



Laboratory Astrophysics and University Contributions In High Energy Density Physics

R. Paul Drake
University of Michigan

2006 NRC PLSC


QuickTime™ and a
TIFF (Uncompressed) decompressor
Work supported by the U.S. Department of Energy under grants DE-FG03-99DP00284, DE-FG03-00SF22021 and other grants and contracts.

We held the 10th-year anniversary HEDLA in March 2006

- Meetings every two years
- ~ 100 attendees from US, Europe, Japan
- Strong multidisciplinary attendance including key people
- Intermittant astrophysics attendees report substantial progress

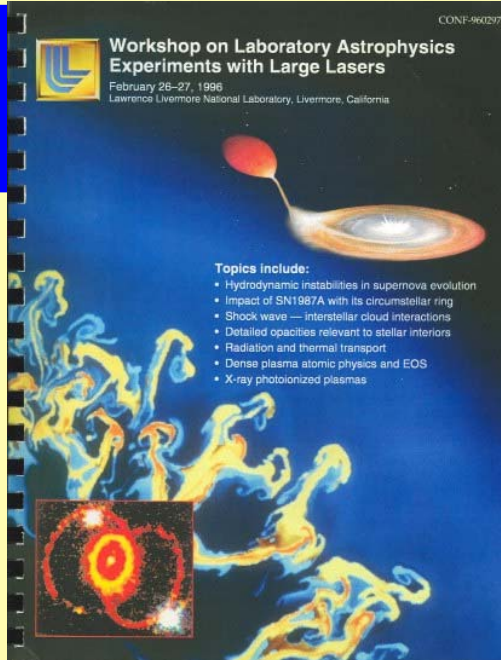
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CONF-960207



Workshop on Laboratory Astrophysics Experiments with Large Lasers

February 26-27, 1996
Lawrence Livermore National Laboratory, Livermore, California



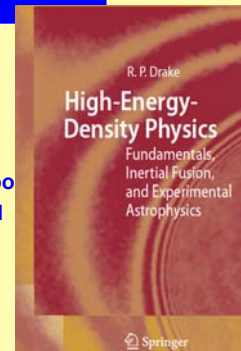
Topics include:

- Hydrodynamic instabilities in supernova evolution
- Impact of SN1987A with its circumstellar ring
- Shock wave — interstellar cloud interactions
- Detailed opacities relevant to stellar interiors
- Radiation and thermal transport
- Dense plasma atomic physics and EOS
- X-ray photoionized plasmas

Who am I and why am I here?



- **Who?**
 - A founder of high-energy-density laboratory astrophysics
 - A professor from Michigan, training graduate students
 - Author of the first graduate text in High-Energy-Density Physics (HEDP); provisor of a well-attended summer school
 - Leader of teams aimed at the National Ignition Facility and code validation experiments
 - Contributor to numerous areas of plasma physics and related fields
- **I'm here**
 - Because I am excited about the national potential of laboratory astrophysics and HEDP
- **I will discuss**
 - HED lab astro, my group, and our research
 - Our place in laboratory astrophysics & in NNSA
 - University roles in HEDP



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High-Energy-Density Physics

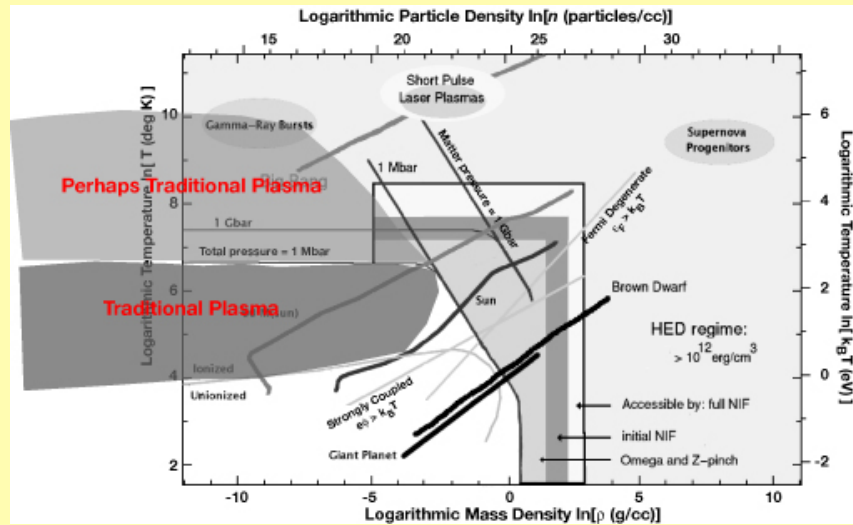


- The study of systems in which the pressure exceeds 1 Mbar ($= 0.1$ Tpasca = 10^{12} dynes/cm²), and of the methods by which such systems are produced.
- **Why does this matter for astrophysics?**
- **Direct answers**
 - pressures > 1 Mbar are important in planets
 - High-temperature dense matter is important in stars
- **Indirect answers**
 - Dynamics of Mach $\gg 2$ systems
 - $T \gg 1$ eV (10^4 K) and/or $\beta = (8\pi p/B^2) \gg 1$ systems
 - Radiation hydrodynamic systems
- We work in my group with high Mach number hydrodynamic and radiative hydrodynamic systems

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The relation of the high energy density regime to traditional plasmas



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Adapted from the NRC Report

HEDP plasmas are typically not traditional



Particles per Debye sphere; traditional plasmas have many

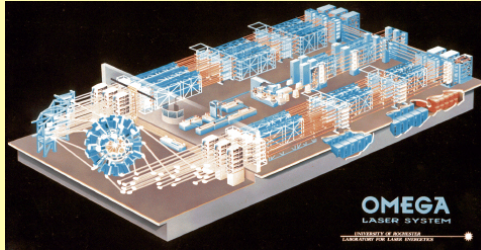
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

From Drake, *High-energy-density physics*, Springer 2006

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Omega is a major tool at present



Omega is at the Laboratory for Laser Energetics, affiliated with the University of Rochester.

Its primary mission is inertial fusion research.

There are lots of kJ, ns lasers around the world

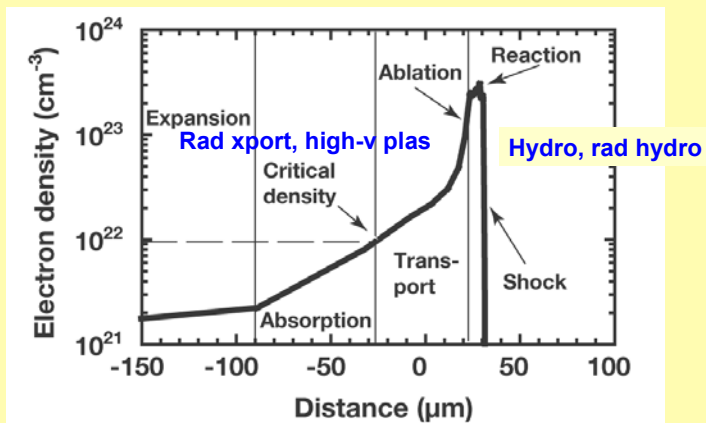


Target chamber at Omega laser

Here is what such lasers do to a material

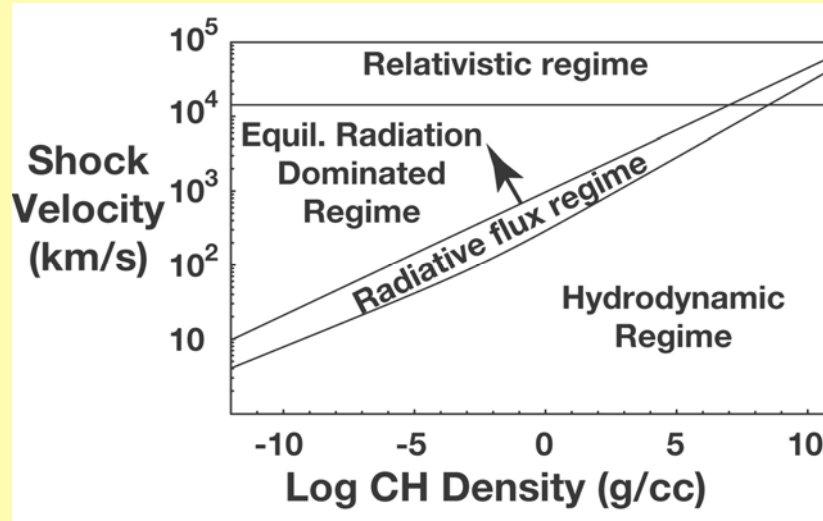


- The laser is absorbed at less than 1% of solid density



From Drake, *High-Energy-Density Physics*, Springer (2006)

Shock waves establish the regime of an experiment



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My group and the research we do



- Graduate students: Amy Reighard, Carolyn Kuranz, Eric Harding, Tony Visco, Forrest Doss
- B.S. Scientist: Mike Grosskopf
 - Leads target fabrication, does simulations
- Undergraduate students
 - Seniors: Trisha Donajkowski, Christine Krauland, Sebastien Lounis, Gurlovleen Rathore
 - Juniors: Donna Marion, Mariano Lowenstern
 - About 10 Freshmen & sophomores

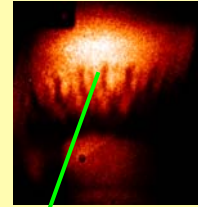
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.



Our research: Hydrodynamics and Radiation Hydrodynamics with Astrophysical Applications



- **Radiation hydrodynamics**
 - Radiative-shock experiments aimed at understanding and validation
 - First-ever Thomson scattering from a shock front
 - Have well-established radiative-shock environment
- **Blast-wave driven hydrodynamics**
 - Instability experiments aimed at understanding supernovae
 - Also useful for validation
 - First ever physics from dual orthogonal backlighting
 - Quantitative data on enhanced **Rayleigh-Taylor spike penetration**
- **The group provides NNSA-relevant, top-quality training**
 - Experience with experiments, simulations, diagnostics, targets, and data



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What we do at Michigan



- **We go to laser facilities for experiments**
- **At Michigan we**
 - Design experiments and measurements
 - Simulate experiments
 - Analyze data
 - Do some instrumentation research
 - and
- **We build targets**
 - Great educational value
 - Rapid innovation
 - Much cheaper than big labs
 - The labs did not think we could do this



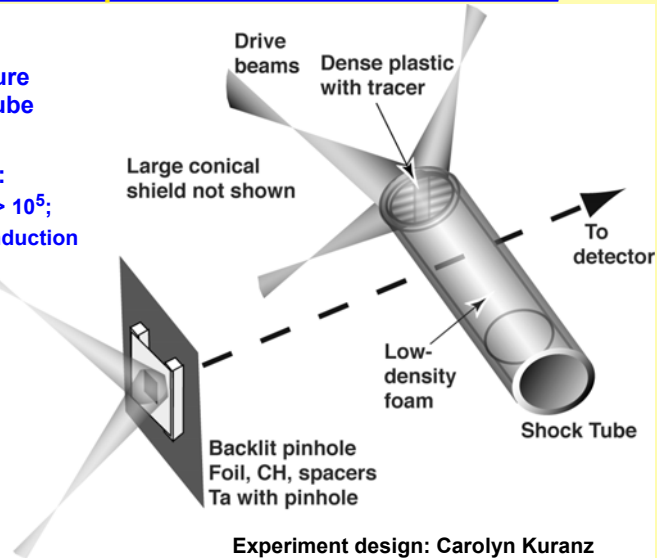
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Here is a typical target for our supernova hydrodynamics experiments



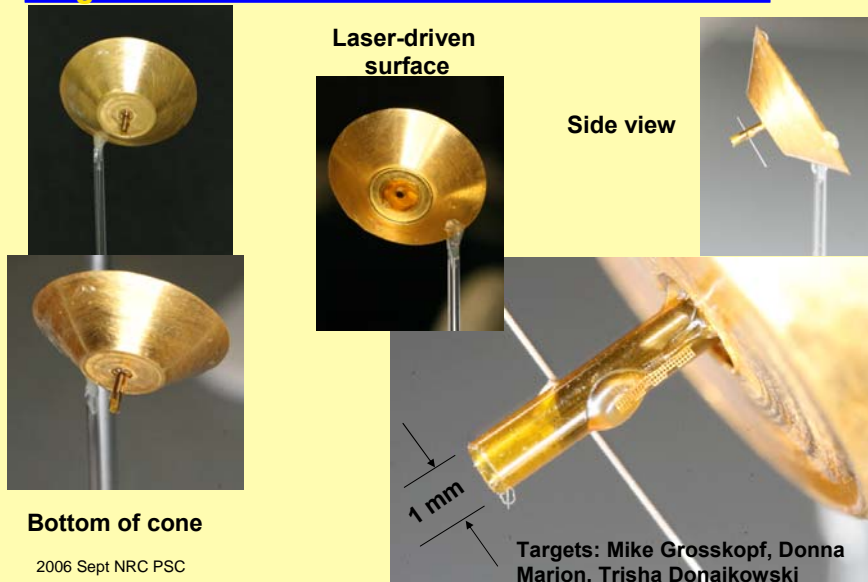
- Precision structure inside a shock tube
- Hydrodynamics:
 - $L \gg \lambda_{\text{mfp}}$; $Re > 10^5$;
 - small heat conduction & radiation



Experiment design: Carolyn Kuranz
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Photographs illustrate precision of as-built target



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Supernova 1987A motivates scaled hydrodynamic instability experiments



- SN 1987A
 - A core-collapse supernova
 - Early high-Z x-ray lines with large Doppler shifts
 - Early glow from radioactive heating
 - The issue is the post-core-collapse explosive behavior
- In 19 years of simulations
 - Only one (Kifonidis, 2006) makes fast enough high-Z material
 - 3D simulations coupling all the interfaces where initial conditions matter are not feasible
 - Experiments will be able to address this fully within a decade
 - We now address a single interface

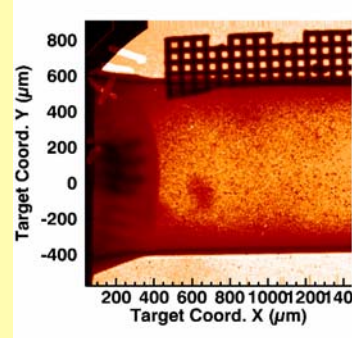
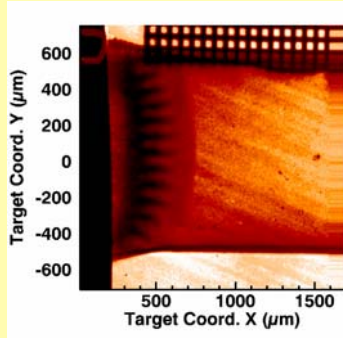


SN1987A, WFPC2, Hubble



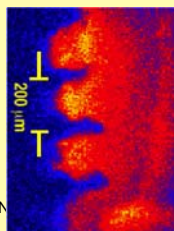
Kifonidis, 2003

We have recently begun getting data from two orthogonal directions



Data and analysis:
Carolyn Kuranz

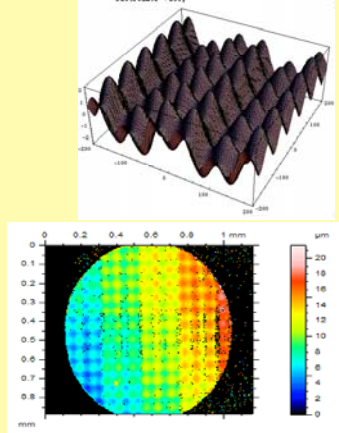
Mid-1990's data



We were the first group to get simultaneous orthogonal physics data (19 of 20 good exposures in May)

Our projects have made sustained and original contributions to the great improvements of the past decade. This has application to much core NNSA programmatic work.

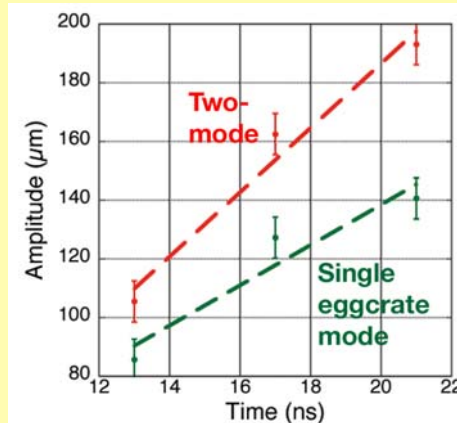
We are now observing the role of complex initial conditions in spike penetration



Interferogram of complex surface on component provided by GA (analysis: Kai Ravariere)

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Preliminary data on mix layer thickness



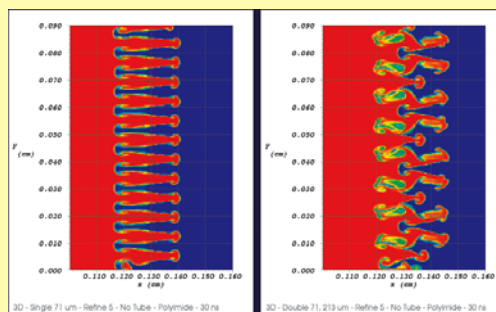
Data and analysis: Carolyn Kuranz

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We collaborate with simulation groups to evaluate our results and validate codes



Preliminary FLASH simulation at 30 ns of recent experiments



**Left: Single eggcrate mode.
Right: Two-mode system.**

- **Work with the FLASH Center (Chicago), to include 3D adaptive modeling, has now begun**

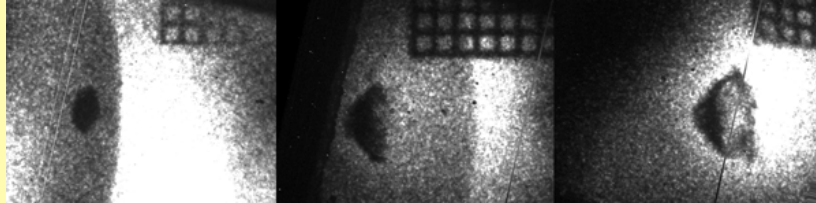
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An example of serendipity: experiments on clump destruction

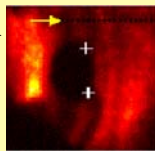


Clump destruction by blast wave (Robey et al. PRL)

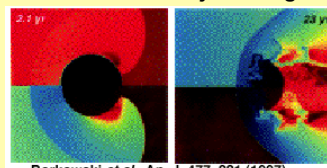


Clump destruction by steady flow (Kang et al. PRE)

QuickTime™ and a GIF decompressor are needed to see this picture.



Simulation of 1987A ejecta-ring collision



Borkowski et al., Ap. J. 477, 281 (1997)

Key scaling parameter: cloud crushing time $\sim d/v_{sc}$

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This has found application



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

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.nubiq girf eee of babeeb ene

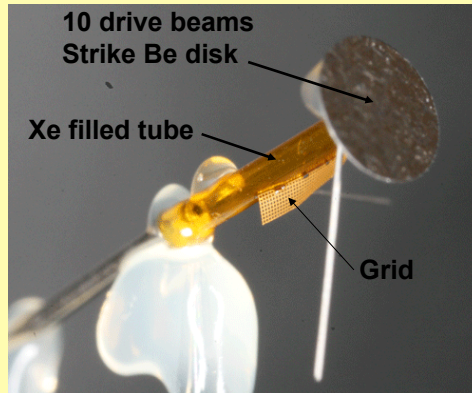
- Experimental results used to help interpret Chandra data from the Puppis A supernova remnant
- Well-scaled experiments have deep credibility
- Una Hwang et al., Astrophys. J. (2005)

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Turning to radiation hydrodynamics: creating a driven radiative shock in the laboratory M

- Laser beams launch Be piston into Xe or Ar gas at > 100 km/s
- Piston drives a planar shock
- Radiography detects dense xenon
- Gold grid provides spatial fiducial
- Parameters
 - 10^{15} W/cm²
 - 0.35 μ m light
 - 1 ns pulse
 - 600 μ m tube dia.

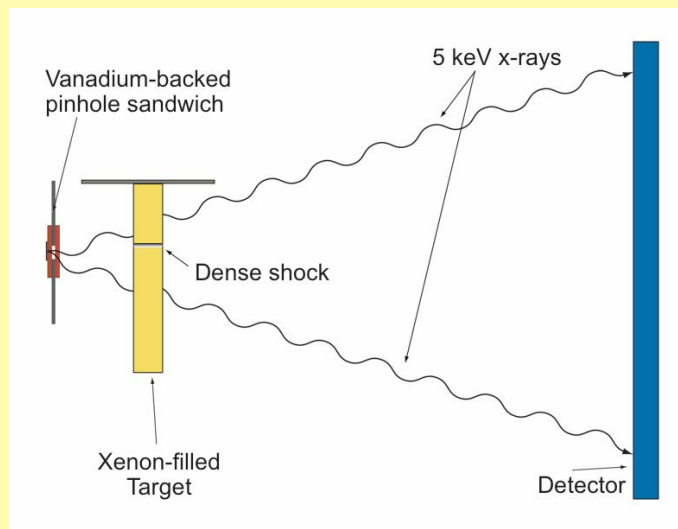


Target: Mike Grosskopf, Donna Marion, Mark Taylor

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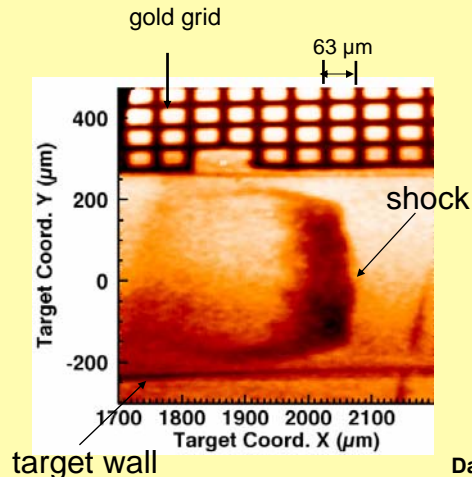
We observe the shocked material with backlit pinhole radiography M



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Here is one example of radiographic data from a radiative shock



- Average velocity 140 km/sec from $t = 0$ to 14.6 ns from laser firing
- Phys. Plasmas paper in print
- Invited talk at APS/DPP this fall

Data and analysis: Amy Reighard

Shot 39927

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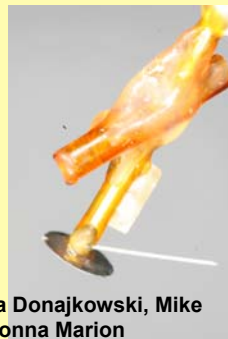
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We recently were the first group to obtain Thomson scattering data from a shock front



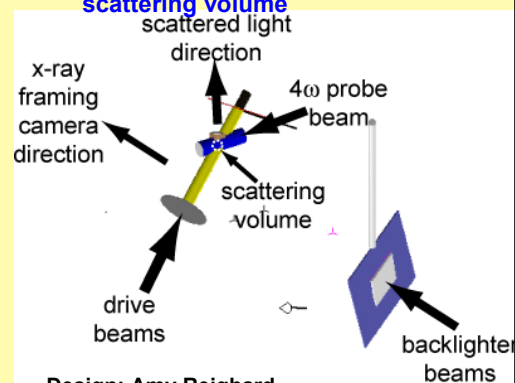
- Target includes 3000 Å windows for probe beam entrance and for scattered light exit.
- Drive beams create shock in argon
- Destroyer beam dissipates output window
- Backlighter beams attempt radiography
- Probe beam penetrates input window
- Streaked spectrometer detects signal as shock moves through scattering volume

- Collaboration with Dustin Froula and Siegfried Glenzer of LLNL



Target: Trisha Donajkowski, Mike Grosskopf, Donna Marion

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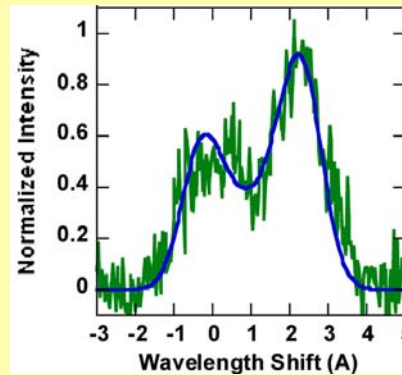


Design: Amy Reighard

The Thomson scattering data are powerful

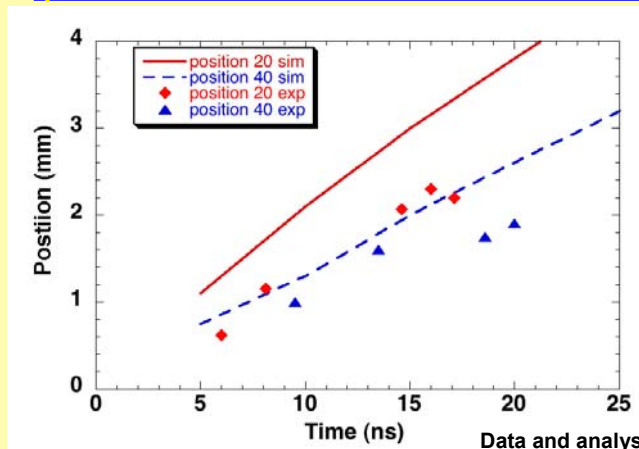


- Scattering is from acoustic waves
- Spectrum gives plasma parameters
- Fitting to data gives
 - 110 km/s fluid velocity
 - $ZT_e = 12 \times 300$ eV
 - $T_e \leq T_i \leq 500$ eV
- Timing, time-dependence, and fundamentals imply that these are the parameters in the post-shock cooling zone
- Publication in draft intended for Physical Review Letters



Data and analysis: Amy Reighard
With Dustin Froula

The trajectories of these shocks are not as predicted



Simulations are with HYADES using settings that give accurate results for thick-target pure-hydro experiments

Data and analysis: Amy Reighard

We plan to obtain further scaling data and are exploring the origin of the discrepancy

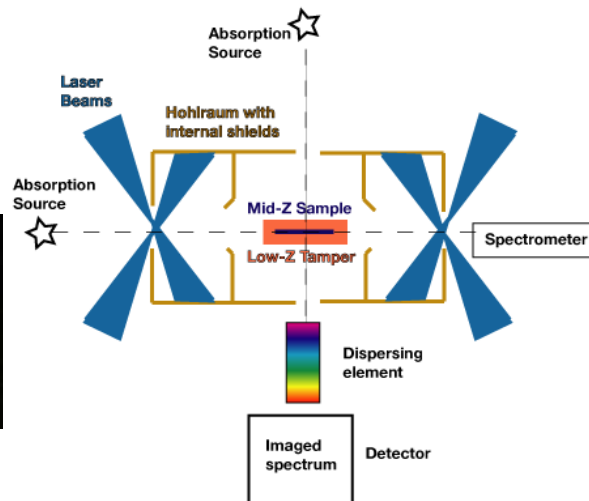
One can study x-ray opacities



- X-ray opacities matter!
 - light curves from Type Ia supernovae
 - Stellar radiative transport
 - Cepheid variables



Credit:
Jha et al.,
Harvard cfa



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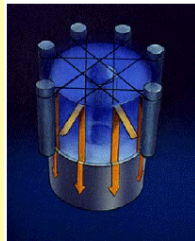
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Z pinches provide another high-energy environment



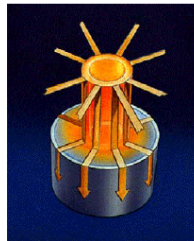
- Today's biggest x-ray barbecue is the Z machine at Sandia, when run as a Z pinch (~ 2 MJ of x-rays)
- Z pinches exploit the attraction between parallel currents

Cylindrical wire array



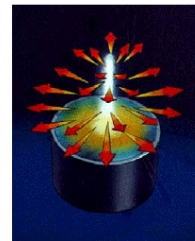
Inward $\mathbf{J} \times \mathbf{B}$ force

Implosion



Inward
acceleration

Stagnation



Shock heating &
Radiative cooling

Credit:
Keith Matsen

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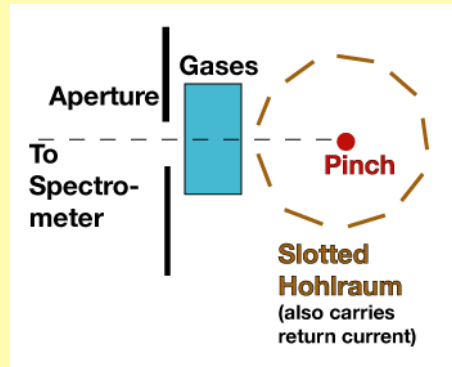
Photoionized plasmas are important



- To resolve discrepancies among existing models
- To interpret emission near black holes regarding whether Einstein had the last word on gravity
- To interpret emission near neutron stars to assess states of matter in huge magnetic fields

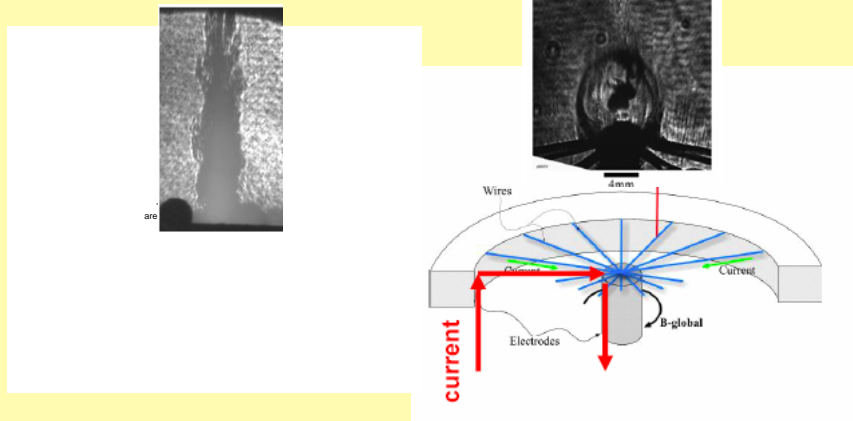


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We are seeing inventive uses of pinches for magnetized dynamic systems



- Jets
- Lebedev et al. here and in print

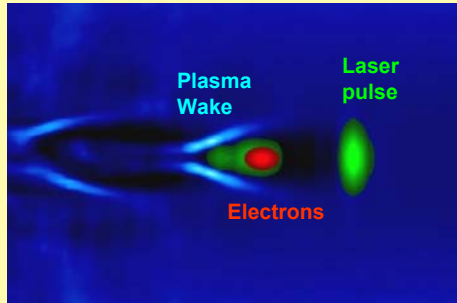
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Particle acceleration is progressing rapidly This should lead to astrophysical applications

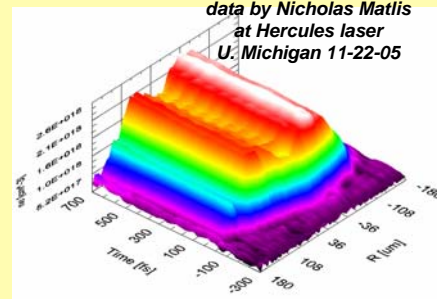


- Electrons can surf the wake on a pressure pulse in a plasma



Credit: LBL OASIS Group

State of the art:
monoenergetic electron
beams of hundreds of MeV



single shot frequency
domain holography

N. Matlis, M. C. Downer, A. M. Maksimchuk,
V. Yanovsky et al. (2006)

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So what matters for astrophysics?



- Relevant structures
 - Magnetic topologies
 - Particle jets
 - Interacting systems
 - Emission mechanisms
 - Diagnostics !!
- The ability to do controlled experiments
 - Create a known system
 - Interact something (e.g., a particle jet) with it



Relativistic Jet Simulations
Hughes, Miller, Duncan, Hardee

http://www.astro.lsa.umich.edu/users/hughes/icon_dir/relproj.html

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Recent reports highlight the scientific opportunities in laboratory astrophysics



- The NRC Committee on the Physics of the Universe April 2002 – *Connecting Quarks with the Cosmos: 11 Science Questions for the New Century*. Recommendation (#6 of 7):
 - “Discern the physical principles that govern extreme astrophysical environments through the laboratory study of **high energy density physics**. The Committee recommends that the agencies (DOE, NSF, NASA) cooperate in bringing together the different scientific communities that can foster this rapidly developing field.”
- The NRC Committee on High Energy Density Plasma Physics Oct. 30, 2002 – *Frontiers in High Energy Density Physics: the X-Games of Contemporary Science*. Recommendations:
 - “federal interagency collaborations should be strengthened in **fostering high energy density basic science**”
 - “significant federal resources should be devoted to supporting high energy density physics research at university scale facilities”

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HEDP facilities have a role to play in the “Quarks to Cosmos” context



- **Dark energy (Type Ia supernovae)**
 - Turbulent hydro, radiation hydro, opacities, radiation transfer, others
- **Gravity**
 - Spectroscopy in photoionized plasmas, relativistic plasma effects
- **Cosmic accelerators**
 - Relativistic acceleration mechanisms
- **New states of matter at high density and temperature?**
 - Atoms at 10^9 Gauss, photoionized plasmas, radiation dominated plasmas
- **Origin of the heavy elements**
 - Supernova hydrodynamics & turbulence, neutrino transport analogs, post-ignition nucleosynthesis studies
- **Matter and light in strong fields**
 - High-field science and photoionized plasmas
- **Reference: OPPORTUNITIES FOR FRONTIER HIGH-ENERGY-DENSITY RESEARCH: CONNECTING NNSA WITH THE QUARKS-TO-COSMOS INITIATIVE**, by B.A. Remington and R.P. Drake



Type Ia

Black hole



Credit: Joe Bergeron

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Our place in laboratory astrophysics



- High Energy Density Laboratory Astrophysics (HEDLA)
 - Radiation Hydrodynamics
 - Hydrodynamics
 - Equation of State
 - Opacity and Radiation Transport
 - Relativistic phenomena (e.g., Weibel)
- Transitional regimes (HEDLA)
 - MHD jets and magnetic towers
- Magnetized plasma laboratory astrophysics (IPELS attendees)
 - Reconnection
 - Alfvén wave physics
 - Instabilities relevant to magnetospheric plasmas
 - Dusty plasmas
 - Probably others
- The Plasma Science Committee could address the entire scope of laboratory astrophysics
- The rest of my remarks will address high-energy-density physics

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Why HEDLA is important to NNSA



- Providing trained young people
 - The scientific population at the NNSA labs is aging rapidly
 - Over the next few years the National Ignition Facility will need a new generation
 - I could have easily placed 5 new Ph.D.s this year
- Advancing NNSA-relevant fundamental science
 - Most work in the labs is programmatic
 - Universities have a role to play in doing detailed, systematic, fundamental work
- Establishing a national community and national advocacy
- We have a marginal role in diagnostic technology
 - More later on this point

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HED Lab astro contributes to the need for an increased university presence



From the High-Energy-Density Physics Study Report

A Comprehensive Study of the Role of High-Energy-Density Physics in the Stockpile Stewardship Program April 6, 2001

The SSP faces a significant conundrum [*aging and retirements*].

One of the foremost goals of the HEDP Program is training U.S. scientists in ... the pillars including HEDP.

A successful NIF and a vigorous HEDP Program may contribute to reversing the observed negative trend in attracting highly talented individuals to the weapons program.

A viable HEDP Program, including NIF, will encourage university presence in HEDP.

- The intellectual vitality, personnel quality, and political influence of the SSP would be positively affected by a larger NNSA university program.

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Michigan aspires to become a major contributor to high-energy-density physics



- Top quality adaptive 3D hydrodynamic computations
 - Gombosi, Powell, Van Leer, Rowe
 - Implicit models now adapted with good parallel scaling
 - Equation of state expertise in materials science
- Established and forefront work in radiation transport modeling
 - Larsen, Martin, Holloway
 - Riemann solvers for time-dependent radiation transport
- Experience with the computer science of such codes
 - Stout and others in EECS
- Experiments at high energy and high intensity
 - Drake, Krushelnik, Gilgenbach, others
 - Can be validation experiments
- Many US citizen grad students
 - a tradition of sending them to the NNSA labs
- We hope to succeed with a proposal to the current Advanced Scientific Computing call

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Beyond Michigan: Current university activity in HEDP including HED laboratory astrophysics

- **About 8 significant experimental programs**
 - It takes ~ 1 M\$ to have a concentrated focus and the potential to produce a regular flow of students
 - Distribution is ~ 5 NNSA, 1 NSF, 1 DOE/HEP
- **Comparatively few substantial theoretical programs**
 - Perhaps 2 substantial programs
 - A modest number of small efforts
- **About a dozen smaller grants**
 - Mostly NNSA, some other
 - 17 universities have faculty on the High Energy Density Science Association distribution list
- **We are seeing some university hiring into this area**
 - The assistant professors need more funding from more sources
 - More funding and a history of stability are needed to increase university hiring
 - There is real potential here!

Turning to the role of universities in and beyond HEDP

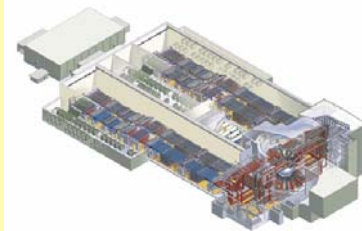
- **Experiments at major facilities**
 - Supporting facilities at universities
- **University diagnostic research**
- **University experimental facilities**

University experiments at the National Ignition Facility



- Only experienced teams can attempt this
- There are several qualified team leaders nationally
- Three teams are now funded to prepare proposals for NIF experiments
 - Drake, Michigan (supernova hydro)
 - Jeanloz, Berkeley (planetary EOS)
 - Neimann, UCLA (laser plasma interactions)
- Each of these teams has several members and lab participation

National Ignition Facility



Preliminary experiment design



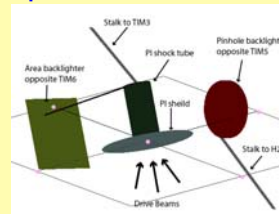
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Science experiments on NIF cannot be productive without staging and training facilities



- NIF will have few shots in strong demand. Success matters.
 - NIF can produce some great science and good experiences
 - It will produce few Ph.D. theses
- Staging facilities needed
 - To test diagnostics
 - To test physics uncertainties
- Training facilities needed
 - To enable science that can't be done on NIF
 - To grow the community by providing opportunity
 - For diagnostic development work
- A specific need for staging for the Michigan-led NIF project was identified at the Supernova Hydrodynamics Experiments Workshop my team held in Tucson this week



Omega target

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Experiments at other major facilities



- Omega is the primary example via the NLUF program at the Omega laser
 - Less than 10 users
 - This program should be expanded
- Use of other facilities is more informal
 - To grow this community more is needed
 - NNSA is moving in this direction
- Supporting university facilities are involved in these efforts
 - Target fabrication, as now at Michigan
 - Diagnostic support facilities, as now at MIT
 - Simulation, data analysis, etc.
- Europe is far ahead of the US in this area, with 3+ very active user facilities on such an intermediate scale

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Diagnostic research facilities are needed!



- Experiments depend essentially on diagnostics
 - Diagnostics are problematic for NIF
- The big labs only do diagnostic development under duress
 - The current system of crash programs that then dissipate is hideously wasteful and expensive
- The HED community needs this element
 - This is a proven mode way to get technology, training, and broad participation!!
 - Other communities use university diagnostic groups extensively and effectively
 - There are few (perhaps one?) groups that develop diagnostics for HED facilities as a major activity
 - Such a program would enable steady transformative progress in HEDP diagnostics
 - It also would create pipeline of trained students advancing the state of the art in diagnostics
 - It needs to be separate, as diagnostics are slow and expensive compared with facility use



X-ray source for diagnostic development and testing

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University experimental facilities also have a role to play



- **Functions of university experimental facilities**
 - Train students in the technical details of experimental systems
 - Accomplish thorough research on some topics
 - The small scale is both limiting and enabling
 - Further broaden the community
- **Existing university experimental facilities**
 - Two-plus ultrafast high-field lasers (NSF funded, NNSA funded)
 - Approx. five Z-pinch or related facilities
 - No kiloJoule class lasers
 - No user facilities within universities
 - LLE is a lab with a mission, neither a science user facility nor really in a university

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The national need in basic HED physics and laboratory astrophysics



- **Seek a more balanced community and a national program**
 - Grow the community outside the NNSA labs
 - The goal should be to attract steady hiring of tenure track faculty
 - Create and sustain staging and training facilities and increase the access to those that exist
 - Start a university diagnostics program
 - Greatly increase university efforts in HEDP theory and simulation
 - Close ties to NNSA are both a strength and a limitation
- **Broad, steady, university support will pay enormous scientific, manpower, and political dividends**
- There is a natural coupling of HEDP and astrophysics
- There is a wide range of laboratory astrophysics beyond HEDP

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