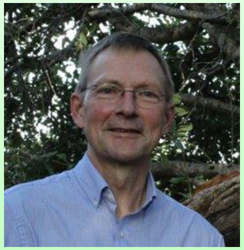
Laser Inertial Confinement Fusion Advanced Ignition Techniques

R. Fedosejevs



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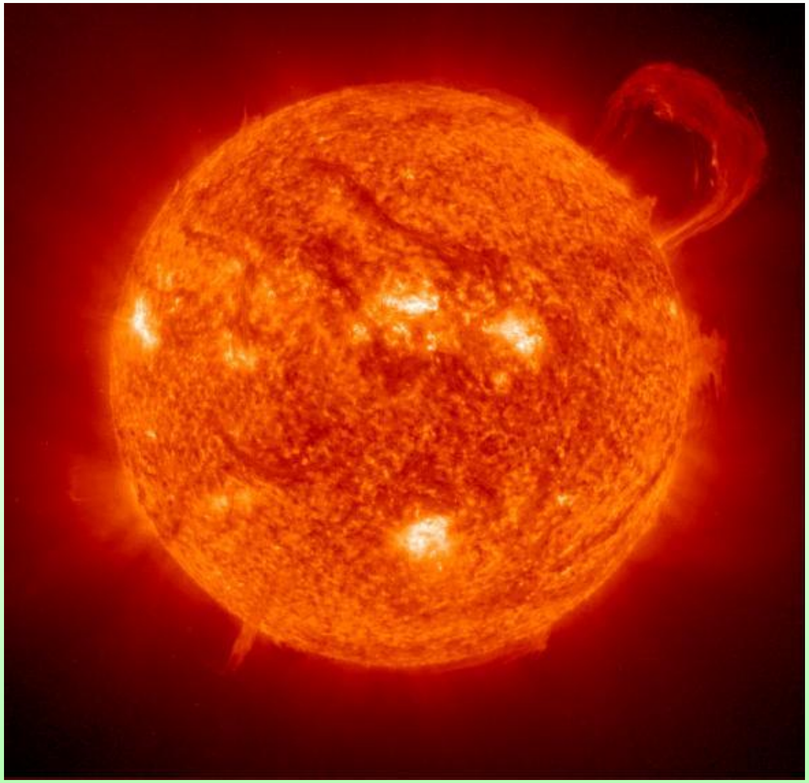
Oshawa, August 30, 2013

Overview

- Introduction to Laser Fusion Energy
- Advanced Ignition Techniques
  - Fast Ignition
  - Shock Ignition
- Status and Issues
- Our Recent Experiments on Fast Ignition and Shock Ignition
- The Way Forward
- Conclusions

Fusion Energy - Bringing the Sun to Earth



The Ultimate Energy Source

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

Deuterium Based Fusion

Reaction: Fuel	Reaction: Product	Ignition Temperature (millions of °C)	Ignition Temperature (keV)	Output Energy (keV)
D + T	^4He + n	220	20	17,600
D + ^3He	^4He + p	350	30	18,300
D + D	^3He + n	400	35	~4,000
	T + p	400	35	~4,000

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

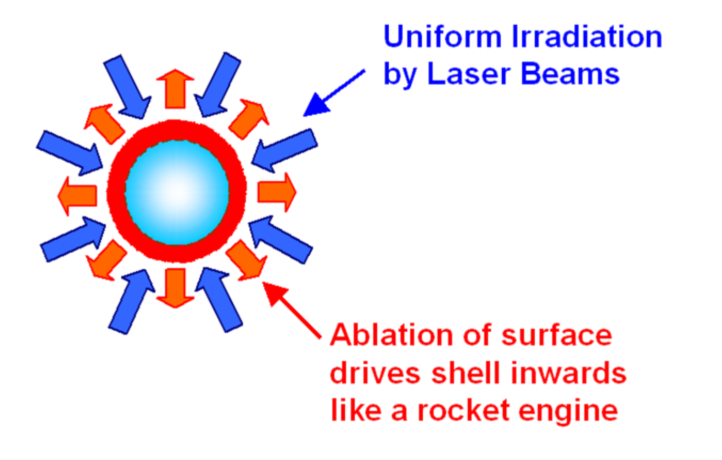
Laser Fusion uses high density n ~10^{25} cm^{-3} but short interaction time τ ~100 ps in the ignition hot spot

Inertial Confinement Fusion (ICF) Approach

Laser Fusion Energy (LFE)

Laser Fusion

Direct Drive

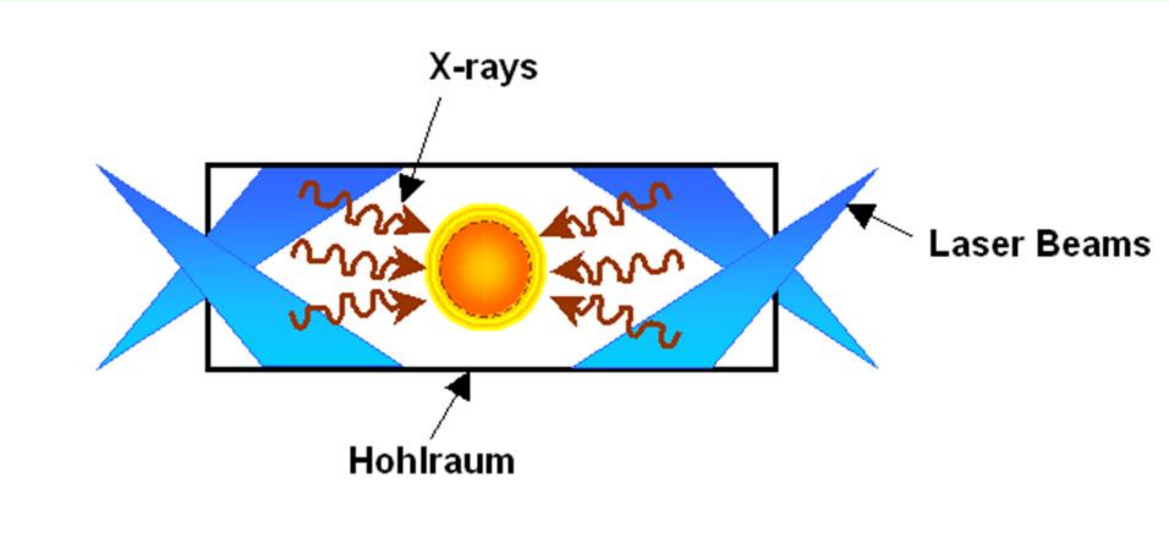


Ignition Conditions:

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

T ~ 6 keV
In central hot spot region

Indirect Drive



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 196 beams**
- **Operating 3 years**

Lawrence Livermore National Laboratory

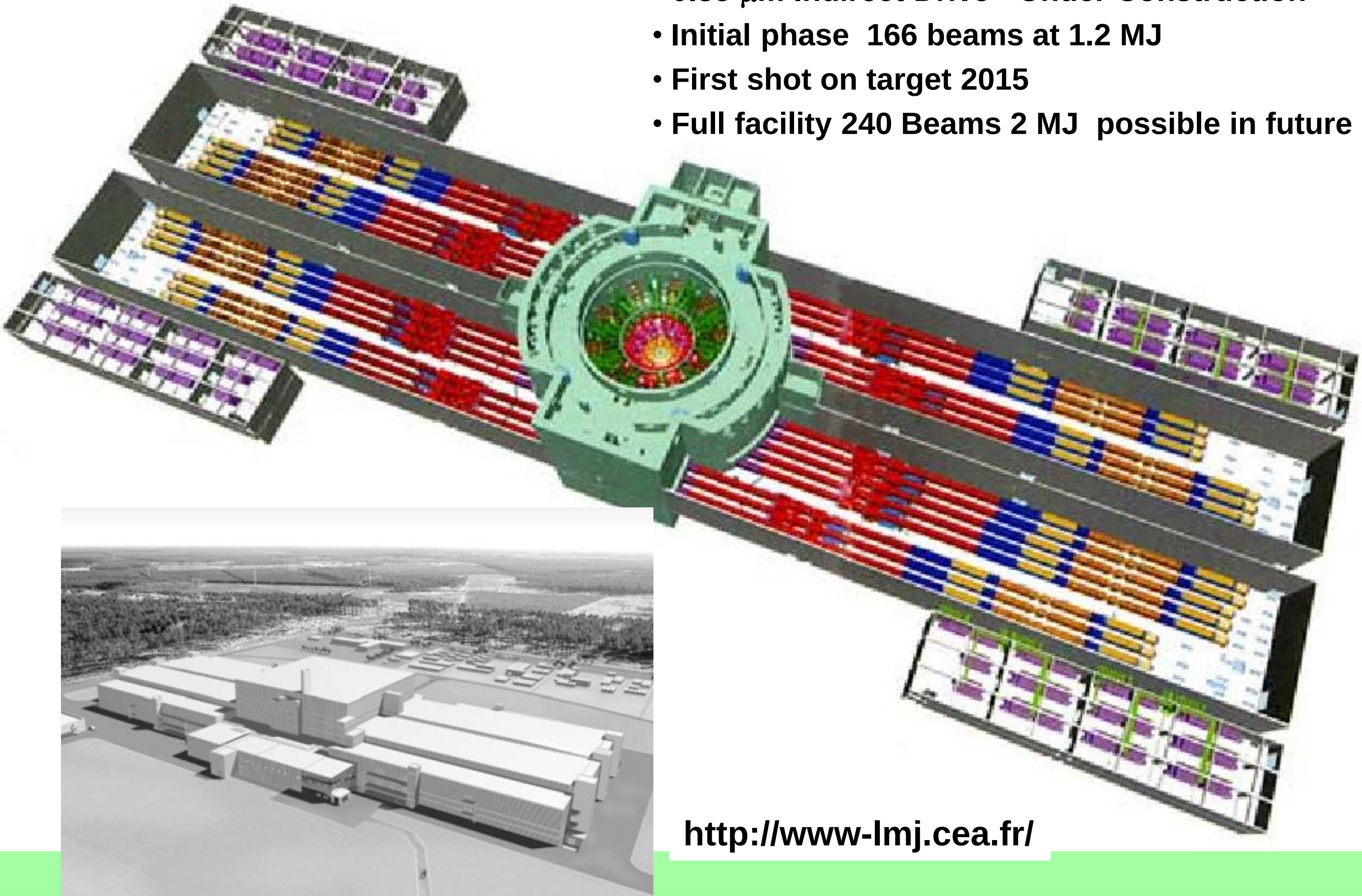
https://lasers.llnl.gov/

Laser Bay

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

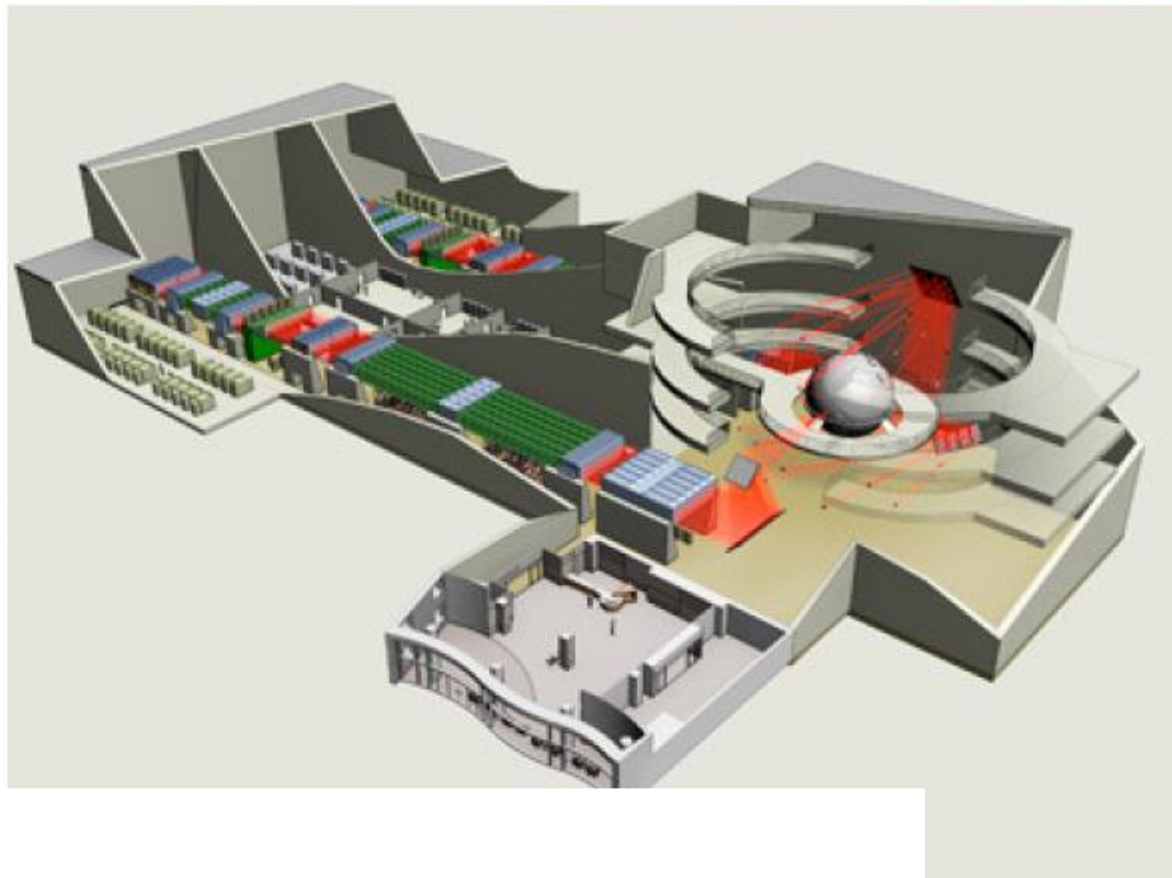
http://www.stfc.ac.uk/906.aspx /

Baseline specifications

1. **Implosion energy:**
   200 kJ in 5ns
   10 m chamber
   2ω or 3ω?

2. **PW beamlines:**
   70kJ in 10ps
   2ω (how?)

3. **Parallel development of IFE building blocks**
   - **Target manufacture**
   - **DPSSL laser**
   - **Reactor designs**



Cost ~ $1B Euro

Planning Started under the Framework 7 Program

LLNL LIFE Power Plant Design Addresses Engineering Requirements for a Real Reactor)

Plant Primary Criteria (partial list)
Cost of electricity
Rate and cost of build
Licensing simplicity
Reliability, Availability, Maintainability, Inspectability (RAMI)
High capacity credit & capacity load factor
Predictable shutdown and quick restart
Protection of capital investment
Meet urban environmental and safety standards (minimize grid impact)
Public acceptability
Timely delivery

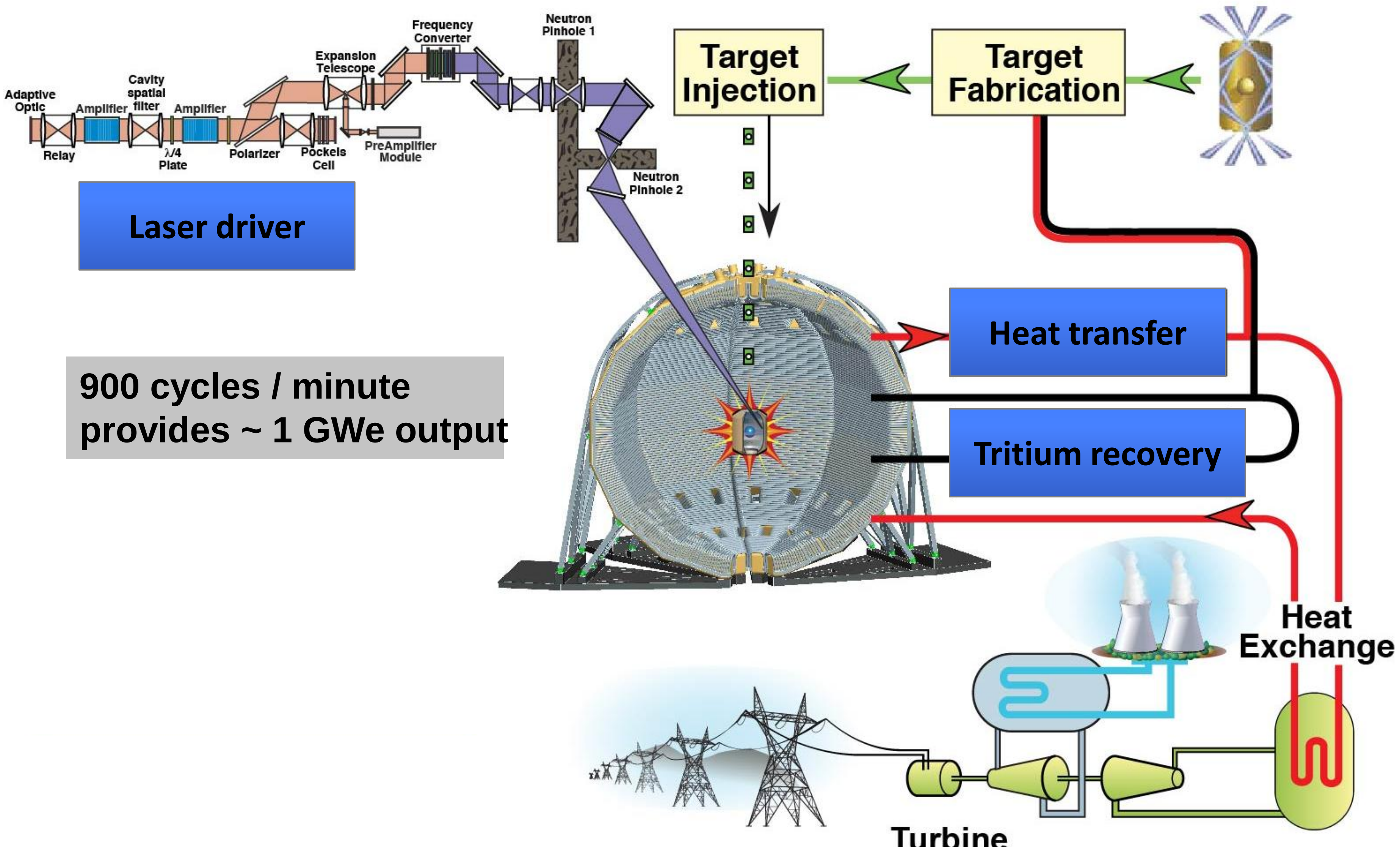
Use of commercially available materials and technologies

Focus on pure fusion, utility-scale, power-producing facility

LLNL : Initial engineering and planning already carried out

https://lasers.llnl.gov/about/missions/energy_for_the_future/

LIFE translates the "single shot" capability of NIF into the requirements for ~1000 MW electrical output



900 cycles / minute
provides ~ 1 GWe output

https://lasers.llnl.gov/about/missions/energy_for_the_future/

NIF Indirect Drive Status

- Best neutron yield of 3 x 10^{15} obtained to date
- ITFX parameter of 0.16 achieved (1 = threshold but scales very strongly with a number of parameters)
- Appears Implosion symmetry not good enough yet
  - need higher resolution x-ray imaging diagnostics
- In progress: (2015 next DOE program review)
  - Adjusted shape hohlraums
  - Smoother targets
  - Diamond and Be ablators instead of plastic
  - More stable lower adiabat implosions (thicker shells)

Rochester Direct Drive Status

- University of Rochester Laboratory for Laser Energetics (LLE) – 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 – potentially could achieve ignition after reconfiguration of optics and modified front end laser at 1.5MJ
- Best neutron yield of 2 x 10^{13} obtained to date
- Scaled ITFX parameter of 0.24 achieved
  - Fuel compression not good enough yet:

    hot spot ρR = 0.2 g cm $^{-2}$ (vs 0.3 g cm $^{-2}$ required)
  - Fuel preheat from burst of hot electrons from laser plasma interaction in corona
- Will improve conditions using:
  - Variable Z layer targets to reduce hot electrons and fuel preheat
  - Smoother targets

Advanced Ignition Techniques

Fast 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

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

$\tau_{dep} \sim 20$ ps

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

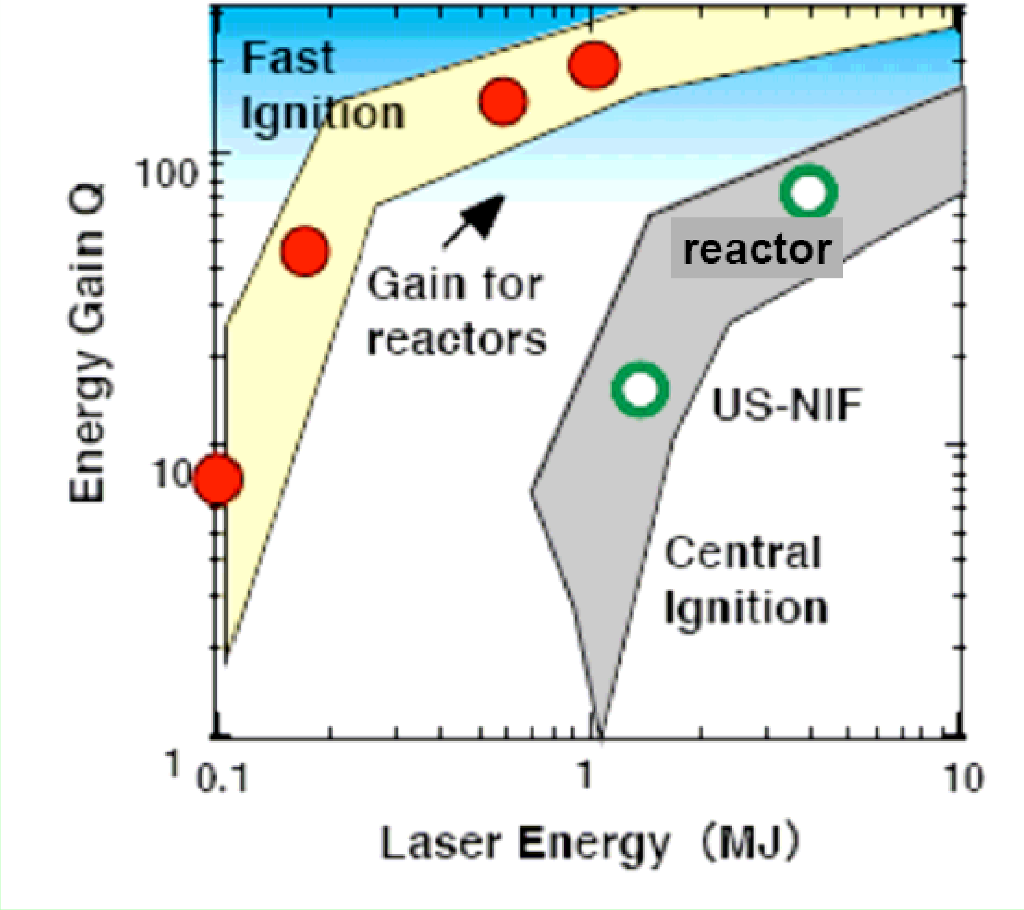
$E_{dep} \sim 20$ kJ

$E_{laser} \sim 200$ kJ

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

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

Energy Gain Scaling for Fast Ignition



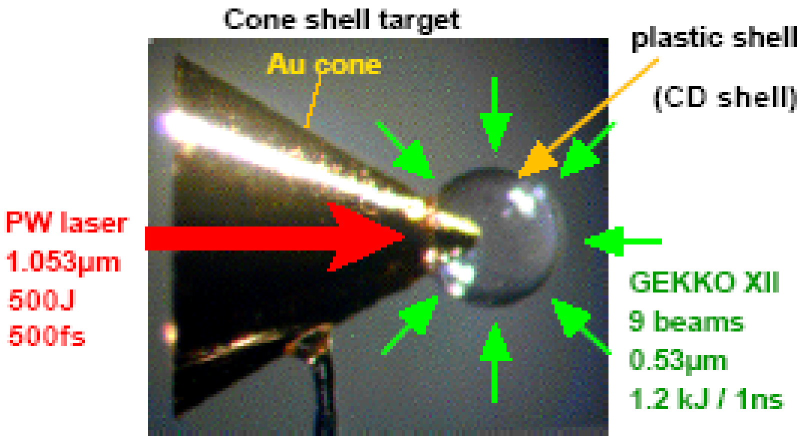
Reduce Laser Requirements almost an order of magnitude:

Smaller and less expensive initial IFE reactors possible

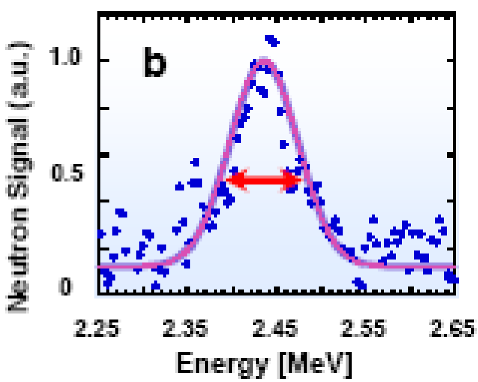
Initial Heating Results Demonstrated at ILE Japan

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

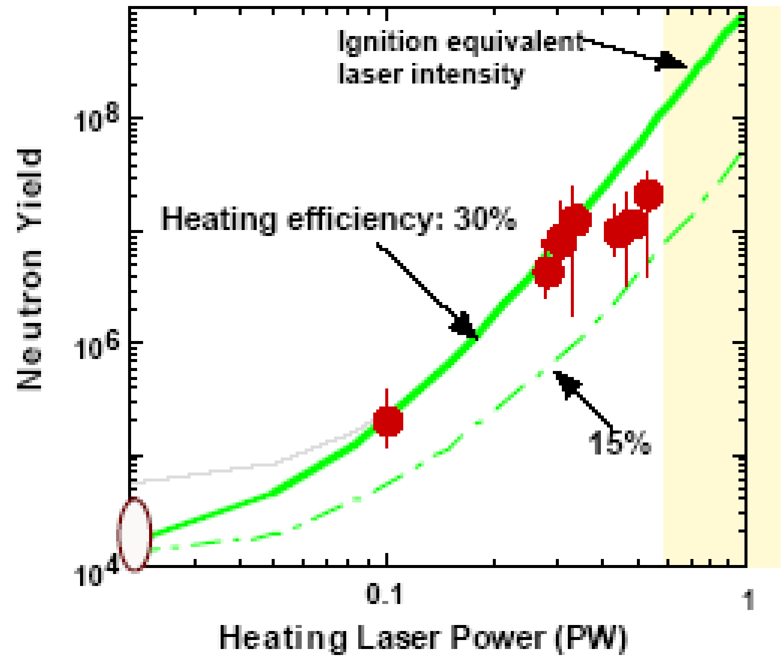
ILE OSAKA



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



Neutron time-of-flight



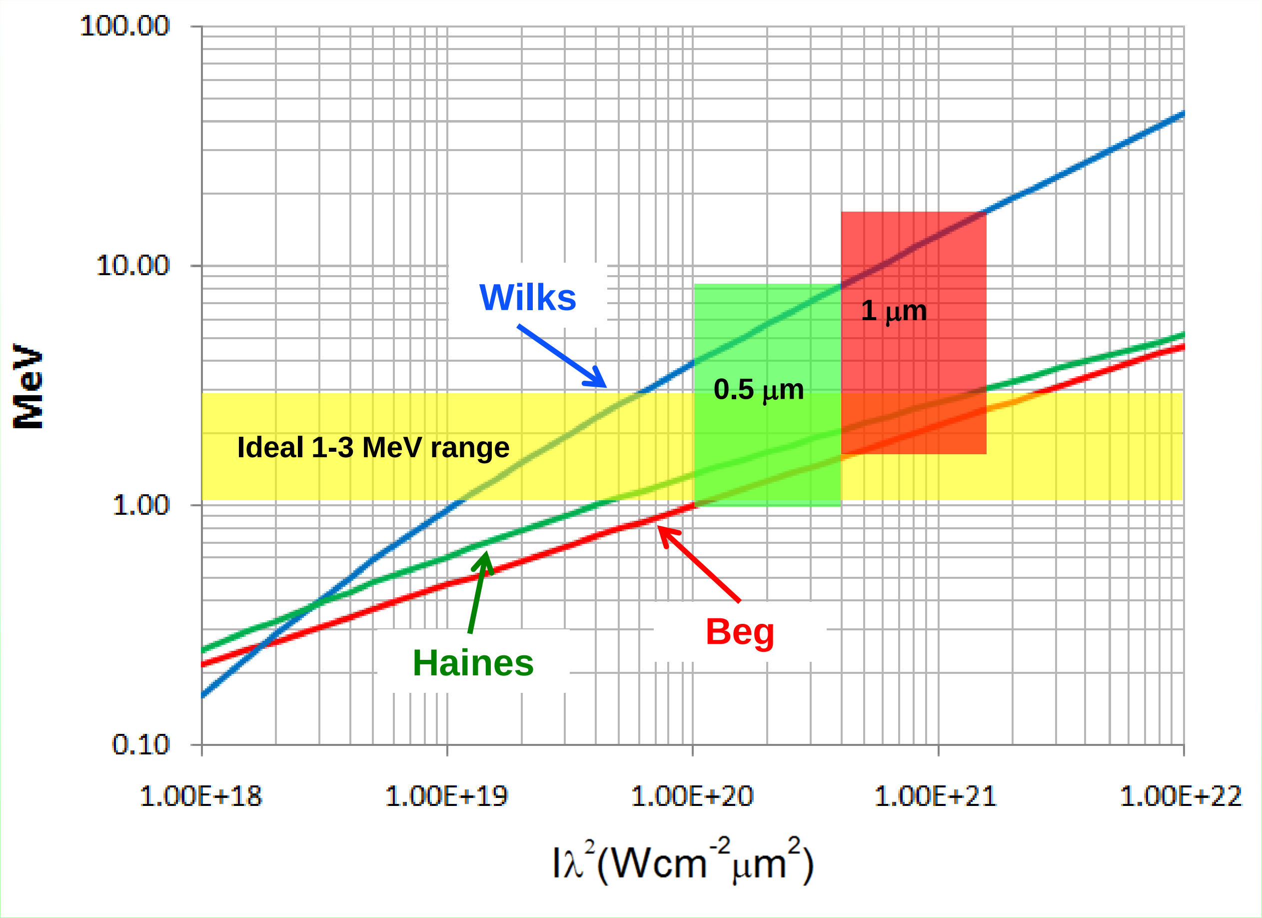
FWHM: 90±5keV keV
Resolution:50 keV

→ 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)

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

-> Requires enhanced magnetic guiding

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

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,*]

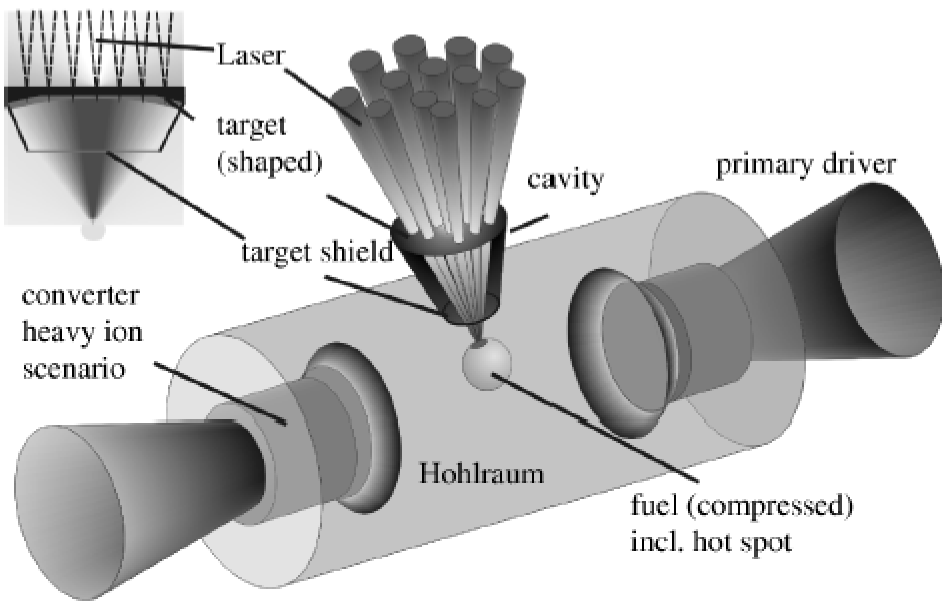


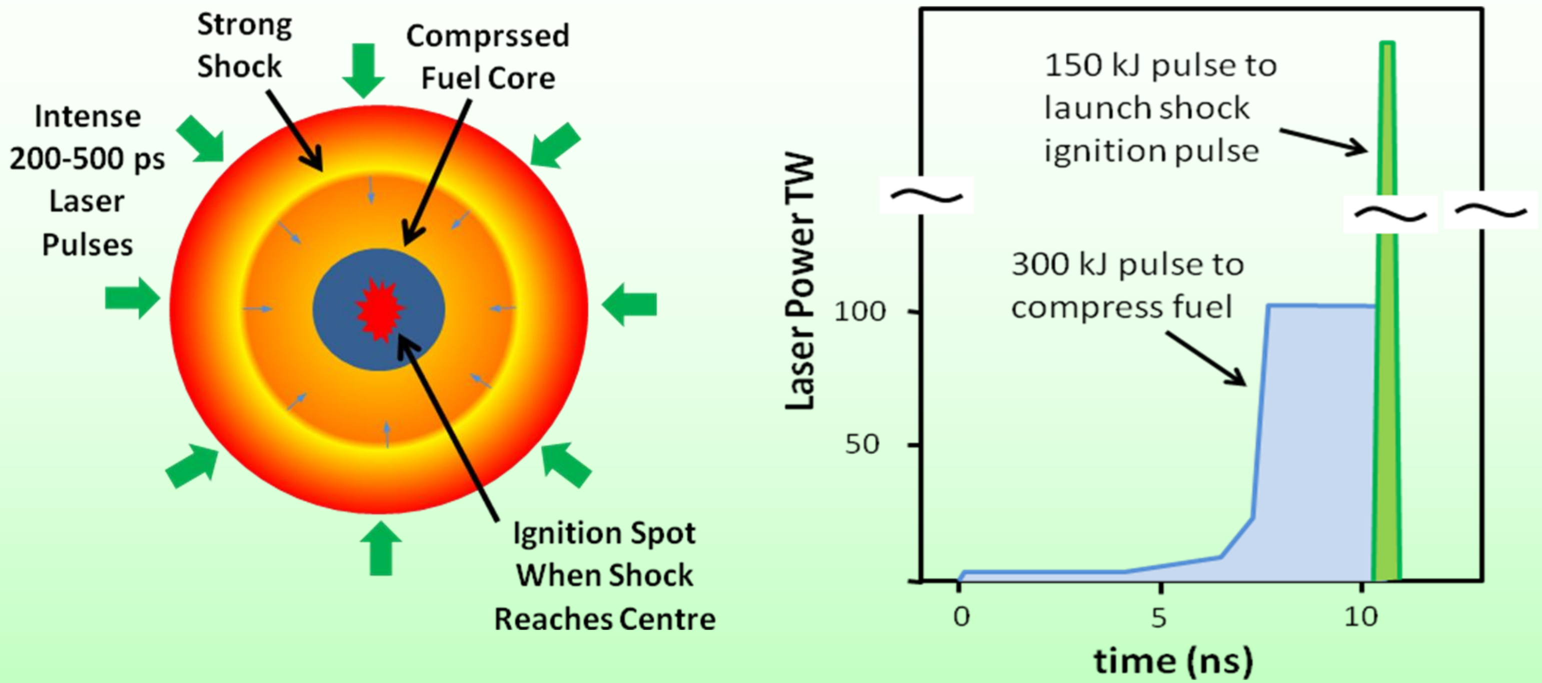
FIG. 1. Indirectly driven fast ignition using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

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

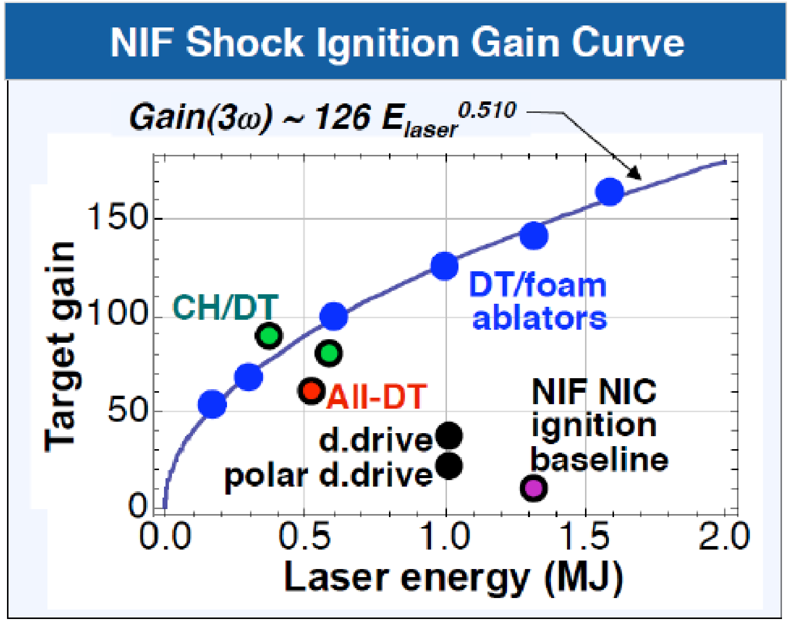
Shock Ignition

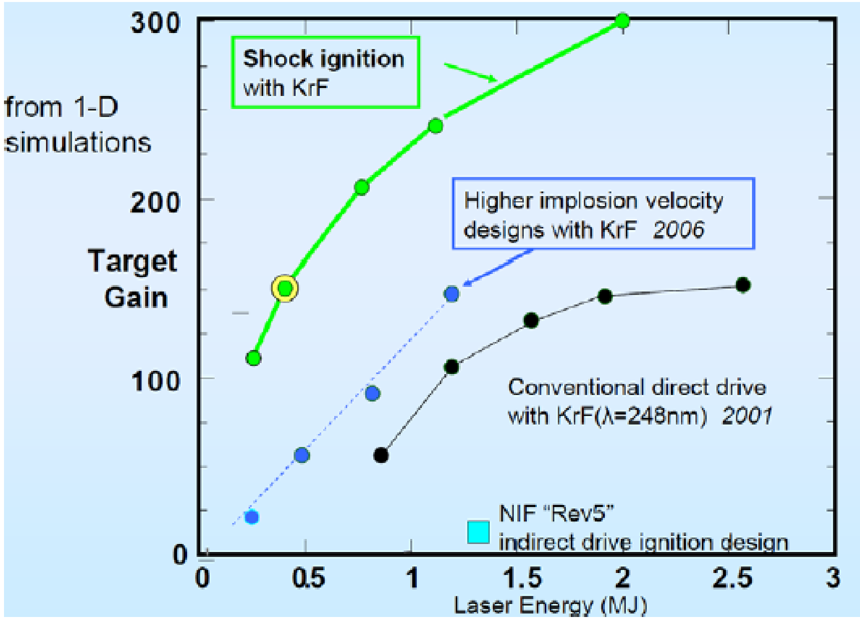
Shock Ignition



- 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



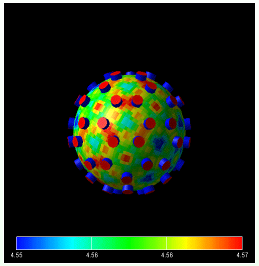


JL Perkins (LLNL)

A. Schmitt (NRL)

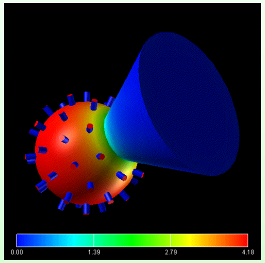
European HiPER Facility Conceptual Designs

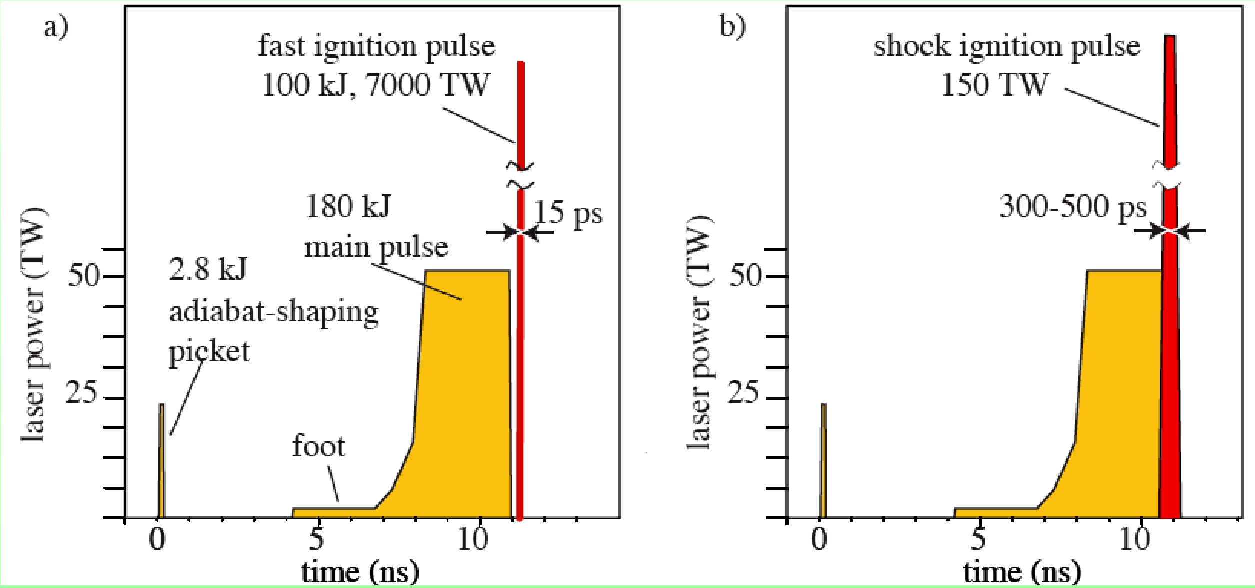
1. Compression laser 250 kJ, 4ns, 3ω
2. Shock Ignition laser 60 kJ, 400 ps, 3ω
3. Fast Ignition laser 100kJ, 15ps, 2ω



Compression + shock ignition = 48 focal spots

Fast ignition = Single Cone



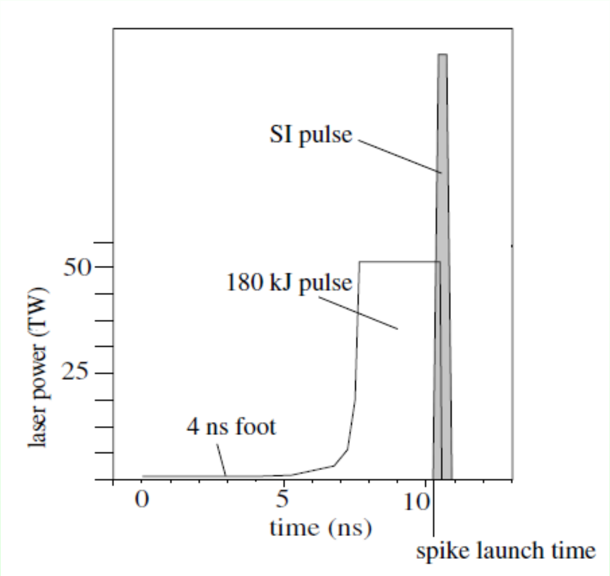


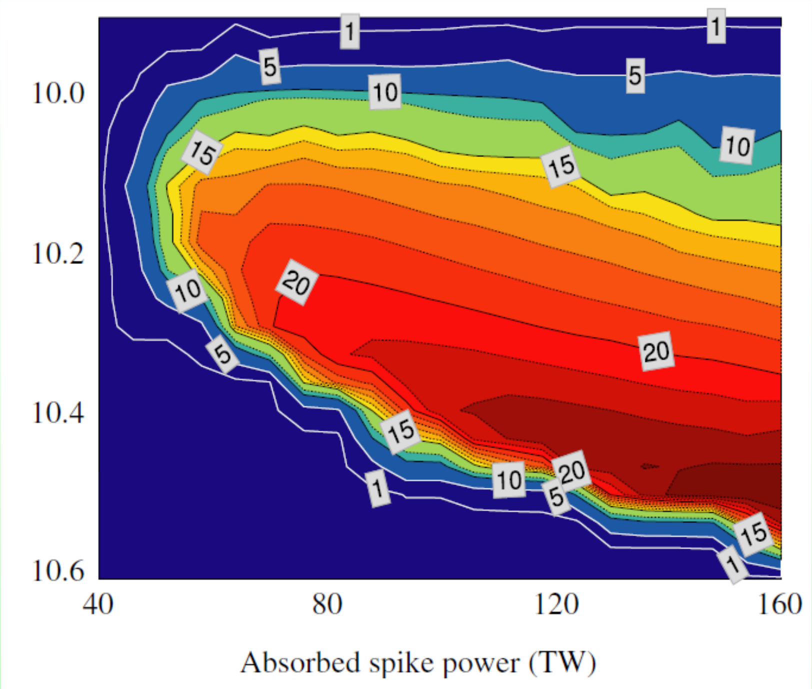
Shock Ignition

- Three critical requirements
  - Minimize backscatter from plasma instabilities in order to absorb greater than 50% of incident energy
  - Control the hot electron preheating of the compressed fuel core
  - Obtain good hydrodynamic coupling efficiency to drive strong shock
- Theory ,simulations and experiments to date look promising
- Possible benefit in reduced Rayleigh Taylor instability levels
- Also possibly polar direct drive could be used for the shock pulse

High Gains at Low Pulse Energies

Yield in MJ versus shock launch time (ns) and absorbed power in 0.5 ns shock spike





Multi-MJ yield versus absorbed power in 500ps spike

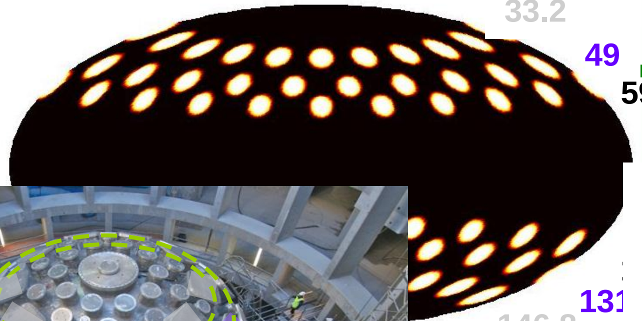
Atzeni Nuclear Fusion 49, 05500, 2009

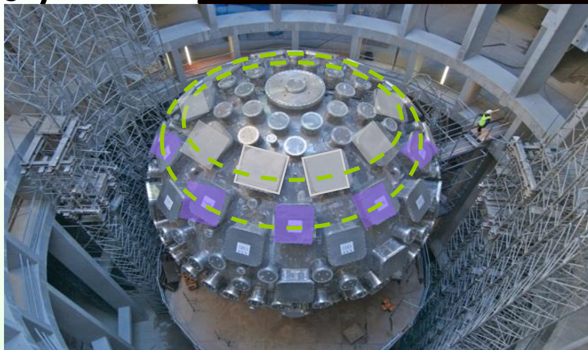
Shock Ignition for LMJ and NIF

- 1.2 MJ, 390 TW
- 40 quadruplets (33°, 49°)

160 beams 40 x 40 cm^2

- May be split and repointed

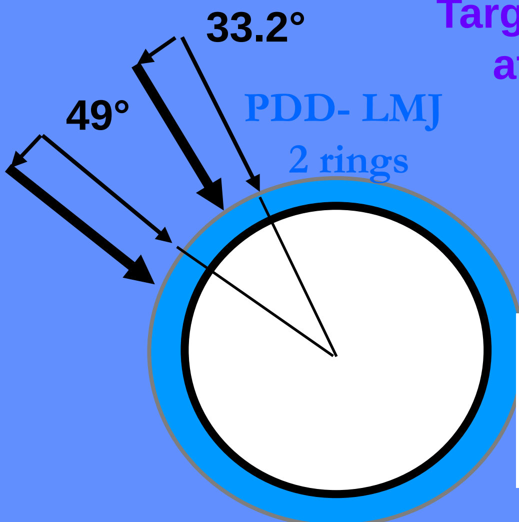




Ribeyre et al., Plasma. Phys. Control. Nuclear Fusion 51, 015013 (2009

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

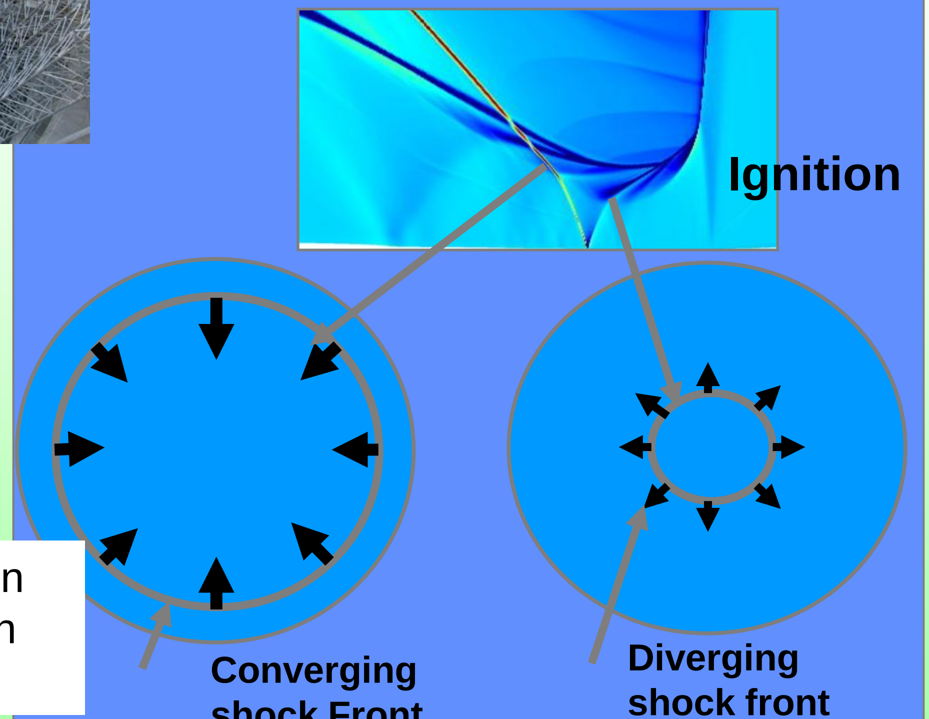
First step:
Target compression at low velocity 250 km/s



Also LLE point design for 700 kJ G =38 with PDD with SI on NIF

Polar Direct Drive configuration:
Need to have a good laser uniformity < 2% ?

Shock ignition



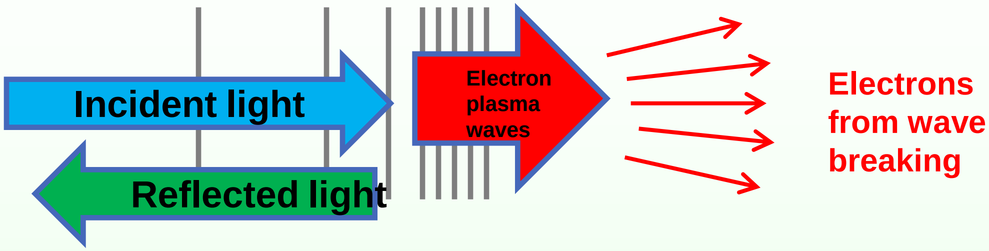
Need to generate a strong shock
200-300 Mbar
1-5x10^{15} W/cm^2 (3ω)

Absorption and Plasma Instabilities

Absorption Mechanisms

- Main Absorption for long pulse through collisional Inverse Bremsstrahlung (IB) absorption
- For short shock ignition pulse absorption both through IB and plasma instabilities:
  - Stimulated Brillouin scattering leading to heated ions 1 keV
  - Stimulated Raman scattering leading to 10 - 100 keV electrons
  - Two plasmon decay instability leading to 20-100 keV electrons
- These plasma instabilities lead to significant back reflection of radiation of the order of 10-50% combined

Stimulated Raman Scattering (SRS)



Density profile (interaction up to n_c / 4 maximum density)

Threshold and Growth Rate

$$\left(\frac{v_{osc}}{c_0}\right)^2 \geq \frac{2}{k_0 L_n} \quad \Rightarrow \quad I_{16} \lambda_{um}^2 \geq \frac{44}{\lambda_{um} L_{n\mu m}}$$

$$\gamma \cong \frac{\omega_0 v_{osc}}{2 c_0} \left(\frac{n_e}{n_c}\right)^{1/4} \cong 5 \cdot 10^{14} I_{16}^{1/2} \left(\frac{n_e}{n_c}\right)^{1/4} s^{-1}$$

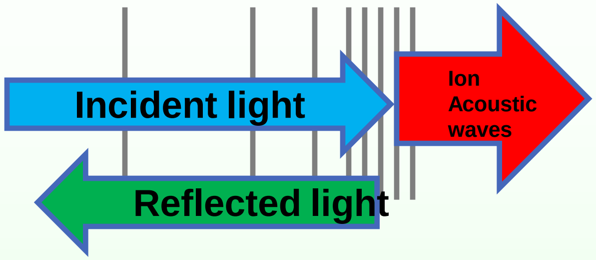
For 0.5 μm Light incident on 200 μm scale length plasma

Threshold ~ 4 x 10^{15} W cm^{-2}

Growth rates ~ 3.5 x 10^{14} s^{-1} at 10^{16} W cm^{-2}

W. Kruer, Physics of Laser Plasma Interactions (1988)

Stimulated Brillouin Scattering (SBS)



Density profile (interaction just below n_c)

Threshold and Growth Rate

$$\left(\frac{v_{osc}}{v_e}\right)^2 \geq \frac{8}{k_0 L_n} \quad \Rightarrow \quad I_{16}\lambda_{um} \geq \frac{0.34}{L_{n\mu m}} T_{keV}$$

$$\gamma = \frac{1}{2\sqrt{2}}\sqrt{\frac{k_0}{\omega_0 c_s}}(v_{osc}\omega_{pi}) \quad \cong \quad 1.4 \cdot 10^{14}\frac{I_{16}^{1/2}\lambda_{um}}{T_{keV}^{1/4}}\left(\frac{n_e}{n_c}\right)^{1/2} \quad s^{-1}$$

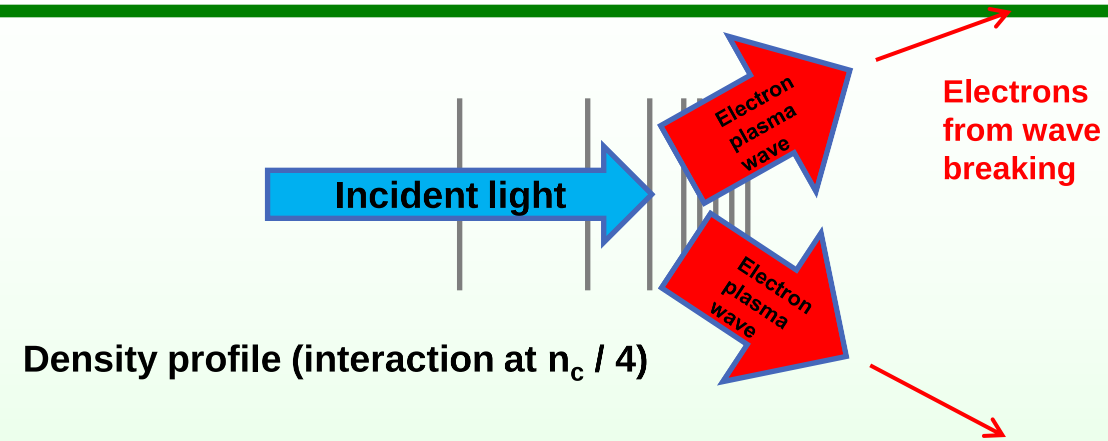
For 0.5 μm Light incident on 5 keV, 200 μm scale length plasma

Threshold ~ 1.5 x 10^{14} W cm^{-2}

Growth rates ~ 8.3 x 10^{12} s^{-1} at 10^{16} W cm^{-2} for $n_e = n_c$

W. Kruer, Physics of Laser Plasma Interactions (1988)

Two Plasmon Decay (TPD)



Threshold and Growth Rate

$$\left(\frac{v_{osc}}{v_e}\right)^2 \geq \frac{12}{k_0 L_n} \quad \Rightarrow \quad I_{16}\lambda_{um} \geq \frac{0.516}{L_{n\mu m}} T_{keV}$$

$$\gamma \cong \frac{\omega_0 v_{osc}}{4 c_0} \quad \cong \quad 2.5 \cdot 10^{14} I_{16}^{1/2} \left(\frac{n_e}{n_c}\right)^{1/4} \; s^{-1}$$

For 0.5 μm Light incident on 5 keV, 200 μm scale length plasma

Threshold ~ 2.6 x 10^{14} W cm^{-2}

Growth rates ~ 8.3 x 10^{12} s^{-1} at 10^{16} W cm^{-2} for $n_e = n_c$

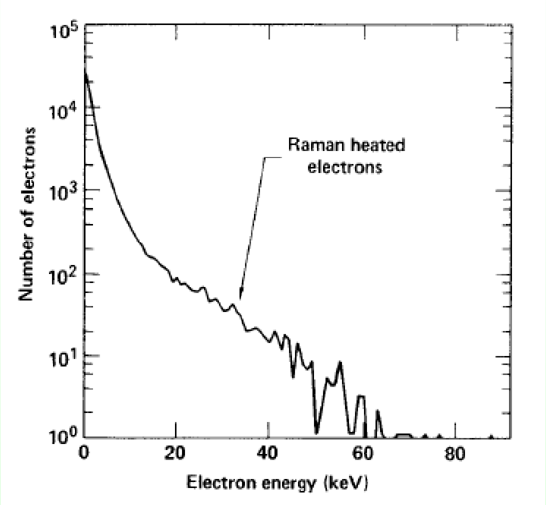
W. Kruer, Physics of Laser Plasma Interactions (1988)

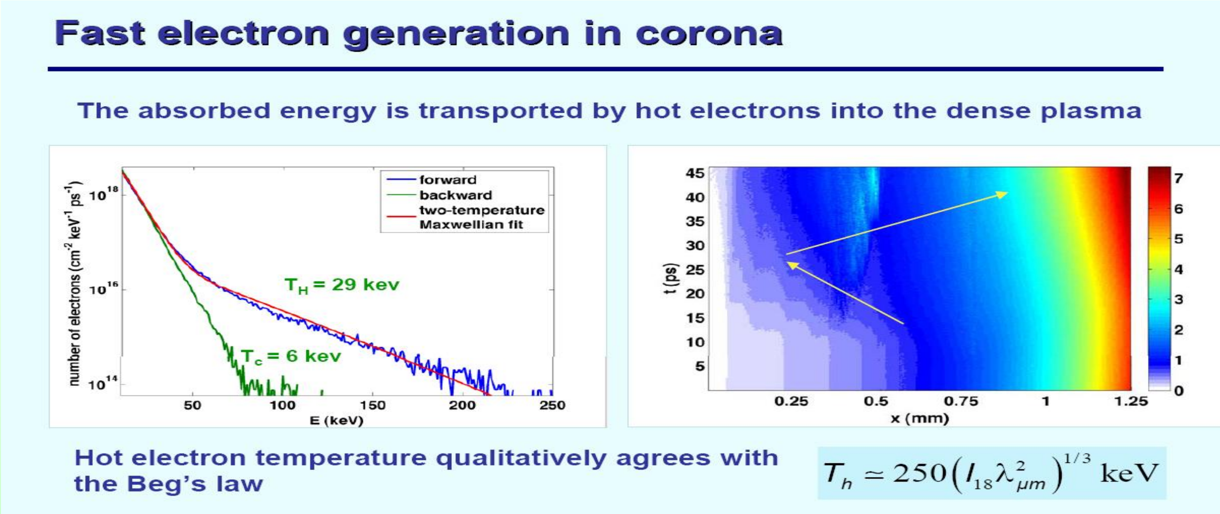
Hot Electron Preheat from SRS

- Originally could not operate at these intensities for main compression pulses because hot electrons would preheat the core increasing the required laser energy by a huge factor
- However, at the time of the Shock Ignition spike the fuel is already partially compressed and the electrons cannot penetrate into the central core
- Calculations show that the hot electrons up to 150keV are stopped in the overdense coronal region leading to enhancement of the shock generation

Hot Electron Preheat from SRS

- **Hot electron spectra**





~ 20 keV at 10^{15} W cm^{-2}

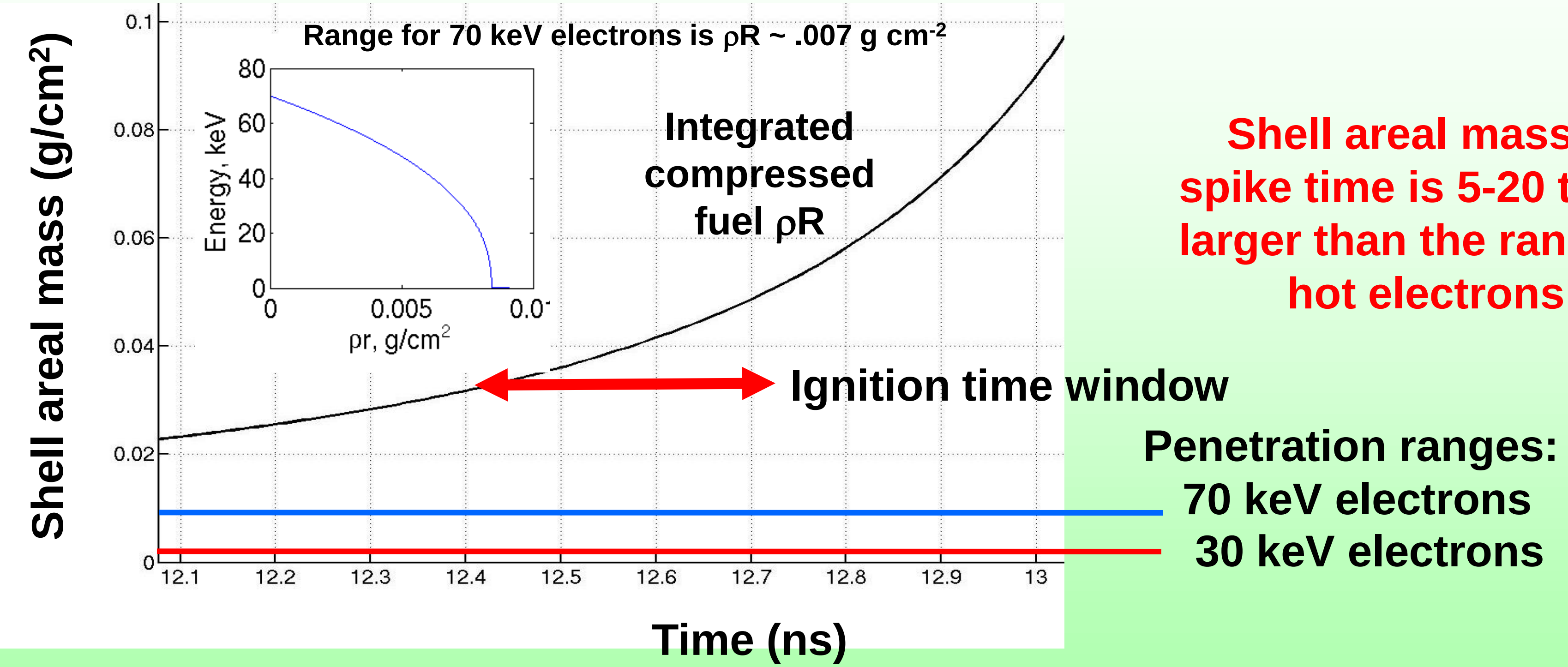
W. Kruer, Physics of Laser Plasma Interactions (1988)

~30 keV at 10^{16} W cm^{-2} at 0.35μm

Klimo O. et al. : PPCF 52 055013 (2010)

Hot Electron Preheat from SRS

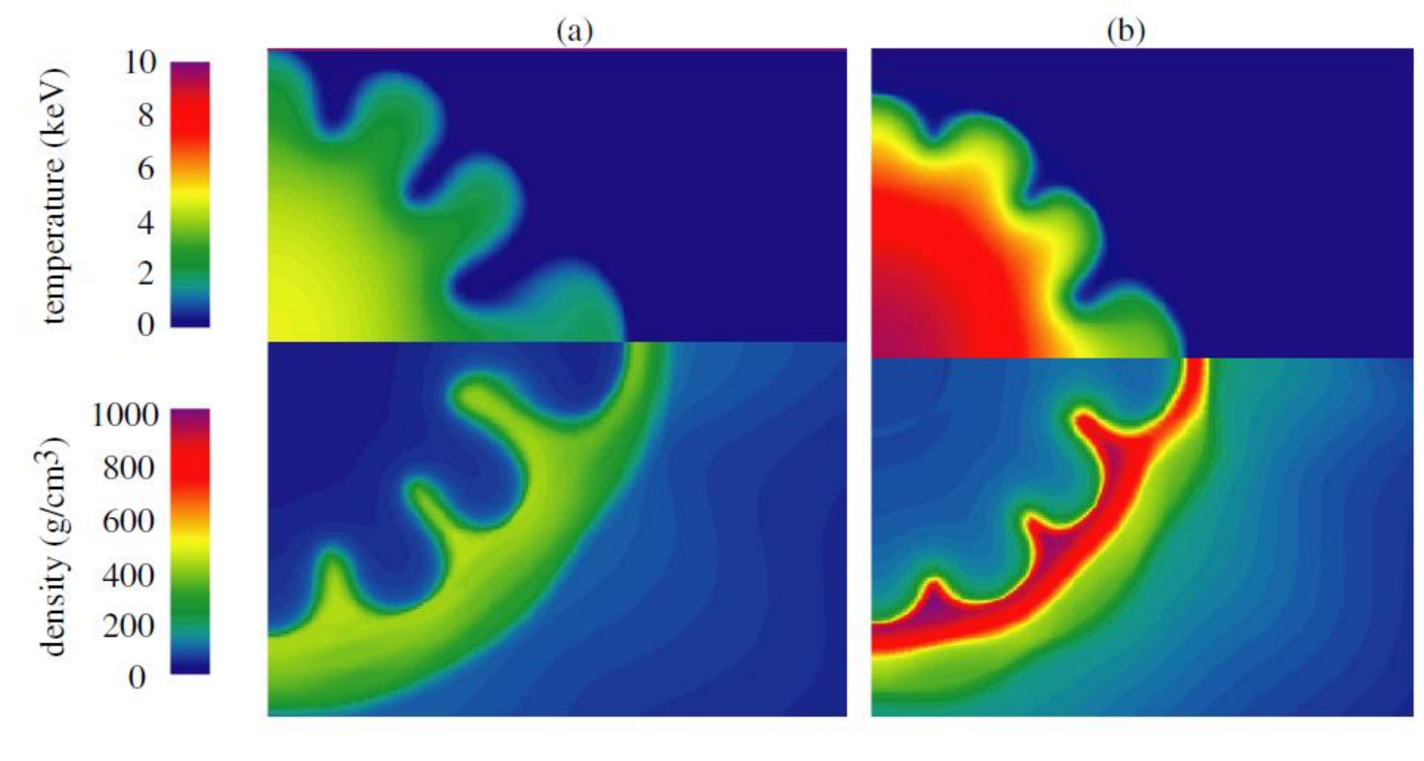
- Hot electron penetration



Shell areal mass at spike time is 5-20 times larger than the range of hot electrons

Betti, R. et al. IFSA 112 022024 (2008)

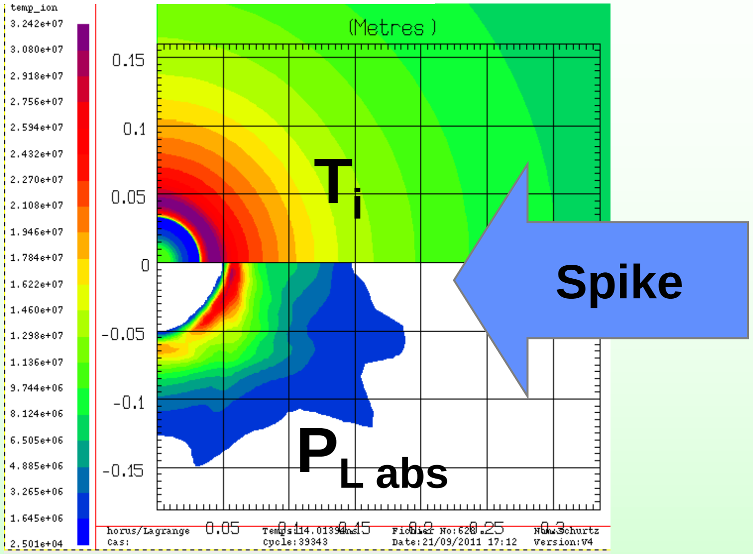
Reduction in Rayleigh Taylor Instability Levels with SI



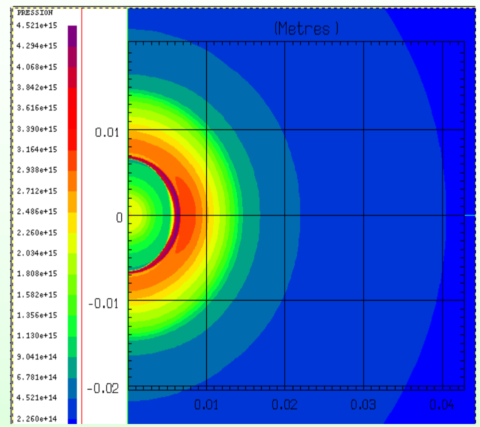
2D CHIC simulations: left - regular implosion, right - Shock Ignition (reduction in instability growth)

Atzeni Nuclear Fusion 49, 05500, 2009

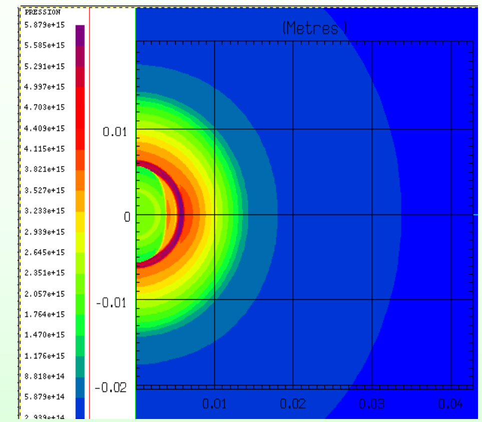
Can use Two-sided Nonuniform Shock Ignition Spike: 2D CHIC simulation of SI for LMJ case @ 350 TW



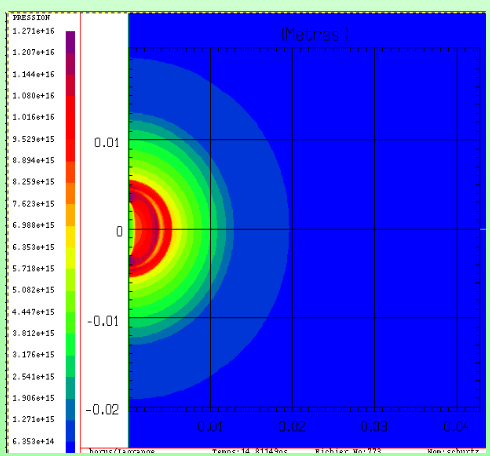
t=14.75 ns, P ~ 4.5 Gbar



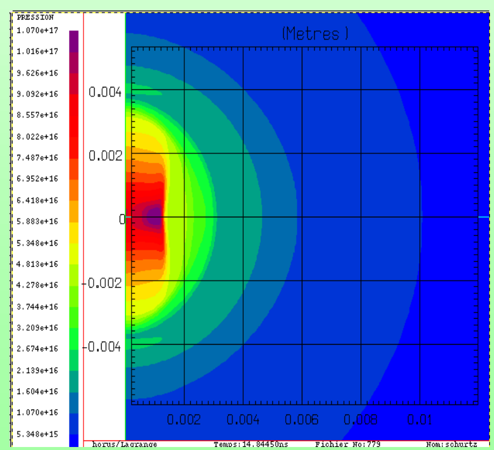
t=14.77 ns, P ~ 5.9 Gbar



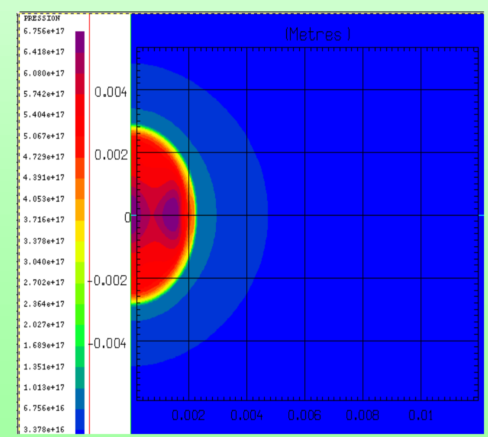
t=14.81 ns, P ~ 12.7 Gbar



t=14.84 ns, P ~ 100 Gbar



t=14.9 ns,
P ~ 650 Gbar, T_i=10 keV



Ribeyre et al. : PPCF 51 015013 (2009)

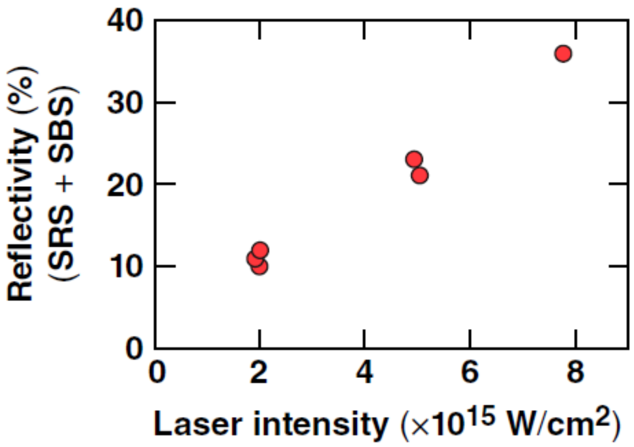
IGNITION

Shock Ignition Results to Date

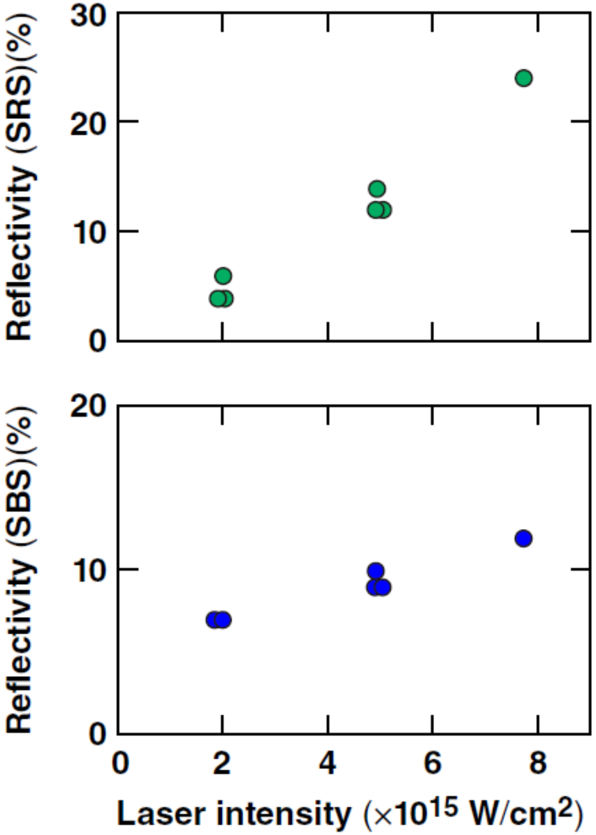
40 beam implosion + SI experiments at LLE University of Rochester Omega facility

Up to 35% of the shock-beam laser energy is lost due to backscatter. T_{hot}~ 45keV

UR LLE



- No measurable signal of the 3/2 harmonic
- SRS dominates back reflection at highest intensity
- SBS reflection is relatively stable at ~10%



E18435

C. Stoeckl, APS 2009; W. Theobald et al, PPCF 51, 124052 (2009);

Shock Ignition

- Shock ignition looks promising as an advanced LFE approach with a number of potential advantages
  - Gain of ~100 with 0.5 -1.0 MJ Laser Energy
  - Absorption still acceptable due to strong saturation of plasma instabilities
  - Electron preheat does not appear to be an issue
  - Smoothing of Rayleigh Taylor density perturbations
  - Nonuniform polar drive shock spike also works at slightly higher drive energy due to smoothing from very hot plasma and electron scattering
  - Initial experimental data is encouraging

Shock Ignition Issues

- Fully integrated 2D and 3D hybrid PIC/Kinetic and hydro simulations required to model full interaction over 100 ps time scales and 1000 μm length scales
- More experiments required on large coronal plasmas to study instabilities, absorption and electron generation in the intensity regime of 10^{15} to 10^{16} W cm^{-2}
- Demonstration of the generation of the strong shocks at 200 Mbar level and higher in such coronal plasmas

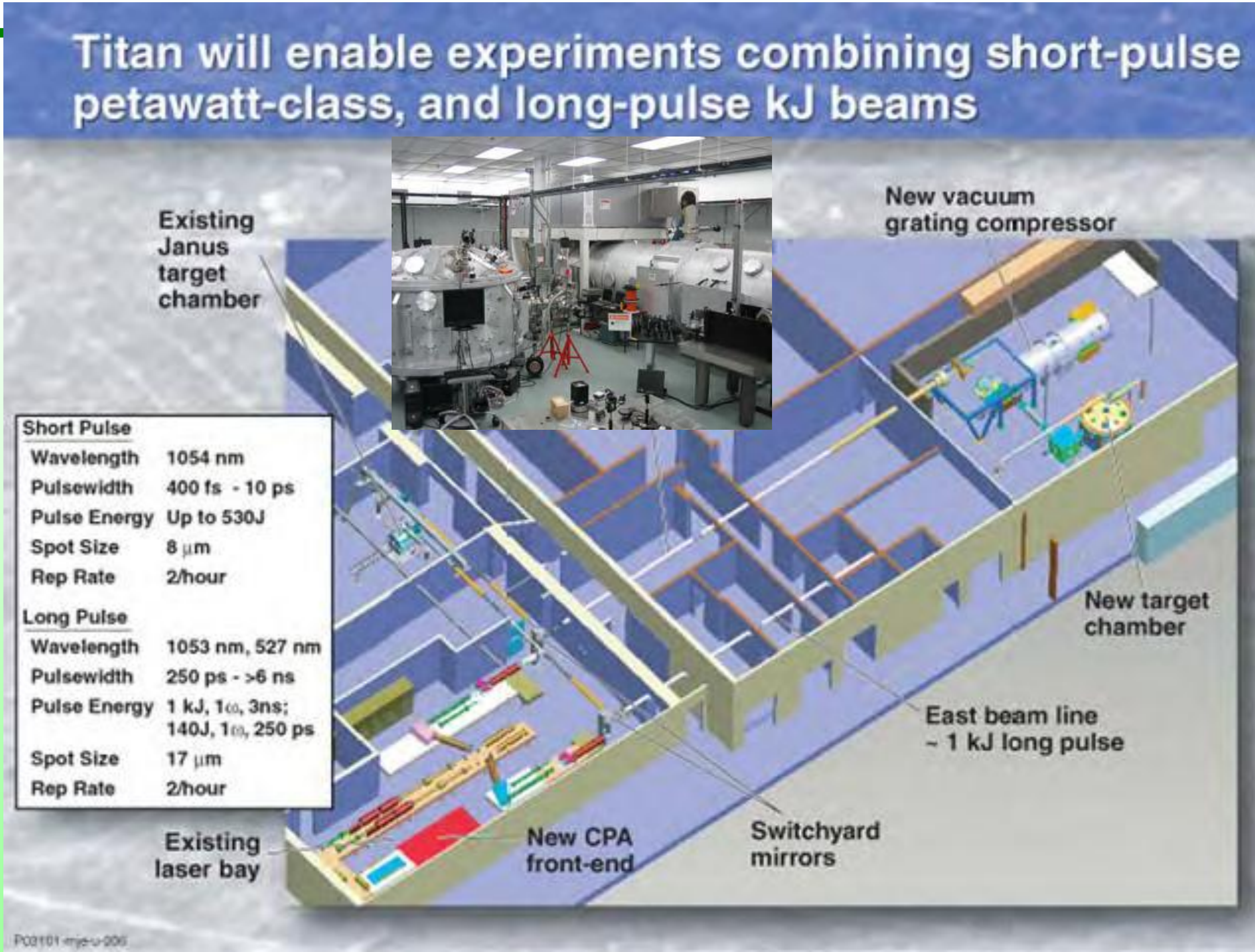
U of A Experiments

Fast Ignition Physics Scaling Experiments at Second Harmonic Wavelength

Using the TITAN Petawatt Laser at the Lawrence Livermore National Laboratory

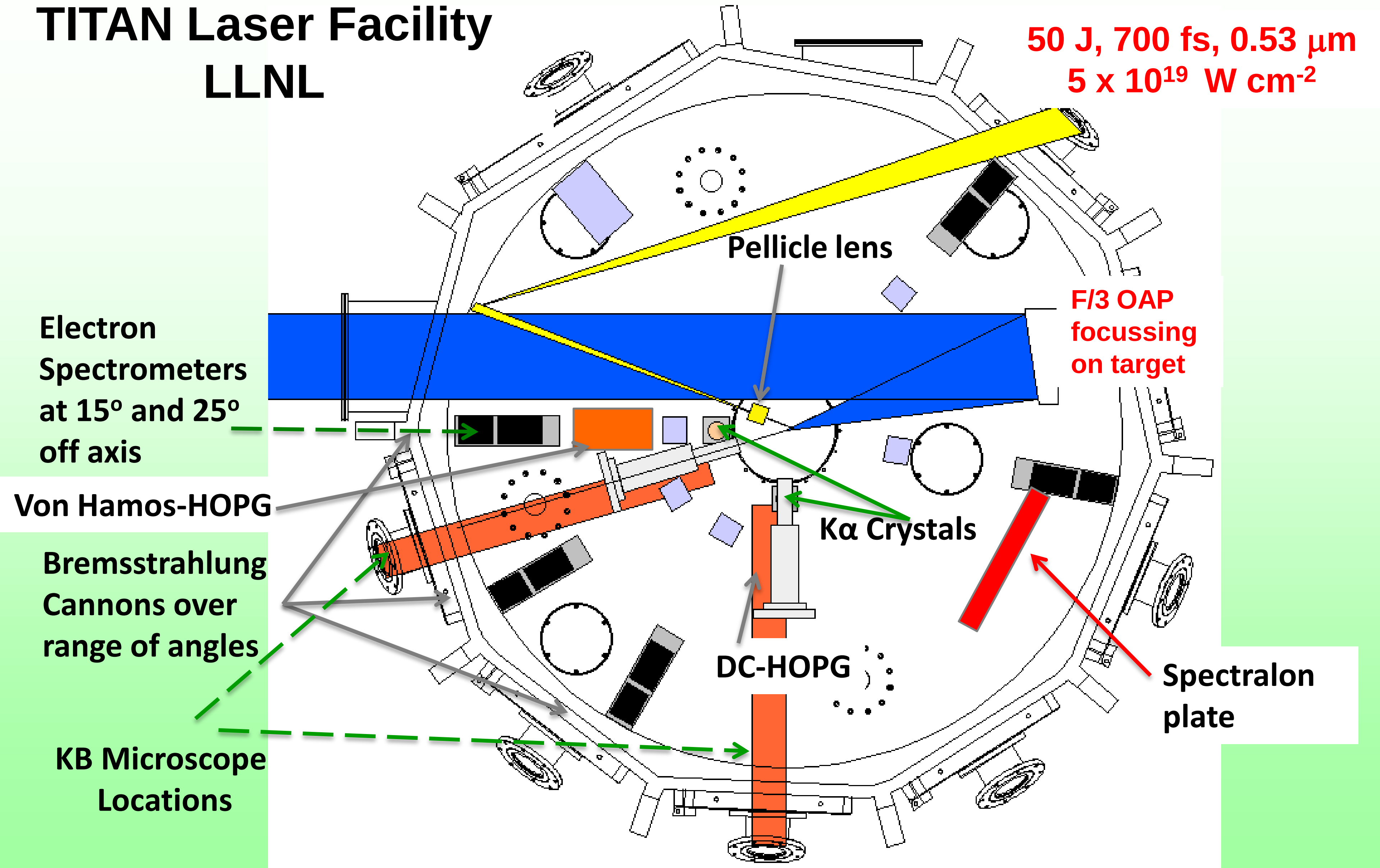
Collaboration with LLNL,UCSD, GA, Ohio State University

Titan Laser Facility



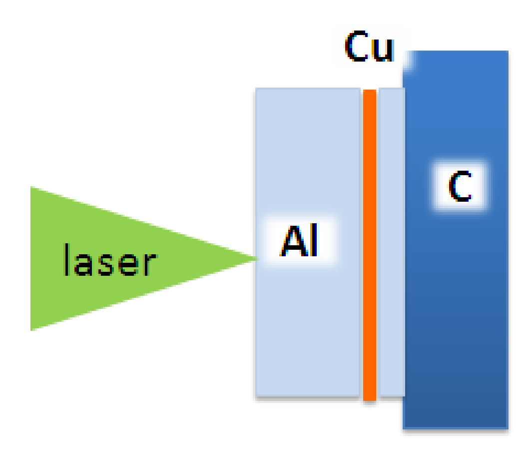
Experimental Diagnostic Layout

TITAN Laser Facility
LLNL

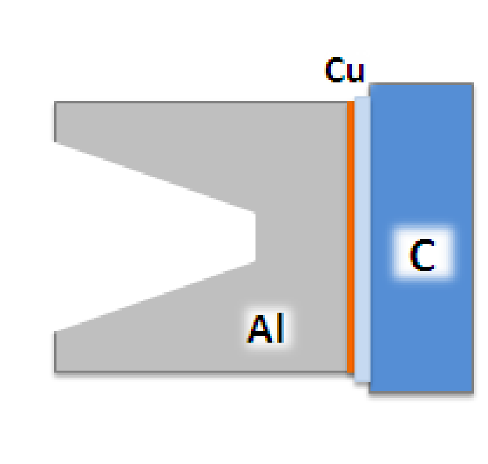


Targets used

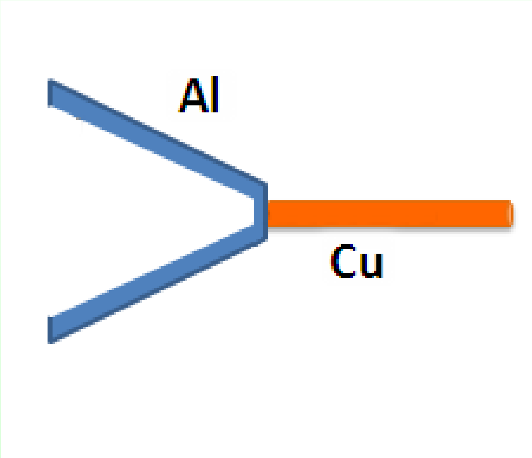
Planar with buried
Cu tracer layer



Solid Al cone with
buried
Cu tracer layer

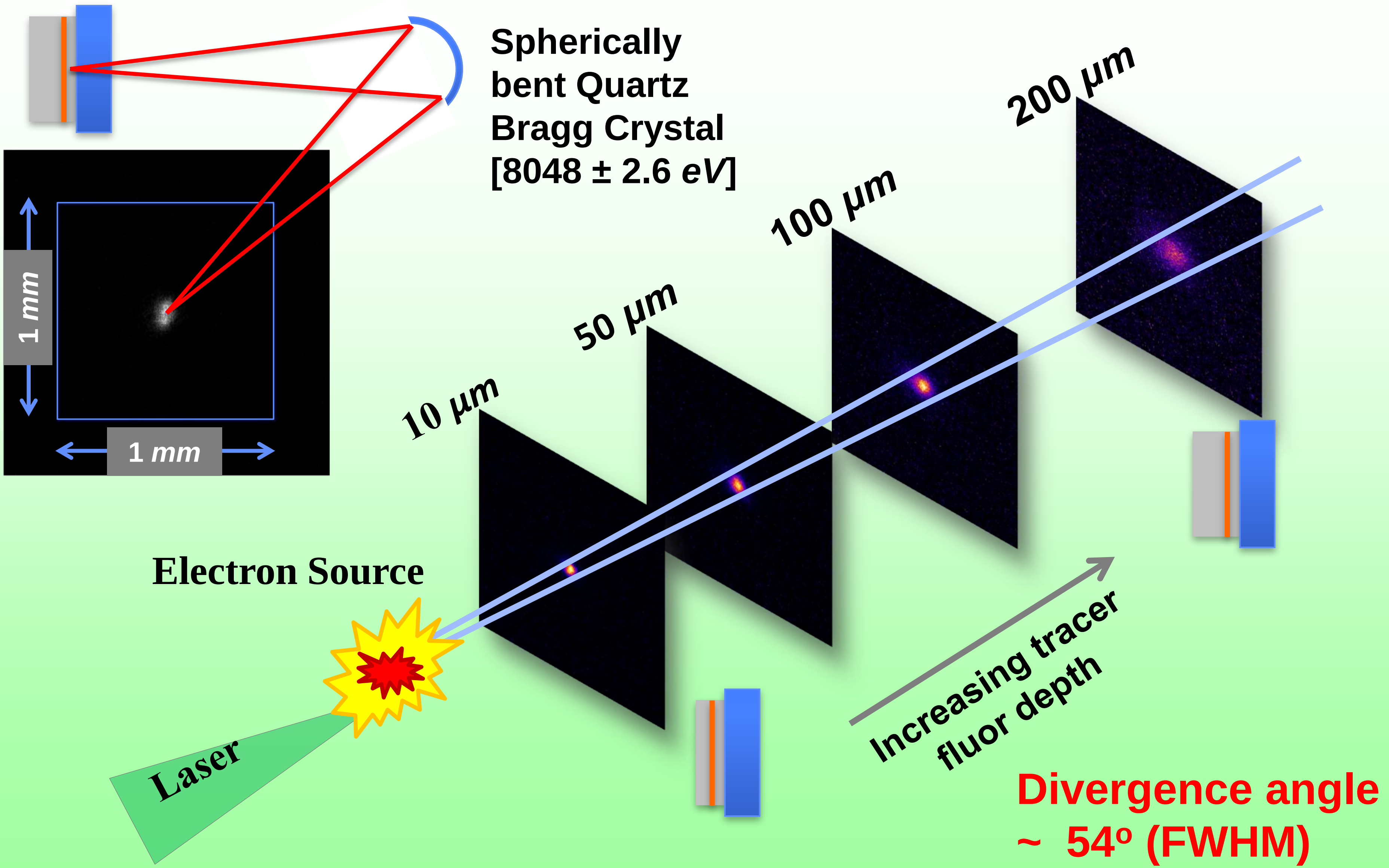


Thin Al cone
Cu wire



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

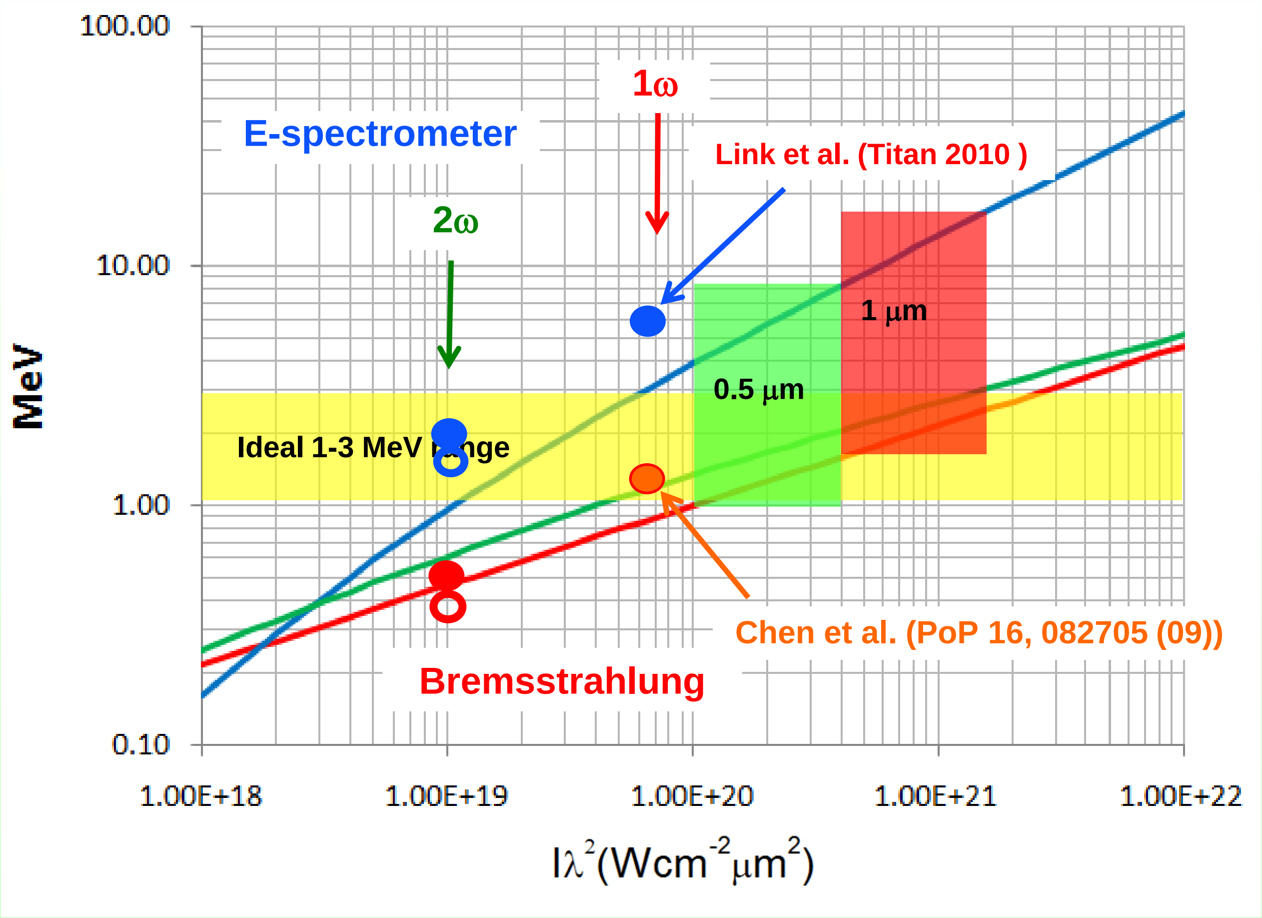
Electron Beam Divergence from Bragg Crystal Imager K_α Images



Divergence angle
~ 54^o (FWHM)

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 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)

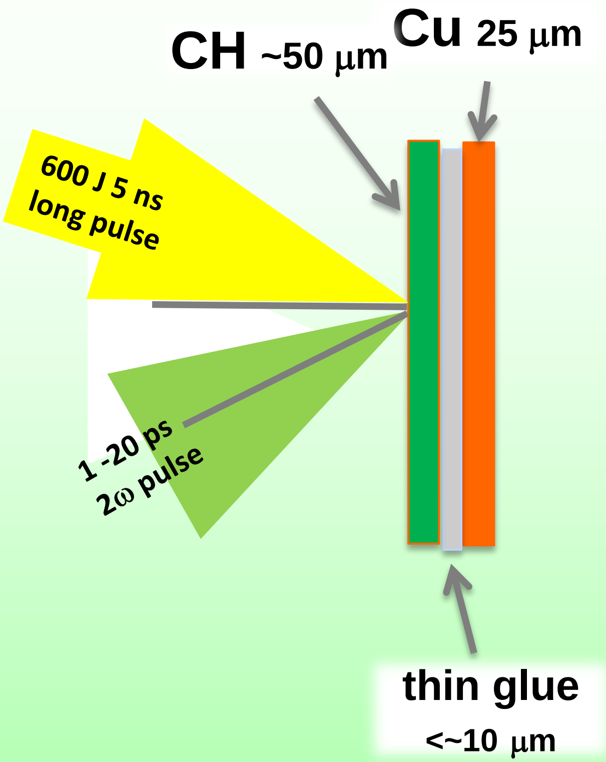
- Major Issue is large electron divergence angle
  - FW ~ 120° – 142° Bremsstrahlung
  - FW ~ 54° K_α imaging
- Absorption and electron yield lower than 1ω as expected for lower $I\lambda^2$ - expect to increase to >30% with higher intensities
  - η_{e-} ~ 11 – 17 %

Conclusions

Fast Ignition

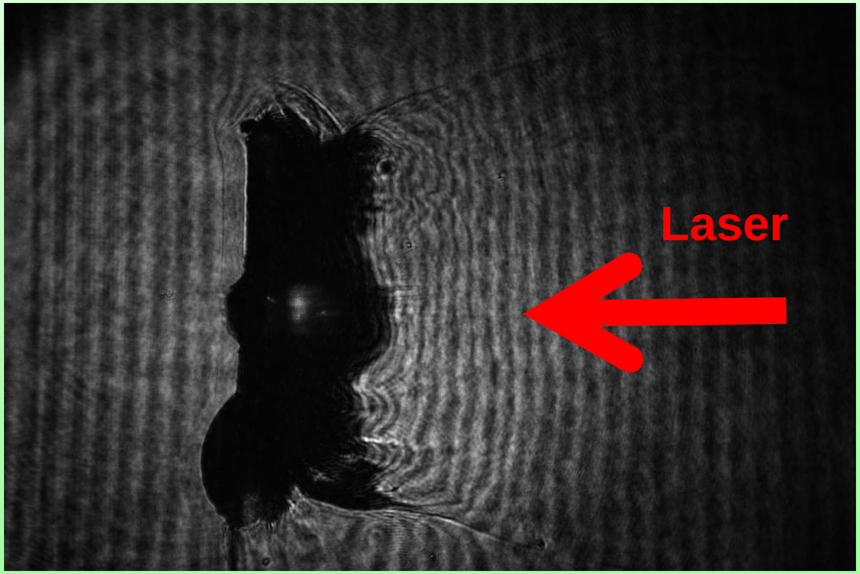
- Conversion efficiency good: 20-30% expected
- Electron Temperature good using second harmonic wavelength (70% optical conversion efficiency expected from 1ω to 2ω)
- Coupling to compressed core plasma a critical issue – will require magnetic guiding schemes:
    - Embedded and compressed fields (Rochester)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

2ω Shock Ignition Experiments at TITAN Laser Facility



Campaign Objectives:

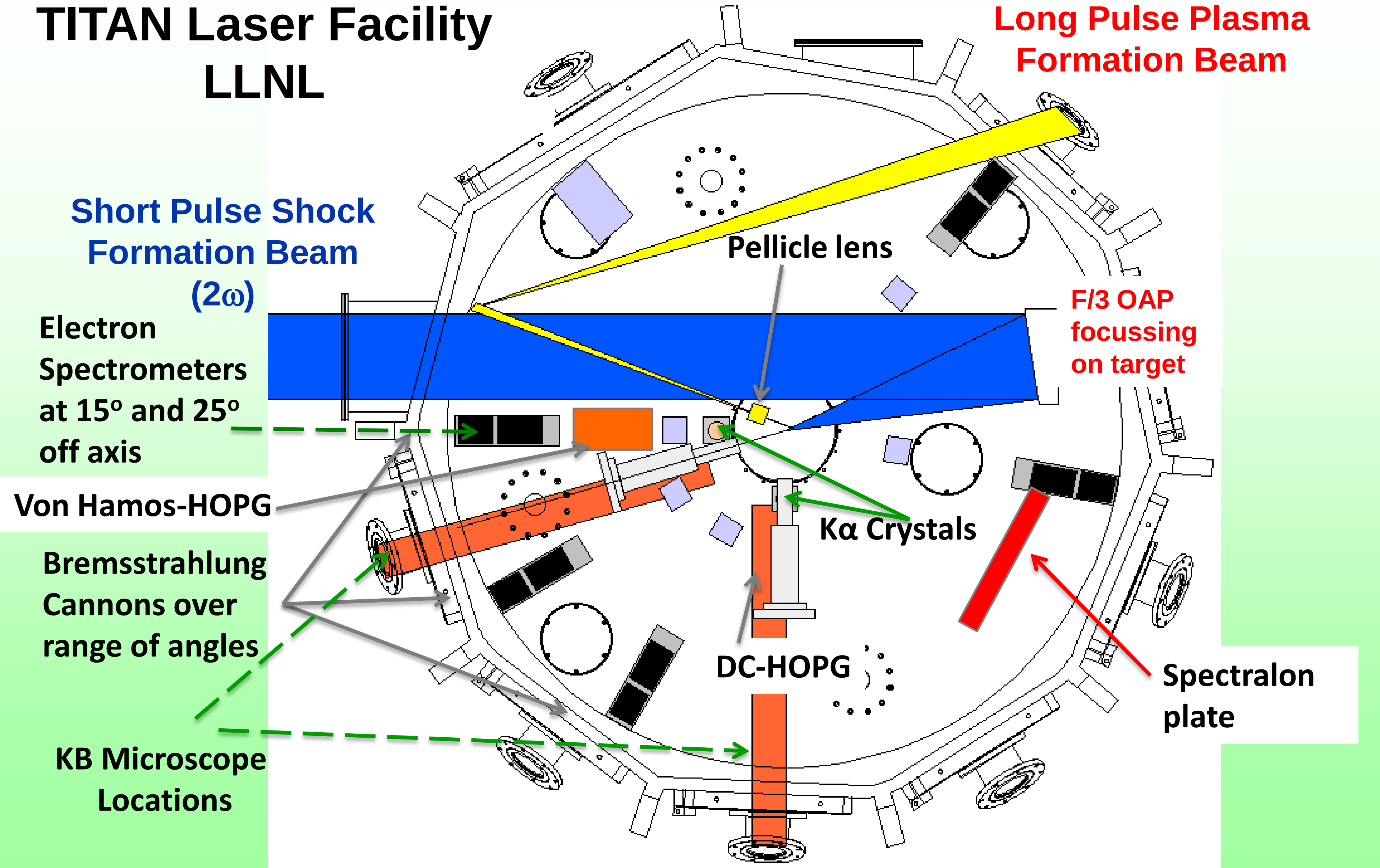
Determine scaling at 2ω of Raman, Brillouin and 3/2ω scattering levels and hot electron generation in preformed hot, long scale plasma relevant to Shock Ignition Fusion



Shock Ignition Studies in Hot (1.5keV) Long Scale Length (150 μm) Plasmas

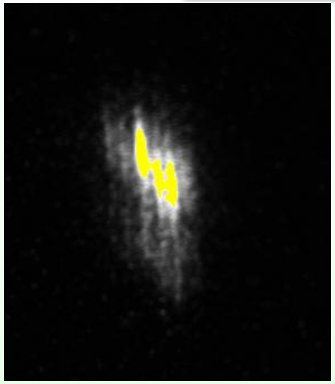
Experimental Diagnostic Layout

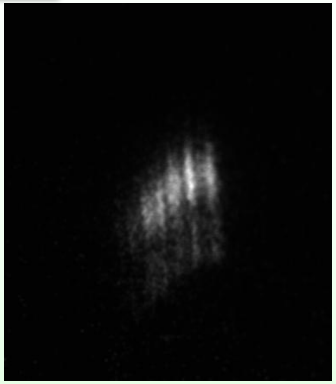
TITAN Laser Facility LLNL

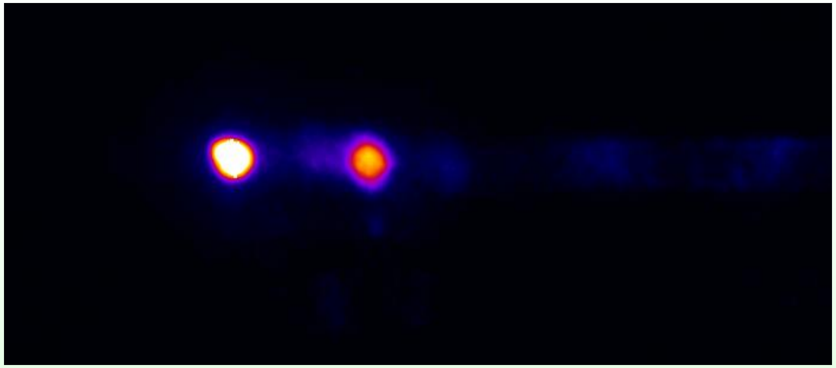


Brillouin, Raman and 3/2 ω Streaks

Time　　5nm　　← Wavelength　　**100**nm







SBS (fast streak)
111102s01
Stretcher at -22ps

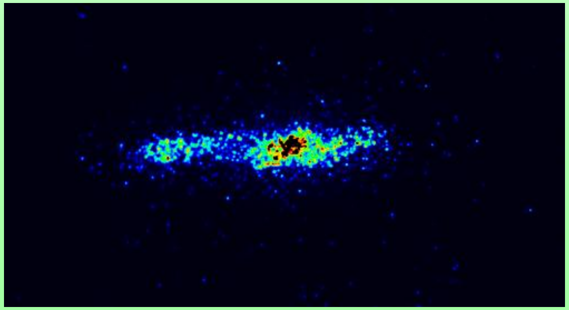
SBS (fast Streak)
111102s02
Stretcher at +20ps

SRS (slow streak)
111102s01
Stretcher at -22ps

Backscatter levels of:
~ 10-20% for SBS
~ 10-15% for SRS

5nm

Time



3/2 w_0
111103s08
Stretcher at +20ps

Conclusions

Shock ignition

- Initial experimental data is encouraging
- However it is still early days for this proposed technique and much more experimental work is required

The Way Forward

- NIF has a reasonable probability of reaching ignition by 2015 via indirect drive
- CEA has a the next chance of reaching ignition by 2020 via indirect drive
- Polar direct drive on NIF has a chance of reaching ignition by ~2018 if funded
- Advanced Ignition Techniques are under development reducing laser energies by 2–5 x
- Shock ignition with polar direct drive could be possible on NIF or LMJ by ~2018-2020 if funded

The Way Forward

- Must finish the job of reaching ignition
- Must finish investigating the scaling of advanced ignition techniques
- Must develop comprehensive 3D modeling simulations of full system interactions
- U of A investigating scaling issues for advanced ignition conditions

Next Steps

- Identify and develop key technologies required for demo reactor
  - High efficiency, rep rate lasers
  - Reactor wall materials
  - Tritium handling and breeding
- Design demo reactor system
  - LIFE reactor design from LLNL
  - HiPER design in Europe
  - LIFT design in Japan

Role for Canada

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

Conclusions

- Laser Fusion Energy probably will be demonstrated some time between 2014 to 2020
- Fusion energy will significantly change the energy supply equation and eventually Canada's role as an energy leader in the world
- Canada should be prepared for this game changing development
- We need to start preparing now for this future

Questions and Discussion?

Thank You