Fast Ignition Review

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Fast Ignition Review

I. Promise of Fast Ignition (FI)

II. The Reality of FI: Issues

III. Focused Efforts on Issues Yield Progress

IV. Current Aggressive Efforts on Divergence

V. Forward Leaning: Plans, Milestones, Metrics

VI. Summary & Conclusions
“CHS” vs “FI”

Central Hot Spot (CHS) Ignition
Isobaric-hot spot from implosion

Fuel Spark
1000 gcm^{-3} \rho_r = 3.0 gcm^{-2}
100 gcm^{-3} \rho_r = 0.3 gcm^{-2}

Fast Ignition (FI)
Isochoric-fast heating

Heat in \(2 \times 10^{-11}s\)

Density
Temp

Fuel Spark
300 gcm^{-3}

300 gcm^{-3}
FI Potentially Has Advantages over CHS

FI is conceived as a “2nd Generation Scheme” for ICE

A Gain ~100 at a compression energy of 1MJ is ideal for IFE
Ignition Schemes in FI

- **Electrons (hole-boring)**
- **Electrons (cone-guided)**
- **Protons**
- **Ions**

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**High Energy Density Physics Group**
**Scarlet Laser Facility (SLF)**
Principle Steps in Cone-Guided FI

1. Compress DT fuel to high $\rho$, $\rho R$ around cone tip; cone tip must survive Gbar implosion pressure

2. Relativistic laser interaction ($I>10^{20} \text{ W/cm}^2$) & electron generation

3. Relativistic electron transport in HED plasmas; collective transport, filamentation, core heating & burn

0.5-1.5 MJ, 20ns compression drive

100-200 kJ, 20 ps ignitor pulse

No code capability currently exists that can model this physics self-consistently; FI program is developing ability to link codes
Min. Ignition Energies (Atzeni 1999)

- Ignition requirement is $\rho r_h < 1.2 \text{g/cm}^2$, $T_h \geq 12 \text{ keV}$
- **Parallel beam of particles** with constant stopping power and range are injected into DT sphere
- Pulse Length Required: $\sim 20 \text{ psec (at 300g/cm}^3)$

![Diagram showing energy vs. power and energy vs. intensity graphs with DT density and uniform density](image)

$20 \text{ kJ Ignition depends on this spatial input of energy}$
## First Hot Electron Yield Enhancement

### Gekko XII (2002)

<table>
<thead>
<tr>
<th>Gekko XII Laser Facility</th>
<th>CD shell + Au cone</th>
<th>Neutron yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 kJ, 1.2 ns flat top pulse, $2\omega$ compression</td>
<td>7 µm CD shell, 500 µm diameter</td>
<td>1000x increase in neutron yield with ignitor pulse</td>
</tr>
<tr>
<td>350 J, 0.5 ps ignitor pulse</td>
<td>Imploded core reaches ~ 50-100 g/cm³ and 30-50 µm diameter</td>
<td>Temp increase from 400 eV to 800 eV</td>
</tr>
</tbody>
</table>

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**Graph:**
- Neutron yield vs. Heating laser power (PW)
  - 30%
  - 15%

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Many Active FI Programs World-wide

US FI Programs
- FSG
- Fusion Energy Sciences
- Los Alamos National Laboratory
- University of Rochester
- General Atomics
- UCLA
- MIT
- UCSD
- Ohio State University
- University of Nevada
- University of Texas
- ILSA
- LLNL
- Los Alamos

Electron FI

Intl. FI Programs
- HiPER
  - Rutherford Appleton Lab
  - LULI
  - Universita di Roma
  - Imperial College, UK
  - University of York, UK
  - Queens Univ., Belfast
  - CEA, France
  - IST, Lisbon
  - UPM, Madrid, ...
  - ILE, Osaka University

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Issues:

- **SCIENTIFIC**
  - Divergence of hot electrons
  - Compression of Target with Cone

- **TECHNOLOGY**
  - Facilities
  - Target Fabrication
  - Ignition Laser Driver
Science Issue: Electron Divergence

X-ray image

CCD
Kα (10 μm res.)
Laser
Kα fluor
Bragg crystal

Full divergence cone angle 40°

Fluor depth

Divergence depends weakly on Intensity

Intensities (Wcm⁻²)

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Scarllet Laser Facility (SLF)
PIC LPI followed by hybrid charge transport calculations predict that the average divergence angle in hot DT is 52°.

Because of this large divergence, the “point design” is pushed towards having the hot electron source as close to the compressed core as possible. Under any reasonable cone-core offset scenario, the modeling result is that the ignition energy required jumps from ~20kJ for collimated electrons to well over 200kJ.

As we discuss below, control of the hot electron divergence is THE major physics and technology issue confronting FI.
Technology Issue: Facilities

1 MJ Compression
100 kJ Ignition

Sub-Ignition
Experimental Facilities

Experimental Facilities
For Benchmarking Codes
Science Issue: 2D Hydro Design

INDIRECT DRIVE
- DT mass = 2.75 mg
- Peak density 310 g/cc
- Drive 1.4 MJ
- **Gain = 106**
- Stand off 110 µ of cone tip from core

Source

Ignite
OMEGA-EP BACKLIT IMPLOSION

- EP-Backlight Compton
  Radiography @ 100 keV
- Empty CD Shell, 40μ thick
- Reentrant Cu Cone
- ρR ~180mg/cm²
Technology Issue: Cones (current GA)

- High Z metal parts
- Foam-lined plastic shells
- Robotic assembly
- LIFE (indirect drive) targets: costed **@$0.30/target** delivered

Stampeded Au cones

4 mm dia foam DVB shells

Cone shell targets assembled with ±10 um accuracy
Full Scale short-pulse laser driver

- Energy TBD (at least 100kJ)
- Pulse Length 20psec
- Possible 2w conversion
- High Contrast ratio
- Wall-Plug Efficiency
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Focused Efforts: Advanced Modeling

3D kinetic PIC (High Resolution)

- PSC PIC code laser absorption
- LSP, ZUMA hybrid codes electron transport

- LASNEX, HYDRA rad-hydro codes implosion & burn
- 2D/3D rad-hydro (hydrodynamics, radiation transport, ionization kinetics, burn, etc.)

3D hybrid transport (kinetic fast electrons with fluid background plasma)
Focused Efforts: Advanced Modeling

- 200kcpu-h @2048 cpus on ATLAS
- Simulate 40 μm diameter laser pulse for 2 ps duration
- $I = 1.4 \times 10^{20} \text{ W/cm}^2$, 120x160 μm box, 50 cells/μm, 32e+32i ppc

These simulations provide the first realistic electron source distributions for subsequent transport calculations.
Focused Efforts: Advanced Modeling

- 3D simulation initialized with axisymmetric profiles at beginning of electron pulse
- 47.7 million zones in HYDRA mesh with 100 million IMC photons run on 1024 processors
- 36 million zones in Zuma mesh – 1 μm resolution on each mesh

Fully integrated 2D/3D capsule implosion, core heating and burn simulations

Electron energy deposition rate
Many Groups Contribute to Modeling

PSC-ZUMA-HYDRA (LLNL)
- PSC PIC code laser absorption
- ZUMA hybrid code electron transport
- HYDRA rad-hydro implosion & burn

LSP (Voss, LLE, OSU, UCSD)
- Graphs showing data with color scales

PICLS (UNR, Reno)
- Graph showing data with a color scale

OSIRIS (ULCA/IST)
- 3D model with data visualization

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High Energy Density Physics Group
Scarlet Laser Facility (SLF)
Fast Electron Core Heating at OMEGA EP

Demonstration of fast electron core heating under well understood conditions
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Control of Hot Electron Divergence

Whether fast electron FI is viable depends on what happens to the hot electrons in this region.

If they leave the cone tip collimated, a point design with ignition energies < 100kJ is likely.

If they leave the cone tip spread into $2\pi$, NO reasonable point design is possible.

TWO DIRECTIONS FOR MODELING AND DESIGN:

- External Magnetic Fields
- Self-generated Resistive Magnetic Fields
Divergence: Applied B Fields

Energy of Input Electrons = 40 kJ

<table>
<thead>
<tr>
<th></th>
<th>Energy coupled to the “ignition region”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu cone</td>
<td>2.7 kJ (7%)</td>
</tr>
<tr>
<td>Al cone with Cu Insert</td>
<td>4.5 kJ (11%)</td>
</tr>
<tr>
<td>Al cone with Cu wire</td>
<td>18 kJ (45%)</td>
</tr>
</tbody>
</table>

Electron collimation by B fields generated by resistivity gradients

\[
\frac{\partial B}{\partial t} = \eta \nabla \times j_h + \nabla \eta \times j_h
\]
Divergence: Applied B Fields

External magnetic field amplified by compression

\[ B_{\text{final}} = B_{\text{seed}} \left( \frac{R_{\text{initial}}}{R_{\text{final}}} \right)^2 \]

Place target in seed field of 0.05 MG; during implosion the core will effectively compress the field region by \(~30\) yielding B during hot electron transport \(~50\) MG

If details of \(B_{\text{initial}}\) configuration can be worked out, FL at 100 kJ appears possible

<table>
<thead>
<tr>
<th>Color</th>
<th>(B_{\text{z0}}) [MG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
</tr>
<tr>
<td>Red</td>
<td>10</td>
</tr>
<tr>
<td>Green</td>
<td>30</td>
</tr>
<tr>
<td>Magenta</td>
<td>50</td>
</tr>
</tbody>
</table>

48 micron spot at 0.53 µm on 450 g/cc >Atzeni opt. 27 µm
Proton FI Concept

Proton FI
Shell-in-cone

Experimental Demonstration
Focused Proton Isocoric Heating

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Proton FI has only recently been subjected to the same level of scrutiny as electron FI

Potential:
- Laser: elec eff. ~80%
- electron: proton eff. ~30%
- Proton frac in hot spot ~30%
- Laser energy for ignition ~180kJ
- Requires, e.g. 2x1020 Wcm^-2 on 200 μm diameter for 4 ps at 1.06 μ
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Going Forward: Short Term Objectives

CODE DEVELOPMENT

- Integration PIC with Hydro 3D/2D
- EOS and Ionization, material properties in transport codes

MODELING

- Long Pulse (Hydro—cone survival)
- Short Pulse LPI (prepulse), Direct Comparison to Experiment
- Direct Support of Point Design Effort

EXPERIMENT:

- Electron Generation and Transport at EP Conditions
- $1\omega$ vs $2\omega$ Dependence of LPI (pre-pulse effects)
- Direct Experiment/Full Scale Modeling (Benchmark)
FIVE YEAR METRICS:
- “HARD” Point Design from Fully Integrated Modeling
- Sub-Critical Integrated Tests on Omega-EP
- Full Scale Hydro compression on NIF

TEN YEAR METRICS:
- Design, Construction and Test of Modules for Ignition Laser
- Test at Full Scale Compression (NIF) → Sub-Ignition (NIF_ARC)
- Capsule Design Realized on Production Scale

TWENTY YEAR METRIC:
- Design, Construction of FI-IFE Power Plant
Fast Ignition continues to hold great promise for IFE
  Fundamentals of intrinsic high gain and relaxed target specs are significant and
  worthy of intense research efforts

Initial implementation of FI concepts, ones that encouraged speculation
  of problem-free development, were overly optimistic
  Nearly 10 years of International Effort has led to paths for solutions to problems;
  only in the last 3 years have we seen the computational and
  experimental capabilities to analyze FI issues competently

Fast Ignition research draws from and leverages 50 years of NNSA
  investment
  Computational and Laser Facilities needed for advances are in place;
  NIF and Omega-EP (both existing) will validate core heating and compression
  prior to any high gain demonstration

Fast Ignition research has a large, scientifically vigorous academic base
  that feeds NNSA's workforce
  FI research gave birth to HEDP science in many universities world-wide
Bibliography

Concept and Basics

Energy Requirements
S. Atzeni, “Inertial fusion fast ignitor: igniting pulse parameter window vs the penetration depth of the heating particles and the density of the precompressed fuel,” Phys. Plasmas 6, 3316 (1999).

Technical/science status


Advanced Modeling