High-intensity laser interactions with near-critical density plasmas: NP-315758

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Motivation for laser-driven ion sources

Why laser driven ion sources?

Laser driven ion sources increasingly attractive due to high source energy and short bunch length.

For example, these sources are well suited for high dose rate radiobiology - e.g. FLASH.

Important characteristics of laser driven source for applications:

- High energy
- High flux
- Different ion species
- High repetition rate
- Minimal debris

Gaseous targets are a great choice, if high energy, high flux ions can be produced…
Physics of laser driven ion sources difficult to diagnose directly


Laser propagation in underdense plasma

Acceleration of ions at critical density surface and plasma boundary

Propagation of “fast” electrons in the target

Ion sources undergo multiple nonlinear and dynamic processes, near-impossible to see experimentally
Diagnosing laser driven ion sources - a new approach?

Nearly all laser driven ion source experiments performed in the near-IR

Typical dynamical scales
- Time: ~10 fs
- Length: ~1 μm
- Density: >~10^{21} cm^{-3}

Can we diagnose it?
- Too quick
- Too short
- Too dense

Rely on simulations, many assumptions
- Reduced dimensionality
- Uncertainty over experimental parameters
- Can only verify by looking at certain outputs e.g. ion beam
Exploiting dimensional scaling of collisionless laser-plasmas

Collisionless laser plasmas can be defined using reference frequency*:

\[
\tilde{t} = \frac{\omega_L}{c} t,
\]

\[
\tilde{x} = \frac{\omega_L}{x},
\]

\[
\tilde{n} = \frac{1}{n} n \propto \frac{1}{\omega_L^2} n.
\]

**Time**  
\(\tilde{t} = \frac{\omega_L}{c} t\)  
**Length**  
\(\tilde{x} = \frac{\omega_L}{x}\)  
**Density**  
\(\tilde{n} = \frac{1}{n} n \propto \frac{1}{\omega_L^2} n\)

- **near-IR**  
  \(~10\; \text{fs}\)  
  \(~1\; \mu\text{m}\)  
  \(>~10^{21} \; \text{cm}^{-3}\)

- **longwave-IR**  
  \(~100\; \text{fs}\)  
  \(~10\; \mu\text{m}\)  
  \(>~10^{19} \; \text{cm}^{-3}\)

**Resolvable**  
**Resolvable**  
Ideal for optical probing

*if e.g. ionisation/QED not important
A unique facility at the ATF for investigating ion source physics

Utilising the ATF’s NIR and MWIR laser facilities, we have a unique and exciting platform for investigating ion source physics dynamics

- CO$_2$ laser - 2 ps, 9.2 μm wavelength drive laser for ion acceleration @ $10^{19}$ cm$^{-3}$
- TiS laser - <100 fs, 800 nm wavelength laser ideal for optical probing such densities

Enables direct dynamic observation of fundamental scale-independent processes driving all laser driven ion sources

Previously: blur due to ionisation and plasma dynamics when temporal overlap between drive and probe
Now: clean images when overlapping drive and probe, allowing measurements of evolving overdense LPI
Proposed Objectives

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. Laser propagation in underdense plasmas preceding the critical surface
2. The dynamics of ion acceleration by shock structures
3. Particle beam propagation through plasmas
Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. **Laser propagation in underdense plasmas preceding the critical surface**

2. The dynamics of ion acceleration by shock structures

3. Particle beam propagation through plasmas
Laser propagation in underdense plasmas

To fully understand the acceleration process laser conditions at the critical surface must be fully understood.

A number of effects can occur as a laser propagates an underdense plasma:

- relativistic self-focussing and dispersion
- laser hosing
- filamentation

Preliminary data taken during AE100
Laser propagation in underdense plasmas

These processes affect laser conditions at critical density surface

- uncertainty in laser energy, focal spot size and shape
- Can enhance or degrade acceleration performance

Self focusing

From Jiang et al. PRL 107 (2011)

Filamentation

Experimental investigation of these concepts

We will use the unique setup to investigate these processes:

- Measure plasma dynamics and transmitted laser properties
- Vary density and density gradients
- Vary laser parameters

We will directly image these phenomena at near-critical densities, not possible with near-IR drivers.


Example with near-IR drive: LPI completely obscured due to high densities.
Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. Laser propagation in underdense plasmas preceding the critical surface

2. The dynamics of ion acceleration by shock structures

3. Particle beam propagation through plasmas
ATF acceleration conditions

CO₂ laser allows near-critical investigations, enabling the study of shock acceleration mechanisms.

Changing the laser and target conditions enables transition of hole-boring (HB) and collisionless shock acceleration (CSA).

\[ P_R = n_c m_e c^2 a_0^2 \]

\[ P_{Th} = n_e m_e c^2 \left[ \sqrt{1 + \frac{a_0^2}{2}} - 1 \right] \]
Proposed areas of study

A number of interesting areas of study:

• Continue work of AE100 and make first detailed optical studies of the ion acceleration phase

At $T_e \sim 1$ MeV, and $1e7$ shock velocity, feature size is $\sim \mu$m scale. In 2 ps, shock moves $\sim 20 \mu$m

$\rightarrow$ sub 100 fs probe needed
Proposed areas of study

A number of interesting areas of study:

• First detailed optical studies of the ion acceleration phase

• Interplay between CSA and HB and how to control this
A number of interesting areas of study:

• First detailed optical studies of the ion acceleration phase

• Interplay between CSA and HB and how to control this

• Improved ion acceleration performance at multi-TW level
Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. Laser propagation in underdense plasmas preceding the critical surface

2. The dynamics of ion acceleration by shock structures

3. **Particle beam propagation through plasmas**
Beam propagation through plasmas

- Energetic electrons are generated in LPI and propagate into upstream plasma
- Their current greatly exceeds Alfvén limit -> balanced by return current
- These counter propagating populations are subject to collisionless instabilities, such as the current filamentation instabilities
- Affects electron beam transport
- Can degrade ion generation
- Proposed mechanism for magnetic field generation in some astrophysical scenarios

Beam propagation through plasmas

Studies with near-IR cannot measure this in dense plasmas directly, only through subsequent impact on particles.

The ATF can study the same physics, but on a different scale:

1) Density achievable by gas jets and ideal for optical probing
2) Filament 10x wider - resolvable using TiS
3) Instability driven over 10x longer time - time evolution can captured using TiS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CO₂ laser@ BNL</th>
<th>Equivalent NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_L ) (( \mu )m)</td>
<td>9.2</td>
<td>0.8</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( \tau_L ) (fs)</td>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>( n_e ) (cm(^{-3}))</td>
<td>1.3x10(^{19})</td>
<td>1.7x10(^{21})</td>
</tr>
<tr>
<td>( \gamma_e )</td>
<td>(~3)</td>
<td>(~3)</td>
</tr>
<tr>
<td>( \alpha = n_b/n_e )</td>
<td>(~0.1)</td>
<td>(~0.1)</td>
</tr>
<tr>
<td>( \lambda_{Fil} ) (( \mu )m)</td>
<td>(~10)</td>
<td>(~1)</td>
</tr>
<tr>
<td>( \tau_f ) (fs)</td>
<td>(~10)</td>
<td>(~1)</td>
</tr>
<tr>
<td>e-folds</td>
<td>(~200)</td>
<td>200</td>
</tr>
</tbody>
</table>
Beam propagation through plasmas

Previously observed the endpoint of current filamentation instability, measuring filamentary density structures after the end of LPI.

Previous measurements were limited because growth phase was not resolvable with old YAG probe. **Ti:S will enable time-resolved characterisation of filamentation.**
Summary - NP-315758 Proposal

- Proposal builds on experience of AE66 and AE100 experiments, exploiting improved laser capabilities

- Objective is to investigate each stage of the ion acceleration process:
  - Laser propagation dynamics in underdense plasmas
  - Acceleration physics at the critical surface
  - Particle beam propagation in plasmas
Thank you for listening. Questions?
## Electron Beam Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>MeV</td>
<td>50-65</td>
<td>Full range is ~15-75 MeV with highest beam quality at nominal values</td>
<td></td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>nC</td>
<td>0.1-2.0</td>
<td>Bunch length &amp; emittance vary with charge</td>
<td></td>
</tr>
<tr>
<td>Compression</td>
<td>fs</td>
<td>Down to 100 fs (up to 1 kA peak current)</td>
<td>A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.</td>
<td></td>
</tr>
<tr>
<td>Transverse size at IP (σ)</td>
<td>µm</td>
<td>30 – 100</td>
<td>It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.</td>
<td></td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>µm</td>
<td>1 (at 0.3 nC)</td>
<td>Variable with bunch charge</td>
<td></td>
</tr>
<tr>
<td>Rep. Rate (Hz)</td>
<td>Hz</td>
<td>1.5</td>
<td>3 Hz also available if needed</td>
<td></td>
</tr>
<tr>
<td>Trains mode</td>
<td>---</td>
<td>Single bunch</td>
<td>Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.</td>
<td></td>
</tr>
</tbody>
</table>

Electron beam not required
## CO₂ Laser Requirements

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Regenerative Amplifier Beam</td>
<td>Wavelength</td>
<td>mm</td>
<td>9.2</td>
<td>Wavelength determined by mixed isotope gain media</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak Power</td>
<td>GW</td>
<td>~3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Mode</td>
<td>---</td>
<td>Single</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Length</td>
<td>ps</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Energy</td>
<td>mJ</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M²</td>
<td>---</td>
<td>~1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repetition Rate</td>
<td>Hz</td>
<td>1.5</td>
<td>3 Hz also available if needed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>---</td>
<td>Linear</td>
<td>Circular polarization available at slightly reduced power</td>
<td></td>
</tr>
<tr>
<td>CO₂ CPA Beam</td>
<td>Wavelength</td>
<td>mm</td>
<td>9.2</td>
<td>Wavelength determined by mixed isotope gain media</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak Power</td>
<td>TW</td>
<td>5</td>
<td>~5 TW operation will become available shortly into this year’s experimental run period. A 3-year development effort to achieve</td>
<td>5TW</td>
</tr>
<tr>
<td></td>
<td>Pulse Mode</td>
<td>---</td>
<td>Single</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Length</td>
<td>ps</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Energy</td>
<td>J</td>
<td>~5</td>
<td>Maximum pulse energies of &gt;10 J will become available within the next year</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>M²</td>
<td>---</td>
<td>~2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repetition Rate</td>
<td>Hz</td>
<td>0.05</td>
<td>Highest available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>Linear</td>
<td></td>
<td>Adjustable linear polarization along with circular polarization can be provided upon request</td>
<td>LP/CP</td>
</tr>
</tbody>
</table>

*Note that delivery of full power pulses to the Experimental Hall is presently limited.*
## Other Experimental Laser Requirements

### Ti:Sapphire Laser System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Stage I Values</th>
<th>Stage II Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Wavelength</td>
<td>nm</td>
<td>800</td>
<td>800</td>
<td>Stage I parameters should be achieved by mid-2020, while Stage II parameters are planned for late-2020.</td>
<td>√</td>
</tr>
<tr>
<td>FWHM Bandwidth</td>
<td>nm</td>
<td>20</td>
<td>13</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Compressed FWHM Pulse Width</td>
<td>fs</td>
<td>&lt;50</td>
<td>&lt;75</td>
<td>Transport of compressed pulses will initially include a very limited number of experimental interaction points.</td>
<td>≤75</td>
</tr>
<tr>
<td>Chirped FWHM Pulse Width</td>
<td>ps</td>
<td>≥50</td>
<td>≥50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chirped Energy</td>
<td>mJ</td>
<td>10</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressed Energy</td>
<td>mJ</td>
<td>7</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy to Experiments</td>
<td>mJ</td>
<td>&gt;4.9</td>
<td>&gt;80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power to Experiments</td>
<td>GW</td>
<td>&gt;98</td>
<td>&gt;1067</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Nd:YAG Laser System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Typical Values</th>
<th>Comments</th>
<th>Requested Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>1064</td>
<td>Single pulse</td>
<td>5mJ+</td>
</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>532</td>
<td>Frequency doubled</td>
<td>X</td>
</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>0.5</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>10</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

25
Special Equipment Requirements and Hazards

• Electron Beam N/A

• CO₂ Laser
  • Please note any specialty laser configurations required here:

• Ti:Sapphire and Nd:YAG Lasers
  • Please note any specialty non-CO₂ laser configurations required here:
    • YAG amplifier for highest possible energies

• Hazards & Special Installation Requirements
  • New magnet installation for particle spectrometer - 0.6T (already ordered)
  • HV for time-of-flight diamond detector
**Experimental Time Request**

### CY2024 Time Request

<table>
<thead>
<tr>
<th>Capability</th>
<th>Setup Hours</th>
<th>Running Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser* Only (in FEL Room)</td>
<td></td>
<td>40 120</td>
</tr>
<tr>
<td>Laser* + Electron Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Laser* = Near-IR or LWIR (CO$_2$) Laser

### Time Estimate for Full 3-year Experiment (including CY2024-26)

<table>
<thead>
<tr>
<th>Capability</th>
<th>Setup Hours</th>
<th>Running Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser* Only (in FEL Room)</td>
<td>120</td>
<td>360</td>
</tr>
<tr>
<td>Laser* + Electron Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Laser* = Near-IR or LWIR (CO$_2$) Laser
Experimental Layout

- f/1 parabolic mirror
- Two-time interferometry
- H₂ gas jet
- Magnetic ion spectrometer
- 400nm fs Ti:S probe
- 9.2μm CO₂ Laser

Laser