Relativistic pair plasma creation using the National Ignition Facility

Presented to NIF/JLF User Group meeting 2016

February 1, 2016

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Goal: Study the relativistic pair plasma for fundamental HEDP and astrophysical applications

**e-e+ plasmas are fundamentally important**

- e- p+ e+
- e+
- e-

Tsytovich & Wharton (1978)
Linear polarization of cyclotron radiation
Nonlinear plasma processes (no 3-wave coupling, $M/m$ larger nonlinear Landau damping)

**Rel. e-e+ plasmas present only in astro. events**

![Gamma-ray burst](NASA/CXC/CfA/R.Kraft et al.)

Surko & Greaves PoP (2004)

**Lab e-e+ plasmas can probe Gamma-ray bursts and pulsar magnetosphere…**

A unique matter-antimatter plasma in the relativistic regime may be established using NIF lasers that could enable us to probe into the physics behind universe’s most violent events.

- Surko & Greaves PoP (2004)

- We’ve been awarded 3 days shot time on NIF in FY17 and FY18 to lay the foundation for eventual pair plasma interaction experiment on NIF.

- This year (FY16), we will try to participate the ARC commissioning experiments testing diagnostic, and possibly experimental layout.
Using our established techniques and scaling to ARC energies and power a new physics regime can be reached.

Achievable n and T from various sources

Chen, et al., HEDP 2011

Rel. shocks can be probed in the lab*

Chen, Fiuza et al., PRL 2015

* Simulations by F. Fiuza
** A. Bret, et al., PoP 2013, 2014
Chen, Fiuza et al., PRL 2015

Development objectives
Experiments were performed on four laser facilities

Titan laser (LLNL)
1-10 ps, 100-350 J
5-10 shots/day

Omega EP (LLE)
1-10 ps, up to 1.3 kJ
Up to 16 shots/day

ORION (AWE)
2 SP beams
0.5-1 ps, up to 500 J

LFEX (ILE)
2-4 beams, 1 ps,
~1 kJ each beam
This experiment is built upon the development on multiple laser facilities over many years

Laser parameters

<table>
<thead>
<tr>
<th>Facility</th>
<th>Pulse length (ps)</th>
<th>Focal spot (um) (68%)</th>
<th>Energy J</th>
<th>Intensity W/cm²</th>
<th>Contrast (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan - LLNL</td>
<td>0.7 – 10</td>
<td>8-15</td>
<td>100 – 350</td>
<td>~10^{18} – 10^{20}</td>
<td>&gt;10^6</td>
</tr>
<tr>
<td>Orion - AWE</td>
<td>0.7</td>
<td>10-15</td>
<td>100- 500</td>
<td>~10^{19} – 10^{20}</td>
<td>&gt;10^6</td>
</tr>
<tr>
<td>OMEGA EP -U. Rochester</td>
<td>10</td>
<td>~25</td>
<td>~ 200-1500</td>
<td>~10^{18} – 10^{20}</td>
<td>10^7 -10^9</td>
</tr>
<tr>
<td>NIF ARC (4-8 beamlets)</td>
<td>1 – 50 ps</td>
<td>65x130</td>
<td>~ 500- 1500 intimid</td>
<td>~10^{18}</td>
<td>&gt;10^8</td>
</tr>
</tbody>
</table>

* f~40x60 with 35x15 cm² beam size. Info from Mark (Arc) Hermann
In those experiments, e-, e+, p+ and γ from gold targets were measured by various diagnostics.

**Experimental setup at Titan**

- **High-energy gamma diagnostics**
  - Step Wedge image
  - Gamma-crystal spectrometer
  - GCS: Seely et al. HEDP 2011
  - Chen, et al., RSI 2012

**Electron positron proton spectrometer**

- EPPS raw images
- Protons
- Positrons
- Electrons
- Particle energy
- EPPS: Chen, et al., RSI 2008
Calibrated electron & positron distributions at various laser energies provide data for the scaling study

- Near Maxwellian electrons
- MeV e-temperature
- Quasi-mono energetic positrons
  - More electrons at higher laser E
  - More positrons at higher laser E
  - Positrons peak shift to higher E
  - Still more electrons
  - Very modest rise in Thot
  - Larger increase in positron production

Measured electron distributions provide input to calculations for electron transport in solid
Laser produced relativistic pairs form jets at the back of the target

Jet angular spread: 10-30 degrees. The jets are shaped by the E and B fields of the target. Its direction is controlled by the laser parameters and target.
Lasers-produced pair jets are approaching those needed for lab astro. experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exp. Value*</th>
<th>Desired for astro. relevant exp.**</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\parallel}$</td>
<td>0.5 - 4 MeV</td>
<td>~ MeV</td>
</tr>
<tr>
<td>$T_{\perp}$</td>
<td>0.2-1 MeV</td>
<td>~ MeV</td>
</tr>
<tr>
<td>$n_{e+}$</td>
<td>$\sim 10^{11-13}$ cm$^{-3}$</td>
<td>$&gt;10^{14-16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$n_{e-}$</td>
<td>$\sim 10^{12-15}$ cm$^{-3}$</td>
<td>$&gt;10^{14-16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$\tau_{\text{Jet}}$</td>
<td>5 – 30 ps</td>
<td>10-100 ps</td>
</tr>
</tbody>
</table>

*Chen, et al. PRL 2010; HEDP 2011; POP 2014

**Fiuza et al., in preparation

The most obvious needs are to (1) increase the density of the pair jets and (2) reduce the electron/positron density ratio.
The dependence of the pair yield on laser energy is \( \sim E^2 \)

This non-linear scaling was found from positron data from Titan, EP and Orion experiments

Chen et al., PRL 2015
Chen et al., POP 2015
The positron scaling indicates that ARC energy may provide very high positron yield.

To determine the actual yield, we need:
(1) Laser intensity;
(2) Pulse contrast;
(3) Focal quality.

Furthermore, ARC is unique relative to the Titan, Omega EP and Orion lasers:
- Titan parabola – f/3
- Omega EP – f/2
- Orion – f/3
- NIF ARC – f/60

The long focal length parabola is favored by wake-field acceleration experiments; its effect to laser plasma interaction needs to be determined.

NIF ARC is being commissioned – the questions will be answered.
Future NIF experiments will address the magnetic collimation and confinement of the relativistic pair jets.

**MIFEDS setup on OMEGA EP**

- The effective divergence of the beam reduced from 30 deg FWHM to 5 deg.
- The charge (e-/e+) ratio in the beam reduced from ~100 to 5.

**e- & e+ spectra after collimation**

Chen, Fiksel, Barnak, et al., POP 2014
Eventually, we will initiate pair interactions mimic the formation of astrophysical-relevant relativistic shocks.

Plasma processes, such as Weibel instability, mediate formation of shocks and particle acceleration.

One critical diagnostic, NIF-EPPS, is available; and will be used on a NIF shot in March 2016

**Specifications**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>Commercial permanent neodymium magnets</td>
</tr>
<tr>
<td>Energy Coverage</td>
<td>Tunable spectral window within the 800 keV to 100 MeV electron energy range</td>
</tr>
<tr>
<td>Resolving Power</td>
<td>$\geq \frac{E}{\Delta E} \sim 1\text{-}100$</td>
</tr>
<tr>
<td>Data Collection</td>
<td>Image Plates</td>
</tr>
<tr>
<td>Location</td>
<td>Equatorial DIMs at $\geq 50$ cm from TCC</td>
</tr>
</tbody>
</table>

Lead engineer: Shannon Ayers
Simple solid gold discs will be used as targets – detailed target requirement will be established.

Lasers create positrons through the Bethe-Heitler process using high-Z targets. Gold is preferred due to its stable chemical property.
Present and projected ARC parameter meet the requirements for our experiment

<table>
<thead>
<tr>
<th>ARC Beamlet</th>
<th>ARC parameters</th>
<th>Test phase (FY17)</th>
<th>Data acquisition (FY18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Initial 4, extend to 8</td>
<td>2-4</td>
<td>4</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>Initially 30 ps, plan to go to 1-2 ps</td>
<td>10-30 ps</td>
<td>Determined in the test phase</td>
</tr>
<tr>
<td>Energy</td>
<td>1.5 kJ per beam</td>
<td>0.5 to 1kJ/beam</td>
<td>maximum</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.05 µm</td>
<td>1.05 µm</td>
<td>1.05 µm</td>
</tr>
<tr>
<td>Focal spot</td>
<td>50% of energy at $\geq 1e17$ W/cm², $\geq 50%$ of energy inside 150 µm spot</td>
<td>$5x10^{17} – 5x10^{18}$ W/cm²</td>
<td>Determined in the test phase</td>
</tr>
<tr>
<td>Prepulse limits at focal spot</td>
<td>$&lt; 10^{12}$ W/cm², $t &lt; -0.2$ ns $&lt; 10$ J/cm², $t &lt; -1$ ns</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

This project will benefit other projects using ARC by measuring the electrons and protons from ARC laser-plasma interaction.
Simple experimental setup

- ARC beams
- Target
- EPPS (DIM 90-45)
- HEIDI with Step Wedge Filter Pack (DIM 90-315)
<table>
<thead>
<tr>
<th>Team</th>
<th>Roles and Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen (PI), Tommasini (Co-I), Williams (Lawrence Scholar)</td>
<td>Design and perform experiment; Design the filter packs for the diagnostics; Data analysis.</td>
</tr>
<tr>
<td>F. Fiuza and team (SLAC)</td>
<td>Using simulations to design the target; Data analysis.</td>
</tr>
<tr>
<td>D. D. Meyerhofer (LANL)</td>
<td>Assistant with all aspect of the project</td>
</tr>
<tr>
<td>L. Willingale and G. Fiksel (U. Michigan)</td>
<td>Perform experiments, assistant with simulations and data analysis.</td>
</tr>
<tr>
<td>M. Nakai and team (ILE, Osaka University)</td>
<td>Perform experiments, collaboration from LFEX on Osaka Gekko facility in Japan</td>
</tr>
</tbody>
</table>
# Shot plan

<table>
<thead>
<tr>
<th>Shot day</th>
<th>Diagnostic PQ (FY15)</th>
<th>Test phase (FY16)</th>
<th>Data acquisition (FY17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot day 1</td>
<td>Ride-along ARC PQ shots for EPPS PQ</td>
<td>Target PQ - backscattering</td>
<td>Scaling – laser energy</td>
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<td></td>
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<td>Target PQ - geometry</td>
<td>Scaling – laser intensity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target PQ - geometry</td>
<td>Scaling – laser intensity</td>
</tr>
<tr>
<td>Shot day 2</td>
<td>Ride-along ARC PQ shots for EPPS PQ</td>
<td>Laser energy ramp</td>
<td>Maximize pair density</td>
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<td></td>
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<td>Maximize pair density</td>
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The data acquisition plan will be revised depends on the findings of Test Phase shots.