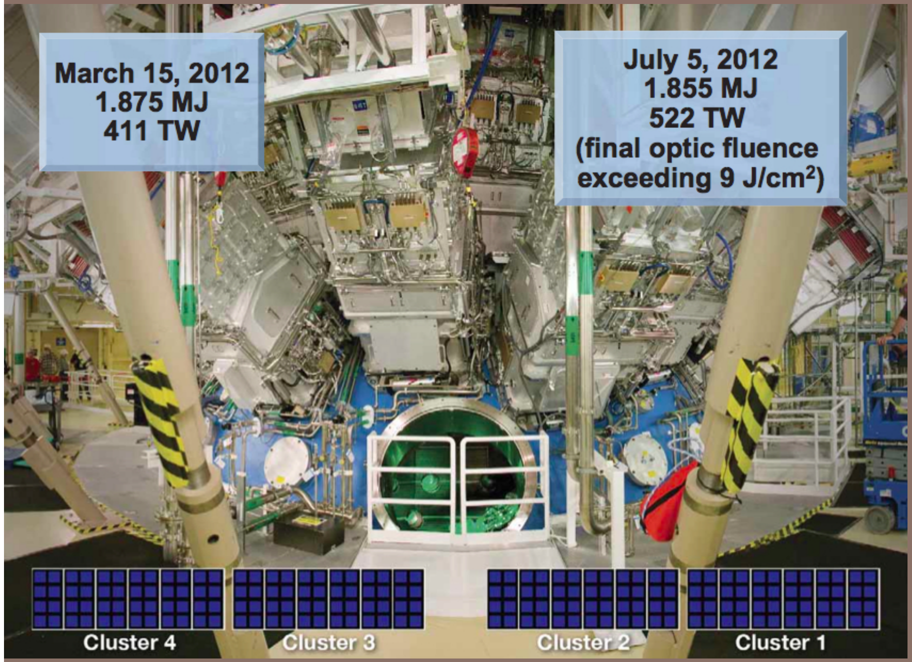
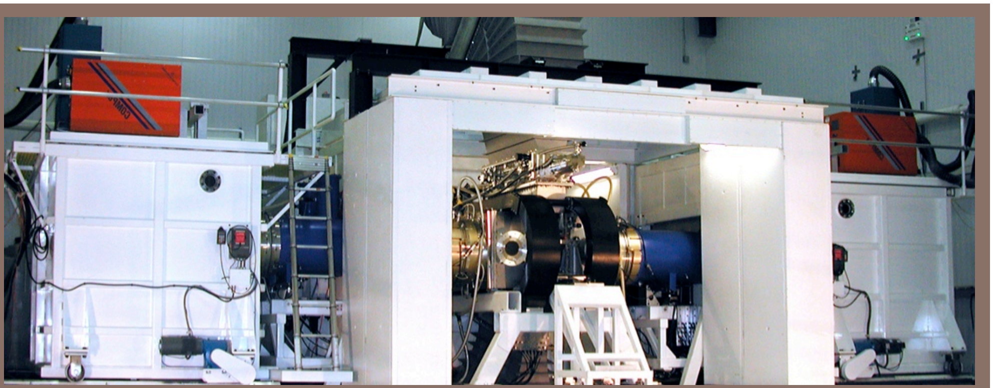
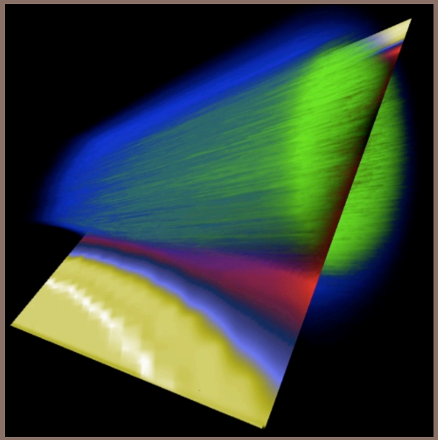
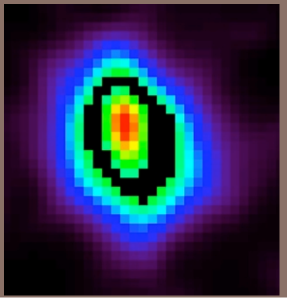






INERTIAL FUSION ENERGY SUMMARY

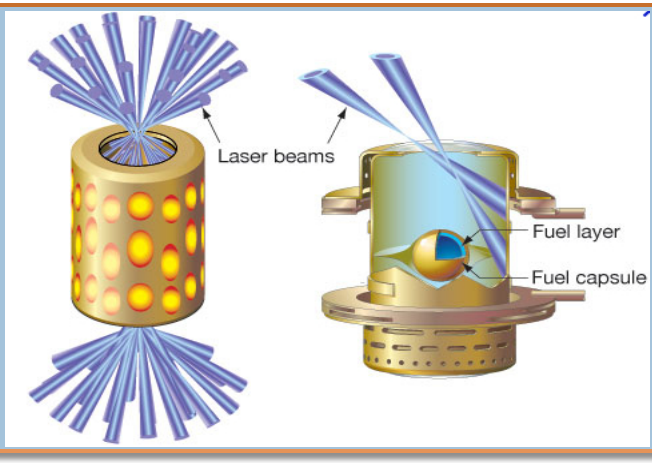
D. E. HINKEL
LAWRENCE LIVERMORE NATIONAL LABORATORY
LIVERMORE, CA USA



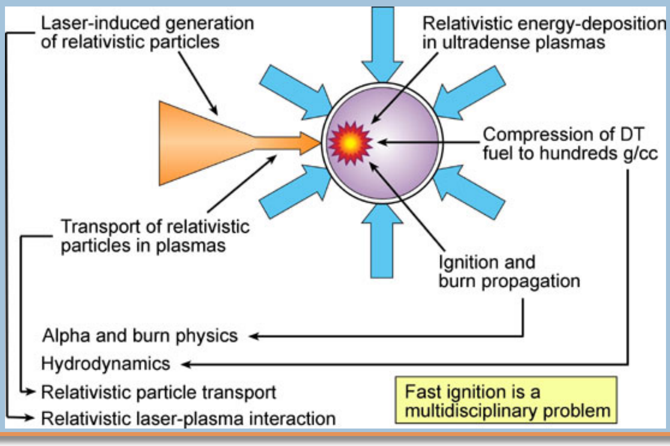
IAEA Fusion Energy Conference 2012

The prospect of inertial fusion energy derives from scientific advancements in different arenas

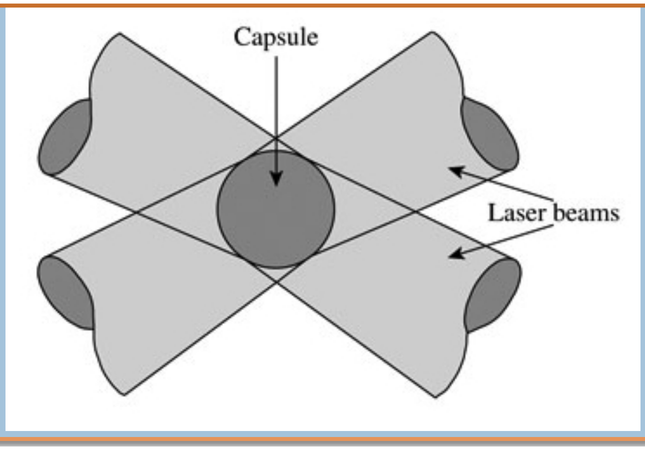
Indirect Drive Laser Fusion: Central Hot Spot Ignition



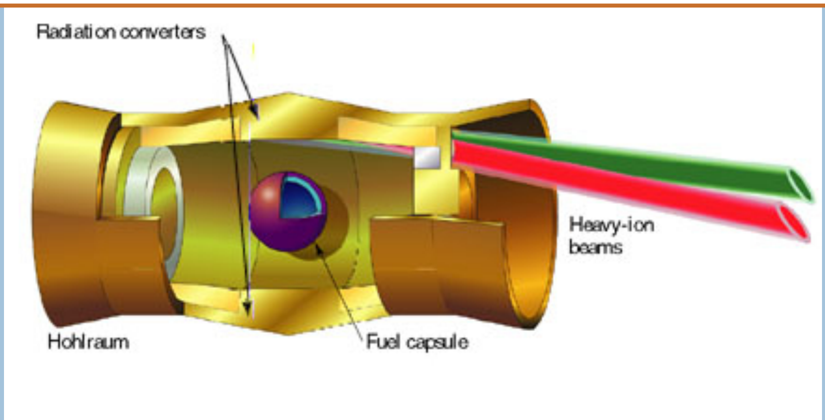
Fast Ignition/Shock Ignition



Direct Drive Laser Fusion: Central Hot Spot Ignition



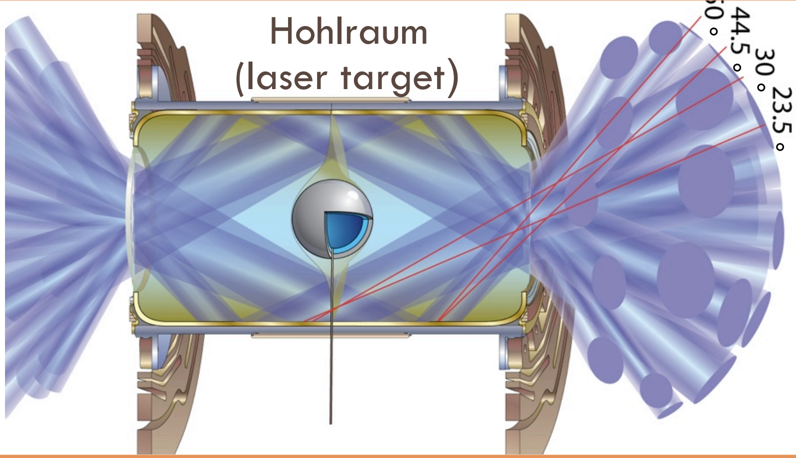
Heavy Ion Fusion



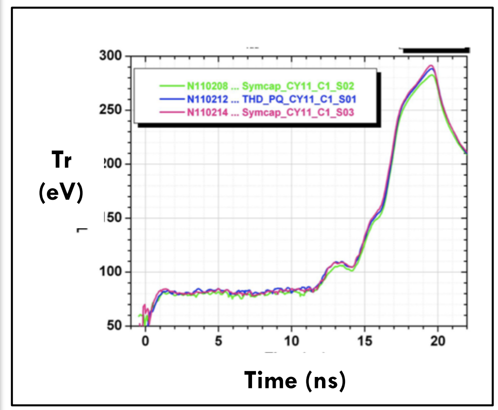
The National Ignition Facility (NIF) provides the opportunity for ignition physics research at full scale

<u>Coupling:</u> laser energy couples to hohlraum and converts to x-rays

Laser Beams (enter through laser entrance hole (LEH)

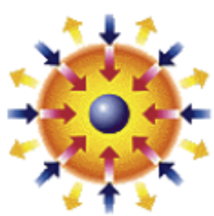


<u>Drive:</u> x-rays bathe capsule, heating it up -- it expands



Ablator heats up

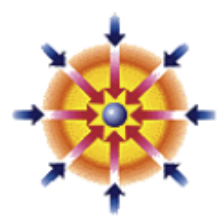
<u>Symmetry:</u> radiation compresses capsule and it implodes



Rocket effect

- <u>conservation of momentum</u>: ablated shell expands outward, rest of shell (frozen DT) is forced inward

<u>Fusion</u> initiates in a central hot spot and a burn front propagates outward



Ignition

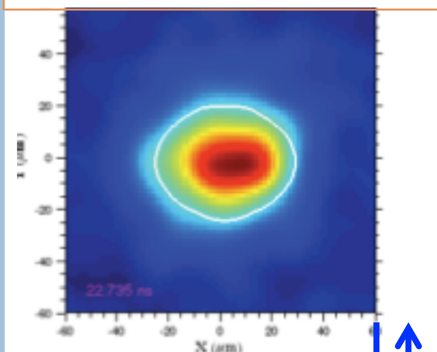
Burn wave

Synergy between different IFE scenarios drives progress in ignition science: energy coupling and drive

NIF: Laser energy couples to hohlraum, converts to x-rays, drives capsule

Symmetry w/Cross-Beam Energy Transfer

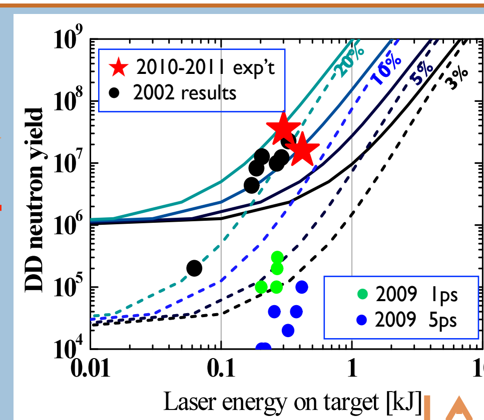
OV/1-4, Moses



Energy Coupling:

- ~ 85%
- Trad > 300 eV

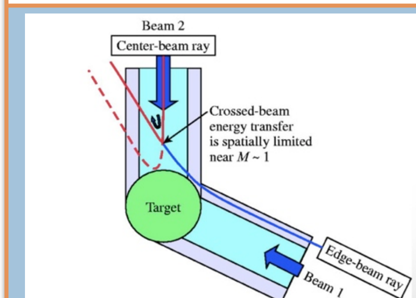
Fast Ignition: laser energy to hot electrons to hydrodynamically assembled fuel



ILE FI Yield: commensurate with 10-20% coupling efficiency

IFE/1-3, Shiraga

Coupling of Direct Drive and 4ω Drivers



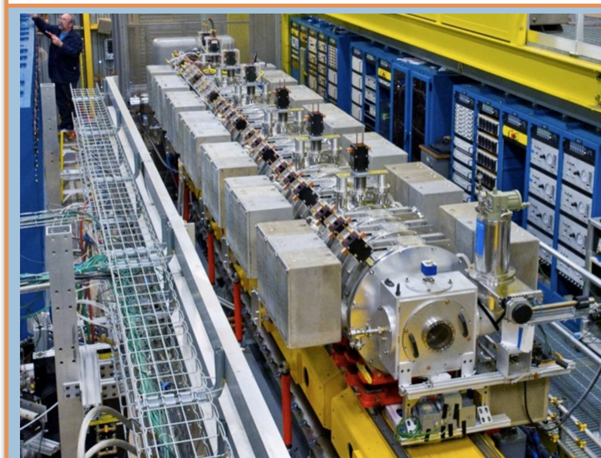
Cross-Beam Energy Transfer: impacts Omega laser coupling

KrF Laser (λ = 248 nm)

- Very uniform illumination
- Shorter wavelength – better laser coupling

IFE/1-4, Sethian

Heavy Ion Fusion



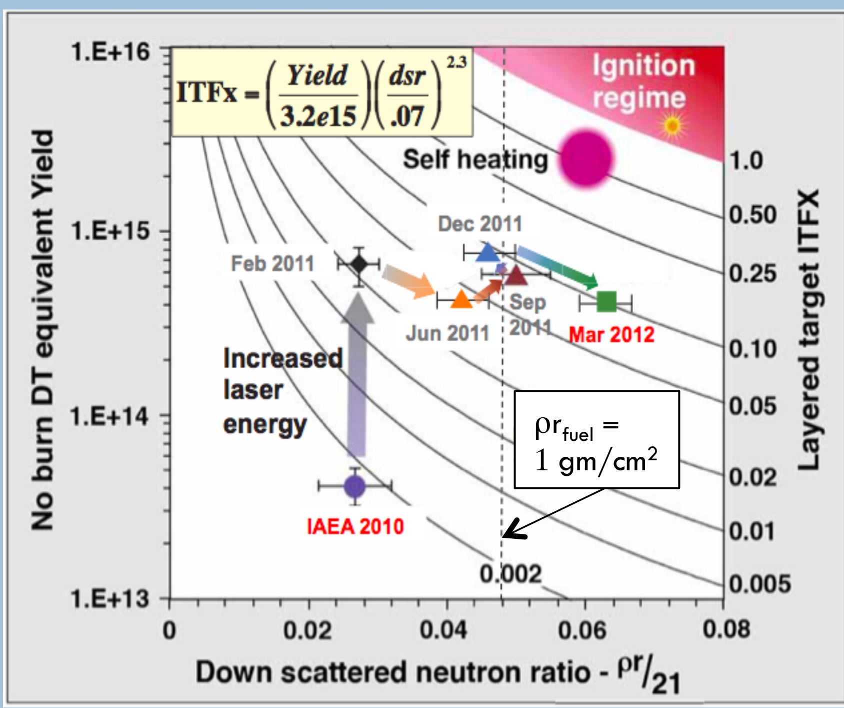
NDCX-II Induction Linac at LBNL now complete

IFE/P6-16, Kwan

Synergy between different IFE scenarios drives progress in ignition science: implosion and burn

NIF Capsule Implosion/Burn: radiation drive capsule implosion, initiating fusion

Adjustments to laser energy and pulse duration, along with shock timing, have demonstrated IFTX ~ 0.1 with fuel ρR at 85% of ignition goal

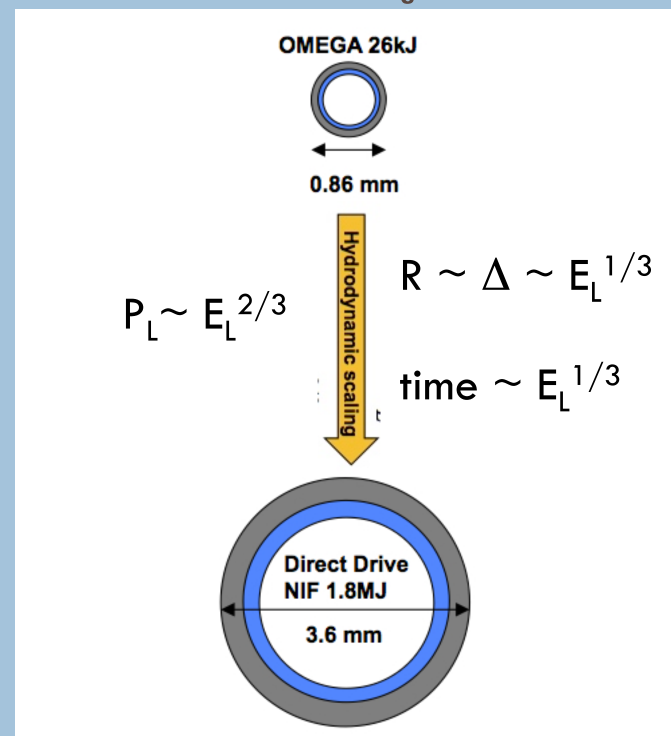


OV/1-4, Moses

ITFx
~ χ^3

Omega DD Implosion/Burn: laser drives capsule implosion, initiating fusion

Hydro-Equivalent Ignition on Omega:
$\chi = [P\tau/(P\tau)_{ig}] \sim 0.16$



Currently at NIF: $\chi \sim 0.5$
Omega: $\chi \sim 0.08$

need a factor of 2!

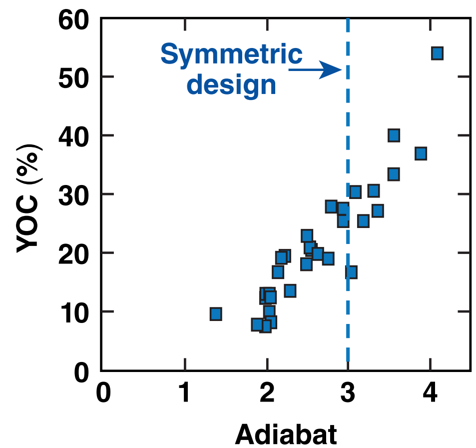
OV/5-3, Betti

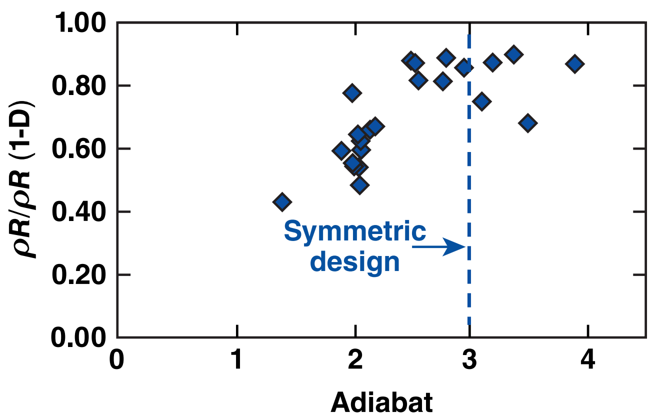
Summary

Direct-drive ICF research has made significant progress since the 2010 IAEA meeting – R.L. McCrory IFE 1-2

- Polar drive will allow for direct-drive ignition experiments on the National Ignition Facility (NIF) with the x-ray-drive beam configuration
- OMEGA symmetric direct-drive cryogenic target implosions are defining the PD design space for the NIF
- Performance continues to improve:
  - neutron yields exceeding 10^{13} (up to ~40% of clean 1-D simulations)
    - ion temperature increased from 2.2 to 3 keV
  - $P\tau$ increased from 1.7 to 2.6 atm-s
- Initial polar-drive implosions have been performed on the NIF

Performance of OMEGA Cryogenic Target implosions

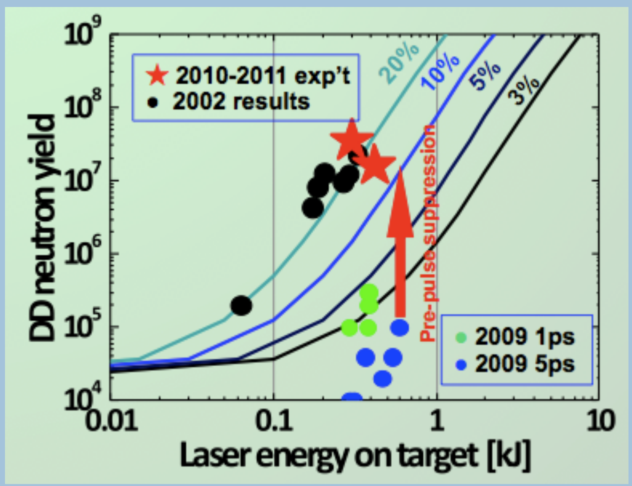


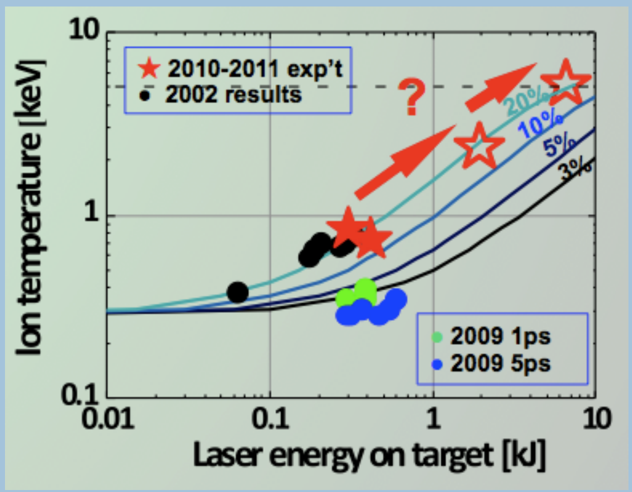


TC10136

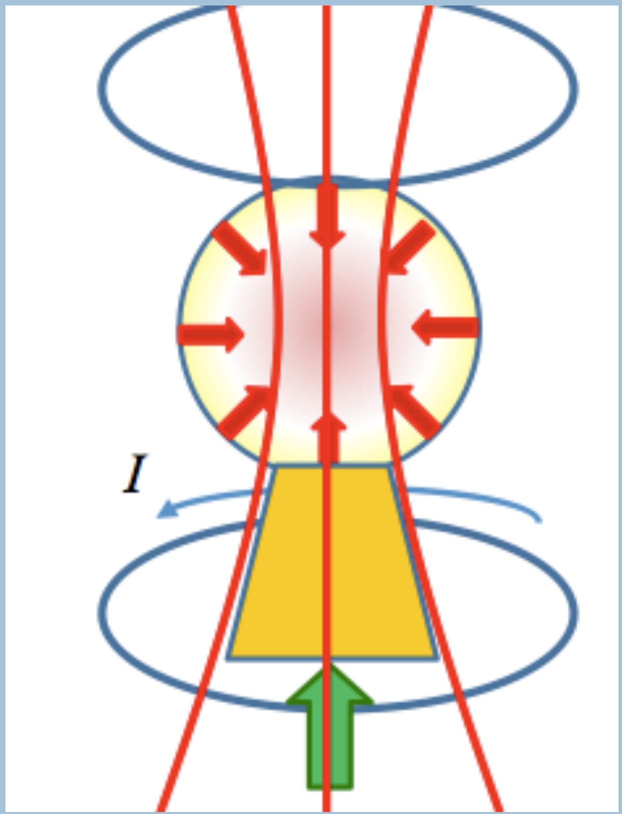
Fast Ignition at ILE: yield and Tion have exceeded previous records, with a path for further improvement

ILE Neutron Yield and Ion Temperature





Magnetic field guiding of hot electron stream should further improve coupling



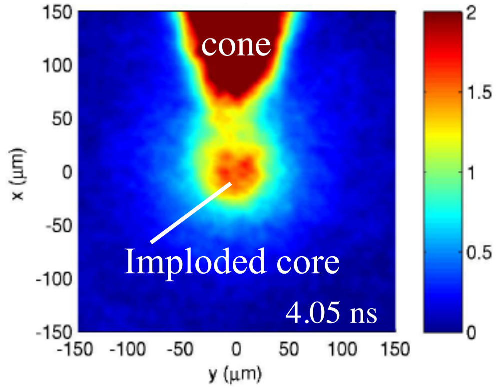
OV/4-2, Azechi

The U.S. fast ignition (FI) team has made significant progress on detailed FI physics study with new platforms at the Omega laser facility

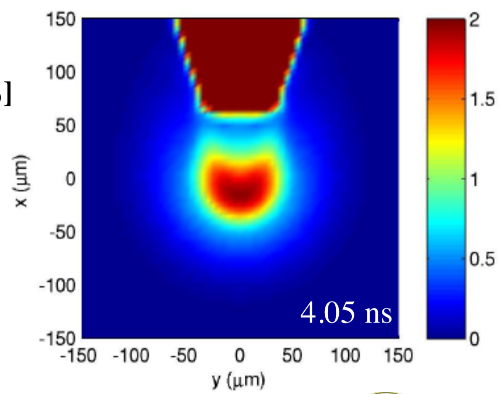
- **Measured highest density (*ρr~0.3g/cm²*) in FI cone-in-shell implosion, consistent with rad-hydro DRACO modeling results**
- **First-time imaging of energy flow into imploded cone-guided FI targets**

8 keV Radiography for fuel assembly (led by LLE)

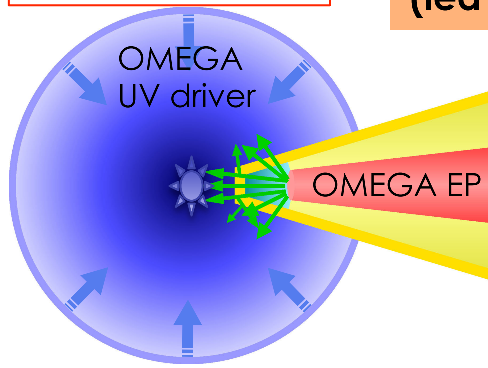
Experiment



DRACO/Spec3l simulation

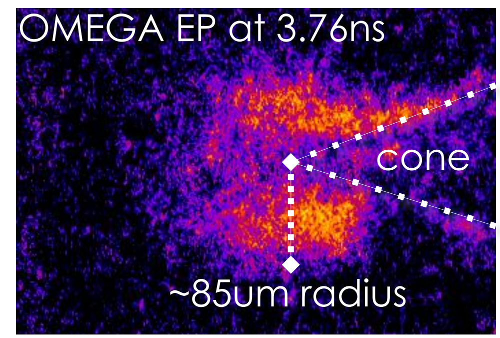


Cone guided FI

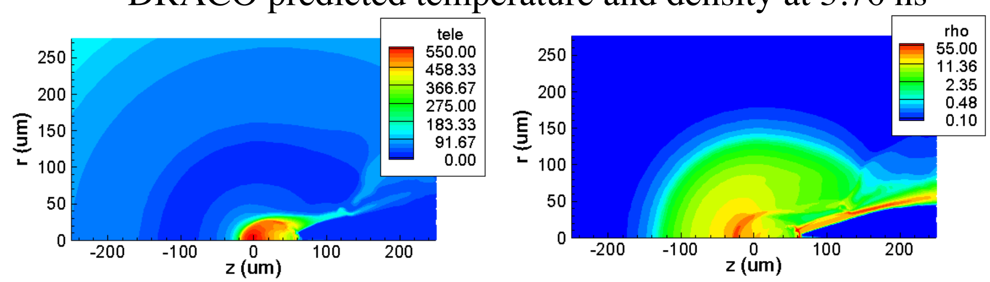


Imaging fast electron energy flow via fluorescence measurements (led by UCSD/GA)

Experiment: Cu Kα image



DRACO predicted temperature and density at 3.76 ns

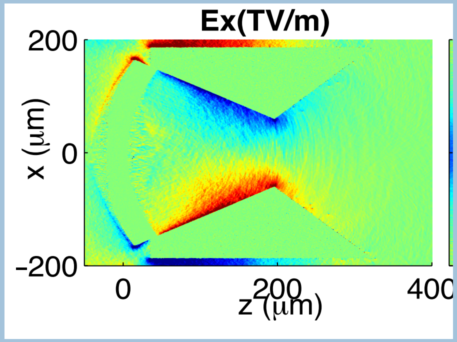


1. W. Theobald et al., Phys. Plasmas 18, 056305 (2011)
2. A.A. Solodov et al., AAC (2012)
3. F.N. Beg et al., SSAA symposium (2012)

Alternate Schemes for achieving ignition

Proton Fast Ignition

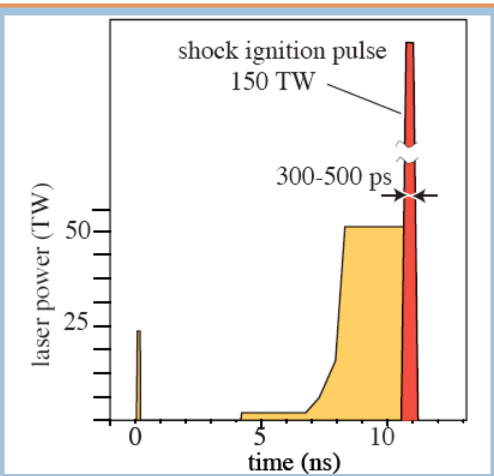
Proton Beam Focusing



IFE/P6-08, McGuffey

IFE/P6-07, Qiao

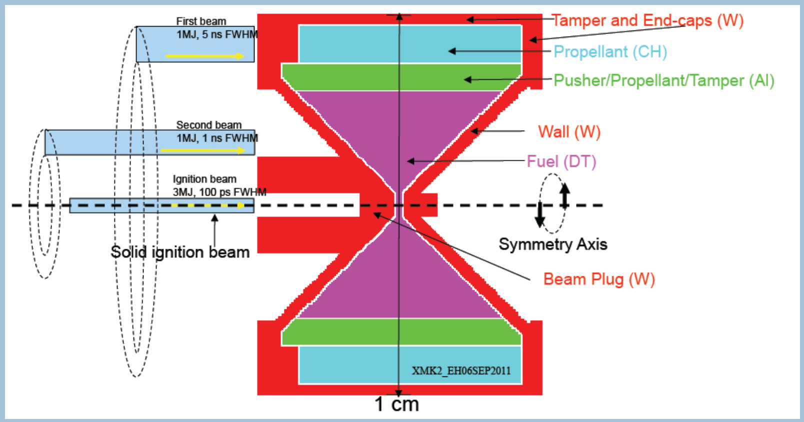
Shock Ignition



- Decouples direct drive compression from ignition, using same laser
- Physics to still be addressed before IFE target design

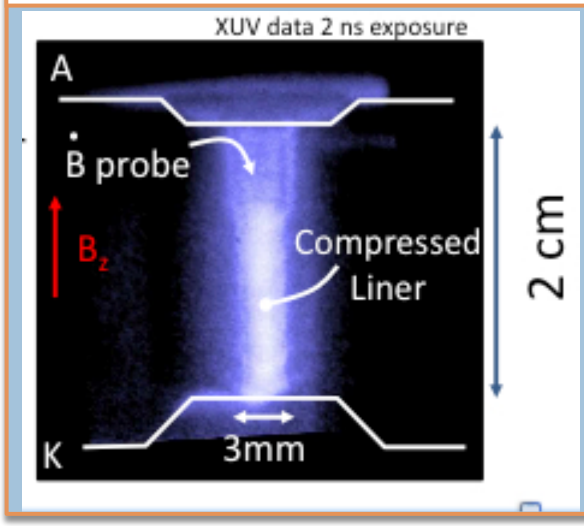
IFE/PD, Jacquemot

Heavy Ion "X"-Target



IFE/P6-16, Kwan

X-ray Pinch



- Axial Magnetic Field Compression Studies

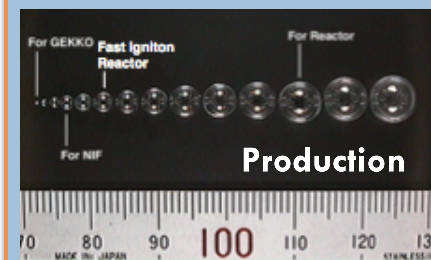
IFE/P6-17, Gourdain

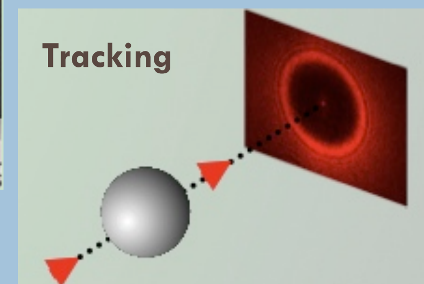
Advances in drivers and technology are crucial to IFE

Lasers

- **KrF (4ω)**
- **2ω, NIF**
- **DPSSL**
  -- high-rep, 10-J class HAMA
  D-D neutron generation
  (Mori, IFE/P6-13)

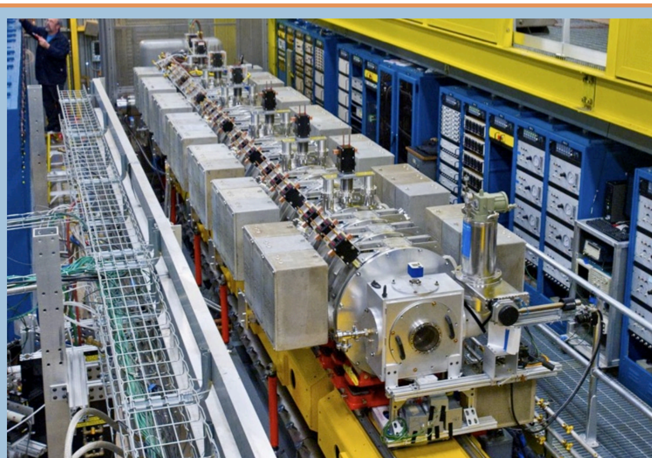
Target Fabrication, Injection, Tracking





OV/4-2, Azechi

Heavy Ion Beams



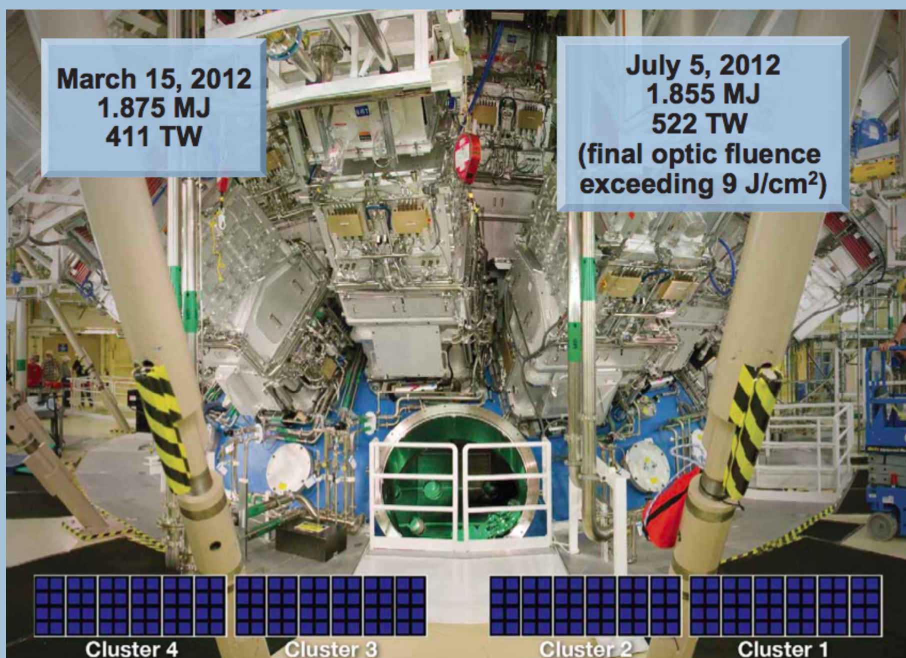
IFE/P6-16, Kwan

Reactor Chamber Protection

- Mitigate chamber damage due to ions, neutrons and cyclic stresses:
  -- liquid walls
  -- "materials on demand", designed at nanoscale with sufficient mechanical strength and radiation resistance
  -- improved rapid change-out techniques

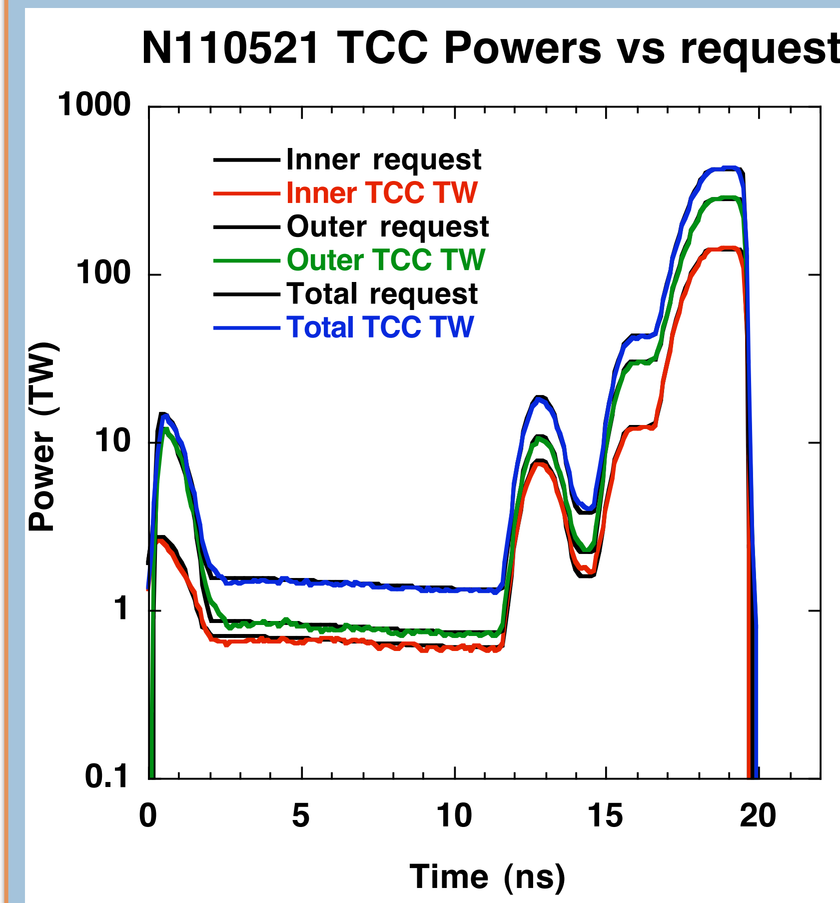
NIF, with its power/energy capability, and its precision, is truly a premier facility for future ignition physics studies

NIF surpassed its milestone of delivering 1.8 MJ of 3ω energy and 500 TW of power on target



OV/1-4, Moses

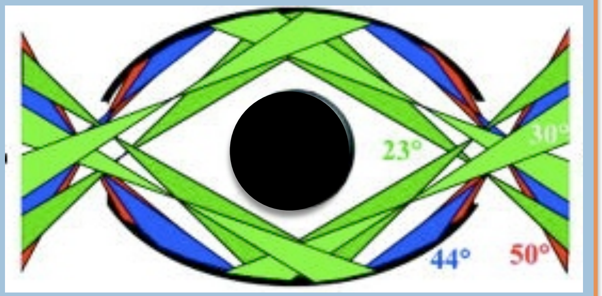
Precision at NIF enables exquisite tuning and reproducibility



Indirect Drive Laser Coupling: NIF plans to field a variety of targets to explore coupling improvements

Improve Inner Beam Propagation

- ***Reduces amount of required cross-beam energy transfer***
- **Change geometry:**
  -- *Rugby Hohlraum*: more headroom over capsule for same wall area



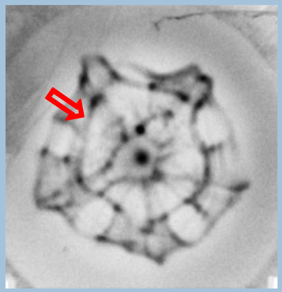
- **Change hohlraum fill:**
  -- *higher-Z fill* (gas, foam, …)
  to increase Te

Reduce SRS/hot electrons

- ***Stimulated Raman Scatter (SRS)***: laser scatters off self-generated electron plasma waves; hot electron production
- ***Stimulated Brillouin Scatter (SBS)***: laser scatters off self-generated ion acoustic waves
- ***Hard x-ray images of capsule***: no evidence of hot electron coupling
- ***SBS-only target:***
  -- fill composition
- ***Increase Te***

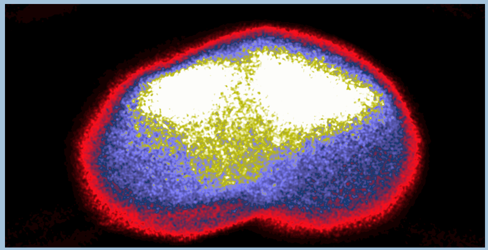
New diagnostics to research energy coupling

- ***Plasma characterization via Thomson scatter***
- ***Proton Deflectometry***



IFE/P6-10, Li

- ***Further characterization of crossed-beam energy transfer***

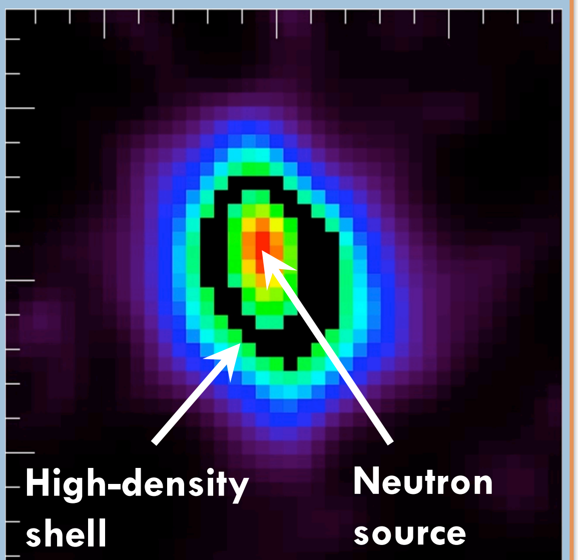


<u>Indirect Drive Symmetry</u>: NIF plans to field backlighter diagnostics

Neutron data suggests low mode asymmetry	Low Mode Asymmetry in Simulations	Present images capture hotspot self-emission only

Neutron data suggests low mode asymmetry

<u>Images of Neutron Source and high-density shell</u>

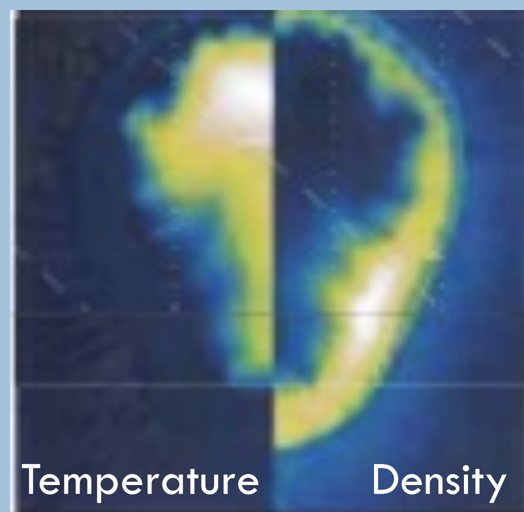


- Hohlraum Drive Asymmetry
- Ablator/Ice low modes

Frenje, IFE/1-1

Low Mode Asymmetry in Simulations

<u>Simulations: </u> 2% low mode asymmetry [P = (1,2,3)]

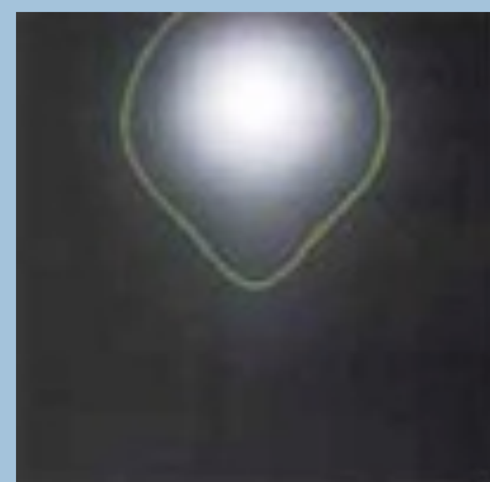


- Simulations begin to match observables

OV/1-4, Moses

Present images capture hotspot self-emission only

<u>Simulated X-Ray Image</u>



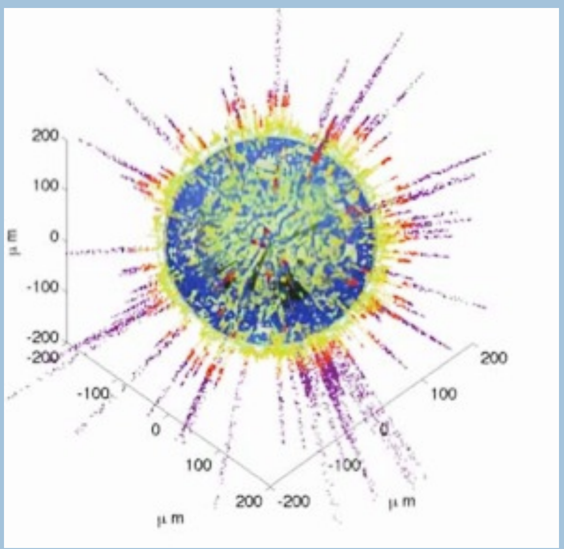
- Backlit experiments to measure cold fuel shape have begun

OV/1-4, Moses

Mix: NIF will explore lower convergence, higher stability implosions

Data: sharp performance boundary due to mix

High Mode Asymmetry: surface roughness, dust, …

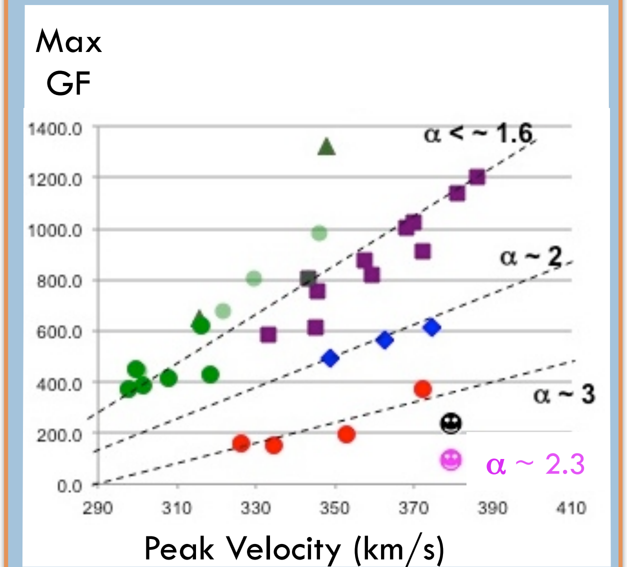


OV/1-4, Moses

- Mitigate by:
  -- "dust-less" capsules
  -- higher adiabat implosion

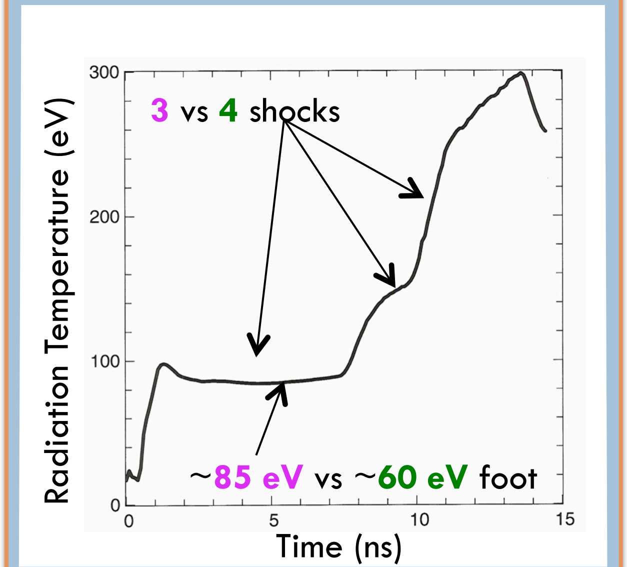
Higher Adiabat Implosions: less convergence, less growth

Max Growth Factor at Fuel-Ablator Interface at PV



NIF High Adiabat Design

Initial α=2.3 Design: Differs from Point Design



- Omega: higher YOC at high adiabat
- NIF: anticipate similar results

There has been significant progress in sculpting the building blocks for IFE

NIF Today

- Great Laser Performance
- Areal Density at 85% of requirement
- Yield and hotspot pressure low

Alternate Scenarios

- Direct Drive Improvements increase performance
- FI Coupling improvements
- Shock Ignition analyses

Technology

- Research and Improvements ongoing in:

  -- Drivers

  -- Targets

  -- Reactor Chambers

NIF Tomorrow

- Explore Coupling
- Diagnose Core Symmetry
- Test more stable, more 1D-like targets

IFE

- An optimized reactor will emerge from our scientific endeavors

THE END

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LIVERMORE, CA USA