Update on Fast Ignition Fusion Energy

R. Fedosejevs

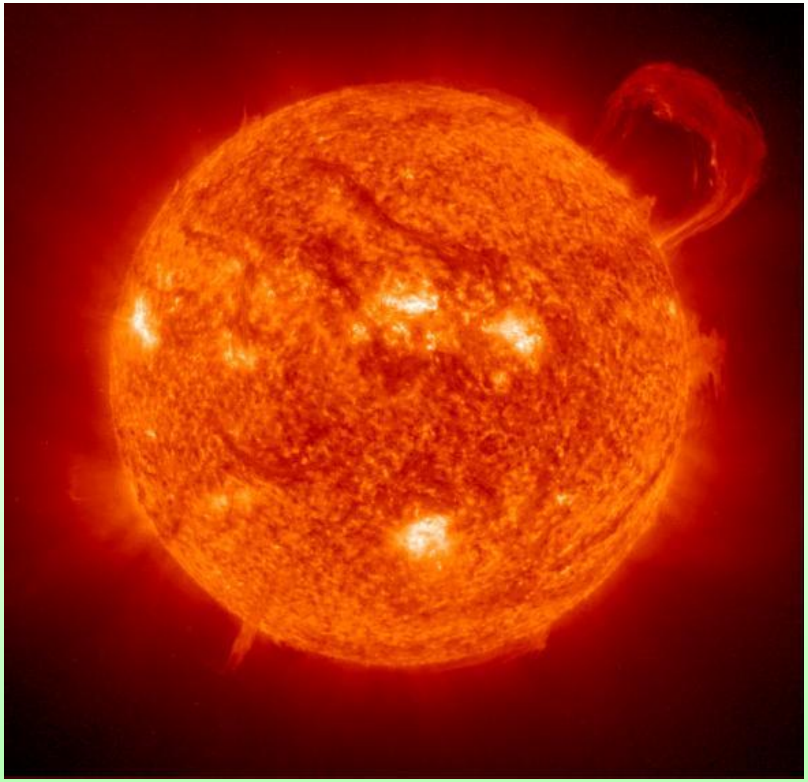
Department of Electrical and Computer Engineering
University of Alberta

Presented at the
Canadian Workshop on Fusion Energy Science and Technology
Ottawa, October 18, 2015

Overview

- Introduction to Laser Fusion Approaches
- Advanced Ignition Techniques
  - Fast Ignition and Shock Ignition
- Electron Fast Ignition Status
- Proton Fast Ignition Status
- University of Alberta Experiments
- The Way Forward
- Conclusions

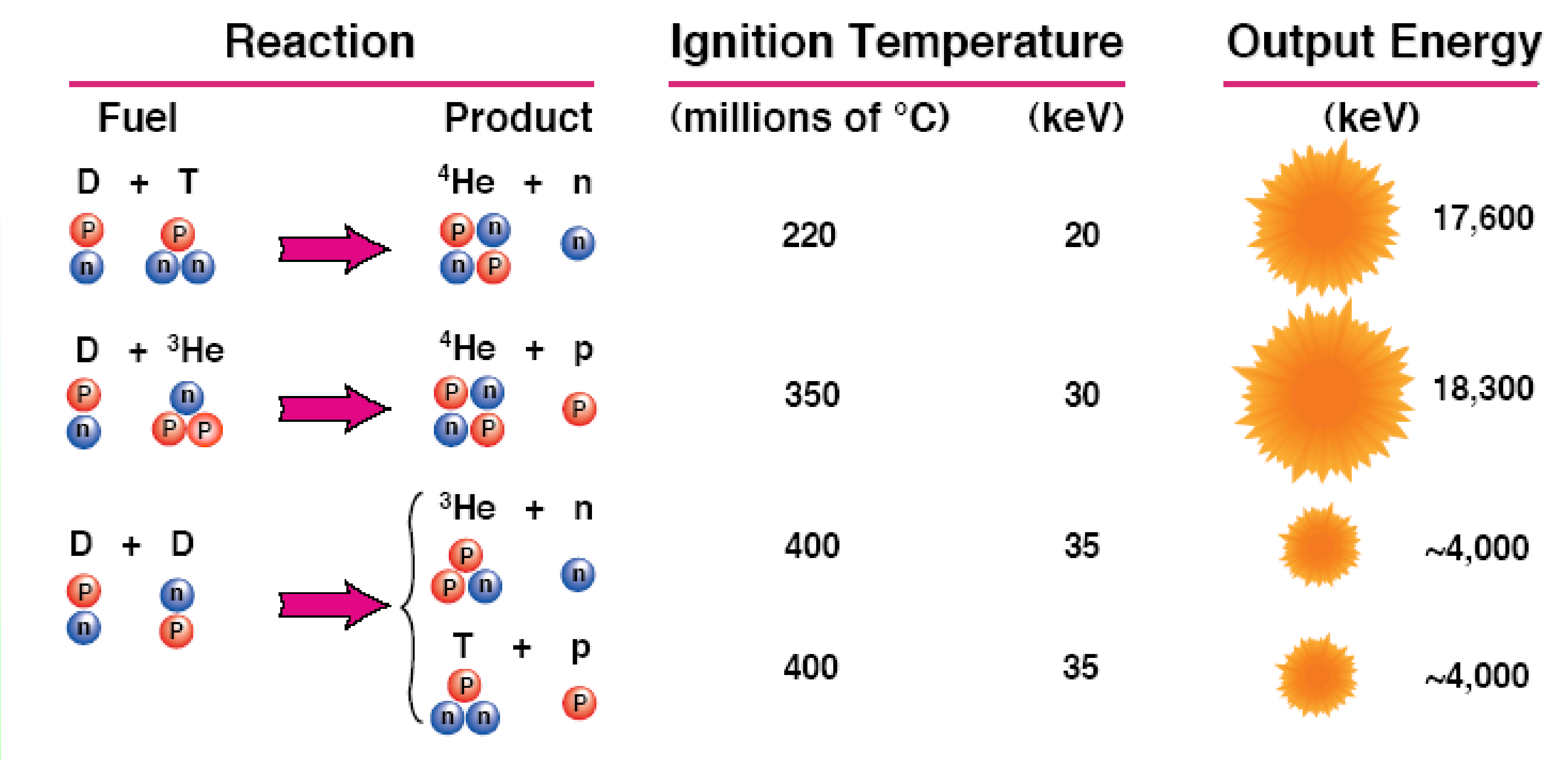
Bringing the Sun to Earth



Fusion the Ultimate Energy Source

http://photojournal.jpl.nasa.gov/catalog/PIA03149

Deuterium Based Fusion



1 part in 6500 of all hydrogen is in the form of deuterium

3 water bottles of DT water fuel and 400 helium balloons ash per day for a GW reactor

Lawson Criterion for Net Energy Yield

Requires very elevated temperatures

~100,000,000 K (~10keV energy per particle)

Requires enough burn time

Lawson Criterion for net release of more energy than heating energy

$$n\,\tau \sim 2 \times 10^{14}\ \mathrm{s\ cm^{-3}}$$

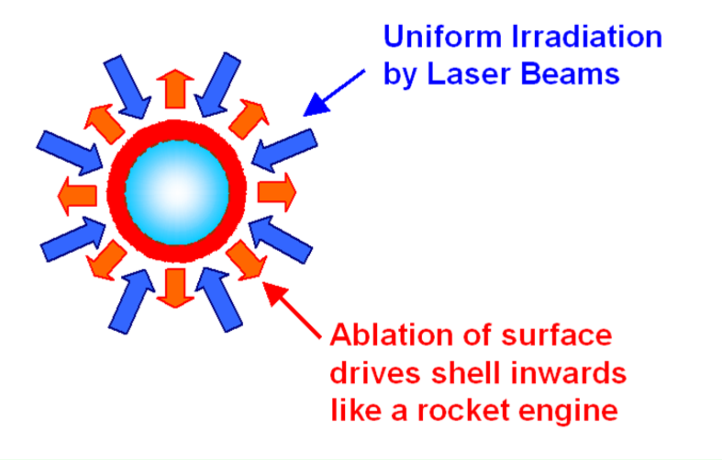
n = ion density, τ = confinement time

Laser Fusion uses high density n ~10^{25} $\mathrm{cm^{-3}}$ but short interaction time τ ~100 ps in the ignition hot spot

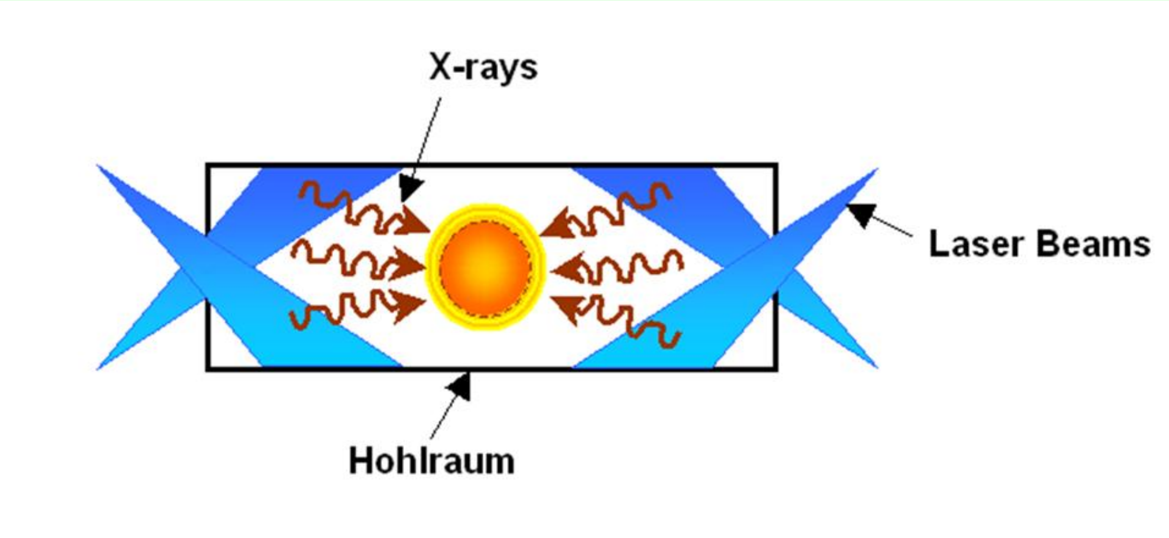
Laser Fusion Energy (LFE)

Laser Fusion

Direct Drive



Indirect Drive



Ignition Conditions:

$\rho \sim 400$ g cm^{-3}

T ~ 6 keV
In central hot spot region

Lawrence Livermore National Laboratory
National Ignition Facility - USA

Goal to reach ignition and produce modest target gains of G = 10-20

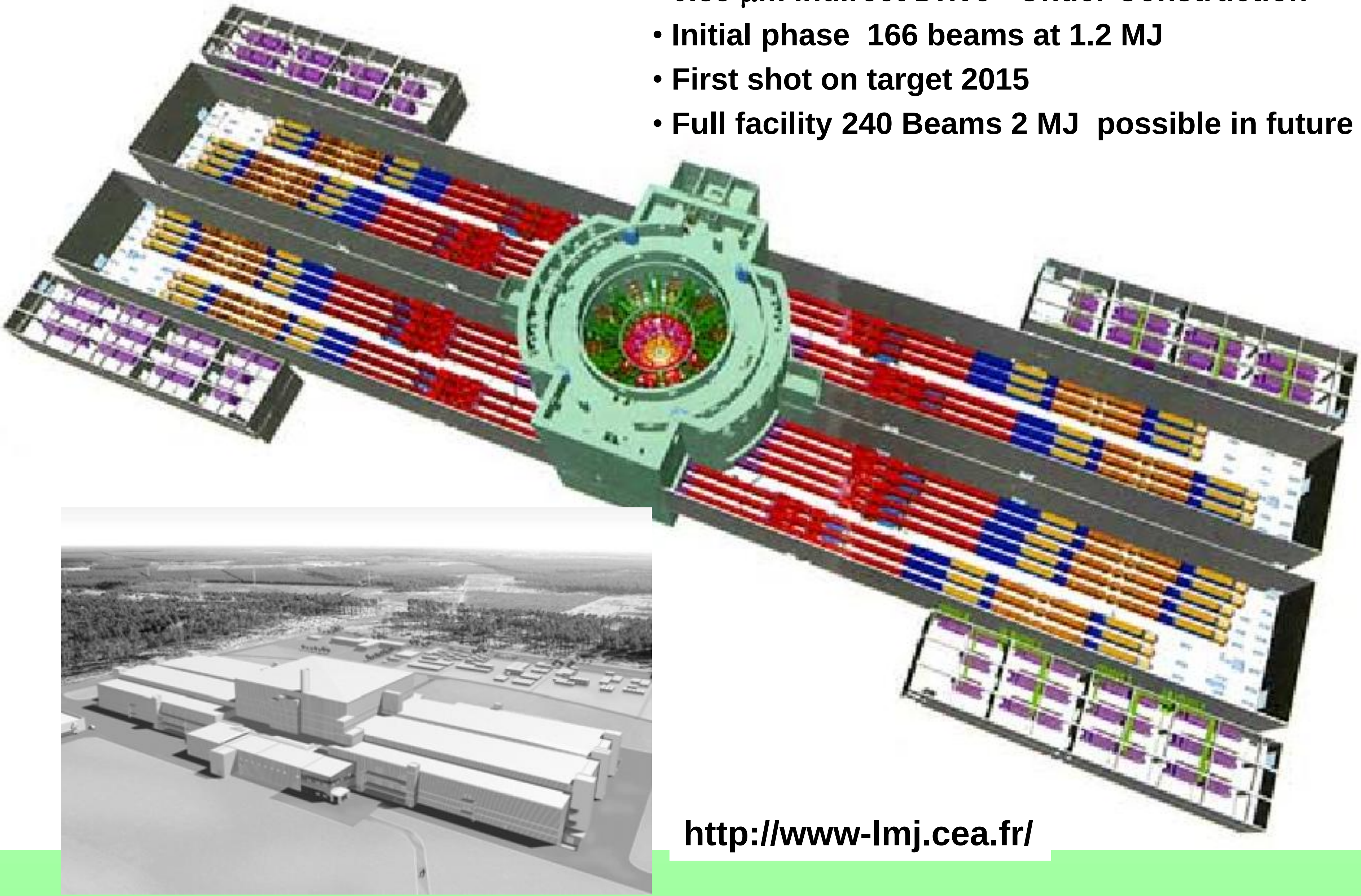
- **Indirect Drive 1.8 MJ**
- **0.35 μm 192 beams**
- **Operating 5 years**

Lawrence Livermore National Laboratory

https://lasers.llnl.gov/

Laser Mega Joule - France

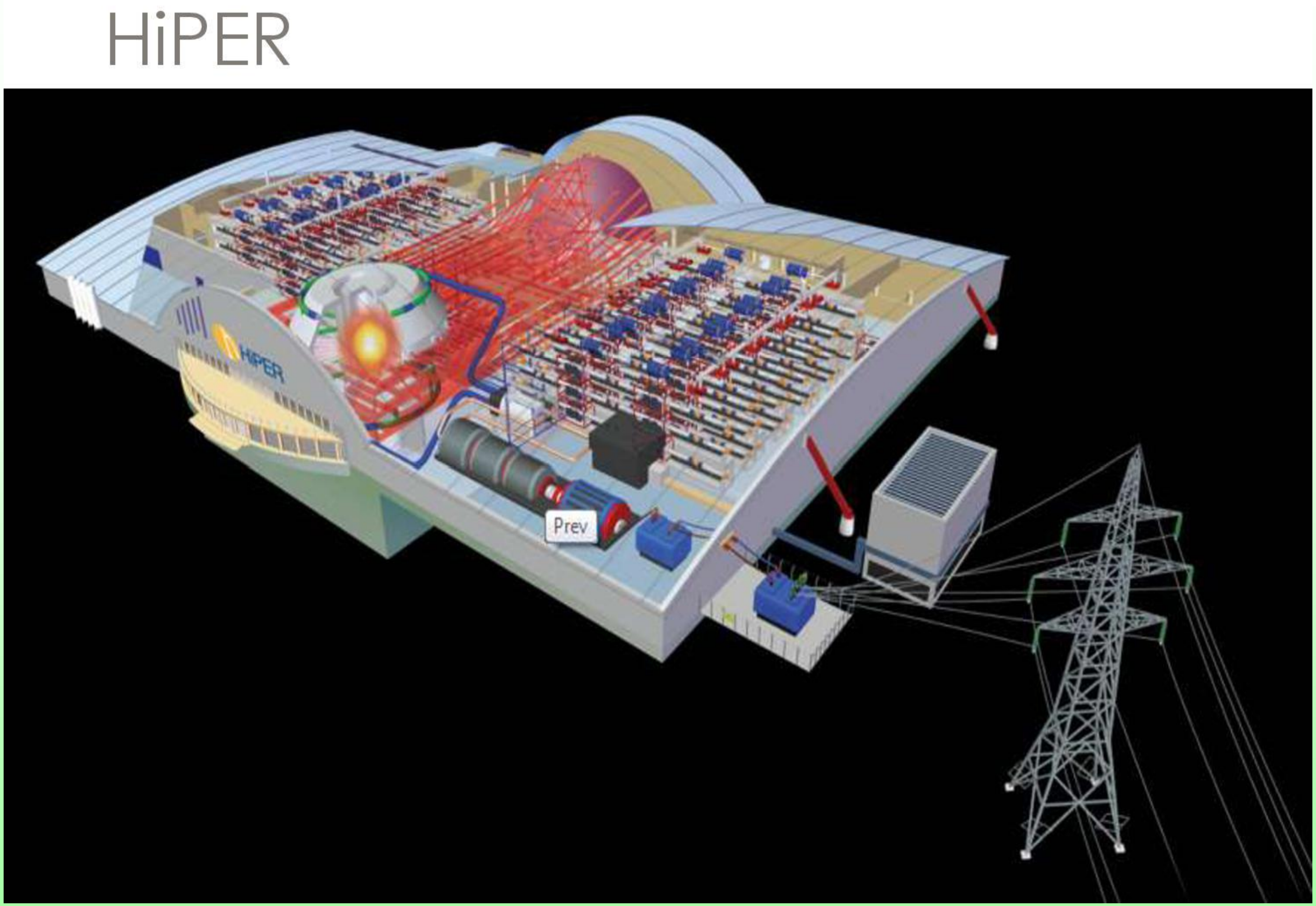
- 0.35 μm Indirect Drive - Under Construction
- Initial phase 166 beams at 1.2 MJ
- First shot on target 2015
- Full facility 240 Beams 2 MJ possible in future



http://www-lmj.cea.fr/

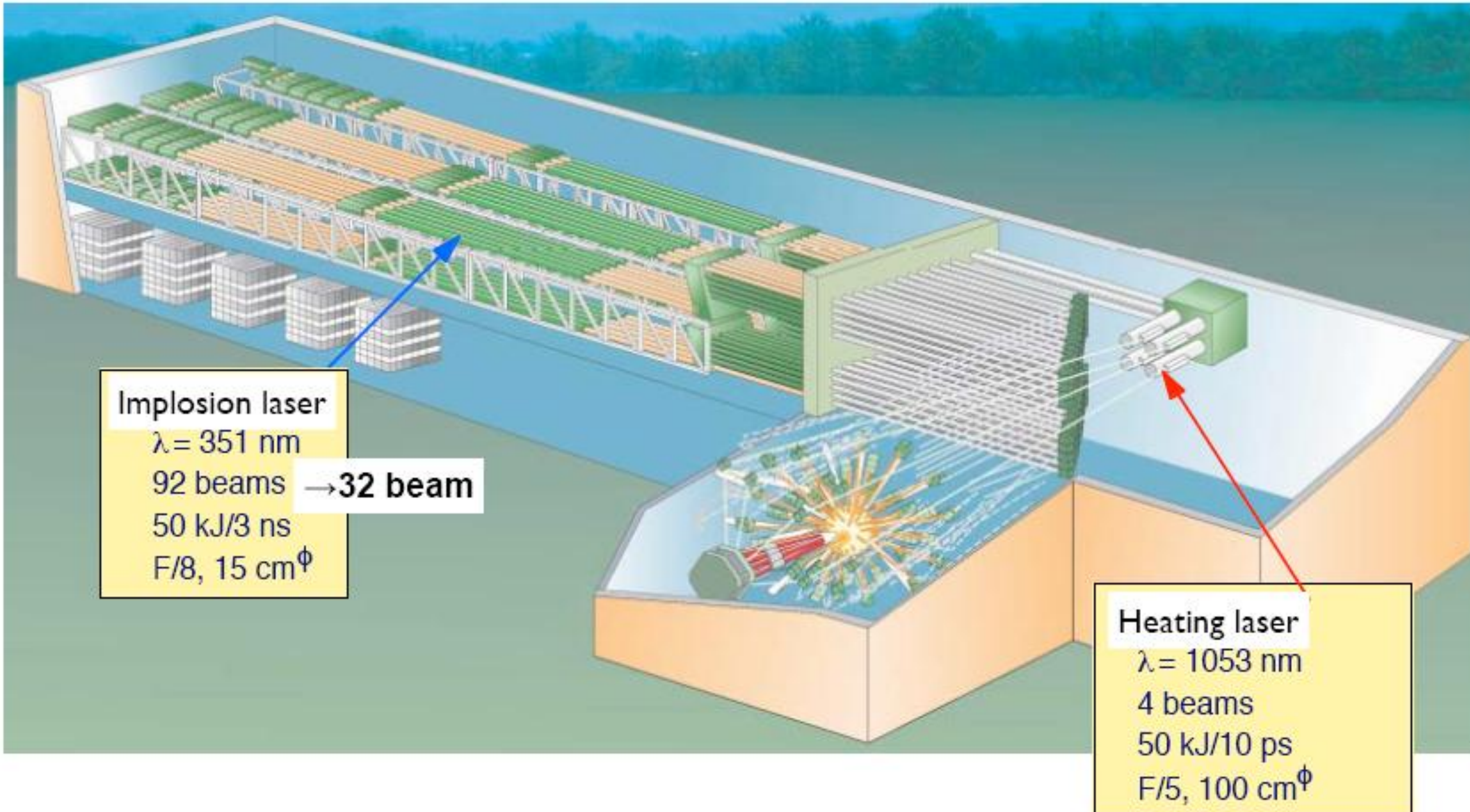
Proposed European HiPER Project
Advanced Ignition Demonstration Experiment

http://www.hiperlaser.org

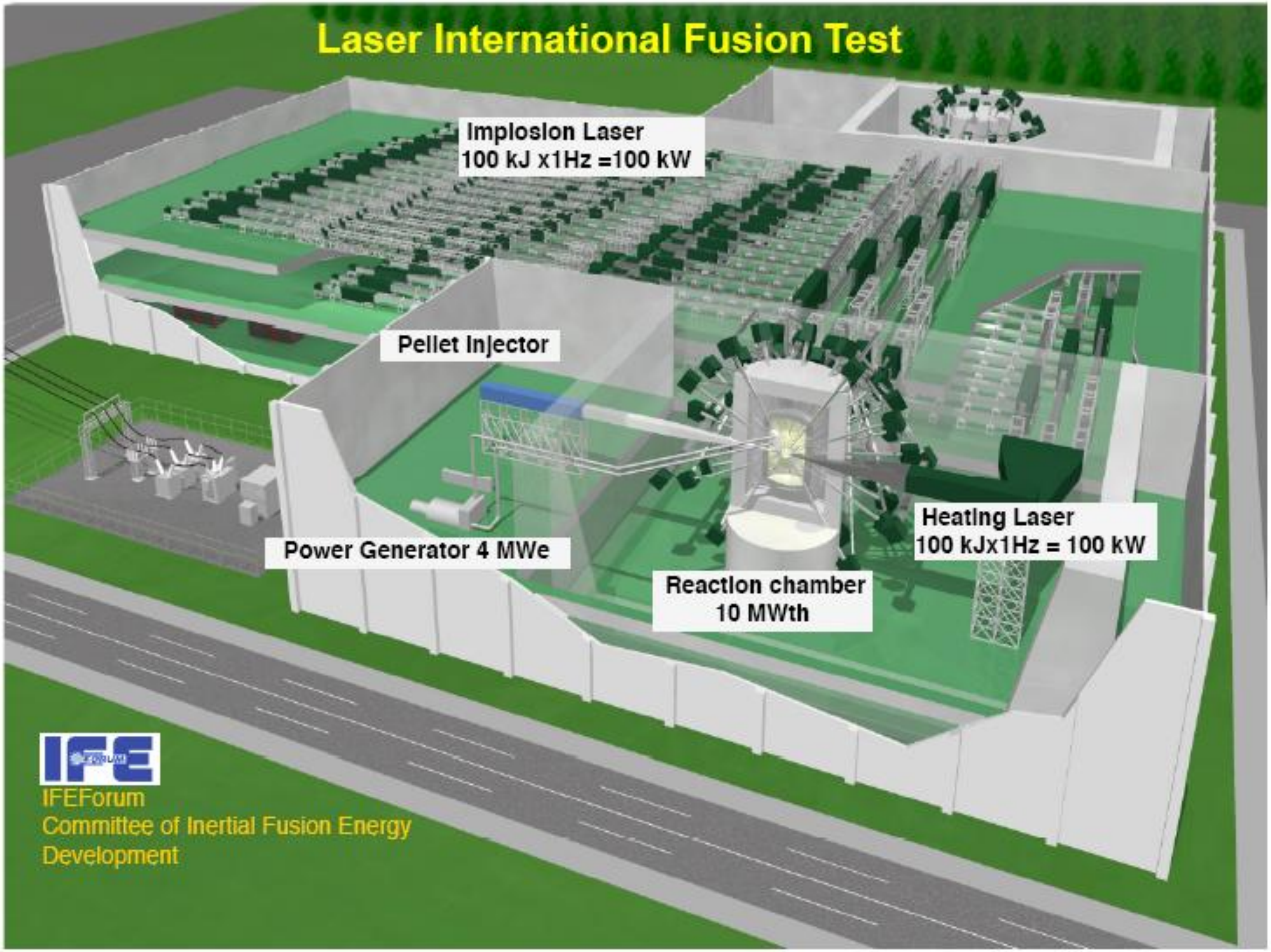


Cost ~ $1-2B Euro Planning Started under the Framework 7 Program

Proposed FIREX-II Ignition and Burn



LIFT Demo Reactor Proposal - Japan



Advanced Ignition Techniques

Fast Ignition and Shock Ignition

Fast Ignition – An Improved Approach

Long Pulse Compression ~ 500kJ

Short Pulse Ignition ~200 kJ

Proposed by Tabak in 1994

**Requires: electrons (1-3 MeV) or
ions (15-20 MeV)
To carry the energy from the laser absorption region to the high density compressed core**

Ignition Requirements

$\rho \sim 300\ \mathrm{g\ cm^{-3}}$

$\tau_{dep} \sim 20\ \mathrm{ps}$

$D_{dep} \sim 40\ \mu\mathrm{m}$

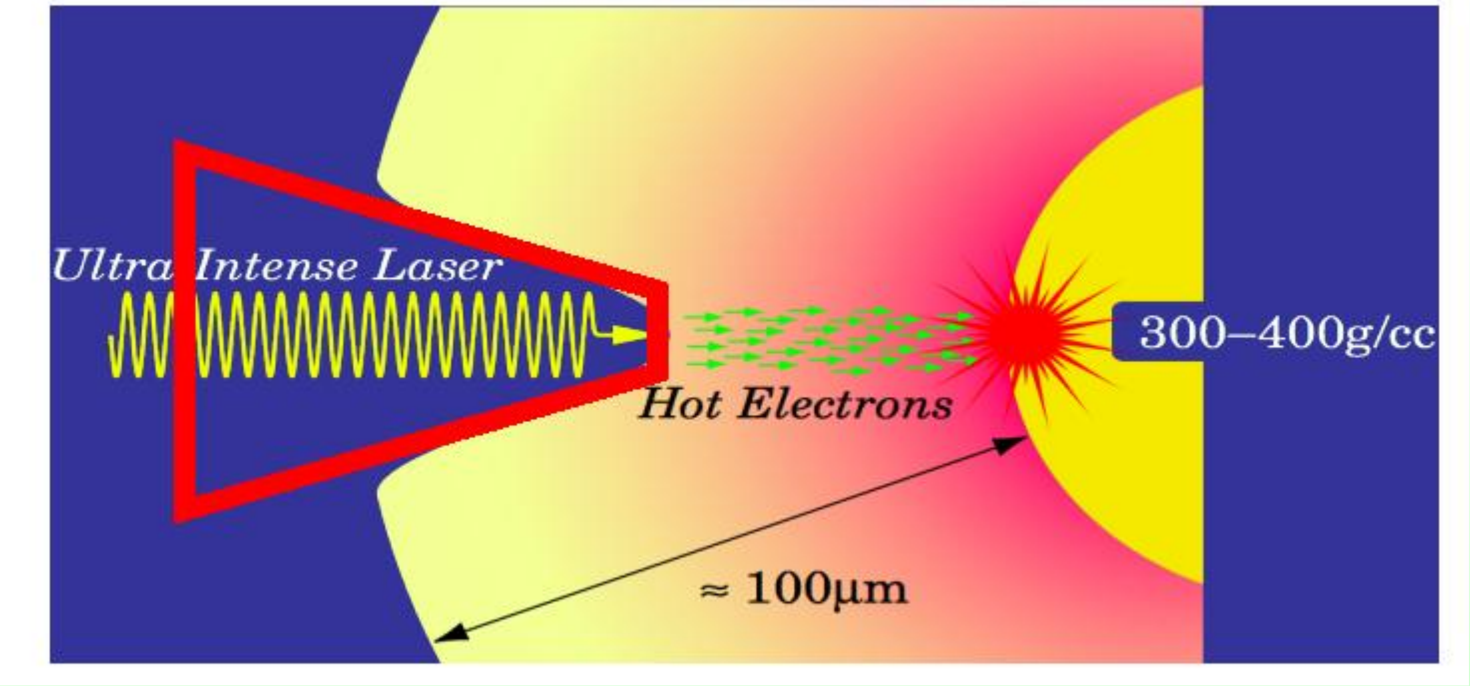
$E_{dep} \sim 20\ \mathrm{kJ}$

$E_{laser} \sim 200\ \mathrm{kJ}$

$\phi_{laser} \sim 20 - 40\ \mu\mathrm{m}$

$I_{laser} \sim 10^{20} - 10^{21}\ \mathrm{W\ cm^{-2}}$

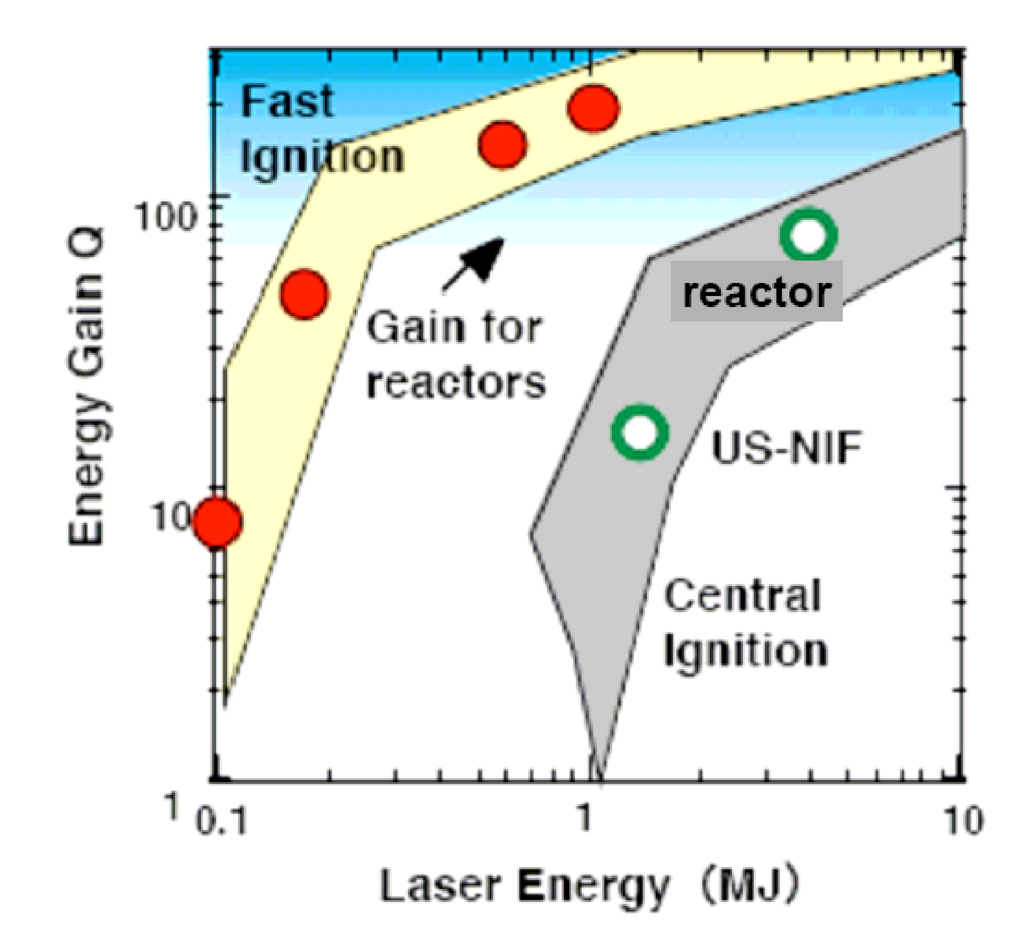
Fast Ignition



Laser cannot penetrate into the core

Therefore deliver in the form of MeV electrons or ions driven by Ultra-intense (PW) short pulse laser

Energy Gain Scaling for Fast Ignition



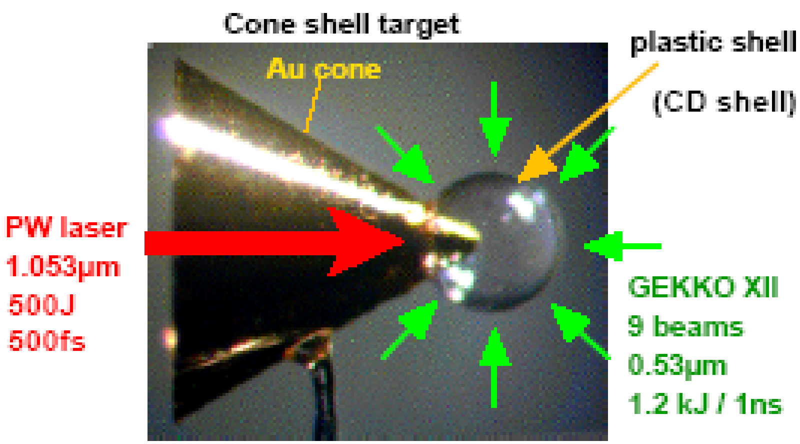
Reduce Laser Requirements almost an order of magnitude:

Smaller and less expensive initial IFE reactors possible

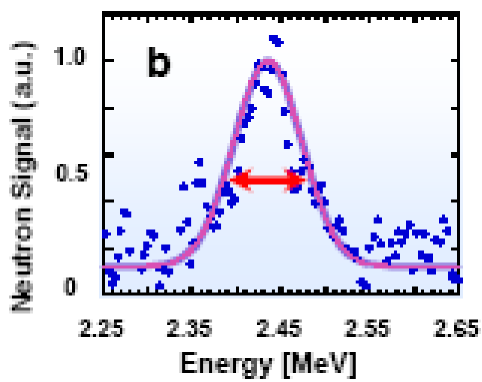
Initial Heating Results Demonstrated at ILE Japan

- Fast ignition experiments by the PW laser demonstrated the heating efficiency of 20%.

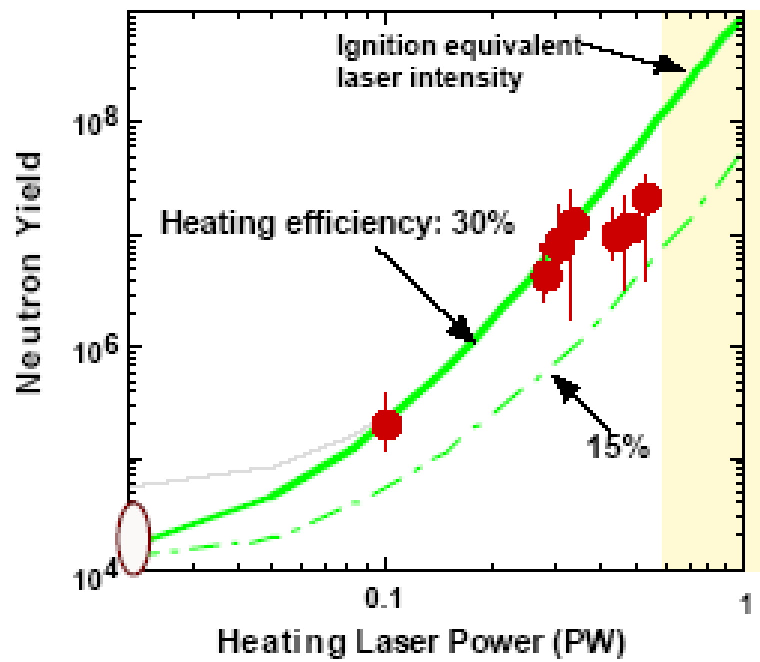
ILE OSAKA



Enforced heating was realized at a heating power equivalent to the ignition condition.



Neutron time-of-flight



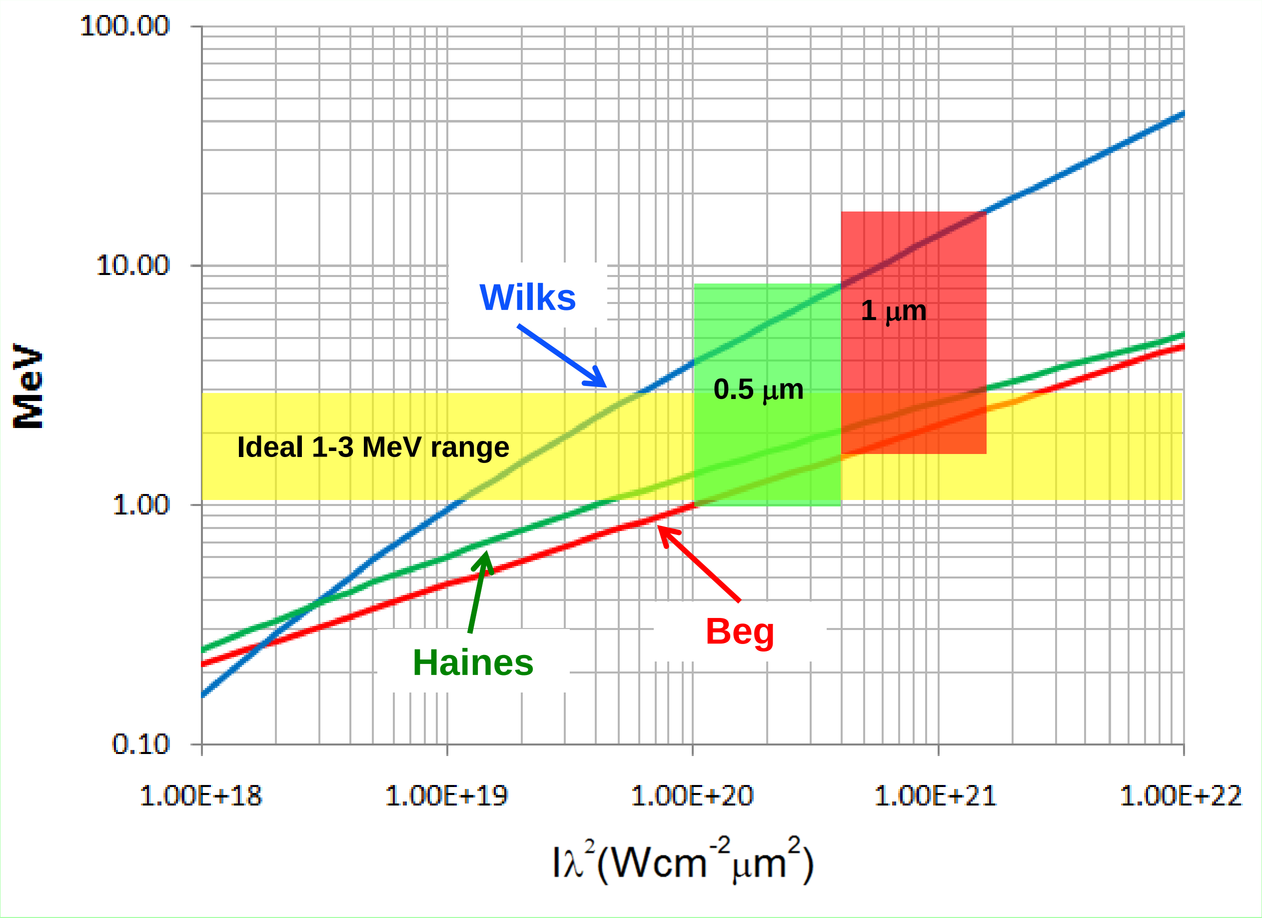
FWHM: 90±5keV keV
Resolution:50 keV

0.86 ±0.1 keV

Kodama et al., Nature 418, 933 (2002)

Electron Energy Scaling

Required electron energies ~ 1-3 MeV



Scaling Laws:

Wilks (Ponderomotive)
PRL 69, 1383 (1992)

Beg (Exp Bremsstrahlung)
Phys.Plasmas 4,447 (1997)

Haines (Energy/Momentum)
PRL 102, 045008 (2009)

Proton Fast Ignition with Protons

VOLUME 86, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JANUARY 2001

Fast Ignition by Intense Laser-Accelerated Proton Beams

M. Roth,[1,2] T. E. Cowan,[1,3] M. H. Key,[1] S. P. Hatchett,[1] C. Brown,[1] W. Fountain,[4] J. Johnson,[4] D. M. Pennington,[1] R. A. Snavely,[1] S. C. Wilks,[1] K. Yasuike,[5] H. Ruhl,[6] F. Pegoraro,[7] S. V. Bulanov,[8] E. M. Campbell,[1,3] M. D. Perry,[1,3] and H. Powell[1,*]

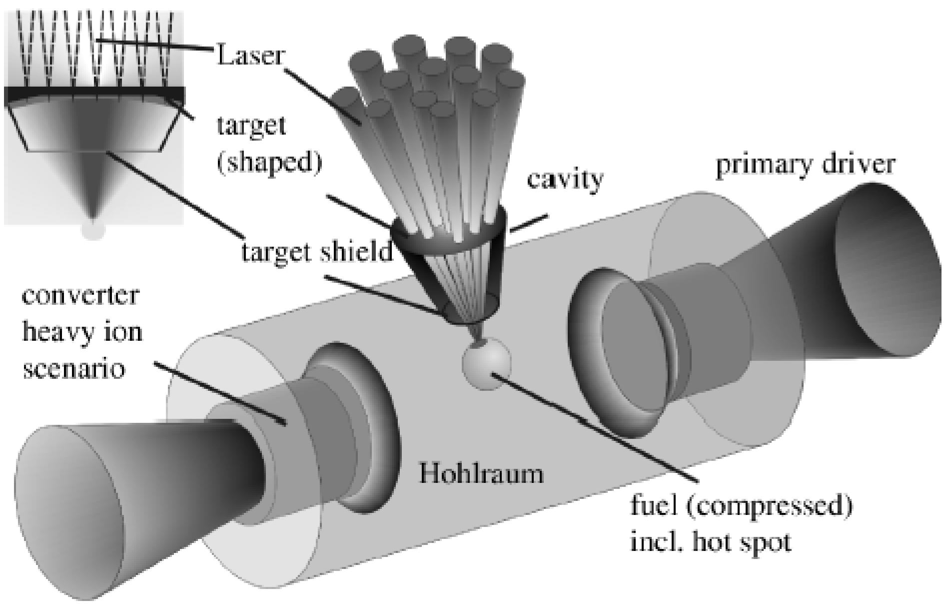


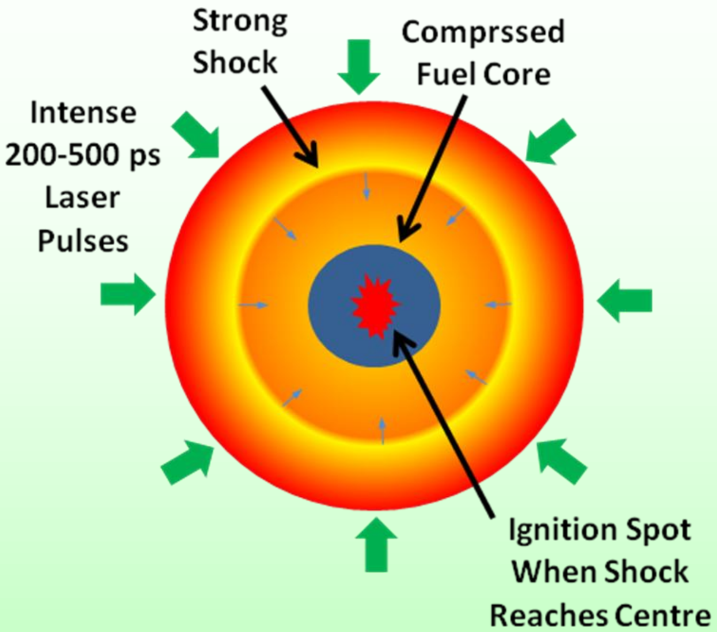
FIG. 1. Indirectly driven fast ignition using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

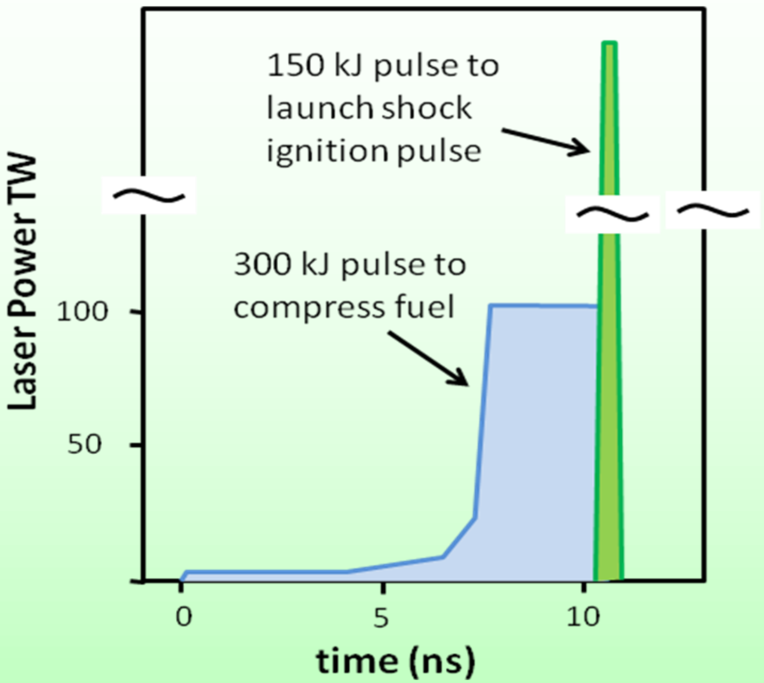
Required proton Energies ~ 15-20 MeV

- Need Conversion efficiency from laser to protons of 10%
- Only achieved in a few experiments to date
- Need to demonstrate guiding and coupling to the core

Shock Ignition

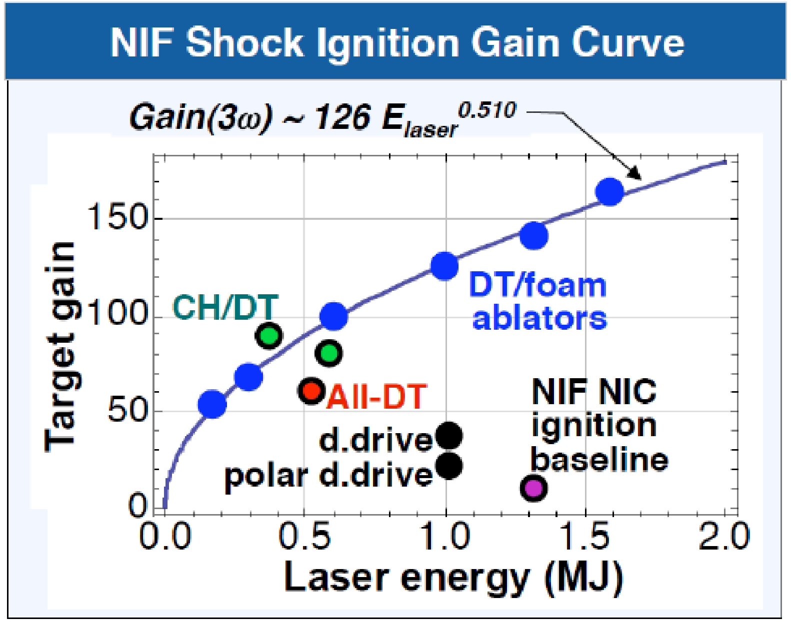
Shock Ignition



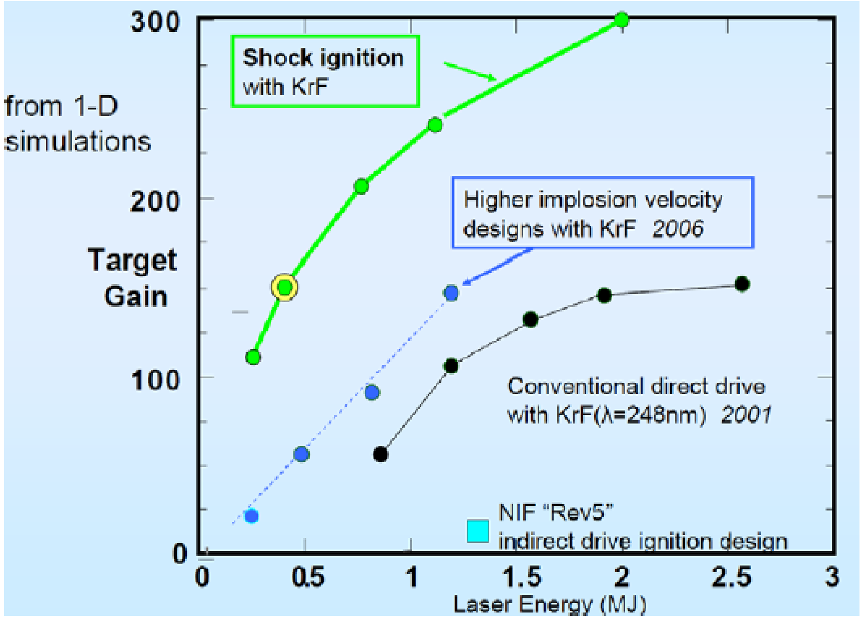


- Strong shock at the end of the compression pulse causes ignition of compressed fuel core
- Recently proposed in detail in 2007 by Betti et al. (PRL 98, 155001 (2007))
- Similar Concept by Shcherbakov, Sov. J. Plasma Phys. 9(2) 240 (1983)

High Gains at Low Pulse Energies



JL Perkins (LLNL)



A. Schmitt (NRL)

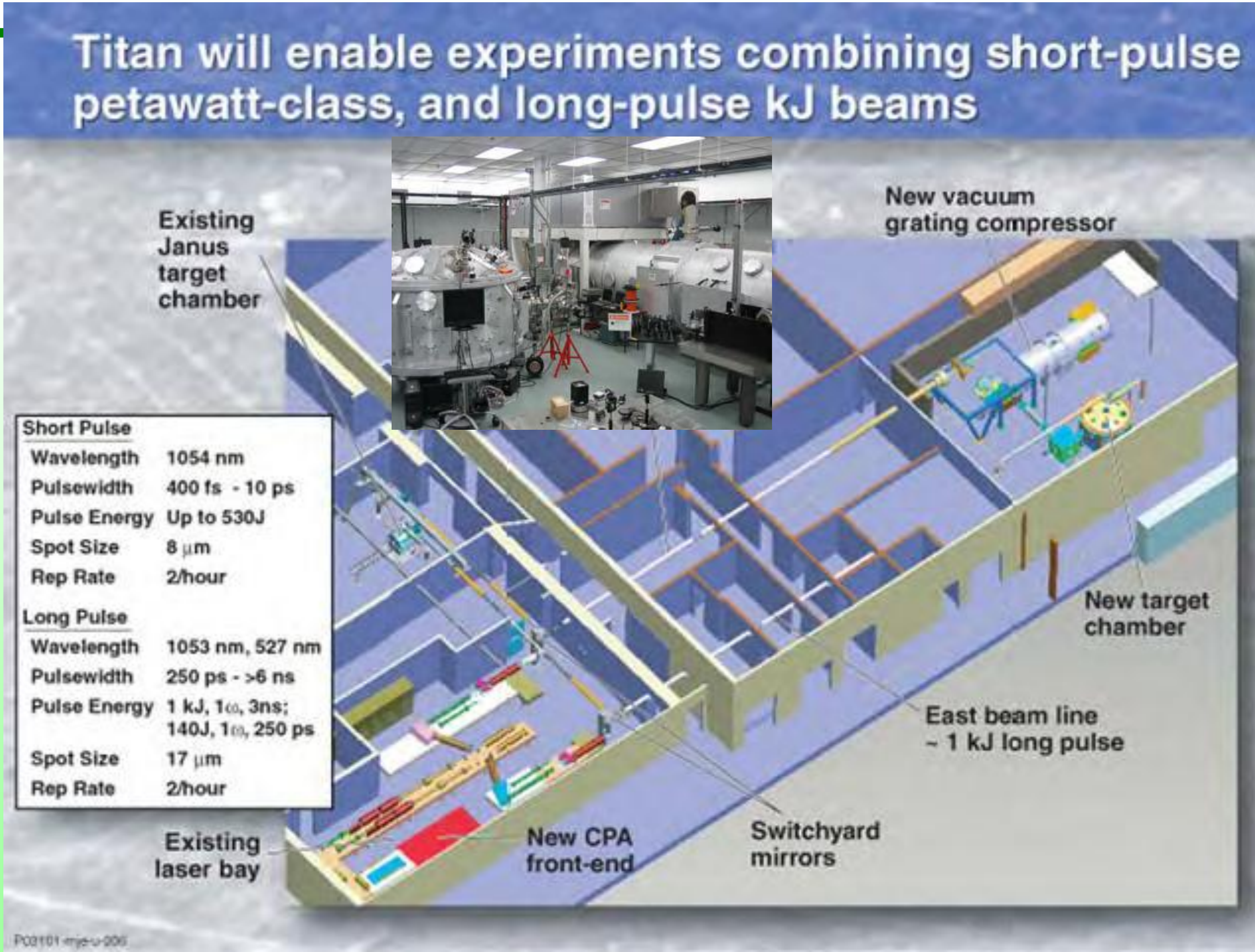
U of A Experiments

Fast Ignition Physics Scaling Experiments at Second Harmonic Wavelength

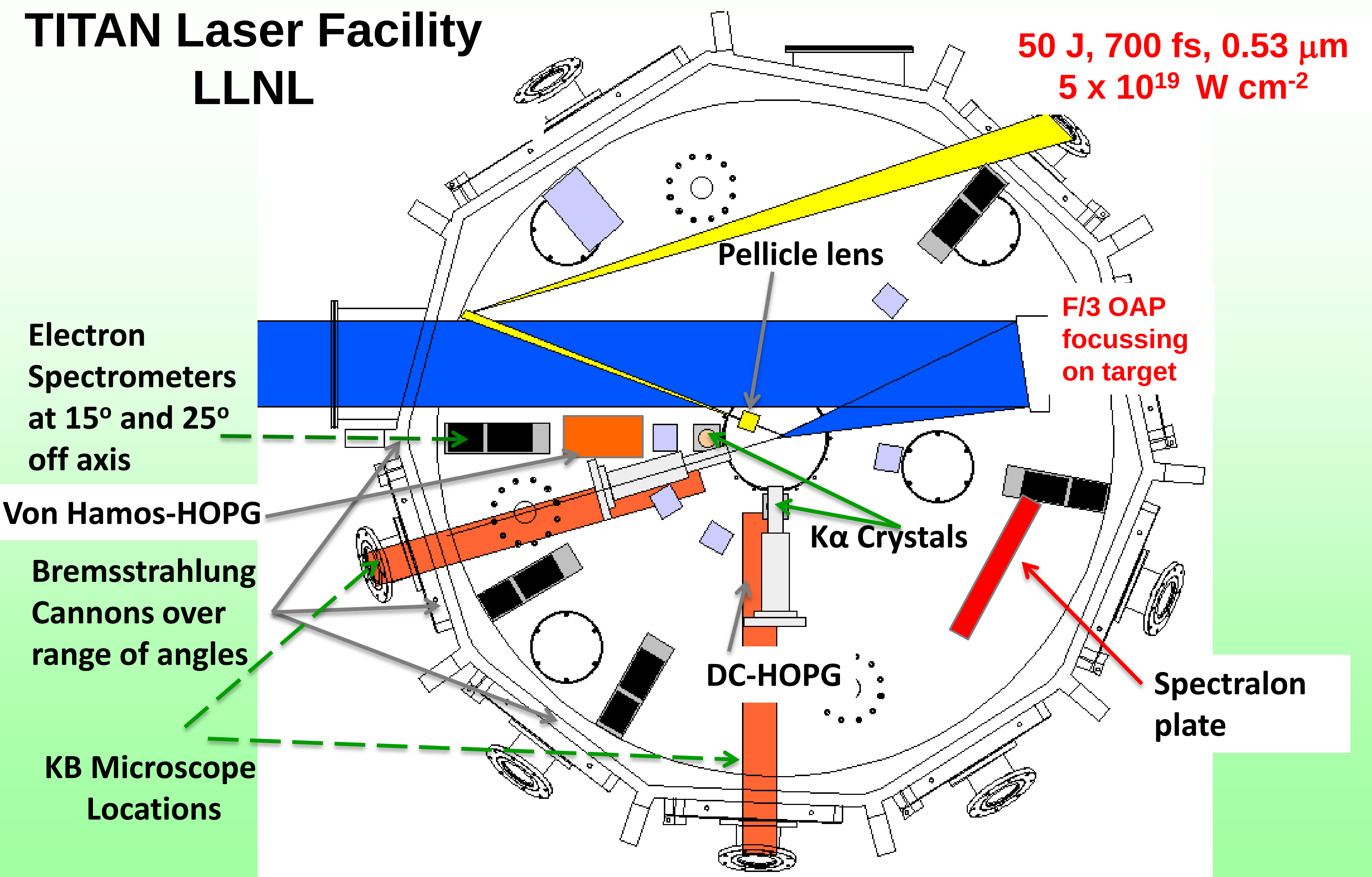
Using the TITAN Petawatt Laser at the Lawrence Livermore National Laboratory

Collaboration with LLNL,UCSD, GA, Ohio State University

Titan Laser Facility



Experimental Diagnostic Layout



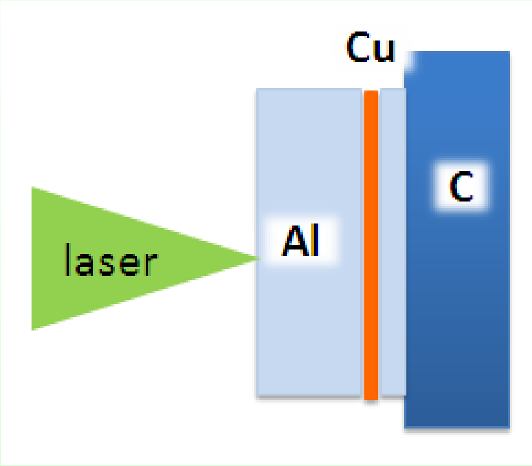
2ω Titan Run Parameters

50 J
700 fs
0.53 μm
5×10^{19} W cm^{-2}
Prepulse < 10μJ or 3mJ injected

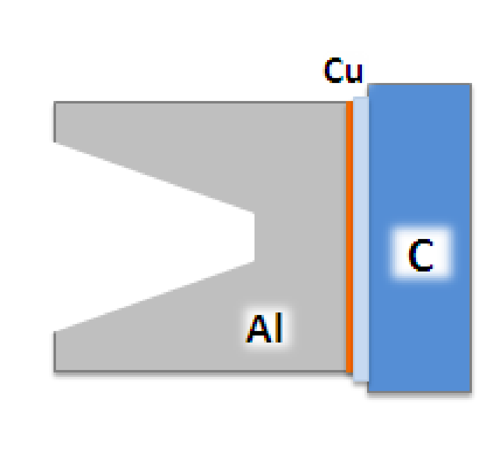
Planar Foil Targets
Buried Cone targets
Cone foil Targets
Cone Wire Targets

Targets used

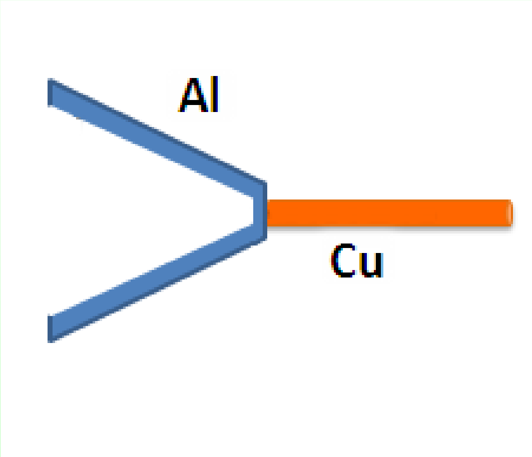
Planar with buried
Cu tracer layer



Solid Al cone with
buried
Cu tracer layer



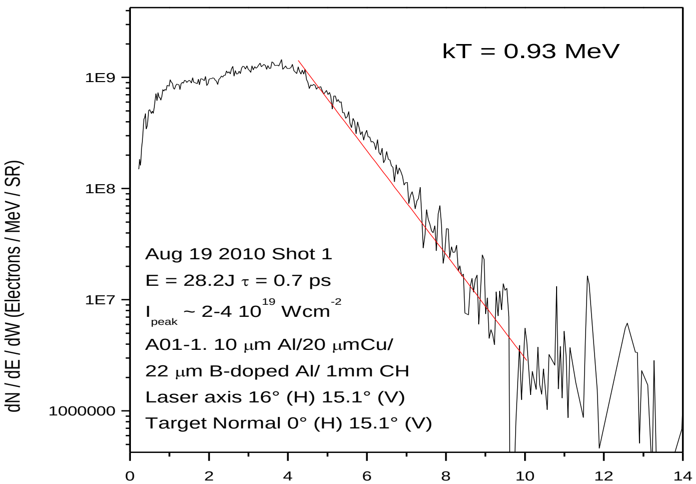
Thin Al cone
Cu wire

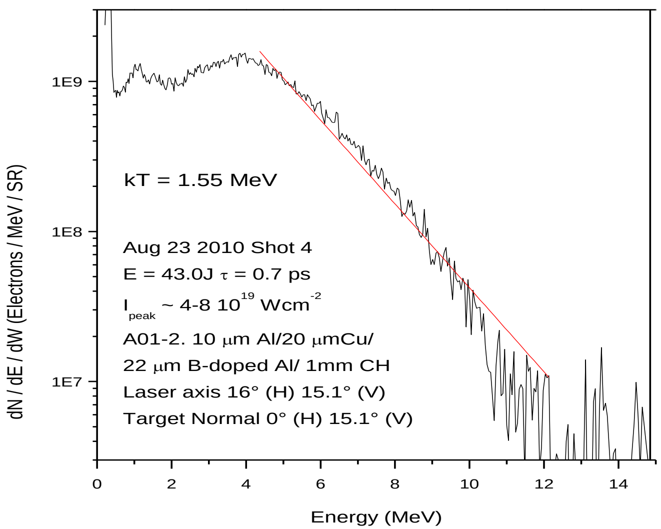


Shots taken with no prepulse (<10 μJ)
or with injected 3mJ 3ns 2ω prepulse

Typical 2ω Escaping Electron Spectra 15º

No Prepulse





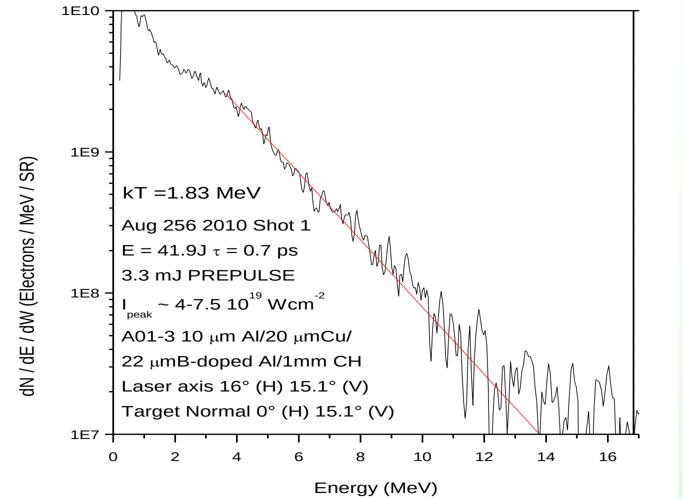
2 ω

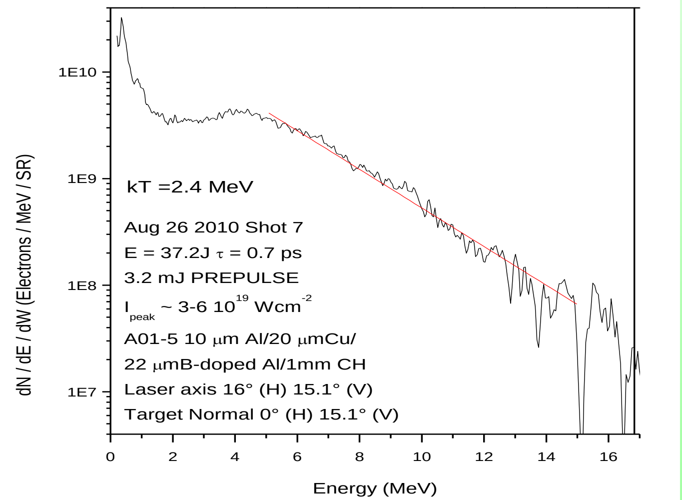
T_{hnpp} ~ 1.5 MeV

T_{hwpp} ~ 1.9 MeV

T_{hnpp} ~ 0.8 T_{hwpp}

With Prepulse



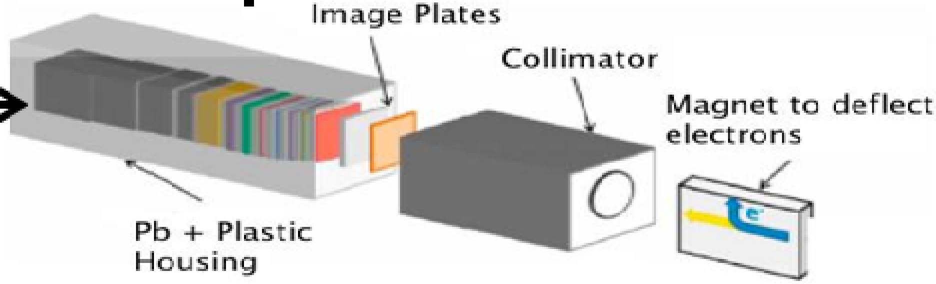


Hard X-ray Bremsstrahlung Cannon Spectrometers

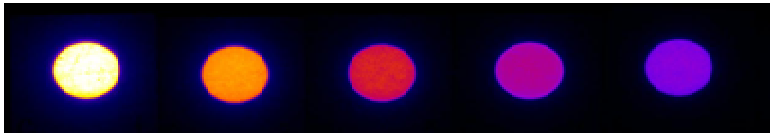
Filtered image plate stack with Pb collimator sensitive up to 500keV

X-Ray Spectrometer Setup

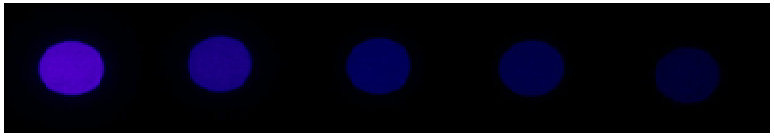
Schematic of X-Ray Spectrometer setup. Image plates and filters are alternated in stacked order



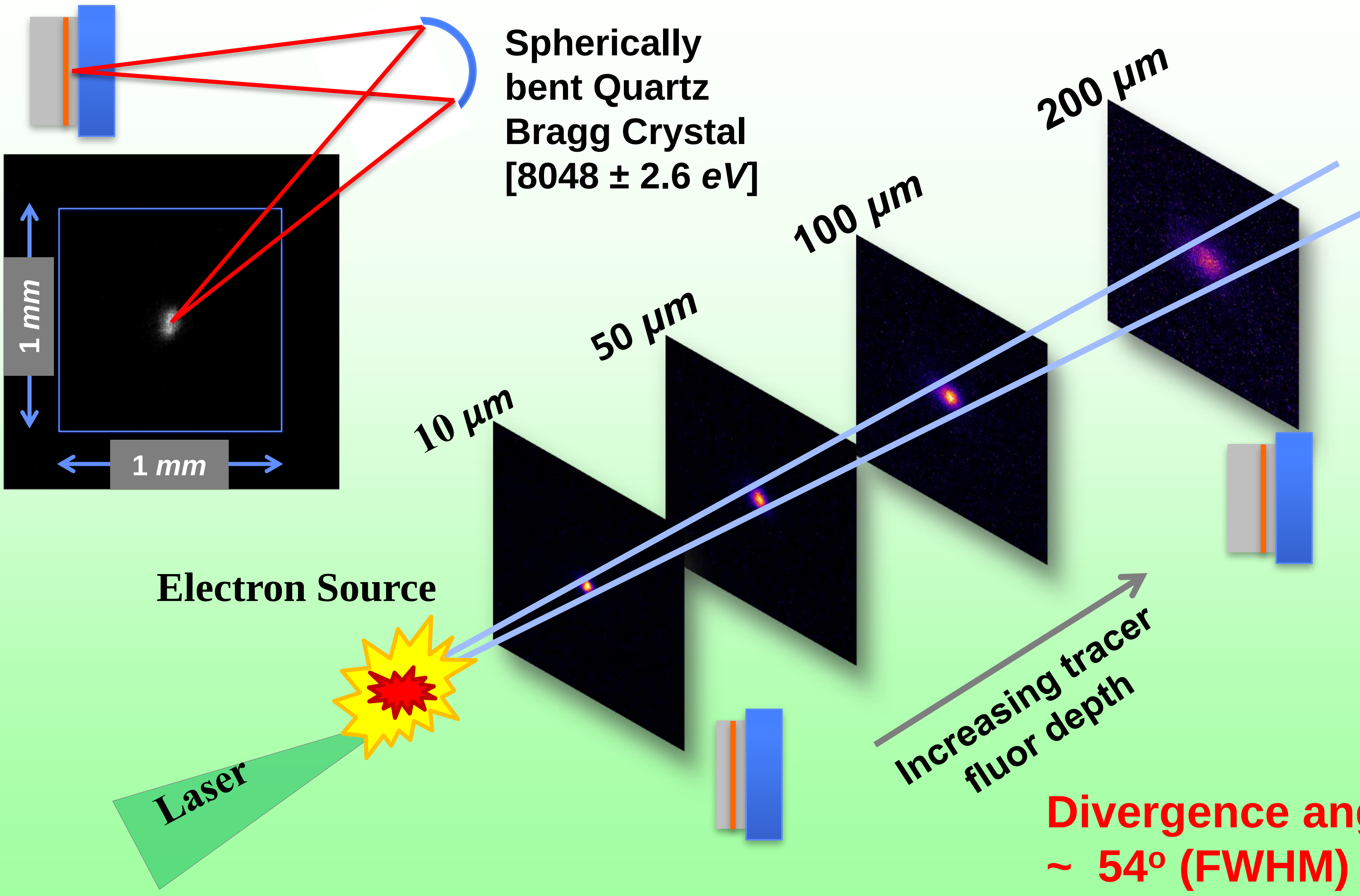
Raw X-Ray Spectrometer data for first 5 channels for 1ω light



Raw X-Ray Spectrometer data for first 5 channels for 2ω light

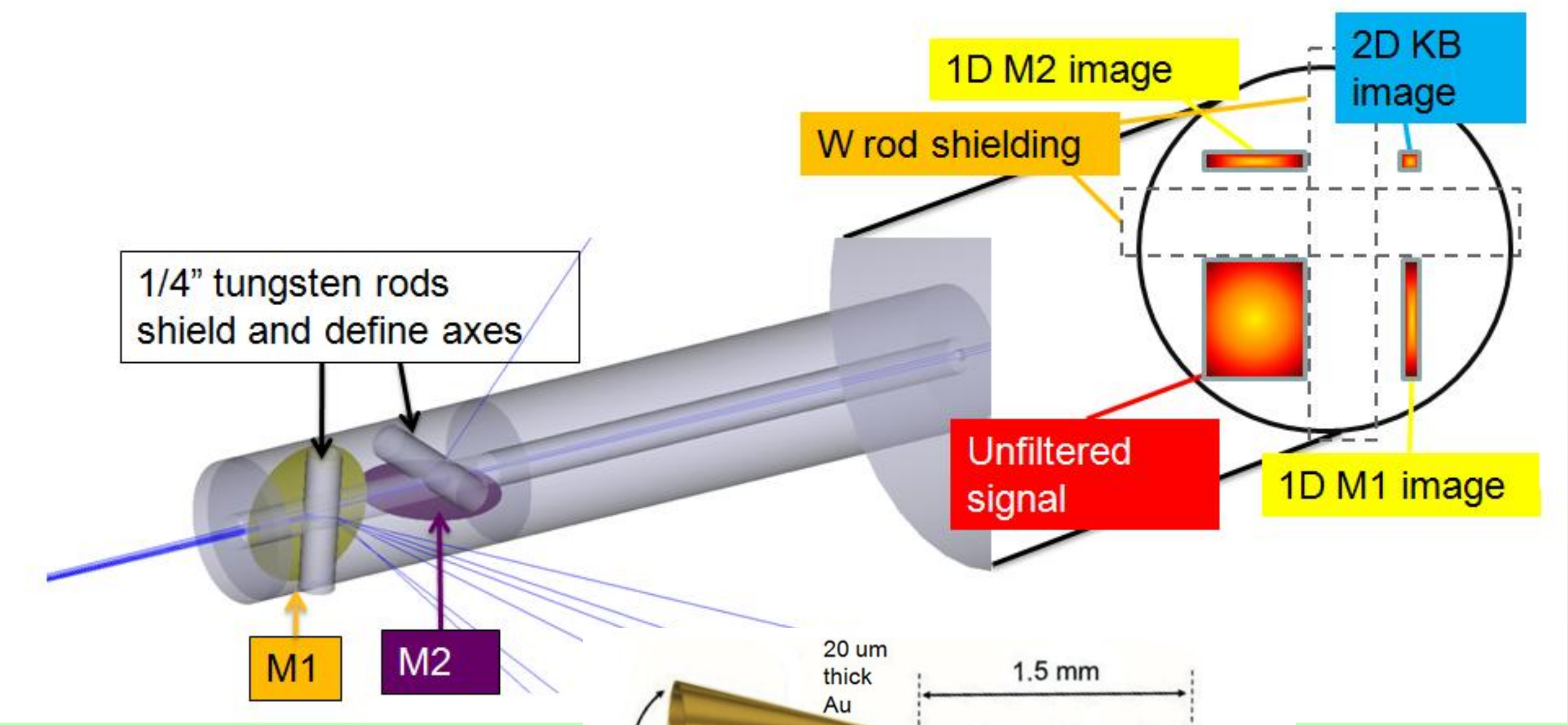


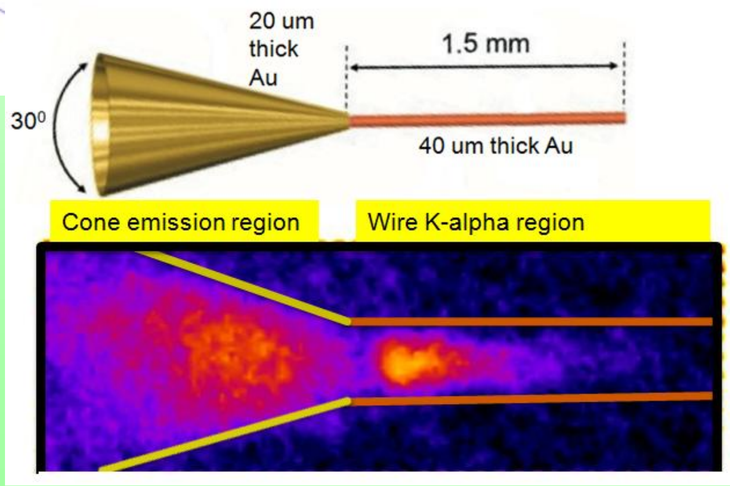
Electron Beam Divergence from Bragg Crystal Imager K_α Images



Divergence angle ~ 54^o (FWHM)

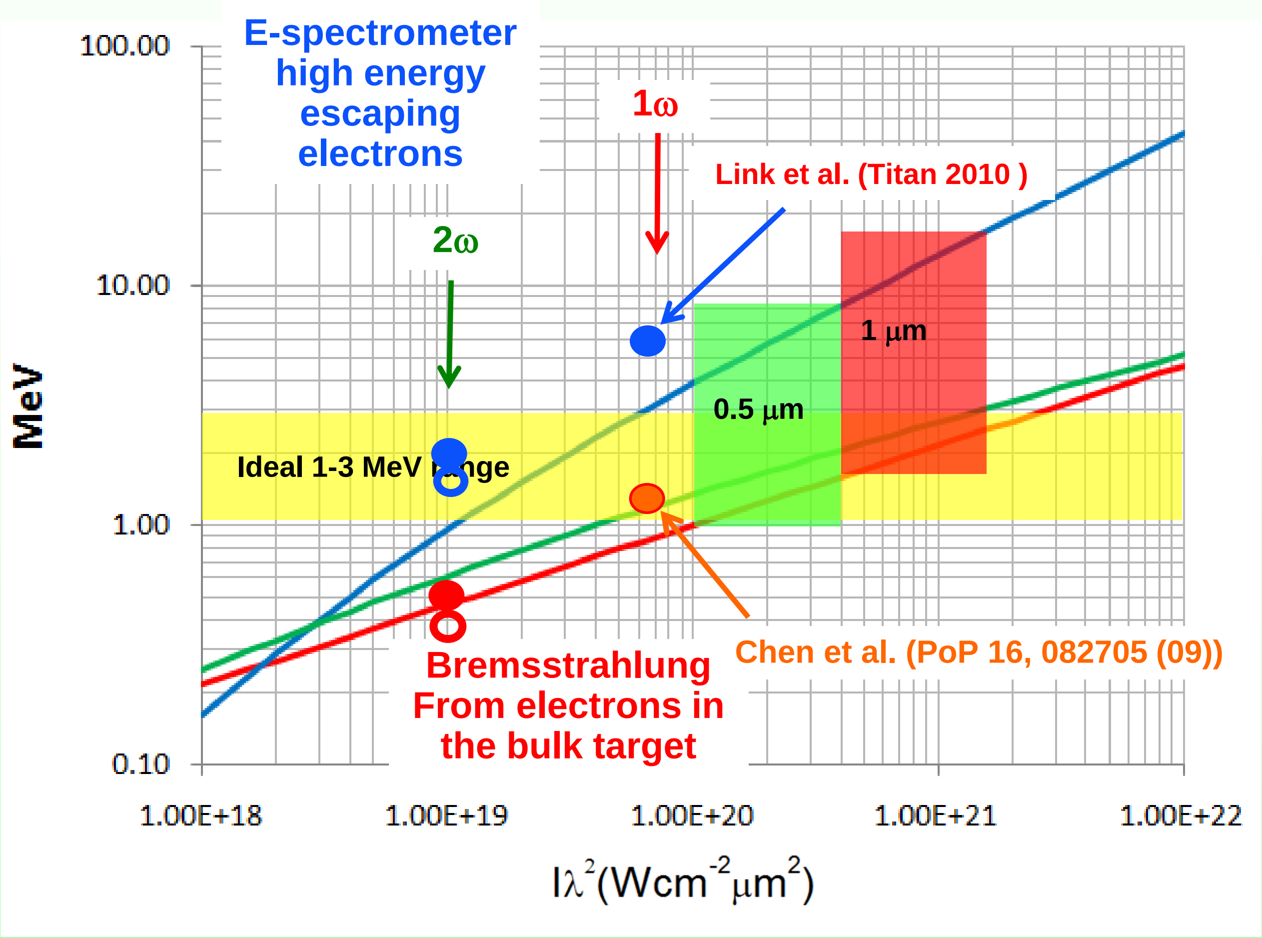
Electron Beam Divergence from Kirkpatrick-Baez 7- 9 keV X-ray Imager





Summary - Electron Energy Scaling

Experimental Results



Scaling Laws:

Wilks (Ponderomotive)
PRL 69, 1383 (1992)

Beg (Exp Bremsstrahlung)
Phys.Plasmas 4,447 (1997)

Haines (Energy/Momentum)
PRL 102, 045008 (2009)

Summary UofA FI Experiments

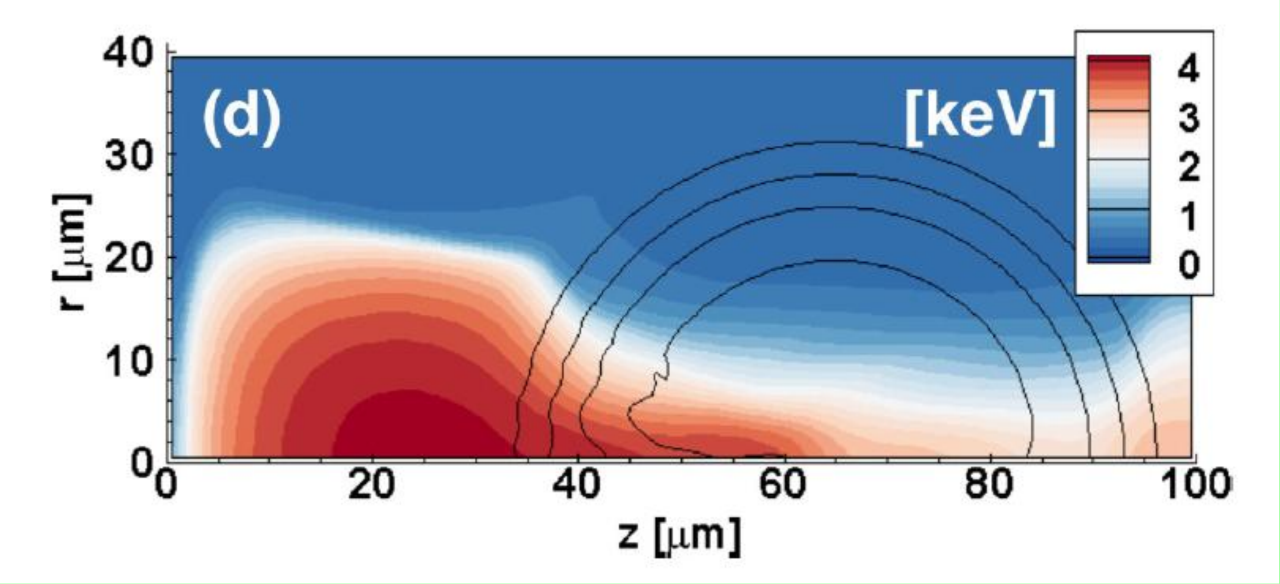
- Successful implementation of 2ω target experiments at 50J 700fs level at the TITAN facility up to 5 x 10^{19} W cm^{-2}
- 2ω Conversion efficiencies over 60% obtained, < 10 μJ pp
- Hot electron temperature scaling inside the target looks good for 2ω FI (follows Beg $(I\lambda^2)^{1/3}$ scaling)

  T_{hot} ~ 0.37 – 0.50 MeV (Bremsstrahlung)
  ~ 1.5 – 1.9 MeV (hotter escaping electrons)

- Major Issue is large electron divergence angle
  - FW ~ 120^o – 142^o Bremsstrahlung
  - FW ~ 54^o K_α imaging
- Absorption and electron yield lower than 1ω as expected for lower $I\lambda^2$ - expect to increase to >30% with higher intensities
  - η_{e-} ~ 11 – 17 %

Firex I – Predicted Electron Heating 1kJ pulse

- Simulation of 820J 1.4ps 1053nm LFEX pulse in cone target
- 1MeV temperature electron spectrum artifically introduced
- 27 % efficient electron coupling to core with perfect collimation (requires imposed magnetic field of the order of 1kT = 10 MG)
- 10% predicted with current 1kT B-field guide
- Goal to reach 5keV heating with 5kJ PW pulse



Fujioka Phys Rev E, 91, 063102, 2015

Status of Fast Ignition with Electrons

1. Conversion efficiency to energetic electrons
   - Experiments indicate 10% to 60% (various conditions)
2. Electron temperatures
   - Experiments indicate temperatures in range (2-10 MeV)
   - Requires 2nd harmonic wavelength
3. Coupling of electrons to core
   - Experiments indicate 10% – 30 % efficiency
   - not good enough

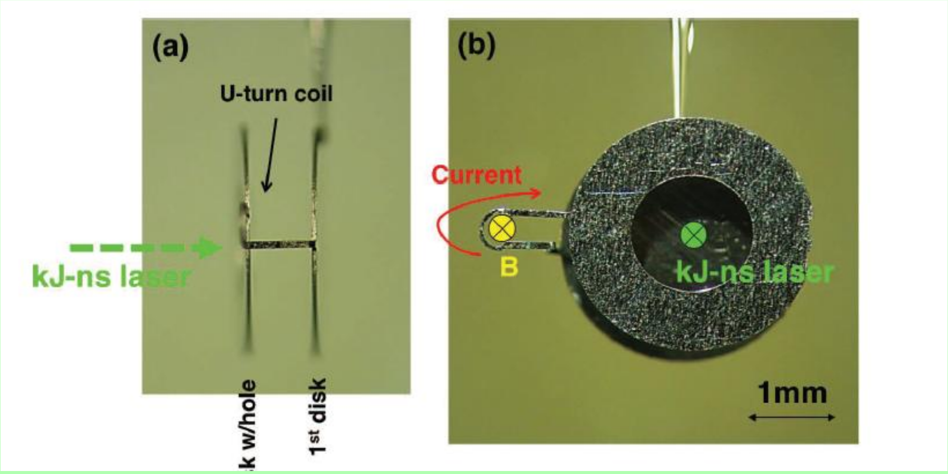
Requires enhanced magnetic guiding

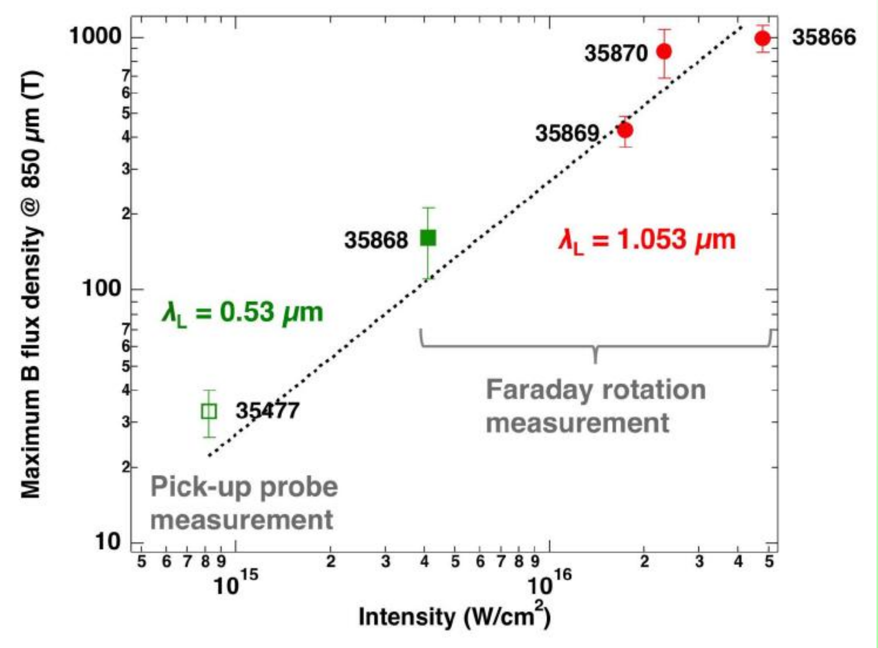
- Using magnetic fields from self driven currents
- Magnetic fields of ~10 MG required

Laser Generated Magnetic fields

Kilotesla Magnetic Field due to a Capacitor-Coil Target Driven by High Power Laser

Shinsuke Fujioka[1], Zhe Zhang[1], Kazuhiro Ishihara[1], Keisuke Shigemori[1], Youichiro Hironaka[1], Tomoyuki Johzaki[2], Atsushi Sunahara[3], Naoji Yamamoto[4], Hideki Nakashima[4], Tsuguhiro Watanabe[5], Hiroyuki Shiraga[1], Hiroaki Nishimura[1] & Hiroshi Azechi[1]

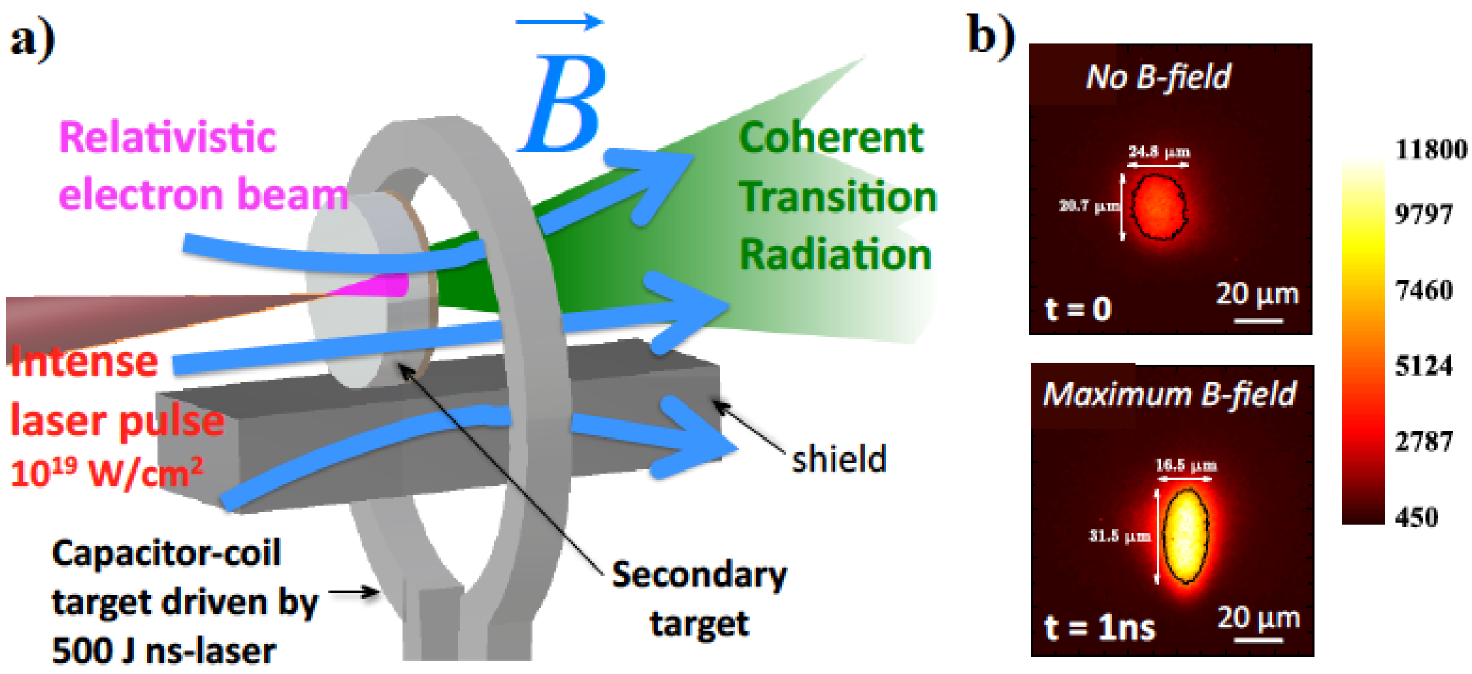




Fujioka Scientific Reports 3, 1170, 2015

Magnetic Guiding with Laser Generated Field

Factor of 2 increase in electron beam intensity with laser B-field



[1] J.J. Santos *et al.*, submitted to New J. Phys., arXiv:1503.00247.

Cylindrical Core Compressed Magnetic Field

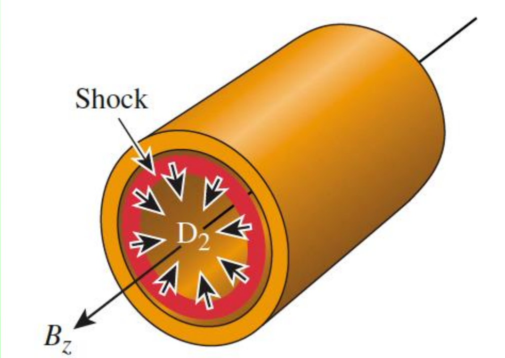
- 30 MG fields compressed with implosion core

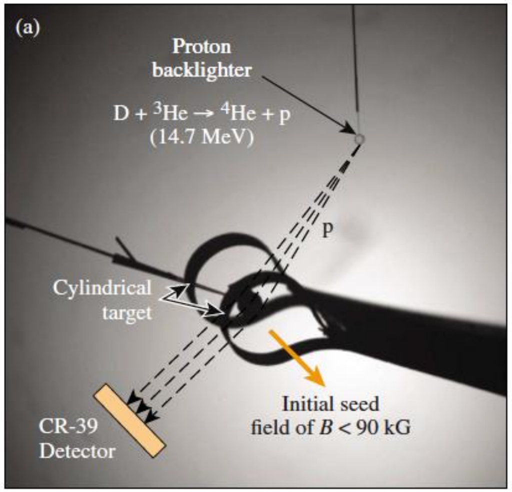
PHYSICS OF PLASMAS 17, 056318 (2010)

Compressing magnetic fields with high-energy lasers[a)]

J. P. Knauer,[1,b)] O. V. Gotchev,[1,2,3] P. Y. Chang,[1,4] D. D. Meyerhofer,[1,2,3,4] O. Polomarov,[2,3] R. Betti,[1,2,3,4] J. A. Frenje,[2,5] C. K. Li,[2,5] M. J.-E. Manuel,[2,5] R. D. Petrasso,[2,5] J. R. Rygg,[6] and F. H. Séguin[2,5]
[1]*Laboratory for Laser Energetics, University of Rochester, 250 East River Road,*

Laser Driven Cylindrical implosion





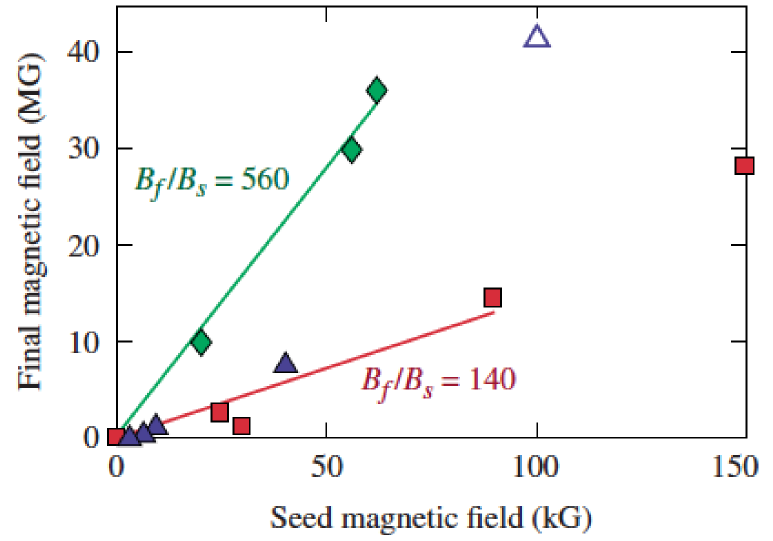


FIG. 9. (Color online) A plot of the final magnetic field vs the initial magnetic field for three different types of flux compression. The data shown by squares are from high-explosive-driven implosions. The triangles show data from electromagnetically driven implosions. Data for laser-driven implosions from this work are shown as diamonds.

Knauer, Phys. of Plasmas 17, 056318, 2010

Spherical Core Compressed Magnetic Field

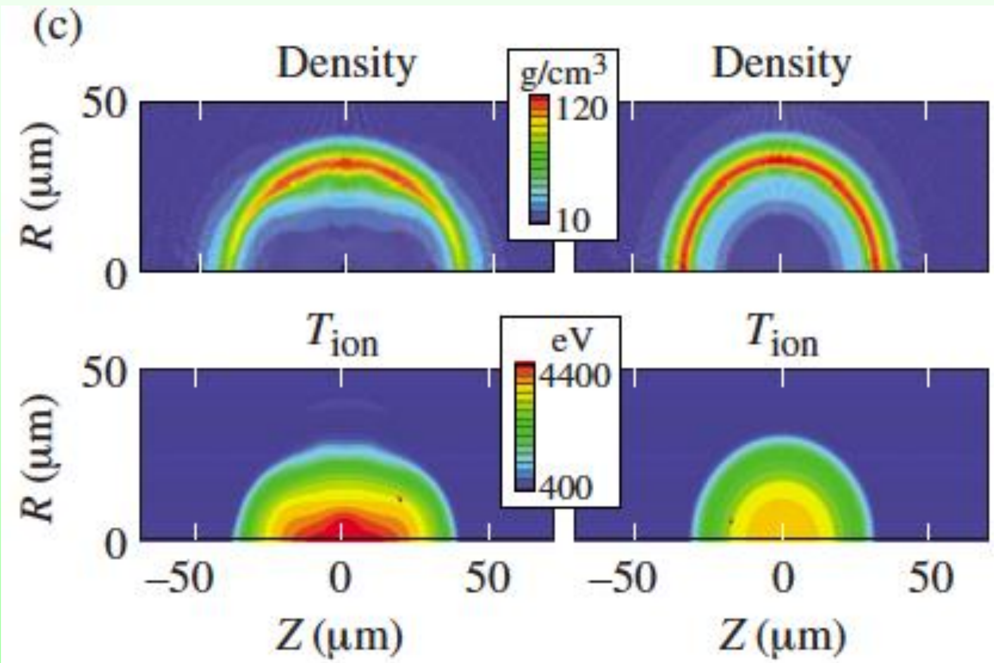
- 50-100 MG spherically compressed fields predicted

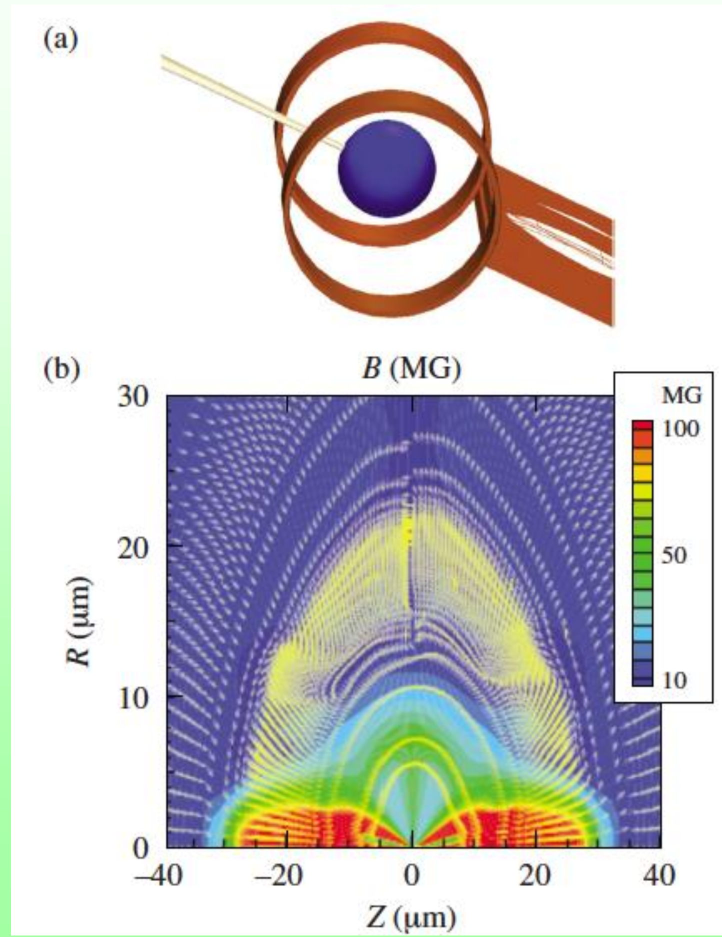
PHYSICS OF PLASMAS 17, 056318 (2010)

Compressing magnetic fields with high-energy lasers[a)]

J. P. Knauer,[1,b)] O. V. Gotchev,[1,2,3] P. Y. Chang,[1,4] D. D. Meyerhofer,[1,2,3,4] O. Polomarov,[2,3] R. Betti,[1,2,3,4] J. A. Frenje,[2,5] C. K. Li,[2,5] M. J.-E. Manuel,[2,5] R. D. Petrasso,[2,5] J. R. Rygg,[6] and F. H. Séguin[2,5]
[1]*Laboratory for Laser Energetics, University of Rochester, 250 East River Road,*

Laser Driven Spherical implosion simulation





Knauer, Phys. of Plasmas 17, 056318, 2010

B-fields Using Circular Polarization

- 7MG fields from 10^{19} W cm^{-2} in underdense plasma

VOLUME 87, NUMBER 21 PHYSICAL REVIEW LETTERS 19 NOVEMBER 2001

Measurements of the Inverse Faraday Effect from Relativistic Laser Interactions with an Underdense Plasma

Z. Najmudin,[1] M. Tatarakis,[1] A. Pukhov,[2] E. L. Clark,[1] R. J. Clarke,[3] A. E. Dangor,[1] J. Faure,[4] V. Malka,[4] D. Neely,[3] M. I. K. Santala,[1] and K. Krushelnick[1]

[1]*Imperial College of Science, Technology & Medicine, Prince Consort Road, London SW7 2BZ, United Kingdom*

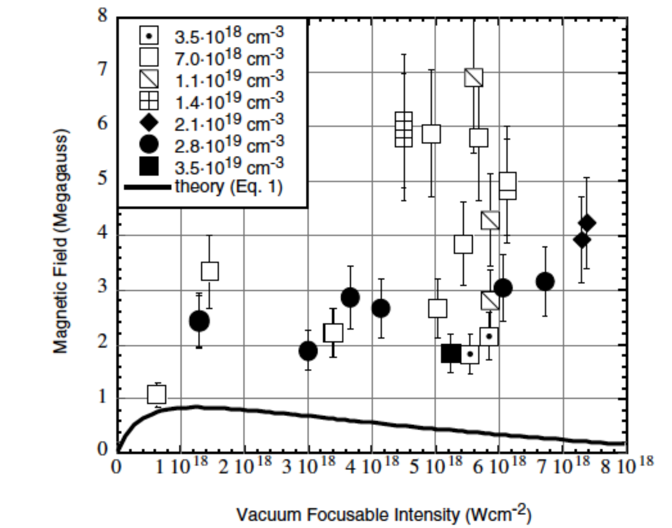


FIG. 3. Measured peak magnetic field versus "vacuum" intensity for various plasma densities (in cm^{-3}). Theoretical curve is from Ref. [8] for $n_e = 3.5 \times 10^{19}$ cm^{-3}.

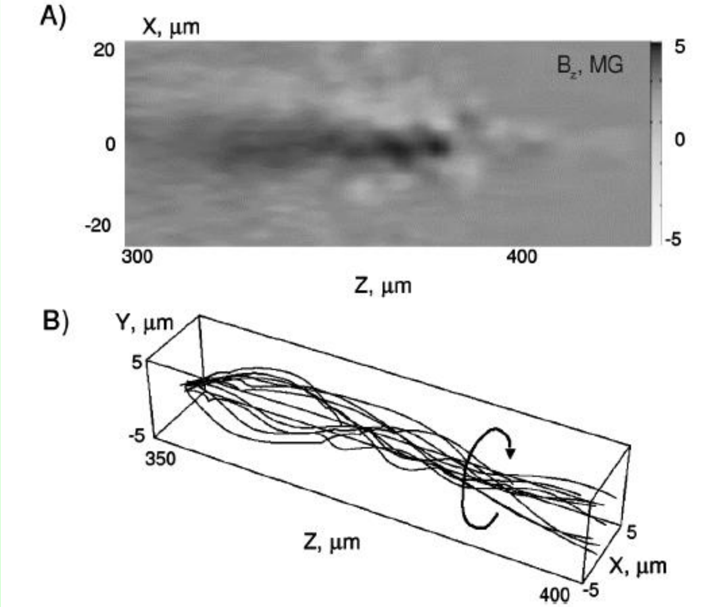


FIG. 4. 3D PIC simulation results. (A) Longitudinal cut of the generated B_z—along the laser beam. The beam has propagated 400 µm through plasma. (B) Trajectories of 10 arbitrarily chosen electrons trapped in the channel. The arrow shows the direction of circulation.

Najmudin, PRL 87, 215004 2001

Laguerre Gaussian Beams with Orbital Angular Momentum

PRL 105, 035001 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

Inverse Faraday Effect with Linearly Polarized Laser Pulses

S. Ali,[1,2,*] J. R. Davies,[1] and J. T. Mendonca[1]
[1]*Instituto de Plasmas e Fusão Nuclear—Laboratório Associado, Instituto Superior Tecnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal*

Megaauss fields predicted with Laguerre Gauss Orbital Angular Momentum Modes

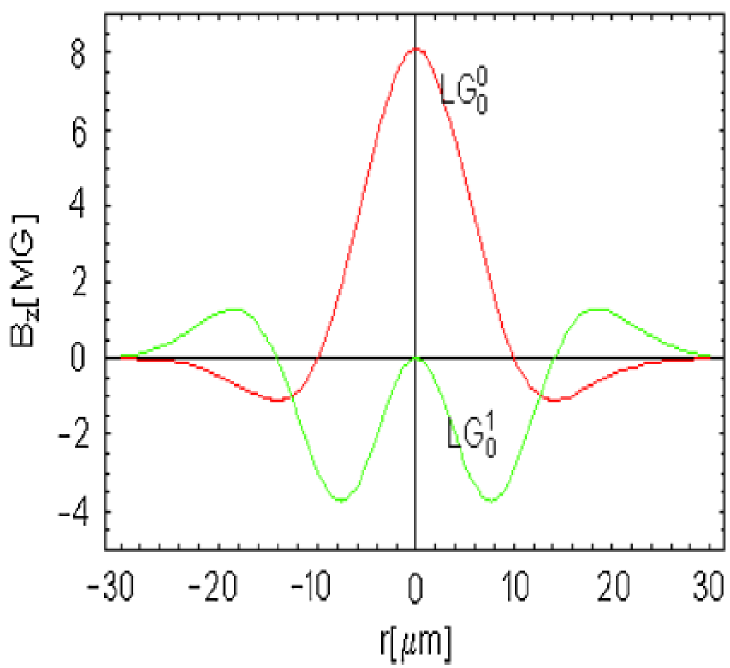


FIG. 2 (color online). The axial magnetic field B_z as a function of r with laser intensity $I_0 = 7.3 \times 10^{22}$ W m^{-2} and the LG polynomials LG_0^0 with $\sigma_z = 1$ and LG_0^1 with $\sigma_z = -1$.

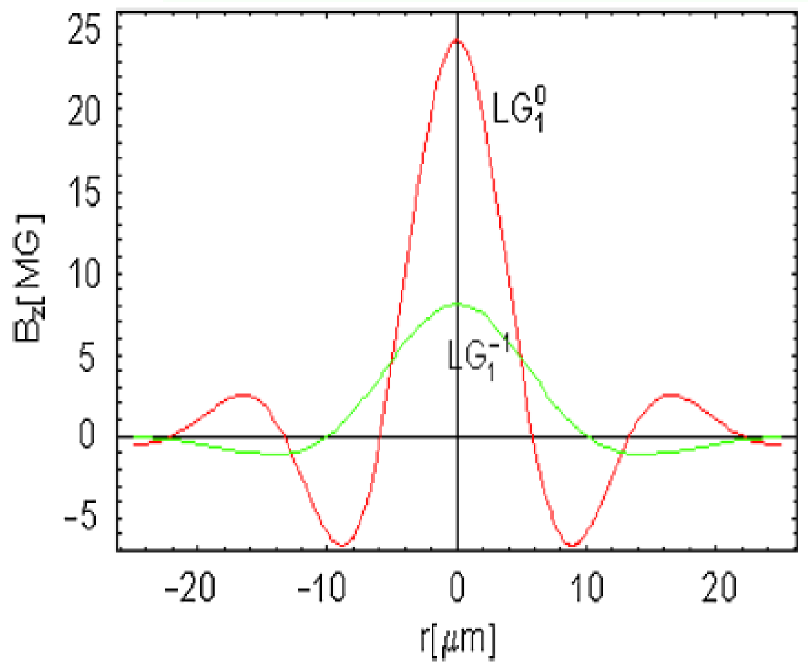
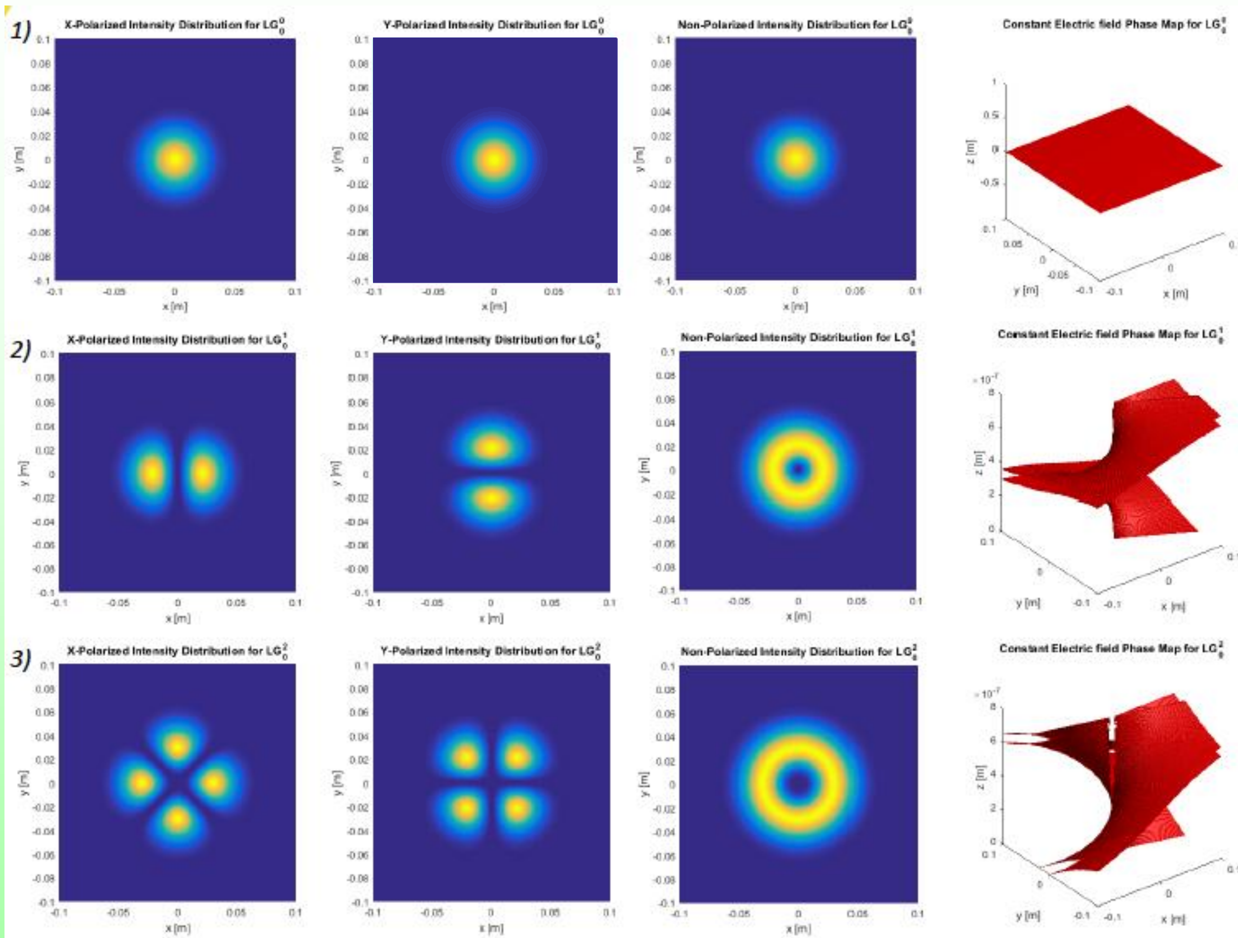


FIG. 3 (color online). The axial magnetic field B_z as a function of r with laser intensity $I_0 = 7.3 \times 10^{22}$ W m^{-2} and the LG polynomials LG_1^0 with $\sigma_z = 1$ and LG_1^{-1} with $\sigma_z = 0$.

Ali, PRL 105, 035001 (2010)

UofA PIC Simulations Starting of OAM Mode Interactions with Plasma



Longman, SLAC High Power Laser Workshop (2015)

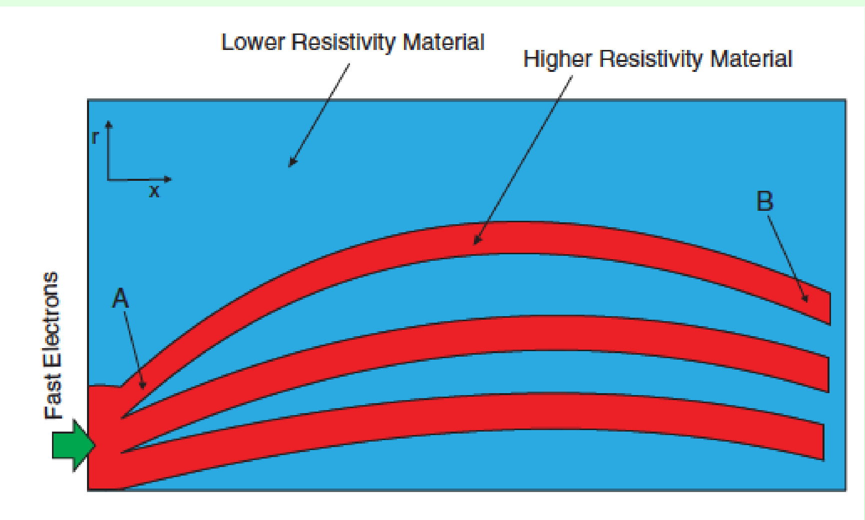
Resistive Switchyard Magnetic Guiding

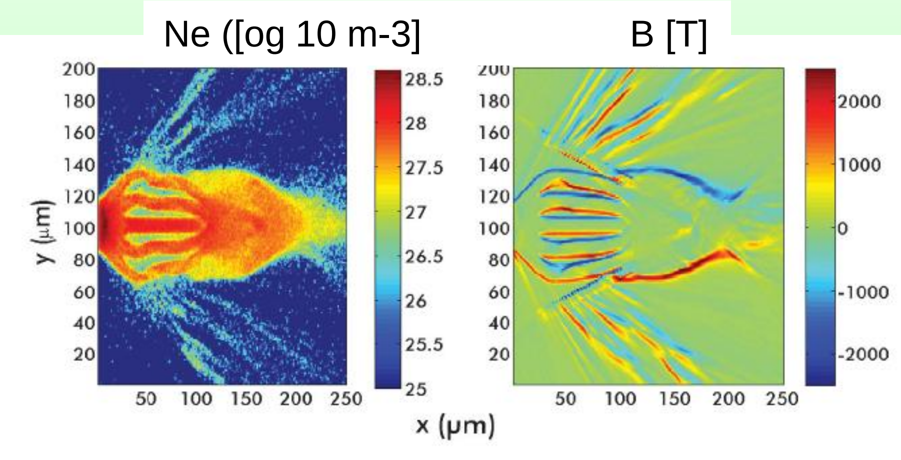
Use resistive strips generating edge magnetic fields to guide electrons – 3D PIC simulations

PRL 108, 125004 (2012) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2012

Focusing of Relativistic Electrons in Dense Plasma Using a Resistivity-Gradient-Generated Magnetic Switchyard

A. P. L Robinson,[1] M. H. Key,[2] and M. Tabak[2]
[1]*Central Laser Facility, Rutherford-Appleton Laboratory, Chilton, Oxon., OX11 0QX, United Kingdom*
[2]*Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94550, USA*
(Received 16 September 2011; published 20 March 2012)





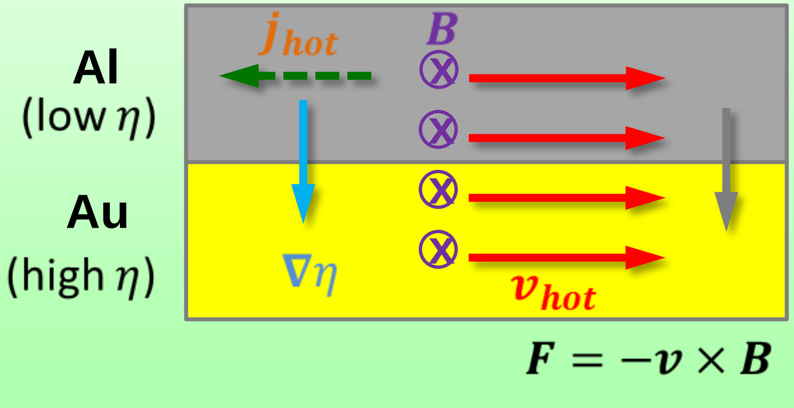
27% energy coupling from 20 kJ, 18ps laser pulse with 140 degree starting full divergence cone angle

Robinson, PRL 108, 125004 2012

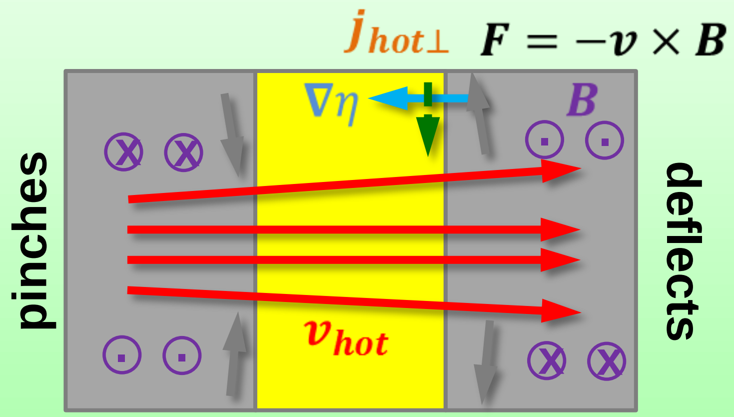
UofA Electron Guiding due to Resistivity Gradients

Electrons are guided to areas of high resistivity by the magnetic fields established by resistivity gradients (electrons bend towards regions of higher resistivity):

1. $\nabla\eta \perp \boldsymbol{v}_{hot}$



2. $\nabla\eta \parallel \boldsymbol{v}_{hot}$



UofA Electron Divergence Measurements at 527 nm

Determine scaling at 2ω for 1054 nm of hot electron generation and transport through resistive layers using the LLNL Titan laser.

Goals:

1. **Measure electron generation efficiency**
2. **Measure divergence in foil targets with buried resistive Z layer**

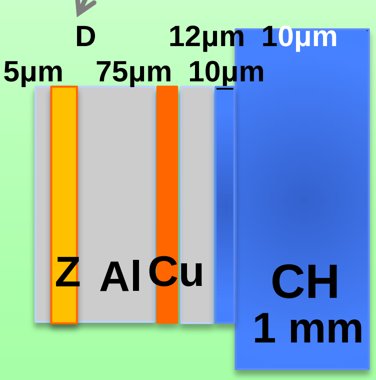
Targets

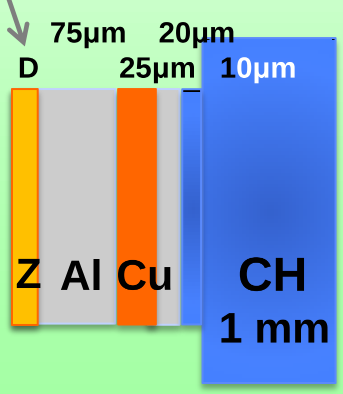
- **Buried variable Z-layers**
- **High (Au) and low (Al) Z material**

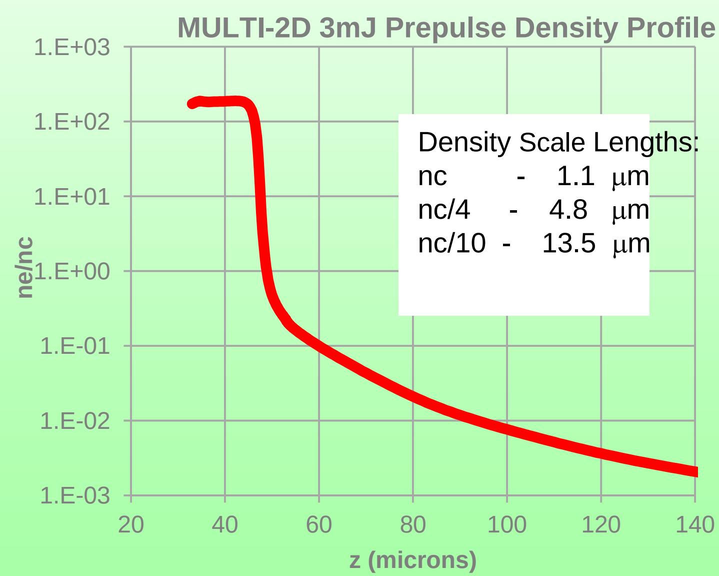
Amount of prepulse

- **~10μJ, due to 2ω conversion**
- **~3 mJ (manually injected)**

Z-layer	Thickness, D (μm)
Al (Z = 13)	25
Au (Z = 79)	10

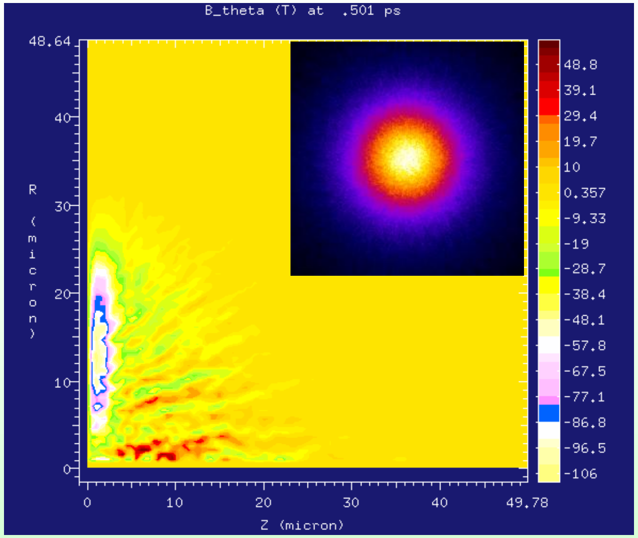




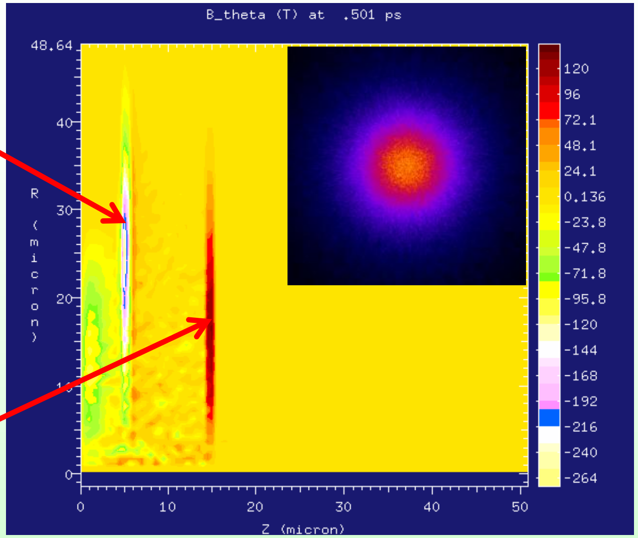


Simulation Results Show Almost Identical Al and Au Spot Sizes

Buried Al

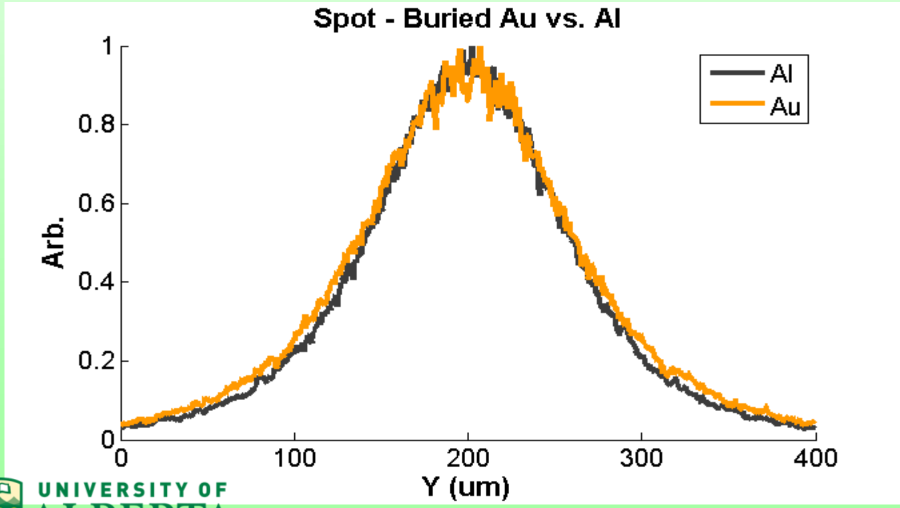


Buried Au



B-field on front Au surface

B-field on rear Au surface



Hybrid PIC modeling [1] with 540 keV temperature source and two contributions to the divergence angle [2] of 30º global and 55º local (HWHM).

1. Honrubia, PPCF 51, 014008 (2009)
2. Debayle, PRE 82, 036405 (2010)

In agreement with the experimental results

UNIVERSITY OF ALBERTA

Two pulse guiding

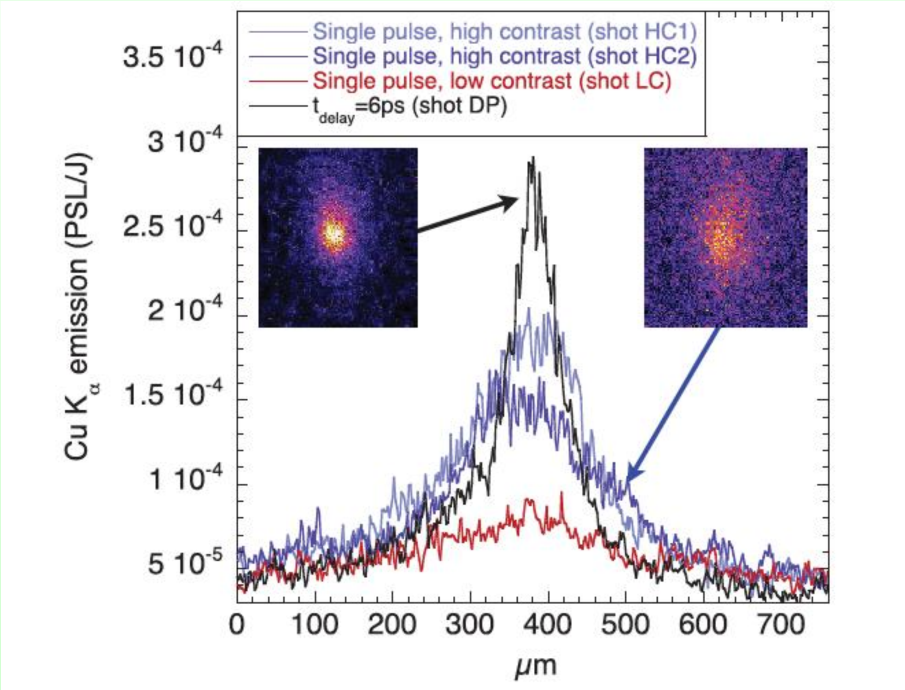
Lower intensity pulse generates an initial guiding field which is strengthened by the main second pulse

PRL **109,** 015001 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

Controlling Fast-Electron-Beam Divergence Using Two Laser Pulses

R. H. H. Scott,[1,2,*] C. Beaucourt,[3] H.-P. Schlenvoigt,[4] K. Markey,[2] K. L. Lancaster,[2] C. P. Ridgers,[5] C. M. Brenner,[6,2] J. Pasley,[7] R. J. Gray,[6] I. O. Musgrave,[2] A. P. L Robinson,[2] K. Li,[8] M. M. Notley,[2] J. R. Davies,[8] S. D. Baton,[4] J. J. Santos,[3] J.-L. Feugeas,[3] Ph. Nicolaï,[3] G. Malka,[3] V. T. Tikhonchuk,[3] P. McKenna,[6] D. Neely,[2,6] S. J. Rose,[1] and P. A. Norreys[1,2]

Peak electron flux enhanced 5x when using high contrast double pulse R = 1:10, 186J 1.4 ps, 1e20 Wcm-2



Robinson, PRL 108, 125004 2012

Three pulse guiding

Simulations show stacking more pulses improves shaping of magnetic field more

PHYSICAL REVIEW E **90**, 063108 (2014)

Controlling the fast electron divergence in a solid target with multiple laser pulses

L. Volpe,[1,2,*] J-L. Feugeas,[1] Ph. Nicolai,[1] J. J. Santos,[1] M. Touati,[1] J. Breil,[1] D. Batani,[1] and V. Tikhonchuk[1,†]
[1]*Univ. Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33405 Talence, France*
[2]*ELI-ALPS, ELI-Hu Nkft, Dugonics ter 13, Szeged 6720, Hungary*
(Received 8 June 2014; published 9 December 2014)

Peak electron flux enhanced 2x when using triple pulse versus double pulse

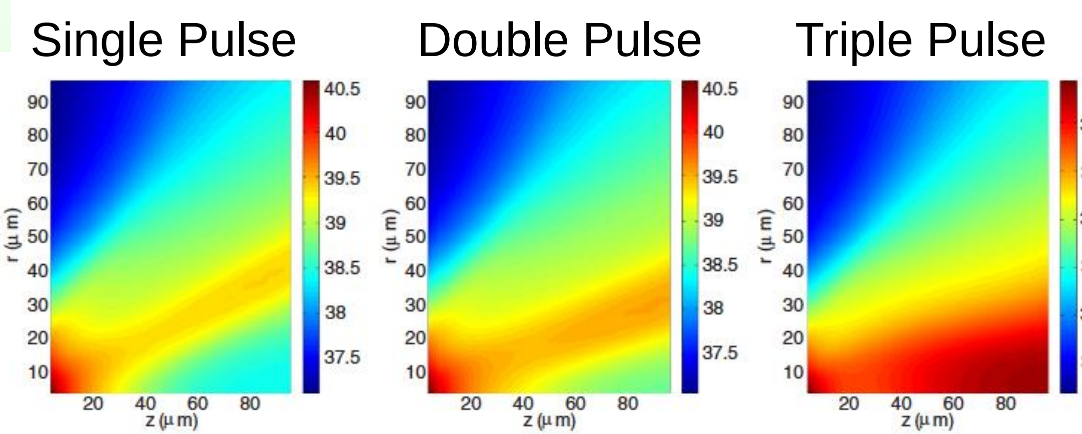


FIG. 4. (Color online) Distribution of the electron-beam density ($\log n_e$) at the end of the process for the double pulse scheme at $t = 10$ ps (case A, center) and for the triple pulses scheme at $t = 13$ ps (case B, right). In the left panel is shown the case C with the energy $E = 40$ J. Other parameters are shown in Table I.

Volpe, Phys. Rev. E 90, 063108 (2014)

Proton Fast Ignition Scaling

- Requires conversion efficiency above 10% and 10 – 20MeV Energies

VOLUME 86, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JANUARY 2001

Fast Ignition by Intense Laser-Accelerated Proton Beams

M. Roth,[1,2] T. E. Cowan,[1,3] M. H. Key,[1] S. P. Hatchett,[1] C. Brown,[1] W. Fountain,[4] J. Johnson,[4] D. M. Pennington,[1]
R. A. Snavely,[1] S. C. Wilks,[1] K. Yasuike,[5] H. Ruhl,[6] F. Pegoraro,[7] S. V. Bulanov,[8] E. M. Campbell,[1,3]
M. D. Perry,[1,3] and H. Powell[1,*]

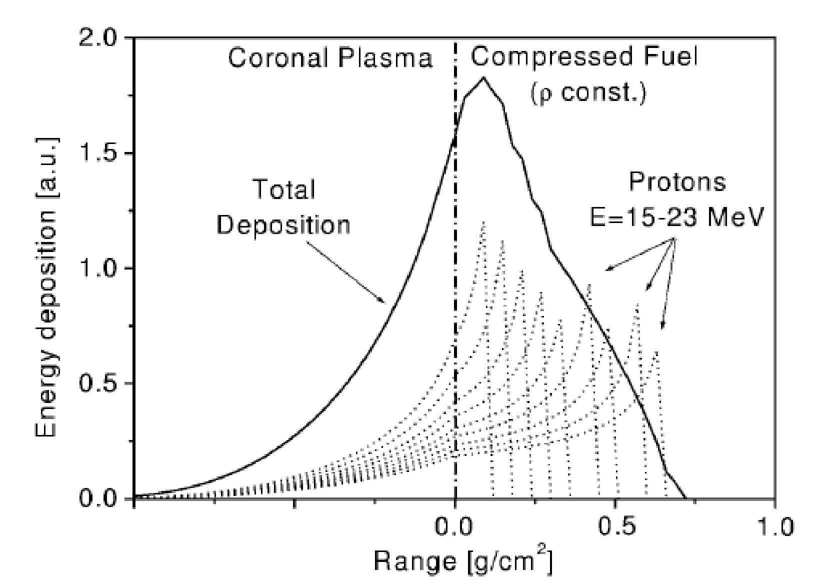


FIG. 3. Simulation of the energy deposition of protons in an isochorically compressed pellet.

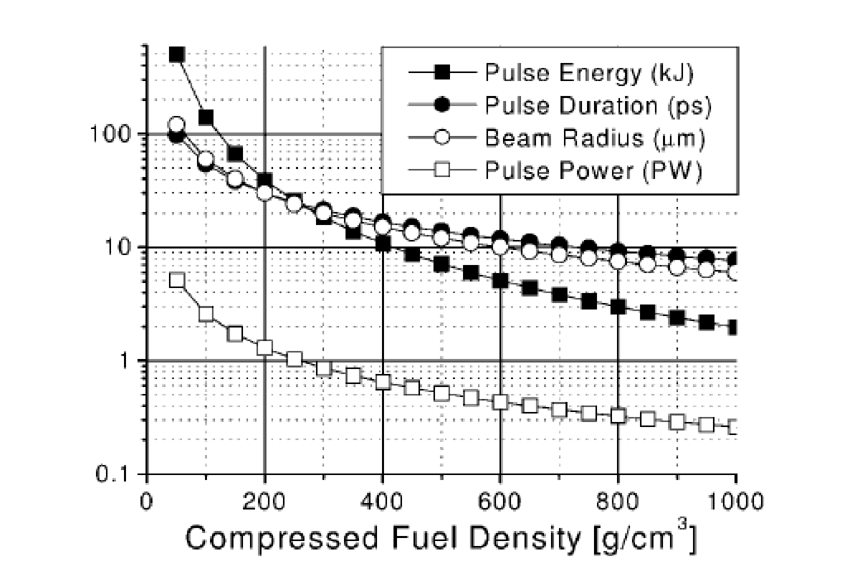


FIG. 2. Optimum parameter range for fast ignition based on 2D simulations by Atzeni.

Roth, PRL 86, 436 (2001)

10% Conversion Efficiency into Protons

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

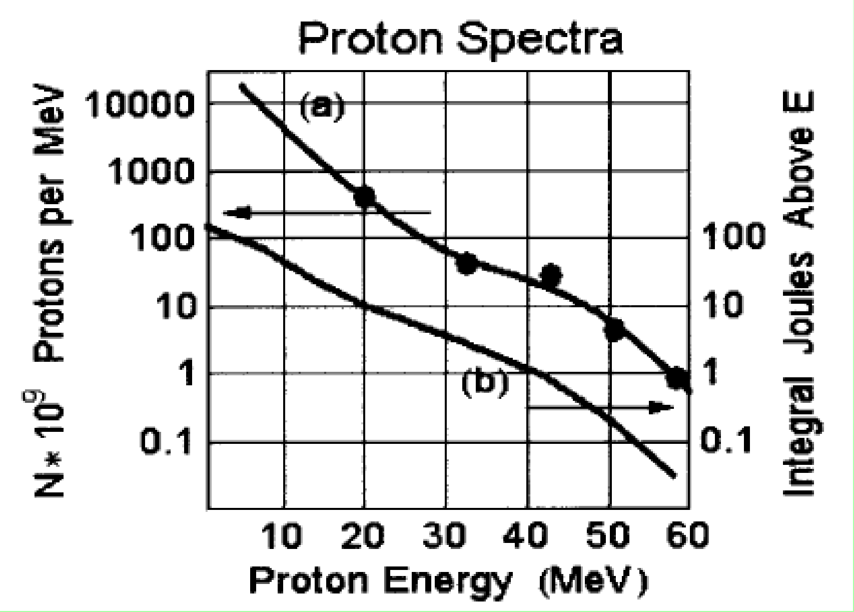
R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

[1]*Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94550*
[2]*Department of Physics, University of California, Davis, Davis, California 95616*
[3]*GSI Laboratory, Darmstadt, Germany*
[4]*University of Alberta, Edmonton, Alberta, Canada T6G 2G7*
[5]*ILE, Osaka University, Suita, Osaka 565, Japan*
[6]*George C. Marshall Space Flight Center, Huntsville, Alabama 35812*

(Received 19 January 2000)

An intense collimated beam of high-energy protons is emitted normal to the rear surface of thin solid targets irradiated at 1 PW power and peak intensity 3×10^{20} W cm^{-2}. Up to 48 J (12%) of the laser energy is transferred to 2×10^{13} protons of energy >10 MeV. The energy spectrum exhibits a sharp high-energy cutoff as high as 58 MeV on the axis of the beam which decreases in energy with increasing off axis angle. Proton induced nuclear processes have been observed and used to characterize the beam.

- High energy pulses were able to generate ~10% conversion efficiency



Snavely, PRL 85, 2945 (2000)

Two pulse proton Enhancement Markey

- 2 pulse irradiation helps proton generation efficiency

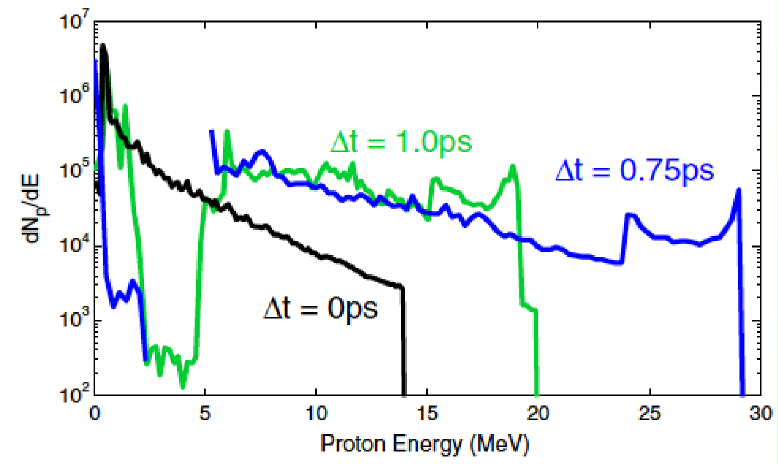
PRL **105,** 195008 (2010) PHYSICAL REVIEW LETTERS week ending 5 NOVEMBER 2010

Spectral Enhancement in the Double Pulse Regime of Laser Proton Acceleration

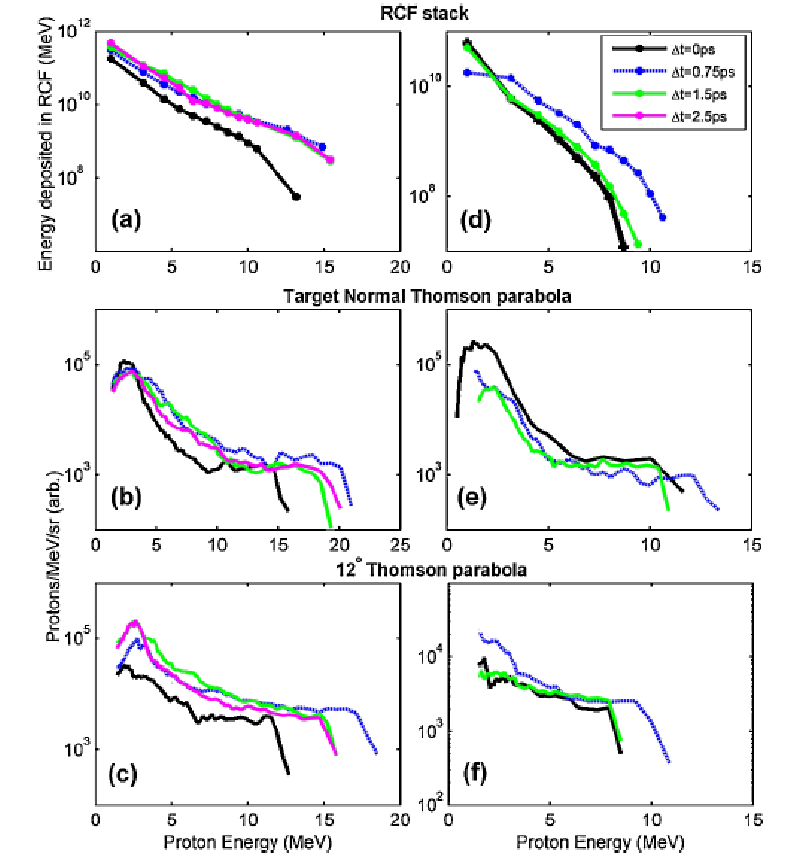
K. Markey,[1,2,*] P. McKenna,[3] C. M. Brenner,[3,1] D. C. Carroll,[3] M. M. Günther,[4] K. Harres,[4] S. Kar,[2] K. Lancaster,[1] F. Nürnberg,[4] M. N. Quinn,[3] A. P. L. Robinson,[1] M. Roth,[4] M. Zepf,[2] and D. Neely[1]
[1]*Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[2]*School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*
[3]*SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom*
[4]*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstrasse 9, 64289 Darmstadt, Germany*

Peak proton energy and proton generation efficiency enhanced by prepulse on the order of 1ps in advance

Simulations show a similar effect



R = 1:10 R = 4:10



Markey, PRL 105, 195008 (2010)

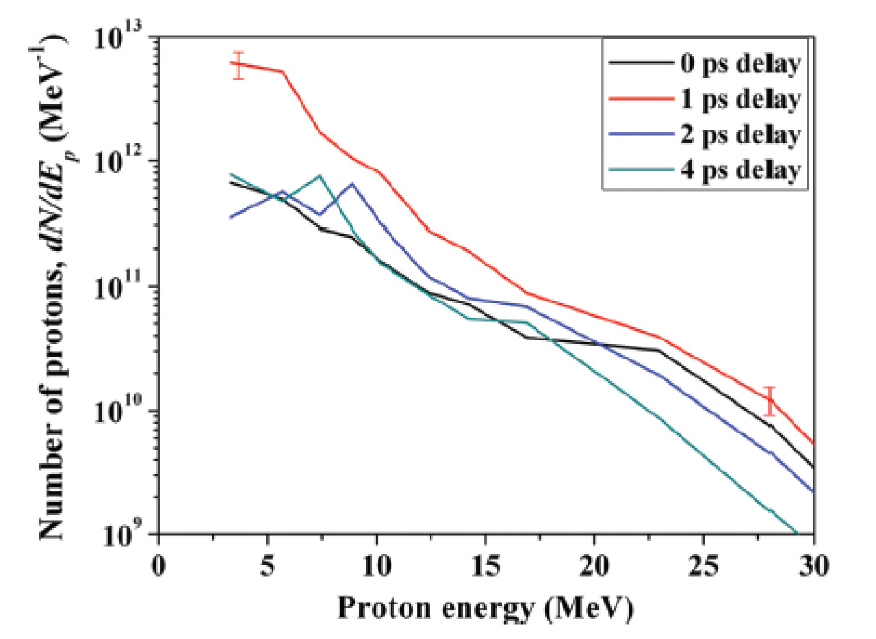
Record 15% proton generation efficiency with 2 pulse irradiation

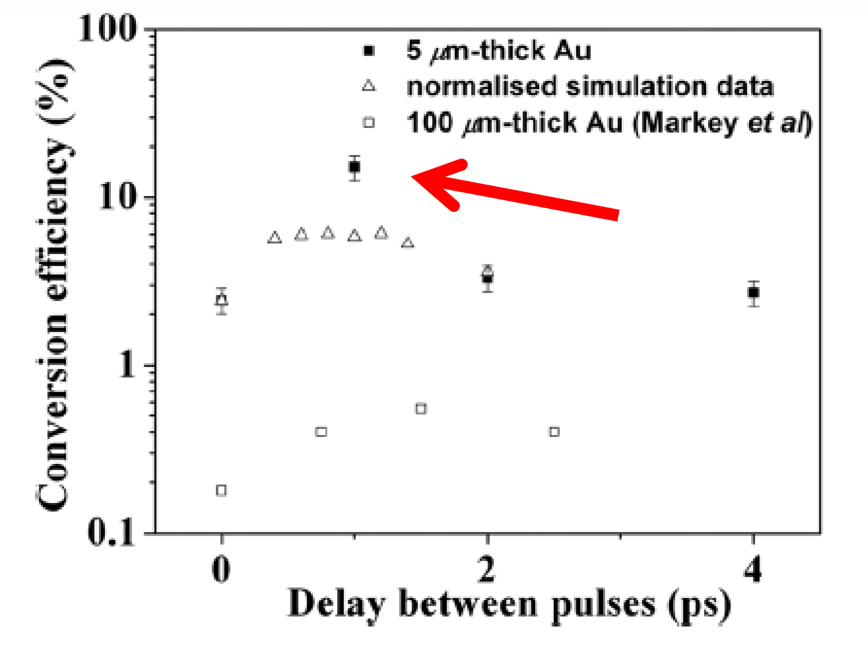
- Optimized 2 pulse conditions give 15% proton generation efficiency

APPLIED PHYSICS LETTERS 104, 081123 (2014)

High energy conversion efficiency in laser-proton acceleration by controlling laser-energy deposition onto thin foil targets

C. M. Brenner,[1,2] A. P. L. Robinson,[2] K. Markey,[2] R. H. H. Scott,[2] R. J. Gray,[1] M. Rosinski,[3] O. Deppert,[4] J. Badziak,[3] D. Batani,[5] J. R. Davies,[6] S. M. Hassan,[7] K. L. Lancaster,[2] K. Li,[8] I. O. Musgrave,[2] P. A. Norreys,[2,9] J. Pasley,[10,2] M. Roth,[11] H.-P. Schlenvoigt,[12] C. Spindloe,[2] M. Tatarakis,[7] T. Winstone,[2] J. Wolowski,[3] D. Wyatt,[2] P. McKenna,[1] and D. Neely[2]





Brenner, APL 104, 081123 (2014)

Demonstration of 50 micron focussing

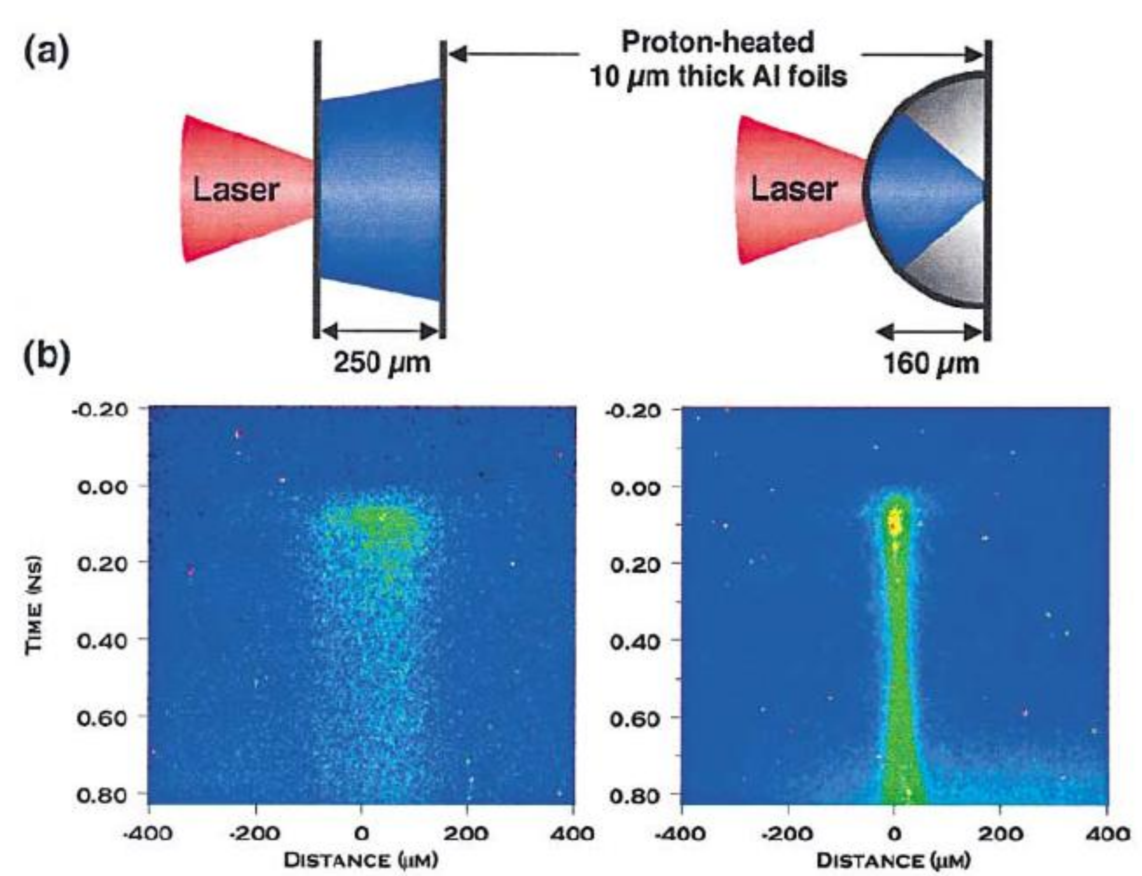
VOLUME 91, NUMBER 12 PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2003

Isochoric Heating of Solid-Density Matter with an Ultrafast Proton Beam

P. K. Patel,[1] A. J. Mackinnon,[1] M. H. Key,[1] T. E. Cowan,[2] M. E. Foord,[1] M. Allen,[1] D. F. Price,[1] H. Ruhl,[2] P.T. Springer,[1] and R. Stephens[3]

[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Department of Physics/220, University of Nevada-Reno, Reno, Nevada 89507, USA*
[3]*General Atomics, P.O. Box 85608, San Diego, California 92186, USA*

50 micron ballistic focal spot demonstrated

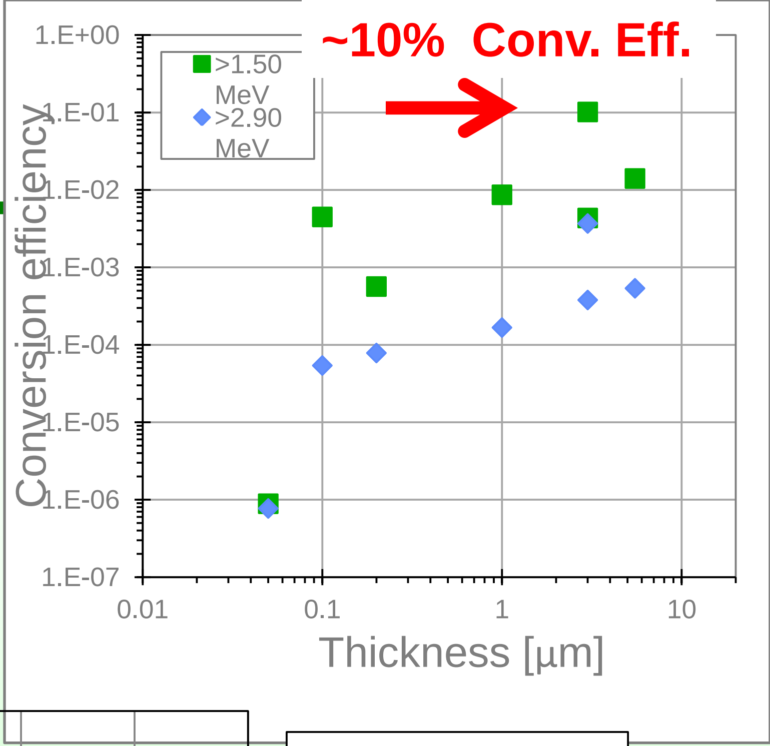


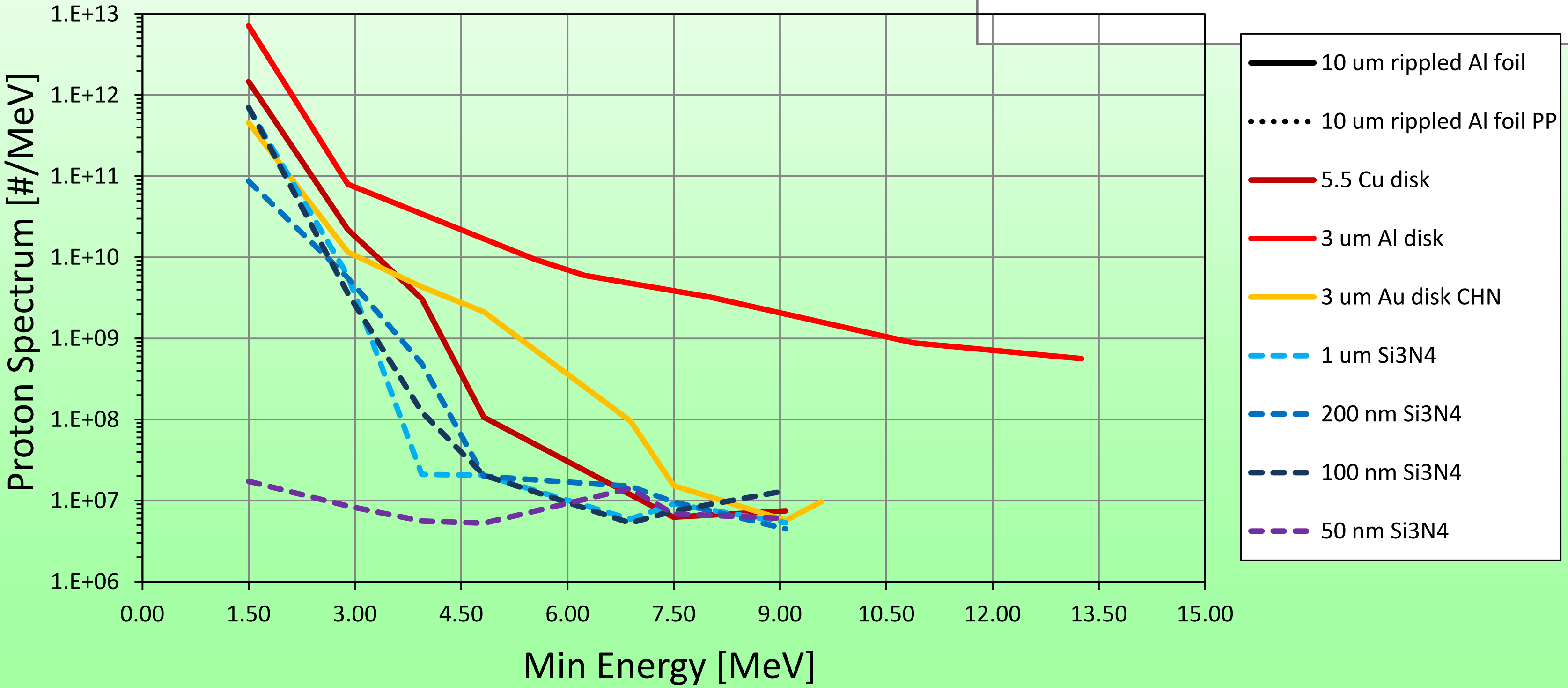
Patel, PRL 91, 125004 (2003)

UofA Proton Results

- **Max energy and conversion efficiency very high for one shot where there may have been a double pulse**

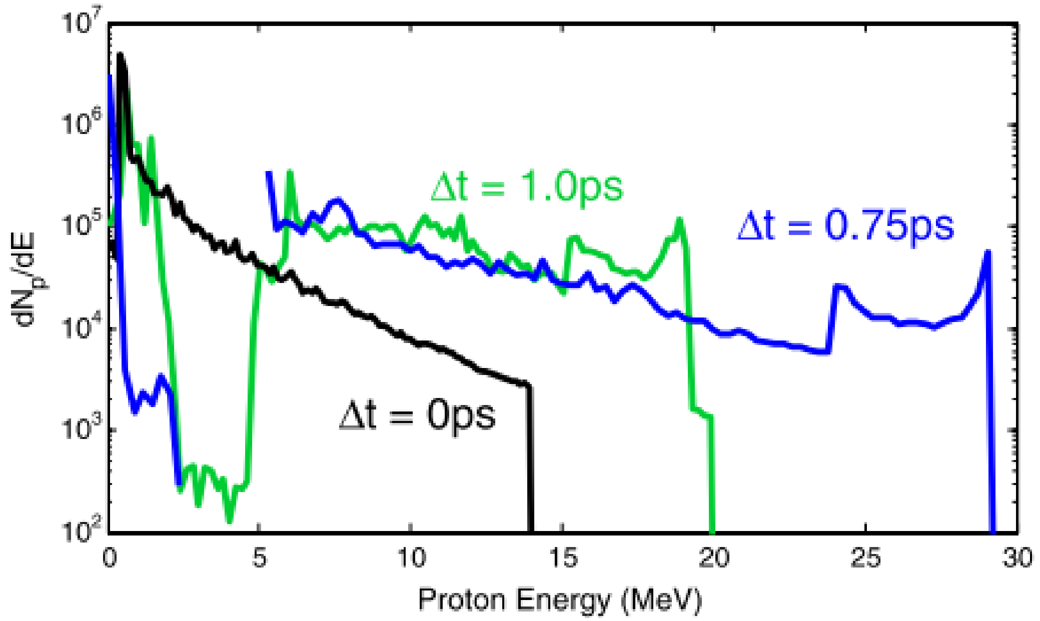
Analysis by Chris McGuffey UCSD



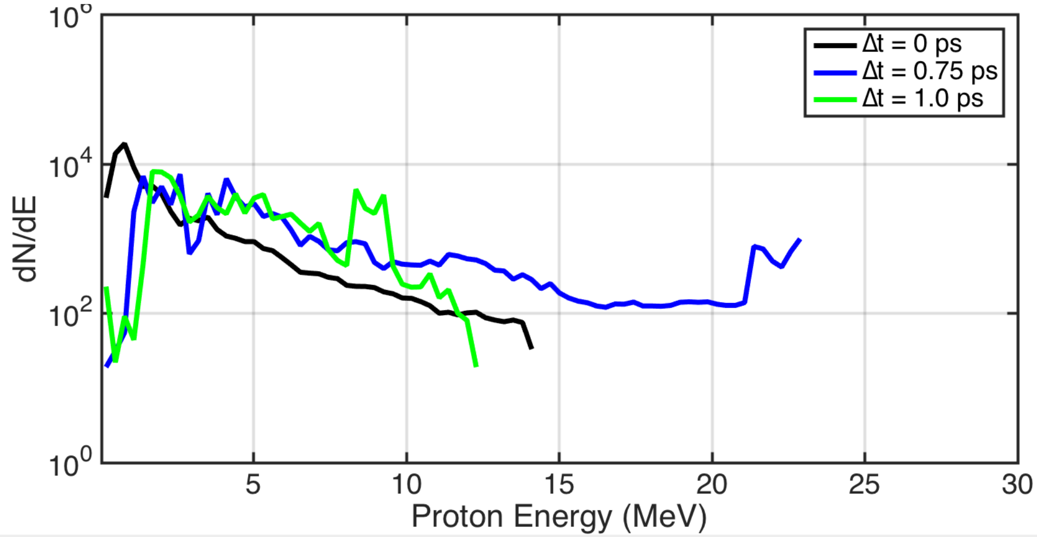


University of Alberta 2 Pulse Simulations

Markey



UofA



Initial University of Alberta Particle in Cell Simulations starting to reproduce some of the features of the 2 pulse simulations from Markey

Fast Ignition Challenges

Fast Ignition

- Conversion efficiency good: 20-30% expected
- Electron Temperature good using second harmonic wavelength (70% optical conversion efficiency expected from 1ω to 2ω)
- Coupling to compressed core plasma a critical issue – will require magnetic guiding schemes:
  - Embedded and compressed fields (Rochester)
  - Laser driven external fields (ILE)
  - Resistive gradient guide fields (Rutherford)
  - Orbital/Circular angular moment modes (UofA)

The Way Forward

NIF Indirect Drive Status

- Neutron yield of ~10^{16} obtained to date
- 20kJ fusion energy yield from 10kJ heating energy into ignition spot
- Alpha heating demonstrated
- Need double the energy into the ignition spot to achieve ignition and burn
- Hope to achieve Ignition in the next several years

Rochester Direct Drive Status

- University of Rochester Laboratory for Laser Energetics (LLE) is the lead lab for direct drive in world
  - 30kJ symmetric implosions at 0.35 μm
  - Conducting polar direct drive experiments at NIF at 1 MJ level
- Best neutron yield of 2 x 10^{13} obtained to date
- Scaled ITFX parameter of 0.24 achieved
  - Working on improving fuel compression from

    hot spot ρR = 0.2 g cm $^{-2}$ to 0.3 g cm $^{-2}$ required
  - Fuel preheat from hot electrons from laser plasma
  - Rayleigh Taylor Instability and fuel mix
- Will improve conditions using:
  - Variable Z layer targets to reduce hot electrons and fuel preheat
  - Smoother targets

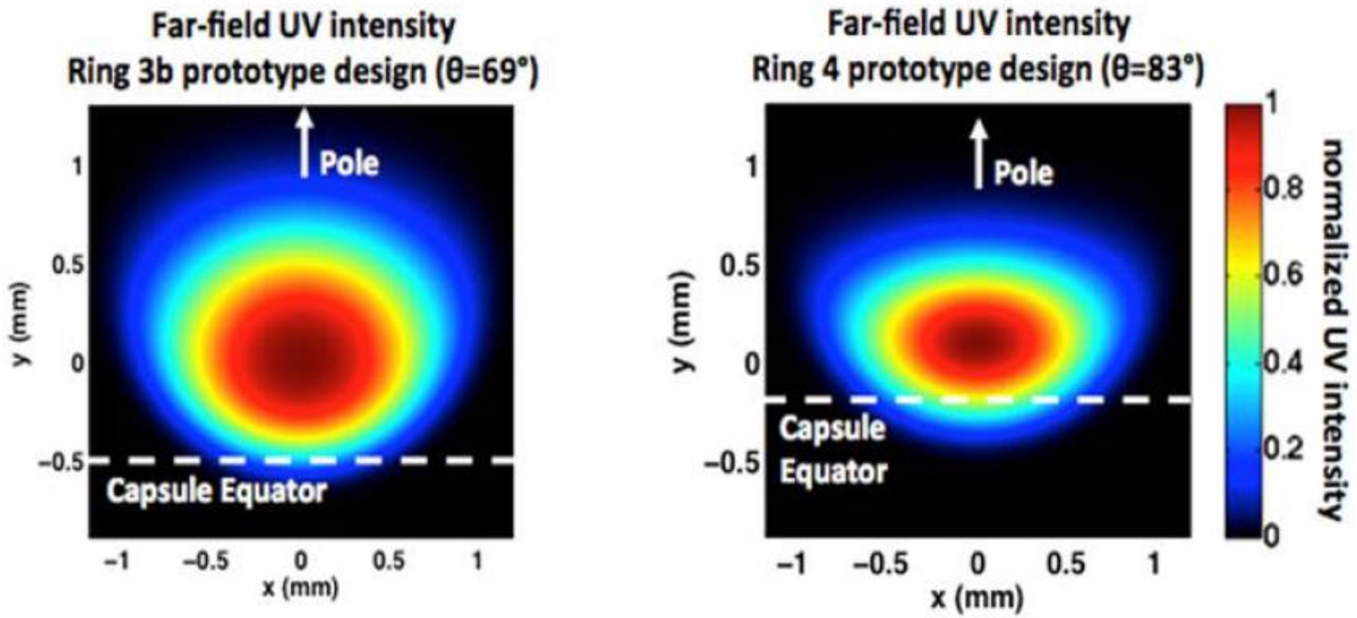
Polar direct Drive on NIF

Planning for more uniform irradiation Polar Direct Drive Experiments is under way at Rochester and LLNL with design of phase plates to give uniform energy absopriotn of the beam

National Ignition Facility & Photon Science

Shaping NIF's Beams for Direct-Drive Experiments

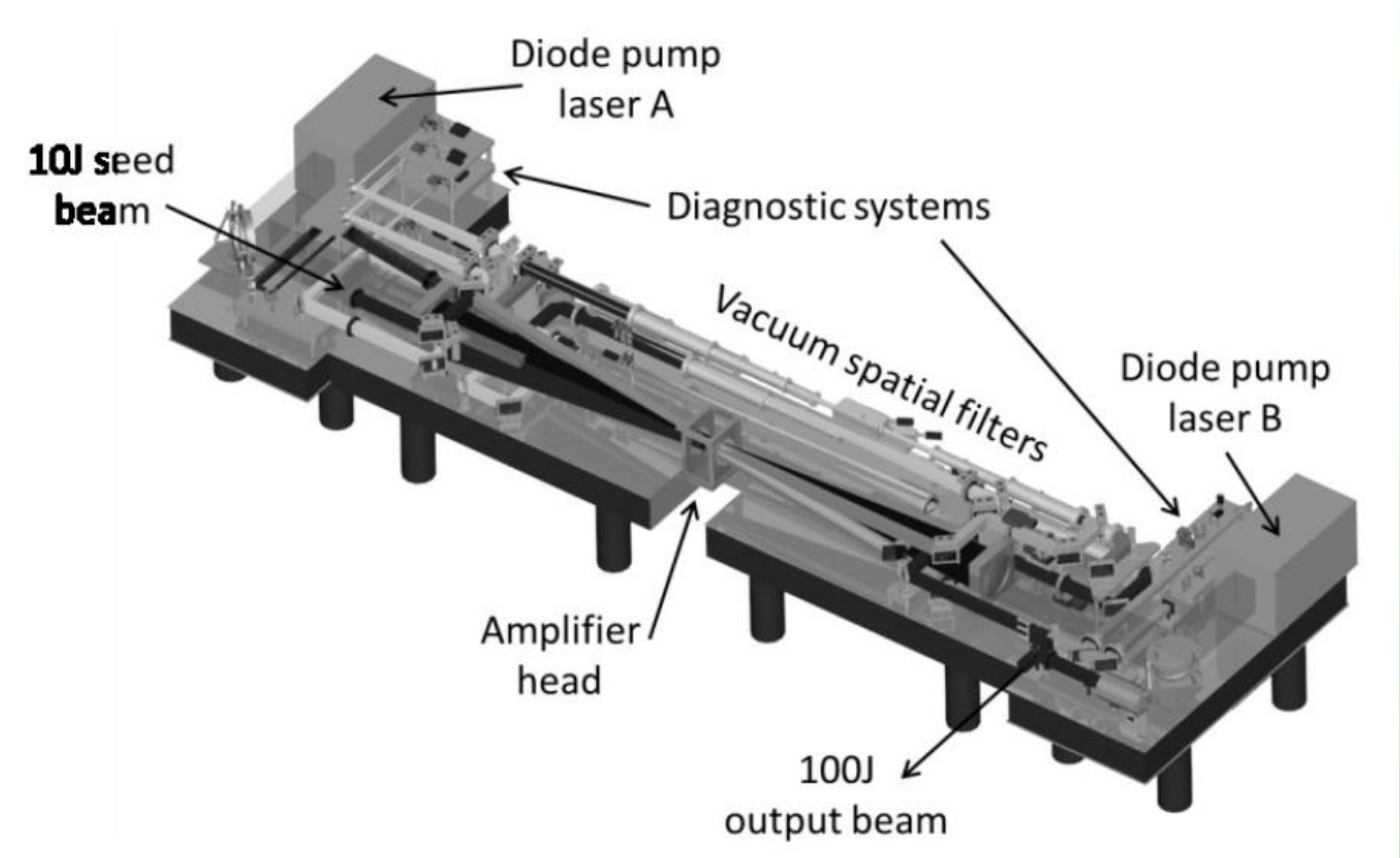
In a partnership with the Laboratory for Laser Energetics (LLE) at the University of Rochester, NIF researchers have been making important advances in the design and production of beam-shaping continuous phase plates (CPPs) for direct-drive inertial confinement fusion (ICF) experiments.



The two images above display two different phase plate spot profiles that are designed to irradiate different parts of the target. The phase plate on the left is incident onto the target at 69°, and the one on the right is incident onto the target at 83° (closer to the target equator, as indicated by the white dashed line). Near the equator, the phase plates are

Pump Lasers Being Scaled up to kJ Level

- Rutherford Appleton Central Laser facility DiPOLE100 100J 10 Hz Pump Laser



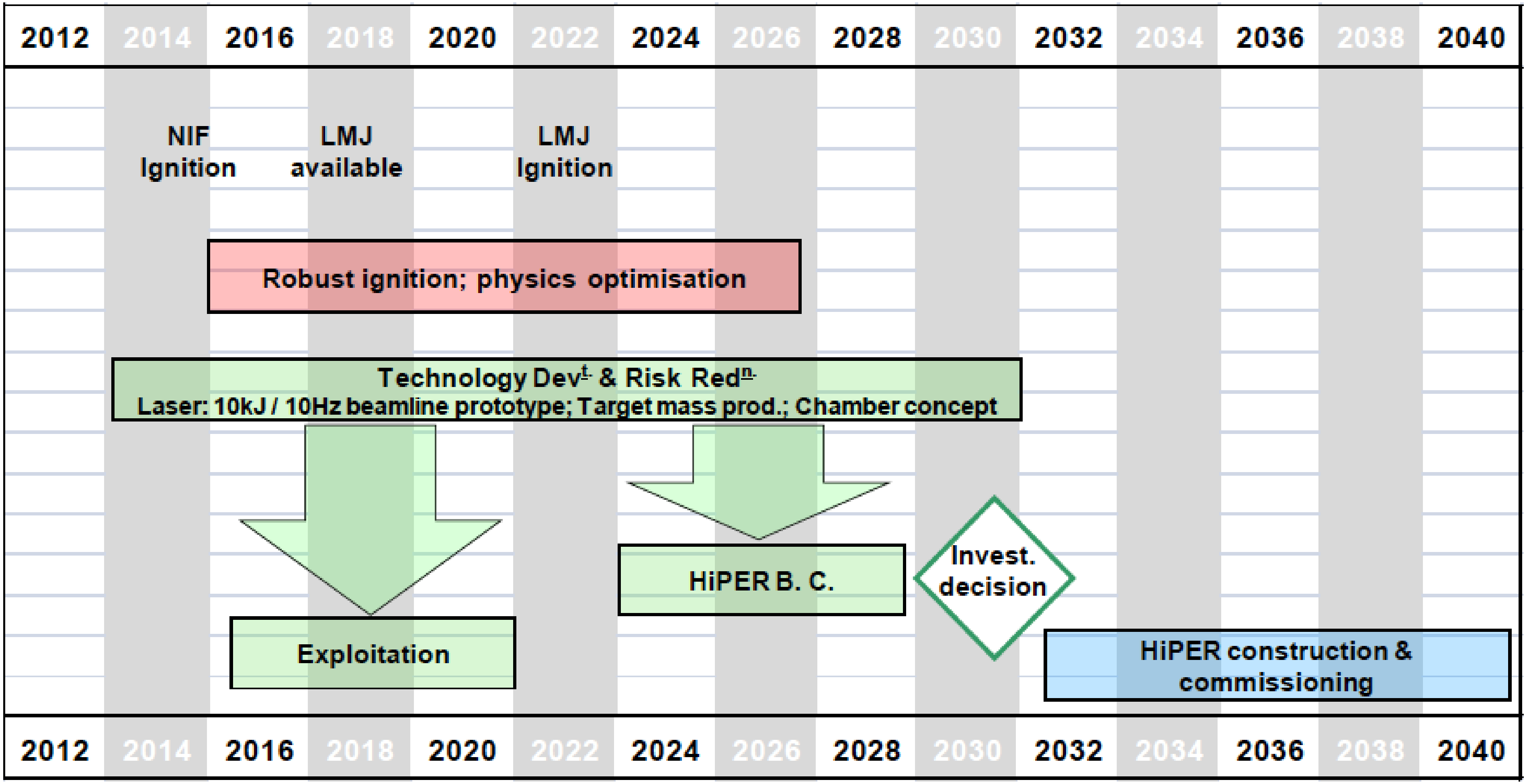
Mason ICUIL 2014

The Way Forward

- Must finish the job of reaching ignition
- Must finish investigating the scaling of advanced ignition techniques
- Many options need to be explored
- Start developing support technologies
- Must develop comprehensive 3D modeling simulations of integrated system interactions
- U of A investigating scaling issues for advanced ignition conditions

European Road Map

- 2013 European Roadmap developed for IFE



Role for Canada

- Establish Fusion Energy R&D programs
  - Carry out critical assessment of best routes to Fusion Energy
  - Start developing critical mass of expertise by collaborating with international partners
  - Develop a balanced program in chosen routes to Fusion Energy
  - Develop detailed modeling capabilities
  - Start R&D programs in critical technology elements for future reactor systems (magnetic systems, heating technologies, lasers, optics, materials, targets, tritium handling, etc.)

Role for Alberta

Establish Laser Fusion Energy R&D program

- ABCtech reported on status of Fusion Energy to Alberta Government in 2014 (http://abctech.ca/energy-distribution)
- Identified Laser Fusion as most rapidly advancing approach at present
- Recommend a Laser Fusion based R & D program

STATUS OF FUSION ENERGY

Impact & Opportunity for Alberta

Volume I

Summary

Prepared by

Alberta Council of Technologies

Alberta/Canada Fusion Energy Program

March 2014
ALBERTA COUNCIL OF TECHNOLOGIES

Gratefully acknowledges the support of:

Alberta Energy

Stantec Corporation

University of Alberta

Alberta/Canada Fusion Energy Advisory Committee

Gary Albach	Nathan Armstrong
Brian Baudais	Will Bridge
Robert Fedosejevs	Peter Hackett
Chris Holly	Jerry Keller
Brian Kryska	Axel Meisen
Rob Pitcairn	Klaas Rodenburg
John Rose	Glenn Stowkowy
Martin Truksa	Gary Woloshyniuk
Perry Kinkaide	Allan Offenberger

A special thank you is extended to the institutions (identified in this report) that were visited and to the many persons who so graciously hosted our site visits, provided the briefing material presented in this status report and thereby assisted our fusion assessment.

Report Authors

Allan Offenberger
Robert Fedosejevs
Klaas Rodenburg
Perry Kinkaide

Contact:

Dr. Perry Kinkaide pkinkaide@shaw.ca 780-990-5874
Dr. Allan Offenberger aao@ece.ualberta.ca 780-483-1740

STATUS OF FUSION ENERGY

Impact & Opportunity for Alberta

Volume II

Appendices

Prepared by

Alberta Council of Technologies

Alberta/Canada Fusion Energy Program

Conclusions

- Laser Fusion Energy Breakeven could possibly be demonstrated some time between 2016 to 2020
- Fusion energy will significantly change the energy supply equation and eventually Canada’s role as an energy leader in the world
- USA, Europe and Japan have plans for next stage engineering demo reactors on the shelf
- Canada should be prepared for this game changing development
- We need to start preparing now for this future
- There is much to do and more resources are required

43rd IEEE International Conference on Plasma Science,
June 19-23, 2016, Banff, Alberta, Canada

The International Conference on Plasma Science (ICOPS) is an annual conference coordinated by the Plasma Science and Application Committee (PSAC) of the IEEE Nuclear Plasma Sciences Society. The program of the 43rd ICOPS covers both traditional areas of plasma science and new areas of growth. The conference offers an outstanding forum for scientists and engineers to learn some of the greatest advances in plasma science and technology in recent years and to discuss future directions.

Sponsors

Questions and Discussion?

Thank You

NIF Low Adiabat Scaling and Alpha Heating

PERFORMANCE OF INDIRECTLY-DRIVEN CAPSULE IMPLOSIONS ON NIF USING ADIABAT-SHAPING*

H.F. Robey[1], V.A. Smalyuk[1], J.L. Milovich[1], T. Döppner[1], B. Bachmann[1], K.L. Baker[1], L.F. Berzak Hopkins[1], E. Bond[1], J.A. Caggiano[1], D.A. Callahan[1], D.T. Casey[1], P.M. Celliers[1], C. Cerjan[1], D.S. Clark[1], S.N. Dixit[1], M.J. Edwards[1], N. Gharibyan[1], E. Giraldez[2], S.W. Haan[1], B.A. Hammel[1], A.V. Hamza[1], R. Hatarik[1], M. Hohenberger[3], D. Hoover[2], O.A. Hurricane[1], K.S. Jancaitis[1], M. Gatu Johnson[4], O.S. Jones[1], J.J. Kroll[1], K.N. Lafortune[1], O.L. Landen[1], T. Ma[1], B.J. MacGowan[1], A.G. MacPhee[1], A. Nikroo[2], A. Pak[1], P.K. Patel[1], J.L. Peterson[1], D.B. Sayre[1], S.M. Sepke[1], B.K. Spears[1], C.R. Weber[1], C.C. Widmayer[1], and C. Yeamans[1]

Robey, IFSA 2015

OVERVIEW OF PROGRESS AND FUTURE PROSPECTS IN INDIRECT DRIVE IMPLOSIONS ON THE NATIONAL IGNITION FACILITY

O. A. Hurricane[1]
[1]Lawrence Livermore National Laboratory, Livermore, CA, USA

Hurricane, IFSA 2015

- Neutron Yields of 10^{16} achieved
- Alpha fusion heating observed
- Core pressures measured up to P = 150-230 Gbar
- Close to required pressure P =300-400 Gbar