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Annual Progress Report and Second Year Proposal

to

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For

# Generation of Radiation by Intense Plasma and E.M. Undulators

Submitted by

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## Synopsis of the Progress Report

This program involves the generation of short wavelength optical radiation by intense plasma and e.m. undulators. In this concept a relativistic electron beam is wiggled by either the oscillating electric field of an intense plasma wave, or by a laser beam causing it to radiate. For both types of undulators the designed parameters are $a_w > 0.1$, $N \sim 100$ and $\lambda_w = 100\ \mu m$ for plasma wave or 10.6 μm for laser light. This progress report describes the work to-date on generating such intense short wavelength undulators. This can be summarized as follows:

a) We have successfully generated up to 200 GW of $CO_2$ radiation in a 200 ps long pulse. This radiation has been focused in vacuum to give $a_w \geq 0.05$ and $N \sim 100$. Thus we are within a factor 2 of the design parameters.

b) A uniform plasma source, θ-pinch, has been constructed and it's density diagnosed using holographic interferometry.

c) Using about 20 GW of laser radiation at two frequencies, 10.27 μm and 9.56 μm, relativistic plasma wave has been excited using the "beat wave" technique. The amplitude of this plasma wave has been inferred to be $n_1/n_o \leq 1\%$. The plasma wave width is thought to be about 2-3 wavelengths.

d) A 1.5 MeV, 9 GHz linac has been procurred using funds from another contract and diagnosed. The electron beam emittance as it exits a 6 μm thick mylar foil, which separates the high vacuum linac structure from the plasma, has been measured to be about 50 π mm mrad.

e) The key problem areas have been identified. These are:

- i) damage to certain optical components in the laser chain because of stimulated Brillouin scattering in the plasma,
- ii) small scale but random deflection of the electron beam by the magnetic field trapped inside the θ-pinch plasma, and

iii) poor focusability of the electron beam due to emittance blow-up due to foil scattering.

Solutions to these problems are currently being sought.

In conclusion, the work is progressing well. As in any research project new problems arise as old ones are solved. We are on schedule and hope to start doing initially e.m. wiggler experiments in FY 88.

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## I. Technical Achievements

### A. Development of a 200 GW, Picosecond $CO_2$ Laser System

The major accomplishment in this first year of funding period is the completion of construction and successful operation of the multi-atmospheric $CO_2$ laser: MARS. This laser will be used both as the e.m. undulator and to drive a plasma wave. The design parameters were 100 J in 100 ps or 1 TW. This energy needs to be equally divided in two co-propagating, and overlapping pulses at 10.27 μm and 9.56 μm. To date we have achieved about 100 J in a less than 400 ps pulse or a power of about 200 GW. If the laser beam is not fired into the plasma no optical coating damage or bulk damage is seen. We think that the present power level is certainly enough to start the e.m. undulator experiments. The present power level is also sufficient to start work on exciting the plasma wave undulator.

We note that is the first ultra-high power, picosecond $CO_2$ laser system based on the "free-induction decay" oscillator in the world and we have had a lot of interest expressed from the laser community about its development.

*Current status.* Up to 10 J/line of laser energy has been focused into the plasma using a f/25 off-axis parabola. The peak intensity is thought to be ~ $10^{13}$ W/cm$^2$. Although the laser pulse is short, intense (up to 10% energy) stimulated Brillouin and Raman backscatter is seen from the plasma. While Brillouin scatter is a good diagnostic of the plasma temperature and Raman scatter is that of plasma density, feedback from these backscattering instabiities is causing optical damage. A possible solution is placing saturable absorber cells which act as diodes that allow intense forward propagating radiation to go through unattenuated but block the unwanted backscatter. This avenue is currently being investigated.

## B. Plasma Source

In our proposed experiment the plasma source is a θ-pinch. In a θ-pinch a sheet of current is pulsed into a single turn coil around an insulating tube containing the gas. The gas in our case is either $H_2$ or He. This current $J_\theta$ induces a magnetic field $B_z$ which varies in time. From Faraday's law an induced electric field $E_\theta$ arises, causing the gas to break down. A thin sheet of plasma is thus formed and as a result of the diamagnetism of the plasma, a current $-J_\theta$ is produced which opposes the circuit current $J_\theta$, keeping the plasma field free. This current crossed with the $B_z$ generates a radially inward force on the plasma which drives the plasma towards the axis. The moment at which the gas breakdown occurs depends on the type of gas, the filling pressure, any preionization and the external circuit parameters. Maximum compression is obtained when the plasma pressure nkT balances the magnetic field pressure.

The parameters of our θ-pinch are listed in Table 1.

**TABLE 1**
Theta Pinch Parameters

| | |
|---|---|
| Total Capacitance | 11.1 μF |
| Charging voltage | 28 kV |
| Coil diameter | 10 cm |
| Coil length | 25 cm |
| Coil material | Copper |
| Coil inductance | 40 nH |
| $E_\theta$ | 530 V/cm |
| Period of the circuit | ~ 5.7 μs |

A typical $\dot{B}$ signal picked up by a single turn loop some 50 cm from the coil is shown in Fig. 1a. In He without preionization, plasma breakdown occurs close to the first minimum of the $\dot{B}$ and maximum compression follows typically 1 μs thereafter as determined by holographic interferometry. Figure 1b shows the plasma density vs. time. Time t = 0 is the time of the peak compression. It can be seen that for ± 200 ns around

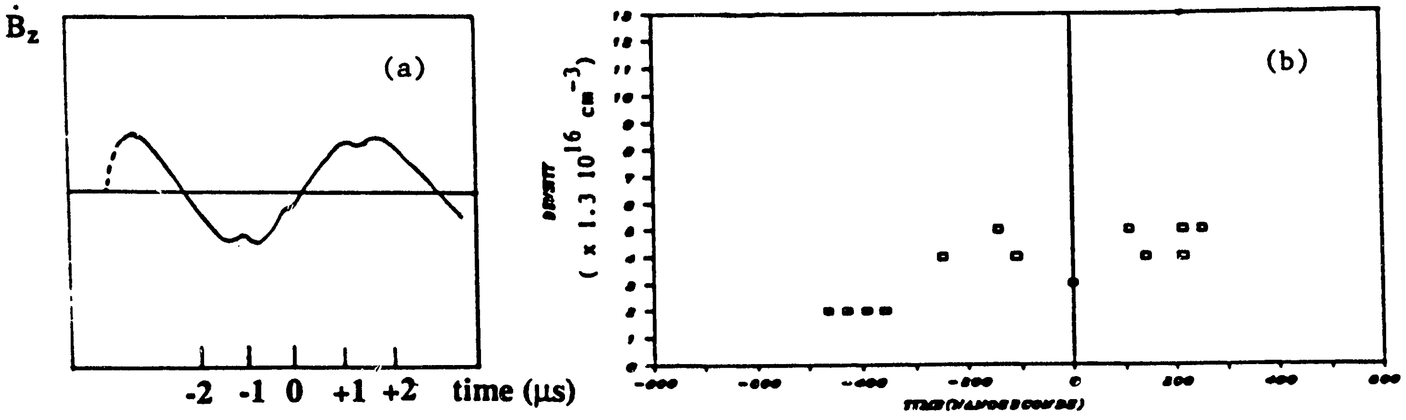


Fig. 1

this time the density is quite close to the resonance value in 120 mT of He without preionization. A more exact measurement of density can only be obtained by using the Raman scattering technique that we have used in our previous experiments. A preliminary attempt was made to transport the electron beam through the θ pinch plasma. A detailed "ray-tracing" computation was initially carried out to see how the electron beam is influenced by the stray fields of the θ pinch as well as any trapped fields. Details of these calculations are summarized in Fig. 2. Figure 2a shows the on axis magnetic field profiles (top) and the electron beam trajectories (bottom) for 5 electrons starting with a radial displacement of 0.5 mm and with various initial angles from the mylar foil of the electron gun. Figure 2b shows what happens when the pinch is fired and assuming that at the peak of compression a trapped field of 1/10 $B_{max}$ exists in the plasma. The electron beam dynamics is now dominated by the θ pinch which acts as a strong solonoidal lens.

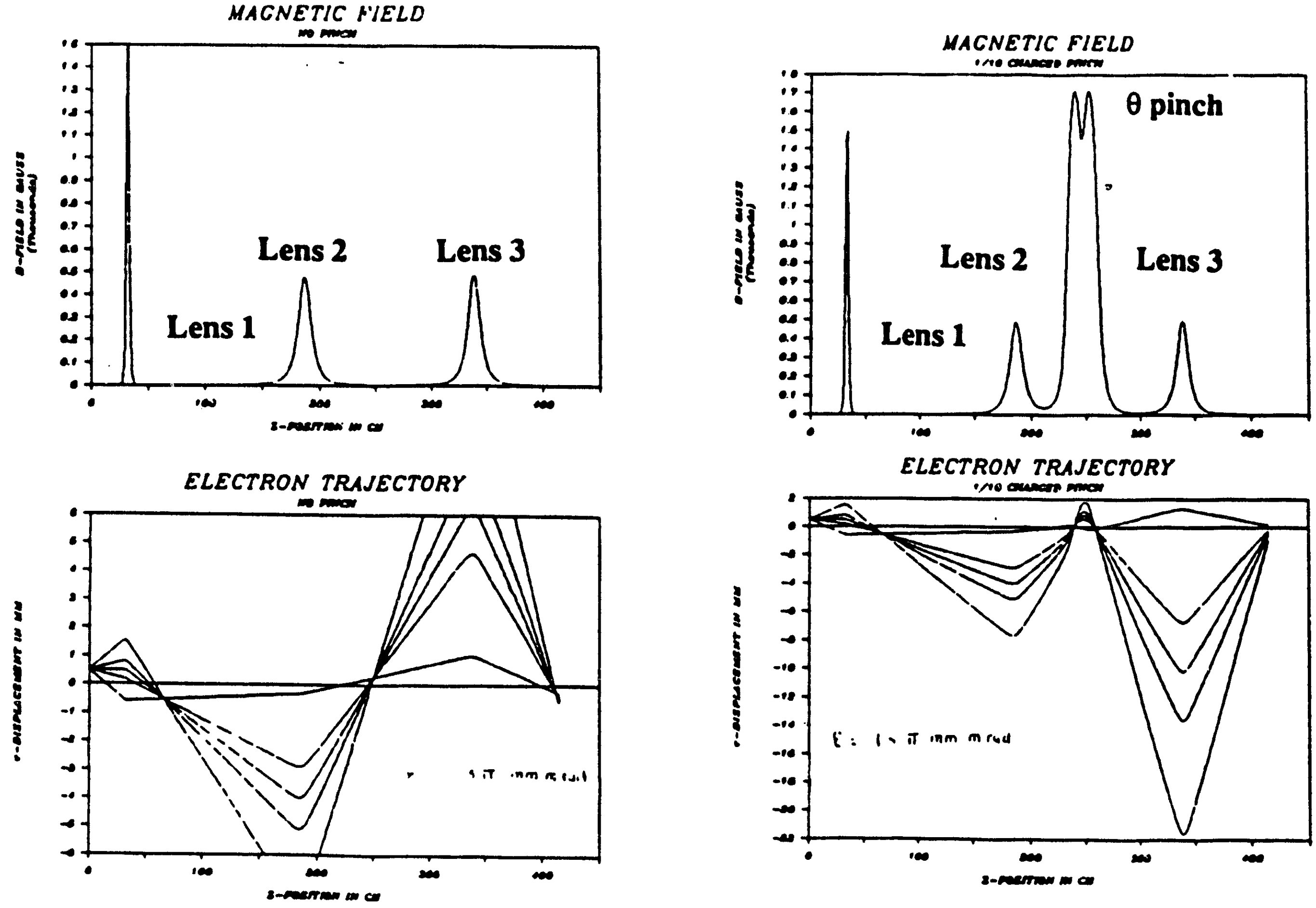
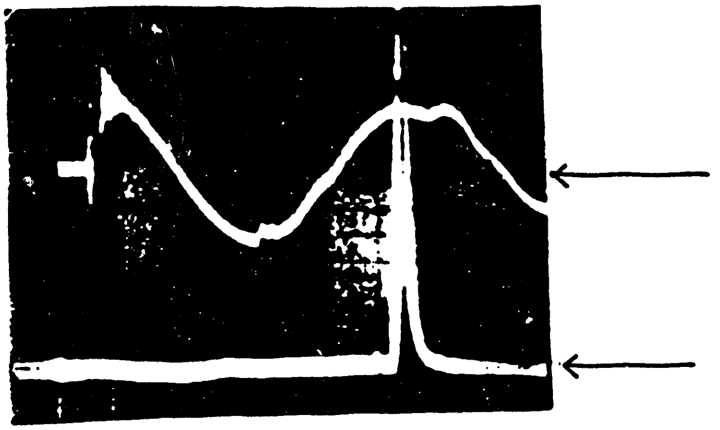


Fig. 2

Electrons make 1/2 of a betatron oscillation and the displacement of the electron with the largest angular spread is such that the electron no longer overlaps with the laser focus which has only a 300 μm radius. In the initial experimental tests we fired the electron beam at the 2nd zero of the magnetic field. Figure 3 shows the results of these tests. A diode placed at the focus of the third lens [or at the output of the electron spectrometer which images this point] shows that an electron pulse only ±50 ns wide is transmitted around the 2nd zero of the magnetic field. We are effectively gating the linac externally.

Obviously this way of sharpening the electron pulse has the advantage of reducing the noise level in the spectrometer by a factor of ~ 50.



**1 μs/div**

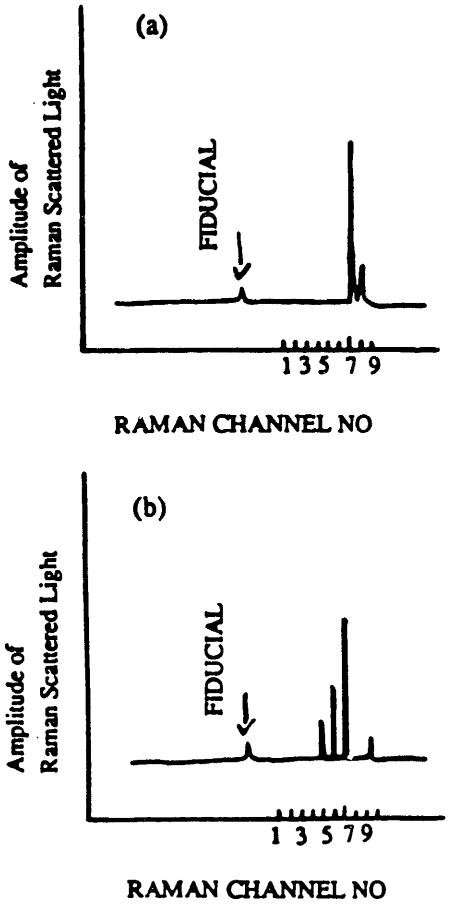
**$\dot{B}_z$ of the θ-pinch**

**Injected Electron Pulse Shape**

Fig. 3

In order to determine if the resonant density of $5.8\times10^{16}$ cm$^{-3}$ could be produced at the second B = 0 we carried out an extensive series of measurements. The technique used was Raman scattering of an intense $CO_2$ laser probe beam. Since the frequency of the Raman backscattered radiation is shifted by the Bohm-Gross frequency we can determine the plasma density rather accurately using this technique. We measured the frequency of the Raman backscattered radiation using an image disector to disperse the radiation and a He-cooled Cu: Ge detector to detect the radiation. We found that at the peak-compression phase of the θ-pinch, 120 mT of He at 24 kV produced an intense

Raman shifted signal corresponding to the resonant density with only 1 J (in ~ 250 ps) of incident $CO_2$ laser energy. Furthermore, this density could be reproducibly generated shot-to-shot. This is shown in Fig. 4(a). On the other hand at the second B = 0, we needed to increase the fill pressure up to at least 350 mT to obtain a signal at the resonant density. Moreover, the Raman scattering occurred over a wide range of densities from $2.53 \times 10^{16}$–$1.0 \times 10^{17}$ $cm^{-3}$.



| Raman Channel No. | Density ($cm^{-3}$) |
|---|---|
| 2 | $1.58\times10^{15}$ |
| 3 | $6.33\times10^{15}$ |
| 4 | $1.42\times10^{16}$ |
| 5 | $2.53\times10^{16}$ |
| 6 | $3.96\times10^{16}$ |
| 7 | $5.7\times10^{16}$ |
| 8 | $7.8\times10^{16}$ |
| 9 | $10^{17}$ |

Fig. 4

*Current status.* Both interferometry and preliminary experiments with shotting 1.5 MeV electron beam through the plasma showed that small-scale magnetic fields can be trapped inside the θ-pinch plasmas. These fields can give random deflecting kicks to the focused electron beam. One option is to bypass the problem by increasing the electron beam energy to 4 MeV. This is currently being explored.

## C. Excitation of a Beat Plasma Wave

As discussed above we have fine tuned the plasma density using Raman backscatter technique to the resonant value of $5.6\times10^{16}$ cm$^{-3}$. Some preliminary work is being done on exciting the plasma undulator. We are not yet using wide wavefront generating optics. By tightly focusing the laser beams into the plasma we have excited the plasma wave and diagnosed it by detecting Stokes and Anti-Stokes sideband radiation in the forward direction. This is frequency downshifted/upshifted by an amount $\omega_1-\omega_p$ and $\omega_o+\omega_p$, respectively. "From knowing" the absolute amount of light scattered in these sidebands we have determined $a_w \sim 1\%$ over a length of 1 cm.

*Current status.* Efforts are currently underway to first increase the plasma wave amplitude to give $a_w \sim 0.1$ with a narrow but long focus. Once that is accomplished we will start work on generating a wide but short focus. This is expected to happen in FY 1988.

## D. Electron Linac

A 1.5 MeV, 9 GHz, x-band linac has been purchased under a separate contract that will be used for these experiments on the e.m. and plasma undulators. Since the linac structure must be maintained under better than $10^{-6}$ Torr vacuum, whereas the plasma chamber is at 100 mT, 6 μm thick mylar foil is used to separate the linac from the experiment. The linac micropulse is 5 μs long and contains micropulses each typically 10 ps long separated by ~ 110 ps. Because of the scatterng in the mylar foil the electron bem exiting the mylar foil has an emittance of 50 π mm mrad. In order to reduce the emittance, we focused the electron beam through a 2 mm diameter aperture. Beam scaping at the aperture leads to an improved emittance of ~ 10 π mm mrad, however the electron current drops from 100 mA peak to about 1 mA peak. This reduction in electron current is a problem for the undulator experiment. One possible solution is differential pumping between the linac chamber and the plasma chamber and removal of the mylar foil. Another possible solution is increasing the electron beam energy to 4 or 6 MeV. This latter possibility is currently being explored.

## E. Current Experimental Thrust

We are currently working on solving the laser to plasma coupling problem. One option is to try to eliminate the stimulated Brillouin scattering by using a heavier gas with a light ion impurity to Landau damp the ion modes. This was not too promising in early runs because the laser intensity is so high that we are in the strongly coupled regime (stimulated Compton scattering). The other option is that by using saturable absorber cells we can propagate the forward going intense pulse without much loss but quench the weak backscattered pulse. Clearly, the condition for this to work is that the population recovery time of the saturable absorber molecules should be much less than the round trip transit time of the laser pulse from the absorber cell to the plasma. We tried using ethanol/methonal (for 9.6) and freon 115 (for 10.27) buffered with He to decrease the population recovery time. The buffering seemed to destroy the saturation characteristic of the gases. Currently we are looking into other organic gases which can be used as saturable absorbers with rapid population recovery times.

The other problem we discovered is the existence of small scale trapped magnetic fields in the plasma. The plasma in a θ-pinch device is generally thought to be field free since plasma can shield out magnetic field lines. However, our experiments have determined that a significant fraction of the magnetic field can be trapped by the plasma as it implodes inwards. At peak of the compression the trapped field can produce localized density islands which can be observed interferometrically (Fig. 5). From pressure balance we have determined that up to 4-10% of the magnetic field at peak compression can be trapped. Furthermore, since the typical diffusion time of the magnetic field is on the order of 1 μs, even at the second B = 0, which occurs 1.5 μs later, the plasma (which is by now quite tenuous) can still have tens of gauss of B field trapped within it.

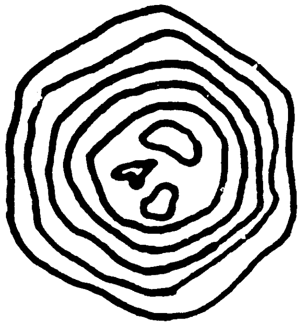


Fig. 5

An independent confirmation of the trapped B field in the plasma was obtained by shooting the electron bunch through the plasma at the second B = 0 with and without the plasma. Two diagnostics were used. The first was a diode placed at the image plane of the third lens and the second was a photographic film placed at this point. Fig. 6 shows the result. Fig. 6(a) shows that, even when no current is flowing through the coil at the second B = 0, the electron signal detected by the diode can be a factor 3-10 less when there is plasma present compared to when there is no plasma. The electron signal is less because of the small kicks the electron beam gets and this is evident in the beam images of Fig. 6(b). One can see that image can shift (usually unpredictably) by one to two diameters when the plasma is present, consistent with a trapped field of 20-30 Gauss over the length of the plasma of 20 cm.

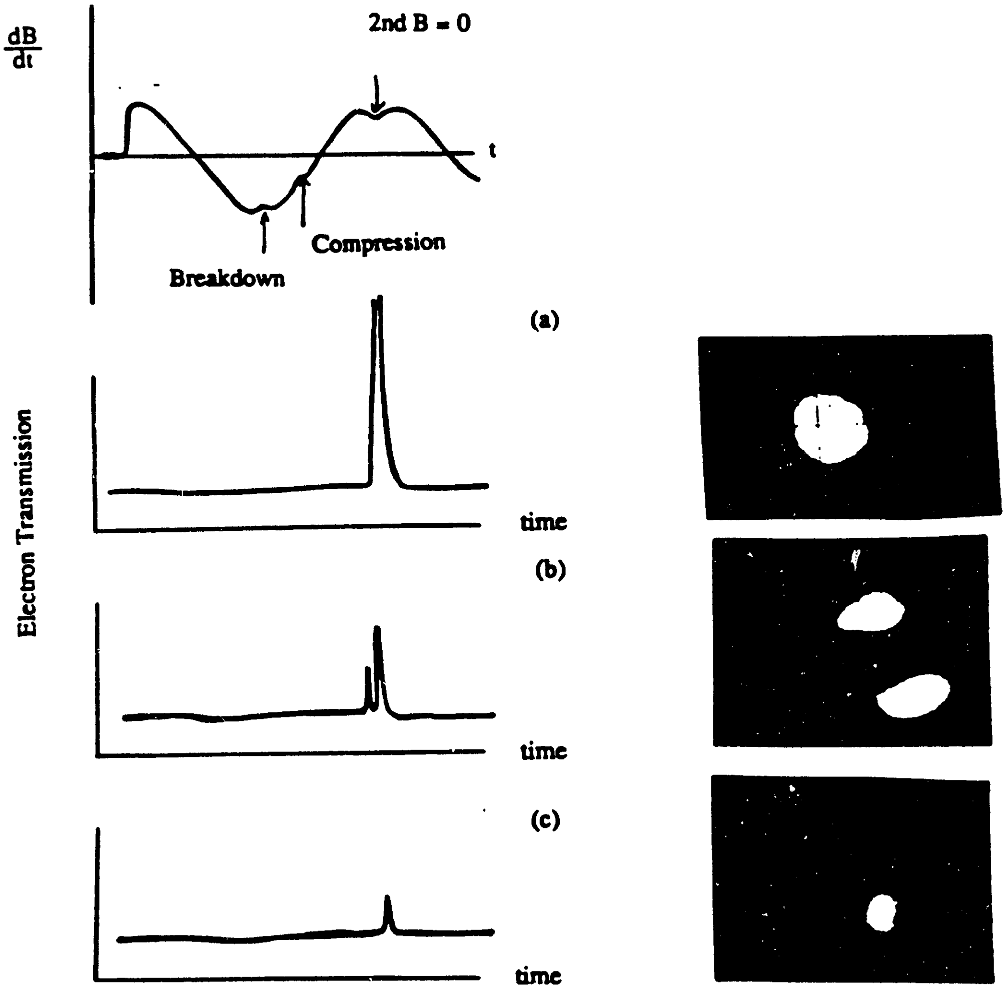


Fig. 6

## II. Progress on the Spectra Technology Sub-Contract

As agreed upon at the time of the award of the grant we subcontracted to Spectra Technology of Bellevue, Washington (P.I.: J. Slater) for an applications study to identify:

a) how radiation sources based on ultrashort wavelength laser or plasma wigglers compare with other more conventional approaches to obtaining synchrotron radiation;

b) which technologies are likely to be most impacted by such a radiation source;

c) who might be interested in taking up this work further to systems level.

Jack Slater and his colleague from Spectra Technology visited UCLA on 12/16/87. After a lengthy discussion and lab tour it was agreed that during the first year Spectra would:

1) carry out a source comparison assuming $n_1/n_o = a_w = 1$ for a plasma wiggler and no emittance growth of the electron beam;

2) discuss with K. J. Kim (LBL) about the possibility of incorporating a bypass beam on the LBL storage ring to carry out this kind of work.

In future Spectra will be involved in analyzing the potential of these undulators for perhaps FEL action and in analyzing the experimental results as they become available at UCLA.

# END

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