Collimation of positrons and electrons using an axial magnetic field at the Jupiter Laser Facility

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There are a few ways to produce positrons, two of which dominate in typical laser-produced HED conditions.

- **Types of particles**
  - Electron
  - Photon
  - Ions

- **Possible positron production mechanisms**
  - Electron-electron: $\sigma \propto \alpha^2$
  - Photon-electron: $\sigma \propto \alpha$
  - Electron-ion: $\sigma \propto \alpha^2 Z^2$
  - Electron-photon: $\sigma \propto \alpha Z^2$
  - Photon-photon: $\sigma \propto \alpha$
  - Ion-ion: $\sigma \propto \alpha^2 Z^4$

Fine structure constant $\alpha = 1/137$

Positrons are dominantly produced by Trident and Bethe-Heitler processes.
Relativistic electrons interact with nuclei to create positrons directly (Trident) or indirectly (Bethe-Heitler)

Trident (single step)

\[ \sigma_{\text{Trident}} \propto Z^2 \]

\[ dP_{\text{Trident}} = n_{\text{ion}} \sigma_{\text{Trident}} d \]

Bethe-Heitler (two step)

\[ \sigma_{\gamma} \propto Z^2 \]

\[ dP_{\text{Brems}} = n_{\text{ion}} \sigma_{\gamma} d \]

\[ \sigma_{e^+/e^-} \propto Z^2 \]

\[ dP_{\text{Pairs}} = n_{\text{ion}} \sigma_{e^+/e^-} d \]

\[ Y_{\text{Trident}} \propto n_{\text{ion}} Z^2 d \]

\[ Y_{\text{BHI}} \propto n_{\text{ion}}^2 Z^4 d^2 \]

These analytic positron yields do not account for absorption in the target.
What is the effective dependence of target material and target thickness on positron yield?

<table>
<thead>
<tr>
<th>Experimental Challenges</th>
<th>Solutions</th>
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<tbody>
<tr>
<td>• <strong>Decreased positron signal</strong> in low-Z and thin targets</td>
<td>• Improve diagnostics</td>
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<tr>
<td>• <strong>Increased scatter and absorption</strong> in high-Z and thick</td>
<td>• Larger lasers (EP, LFEX, ARC)</td>
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<td>targets with exiting particles ejected into high angles</td>
<td>• High rep-rate laser to build statistics</td>
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<td></td>
<td>• Magnetic collimation to increase observed signal</td>
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<td>• Previous success with MIFEDS</td>
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<td>• Building on previous work with coils (Pollock, Manuel)</td>
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</tbody>
</table>

Magnetic collimation facilitates low-signal positron experiments at JLF
A loop-current acts as a magnetic lens to collimate electrons and positrons

Particles are collimated only for a small energy range

D. Barnak, APS DPP 2014 TO6.13
At the Titan laser, particle focusing increased positron signal by \(~20\times\)
Experiments at the Titan laser were performed to investigate the effective scaling of positron production

Experiment 1:
- Positron yield vs target thickness

Experiment 2:
- Positron yield vs target material

Titan Laser
~300 J, 10 ps

Electron-Positron-Proton Spectrometer

Target

13 mm  19 mm  40 cm
Our magnetic lens design relied on previous work with similar coil geometries

- Bitter-magnet* coil geometry ("Slinky")
- Large thermal mass
- Repeatable, reusable

- Copper rounds are welded together to form multiple loops
- Kapton insulation installed between Cu layers

*F. Bitter. RSI, 10(12) 1939.

Ultem plastic was used as holder structure without epoxy encapsulation

Fiberglass bolts

Cable Contac

Ultem

Kapton insulators

Copper Slinky Coil

Offline calibration testing provided a maximum discharge current and magnetic field

(all safety procedures were followed)
The Slinky coil is capable of peak magnetic fields >10 T over a large volume.
A focal length can be determined for an axisymmetric magnetic field as a function of energy $FSC$

- Focal length can be expressed in terms of particle energy

D. Barnak, APS DPP 2014 TO6.13
As target thickness increases, Bethe-Heitler becomes the dominant pair production mechanism over Trident.

The Trident mechanism scaling has yet to be observed experimentally.

Positron yield is consistent with production by the Bethe-Heitler mechanism.

Not enough signal for thin targets to observe the change in scaling from BH to Trident.

Analytic Positron Birth Yield

\[ Y_{\text{Birth}}^{\text{Trident}} \propto d \]

\[ Y_{\text{Birth}}^{\text{BH}} \propto d^2 \]

Positron yield for tantalum targets

Scattering and absorption in the target reduces the number of emitted positrons.
Only a fraction of the total positrons created are emitted from the target

Geant4 simulations with 1mm targets (Bethe-Heitler production only)

\[ N_{\text{born}} \propto (Z^2 \rho/A)^{1.9} \]
\[ N_{\text{exit}} \propto (Z^2 \rho/A)^{1.4} \]
\[ N_{1\text{SR}} \propto (Z^2 \rho/A)^{1.3} \]

Analytic Positron Birth Yield

\[ Y_{BH} \propto \left( \frac{Z^2 d \rho}{A} \right)^2 \]

\( Z \) = Atomic number
\( d \) = Target thickness
\( \rho \) = Target density
\( A \) = Atomic weight

The Bethe-Heitler process has an effective scaling \( \ll Z^4 \)
Results suggests that the effective positron yield for mm-scale targets is $\sim Z^2$

Analytic Positron Birth Yield

$$Y_{BH} \propto \left( \frac{Z^2 d\rho}{A} \right)$$

Target list

<table>
<thead>
<tr>
<th>Material</th>
<th>Thinnest Thicknesses (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>▲ Cu</td>
<td>29</td>
</tr>
<tr>
<td>▣ Mo</td>
<td>42</td>
</tr>
<tr>
<td>◆ Sn</td>
<td>50</td>
</tr>
<tr>
<td>▪ Ta</td>
<td>73</td>
</tr>
<tr>
<td>★ W</td>
<td>74</td>
</tr>
<tr>
<td>▼ Au</td>
<td>79</td>
</tr>
</tbody>
</table>
Multi-focusing effects were observed in electron and positron spectra.
Electron focal energies are dependent only on the field strength of the magnetic lens.

Various target materials

800 μm Ta Targets

Various target thicknesses (Ta)
Lower energy particles make multiple passes through focus to be re-collimated.

Possible mechanism for achromatic focusing of positrons and electrons.
The OMEGA Facility’s MIFEDS device was successfully deployed to JLF

MIFEDS demonstrated a non-axially symmetric magnetic field spatially separates positrons and electrons*

*D. Barnak, APS DPP 2014 TO6.13

Replaceable coil head

Control circuits

Capacitors

Transmission line

Parabola

Target

MIFEDS installed in Titan
Future work

- Refine particle collimation technique for greater efficiency
- Continue investigation into possible multi-focusing of particles
- Positron and pair plasma confinement schemes

G. Fiksel
JLF challenges and recommendations

- Trigger timing stability ✔
- Reducing on-target energy fluctuations
- Increasing number and reliability of on-shot laser diagnostics
  - Measuring (and controlling) prepulse
  - Single-shot autocorrelator, integrated laser spectrum
- Increasing stability and quality of probe beam
- Precision in-chamber alignment cameras (shadowgraphs)
- Data storage servers (access from off-site, retention of data for $n$ years)
- Staff retirements – could always use a few extra JLF staff
- Bring back Callisto!!

Very excited about the direction of JLF
Thanks to all JLF staff for their help to improve the quality of the facility!
Particle focusing increased positron signal by ~20x

800 um Ta Target ($E_L \sim 275$ J)

Raw image plate – Positive side

Increasing Energy

Reference
B = 0 T  (Shot 4)

Coil On
B = 2.2 T  (Shot 19)

Signal+Background

Background

Proton Signal
MIFEDS in the Titan Chamber.

Any DIM-based diagnostics now has a dedicated mounting assembly at JLF.
Ray tracing and particle-in-cell codes demonstrate focusing effects

Particle ray tracing simulations

Coils
Magnetic fields
13 MeV Positrons
H. Chen et al., PoP (2014)
Simulation by G. Fiksel

Particle-in-cell (LSP) simulation
Simulation by Tony Link
MIFEDS Diagnostic in JLF Titan Cradle

Mechanical Installation Plan
1. Assemble MIFEDS into Titan Cradle
   • In JLF Setup room on the optic table
   • Attach LLE lifting bar onto MIFEDS in shipping crate
   • Lift with portable hoist and set in MIFEDS Titan cradle
   • Using ten 10-32 SHCS bolt in place
2. Test Positioning plan to move the coil into alignment
   • Using Nudgers, Leveling feet and CCD microscope at coil
   • Lock down clamps
3. Install Moving Handle Support under MIFEDS Cradle
   • Slide 80/20 handle support from the back
   • Tighten ¼-20 socket button head hardware
   • Install Nose cone protection cage
4. Move MIFEDS / Titan Cradle into Titan chamber
   • NOTE: No touching MIFEDS, use Moving Handle Support only
   • Using JLF lift cart at optic table height slide MIFEDS onto cart
   • Strap MIFEDS down to cart with ratchet straps on handle support
   • Move into Titan
5. Install MIFEDS into Door “D”
   • Open door “D”
   • Position lift cart to Titan chamber optic table height
   • Insert threshold between cart and Titan optic table
   • Using three people - one inside chamber and two outside
   • Carefully slide MIFEDS into chamber
   • Remove Moving Handle Support
   • Close door “D”
   • Install extension tube over back end of MIFEDS
6. Position Coil at Target Chamber Center
   • Install kinematic CCD microscope
   • Nudge and level into TCC
   • Lock down the three bread board clamps to secure MIFEDS
7. Install vacuum side electronic cabling
   • Connect cables on the back side of MIFEDS
   • Connect cables to vacuum feed through port

Note:
• MIFEDS weight is 94 lbs.
• MIFEDS is operated in Titan horizontally only
• Will be operated in Door “D”
MIFEDS Diagnostic in JLF Titan Cradle

- Door “D”
MIFEDS Diagnostic

Back side of airbox showing electrical wiring
- This view is what I see from the drawing LLE provided
- Titan chamber will need inside cables at 10 feet, LLE supplied
- All vacuum feedthroughs, LLE supplied
  - Two multi-pin connectors - 18- and 19-pin
  - Two BNC connectors

Four BNC connectors
19 pin MS connector
18 pin MS connector
2 ¾ CF flange
Plugged port
MIFEDS in Titan
Laser-produced positrons can be used to explore many aspects of exotic physics

- Relativistic pair plasma physics
- Positron source for accelerators

How does positron yield scale with laser and target parameters?

LLNL – HED physics website
Positron Generation

\[ e^+ \text{ Birth Locations} \]
Colors and arrows

Summary box is now full width bleed