High Power Laser for Energy Research

Conceptual/Artistic View
Obtain fusion energy from a freely expanding plasma
Fusion conditions maintained due to the inertia of the plasma
A containable yield requires a few mg of DT which means that the initial density must be 1000 times that of DT ice

$$n \propto m/R^3, \quad \tau \propto R \quad : \quad n\tau \propto m/R^2$$
By 2011 the National Ignition Facility (NIF) in the US should demonstrate gain with laser fusion
Objective is a gain of 10
Will be the first demonstration of gain from fusion without the use of a fission bomb
ICF has already achieved gain using the X-rays produced in underground tests to implode spheres in surrounding chambers
At NIF they have already designed the cover of Time magazine 2011!
**Laser MégaJoule (LMJ) in France will follow suit a few years later**
Very similar to NIF
192 laser beams will deposit 1 MJ in a U/Au cylinder (hohlraum) in a few ns producing X-rays that will implode a hollow sphere lined with DT ice.
Fusion on NIF

High Power Laser for Energy Research
The not so good news ...

High Power Laser for Energy Research

- NIF and LMJ cost $\sim 10^{10}$ €
- NIF and LMJ are military projects primarily intended to substitute underground tests
- The gain will be ten times too small for a power station which will require a gain of 100
- NIF and LMJ will shoot once a day whereas a power station will need to shoot at least once a second
There are more efficient methods

High Power Laser for Energy Research

- Direct Drive: using the lasers to heat the sphere directly halves the energy needed (Gekko and Omega)
- NIF and LMJ use indirect drive because X-rays are tried and tested and are the basis of H-bombs
- Fast Ignition: using PetaWatt lasers to initiate fusion in a small hot spot could further lower the energy
- Conventional ICF requires an implosion velocity sufficient to heat the fuel to fusion conditions when the walls collide, if this is not necessary less energy is required for compression
- In conventional ICF the hot spot has a lower density than the rest of the fuel since it is in approximate pressure balance, requiring more energy in the hot spot. The heating in fast ignition could be more efficient
Fast Ignition

Experiments at Osaka and very recently at Omega have shown 20% coupling of laser energy to a compressed sphere using a gold guide cone. Had only a tenth of the energy we think is necessary. NIF plans to install PW beams to study fast ignition and might reach a gain of 100 this way.

The Origins of HiPER (‘04)

Could direct drive and fast ignition reach a gain of 100 with less than 1 MJ?
Preliminary Calculations

High Power Laser for Energy Research

Cost ~ $10^9$ €; 10% of NIF, LMJ

300 kJ in the compression lasers and 70 kJ in the ignition lasers should do the trick
3. Some Science...

The Basics of ICF
Fast Ignition
What we do on Fast Ignition
Basics of ICF: Thermonuclear Fusion

• To produce energy from thermonuclear fusion of DT we need to maintain at least keV temperatures until a significant fraction has “burnt”
  - \[ D + T \rightarrow ^4_2\text{He}(3.5\text{MeV}) + n(14.1\text{MeV}) \]
  - For any other fuel the requirements in temperature and time are far more stringent

• At this temperature all materials are plasmas so the fuel cannot come into contact with the reactor vessel
  - Confine the fuel away from the walls with magnetic fields
    • Magnetic Confinement Fusion or Magnetic Fusion Energy
  - Let the fuel expand freely in the middle of the vessel
    • Inertial Confinement Fusion or Inertial Fusion Energy
Basics of ICF: Confinement Time

• A free plasma will expand at the adiabatic sound speed $c_s$, so we define the “confinement” time to be

$$\tau \sim \frac{R}{c_s} = R \left[ \frac{3m_i}{5kT_e} \right]$$

• where $R$ is the initial size of the plasma

• We will crudely assume that during this time the temperature and density are constant and that after this fusion ceases
  – The only real justification for this is that more detailed models give similar results
Basics of ICF:
Burn Fraction

• The burn rate is given by

\[ \frac{dn_i}{dt} = -\frac{n_i^2}{2} \langle \sigma v \rangle \]

• Where \( n_i \) is ion number density, \( \sigma \) is cross section, \( v \) is velocity and \( \langle \rangle \) indicate the average over a Maxwellian distribution.

• Using our crude confinement time model the burn fraction is given by

\[ f = \frac{\rho R}{\rho R + 2 m_i c_s / \langle \sigma v \rangle} \]

• Where \( \rho \) is \( m_i n_i \) (standard notation in ICF is \( \rho \) rather than \( n_i \)).

• The crucial parameters of ICF are \( \rho R \) and \( 2 m_i c_s / \langle \sigma v \rangle \)
Basics of ICF:
The Burn Parameter

• $2m_i c_s / \langle \sigma v \rangle$ is known as the burn parameter

• For DT at 10 keV it is 62.8 kg m\(^{-2}\) (6.28 g cm\(^{-2}\))

  $f = \frac{\rho R}{\rho R + 62.8}$

  – Numerical modelling confirms this for $\rho R > 62.8$ kg m\(^{-2}\), at lower values the burn is lower than predicted by this formula

• ICF requires a $\rho R$ greater than 62.8 kg m\(^{-2}\)
Basics of ICF: The Need for Compression

• The density of frozen DT is 200 kg m\(^{-3}\), so a \(\rho R\) of 63 kg m\(^{-2}\) gives a radius of 0.31 m and a mass of 25 kg

• The yield would be 4.2 PJ = 1 Megaton of TNT

• To give a containable yield the mass cannot exceed 10 mg, giving a radius of 190 \(\mu\)m and a density of \(3.2 \times 10^5\) kg m\(^{-3}\) (\(10^{32}\) ions m\(^{-3}\)), 1600 times solid density
  – This can be reduced by surrounding the fuel with a heavier element (tamping), but even with the heaviest elements this cannot remove the need for compression, and if the fuel has to be compressed it is very difficult to avoid mixing, which leads to high bremsstrahlung loses
Basics of ICF: Compression

• Compression is achieved by ablation of a thin spherical shell (plastic or Beryllium) lined with DT ice
  – The reaction force pushes the shell inwards
  – Ablation pressure \( P_A \propto (I_{\text{abs}}/\lambda)^{2/3} \)
    • Where \( I_{\text{abs}} \) is the absorbed driver intensity
  – The minimum internal energy of the compressed fuel is achieved if its degenerate, giving
    \[
    U = 58 \left( \frac{\rho R}{60} \right)^{5/3} \left( \frac{R}{10^{-4}} \right)^{4/3} \text{kJ}
    \]
  – Radiation absorption ~ 70 – 80% and hydrodynamic efficiency ~ 15% so the driver energy must be at least 10 times this value
  – 1000 times compression has been achieved
Basics of ICF: X-ray Drive

• Short wavelengths give a greater ablation pressure but must be absorbed by a solid → X-rays
  – Can be generated by heating a high Z cavity (hohlraum) with laser or ion beams (not yet possible), by a wire array Z-pinch or by fission (H-bomb, underground tests)

Laser Driven Gold Hohlraum (NIF, LMJ)
Laser to X-ray conversion efficiency ~ 60%

Sandia Z-machine
2 MJ, 290 PW, 400 times compression
Basics of ICF: Direct Drive

• Can irradiate directly with laser or ion beams
  – Almost twice the efficiency but uniformity a problem
  – Ion beams cannot yet achieve the required intensity
  – Need a laser wavelength < 0.5 µm
    • Third harmonic in glass (preferred option) or KrF
  – Nothing to do with bombs (NIF and LMJ are military projects)

Direct drive on the Omega 60 beam, 40 kJ laser at Rochester, US.
Basics of ICF: Ignition

- When the shell stagnates on axis the kinetic energy will be converted to heat and the driver will start to heat the target leading to ignition.
Basics of ICF: Hotspot Ignition

- It is not necessary to heat all of the fuel, it is enough to heat a region with a $\rho R$ of 4 kg m$^{-2}$ ($cp$ 60 kg m$^{-2}$)
  - Sufficient to stop the alpha particles generated so that it self-heats and the burn spreads (like using a match)
  - Lower ignition and implosion energies = higher gain
- Could be achieved by driving shocks into the target using careful control of the compression beams
  - Since this occurs on a hydrodynamic time scale pressure balance must be maintained (isobaric) so the hotspot must have a lower density, making it less efficient than ideal isochoric (equal density) ignition
- Isochoric ignition requires heating in a time less than the hotspot confinement time - **Fast Ignition**
Fast Ignition: Proposed Ignitors

• Laser generated electron beam
  – A laser accelerates electrons from the corona into the core
    • The “conventional” scheme

• Laser generated ion beam
  – A laser accelerates ions from a solid target
    • Suggestions include accelerating a thin layer on the back of a thicker target and directly pushing a thin layer

• An ion beam
  – Does not yet exist

• A high velocity macroscopic object (impact ignition)
  – Suggestions include a pellet or a section of the shell separated by a cone
    • Driven by ablation, explosives or other means
Fast Ignition: Schemes with Cones

- The fuel is compressed in a high mass number cone
  - The ignition beam does not have to propagate in the corona
  - The ignition laser interaction conditions can be controlled
  - The ignition beam might be generated closer to the core
  - The compression energy is lowered
  - The compression might be reduced
  - The cone material might mix with the fuel
A gold cone in a glass microballoon used in experiments at Osaka
Fast Ignition:
The Numbers

• The minimum temperature is 10 keV

• The maximum heating time is: \( t = 15 \left( \frac{4 \times 10^5}{\rho} \right) \) ps

• The minimum hotspot radius is: \( R = 12 \left( \frac{4 \times 10^5}{\rho} \right) \) \( \mu \)m

• The minimum hotspot energy is: \( U = 4.6 \left( \frac{4 \times 10^5}{\rho} \right)^2 \) kJ

• The minimum heating power is: \( P = 0.15 \left( \frac{4 \times 10^5}{\rho} \right) \) PW
Fast Ignition: 
A First Estimate

• Assume 50% laser absorption, 25% coupling to the hotspot, the maximum pulse duration, a spot radius equal to the hotspot and $\rho = 4 \times 10^5$ kg m$^{-3}$ ($10^{32}$ m$^{-3}$)
  – Laser pulse duration 15 ps
  – Laser spot radius 12 µm
  – Laser energy 37 kJ
  – Laser power 1.2 PW
  – Laser intensity $2.7 \times 10^{24}$ W m$^{-2}$

• For electrons the mean energy must be less than 2 MeV if the majority are to deposit their energy in the hotspot. Assuming ponderomotive scaling
  – Laser wavelength 0.26 µm ($I\lambda^2 0.18$ TW)
  – Too Small
Fast Ignition: The Central Question

• What fraction of the laser energy can be coupled to the hotspot?
  – Without using a wavelength less than 0.35 µm
    • Ideally 1 µm
  – If you can’t exceed 10% you might as well put the energy in the compression beams
Main features of a compressed target
1. **Review of laser concept**
   1. Coherence
   2. Conventional laser chains

2. **Types of X-ray lasers**
   1. Plasma-based X-ray lasers
   2. High Harmonic Generation
   3. X-ray Free Electron Lasers
   4. Second generation X-ray lasers

3. **Examples of applications**
Introduction: aspects of coherence. I: Light as wave

From Maxwell equations => e.m. Wave equation in vacuum

\[ \nabla^2 E - \varepsilon_0 \mu_0 \frac{\partial^2 E}{\partial t^2} = 0 \]

\[ v = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = c \]

Speed of light

Spectral decomposition in Fourier series of solutions of plane waves

\[ E(r,t) = E_0 e^{i(k \cdot r + \omega t)} \]

Onda plana segundo $k \cdot r$

\[ \begin{align*}
  k &= \frac{2\pi}{\lambda} \\
  \omega &= \frac{2\pi}{T}
\end{align*} \]

sentido em relação a $k$
There is no means of following $E(r,t)$ - just intensity

Ex: T for HeNe is 2fs

Use of intensity is non-linear!

Relationship between field and intensity [energy/surface/duration]
Introduction: aspects of coherence

Equation for interference

\[ E_1 = (I_1)^{\frac{1}{2}} e^{i\varphi_1}; \quad E_2 = (I_2)^{\frac{1}{2}} e^{i\varphi_2} \]

\[ I = I_1 + I_2 + 2(I_1 I_2)^{\frac{1}{2}} \cos(\varphi_1 - \varphi_2) \]

\[ \varphi_1 = k_1 z - \omega_1 t \]
\[ \varphi_2 = k_2 z - \omega_2 t \]

Interference reveals the correlation between two waves (spatial and/or temporal)
Only coherent sources exhibit diffraction

Diffraction occurs when light interferes with object of size comparable to wavelength

Applets found in http://www.falstad.com/mathphysics.html

There is a well known relationship between diffraction pattern and object:

**Fourier transform**
To understand X-ray lasers

1. What’s a laser
2. What are X-rays
LASER is an acronym for Light Amplification by the Stimulated Emission of Radiation.

In 1917, Albert Einstein was the first to postulate the existence of Stimulated Emission, the process that makes lasing possible.
What is simulated emission?

Photon from simulated emission is an exact replica of the incident photon.
Keeps wavelength (energy), direction, phase, polarization

=> Stimulated emission is intrinsically coherent phenomenon.
How to make a laser, I
Population inversion

Aligning several emitters, a cascade of photons is stimulated.
How to make a laser II
Use of cavity; laser chain

Oscillator

![Diagram showing laser cavity and amplifying medium]

Usually several amplification stages
+optics
With lasers radiation: highest intensities ever achieved

Intensity on target:

\[
\text{Intensity} = \frac{\text{Energy}}{\text{Pulse Duration} \times \text{Surface}}
\]

Ideal source:
Pulse duration limited by Heisenberg relation
\[
\Delta E \Delta t \geq \frac{\hbar}{2\pi}
\]
Spot size diffraction-limited:
\[
d = 2.44 \lambda \frac{f}{a},
\]

IR lasers: 300fs, 100J, 10\(\mu\)m spot: \(10^{20}\)W/cm\(^2\)
With lasers radiation: highest intensities ever achieved
• Short pulse duration (femtosecond) unlike synchrotron
  ⇒ Biology, pump-probe experiments, plasma physics
• Strong energy (~mJ)
  ⇒ Biology, plasma physics, High XUV Fields
• High spatial coherence + good wavefront
  ⇒ XUV Holography, XUV interferometry, micro-focussing
• Polarization
  ⇒ Atomic physics, spatial filtering
• High repetition rate
• Short wavelength is often better
Going further in electromagnetic spectrum

Semantics:
soft X-rays
With X-rays we can see the invisible

Few materials are transparent at visible light, most are transparent for X-rays

Visible: 400-700nm: 1/2 micron
Order of magnitude: Cell

X-rays: $10^{-10} \text{m} (10\text{nm}-\text{Å})$
Order of magnitude: Molecule, Atom
X-ray basics: handling X-rays

X-ray optics:
1. Mirrors do not work at normal incidence
X-ray basics: handling X-rays

X-ray optics:
2. Multilayers/Bragg lenses do work at 90º

\[ m\lambda = 2d \sin(\theta_m) \]
X-ray basics: handling X-rays

X-ray diffraction: Bragg crystals

\[ M\lambda = 2d\sin(\theta_m) \]
X-ray detection: films or CCD
1. Review of laser concept
   1. Coherence
   2. Conventional laser chains

2. Types of X-ray lasers
   1. Plasma-based X-ray lasers
   2. High Harmonic Generation
   3. X-ray Free Electron Lasers
   4. Second generation X-ray lasers

3. Examples of applications
X-rays are naturally present in plasmas

Natural plasmas
Hot plasmas are highly ionized.

![Graph showing ionization levels of different elements]

**Nomenclature**

<table>
<thead>
<tr>
<th>Element</th>
<th>Li</th>
<th>Be</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>F</th>
<th>Ne</th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>C</th>
<th>Ar</th>
</tr>
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</table>

1 eV ~ 11500°C
Transitions between internal layers have >keV energy (X-rays)

K emission

K absorption

1.5 keV

7.8 Å
Under special conditions plasmas can produce X-ray lasers.

2 mechanisms of population of superior level - electronic collisions - ionization

Emptying of the lower level
Very fast

Full shell: stable ion, Abundant, for different ne/Te conditions

FIG. 3. Simplified Grotrian diagram of Ne-like Ge showing the laser transitions of interest and the dominant excitation and deexcitation processes responsible for the creation of population inversions between the 3p and 3s levels. The laser levels are labeled in both LS and jj notations. (See C. Keane, Ref. 54.)
What are favorable conditions for population inversion

1. Challenge for atomic physicists: find suitable ion and transition

<table>
<thead>
<tr>
<th>Atomic number and symbol of the Element</th>
<th>Wavelengths (nm)</th>
<th>Scheme</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>76Au</td>
<td>3.36</td>
<td>Ni-like</td>
<td>MacGowan et al 1992</td>
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<tr>
<td>74W</td>
<td>4.32</td>
<td>Ni-like</td>
<td>MacGowan et al 1992</td>
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<td>73Ta</td>
<td>4.48</td>
<td>Ni-like</td>
<td>MacGowan et al 1992</td>
</tr>
<tr>
<td>72Hf</td>
<td>4.65</td>
<td>Ni-like</td>
<td>Daido et al 1999b</td>
</tr>
<tr>
<td>70Yb</td>
<td>5.609, 5.026</td>
<td>Ni-like</td>
<td>MacGowan et al 1988</td>
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<td>67Ho</td>
<td>5.63, 6.20</td>
<td>Ni-like</td>
<td>Daido et al 1999b</td>
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<tr>
<td>65Dy</td>
<td>5.85, 6.41</td>
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<td>63Tb</td>
<td>5.9, 6.7</td>
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<td>Daido et al 1997</td>
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<td>64Gd</td>
<td>6.33, 6.86</td>
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<td>Daido et al 1999b</td>
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<td>63Eu</td>
<td>6.583, 7.100</td>
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<td>Lu et al 2002</td>
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<td>13.89</td>
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<td>46Pd</td>
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<td>42Mo</td>
<td>18.90</td>
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<td>41Nb</td>
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<td>40Zr</td>
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<td>Li et al 1998</td>
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<td>38Y</td>
<td>24.01</td>
<td>Ni-like</td>
<td>Li et al 1998</td>
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<td>36Kr</td>
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<td>Sebban et al 2001b</td>
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<td>47Ag</td>
<td>9.9963, 10.0377</td>
<td>Ne-like</td>
<td>Fields et al 1992</td>
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<tr>
<td>42Mo</td>
<td>10.64, 15.10, 15.27</td>
<td>Ne-like</td>
<td>MacGowan et al 1987b</td>
</tr>
</tbody>
</table>
2. Find the suitable experimental conditions

Often requires multiple pulses of different duration

300ps after the peak of a 300ps duration background pulse of peak irradiance $2 \times 10^{13} \text{Wcm}^2$ is incident onto the target.

Once population inversion is achieved, a long medium is used.
Once population inversion is achieved, a long medium is used.

Radiation transfer

\[ \frac{dI(\nu)}{dz} = G(\nu)I(\nu) + E(\nu) \]

Spontaneous emission rate

\[ E(\nu) = N_u A_u f(\nu) \hbar \nu \frac{\Omega}{4\pi} \]

Gain including stimulated emission probability

\[ G(\nu) = \sigma(\nu) \left( N_u - \frac{g_u}{g_1} N_1 \right) \]

Figure 12. The measured variation with length of the output of Ni-like Sm at 7.3 nm pumped with double 75 ps pulses (data points) (taken from Lin [93]). The solid curve is a fit of equations (43) and (45) with \( R = 10^{-6} \) and \( g_0 = 9.5 \text{ cm}^{-1} \).
Once population inversion is achieved a long medium is used

Although it is coherent (not fully)
The source is not a mode-locked laser:
No cavity, just ASE
Starting from noise!
Advantages
- Very energetic (up to 10mJ - $10^{12}$ph)
- relatively short (down to 2 ps)

Disadvantages:
- Poor optical quality
- Not very “hard” : limits to <4nm