The National Ignition Facility

Nuclear Physics Summer School

Santa Fe, July 2012

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Fusion in the Cosmos

$1 + 2 \rightarrow X$ **Reaction Rate:** $n_1 n_2 < \sigma v >$

Set of reactions taking place depends on:

- **Starting fuel**
- **Temperature**
- **Density**
- **Burn Time**

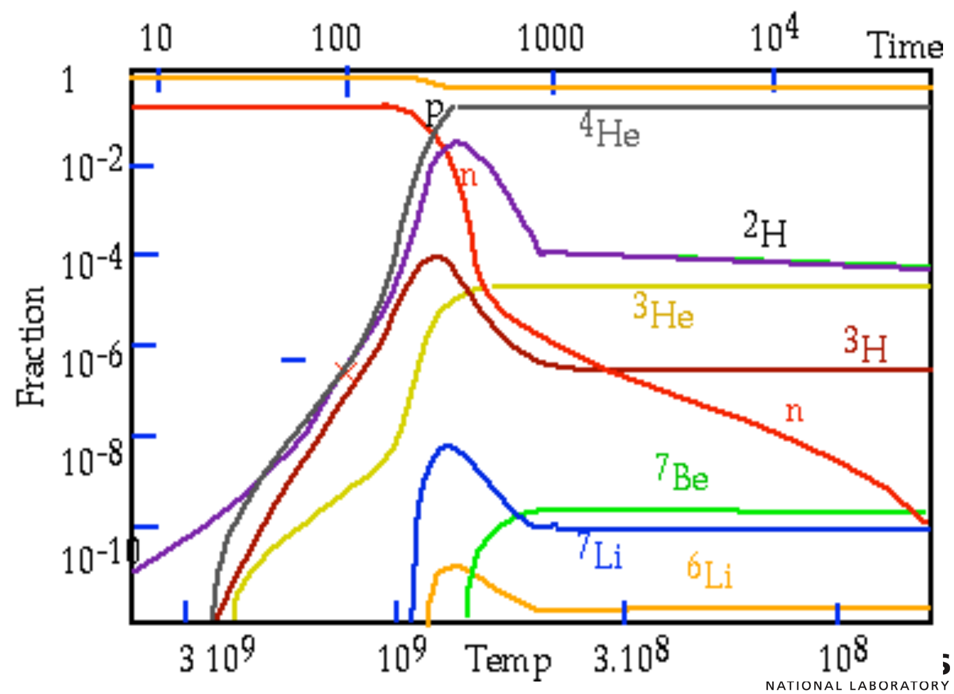
Example, BIG BANG Nucleosynthesis

Neutrons & Protons

T ~ 1 - 0.1 MeV

ρ ~ 4×10^{-31} g/cm^3

Time ~ 10^4 seconds



Fusion in the Cosmos vs. Laboratory

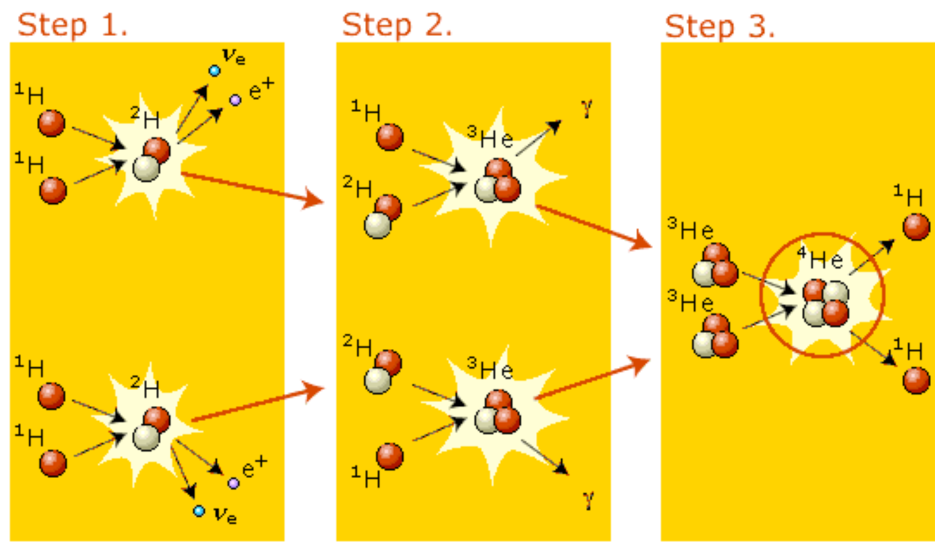
Hydrogen burning in the Sun

Protons

p+p→ d+ ν_e+e$^+$ (weak interaction)

p+d→ 3He + γ

^{3}He +^{3}He → ^{4}He +p + p



	density (kg/m3)	**temperature (K)**	**confinement time**
BBN	10^{-28}	10^8-3×10^9	10^4 sec
solar core	10^5	1.6×10^7	age of the sun
magnetic confinement	10^{-5}	10^8	several sec
inertial confinement	10^6	10^8	10^{-11} sec

Fusion Ignition

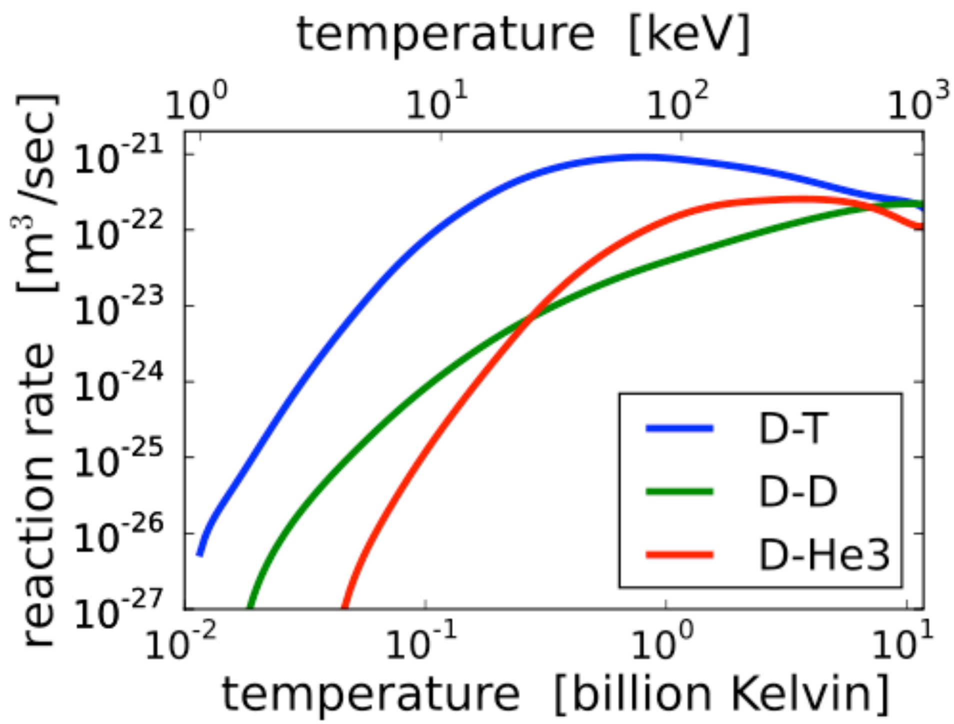
In the laboratory the main plasma fusion reactions studied are:

$$d + t \rightarrow \alpha + n$$

$$t + t \rightarrow \alpha + 2n$$

$$d + d \rightarrow t + p$$

$$d + d \rightarrow {}^3He + n$$

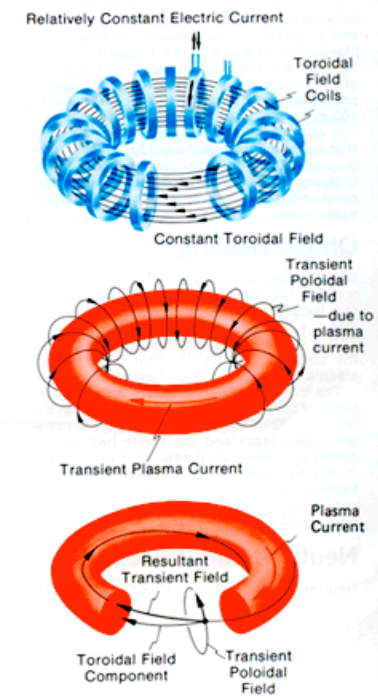


Reaction Rate: $n_1 n_2 < \sigma v >$

To achieve fusion ignition:

1. Maximize the density
2. Maximize the temperature
3. Hold system together for sufficient time

Achieving the Required Conditions



Magnetic Confined Fusion:

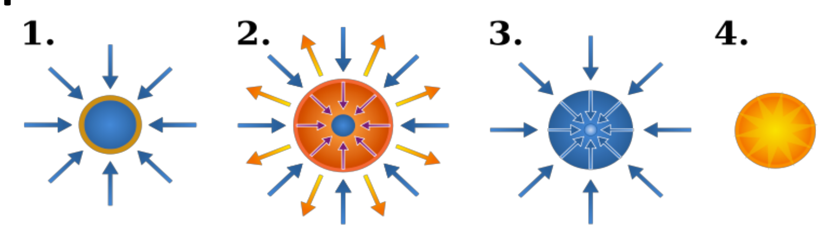
- *Electric conductivity contains plasma with magnetic fields*
- *Balance between magnetic pressure and plasma pressure*
- *Individual particles spiral along magnetic field lines*
- *Pressure ~ 1 bar; confinement time ~ few seconds*

- **ITER designed to achieve 500 MWatts for 50 MWatts input**

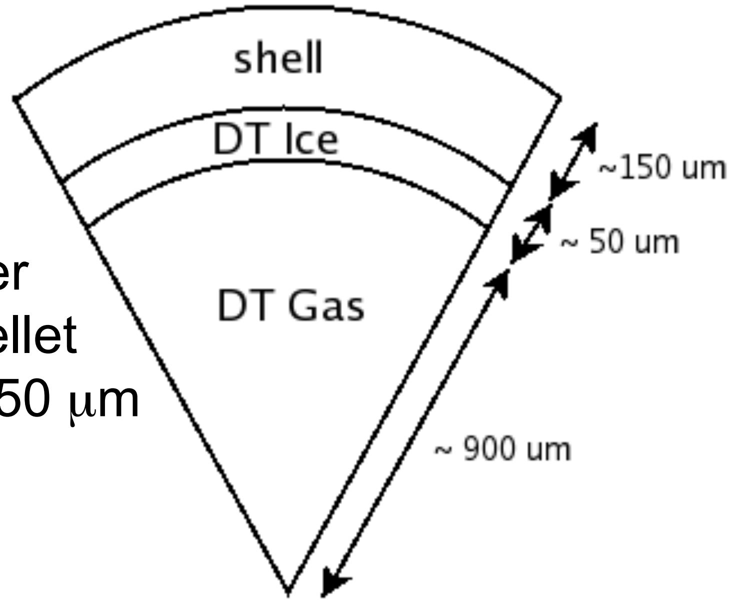
Inertial Confined Fusion:

- *Compress pellet of fuel by lasers, ions, or electrons (the drive)*
- *Transfer implosion energy into internal energy*
- *Initiate burn in central hotspot and propagate the burn into surrounding fuel*
- *Pressure in center ~ 1Gbar; confinement time ~ 50 psec*

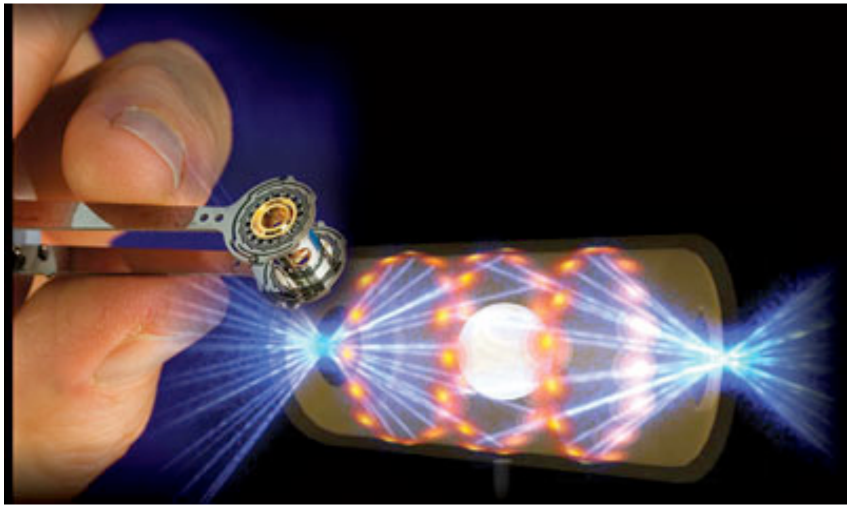
- **NIF designed to achieve ~20 MJ for 1-2 MJ input**



NIF



Designed to use 1.8 MJ laser energy to compress a DT pellet from a radius of ~1 mm to ~50 μm => 20 MJ DT energy



Capsule at center of a hohlraum
Hohlraum generates a 300 eV X-ray bath

X-rays ablate outer shell of capsule
⇒Compress radius by a factor of 30
⇒ T~ 10-30 keV
⇒ $\rho \sim 10^{25}$-10^{26} cm^{-3}

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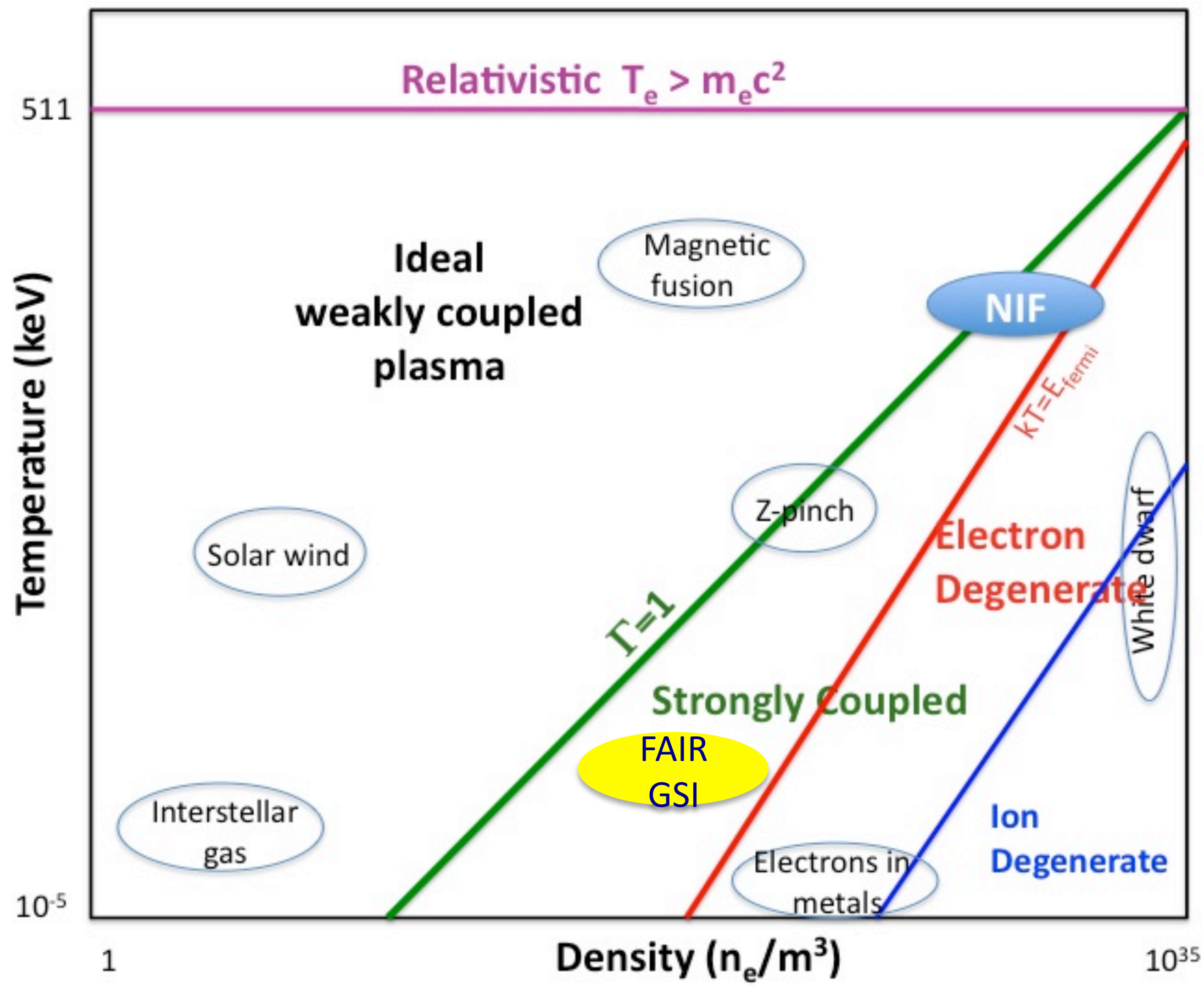
Across the Capsule the Plasma varies from Weakly to Strongly Coupled



Coupling:

$$\Gamma = \left(\frac{e^2}{4\pi R}\right)/(kT)$$

Electron Degeneracy:

$$kT / E_{Fermi}$$

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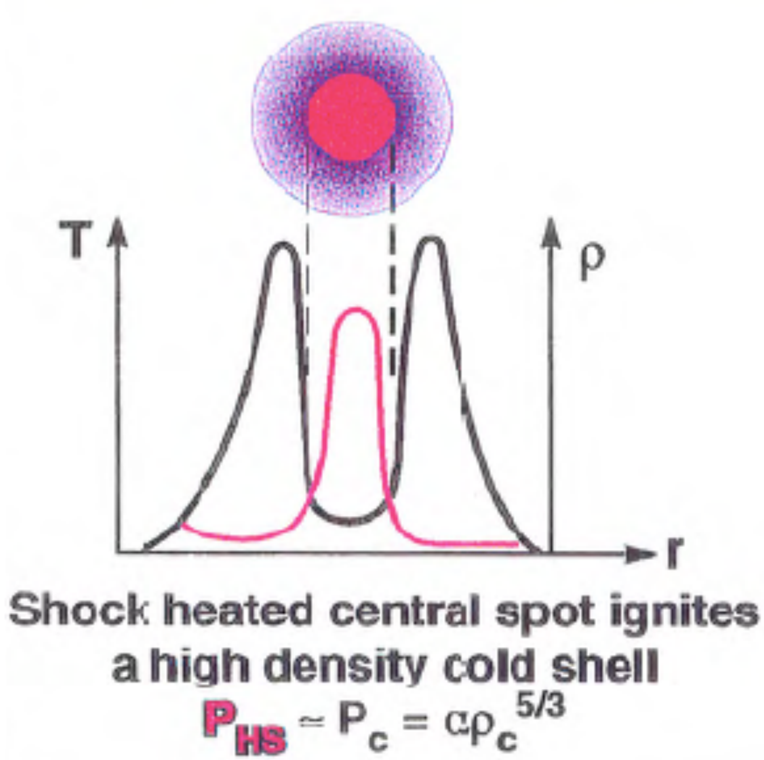
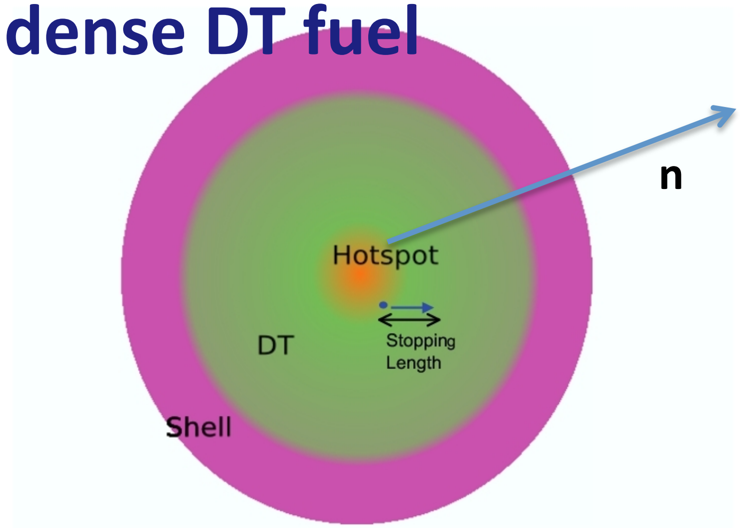
Burn Ignites in Central Lower-density Hotspot and Propagates into cold dense DT fuel





Hotspot:

T ~ 10-30 keV

$\rho \sim 10^{25}\ cm^{-3}$

g ~ 0.1

Outer cold fuel:

T~ 0.5-2 keV

$\rho \sim 10^{26}\ cm^{-3}$

g ~ 1

$$g = \frac{e^2}{4\pi\lambda_D\theta} = \frac{\text{Potential Energy}}{\text{Thermal Energy}}$$

$$\Theta = \frac{\theta_e}{E_{Fermi}} \approx 1.35$$

Burn: $d + t \rightarrow n\ (14\text{MeV}) + \alpha\ (3.6\text{MeV})$

Escape

Heat colder fuel through alpha stopping

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NIF currently not achieving ignition

- Discuss problems in last section of this talk
- Next section if NIF works (or partially works), what is the role of nuclear physics?

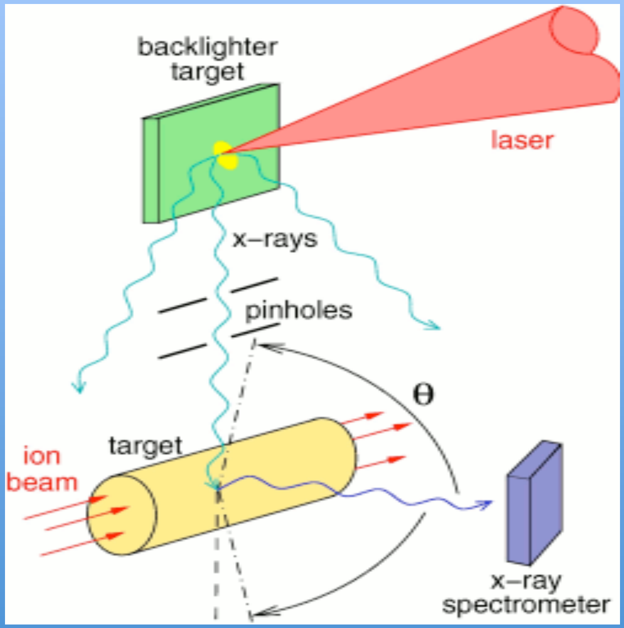
Nuclear-Plasma Physics

An Emerging Field

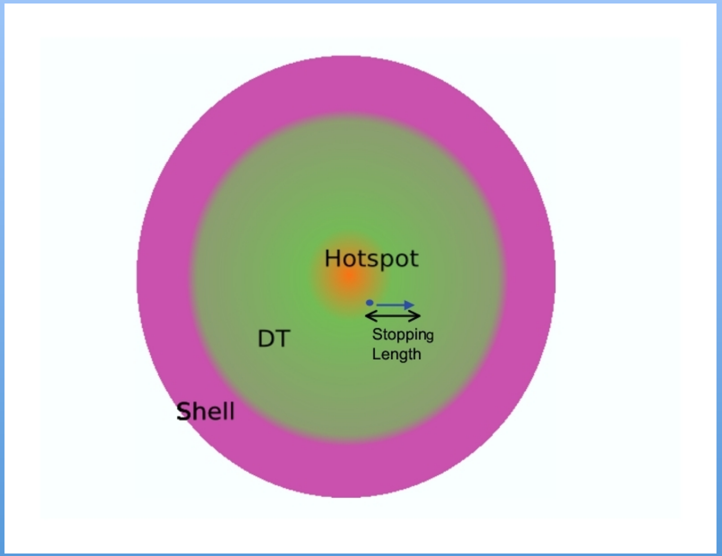
Warm Dense Matter Studies in Nucl. Phys. Close synergy between FAIR GSI and NIF

Warm Dense Matter: High-density finite-temperature regime
Free and bound electrons become correlated
System exhibits long- and short-range order

FAIR GSI
Heat Condensed matter to above T_{fermi}



NIF
Outer Cold Dense Fuel of capsule



Some Areas that could be Studied

- Fusion reaction rates, and outputs
- Stopping Powers in strongly coupled plasmas
- Hydrodynamical Mixing & Turbulence
- Shell Velocity and Shock Timing
- Excited State nuclear physics – population & cross-sections
- Important cross checks on other diagnostics, $\langle\rho r\rangle$, capsule radius, etc.

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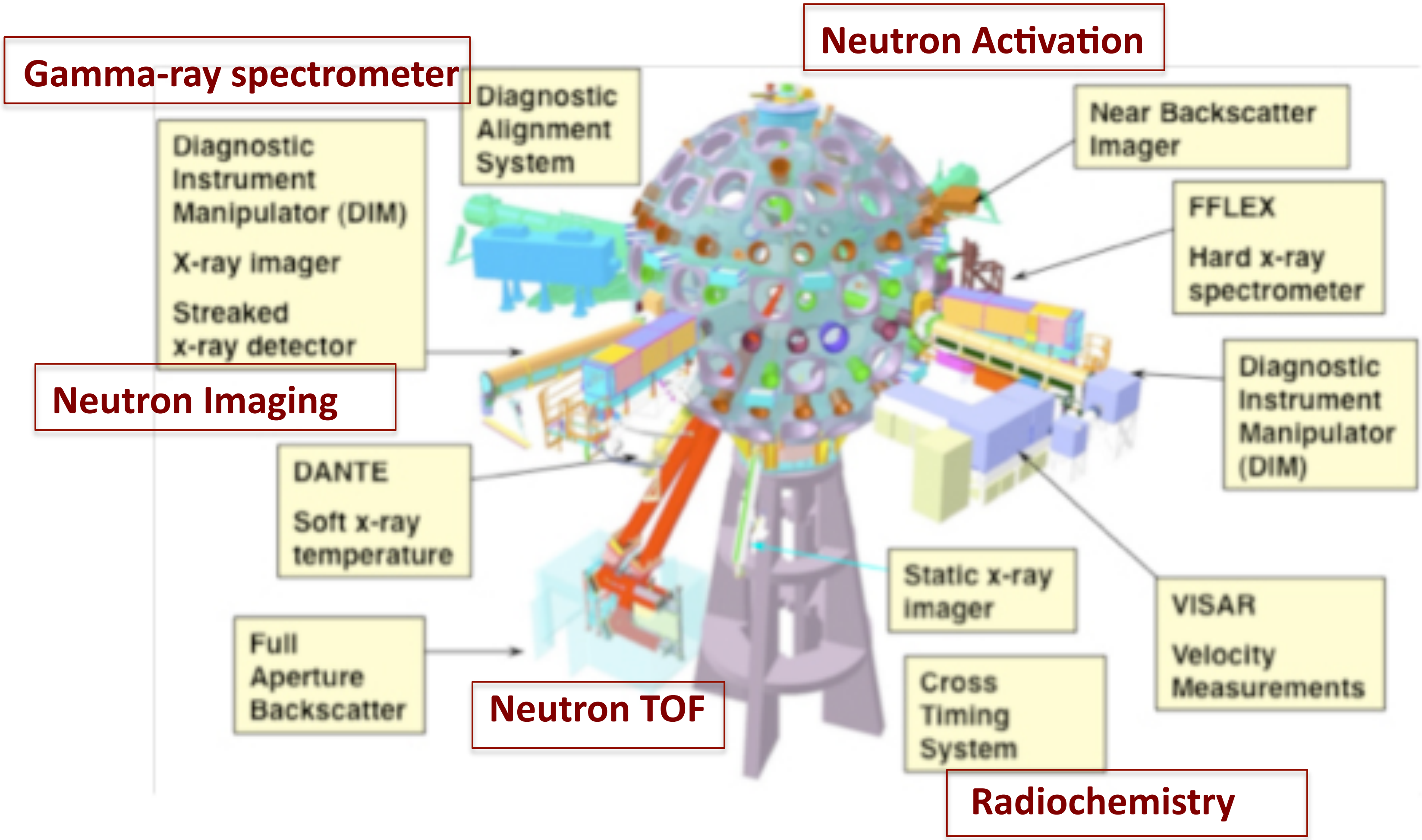
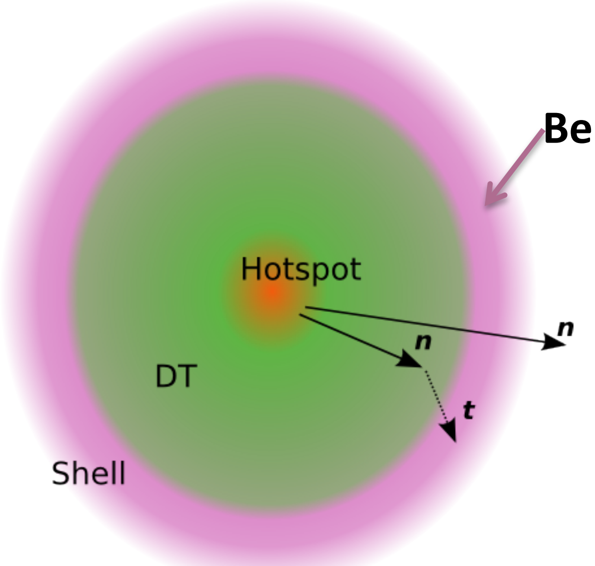
The Diagnostics

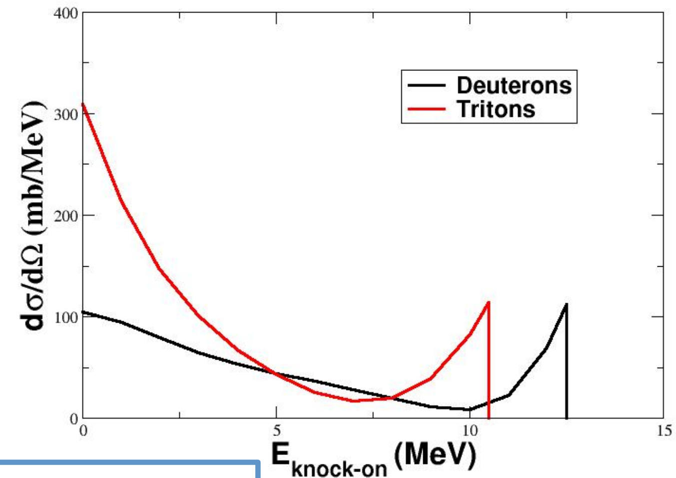


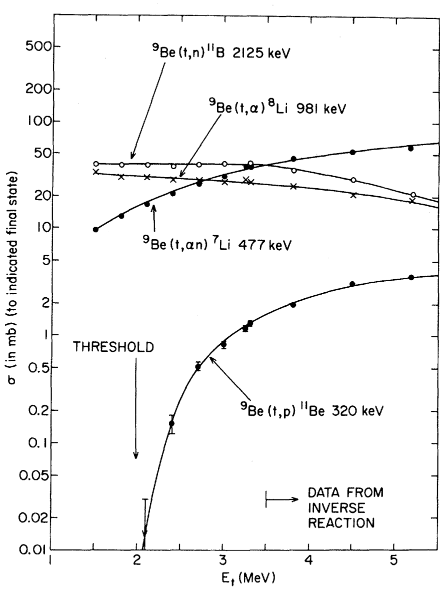
Diagnostics available: Yield, burn history, T_{HS}, R_{HS} (two planes), R_{CF}, $<\rho r>_{CF}$, NTOF, NA, V_{imp}
Neutron imaging 14 MeV, DS, RIFs

Under development (or proposed) :
Gamma-rays Spec., Radiochemistry, Thompson scattering $(T(e)_{CF})$, …

Knock-on CPs Ideal Probes of the Plasma Conditions







Cross section ~ 10s mbarns

Two classes of reactions

Reaction-in-flight DTs

d+t → α + **n***

Reactions with the shell

^{9}Be(t,α)^{8}Li (β^{-}, 840ms)

^{9}Be(t,p)^{11}Be(β^{-}, 13.8s)

^{9}Be(t,nα)^{7}Li

^{9}Be(t,n)^{11}B (γ;2.125 MeV)

^{9}Be(α,n)12C(γ; 4.4 MeV)

^{13}C(t,p)^{15}C(β^{-}, 2.5s)

^{13}C(t,α)^{12}B(β^{-}, 21 ms)

Typical set of reactions that could be measured via Radiochemistry and/or γ-ray spectroscopy

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Stopping Power

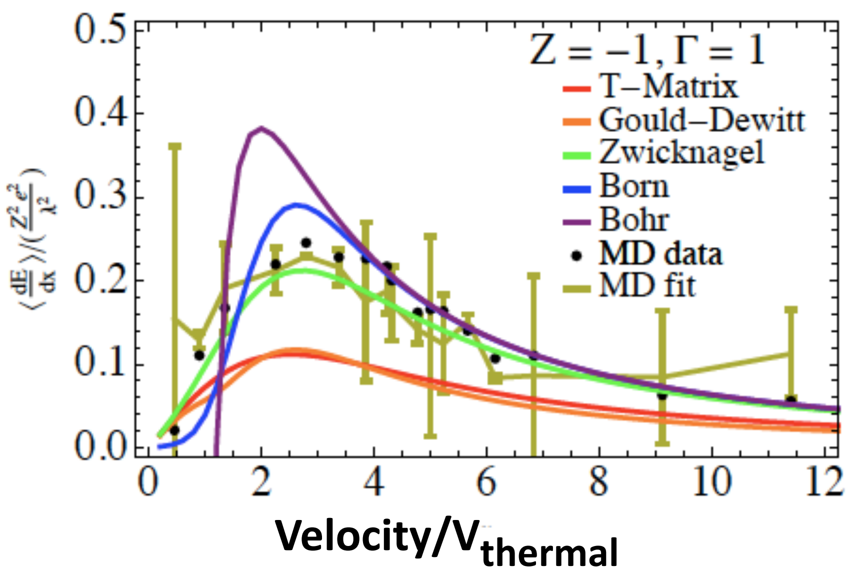
Stopping Powers in Strongly Coupled Plasmas

General Form of stopping not analytic, but models generalized to:

$$\frac{dE}{dx} = -\frac{(Ze)^2}{v_t^2}\omega_p^2 G\left(\frac{m_e}{m_t}, \frac{E_t}{\theta_e}\right) \ln\Lambda + \text{equivalent ion term}$$

G governs the dependence on E/θ

lnΛ a function of plasma temperature & density



(Figure from M. Murillo)

- Theories don't agree in strong coupling limit
- Theories perturbative in 1/lnΛ;
- lnΛ < 1, theories breakdown

Cold fuel at NIF in the lnΛ < 1 regime

The Knock-on Charged Particle Fluence at NIF Directly Probes Stopping in Strongly-coupled Plasma

If the density is uniform in the region where the knock-ons are born then:

$$\frac{d\psi_{k.o.}}{dE}(E_f) = \frac{Q_o}{|dE/dx(E_f)|}\int_{E_f}^{E_{0\max}} dE_0 \; q_o(E_0)$$

Spectrum after transport

Spectrum at birth

$$Q_0 = \Phi_{14} n_{dt} \sigma_{k.o.}$$

Determine of the shape of the knock-on fluence
=> Determine of dE/dx

Knock-ons in cold fuel at NIF ideal probe of stopping in **lnΛ < 1** plasma regime

Interaction of K.O.s with Ablator Shell vs. Cold Fuel

Shell:

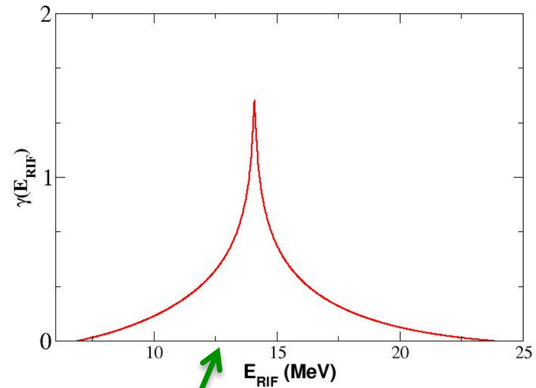
Several reactions possible.

Difference in excitation functions => extract form of $G(\frac{m_e}{m_t}\frac{E_t}{\theta_e})$

Turbulence and Instabilities mix the shell material into the fuel

⇒ Location of shell during the burn unknown

⇒ Difficult to determine $\ln\Lambda$



Fuel:

Reaction-in-flight neutron from d+t → α+n

$$\frac{dN_{RIF}}{dE_{RIF}} \approx (2\times10^{9}\,keV^{-1})\left(\frac{N}{10^{16}}\right)\left(\frac{\theta_e}{1keV}\right)^{3/2}\left(\frac{\sigma_{k.o.}}{1b}\right)\left(\frac{\sigma_{DT}}{0.1b}\right)\gamma(E_{RIF})\frac{1}{\ln\Lambda}$$

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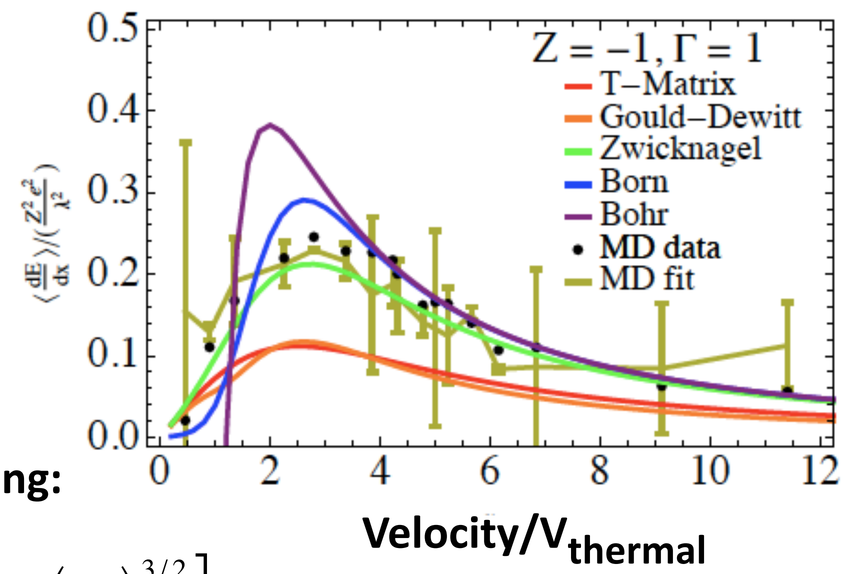
Experimental Program to Deduce Stopping

•Theories disagree on form of stopping in strongly coupled limit

•Agree on approx general shape as a function of velocity of the ion

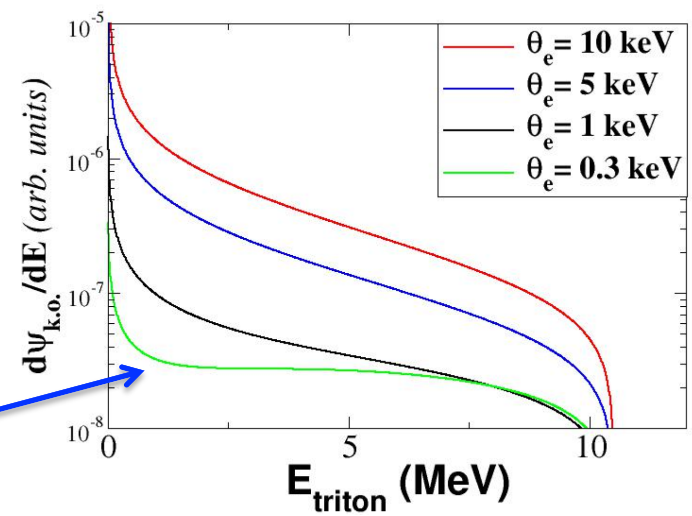


Parameterization of different forms of stopping:

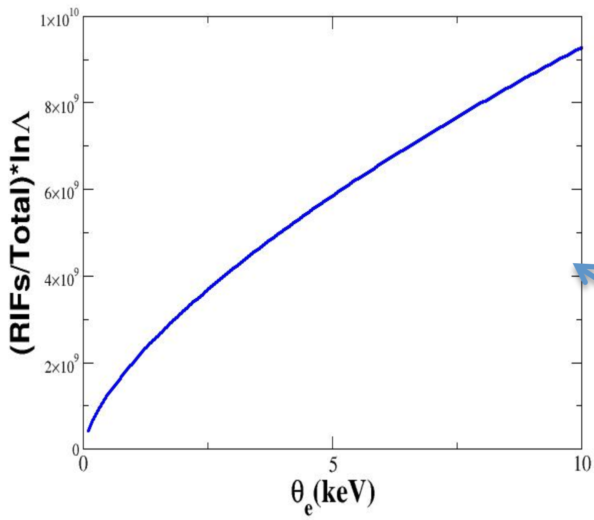
$$\frac{dE}{dX} = A\, e^2 Z^2 \ln(\Lambda)\left(\frac{m_e}{m_{D,T}}\right)^{1/2} E^{1/2}\left(\frac{n_e}{\theta_e}\right) 1\Big/\left[1+B\left(\frac{E}{\theta_e}\right)^{3/2}\right]$$

Deduce parameters from K.O. reactions

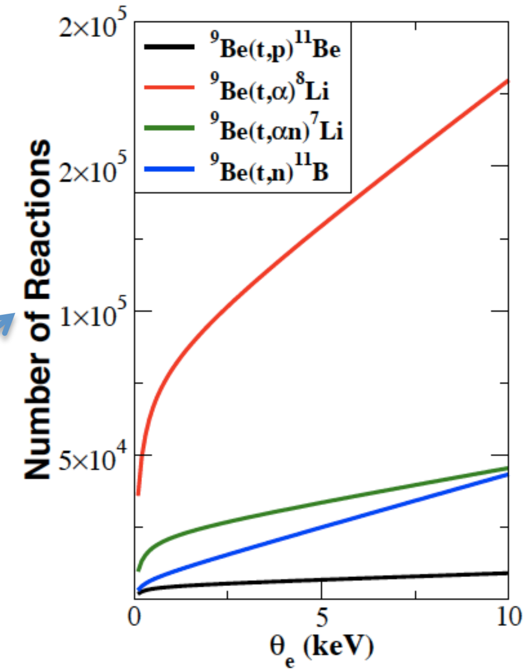
Stopping-induced change in K.O. triton fluence assuming *weak coupling* (A=1, B=1)



Combination of RIFs and Knockon+shell Reactions provide the needed information to "deduce" the stopping



- Calculations here used Li-Petrasso (A=B=1)
- In general, deduce A &B



A Parallel Stopping Power in WDM Program is being at GSI

Study
of
Turbulent Transport
and
Mix Models for ICF and Astrophysics

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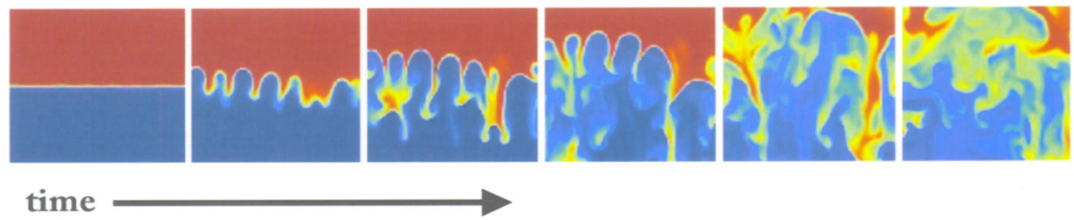
Study of Hydrodynamical Mix at NIF

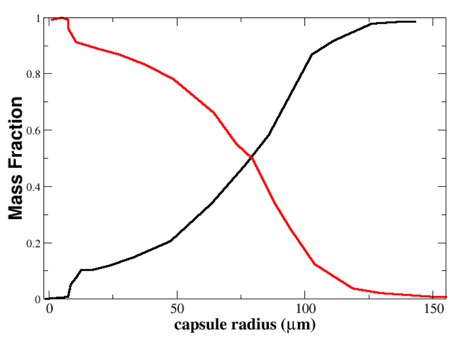


Goal: Combine Theoretical / Computational / Experimental tools to study mix in convergent compressible geometries with thermonuclear burn at NIF

Experimental development of diagnostics for NIF

- neutron imaging – study mix-induced spatial distribution of burn
  study mix effects on reaction-in-flight neutrons
- radiochemical assay of charged-particle reactions – study nature of the mix

Theoretical program to design capsules with varying degrees of mix, design diagnostics to extract mix from CP reaction, couple with theoretical Mix model validation



Predicted mix fraction 100 ps before peak burn for DD capsule

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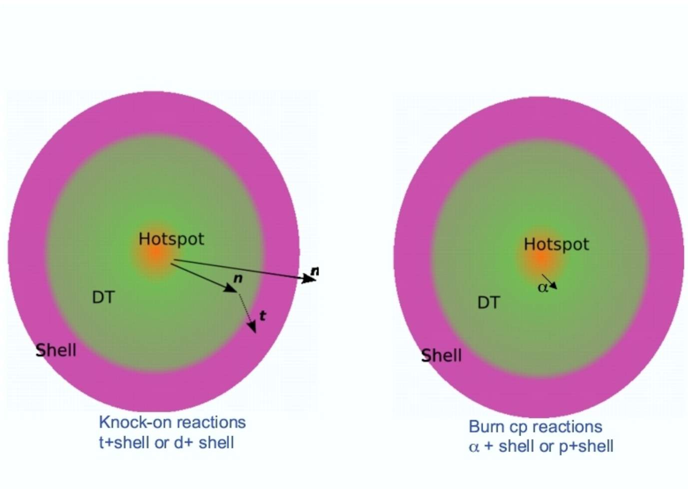
Different CP Reactions Probe Nature of Mix differently – Atomic, Jetting, Chunk, …

Knock-on CP reactions sensitive to ablator mixing in dense cold regions of fuel



Burn CP reactions sensitive to ablator mixing within stopping length of hotspot

Reaction	β-energy	No Mix	Atomic
$^{9}Be(t,\alpha)^{8}Li$	13 MeV	$1.6x10^{12}$	$6.1x10^{13}$
$^{13}C(t,p)^{15}C$	9.8 MeV	$8x10^{10}$	$3x10^{12}$
$^{18}O(t,n)^{20}F$	5.3 MeV	$1.6x10^{9}$	$4.7x10^{10}$

Reaction	No Mix	Atomic	Jetting
$^{20}Ne(p,\gamma)^{21}Na$	$2.5x10^{11}$	$5.2x10^{10}$	$7.3x10^{11}$
$^{16}O(p,\gamma)^{17}F$	$4.3x10^{11}$	$6.3x10^{10}$	$8.7x10^{11}$

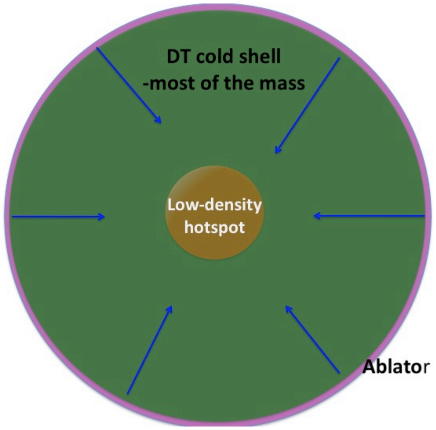
Mix induces order of magnitude increase in number knock-on reactions
Suppresses reactions with burn CP particles, unless jetting occurs

By measuring several reactions, can deduce the nature of the mix taking place

NIF
Currently Failing
to
Achieve Ignition
by
factor ~ 10^3

Ignition Conditions

Enough energy delivered to central "hotspot" to reach required (T, ρ) conditions
- including radiative and conductive energy losses.



- Minimum implosion velocity *(3.4x10^7 cm/sec)*
  - *Cold fuel delivers ½ mv^2 to HS*
- Spherical implosion
  - *Efficient transfer of the shell kinetic energy to thermal hot spot energy*
  - *Avoid converting kinetic energy into asymmetric fuel mass motion at peak burn*
- *Minimum pre-heat*
  - *Maximum compression of hotspot*
- *Minimum hydrodynamical mixing of ablator shell into HS*
  - *High-Z material from ablator can cool the hotspot too much*

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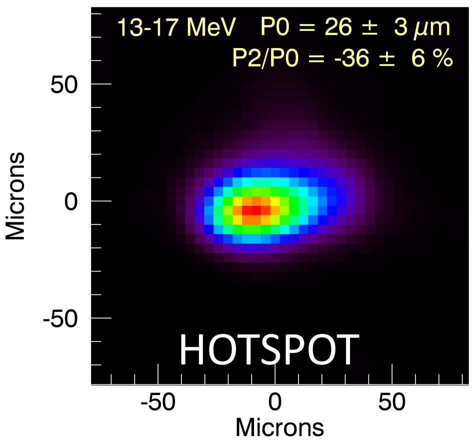
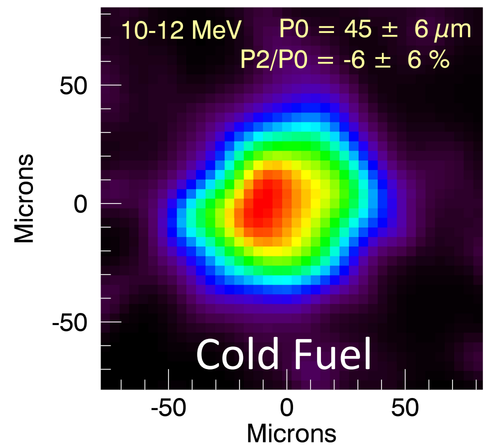
Experimental Data show that the Imploded NIF Capsules are Very Non-Spherical

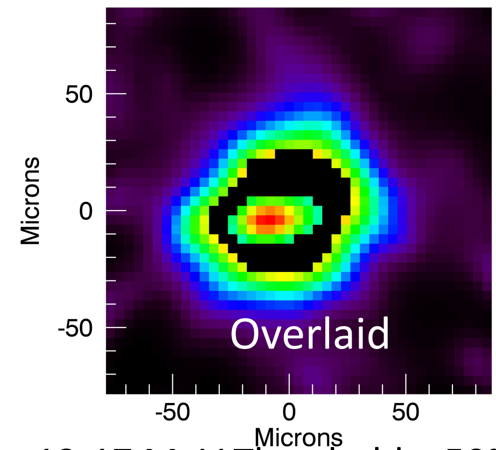
Neutron Imaging (Equatorial Plane):



P0: 26 ± 2 ± 2 μm
P2/P0: -38%



P0: 40 ± 4 ± 4 μm
P2/P0: -11%

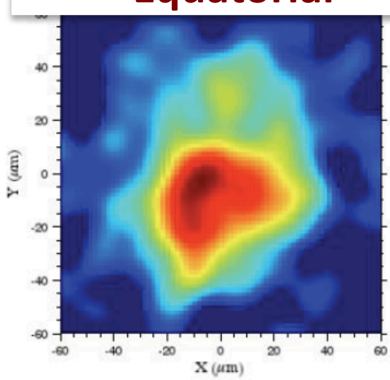


13-17 MeV Threshold > 50%
10-12 MeV Threshold < 60%

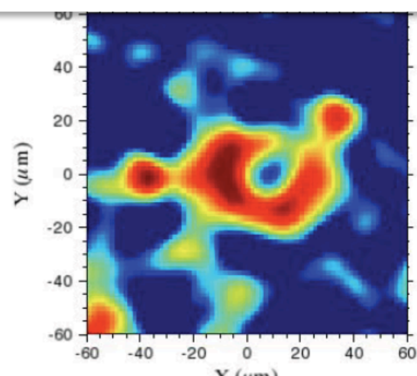
Hotspot radius= 26 mm +/-2 +/-2 mm
P2 asymmetry ~ -30%

Cold fuel radius=40 +/-5 mm; P2 ~ 10%
Hotspot and cold fuel not co-centered

Equatorial



Polar



X-ray Images also see clear 3-D asymmetries in hotspot shape

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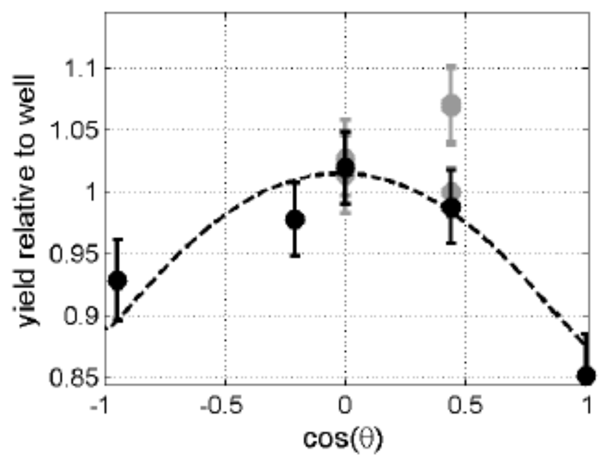
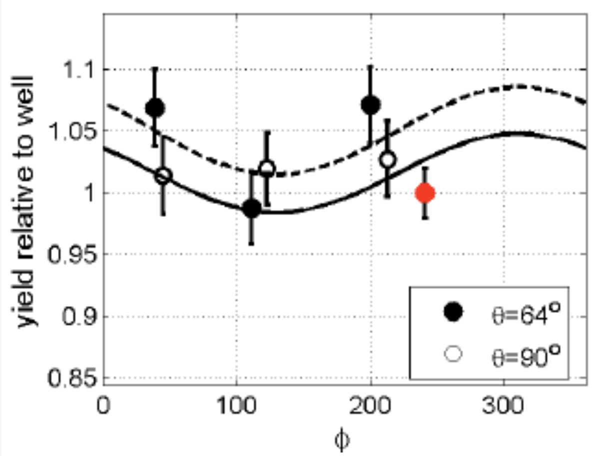
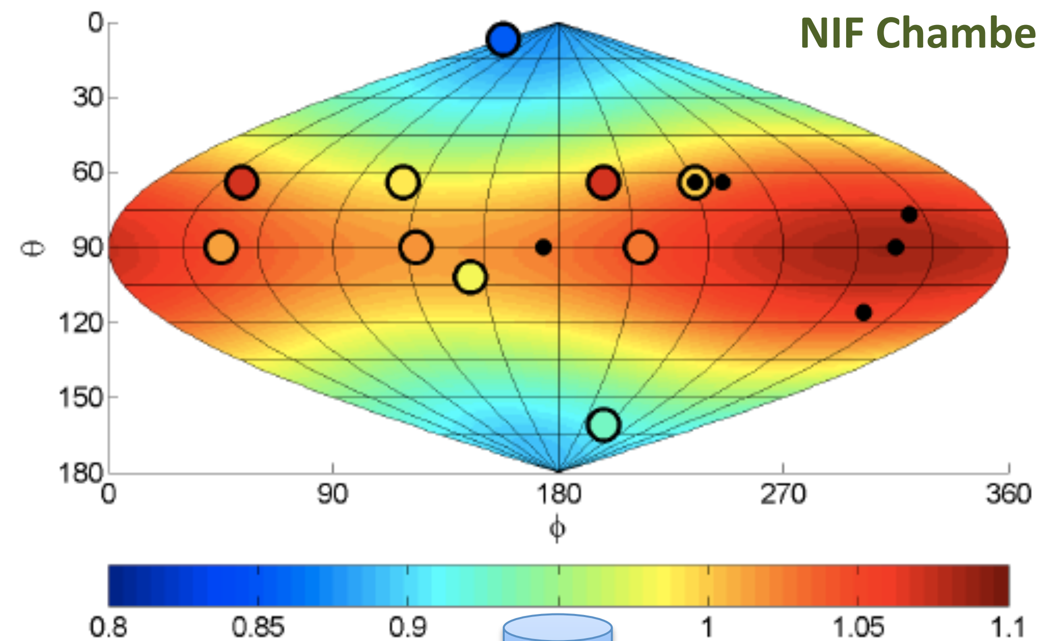
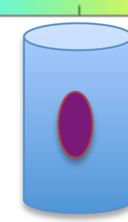
Neutron Activation Pucks around the NIF Chamber see Asymmetries in both θ and φ directions









See significant ρR variations

- ρR~1 g/cm^2 in DT => 20% of the neutrons are down-scattered
- 10% variation in the yield => 50% ρR variation

ρR variations also seen in Neutron Time of Flight (NTOF) and Magnetic Recoil Spectrometer (MRS) data

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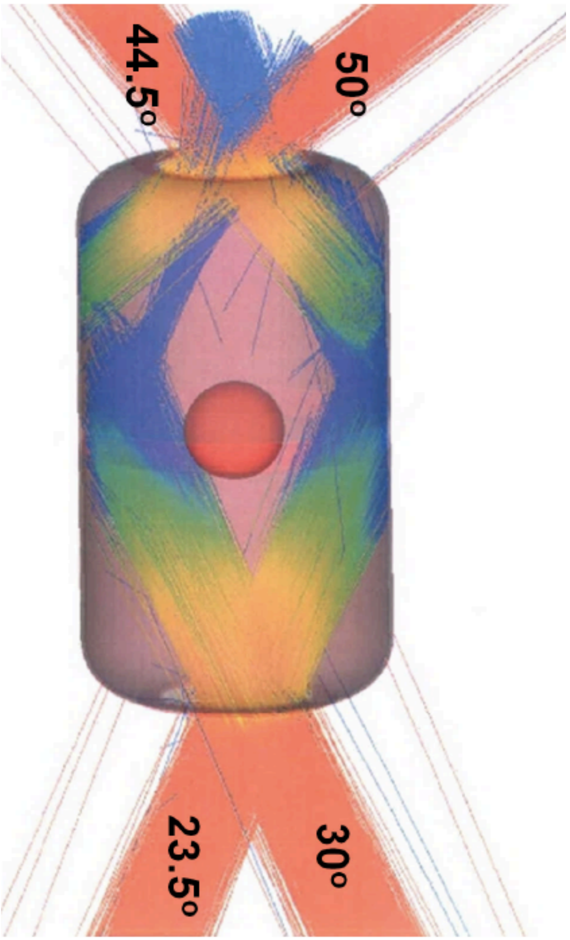
Possible Sources of Initial 3-D Asymmetries



1) **Intrinsic 3-D radiation asymmetry due to 3-D illumination pattern, after laser tuning campaign**
2) **Gas fill tube**
3) **Possible additional LPI effects**
4) **…**

3-D Radiation hydrodynamic calculations using Hydra (Jones et al.):
After laser tuning, small residual P4, A4 (M4) asymmetries remain due to intrinsic variations in the brightness of the inner cones

These small asymmetries grow significantly as capsule radius converges by factor ~30

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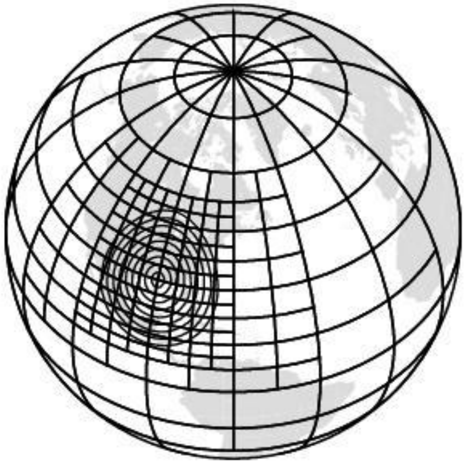
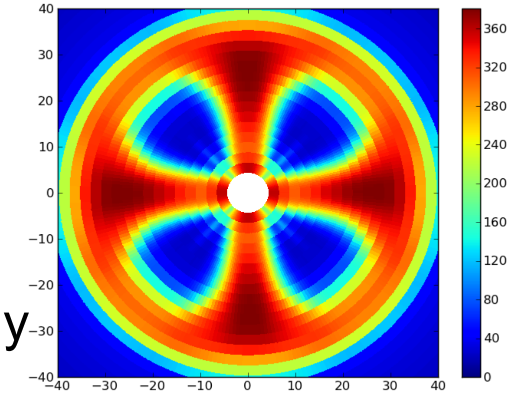
Asymmetric Drive Hugely Affects the Final State of the Capsule

- 3-D hydro simulations (Hui Li) to study the implosions with initial low-mode asymmetries.



- Asymmetry evolution depends on the initial amplitude and pattern
- Introduces non-radial motion, $\mathbf{V}_\theta$ and $\mathbf{V}_\phi$
- Capsule burn can take place while huge fingers of cold fuel are still moving



- Cold fuel penetrating the hotspot
- Inefficient transfer of energy to thermal hot spot energy

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3-D Simulations

3-D HYRDA Simulation: Pre-NIF Data

Jones et al.

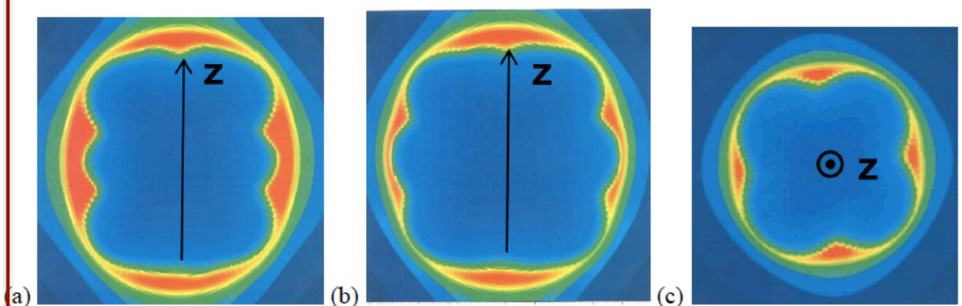


Figure 2. Density slices at maximum compression, (a) ϕ=0 , (b) ϕ=90, (c) z=0

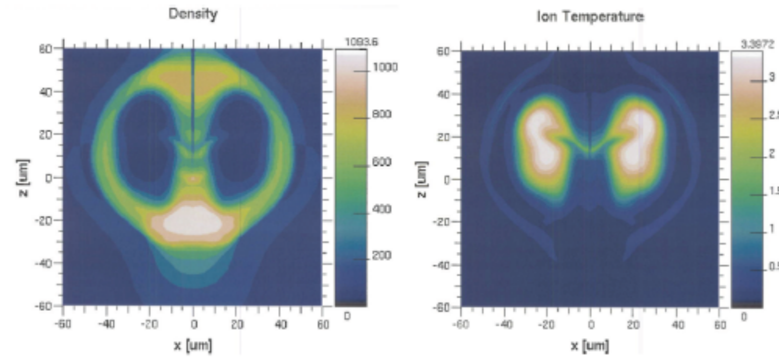
Relatively small asymmetries 1- 10%

M=4 component 3%

Significantly under predicted Expt P2, P4, M data

2-D HYDRA Simulation: Using NIF data

Jones and Wilson



Very large asymmetries

Some expt. data input into calculations

=> Significant P2 and P4

Suggests that 3-D affects not understood or poorly modeled

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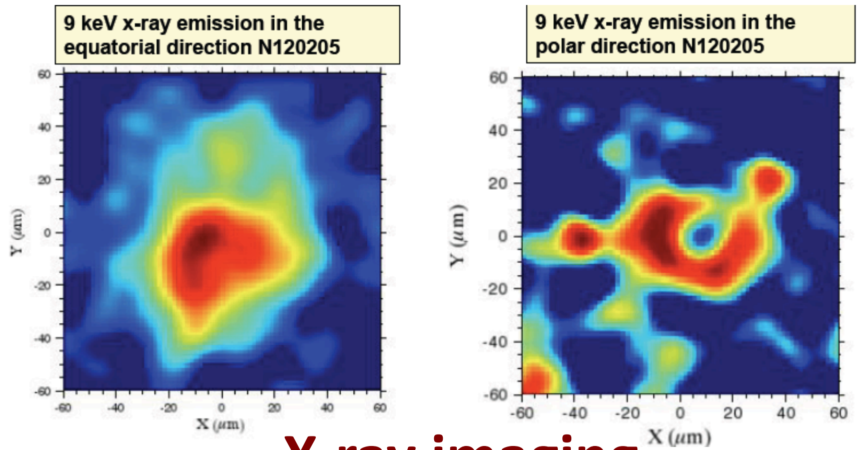
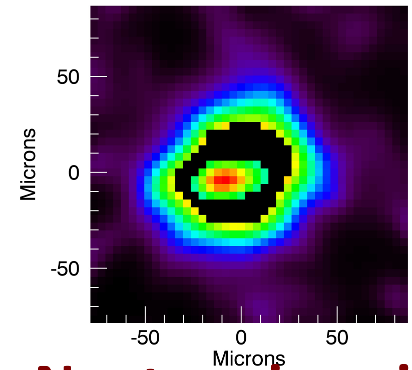
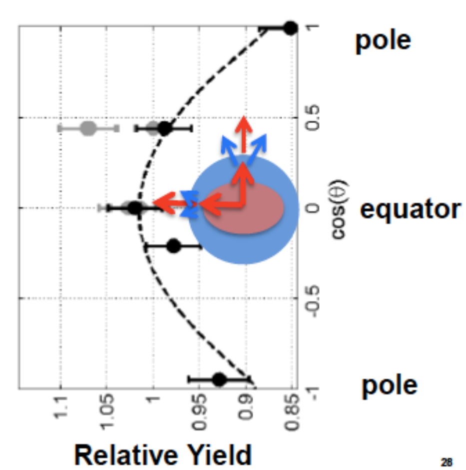
3-D Asymmetries in NIF Observables Show a Recurring Pattern



X-ray imaging



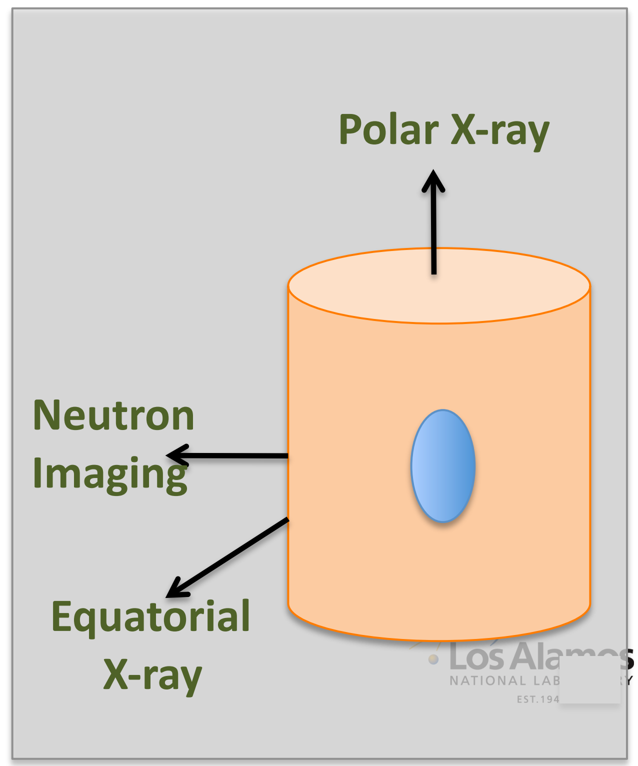
Neutron imaging



Neutron activationpucks

- Watermelon shape
- Radius 26 μm
- P2/P0 ~ 20-40%
- Axis in polar direction
- Very different polar shape

- v_{imp} ~ 3x10^{7} cm/sec (90%)
- <ρr> cold fuel ~0.8 gm/cm^{2}
- HS T~ 4 keV
- Burn ~ 150 ps
- Yield ~ 5x10^{14}



Nuclear Physics Probes to understand current NIF Status

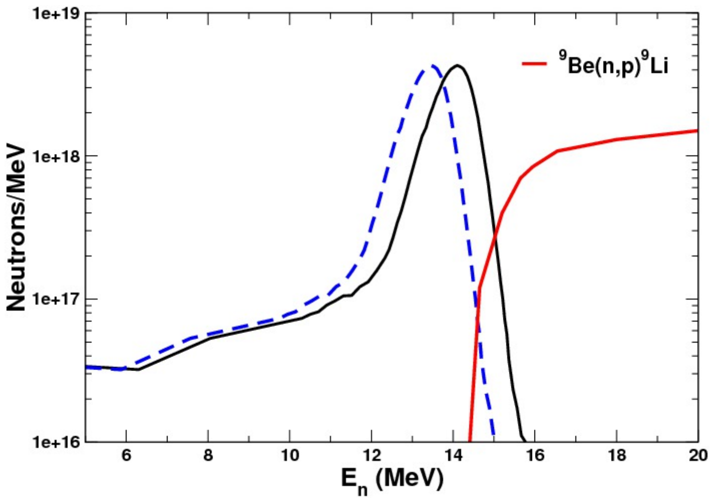
Example:

Determine if Cold Fuel is moving during the burn

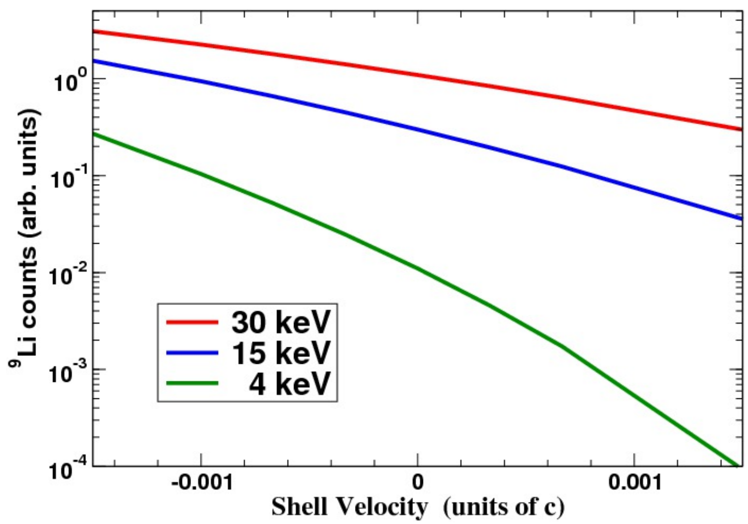
=> Impeding conversion of implosion energy to thermal HS energy

Threshold for ^{9}Be(n,p)^{9}Li results in the reaction being a sensitive probe of the Ablator Velocity

E_{th} = 14.27 MeV



If one well defined velocity during the burn:



Note:

The ^{9}Be(n,p)^{9}Li reaction shuts off once ablator velocity changes sign

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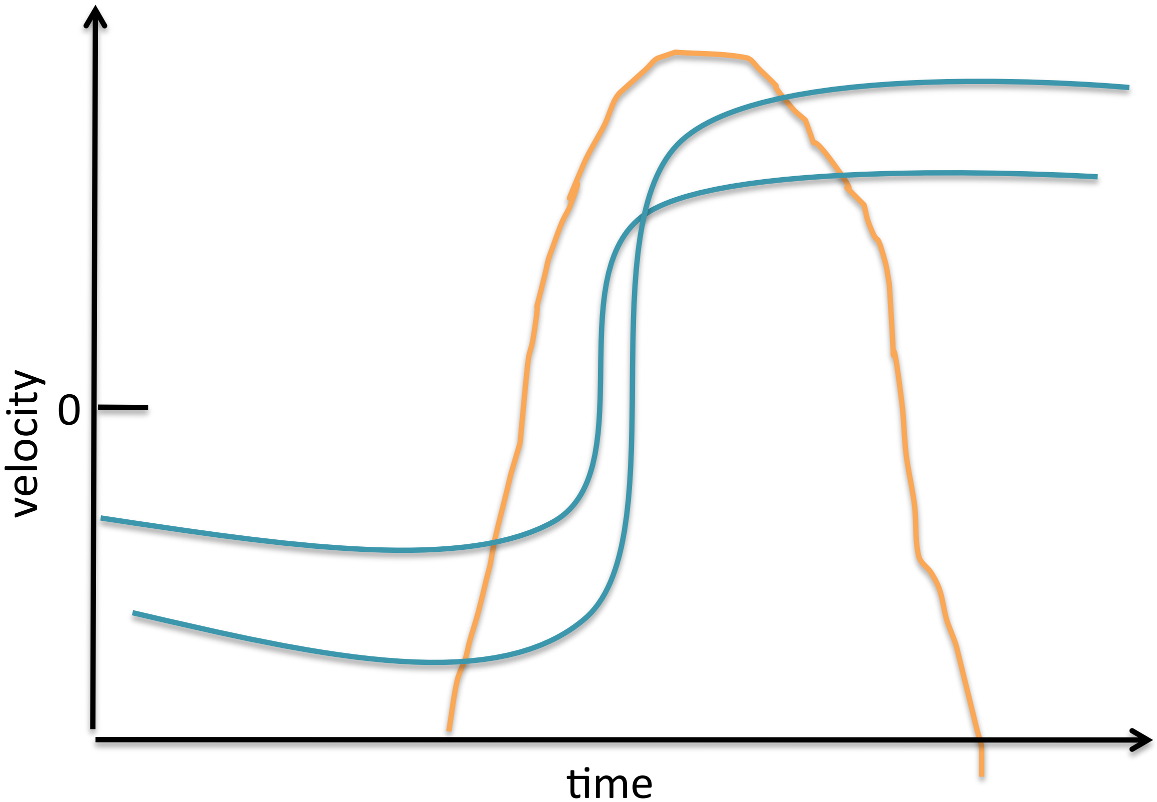
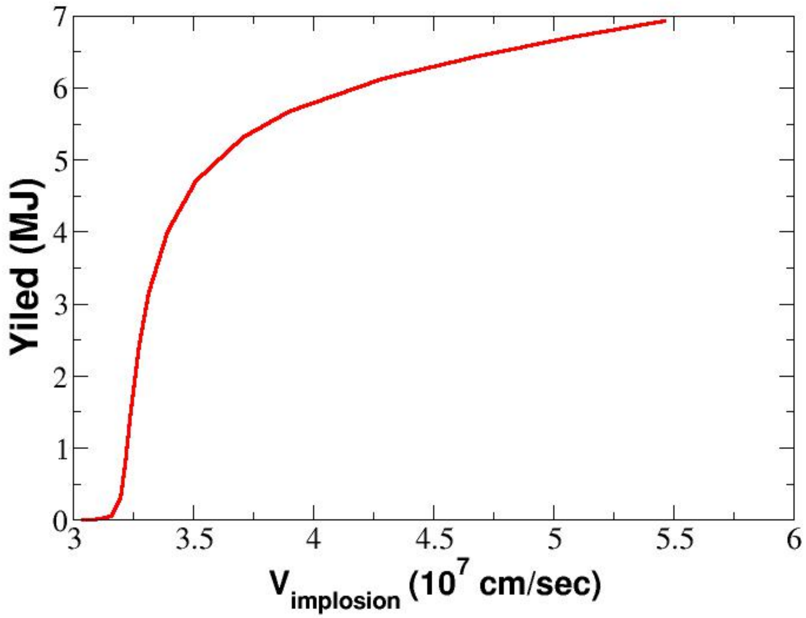
Timing of Peak Burn versus Ablator Velocity

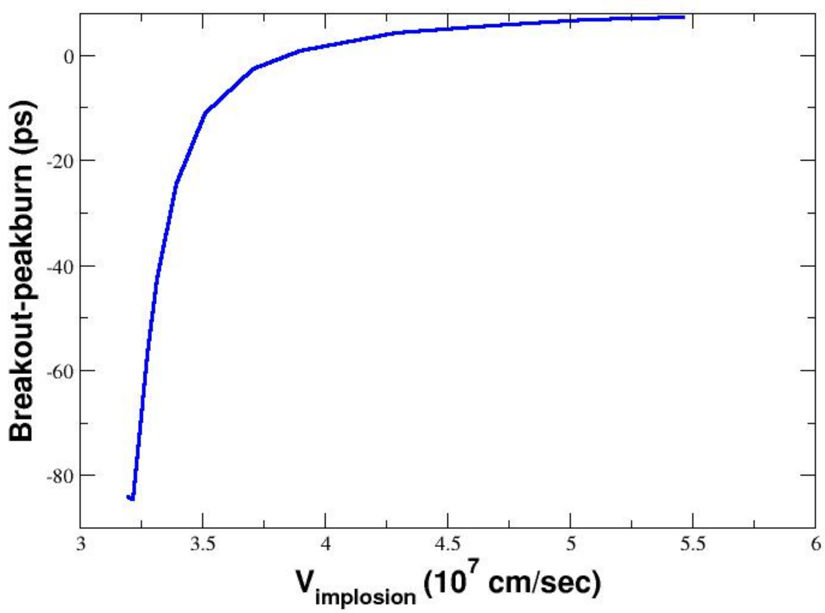


The production of ^{9}Li depends both on the implosion velocity and relative time between peak burn and fuel turn-around

As Vary $V_{implosion}$
=>Time between Shock Breakout and Peak Burn varies.

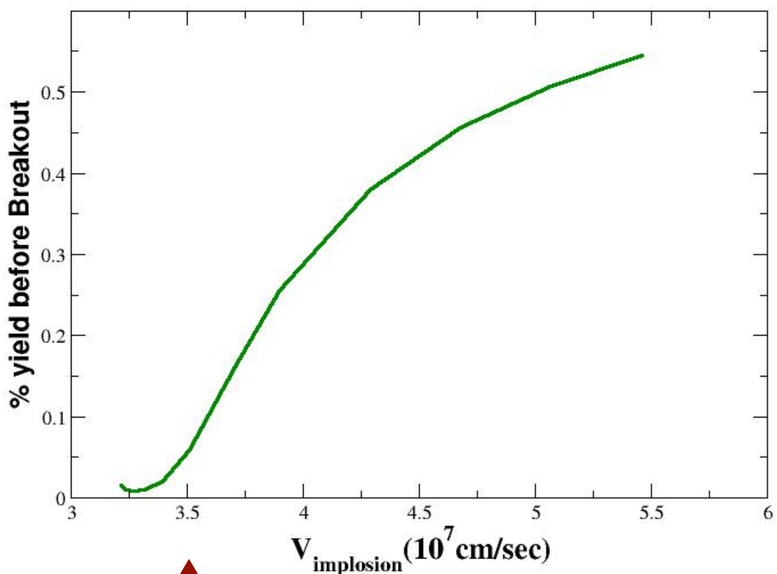
Ran series of 1-D simulations for DT capsules with Be shell
V_{imp} treated as input parameter that was varied

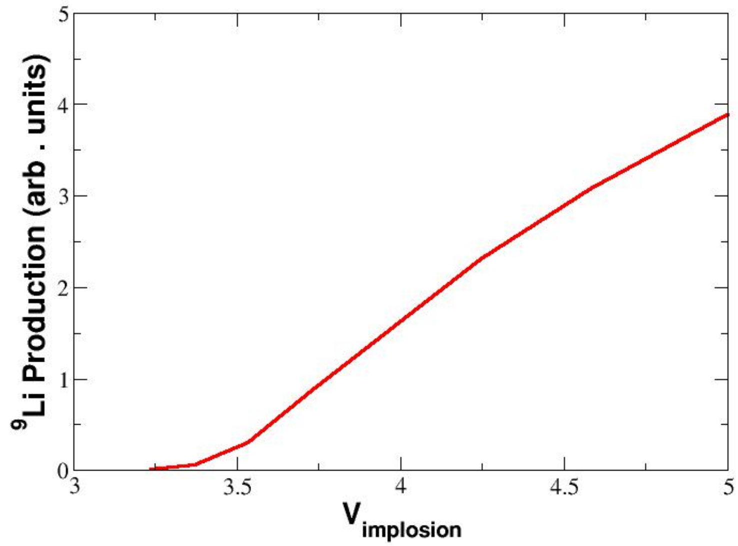




$V_{implosion}$ measured => can deduce if cold fuel is moving at unexpected rate

$^{9}Be(n,p)^{9}Li$ Probes Velocity/Breakout-Timing





Be Shell contains ^{28}Si as a contaminant

Ratio of $^{28}Si(n,p)^{28}Al/^{9}Be(n,p)^{9}Li$ almost identical function

SUMMARY

- **NIF is a unique opportunity to use nuclear probes to study new physics**
  - WDM emerging field in nuclear physics
  - Strong parallels between proposed programs at GSI FAIR & NIF

- *Examples presented here:*
  - *Stopping Powers*
  - *Turbulent transport Models for ICF and Astrophysics*

- **NIF currently not achieving ignition Y ~ 5×10^{14} ($Y_{ignition}$ ~ 10^{18})**
  Nuclear physics can play an important role to help achieve ignition

Example:

- Determine if Cold Fuel is moving at peak burn via $^{9}Be(n,p)^{9}Li$ reaction
=> inefficient transfer of energy to the central hotspot

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