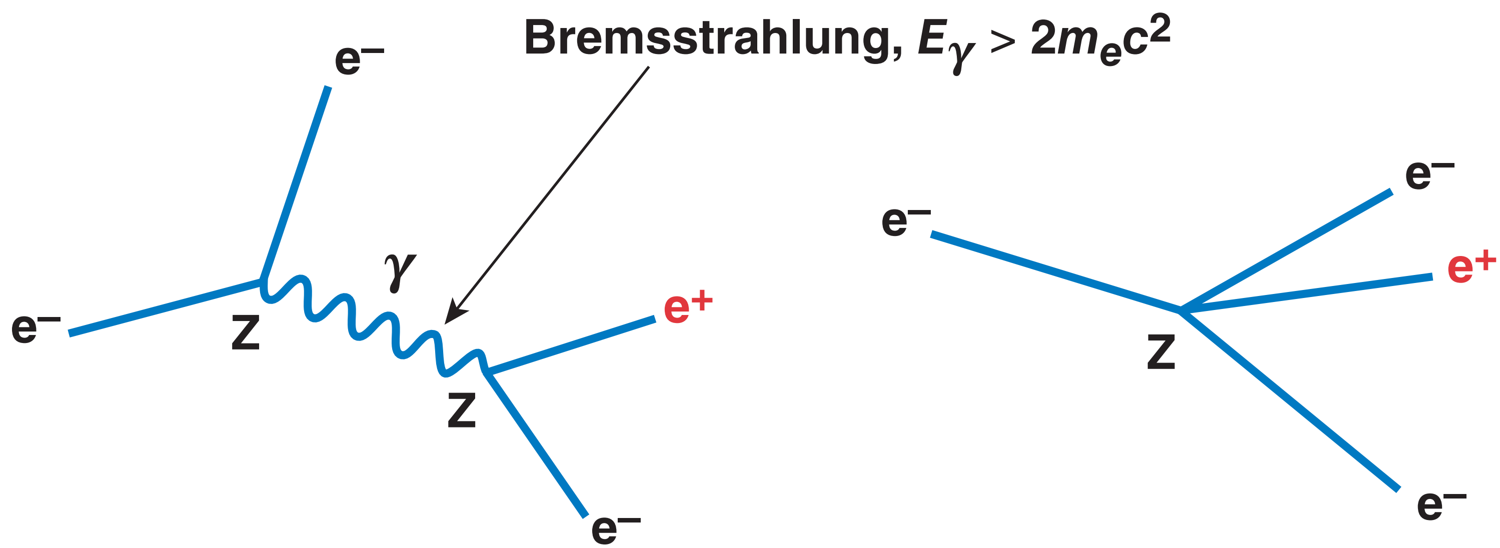
Laboratory Demonstration of e^+e^- Pair-Plasma Production on OMEGA EP



J. Myatt
University of Rochester
Laboratory for Laser Energetics

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Summary

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

- We estimate between 10^{11} and 10^{12} positrons can be made on OMEGA EP, assuming 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 ~10^{19} W/cm^2).
- If the pairs can be confined to a volume of ~10^{-4} cm^3 we will have produced the first ever pair *plasma* 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

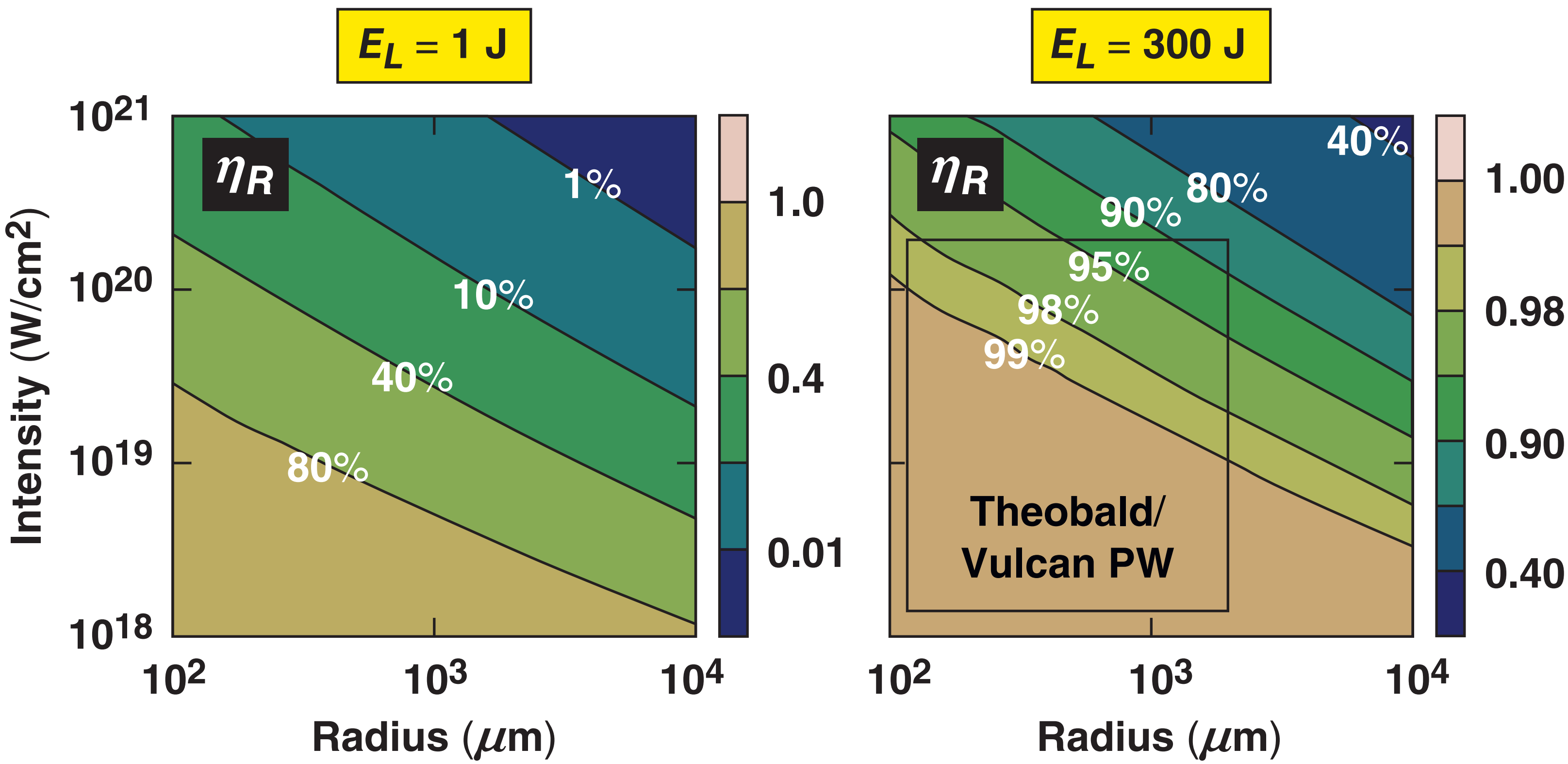
- Of the two mechanisms that are important for OMEGA EP parameters, the Trident process is dominant for targets thinner than a few hundred microns.
  - "Trident" process: $e^- + Z \rightarrow e^- + Z + e^+ + e^-$

- Probability of positron production (per electron) is calculated to be between $W_+ \backsimeq (10^{-4}$ to $10^{-3})$.*
  - assuming MeV electron temperatures
  - all electrons stop in the target
  - refluxing of hot electrons from sheath assures this

*Gryaznykh *et al.*, JETP Lett. (1998).

For targets less than ~1 mm in size and for laser energies of a few hundred joules, essentially all of the hot electrons reflux

- This is in contrast to smaller laser energies ~1 J

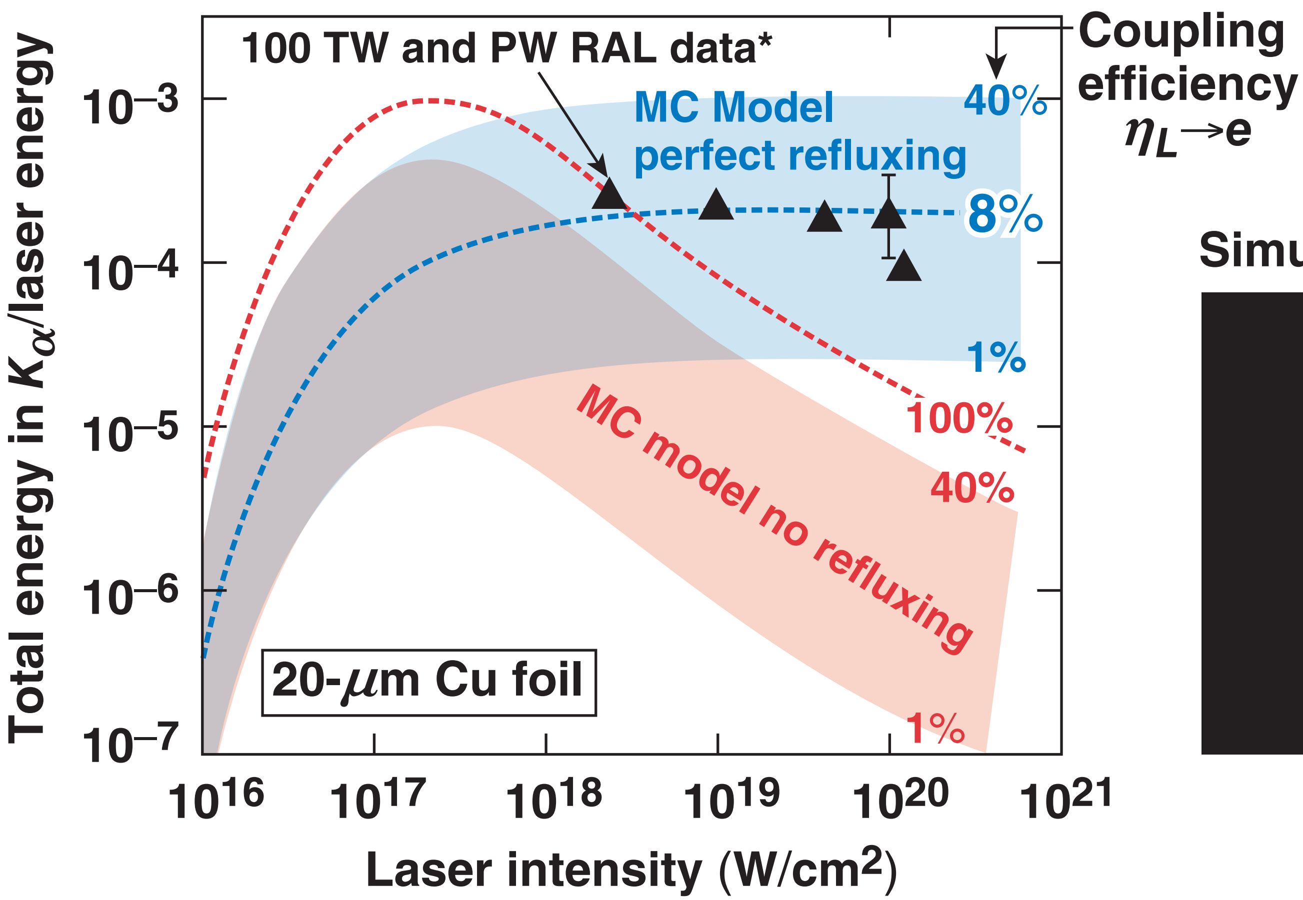


TC7343

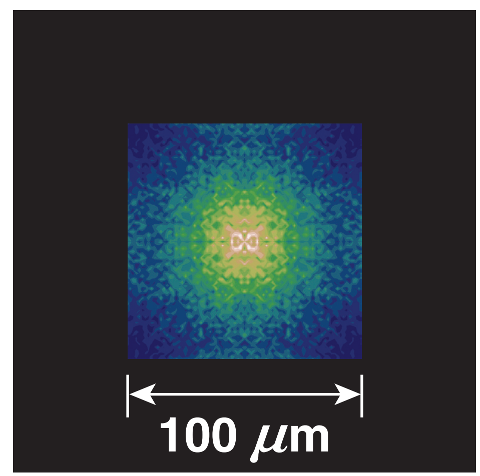
K_α emission from small mass targets provides strong evidence for near-perfect hot electron refluxing

UR LLE

- *K*-shell yield is the same as an infinitely thick target, but without the reabsorption (the same applies to bremsstrahlung).



Simulated K_α image



*W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).

TC7344

Pair creation via the Bethe–Heitler conversion of bremsstrahlung must also be considered

- For Au targets ($Z = 79$) greater than ~100 μm 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 ($E_e > 1.02$ MeV).

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

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

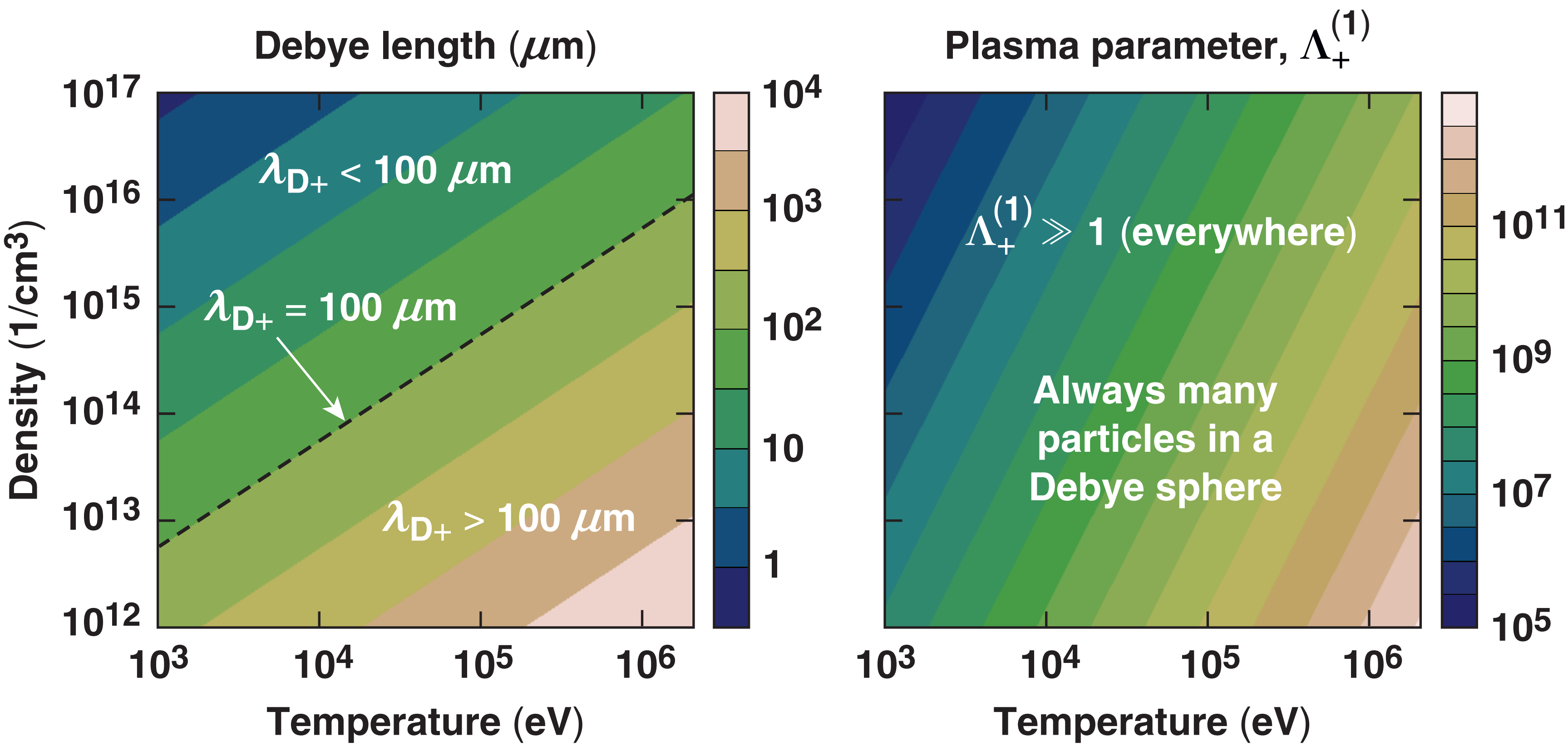
  – $\Delta I/I_0 = 1 - \exp[-x(\text{mm})/7.2] \sim 1\%$ at $x = 100\ \mu$m

TC7222

For the positrons to be considered a plasma, not only must $\Lambda_+^{(1)} \equiv n_+\lambda_{D+}^3 \gg 1$, but also $\Lambda_+^{(2)} = \ell_{system}/\lambda_{D+} \gg 1$

UR LLE

- Positron temperature is computed to be high ~ 1 MeV
- For Debye length to be less than $\simeq$100 μm, require $n_+ > 10^{16}$ cm^{-3}



TC7223

Positron expansion makes it difficult to obtain the required density of $\gtrsim 10^{16}$ cm^{-3}

- Unlike hot electrons, positrons do not reflux

- Spherical expansion must be limited to a radius of 300 μm
  - free expansion at *c* for 1 ps
  - $\Lambda_+^{(2)} = 2.4\left(N_+ / 10^{11}\right)^{1/2}\left(1\ \text{MeV}/T_+\right)^{1/2}\left(1\ \text{ps}/\tau_p\right)^{1/2}$

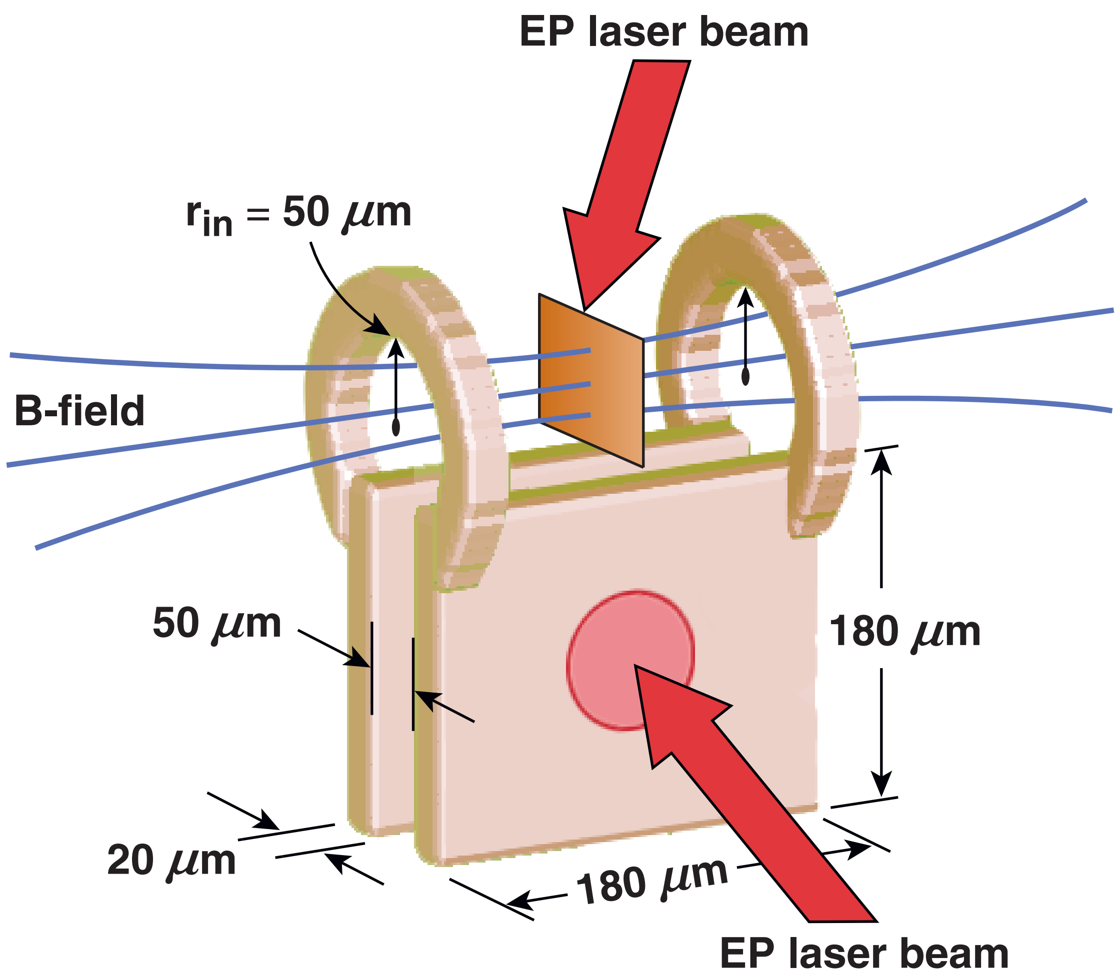
- Limit expansion to one dimension only
  - magnetic field, ponderomotive force*
  - $\Lambda_+^{(2)} = 86\left(N_+ / 10^{11}\right)^{1/2}\left(1\ \text{MeV}/T_+\right)^{1/2}\left(\tau/1\ \text{ps}\right)^{1/2}\left(100\ \mu\text{m}/r_{\text{conf}}\right)$

- Cooling or moderating positrons helps
  - not currently considered

*E. P. Liang *et al*., Phys. Rev. Lett. 81, 4887 (1998).

TC7345

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

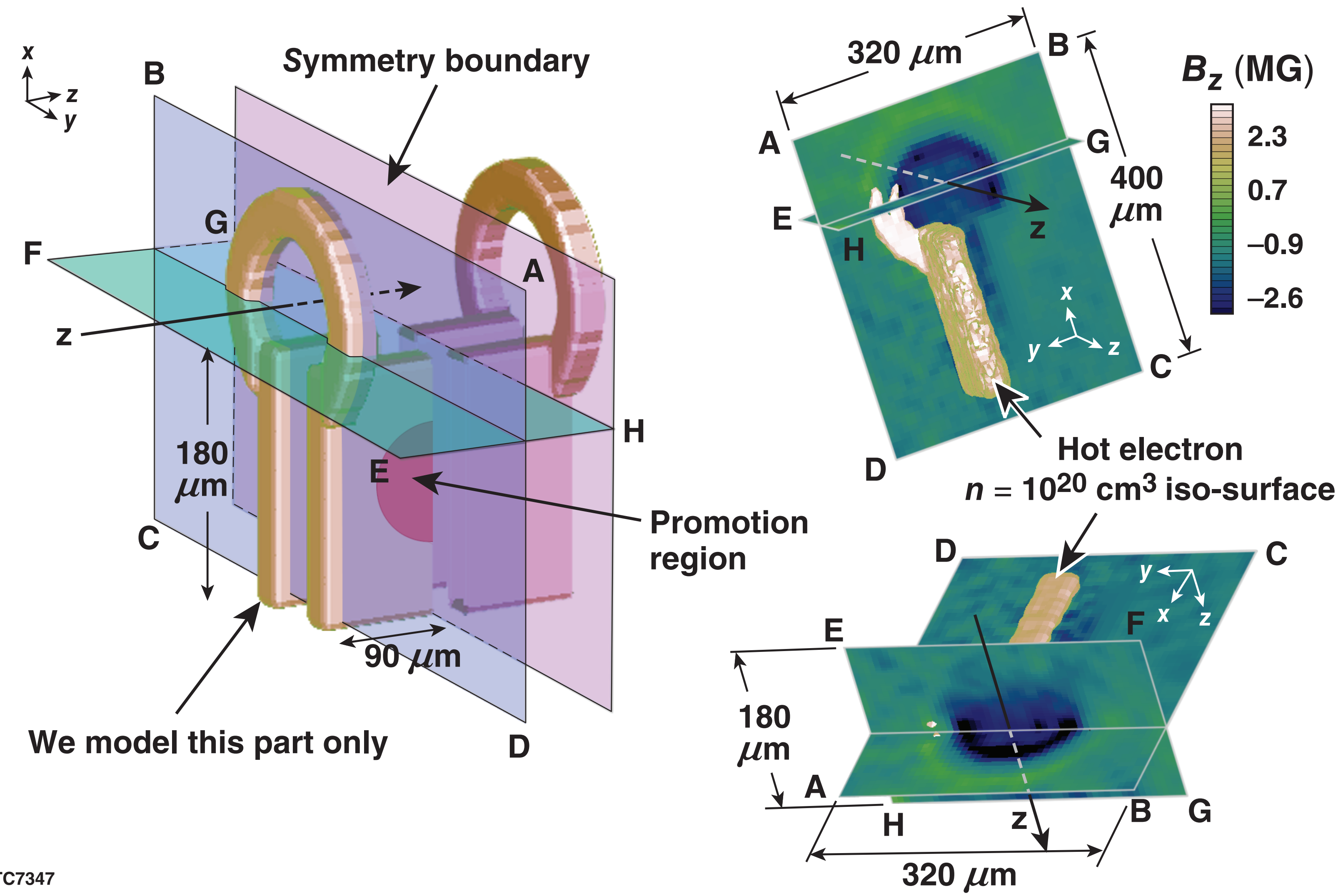


- One EP beam interacts with suitable target (LHS)
- Other beam creates positrons in second target which is immersed in the B-field created by the first beam
- Positrons expansion is influenced
- Targets similar to LHS have been fielded (*)

*H. Daido *et al*., Phys. Rev. Lett. 56, 846 (1986); N. C. Woolsey *et al*., Phys. Plasmas 8, 2439 (2001).

TC7346

The first part of the scheme has been investigated with *LSP* indicating that we can achieve MG magnetic field strengths



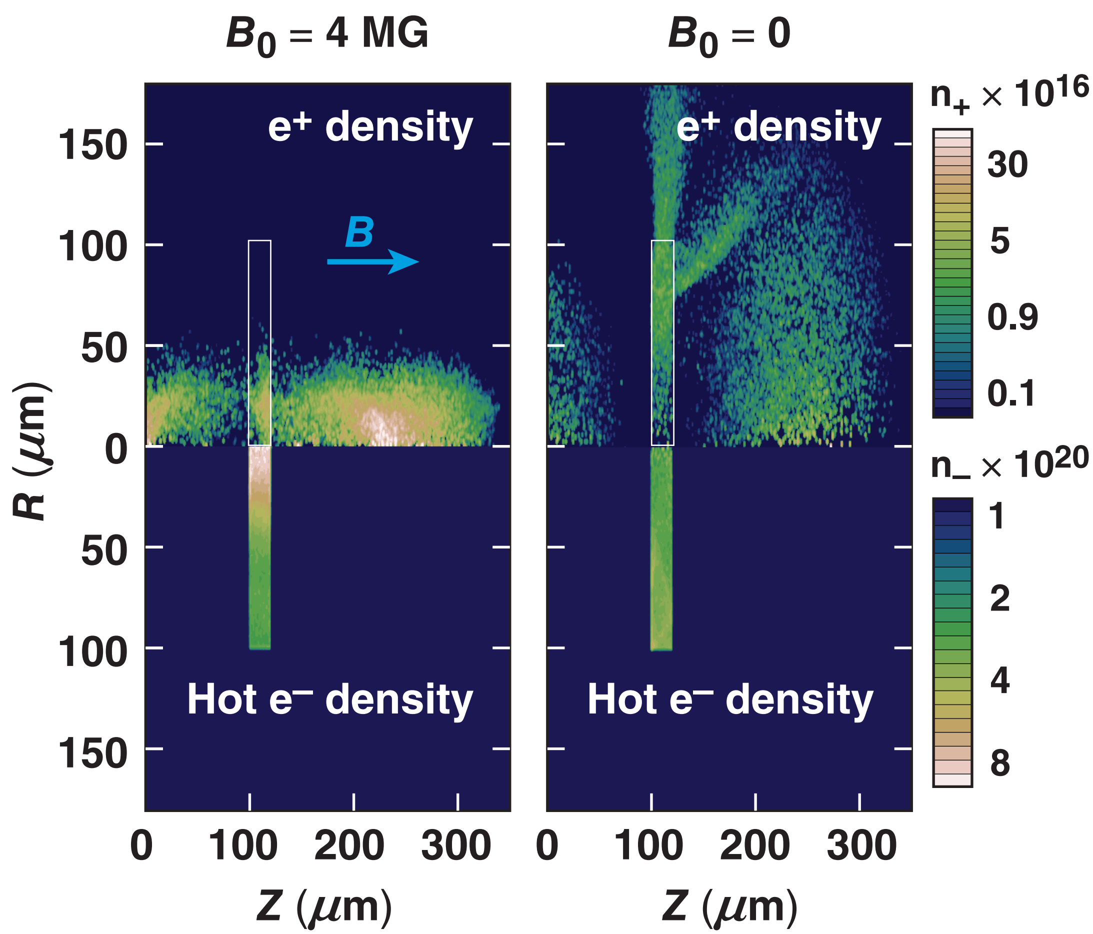
TC7347

One megaguass magnetic fields are attainable and would be sufficient to confine radial positron expansion to within a few hundred microns

- Positron synchrotron frequency $\omega_{Ce} = eB/\gamma mc$
  - $\omega_{Ce} = 1.76 \times 10^{13} (B/1\ \text{MG})(1/\gamma)$ rads s^{-1}
- Gyroradius $r_{Ce} = \beta_{\perp} c/\omega_{Ce}$
  - $r_{Ce} = 17(1\ \text{MG}/B)(\gamma)\ \mu$m
- From 1-D expansion on previous slide: $\Lambda_{+}^{(2)}$ ~40
  - even better if *v* << *c*
- Dynamics could be very interesting
  - electrons are refluxed but positrons are accelerated by the sheath
  - positrons and the neutralizing electron cloud would be expelled along the magnetic field

TC7348

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.

TC7349

Diagnosing the pair plasma provides some significant challenges

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- The presence of positrons can be diagnosed by observing their annihilation radiation
  - once the positron slows down to an energy near that of an atomic electron, annihilation takes place, producing two back-to-back gamma photons of energy ~m_0c^2 = 511 keV each
- 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 μm
- The probe beam would need to be in the submillimeter range

Summary/Conclusions

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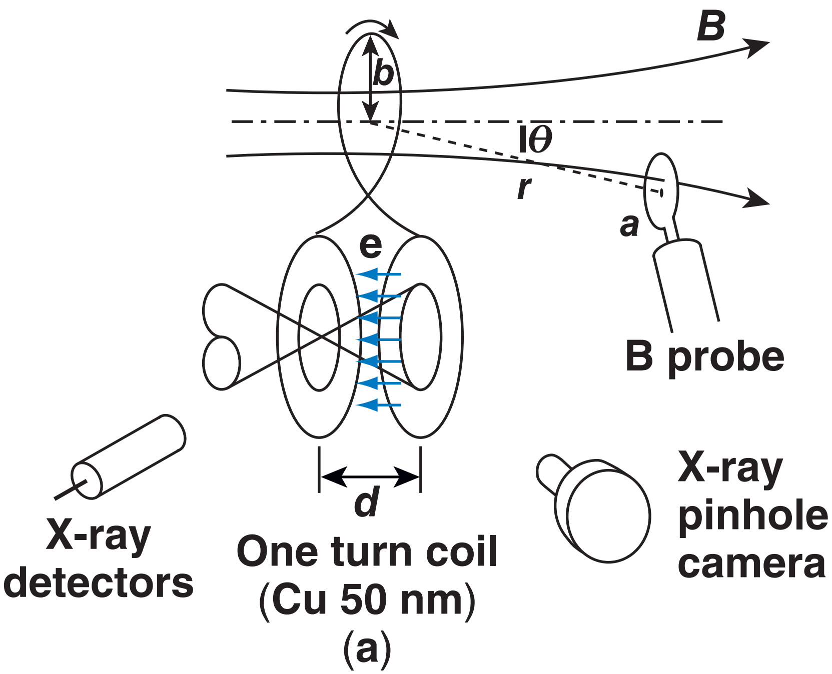
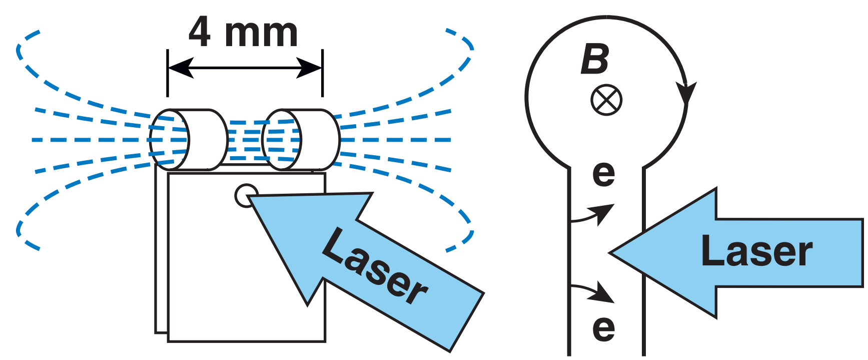
One of the OMEGA EP beams can be used to create a confining magnetic field

B ~0.6 MG



B ~0.4 MG



H. Daido *et al*., Phys. Rev. Lett. 56, 846 (1986).

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