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3/1/2023

Funding: NNSA Office of Defense Nuclear Nonproliferation Research and Development  
Funding Status: Received
Background: Long range radiation detection scheme

- Laser-driven avalanche breakdown in a radiation field propagated from outside the range of the decay particles.
- Need Mid-IR to Long wave IR laser to suppress multiphoton ionization of neutrals in air.
- Measure reflected laser light characteristics to determine breakdown timing.

![Graph showing Seed Electron Generation vs. Source-Focus Distance (cm)]

- **Seed Density (cm⁻³)**
- **Source-Focus Distance (cm)**

Seed Electron Generation:
- 1.4mCi Fe-55: 6keV gamma
- 4mCi Cs-137: 662keV gamma
- 20mCi Po-210: 5.4MeV alpha
- Background Seed Estimate

**Legend:**
- Blue line: 1.4mCi Fe-55: 6keV gamma
- Orange line: 4mCi Cs-137: 662keV gamma
- Yellow line: 20mCi Po-210: 5.4MeV alpha
- Dashed line: Background Seed Estimate

**Note:**
- Electric Field
- Mid-IR Laser Light
- Radiation
- Seed Electrons Initiate Avalanche Breakdown
- Detection
- Laser Reflection
- Optical Emission

Date: 8/16/2023
Background: Short Pulse IR Avalanche Breakdowns

- Avalanche breakdowns are local
  - Centered around *seed electrons*
  - Bounded by *diffusion* during pulse
- Discrete plasma sites
  - *Discontinuous* plasma density
  - Each site surrounded by neutrals

- Short $\lambda$
  - Enough unwanted MPI seed electrons that their separation is smaller than the diffusion length
- Long $\tau_p$
  - Enough time that the diffusion length is greater than the seed separation.

Short pulse: 100 ps, $\lambda=4$ µm
Long pulse: 100 ns, $\lambda=10.6$ µm

Discrete model necessary for:
- $\lambda>2\mu m$
- $\tau_p<1$ ns
Background: Short Pulse IR Avalanche Breakdowns

Electron motion is limited by diffusion, leading to discrete countable sites

\[ r_d \sim \sqrt{\frac{2k_B T}{m v_{en}}} \approx 0.3 \sqrt{\tau \text{[ps]} T_e \text{[eV]}} \text{ } \mu\text{m} \]

What this looks like experimentally:

\[ r_d < N_e^{-\frac{1}{3}} \]

1 mm
Breakdown time advance from backscattered spectra

Shot-by-shot spectra of the backscattered pulse

Pump pulse:
50 ps, 3.9 \( \mu \)m 15-35 mJ focused 1m at f/33
20Hz

Publications


AE122 07/2022: Experimental Setup

- $\lambda = 9.2 \, \mu m$, 70 ps FWHM duration, 50 mJ - 1 J energy range
- Diagnostics: backscatter photodiodes (MCT) ~ns time resolution, images of plasma fluorescence
- ~f/200 geometry: 2.1 mm FWHM beam waist diameter, ~2 m Rayleigh range, 0.21 TW/cm$^2$ breakdown threshold

![Experimental Setup Diagram]
AE122 07/2022: Fluorescence images

Source covered with foil

Source uncovered

2 cm
AE122 07/2022: Fluorescence images

- Image taken at ~40 inches from focus with 1.5” collection lens
- Scaled back to 10 m this would require a ~12” collection optic
- Readily reproduce this image at 10 m standoff distance
AE122 07/2022: Amplified back-reflection diagnostic

• Laser path shown below
• Gain lifetime of CO$_2$ is $\sim$1 µs. Back reflected light is amplified by the laser and detected by *in-situ* regenerative amplifier energy monitor (MCT)
AE122 07/2022: Amplified back-reflection diagnostic

- Gain lifetime of CO$_2$ is $\sim$1 $\mu$s. Back reflected light is amplified by the laser and detected by *in-situ* regenerative amplifier energy monitor (MCT).
- Temporally resolved ($\sim$1 ns), not spatially resolved.
- Sample trace:

![Sample trace diagram](image-url)
AE122 07/2022: Source longitudinal position scan

- Move source along laser propagation direction, keeping transverse distance constant
  - Laser propagation direction
  - 24 in

- Temporal profile of back reflection indicated position of source
  - i.e. source moved 2 ft, spike in back reflection shifted 4 ns.

In the diagram:
- Increased signal due to Po-210
AE122 07/2022: Results

- Mean of peak voltage on MCT
- Increase as the source gets closer to the peak intensity
- Appears to distinguish presence of Po-210 at 50 m path
- Near background level when source is placed at 0 in, near the edge of the focal volume
- Downstream of best focus was inaccessible in the experimental configuration
AE122 07/2022: Conclusions

• Successfully distinguished presence of Po-210 with time resolved MCT detectors at >10 m using direct back reflection.

Insights:

• Direct back-reflection into the laser amplifier can serve as a self-aligned, high sensitivity diagnostic
  − Po-210 only irradiated ~1% of focal volume, γ-source should significantly improve signal level by irradiating larger fraction of focal volume
  − Possibly install a spectrometer instead of a single MCT detector
  − Need to understand integrated back reflection signal as a function of seed density from a 2 m long focal volume, which will include multiple scattering

• Long focusing geometry (f/200) could readily be extended to 100 m scale
Proposal 312793: Propagation range

- Extend propagation length to 50 - 100 meters
- Use 0.5 m diameter focusing optic for f/200 geometry (same as AE122 experiment)
Proposal 312793: Radioactive source

- Irradiate ~2.5 m long focal volume (70 mCi Cs-137 source available at BNL)
  
  ~3 cm with elevated seed density

Po-210
5.3 MeV α-particles, 3 mCi

Cs-137
662 keV γ-rays, 70 mCi

*much larger range of γ-rays allows the source to generate seed ions over the full focal volume
Proposal 312793: Diagnostics

• Amplified back-reflection MCT photodiode
  – Propagation and back-reflection total “time-of-flight” ~668 ns for 100 m propagation
  – May require focusing onto 1 mm$^2$ MCT photodiode to increase signal, if signal strength falls as $r^{-2}$, then collection area will need to increase by 100x going from 10 m to 100 m propagation. >100 mm$^2$ collection lens will be required to maintain signal level

• Non-normal back-reflection MCT that will be placed at various stand-off distances

• Optical telescope to measure the plasma fluorescence at various stand-off distances
  – Brightness of plasma fluorescence goes with the number of individual breakdown sites. Cs-137 will produce $10^3$ – $10^4$ times the number of seeds over the entire focal volume
Proposal 312793: Experimental Schematic

- Beam focused using telescope
  - 0.15 m diameter expansion optic (−4 m focal length)
  - 0.5 m diameter focusing optic (+8 m focal length)
  - Spacing tuned to generate focus at 50 – 100 m

- Not shown: Amplified back-reflection MCT photodiode is in the laser chain and used to monitor pass-by-pass regenerative amplifier output

- Breakdown plasma
  - ~10 cm

- Cs-137 70 mCi

- CO$_2$ amplifier

- Optical telescope

- 8 m spherical mirror

- -4 m spherical mirror

- off-normal MCT photodiode and collection optic

- High magnification fluorescence imager

- los alamos national laboratory

8/16/2023
# Proposal 312793: Experimental Schedule

## Experiment Goals/milestones

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Goals/milestones</th>
</tr>
</thead>
</table>
| Demonstrate detection of radioactive material at 50 - 100 m range (3 weeks, 25% dedicated to setup) | - Optics setup for 50 - 100 m range experiments  
- Calibrate and optimize the backscatter spectrum diagnostic  
- Calibrate fluorescence telescope and noise level in outdoor and indoor conditions.  
- Measure seed density as a function of source distance and validate models for γ-ray sources.  
- Demonstrate detection of radioactive material at 100 m |
<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>N/A</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>N/A</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. NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level</td>
<td>N/A</td>
</tr>
<tr>
<td>Transverse size at IP (σ)</td>
<td>µm</td>
<td>30 – 100 (dependent on IP position)</td>
<td>It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.</td>
<td>N/A</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>µm</td>
<td>1 (at 0.3 nC)</td>
<td>Variable with bunch charge</td>
<td>N/A</td>
</tr>
<tr>
<td>Rep. Rate (Hz)</td>
<td>Hz</td>
<td>1.5</td>
<td>3 Hz also available if needed</td>
<td>N/A</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>N/A</td>
</tr>
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</table>
## 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><strong>CO₂ Regenerative Amplifier Beam</strong></td>
<td>Wavelength</td>
<td>µm</td>
<td>9.2</td>
<td></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>
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<td></td>
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<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></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>---</td>
<td>Linear</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ CPA Beam</strong></td>
<td>Wavelength</td>
<td>µm</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak Power</td>
<td>TW</td>
<td>5</td>
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<td>~10 GW</td>
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<tr>
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<td>Pulse Mode</td>
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<td>Single</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Pulse Length</td>
<td>ps</td>
<td>2</td>
<td>Uncompressed pulse duration desired</td>
<td>~70 ps</td>
</tr>
<tr>
<td></td>
<td>Pulse Energy</td>
<td>J</td>
<td>~5</td>
<td></td>
<td>&lt;5 J</td>
</tr>
<tr>
<td></td>
<td>M²</td>
<td>---</td>
<td>~2</td>
<td></td>
<td>~2</td>
</tr>
<tr>
<td></td>
<td>Repetition Rate</td>
<td>Hz</td>
<td>0.05</td>
<td></td>
<td>0.05 Hz</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>Linear</td>
</tr>
</tbody>
</table>

*Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.*
## Other Experimental Laser Requirements

<table>
<thead>
<tr>
<th>Ti:Sapphire Laser System</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>N/A</td>
<td></td>
</tr>
<tr>
<td>FWHM Bandwidth</td>
<td>nm</td>
<td>20</td>
<td>13</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Compressed FWHM Pulse Width</td>
<td>fs</td>
<td>&lt;50</td>
<td>&lt;75</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Chirped FWHM Pulse Width</td>
<td>ps</td>
<td>≥50</td>
<td>≥50</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Chirped Energy</td>
<td>mJ</td>
<td>10</td>
<td>200</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Compressed Energy</td>
<td>mJ</td>
<td>7</td>
<td>~20</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Energy to Experiments</td>
<td>mJ</td>
<td>&gt;4.9</td>
<td>&gt;80</td>
<td>N/A</td>
<td></td>
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<tr>
<td>Power to Experiments</td>
<td>GW</td>
<td>&gt;98</td>
<td>&gt;1067</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nd:YAG Laser System</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>N/A</td>
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</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>14</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>532</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>mJ</td>
<td>0.5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Pulse Width</td>
<td>ps</td>
<td>10</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Special Equipment Requirements and Hazards

• Electron Beam
  • N/A

• CO$_2$ Laser
  • Access to uncompressed 70 ps pulse with <5J energy
  • Extended propagation range (outside laser/accelerator rooms), along with necessary beam enclosure according to BNL safety regulations.

• Ti:Sapphire and Nd:YAG Lasers
  • N/A

• Hazards & Special Installation Requirements
  • 50 - 100 meter propagation range, indoor or outdoor interaction site
  • Equipment: Routing and focusing optics
  • Hazards: BNL owned 70 mCi Cs-137 source
## Experimental Time Request

### CY2023 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 Laser Areas)</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>Laser* + Electron Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

### Total Time Request for the 3-year Experiment (including CY2023-25)

<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 Laser Areas)</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