Second generation beatwave experiments at UCLA

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Abstract

The NEPTUNE Laboratory, under construction at UCLA, will be a user facility for exploring concepts useful for advanced accelerators. The primary programmatic goal for the laboratory is to inject extremely high-quality electron bunches into a laser-driven plasma beat wave accelerator and explore ideas for extracting a high-quality $\Delta E/E < 0.1$, $\varepsilon < 10 \pi$ mm mrad), high-energy (100 MeV) beam from a plasma structure operating at about 1 THz and about 3 GeV/m. The lab will combine an upgraded MARS CO\textsubscript{2} laser and the state-of-the-art SATURNUS RF gun and linac, also undergoing an upgrade. The new MARS laser will be about 1 TW (100 J, 100 ps), up from 0.2 TW (70 J, 350 ps). This allows for doubling the spot size of the laser beam and thereby quadrupling the interaction length while still driving gradients of 3 GeV/m. The large diameter of the accelerating structure relative to the injected electron bunches (10:1) will minimize the deleterious effects of the radial dependence of the accelerating field and soften the radial focusing thus permitting, in principle, the extraction of a high-quality accelerated beam. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the previous 10 years, many experiments have demonstrated the proof-of-principle of high-gradient laser- or laser-beam-driven plasma accelerators [1]. In fact, accelerating gradients as high as hundreds of GeV/m have been inferred in the high density laser/plasma experiments [2]. But for applications to high-energy physics (HEP), the main question regarding plasma accelerators is no longer if they will work, in principle, but rather, what can plasma accelerators deliver in terms of beam quality and number of electrons per bunch. We refer to experiments of this type as “second generation” plasma accelerator experiments: those which begin to deal with the practical spatial and temporal aspects of the plasma accelerator structure and its control. The first step is to inject a fully characterized electron beam into a plasma accelerator and characterize the accelerated beam parameters at the output. Plasma wave diagnostics and 3-D
computer codes can then be used to understand the wave-particle dynamics providing feedback for experimental improvements.

Of the several plasma-based high-gradient accelerator concepts, the plasma beat wave accelerator (PBWA) concept is experimentally the most developed [3]. Here, a two-frequency laser beam of relatively low-intensity \( a_{1,2} = E_{1,2} / mc \omega_{1,2} \approx 0.1 \), where \( a_j \) is the normalized transverse quiver momentum of an electron in a laser field of strength \( E_j \) and frequency \( \omega_j \) resonantly drives up a longitudinal electron plasma wave (EPW) of frequency \( \omega_p \approx \Delta \omega \equiv \omega_1 - \omega_2 \). For a given \( \Delta \omega \), this is a condition on the plasma density \( n_e \) since \( \omega_p^2 = 4 m_n e^2 / \hbar m \). For a \( \text{CO}_2 \) laser operating at 10.59 and 10.27 \( \mu \text{m} \), this resonant density \( n_{\text{res}} \) is \( 9.4 \times 10^{15} \, \text{cm}^{-3} \). For equal intensities in the two lines, the \( \text{CO}_2 \) envelope is 100\% modulated so that a series of pulses separated by the beat frequency are produced. With a roughly Gaussian intensity profile in time reaching a peak \( a_{1,2} \sim 0.14 \) in 100 ps, the plasma wave will grow to the desired 3 GeV/m longitudinal field strength in about 60 ps. This is \( \sim 60 \) beats of the electromagnetic beatwave and thus 60 EPW periods and \( \sim \) one ion period for \( \text{H}_2 \) (2\(^{-0.5}\) ion periods for \( \text{D}_2 \)). The phase velocity of the plasma wave is equal to the group velocity of the \( \text{CO}_2 \) pulse train which corresponds to a Lorentz factor \( \gamma_p \approx \omega_p / \omega_0 \approx 34 \) where \( \omega_0 \equiv (\omega_1 + \omega_2) / 2 \).

A \( \text{CO}_2 \) laser beatwave experiment is in many ways the ideal test-bed experiment for a plasma accelerator. Some of the current experimental advantages of the long-wavelength \( \lambda \) \( \text{CO}_2 \) driver include:

- A large EPW driving force for a given laser intensity (force \( \propto a_1 a_2 \propto \lambda^3 \)).
- A large EPW spot size for a given focusing f/number.
- The resonant density is typically low \( \Rightarrow \) relatively large structure wavelength (\( \sim 350 \, \mu \text{m} \)).
- An efficient EPW driving scheme (beatwave) \( \Rightarrow \) required peak intensities are low.

In particular, the large EPW spot size and wavelength \( \lambda_p \) will make the task of injecting into the "good acceptance" of the accelerator, both transverse and longitudinally, substantially easier.

Section 2 of this paper will describe the NEPTUNE Laboratory [4] with an emphasis on the laser system and experimental area. The electron gun and beamline are described in detail elsewhere in these proceedings [5]. Section 3 will describe the numerical modeling of the plasma wave structure and the beam transport through this model EPW. Finally, the status and conclusions are given in Section 4.

2. The NEPTUNE Laboratory

The experiments will take place in the new NEPTUNE Laboratory [4] currently being outfitted with electron and laser beam apparatus. The new lab is essentially the combination of two separate state-of-the-art facilities at UCLA: namely the MARS Laser Laboratory, where the 0.2 TW \( \text{CO}_2 \) MARS Laser has been used for a series of PBWA experiments as well as experiments on wave–wave coupling and basic laser-plasma interactions, and the SATURNUS Accelerator Laboratory where an extremely high brightness RF gun and novel "plane-wave-transformer" (PWT) linac has been used in plasma lens [6] and FEL experiments [7]. The contents of these two labs are being upgraded and combined.

The purpose of the MARS Laser upgrade is twofold. First, a means of synchronizing the \( \text{CO}_2 \) pulse, and hence the accelerating structure, to the electrons from the photocathode is required. Secondly, more laser power is needed to drive plasma waves over a larger area and longer interaction length. The former is accomplished through a new "front-end" to the laser while the second latter is primarily accomplished using a new preamplifier prior to the large-aperture final amplifier.

2.1. The \( \text{CO}_2 \) laser front end

In the prior configuration of the MARS laser, a technique called Optical Free Induction Decay [8] was used to generate sub-100 ps pulses to inject into the amplifier chain. This passive, experimentally simple technique was adequate since the electron source was a pulsed X-band magnetron-driven linac. There was no control over the startup
phase of the magnetron so no attempt was made to phase-lock the micropulses from the linac to the peak of the PBWA as it grew in time. The 107 ps separation of the micropulses was short enough to ensure that some electrons would interact with the PBWA on most shots, although the probability of hitting the peak amplitude of the PBWA in time was < 1 in 10 shots. Multiline operation was obtained by placing a gas cell in the oscillator cavity and adding the appropriate amount of narrowband absorbing gases to balance the net gain and oscillation delay of each line. This technique was susceptible to gain competition between the two lines and the resultant shot-to-shot variation in line ratio.

The fix is to use active optical switching of the CO\textsubscript{2} oscillator pulse, using the same 1 μm wavelength, 70 ps pulse from Nd: YAG laser oscillator to both switch out a 100 ps CO\textsubscript{2} pulse and, after pulse compression down to 3 ps and frequency converting into the UV, to liberate the electrons from the photocathode. The 1 μm pulse can act as a switch for the 10 μm CO\textsubscript{2} pulse by forming a transient solid-state plasma on two pieces of germanium, set at Brewster's angle for the CO\textsubscript{2}[9]. This technique, known as semiconductor switching and shown schematically in Fig. 1, is currently used at the ATF at Brookhaven [10]. Now, by simply translating an optical delay line, one can ensure that the few ps electron bunch from the photocathode will always interact with the peak fields of the PBWA, approximately 60 ps after the CO\textsubscript{2} beam reaches the interaction point.

Another dramatic improvement, already tested and ready for implementation, is to use three-mirror oscillator cavity for generating the required two-frequency pulse for the beatwave. Essentially, each frequency will have its own cavity by using a grating to send the two frequencies to two separate rear mirrors as shown in Fig. 1. The two cavities share the same energy-storage gain section (a TEA laser) but have individual low-pressure (seeding) lasers (LPL). This eliminates gain competition since each cavity is separately seeded with the appropriate laser frequency and both can extract energy from the TEA laser [11]. This stabilizes the shot-to-shot ratio of the two frequencies.

![Fig. 1. Schematic of the front end of the upgraded MARS laser.](image)

The incoming 1 μm laser pulse (80 ps duration) is directed onto two semiconductor switches-germanium plates set at Brewster's angle. The p-polarized CO\textsubscript{2} beam is normally 100% transmitted until the 1 μm pulse produces a transitory critical density solid state plasma, thus reflecting the CO\textsubscript{2} light within 10's of ps. The second switch cuts of any tail remaining on the pulse.

### 2.2. CO\textsubscript{2} Preamplifier

The old MARS laser used a one atmosphere, double-passed preamplifier followed by a 2.5 atm, triple-passed power amplifier. Most of the pulse stretching (3× of the original sup-[100 ps OFDI pulse) occurred in this preamplifier. The new laser will use a 5–10 atm preamp run in the “regenerative amplifier” mode. Now, pressure broadening of the spectral gain curve will support the short pulse. In this mode, the pulse is electrooptically switched into an optical cavity containing the gain medium and after gain saturation, about 10 round trips, the
pulse is switched out with no degradation of the pulse shape and duration. Also, due to the large number of passes through the prepam, the switched-out laser power is high enough that the final, now 3 atm, large-aperture (20 cm) amplifier need only be double passed to achieve the 1 TW goal (100 J in 100 ps). Making fewer passes on the 3 atm section will help ensure that the pulse remains short.

2.3. Linac and experimental area

The 17 MeV beamline [5] and PBWA interaction chamber are shown schematically in Fig. 2. A modular, earthquake-restrained concrete vault was built to house the linac, interaction chamber, and beam dump. A 3 ft. thick dividing wall separates this vault from the diagnostic room, also a shielded vault. This ensures that X-rays from the linac dark current, beam dump, and e-beam sustained MARS amplifier will not interfere with the accelerated-beam diagnostics.

Three laser beams are brought into the main vault through holes in the ceiling: The CO$_2$ interaction beam, a 60 ps green diagnostic beam, and the ~3 ps (variable) pulse to drive the photoinjector. The CO$_2$ beam is focused with an f/20 off-axis parabolic mirror into the interaction chamber to a spot size $w_0$ ($1/e$ radius for the fields) of about 280 $\mu$m ($\approx 1.2$ times diffraction limited). This gives a Rayleigh length $Z_R = \pi w_0^2 / \lambda \approx 2.4$ cm where $\lambda$ is the average wavelength of the two laser lines. The interaction chamber is filled with about 140 mT of either H$_2$ or D$_2$ gas which becomes fully ionized to the resonant density over a Rayleigh range in the first 20 ps of the CO$_2$ pulse. To protect the linac section, low-conductance tubes and a small (~3 mm) pin hole near the laser focus will reduce the flow rate of the gas and allow differential pumping to maintain $\sim 10^{-7}$--$10^{-9}$ in the high-field parts of the linac in steady state. The pinhole will transmit $\approx 95\%$ of the laser beam with the laser focused up to $\sim 0.6$ cm beyond the pinhole.

The CO$_2$ beam folds into the axis of the electron beam by reflection off a mirror located at an intermediate waist in the electron beam. The electrons expand from this waist to the final focusing triplet where they are strongly focused to a spot size of about $\sigma_x \approx \sigma_z = 30$--$50$ $\mu$m. These 17 MeV electrons are then refocused into the beam dump which also houses a phosphor and CCD camera for online energy diagnostics. A low-field dipole (bumper magnet) sweeps electrons of $<25$ MeV into a

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Lambertson (or septum) magnet while allowing high-energy (> 35 MeV) electrons to pass into the diagnostic vault. The spectra of the electrons from the PBWA are obtained in a single shot (repetition rate of the CO$_2$ pulses $\sim \frac{1}{100}$ s$^{-1}$) using a double-focusing electron spectrometer [12] with a range of about a factor of $3.5 \times$ in energy, e.g., 35–120 MeV. Other single-shot diagnostics being considered or in design are: coherent Smith–Purcell radiation and coherent optical transition radiation for micro-bunch diagnostics; multiple-plane 2-D beam profilers (for example, scintillation fiber hodoscopes) for beam envelope/emittance diagnostics; and isochronous transport lines for energy-selective measurements.

Future variations on the experimental hardware may include; chicane pulse compression [5] of the 17 MeV beam to increase the peak current an order of magnitude (the four magnets of the chicane can be seen in Fig. 2); an integrated PWT linac/RF gun for direct production of sub-ps pulses at 20 MeV [13,14]; a plasma klystron for pre-bunching the electrons into the buckets of the plasma wave [15]; CO$_2$-gating of the photoinjection optical beam for phasing the electron microbunches to the plasma wave [16]; and optical injection of background plasma electrons via ponderomotive or wakefield acceleration [17,18]. Some of these advanced injection schemes as well as the microbunch diagnostics will be studied in parallel to the PBWA experiment.

3. Modeling of the experiment

In this section we describe the numerical methods used to predict the output of the PBWA. We describe the model for the electron plasma wave and, using electron phase-space data from a PARMELA simulation of the linac, push electrons through the dynamic plasma wave fields yielding a prediction for the output beam characteristics.

3.1. Plasma wave modeling

Our numerical model for calculating the tunnel-ionization buildup of the plasma density and subsequent growth of the plasma wave (both driven by the CO$_2$ laser pulse) was described in detail in Ref. [19]. The radial variation in the pump intensity along with the nonlinear (amplitude-dependent) plasma wave frequency causes the EPW phase fronts to curve slightly. In terms of the accelerating fields $E_r(r, z, t)$ and focusing (radial) fields $E_z(r, z, t)$ of the plasma wave, the result of this curvature is to shift the phase of $E_r$ with respect to $E_z$ as one moves further off axis. For electron betatron oscillations having a maximum radial excursion $r_{\text{max}}(z, t) \ll w(z)$, the local laser spot size, this radial phase variation can be neglected to a first approximation. This is a good approximation for the NEPTUNE experiment where the electron spot size will be $\sim 0.1 w_0$, where $w_0$ is the minimum spot size of the laser beam.

However, since the laser propagates through an axial focus, the EPW amplitude will vary along its propagation direction with an approximately Lorentzian profile. Now, the amplitude-dependent frequency of the EPW will result in a $z$-dependent phase relationship between the injected electrons and the accelerating buckets of the wave. As the electrons approach $z = 0$, they will advance in phase; that is, they will move forward in the wave frame and therefore sample a lower accelerating field than they would without this phase advance. If the maximum EPW amplitude is near “relativistic saturation [20]”, this phase excursion can substantially reduce the maximum $|E_r|$ seen by an electron since $> 90^\circ$ phase changes (putting an electron originally at the maximum accelerating field into small or even decelerating fields) are possible. We have chosen to inject electrons well before relativistic saturation where the average gradient is still about 3 GeV/m but where this phase excursion is small compared to the 90$^\circ$ of useful (focusing and accelerating) phase of the EPW. Note that similar phase excursions will also occur in a laser wakefield acceleration (LWFA) scheme if the laser intensity varies along $z$. In this case, an additional nonlinearity which may affect the energy gain of a witness electron is the intensity-dependent group velocity of the laser pulse [21].

Under these approximations, i.e., relatively small betatron excursions and nearly linear EPW amplitudes, we can describe the radial fields using the linear, 2-D analytic result of Fedele et al. [22]
which gives the EPW fields driven by a Gaussian laser beam at \( n_e = n_{res} \) and neglecting relativistic saturation. The result is that \( E_r \) lags \( E_z \) by 90° and that otherwise, \( E_r(r, z, t) \propto r E_z(r, z, t) \). We include the small axial nonlinearities by calculating \( E_z(0, z, t) \) using the fluid model for arbitrary \( a_{1,2} \) and \( n_e \) from Tang et al. [23]. Using the expected Gaussian beam parameters and temporal profile of the CO₂ laser beam, this calculated \( E_z(0, z, t) \) becomes the coefficients for \( E_r(r, z, t) \). For the NEPTUNE experiments with the large laser spot size (\( k_p \omega_0 \approx 5 \), the maximum \( E_z \) (located approximately at \( r = w_0 \)) is about \( \frac{1}{2} \) of the maximum \( E_z \). Here \( k_p = \omega_0/c \) is the wave number of the plasma wave.

### 3.2. Electron accelerating modeling

The entire beamline, including the RF gun, PWT linac, and electron optics was modeled using the code PARMELA up to the interaction point for a 40 pC, 3 ps FWHM electron pulse. The normalized emittance was about 0.33π mm mrad, the energy spread was about 0.1%, and the spot size was nearly round with \( \sigma_x \approx \sigma_y \approx 30 \mu m \). The particle phase-space data from 10 cm before the electron final focus was dumped to a file and subsequently used as the initial condition of the electron beam to be pushed through the EPW fields described in Section 3.1. It was found that the output characteristics of the beam using this procedure were nearly identical to using an “ideal” beam of the same emittance and energy spread – a beam with a Gaussian distribution in transverse position and momentum with flat-top current in time. It was therefore convenient to use an ideal beam in favor of the PARMELA output in order to precisely label the injection phase of each electron for studying the single-particle dynamics within the wave.

A second approach to modeling was to use the PARMELA output just after the gun, converted to an equivalent envelope description of the beam, in an envelope code (TRACE3D) to model the general characteristics of the beamline. In this way, the variation of the electron beam at the entrance to the plasma accelerator for fixed magnet settings, induced by fluctuations in space-charge forces due to fluctuations in the photocathode laser beam energy could be studied. Due to strong final focusing, the spot size stayed below 40 μm for a charge fluctuation of ±7% and below 50 μm for a ±10% variation in charge. Since the UV beam is frequency quadrupled from the fundamental frequency, this implies a necessary stability of the fundamental of ±1.8–2.5%. The theoretical basis for understanding the stability of these lasers has recently been published and used to stabilize a regenerative amplifier (the primary source of noise) down to 0.42% RMS [24] so the required stability should be achievable.

For the numerical simulation, the intensity of each laser line was set to \( 2.4 \times 10^{14} \) or \( a_t = a_2 = 0.14 \). At this intensity, the plasma becomes fully ionized at the best focus (\( z = 0 \)) < 15 ps into the 100 ps rise-time pulse. At the time of electron injection, 60 ps into the pulse, the laser will have ionized \( \approx 2.9 \) Rayleigh lengths on either side of the laser focus, or out to \( z = \pm 7 \) cm. The simulation had a sharp gas boundary (experimentally produced by the pinhole for differential pumping) at \( z = -6 \) cm and the electrons were focused at this boundary. The electrons were focused to this plane for two reasons. First, since the plasma wave amplitude is zero for \( z < -6 \) cm, the electrons did not have to travel radially across any plasma wave fields. Thus, there is a definite accelerator “aperture” for the electrons to enter. The second reason to inject at \( z = -6 \) cm is to attempt to “beta match”: i.e., set the beta \( \beta \) of the accelerating structure to \( \beta^* = x^2/c^2 \) of the focused electron beam. Here, \( \sigma \) is the spot size of the focused electron beam which has an emittance \( \epsilon \). At the waist, \( \epsilon \approx \sigma \theta \) where \( \theta \) is the characteristic focusing angle which increases for tighter (larger in angle) focusing. So \( \beta^* \) characterizes the external focusing for a beam of a given emittance. Likewise, \( \beta \propto dr/dz|_{max} \) of the electron trajectory within the EPW, characterizes the internal focusing of the accelerator and matching these two functions will, in principle, minimize emittance blowup during the acceleration process [25]. The beta function of the plasma wave is found by solving the radial harmonic oscillator equation \( r'' + k_r^2 r = 0 \) where \( k_r^2 \) is proportional to the radial field \( E_r(r) \) (the restoring force) and \( \beta \equiv k_r^{-1} \). The result, using the analytic radial fields

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from Ref. [21] is
\[
\beta \approx w_0 (1 + (z/Z_{cr})^2)^{1/2} (\gamma(z)/4/\delta n(z)/\sin \phi)^{1/2},
\] (1)
where the first two factors describe how the waist size varies with \( z \), \( \delta n(z) = \bar{n}/n_0 \) is the \( z \)-dependent normalized plasma wave amplitude, \( \gamma \) is the Lorentz factor for the injected electron, and \( \phi \) is the injection phase with \( \phi = 0 \) the point of maximum electric field and zero focusing fields.

Fig. 3a shows the tuneability of \( \beta^* \) due to variation in the focusing strength of the triplet. It is typically between 0.5 and 1.0 cm. The initial beta of the plasma accelerator at the entrance aperture (where \( z \) is now the location of the plane of injection) is shown in Fig. 3b along with the axial variation of the plasma wave amplitude at 60 ps. Here, \( \gamma \) was taken as a constant 33 (16 MeV) to highlight the variation of \( \beta \) at different injection planes. During acceleration, however the actual \( \beta \) will not decrease as much as shown in Fig. 3b since \( \gamma \) will be increasing. In this case of an axial varying focusing strength, beta matching is not a straightforward concept. Moreover, the beta function for a plasma wave is a strong function of injection phase, going
to infinity at $\phi = 0$ where the radial fields are zero (the $1/\sin \phi$ factor in Eq. (1). Thus, a short electron pulse ($<10^\circ$ in phase) can have a single initial $\beta$. Even in this case, the best one can hope for is "adiabatic matching" where the increase in $\gamma(z)$ due to acceleration tends to balance the increase in $\delta n(z)$ keeping the instantaneous $\beta$ roughly constant and thereby minimizing the emittance blowup. Note that this is not an issue for guided laser beams of constant intensity.

The results of injecting the "ideal", 3.4 ps long beam into the model plasma accelerator are shown in Fig. 4 after the beam has propagated 24 cm ($10Z_R$) beyond the laser focus. In Fig. 4a one can see that the peak energy in the three accelerating buckets is increasing in time as the plasma wave has not yet saturated. The $\frac{1}{3}$ ps to the left of the peaks is the focusing and acceleration phase of the wave and we see the expected rise from the injected gamma of 33 to the maximum gamma at $\phi \approx 0 + 2\pi n$; $n = 1, 2$. To the right of the peaks, the electrons have been radially expelled since the radial field has changed sign. One can see by inspection of Fig. 4a that there is a nearly perfect correlation between injection phase and output energy and that prebunching the beam to $\sim 100$ fs would lead to an energy spread $\Delta \gamma \sim 40$. The longitudinal phase space [Fig. 4b] shows that spatial bunching of the high-energy electrons has occurred after an effective interaction length $\pi Z_R = 7.5$ cm which is about $\frac{1}{3}$ of the dephasing length. An enlarged view of the third peak shows that the bunch length is 30 fs or 9 $\mu$m (tail to tail) for $180 < \gamma < 200$ and could shorten another factor of two if dephasing would occur. Dephasing occurs when the highest energy electron has traveled from $\phi = 0$ to $\pi/2$ in the frame of the wave so that it is just entering a decelerating field. At this time, the distribution in phase space will be almost vertical whereas in Fig. 4b one can see that the high-energy bunches are leaning to the left (direction of travel is to the right). The output spectrum on a linear scale is shown in Fig. 4c. Each simulation electron is worth $10^5$ experimental electrons so that there are millions of electrons in the high-energy bins. Recalling that the detectors will be after a septum magnet, the detected spectrum will roll off towards lower energy beginning at $\gamma \sim 70$.

![Fig. 4](image)

**Fig. 4.** Output of a numerical push of a 3.4 ps stream of 2500 electrons through a model beat-excited electron plasma wave accelerator. Three accelerating buckets were uniformly filled. All output parameters are obtained 24 cm from the laser focus. (a) Output energy vs. relative time of injection. (b) Final longitudinal phase space. (c) Final electron spectrum for energy bins of $\Delta \gamma = 5$.

To observe the emittance of the highest-energy portion of the beam, the numerical push was done once again but with many more particles spread over a smaller injection phase. Fig. 5 shows the

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transverse phase space ($y'$ vs. $y$) for our model at the longitudinal location 24 cm beyond the laser focus. Once again we focus on the electrons with $180 < \gamma < 200$. Also, in Fig. 5 are histograms of $y'$ (integrated over $y$) and of $y$ and of $y$ (integrated over $y'$). Using the usual expression for RMS emittance, we find that the normalized RMS emittance ($\gamma = 190$) is $15\pi \text{ mm mrad}$. However, that value is dominated by particles in the tail and halo. The “core emittance” can be estimated by simply taking the $1/e$ half-widths of the two histograms to get an estimate of $\pi \times 0.4 \text{ mrad} \times 0.08 \text{ mm} \times 190 = 6\pi \text{ mm mrad}$. The ellipse is slightly rotated so the histograms overestimate the phase space area. We should point out that although the beta matching at the injection plane was better in the vertical direction, the emittance in both the $x$ and $y$ directions were nearly identical suggesting that “adiabatic matching” did not occur for this particular axial plasma wave profile. It is this mismatch exacerbated by the mismatch caused by injecting over $20\degree$ in phase which is most responsible for the emittance degradation as opposed to linearity of the focusing fields.

4. Present status and conclusions

The NEPTUNE Laboratory construction project is on track for plasma beat wave experiments to begin in late 1998. Upgrades in the electron beamline hardware and software and upgrades in the CO$_2$ laser system and timing capabilities will allow for injection of high-quality electron bunches into a large aperture plasma accelerator. A simple model of the plasma wave growth and subsequent electron acceleration suggest that 100 MeV electrons will be observed. For a 3 ps, 40 nC injected
bunch, it is expected that $5 \times 10^6$ electrons will reside in a $\pm 5\%$ bandwidth about $\gamma = 190$, limited by the peak current of the injected bunch.

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