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Laser Wakefield Electron Acceleration over 100 MeV driven by a Femtosecond Terawatt Laser Pulse

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Abstract

The laser wakefield electron acceleration over 100 MeV has been carried out in an underdense plasma driven by a 2 TW, 90 fs laser pulse synchronized with 17 MeV RF linac electron injector at 10 Hz. The electron acceleration was enhanced at a pressure corresponding to the plasma density higher than the resonant density due to gas ionization and self-channeling effects. The wakefield excitation has been confirmed by measuring the electron density oscillation of the plasma wave with the frequency domain interferometer.
52.75.Di,52.40.Nk, 52.35.Mw

Laser-driven particle accelerators have been conceived to be the next-generation particle accelerators, promising ultrahigh field particle acceleration and a compact size compared with conventional accelerators [1]. It has come to be known that laser wakefield acceleration has great potential to produce ultra-high-field gradients of plasma waves excited by intense ultrashort laser pulses [2,3]. Recently a wakefield of the order of 10 GeV/m in a plasma has been directly observed by the use of a compact terawatt laser system so called T^3 lasers [4]. In a homogeneous plasma, however, diffraction of the laser propagation limits the laser-plasma interaction distance to the extent of the vacuum Rayleigh length. This effect deducts the advantage of ultrahigh gradient acceleration from laser-driven accelerators. It would be of importance for practical application of the laser wakefield accelerator concept to be able to generate a high energy gain as well as high gradient acceleration. Therefore it is essential for laser wakefield acceleration to achieve a long interaction of an intense ultrashort laser pulse with an underdense plasma in order to increase the energy gain from tens of MeV to the order of GeV. Although a self-modulated laser wakefield can generate the accelerating field exceeding 100 GeV/m, this mechanism could produce at most the energy gain of ~ 100 MeV because of a short acceleration length limited by dephasing of accelerated electrons or depletion of pump pulses [3]. In order to exceed a limit of the acceleration length restricted by diffraction, optical guiding has been proposed as a promising way of propagating a high-power laser pulse over many Rayleigh lengths in a plasma [5]. A laser beam may be guided through a plasma of which the refractive index along the optical axis is sufficiently so high as to compensate diffraction. The relativistic self-guiding in a homogeneous plasma has been predicted to occur above the critical power, given by $P_c = 17(\omega_0^2/\omega_p^2)$ GW where ω_0 is the laser frequency and ω_p is the plasma frequency [6]. Recent experiments using intense femtosecond laser pulses report that a long distance self-channeling has been observed under the critical power of the relativistic self-focusing [7]. We have also observed self-channeling of a 2 TW laser pulse with 90 fs duration occurred over a few cm even under the relativistic critical power [8]. We made an attempt to demonstrate laser wakefield acceleration by intense ultrashort laser pulses propagating through self-channeling in a plasma. Here we report the experimental results of laser wakefield acceleration of an externally injected electron beam synchronized with laser pulses.

The laser wakefield results from the ponderomotive force exciting the density oscillation of a plasma with the frequency $\omega_p = \sqrt{4\pi e^2 n_e/m_e}$ for the ambient electron density n_e in a plasma. Assuming a Gaussian laser pulse of a temporal $1/e$ half-width σ_z with the peak power P, a peak amplitude of the accelerating wakefield is

$$eE_z = \frac{\Omega_0 P}{\sqrt{\pi} m_e c^2}\left(\frac{\lambda_0}{\lambda_p}\right)\left(\frac{k_p\sigma_z}{2Z_R}\right)\exp\left(-\frac{k_p^2\sigma_z^2}{4}\right), \quad (1)$$

where Ω_0 is the vacuum resistivity (377Ω), λ_0 is the laser wavelength, λ_p is the plasma wavelength, $k_p = 2\pi/\lambda_p$ and Z_R is the vacuum Rayleigh length, i.e. $Z_R = \pi R_0^2/\lambda_0$, where R_0 is the spot radius at the focus. The maximum amplitude is achieved at $\lambda_p = \pi\sigma_z$. The maximum energy gain of relativistic electrons is given by $\Delta W = eE_z L_{ac}$ with the acceleration length L_{ac}. Diffraction limits the acceleration length to $L_{ac} \simeq \pi Z_e$, where Z_e is the effective Rayleigh length for the laser propagation in a plasma. For the resonant plasma density, $n_e = 1/\pi r_e \sigma_z^2$ where r_e is the classical electron radius,

$$\Delta W_{\max}[\text{MeV}] \simeq 850 P[\text{TW}]\lambda_0[\mu\text{m}]/\tau_0[\text{fs}] \times (Z_e/Z_R), \quad (2)$$

where τ_0 is the FWHM pulse duration, $c\tau_0 = 2\sqrt{\ln 2}\sigma_z$. Note that the maximum energy gain is independent of a focal spot size of laser pulses for Gaussian propagation in a homogeneous plasma where $Z_e = Z_R$.

We have constructed the LWFA test facility consisting of the T^3 laser system and the electron beam injector [9]. The Ti:sapphire T^3 laser system based on the chirped-pulse amplification at $\lambda_0 = 790$ nm produces output pulses compressed by a grating compressor to 90 fs with an energy of > 200 mJ corresponding to a peak power of > 2 TW at the repetiton rate of 10 Hz. It is necessary to inject an electron beam with an appropriate initial energy so that electrons can be trapped and accelerated by wakefields. We used the 2856 MHz RF linac as an electron injector to produce a 17 MeV single bunch beam with a 10 ps FWHM pulse duration containing ~ 1 nC at the repetition rate of 10 Hz.

The setup for acceleration experiments is shown in Fig. 1. Focusing optics and the injection electron beamline were installed in the vacuum chamber filled with He gas. Laser pulses were focused with f/10 off-axis parabolic (OAP) mirror with a focal length of 480 mm. The measured focal spot radius was 13μm. Since the focusing force of the radial wakefield exists at $r < R_0/2$, electrons injected to the diameter less than a half laser spot size would be trapped and accelerated by the wakefield. An electron beam from the injector is brought to a focus in the chamber with the FWHM beam size of 0.8 mm through a beamline consisting of a triple focusing magnet and a permanent quadrupole (PMQ) triplet. The RF linac and the beamline were separated with a 50μm thick titanium window from the interaction chamber to maintain ultrahigh vacuum in the electron injector. Since this window caused emittance blow-up due to multiple scattering of electrons, the collimator slit was installed at the downstream of the window to reduce the beam emittance. Beam collimation reduced an electron charge to ~ 100 pC per pulse. An electron pulse was synchronized to laser pulses with the phase locked control of the mode-locked osillator. The phase locked loop maintained synchronization of the oscillator repetition period (79.33 MHz) with every 36th RF period of the linac (2856 MHz). We measured a timing jitter between the laser pulse and Cherenkov radiation from the electron beam with the streak camera with a time resolution of 200 fs. Synchronization between two pulses was achieved within the rms jitter of 3.7 ps.

The energy of accelerated electrons was measured with the magnetic spectrometer consisting of a dipole magnet and an array of 32 scintillation detectors. The pulse heights of the detectors were recorded with ADC triggered by a gate signal synchronized with the linac electron pulse. Injected electrons undergoing no acceleration were swept out of the detectors by the spectrometer magnet following a PMQ doublet. The spectrometer covered the energy range of 10 ~ 300 MeV. The energy calibration of the spectrometer was made by varying the magnetic field to measure a 17 MeV electron beam from the RF linac.

The timing between laser and electron pulses was adjusted by changing a phase delay of the reference RF to the phase locked loop so that streak images of two pulses were overlapped. After a He gas was filled in the acceleration chamber, fine adjustment of overlapping two spots of laser and electron beams was carried out within 50 μm. Two sets of pulse height data of the scintillator array were taken with pump laser pulses and without them as a background. The pulse height was averaged over 500 to1000 shots to reduce a signal fluctuation. A net pulse height proportional to the number of electrons accelerated was obtained from subtracting the data without the pump pulses from the data with them. The number of electrons was estimated to be ranged from 2 to 4 per ADC count for all detectors.

In the acceleration experiment the gas pressure of He was scanned from 1 Torr to 300 Torr. Fig. 2 shows energy gain spectra of electrons accelerated in the wakefield pumped by the laser peak power of 0.9 TW and1.8 TW. The maximum energy gain up to 300 MeV was obtained from these data. In order to make a proof of wakefield acceleration, we have measured off-timing interaction of electrons with respect to the pump laser pulse. When the electron pulse preceded the pump laser pulse, no acceleration of electrons was observed. Accelerated electrons visibly appeared as the electron pulse was delayed. No accelerated electron was observed at a delay of 1 ns. We have investigated the self-trapping of plasma electrons due to wakefiels without the elctron beam injection as the gas pressure was increased up to 760 Torr. We observed no electron accelerated to higher energies than $\sim$ 1 MeV. It implies that the large amplitude wakefield excitation caused by the stimulated Raman instability may be suppressed for ultrashort laser pulses of 100 fs in contrast with the self-modulated laser wakefield.

The side scattered laser light from the plasma region were imaged onto a CCD camera synchronized with a 10 Hz laser trigger through a 10 nm FWHM interferential filter to measure the laser intensity distribution. Fig. 3 shows an intensity profile of the scattered light projected onto the propagation axis for various gas pressures. The laser pulse was focused at the position of 0 mm on the propagation axis in vacuum. Since the wakefield amplitude is proportional to the laser intensity, the lineout width of the scattered light proportional to the laser intensity gives a good estimate of the acceleration length. The acceleration field gradient was obtained from the measured maximum energy gain and the FWHM length of the scattered light lineout equal to $2Z_e$. Fig. 4 shows the peak accelerating

gradient for the laser peak powers of 0.9 TW and 1.8 TW as a function of the gas pressure of He. The data indicate a good agreement with theoretical prediction based on the linear fluid model below 10 Torr, assuming the focal spot radius of 13 μm. It is found that acceleration occurs even at much higher pressures than a plasma wake resonance. Recent particle-in-cell simulations elucidate that a large amplitude wakefield can be excited by self-modulation of the laser pulse induced in rapidly ionizing plasmas at the pulse front [10]. In Fig. 4 the acceleration gradient jumps to $\sim$ 15 GeV/m above 20 Torr for 1.8 TW. It has been observed that the lineout of the scattered laser light was turned out to be a constant length of $\sim$ 1 cm above 20 Torr. These phenomena suggest that self-channeling accompanied by the electron density depletion may take place above 20 Torr. The onset of self-channeling is also inferred from the spectra of the forward scattered laser light shown in Fig. 5. When the pressure turned out to be as high as 20 Torr, a drastic blue-shifting of the laser light was induced above 0.5 TW. As the peak power increased to more than 2 TW, a whole spectrum of the incident laser pulse at 790 nm was shifted to 750 nm. It has been known that a large amount of the self-phase modulation results from a long distant self-channeling [7]. In our experiment we have not observed red-shifting nor forward Raman scattering.

In order to make confirmation of wakefield excitation by an ultrashort laser pulse in an underdense plasma, we measured the plasma wave oscillation with the frequency domain interferometer [4] to be reported elsewhere. Fig. 6 shows the electron plasma wave measured at 2 Torr for the pump peak power of 1 TW. The frequency of the density oscillation is deduced to be 1.7×10^{13} rad/s from the measured period of the density oscillation, while the plasma frequency is 2.1×10^{13} rad/s assuming a fully ionized plasma at 2 Torr. A frequency decrease of the plasma wave may result from nonlinear wakefield excitation. The density perturbation was $\delta n/n_e \sim 10\%$ corresponding to the longitudinal wakefield of $\sim$ 3 GeV/m. This measured amplitude is in good agreement with the accelerating wakefield theoretically expected.

In conclusion we have carried out electron acceleration by wakefields excited by intense ultrashort laser pulses delivered from a 2 TW, 90 fs T^3 laser system synchronized with the 17

MeV RF linac electron beam injector at the repetition rate of 10 Hz. We have observed high energy electrons accelerated over 100 MeV up to 300 MeV by the wakefield of $\sim$ 15 GeV/m excited over a few cm long underdense plasma. Acceleration enhancement at higher pressures of He gas than the resonant pressure may be elucidated from the pulse self-modulation due to ionization and self-channeling of the laser pulse in a plasma. These effects help to achieve an efficient electron acceleration up to the higher energy than 1 GeV. A direct measurement of the electron density oscillation by the frequency domain interferometry verified wakefield excitation consistent with the results of acceleration experiments.

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FIGURES

FIG. 1. Schematic of the experimental setup.

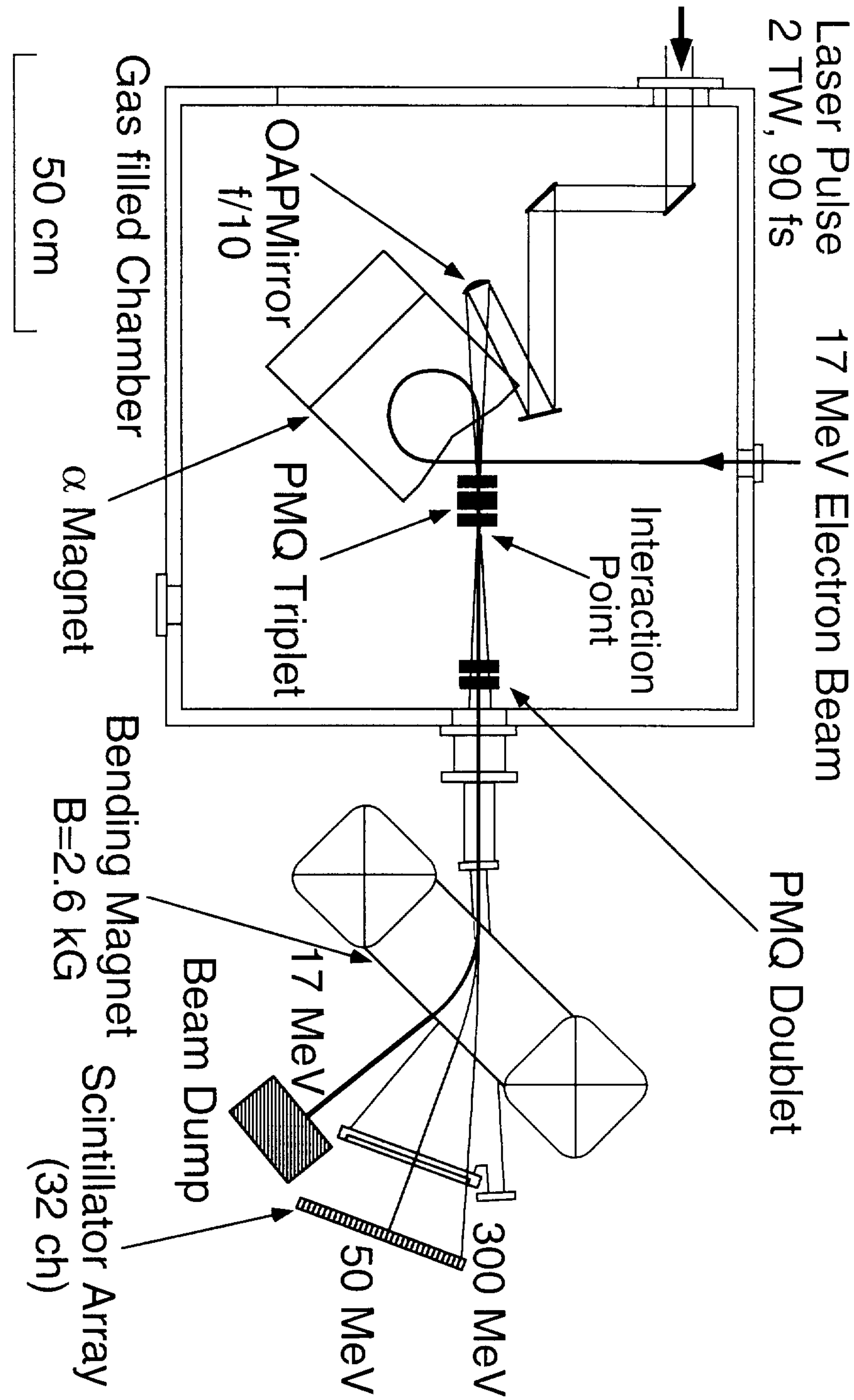
FIG. 2. Energy gain spectra of accelerated electrons for a) 3.4 Torr, P=0.9 TW, b) 20 Torr, P=0.9 TW, c) 2 Torr, P=1.8 TW, and d) 20 Torr, P=1.8 TW.

FIG. 3. The lineouts of the side scattered laser light at various He gas pressures for P=2.5 TW. The laser pulse propagates from the right to the left of the figure.

FIG. 4. The peak accelerating field gradient deduced from the maximum energy gain and the acceleration length. The solid curve shows theoretical expectation for the spot radius R_0 = 13μm.

FIG. 5. Forward scattered spectra measured in a He gas of 22 Torr as the laser pulse energy increases.

FIG. 6. Measurement of the plasma density oscillation excited by a 1 TW pump power in a He gas of 2 Torr. The solid curve shows a fit of the plasma wave with oscillation period of 360 fs.



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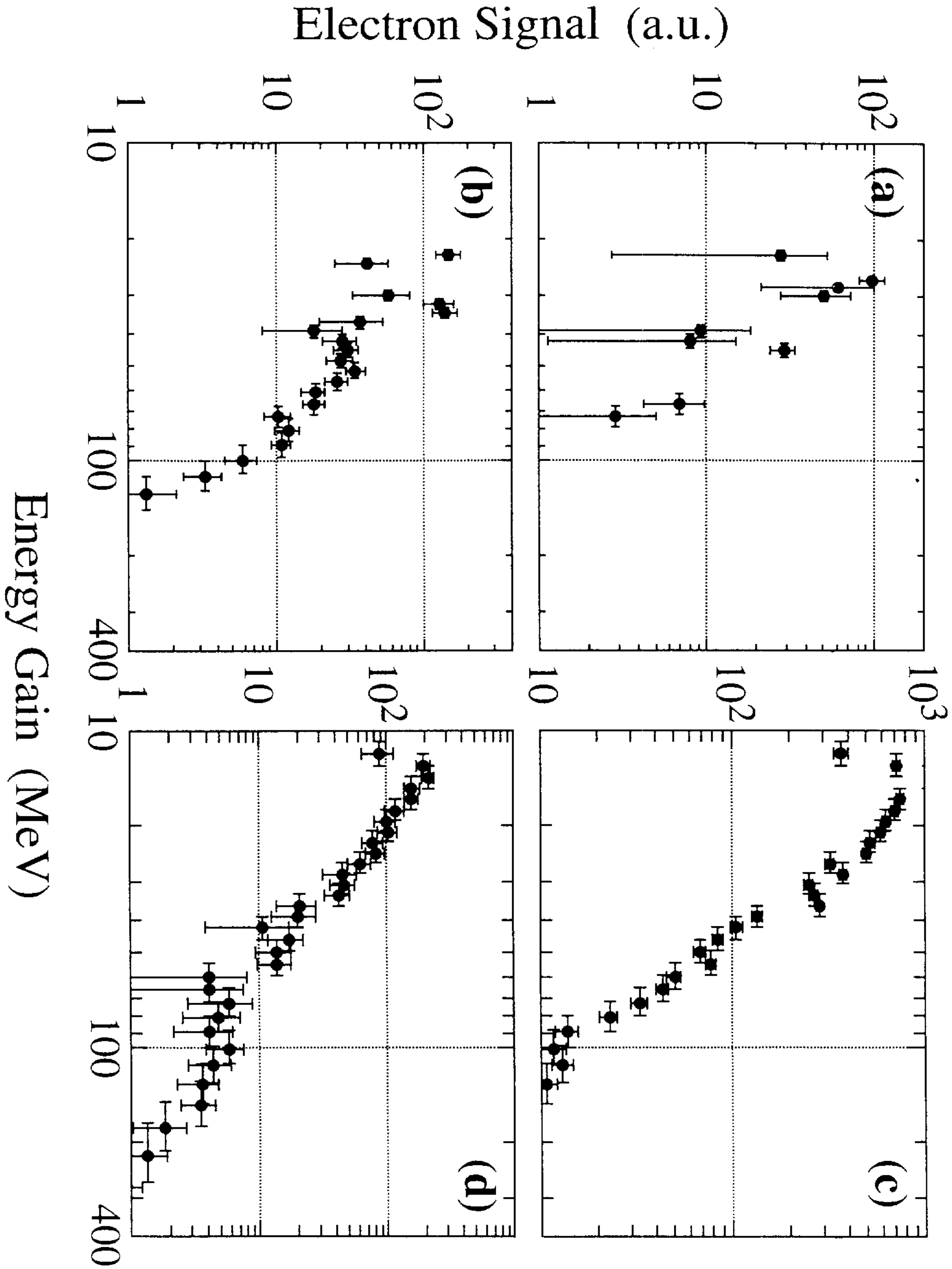

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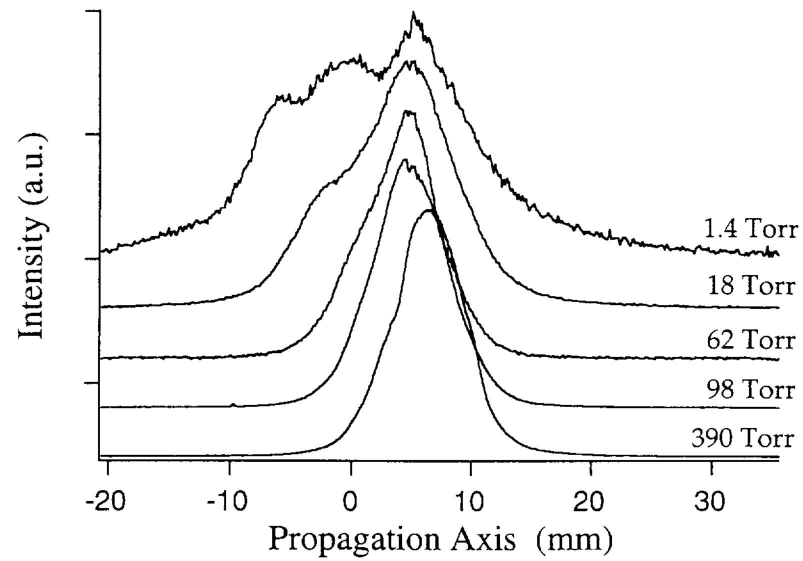

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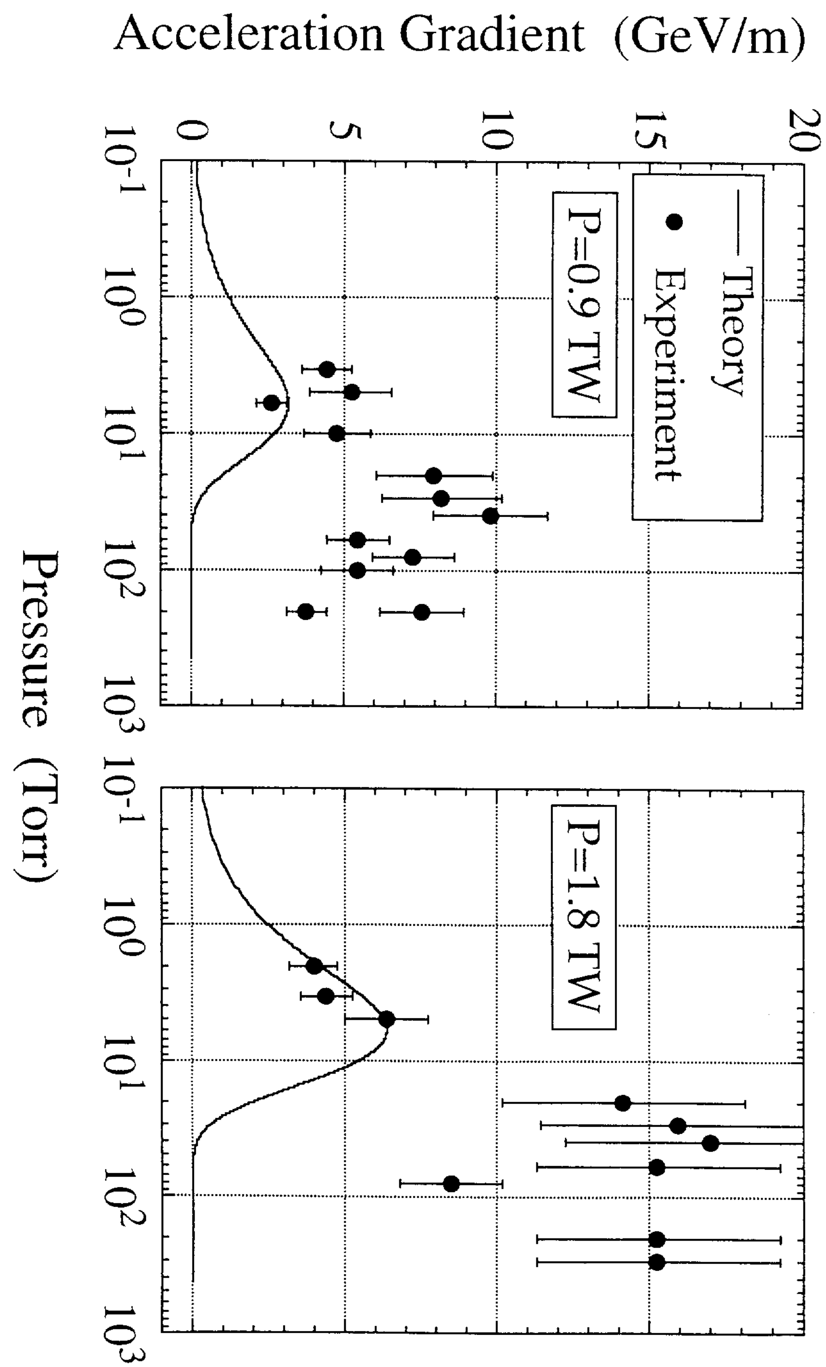

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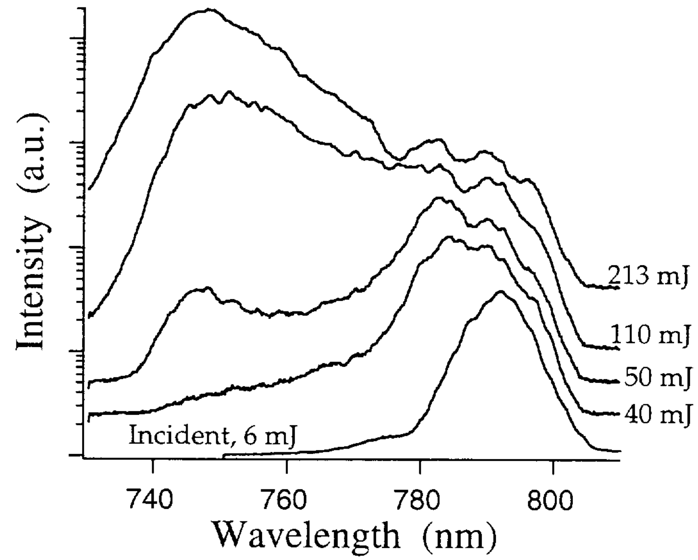

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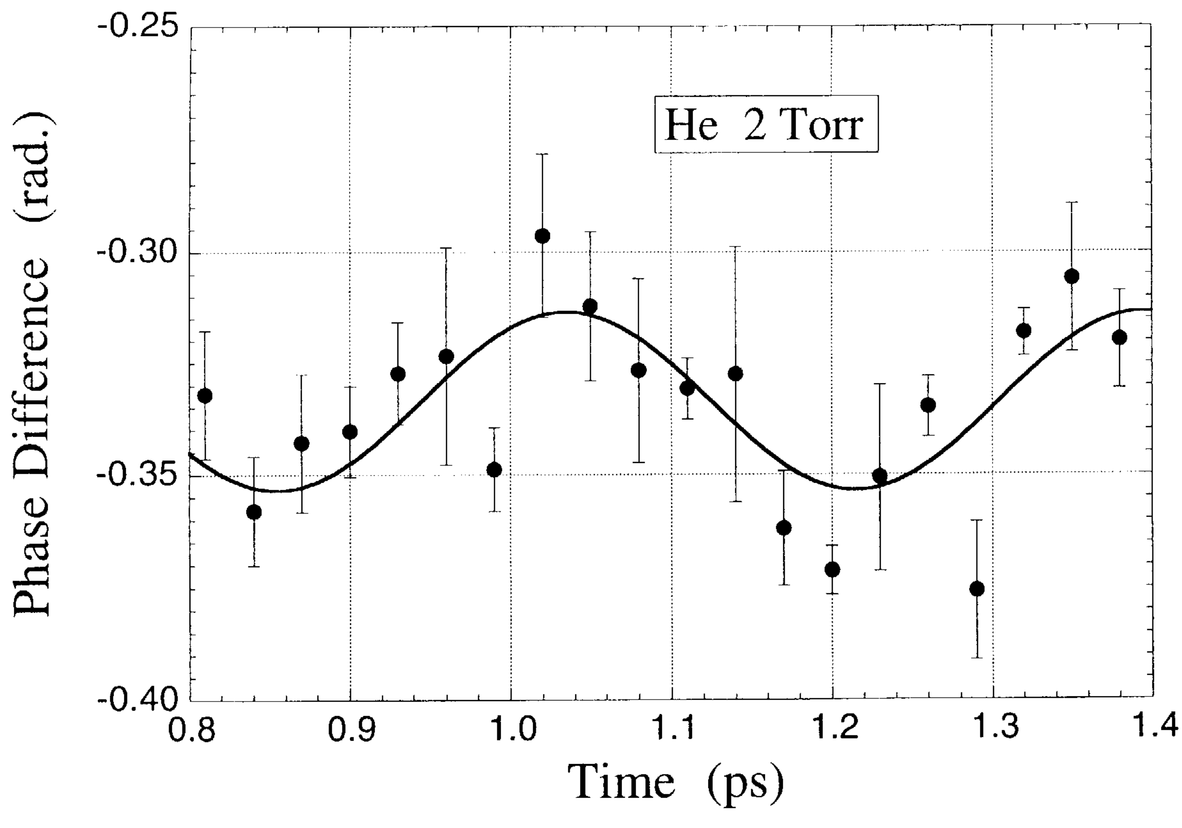

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