LA-UR- 12-01172

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Title: Inertial and Magnetic Fusion Concepts in High Energy Density Plasma Physics at LANL

Author(s): K. Flippo, D. T. Offermann, J. Ren, J. Cobble, M. J. Schmitt, M. Geissel, M. Schollmeier, A. Sefkow, S. A. Gaillard, T. Kluge, M. Bussmann, J. Rassuchine, T. Burris-Mog, K. Zeil, S. Kraft, J. Metzkes, T. E. Cowan, with contributions from: T. Lockard , C. Plechaty, R. Presura, Y. Sentoku, R. Mancini, T. Kwan, B. Albright, J. C. Fernández, D. C. Gautier, B. M. Hegelich, J. L. Kline, S. Letzring, S. Palaniyappan, R. C.

Intended for: Advanced Accelerator Workshop 2012

Los Alamos NATIONAL LABORATORY EST.1943

Abstract:

High Energy Density Laboratory Plasma (HEDLP) science is one of the few areas in physics where the US, compared to the rest of the world, has a significant lead. This includes, specific to fusion, Inertial Confinement Fusion (ICF) and several alternative concepts known collectively as Magnetized Target Fusion (MTF) or Magneto-Inertial Fusion (MIF). MIF concepts are basically a mixture of Magnetic Confinement Fusion and ICF, where the ICF fuel can now be less dense and compressed less due to the insulating effects of the applied magnetic field. A very brief history of the Controlled Thermonuclear Reactor program at Los Alamos is presented to illustrate how the more modern concepts for fusion came about, and how our very recent work in laser-accelerated electrons and ions is poised to further bring about important changes and additions to these concepts. This work has focused on a small subset of HEDLP, ultra-high intensity laser matter interactions, which has been producing high energy particles for over 10 years and now the technology is reaching a maturity where the physics can be controlled and applied to the aforementioned problems as well as a host of others from hadron cancer therapy to nuclear material detection. These interactions create Megagauss magnetic fields and Megaamp current beams of MeV kinetic energy. In general HEDLP has great breadth encompassing high energy density hydrodynamics, radiation-dominated dynamics and material properties, magnetized high energy density plasma physics, nonlinear optics of plasmas, relativistic high energy density plasma physics and warm dense matter physics. The extremes (temperatures, pressures and field strengths) of the field have led some to brand it the X-games of physics. Yet, all eXtreme hype aside, HEDLP science has a bright future with the potential to be the next technological and economic driver of the 21st century.

Notes

70 years of Fusion History (at LANL) (don't get discouraged!)

1941 Enrico Fermi suggests to Edward Teller that an atomic bomb might heat deuterium sufficiently to ignite a thermonuclear reaction. [1]

1945 (Oct) Edward Teller advocates to Oppenheimer for an H-bomb...the "super". Oppenheimer refuses.[1]

Jan 31st 1950 Truman announces decision to develop the thermonuclear bomb.[1] Los Alamos hires James Tuck from Univ. of Chicago

1951 "Project Sherwood" the Controlled Thermonuclear Research (CTR) program started by Englishman James "Friar" Tuck at Los Alamos with the Physics Division. He decided to use pulsed pinches[2] from the Thomson-Blackman patent (1946) and Willard Bennett (1934) instead of stellerators or mirrors. Program is in P-Division (P-4)

1951 First thermonuclear tests "Operation Greenhouse" in the Pacific tested "George" and "Item".

1952 November,"Mike" tests first H-bomb on Enewetak Atoll. [1]

1953 Perhapsatron built demonstrated kink instabilities led to plasma hitting the wall. Led to M.N. Rosenbluth's M-theory showing higher voltage led to high temperature. I all a series of 5 machines were built ('53-'60) [2]

1956 AEC (Atomic Energy Commission) allows Los Alamos to partner with industry to develop fusion reactors! Los Alamos begins to declassify fusion work.

1957-1958 Scylla I (theta pinch) produces world's first "controlled" thermonuclear reactions in the basement of the administration building, now the site of the NSSB (X-division) ; Los Alamos becomes an open city, gates into townsite come down. Declassification complete.

Fig. Sherwood Building (TA-3-105)

1958 Atoms for Peace Conference in Geneva where Los Alamos displays a copy of Scylla I, a Marshall Plasma Gun, and a Perhapsatron. Scylla I moved to Sherwood Building ('58-'63)

1958 Columbus I (linear z-pinch) machine built to take advantage of the M-Theory in a linear configuration. 100,000 V

1962 – 1973 Scylla IV Reached fusion ignition temps, highs of the Scylla machines. (5-6 Million Degrees C)

1965 Abraham Hertzberg visits LASL, circa this time Boyer and company realize that if the gas in the pinch was heavy, it might lase. [5]

1968-1970 Scyllac Building built

1968 Classified Laser program at AFWL at Kirkland AFB, Eight card restrictions on gas-dynamic lasers, CO_2, by Arthur Kantrowitz, that LASL people were read into the program,

1969 (June) Rover program people interested in lasers, use "spare" money to investigate 3 branches, Chemical, glass and CO_2 lasers in J-Division (Nuclear Weapons Test Div).[5] LASL demonstrates e-beam controlled CO_2 laser[3] Lasers Single Beam System (SBS)? MARS 1ns/1kJ CO2 Early CO2 lasers?

1970- 1978 Scyllac Experiments demonstrated toroidal theta pinch plasma confinement for D-T burning. First in a sector ('71-'73) then a full torus ('74-'78)

1970 Bradbury retires, Agnew creates Laser Activities Office (Boyer director) Single beam CO2 laser ~<1J?

1971 Speaker is born

1972 LASL initiates Laser Research and Technology Division (L Division) for the National Laser Fusion Program[4]

1973 Magnetic Fusion research moves to Q-Division; Single Beam System (SBS) CO2 laser operations. 10J ,1ns. Fabrications begins for Helios Laser Prototype (Gemini)

1974 Magnetic Fusion research moves to CTR Division. Research on shooting rhesus monkey's in the eyes with a Nd-YAG laser are published, pigs and rabbit were shot in 1975 with CO_2 lasers.[4] TBS 250J

1975 Completion of TBS 2500 J system (prototype for Helios)

1976 Upgrade of SBS to 250J, 1ns; First TBS experiments started 2-4TW, 1.25kJ/beam 1ns; Designs for Antares Laser 100-200TW 100kJ 1- 0.25 ns pulse (first called the High Energy Gas Laser Facility HEGLF).

1977 First fusion reactions (neutrons observed) generated by the TBS (Gemini) CO_2 laser at LASL "proving" that infrared light was a go for laser fusion.

1977 TSTA (Tritium System Test Assembly) closed in 2003

1978 ZT-40 a toroidal z-pinch is built (reverse field technology) Spheromak the last Perhapsatron. Scyllac decommissioned, Fast Liner Experiment built ("beer-can crusher"). Dick Siemon spends the year teaching at Wisconsin returns because of "big science" draw.
Helios an 8 beam CO_2 laser is completed at LASL (10.6 um wavelength) 10 shots/day 8kJ;

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1989 Started building ZT-H (reversed toroidal theta pinch ~ms life time) 150 eV 10^12 /cm3, a $70 Million project, spent about $20M/year. Most of the hardware was delivered. The large generator (1430 MVA) needed for the project was also purchased and delivered.

1990-1991 DOE MFE program slashed for FY 1991 to focus on Tokamaks (ITER). Los Alamos shuttered CTR division[2], remaining fusion work moved to Physics Division. ZT-H cancelled and the large generator now supplies current for the NHMFL magnets. Aurora laser is retasked for higher intensity and lower operating costs and decreased pulse duration ~200ps – Mercury (until 1993).

1992 Trident laser moved from KMS to LANL operational in circa 1993.

1999 US pulls out of ITER to support alternative fusion concepts

2000 MTF (Wurden) FRXL (CTX + Fast liner), RSX (intrator)

2003 Trident Upgraded to 30 TW

2007 Trident Upgraded to 200 TW; MaRIE facility (with Lasers) proposed.

2009 PLX proposed and awarded

2011 First PLX experiments

Scyila kink and sausage instabilities

Sylac unstable

LANL legacy Compact Torus, Field Reverse Configuration, Field Reverse Pinch, these are still being applied today.

[1] American Experience "Race for the Superbomb"

[2] Controlled Thermonuclear Research at Los Alamos: The history of the Sherwood and Scyllac Buildings (TA-3-105 and TA-3-287)

[3] Overview of Laser Fusion Eugene E. Stark Jr. LASL 1978 (LASL-77-24)

[4] Safety aspects of the laser fusion research at the Los Alamos Scientific Laboratory, D. C. Winburn, Optics and Laser Technolgy, 8 265 (1976)

[5] AIP history Oral History Transcirpt with Dr. Keith Boyer

Inertial and Magnetic Fusion Concepts in High Energy Density Plasma Physics at LANL

Kirk Flippo, LANL, Plasma Physics P-24

Advanced Accelerator Concepts Workshop

2012

Los Alamos
NATIONAL LABORATORY
EST. 1943

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Sandia National Laboratories

S. A. Gaillard, T. Kluge, M. Bussmann, J. Rassuchine
T. Burris-Mog, K. Zeil, S. Kraft, J. Metzkes, T. E. Cowan

Helmholtz-Zentrum Dresden-Rossendorf

T. Lockard , C. Plechaty, R. Presura,
Y. Sentoku, R. Mancini

University of Nevada, Reno

Trident ***Crew: F. L. Archuleta, R. P. Gonzales, T. R. Hurry, R. P. Johnson,***
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Los Alamos National Laboratory

LA-UR-11-06510

OUTLINE

Brief History of Fusion at LANL

HEDP Physics Overview

Some Applications of Ion Acceleration

Short-Pulse Laser Radiation Sources and Ion Acceleration

High Contrast Laser Ion Acceleration
Adding More Laser Energy
Ion Focusing

Magnetized Target Fusion:
Fusion Cuisine

A Brief History of Fusion at LANL

Los Alamos
NATIONAL LABORATORY
EST. 1943

LA-UR-11-06510

NNSA

LANL Org Chart circa 1943

J. Robert Oppenheimer
Lab Director

Ed Condon
Administrative Officer

W. R. Dennes
Administrative Officer

Dana P. Mitchell
Procurement

Arthur L. Hughes
Director of Personnel

B.E. Brazier
Construction and Maintenance

Hans Bethe
Theoretical Physics Div.

Ed Teller
T Group 1

Robert Serber
T Group 2

Victor Weisskopf
T Group 3

Richard Feynman
T Group 4

Donald A. Flanders
T Group 5 (computation)

Robert Bacher
Experimental Physics Div.

Robert R. Wilson
P Group 1 (cyclotron)

John H. Williams
P Group 2 (electro-gen.)

John Manley
P Group 3 (D-D source)

Darol Froman
P Group 3 (electronics)

Emilio Segre‘
P Group 3 (radioactivity)

Joseph Kennedy and Cyril Stanley Smith
Chemistry and Metallurgy Div.

Charles A. Thomas
Coordinator
(UC Berkeley/Iowa State College/Univ. Chicago)

William S. Parsons
Ordnance Division

Edwin M. McMillan
O Group 1

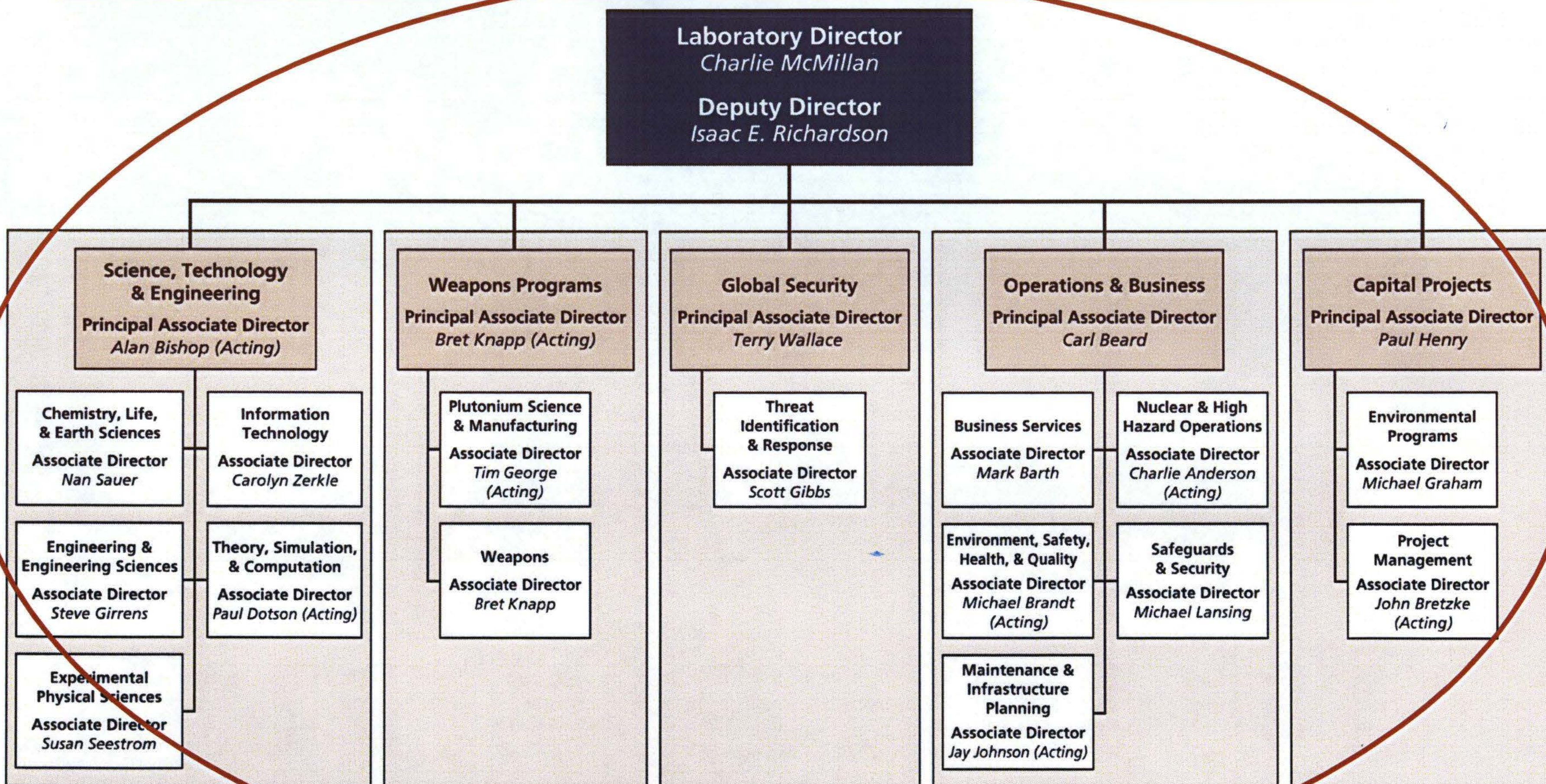
Kenneth T. Bainbridge
O Group 2

Robert B. Brode
O Group 3

Charles L. Critchfield
O Group 4

S.H. Neddermeyer
O Group 5

LANL Org Chart 2012



11/03/11

300 x Expansion in Upper Managers

Los Alamos
NATIONAL LABORATORY
EST. 1943

70 years of Fusion History at LANL: Just the Beginning

Early Thermonuclear Fusion Research

1941

- Enrico Fermi suggests to Edward Teller that an atomic bomb might heat deuterium sufficiently to ignite a thermonuclear reaction. [1]

1945

- (Oct) Edward Teller advocates to Oppenheimer for an H-bomb…the "super". Oppenheimer refuses.[1]

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- (Jan 31st)Pres. Truman announces decision to develop the thermonuclear bomb.[1] Los Alamos hires James L. Tuck from Univ. of Chicago

1951

- "Project Sherwood" the Controlled Thermonuclear Research (CTR) program started by Englishman James "Friar" Tuck at Los Alamos with the Physics Division. He decided to use pulsed pinches[2] from the Thomson-Blackman patent (1946) and Willard Bennett (1934) instead of stellerators or mirrors. Program is in P-Division (P-4)
- First thermonuclear tests "Operation Greenhouse" in the Pacific tested "George" and "Item".

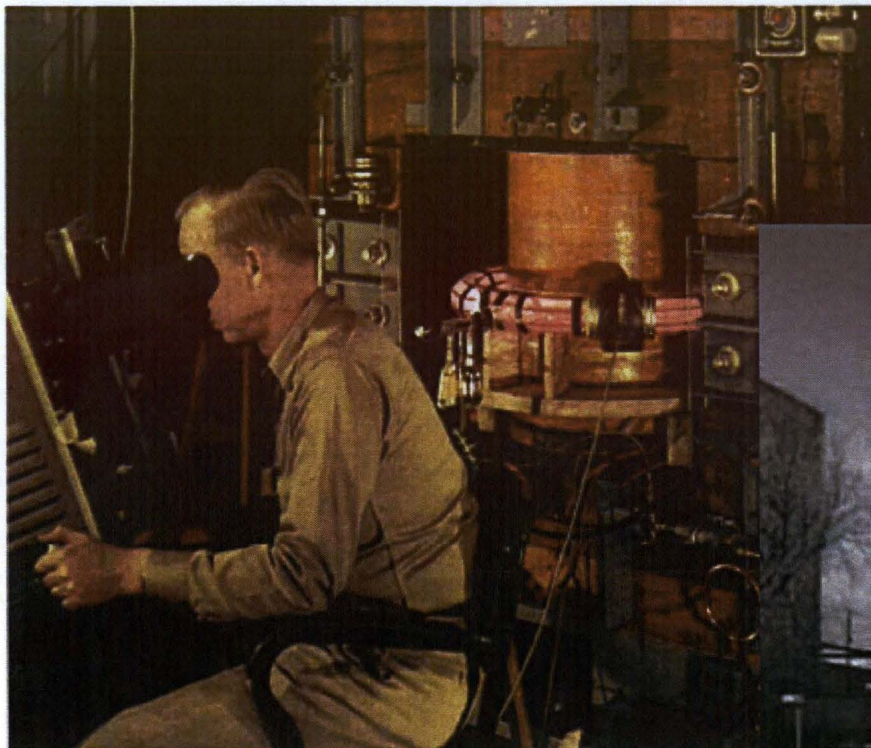
1952

- November "Mike" tests first H-bomb on Enewetak Atoll. [1]

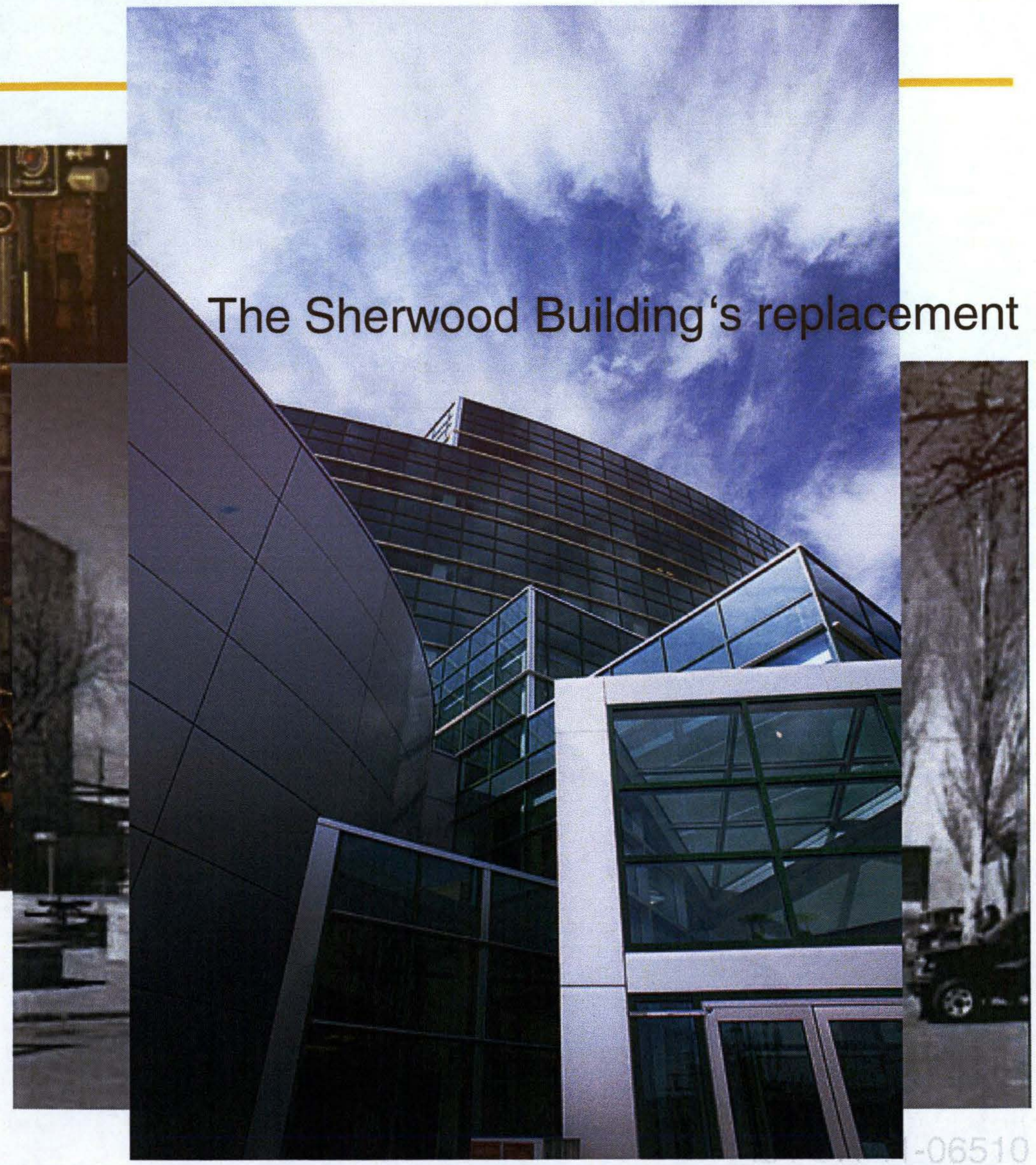
1953

- ***Perhapsatron*** built, toroidal z-pinch, plagued by kink instabilities; Led to plasma hitting the wall and to M.N. Rosenbluth's M-theory showing that higher voltage led to high temperature.
  - In all a series of 5 machines were built ('53-'60) [2]

The Perhapsatron and Building



The first Perhapsatron



The Sherwood Building's replacement

The NNSB Building in its place

70 years of Fusion History at LANL: Early Pinch Fusion Experiments

1956

- AEC (Atomic Energy Commission) allows Los Alamos to partner with industry to develop fusion reactors!
- Los Alamos begins to declassify fusion work.

1957-1958

- (Dec-Jan) Scylla I (theta pinch) produces world's first "controlled" thermonuclear reactions in the basement of the administration building, now the site of the NSSB (X-division)
- Los Alamos becomes an open city: gates into the townsite come down.
- Declassification of Sherwood program complete in time for Geneva.

1958

- Columbus I (linear z-pinch) machine built to take advantage of the M-Theory in a linear configuration. 100,000 V
- Atoms for Peace Conference in Geneva where Los Alamos displays a copy of Scylla I, a ***Marshall Plasma Gun*** (coaxial plasma gun) and a Perhapsatron.
- Scylla I moved to Sherwood Building ('58-'63)

1962

- Scylla IV (linear theta pinch) Reached fusion ignition temps, highest of the Scylla machines. (5-6 Million Degrees C) (1962 – 1973)

70 years of Fusion History at LANL: A Split

Laser Fusion

1965
- Abraham Hertzberg visits LASL, circa this time Keith Boyer and company realize that if the gas in the pinch was heavy, it might lase.[5]

1968
- Classified Laser program at AFWL at Kirkland AFB, "Eighth card" restrictions on gas-dynamic lasers, CO_2, by Arthur Kantrowitz, that LASL people were read into the program.

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- LASL demonstrates e-beam controlled CO_2 laser[3] Single Beam System (SBS)
- MARS 1ns/1kJ CO2 Early CO2 lasers?

1970
- Director Bradbury retires, Director Agnew creates Laser Activities Office (Boyer director)
- Single beam CO2 laser ~<1J?

Magnetic Fusion

1968
- Scyllac Building started (finished in 1970)

1970
- Scyllac (Scylla Closed) toroidal theta pinch experiments start

1971
- Scyllac demonstrates a toroidal theta pinch plasma confinement sufficient for D-T burning in a sector ('71-'73) , building full torus
- Speaker is born

Syllac circa 1977

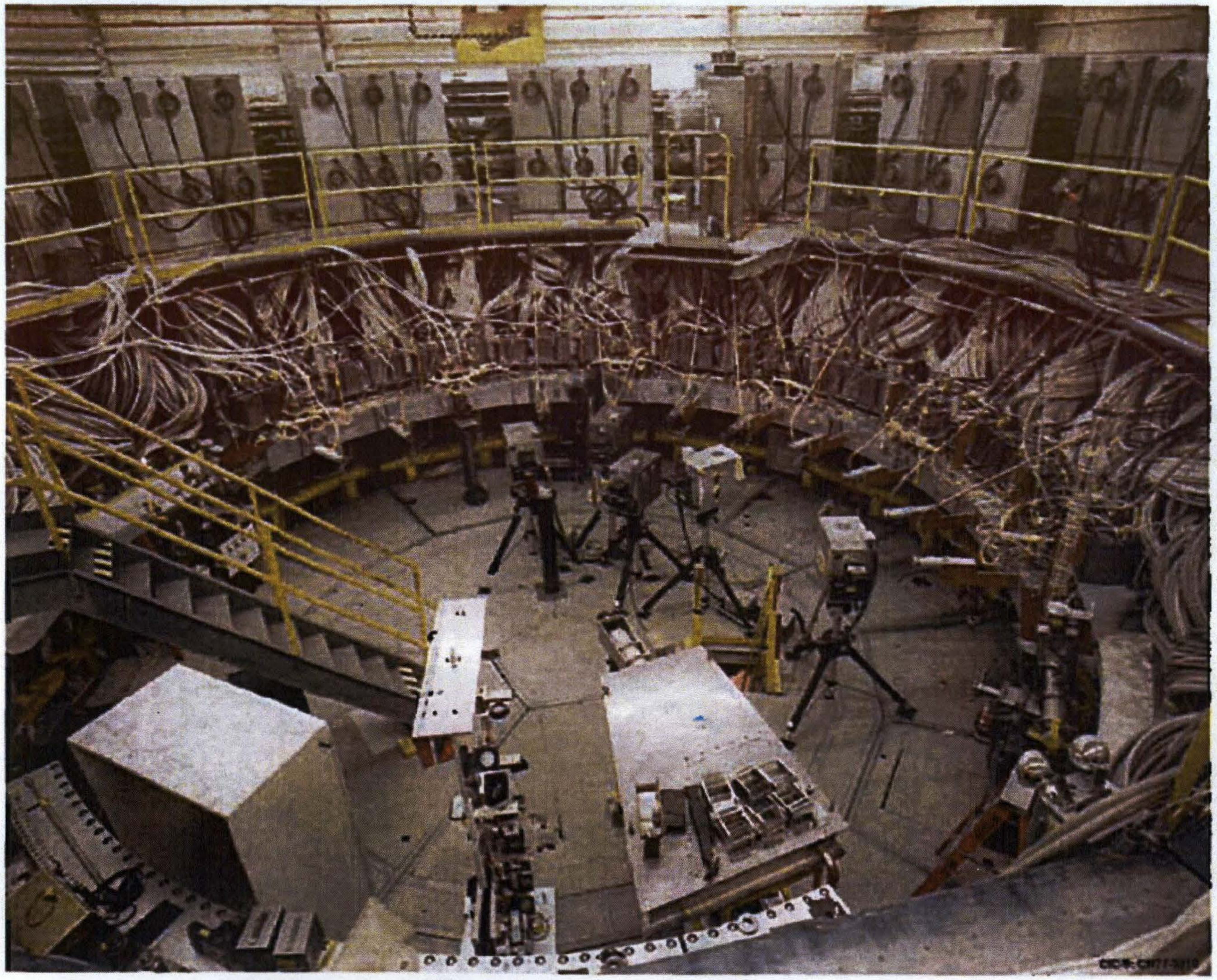

Fig. 14. Scyllac, circa 1977

70 years of Fusion History at LANL

Laser Fusion

1972

- LASL initiates Laser Research and Technology Division (L Division) for the National Laser Fusion Program[4]

1973

- Single Beam System (SBS) CO_2 laser operations. 10J, 1ns.
- Fabrications begins for Helios Laser Prototype the Two Beam System (TBS) (to renamed Gemini)

1974

- Research on shooting rhesus monkey's in the eyes with a Nd-YAG laser are published

1975

- Pigs and rabbits were shot in the eyes with CO_2 lasers[4].
- Completion of TBS 2500 J system (prototype for Helios Laser)

Magnetic Fusion

1973

- Scylla decommissioned
- Magnetic Fusion research moves to Q-Division

1974

- Scyllac full Torus (until '78) demonstrates sufficient confinement for D-T burning.
- Magnetic Fusion research moves to CTR Division.

70 years of Fusion History at LANL

Laser Fusion

1976

- Upgrade of SBS to 250J, 1ns;
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1979

- Antares downgraded to 24 beams, 30kJ "with DOE concurrence"

Magnetic Fusion

1976

- 200th 4th of July! Cool $2 bills!

1977

- TSTA (Tritium System Test Assembly) closed in 2003

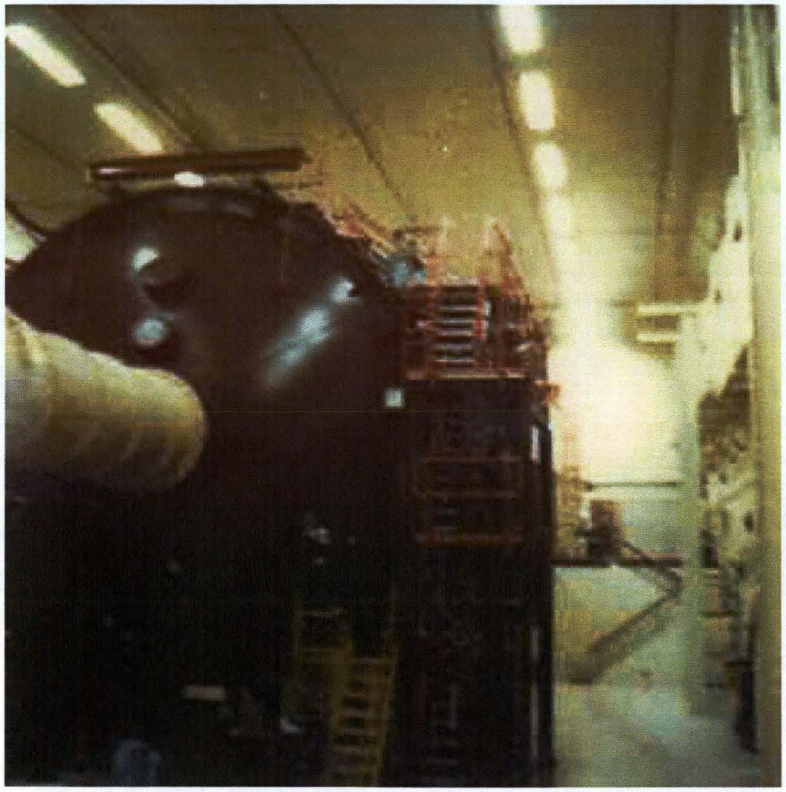
1978

- ZT-40 a toroidal z-pinch is built (reverse field technology) spheromak the last Perhapsatron.
- Scyllac decommissioned, Fast Liner Experiment built ("beer-can crusher") using capacitors.
- Dick Siemon spends the year teaching at Wisconsin.

1979

- Compact Torus Experiment (CTX) and FRXC (theta pinch field reverse configuration) built

Antares and the ZT-40 circa 1979, the Last of the Perhapsatrons



Antares

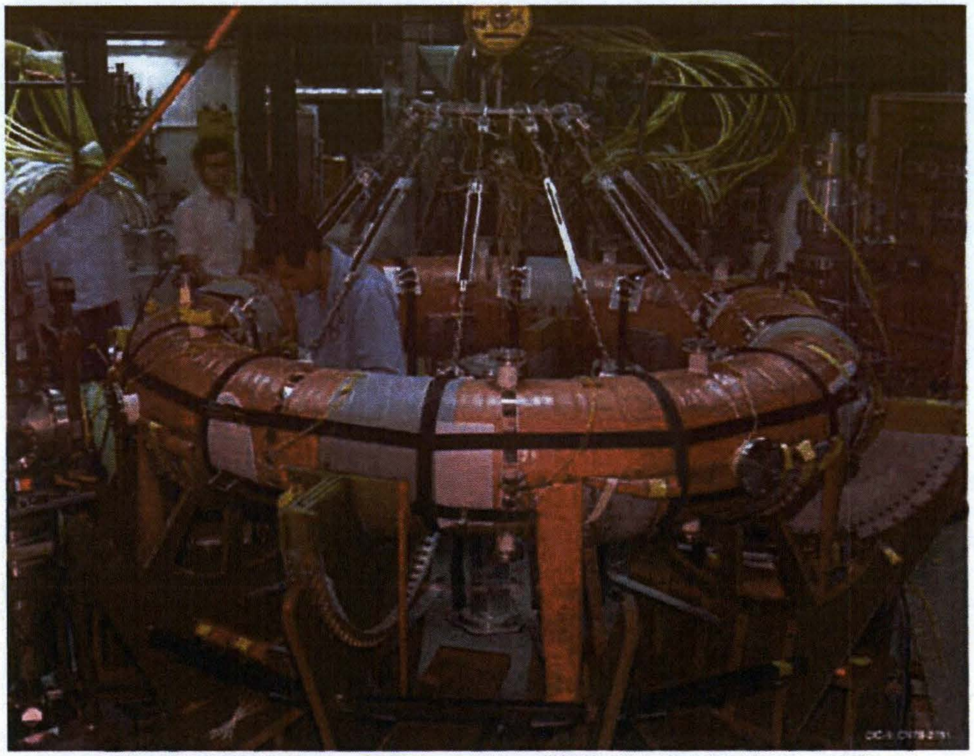


Fig. 10. ZT-40 Ceramic Torus, circa 1979, TA-3-105, Room 160

Oddly lasers have become smaller, and tori larger!

70 years of Fusion History at LANL

Laser Fusion

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- Helios (9kJ, 10^{16} W/cm^2) is shut down. Antares laser built (Dec. two amplifiers, 24 beams 30kJ in 1-5ns, was designed to have 72 beams)
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- Aurora Laser (KrF) completed, 10 kJ 96 beams

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- LABSII XeCl laser built 250 mJ 10Hz 175fs 10^{19} W/cm^2

Magnetic Fusion

1988

- CTX work ends (400eV, 1ms, MA current)

1989

- FRXC work ends
- Started building ZT-H (reversed toroidal theta pinch ~ms life time) 150 eV 10^{12} /cm^3, a $70 Million project, spent about $20M/year. Most of the hardware was delivered. The large generator (1430 MVA) needed for the project was also purchased and delivered.

Seems like everything is cooking along, fusion is around the corner

CTX and FRXC

Fig. 13. Compact Torus (CTX), circa 1979, TA-3-105, Rooms 186&189 (West Wing)

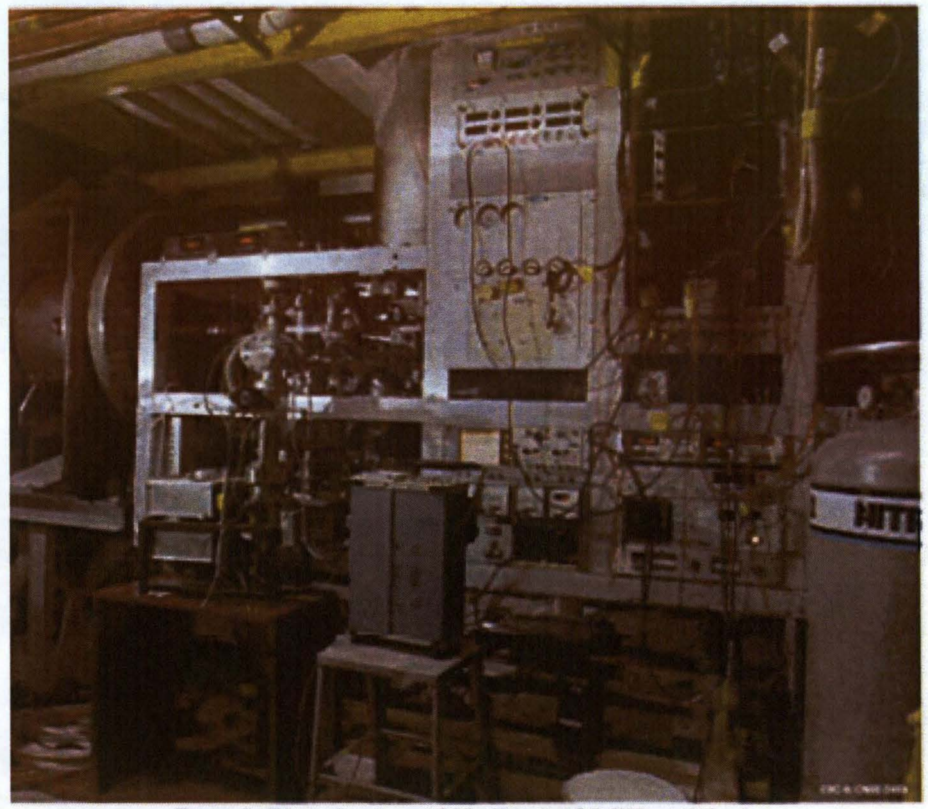


Fig. 12. FRX-C, circa 1990, TA-3-105 (West Wing)

70 years of Fusion History at LANL

Laser Fusion

1990 (Watershed Year)

- DOE Inertial Confinement Fusion (ICF) funding slashed for FY 1991 to focus on NIF.
- (Oct) Aurora laser is retasked for higher intensity and lower operating costs and decreased pulse duration ~200ps – Mercury (until 1993).
- KMS Fusion in Ann Arbor is shuttered fire sale ensues (1991)

1992

- **Trident** laser moved from KMS to LANL operational in circa 1993.

2003

- **Trident** Upgraded to 30 TW

2007

- **Trident Upgraded to 200 TW**; MaRIE facility (with Lasers) proposed.

Magnetic Fusion

1990 (Watershed Year)

- DOE MFE program slashed for FY 1991 to focus on Tokamaks (ITER).
- (Oct) ZT-H cancelled and the large generator now supplies current for the NHMFL magnets.
- (Oct) Los Alamos shutters CTR division[2], remaining fusion work moved to Physics Division.

1999

- US pulls the plug on ITER

2000

- FRXL (2001 1st plasma) and RSX funded at LANL

2002

- US plugs back into ITER (after it is realized that it is going to be built anyway)

2006

- (Nov) ITER Agreement finally signed in Paris

2009

- PLX proposed and awarded (first experiments in 2011)
- RSX ends

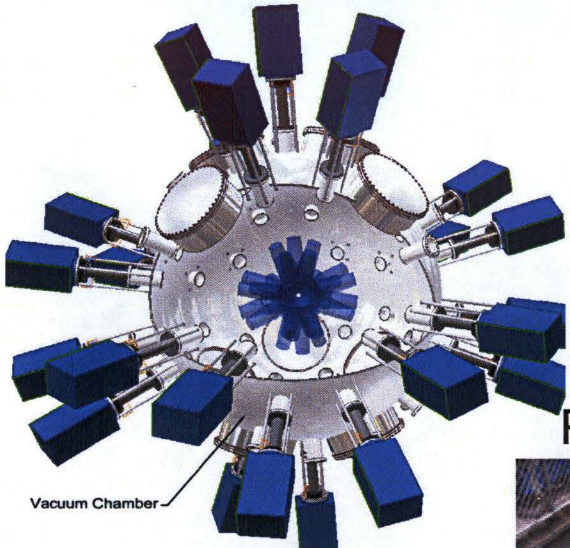
2012 ITER need $200M more, from where?

[1] American Experience "Race for the Superbomb"
[2] Controlled Thermonuclear Research at Los Alamos: The history of the Sherwood and Scyllac Buildings (TA-3-105 and TA-3-287)
[3] Overview of Laser Fusion Eugene E. Stark Jr. LASL 1978 (LASL-77-24)

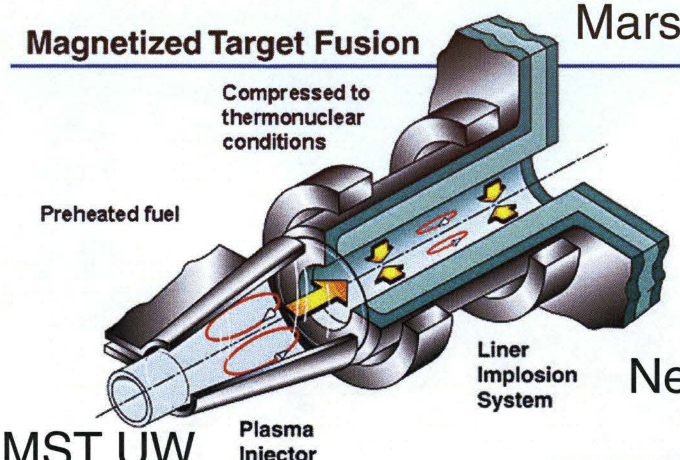
What did we Learn in 70 Years? Go Back to the Future

Bottom Line: LANL legacy gave us the Compact Torus, Field Reverse Configuration, Field Reverse Pinch, Liners and CO_2 Lasers, these are being applied today as one future of fusion

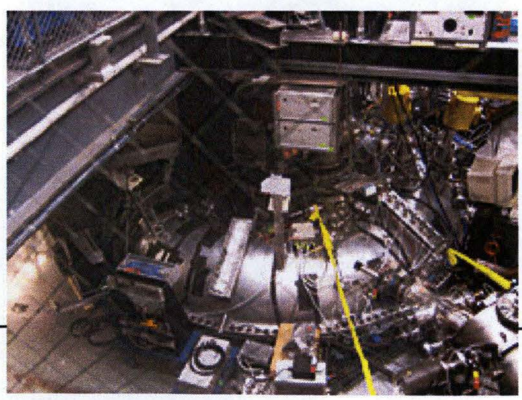
PLX HyperV/LANL/DOE
Plasma Liner



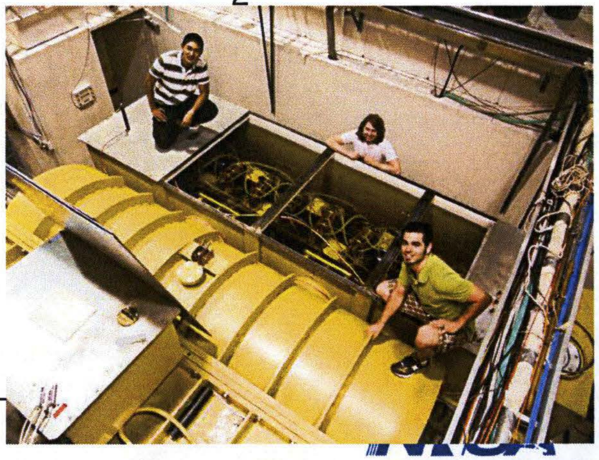
FXRL at LANL (Wurden)
Marshall Gun and FRC



MST UW
Reverse Field Pinch



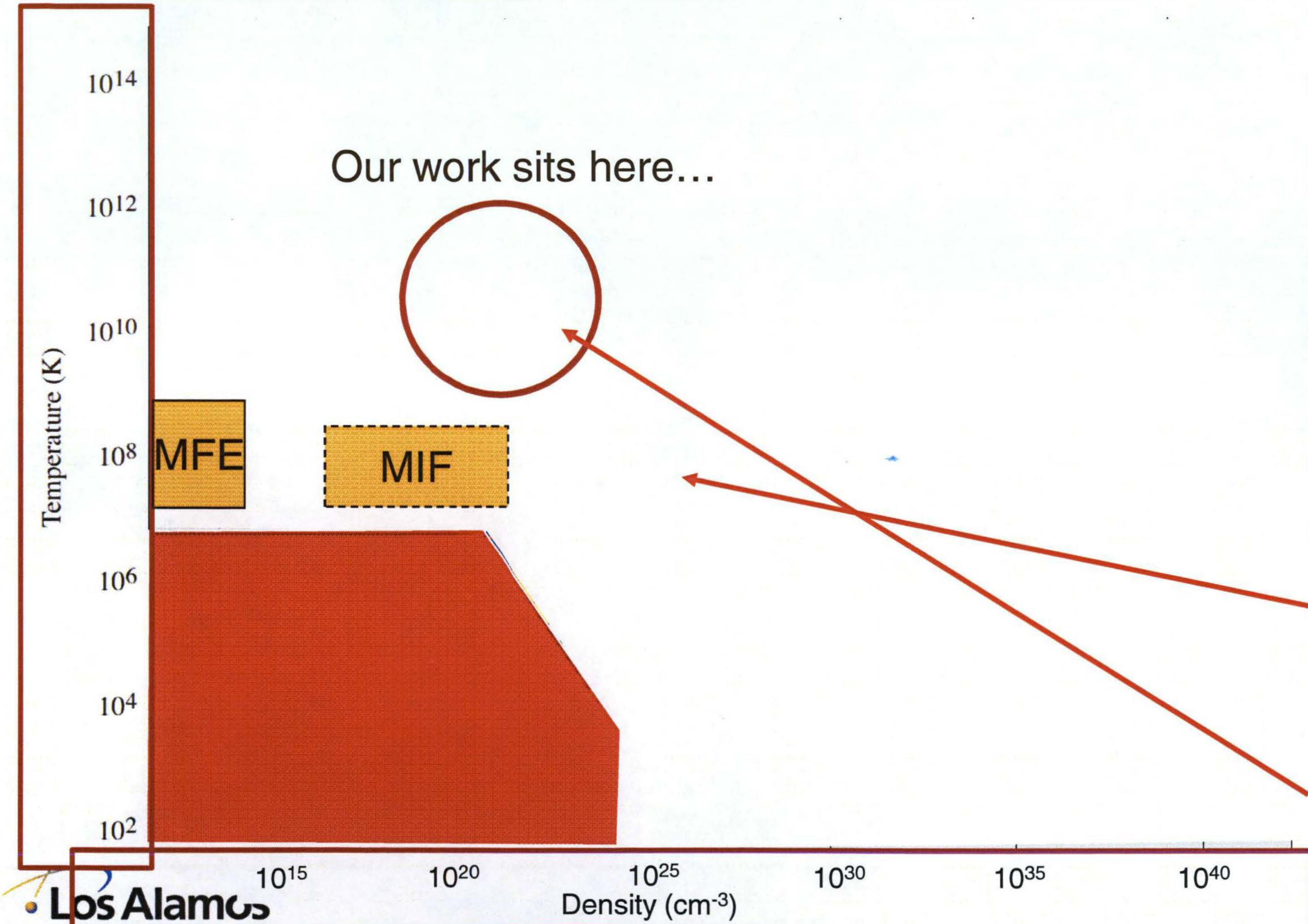
Neptune High Pressure
CO_2 laser UCLA



HEDP Overview

LA-UR-11-06510

The Universe: One of the Worst Plots Ever ...but we will make do...



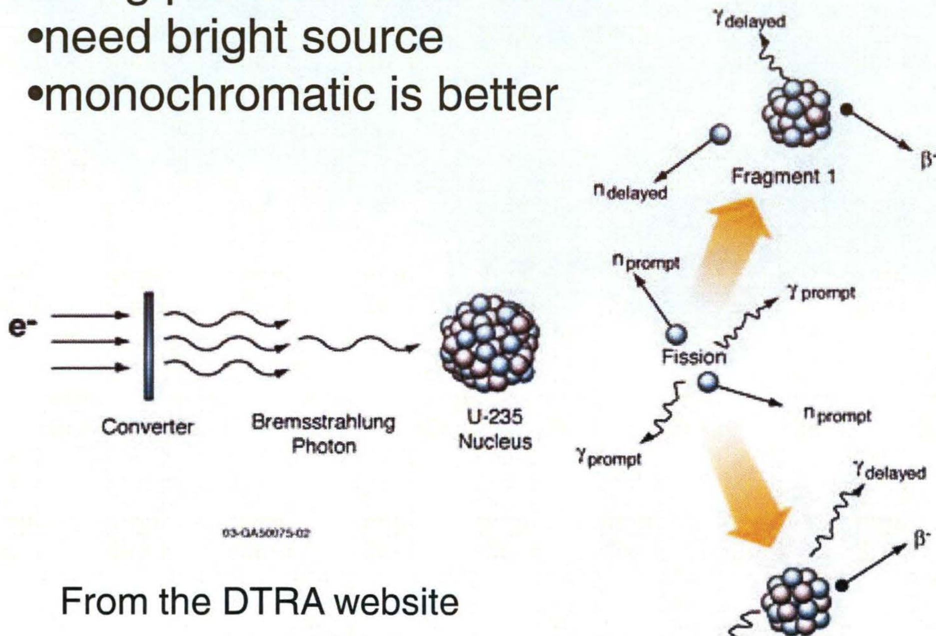
1. Astrophysical Phenomena
2. Asto Fundamental Physics
3. Lab Astrophysics
4. Heavy Ion-Driven HEDP
5. Plasma Wakefield Accelerators
6. Quark-Gluon Plasmas
7. Warm Dense Matter/Extreme Materials
8. Compressible Dynamics
9. Radiative Hydrodynamics
10. Inertial Confinement Fusion (ICF)
11. Relativistic Matter
12. Attosecond Dynamics
13. Ultra-fast X-ray Science
14. Laser Acceleration of Particels
15. Inertial Fusion – Fast Ignition

Source: Frontiers For Discovery In High Energy Density Physics, National Task Force on High Energy Density Science, July 20, 2004

Some Applications of Ion Acceleration

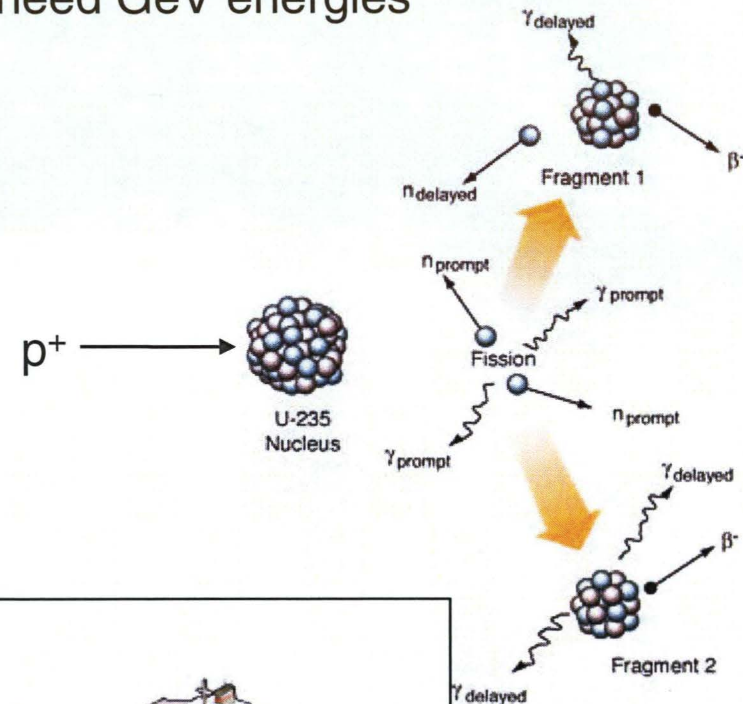
Active Interrogation (Large Standoff) for Special Nuclear Material

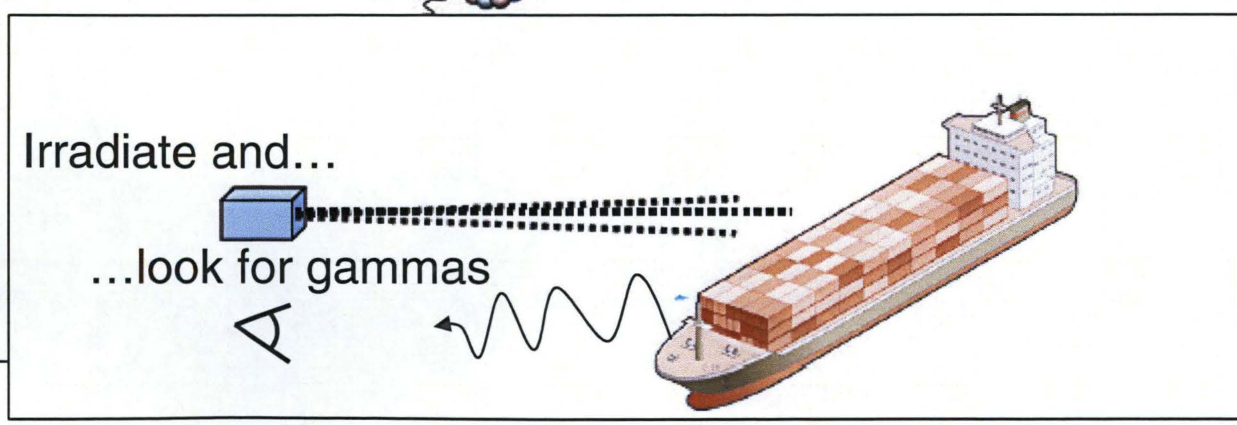
Using photons to find SNM
•need bright source
•monochromatic is better



From the DTRA website

Using Ions (p^+, d^+) to find SNM
•need GeV energies





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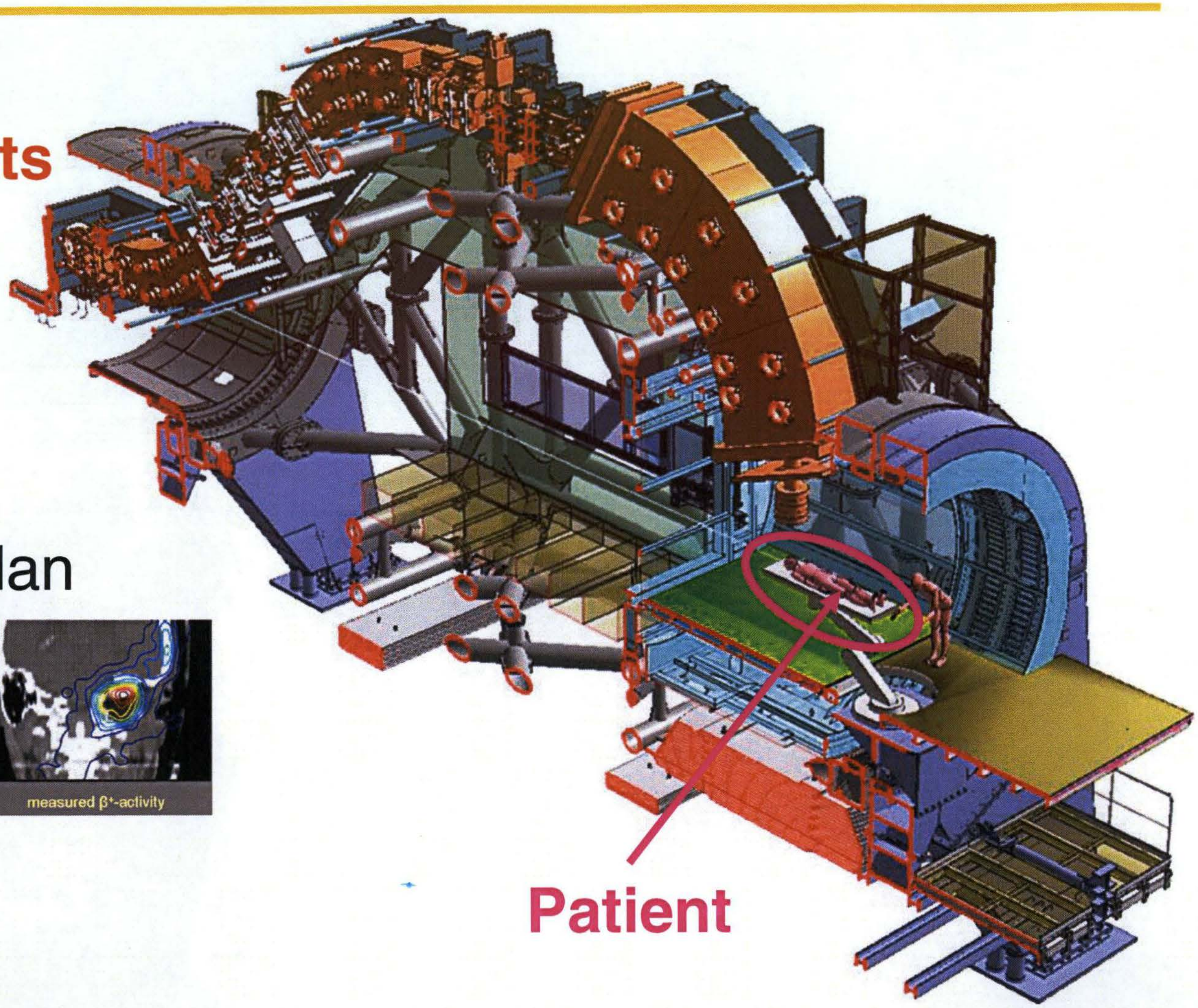
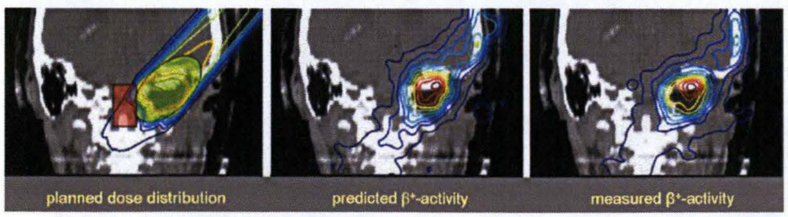
Current Hadron Therapy is done with Massive Machines

Conventional ion gantry with **magnets**

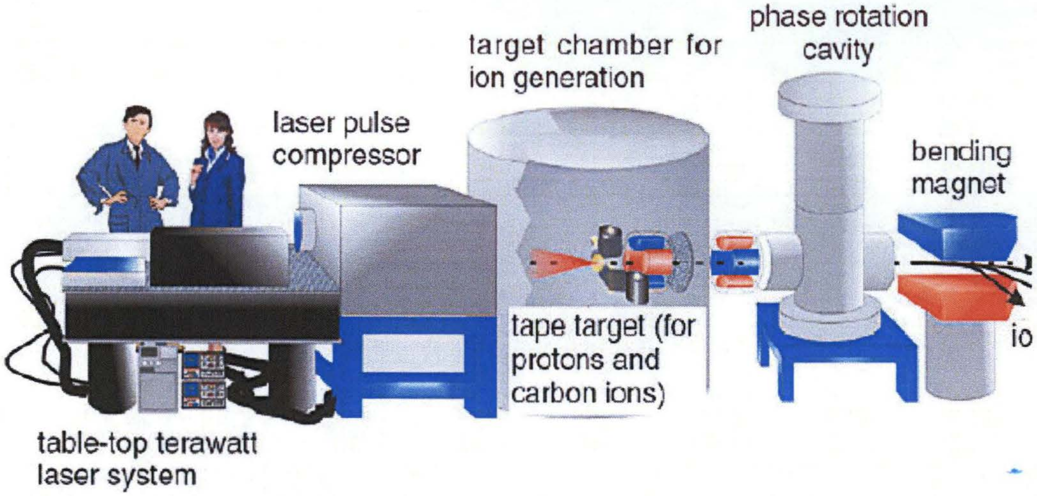


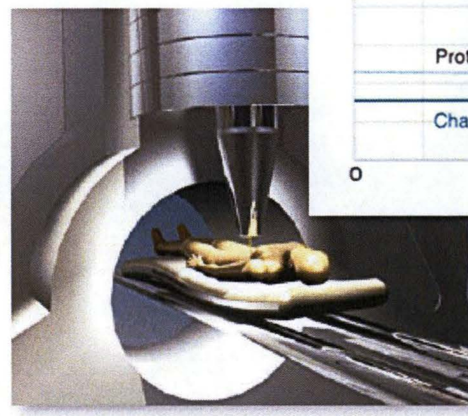
Typical treatment plan

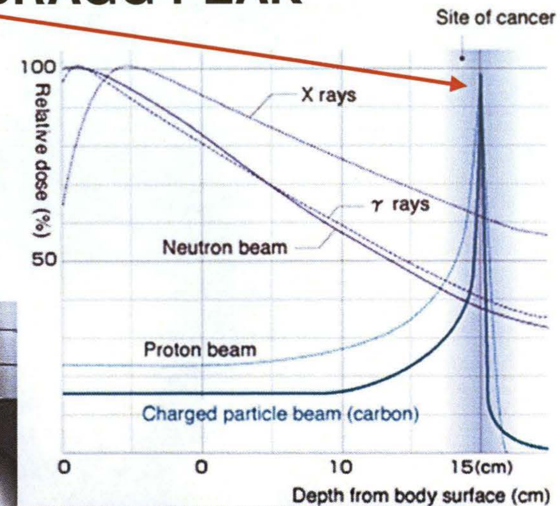


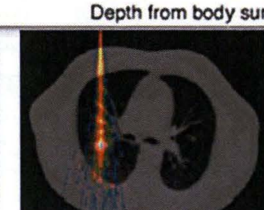
Cancer Hadron Tumor Therapy using Affordable, Compact Laser-Driven Ion Sources

Ions can deliver much more of their energy to the tumor compared to x-rays and electrons due to BRAGG PEAK



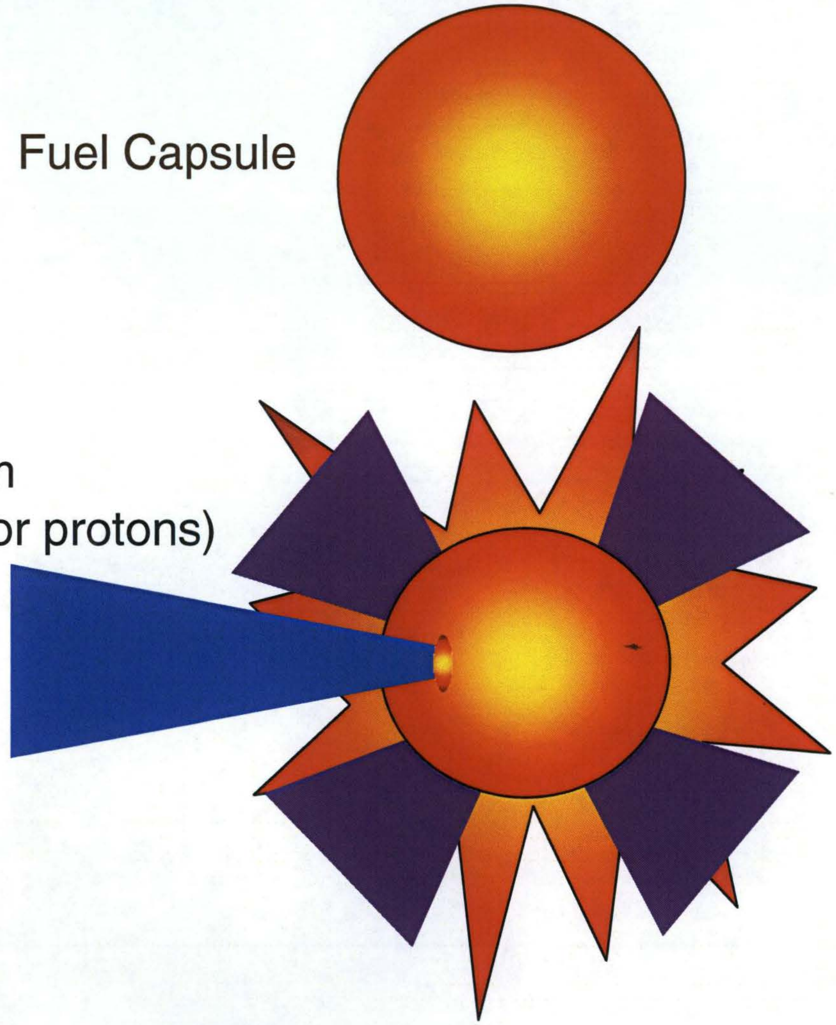






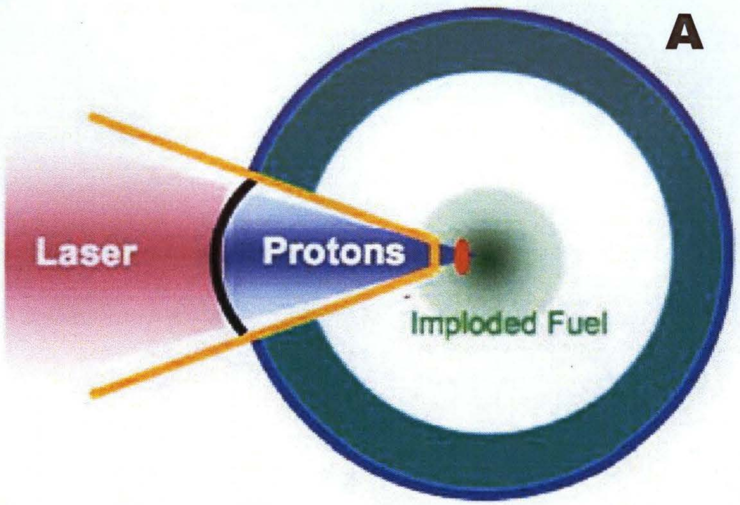
Threshold for proton therapy of the eye is about 60 MeV!

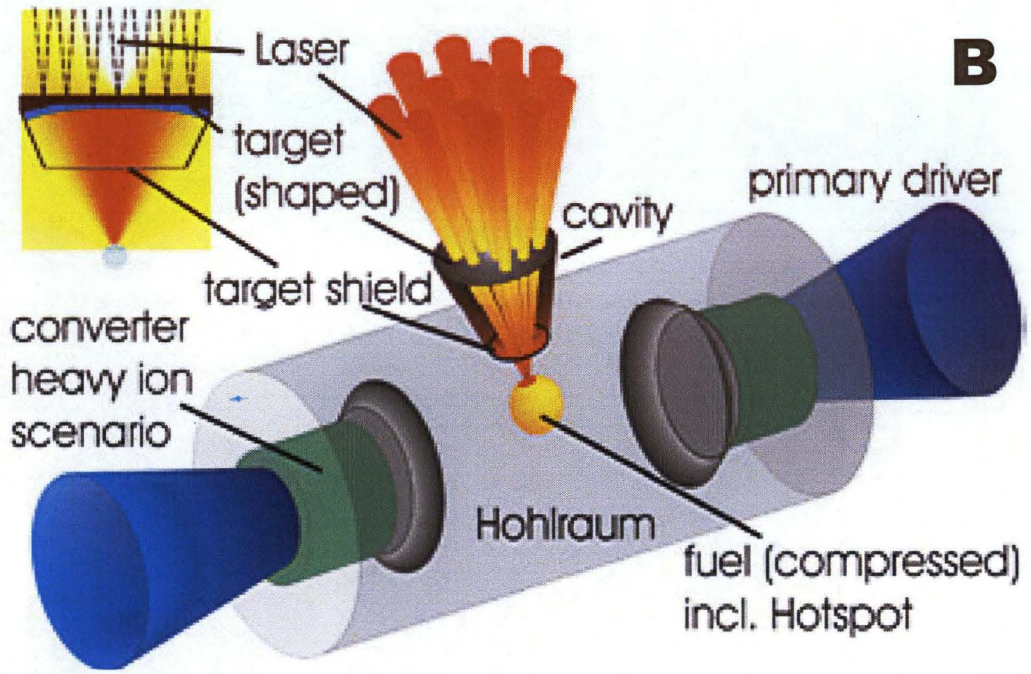
ICF Fast Ignition using Protons: a Way to Save Driver Energy



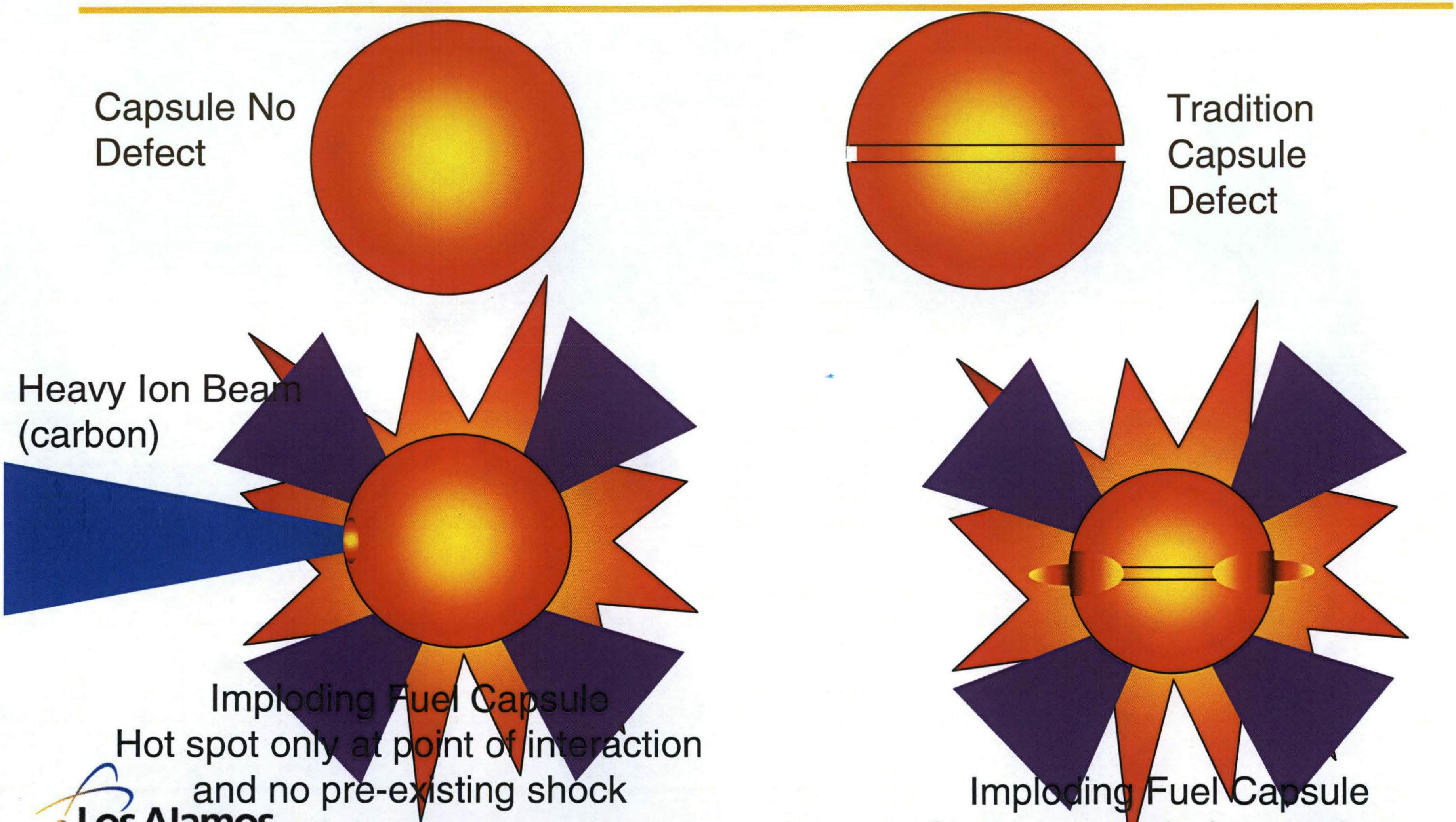
Hot spot only at point of interaction and no pre-existing shock

Fast Ignition using Protons, Deuterons, or Carbon





Dynamic Defect Production using Ion Beams



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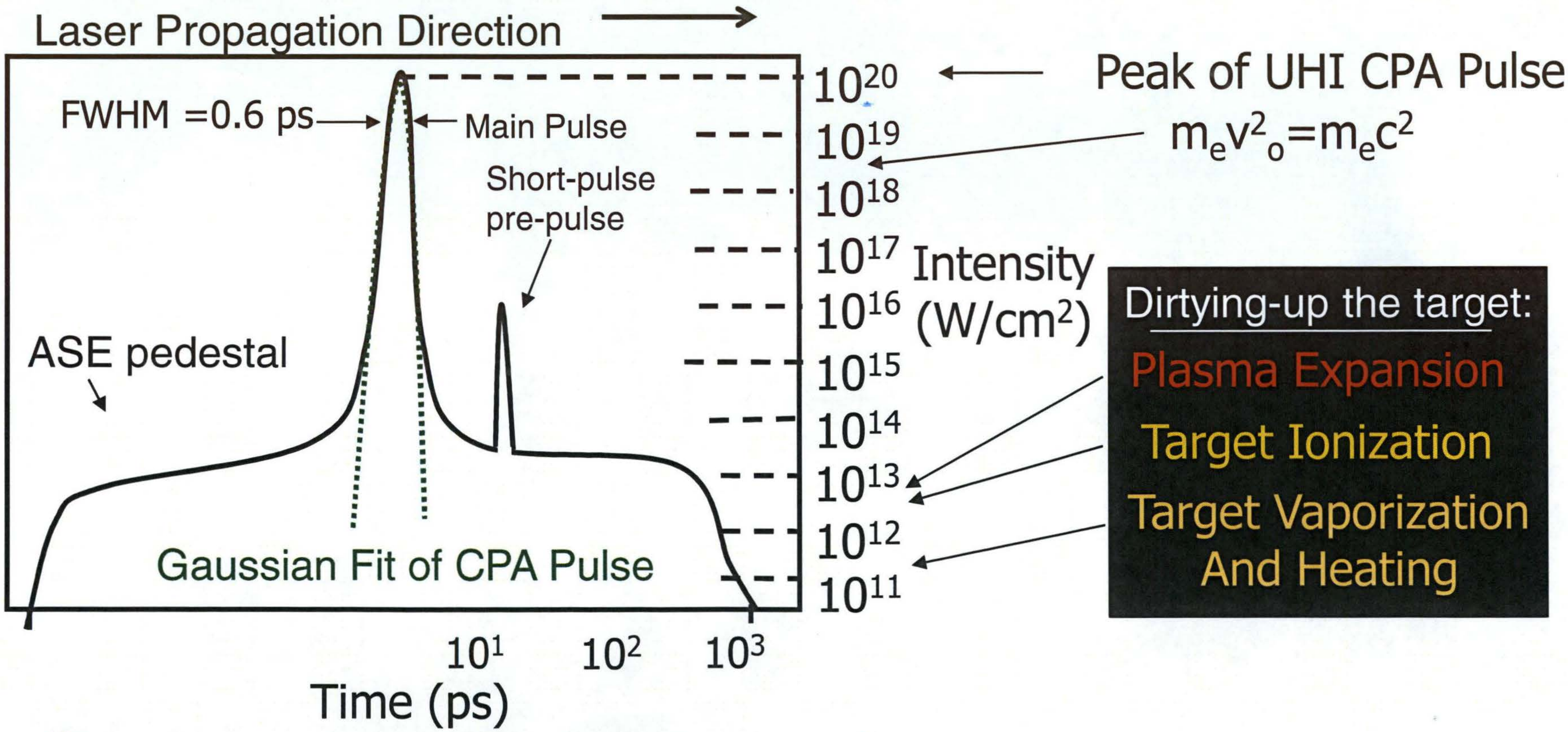
Short-Pulse Laser Radiation Sources and Ion Acceleration

LA-UR-11-06510

First, the Dirty Truth about Short-Pulse Lasers

No ultra-high intensity (UHI) laser Interacts with a non-ionized solid density target.



1.053 μm CPA pulse, ω_o typical ASE pedestal 10^{-7}

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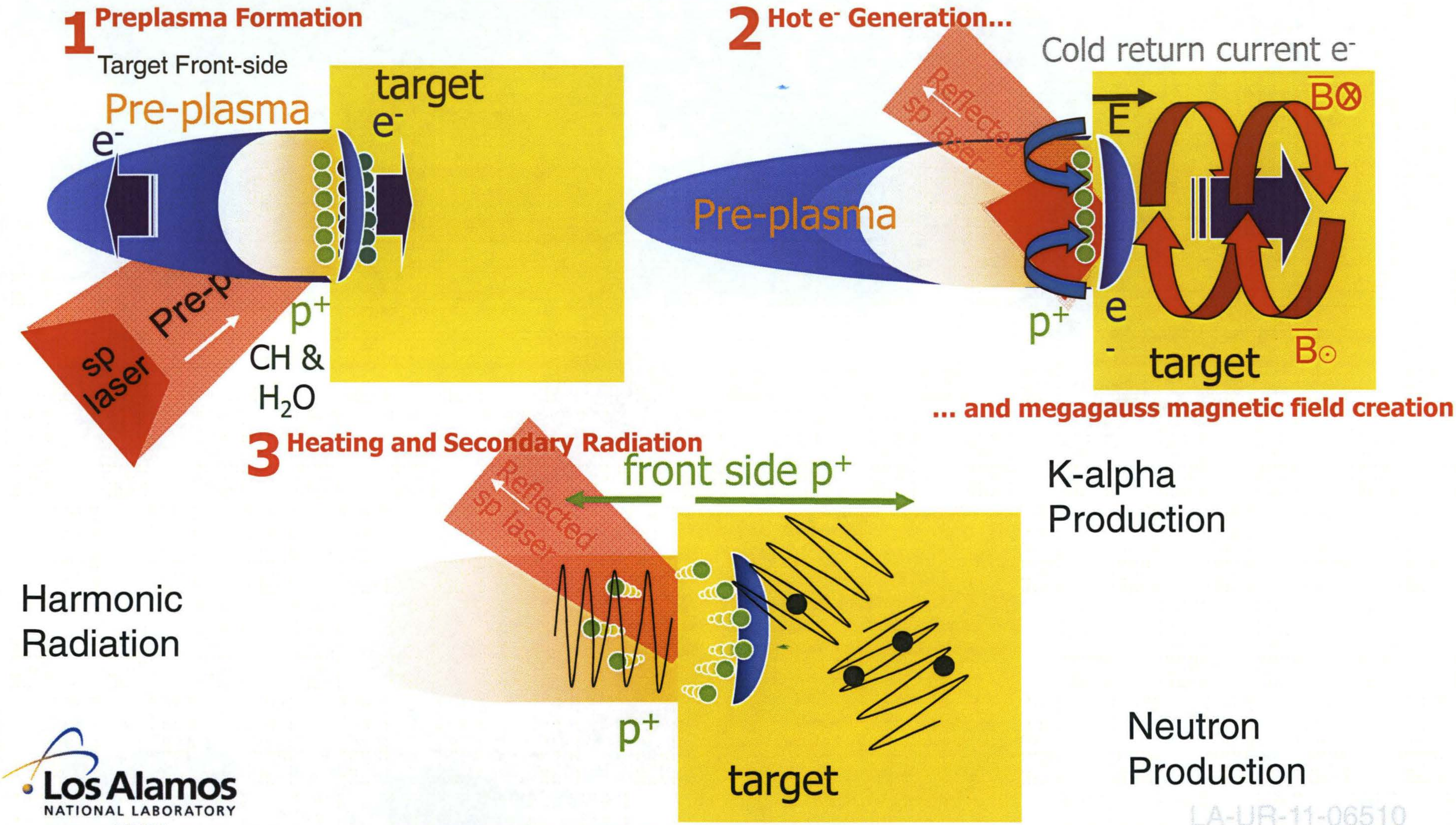
Overview of Ultra-Intense Laser-Matter Interactions as Radiation Sources



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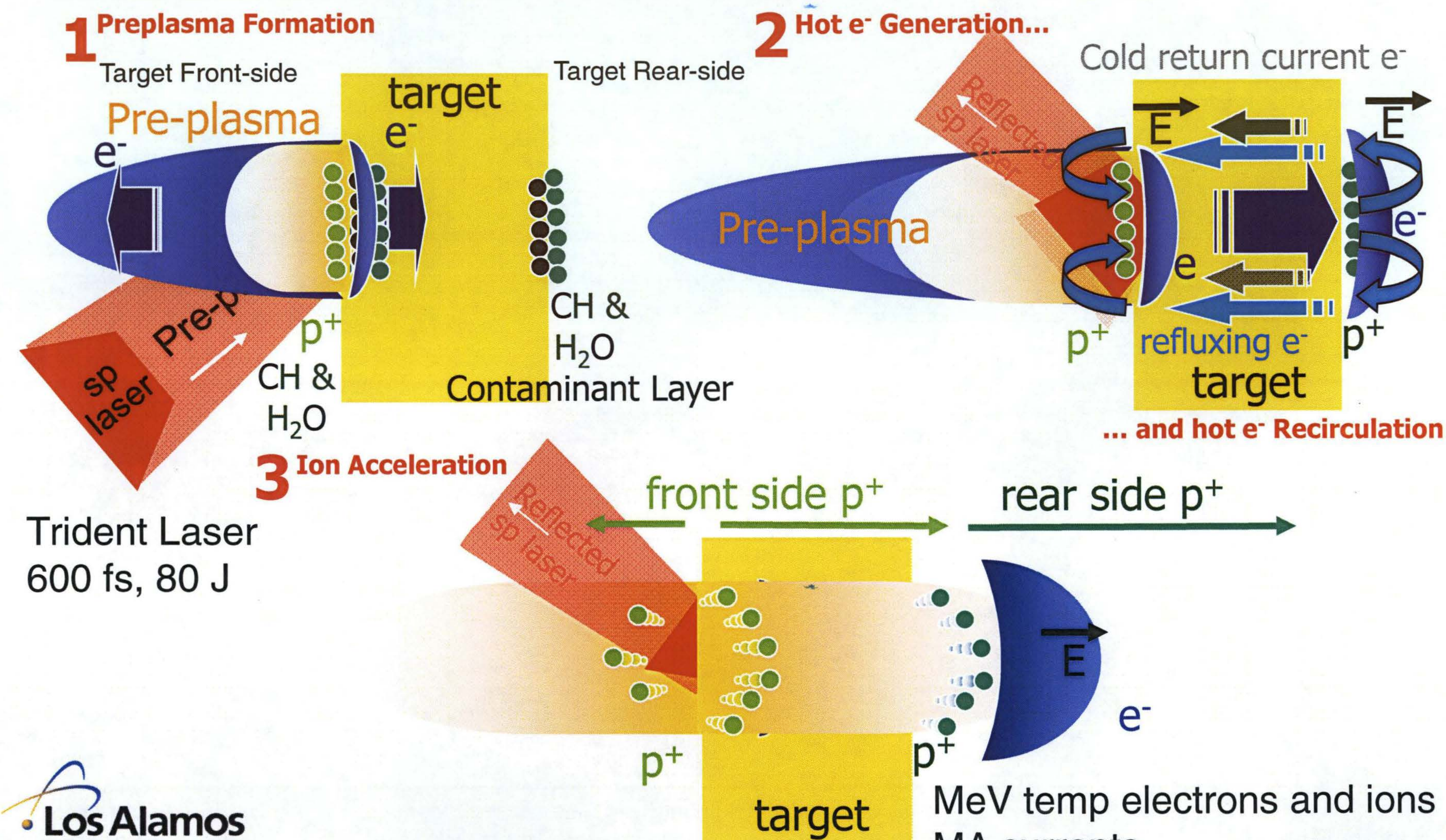
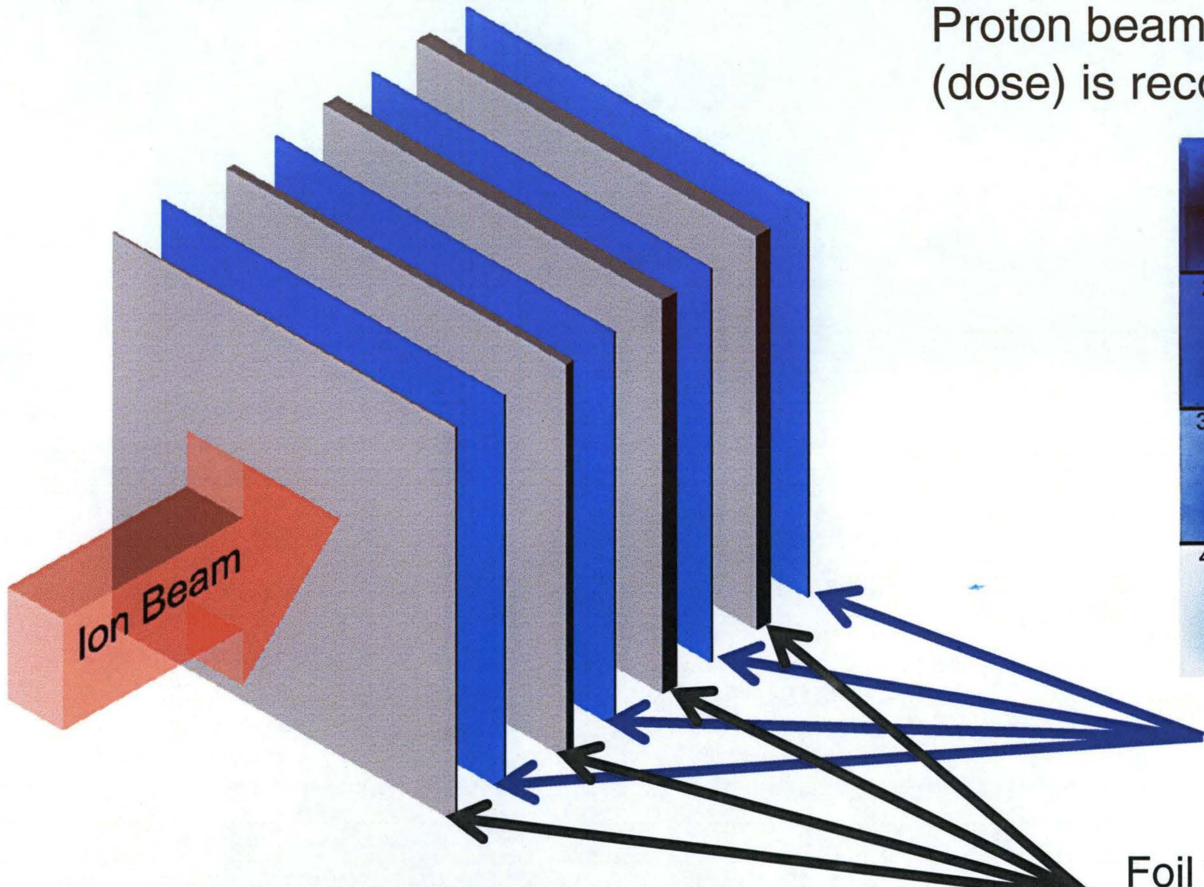
Thinner Targets Allow for Laser-Ion Acceleration: Target Normal Sheath Acceleration (TNSA)



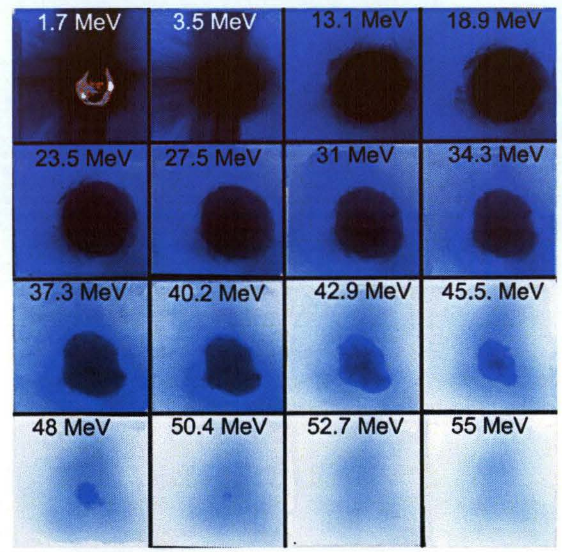
Trident Laser
600 fs, 80 J

MeV temp electrons and ions
MA currents
TV and MG fields

Stacked Layers of RadioChromic Film (RCF) Measure the Proton Beam Profile and Spectrum



Proton beam profile and number (dose) is recorded in the stack

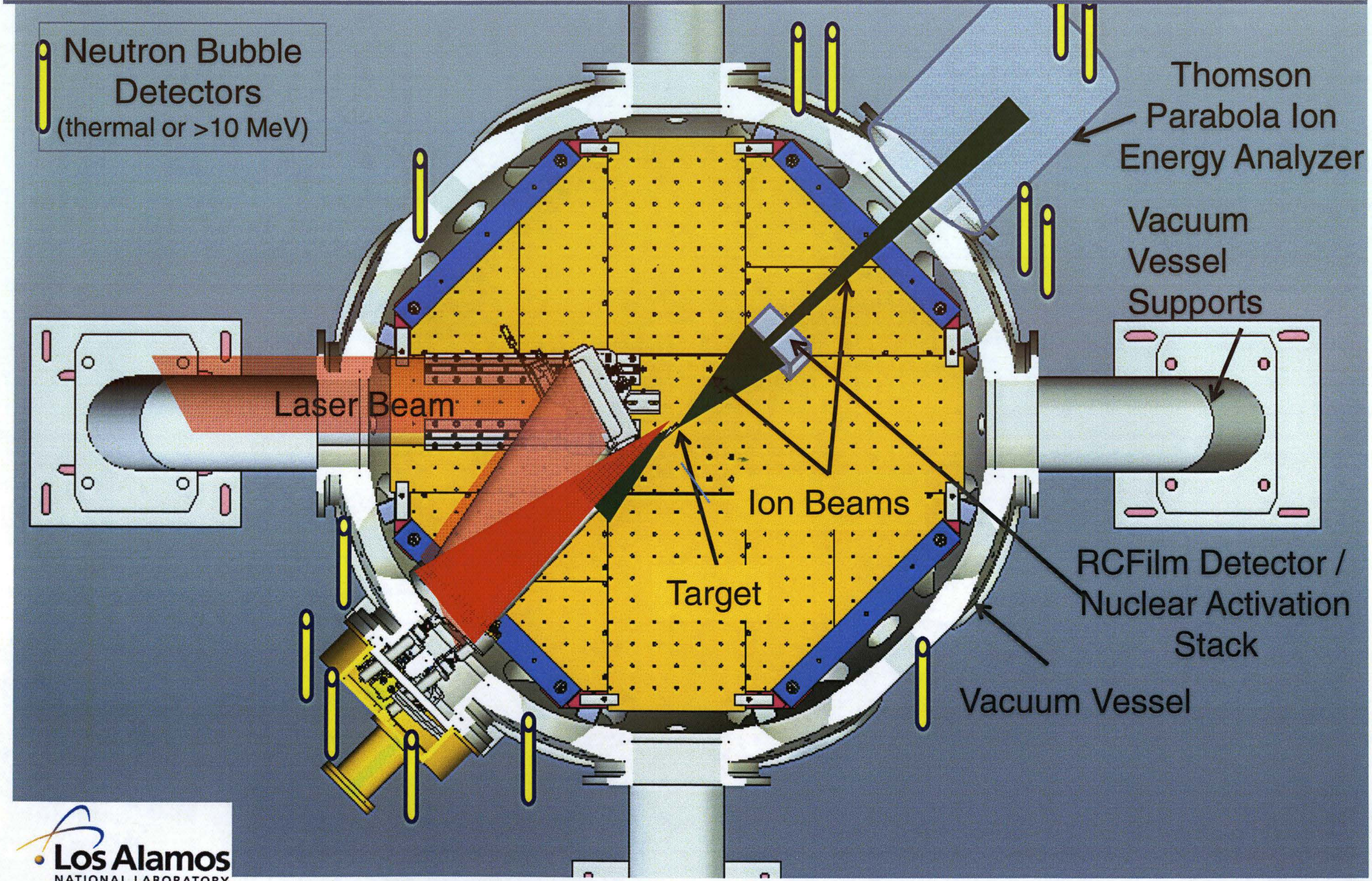


Each layer of film is sensitive to protons

Foil filter layers stop sequentially lower energy protons, giving spectra resolution

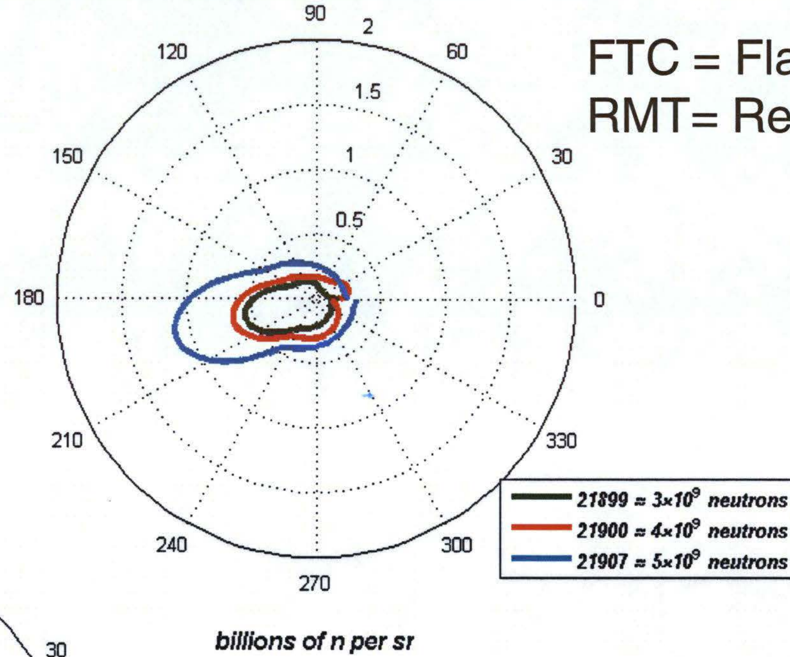
A self-developing film (like Polaroid™), but sensitive to ionizing radiation

Trident North Target Chamber Top Setup View



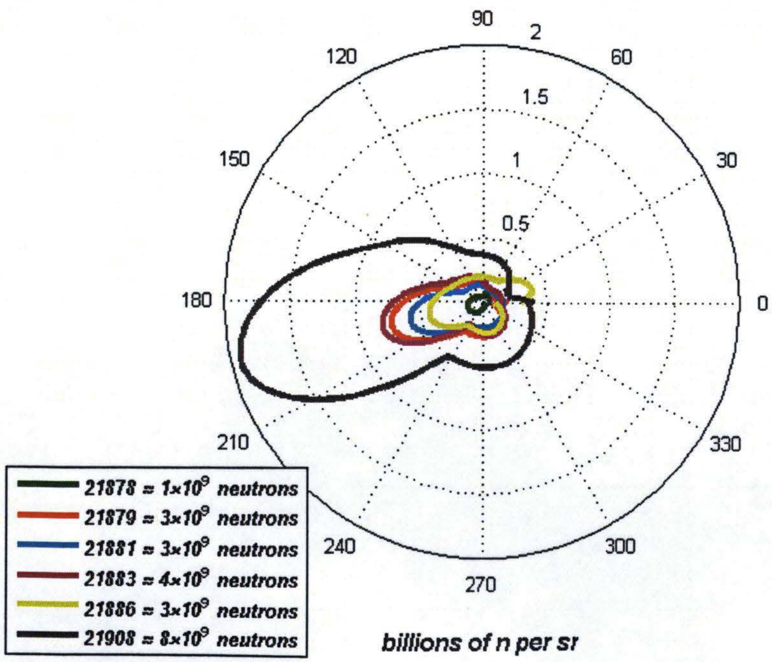
Billions and Billions of Neutrons are Distributed in 3 Lobes: Normal, Side, and Focusing Optic

Low Contrast FTCs, 10 µm, 80 J, 650 fs

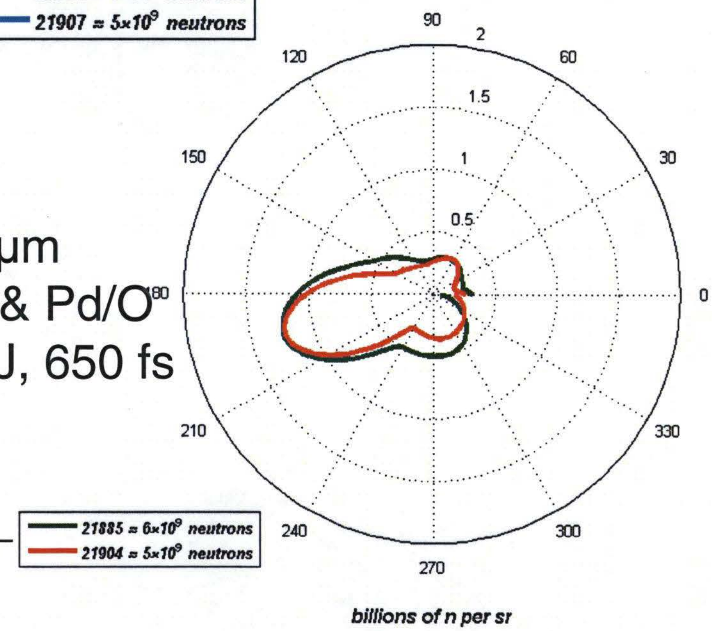


FTC = Flat-Top Cone
RMT= Reduced Mass Target

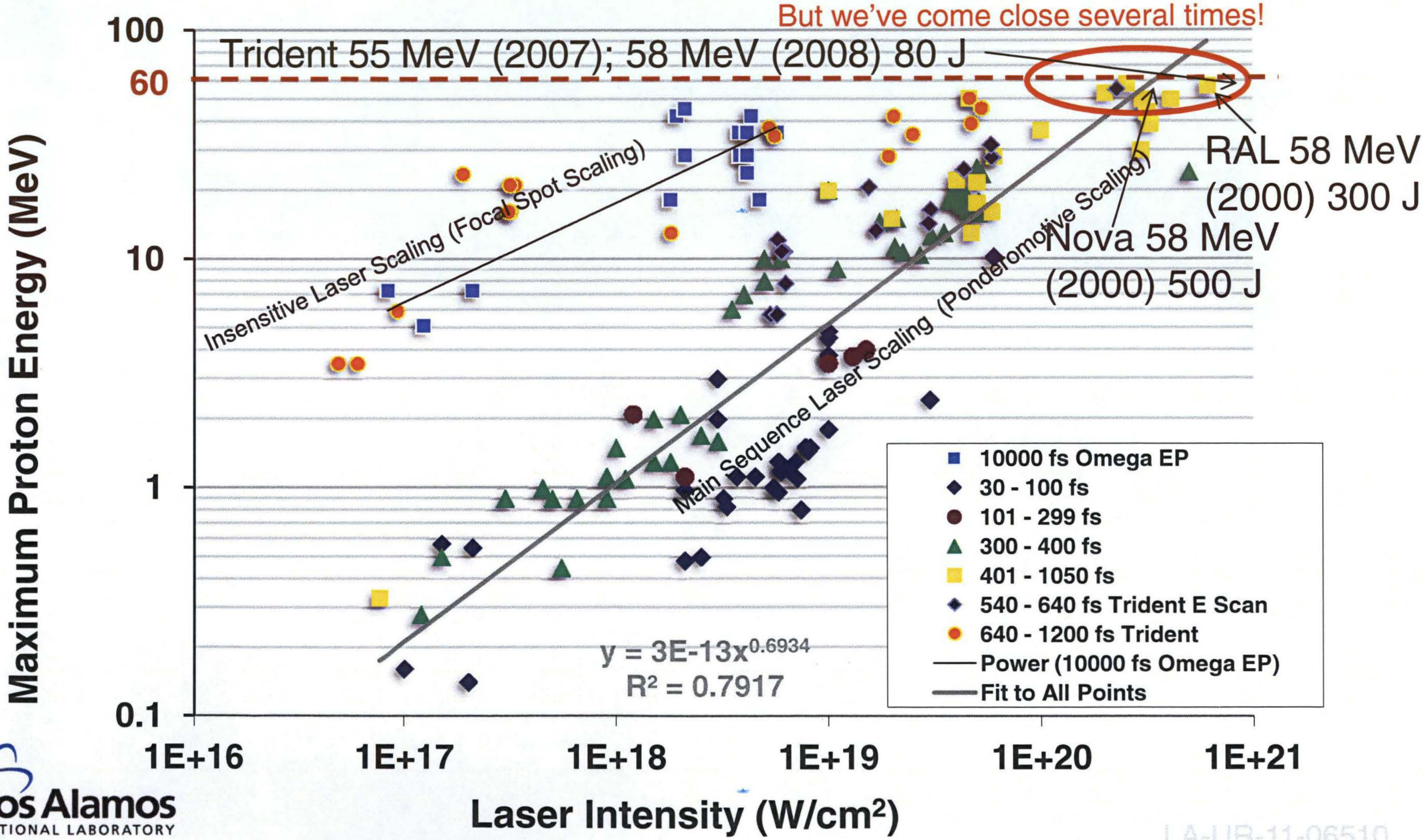
High Contrast FTCs, 10 µm, 80 J, 650 fs



10 µm
Pd & Pd/O
80 J, 650 fs



TNSA's Dirty Little *Secret*: the 60 MeV Barrier - We were Stuck there for a Decade!



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S. Gaillard *et al.*, *Physics of Plasmas* **18**, 056710 (2011)
K. A. Flippo *et al. J. Phys.: Conf. Series* **244** 022033 (2010) M. Schollmeier *et al. Phys. Rev. Lett (in prep)*

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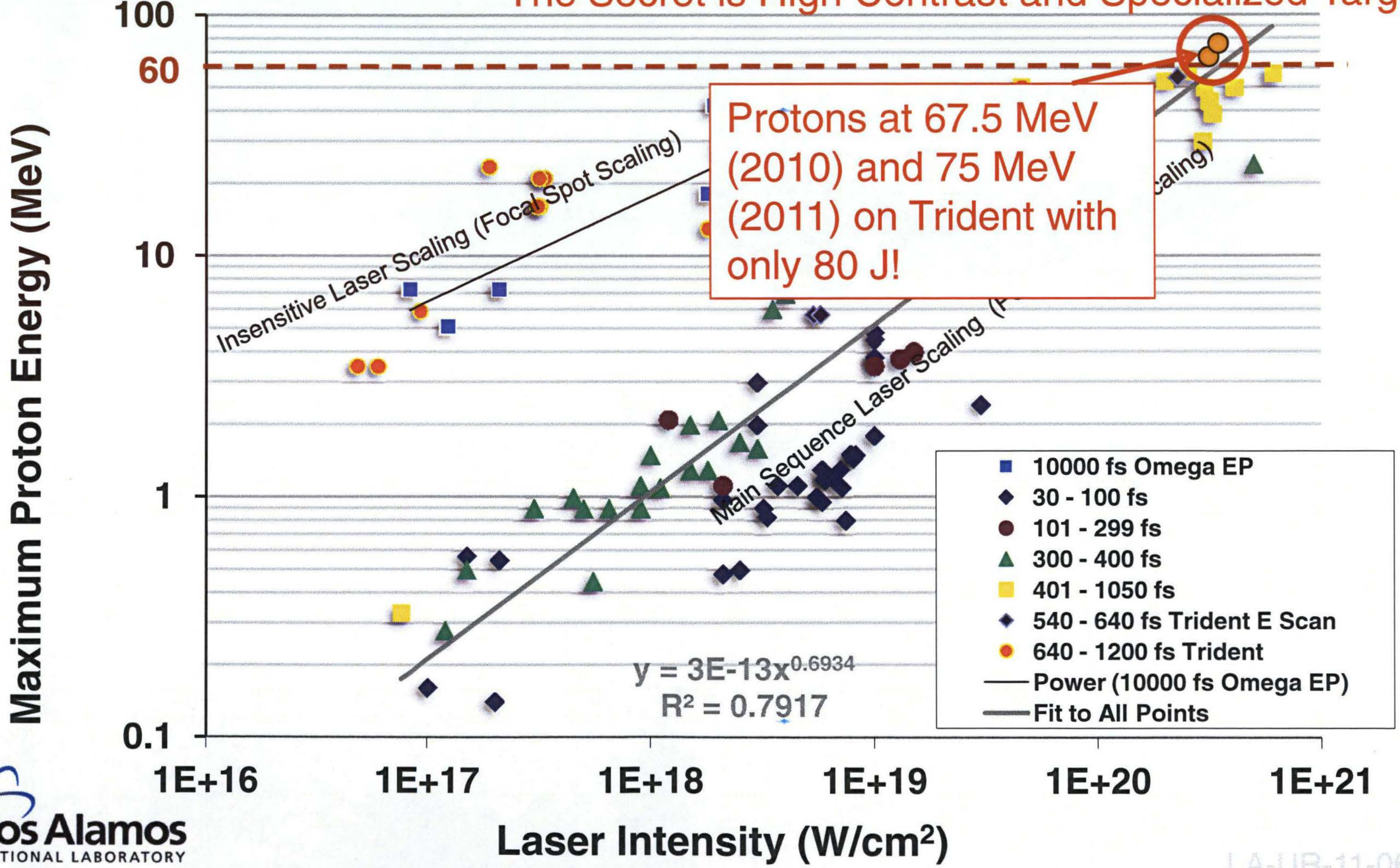
But Recently Using Small Targets we have Succeeded … 65 MeV then 75 MeV (5x less E_{Laser})

The Secret is High Contrast and Specialized Targets



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LA-UR-11-06510

S. Gaillard *et al.*, *Physics of Plasmas* **18**, 056710 (2011)
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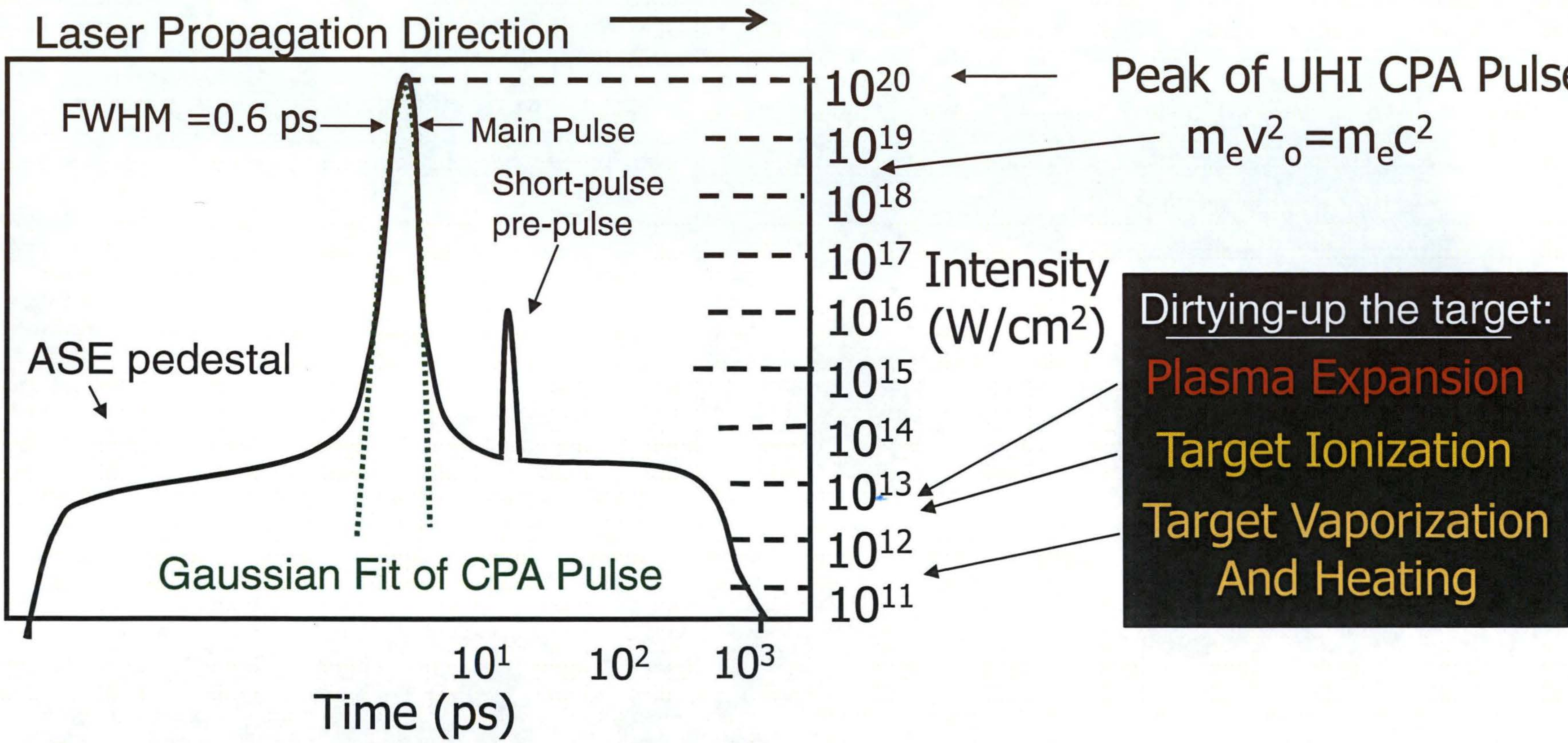
Short-Pulse Laser Radiation Sources and Ion Acceleration

High-Contrast Laser
Ion Acceleration and X-rays

Using Flat Foils (and Reduced Foils)

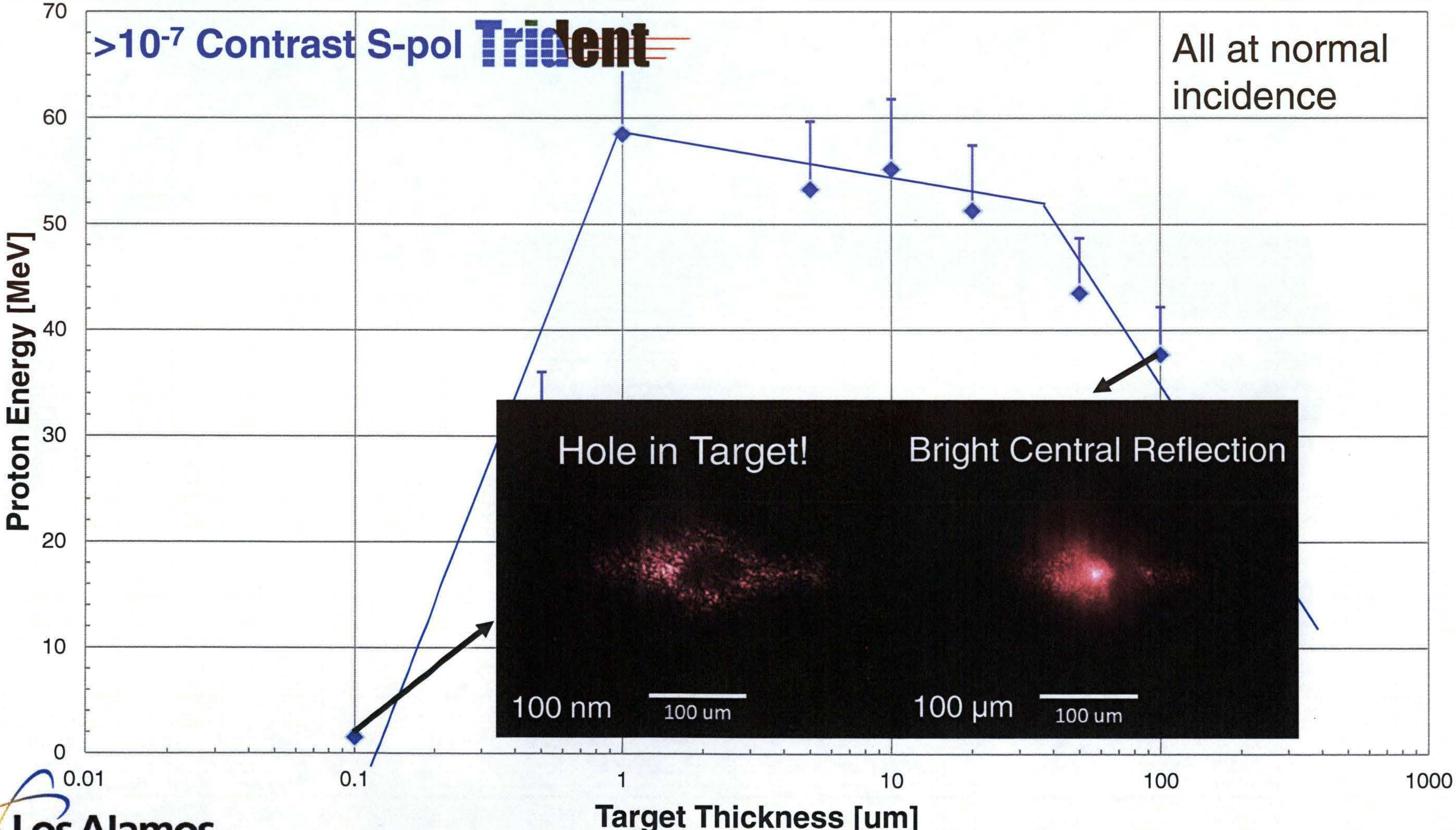
The Dirty Truth about Short-Pulse Lasers

No ultra-high intensity (UHI) laser interacts with a non-ionized solid density target.



1.053 µm CPA pulse, ω_o typical ASE pedestal 10^{-7}

"low contrast": Proton Energy is Flat with Target Thickness, with a Shock Breakout Drop for Thin Targets



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K. Flippo *et al.*, IEEE Trans. on Plasma Sci. **39,** Part 1 2428 (2011)

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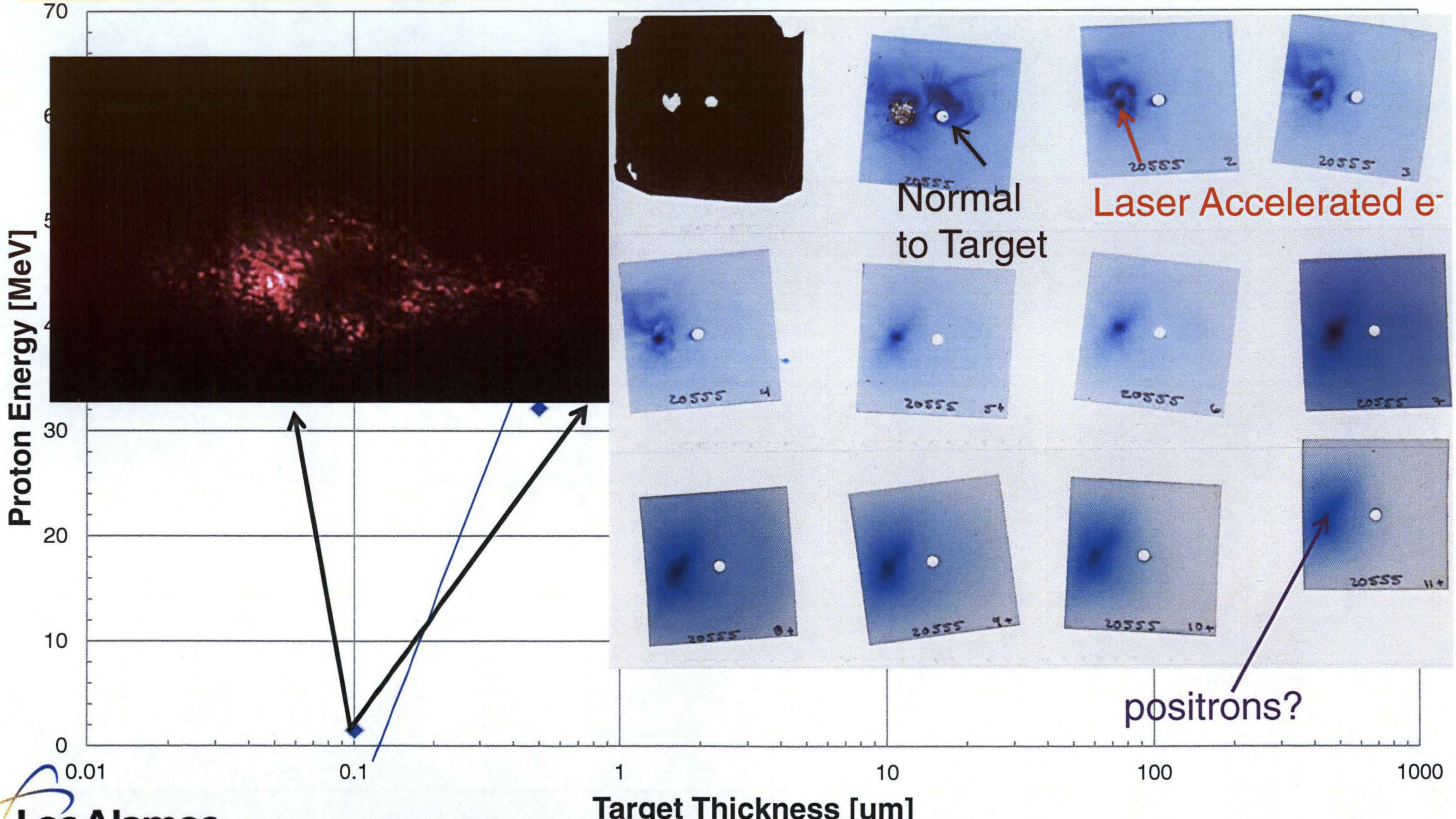
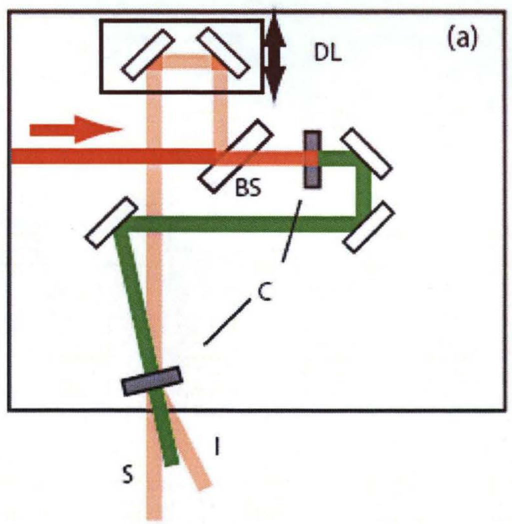
Electron Beam from Thin Targets can be Converted into Positrons

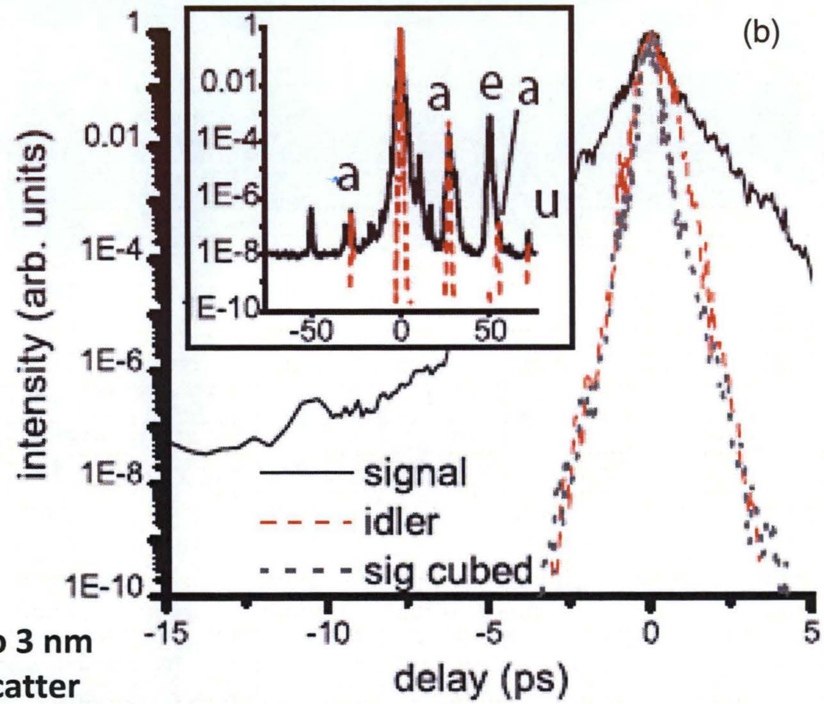


We can tell protons for electrons due to the Bragg peak!

Improving the Laser Contrast: An OPCPA Based Cleaner for Trident

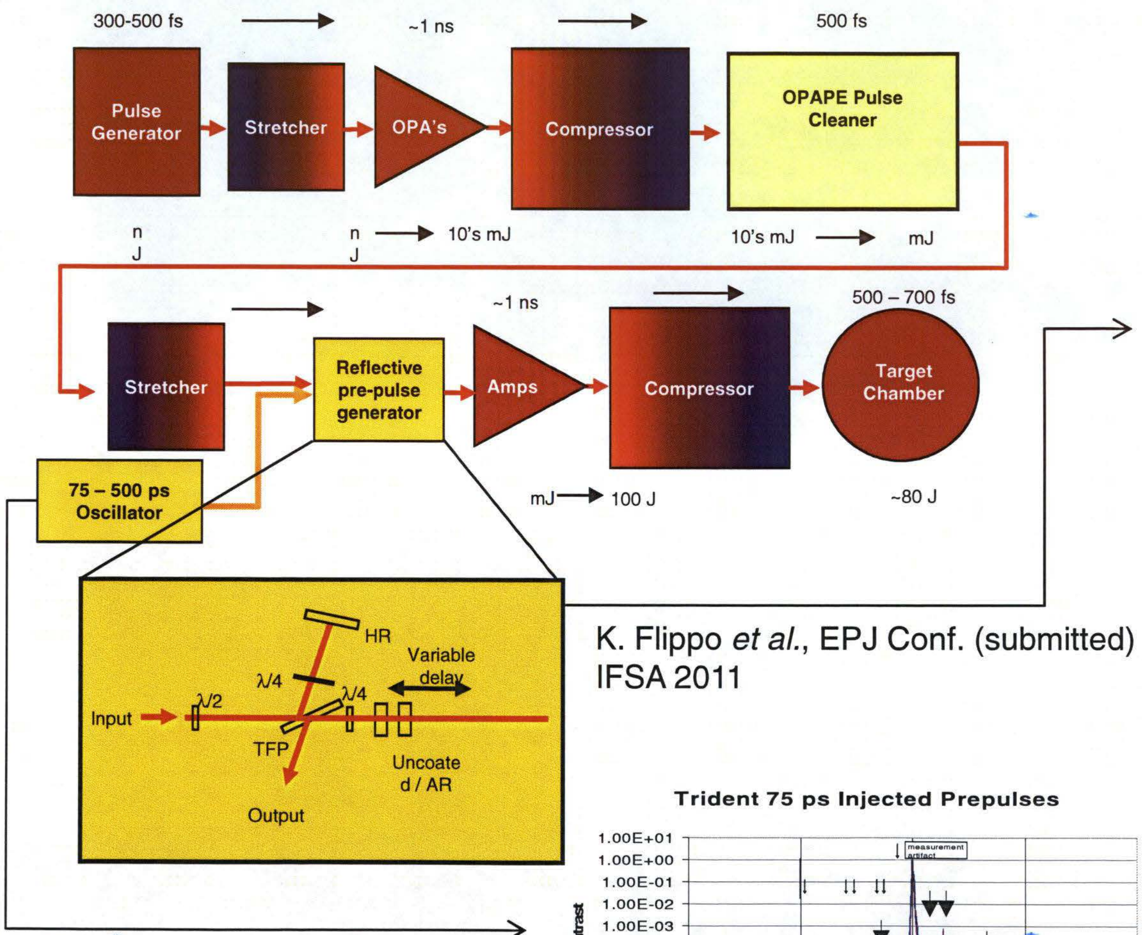
A new laser cleaning scheme was invented at LANL, called Short-Pulse Optical Parametric Amplified (SPOPA) cleaning **(a)**, based on OPCPA, which has made TRIDENT the world leader in high-contrast ultra-high-intensity lasers, by reducing the contrast to better than 10^{-10}, beyond the ability to measure it directly (**b**).

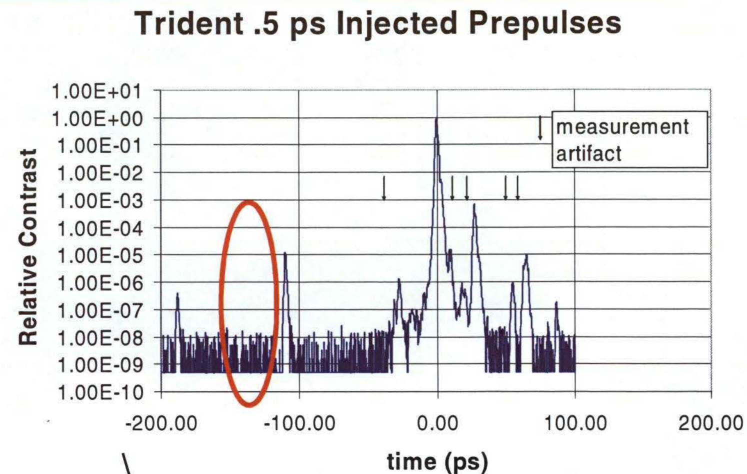


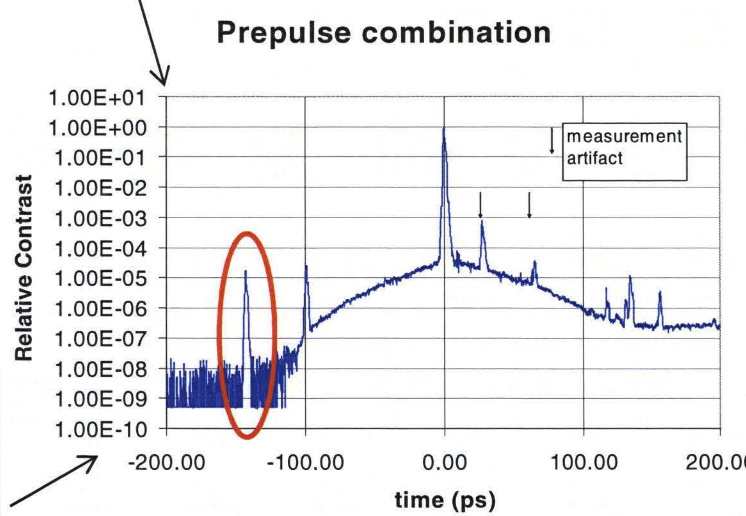


The new high contrast was tested down to 3 nm targets with a diagnostic called the Backscatter Focal Diagnostic (BFD) which captures an image of the laser light on the target. This is shown in the figure below. The target can be seen to be destroyed by the normal contrast at 100 nm, but survives intact to 10 nm.

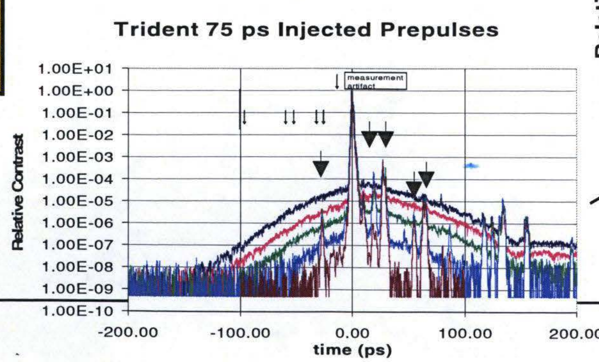
World's Best Laser Contrast: A New "Dial-A-Contrast" Capability to Trident



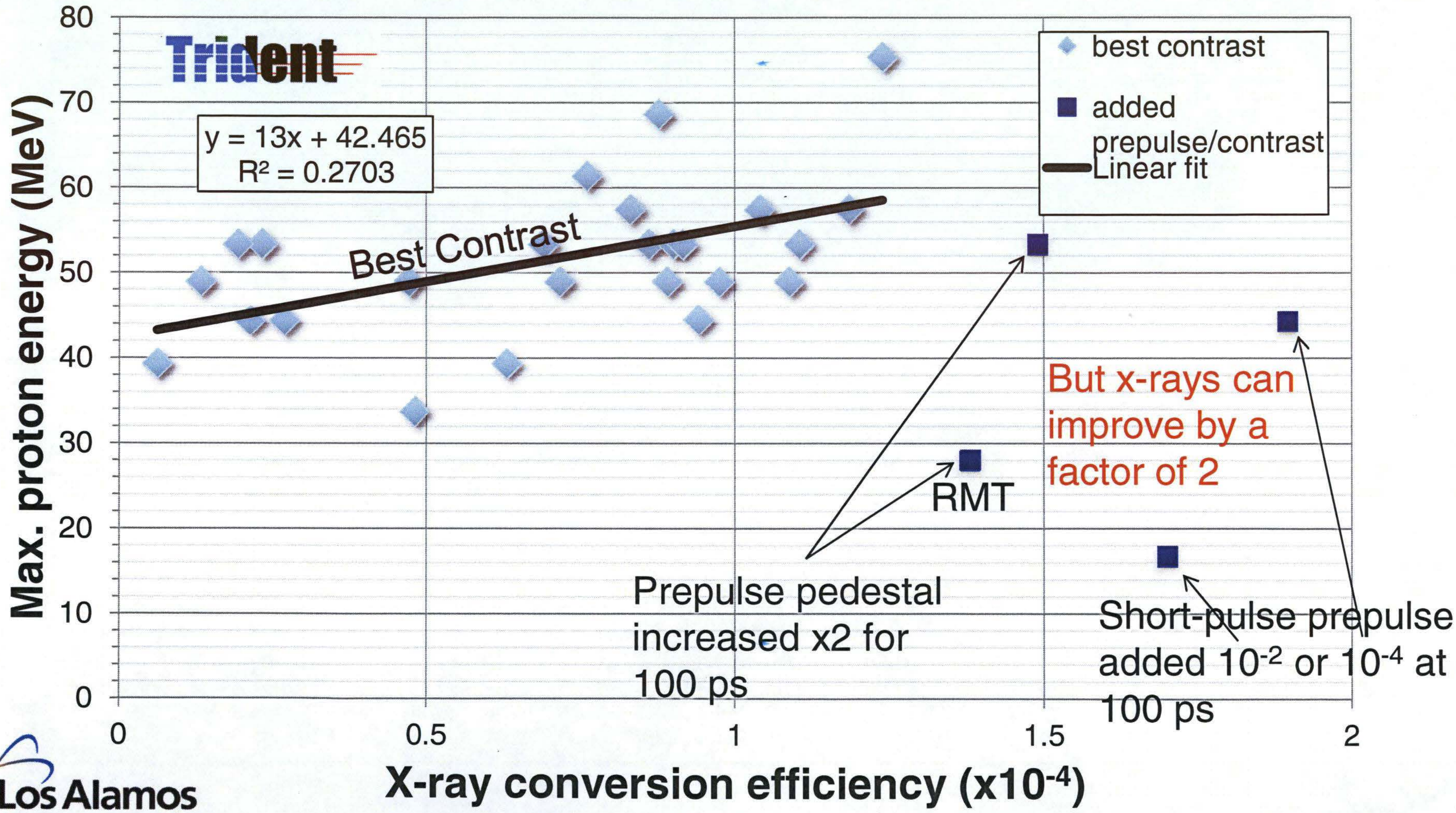




K. Flippo *et al.*, EPJ Conf. (submitted)
IFSA 2011



Adding Prepulse (Short-Pulse and Pedestal) Increases X-ray Yields but Not Proton Energies



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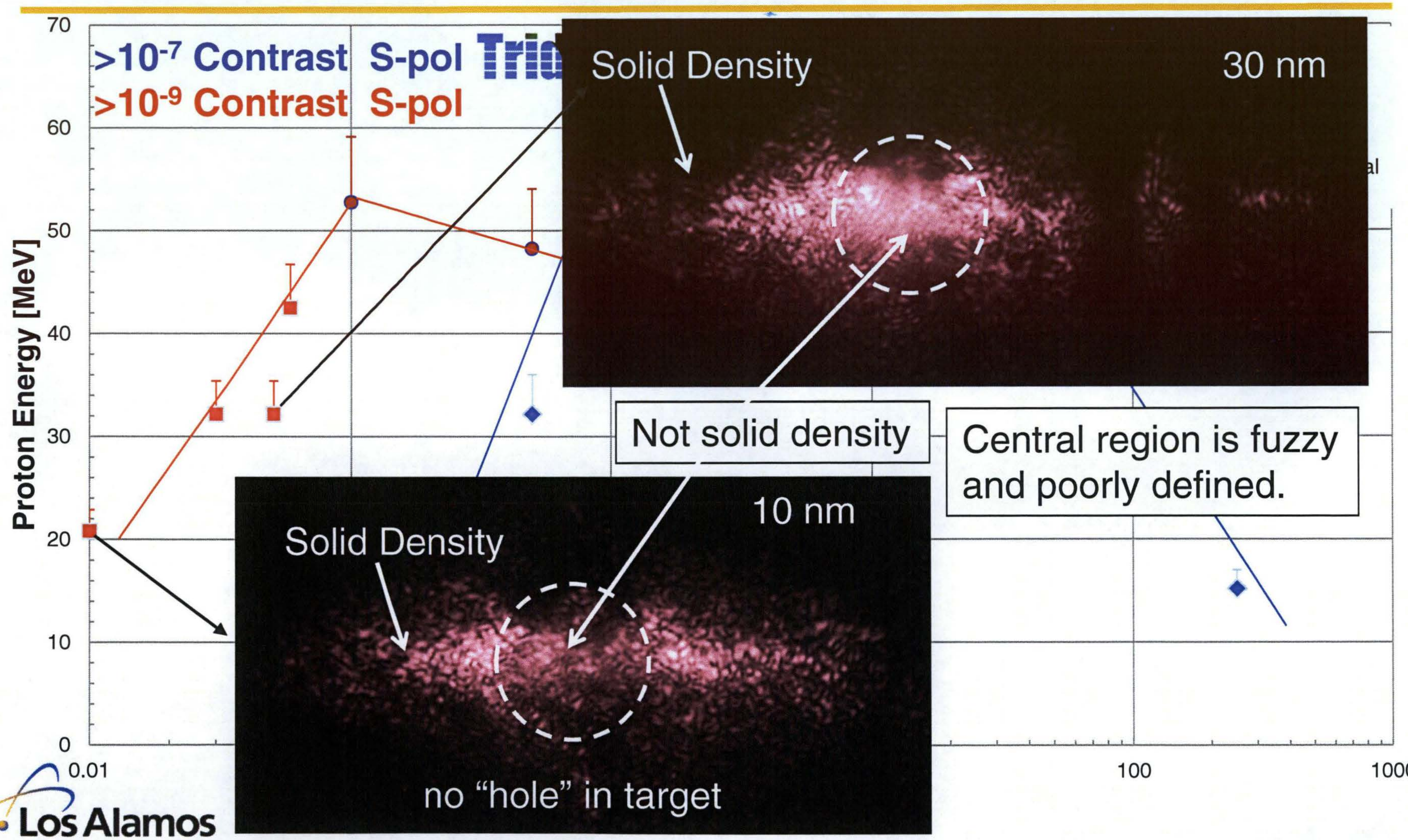
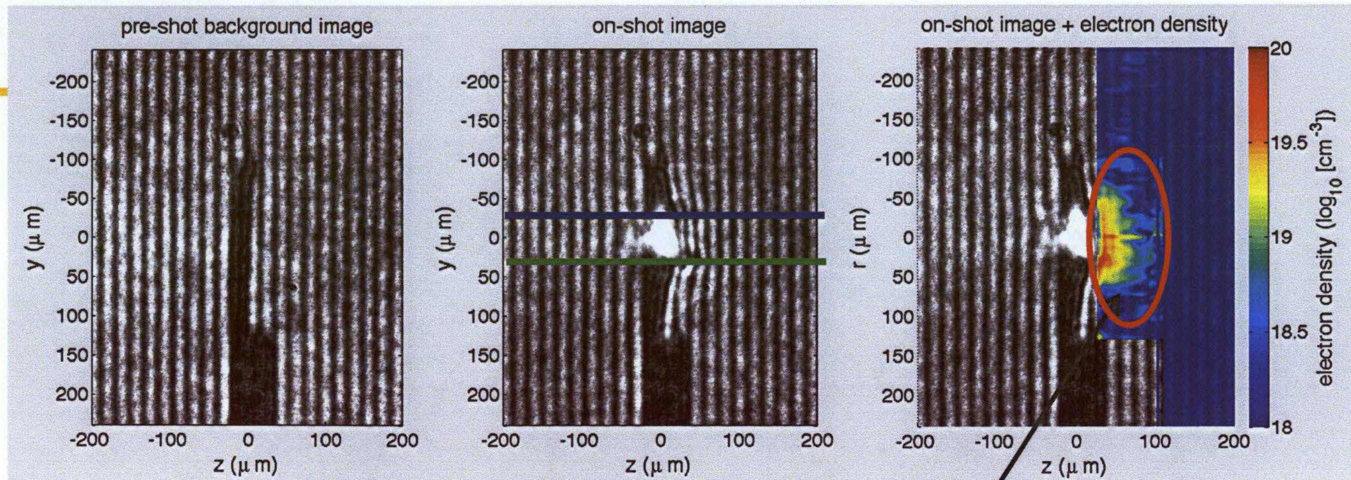
High Contrast leaves “Something” to Interact with the Laser at the Target Plane, but Not a Solid



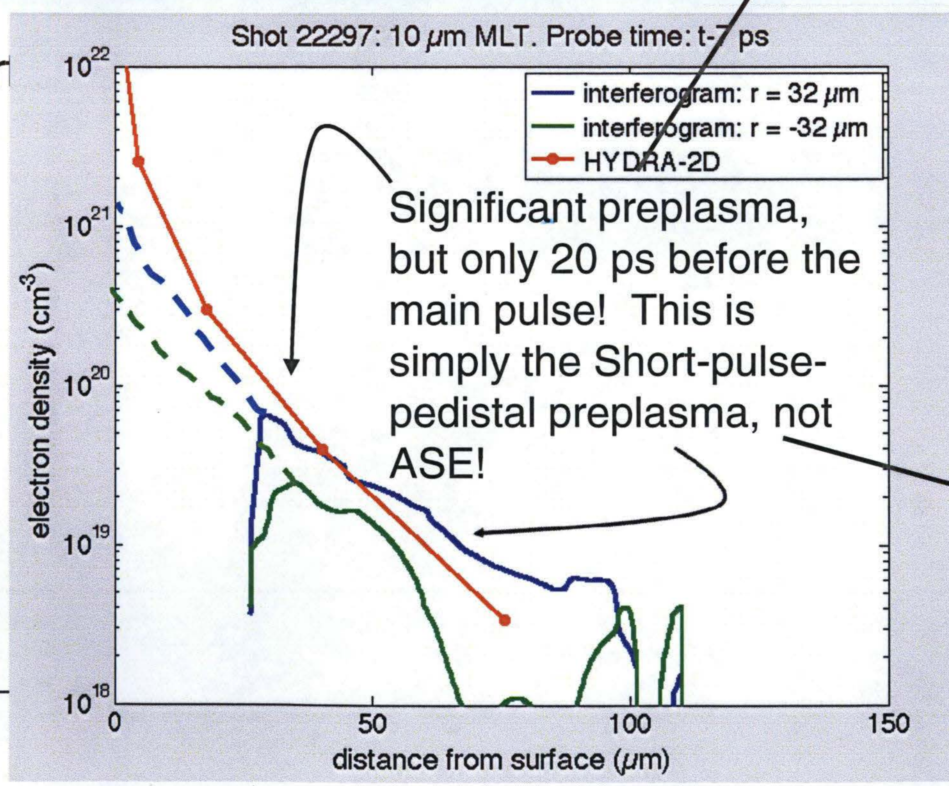
We've Measured an Overdense Plasma 10s of μm Long

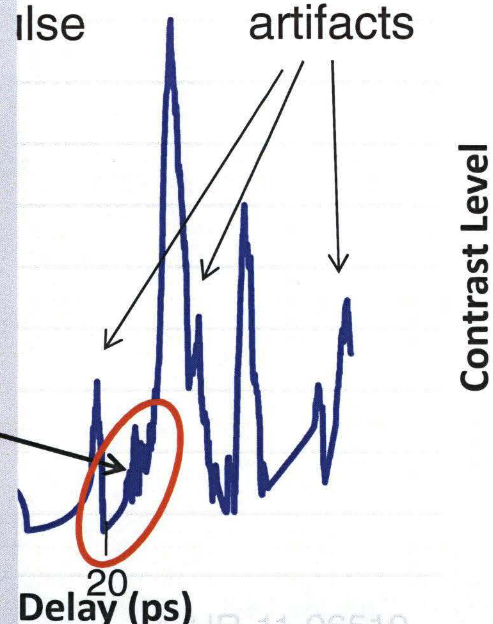


Trident

Inter ... ulse

Simulations and data agree at 50 microns in front of the target ~$4x10^{19}$ /cm^{-3} and show significant plasma out to **100 microns**





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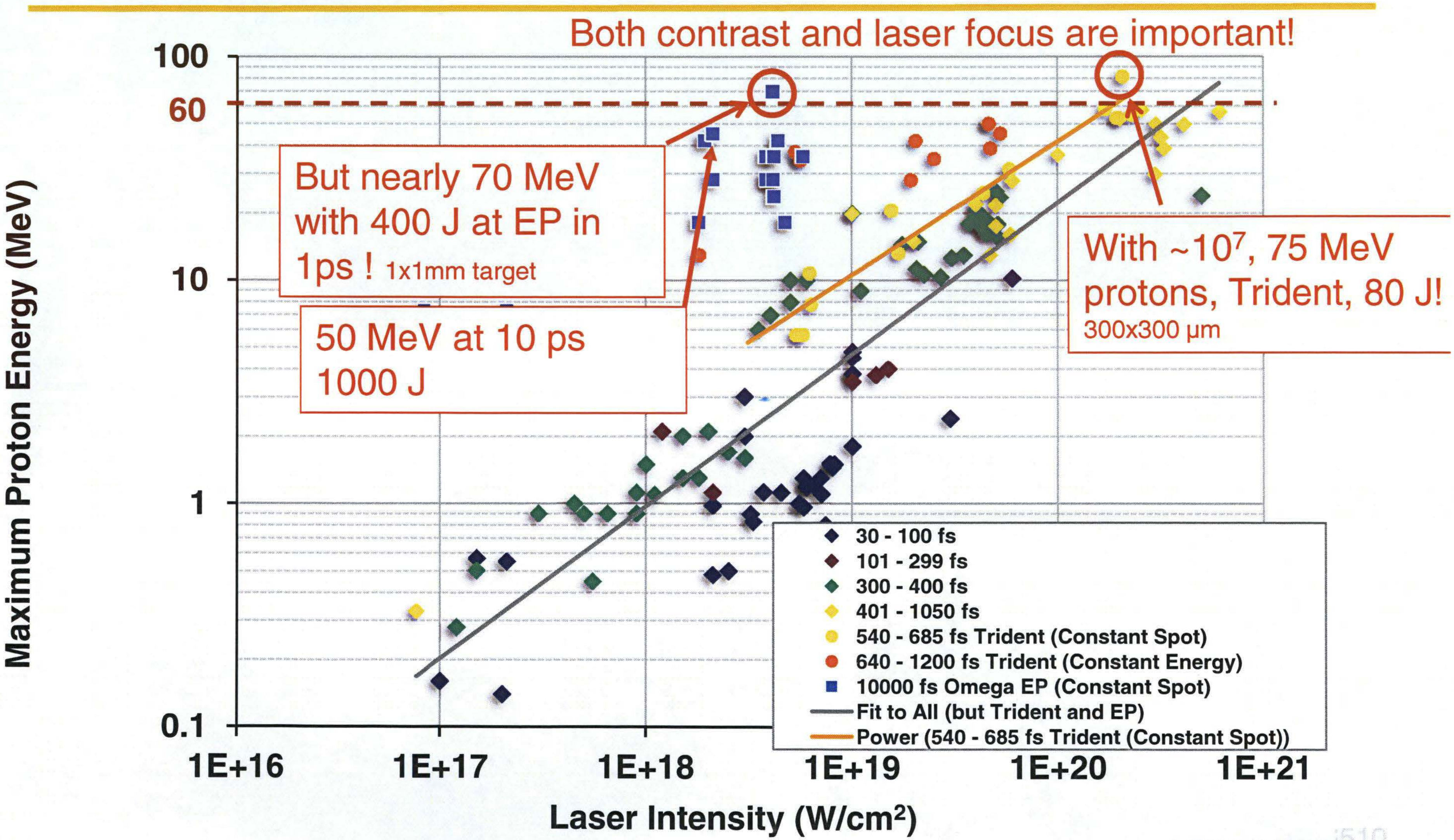
What Happens with More Laser Energy? Using the Omega EP Laser at 1000 J



Short-Pulse Laser Radiation Sources and Ion Acceleration

Adding More Laser Energy

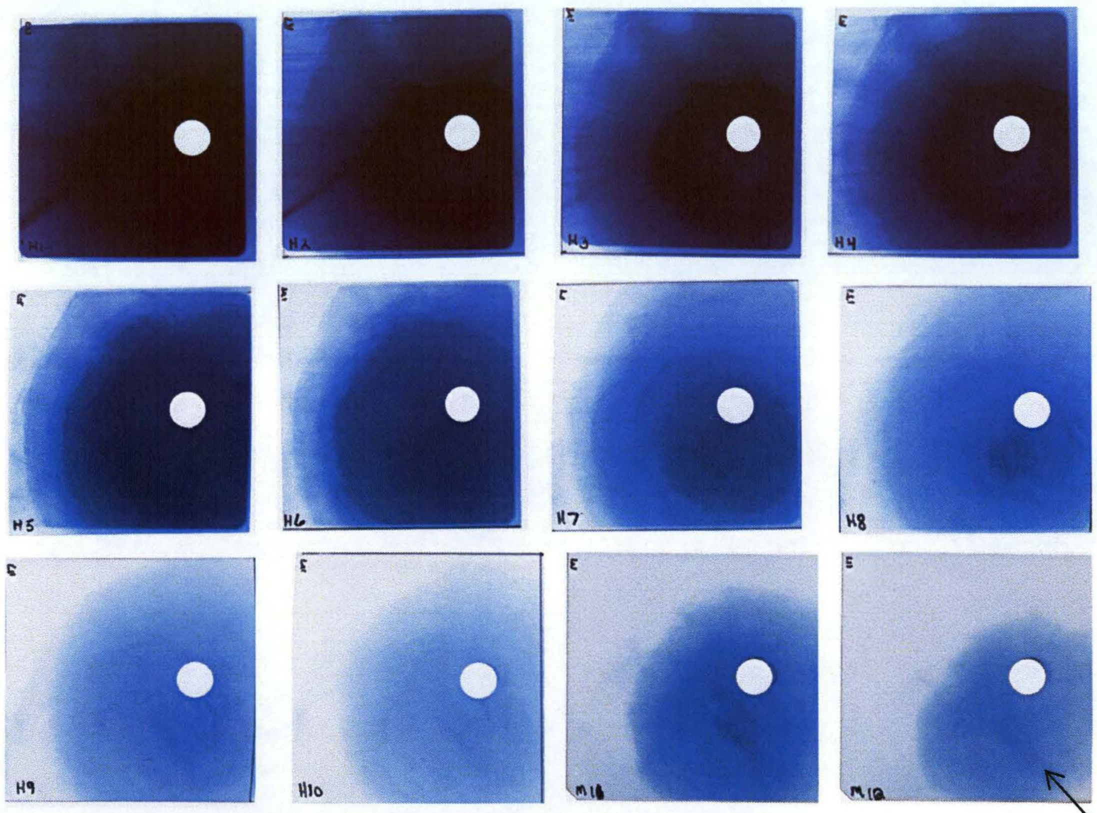
And a Significant Flux of Protons (> 10^8 ions) at 60+ MeV on the Omega EP Laser (1 ps, 400 J)

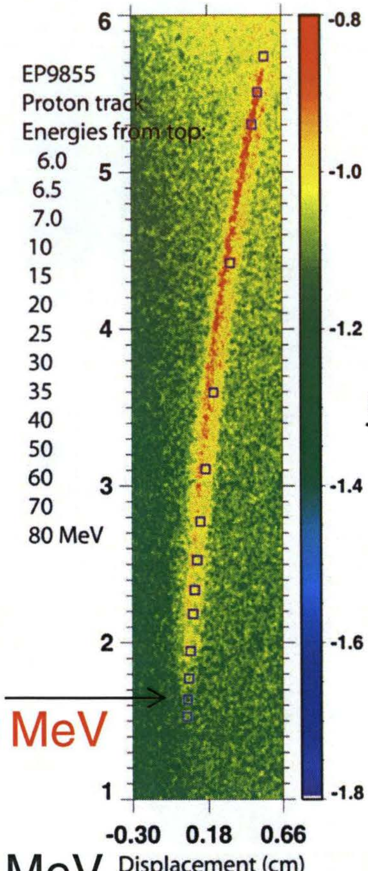
Proton Beam Profile

5 MeV

10 MeV

28 MeV



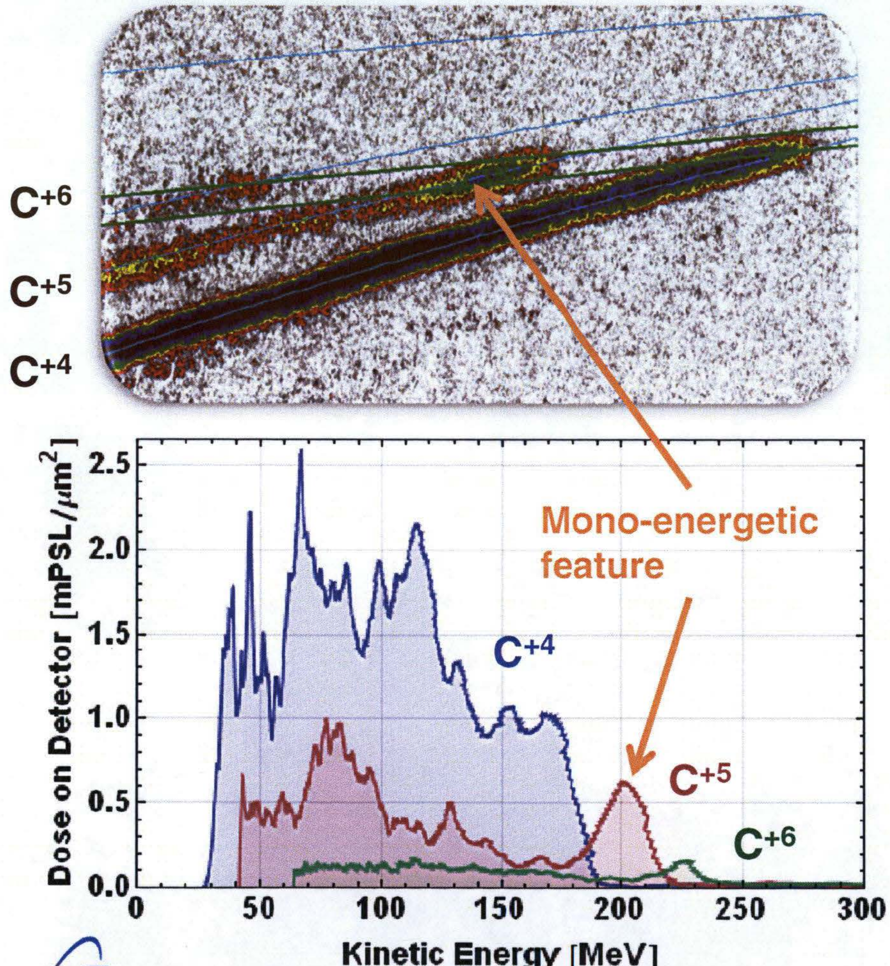


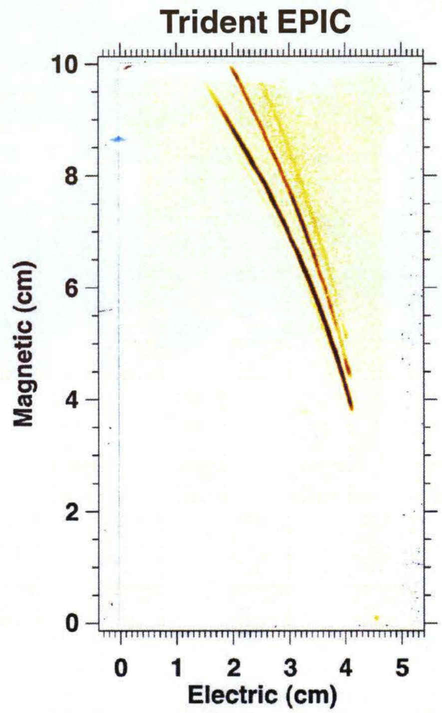
70 MeV

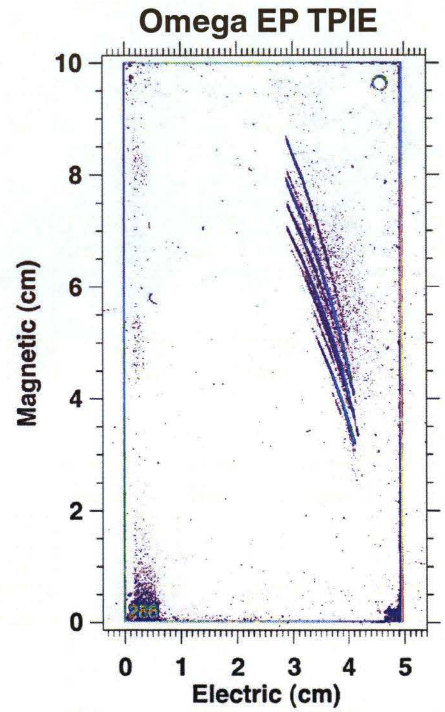
60 MeV

~70 MeV Measured by TPIE

Heating the Target gets rid of Protons; the Next Highest q/m Species can be Accelerated

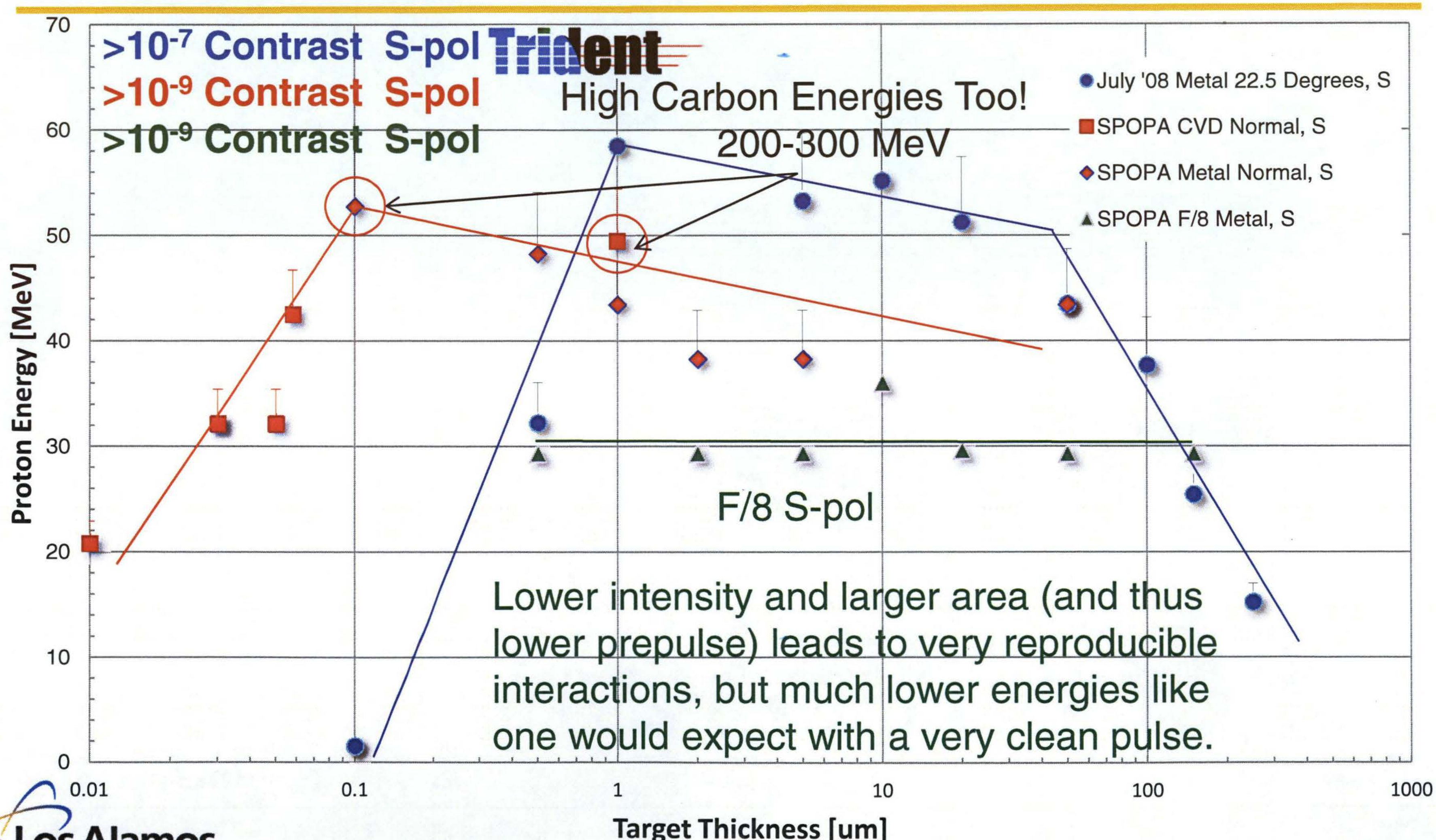






- The electric field seen by slower moving ions is screened by the ions which move ahead of them
- Mono-energetic features appear where ions stay ahead of the species fronts

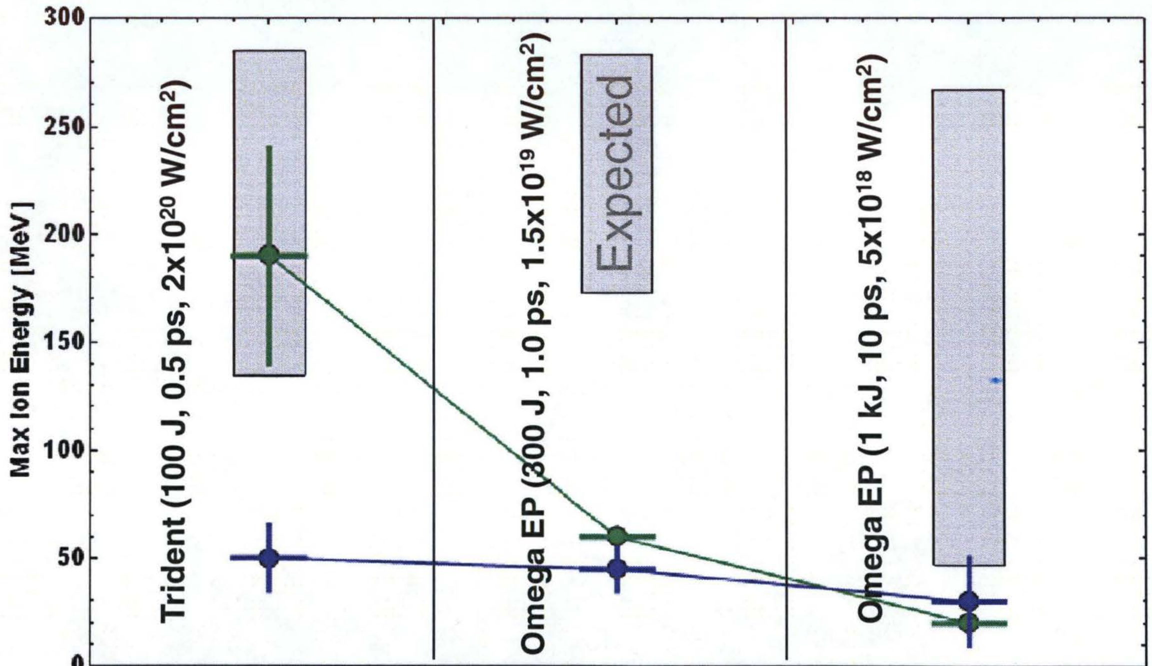
Lower Intensity Improves Repeatability



Carbon Ions Sample a Smaller 'Average' Electric Field than Protons

- **Preliminary!!** Data is still being analyzed, so averages may shift from what is shown here

$$E_{peak} = 2ZkT\left(\ln\left(\sqrt{\frac{2Z}{m}}\omega_p t\right) - \frac{1}{2}\right)^2 \qquad kT = m_e c^2\left(\left(1 + \frac{I[W/cm^2]\lambda^2[\mu m^2]}{1.37\times10^{18}}\right)^{1/2} - 1\right)$$



- Gray boxes are predictions for peak carbon energy based on proton performance for 'normal' targets (blue dots)
  - Mora's Isothermal Model
- Green dots are C+6 data for contaminant free, CVD targets
- Blue dots are H+1 from unheated CVD targets

Short-Pulse Laser Radiation Sources and Ion Acceleration

High-Contrast Laser
Ion Acceleration and X-rays

From Flat-Top Cone Targets

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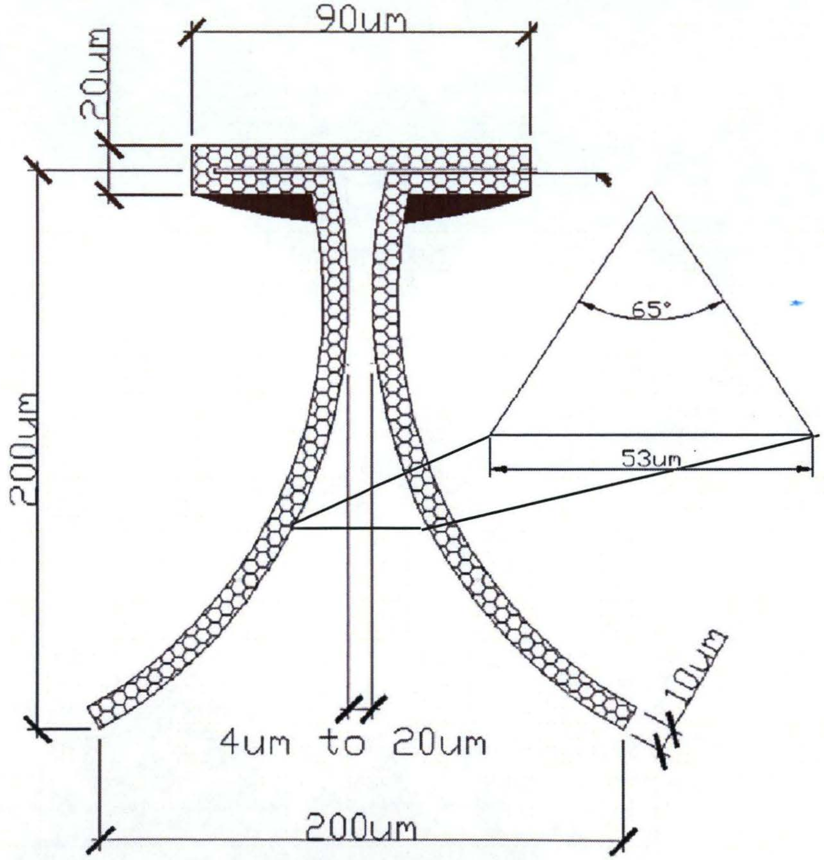
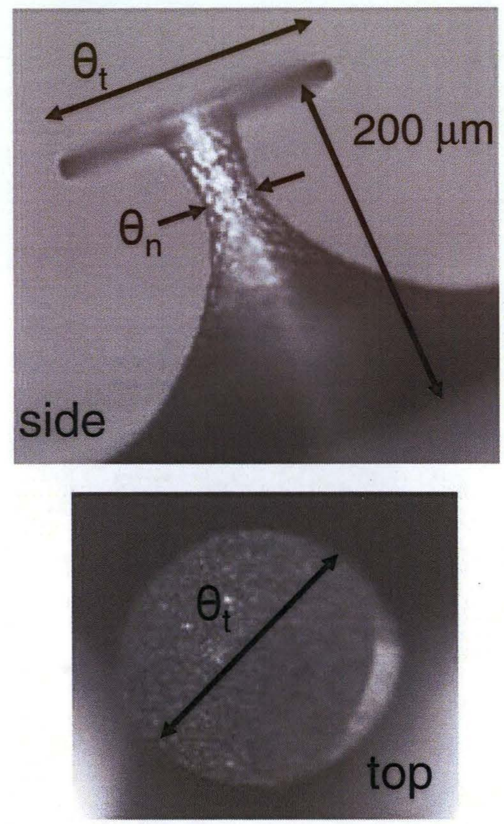
Flat-Top Cones (FTCs) can Funnel Laser Light and Direct Energy…

Typical Target Shape and Dimensions



Flared Flat-Top Cone



θ_n= 15 -135 μm

θ_t= 75 - 440 μm

Flat-Top Cone Targets have been shown to Increase Ion Energies by Making Hotter Electrons (2008)

Au, 10 μm thick	Flat Foil	FTC
Proton energy (MeV)	19	>30
Conversion Efficiency (%)	0.75	2.5

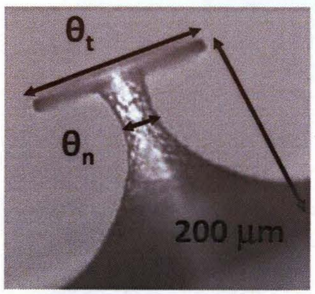
~20 J, 10^{19} W/cm^2

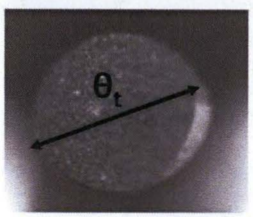
Laser-cone target coupling efficiency is improved

- better guiding of the laser light
- hot e- convergence toward the cone tip

Y. Sentoku et al. PoP ***11*** *(2004)*

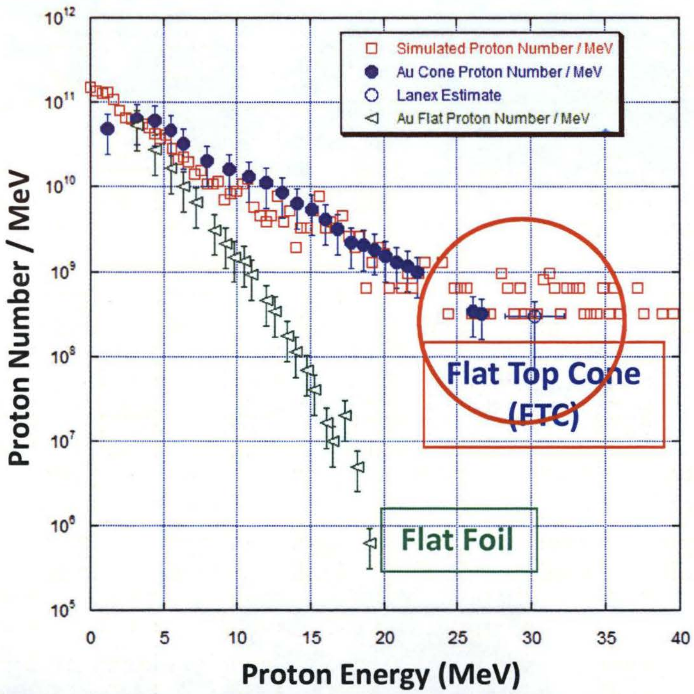
K. Flippo, E. d'Humières, S. Gaillard et al., PoP ***14*** *(2008)*

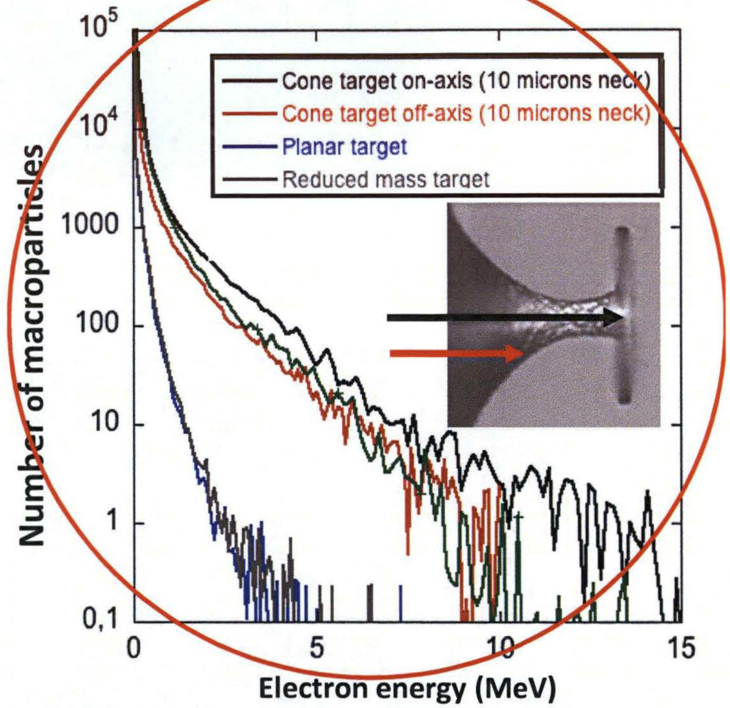




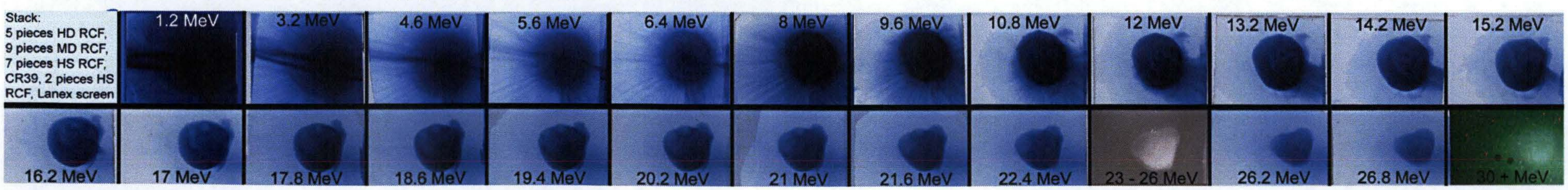
Θ_{n_best}= 25 μm

Θ_{t_best}= 100 μm





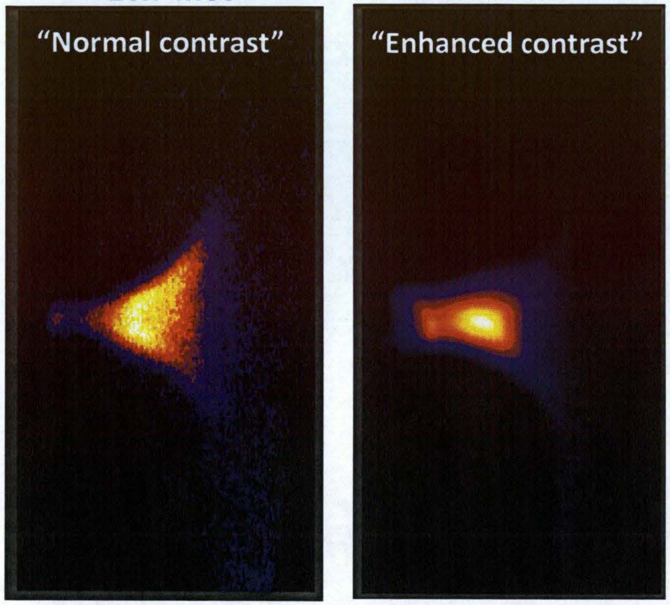
RadioChromic Film stack recording (mainly) the Proton beam emission



With Enhanced Contrast, Cu Kα Imaging Shows More Absorption Near the Flat-Top (2010)

20518: 10^8, 76 J, 610 fs 26.7 MeV

21194: 10^{10}, 80 J, 570 fs 28.3 MeV

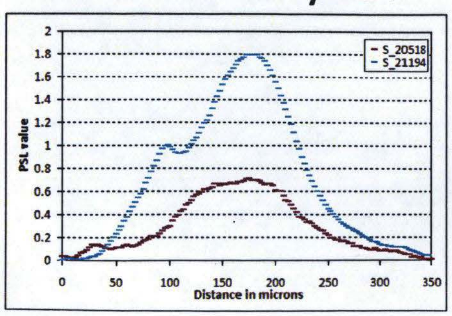


Similar to the Dec. 2006 LULI data (1ω, 20 J) vs (2ω, 10 J)

*J. Rassuchine et al., PRE **79** (2009) published in*

S. A. Gaillard et al. J. Phys. Conf. Series (2010)

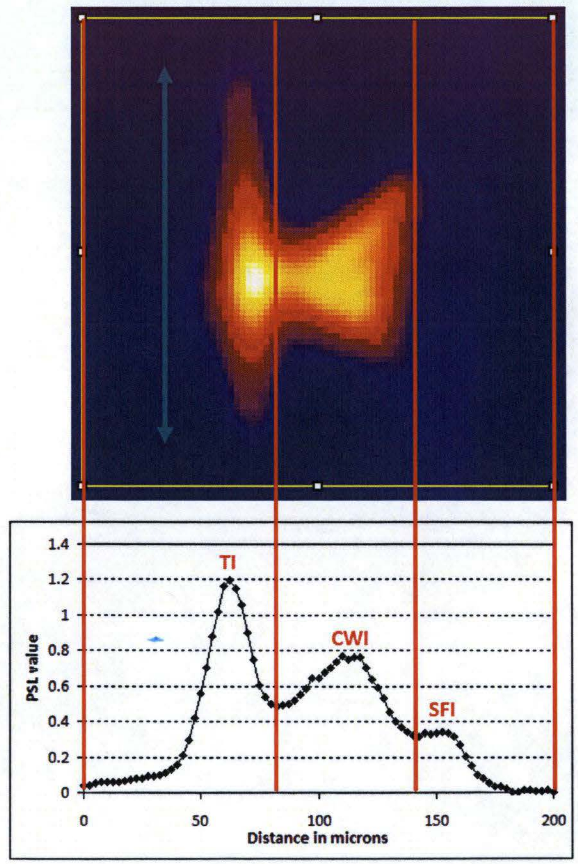
contrast ↗ => Kα yield ↗

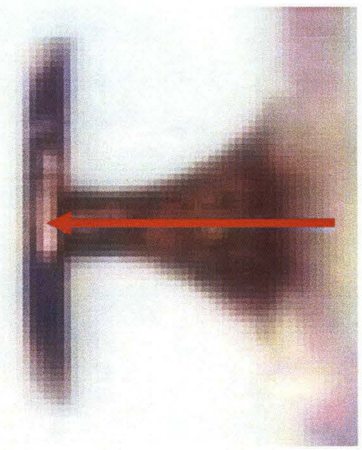


From the Cu Kα image, we can determine the localization of the laser interaction (or the relative electron number):

- top interaction (TI)
- cone walls interaction (CWI)
- supporting foil interaction (SFI)

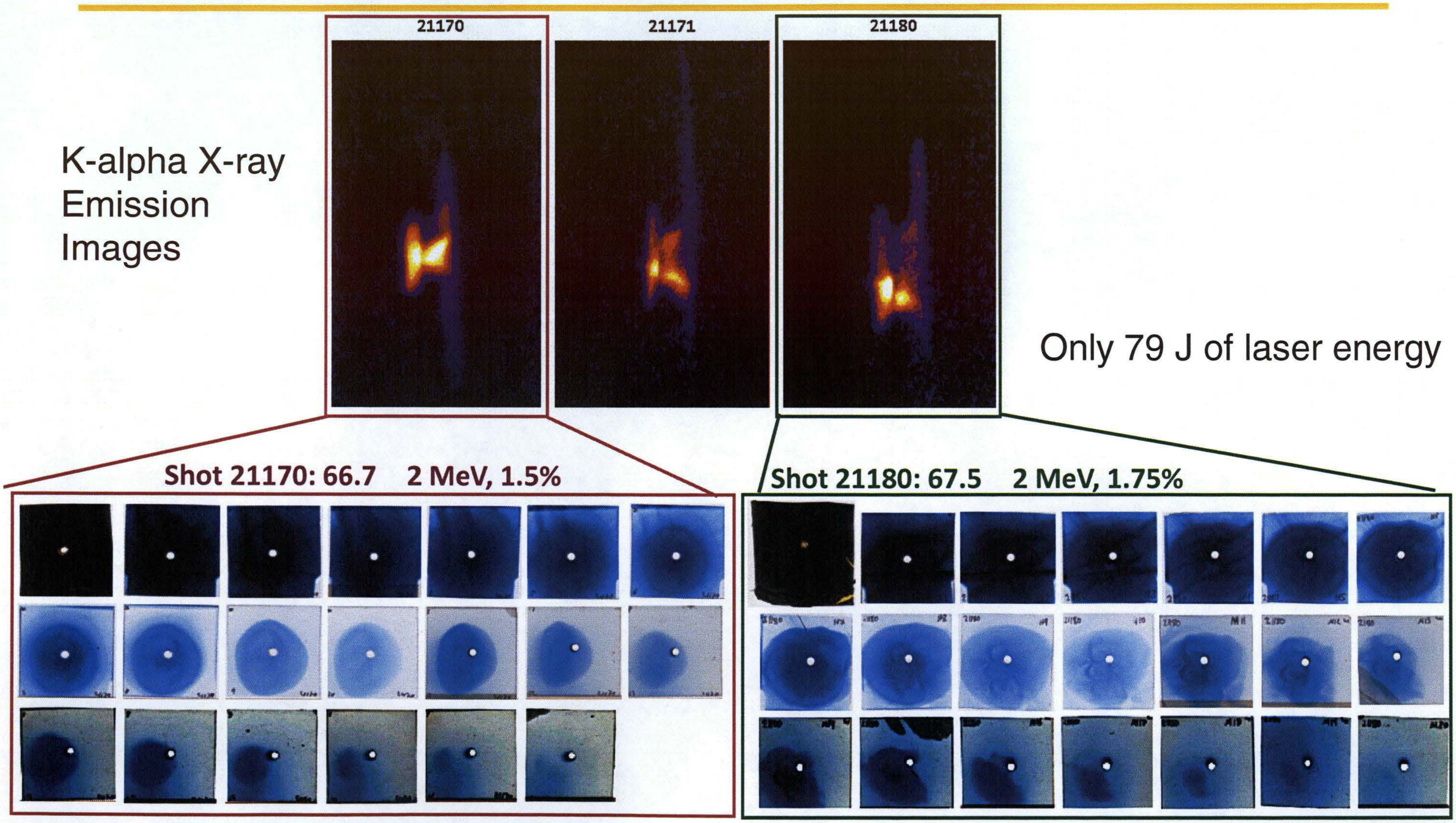
and correlate it with the proton acceleration





~68 MeV From Flat-Top Cones when the Laser Grazes One Wall of the Cone (2011)

K-alpha X-ray Emission Images



Only 79 J of laser energy

S. Gaillard *et al.*, *Physics of Plasmas* **18**, 056710 (2011)

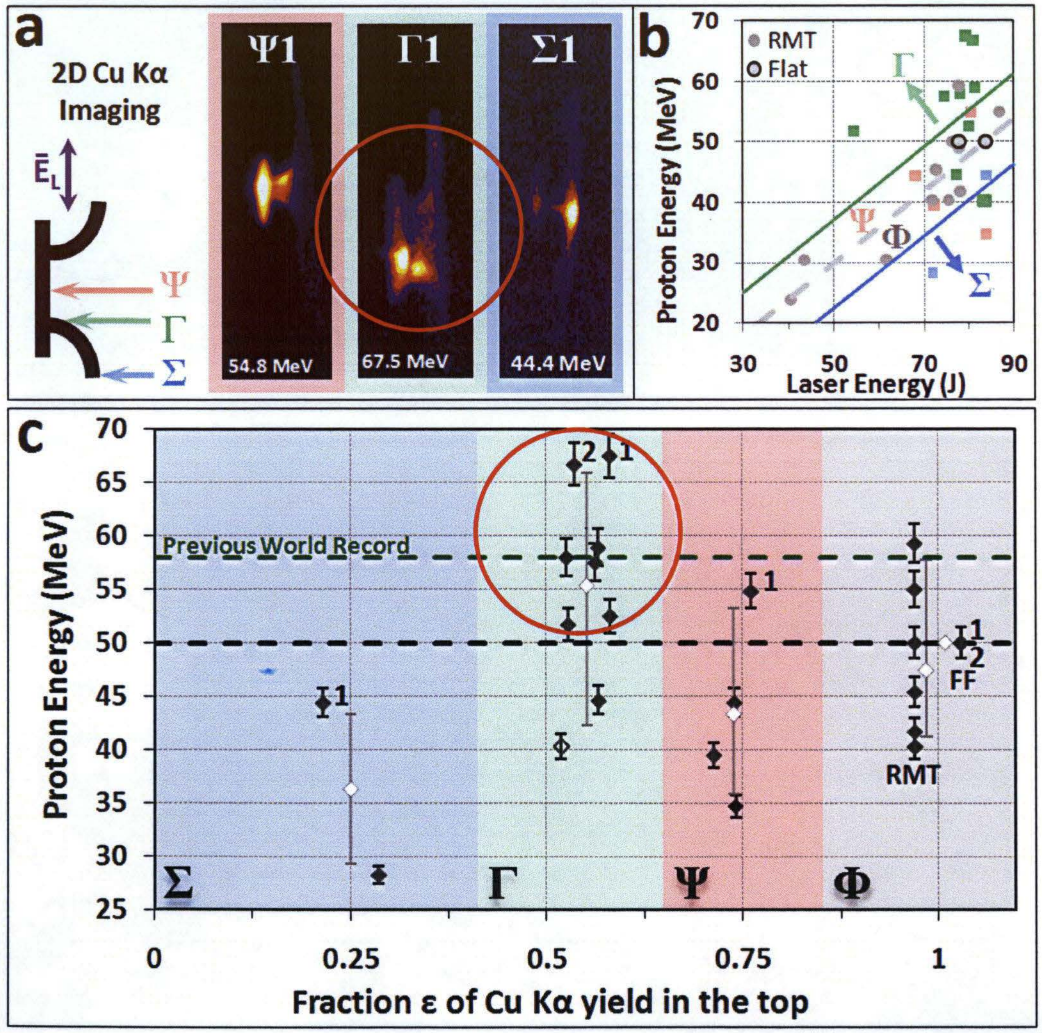
Grouped by Emission from Regions: Correlation with Performance and Grazing (2011)

Group Φ: RMTs and flat-foil (FF) targets shown for comparison

Group Ψ: show prevailing top emission, indicating the laser axis **aligned** with cone axis

Group Σ: emission mainly from the cone walls or the supporting foil; indicating the laser is **misaligned** not making it to the flat top.

Group Γ: highest proton energy group, obtained when emission is **asymmetric** and the top and the cone walls emission balances

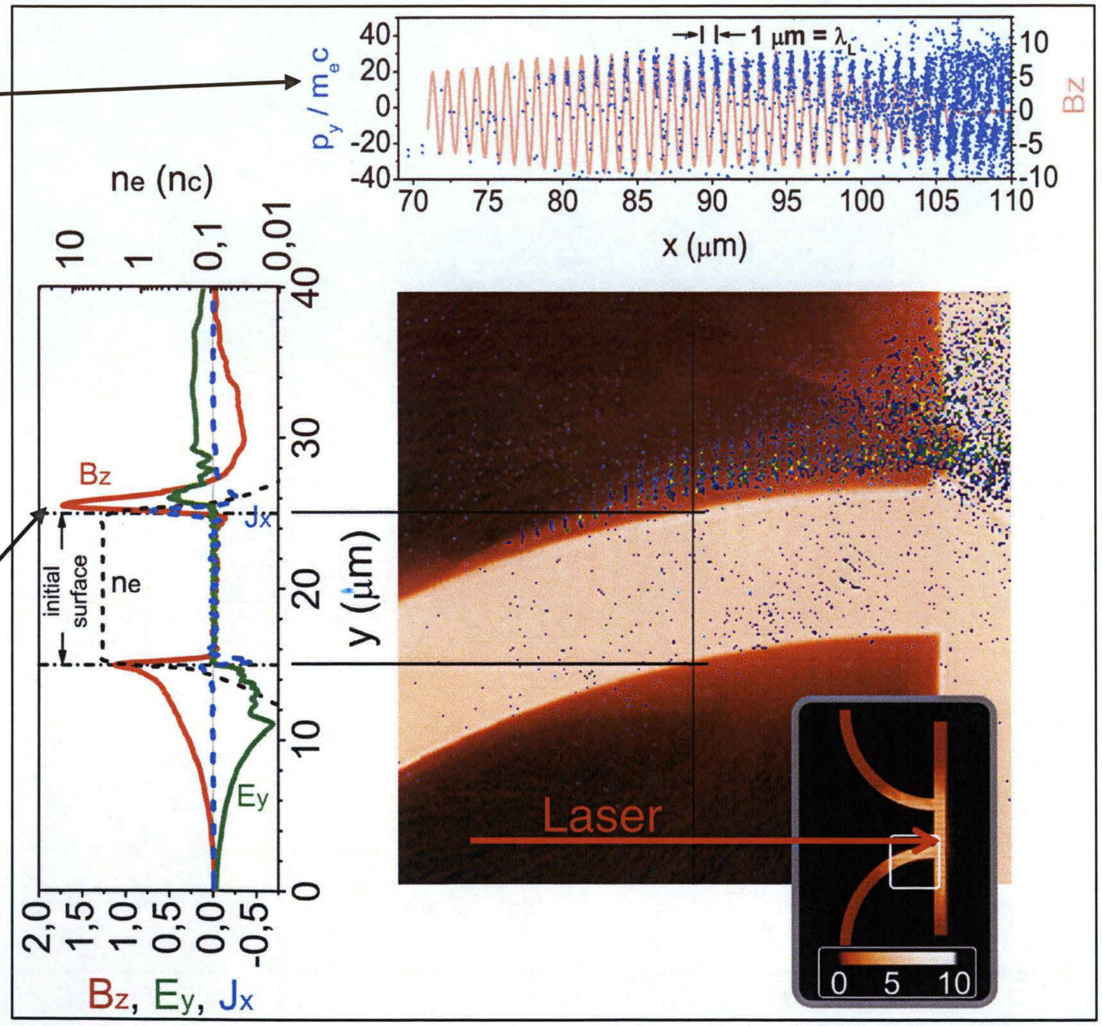


S. Gaillard *et al.*, *Physics of Plasmas* **18**, 056710 (2011) ; T. Kluge, S. A. Gaillard, et al. AIP Conf. Proc. 1299, 715 (2010)

This Led to the Discovery of Direct Laser Light Pressure Acceleration (DLLPA) of Electrons

Electrons bunched at 1 μm with laser field (Bz)

Electrons trapped near the surface in potential well between magneto- (Bz) and electrostatic- (Ey) fields



Short-Pulse Laser Radiation Sources and Ion Acceleration

Ion Focusing

(needed for most applications to concentrate delivery)

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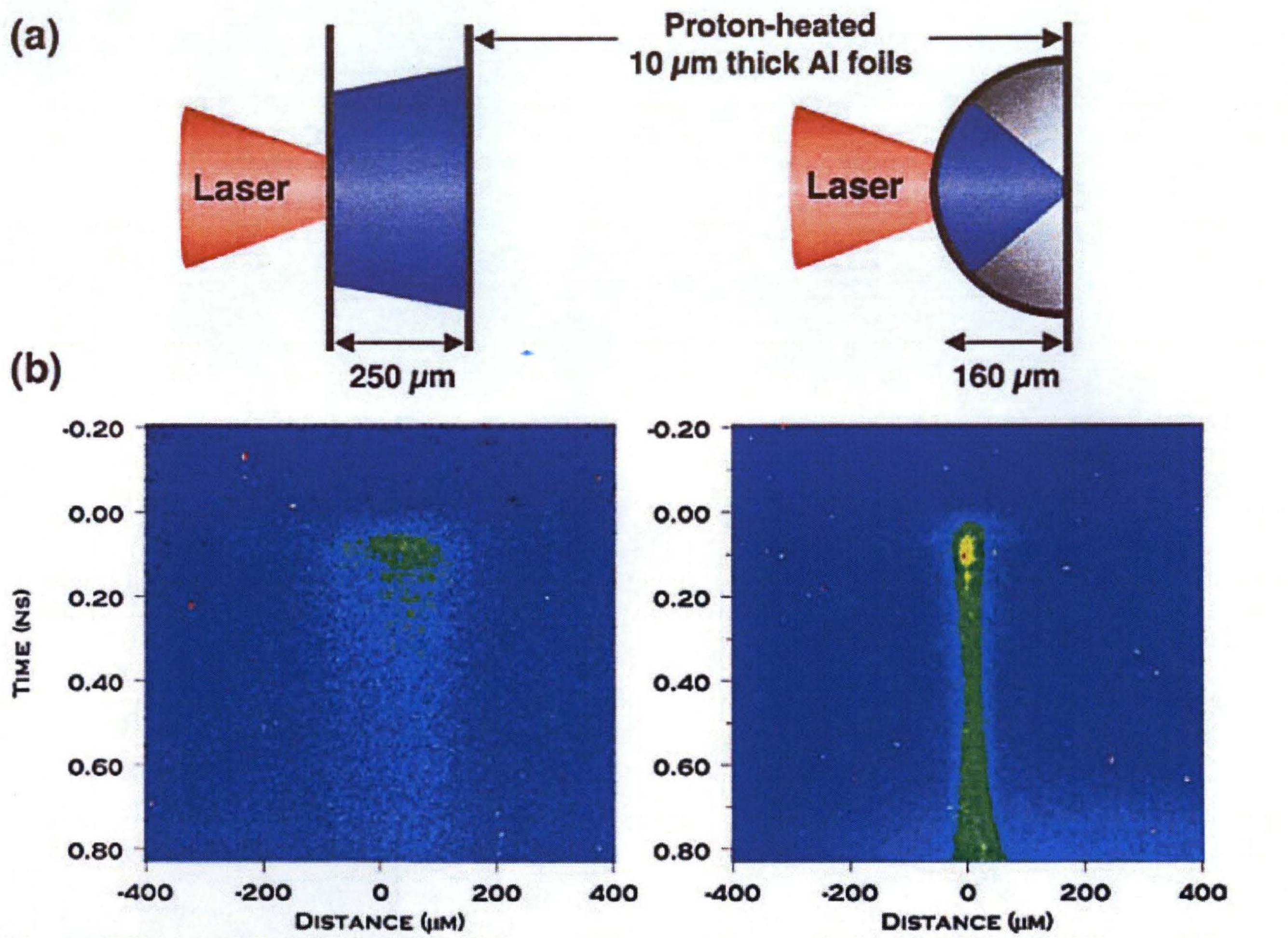
Experiments in 2003 showed "Ballistic" Ion Focusing using the LLNL Titan Laser

Work done by LLNL Patel *et al. PRL* 91 125004 (2003) using the LLNL Titan Laser showing target heating via a streak camera



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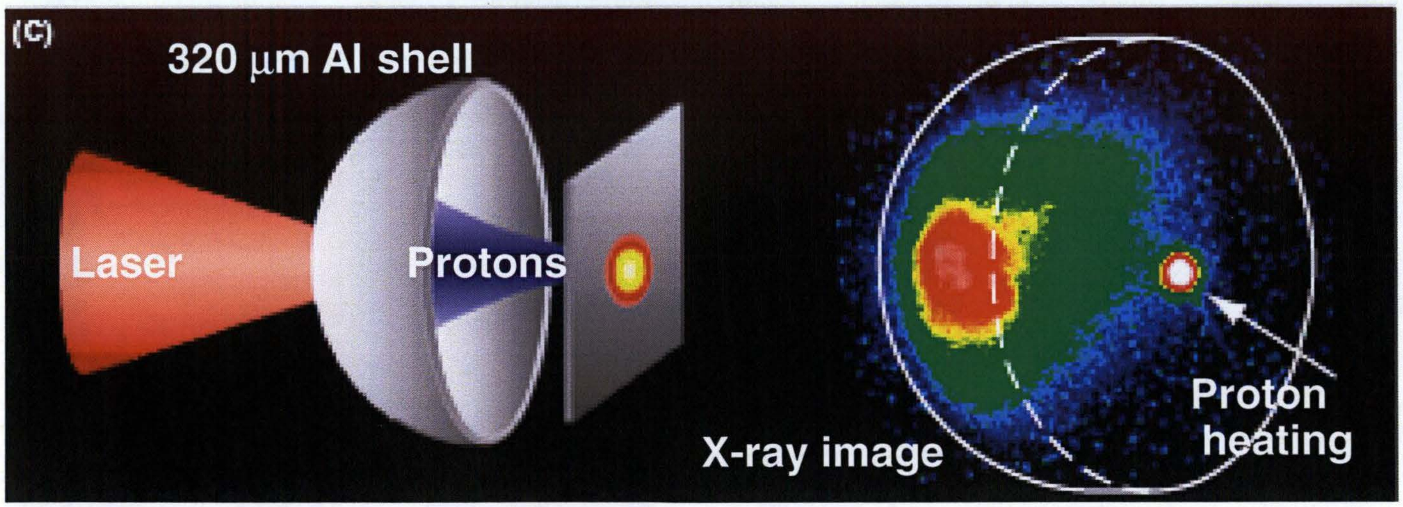
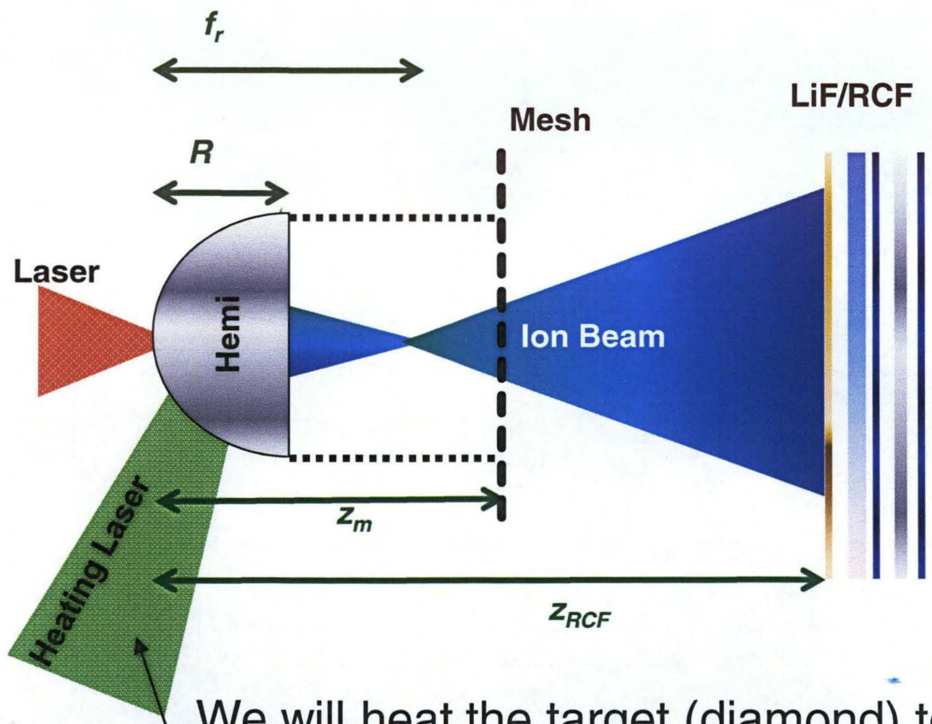
Experiments in 2007 showed "Ballistic" Ion Focusing using the Gekko PW Laser (Japan)

Work done by LLNL focusing data from the Gekko PW laser in Snavely *et al PoP* **14** 092703 (2007), showing secondary target heating via x-ray imaging on the Gekko PW laser

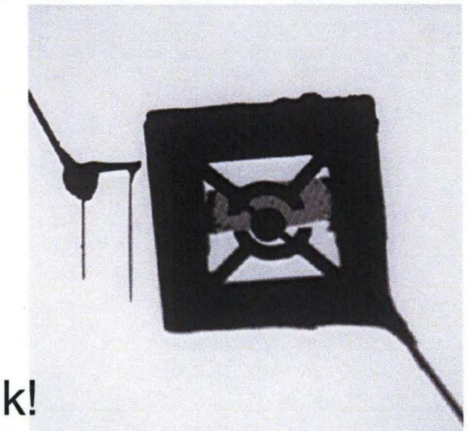


Focusing Carbon Ion Beams: Laser Ion Focusing Targets for Carbon Ions (and p^+)



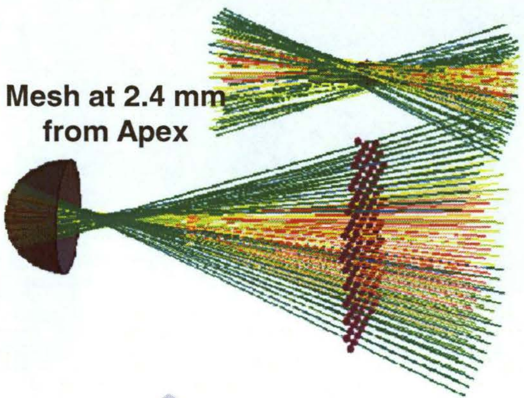
Tracing rays through the projected image of a 'witness' mesh in Ion beam path determines the location of the 'virtual' source

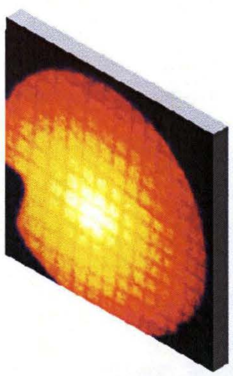
Target Viewer Image (Omega EP)



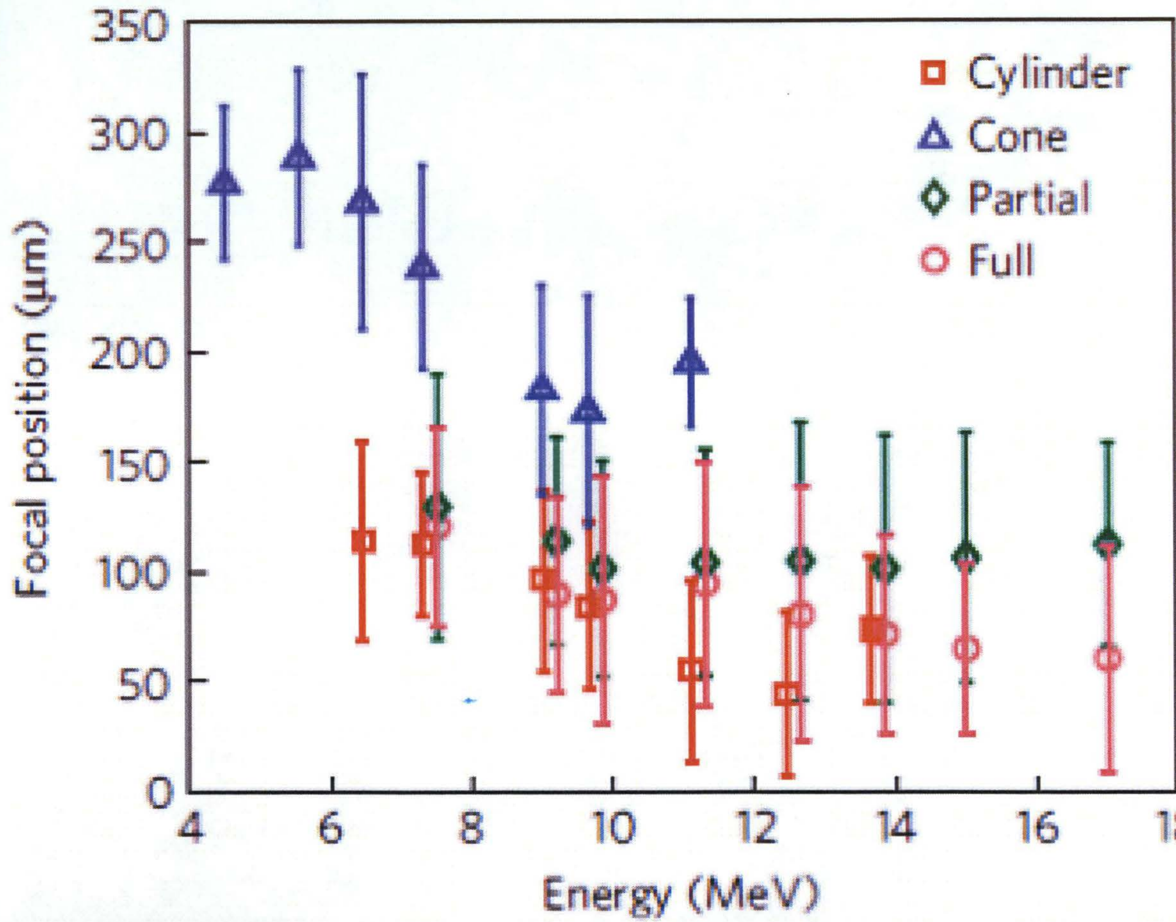
We will heat the target (diamond) to 900 C to get rid of the water and hydrocarbon junk! This lets us accelerate Carbon only!

Protons Show a Non-Ballistic Focusing Behavior when Deconvolved from Mesh Data





Grid on RCF



Protons: T. Bartal, et al. *Nat. Phys.* Online (2011) DOI:10:1038/nphys2153

LSP Simulations Show Non-Ballistic Focusing of Proton with Tracer Particles

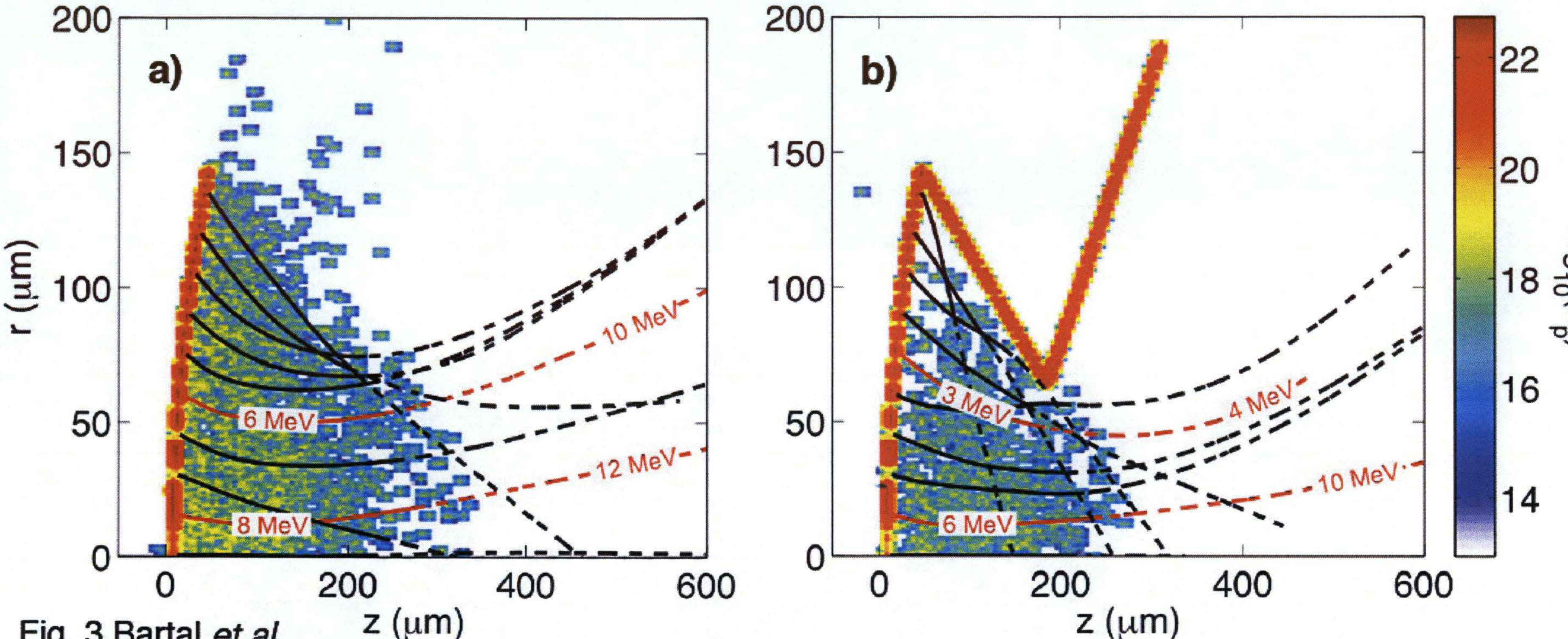


Fig. 3 Bartal *et al.*

Protons: T. Bartal, et al. *Nat. Phys.* Online (2011) DOI:10:1038/nphys2153

LSP is a hybrid Fluid/PIC code

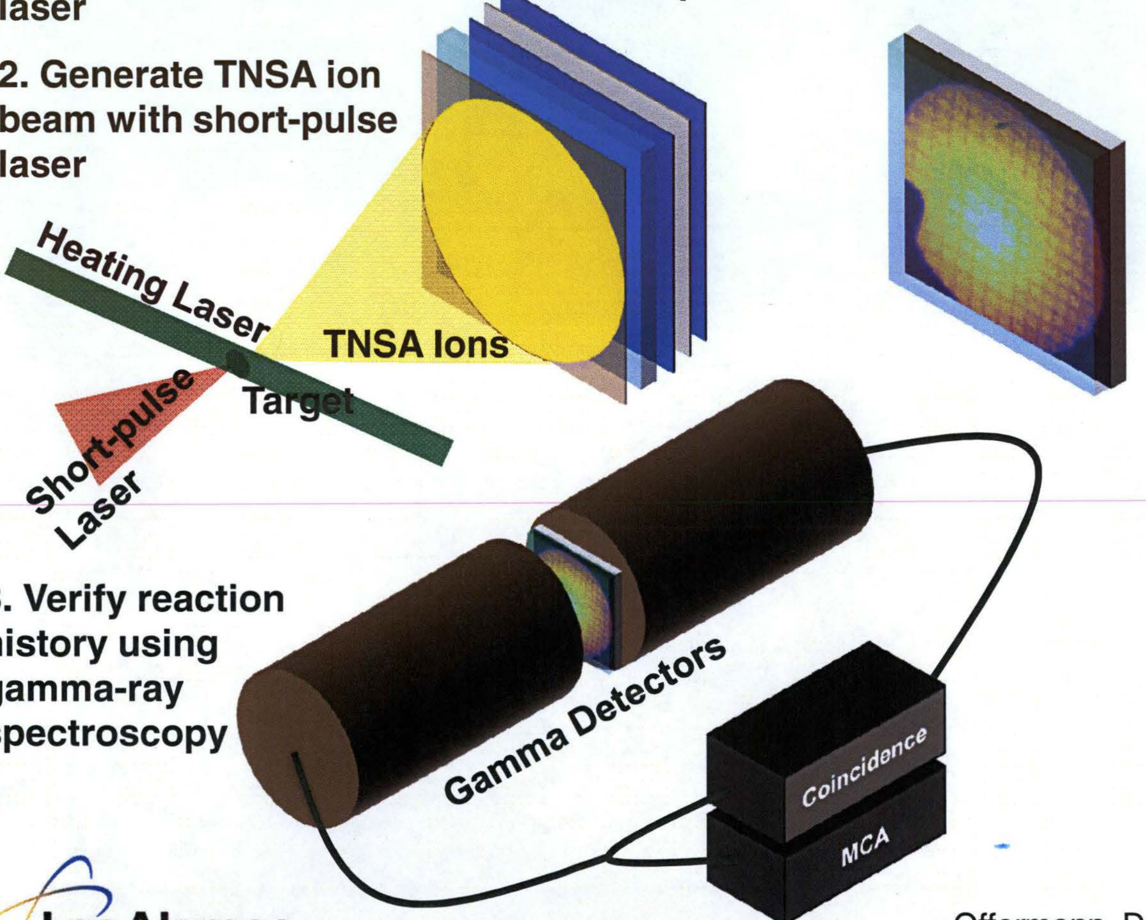
An Innovative Carbon Ion Dependant Nuclear Activation Beam Profiler was developed

1. Heat target with CW laser

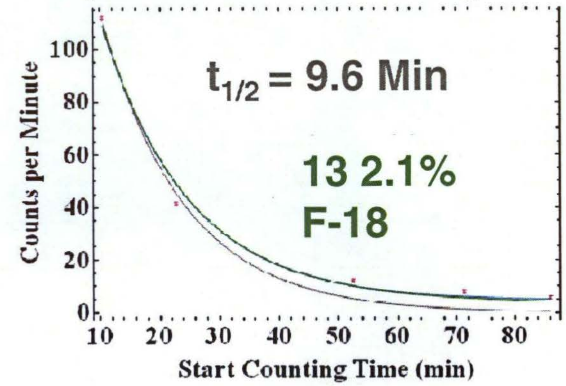
2. Generate TNSA ion beam with short-pulse laser

3. Start autoradiograph

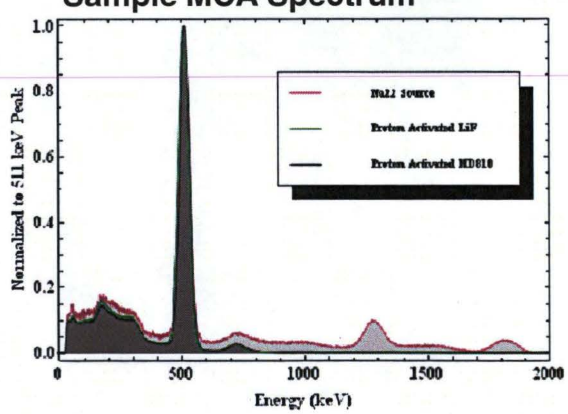
3. Verify reaction history using gamma-ray spectroscopy



Sample Coincidence Counting Data

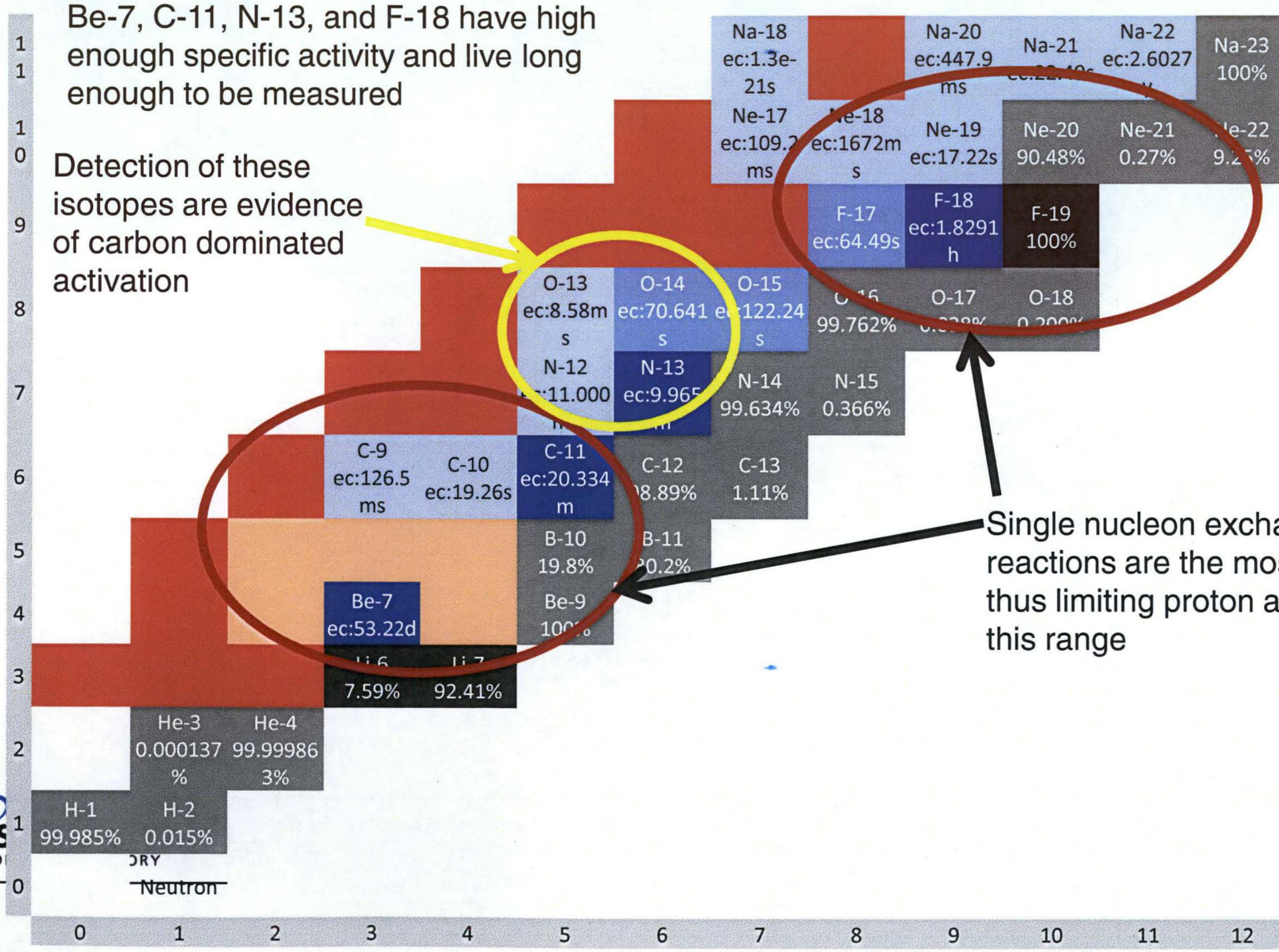


Sample MCA Spectrum



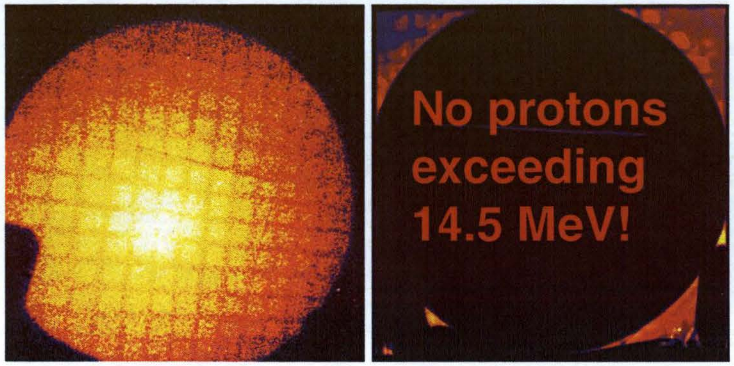
Offermann, D.T., *et al.* JPCS. **244**, 022053 (2010)
Offermann, D.T., *et al.* Rev. Sci. Instrum. **In Preperation** (2012)

Nuclear Activation of LiF by Carbon Produces Nitrogen-13, Proton Activation is Unlikely



3-11-06510

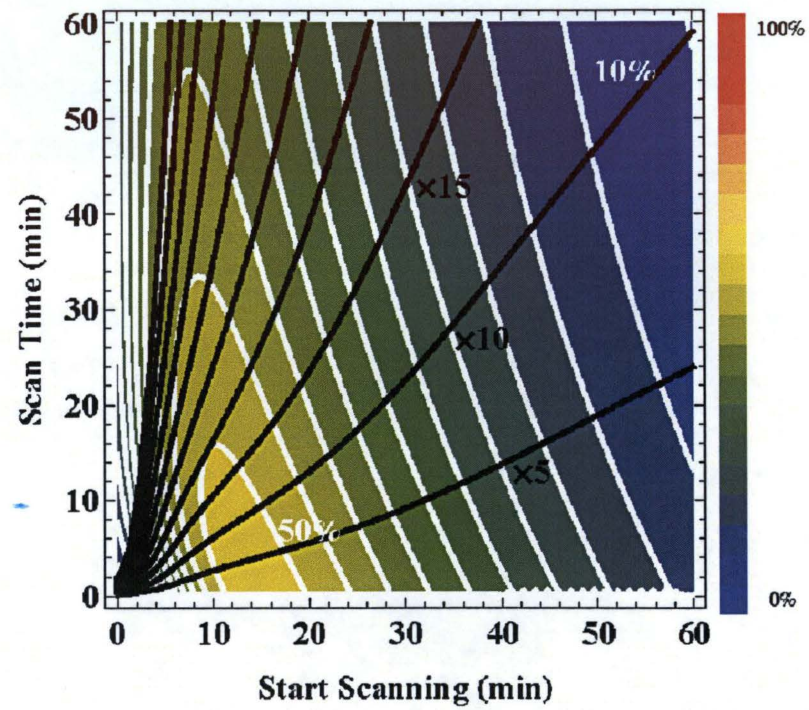
The Ratio of N-13 to F-18 serves as Verification of the Carbon Beam vs. Proton Beam



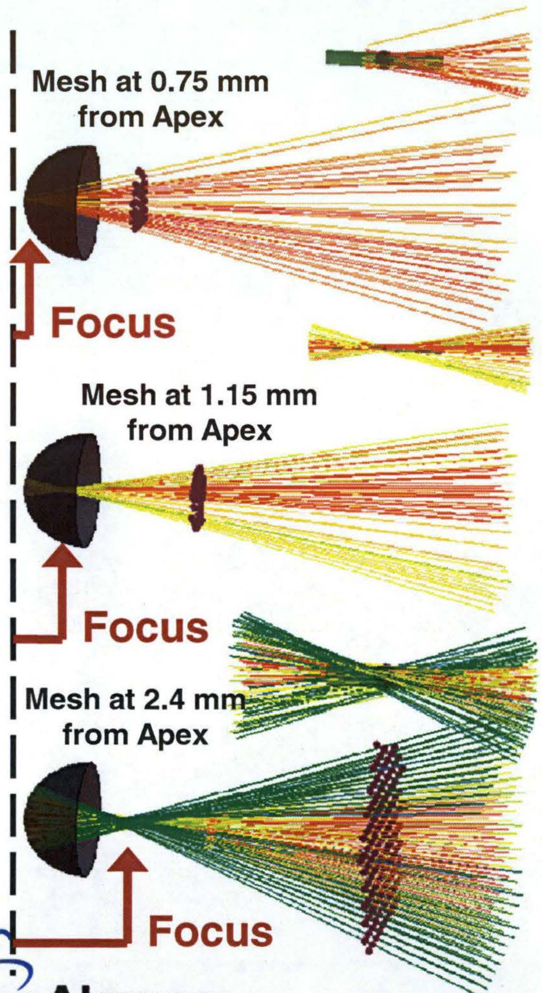
LiF Autoradiograph **HD 810 14.5 MeV, H+**

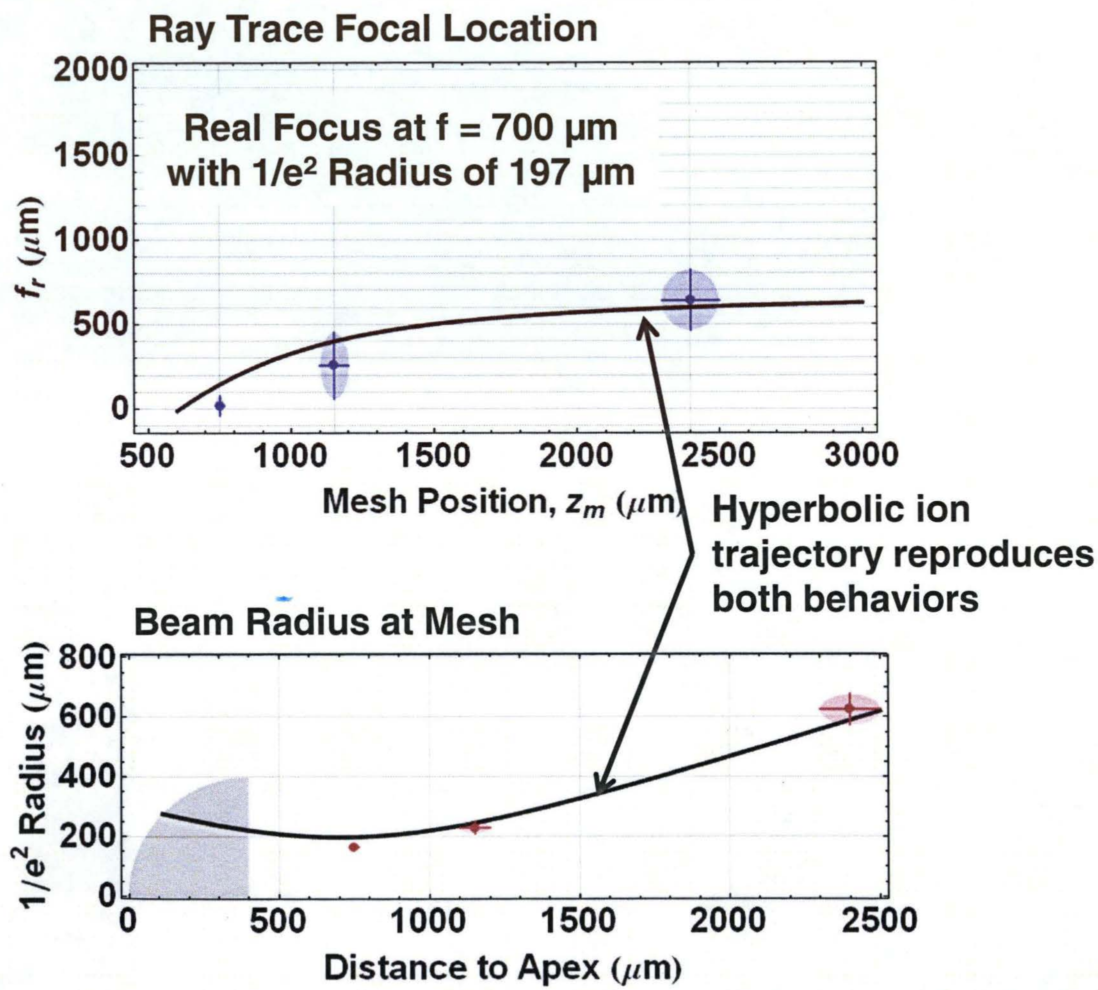
- Typical carbon spectra from Trident experiments with heated targets produces initially equal quantities of N-13 and F-18, both are produced by the carbon ions
- Without heating, the amount of F-18 produced by protons is more than 10 times that of any other isotope

Percentage of signal from N-13 as a function of scan time (calculated)



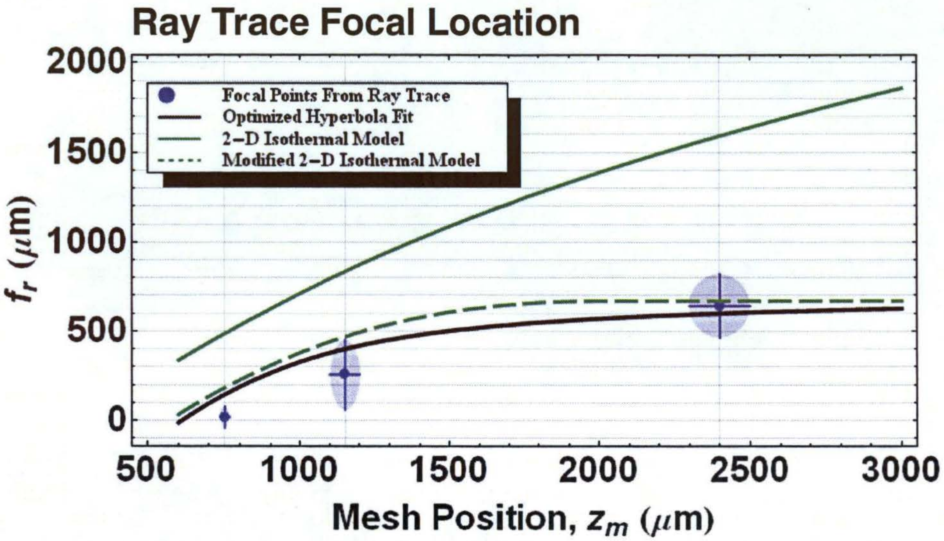
Ray Tracing of Trident Data Reveals 'Curved' Beam Trajectories!

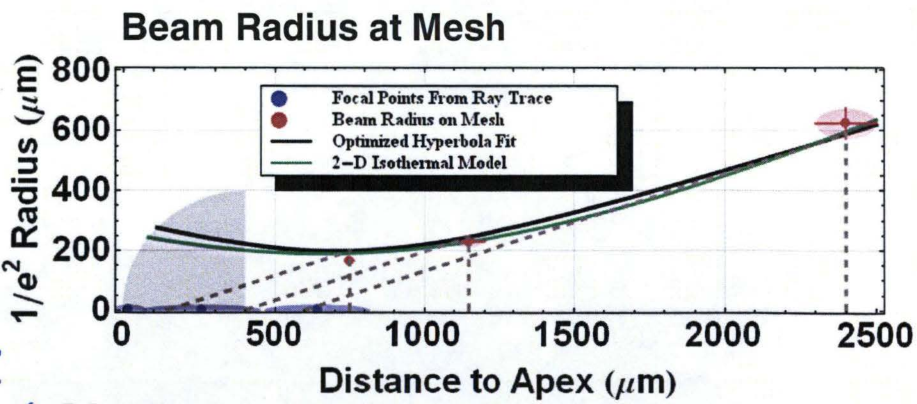




Offermann, D.T., *et al.* Phys. Rev. Lett. **In Preparation**(2010)

2-D Isothermal Model Shows How Carbon Ions Move to a Focus, Stagnate, and then Expand





2-D Isothermal Model

Ion front is a 2-D sheet with a velocity in the z direction,

$$v_z = \sqrt{2E/m}$$

The self-similar solution in the isothermal case is

$$\rho(t,r) = \frac{M}{2\pi\sigma(t)^2}\exp\left(\frac{-r^2}{2\sigma(t)^2}\right)$$

$$u(t,r) = \frac{\dot{\sigma}(t)}{\sigma(t)}r$$

where *σ(t)* solves,

$$\ddot{\sigma}(t) = \frac{c_s^2}{\sigma(t)}, \sigma(0) = \sigma_0, \dot{\sigma}(0) = -\frac{\sigma_0}{\eta R}\sqrt{\frac{2E}{m}}$$

Best fit for E = 50 MeV: η = 3.13
σ_0 = 260 µm, c_s = 7.3 µm/ps

Offermann, D.T., *et al.* Phys. Plasmas **18** 056713 (2011)

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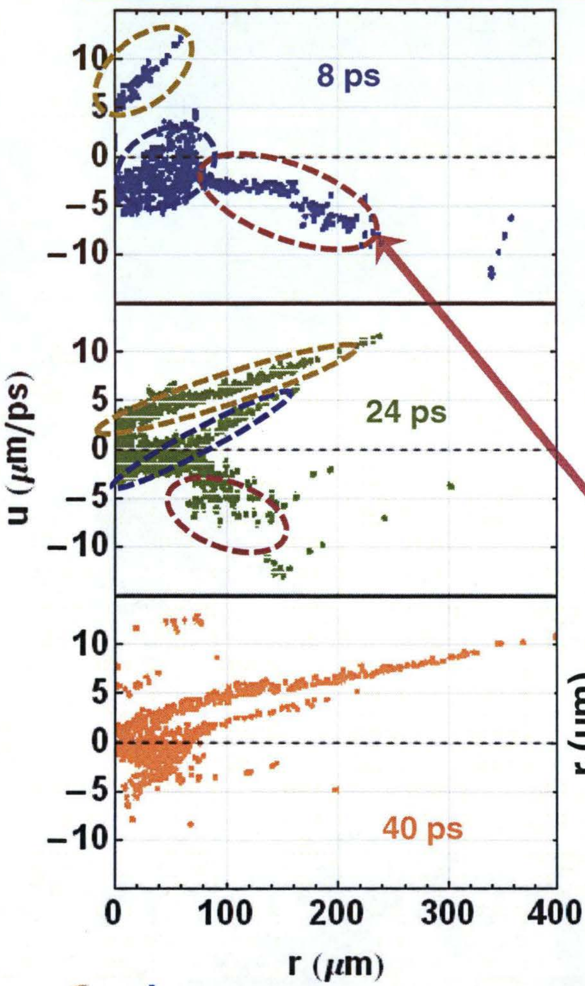
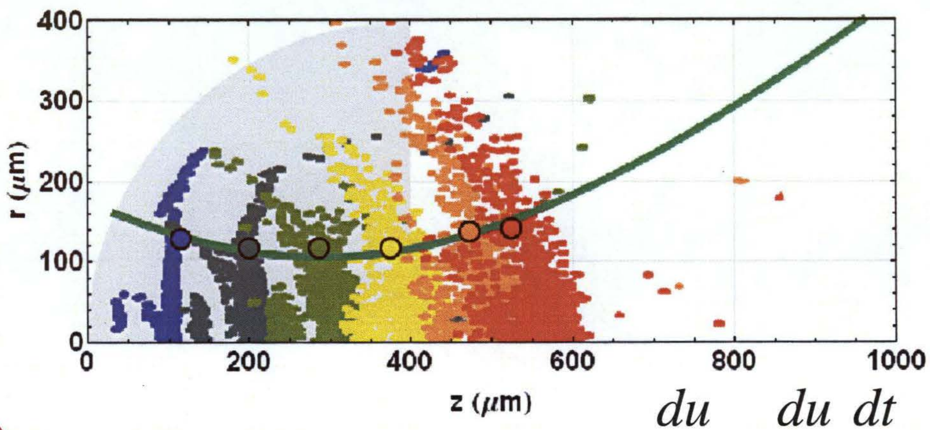
LSP Shows Region of Ions which Reproduce Behavior Described in the 2-D Isothermal Model

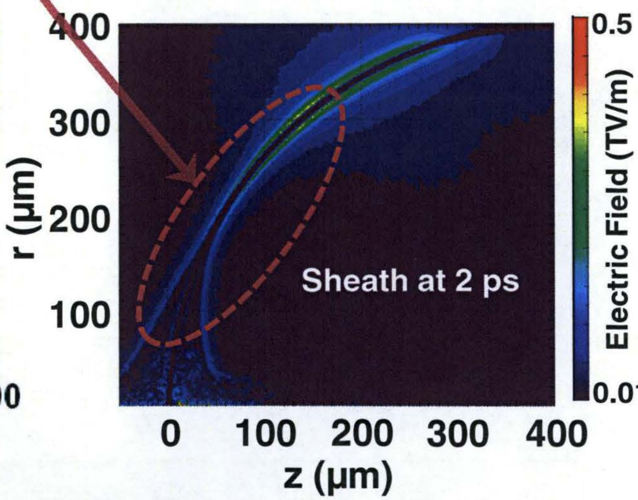


(11 ± 1) MeV Carbon Ions at 8, 16, 24, 32, 40, and 44 ps

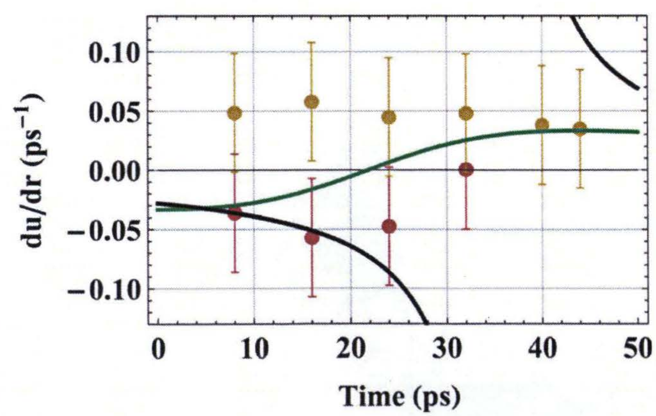


For E = 11 MeV,

- $\eta = 1$,
- $\sigma_0 = 175$ μm,
- $kT_e = 700$ keV



$$\frac{du}{dr} = \frac{du}{dt}\frac{dt}{dr} = \frac{a_r(t)}{u(t)} = \frac{\dot{\sigma}(t)}{\sigma(t)} \neq 0$$



LSP is a hybrid Fluid/PIC code

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Carbon: D.T. Offermann, et al. PoP 18 056713 (2011)

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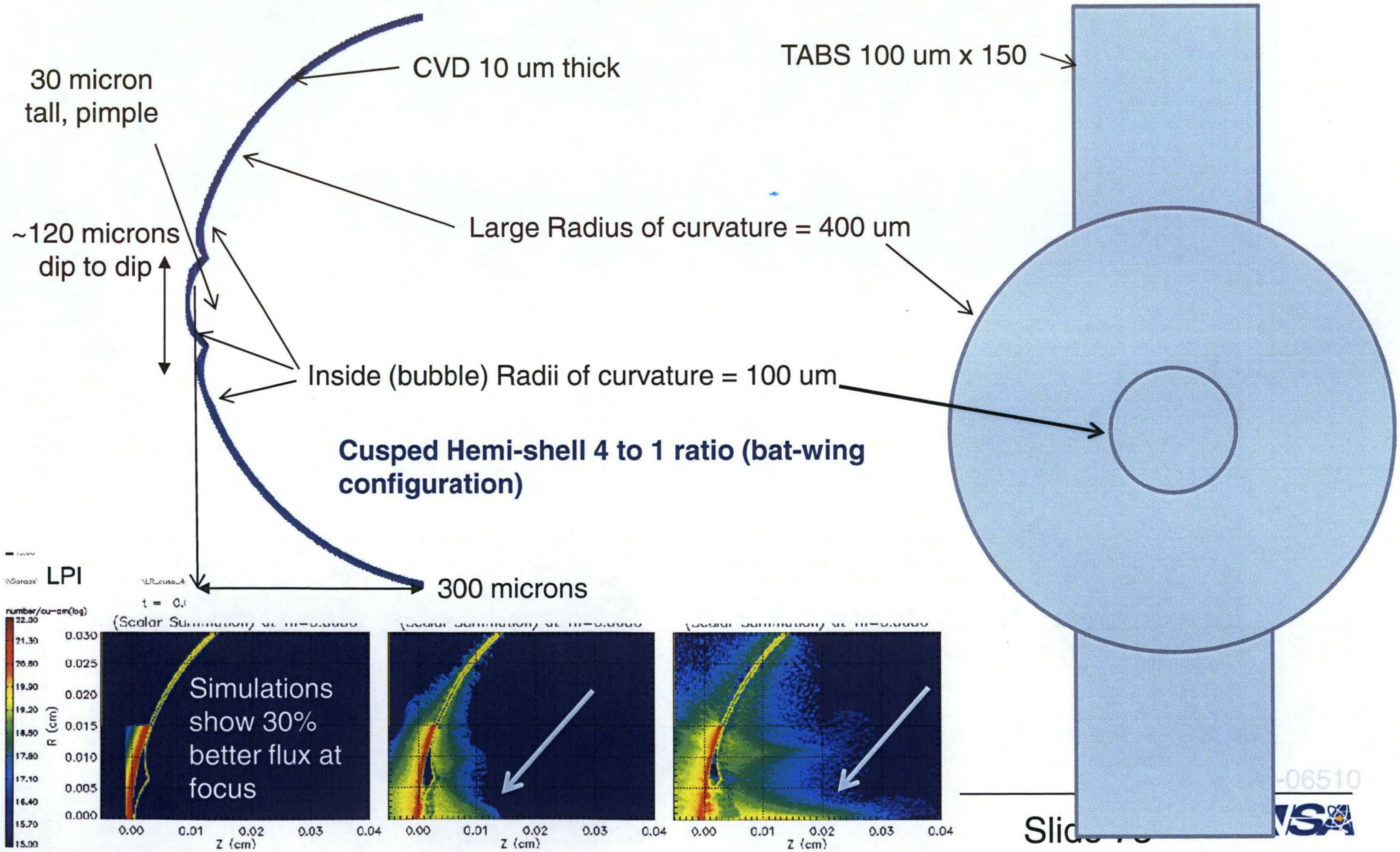
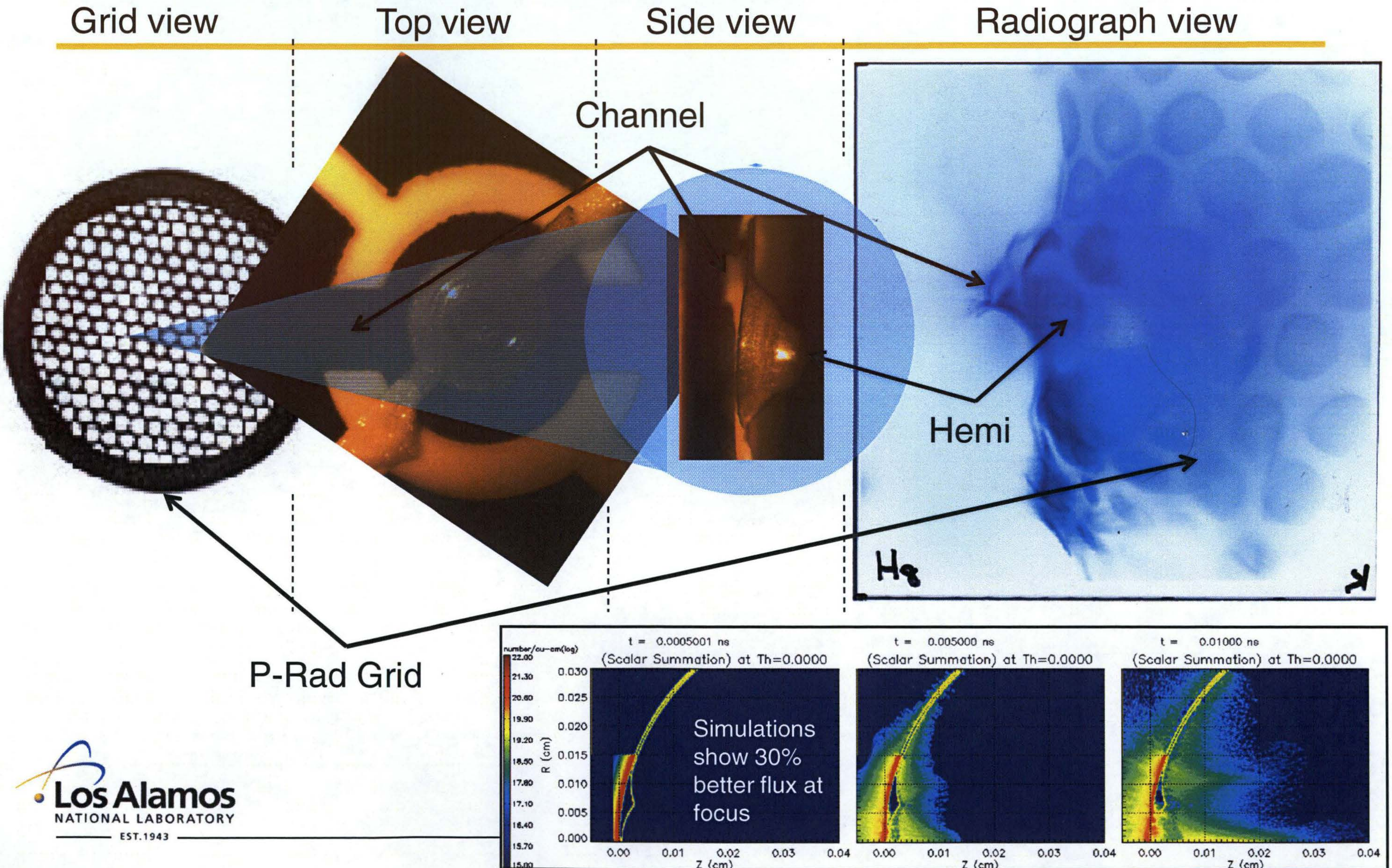
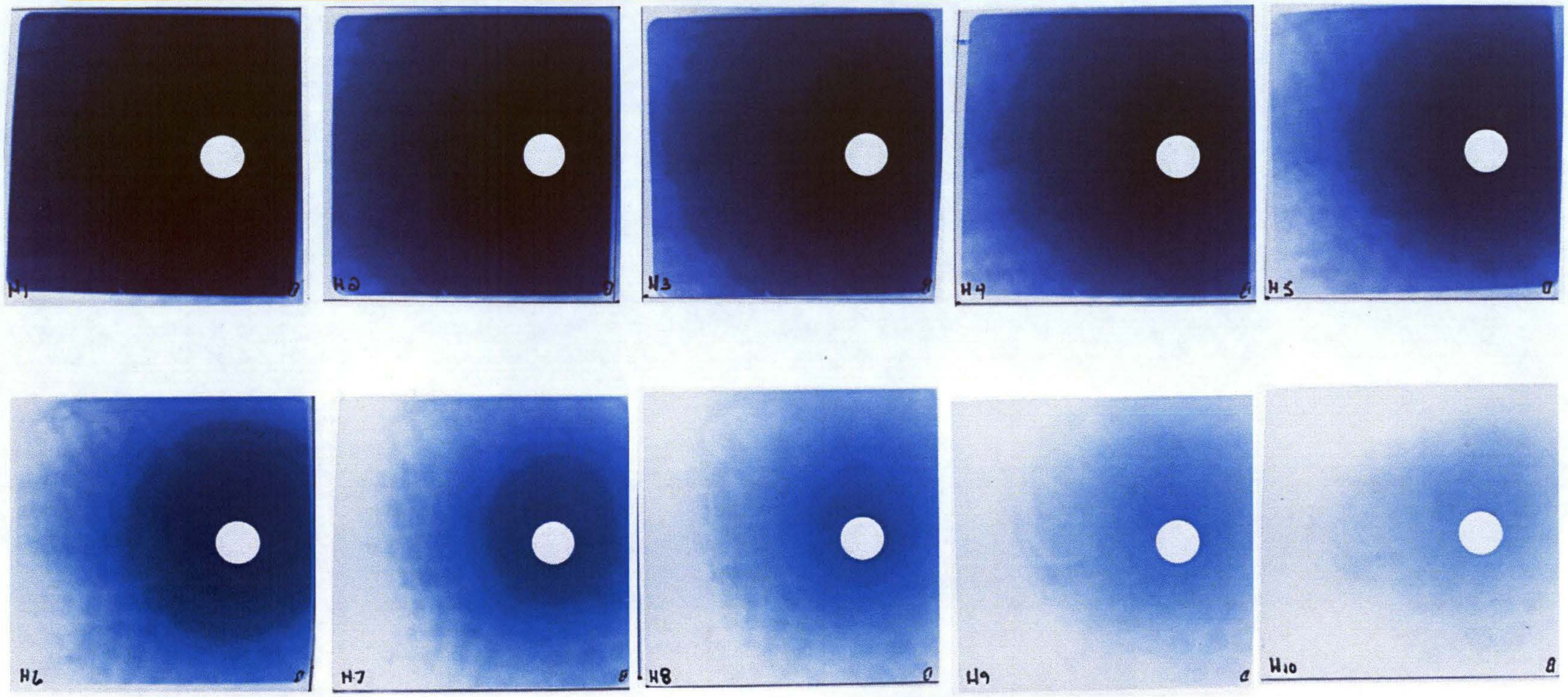
A New Target Design was developed: 30% Better Carbon Ion Focusing in Simulations



Radiograph of a Cusped Hemi



Preliminary Results indicate No Detrimental Effect on Proton Energy or Total Flux, but ....



...grid is too distorted to measure focusing, perhaps due to mixing of beam components, analysis ongoing...

51 MeV

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Magnetized Target Fusion: Fusion Cuisine

(proposed)

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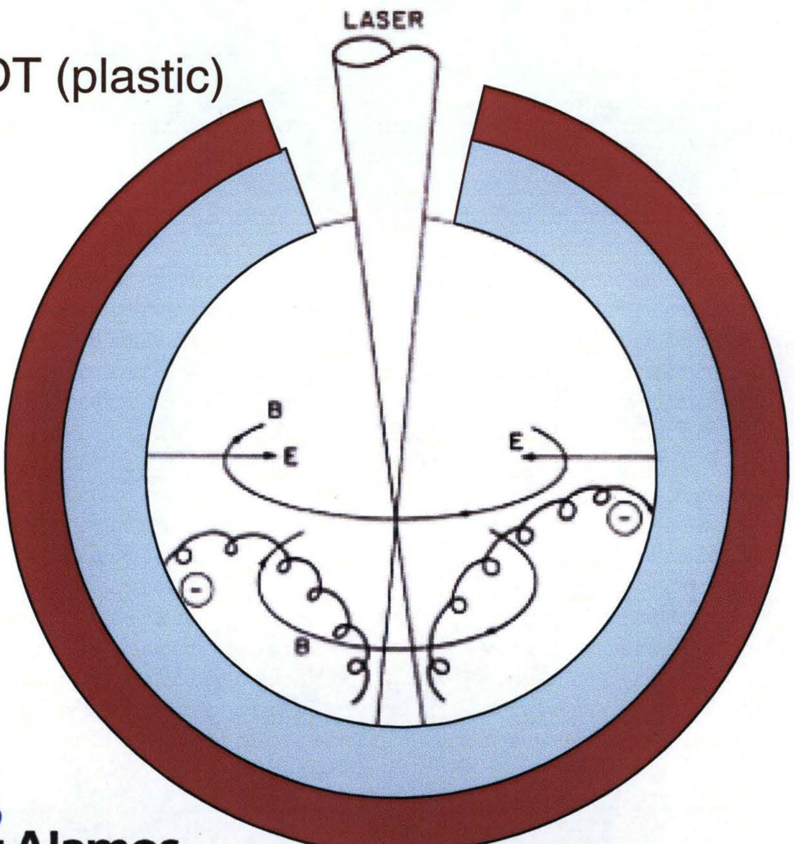
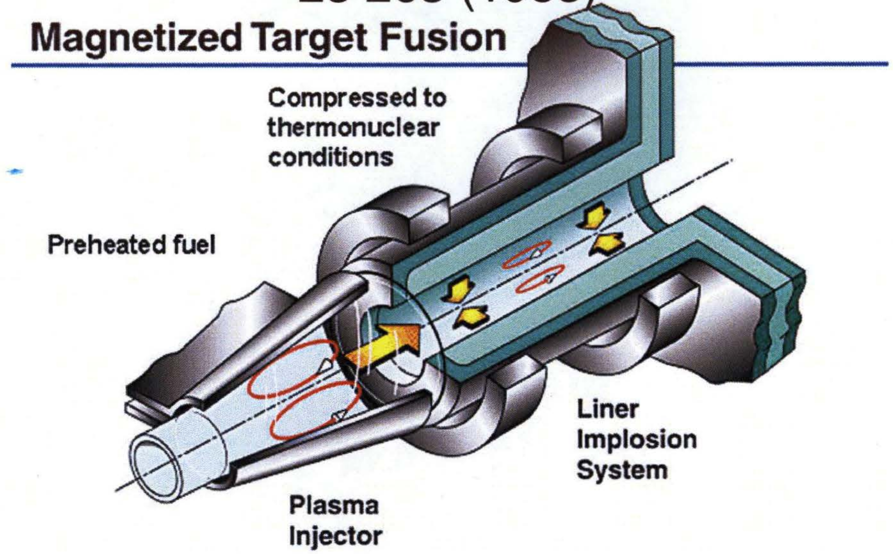
ICF+MCF = Magneto-Inertial Fusion (MIF) / Magnetized Target Fusion (MTF)

Hasegawa et al Phys. Rev. Lett. 56 139 (1986)
Magnetically Insulated ICF (MICF)

Solid DT (plastic)



FXRL at LANL (Wurden)
Magneto-Inertial Liner Fusion
quickly renamed MTF
for obvious reasons
Lindemuth and Kirkpatrick Nuc. Fus. 23 263 (1983)



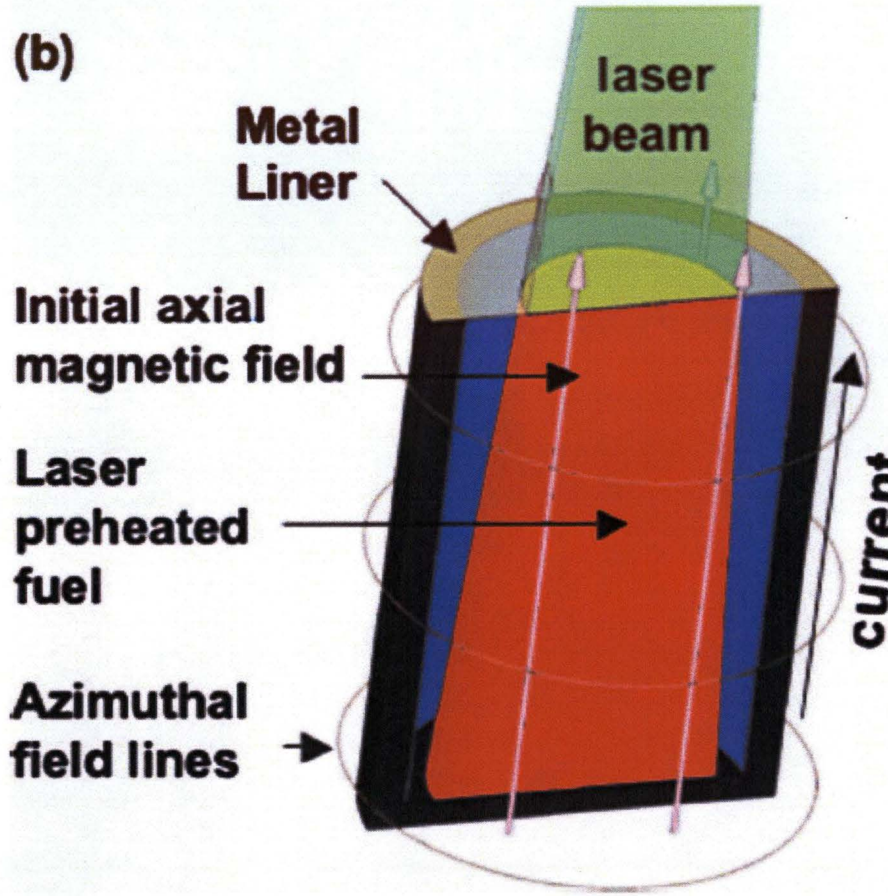
$\nabla n \times \nabla T$ 1 MG magnetic field

Confinement time ↑ 10^2 and driver energy ↓ 2 or more, n ↓ compared to ICF

Magnetized Target Fusion (MTF) / Magneto-Inertial Fusion (MIF)

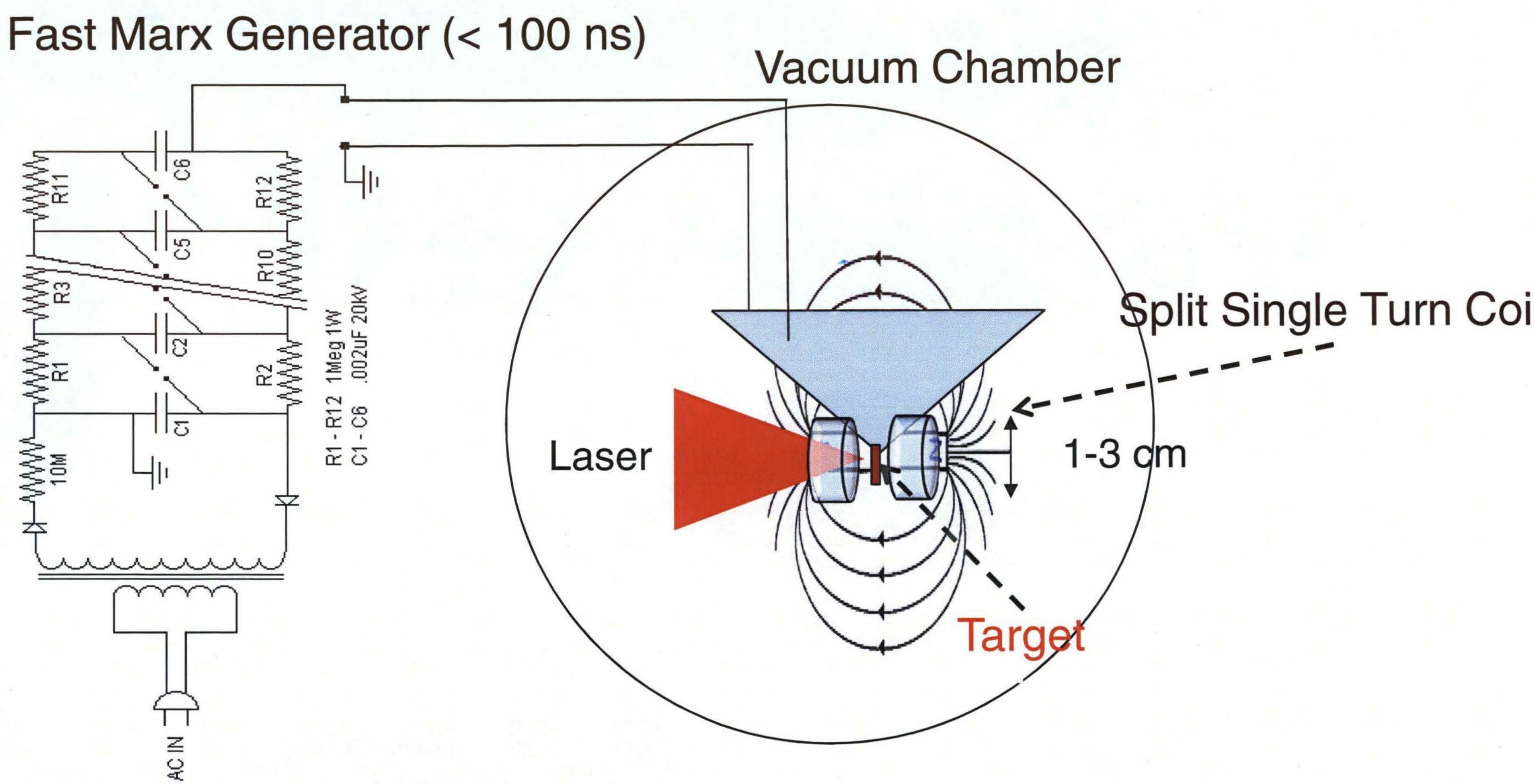
Slutz et al. Phys. Plasmas 17 056303 (2010)
Magnetize Liner Inertial Fusion (MagLIF), Sandia

- External B field (30 T)
- Laser (6.5 kJ) initiated DT plasma,
- Z implosion

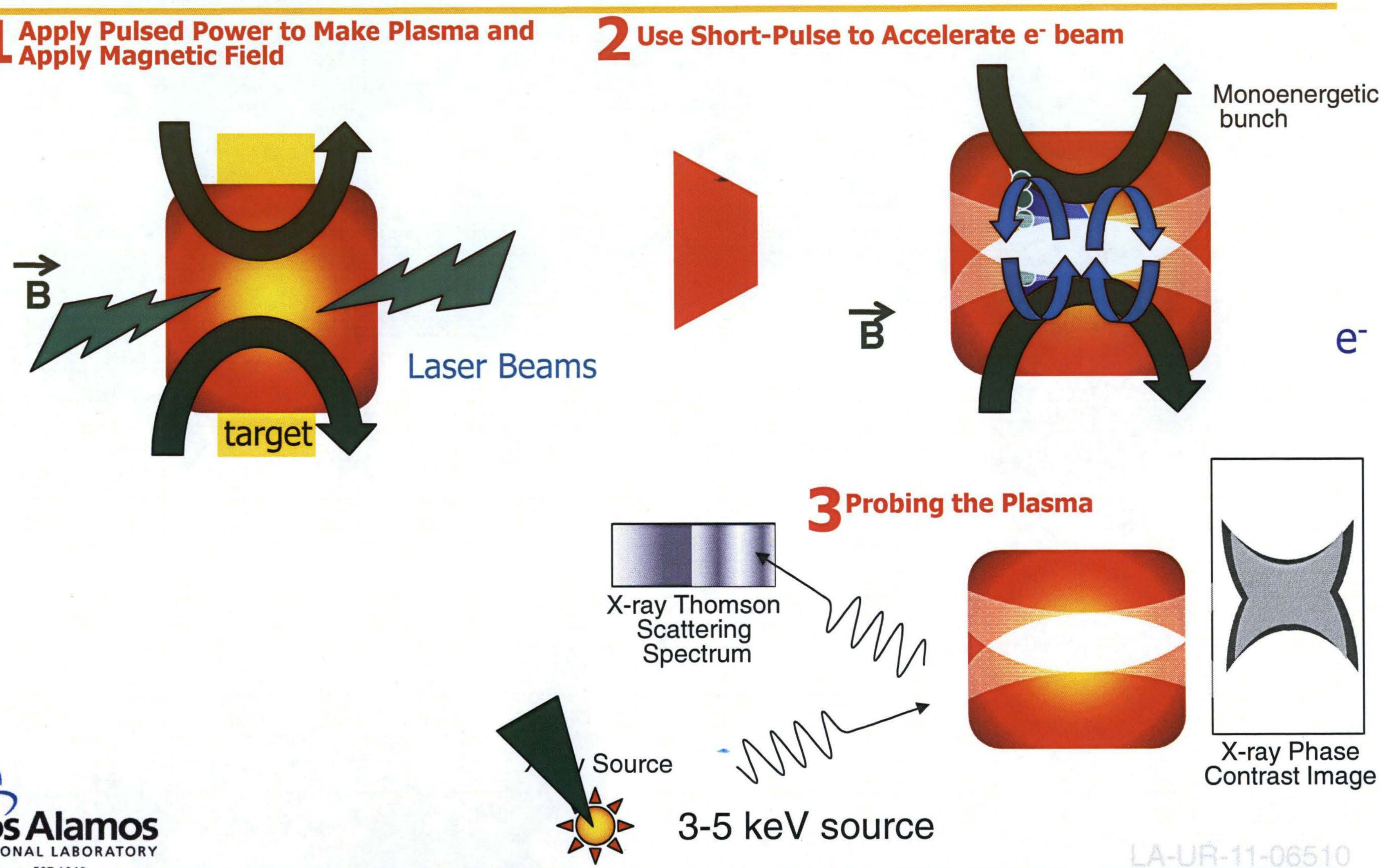


Confinement time ↑ 10^2 and driver energy ↓ 2

Our Proposed Future Work would marry a 100 Tesla Magnet with Trident for HEDLP Experiments and MIF



Magnetically Confined Critical Dense Plasma with Pulsed Power (Phase 1)



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At LCLS-MEC such a setup could use x-ray polarimetry to see the fields

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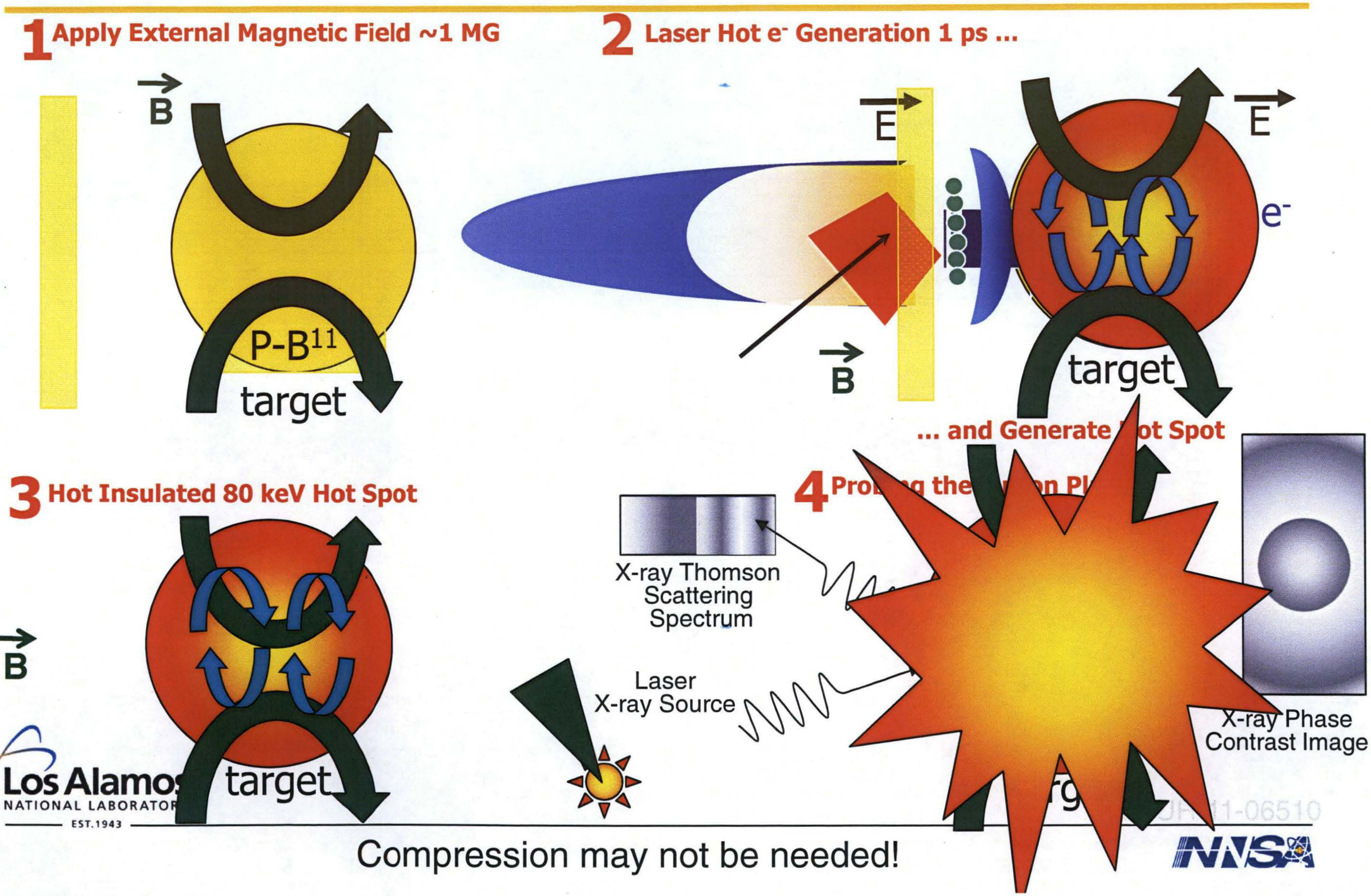
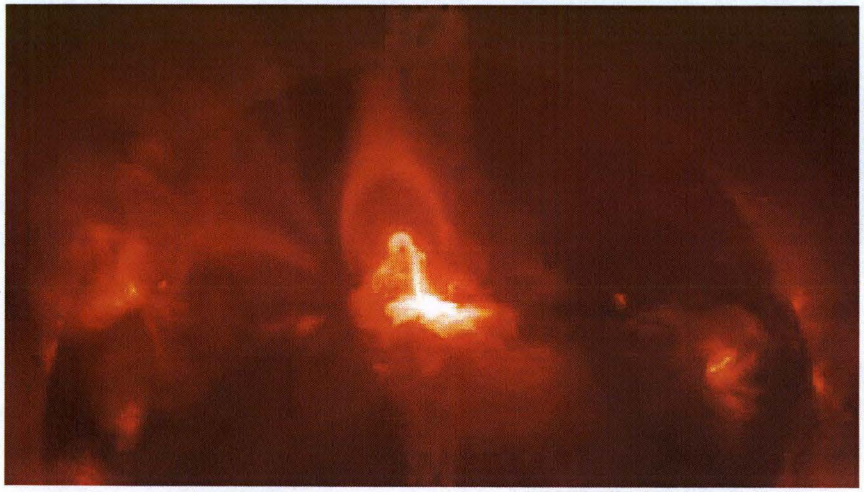
To Produce Fusion in the Lab (P-B^{11} MIF) via the Tri-Alpha Process (Phase 2)

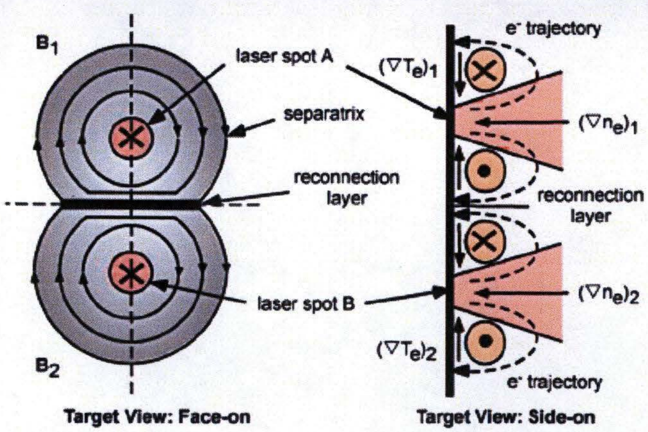


Compression may not be needed!

Other Plasma Studies can be done with Such a System: Magnetic Reconnection

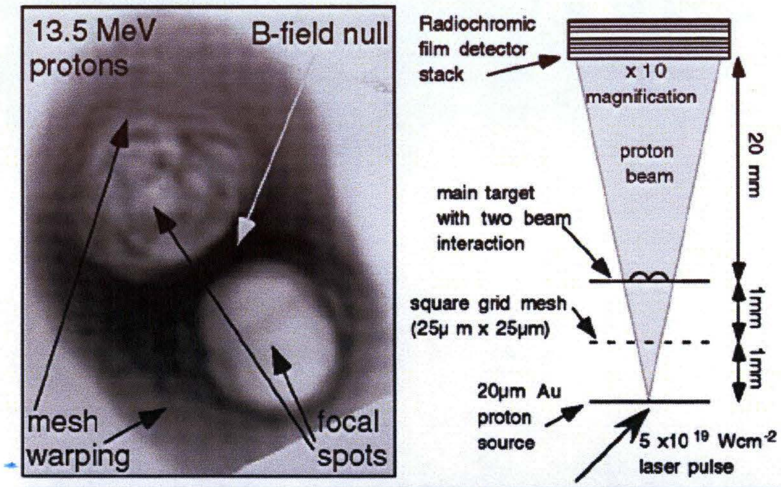
Solar Cosmic Ray Acceleration during Magnetic Field Line Reconnection

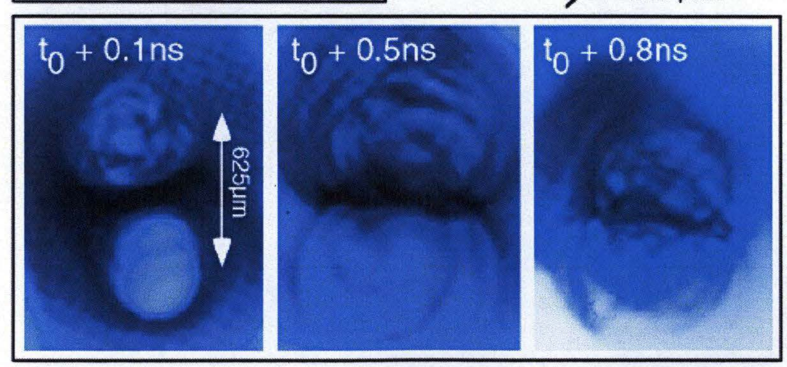




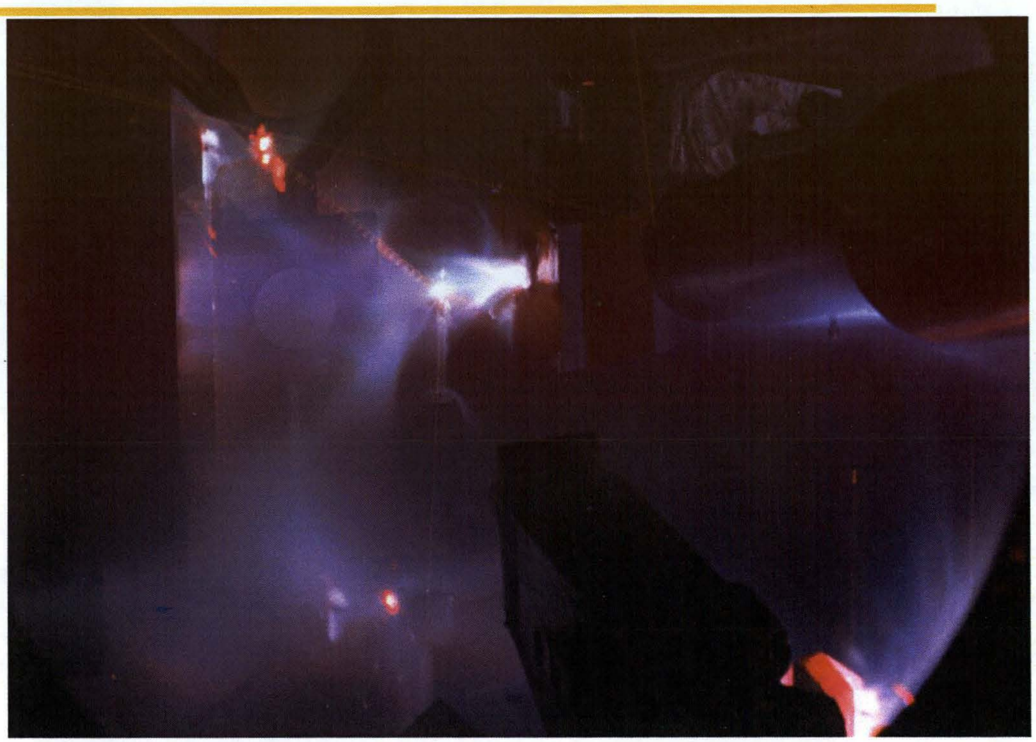
Courtesy of M. Roth

In solar flares the synchrotron losses become dominant for relativistic electrons accelerated via the magnetic field reconnection mechanism with the energy above 10 GeV





Summary & Conclusions



- Older Concepts of fusion are once again *en Vogue*
- Protons in excess 75 MeV can be created at 80 J at high contrast from RMTs and 65 MeV with FTCs along with billions of neutrons and x-rays
- OMEGA EP produced ions up to 70 MeV at 1 ps and 400 J and 50 MeV at 10 ps and 1000 J with the right choice of target
- Reducing prepulse can stabilize variability at the cost of maximum energy, no brainer
- Ions are focused in a non-ballistic fashion which needs new designs for longer range focusing of ions
- Carbon and protons do not behave the same way in different laser pulse duration experiments
- MIF using ion beams or the laser directly (e^-) could make the Tri-alpha process cheap to achieve