Fast Ignition Program

E. Michael Campbell

- Promise
- Status
- Challenges
- Implementation
- Plan

Presented at
FESAC Development Path Panel
General Atomics

January 14, 2003
The original FI concept uses laser generated MeV electrons to ignite DT fuel at about 300 g cm\(^{-3}\).

Hole boring or cone for laser to penetrate close to dense fuel

1 MeV electrons heat DT fuel to 10 keV

Pre-compressed fuel 300 g cm\(^{-3}\)

100 kJ, 20 ps

Fast ignition

Ignition spot energy

\[ E = 140 \left(\frac{100}{\rho}\right)^{1.8} \text{ kJ} \]

e.g. \( \rho = 300 \text{ g cm}^{-3} \), \( E = 17 \text{ kJ} \) in <20 ps

to \( r = 19 \mu\text{m} \) hot spot

at \( 7 \times 10^{19} \text{ W cm}^{-2} \)

Atzeni. Phys. Plasmas 6 3316 (1999)

Tabak et al. Phys Plasmas 1,1626,(1994)
Fast Ignition concept leads to an attractive system

- Low threshold to reach ignition
  ⇒ Use lower brightness drivers
- High gain for efficient power plant
- No central hot spot required - relaxes drive symmetry and target smoothness requirements - driver configuration and target fabrication advantages
- Compatible with any driver
Fast Ignition may allow longer wavelength laser implosion systems - The advantages are significant

- **Efficiency**
  - Typical energy efficiency for conversion of 1053 nm to 351 nm is 50% (NIF, Omega)

- **Aperture**
  - Damage threshold for 1053 nm is ~35 J/cm², 532 nm is 25 J/cm² and 351 nm is ~12-15 J/cm²

  2x the pulsed power (or diodes!)

  40%-70% reduction in aperture!
Allows flexible reactor development

- Relax construction constraints
  - Flexible drivers and driver locations
  - Possible self T-breeding
- Target injection
  - Not so temperature sensitive
  - Reentrant cone protects from hot gas
FI program leverages both NNSA and international capabilities

- **Laser coupling and transport (LLNL, LANL, LULI (France), RAL (UK), GEKKO (Japan))**
  - $E_{\text{laser}} \sim 140 \left( \rho/100 \right)^{-1.8} \eta^{-1} \text{ kJ}$

- **Compression (LLE, SNL, GEKKO, RAL)**
  - $E_{\text{comp}} \sim 1.4 \times 10^3 \rho^{-4/3} (\rho R)^3 \eta^{-1}_{\text{comp}}$

- **Integral experiments (GEKKO, RAL)**
U.S. Fast Ignition research is linked to world-wide effort

- Requires facilities with powerful short-pulse (ps) lasers
- Substantial programs in England, France, Japan
  - Japanese researchers are staking their program on it
- United States program is important
  - Nova was first PW in ‘96
  - Proceeding with DoE high energy PW initiative
  - Next-step PW facility at SNL, NIF, Omega

Central Laser Facility
Rutherford Appleton Lab, UK

Institute for Laser Engineering
Univ. of Osaka, Japan

GSI & Technische Universitat
Darmstadt, Germany

Max-Planck-Institut
Garching, Germany
Layered, planar targets have been utilized to study laser-plasma coupling and transport with 100 TW, 0.1 to 1 ps lasers.

- CCD
- Laser
- Bragg crystal
- Ti and Cu Kα (10 µm res.)
- Kα fluor
- Electrons
- CCD
- Planckian 18 nm XUV (5 µm res.)
- XUV mirror
Ignition energy transport requires more understanding

- Initial steps look good
  - Efficient electron production
  - Produce well defined beam
  - Can heat compact spot the size of $K_\alpha$ beam

- But beam and heated spot is much larger than the laser focal spot

---

**$K_\alpha$ imaging of electrons shows production of collimated beam**

**Thermal XUV shows 30 eV heating in 120 µm hot spot**
Resistivity dominates our current experiments but it will be negligible in full scale fast ignition

- Ohmic fields strongly affect electron transport in cold metals
- Facilities at Vulcan & Gekko allow testing in compressed plasmas

⇒ Currently developing new experimental geometries for such experiments
Fuel assembly targets with cones are a focus for FI research

- Shell/cone interface hydro entrainment of cone material
- Preheat of cone ahead of imploding shell
- Cone tip-dense core transport distance
- Avoidance of ‘hollow centre’ in compressed core
- Drive symmetry and surface smoothness requirements

Validate fuel assembly concepts in ‘hydro-equivalent’ targets
Fuel assembly seems straightforward

LLNL designed NIF scale capsule (absorbs ~180kJ*)
can be imploded to $<\rho R>_{DT} = 2.18 \text{ g cm}^{-2}$.
* expect 10% overall coupling efficiency, or better

- Basic target design works
  - Target compresses to ignitable mass in Lasnex
  - Initial expts show agreement with model
  - Other variations being tested at SNL and Omega

Expt at Omega

Omega expts match simulations

Blob has hollow core, is ~100 µm from cone.
Fuel assembly experiments with cone-focused targets leverage the OMEGA direct-drive program.

Direct-drive cone targets shot on OMEGA in FY02 (LLNL, GA)

FY02

FY03

FY05

Pinhole camera (H8)

The full suite of OMEGA diagnostics will be applied to these implosions.
A z-pinch driven fast-ignitor concept is being developed

- Z hohlraum designs should allow $\rho = 90-100$ g/cc, $\rho_r = 0.4$ g/cm$^2$
- Simulations for ZR with cryo-DT capsule give $\rho = 160$ g/cc, $\rho_r = 0.65$ g/cm$^2$

*D. Hanson, R. Vesey, et al., 6th Fast Ignitor Workshop, 2002*
Fast ignition imploded fuel designs are being validated with experiments on Z

- Preliminary image analysis agrees qualitatively with 2D simulations
- 2D simulations give polar-averaged peak $\rho = 60$ g/cc, $\rho_r = 0.3$ g/cm$^2$

D. Hanson, R. Vesey, et al., 6th Fast Ignitor Workshop, 2002
GEKKO laser: 12 green laser beams
$E = 10 \text{ kJ}$, $t = 1\text{-}2 \text{ nsec.}$
Uniform irradiation (phase plates) for high
density compression.
$I \approx 10^{14} \text{ watts/cm}^2$

PW laser: 1 beam ($\sim 400 \text{ J}$)
At 1 micron.
PW peak power is utilized for fast heating.
$I \approx 10^{19} \text{ watts/cm}^2
The experiments were carried out with a Au-cone CD shell. The CD shell was imploded with 9 beams of the GEKKO XII laser.

**Parameters for Integral Fast Ignition Experiments**

- **PW for heating**
  - 1 beam / 300 J
  - 1.053 µm / 0.5ps

- **GXII for implosion**
  - 9 beams / 2.5 kJ/0.53 µm
  - 1.2ns Flat Top w/ RPP

- **Au cone**
  - 30° open angle (the picture: 60deg)
  - Thickness of the cone tip: 5µm
  - Distance of the cone top: 50µm from the center

- **CD shell**
  - 500µm/6-7µmt

- **IL = 10^{19} W/cm^2**
Peta watt laser heating experimental results of cone guide target

Required timing is 50ps

800keV

IF/OV1
T.Yamanaka
Integral FI experiments are well matched by Simulations

By assuming 30\(\mu\)m\(\phi\) beam spot and 40% energy coupling efficiency from laser to REB

Heating Laser power, \(P_{lh} = I_{REB} \times \pi r_b^2 / \eta_h = 1.77E-5 \times I_{REB}\)

\(\frac{\text{Neutron Yield}}{\text{Heating Laser Power (PW)}}\)

\(\langle T_i \rangle \text{ [keV]}\)

\(T_h = 500\text{keV}\)

\(T_h = 2\text{MeV}\)

\(\circ\) Sub – MeV electrons play important roles in core heating.

\(\circ\)
Protons and ions are accelerated in relativistic laser-solid interactions by three principal mechanisms:

I. Thermal expansion
   \[ T_i \sim 5-10 \times T_e \]

II. Front-surface charge separation
   Static limit: \[ T_i \sim T_e \]

III. Target Normal Sheath Acceleration
   \[ E_i \sim 10 \times T_e \]
   - Electrons penetrate target & form dense sheath on rear, non-irradiated surface
   - Strong electrostatic sheath field ionizes surface layer
     \[ E_o \sim kT / e\lambda_d \sim MV/\mu m \]
   - Rapid (~ps) acceleration in expanding sheath produces very laminar ion beam
Proton ignition is a newer concept avoiding the complexity of electron energy transport.

- Same driver and fuel assembly options
- Novel physics of Debye sheath proton acceleration

- Simpler proton energy transport by ballistic focusing
- Larger laser focal spot-easier to produce

PW ION-Plasma coupling experiments have begun: 100TW, 100fs expt. at JanUSP shows proton focusing and enhanced isochoric heating of a 10 micron Al foil.

Streak images of visible Planckian emission.
A credible US pathway for FI progression from Concept Exploration to Proof of Principle is emerging.

- NNSA funds facility (incl PW)
- OFES funds specific science

**Proof of Principle**
- Multi-KJ PW laser added to Omega, ZR, NIF
- Demo significant core heating of relevant imploded fuel assembly

**Omega, ZR, NIF**

**Concept Exploration**
- Implosions
- Laser-plasma interactions
- Transport

**Multi-KJ Petawatt S&T**
- Gratings
- OPA’s
- Facility Issues
New DOE facilities proposed for FY06/07 would support a ‘proof of principle’ study of fast ignition

SNL Z Beamlet / Z

HEPW at NIF

Omega EP
Integrated 2-20kJ short pulse experiments will better define ignition requirements

- Revisit key physics issues at FI relevant intensities with order of magnitude higher short pulse energy and pulse duration
- Conduct 2 to 20 kJ HEPW integrated experiments with FI relevant resistive and other effects at new DOE facilities
- Develop integrated model- hydro and burn, hybrid PIC electron transport, 3D PIC interaction physics, relativistic propagation - use new teraflop computers
- Cryo target fabrication and cryo -experiments
- Design full scale ignition expts
Significant hurdles specific to fast ignition

- ~10 kJ short pulse lasers for ignition energy
  - High damage threshold gratings
  - Good focus
- Cone design
  - Generate electrons efficiently
  - Minimize contamination of fuel
- Target design
  - Allow efficient transport & heating
- Pointing and timing

Nuclear burn sensitive to e-beam spread

Simulated D-D neutron burn images

Laser μFocusing using a Conical Target

Contour plot of the square root of laser intensity
Efficient, **Damage resistant** dielectric gratings are required for FI
Proposed Roadmap for IFE by Fast Ignition

- **Concept exploration**
  - FY03

- **Proof of principle**
  - FY06

- **Ignition and IRE**
  - FY09

- **ETF**
  - FY12

- **NNSA HEPW lasers**
  - FY15

- **Integrated modeling**

- **Driver/power plant scenarios/designs**

- **IRE 10Hz HEPW**

- **Japan**
  - Firex I:
    - breakeven
  - Firex II:
    - Burn
FI Research would require a n OFES-NNSA Partnership

• Concept exploration
  – OFES: $3-5M/year for modeling, experiments, targets
  – NNSA: $5-10M/year to develop laser technology
    (damage resistant gratings), design PW facilities

• Proof Of Principle
  – OFES: $5-10M/year for modeling, experiments, targets
  – NNSA: Add multikilojoule PW lasers to Ω, Z, NIF (estimate $30-50M per facility)
NNSA has identified need for adding PW to existing facilities

- Radiography
  - High energy ($h\nu > 30$ keV) xray backlighting
  - Proton Radiography (under development)
- Ultra-high energy density physics
  - $P > 1$ Gbar
  - $T_R \sim 1$ keV
- Isochoric heating
  - Ions, high energy photons (under development)
Unused slides
**Goal:** Show sufficient physics agreement between modeling and experiment to propose PoP step

**Activities:**
- **Fuel assembly:** experiments and hydro modeling
- **Heating/Transport:**
  - Experiments, with conductivity and scattering closer to compressed DT plasma
  - Modeling of cone, of experiments
  - Evaluate “ion ignition”
- **Subscale modeling:**
  - 3D PIC (absorption, electron production)
  - Hybrid models benchmarked against experiments (electron transport)
Goal: Show integrated understanding of the gain curve, and of components required for IFE reactor design to give confidence in attractive reactor design

<table>
<thead>
<tr>
<th>Activities:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Integrated proof of principle experiments using the proposed NNSA HEPW facilities</td>
</tr>
<tr>
<td>• Integrated full scale models coupling hydro, optical properties, ignition and burn leading to an ignition target design</td>
</tr>
<tr>
<td>• Final Optics R&amp;D</td>
</tr>
<tr>
<td>• Target Fabrication R&amp;D</td>
</tr>
<tr>
<td>• Reactor Design Studies</td>
</tr>
<tr>
<td>• Demonstrate a full scale short pulse beamline</td>
</tr>
</tbody>
</table>
Goal: Demonstration of high gain targets and full design of reactor including target factory and injection system

Activities:
• High gain ignition
• Integrated Research Experiment for final optics and target injection
• Reactor engineering design
• Cryo targets with path to mass production
• Pellet factory engineering design
• Driver demonstration
OMEGA EP is designed to perform integrated fast-ignition experiments with cryogenic implosions

Channeling beam:
- $I > 10^{18}$ W/cm$^2$
- $E \sim 0.5$ to 2.6 kJ in 100 ps
- $r_{focus} \sim 15 \mu m$

Igniter beam:
- $I > 10^{19}$ W/cm$^2$
- $E \sim 0.5$ to 2.6 kJ in <10 ps
- $r_{focus} < 10 \mu m$

Fuel $\rho r$ up to 0.5 g/cm$^2$ and $\rho$ up to 500 g/cm$^3$
Simulations show that a 1-kJ, 1-MeV electron beam raises the $T_{\text{ion}}$ in the high-density fuel shell to $\sim 10$ keV.
Planned modification of NIF will provide a quad of HEPW beams in suitable for FI expts

Indirect drive configuration

Existing beam path conversion concepts

Indirect drive port

Equatorial ports for HEPW

Original NIF

HEPW adapted NIF
A ‘proof of principle’ FI experiment at NIF has been designed in detail using Lasnex modeling.

250kJ Hohlraum drive with 8 fold 2 cone symmetry (8 quads per LEH)

CD shell 740 μm radius, 160 μm wall Imploded to 45 μm radius, 250 gcm⁻³ ρr =1.0 gcm⁻²

4 HEPW ignitor beams total of 20kJ, 20ps driving electron or proton ignition
Direct-drive ignition and fast ignition may be possible on the NIF with the indirect-drive beam configuration.

Aitoff projection of intensity on a capsule:

NIF direct-drive distribution using 24 ($\times$4) beams in indirect-drive illumination

\[ \sigma_{\text{rms}} = 48\% \]
\[ \text{peak-to-valley} = 157\% \]

NIF direct-drive intensity distribution with 24 ($\times$4) beams repointed to a pattern similar to OMEGA 24

\[ \sigma_{\text{rms}} = 6\% \]
\[ \text{peak-to-valley} = 22\% \]

The penalty from asymmetric illumination may be mitigated by the clever use of phase plate design, beam pointing, pulse shaping, and ice layer/capsule shimming.
Pulsed power—a new testbed for xray driven fuel assembly FI studies

- Rapid Progress in Z pinch physics has provided ~2MJ and ~200TW of xrays for fuel assembly
- The Beamlet laser from LLNL has been successfully coupled to Z
- Modifications are underway
  - Increase xray energy to >3 MJ
  - CPA modification to beamlet
    - > 1kJ in 1-5 psec