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A journey from nuclear criticality methods to high energy density radflow experiments

Presentation to the Department of Nuclear Engineering
North Carolina State University

Dr. Todd Urbatsch, XTD-IDA
PL, Science Campaign 4.3 Radflow

November 10, 2016

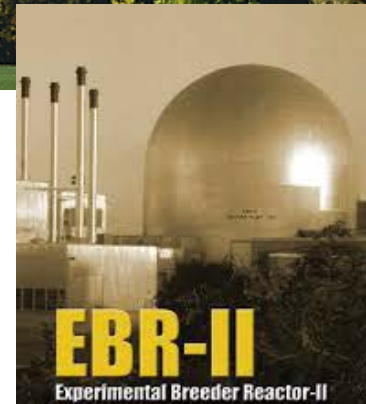


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What you're in store for...

- **I will share with you with some of my experiences,**
 - Iowa farm
 - Iowa State University Nuclear Engineering
 - EBR-II at Argonne-West
 - Monte Carlo Criticality Methods at the University of Michigan
- **my many years at Los Alamos,**
 - a little about New Mexico, Los Alamos, LANL, and the XTD-IDA group
 - Implicit Monte Carlo thermal radiation transport, the Jayenne Project
- **my current Los Alamos life with the Radflow science campaign,**
 - opacity experiments
 - hohlraum design
 - radflow experiments and diagnostics
- **and LANL employment opportunities**

From the Iowa farm to a land grant university to Idaho



Criticality acceleration methods at Michigan



ITERATIVE ACCELERATION METHODS FOR MONTE CARLO AND DETERMINISTIC CRITICALITY CALCULATIONS

by
Todd James Urbatsch

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Nuclear Engineering and Scientific Computation)
in The University of Michigan
1995

Doctoral Committee:

Professor E. W. Larsen, Chairperson
Professor W. R. Martin
Professor J. C. Lee
Professor T. I. Gombosi

$$\mathbf{T}\psi = \mathbf{S}\psi + \frac{1}{k}\chi\mathbf{F}\psi \quad (1.1)$$

where

$$\mathbf{T}\psi = \Omega \cdot \nabla \psi(\mathbf{r}, E, \Omega) + \sigma_t(\mathbf{r}, E)\psi(\mathbf{r}, E, \Omega), \quad (1.2)$$

$$\mathbf{S}\psi = \int \int \sigma_s(\mathbf{r}, \Omega' \cdot \Omega, E' \rightarrow E)\psi(\mathbf{r}, E', \Omega') d\Omega' dE', \quad (1.3)$$

$$\mathbf{F}\psi = \int \int \nu \sigma_f(\mathbf{r}, E')\psi(\mathbf{r}, E', \Omega') d\Omega' dE'. \quad (1.4)$$

We manipulate the transport equation, Equation 1.1, as follows,

$$(\mathbf{T} - \mathbf{S})\psi = \frac{1}{k}\chi\mathbf{F}\psi \quad (1.5)$$

$$\psi = \frac{1}{k}(\mathbf{T} - \mathbf{S})^{-1}\chi\mathbf{F}\psi, \quad (1.6)$$

and operate on both sides by the fission operator, Equation 1.4,

$$\mathbf{F}\psi = \frac{1}{k}\mathbf{F}(\mathbf{T} - \mathbf{S})^{-1}\chi\mathbf{F}\psi, \quad (1.7)$$

obtaining an analytic integral transport equation for the fission source

$$f = \frac{1}{k}\mathbf{L}f, \quad (1.8)$$

where

$$f = f(\mathbf{r}) = \mathbf{F}\psi = \text{fission source}, \quad (1.9)$$

$$\mathbf{L} = \mathbf{F}(\mathbf{T} - \mathbf{S})^{-1}\chi = \text{fission matrix}. \quad (1.10)$$

A Wolfpack interlude



Methods to accelerate MC eigenfunction convergence

- Fission Matrix Acceleration Method
- Fission Diffusion Synthetic Acceleration
- Hybrid MC-Eddington factor method

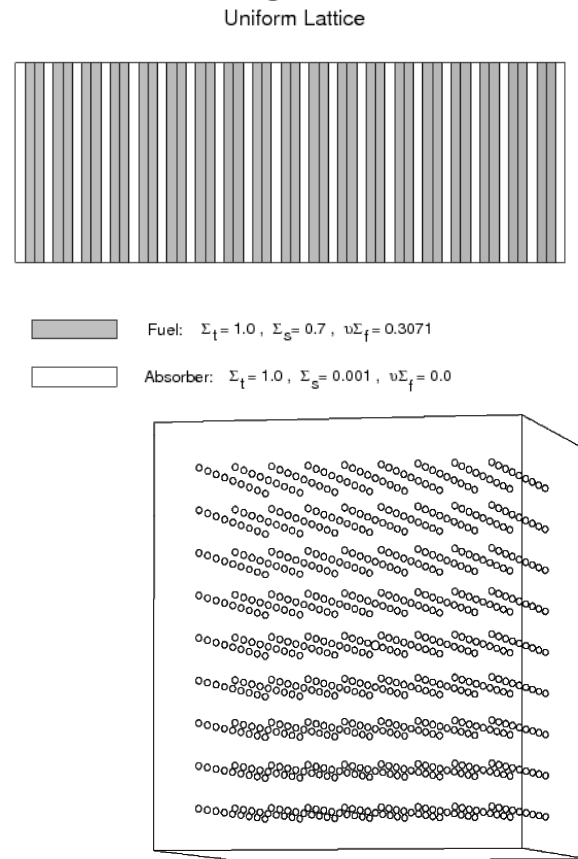


Figure 6.17: Three-dimensional rendering of the “ k_{eff} of the world” problem without the inner water reflector surface by Sabrina. The larger critical sphere is located in the center.

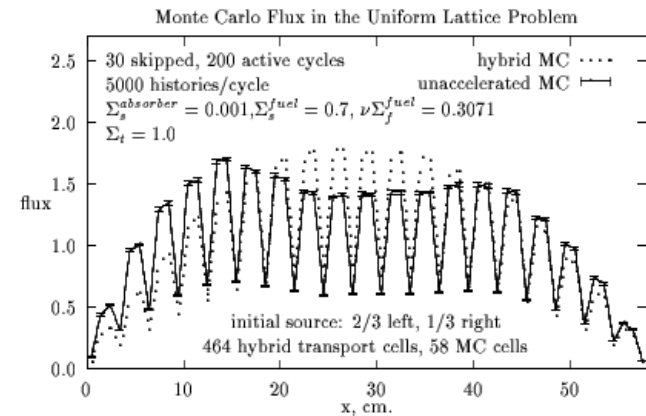


Figure 8.2: Collision flux estimate after 230 total cycles for unaccelerated Monte Carlo and hybrid Monte Carlo in the uniform lattice test problem.

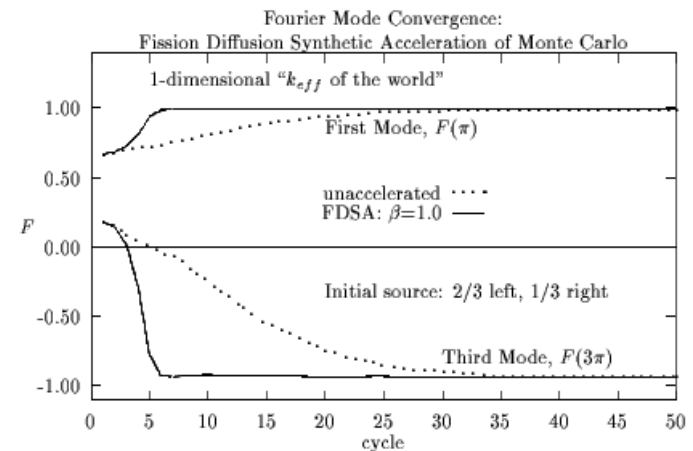
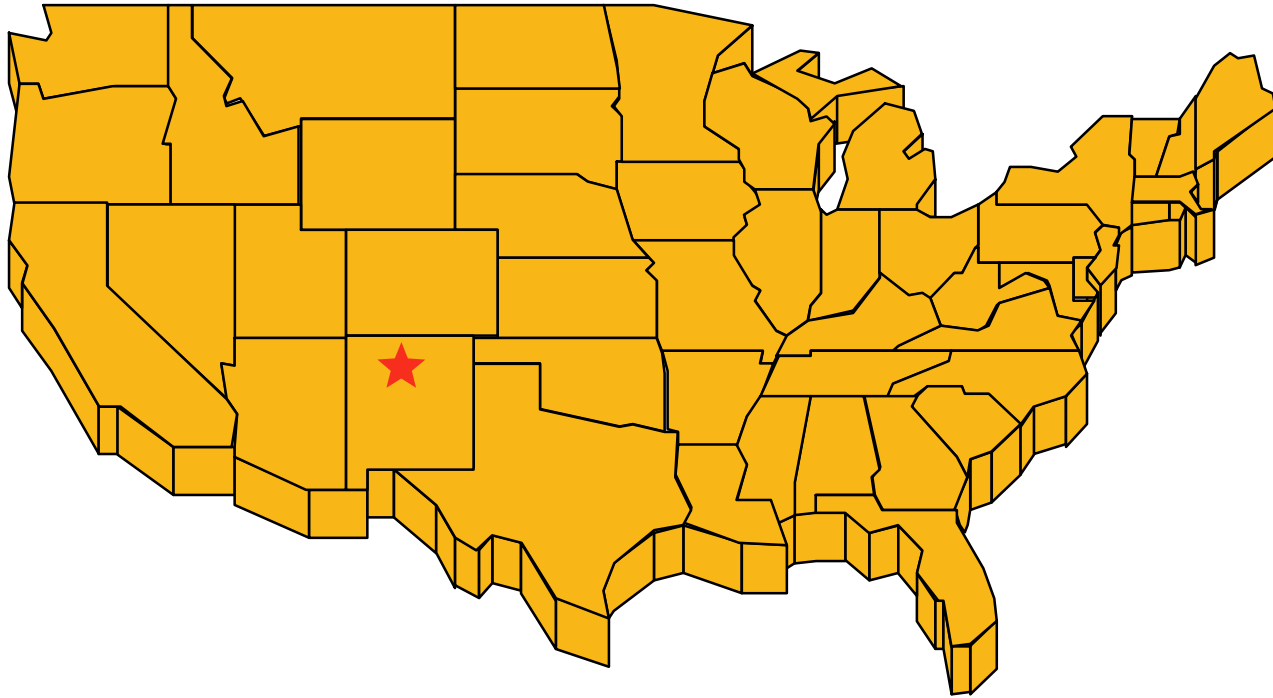


Figure 7.8: The first and second Fourier mode coefficient convergence for the “ k_{eff} of the world” problem with unaccelerated Monte Carlo and FDSA with $\beta=1.0$.

Los Alamos, New Mexico

Where is Los Alamos? Where is New Mexico?

Los Alamos is located in northern New Mexico, approximately 35 miles northwest of Santa Fe, on the Pajarito Plateau in the Jemez Mountains, the southern reaches of the Rockies.



New Mexico History and Culture

- Traditional Hispanic and American Indian art, culture and food
- Santa Fe Opera
- Theater and music events
- Galleries and museums
- Historic railroads
- Civil war battlefield



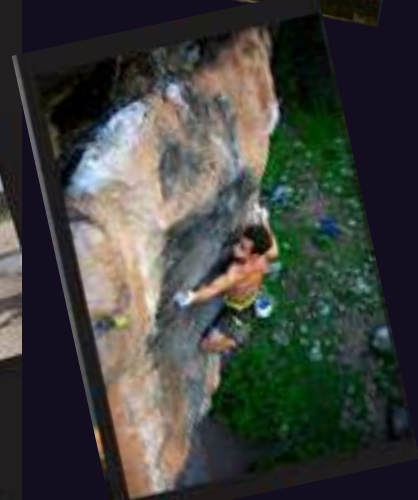
The Pajarito Plateau in the Jemez Mountains





Los Alamos County
where discoveries are made...

Los Alamos, New Mexico
Located in the Jemez Mountains
Elevation: 7200 Feet
Population: 17,000



Skiing right at the edge of town



Approximately 37 major named trails; 280 skiable acres
(20% Easy; 50% Intermediate; 30% Most Difficult)

1 Quad Chair, 1 Triple Chair, 3 Double Chairs, 1 Rope Tow

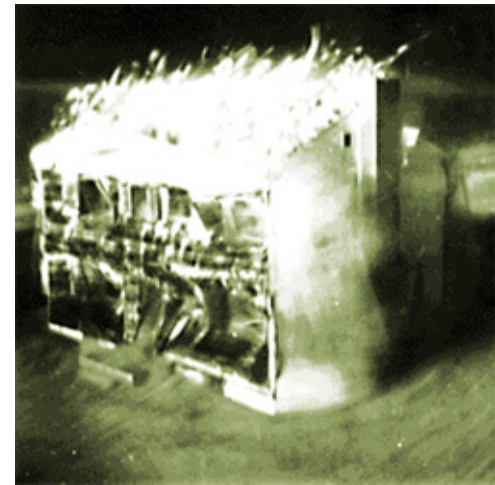
lodge elevation: 9200 feet
peak elevation: 10441 feet
vertical drop: 1410 feet

Los Alamos National Laboratory

Los Alamos during the Manhattan Project



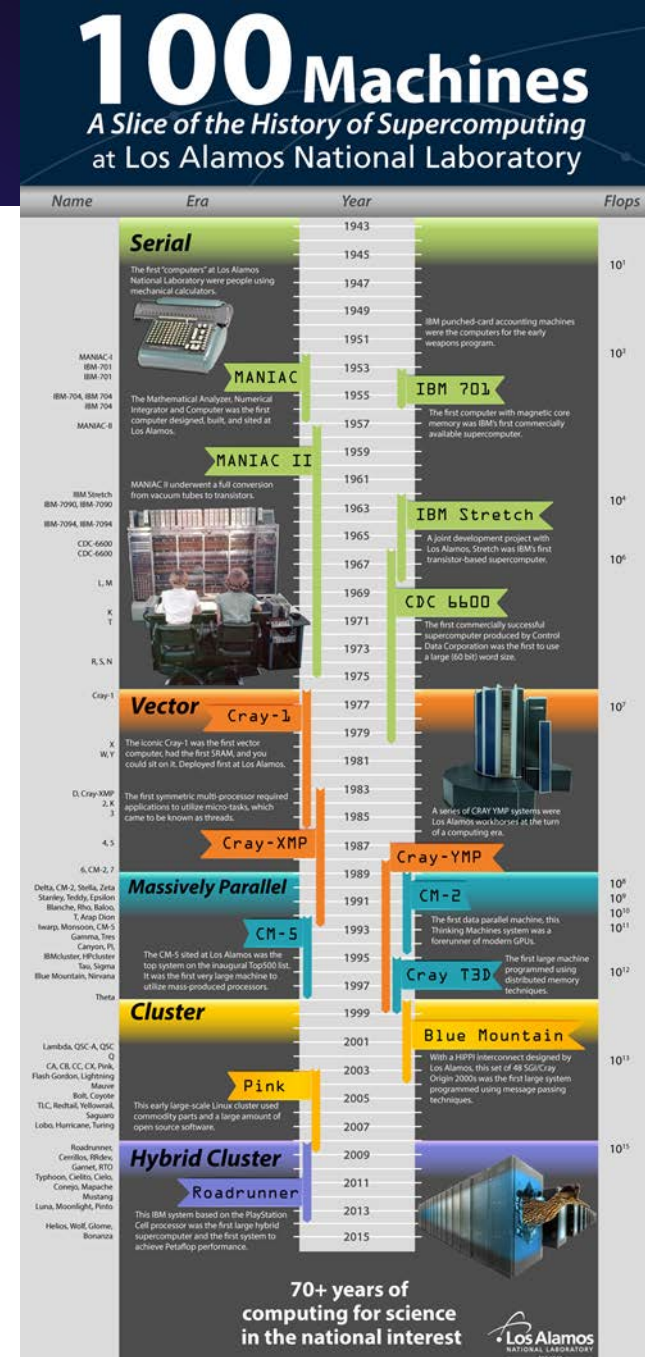
1943 - Los Alamos National Laboratory was created as part of the Manhattan Project



The modeling and simulation campus



The Nicholas C. Metropolis Center for Modeling and Simulation, the most capable simulation facility in the world.



We are essential to ensuring the U.S. nuclear deterrent

Mission Focus

- Los Alamos helps ensure the safety, security, and effectiveness of the nation's deterrent
- Los Alamos is the design agency for four of seven weapons systems in the nation's arsenal



W78



W76
W88

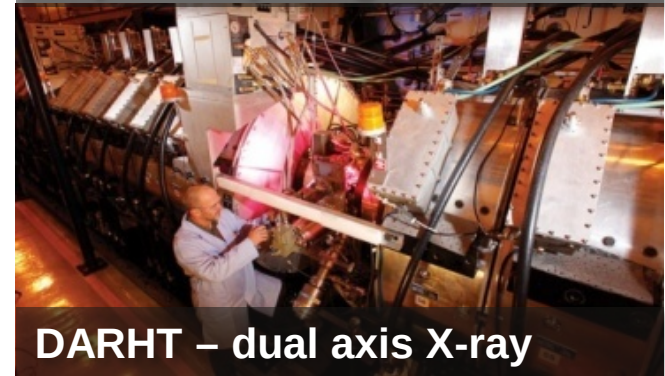


B61

We use science-based stockpile stewardship to annually assure the Secretary of Energy, Secretary of Defense, and the President that the stockpile is safe, secure, and effective



Supercomputing



DARHT – dual axis X-ray

Non-nuclear testing, modeling, simulation, and other tools and capabilities provide assurance

The Jayenne IMC Project

Thermal Radiation Transport: the Jayenne Implicit Monte Carlo Project at Los Alamos

- Radiation Transport Equations:

$$\frac{1}{c} \frac{\partial I}{\partial t} + \mu \frac{\partial I}{\partial x} + \sigma_p I = \frac{1}{2} \sigma_p \pi c T^4$$

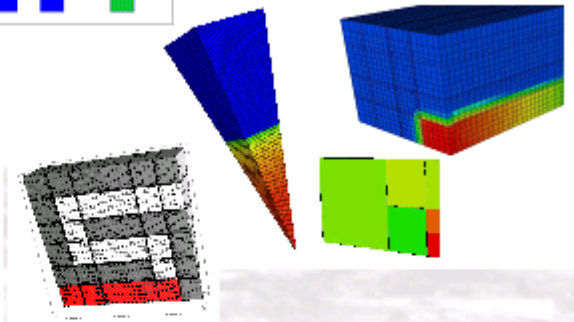
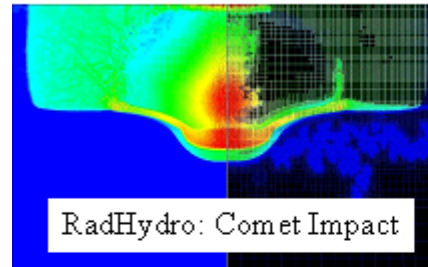
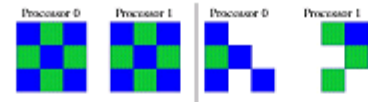
$$C_v \frac{\partial T}{\partial t} = \sigma_p \int_{-1}^1 I d\mu - \sigma_p \pi c T^4$$

- IMC Equations:

$$\frac{1}{c} \frac{\partial I}{\partial t} + \mu \frac{\partial I}{\partial x} + \sigma_{p,n} I =$$

$$\frac{1}{2} (1 - f_n) \sigma_{p,n} \int_{-1}^1 I d\mu + \frac{1}{2} f_n \sigma_{p,n} \pi c T_n^4$$

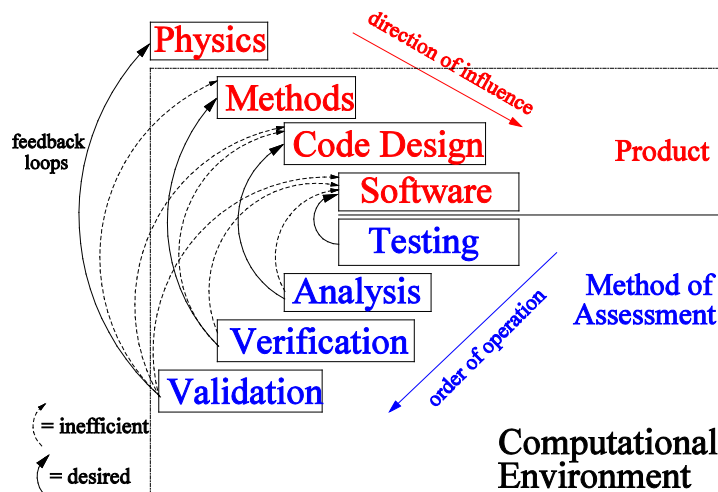
$$C_v \frac{\partial T}{\partial t} = f_n \sigma_{p,n} \left(\int_{-1}^1 I d\mu - \pi c T_n^4 \right)$$



- Solves the system of equations defined by the Fleck-and-Cummings Implicit Monte Carlo method (JCP, '71) for nonlinear thermal radiation transport
- Originated October 1997 by T. Urbatsch and T. Evans
- One of a few original LANL software programs due to DOE's ASC Program
- One of earliest uses of OO/C++ for large-scale scientific codes
 - Gray or Multigroup
 - R, RZ, or XYZ
 - Domain-replicated or decomposed parallelism
 - Orthogonal Structured or AMR meshes
 - Reproducible or non-reproducible

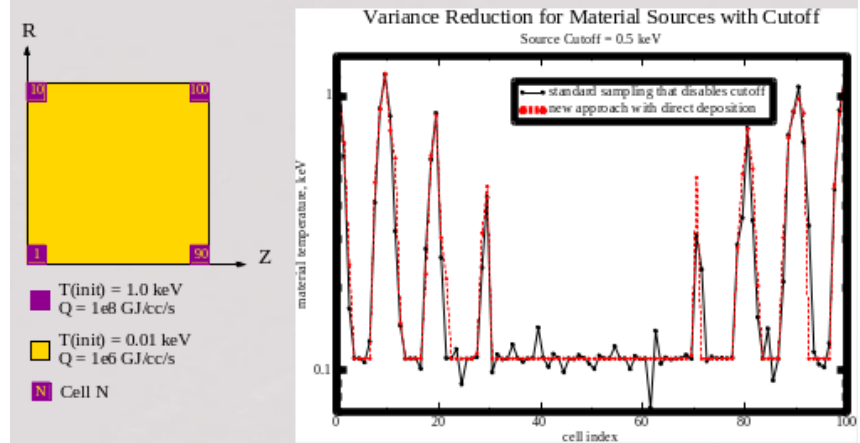
R&D in large-scale software, methods, and algorithms in the Jayenne IMC Project

- **Object-oriented, levelized design**
 - Unit tests, regression testing
 - Buggy Pageant
- **Asynchronous Transport**
- **Discrete Diffusion Monte Carlo**
- **Timestep control theory**
- **Adapted to IBM's Cell processor**
 - IMC on Roadrunner in 2011
- **Analysis of spatial discretizations**



Variance Reduction with Material Sources

- The Jayenne Project algorithms have a “source temperature cutoff” whereby no source particles are sampled in cells that are below a user-specified temperature.
- Naturally, this cutoff was disengaged in the presence of sources, and the IMC method partitions material sources into material and radiation sources.
- Sometimes, the noise would outweigh the signal.
- We have recast the equations, so that if a cell's temperature is below the cutoff and if it is expected to be stable, we bypass the IMC partitions and put any material source directly into the material.
- We observed a reduction in variance, and the algorithm switches over to the usual IMC partition after the cell's temperature is above the cutoff.



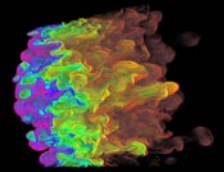
Integrated Design & Assessment Group in the Applied Theoretical Design Division

Org charts are a little more entertaining with pictures

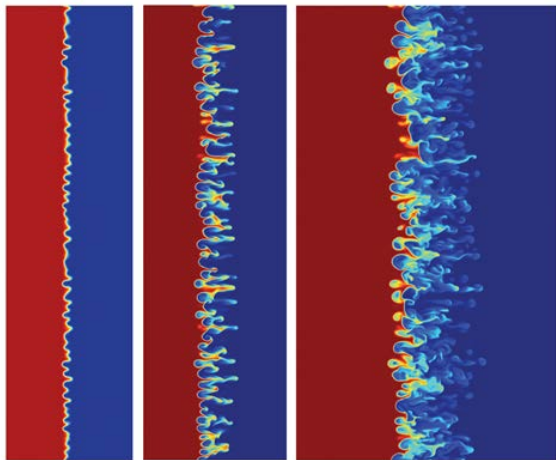


10/25/16

X-Theoretical Design is responsible for assessing performance and safety of the enduring stockpile



- XTD applies a combination of experiment, codes and expertise to address issues related to all aspect of nuclear weapons performance
- There are approximately 35 people in XTD-IDA
 - We execute simulations of nuclear explosives packages to assess the performance of the system as a whole
 - diverse scientific backgrounds including nuclear engineering, astrophysics, applied mathematics, mechanical engineering, plasma physics, and hydrodynamics
 - Our expertise includes radiation hydrodynamics, complex fluid flow, thermonuclear burn, neutral particle transport, astrophysics, high-energy density experiments, etc.
- We focus on the current stockpile with an eye to the future stockpile

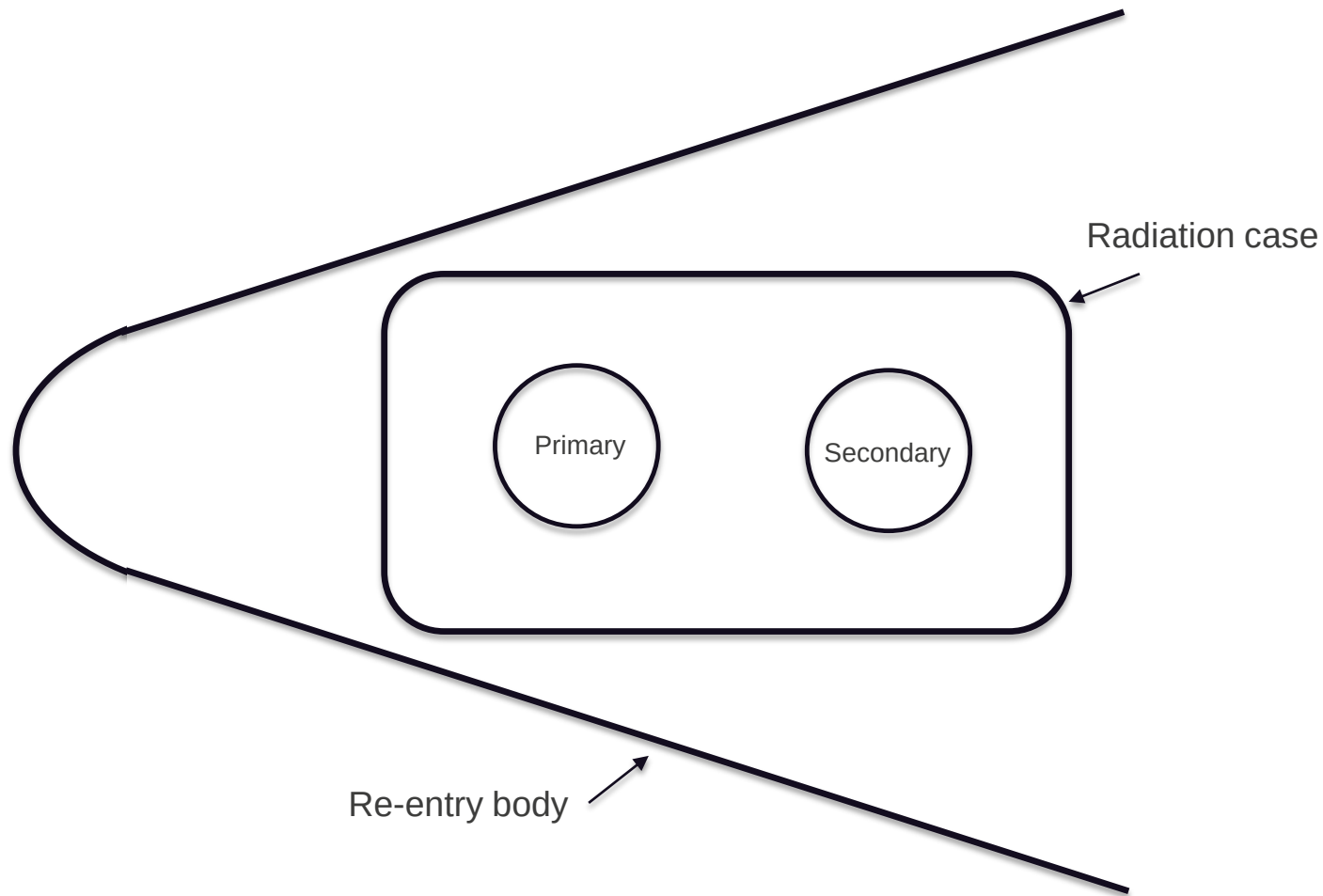


What is the challenge of stewardship and why is assessing the nuclear deterrent so difficult?

- Operating conditions of a nuclear weapon exist nowhere else and cannot be fully replicated in a lab setting
- Temperatures >100 million degrees
- Material velocities >1 million miles per hour
- Pressures >10 million atmospheres
- Time scales nanoseconds



In thermonuclear weapons, radiation from a fission explosive (primary) can be used to compress and ignite a secondary containing thermonuclear fuel.



The Radflow Project in the Science Program

Radflow in the Science Program

The radflow project performs experiments, simulations, and theoretical analysis in support of the design, assessment, and increased predictive capability regarding radiation flow in multiphysics phenomena

- **Opacity**

- Theory, LTE, nonLTE
- Experiments
 - Z
 - Omega
 - NIF

- **Radflow experiments**

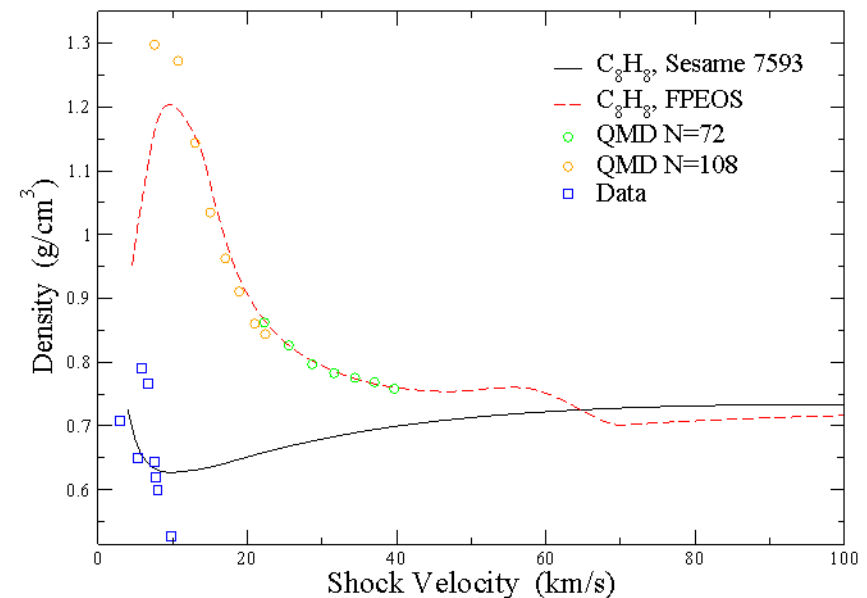
- Source characterization
- Temperature diagnostics
- Angle diagnostics

- **Target fabrication**

- **Warm dense foam Equations of State**

- **Secondary Assessment Technologies**

WDFEOS: QMD results differ

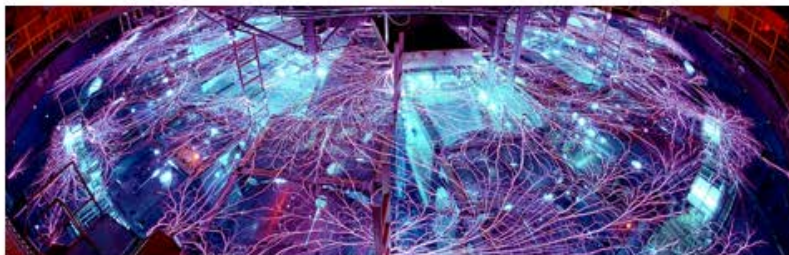
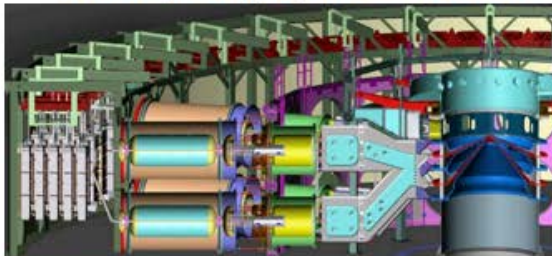


Experimental facilities for radflow



Omega Laser Facility
Laboratory for Laser Energetics
University of Rochester
Rochester, New York

Z-Pinch
Sandia National Laboratory
Albuquerque, New Mexico



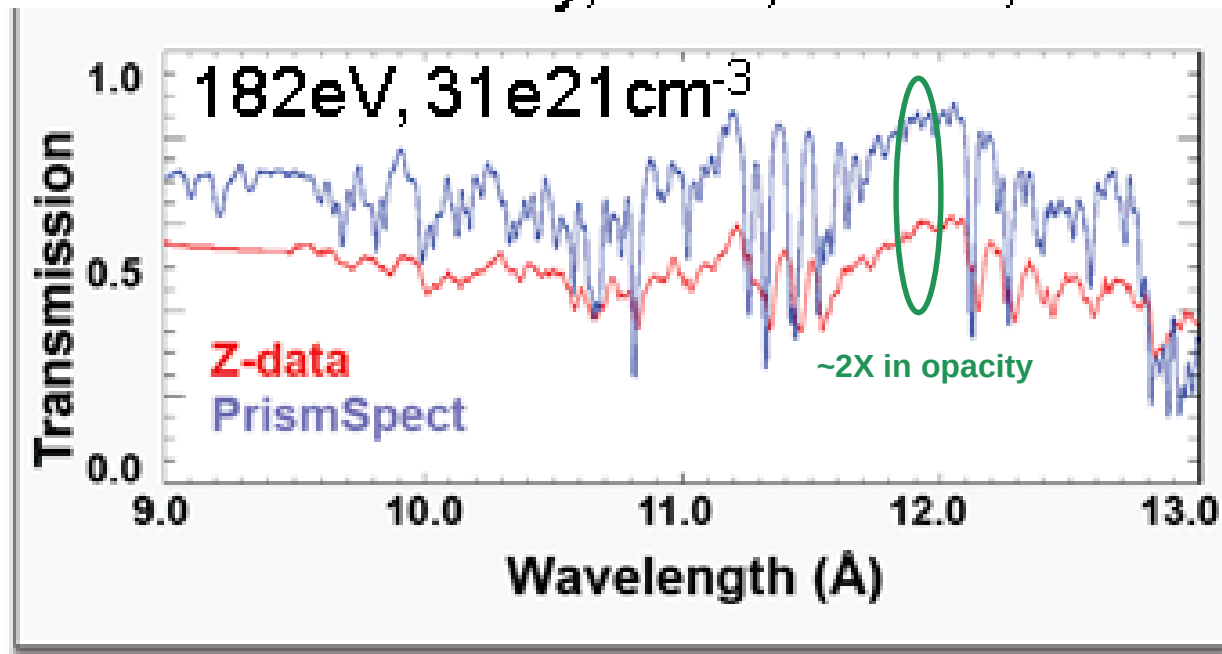
National Ignition Facility
Lawrence Livermore National Laboratory
Livermore, California



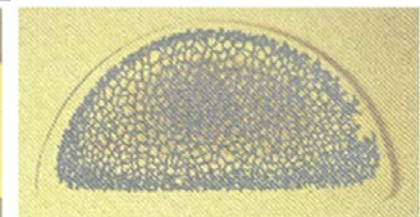
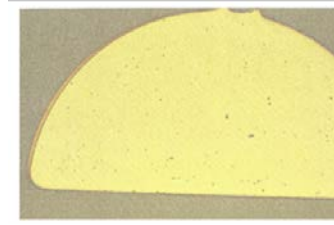
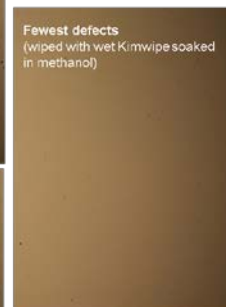
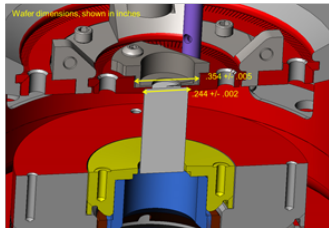
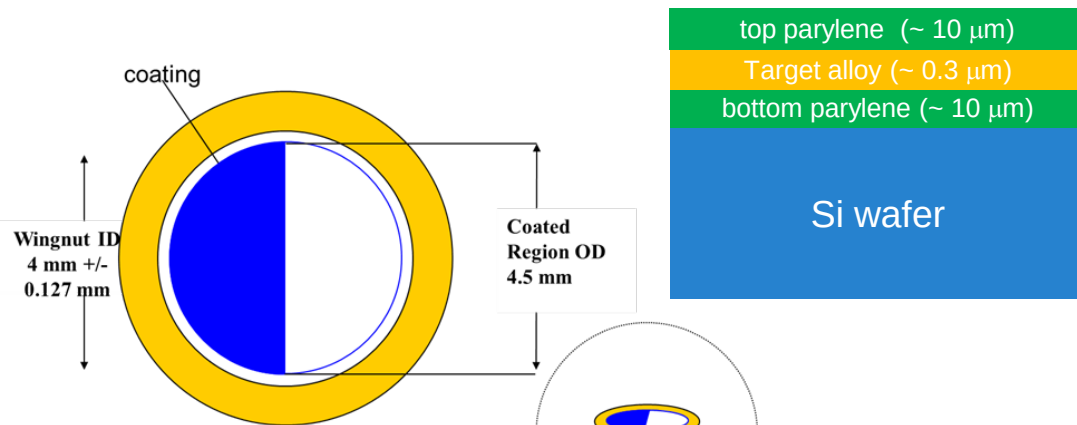
On Z, we are unable to accurately predict the opacity of iron at higher temperatures

- **Opacities are calculated *ab initio* in LANL's ATOMIC code**
 - Variations of models in LANL's ATOMIC opacity code cannot explain the Fe differences.
 - Uses well-known atomic physics, but opacities are sparsely validated.
 - New LTE opacity tables: <http://aphysics2.lanl.gov/opacity/lanl/>
- **Results from Sandia National Laboratory's Z-pinch dynamic hohlraum**
 - Opacities of lighter materials are predicted by theory, but not for higher temperatures or for all materials
 - No discernable pattern to when we can predict and when we cannot

Bailey, et al., Nature, 2015



Target fabrication: making foils for Opacity-on-Z

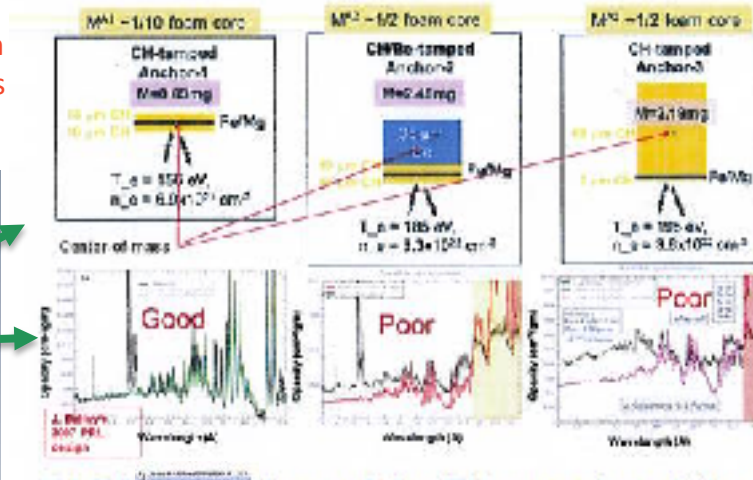
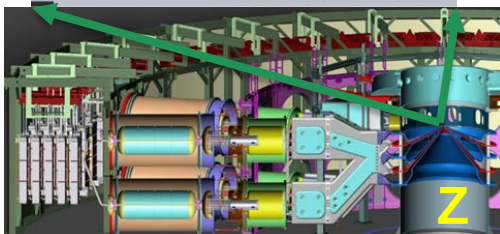
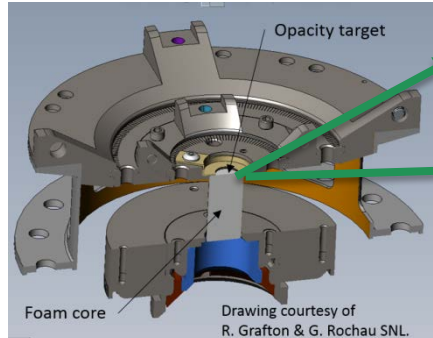


LANL's opacity program is focusing on whole-system modeling and multiple platforms to help explain the incorrectly predicted iron opacity on SNL's Z-machine.

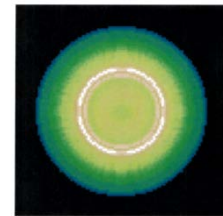
• Modeling Z's whole dynamic hohlraum

- Cassio simulations show many undesirable sensitivities
- Lasnex cutoff problems indicate that the foil could be affecting the unperturbed transmission, especially for lower drives.
- Lasnex whole-system calculation show possibility of foam jetting into the target.
- Lasnex/Cassio comparisons show the effect of Cassio not having MHD

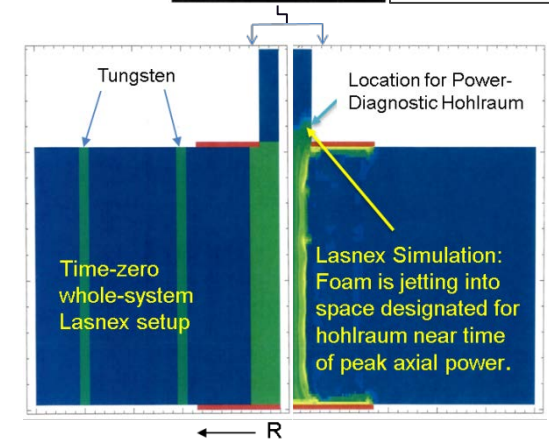
Opacity foils with different tampers



Cassio calculations show opacity foil tilting at an angle, but better modeling removed the tilt. Implies a sensitivity



Axial x-ray image of DH aperture



Modeling Z's whole dynamic hohlraum

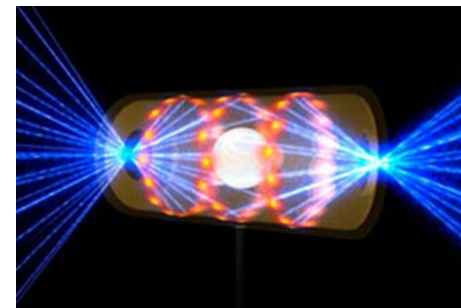
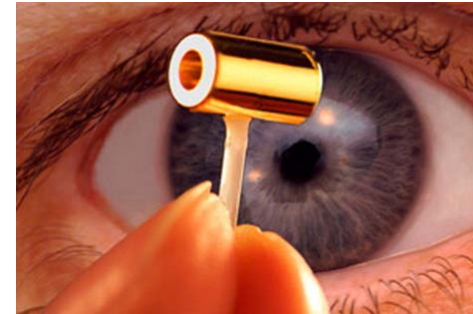
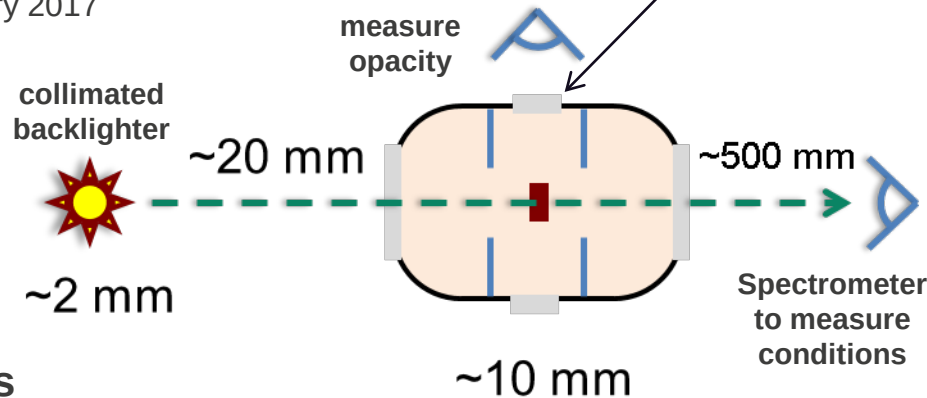
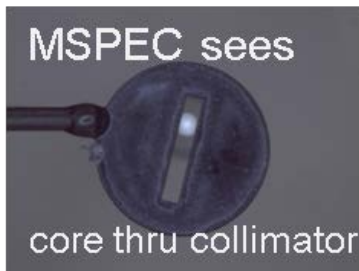
- Source characterization shots in 2008/2014 after the Z-refurbishment are being re-evaluated with Lasnex MHD, showing that foam could have interfered with the gold hohlraum.

Slide 31

LANL is leading a collaborative effort to replicate the Z opacity experiments on NIF.

LANL, LLNL,
SNL, LLE, NSTec

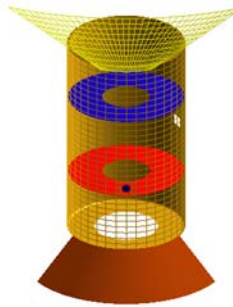
- **Long history of planning for and building up to these experiments**
 - “NIF System-Design Requirements...,” TS Perry and BH Wilde, UCRL-ID-120738, April 1995.
 - “..Spectrometer Design for NIF...,” Young, Schneider, Heeter, Springer; JOWOG-37, 2002.
 - “A Multi-year Plan for Opacity,” Bailey, et al., mtg at LLNL, 2013, refined at HED mtg 2014.
 - Relies on techniques developed at Nova, Omega, and Z.
- **NIF shots in 2015-2016**
 - Facility feasibility shots, test backlighter, spectrometer
 - Integrated setup, test new McFee hohlraums
- **Hohlraum modeling and testing**
 - Calculated sample temperature > 190eV
 - First hohlraum NIF shot January 2016
 - First opacity sample January 2017



- **Planned opacity shots**
 - 2016: OpSpec 0.5-2.5 keV
 - 2017 initial Fe data
 - 2018: higher Z

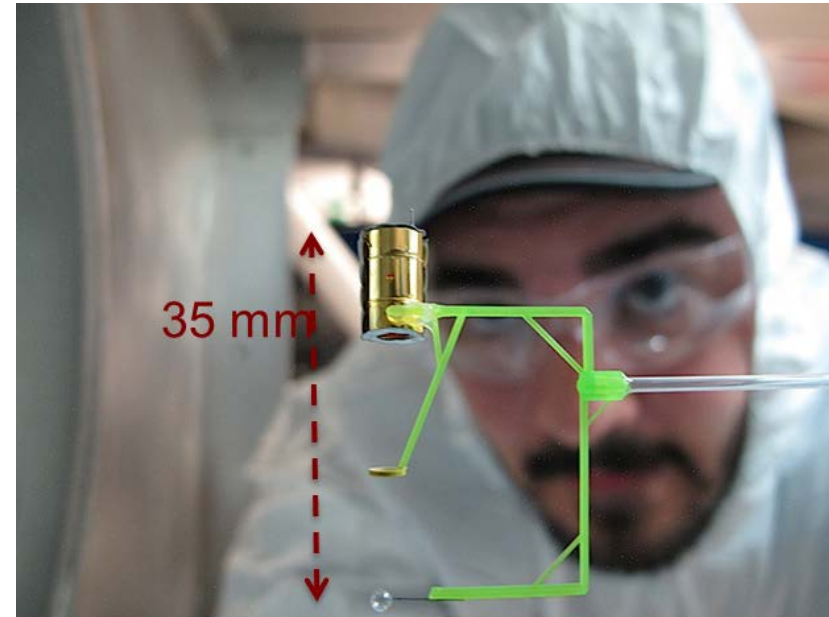
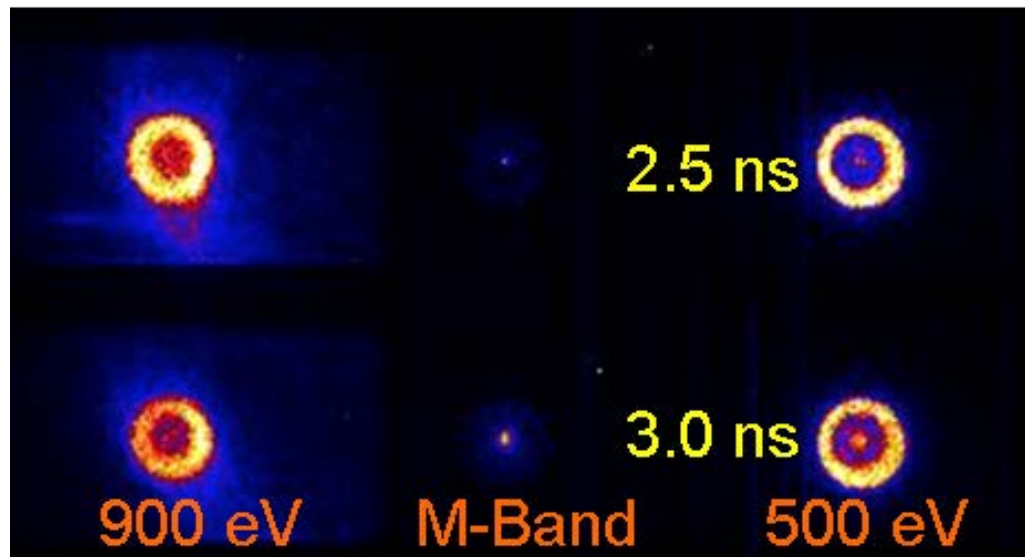
Slide 32

A new platform brings new issues and challenges



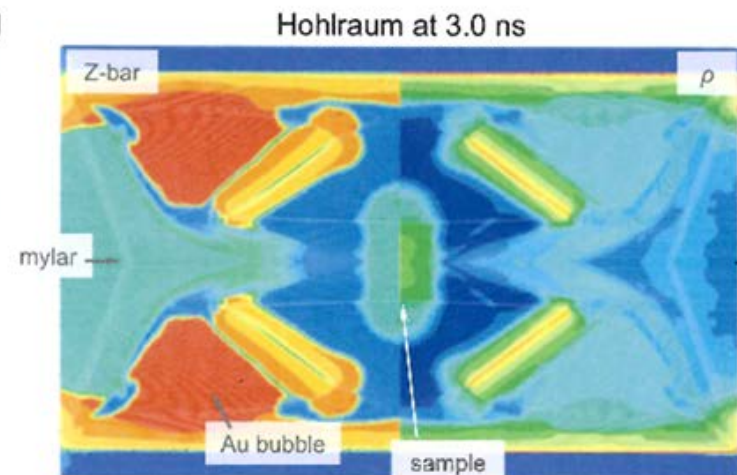
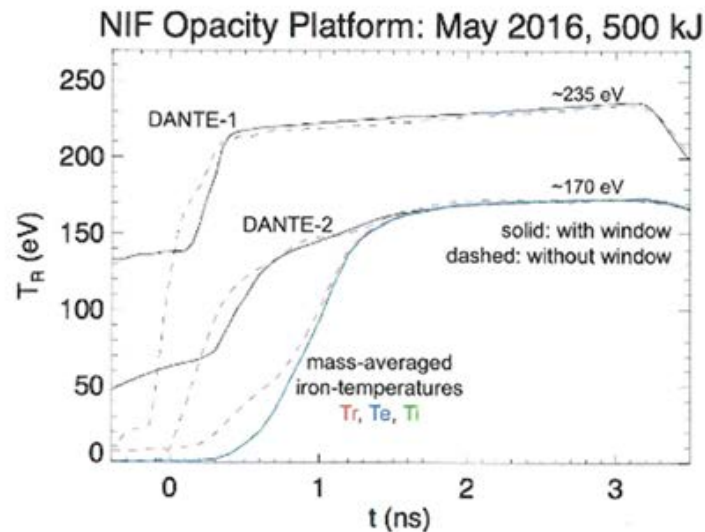
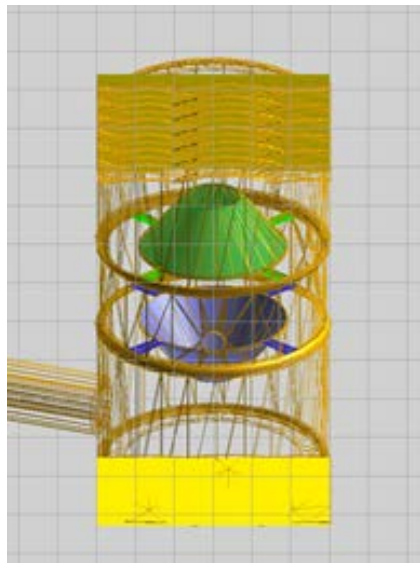
- We cannot model hohlraums predictively
- The gold blowoff is stagnating on axis and will corrupt the spectrum
- Baffle emission interfering

Images down the axis of the hohlraum

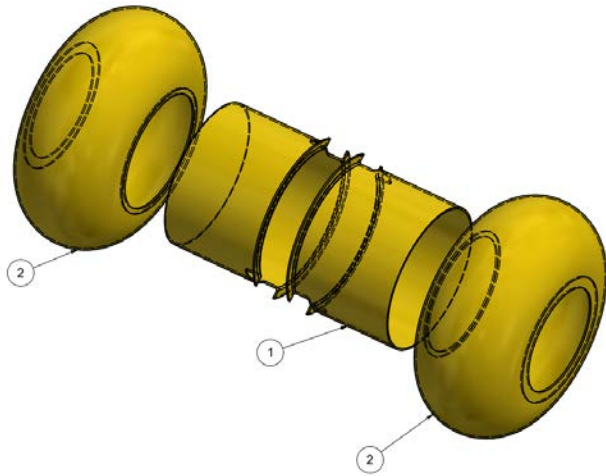


Attempts at higher temperatures, delaying stagnation

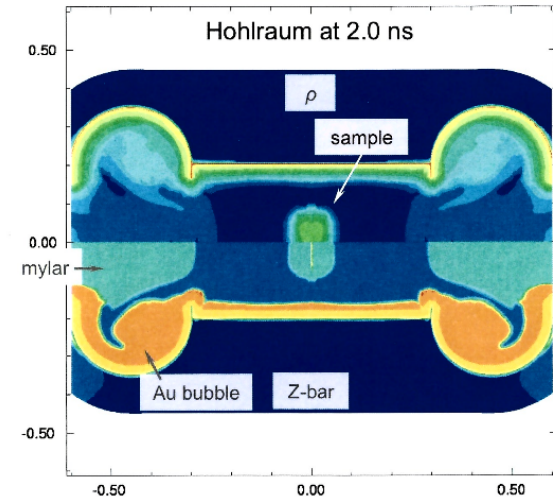
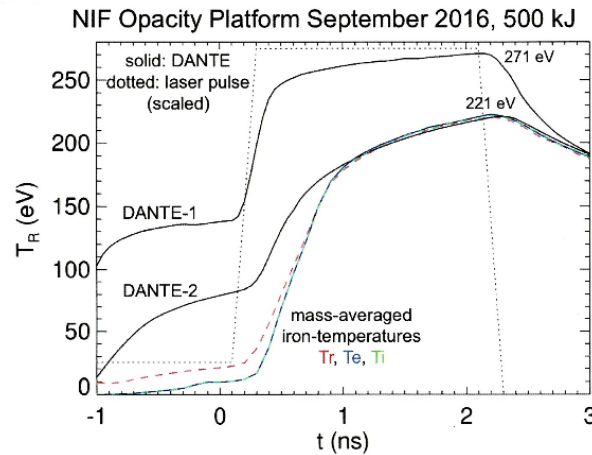
- The experimentalists are designing hohlraums faster than designers and their simulations! But, they do make designs that can be simulated tractably.
- NOVA-based hohlraums couldn't get up to the higher temperatures



McFee hohlraums have reached the higher temperatures

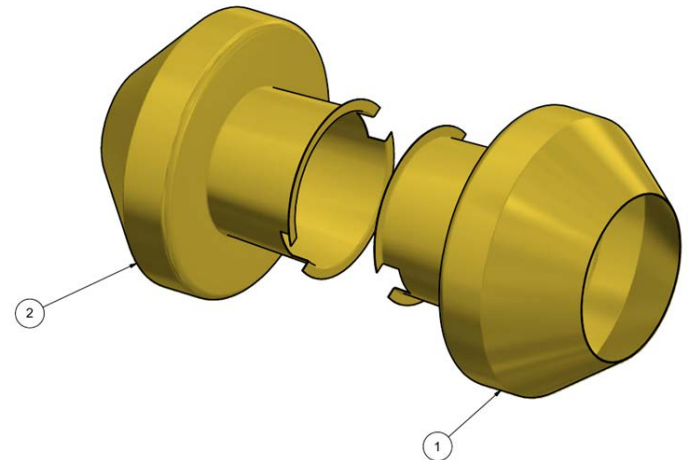
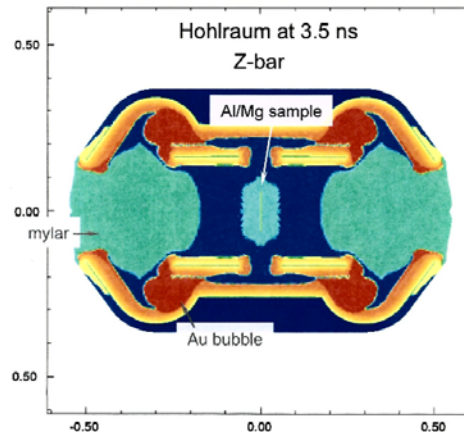
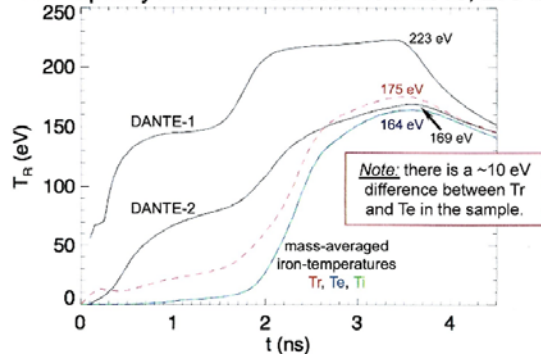


Synthetic DANTE post-processing of the September 8th McFee-hybrid hohlraum with an added mylar window



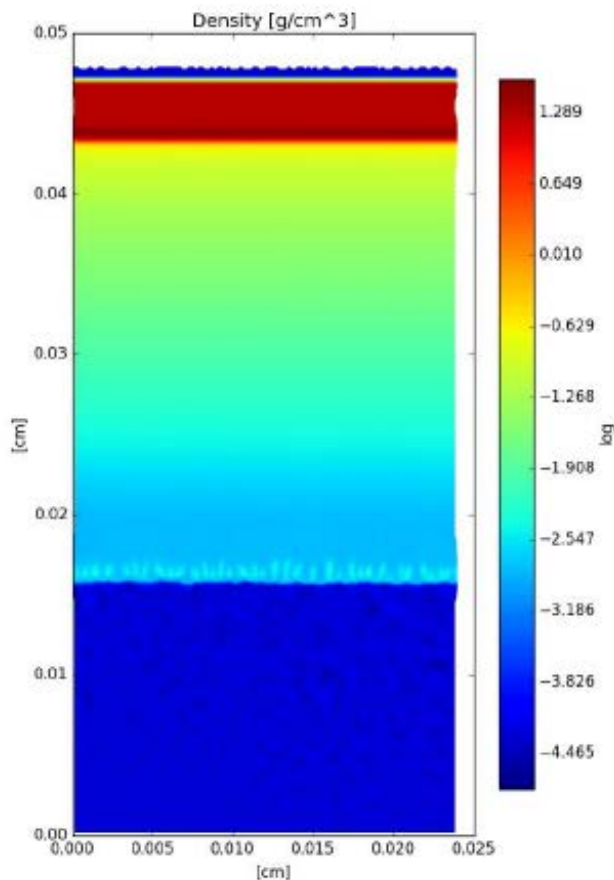
Synthetic DANTE post-processing of the October 10th McFee-Lampshade hohlraum with modified laser pulse

NIF Opacity Platform: October 10th 2016, 270 kJ

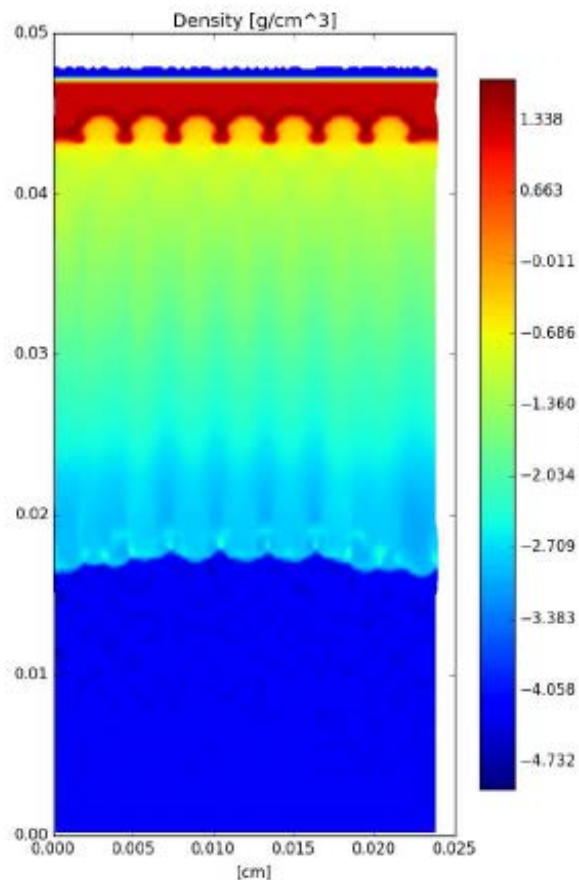


Isaac Meyer, 2016 summer student, UC Berkeley, studied textured/foamed hohlraum walls for slowing ICF ablation

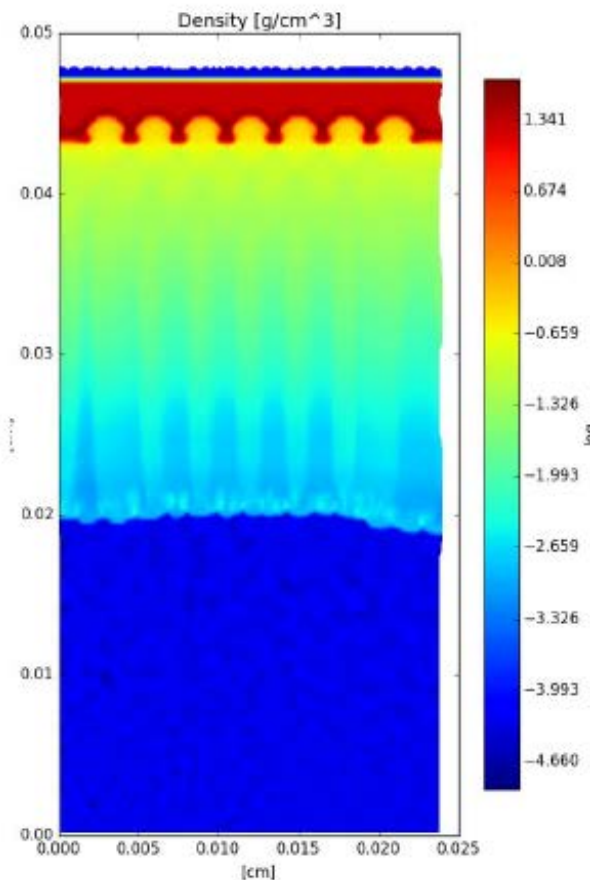
Control



Circle Pattern

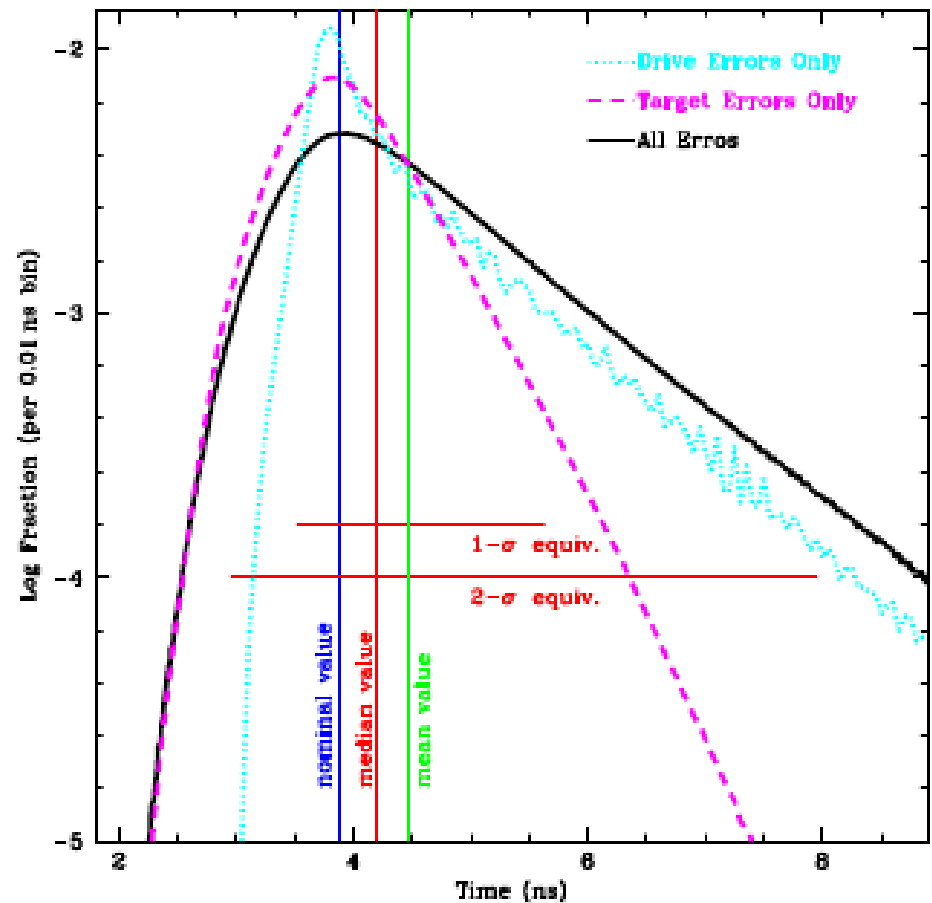
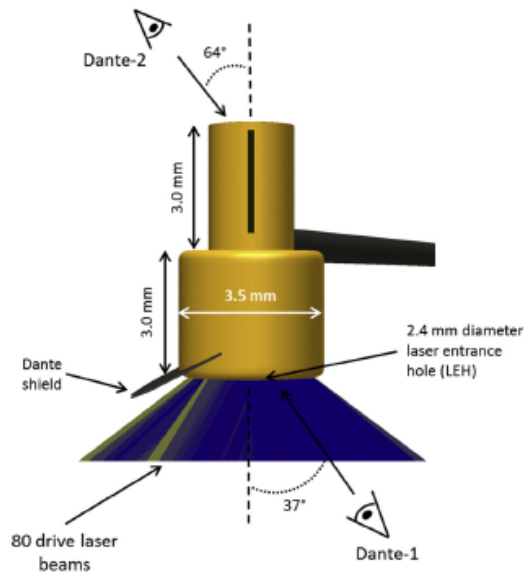


Circle Pattern with Foam

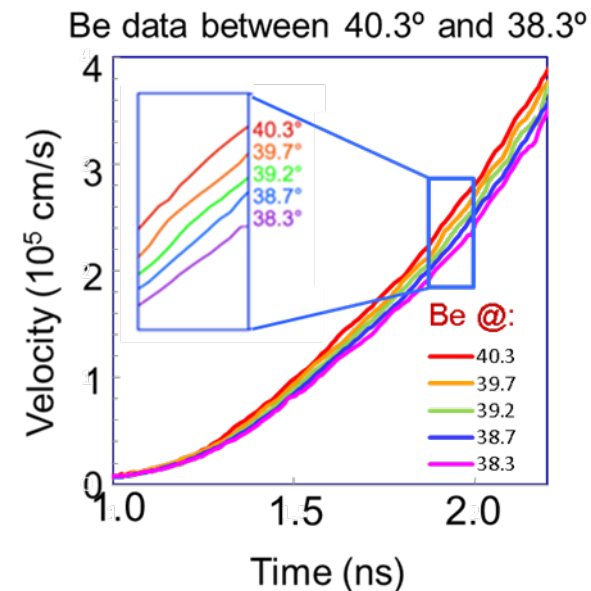
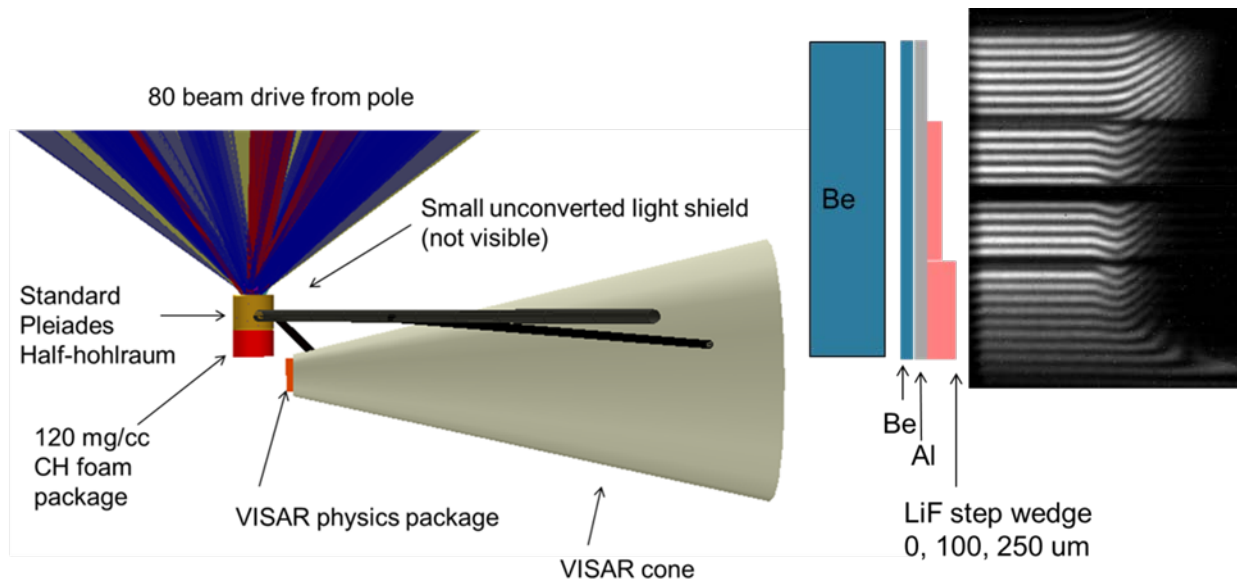
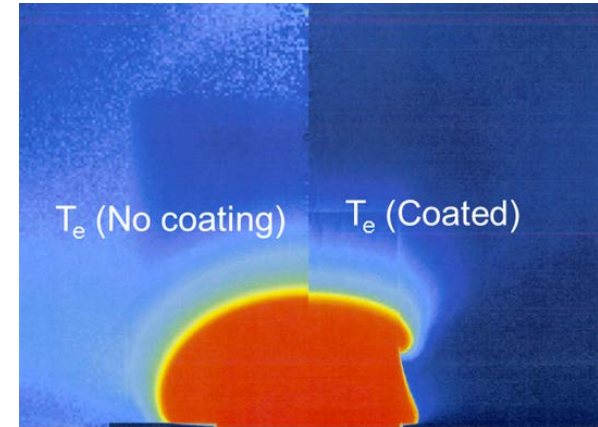
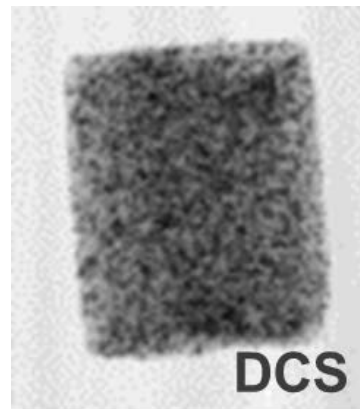
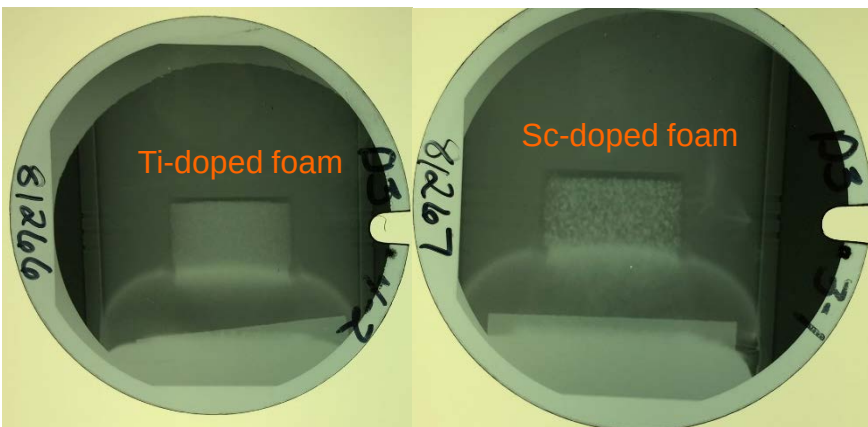


Do we know the sensitivities in our radflow experiments?

- Simulations of the Pleiades experiment show that the breakout times have a skewed distribution (Fryer, et al., HEDP, 18 (2016) 45-54)
- assuming Gaussian distributions in
 - average density, inhomogeneity
 - drive total flux, spectral power
 - drive angle cosine power
- which lead to a systematic error



Temperature diagnostic development at Omega; Angular diagnostic development at NIF



Job opportunities at LANL, XTD-IDA, and Radflow

- **jobs.lanl.gov**
 - Radflow postdoc, “Designing HEDP Radflow Experiments,” Job #IRC46938
 - Entry-level positions, postdocs in XTD, XCP, CCS, and throughout the lab
 - Director Charlie McMillian says this is a good time to start a career at LANL
- **We’re looking to enhance our experimental design capability**
- **LANL should have an increasing number of job openings in the next few years. Jobs ranging from theoretical to computational to design to novel physics and radiation experiments.**

Project members, contributors, collaborators

Opacity-on-Z: Manolo Sherrill, Heidi Morris, Bob Watt, Darrell Peterson, Jim Bailey (SNL), Greg Rochau (SNL)

Target fab on Z: Igor Usov, Kevin Hubbard, Doug Vodnik

Theory and physics: Bernie Wilde, Chris Fontes, Peter Hekel, James Colgan

Codes: Rick Rauenzahn, Zach Medin, William Dai, Tony Scannapieco

Opacity-on-NIF: Ted Perry, Evan Dodd, Bob Heeter (LLNL), Wes Even, Barbara deVolder, Ian Tregillis, Lynn Kot, Jim King (NSTech), Patrick Ross (NSTech), Isaac Meyer (UC Berkeley), John Scott, Kirk Flippo, Tana Cardenas

COAX, VISAR, Pleides: Nick Lanier, Heather Johns, Jonathan Hager, John Kline, Chris Fryer, Alistair Moore (AWE/LLNL), John Morton (AWE), John Oertel, Chris Hamilton

WDFEOS: Carl Greeff, David Montgomery, Chris Fryer, Heather Johns, Katja Falk (ELI Beamlines, Czech Republic)

...and many more.

Abstract

Los Alamos National Laboratory is a nuclear weapons laboratory supporting our nation's defense. In support of this mission is a high energy-density physics program in which we design and execute experiments to study radiation-hydrodynamics phenomena and improve the predictive capability of our large-scale multi-physics software codes on our big-iron computers. The Radflow project's main experimental effort now is to understand why we haven't been able to predict opacities on Sandia National Laboratory's Z-machine. We are modeling an increasing fraction of the Z-machine's dynamic hohlraum to find multi-physics explanations for the experimental results. Further, we are building an entirely different opacity platform on Lawrence Livermore National Laboratory's National Ignition Facility (NIF), which is set to get results early 2017. Will the results match our predictions, match the Z-machine, or give us something entirely different? The new platform brings new challenges such as designing hohlraums and spectrometers. The speaker will recount his history, starting with one-dimensional Monte Carlo nuclear criticality methods in graduate school, radiative transfer methods research and software development for his first 16 years at LANL, and, now, radflow technology and experiments. Who knew that the real world was more than just radiation transport? Experiments aren't easy and they are as saturated with politics as a presidential election, but they sure are fun.