Relativistic Electron Beams, Forward Thomson Scattering, and "Raman" Scattering

A. Simon

Laboratory for Laser Energetics, U. of Rochester

Experiments at LLE (see abstract by D. Hicks at this meeting) show that surprisingly high potentials (+0.5 to 2.0 MV) develop in plasmas irradiated by high-energy lasers. The highly conducting plasma will be a near equipotential and should attract return-current electrons in a radial beam-like distribution, especially in the outer low-density regions. This will initiate the BOT instability, creating large plasma waves with phase velocities close to c. Coherent Thomson scattering of the interaction beam from these waves must occur primarily in the forward direction. This will appear to be "backward SRS" upon reflection from a critical surface. We will show that the resulting spectrum is fairly broad and at short wavelengths. Collisional absorption of the scattered EM wave limits the reflectivity to low values (depending on the density scale length). Thus, a distinct difference exists between the spectrum for thick targets (n_c surface present) and thin targets (gasbags, etc., from which primarily a narrow absolute-SRS backward emission occurs, at the peak density). The thick-target, reflected-wave angular distribution will be concentrated in the backward direction. The corresponding plasma-wave k-vector will be a fraction of k_0. The variation of the spectrum with potential and angle will be discussed. Comparison will be made with recent results at LLE and LLNL. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, UR, and NYSERDA.

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Summary

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- Raman scattering continues to elude explanation on the basis of linear SRS theory.
- Experiments have shown the existence of very large and robust positive potentials on targets irradiated by high-energy laser beams.
- This suggests a new model for the source of directed electron beams, and for reconciling theory and experiment via enhanced Thomson scattering.
- Relativistic analysis becomes necessary for the more recent experiments—there are some interesting new effects.
- Future experiments should study correlation between the potential and the Raman spectrum.

Can the SRS linear theory and observations of Raman scattering be reconciled?

- The answer still seems to be no! Even though we now have much smoother laser beams and improved diagnostics, the following problems remain:
  - The famous gap! The threshold should decrease linearly with increasing density and become absolute at $n_c/4$.
  - We often see emission at densities so low that Landau damping should dominate.
  - Qualitative differences between thick-target spectra and those from underdense targets.
  - The angular variation of the intensity and spectrum does not follow linear SRS prediction.
  - Unexplained scintillation in time
  - Spiky structure in λ_s and time
  - “White noise” flashes

Enhanced Thomson scattering (ETS), owing to electron beams in the plasma, was proposed in 1984

- The proposal was based in part on Perkins and Salpeter’s explanation of the enhanced plasma line in ionospheric scattering (1965).
- When available, the theory used hot x-ray temperature to select the beam velocity, and this readily reproduced the observed spectrum; however, the source of electron beams remained a problem.
- The original postulate, that the beam source was at $n_c/4$ or at n_c and involved the two-plasmon or critical surface instabilities, had three difficulties:
  - The beam started out in the wrong direction.
  - No predictive capability existed for the beam velocity or density.
  - Raman was often seen in the absence of n_c or $n_c/4$ surfaces.

Recent measurements of high plasma potentials have changed the picture

- There is strong evidence that robust plasma potentials persist while the laser beam is on target.
- The highly conducting positive plasma should produce a radial electrostatic field that induces a directed electron return current (drawn from the outer circulating cloud). This return current might be expected to be beam-like in the outer regions of the plasma.
- ETS from these beam-induced waves now becomes a candidate for reconciliation of theory and experiment.

What is different about this picture?

- The electron beams start off in the right direction.
- The potential, and its variation in time, becomes critical to the beam's existence.
- There is now the possibility of observing a correlation between the plasma potential and the Raman spectrum.
- High-energy irradiations have shown evidence of very high potentials that should produce relativistic beams. ETS theory has been extended to encompass such cases. The relativistic results show some interesting features.

Here are some characteristics of ETS from a plasma with a relativistic beam

- Relativistic-beam ETS will occur primarily in forward directions (typically up to 20° from forward) for plasma potentials above 115 kV; hence, reflection is necessary to produce backward scatter.
- Enhanced plasma waves will be in the $k_0/3$ to $k_0/5$ range. Thomson probe experiments have not looked at this region.
- The ETS matching conditions ($v_\phi \cong c$) are satisfied only below the 0.1-n_c range.
- The resonant k_p and ω_p both decrease as beam velocity increases (for forward scatter).
- Of course, the theory, as before, can only identify wavelength bands within which ETS can occur. It cannot predict the scattered intensity or even its variation within the band.

Can ETS explain more recent experiments with greater laser energy, scale lengths, and with smoothing?

- **Thick targets (e.g., hohlraums, OMEGA pellet compression, etc.) allow reflection of ETS from critical surfaces; however, absorption will limit reflectivity to low values (typically, a few percent). A fairly broad wavelength band will occur and correspond to quite low densities (0.1 n_c or less).**

- **Underdense targets (e.g., gasbags) will not reflect forward ETS; however, true absolute SRS should occur at the density profile peak and produce a narrow backscatter line.**

As an example we have applied this picture to the LSP plasma experiments at LLE[1]

- UV light at up to 20 kJ irradiated thick CH foils and solid targets (DPP smoothing used).
- Direct backscattering was observed with reflectivities less than 5%.
- The scattered light is in the 450- to 550-nm range. For such λ_s and plasma temperature ($\cong$ 4 keV) very strong Landau damping would occur in a Maxwellian plasma.
- A plasma potential of 1.5 MV would create ETS that reproduces the observed spectrum (see next viewgraph). Unfortunately, no potential measurement was made, but this value is consistent with the range of potentials observed in OMEGA compressions (see KO2.09, this meeting).

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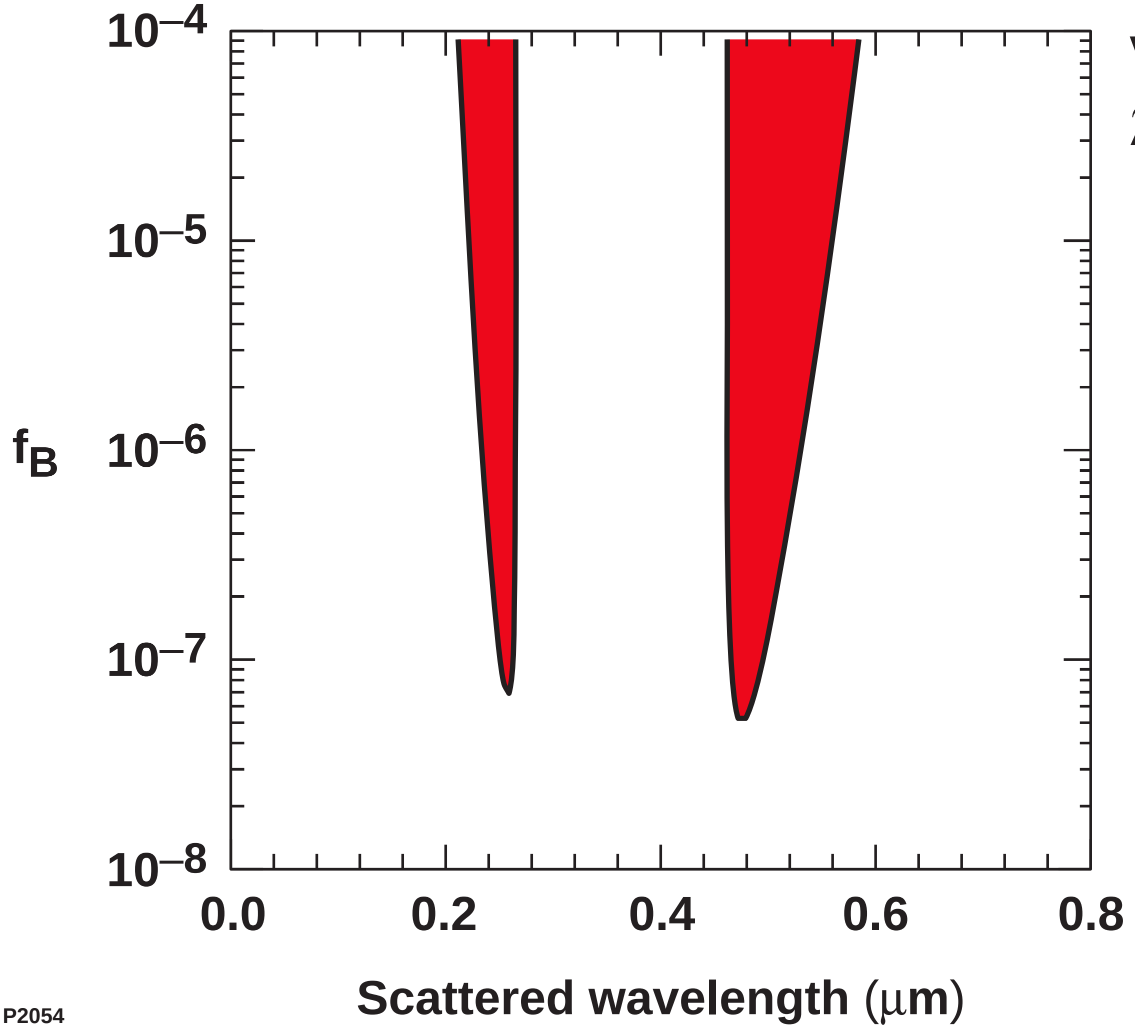
[1] S. P. Regan *et al*., Phys. Plasmas 6, 2072 (1999).

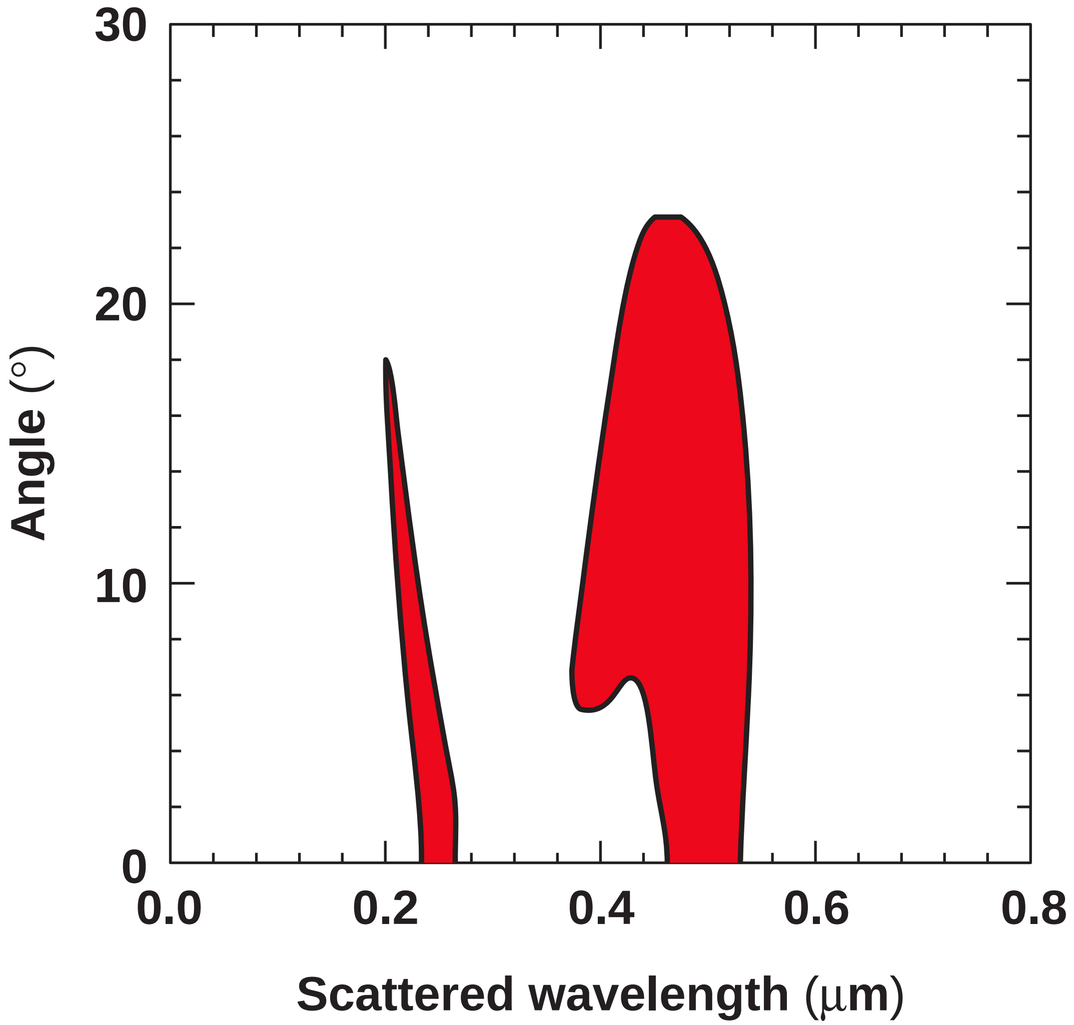
Forward ETS wavelength zones versus beam number fraction



V = 1.5 MV, T_c = 4.0 keV,

λ_0 = 0.35 μm, ΔE_B = 80 keV

Angular variation of ETS scattering



$f_B = 10^{-6}$, $V = 1.5$ MV,
$T_c = 4.0$ keV, $\lambda_0 = 0.35$ μm,
$\Delta E_B = 80$ keV

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