Report from a Workshop on the Science of Fusion Ignition on NIF

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Workshop background

- NIF has acquired a wealth of exquisite data at conditions never before achieved in the laboratory
  - laser-plasma interactions at unique power densities and scale lengths
  - tailored high temperature thermal radiation environments
  - multi-terapascal shock propagation
  - greater than 10,000-fold compression, and near petapascal pressures
  - fusion neutron and charged particle production and transport at high temperatures and densities
- New phenomena have been observed
  - plasma mediated cross-beam power transfer,
  - suppression of Raman backscattering
  - non-LTE hohlraum kinetics
  - possible equation-of-state, opacity, kinetic, hydrodynamic, and nuclear anomalies

An international workshop was organized to discuss the science that has been learned in the National Ignition Campaign, identify new science questions that have arisen, and begin to lay the lines of experimental and theoretical inquiry that would build on and address these over a multi-year time frame

Goals

- Engage and expand the community of scientists interested in exploring science of ignition on NIF
- Form the basis for future efforts to explore underlying physics needed to understand ignition designs for a range of applications
- Identify paths leading to improved integrated design capabilities
- Maximize the utility of NIC results for broader ICF/IFE community

Charge to the Workshop

- Identify the key physics that underlies indirect drive inertial fusion ignition;
- Review and summarize our understanding of this key physics, including new insights and questions raised by recent experimental results;
  - Assess what we know and how well we know it including key areas of disagreement between data and models
- Propose research directions that would address continuing gaps in understanding key physics
  - Identify likely model deficiencies and approaches to improving the models
  - Identify possible experiments using HED facilities that could expedite further understanding
- Assess the likely impact of each of these modeling or experimental areas in furthering progress in understanding ignition science

Workshop Plan

- Attendance by invitation – ~100 divided roughly half National Lab ICF community, half broader community
  - to allow ~6 panels of ~12-15 each
- Plenary overview of NIC status and campaign results (half-day)
- Parallel breakout sessions focused on physical processes (1½ day)
- Plenary out briefs from breakout panels

Panel structure reflects elements of indirect drive ignition research

1. Laser propagation and X-ray generation
2. X-ray transport and ablation physics
3. Implosion hydrodynamics
4. Stagnation properties and burn
5. HED properties and processes: opacity, EOS, etc.
6. Integrated modeling

Organization

- Co-Chairs: Goldstein and Rosner
- Steering group: Collins, Edwards, Wan, Barnes, Herrmann, Sangster, Wootton, Betti, Correll
- Panel Leads:
  - Laser propagation and X-ray generation (Rosen, Joshi)
  - X-ray transport and ablation physics (Hammer, Meyerhofer)
  - Implosion hydrodynamics (Hurricane, Goncharov)
  - Stagnation properties and burn (Betti, Frenje)
  - HED Properties and processes (Collins, Wark)
  - Integrated modeling (Marinak, Lamb)

Participation statistics

- 158 registered
  - Laser propagation and X-ray generation - 23
  - X-ray transport and ablation physics - 16
  - Implosion hydrodynamics - 20
  - Stagnation properties and burn - 24
  - HED Materials cross-cut: opacity, EOS - 29
  - Integrated modeling - 16
- LLNL-47, LANL-20, SNL-12, LLE-14, Other-65
- 23 International scientists from 7 countries
- 47 Academics, including 16 international


Platform
Experimental
Control
Parameters

Lindl's ignition report card

- We are one year into the campaign to carry out precision optimization of ignition scale implosions

- We have achieved hohlraum temperatures in excess of the 300 eV ignition goal with hot spot symmetry and shock timing near ignition specs

- Slower rise to peak power and longer "no-coast" pulses result in lower hot spot adiabat and main fuel ρr at about 85% of the ignition goal

- Nuclear data indicates that long wavelength variation in the main fuel density may be contributing to performance degradation

- Mix performance boundary with more mass remaining than the point design will require thicker shells (+20-30%) to reach ignition velocity without mix

Kilkenny's measurement report card

Hohlraum Energetics

FABS31
on NIF

How are we doing?
— Good global measurements
— LEH radius(t)?
— n(r,t), T(r,t) ?

Implosion phase

<u>How are we doing?</u>
-Good global measurements
-Starting to see microscopic features of shell and fuel during the implosion- improve xray backlighting

Assembly, burn phase


<u>How are we doing?</u>
-Good global measurements
-Beginning to see DT distribution
-Beginning to measure mix

The workshop report has been issued

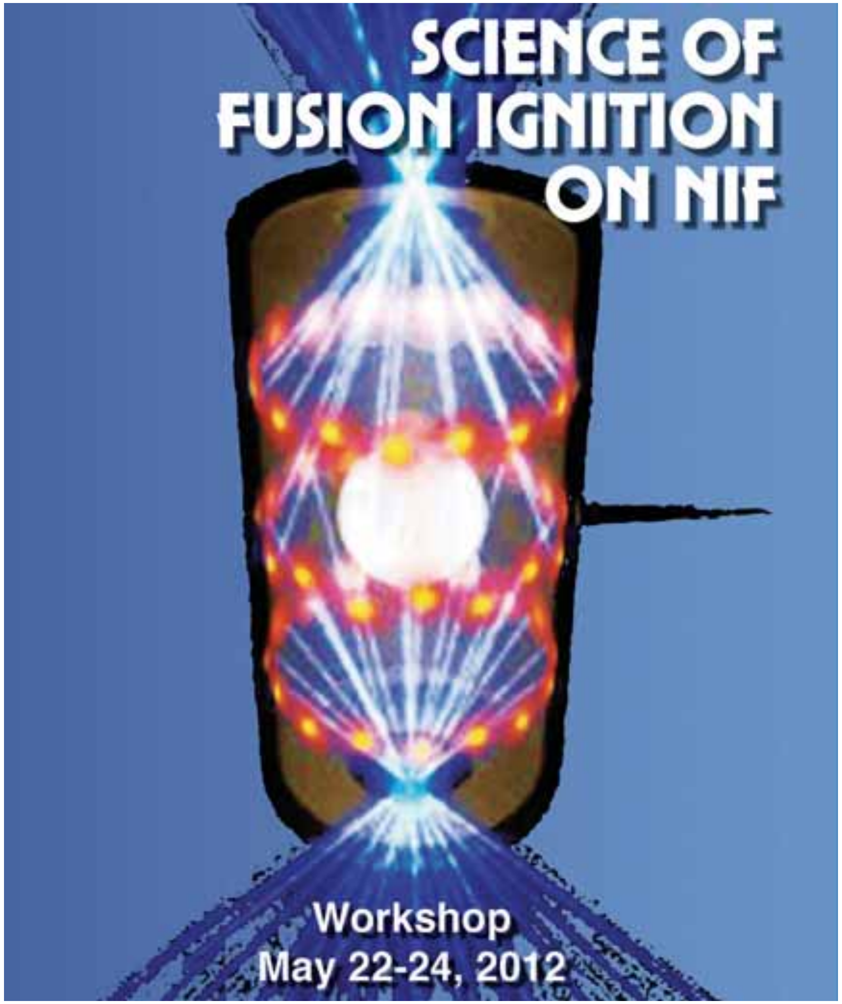


TABLE of CONTENTS

available for download at https://lasers.llnl.gov/workshops/science_of_ignition/

Panel	Priority Research Directions
1. Laser propagation and X-ray production	Hohlraum plasma characterization
	Electron plasma wave science
	Ion wave science
2. X-ray transport and ablation physics	Capsule x-ray drive
	Ablator hydrodynamics
	Ablator radiative coupling
3. Implosion hydro-dynamics	Investigation and control of ablator front instability
	Mix in extreme high-acceleration implosions driven by multiple strong shocks
	Hotspot formation and fuel shape physics
4. Stagnation and burn	The origin and 3D structure of ρR asymmetries
	In-flight characteristics of the DT fuel
	Probing energy balance at stagnation
5. HED Properties and Processes	Equations of state for ultra-dense matter and conduction dominated “gas shocks”
	LTE and non-LTE opacity research for ignition
	Develop an understanding of transport and kinetic phenomena in ignition
	Nuclear science for ignition
6. Integrated modeling	A science-based validation campaign
	Improved modeling of hohlraum energetics
	Kinetic effects on thermonuclear yield

Panel 1: Laser Propagation and X-ray Production

- Observations:
  - hohlraum plasma cooler than expected;
  - x-ray flux that matches measured implosion velocities doesn't agree with x-ray flux measurements (Dante)
  - LPI effects not included in model may contribute to low yields
- Physics: LPI, non-LTE kinetics
- Research Directions: measure hohlraum plasma conditions; validate high-flux model; try a hotter hohlraum

Panel 2: X-ray Transport and Ablation Physics

- directions identified by this panel were driven primarily by the discrepancy between the measured implosion velocities and simulations based on the x-ray drive measured by the Dante diagnostic.
  - either the measured drive is not that "seen" by the capsule, or the ablation process is not being accurately modeled
- Experiments recommended to resolve this

Panel 3: Implosion Hydrodynamics

- Observations: the pressure drive, onset of mix, and the stagnation pressure are currently not adequately modeled
- Physics: growth rate of ablation front instabilities, thermal conductivity, and parameterization of mix and its dependence on initial conditions
- Research Directions: take apart the physics of the ablation front instability; experimentally study scaling of hot-spot mix and develop improved sub-grid models

Panel 4: Stagnation and Burn

- Observation: even when implosion modeling is tuned to reproduce shock timing and implosion velocity measurements, the observed stagnation pressure of the hotspot and cold fuel are significantly lower than predicted, resulting in low yields.
  - most likely 3D in nature and associated with an incomplete conversion of the kinetic energy of fuel shell into compression of the hotspot.
  - Low-mode ρR asymmetries can reduce the pressure at stagnation and also increase the onset of hotspot mix.
- Physics: origin and growth of 3D structure
- Research Directions: develop radiography and spectroscopy to better probe energy balance and density distribution in the hotspot and fuel at stagnation

Panel 5: HED Properties and Processes

- Observation: While many processes are represented in the simulations, they have generally not been experimentally tested over the range of conditions attained in ignition experiments.
- Physics: EOS, opacity, non-LTE kinetics, strong shock and release states, transport, nuclear cross sections
- Research Directions: concerted experimental benchmarking and theoretical development.

Panel 6: Integrated Modeling

- Observations: current simulation capability has been extensively tested against experiments at Shiva, Nova and OMEGA, but recent experiments have clearly called into question the ability of the codes to predict important observables under NIF conditions
  - Need for drive multipliers
  - Hotspot pressure deficiency
  - Neutron yields
- Physics: EOS and opacity models, non-LTE, non-Local transport, non-Maxwellian distributions, barodiffusion
- Research Directions: systematic code validation; benchmark hohlraum energetics model; kinetic and field effects on yield

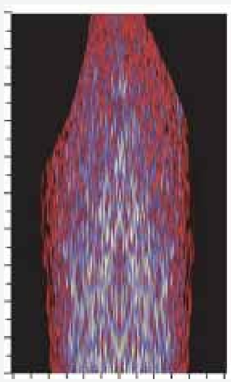
Examples of workshop research directions currently underway

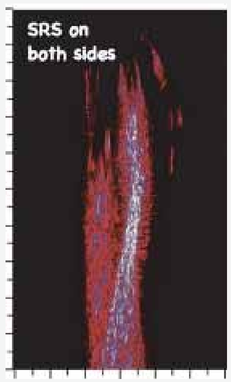
- Improve NLTE and kinetic descriptions towards a better calculation of LPI (1)
- Measure x-ray flux at the capsule (2)
- Alternate ablator experiments (3)
- Perform implosions at higher adiabat (3)
- 2D radiography of cold-fuel ρR variations (4)
- Validate DT, CH (and other ablator) eos (5)

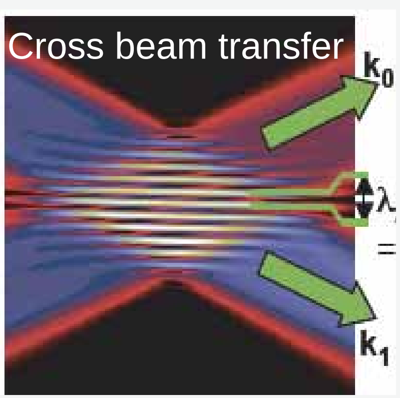
Improve NLTE and kinetic descriptions towards a better calculation of LPI

LPI model improvement

pF3D light transmitted | **pF3D SRS reflected**

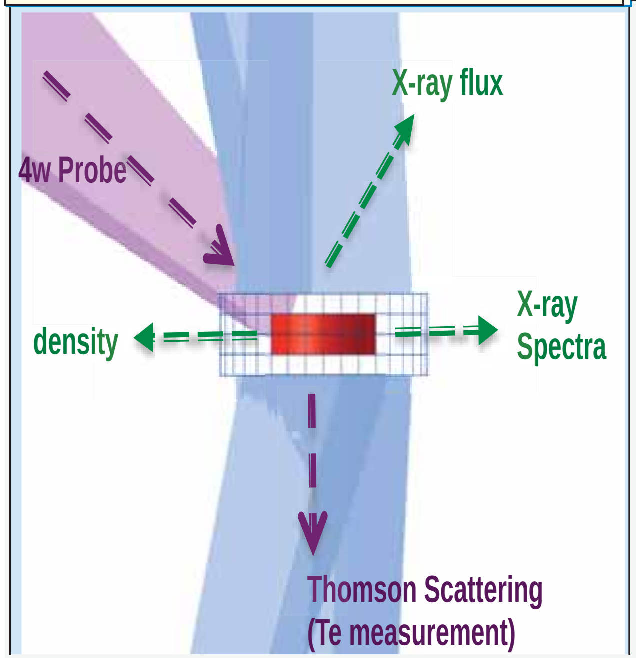






Combining Opacity and Thomson scattering of Au provides benchmarking opacity and transport data

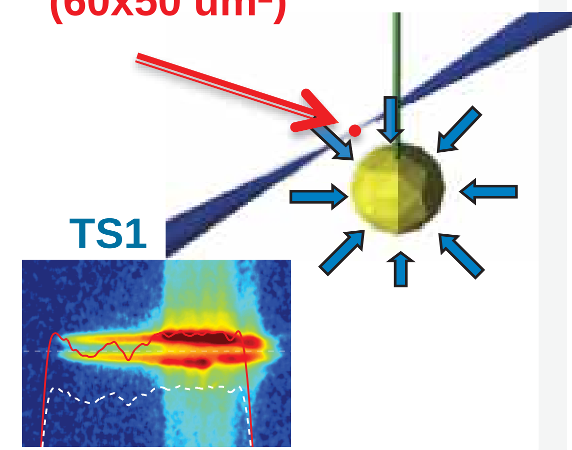
Au opacity, 10^{21}/cc, 2KeV



Omega shots Planed for 4th quarter

TS and Emissivity of Au ball

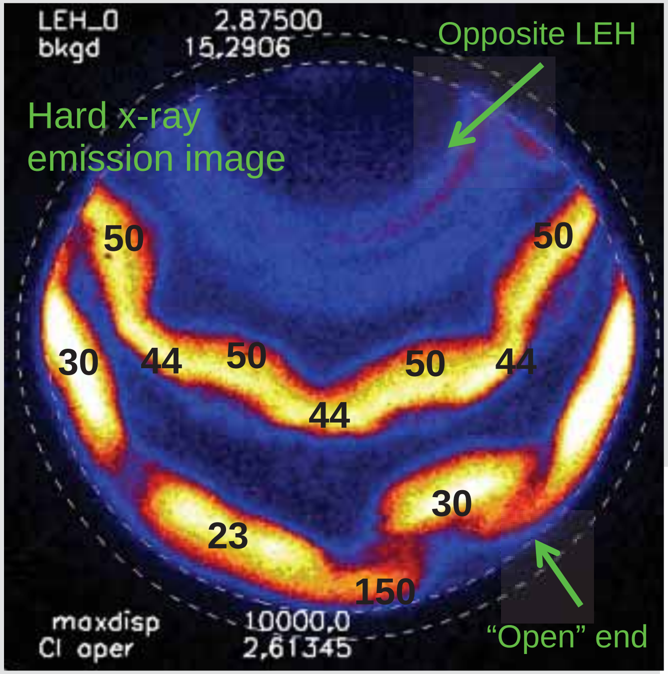
Thomson volume ($60x50\ um^2$)



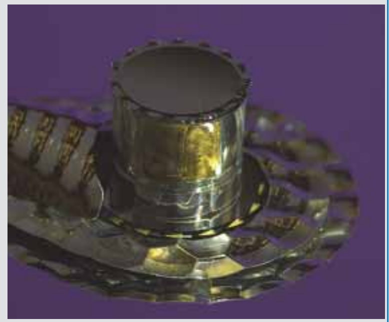
Omega shots last month
NIF shots next year

Two classes of NIF experiments were fielded to isolate the performance of the ignition hohlraum

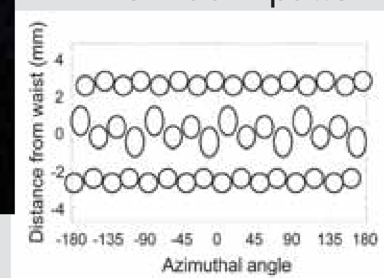
Viewfactor: Aug. 2012



Removes one LEH from hohlraum



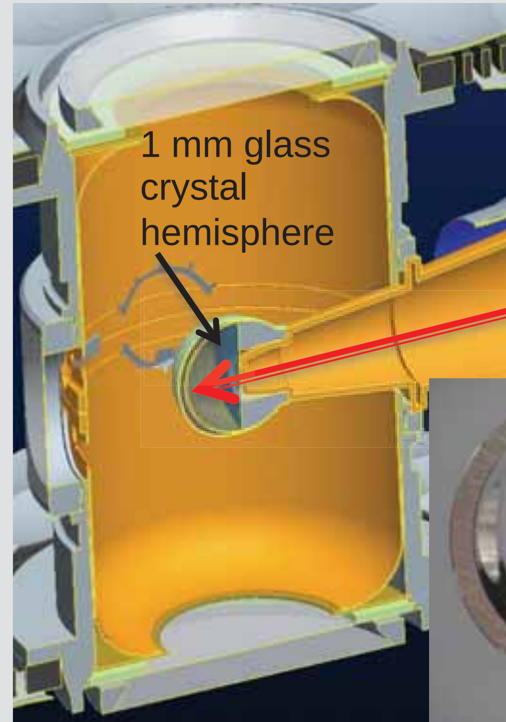
Hohlraum pattern



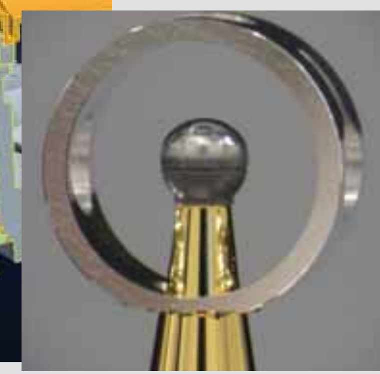
Measures the x-ray emission from the hohlraum as seen by the ignition capsule (is 15% low)

First direct measure of the "cross-beam" transfer used to tune implosion symmetry

Crystal Ball: Aug. 2012



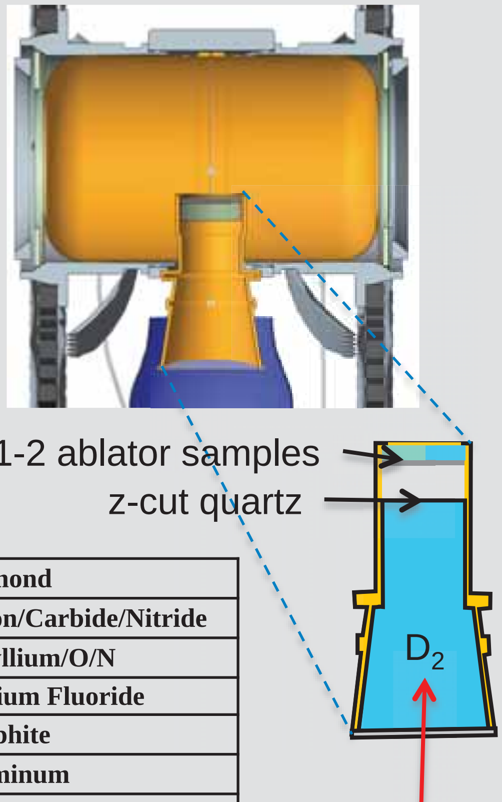
VISAR measures shock speed



Measures hohlraum-capsule energy coupling through the entire ignition laser pulse

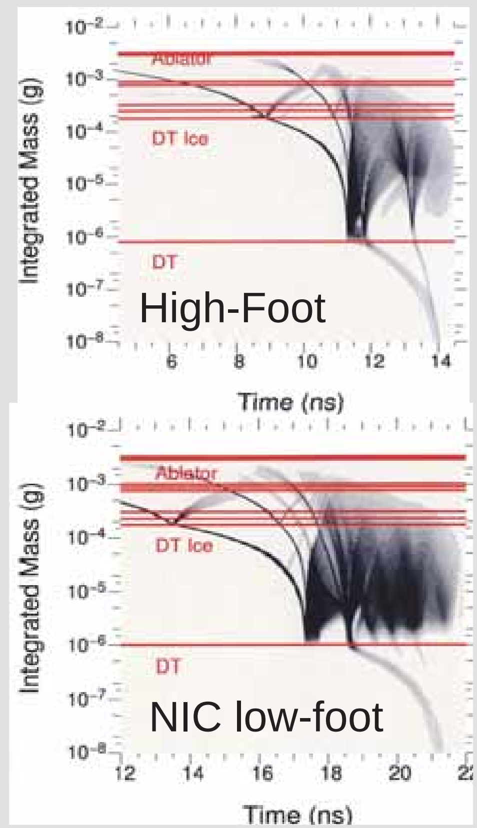
New platforms have been developed to explore alternate ablators, pulse-shapes, and instabilities

Planar Ablator

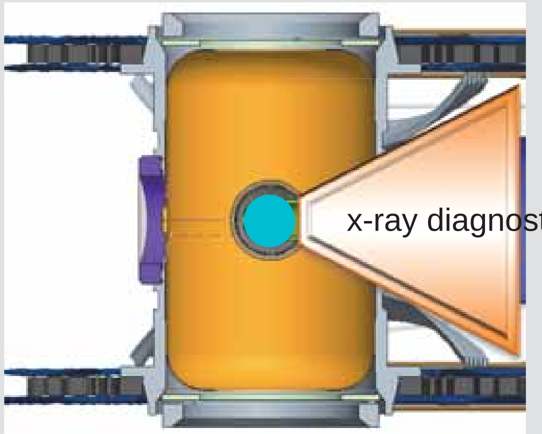


Diamond
Boron/Carbide/Nitride
Beryllium/O/N
Lithium Fluoride
Graphite
Aluminum
Plastics

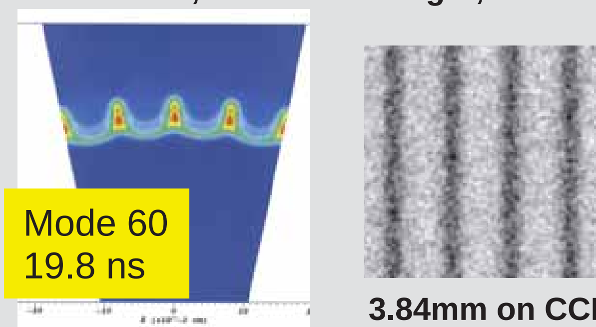
High-Foot: 3-shock, higher adiabat implosion



Richtmyer-Meshkov & Rayleigh-Taylor instability growth

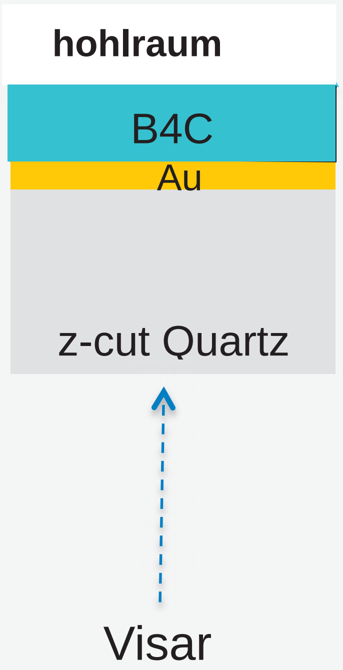
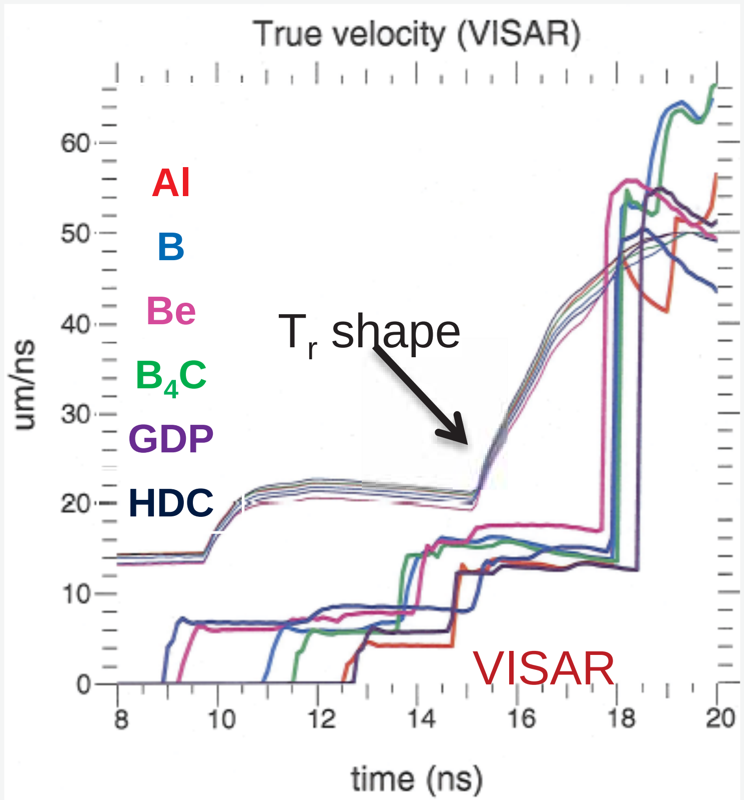
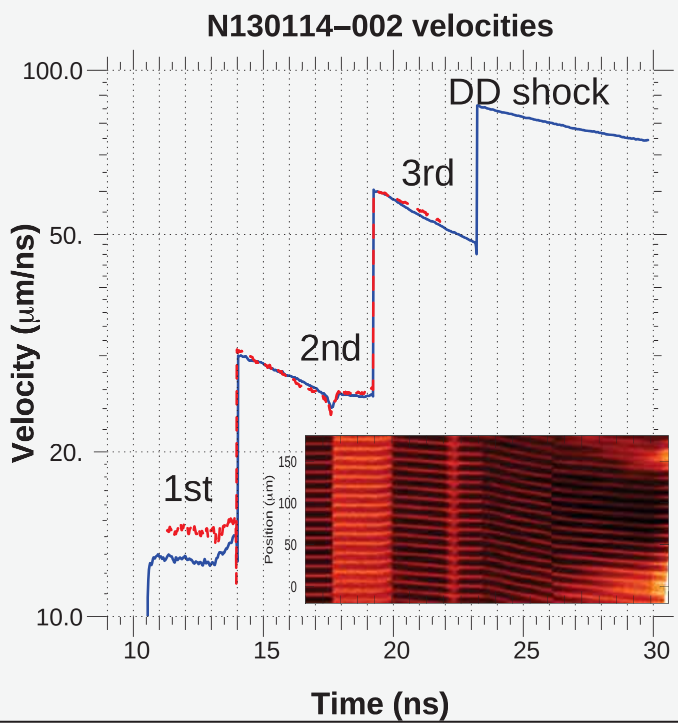


L=60, 80um wavelength, a0=3um

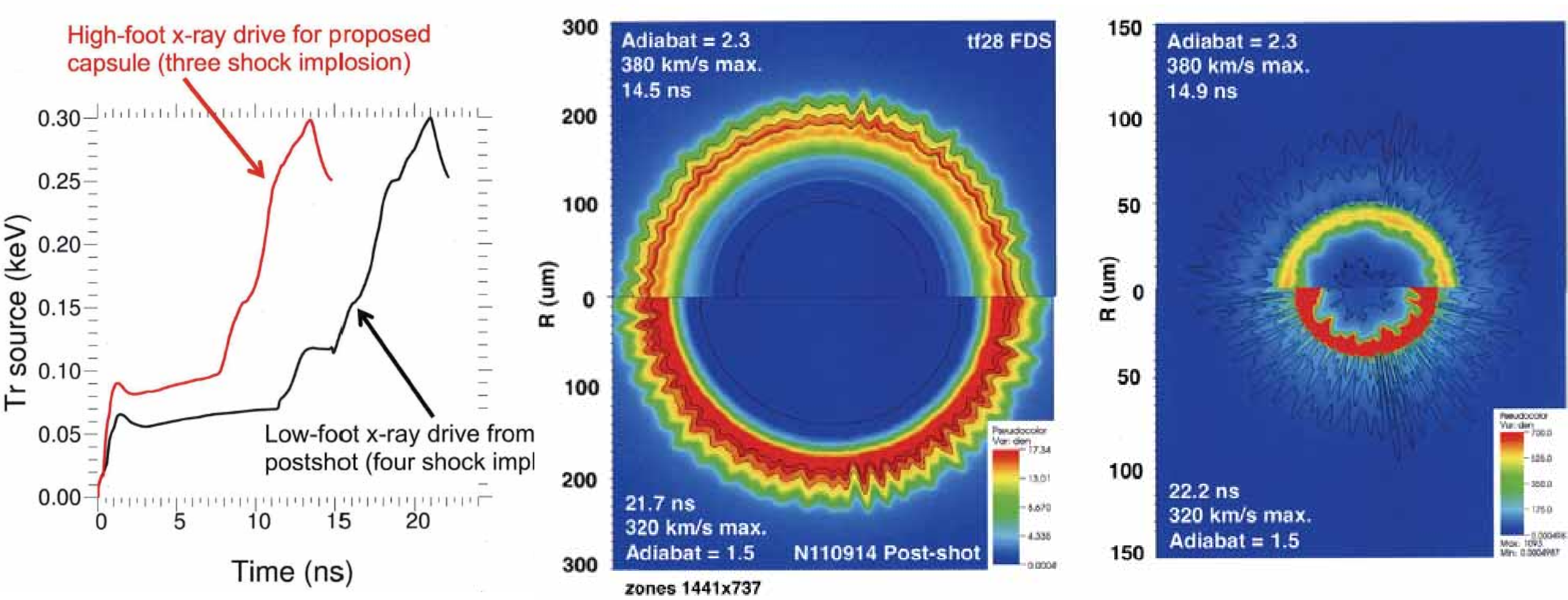


Growth from optical depth

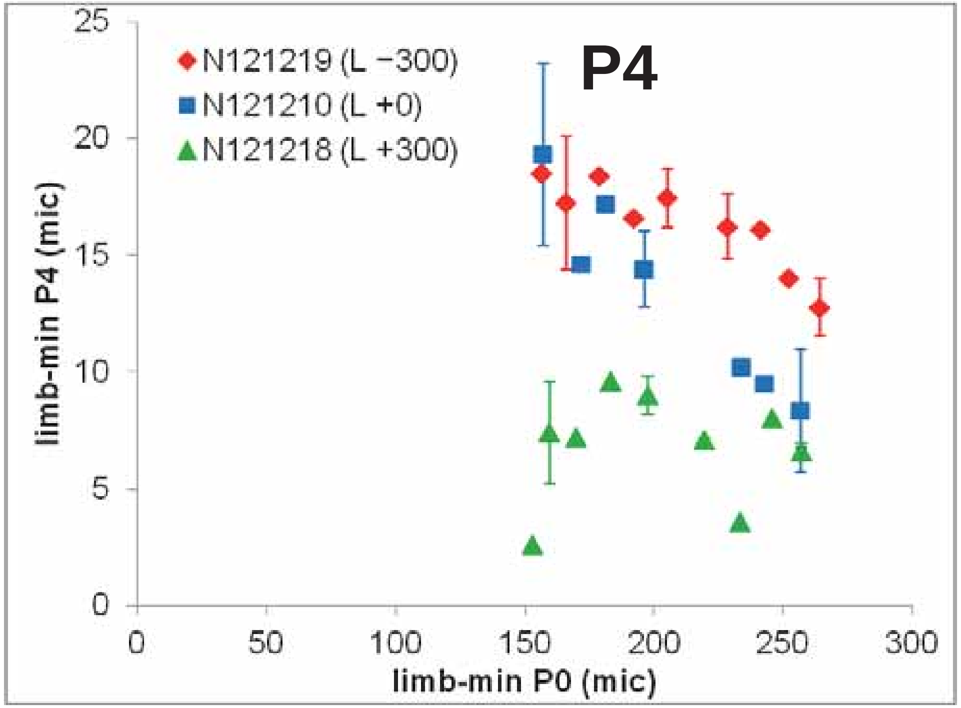
The first "Planar ablator" to evaluate the performance of several ablators with an ignition-like pulse

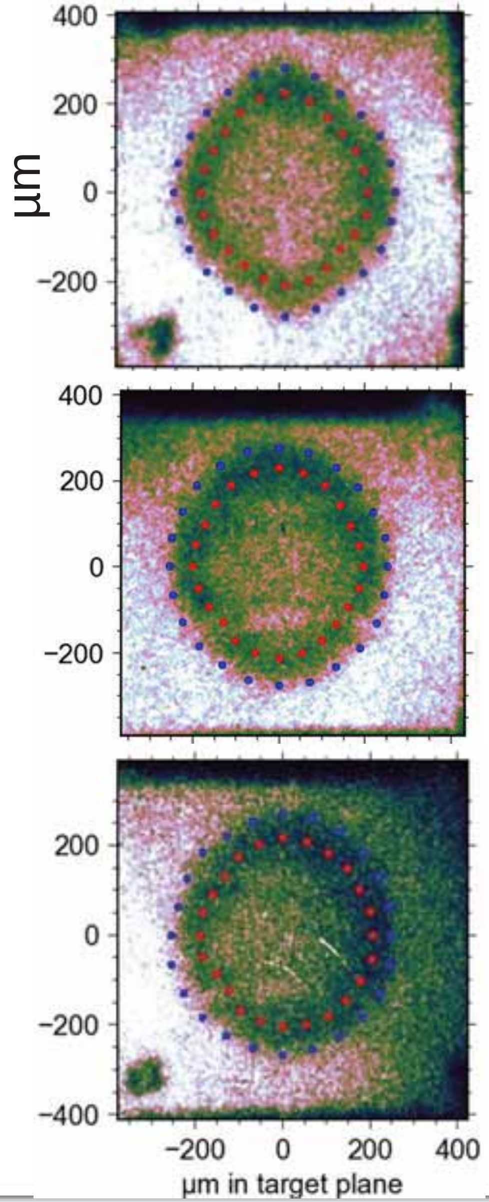
Target	High-foot like pulse shape 420TW Peak Power simulations for several ablators	First experiment was on B4C ablators and is being used to test simulations
		

The high-foot platform manipulates the pulse shape to create a more forgiving implosion



New technique to measure shell uniforminty is being used to improve hotspot conditions





N121219
Short

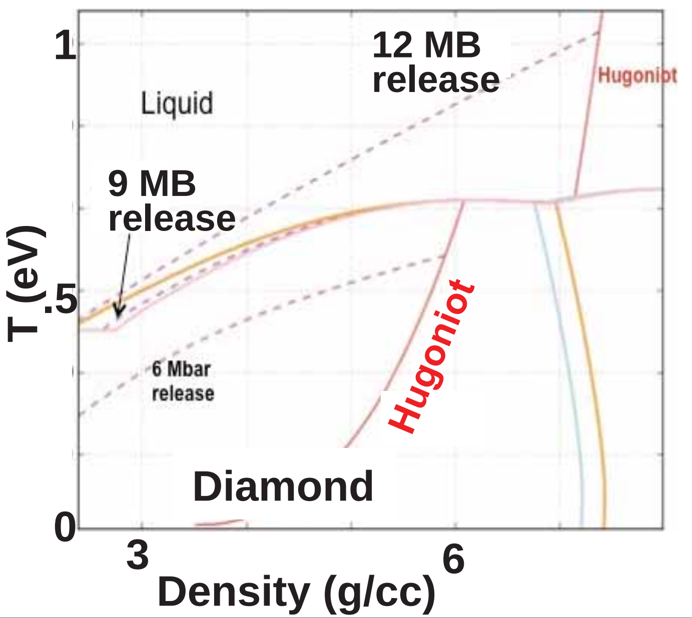
N121210
nominal

N121218
Long

Here we show hohlraum length scan effect on shell shape

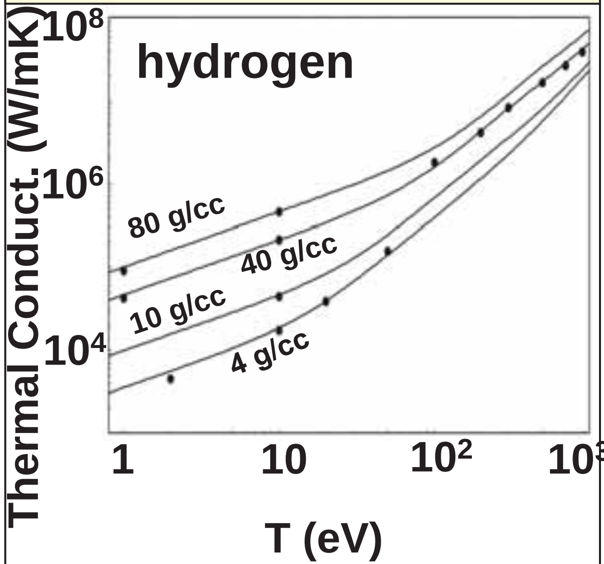
Basic physics models for NIF-EOS, transport, and opacity are being improved

EOS development DT, CH and alternative ablators



- New QMD/Purgatorio-based diamond EOS
- First B4C EOS is being developed
- QMD-based Be EOS is ready for use.

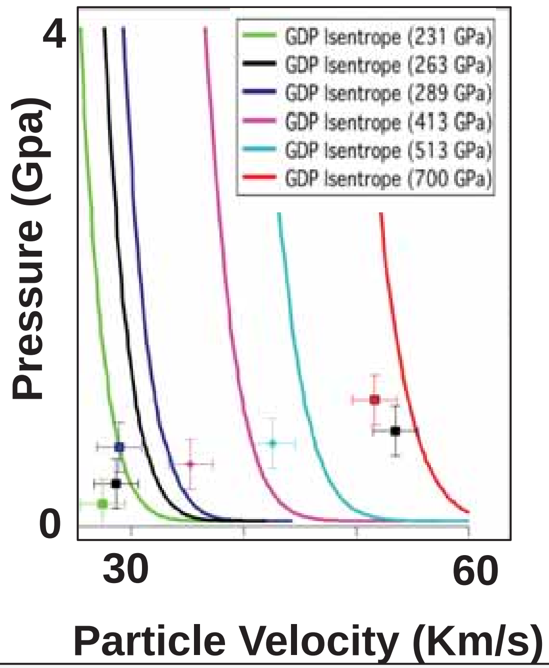
Thermal conductivity improvement



Quantum-MD for thermal conductivities

Enables intelagent variation of conductivities for sensitivity study

New technique and data for measureing release of CH,DT



Current EOS overestimates CH release into ~0.6 mg/cc methane

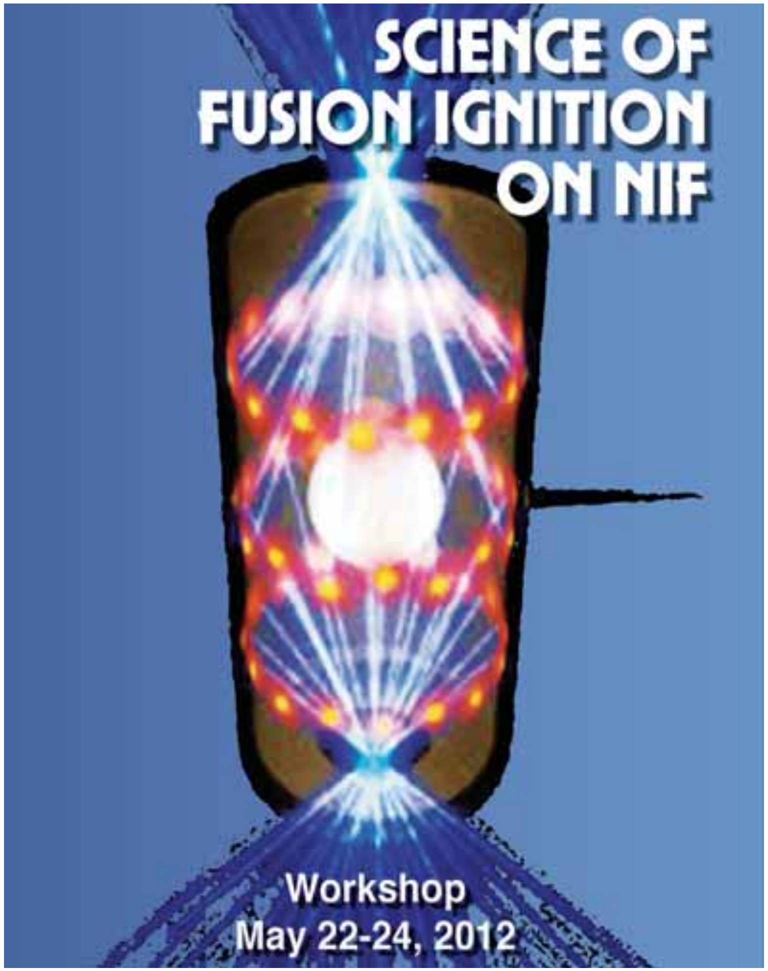
DT and CH Hugoniot experiments on NIF are planed for 3rd quarter

First EOS data on alternate ablators at Omega in 2 months

Additional workshop outcomes

- The results of the world's first ignition experiments were vigorously discussed among ~150 scientists
- Status of the ignition program was disseminated -and open to challenge - in a recognized and recognizable scientific forum, akin to Office of Science "research needs workshops"
- A broad community was invited to contribute their insight and participation

UK EPSRC* has issued a call for "physics of NIF ignition" based on the 2012 Ignition Science Workshop



Energy

The Physics of Ignition: Collaboration with the National Ignition Facility

Background

Since completion of the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in 2009, an experimental, computational, and theoretical effort to demonstrate fusion ignition at NIF has been underway. Having made significant progress towards the demonstration of ignition since then there are still a number of physics challenges to be overcome before ignition is likely to be demonstrated. A May 2012 workshop examining these challenges identified a number of opportunities for scientific research in support of the ignition effort. The workshop report is available at: https://lasers.llnl.gov/workshops/science_of_ignition/.

Research grant applications wanted

In order to take advantage of these scientific opportunities the EPSRC is making available £2 million to fund collaborative projects with NIF to help achieve the goal of ignition. Funds will be made available to allow researchers based in the UK to join existing teams at NIF and help solve some the physics challenges related to achieving ignition. Shots on the NIF laser are not being specifically allocated for this call.

Applications should be focussed on the topics outlined in the workshop report, including the following:

- Hohlraum physics, including laser plasma interactions, magnetic field generation and electron transport;
- X-ray generation, including opacity, non-LTE effects and radiation transport;
- Implosion physics including implosion symmetry, hydrodynamic instabilities and associated phenomena;
- Stagnation and hot spot formation, including thermonuclear burn, magnetic field generation and electron transport, multispecies plasmas, hydrodynamic instability, and kinetic effects;
- Materials properties of ignition targets including equation of state, opacity, non-LTE effects, and thermal transport;
- X-ray, gamma ray and nuclear particle transport and emissions.

Applicants will be expected to send a one page outline to EPSRC no later than 16:00 on **Wednesday 02 January 2013**.

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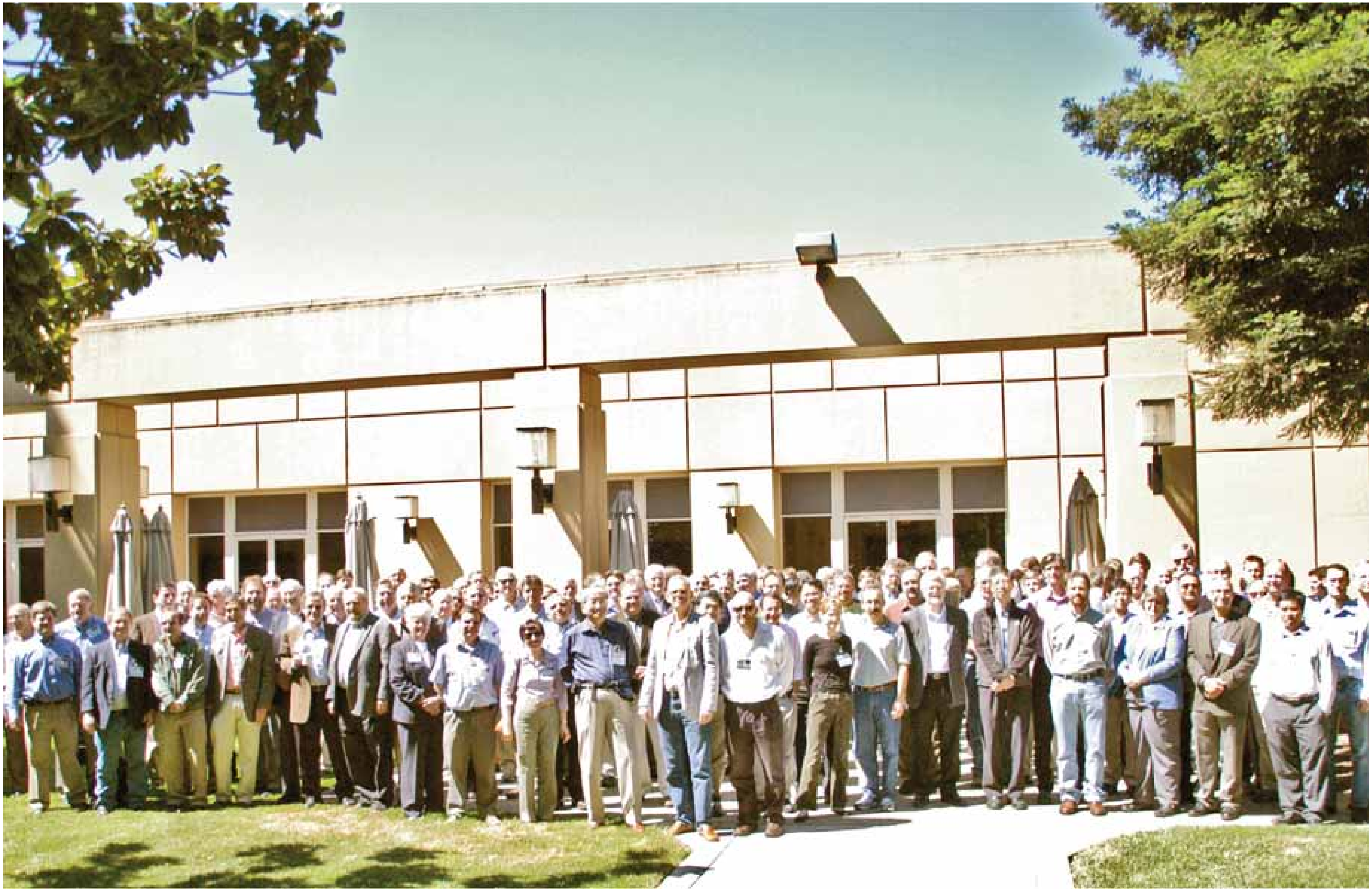
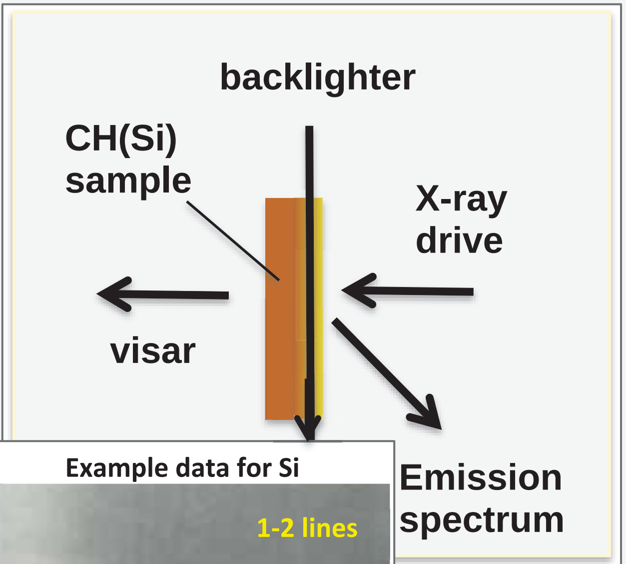
*Engineering and Physical Sciences Research Council

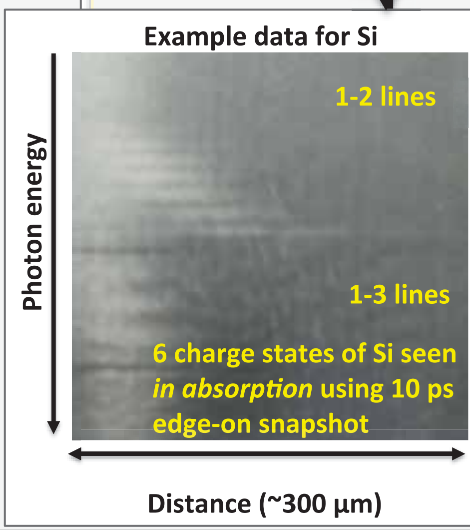


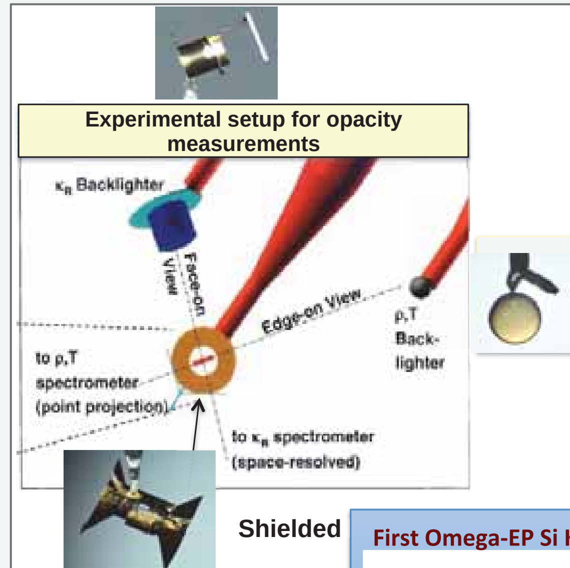
Old slides to follow

Upcoming ablation experiments at Omega will measure micro-physics of ablation to test physics models

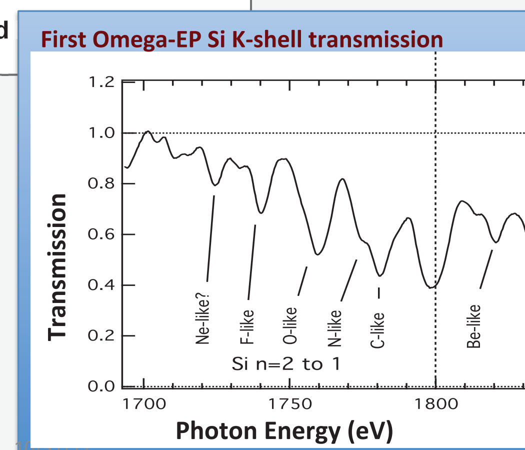
Ablation dynamics experiment designed to determine physical states at and between the ablation front and drive source at given Tr







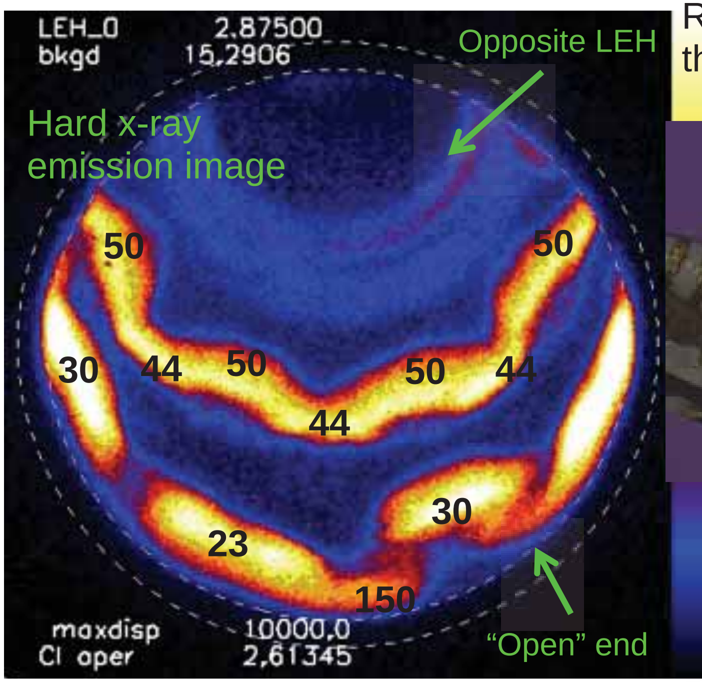
Ablator opacity experiment designgted to determine radiation transmission and emission at a given set of physical states



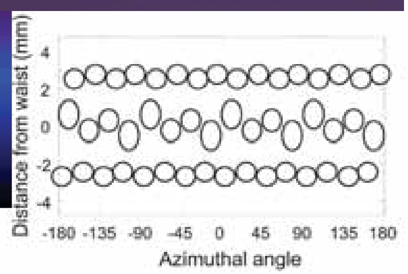
Simulated & experimental drive pressures disagree, in particular when shock or release waves interact with the ablation front

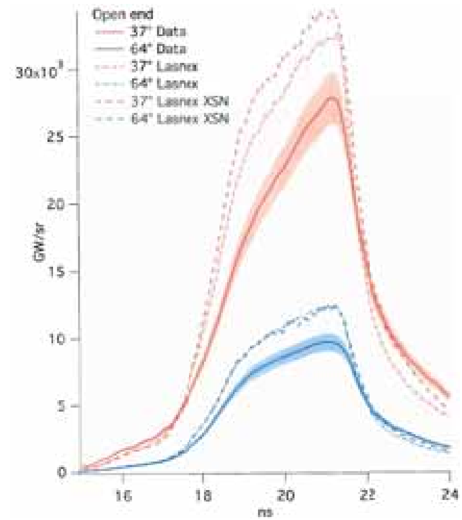
Viewfactor experiments in August indicated that the capsule "sees" less x-ray energy than predicted

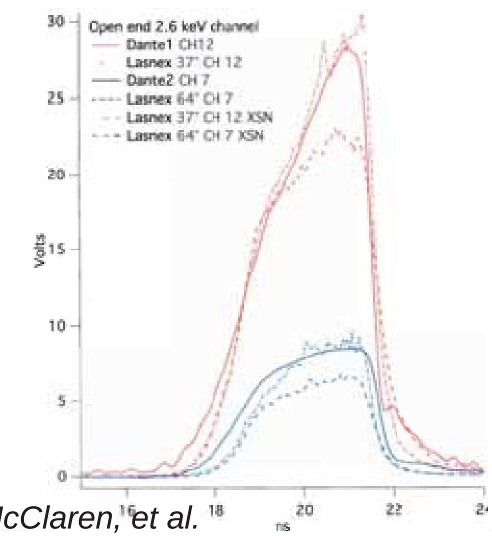
Viewfactor: Aug. 2012



Removes one LEH from the ignition hohlraum



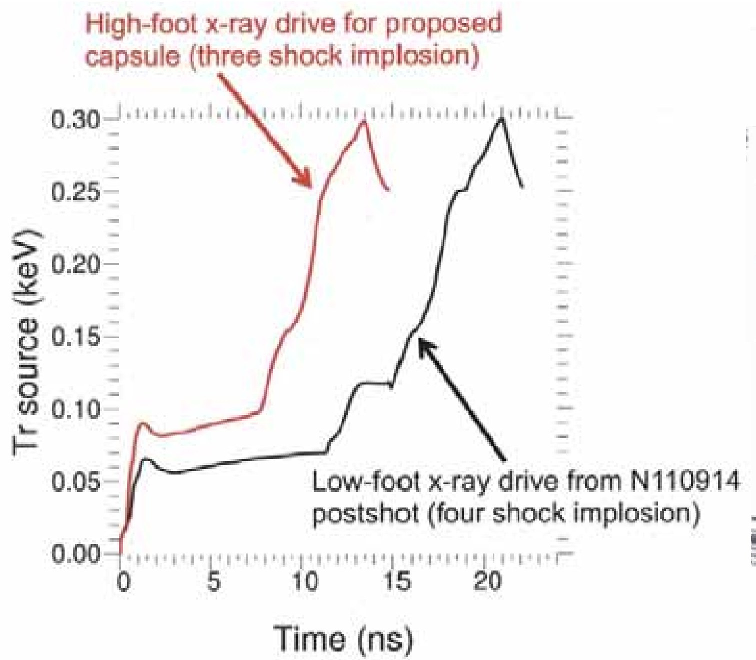




- Measures the x-ray emission from the hohlraum as seen by the ignition capsule (is 15% low)
- First direct measure of the "cross-beam" transfer used to tune implosion symmetry

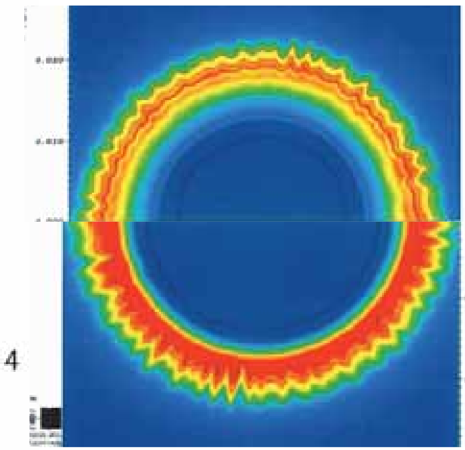
Jim Hammer, Omar Hurricane, Steve McClaren, et al.

New “high-adiabat” platform is designed to deliver more 1D, lower convergence implosion



Simulated at ~ 200μm

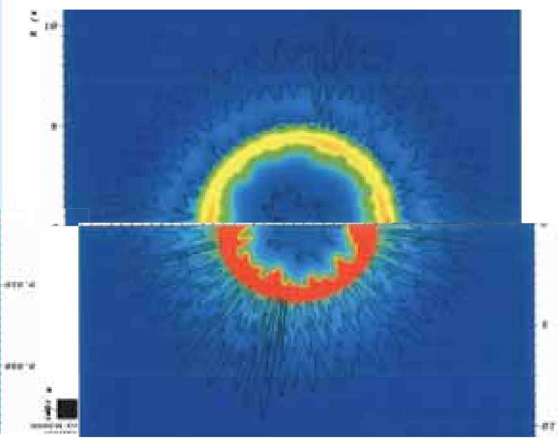
α~2.3, 380 km/s 14.5 ns



α~1.5, 320 km/s 21.7 ns

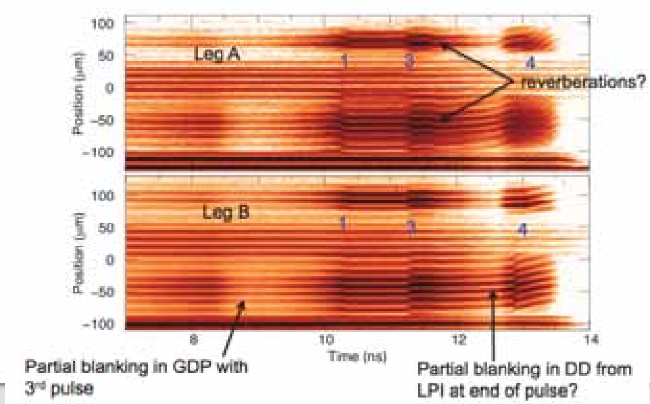
Simulated at min. radius (~50 & 30μm respectively)

α~2.3, 380 km/s 14.9 ns



α~1.5, 320 km/s 22.2 ns

- 3 shock design, no shock #2



N121023: 1st high-foot keyhole exhibited the best pole-waist symmetry ever

Omar Hurricane