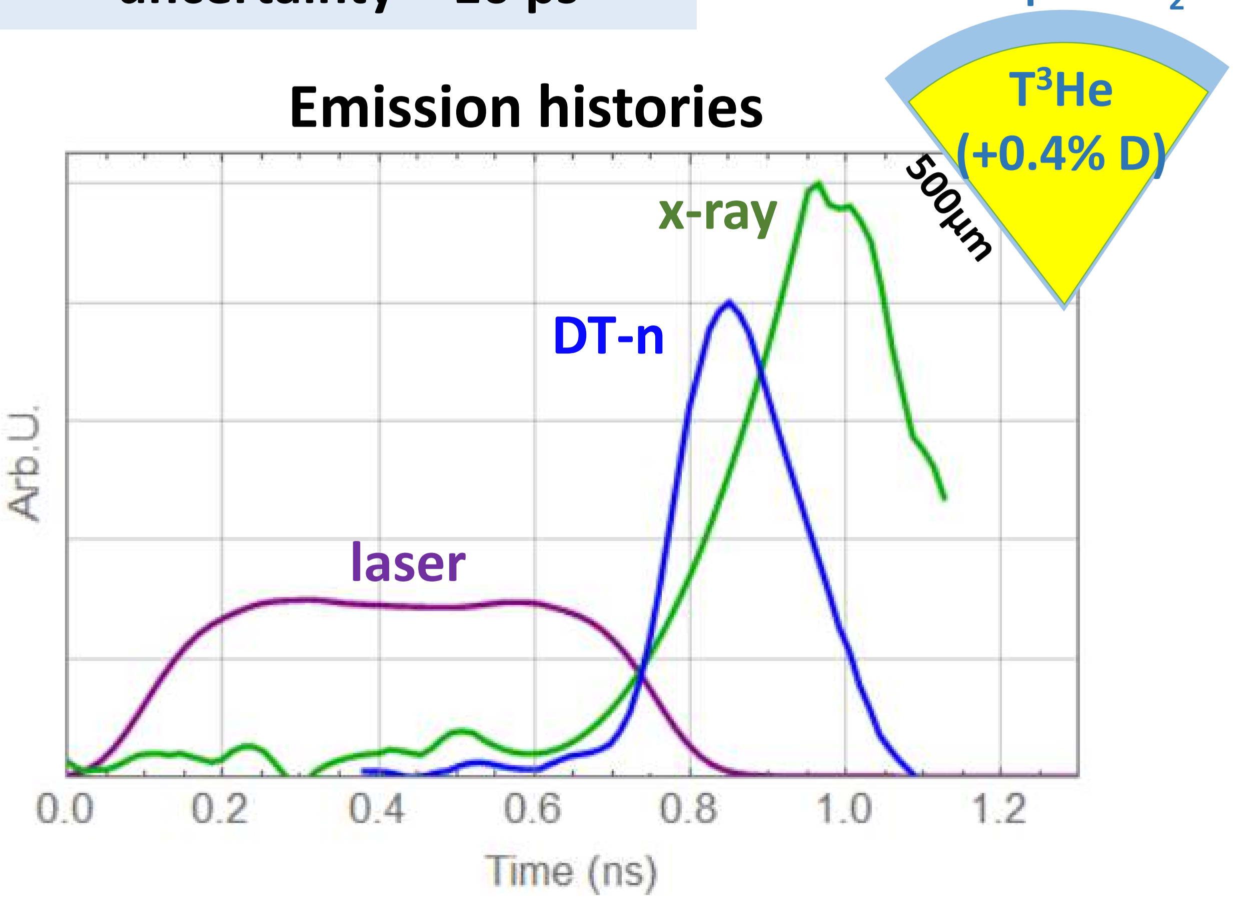
This has enabled measurements of x-ray bang-time, nuclear bang-time and their time differences with high relative precision

OMEGA



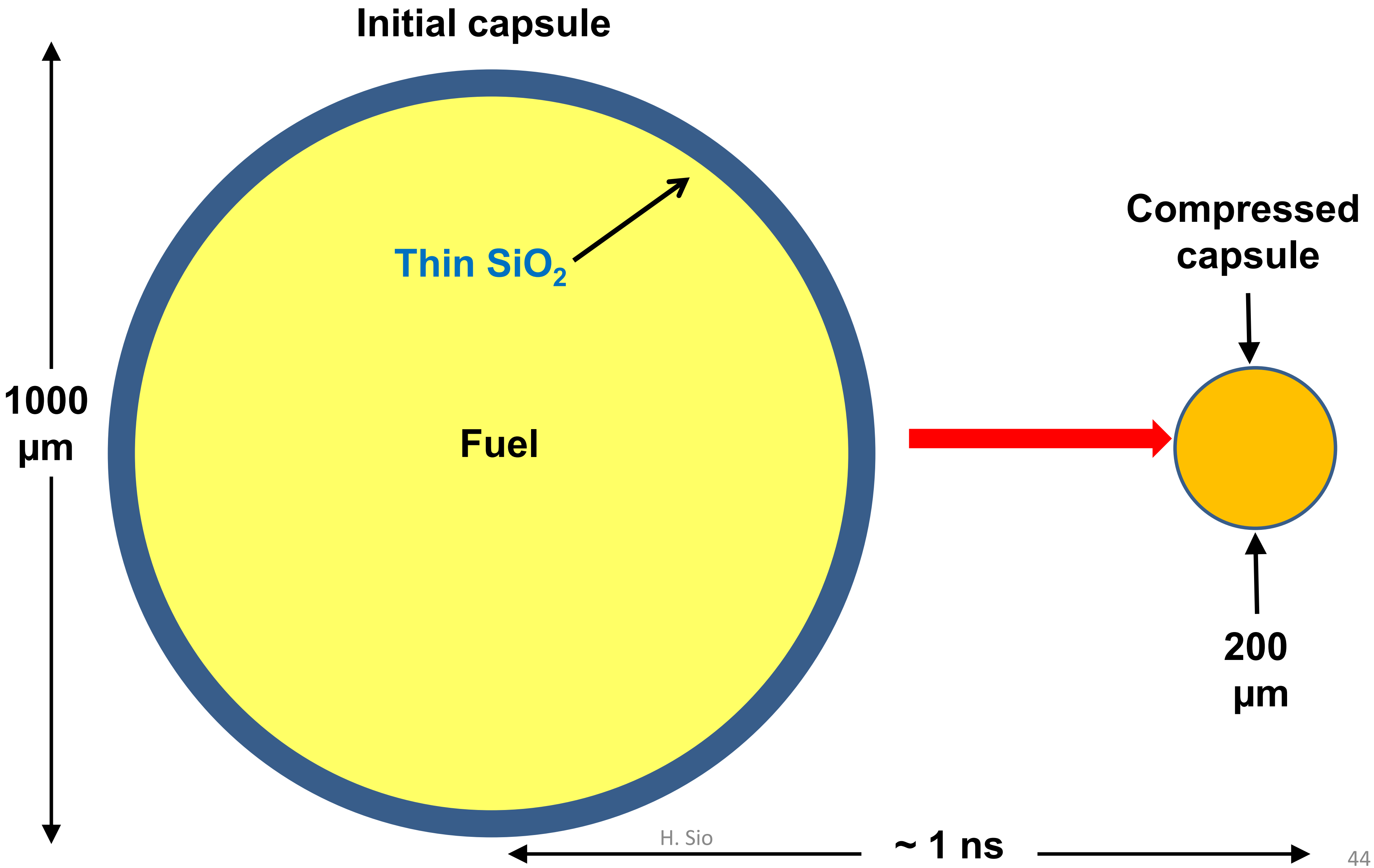


Relative x-ray, DT-n timing uncertainty ~ 10 ps

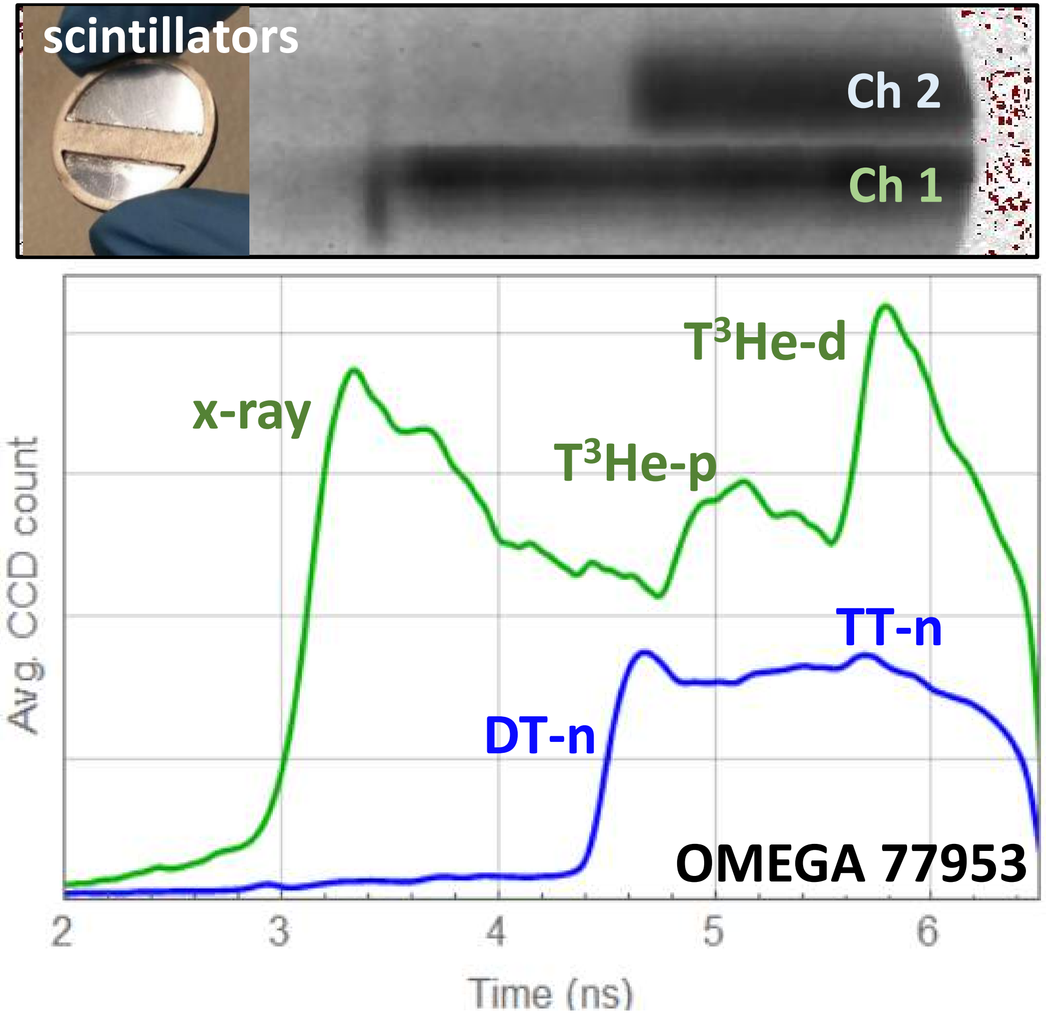


In thin-shell, low-convergence implosions (~ 5x compression) nuclear burn is entirely shock driven

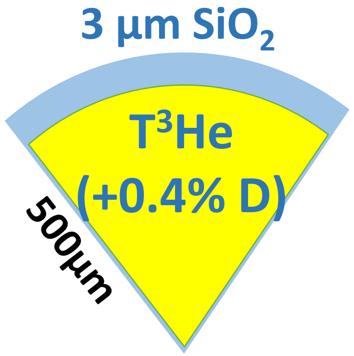
OMEGA



Multiple nuclear-reaction and x-ray-emission histories are also being measured simultaneously



OMEGA



T + ^{3}He → ^{4}He (4.8 MeV) + **d (9.5 MeV)**
^{4}He + p (<10 MeV) + n
^{5}He + **p (9.3 MeV)**

D + ^{3}He → ^{4}He (3.6 MeV) + **p (14.7 MeV)**

D + T → ^{4}He (3.5 MeV) + **n (14.1 MeV)**

The Particle X-ray Temporal Diagnostic (PXTD) is being used to provide time-resolved data on several nuclear reactions, as well as the core x-ray continuum

- Using PXTD, x-ray and nuclear signals are relatively timed to within ~ 15 ps, as measurement on the same diagnostic eliminates cross-timing and jitters

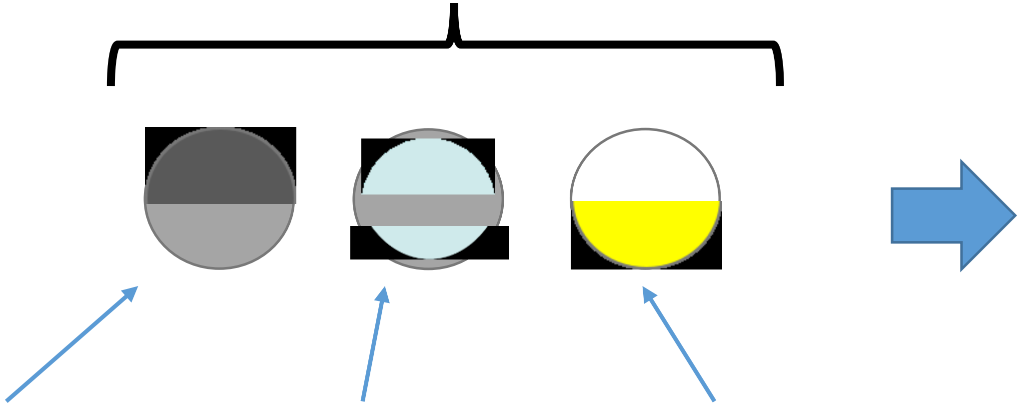
- The PXTD has been fielded to measure:
  - DD, D^3He nuclear reaction histories in D^3He implosion
  - DT, D^3He, T^3He reaction histories in TD^3He implosion
  - Multiple x-ray emission histories at different x-ray energies

- Precise measurements of the x-ray and nuclear histories, and their time difference, are being used to study kinetic and multi-ion effects during the shock phase of ICF implosions

- Measured Ti(t) and Te(t) will be used to infer ion-electron equilibration rate in different plasma conditions

Additional filters and two optically separated scintillators enable measurements of *both* D^{3}He-p and DD-n reaction histories

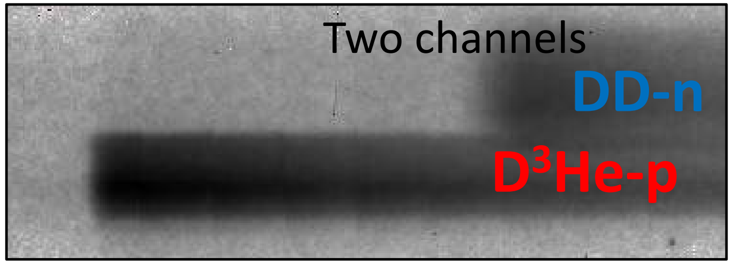
nosecone



Different
Front filters

Optically-isolated
Scintillator halves

Adjustable
light attenuation



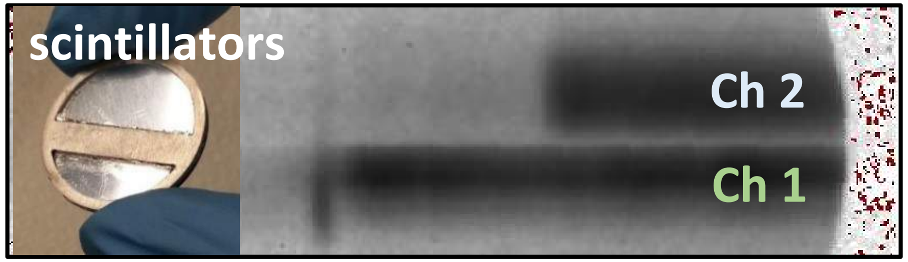
Normally, D^{3}He-p generates ~ 500x more scintillator light than DD-n, making measurement of both D^{3}He-p and DD-n very difficult

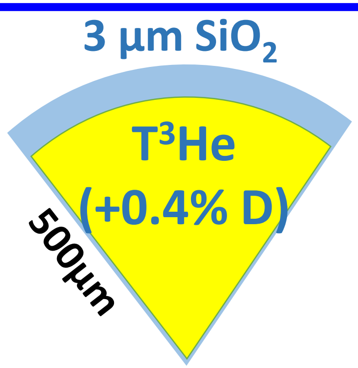
Different emission histories can be relatively timed to within ~ 15 ps because all measurements are done on the same diagnostic

Uncertainty sources	Δ (bang-time) uncertainty (ps) between			
DROP SYSTEMATIC KEEP 2nd and 4th COLUMN	D^3He-p and x-ray	D^3He-p and DT-n	D^3He-p and DD-n	D^3He-p and DD-n
RANDOM	at 9 cm	at 9 cm	at 3 cm	at 9 cm
D^3He-p TOF	5	5	5	5
neutron TOF	~	< 1	3	8
Sweep nonlinearity	5	< 5	5	5
Photon statistics	< 5	< 5	5-10	10—15
Fitting	0-5	0-5	0-10	0-10
total (random)	5-10	5-10	10-15	15-25
SYSTEMATIC				
D^3He-p TOF	5	5	5	5
distance	3	< 1	3	8
total (systematic)	5	5	6	10

Multiple nuclear-reaction and x-ray-emission histories are also being measured simultaneously

OMEGA





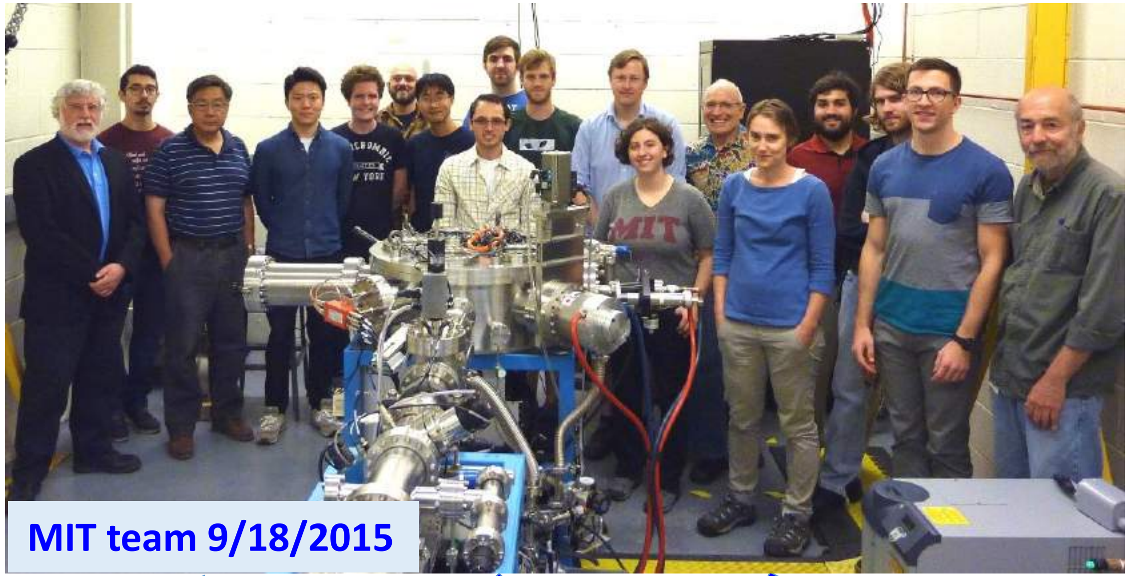
T + ^{3}He → ^{4}He (4.8 MeV) + **d (9.5 MeV)**

^{4}He + p (<10 MeV) + n

^{5}He + **p (9.3 MeV)**

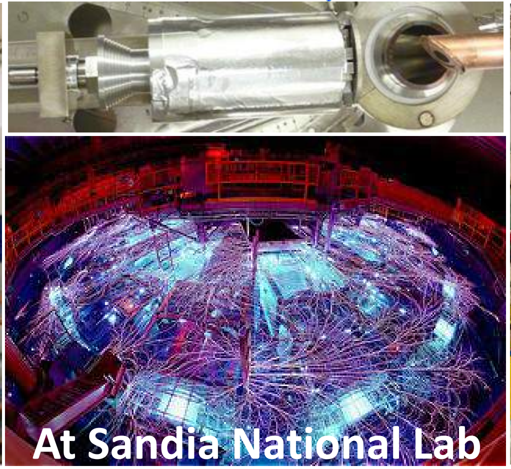
D + T → ^{4}He (3.5 MeV) + **n (14.1 MeV)**

Studying ICF & HED Physics at NIF, OMEGA & Z using MIT-developed nuclear diagnostics & platforms



OMEGA Laser facility

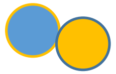
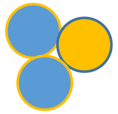
Z



National Ignition Facility (NIF)

At the same time, standard hydro codes use a single average-ion fluid and neglect multi-ion physics

Experiment

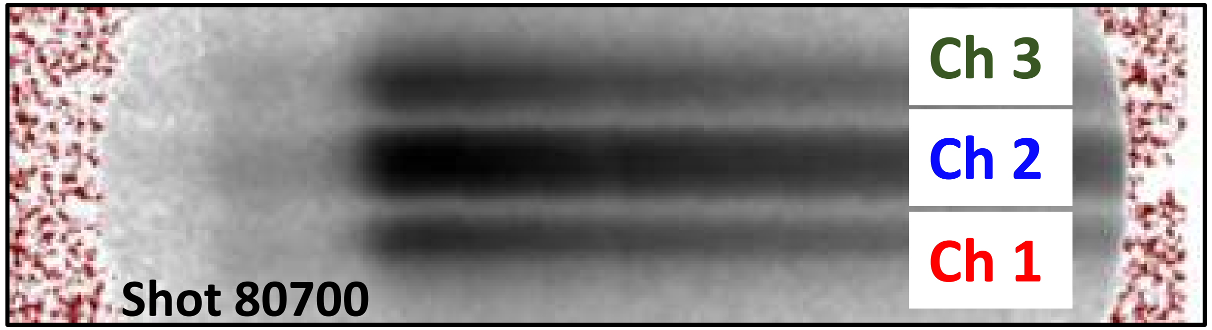
Species (%)		Mass	Charge
D (50%)		**2 amu**	**+1 e**
T (50%)		**3 amu**	**+1 e**

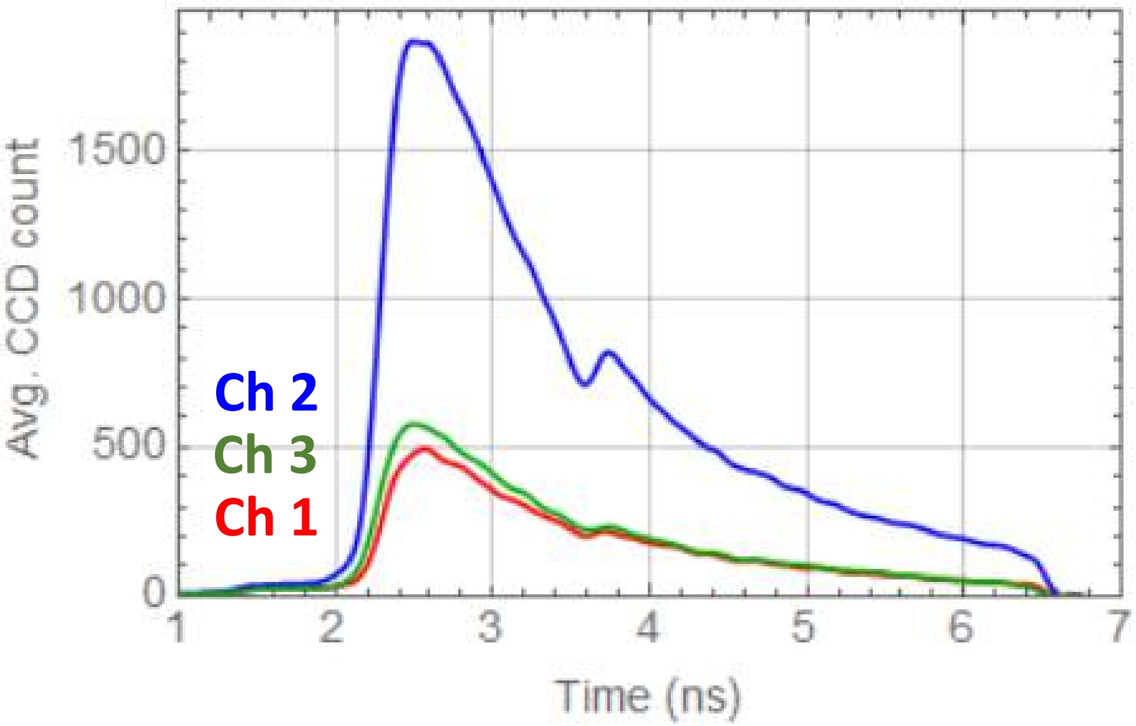
Hydrodynamic Simulation ("Average-ion fluid")

Species	Mass	Charge
"DT"	**2.5 amu**	**+1 e**

Multi-ion effects
may produce anomalous behavior

A flat-field shot is used to characterize the relative light collection efficiency of each streak channel

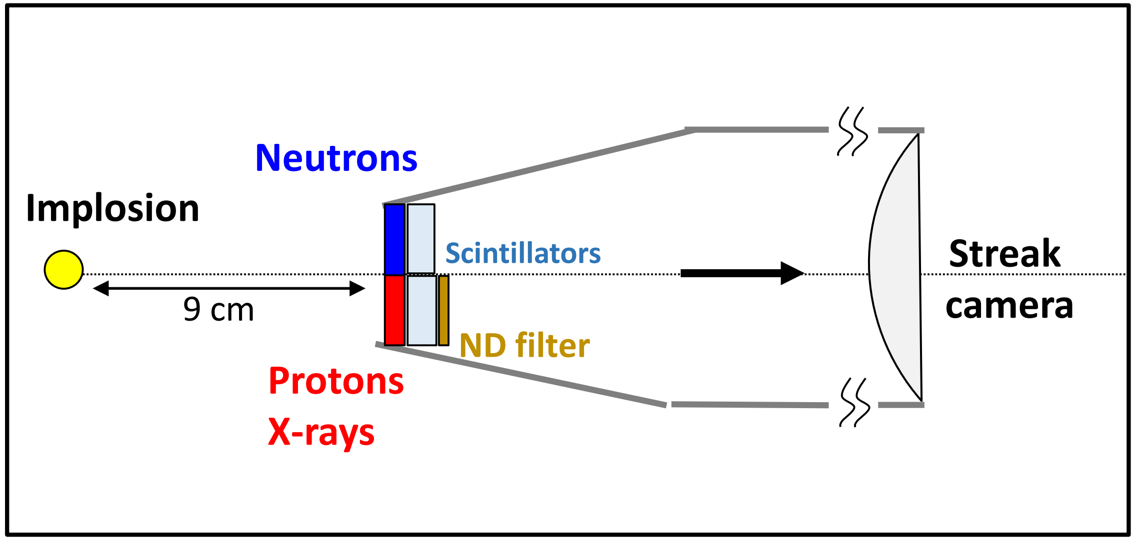




	Relative light collection efficiency
Channel 1	0.27
Channel 2	1.00
Channel 3	0.30

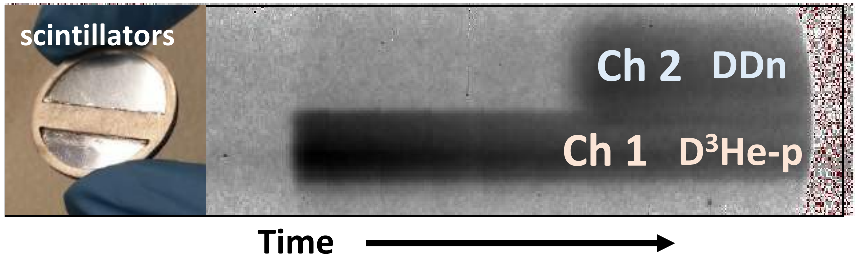
Thinner scintillator, as well as vignetting of the optics, led to less light collection on the side channels, relative to the center

Particle Xray Temporal Diagnostic (PXTD) has been used to provided time-resolved data on several nuclear reactions, as well as core x-ray continuum

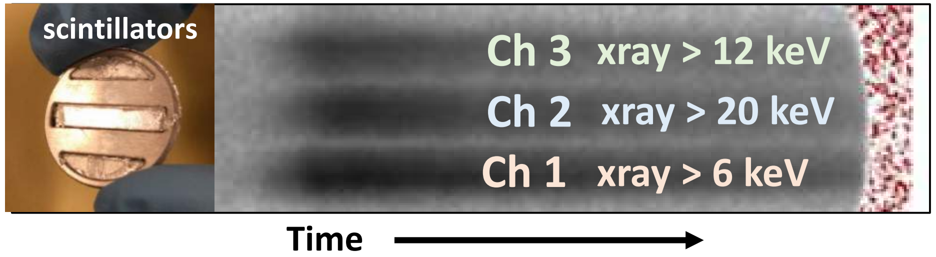


Timing precision between two signals on PXTD	
DT-n, D^3He-p, x-ray (fast)	~ 10 ps
DD-n (slow)	~ 20 ps

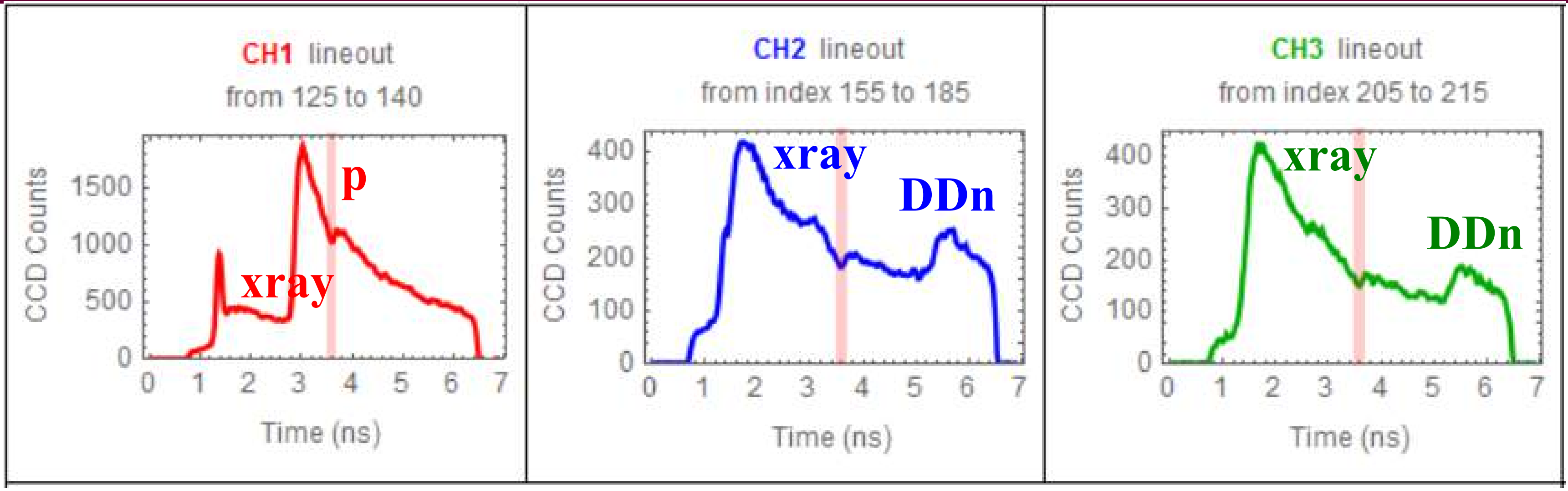
Shot 75694
Streak of D3He protons and DD neutrons

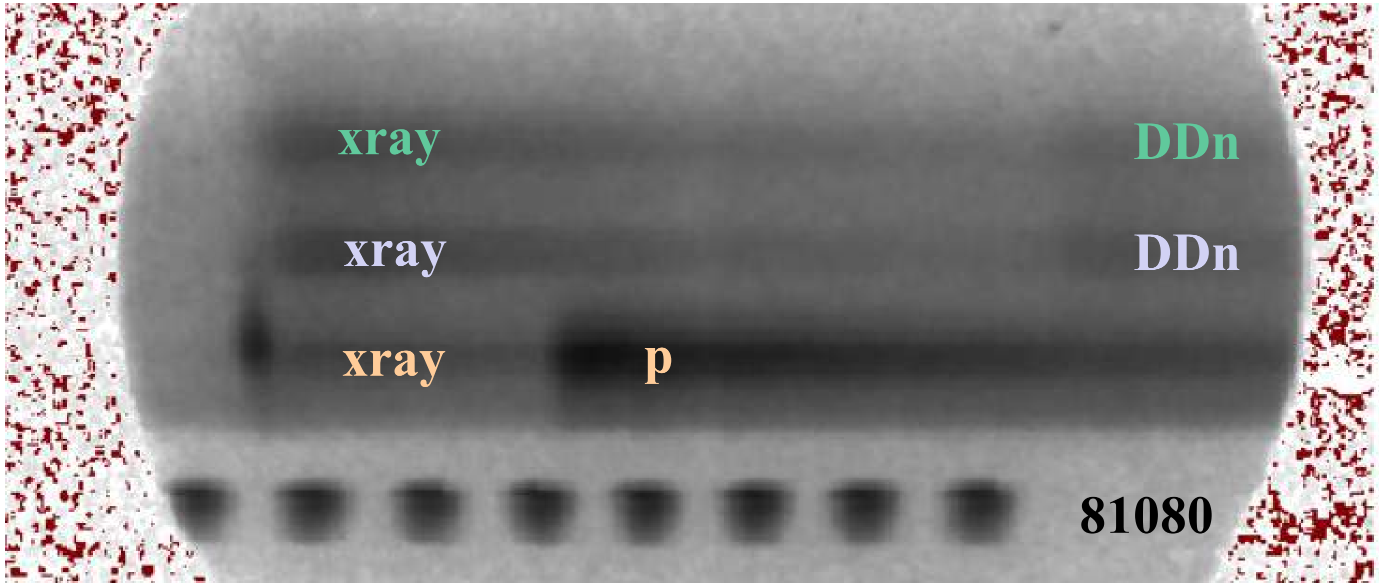


Shot 80705
Streak of X-rays at three different energies



Om160414 ieRate-16A summary - PXTD



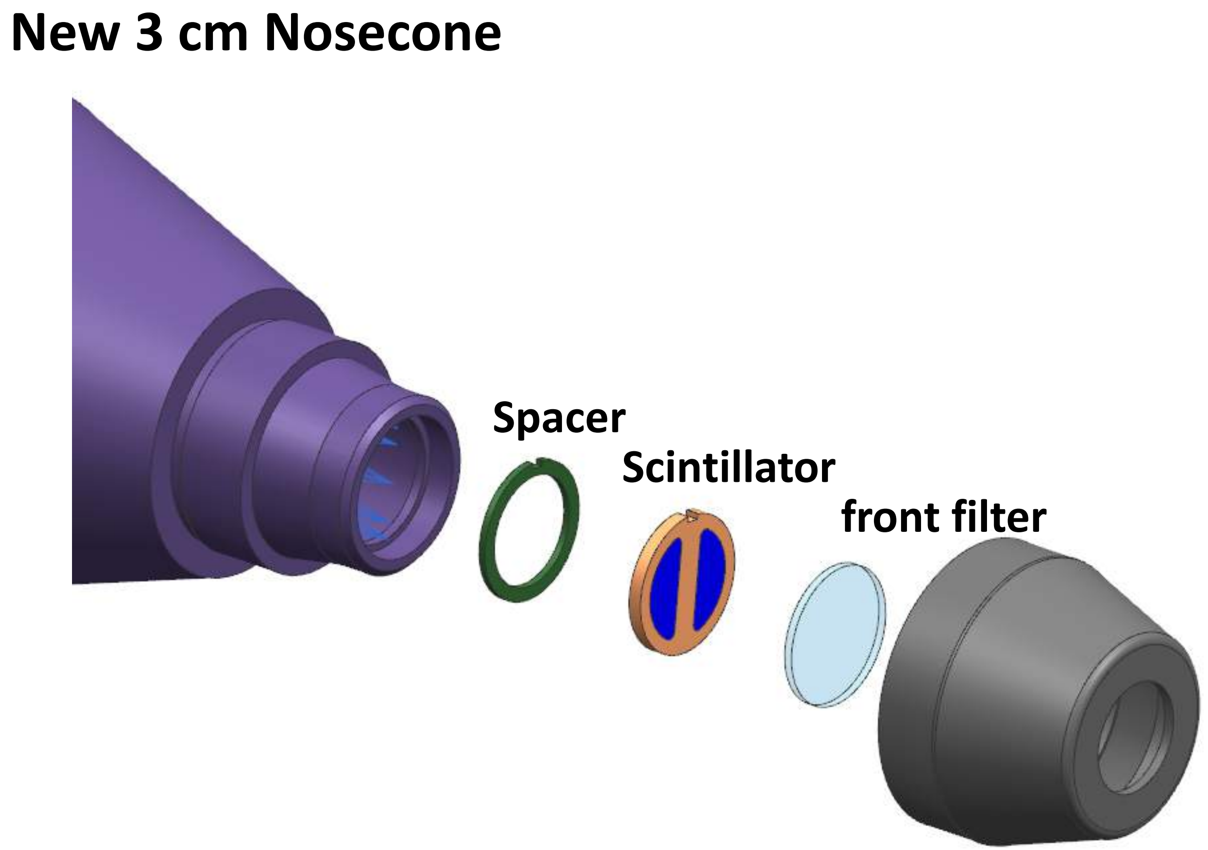


Ch3 > 31 keV

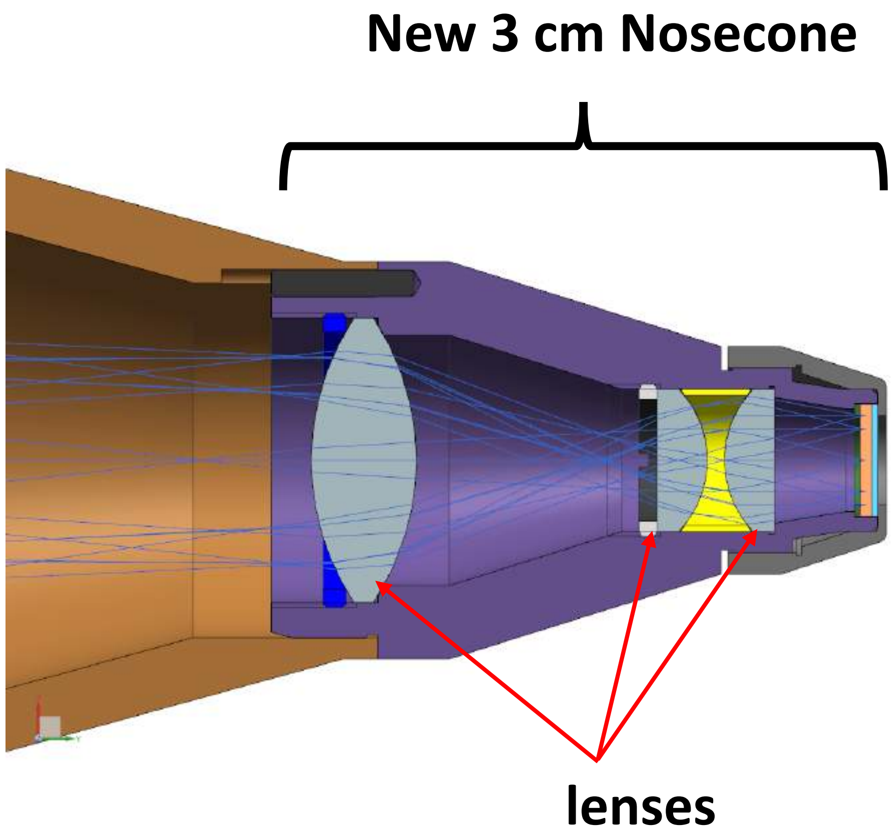
Ch2 > 46 keV

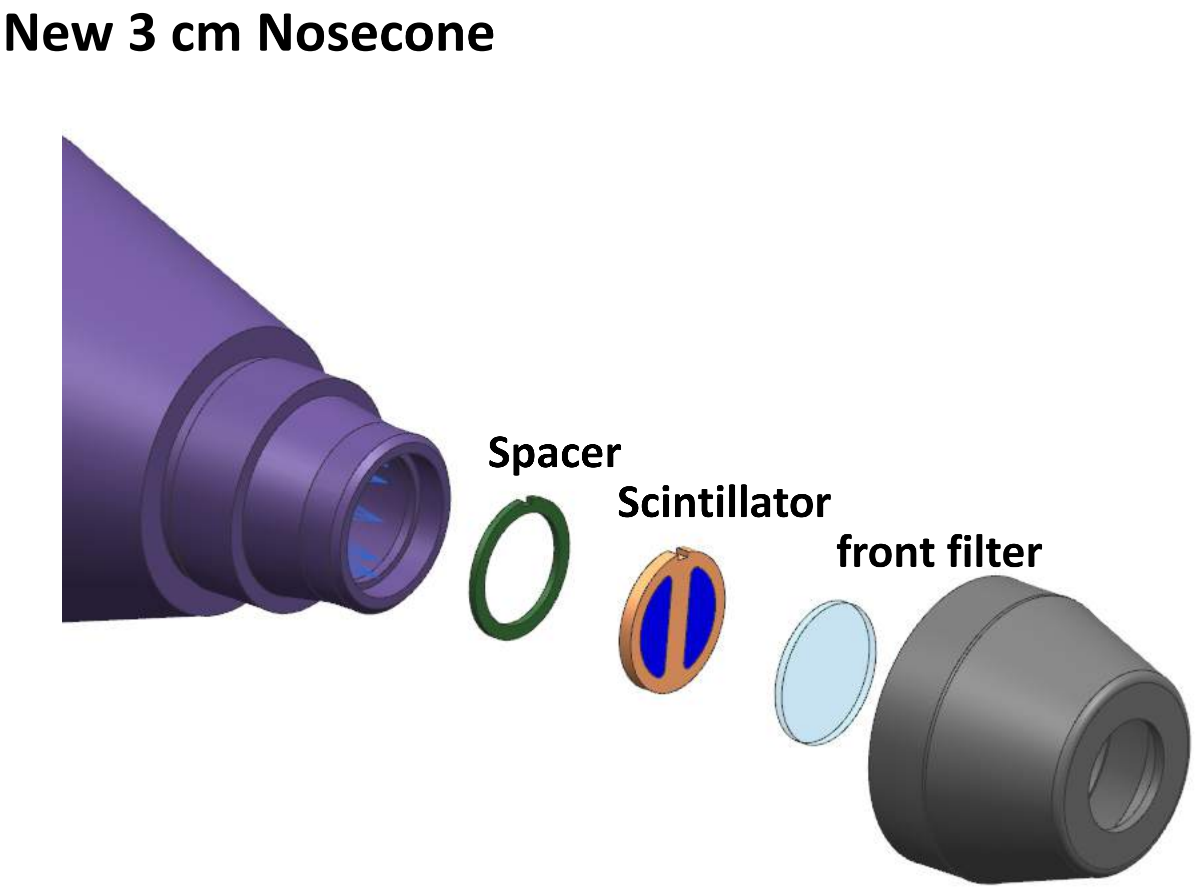
Ch1 > 17 keV

An engineering design has been completed to place the PXTD nosecone at 3 cm away from the implosion to improve the DD-n reaction history measurement

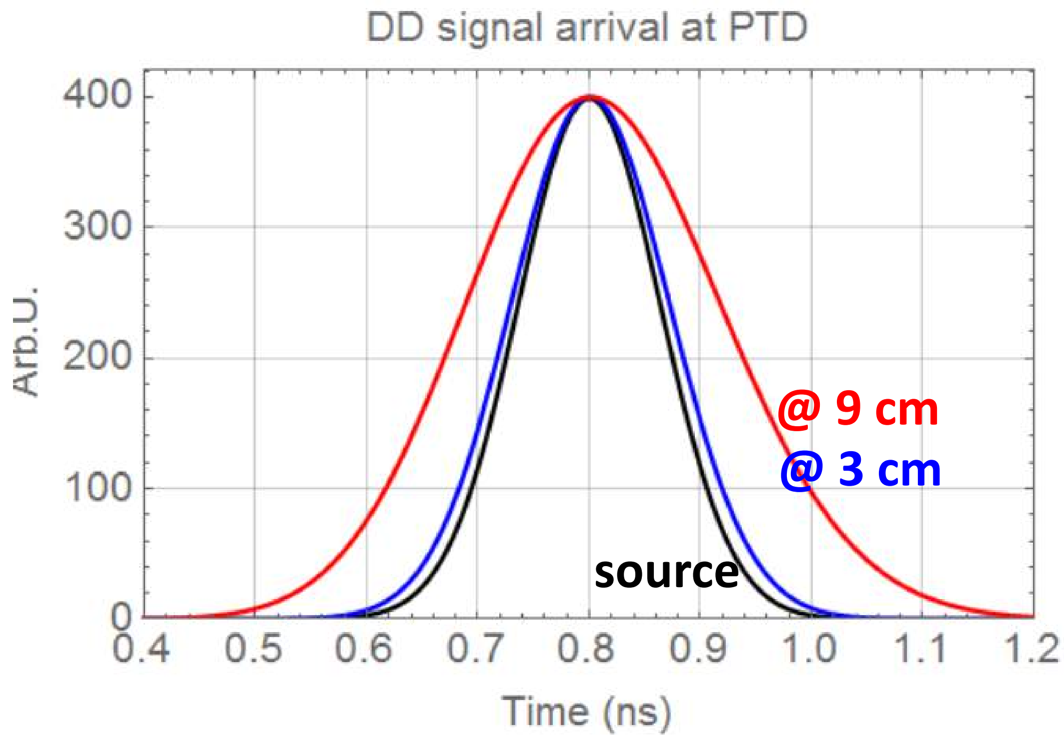


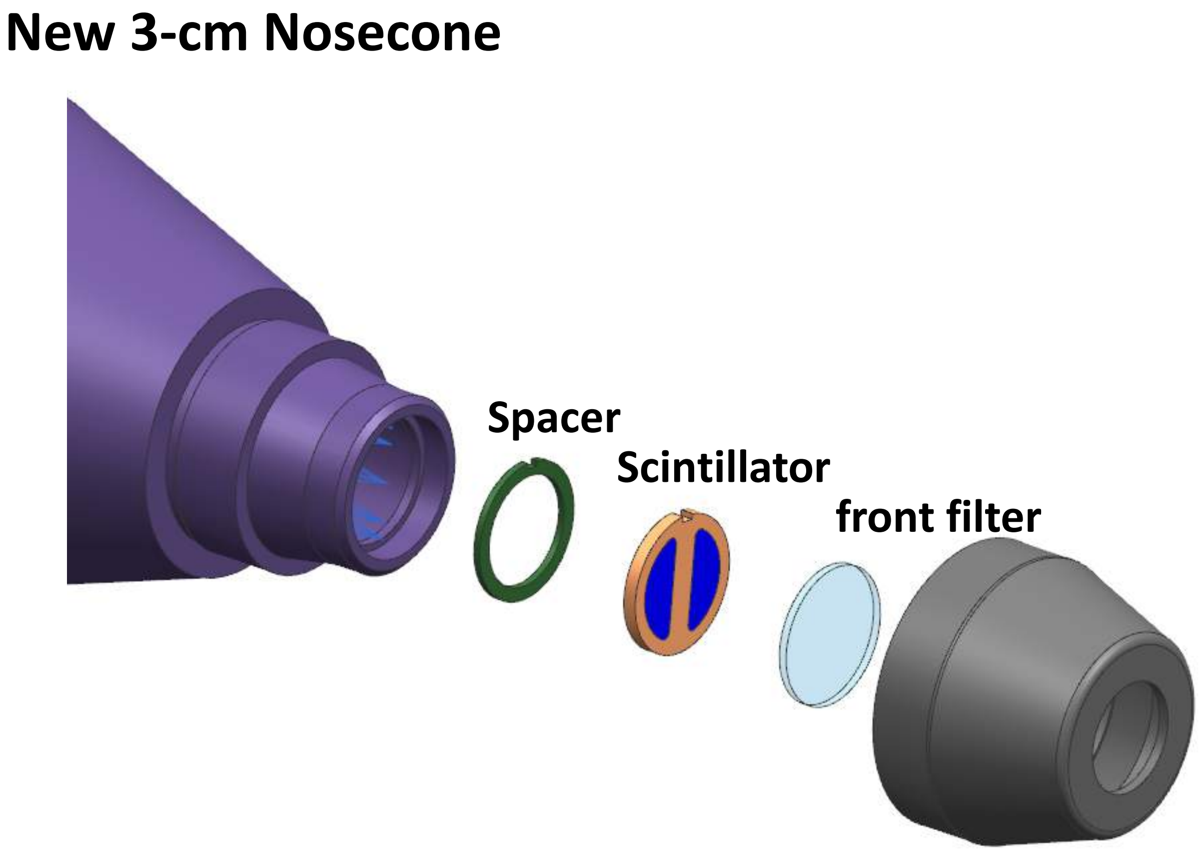
Three new lens are added to relay scintillator light from 3 cm from the implosion





The 3-cm design will significantly reduce temporal broadening of the DD-n signal





Recent experimental and theoretical work seeks to push beyond the average-ion hydrodynamic framework for ICF

Average-ion Hydrodynamic

LASNEX, LILAC, HYADES, DUED, ARES, and others

Le Pape *et al.* [perfectly hydro implosion] (2014)

Extensions

Ion kinetic effects

Theory/computation:

- Larroche (2003, 2012) [FP simulations]
- Skupsky, Li (2007) [non-local ion trans.]
- Molvig, Albright *et al.* (2012, 2013) [Knudsen layer reactivity reduction]
- Bellei *et al.* (2014) [kinetic shock models]
- Tang *et al.* (2014) [Knudsen effects]
- Amendt, Hoffman, Knapp, others (ongoing)

Experiments:

- Rinderknecht *et al.* (2014) [ion diffusion]
- **Rosenberg *et al.* (2014) [hydro to kinetic]**
- Herrmann, others (ongoing)

Multi-ion fluid effects

Theory/computation:

- Amendt *et al.* (2010) [baro-diffusion]
- Kagan *et al.* (2012, 2014) [electro-, thermo-diffusion]
- Bellei *et al.* (2013) [species separation]

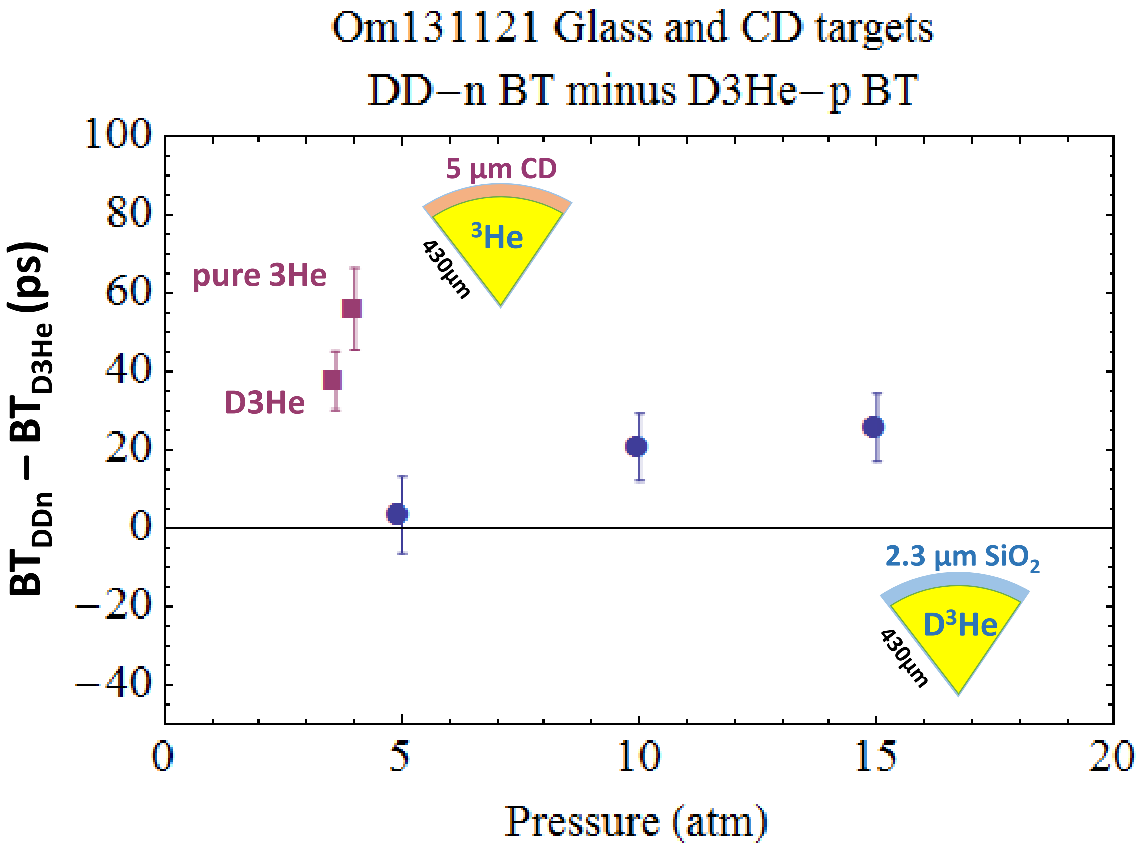
Experiments:

- Rygg *et al.* (2006) [yield anomaly]
- Herrmann *et al.* (2009) [yield anomaly]
- Casey *et al.* (2012) [fuel stratification]
- Rinderknecht, others (ongoing)

From M. Rosenberg, Anomalous 2014

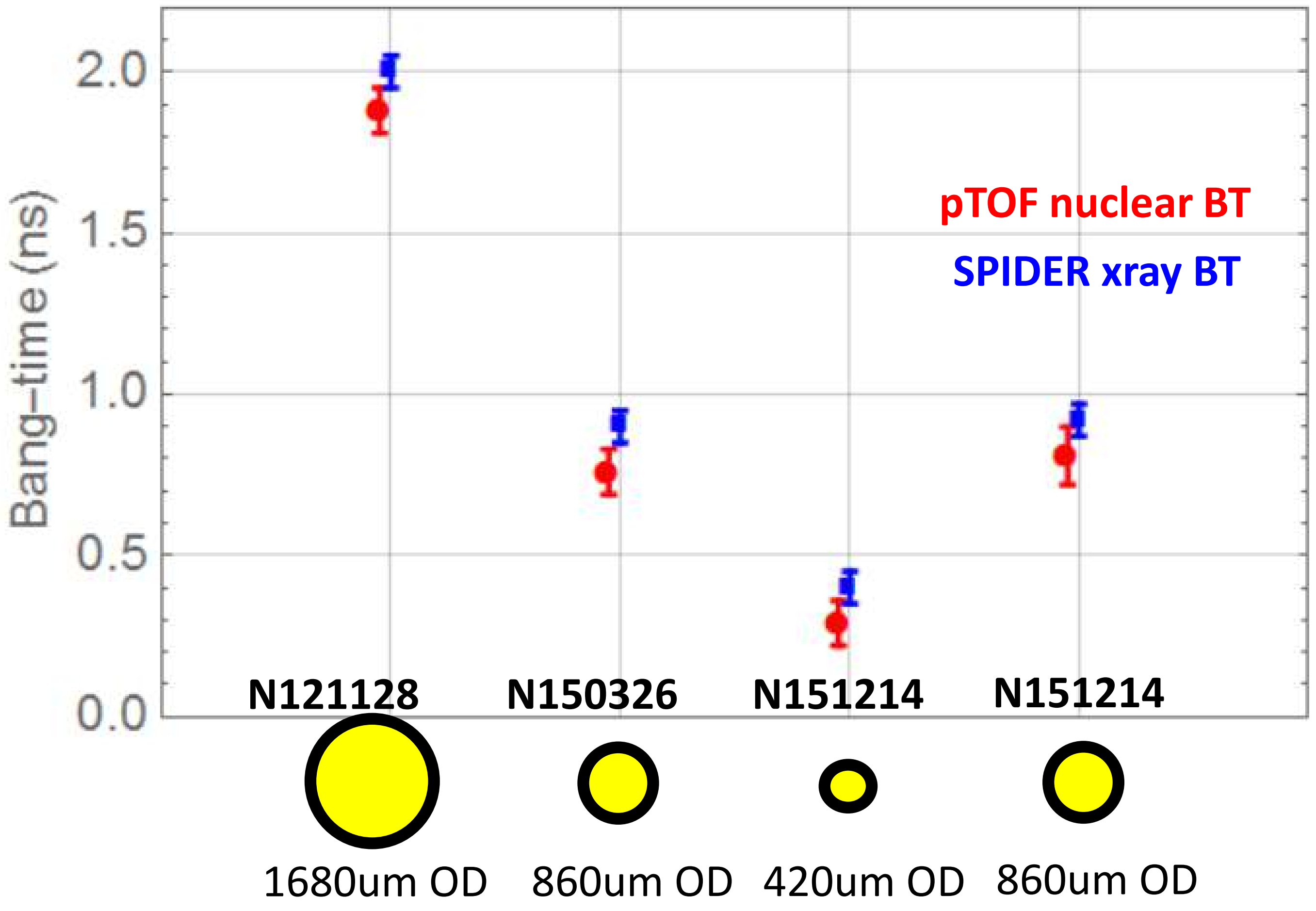
D^3He-p and DD-n burn histories were measured in implosions with different initial gas-fill pressure

Thin CD shell targets are expected to behave differently, as deuterium in the shells also participate in the fusion burn



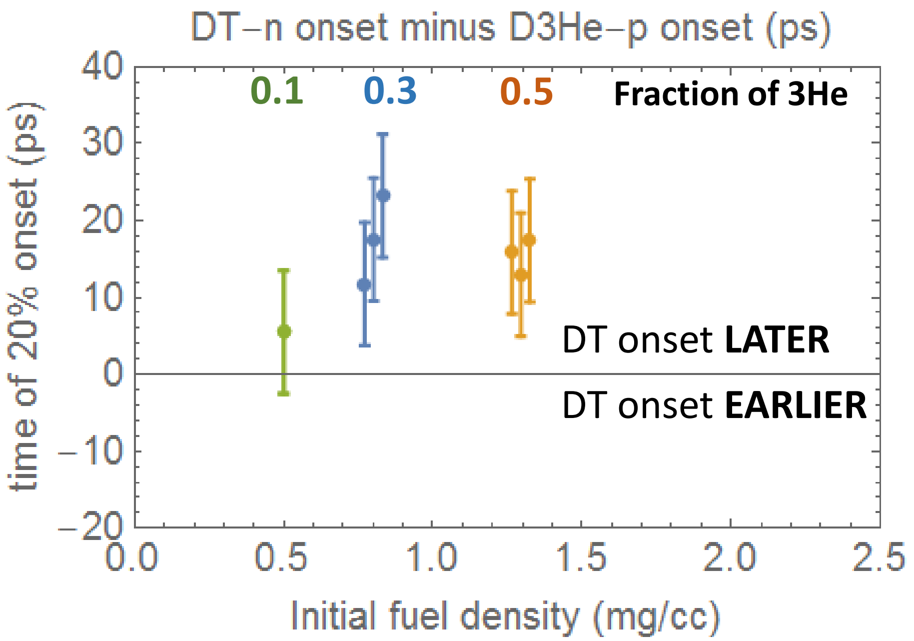
Plotting random uncertainty
Average of 2 to 3 shots

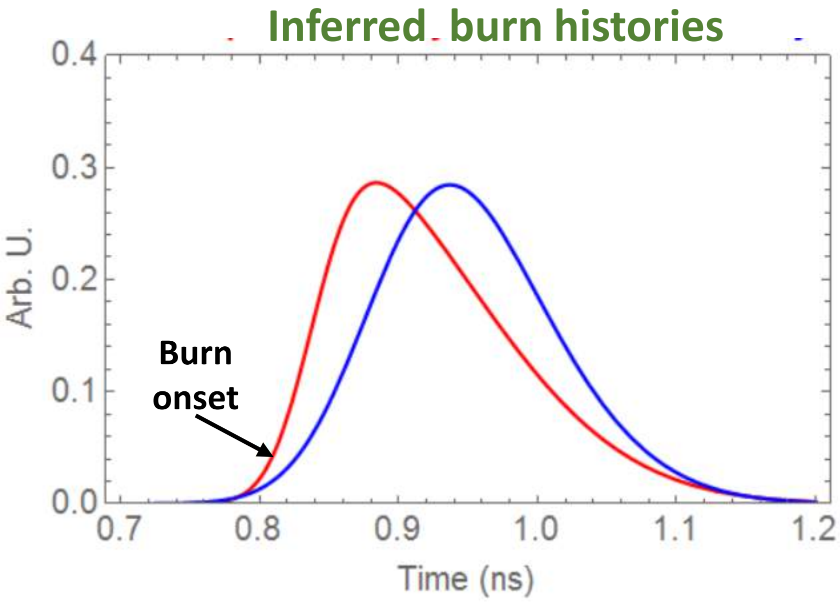
In NIF exploding pusher implosions, nuclear and xray bang times are measured with two different diagnostics to a precision of ~70ps

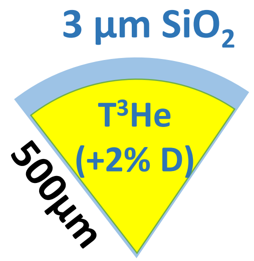


On OMEGA, we can make x-ray and nuclear bang-time measurements with much higher precision using PXTD (10-20 ps vs. ~ 70 ps)

In DT^{3}He implosions, DT burn onset were found to be consistently ~ 20 ps later than D^{3}He burn onset







Onset defined as time of 20% rise of the burn history

Points artificially spread horizontally apart for clarity

* G. Kagan and X.Z. Tang, Physics Letters A **378**, 1531 (2014))

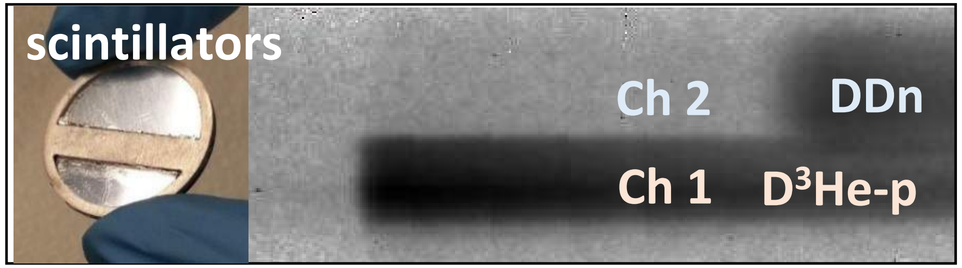
Different emission histories can be relatively timed to within ~ 15 ps because all measurements are done on the same diagnostic

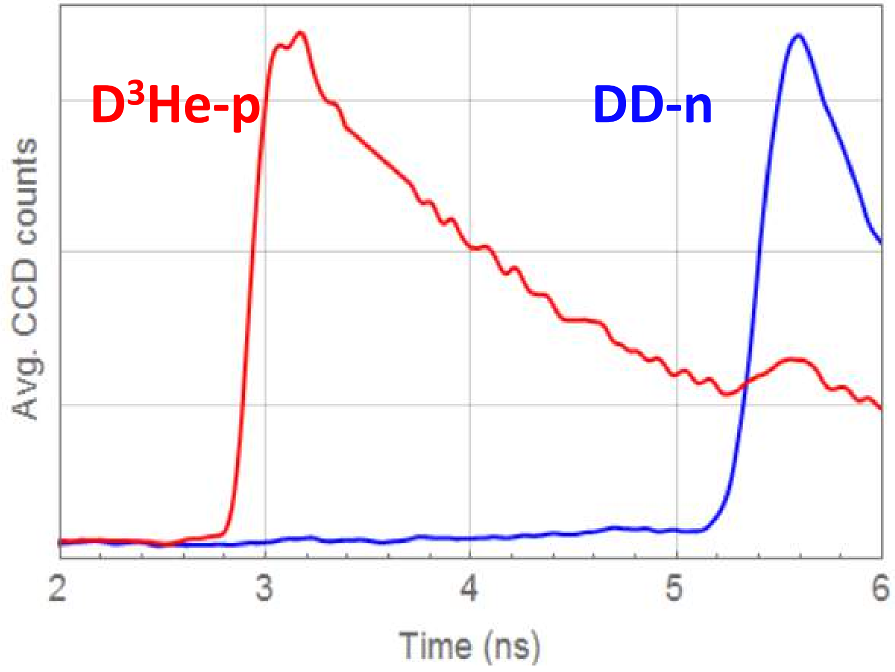
Uncertainty sources	Δ (bang-time) uncertainty (ps) between	
	D^3He-p and DT-n	D^3He-p and DD-n
RANDOM	at 9 cm	
D^3He-p TOF	5	5
neutron TOF	< 1	8
Sweep nonlinearity	< 5	5
Photon statistics	< 5	10—15
Fitting	0-5	0-10
total (random)	5-10	15-25

A 3-cm nosecone design has been completed and will reduce timing uncertainty between D3He-p and DD-n to 10-15 ps.

One of the motivations for PXTD is to measure changes in DD and D^3He reaction histories as implosions become more kinetic

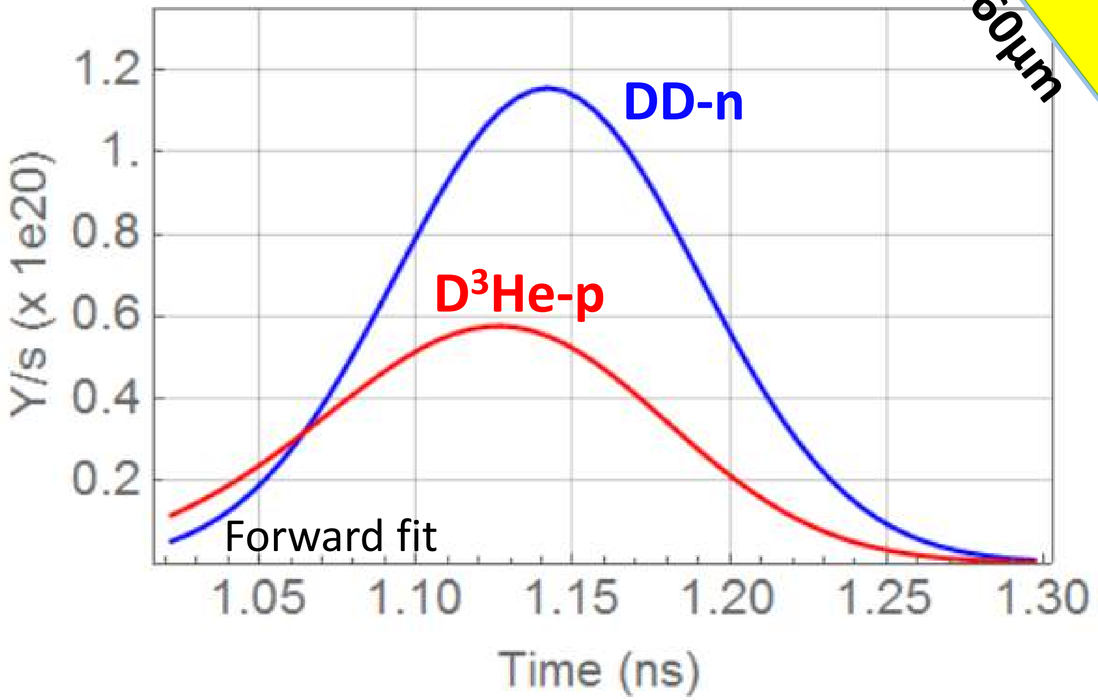
OMEGA 75703



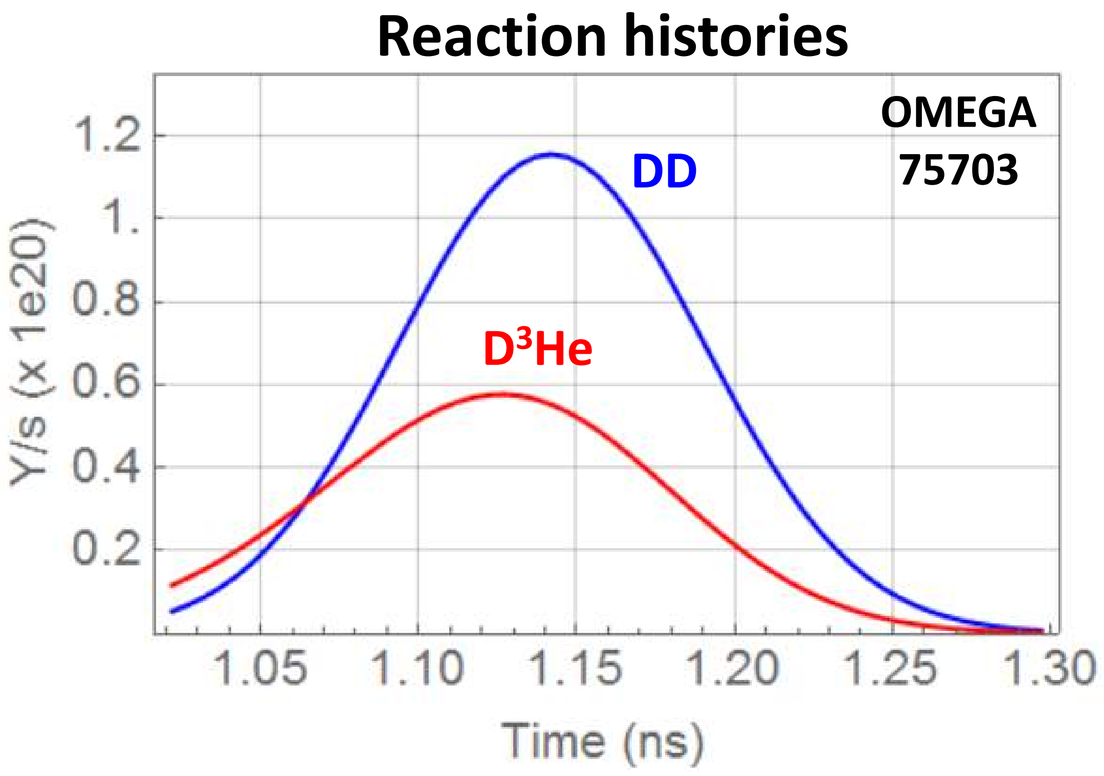


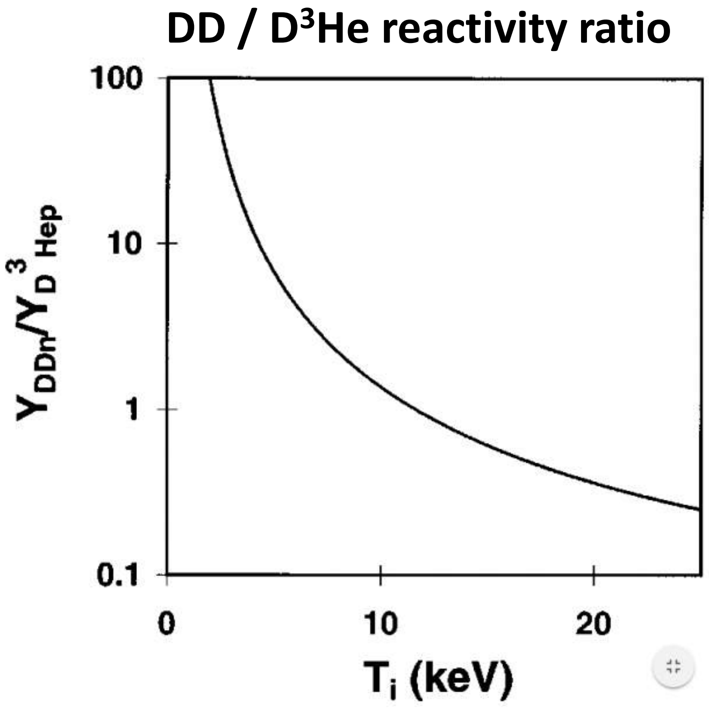
Ongoing work with LANL to compare with multi-ion-fluid and fully kinetic-ion simulations

DD and D^3He Reaction histories



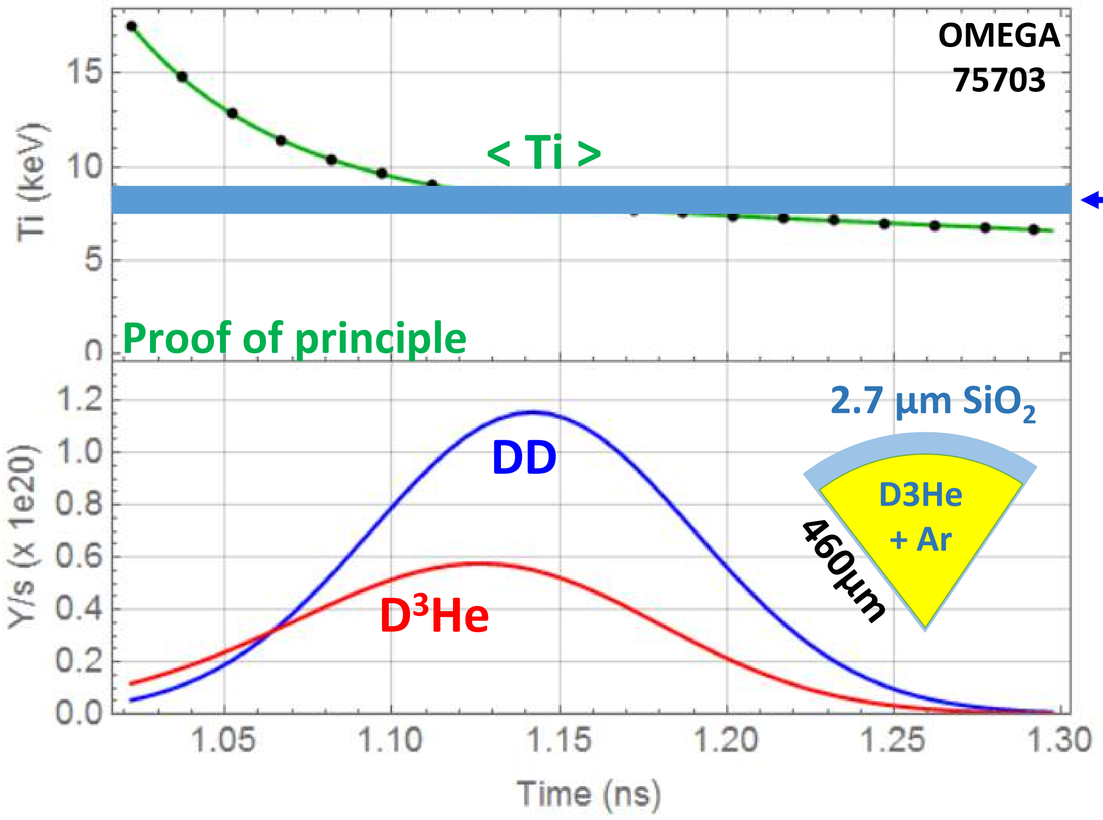
The ratio of two nuclear reaction histories (DD / D³He, or DT / D³He) is being used to infer spatially-averaged Ti(t)





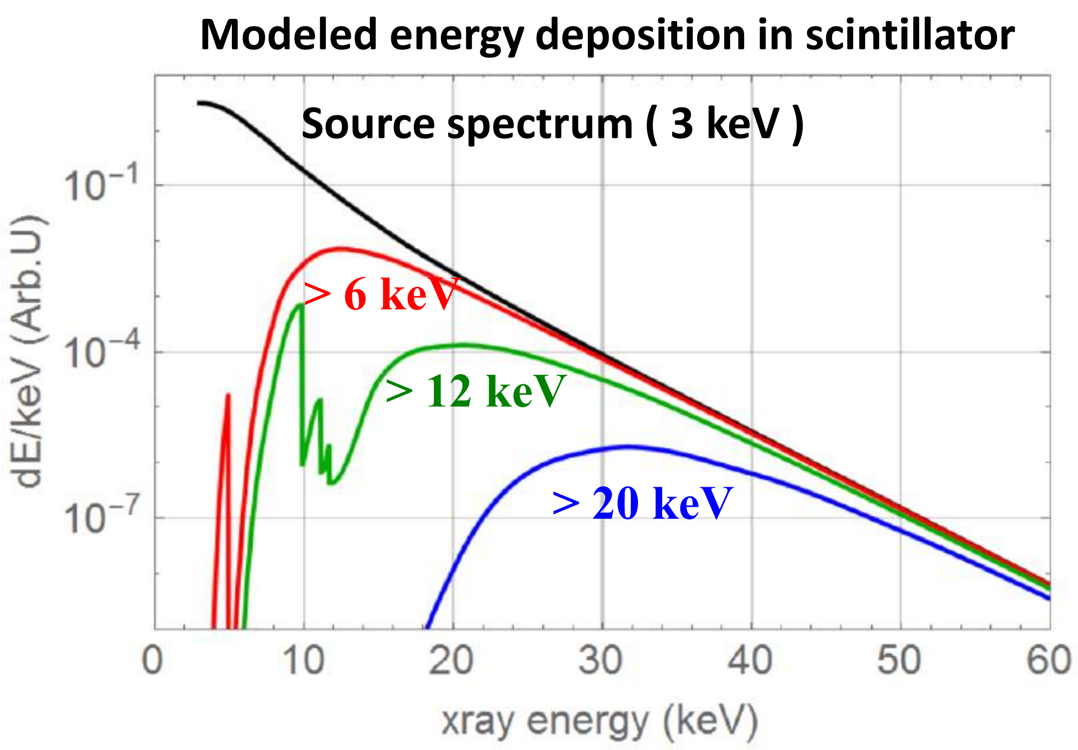
The ratio of two nuclear reaction histories (DD / D^3He, or DT / D^3He) is being used to infer spatially-averaged Ti(t)

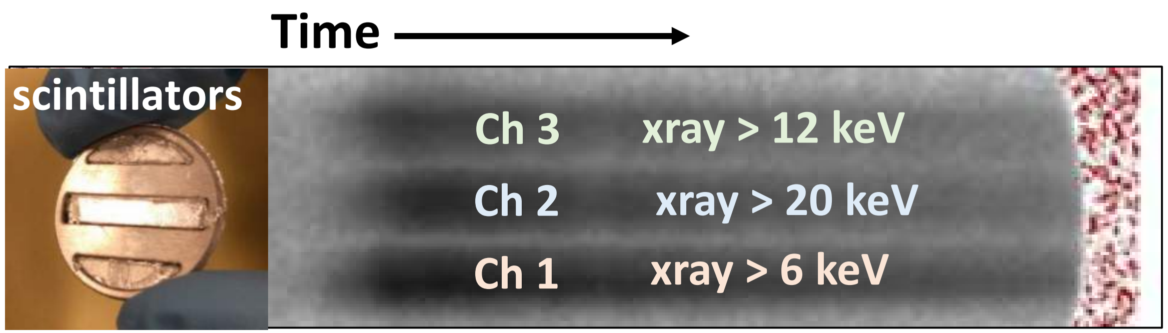
Reaction histories and < Ti(t) >



nTOF ion temperature

X-ray emission histories at different energy bands are used to infer spatially-averaged, time-resolved Te(t) from the slope of the Bremsstrahlung continuum



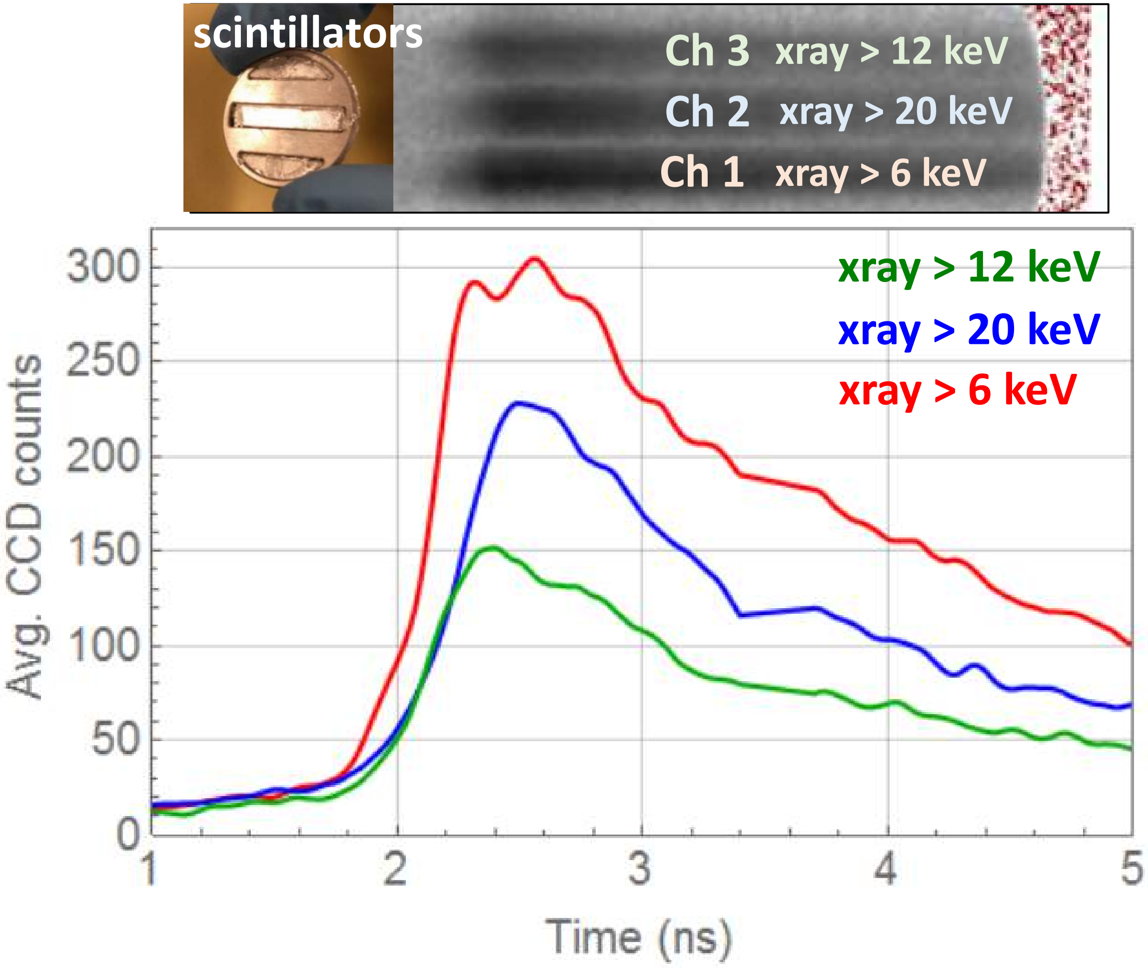


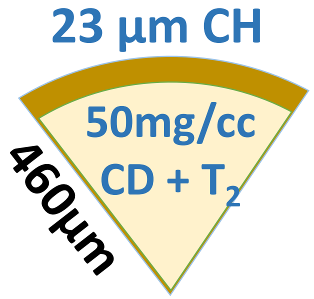
X-ray energy deposition in scintillator depends on

- x-ray filter transmission
- Scintillator thickness
- Scintillator inelastic and photoabsorption cross-section

X-ray emission histories provide x-ray bang-time and burnwidth at different x-ray energies

The three PXTD channels are filtered differently to probe different parts of the x-ray continuum





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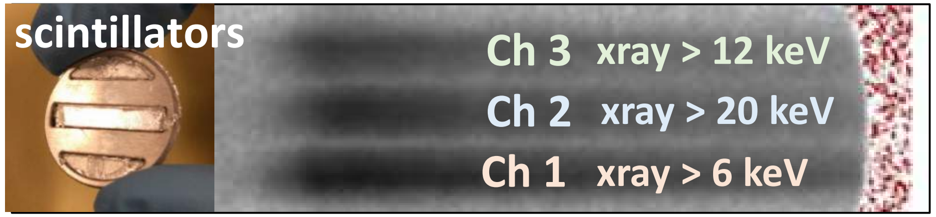

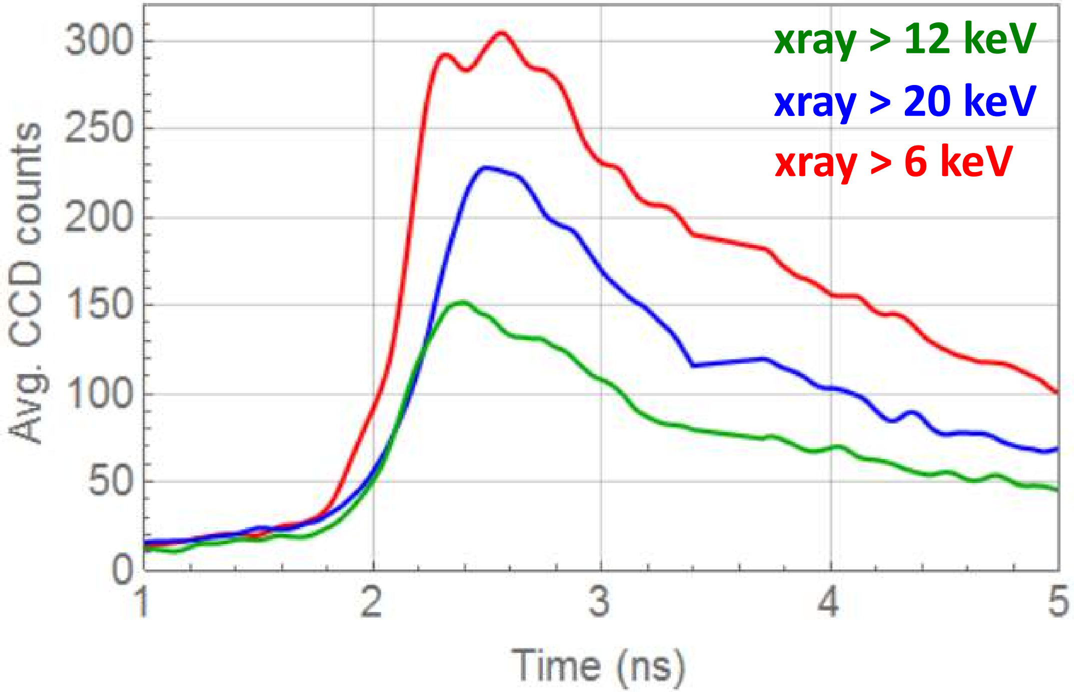

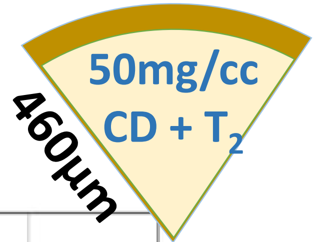

x-ray emission histories