Progress on the development of ion-based fast ignition

presented by:
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Collaborators and acknowledgements:

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Summary of fast ignition (FI)

- FI is isochoric ignition (conventional is isobaric)
- Long-pulse (> 10 ns) driver to compress DT to 300 – 500 g/cm$^3$, $\rho r \sim 3$ g/cm$^2$
- Particle beam must deposit $\sim 10$ kJ in $\sim 25$ ps ($\sim 4$ PW) within hot-spot (HS) volume ($\sim 25$ -- 50 $\mu$m)$^3$, i.e., $\sim 10^{22}$ W/cm$^3$ → laser driver

Alternative schemes:

M. Tabak et al., PoP 1 1626 (1994)


M. Roth et al., PRL 86 436 (2000)

We consider a laser-driven $Z > 1$ ion ignitor beam (e.g., C).
Issues relating to ion-driven fast ignition:

• Fuel assembly
  – shield ion-source from implosion → want large standoff
  – cone → difficult implosion

• Laser conversion efficiency to particle beam
  – Laser → hot e⁻
  – Hot e⁻ → ion ignitor beam

• Fuel $\rho r \sim$ particle range → laser $I$
  – $e^- \rightarrow \sim 1$ MeV → $I \sim 5 \times 10^{19}$ W/cm$^2$
  – Protons $\rightarrow \sim 13$ MeV → $I \sim 10^{20}$ W/cm$^2$
  – $C \rightarrow \sim 440$ MeV $\rightarrow I \sim 10^6$ W/cm

• Req. power density & $I$ → beam area (BA)
  – BA $\gg$ hot spot area → focus beam
  – Problem for e⁻-based FI

• Finite particle beam energy spread $\delta E/E$
  – High $\delta E/E$ → wasted ignitor energy

• Particle-beam transport
  – Arrival time spread → $\delta E/E$ trade versus standoff
Quasi-monoenergetic low-Z ions (e.g., C) have potential advantages as a fusion ignitor beam.

- **Potential advantages** over electron* or proton-based\(^1\) FI:
  - Quasi-monoenergetic-ion source may be placed far from the fuel
  - Sharper deposition (higher efficiency)
  - Most robust particle-beam transport
  - Many fewer ions than protons required
  - Required thin targets and very high laser contrast now demonstrated!

- **Potential issues**:
  - Laser – ion conversion efficiency: \(\sim 10\%\) desired
  - Focusing C ion beam: only proton focusing demonstrated

<table>
<thead>
<tr>
<th>Beam Ion</th>
<th>Energy (MeV)</th>
<th>Number of Ions</th>
<th>Laser Irrad. (W/cm(^2))</th>
<th>Minimum areal densities, layer thickness @ 0.1 mm(^2)</th>
</tr>
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<tbody>
<tr>
<td>Protons</td>
<td>7 – 19</td>
<td>(10^{16})</td>
<td>(\sim 10^{20})</td>
<td>(10^{18}) cm(^{-2}), (\sim 2) µm (CH)</td>
</tr>
<tr>
<td>C</td>
<td>400-480</td>
<td></td>
<td></td>
<td></td>
</tr>
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\* Tabak et al., PoP 1, 1626 (1994); \(1\) Roth et al., PRL 86, 436 (2001);
\(2\) D. Clark & M. Tabak, Nucl. Fus. 24, 1147 (2007)
Two key technological requirements to study ion acceleration at the ~ GeV level are now in place:

• **Ultra-thin targets (10-100 nm)**
  – Have settled on diamond-like C (DLC) as a technologically convenient species
  – As part of our collaboration with LMU (Munich), they have provided DLC targets in thicknesses of 3, 5, 10, 30, 50 & 60 nm.

• **Laser pulses with ultrahigh contrast (~ $10^{10}$) and no prepulse**
  – Have discovered that post-pulses can turn into prepulses.
  – Invented new scheme for pulse cleaning (“SPOPA”).*
  – Improved laser contrast ratio on Trident ($10^7$): prepulses < $5 \times 10^{-10}$ & ns pedestal < $2 \times 10^{-12}$.
  – These targets (down to 3 nm) have been fielded successfully on Trident with new high-contrast front end.


Target damage measurement @ $5 \times 10^8$ W/cm$^2$
Ion-driven FI design issues

• Assume fuel assembly design as given

• Does it matter which ion species?

• What is the operating space for high gain?
  – Ion-beam requirements (e.g., ion energy)
Integrated LASNEX designs in 2D for proof of principle experiments using the LASNEX hydro code

• Simulated experiment (preliminary design):
  – Capsule with cryogenic DT, plastic ablator
  – Various ignitor beam species

• Capsule implosion
  – Compression with radiation source
  – 14.2 ns pulse (foot + \( P \sim t^{3.5} \) pulse)
  – Energy absorbed: 35.5 kJ
  – Fuel density: \( \rho_{\text{DT}} \sim 150 \text{ g/cc} \)

• Two (symmetric) ignitor beams
  – Vary ion energy (C: 375 – 750 MeV ± 10%)
  – Beam energy: 7.2 kJ Ea.
  – Gain \( \equiv \) fusion energy / (35.5 + 14.4) kJ

\[ T_r (\text{keV}) \]
\[ \text{time (ns)} \]

\[ \text{Vary ion energy} \]
Fusion gain is similar for all ignitor ion species when properly optimized.

- Beams are a pair of counter-propagating 7.2 kJ ion beams injected along capsule symmetry axis

- Energy spread: +/- 10%

- Beams injected so that deposition occurs at time max DT fuel density in compressed capsule

- Maximum gain peaks with slight beam overlap.
  - Importance of ion-stopping model.
Requirements for high gain with C ignitor beam have been explored with the SARA* code.

- **SARA design code:**
  - Hydrocode
  - Multi-group radiation transport
  - Fusion burn
  - Ion-beam package with Monte Carlo transport

- **C ion ignitor beam**
  - $\delta E/E = 10\%$ (unless otherwise indicated)
  - Assumed to be focused to 31 $\mu$m in diameter

- **Three DT fuel assemblies considered**
  - Isochoric sphere @ 500 g/cc
  - Supergaussian (SG)
  - Direct drive (DD) implosion, 485 kJ laser energy

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For a C ignitor beam, energy minima for ignition & high gain (~ 50 – 100) lie @ 300 – 500 MeV ion energies.*

- Details of the DT density profile matter due to finite beam-energy losses on the way to the fuel core.
- C-ion energy spread should be modest (~ 10%).

Summary of laser-driven ion acceleration:

- Laser couples to target electrons
  - Ponderomotive force \(-q^2 \nabla E^2 / 4m \omega^2\)
  - Heating (with linear polarization)
  - Pressure (circular polarization)

- Relativistic e\(^-\) population out of equilibrium
  - \(\lambda^2 > 1.33 \times 10^{18} \text{ Wcm}^{-2} \mu\text{m}^2\)
  - KE > rest mass
  - High energy Effic.
    - \(\sim 30 – 50\%\)
  - Directed motion
  - Expansion

- Relativistic e\(^-\) population couples to ions
  - Charge separation
  - Kinetic instability

- Directed ion beam
  - MeV – GeV
  - Born in ps
  - Neutralized \(\rightarrow\) high current

- Very large multi-scale computational problem in relativistic laser-plasma interactions
We are applying unique LANL resources to discover & model ion-beam generation physics.

- World’s most powerful PIC code (VPIC) on the world’s most powerful supercomputer (Roadrunner): first sustained ~ Petaflop performance, $10^{12}$ particles
- VPIC has been extensively validated in relativistic laser matter interactions, LPI, magnetic reconnection, etc.

## Ion Acceleration Mechanisms:

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## Laser-based ion acceleration mechanisms:

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<td>Radiation Pressure Acceleration (RPA)(^3)</td>
<td>~ GeV</td>
<td>Charge separation</td>
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<td>Aka Plasma Piston</td>
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**BOA**

- \(n_{\text{crit}} = \omega_{\text{pe}} 5500.00\)
- 30 nm C foil + proton impurities
- Laser carbon

**RPA**

- 100 nm H @ 100 \(n_{\text{crit}}\)
- Laser
Stages to reach the Breakout Afterburner (BOA) phase of ion acceleration (discovered with VPIC)

1. TNSA
   - SP laser
   - cold electrons
   - hot electrons

2. Enhanced TNSA
   - all electrons hot

3. BOA
   - SP laser
   - Buneman instability
   - mono-energetic ion acceleration stage
   - energy broadening + ion acceleration stage

- volumetric e⁻ heating
- e⁻ drift
Discovery of the laser-breakout afterburner* (BOA): a path to high efficiency & high energy ion beams

- **Requirements:**
  - $I \sim 10^{20} \text{ -- } 10^{21} \text{ W/cm}^2$
  - Ultra-thin targets (e.g., ~ 30 nm C)
  - Ultra-high laser contrast ($\sim 10^{10}$)

- **1D, 2D, 3D Simulations using VPIC code**
  - Start with solid density C, including cases with H contaminants

- **Ion acceleration mechanism:**
  - Enhanced TNSA
  - Laser penetration across target
  - Electron heating & drift relative to ions
  - Electron energy $\rightarrow$ ion energy via kinetic Buneman instability.

- **Initial simulations** ($I \sim 10^{21} \text{ W/cm}^2$, 30 nm targets, C):
  - 35% (in 1D), 15% (in 2D) of all ions accelerated to 0.3 GeV ± 7%, 4% efficiency.
  - C-ion acceleration is “immune” to surface or volumetric proton contamination!

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* L. Yin et al., Phys. Plasmas 14, 056706 (2007); Laser and Part. Beams 24, 291 (2006);
High laser-pulse contrast on thin targets improves Carbon acceleration.

- Up to 200 MeV Carbon with 40 J laser energy on target at high contrast using plasma mirrors.
- Compared to 36 MeV C\textsuperscript{5+} with 20 J at low contrast.
- Would expect 75 MeV from TNSA scaling [Fuchs, Nature Phys. 2007]
- VPIC predictive capability
- Probably accessed Enhanced TNSA

\* B. M. Hegelich, et al., Nature

Results

\begin{itemize}
  \item \texttt{C6+ for 50nm Diamond Target}
  \item \texttt{“1D” VPIC Simulation}
  \item \texttt{~ 10\textsuperscript{6} \times 50 MeV} \times 100 msrd = \texttt{5 \times 10\textsuperscript{9} ions}
  \item \texttt{Trident 20 J}
  \item \texttt{TNSA cutoff}
\end{itemize}
Higher laser greatly improves performance: ion energy and number of particles.

- Trident shot #20570: 9/2008 with high-contrast front end
- Target: 58nm DLC foil
- Laser pulse on target: 90.1 J in 0.54 ps
- Focal spot radius: 3.5 μm (46% of energy)
- Intensity: $2 \times 10^{20}$ W/cm²

Results

Preliminary
Summary:

• The FI requirements & issues have been summarized.

• A novel FI concept based on a laser-driven C-ignitor beam has been presented

• FI designs yield encouraging results

• Technological advances to study beam generation are now in place
  – Ultrahigh laser-pulse contrast
  – Ultrathin laser targets

• Experiments to validate ion acceleration mechanisms are now beginning

Please visit us in the Thursday PM poster session!
Outline:

- Summary of general fast ignition (FI) requirements, issues & challenges
- Why ion-based FI
  - *E.g.*, C-ion based
- Requirements from ion-based FI designs
- Realizing the required laser-driven ion beams
- Initial results
- Summary
3D simulation of RPS Carbon acceleration

Circular polarization, 30nm C and $I_0 = 10^{21}$ W/cm$^2$ & 312 fs pulse

Our largest simulation to date on ion acceleration (run on Roadrunner base system):

- Physical domain 25x25x20 $\mu$m w. solid target density
  $14 \times 10^9$ cells, $21 \times 10^9$ particles, 4096 processors
- Contrasting with sim. size at the time of the proposal:
  $0.5 \times 10^9$ cells, $2.2 \times 10^9$ particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.

- VPIC has been modified to run efficiently on Roadrunner (Opteron hosted hybrid supercomputer with 12960 IBM Power Xcell 8i chips)
- We anticipate an additional factor of $\sim 10$ in speed over Opteron, enabling routine trillion-particle PIC simulations
- We have obtained a significant allotment of time (13 million hours, $>1/3$ of time when whole system is available) on the full 3 Pflop/s (single precision) Roadrunner system
Max proton energies on Trident with thin targets match or exceed published, contrast-limited scaling laws.

Enhanced Trident exceeds scaling laws by an order of magnitude at low irradiance. At high irradiance, it approaches scaling laws, i.e., contrast limited.

**Petawatt Performance at 120 TW**
- Trident: 50 MeV at $5 \times 10^{19}$ W/cm²
- NOVA Petawatt: 58 MeV at $3 \times 10^{20}$
- RAL PW: 53 MeV at $6 \times 10^{20}$
Simulations have been carried out with the SARA-2D code

- Comparison with Atzeni et al. ignition energies of DT at 400 g/cm³ by monoenergetic proton beams [Atzeni, Temporal and Honrubia, NF 42, L1 (2002)].

- Graph showing minimum ignition energy (kJ) as a function of proton beam energy (MeV) with data points for SARA-2D and Atzeni et al.
Brief Overview of Laser-Ion Acceleration
Target Normal Sheath Acceleration (TNSA)

1. Preplasma Formation
   - Pre-plasma
   - Target

2. Pre-pulse
   - Hot e Generation
   - Reflected sp laser
   - Target

3. Ion Acceleration
   - Cold return current e
   - Refluxing e
   - Recirculation
   - Pre-plasma
   - Target

- Pre-plasma formation
- Hot electron generation
- Ion acceleration

Laser-driven TNSA proton beams have extremely low transverse emittance.

- Hot e $\rightarrow$ MV/µm electrostatic fields at the target rear surface (virtual cathode).

- Measured transverse emittance of TNSA proton beams at Trident (LANL) and LULI (Ecole Politechnique).

- For 8 MeV component of the Trident beam, the upper bound on the transverse normalized beam emittance is $0.004 \text{ mm mrad}$, $\sim 100\times$ better than typical LINACs.*

Laser-produced ion beams have been focused.

- Neutralized beam: not bound by usual current and space-charge limits
- May be focused with quadrupole lenses and ballistically

Quadrupole lens focusing

Ballistic (shaped target)


M. H. Key et al., Fusion Science & Technology 49 (2006) 440
M. H. Key, Phys. Plasmas 14 (2007) 055502
Overview of Radiation-Pressure Acceleration of Ions

1. Ponderomotive push
   - Circularly polarized SP laser
   - Cold electrons

2. Charge separation
   - SP laser
   - Electrons displaced

3. Ion acceleration
   - SP laser
   - Electrons displaced
Radiation Pressure Acceleration (RPA) is another path to ~ GeV laser-driven ion beams.*

The key to realizing RPA is to push on the target electrons, rather than heating them.

- Uses *circularly* polarized light
- Electrons pushed by light pressure, minimal heating
- Charge-separation electric field bunches ions
- Mono-energetic ions are accelerated to high energies
- Requirements:
  - \( I \sim 10^{20} \text{ -- } 10^{21} \text{ W/cm}^2 \) with ultra-high laser contrast
  - Ultra-thin targets (e.g., \( \sim 30 \text{ nm C} \))
  - Circularly polarized light

VPIC has been used to study RPA acceleration of C, showing acceleration to ~ GeV.

- Requirements:
  - $I \sim 10^{21} \text{ W/cm}^2$ with ultra-high laser contrast
  - Ultra-thin targets (e.g., ~ 30 nm C)
  - Circular polarization

- 1D simulations using solid density C and 208 fs pulse (blue curve)
  - 60% of ions accelerated to $450 \text{ MeV} \pm 10\%$, 13% conversion eff.
  - 1D scaling with pulse length
  - C-beam energy increases with pulse length

- Concern: effects of higher-dimensions

- 3D VPIC simulations show:
  - high sensitivity to curvature, which may negate benefits of circular polarization
  - ~ GeV energies

- Further optimization is needed.

RPA deserves further consideration for ~ GeV ion acceleration.
VPIC demonstrates that proper tailoring of the laser pulse enables RPA acceleration of C in 2D.

- 2D Simulation conditions (example, idealized case):
  - $I \sim 10^{21}$ W/cm$^2$
  - Supergaussian in space $\sim \exp\{-[r^2/(2w^2)]^3\}$ where $w = 10$ micron
  - Supergaussian in time with $w = 9$ fs
  - Circular polarization

- Results at 104 fs:
Contrast:
The dirty truth about short-pulse lasers

Contrast comes in several varieties:

- Amplified Spontaneous Emission (ASE) Contrast: a laser pulse is only as good as its regen.
- Pre-pulse contrast, reflections can lead to pre-pulses from saturation effects of post-pulses
- Extinction ratio, a laser pulse is only as good as its Pockel’s Cells to extinguish pulse train

1.053 micron pulse, $\omega_0$ typical ASE pedestal $10^7$

Gaussian Fit of CPA Pulse

Short-pulse pre-pulse

ASE pedestal

FWHM = .6 ps

Peak of CPA Pulse

$m_e v_o^2 = m_e c^2$

Intensity (W/cm²)

Power $10^{19}$

$10^{18}$

$10^{17}$

$10^{16}$

$10^{15}$

$10^{14}$

$10^{13}$

$10^{12}$

$10^{11}$

Time (ps)

$10^1$ $10^2$ $10^3$ $<10^{11}$

Plasma Expansion

Target Ionization

Target Vaporization

Have just achieved this.

A 3 -- 4 order improvement!
We used high-contrast laser pulses produced with plasma mirrors to validate our understanding of pre-pulse effects.

- Done while awaiting for high-contrast front end on Trident.
- **We shot ultra-thin DLC targets (10-50 nm)**
  - Provided by LMU
  - Hosted 2 LMU grad students and 1 QUB grad student for the run.

- Laser pulse contrast was enhanced by using two consecutive plasma mirrors in the focusing chain.
  - Improve contrast by $\sim 10^4$ (based on published results)
  - Paid high energy penalty
  - Demonstrated good performance down to 30 nm thickness.
LANL has extended TNSA acceleration to heavy ions based on a reliable laser heating technique.
Joule heating of Pd foils (evaporate surface impurities) yields on beam with a significant yield of highly ionized heavy ions.

- Trident 30 TW data
- Pd$^{22+}$ ions (assuming 10° beam):
  1.75 X 10$^9$ $\geq$ 1 MeV/u $\rightarrow$ 0.23% of laser energy;
  2.4 X 10$^{10}$ total $\rightarrow$ 1.1% of laser energy
- Pd$^{4+}$ ions (not shown):
  1.1% of laser energy
- High-energy cutoff consistent with theory
CW laser heating of Ni foils has resulted in ~ 1% laser conversion efficiency into a Ni\(^{18+}\) ion beam.

- Target: Ni, 15 µm thick.
- Ni\(^{18+}\) → 0.8 % of laser energy on old 30 TW Trident.
- High-energy cutoff (reduced model by Albright et al.*
  \[ E_{I,\text{max}} \sim 2T_h Z^j \]) is higher than expected.
  - Self focusing probably increased intensity.

Path towards control of ion energy spectrum & higher energy/nucleon
We inadvertently exploited a surface catalytic reaction to create a nearly mono-energetic beam.*

Target: Pd 20 µm, J-heated; Trident shot #16159

Monochromatic highly ionized C beam!

Tailored surface conditions (e.g., thin films) are the key to new ion acceleration regimes.

* B. M. Hegelich et al., Nature 439, 441 (2006)
Heating certain metals (e.g. Pd) to 800 - 1000° C catalyzes a reaction leaving a few C monolayers on the surface.

- The chamber atmosphere (~ $10^{-6}$ torr) provides a source of hydrocarbons.
- Heating the target to 400 - 600° C liberates all the H.
- Heating the target to 600 - 800° C leaves a carbon layer.
- Heating the target to 800 - 1000° C results in a C monolayer
- Heating the target above 1000° C liberates all surface contaminants.
Our understanding of TNSA has allowed the development of reduced models for ion-acceleration dynamics.*

1D hybrid code BILBO (Backside Ion Lagrangian Blow Off):
- Analytic solution to Vlasov-Maxwell system
- Threshold ionization model
- Hot electron cooling model (3D effect)

* B. J. Albright et al., Phys. Rev. Lett. 97, 115002 (2006);
  B. M. Hegelich et al., Nature 439, 441 (2006)
If a thin layer on a substrate works well, how about no substrate? Breakout After-burner (BOA)
Stages to reach the Breakout Afterburner (BOA) phase of ion acceleration

1. TNSA
   - SP laser
   - Cold electrons
   - Hot electrons

2. Enhanced TNSA
   - All electrons hot

3. BOA
   - SP laser
   - Volumetric e⁻ heating
   - Energy broadening + ion acceleration stage
   - Mono-energetic ion acceleration stage
   - Buneman instability
   - e⁻ drift