Design of a Pair-Plasma Production Experiment for OMEGA EP

Bremsstrahlung, $E_\gamma > 2m_ec^2$

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**Summary**

OMEGA EP can potentially produce an electron–positron-pair plasma containing between $10^{11}$ and $10^{12}$ positrons.

- The calculations assume a total laser energy of 5 kJ and a 40% conversion efficiency of laser energy into hot electrons.

- For the generation of pairs, total available energy is more important than obtaining higher laser intensities (assuming a laser intensity of at least $\sim 10^{19}$ W/cm$^2$).

- If the pairs can be confined to a volume of $\sim 10^{-4}$ cm$^3$, the first-ever pair plasma will be produced in the laboratory.

- Flexibility of having two beams could help confine the pairs.
Pair creation due to the Trident process can be estimated since the cross section is well known

- Of the two mechanisms that are important for OMEGA EP parameters, the Trident process is dominant for targets thinner than a few hundred microns.
  - “Trident” process: $e^- + Z \rightarrow e^- + Z + e^+ + e^-$

- Probability of positron production (per electron) is calculated to be between $W_+ \simeq (10^{-4}$ to $10^{-3})$ [Gryaznykh et al. JETP Lett. (1998)].
  - assuming MeV electron temperatures
  - all electrons stop in the target
    - refluxing of hot electrons from sheath fields assures this
For targets less than \( \sim 1 \) mm in size and for laser energies of more than few hundred joules, essentially all of the hot electrons reflux

- A large target is not required for high yield.
For small targets, the Bethe–Heitler process is less important than Trident

- For Au targets ($Z = 79$) greater than $\sim 100 \mu m$ thick, this process becomes competitive with Trident:

$$e^- + Z \rightarrow e^- + Z + \gamma, \quad \gamma + Z \rightarrow Z + e^- + e^+$$

- The bremsstrahlung efficiency is well known ($E_{\gamma} > 1.02$ MeV):

$$\frac{(dE/dx)_{\text{rad}}}{(dE/dx)_{\text{coll}}} \sim 10\%$$

- Pair production is the dominant attenuation mechanism for gamma photons at these energies.

- Most of this radiation escapes the target unless it is thick.

- For 1 MeV, $\gamma$ rays in Au $\mu \rho = (0.1) (19.3) = 1.93 \text{ cm}^{-1}$.

- $\Delta I/I_0 = 1 - \exp [-x(\text{mm})/7.2] \sim 1\%$ at $x = 100 \mu m$
For the positrons to be considered a plasma, two conditions need to be met

- Many particles in a Debye sphere: \( \Lambda_+^{(1)} \equiv n_+ \lambda_{D+}^3 \gg 1 \)
- System must be larger than the Debye length: \( \Lambda_+^{(2)} = \rho_{\text{system}} / \lambda_{D+} \gg 1 \)
Positron expansion makes it difficult to obtain the required density of \( \gtrsim 10^{16} \text{ cm}^{-3} \)

- Unlike hot electrons, positrons do not reflux.

- Spherical expansion must be limited to a radius of 300 \( \mu \text{m} \),
  - free expansion at \( c \) for 1 ps
  - Debye length is similar to system size
  - \( \Lambda_{+}^{(2)} = 2.4 \left( N_{+} / 10^{11} \right)^{1/2} (1 \text{ MeV} / T_{+})^{1/2} (1 \text{ ps} / \tau_{p})^{1/2} \)

- Limit expansion to one dimension only.
  - system size \( \sim 100 \) Debye lengths
  - \( \Lambda_{+}^{(2)} = 86 \left( N_{+} / 10^{11} \right)^{1/2} (1 \text{ MeV} / T_{+})^{1/2} (\tau / 1 \text{ ps})^{1/2} \left( 100 \mu \text{m} / r_{\text{conf}} \right) \)
  - magnetic field, ponderomotive force*

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The flexibility of multiple EP beams can be utilized to magnetize a foil target.

- One EP beam interacts with suitable target.
- Other beam creates positrons in second target, which is immersed in the B-field created by the first beam.
- Expansion of positrons is influenced.
- Similar targets have been fielded.*

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The first part of the scheme has been investigated with LSP indicating that MG magnetic field strengths can be obtained.
One-MG magnetic fields are attainable and would be sufficient to confine radial positron expansion to within a few hundred microns

- Positron synchrotron frequency \( \omega_{\text{Ce}} = \frac{eB}{\gamma mc} \)
  \[ \omega_{\text{Ce}} = 1.76 \times 10^{13} \left( \frac{B}{1 \text{ MG}} \right) \left( \frac{1}{\gamma} \right) \text{ rads s}^{-1} \]

- Gyroradius \( r_{\text{Ce}} = \frac{\beta_{\perp} c}{\omega_{\text{Ce}}} \)
  \[ r_{\text{Ce}} = 17 \left( \frac{1 \text{ MG}}{B} \right) (\gamma) \mu\text{m} \]

- From 1-D expansion on previous slide: \( \Lambda_{+}^{(2)} \sim 40 \)
  \[ \text{even better if } v << c \]
**LSP** calculations confirm that an external axial magnetic field of 4 MG is sufficient to achieve the required positron density.

- An external magnetic field has been imposed in the **LSP** calculations.
- The positrons are emitted in a jet along the direction of the imposed field.
- Interesting dynamics are observed in the absence of an external magnetic field.
- This arises due to a self-generated azimuthal magnetic field.
Diagnosing the pair plasma provides some significant challenges

- The presence of positrons can be diagnosed by observing their annihilation radiation (back to back photons at 511 keV)
- Pair plasmas are “symmetric,” leading to a difference in the linear-mode structure compared to “asymmetric” e–i plasmas
- Cutoffs for $x$ waves differ from e–i plasmas
- No Faraday rotation
- Unfortunately, collective waves have long wavelengths $>100 \, \mu$m
- The probe beam would need to be in the submillimeter range
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