LASER-ELECTRON BEAM INTERACTION APPLIED TO OPTICAL AMPLIFIERS AND OSCILLATORS

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Coherent energy exchange between a laser and a free electron beam has potential applications for particle acceleration and for optical signal amplification and oscillation. A laser electron accelerator can provide high acceleration gradients and short duration electron pulses, and the optical electron beam amplifier can be broadly tunable with high gain and high average power.

There are several ways to achieve this energy exchange. If the interaction extends over many wavelengths then momentum matching is required, either by having a slow wave circuit to retard the electromagnetic wave or by using a medium for which the phase velocity of the wave is less than or equal to the electron velocity. For short interaction lengths there is uncertainty in the final state electron momentum so that momentum conservation is not necessary. Short lengths may be obtained either by focusing the light or by using a light guide.

Recently, we have observed momentum modulation of a relativistic electron beam by a Nd:YAG laser. The electrons, at 100 MeV energy, interacted with the laser light in helium gas at standard temperature and pressure. At an angle of 6.55 mrad between the two wavevectors, corresponding to the Cerenkov angle, a given electron remained in a field of constant phase as it passed through the light beam.

Figure 1 is a drawing of the experimental arrangement, showing the trajectories of the electrons and light. The particle momentum was measured by a mass spectrometer, and the angle between the wavevectors was controlled by a rotatable mirror. Figure 2 is a photograph of the experimental arrangement with the helium gas bag removed. Electrons entered the interaction region through a 1/4-mil mylar window, shown at the lower left corner of the photograph, and passed into the mass spectrometer at the upper center.

Parameters for the experiment were as follows:

1. Electron beam parameters
    - 100 MeV
    - Measured divergence (half-angle) = 0.54 mrad
    - 0.6-mm diameter beam
    - $\Delta E = 63$ keV (FWHM)
    - 13 nsec duration
2. Laser Parameters
    - Nd:YAG
    - $\lambda = 1.06\ \mu$
    - Power = 2.0 MW
    - < 0.1 mrad divergence in the interaction region

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20 nsec duration
0.65 mm spot size
0.3 cm^{-1} line width

3. Medium Parameters
Helium at standard temperature and pressure (STP)
Cerenkov angle = 6.55 mrad at 100 MeV

Figure 3 illustrates the experimental results. Since electrons are equally likely to be accelerated as decelerated, the primary effect of the interaction is to change the linewidth of the electron energy spectrum. The ordinate in figure 3 is the full-width, half-maximum of the spectrum, and the abscissa is the separation between the axes of the electron and laser beams in mils. Each beam has a diameter of approximately 25 mils. The theoretical curve, obtained from a Monte Carlo simulation that included electron scattering and laser multimoding is shown as the solid line in figure 3. It is seen that the 2 MW, TEM mode laser changes the energy spectrum linewidth by approximately 40 keV for a single pass through the electron beam.

Momentum modulation of an electron beam, as demonstrated by the experimental results, may be used for amplification of radiation. An optical klystron amplifier would be similar in appearance to a microwave klystron, with a bunching section, a drift space, and an output coupler. At relativistic velocities the electromagnetic field produces primarily momentum modulation rather than velocity modulation. However, this does not preclude klystron bunching at optical wavelengths, because very little velocity modulation is required to shift the electron position by a fraction of an optical wavelength.

Figure 4 illustrates a possible configuration for an optical klystron, where a vapor (e.g., benzene or pentane) is used for index matching. Electrons pass through a membrane or thin foil into the interaction region, where an optical interferometer is used to resonate the electromagnetic radiation. The angle between the interferometer axis and the electron beam direction is the Cerenkov angle. After passing through the buncher section, the velocity modulation of the particles is converted to current modulation, where the amplitude of the current, I_1, at the bunching frequency is given by

$$I_1 = 2I_0 J_1(X) \qquad (1)$$

where

$I_0 \sim$ dc electron beam current

$X \sim \frac{\Delta v}{v} \frac{\omega}{\omega_p} \sin \frac{\omega_p z}{v}$

$J_1 \sim$ the Bessel function of first kind and order

$\Delta v/v \sim$ fractional velocity modulation for an electron seeing maximum field strength.

$\omega_p \sim$ plasma frequency for the electron beam

z ~ distance down the drift region measured from the buncher

v ~ electron velocity

To obtain maximum bunching at the fundamental frequency, the drift distance z should be such that $X = 1.84$, so that $J_1(X)$ is maximized. For relativistic electrons,

$$\frac{\Delta_v}{v} \cong \left(\frac{E_0}{E}\right)^2 \frac{\Delta_E}{E} \tag{2}$$

where

E_0 ~ rest energy = 0.511 MeV

E ~ electron kinetic energy

$\frac{\Delta_E}{E}$ ~ fractional energy change of the electron seeing the maximum field.

From equations (1) and (2) the optimum bunching distance may be determined.

At the output coupler the electron beam current, modulated at the frequency applied to the buncher, excites an electromagnetic field in another interferometer. The extracted power may be an appreciable fraction of the dc power in the electron beam, whereas the input power is only that amount required to establish a field in the presence of resonator losses. Therefore, high power gain is possible. In contrast to the quantum amplifier, there is no feedback path to provide self-sustained oscillations. Frequency may be tuned by adjusting the interferometers, and, if an oscillator is desired, this may be obtained by providing a feedback loop from the output interferometer to the buncher.

Some of the problems associated with the optical klystron are:

1. As the electrons pass through the membrane and index matching medium, an energy spread occurs resulting from ionization and bremsstrahlung. The coherent energy from the laser must exceed this random spread.

2. There is an energy spread for the incident electrons, and this must also be small compared to the coherent modulation.

3. Electrons are scattered in different directions because of the nuclear coulomb forces in the various media. If Cerenkov synchronism is satisfied along one direction, phase mismatch will occur along the other directions. This effect must be small.

4. There is a loss of mean energy for the electrons, and this also introduces some phase mismatch.

To overcome these problems it is necessary that the field in the buncher introduce an energy modulation in excess of the random energy, and that the phase mismatch effects be sufficiently small so that most electrons remain in a field of constant phase in transit through the buncher.

As an example, consider an optical klystron to amplify 10-μ radiation, with an electron beam at 6 MeV energy and an energy spread $\Delta E/E = 10^{-3}$. Current density is 3 A/cm^2, and the beam area is 1 cm^2. The index matching medium is a vapor (e.g., benzene or pentane) at several atmospheres pressure to provide an index of refraction equal to $(1 + 8.5 \times 10^{-3})$. A 1/4-mil mylar membrane separates the vacuum from the vapor (differential pumping might be preferable), and it is assumed that the loss in both interferometers is 0.4 percent per round trip pass. Each electron pulse is 1 μsec long with a repetition rate of 60 pps.

For these parameters the Cerenkov angle is 6°, and with an input power of 12 kW the optimum bunching distance is 9.1 cm. Most electrons remain in a field of constant phase and the energy introduced by the laser is well in excess of the random energy spread. Output power is 0.54 MW (0.54 J per pulse, 60 pps), corresponding to a 3 percent efficiency, where efficiency is defined as the ratio of the output power to the dc electron beam power. Power gain, that is, the ratio of output to input power, is 45. Harmonic bunching distances and power are as follows:

Harmonic	Optimum bunching distance, cm	Harmonic power, MW
1	9.1	0.54
2	7.4	0.38
3	6.9	0.30

Since the input is 12 kW, harmonic generation is achieved with power gain.

With a high power linear accelerator as the electron source, extremely large peak and average power tunable optical radiation may be obtained. For example, the 140 MeV Linac at Oak Ridge has a peak current of 15 A and an average current of 0.8 A. With 5 percent conversion efficiency a tunable optical source could be developed at a peak power of 10^8 W and an average power of 5.6 MW.

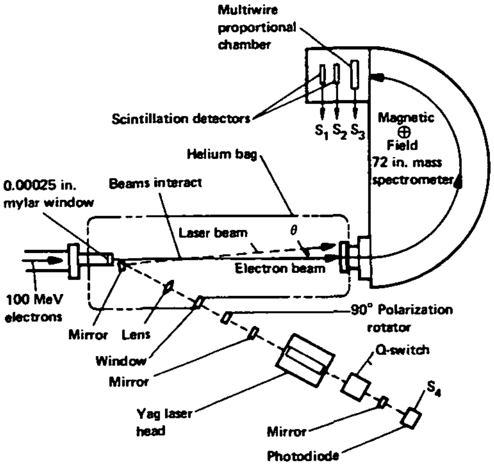

Figure 1.– Experimental setup showing trajectories of electrons and light.

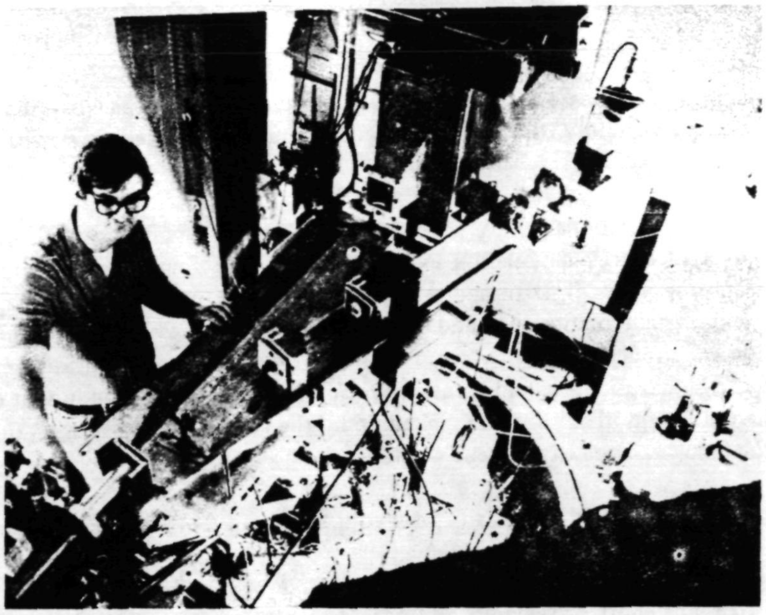

Figure 2.– Experimental setup with the helium bag removed.

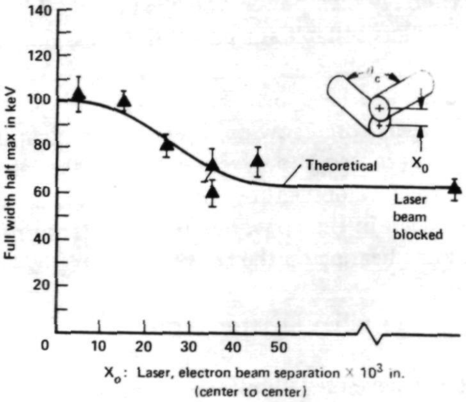

Figure 3.– Experimental results; full-width, half-maximum of the spectrum *vs* separation between axes of the electron and laser beams.

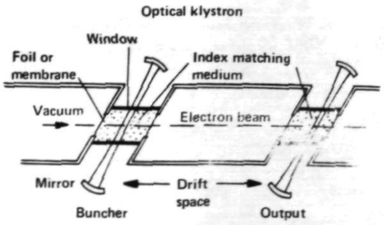

Figure 4.– Optical klystron configuration.

DISCUSSION

Max Garbuny, Westinghouse – Two questions occur. Why not use a liquid or solid rather than the gas? Would this not give higher conversion efficiency? Secondly, the Klystron effect reminds one of the Schwarz-Hora effect which, of course, remains in doubt.

Dick Pantell: Yes, I shall answer both questions. I have gone through an analysis with regard to liquids and solids and the problem is to have a coherent energy modulation in excess of the straggling or the random energy spread that you pick up in going through the material. It turned out that the gas was optimum in this regard. The other point you mentioned was the experiment of Schwarz and Hora where it was suggested that there was a possible modulation of the wavefunction of an electron. Other people have not been able to duplicate this experiment. I made a calculation of the straggling, that is, the random energy spread they would have had in that experiment and it was far in excess of the coherent energy that could be picked up by the laser. So, at least using the principle that I've considered, I don't think the Schwarz-Hora experiment would work.

Karlheinz, Thom, NASA Headquarters – Could you clarify how your work applies to laser energy conversion?

Dick Pantell: Yes, as was stated this morning by Dr. Lundholm, the entire system you're considering has elements of generation of high power, perhaps short wavelength and even tunable radiation, transmission-reception and conversion. What I have discussed is the generation of optical or infrared power. For example, with the Klystron configuration which I used, if one puts in a feedback loop from the output coupler to the buncher (this only takes a small fraction of the output since you have a gain of 45 in the power) then one has an oscillator. Depending on the electron beam you use, one has an oscillator of extremely high power which is tunable. I believe these concepts fit in the category of very high power oscillators and amplifiers suitable for power transmission.

Ken Billman, NASA Ames Research Center – Dick you have answered Karlheinz's question, but I would like to add a small comment since there will be similar papers tomorrow on lasers, rather than laser energy-converters. I decided to devote a small fraction of our time in this meeting to developments in the laser area which, to my best judgement, are new and potentially important to the development of convertors. This development in the laser area is entangled with the necessary developments we need in the converter field. So tomorrow you will hear a lot of short summaries of laser developments that may have a bearing on the converter problem.

Ned Rasor, Rasor Associates – Have you considered the reflex klystron for this?

Dick Pantell: No, it's an interesting suggestion, but I haven't. I think you want to use a magnetic field to bend the electrons back, and it probably should work.

Ernest Brock, LASL – You might also consider using a multicavity klystron.

Dick Pantell: Yes, the high efficiency microwave oscillators and amplifiers do use multicavity configurations. That would be something to do eventually.

Ken Billman, Ames Research Center – Everyone wants you to "run before you walk", Dick!

Dick Pantell: Yes!