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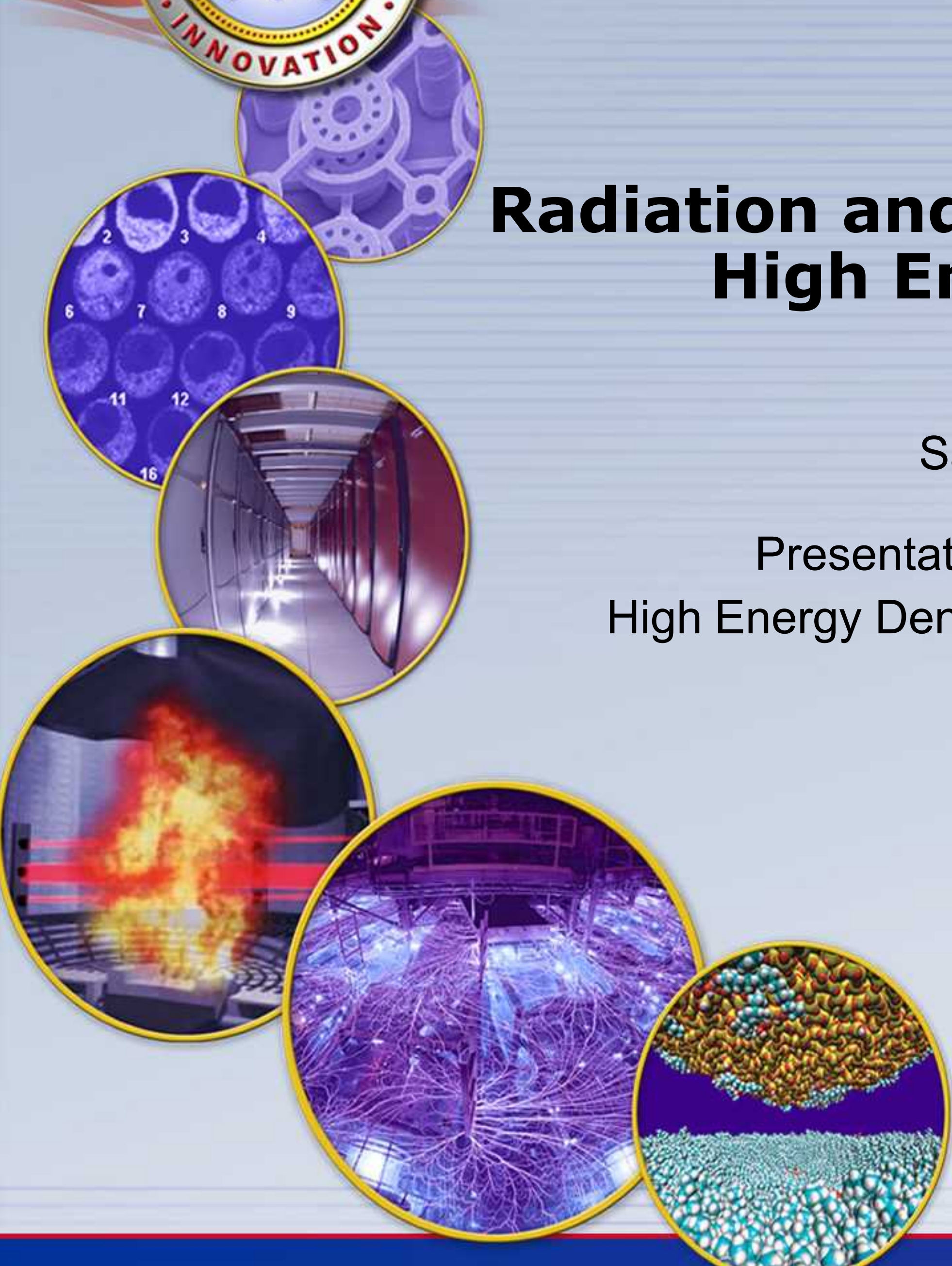


Radiation and Magneto-Hydrodynamics of High Energy Density Plasmas

Mark C. Herrmann
Sandia National Laboratories

Presentation to the Scientific Opportunities in
High Energy Density Laboratory Plasma Physics Workshop

August 26, 2008

Sandia National Laboratories

Many thanks to the following people who have shared their thoughts on this topic with me

Paul Drake
University of Michigan

Steve Libby, Mordy Rosen, Peter Amendt, Dmitri Ryutov, Jim Hammer, Omar Hurricane, John Perkins
Lawrence Livermore National Laboratory

Brent Blue, Tina Back
General Atomics

Dan Sinars, Mike Cuneo, John Porter, Keith Matzen
Sandia National Laboratory

Also thanks to all those I borrowed viewgraphs from

Why are we interested in understanding the Radiation and Magneto-Hydrodynamics of High Energy Density Plasmas?

We want to understand because plasmas dominated by radiation and/or magnetic fields are unlike any conditions in our common experience

Understanding Radiation and Magneto-Hydrodynamics(Rad-MHD) of High Energy Density (HED) Plasmas can enables us to control HED Plasmas

- **Control allows us to reach ever higher energy density conditions (e.g ignition)**
- **Control allows us to create HED plasmas and then measure their fundamental properties**
- **Control allows us to create HED plasmas in the laboratory that shed light on plasmas in the universe**

As shown by the diversity of topics at this meeting it is a very exciting time to be working in the area of HEDP

Outline

Radiation/MHD for:

- Achieving higher energy densities
  - Capsule Implosions
  - Magnetically Driven Implosions
- Measuring fundamental material properties
  - Magnetically driven flyers (an example)
- Shedding light on observations of the universe
  - Radiating shocks (an example)

Codes

Precision Diagnostics

Opportunities

Fusion fuel must be brought to a pressure of several hundred billion atmospheres to achieve the goal of ignition

For ICF conditions: $\rho R \approx 0.6\,\mathrm{g/cm^2}$ $\quad T \approx 5\,\mathrm{keV}$ $\quad \rho R\,T \approx 3.0\left(\frac{\mathrm{g\,keV}}{\mathrm{cm^2}}\right)$

$$P(\mathrm{Bar}) = 8 * 10^8 \rho\left(\mathrm{gm/cm^3}\right) T_i(\mathrm{keV}) \qquad P\,R \sim 2.4 \bullet 10^9\,\mathrm{B-cm}$$

$$\mathrm{E} \sim \frac{3}{2} PV \sim 1.5\,10^9 R(cm)^2 (\mathrm{J})!$$

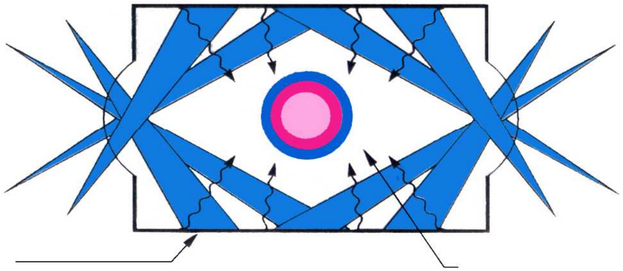
$$\mathrm{E} \sim 15\,\mathrm{kJ} \Rightarrow R \sim 30\,\mu\mathrm{m} \Rightarrow P \sim 800\ \mathrm{GB}$$

Calculations of NIF capsules without burn reach similar (~500GB) pressures

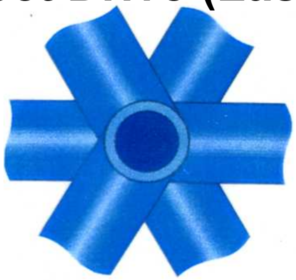
Assembling a fraction of a milligram of DT to this pressure is a very challenging radiation hydrodynamics problem!

High Mach number implosions are needed to reach these pressures

Indirect Drive (X-ray)



Direct Drive (Laser)



In either direct or indirect drive, ablation pressures are of order ~ 50-100 MB

We need to get pressures to >1000X that for ignition!

For hollow shell spherical implosions, scaling laws suggest that $P_{stag} \sim P_{drive}$ M^3 which implies

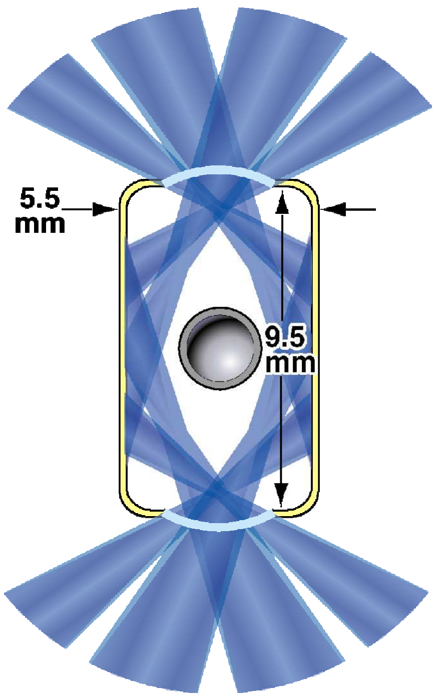
$M = v/c_s \sim 10$

High Mach number implies:

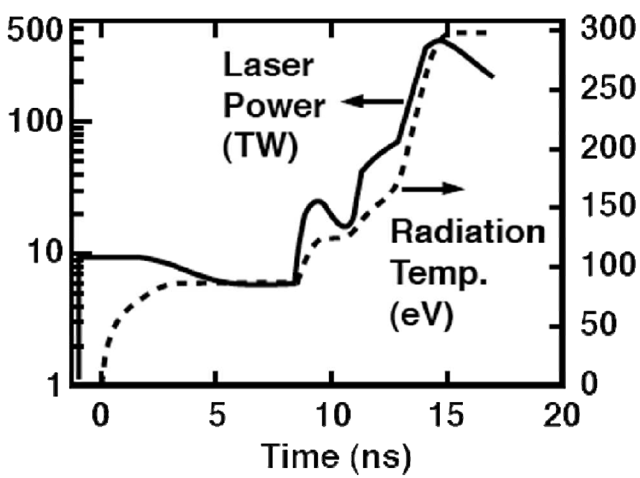
- high velocities
- thin shells
- large convergence ratios
- precise shock timing

All lead to constraints on the Rad-Hydro environment

The National Ignition Campaign has designed an exquisitely controlled radiation hydrodynamic environment



Typical Pulse Shape



All of these issues stress different aspects of radiation hydrodynamics:

Hohlraum energetics - A few % in radiation flux
- Conversion efficiency of laser heating
- Radiation matter coupling
- Marshak wave losses to the wall

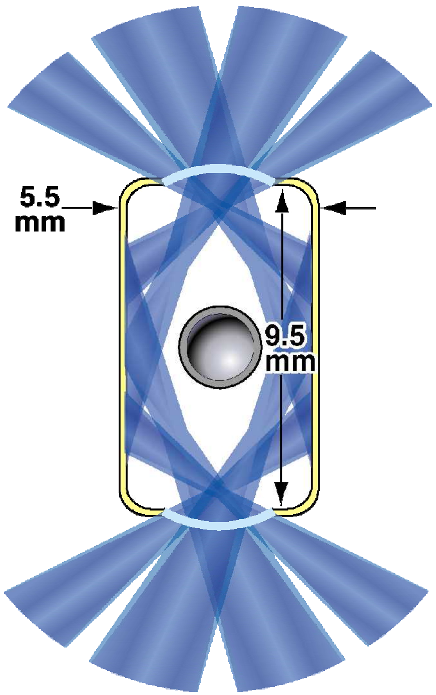
Capsule absorption -- ~1 % in ablator mass remaining
- Coupling efficiency
- Ablation dynamics
- Implosion dynamics

Implosion Symmetry-- ~ <1% uniformity of radiation flux
- Hydro coupling
- Radiation transport
- Implosion dynamics

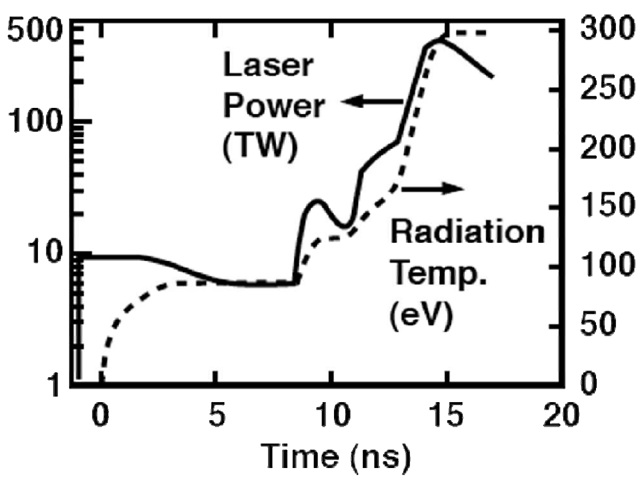
Pulse Shaping -- ~50 ps shock timing
- Shock timing
- Equation of state

Stagnation dynamics -- Rad-Hydro

While the approach to ignition will be experimentally guided, the precision data gathered by the NIC will enable an increased understanding of Rad-hydro



Typical Pulse Shape



Measurements during the ignition campaign

Hohlraum energetics- A few % in radiation flux

Capsule absorption -- ~1 % in ablator mass remaining

Implosion Symmetry-- ~ <1% uniformity of radiation flux

Pulse Shaping -- ~50 ps shock timing

Integrated nature of experiments may make teasing out the important issues a challenge

Making sure this data is studied and published is important for the field

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- Measuring fundamental material properties
    - Magnetically driven flyers (an example)

- Shedding light on observations of the universe
    - Radiating shocks (an example)

Codes

Precision Diagnostics

Opportunities

Magnetically-driven systems reach high energy density (1MB) at 5 Megagauss

The magnetic field acts like a pressure in the momentum equation:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{\mathbf{J}\times\mathbf{B}}{c} - \nabla P = \frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B} - \nabla\left(P + \frac{B^2}{8\pi}\right)$$

For cylindrically symmetric Zpinches this term is zero

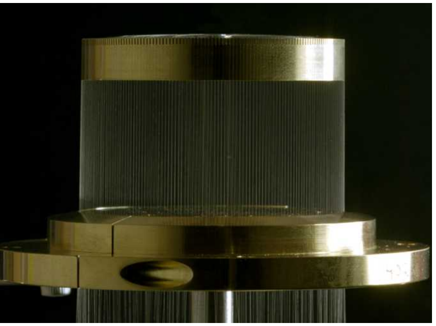
A 5 Megagauss (500 T) magnetic field applies a pressure of 1 MB to a conductor

A current of 1MA at 400 microns radius is 5 10^6 G = 1 Mbar of pressure

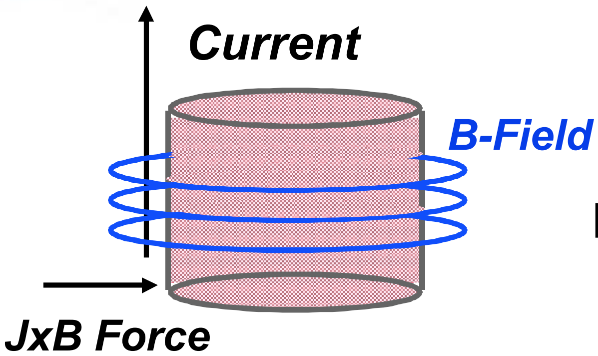
A current of 25 MA at 1cm radius is 5 10^6 G= 1 Mbar of pressure

Magnetically-driven implosions efficiently convert energy from electrical to radiation

wire array



2 cm



kinetic and electrical energy

↓

internal (shock heating)

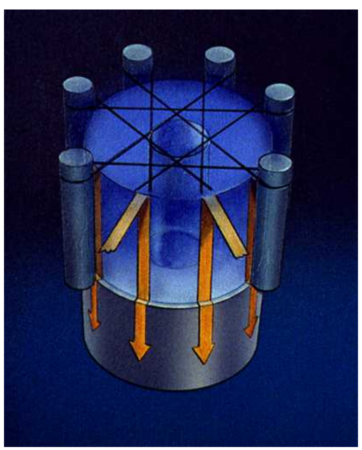
↓

x rays

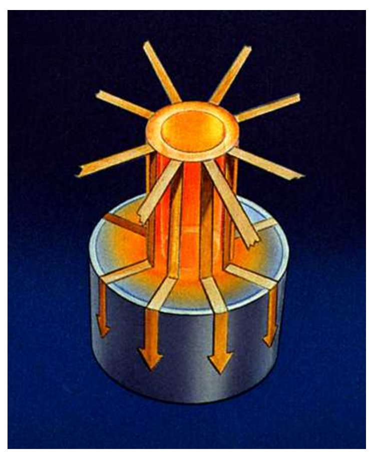
electrical energy

↓

kinetic energy



Initiation



Implosion

Stagnation

Z

x rays
6 ns
~1.6 MJ
~200 TW

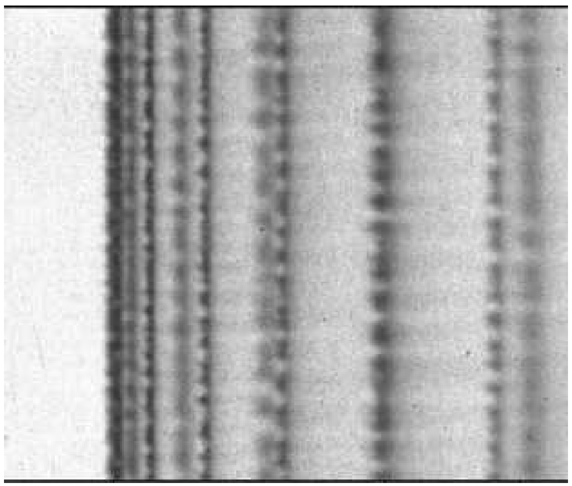
electrical to x-ray ~15% efficient

Why do wire arrays perform like they do?
What limits the performance? Can we do better?

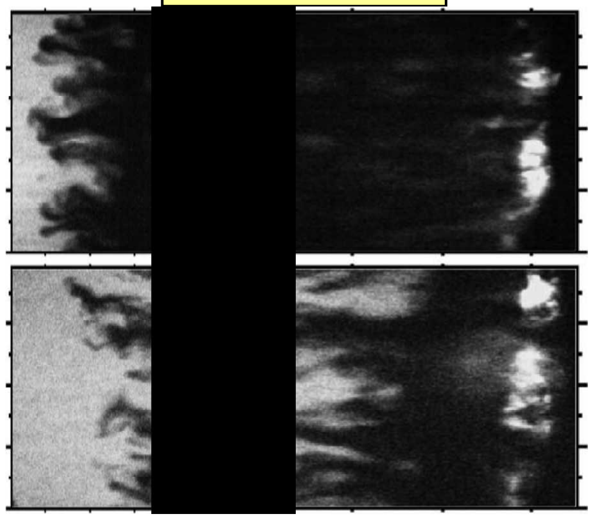
X-ray backlighting has led to rapid progress in the understanding of wire-array magnetically-driven implosions

Tungsten Wire Array implosions radiographed at 6.151 keV

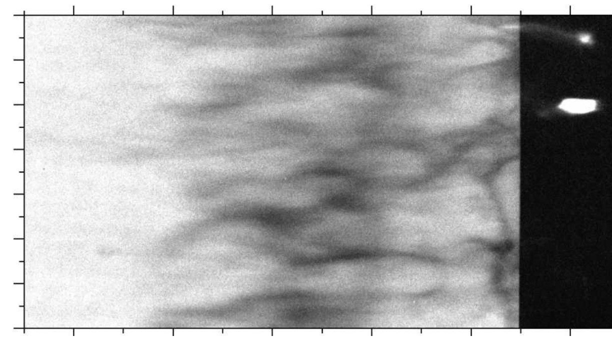
Ablation

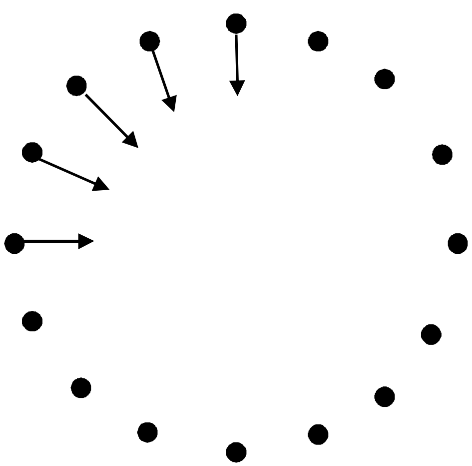


Implosion



Stagnation & X-ray production





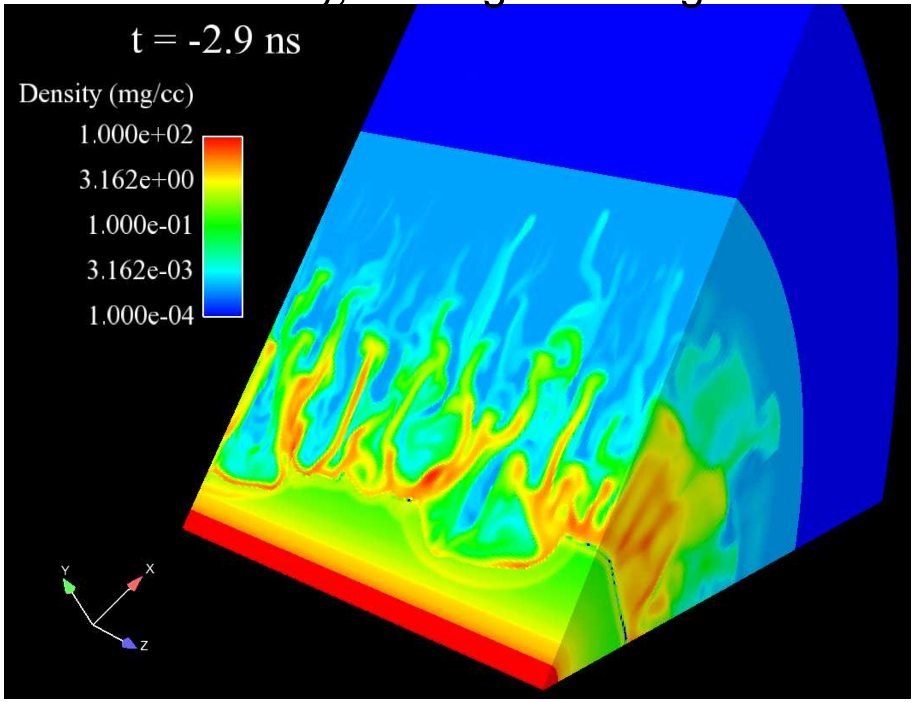
Magnetic Rayleigh-Taylor and other instabilities strongly affect wire array zpinches from the very beginning

Few carefully benchmarked magnetic Rayleigh-Taylor experiments have been done

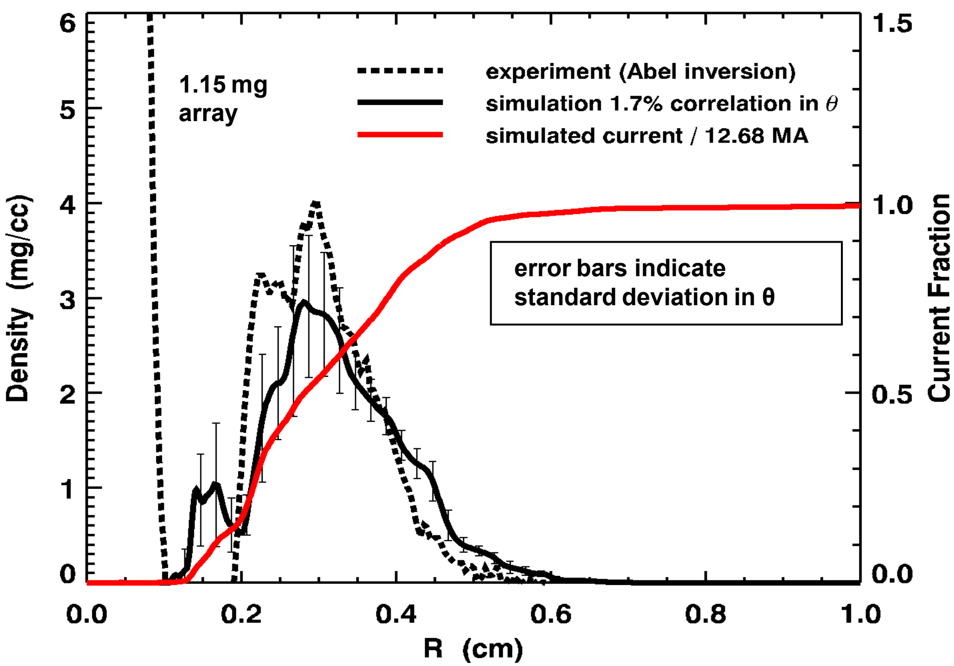
Late in time current delivery to small radius is limited by mass "left behind"

3D Rad/MHD simulations are just beginning to be applied to magnetically-driven implosions

Density, 60 Degree Wedge



Z-Pinch Plasma Density vs. R



3D (and even 2D!) Rad/MHD codes are just now becoming usable tools. Many issues remain to be worked through and benchmarked with experimental data.

The physics of shorting/current delivery is important to study and understand

R.W. Lemke *et al.*

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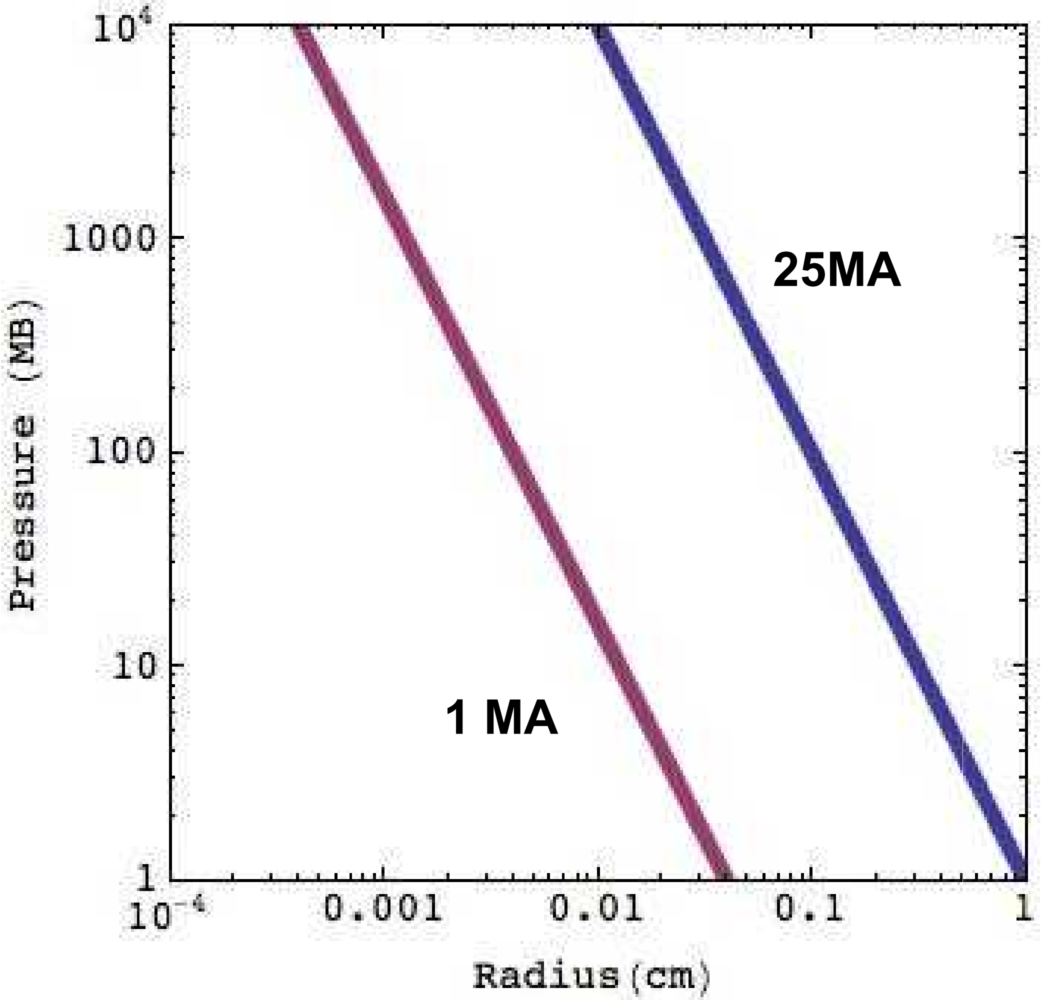
Magnetically driven implosions behave differently than radiation or laser driven implosions

Magnetic Pressure versus radius for a cylinder carrying current



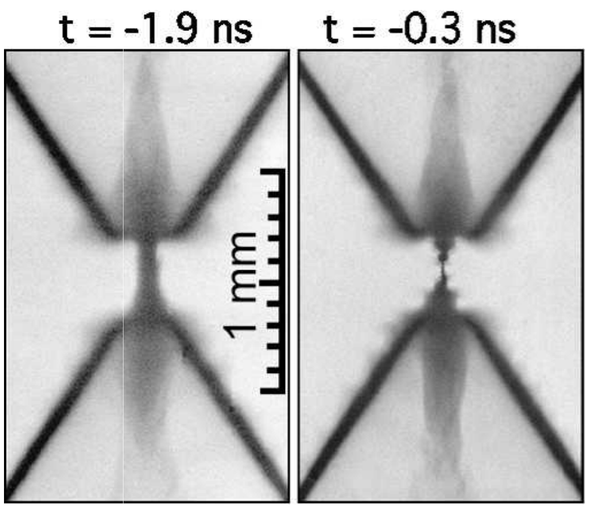
A current carrying cylinder is driven more strongly the farther it converges

25 MA at 1 mm radius has a magnetic pressure of 100 MB, like a 300 eV radiation source!

Fundamental question:
What limits the delivery of current to small radius?

200 kA X pinches are an extreme example of current reaching small radius

- **Diameter: 1.2±0.5 μm**[a]
- **Duration: 10-100 ps**[b]
- **T_e: ~1 keV (Ti[b], Mo[c])**
- **n_i: ≥0.1 * Solid density**[b,c]
- **Matter pressure at ~ 1g/cc and 1 keV is ~ 1 GB**
- **200 kA at 1micron radius has magnetic pressure of ~ 1GB!**



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

[a] B.M. Song *et al.*, Appl. Optics 44, 2349 (2005).
T.A. Shelkovenko *et al.*, RSI 72, 667 (2001).

[b] S.A. Pikuz *et al.*, PRL 89, 035003 (2002).
D.B. Sinars *et al.*, JQSRT 78, 61 (2003).

[c] S.B. Hansen *et al.*, PRE 70, 026402 (2004).

What enables the current to get to 1 micron?
What stops it at 1 micron?
What happens as we increase the current?

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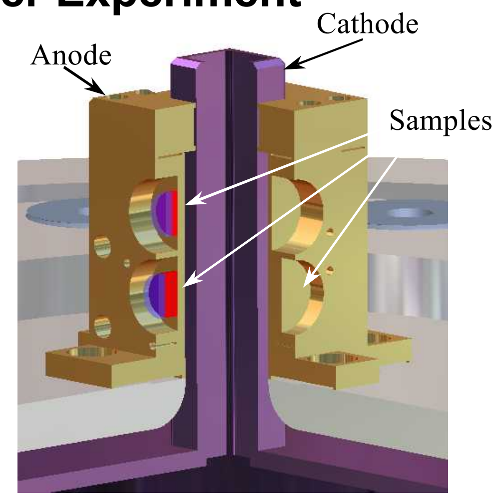
Codes

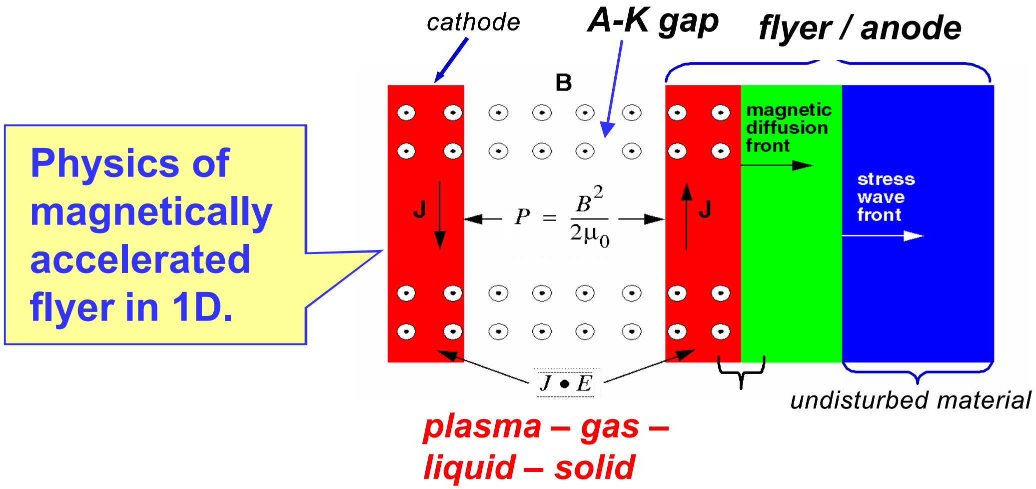
Precision Diagnostics

Opportunities

Magneto-hydrodynamics understanding enables the design of high velocity flyer plate experiments

Setup for High Velocity Flyer Experiment

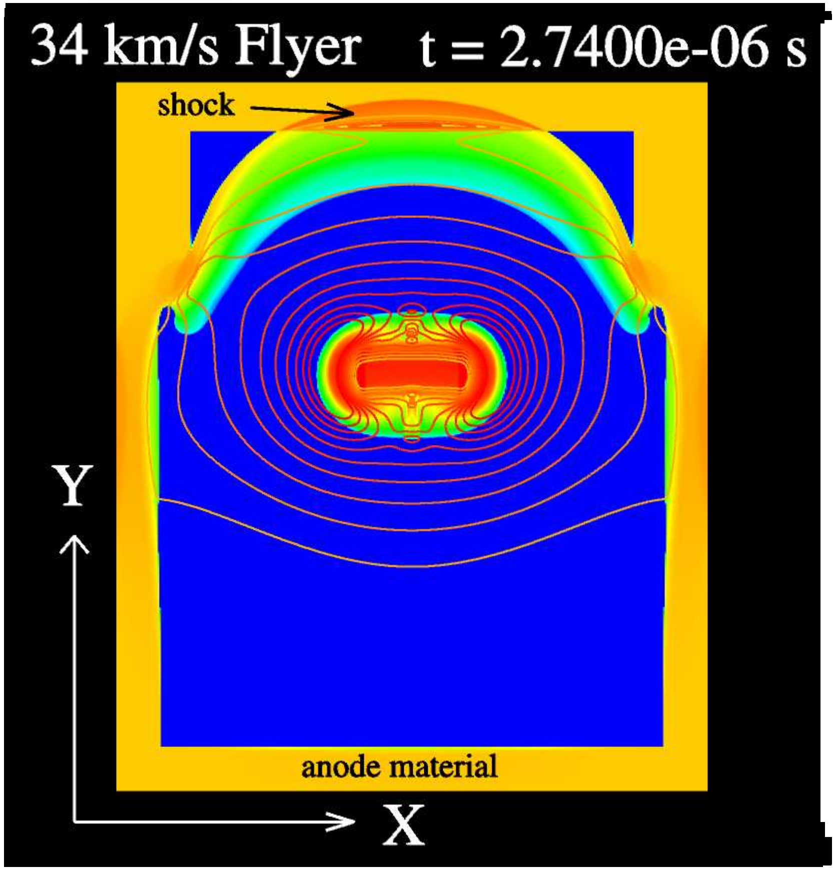


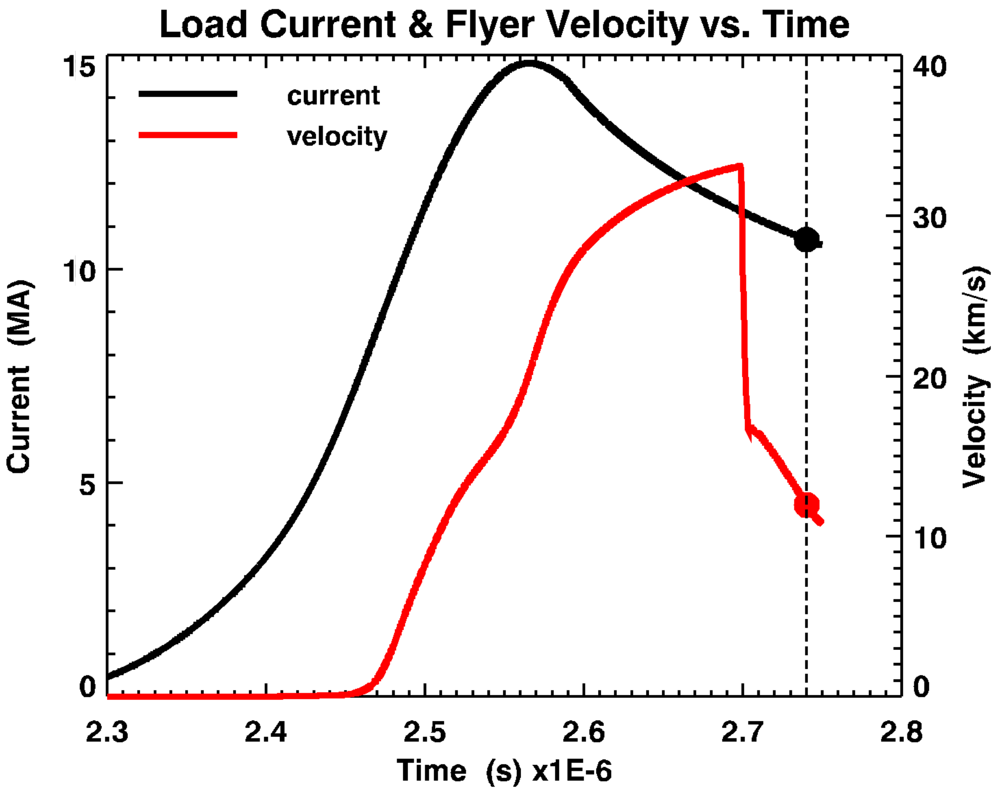


Goal is to create uniform, unmelted flyer at the appropriate velocity to get the highest data quality at the desired shock pressure

Many Laser Driven (Direct and Indirect), Zpinch Driven analogs for measuring fundamental properties (e.g. EOS or Opacity)

Snapshots from 2D numerical simulation show dynamics of flyer in high velocity experiment



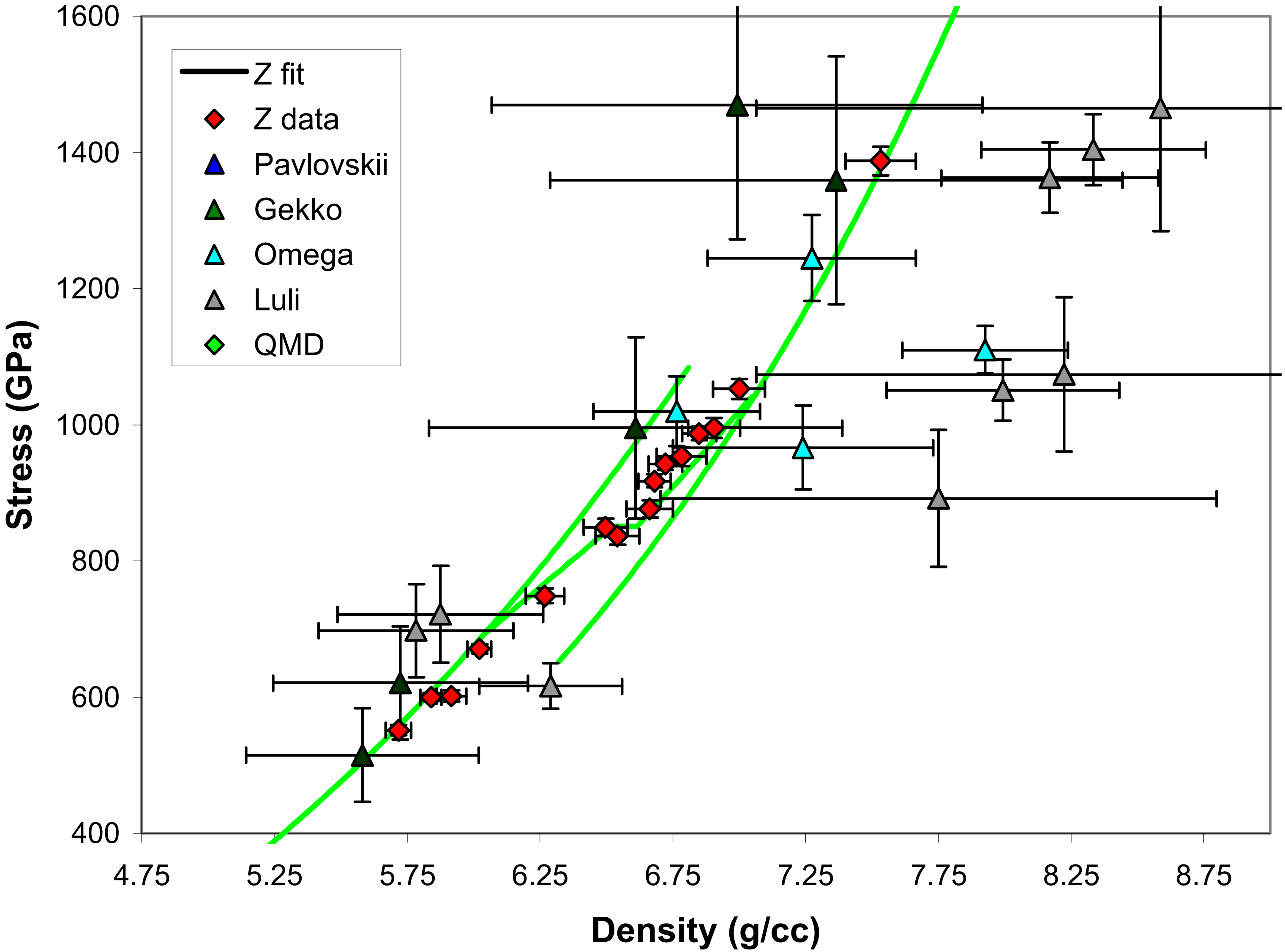


In these experiments conditions are much better defined (less integrated, typically single measurement, but conditions are also much less extreme)

Note velocity predictions have been in good agreement with experiment

Data for Diamond melt was obtained in this way

Stress versus density for Diamond



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Opportunities

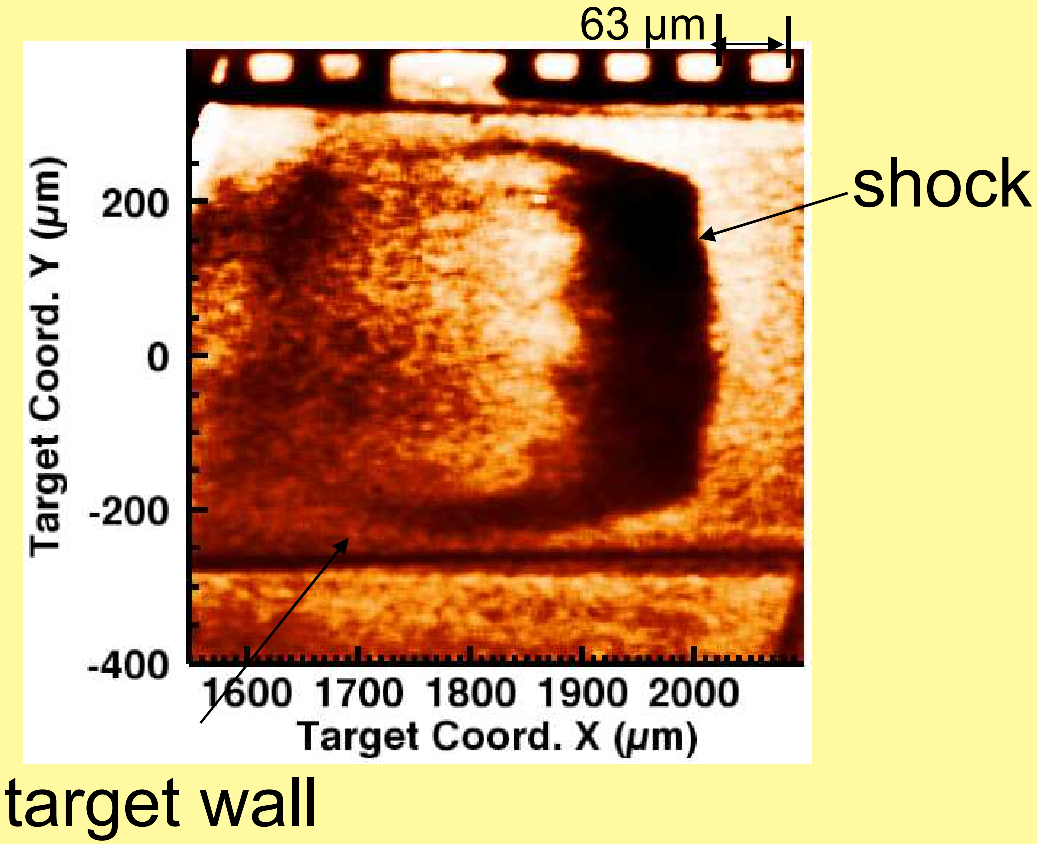
Radiating shocks appear throughout the universe

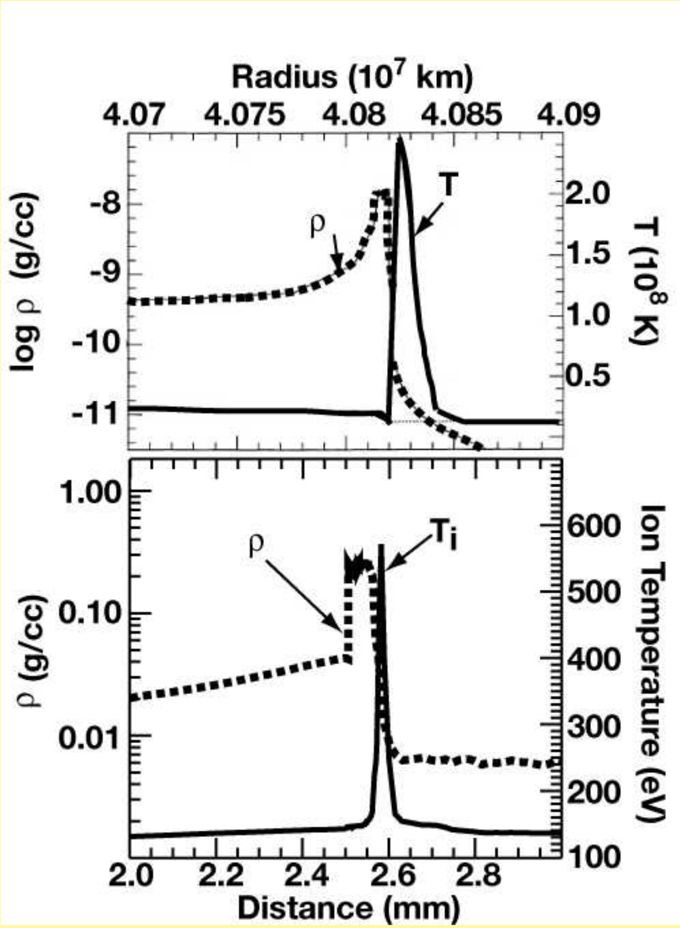
Thanks to Paul Drake, Aaron Edens

Radiative shocks on Omega have structural similarity to simulations of SN 1987A

- **Any fast enough shock becomes radiative**
  - **When the upstream radiation from the shock exceeds the incoming shocked energy flux:**

$$R_r = \frac{4(\gamma+1)}{\gamma}\frac{\sigma T_i^4}{\rho_o u_s^3} > 1$$





Structural similarity to SN 1987A

A.B. Reighard, et. al., Phys. Plasmas 2006, 2007
Ph.D. thesis, 2007

Thanks to Paul Drake

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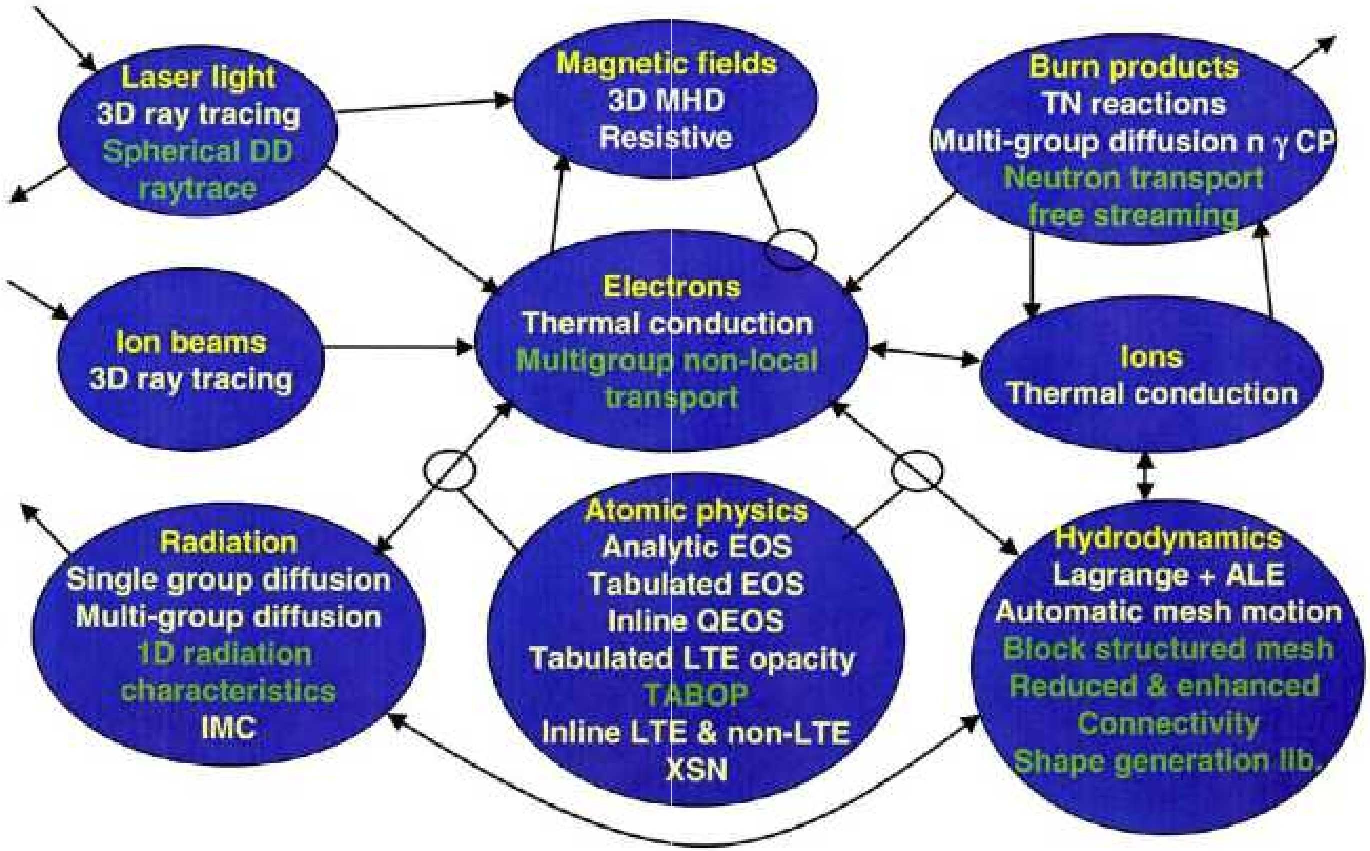
Precision Diagnostics

Opportunities

Multiphysics computational tools are indispensable aids in studying the science of HEDLP

HYDRA Physics Schematic from M. Marinak



Almost all interesting problems are not single physics issues, rather they have complicated interplays across physics areas

In developing the HEDLP community more open access to better Rad/MHD simulation tools is critical

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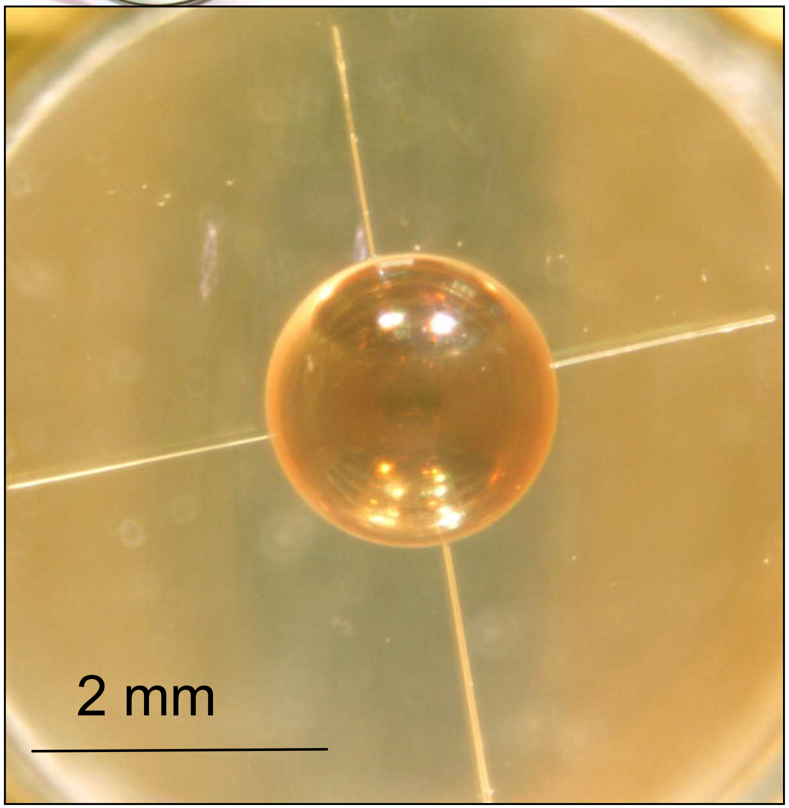
Codes

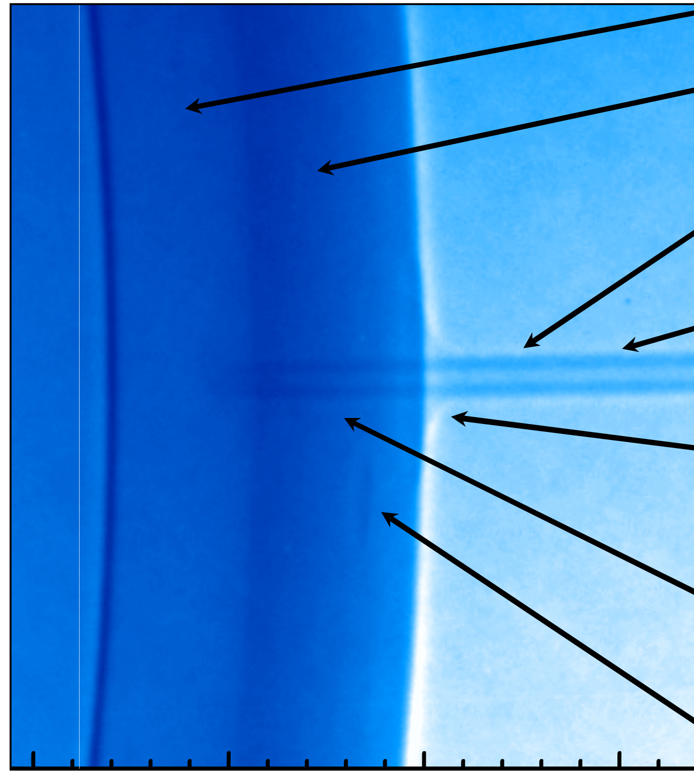
Precision Diagnostics

Opportunities

Precision metrology of targets is critical for doing high quality science

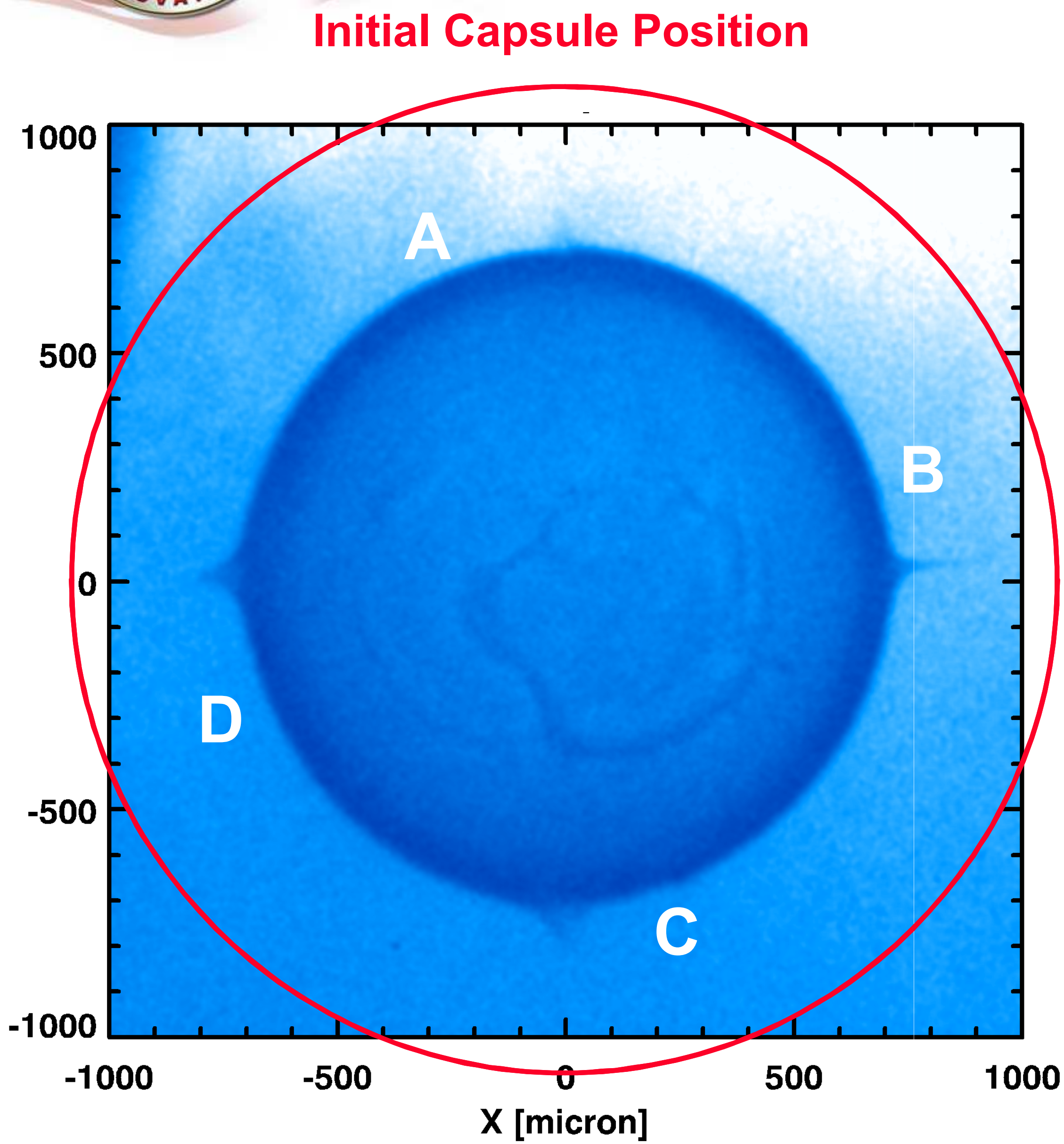


Optical image of CH capsule with 4 fill tubes (12-45 micron OD) attached around an equator



High resolution Xradia image of as built configuration gives important details for simulation

An image at convergence ratio 1.55 shows the perturbations from all 4 tubes developing

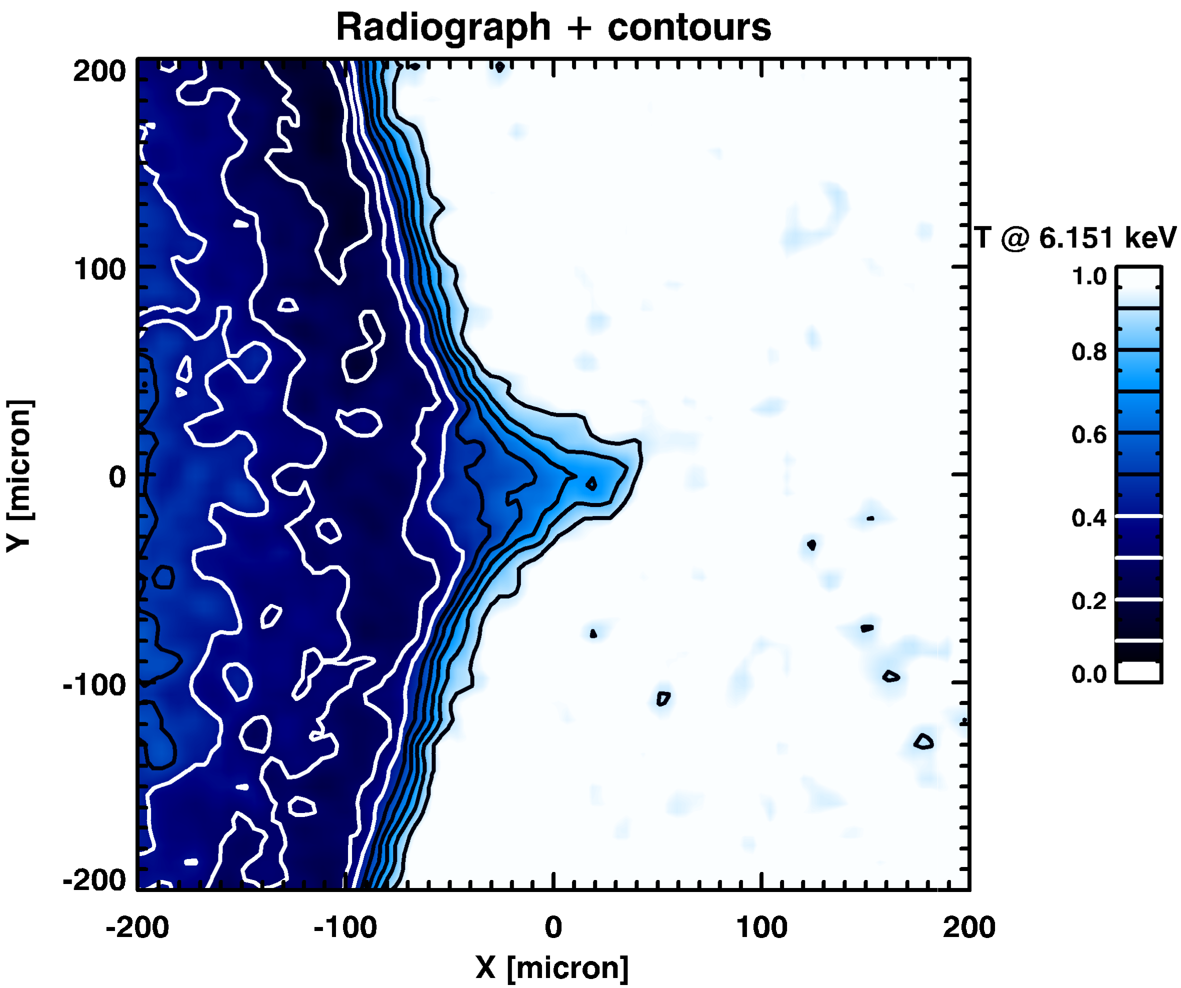


Tube	Diameter (microns)	Wall Thickness (microns)
A	12	3.5
B	26	7.7
C	31	8.0
D	44	12.0

Large field of view high spatial resolution monochromatic crystal imaging system leads to very high data quality.

Capsule implosion at 6.151 keV

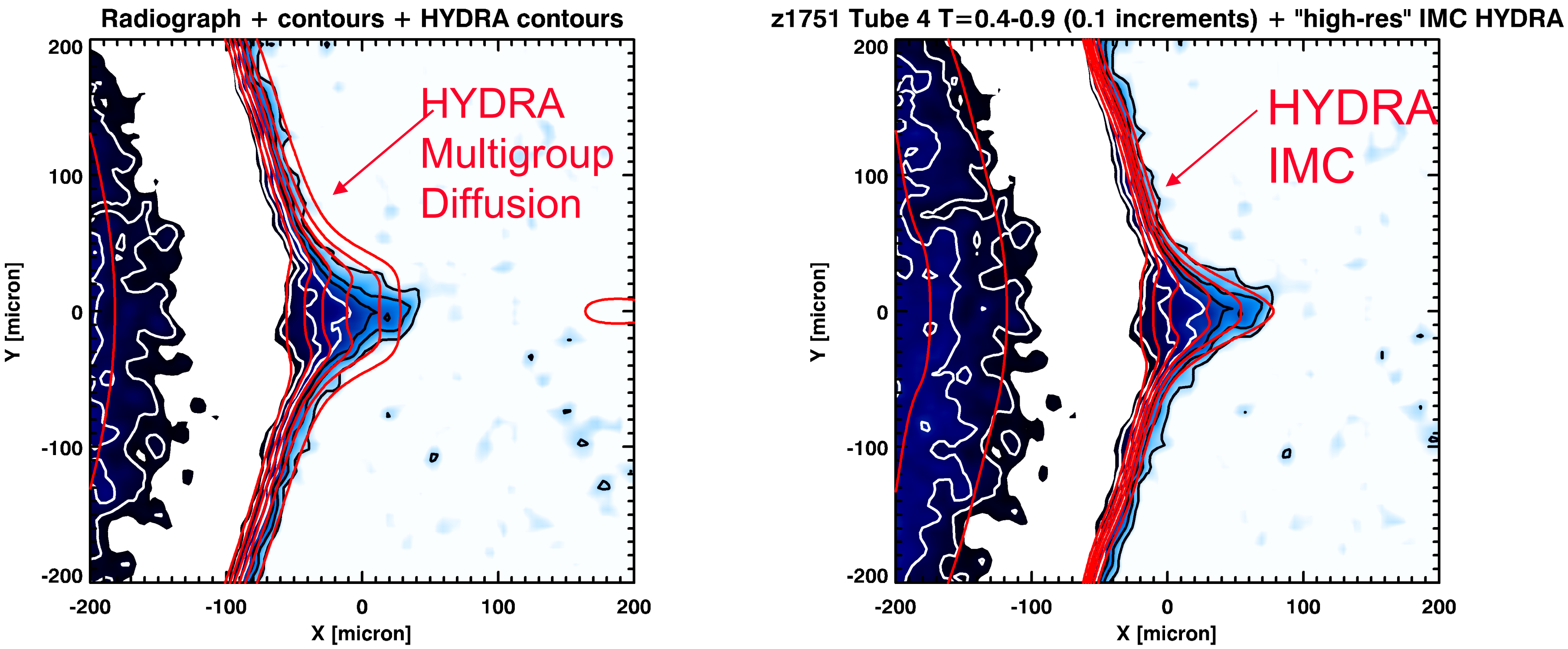
High quality data enables detailed, quantitative comparison with simulation



Tube D - 45 micron OD
CR = 1.55

- Good Signal-to-Noise ratio enables contour plot of experimental transmission values
- Note that each lower transmission contour is surrounded by its higher transmission neighbor
- In contrast, If the image was noisy, it would be dominated by isolated islands of transmission

Radiation Transport model leads to noticeable differences in the shape of the perturbation



Tube D - 45 micron OD CR = 1.55

G.R. Bennett, et al., PRL, (2007)

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Precision Diagnostics

Opportunities

Opportunities which can be addressed in the next 5 to 10 years

Creating and measuring high Mach number implosions in the laboratory, and achieving thermonuclear ignition

How do magnetically driven implosions work? What limits are there on current delivery in magnetic implosions? How do X-pinches work?

Development of widely accessible codes for simulating HEDLP plasmas

Increase in precision diagnostics to better probe HEDLP and constrain our understanding

My 2 cents:

What the field needs now is work that builds a firmer foundation on which to launch from for its most ambitious goals:

New measurements which provide new insights and new constraints on our Rad/MHD simulations

More thorough exploration (and documentation) on some of the basic problems (e.g. radiation transport)

Widely accessible computational tools

Large 3D calculations allow us to studied phenomena which have been too hard to model in the past

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Perturbation growth at the fuel ablator interface in an ICF capsule

Growth is very sensitive to detailed density profile (which depends on temperature profile, which depends on ablator opacity, equation of state, and thermal conductivity)

Measuring this growth in an imploding capsule is challenging

Calculations by Bruce Hammel, LLNL