Joint Program in HEDLP: OFES Perspective

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www.ofes.fusion.doe.gov

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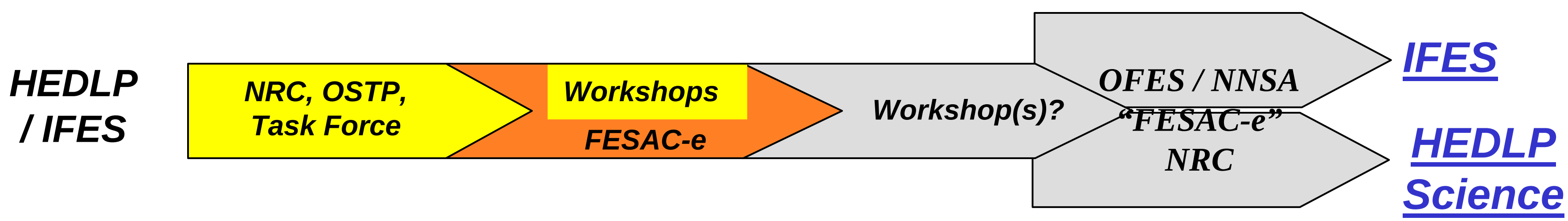
Joint Program in HEDLP

- OFES interests in the Joint Program
  - Improve stewardship of Federal Government HEDLP program
  - Energy-related HEDLP studies to support case for IFES research in future
- Interested in exploiting scientific opportunities in large NNSA facilities
- Competition and diversities will be encouraged in the program
- First joint solicitation planned in FY2008 for FY2009 funding
- Planning follows same paradigm as for other OFES planning activities
  - FESAC to inform development of HEDLP program scientific roadmap for the next decade
  - Expect to follow with Workshop and consolidation of issues



HEDP-Research Topics
& Related Federal Research Categories

Federal Research Categories	**Research Examples**
Astrophysics (NASA, NSF)	Astrophysical jets Neutron star interiors Core-collapse supernovae
High Energy Density Nuclear Physics (DOE/NP)	Quark-gluon plasmas; Nuclear astrophysics
High Energy Density Laboratory Plasmas (DOE/NNSA, DOE/FES)	**Radiative hydrodynamics** **Laser-plasma and beam-plasma interaction** **Fusion burn** **Materials under extreme conditions** **Dense plasmas in ultrahigh fields** **Laboratory astrophysics**
Ultrafast, Ultraintense Laser Science (NSF, DOE/BES)	Ultraintense x-rays for material science studies; applications of ultraintense lasers to chemistry and materials; advanced accelerators

Current OFES research in HED plasmas

- Scientific Themes
  - Develop the physics basis of pulsed, high density approach to fusion energy by studying HED plasmas
  - Create, probe, and control new states of HED plasmas
- Research covers fundamental areas of HEDLP physics
  - Warm dense matter
  - Laser-plasma, radiation-matter interaction
  - Relativistic plasmas
  - Dense plasma in high magnetic fields
  - Compressible, radiative MHD
- Research in support of three applications in IFES
  - Heavy ion fusion
  - Fast and shock ignition
  - Magneto-inertial fusion

Current OFES Research in HEDLP

- Warm Dense Matter (Heavy ion fusion)
  - $8.14M, 5 grants, 3 labs, 1 university, 1 industry
- Laser-plasma, radiation-matter interaction and relativistic plasmas (fast Ignition, shock ignition)
  - $5.4M, 9 grants, 4 labs, 5 universities
  - $1.1M, Fusion Science Center at U. Rochester
- Dense plasma in high magnetic fields, compressible, radiative MHD (Magneto-inertial fusion, astrophysical jets, and other)
  - $4.71M, 17 grants, 4 labs, 10 Universities, 4 industries

HED projects in the past ICC program have been consolidated to the Joint Program in HEDLP in FY 2008

- HED ICCs consolidated into the Joint Program in HEDLP
  - Form the core of the program in dense plasmas in high magnetic fields (magnetized HEDLP):
    - Solid-liner MTF
    - Plasma-jet driven MTF
    - Dense-plasma wall interactions
    - Magneto-kinetic compression of FRC
    - Staged Z-pinch
- In addition, the SSPX group at LLNL has been re-directed towards a program in fast ignition and HED science to take advantage of major NNSA facilities.

With the limited funding at present, the OFES focus in IFES related HED research is modest ……

- In particular, we focus on studying ways to lower the implosion velocity and increasing coupling efficiency as one avenue towards higher fusion gain, while achieving ignition
  - Long-term, IFES requires higher gains, suitable targets and drivers, at reasonable costs
- Addressing the physics basis for three different approaches to achieve lower implosion velocity and higher coupling efficiency
  - Decoupling ignition from fuel assembly so that the dense fuel can be assembled with low implosion velocity
    - Fast ignition, shock ignition
  - Embedding an intense magnetic field in the target to slow down thermal losses from the hot spot, thus lower the implosion velocity required
    - Magneto-inertial fusion (magnetized target fusion)
  - Heavy ions have potentially higher efficiency in coupling to the target hydro
    - Heavy ion fusion

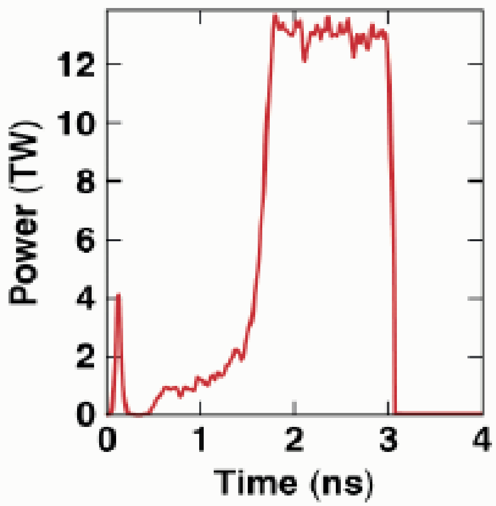
With our international partners, we are working towards testing the Fast Ignition concept …..

- Develop the scientific knowledge base to enable design of ignition-class FI experiments in the next 5 years
  - Develop low-velocity, low-adiabat fuel assembly
  - Unravel the physics of ignitor energy creation and transmission
  - Develop modeling capability for designing integrated FI
- Currently funded research emphasizes electron fast ignitor
  - We would like to mount a major effort in ion fast ignitor, subject to receiving high-quality, competitive proposals
- Proposed program schedule
  - Develop scientific knowledge base to enable design of Q ~ 0.1 integrated FI experiment (2010)
  - Field integrated FI experiments and demonstrate Q ~ 0.1 (2012)
  - Design and field ignition class experiments on NIF (2015)

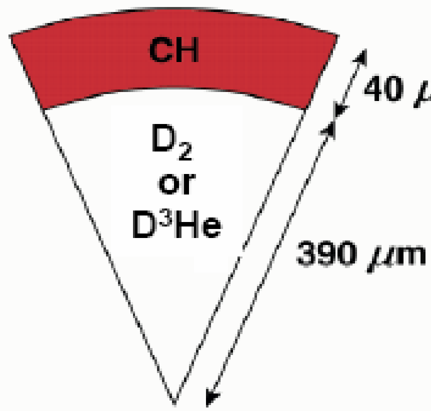
Slow implosions with low adiabat were tested on OMEGA D-^{3}He fusion proton energy loss measured the high ρR

$E_L \approx 20$kJ $P \approx 25$-34atm $\alpha \approx 1.3$ $V \approx 2 \cdot 10^7$cm/s

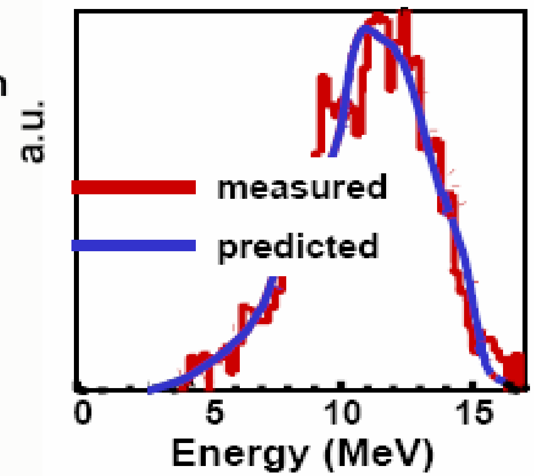
Laser pulse



Target



Secondary proton spectrum



- Peak ρR is 0.26g/cm,^{2} the highest ρR to date on OMEGA
- Empty shells would achieve $\rho R \approx 0.7$g/cm^2 and stop 4MeV electrons

Warm (CH) thick-shell cone-target implosions in '08

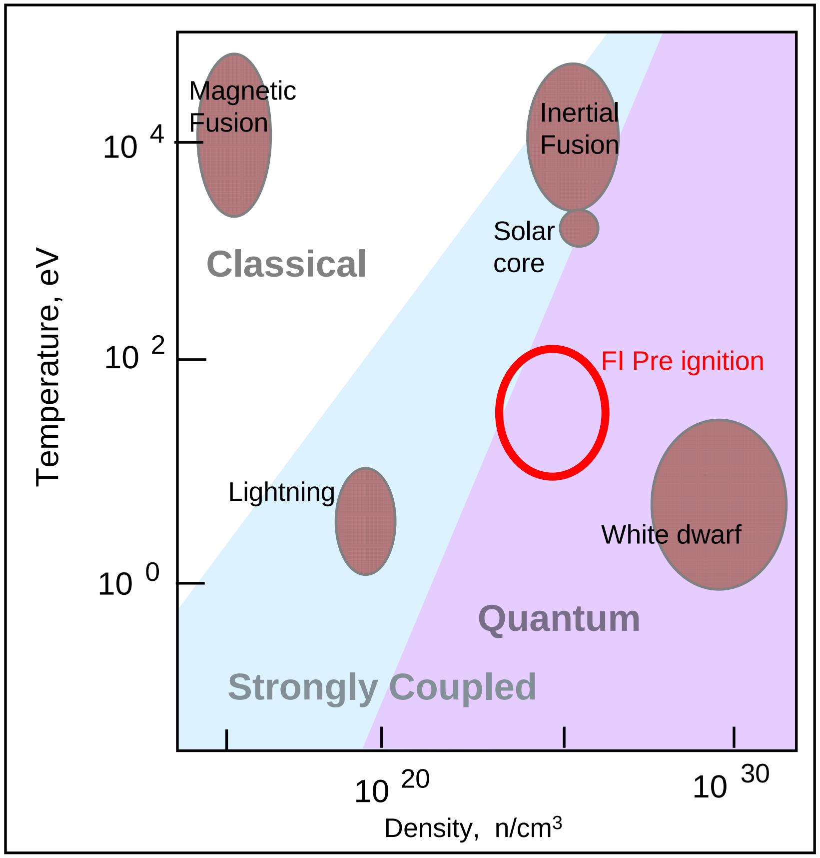
C. Zhou, W. Theobald, R. Betti, P.B. Radha, V. Smalyuk, *et al*, Phys. Rev. Lett. 98: 025004 (2007)

We are developing a predictive understanding of the igniter physics – energy transmission

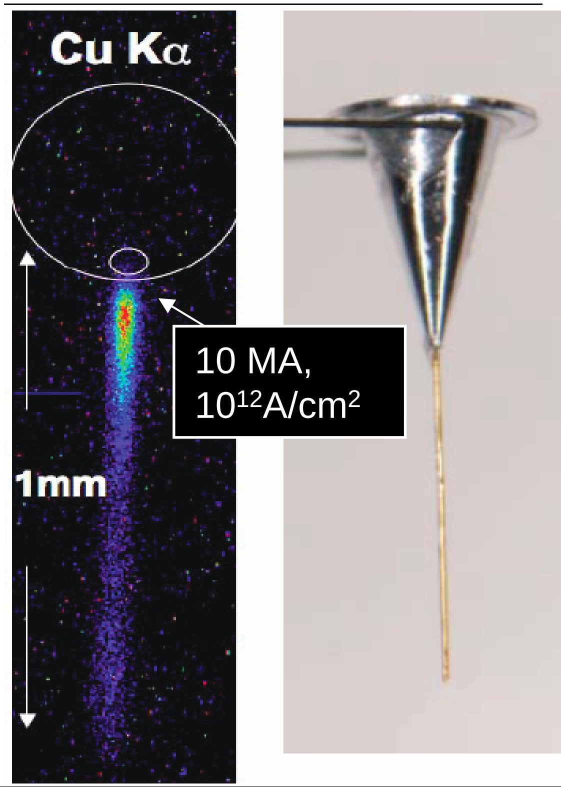
- We do not yet have predictive capability for the transport of relativistic electrons in dense plasmas against an adverse density gradient

- Involves new regimes of high energy density plasmas
  - Equation of states
  - Transport properties
    - Electrical, thermal
    - In the presence of magnetic fields
  - Beam and plasma instabilities
    - Weibel instabilities

- Experiments are required to guide and benchmark the codes



Experiments to develop and benchmark the codes include ………



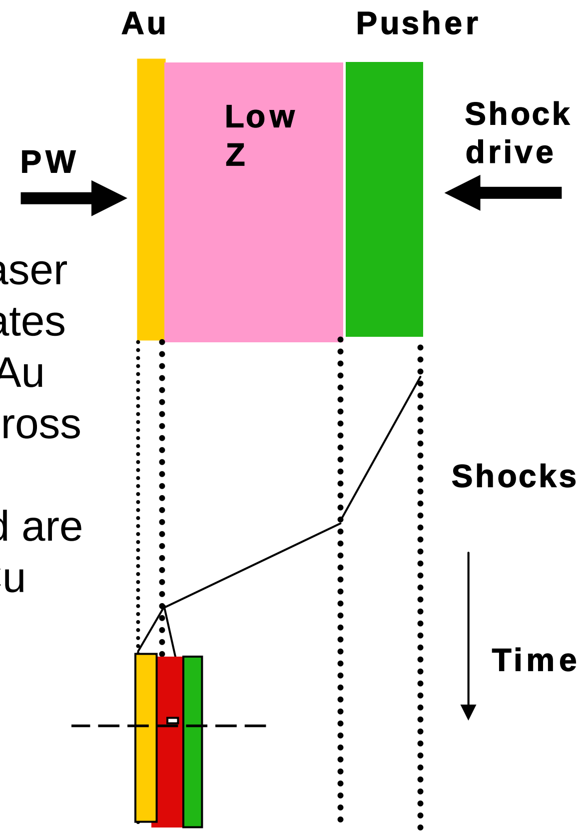
Cone-wire experiment to study relativistic electron transport in dense plasmas

Understand transport in cold metal OK - need to extend work to hot plasma

Shock driven foam experiment emulates FI cone tip at stagnation

- Explores the bottle-neck issue

- 50 J 1 ps laser pulse generates electrons in Au
- Electrons cross the Au/CH interface and are counted in Cu



300 J, 1 ns

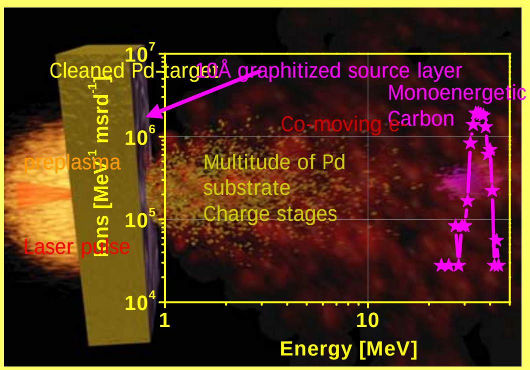
Accelerates Al/Cu flyer plate

Compresses foam to 1 g/cc

Heats it to 20 eV

In ion fast ignitor research, beam focusing and photon-ion energy conversion efficiency need to be characterized

At Los Alamos National Laboratory Trident Laser Facility, laser-driven mono-energetic ion acceleration was first demonstrated

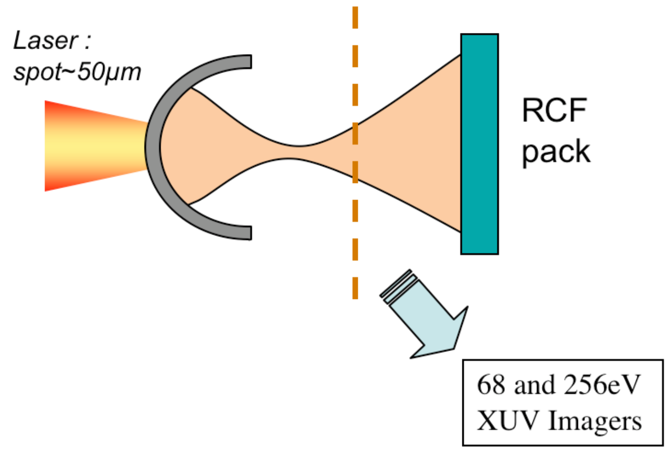


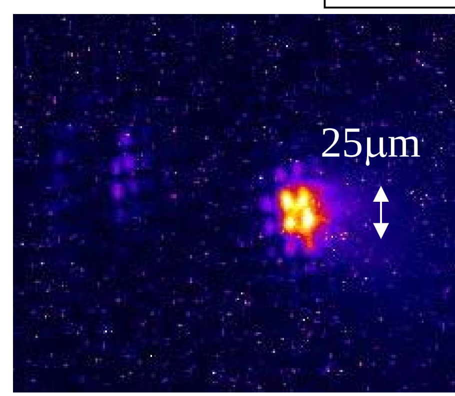
1st experimental demonstration of laser-driven, mono-energetic ion acceleration[1]:
Carbon 6+, 3 MeV/amu, 10^9 particles, ~1kA, longitudinal emittance 10^{-6} eVs

With maxwellian energy distribution:
Range of species: H, Be, C, O, F, Ni, S, Pd, Pt
MeV/amu ion energies, up to 10^{13} ions per pulse[2].

[1] Hegelich et al., Nature 439, p441 (2006).
[2] Hegelich et al., Phys. Plasmas, 12, 056314 (2005).
[3] Flippo et al., PRL, submitted Feb. (2007)
[4] Yin et al., Phys. Plasmas 14, 056706, (2007)

At Lawrence Livermore National Laboratory Titans laser facility, focusing of laser-driven proton beam is being explored

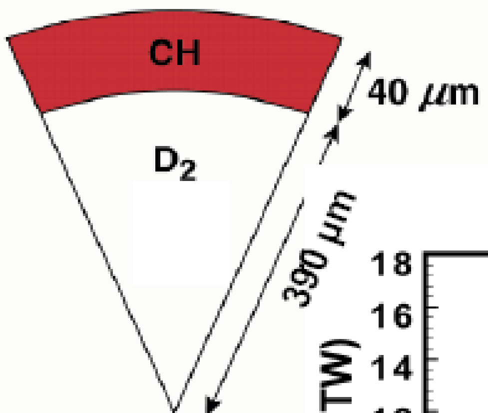




256eV XUV

The shock ignition concept has been tested on OMEGA

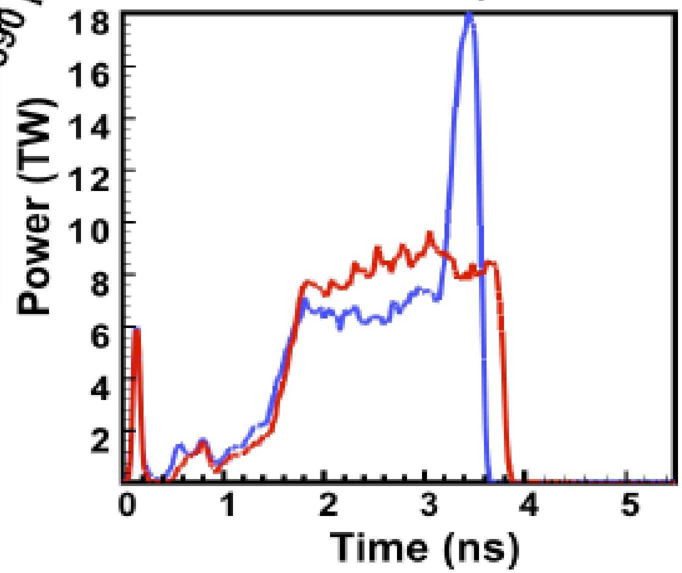
Target

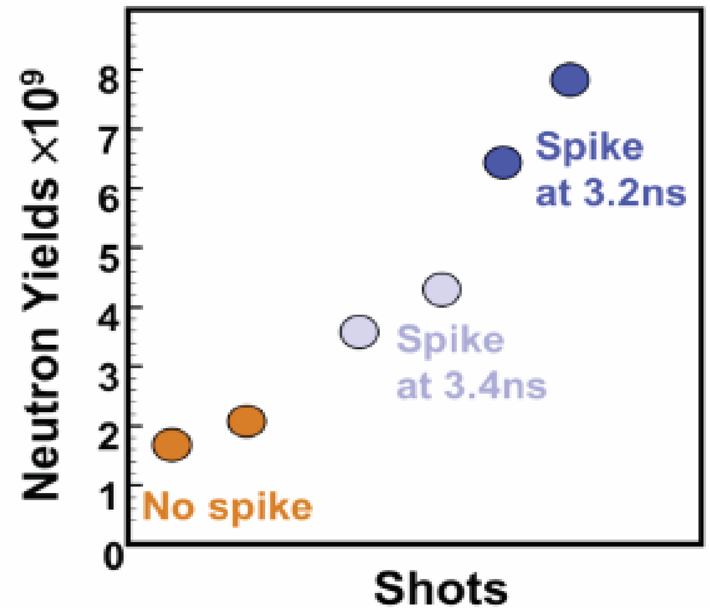


W. Theobald,
R. Betti,
C. Zhou,
C. Stoeckl
(UR-LLE)

E_L=17-18kJ
$\alpha\approx$1.3

Pulse shape with and without shock spike



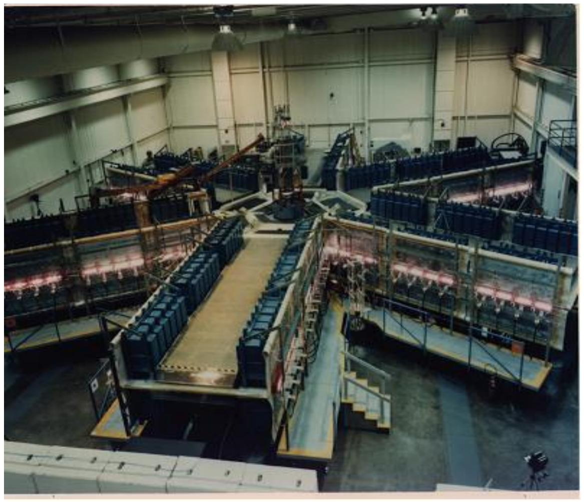


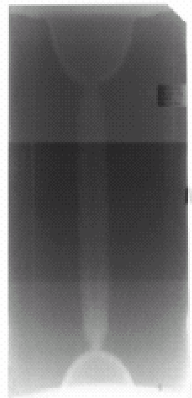
The neutron yield increases considerably when a shock is launched at the end of the pulse

More experiments with CH targets in '07-'08, cryo-targets in '09

Multi-MJ pulsed power facilities ready for implosion experiments for magneto-inertial fusion (MIF) research

By 2012, (1) develop predictive understanding of the dominant physical processes governing MIF, (2) create multi-keV, multi-MG, HED plasmas





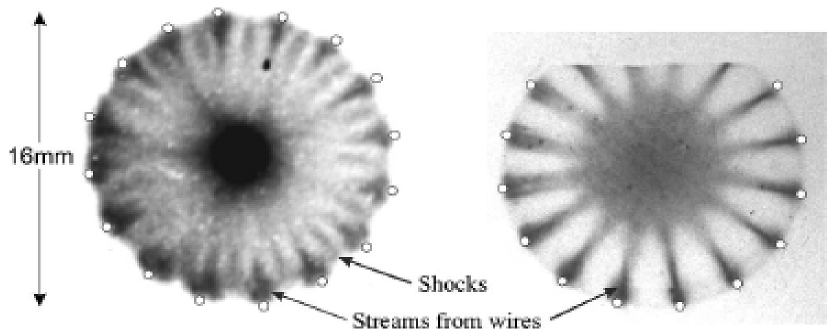
- **Air Force Reseach Lab Shiva Star pulsed power facility:** 9 MJ, 12 MA
- imploded a 30-cm long, 10 cm diameter, 1.1 mm thick Al liner in 24 μs reaching 0.5 cm/μs, with 16x radial convergence
- ***Integrated MIF implosion experiment to begin in 2008***
  - *Experimental system near completion*

LANL FRX-L pulsed power facility

Demonstrated FRC ~ 5 x 10^{16} cm^3,
300 eV, ~ 10 μs

Attractive concepts for driving MIF are being investigated

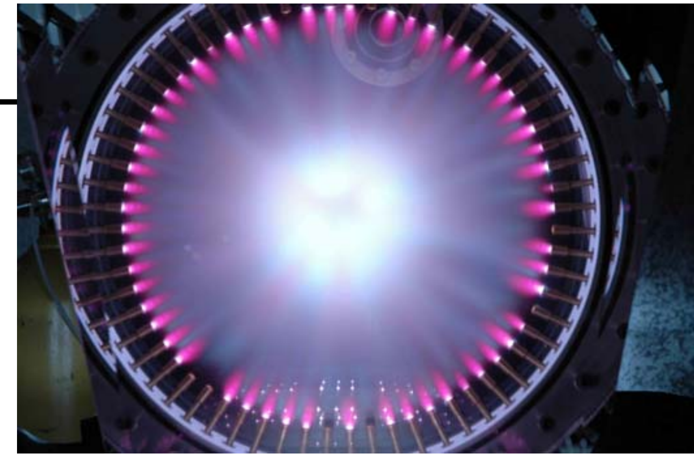
• Converging array of plasma jets can be merged to form plasma shells (liners) for imploding a magnetized plasma



• Very high Mach-number plasma flows have been seen in wire-array Z-pinch

• Radial plasma flows stagnate on axis forming dense HED plasmas

(Bott, et. al. Phys Rev E, 74, 2006)



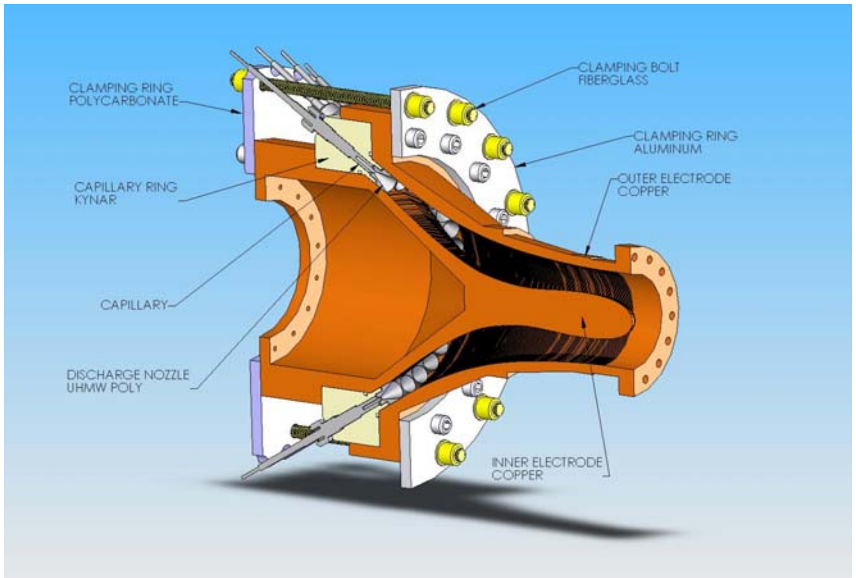
Plasma jets from capillary discharges merge to form a plasma liner (Witherspoon, 2007)

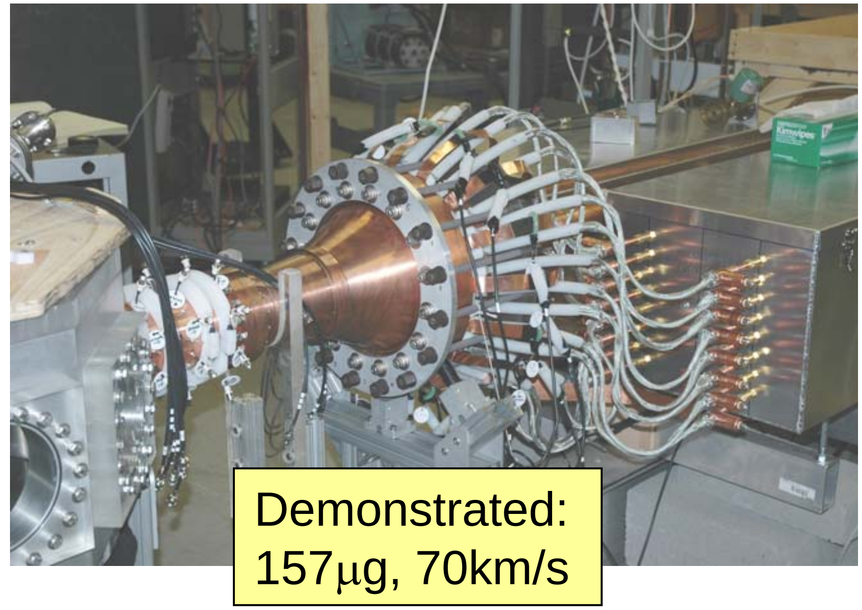
• Address 3 major issues for MIF

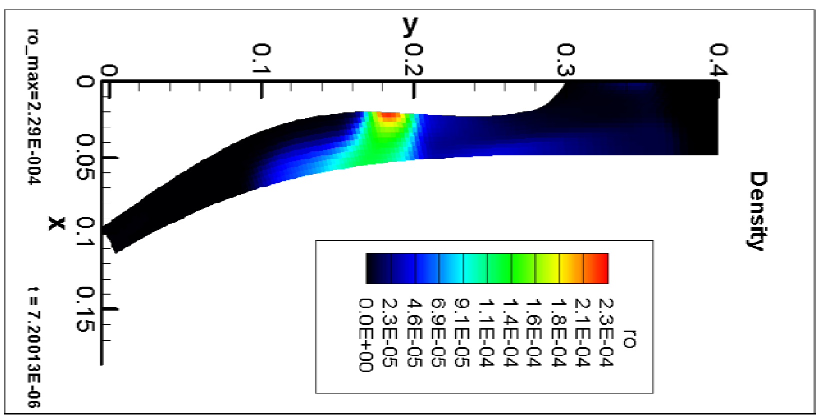
  • Standoff delivery of liner
  • Repetitive operation
  • Liner fabrication and cost

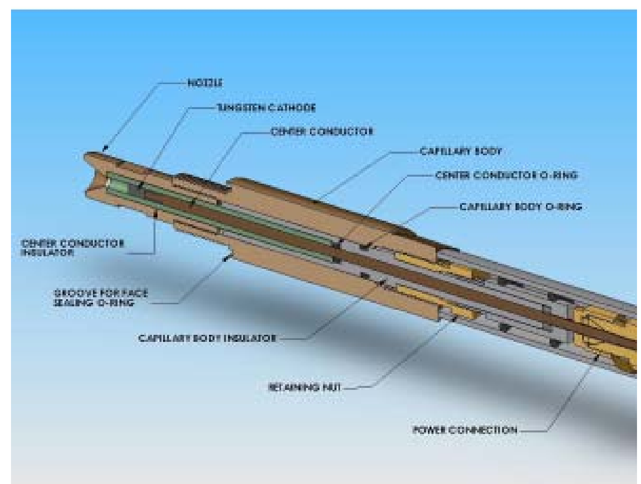
• The next step is to mount a major study to merge plasma jets to produce stagnation pressures exceeding 1 Mbar, subject to receiving high-quality, competitive proposals

Advanced coaxial plasma gun to accelerate plasma slab without the blow-by instability is under development



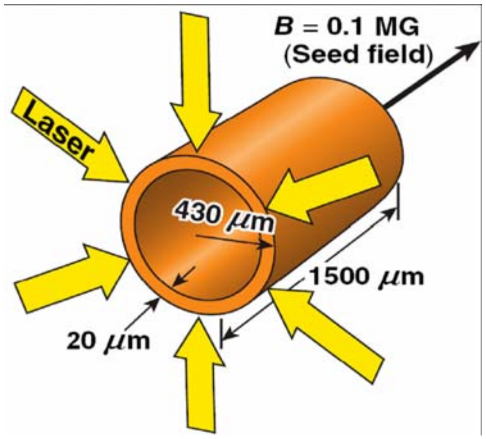


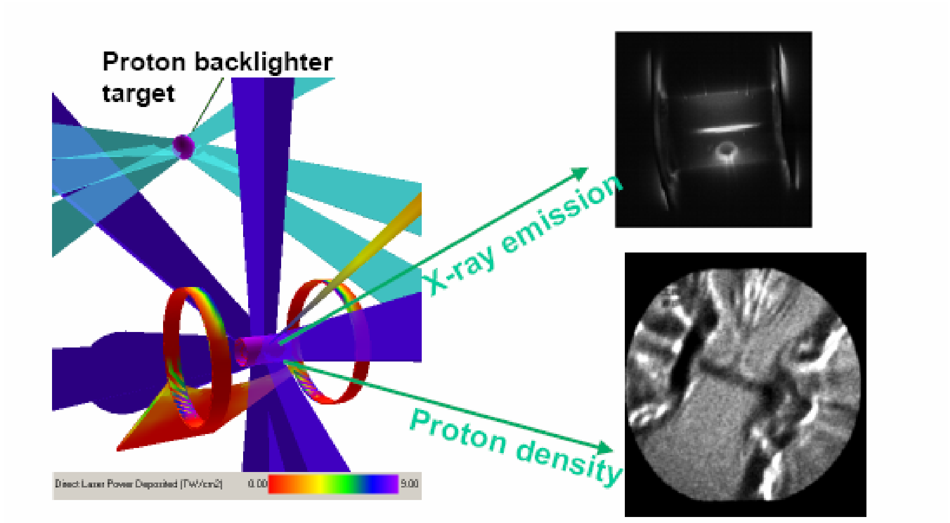




At OMEGA, Rochester, flux compression experiments for High-Gain MIF is underway …..

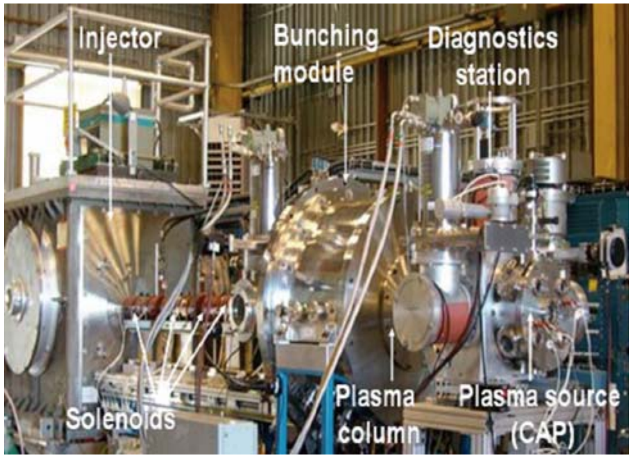
- A magnetized cylindrical target is imploded to compress a seed magnetic flux
- A ~0.1 MG seed magnetic field is generated with a double coil driven by a portable capacitive discharge system
- Mono-energetic 14.7 MeV proton beam deflectometry is used for measuring the compressed magnetic fields
- Experimental system is undergoing preliminary shake-down tests
- **So far the tests have produced one shot in which an initial field of 3T is compressed, resulting in a measured compressed field of 1300 T at one instant in time**
- More tests are planned in April

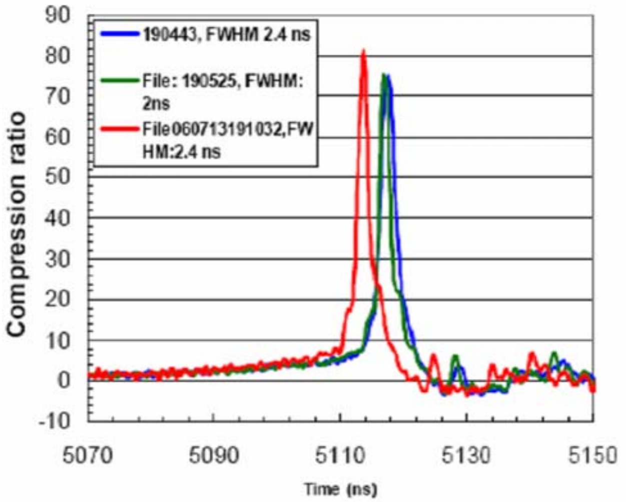




Current Activities in Heavy Ion Fusion Science

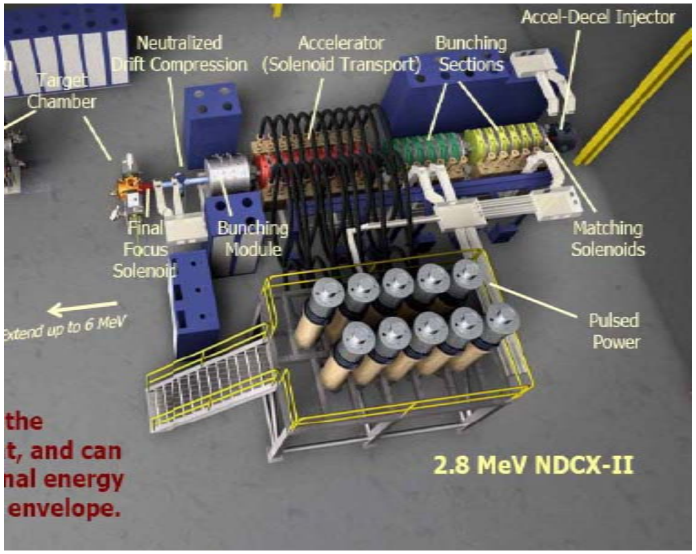
- Directed at investigating HED physics of IFES
  - Bright, intense ion beams are required
- Neutralized drift compression: NDCX-1 has compressed ion beams from 200 ns down to 2 ns with 60x beam intensity longitudinally
- Initiated isochoric target heating experiments in jointly with GSI, Germany,
- Measurements of electron cloud effects on intense heavy-ion beam transport in both quadrupole and solenoid magnets.
- Computer simulation models matching experiments in both neutralized beam compression and e-cloud studies.
- Running HYDRA code to explore new heavy ion fusion direct drive target concept





Program Plan for Heavy Ion Fusion Science

- NDCX-I (by 2008)
  - Demonstrate intensity amplification of ~ 1000X with combined longitudinal and transverse compression
  - Conduct first beam-on-target WDM experiments in 2008 (~ 0.5 eV and solid density; transient darkening experiment)



- Develop NDCX-II (2011)
  - 2.8 MeV, high-intensity beam
- WDM studies at ~ 1 eV
- HED physics for IFES
  - Hydrodynamics experiments for stability and ion ablative direct drive target physics
  - Explore heavy ion fusion in two-sided polar direct drive

Summary

- Current OFES interest emphasizes IFES-motivated HEDLP, but plans to expand program to include HED astrophysics that most overlap with this portion of the HEDLP space.
  - Complements NNSA's interests and stewardship of HEDLP
- Limited funding at present forces OFES to adopt a modest approach and focus on pursuing research in optimizing gain-efficiency product for IFES
  - Lowering implosion velocity and increasing coupling efficiency
  - Decoupling ignition from fuel assembly
  - Suppressing thermal transport by embedding an magnetic field in the target
  - Increasing coupling efficiency by using heavy ion beams
- The research covers the fundamental areas of HEDLP in:
  - Warm dense matter
  - Laser-plasma, radiation-matter interaction
  - Relativistic plasmas
  - Dense plasma in high magnetic fields
  - Compressible, radiative MHD