EXPERIMENTAL WORK AT UCLA ON THE PLASMA BEAT WAVE ACCELERATOR

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ABSTRACT

We report on the status of the experimental work at UCLA on the Plasma Beat Wave Accelerator (PBWA) The object of the current phase of experiments is to demonstrate controlled acceleration of externally injected particles by the relativistic plasma wave excited resonantly by beating two laser beams at the plasma frequency There are four separate technologies that are being developed for this experiment The first is a multi atmospheric, sub nanosecond CO_2 laser for driving the plasma wave; the second is a 1 5 MeV LINAC for injection; the third is a θ pinch plasma source for producing high density, relatively homogeneous plasmas and; the fourth is an ultra sensitive particle diagnostic system These four technologies are currently being integrated and experiments are expected to begin in the Fall 1987

1 INTRODUCTION

In this paper we shall describe the status of the proof of principle experiment designed to demonstrate controlled acceleration of externally injected electrons by a plasma density wave moving nearly at the speed of light The plasma wave is excited by resonantly beating two lasers in a plasma in such a way that their frequency difference $\Delta\omega$ is the plasma frequency ω_p This scheme is called the plasma beat wave accelerator (PBWA) and has been discussed in numerous previous publications[1,2,3,4,5] The parameters of the proposed acceleration experiment are shown in Table 1 We shall now describe the progress made on the CO_2 laser, the injector linac, the plasma source and the particle diagnostic system

2 LASER SYSTEM

As can be seen from Table 1 we propose to use a CO_2 laser for this experiment CO_2 laser is ideal for a proof of principle exeriment for two reasons: First, the growth rate of the plasma wave scales as $\alpha_1\alpha_2$ and the saturation amplitude scales as $(\alpha_1\alpha_2)^{1/3}$ where $\alpha_{1,2} = eE_{1,2}/m\omega_{1,2}c$ is the normalized oscillating velocity of the electrons in the laser field Since α scales as $\sqrt{I}\,\lambda$ where I is the laser intensity and λ the laser wavelength, with a longer wavelength laser we need less intensity and consequently a modest size laser Second, a CO_2 laser can be easily operated on two frequencies, can be amplified with not too severe a phase front distortion and can be focused over a relatively long length because the Rayleigh length is long

TABLE 1

Parameters of proposed acceleration experiment

Laser wavelengths	λ_0	9.56 μm
	λ_1	10.27 μm
Resonant density	n_0	5.8×10^{16} cm^{-3}
Electron quiver velocity/c		0.07
Phase velocity of wave γ_{ph}		14
n_1	expected	0.04
	maximum	0.19
Pulse risetime		200 ps
Saturation time		113 ps
Accelerating field	expected	1 GeV/m
	maximum	4.75 GeV/m
Acceleration length		1.7 cm
Focal spot size		600 μm
Rayleigh length		6 cm
Injection energy	minimum	500 keV
	maximum	2.4 MeV
Energy gain	expected	16 MeV
	maximum	47.4 MeV

Unfortunately, with the choice of wavelengths easily available using the various rotational vibrational lines of the CO_2 molecule, plasma waves with Lorentz factors in the range 10-30 can be excited thus limiting the energy that the particles can gain to between a few tens to a few hundreds of MeV Here the Lorentz factor $\gamma_{ph} = (1 - v_{ph}^2/c^2)^{-1/2}$ and the energy gain is given by $E_{gain} = 4\gamma_{ph}^2 mc^2 (n_1/n_0)$ The parameters of the laser needed for our experiment are also given in Table 1 There are three main components to this laser An oscillator is used to produce the two frequency, 200 ps long pulse with an energy of about 100 μJ The oscillator uses the "Free induction decay" technique[6] for generating a short pulse from a 100 ns long pulse from a conventional TEA module. Figure 1 shows schematically the sequence of events that lead to the generation of a subnanosecond pulse. A 100 ns pulse is switched off by an overdense spark in an optical shutter within a few tens of picoseconds at the peak of the pulse. This transmitted pulse is subsequently absorbed in a 2 meter long, hot CO_2 cell. The temperature of the hot CO_2 is maintained at 400 °C to populate the lower lasing level and thereby increase the absorption The pressure is maintained at 40 Torr. The gas pressure inside the hot cell determines the collision time and therefore the dephasing time of the coherent polarization induced by the pulse in the gas At our working gas pressure we have routinely obtained a detector limited pulse duration of < 400 ps The theoretically expected pulse duration is about 200 ps at this pressure Since no suitable IR detectors are available to measure such short laser pulses, a Kerr effect technique, where the CO_2 pulse induces birefringence in CS_2 which can be used to depolarize an optical beam, is being developed to measure these

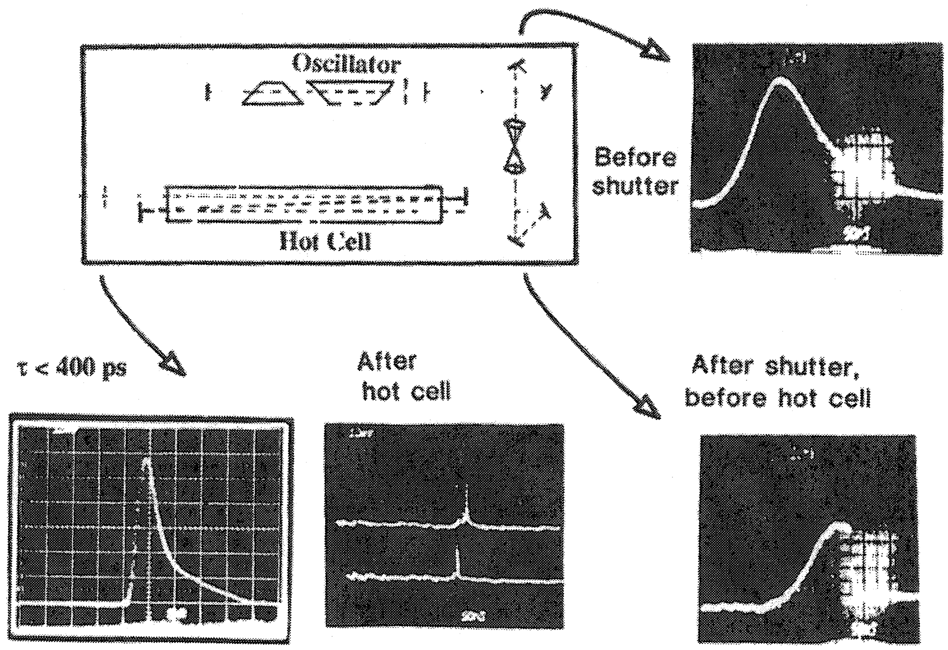


Fig 1 Short pulse generation using the "Free Induction Decay" technique

pulses The pulse duration of the amplified pulse is related to that of the input pulse by

$$T_{out}^2 = T_{in}^2 + \left[16 \ln 2 \ \frac{\ln g_0}{\Delta\omega_a^2}\right]$$

where $\Delta\omega_a$ is the homogeneous linewidth Thus it can be seen that if the preamp gain is small, no significant pulse broadening is obtained even at 1 atmosphere However, the main amplifier has a gain of e^{18} and we have to go to a multi-atmospheric system to increase $\Delta\omega_a$ and thereby minimize the pulse broadening due to gain dispersion We thus use a 3 atmosphere, E beam pumped module (MARS) as the power amplifier The schematic of the complete laser system is shown in Fig 2 We discovered that parasitic oscillation suppression cells containing Freon 12 (9 0 µm R-band), methanol (9 µm P band), Freon 115 (10 µm R band), SF_6 and Freon 152A (10 µm P band) are necessary inside the main MARS amplifier To date we have single passed the MARS laser and obtained 10 mJ in a single short pulse For the experiment we need 20 J/line which we hope to get by triple passing the MARS amplifier.

5 ELECTRON LINAC AND BEAM TRANSPORT

We use a 9 GHz, x band linac as the injector for our experiment Since the linac structure must be maintained under better than 10^{-6} Torr vacuum, whereas the rest of the experiment is under 100 mT, a 6 µm thick Mylar foil is used to separate the linac from the experiment The linac macropulse is 5 µs and is expected

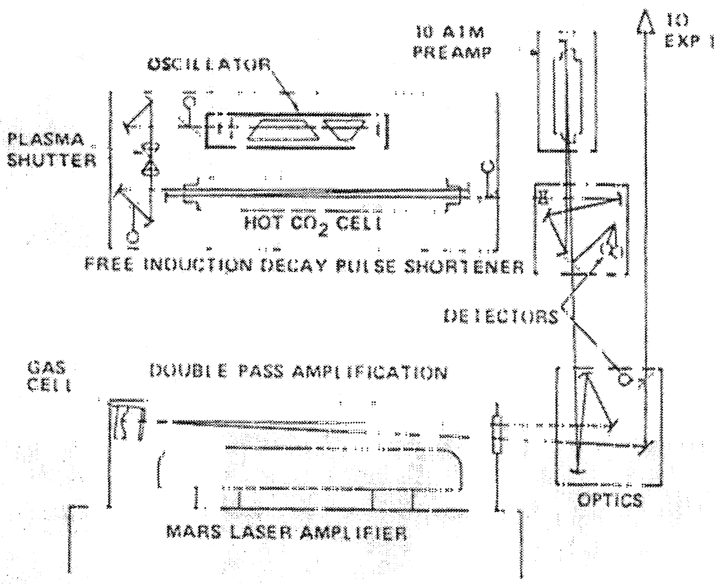


Fig. 2 Schematic diagram of the high power CO_2 laser facility MARS

to contain micropulses each typically 10 ps long separated by 110 ps The electron beam exiting the Mylar foil has an emittance of 50 π mm mrad. Figure 3 shows the trapping threshold vs wave amplitude for particle making various angles w r t. the wave for a $\gamma_{ph} = 10$. It is readily seen that the trapping threshold rapidly increases as the particles' parallel velocity drops because they make larger and larger angles w r t the wave In our experiment we therefore wish to reduce the emittance of the injected particles by beam scraping We use a solonoidal lens to focus the beam to a spot size of 1 cm An off axis parabolic mirror with a 1 5 mm hole is used to reduce the beam emittance to 10 π mm mrad This mirror is used to focus the laser beam coaxially with the electron beam at the center of the plasma chamber From the beam current measurements we

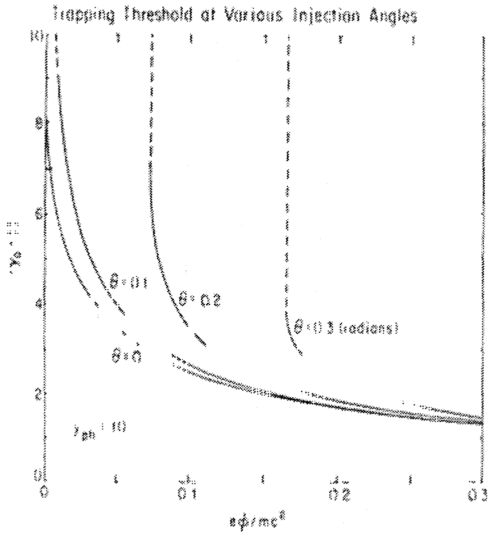


Fig 3 Injection energy vs plasma wave amplitude for various injection angles

estimate that the microbunches exiting from the linac contain typically 7 × 10^6 electrons; however, this number is down to 2 × 10^5 electrons by the time they emerge through the momentum selecting aperture in the focusing mirror The electron beam transport system is shown in Fig 4 A second solonoidal lens is used to focus the electron bunches to a spot size of about 1 mm A third lens then reimages this spot on the input aperture of the electron spectrometer

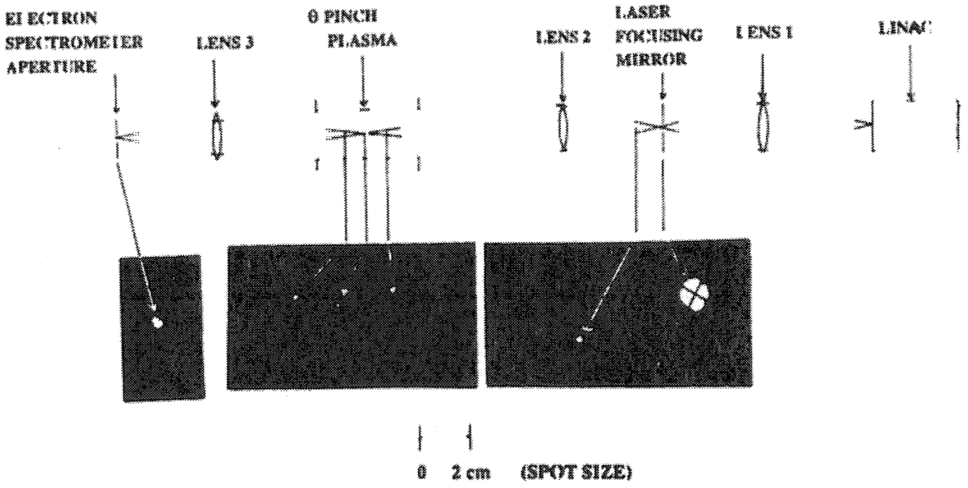


Fig 4 Electron beam transport system of the UCLA PBWA experiment

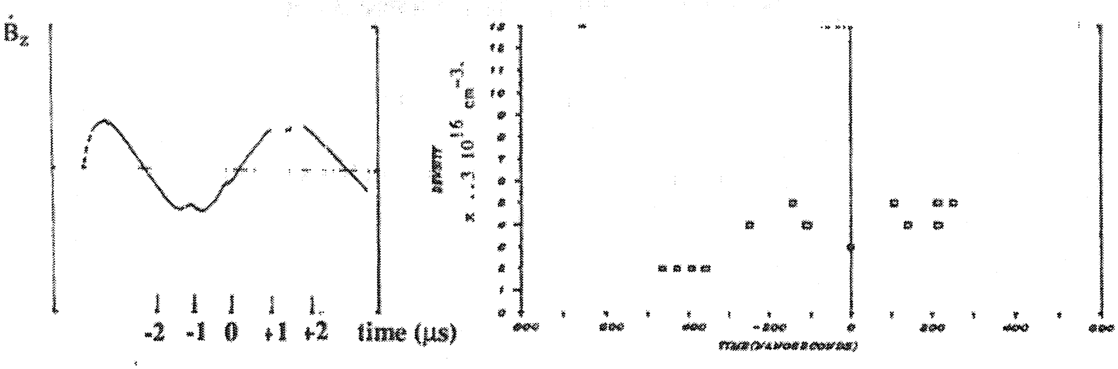
4 THE PLASMA SOURCE

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_θ induces a magnetic field B_z which varies in time From Faraday's law an induced electric field E_θ 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_θ is produced which opposes the circuit current I_θ, 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 2 A typical $\dot{B}$ signal picked up by a single turn loop some 50 cm from the coil is shown in Fig 5a 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 5b 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 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 incluenced by the stray fields of the θ pinch as well as any trapped fields Details of these calculations are summarized in Fig 6

TABLE 2
Theta Pinch Parameters

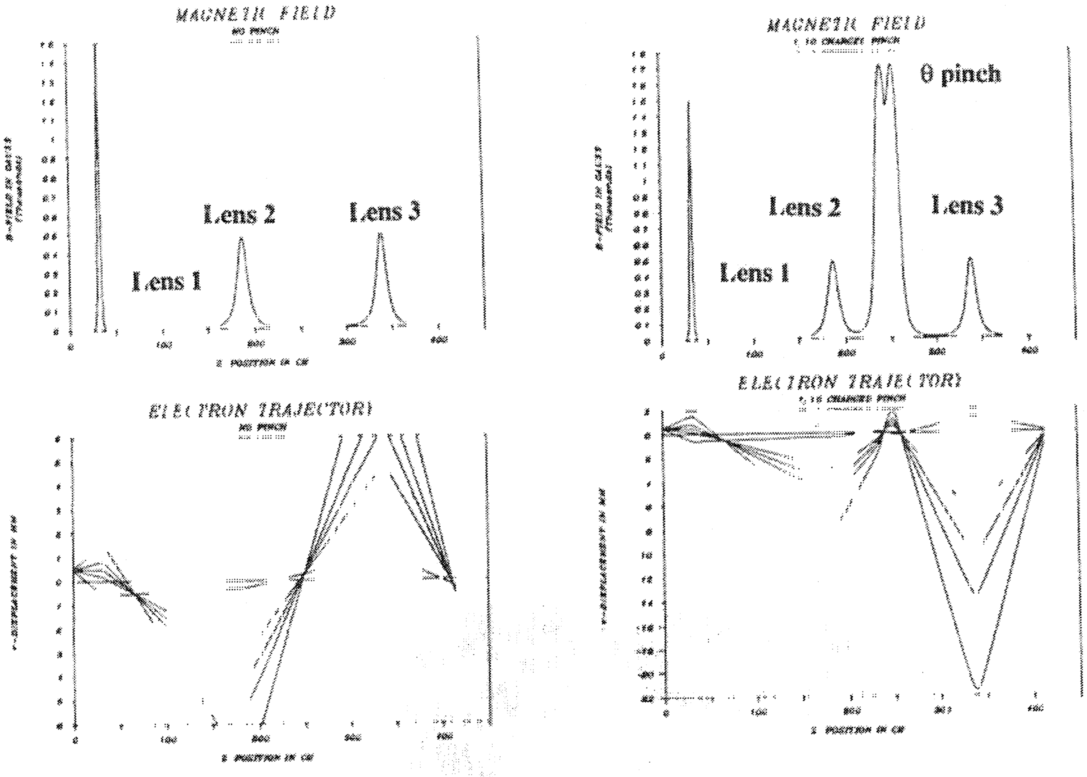
Total Capacitance	11 1 μF
Charging voltage	28 kV
Coil diameter	10 cm
Coil length	25 cm
Coil material	Copper
Coil inductance	40 nH
E_θ	530 V/cm
Period of the circuit	5.7 μs



(a) (b)

Fig 5 (a) dB/dt vs t signal picked up by the current loop and (b) density vs time as measured by holographic interferometry

Figure 6a 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 6b 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 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 7 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 We are not sure that at the 2nd B = 0 the plasma density near the resonant value can be maintained but if this can be achieved there is clearly an advantage in operating this way



(a) (b)

Fig 6 Ray tracing calculations showing trajectories of test electrons without (a), and with (b) the θ pinch on. The plasma is assumed to have a trapped field of 1/10 B_{max} at the peak of the compression.

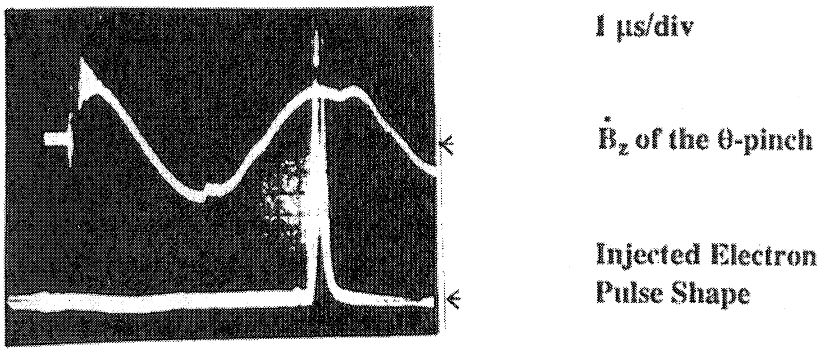
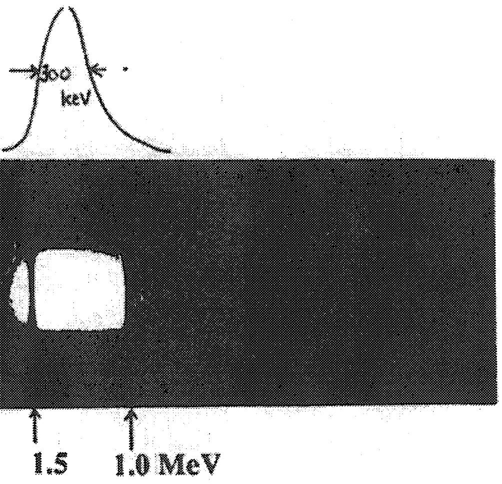


Fig 7 Experimentally measured sharpening of the injected electron pulse shape through the plasma when the electron beam is fired at the second B = 0

5 DETECTION SYSTEM

A 180° focusing spectrometer is used to disperse and image the electrons. The dispersion is achieved using a static magnetic field of 3 kG. The detectors are an array of Si surface barrier detectors. The output of the detectors is amplified using charge sensitive preamplifers and then amplifiers. The output can be digitized using A/D converters and then analyzed using a desk top computer. The input pulse is sufficiently intense that it's spectrum can be directly recorded on film. This is shown in Fig. 8. The spectrum is seen to peak around 1.4 MeV with a full width at half maximum of 300 kV. Currently efforts are under way to reduce the noise level in the spectrometer and detection system so that we will be able to measure single particles at energies > 10 MeV.



Injected Electron Energy Spectrum

Fig. 8 Photographically measured injected electron spectrum at the output of the electron spectrometer

6 CONCLUSIONS

In this paper we have described the status of the experimental program on the PBWA at UCLA. The outstanding problems we have to solve before we can do the "acceleration" experiment are 1) to increase the laser energy to give 20 J/line; 2) ensure that the resonant density can be obtained at the 2nd zero of B field of the θ pinch or alternatively find a way of transporting the electron beam reliably at the peak of the compression; 3) reduce the noise level in the electron detection apparatus so that single particles of energy greater than 10 MeV can be detected.

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REFERENCES

1 C. Joshi et al., Nature 311, 525 (1984)

2 C. Clayton et al., Phys. Rev. Lett. 54, 2343 (1985)

3 C. Darrow et al., Phys. Rev. Lett. 56, 2629 (1986)

4 IEEE Special Issue on Plasma Based High Energy Accelerators, ed. by T. Katsouleas, PS 15, No. 2 (April, 1987)

5 T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

6 E. Yablonovitch and J. Goldhar, Appl. Phys. Lett. 25, 580 (1974)

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Discussion

J. Nation, Cornell University

Is the steepening of the plasma wave that you see, the sort of quasi soliton type of train of waves that Charlie Snyder analysed and if so do you get a nonlinear slowing of these waves and is that significant from the point of view of your experiments?

Reply

I do not think so. The only answer to that can come from computer simulation of our experiments. Experimentally we observe that within the accuracy of measurement the harmonic ???? Now if the waves have slowed down a little then there might be a slight variation of k and so the harmonic wave form is slipping. But we simply do not know. That kind of accuracy is not present in these experimental techniques at the high frequency.