A Linear Collider Based on Nonlinear Plasma Wake-field Acceleration*

J. Rosenzweig, N. Barov, E. Colby¥
Dept. of Physics and Astronomy, UCLA
405 Hilgard Ave., Los Angeles, CA 90095-1547

P. Colestock
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510

ABSTRACT

A proposal for a linear collider based on an advanced accelerator scheme, plasma wake-field acceleration in the extremely nonlinear regime is discussed. In this regime, many of the drawbacks associated with preservation of beam quality during acceleration in plasma are mitigated. Experimental progress towards high-gradient acceleration in this scheme is reviewed. We then examine a linear collider based on staging of many modules of plasma wake-field accelerator, all driven by a high average current, pulse compressed, rf photoinjector-fed linac. Issues of beam loading, efficiency, optimized stage length, and power efficiency are discussed. A proof-of-principle experimental test of the staging concept and the Fermilab Test Facility is discussed.

I. PLASMA WAKE-FIELD ACCELERATION

Much progress has been made in recent years in the experimental demonstration of acceleration in plasmas. The basic mechanisms for excitation of electron plasma waves which support accelerating fields has been verified, and accelerating gradients in excess of 30 GeV/m have been observed[1,2]. Despite this progress, however, many problems concerning preservation of the beam quality during acceleration in high gradient plasma waves remain experimentally unaddressed; plasma wave fields tend to be nonuniform in their accelerating fields, and nonlinear in transverse focusing fields. It is critical, from the point of view of application of plasma acceleration to high energy physics, that these concerns be mitigated.

Operation of the plasma wake-field accelerator (PWFA) in the extremely nonlinear ("blowout", where the beam is denser than the plasma) regime was originally proposed by Rosenzweig, Breizman, Katsouleas and Su in 1991[3]. While this system is *nonlinear* from the point of view of the plasma response (all of the plasma electrons are driven out of the beam channel by the intense fields of the driving beam), it will be seen that the attributes of the accelerating and focusing fields are what accelerator physicists term *linear*. Development of this regime represents the first serious attempt at formulating a version of a plasma accelerator which has the attributes of a standard rf linear accelerator. These attributes include:

- focusing which, for electrons, is linear in offset from the symmetry axis, and independent of longitudinal position within the wave. This focusing is purely electrostatic and dependent only on the plasma ion charge density n_0,

$$F_r = -eE_r = -2\pi e^2 n_0 r \equiv -\tfrac{1}{2} m_e c^2 k_p^2 r. \qquad (1.1)$$

  It should be noted that this wave is suited only for accelerating electrons, as positrons are defocused by the presence of the ion fields.
- Acceleration which is dependent only on longitudinal position within the accelerating wave, and not on transverse offset. The maximum strength of the acceleration in this regime is typically larger than the so-called wave-breaking limit

$$eE_{WB} = m_e c^2 k_p \cong \sqrt{n_0(\mathrm{cm}^{-3})}\ (\mathrm{eV/cm}). \qquad (1.2)$$

  As we typically have plasma densities in the range $n_0 \approx 10^{14}\ \mathrm{cm}^{-3}$, this implies accelerating gradients in excess of 1 GeV/m.
- Operation at high gradient at mm wavelengths, due to lower plasma densities and relativistic lengthening of the plasma oscillation period. This relatively long wavelength is an advantage for beam dynamics, and the smaller plasma density mitigates transverse emittance growth due to multiple scattering of the beam off of plasma ions.

We now review the characteristics of this regime in more detail, in order to illuminate the goals of our straw-man design and experimental program. Under the condition that the drive beam is much denser than the plasma, the plasma electrons are ejected from the beam channel, and the acceleration fields are entirely electro-magnetic. This implies that the acceleration must be independent of *r*, as in an m=0 TM mode traveling wave accelerator. This is in fact a profitable way of looking at the physics of the driven plasma wave's fields. There is a cavity (traveling near the speed of light!), with currents on the boundary, supporting an m=0 TM mode. Inside of this cavity, the only source is a uniform background of pos-itive charges due to ions, which gives the linear focusing.

This regime has been studied using PIC codes (both ISIS and a new code developed by N. Barov of UCLA) and

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¥Also at Fermi National Accelerator Laboratory.

a fluid model[3]. An example of the fluid code output is shown in Figure 1, which displays a typical case of PWFA in the blow-out regime, where a beam of twice the density (now moving to the left in the simulation) of the ambient plasma completely rarefies the beam channel, producing a pure ion channel and a nonlinear accelerating field. Figure 2 shows the dependences of the transverse and longitudinal wake-fields as a function of radius in the accelerating (for electrons) portion of the wave. It can be seen that the fields are indeed of the form discussed above, with linear focusing no transverse dependence on the accelerating field, promising great improvements in beam quality over plasma beatwave, laser wake-field or PWFA in the linear regime. In fact, the accelerating and focusing fields in this regime are conceptually identical to a conventional linac with an applied linear focusing lattice.

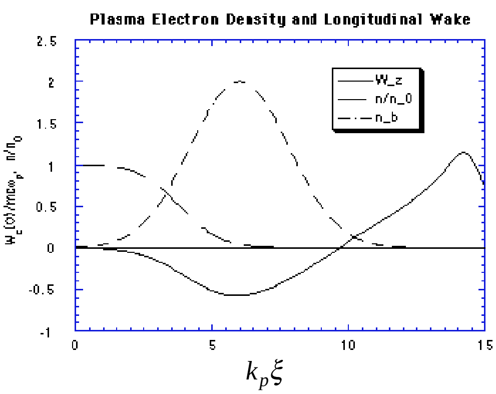

Figure 1. PWFA in the blow-out regime, beam completely rarefies plasma electrons from the beam channel. Longitudinal coordinate is stationary within the wave $\xi \equiv z - v_b t$.

The linearity of the focusing is, as stated before, due to the total rarefaction of the plasma electrons from the beam channel. This also implies other useful aspects of this system, in that beam loading within the rarefaction channel cannot change the transverse focusing.

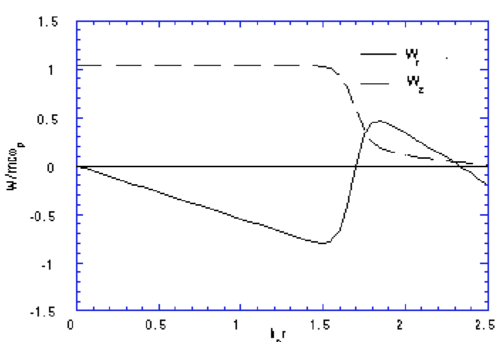

Figure 2. Transverse and accelerating fields as a function of radius at accelerating phase of case in Figure 1, showing uniform acceleration, linear focusing within rarefaction channel.

Although the blow-out regime of the PWFA has significant differences with respect to the linear regime, it also retains some advantageous aspects of the linear behavior. Most notably, ramping of the drive beam on a scale length longer than k_p^{-1} allows for a transformer ratio in excess of unity. The fact that the approximately linearly ramped pulse gives this behavior in the blowout as well as linear regimes merely reflects the degree to which the plasma response can be viewed as a generalized inductance. In this view, the decelerating field inside is nearly constant $E \propto L(dI/dt)$, which is the condition found for optimum transformer ratio generation[4].

All of the field characteristics discussed so far concern the quality of the wake-fields in the rarefaction region, where the high quality accelerating beam must be located. The transverse wake-fields for the drive beam, however, are not so uniform, because the plasma must take a finite time to respond to the beam. Because of this, the leading edge of the beam expands as if it were (ignoring small Coulomb scattering effects) in free space. On the other hand, the main body of the drive beam can be stably matched to the uniform focusing of the electron-rarefied ion channel. If the beam density is high enough, and the emittance is low, then the erosion of the beam head is not an important effect in our experimental parameter regime.

We have explored this question in great detail, with the results applied to our experimental situation and published for general use[5]. The paper presents an analytical model of how rarefaction must proceed, assuming the entire beam is in fact matched to the ion channel focusing. Given the constraint that the length of a symmetric beam must satisfy $k_p\sigma_z < 2$ (or else the wake-field behind the beam is diminished) the condition that the plasma electrons be rarefied before the arrival of the longitudinal beam center yields the constraint on the beam parameters,

$$N_b \geq \frac{9\varepsilon_n}{\sqrt{4\pi\gamma r_e}}. \tag{1.3}$$

This condition can be satisfied by a high quality rf photoinjector. It is, however, a bit of an optimistic model, as beam-head erosion modifies this result. We have studied the effects of beam head erosion, as well as finite plasma density rise length with (1) Maxwell-Vlasov beam/plasma electron fluid computational mode, (2) superparticle beam/plasma electron fluid computational model, and (3) a fully self-consistent PIC code.

These studies have had a direct impact on experimental design and data interpretation. The most fundamental finding was that, while the scaling of Eq. 1.3 with emittance and energy is correct, the constant of proportionality is much larger, due to beam-head erosion effects. These results imply that one needs approximately a factor of 5 larger charge to achieve rarefaction.

The work performed by our group concerned the monopole stability (confinement) of the drive beam. It was thought several years ago that a dipole mode (the electron hose instability[6]) would cause problems for this type of PWFA, but it has been shown in 3-D simulations of short ($k_p\sigma_z < 2$), symmetric beams, that the instability has a negligibly small effect[7]. For long, ramped pulses, electron hose remains a serious concern.

As a final comment on the physical mechanisms in the nonlinear PWFA, we compare it (favorably) to similar schemes using laser drivers. In laser-based schemes, the laser needed is at the state of the art, especially when one considers the repetition rate, which lasers have serious limitations on due to material heating. It is also certain that the cost of a modular, staged accelerator is much larger for the laser approach; an inexpensive approach to the PWFA is outlined in the next section. And, perhaps most critically, electron beam-based wake-field accelators are easily phase-locked; when one uses the same rf wave and compressor to create both the drive beam and witness beam, both beams will be well locked to the rf clock[8].

II. PREVIOUS EXPERIMENTAL WORK

The initial tests of the plasma wake-field accelerator in the regime where $n_b < n_0$ were performed at the Argonne Advanced Accelerator Test Facility[9]. In this round of experiments, several relevant results have been obtained:

- Measurement of drive beam energy loss in plasma.
- Picosecond time-resolved acceleration/deceleration of trailing witness beam in linear plasma wake-fields.
- Measurement of witness beam deflections by transverse wake-fields.
- Measurement of >10 MeV/m nonlinear plasma waves.
- Time-resolved imaging of self-focused electron beam at end of plasma.

Additional experiments of note in this area are thin lens focusing experiments in the $n_b < n_0$ regime performed at UCLA[10] and KEK.

Based on the succes of the initial tests at ANL, the promising theoretical predictions concerning the blow-out regime of the PWFA, and the existence of a new rf photoinjector at ANL, the Argonne Wake-field Accelerator (AWA), a new collaboration was formed between UCLA and ANL to perform a new round of experiments. The initial proposal for using the AWA to generate the drive beam assumed an optimistic set of parameters: 100 nC of charge, rms bunch length of 0.75 mm, and normalized emittance of 400 mm-mrad. The predicted performance of this beam in a $n_0 = 2\times10^{14}$ cm^{-3} plasma gives a robust blowout ($n_b / n_0 \approx 8$), and a gradient of nearly 2 GeV/m. The actual performance of these experiments which hve been underway for over one year, have deviated considerably from these predictions, because the beam performance has been degraded in all parameters given above, and blow-out has not been straightforward to achieve. Nevertheless, we have observed the following[11]:

- Creation of a stable drive and witness beam pair in an rf photoinjector.
- Deceleration of the drive beam and acceleration of the witness beam at the 10-20 MeV/m level.
- Time resolved drive beam guiding with $n_b \approx n_0$

Further improvements to the experimental effort are discussed below.

III. STAGED PWFA — A COLLIDER MODEL

Given the promise that the nonlinear PWFA shows in terms of both preservation of beam quality and achieving high gradient acceleration at moderately short wavelength, it is reasonable to ask whether this type of acceleration mechanism is appropriate for high energy physics colliders. We will therefore consider in this section a "straw-man" design for a collider based on the nonlinear PWFA. This exercise will point out the issues that must be addressed in a proof-of-principle staging experiment.

One limitation of this technique for creating an electron-positron collider is apparent from the beginning - that positrons are not easily accelerated using in this type of plasma wave. Therefore one is by definition considering alternative schemes such as e-e, e-γ or γ-γ colliders. We will therefore present the design from the accelerator point of view, leaving the details of the interaction region purposely vague.

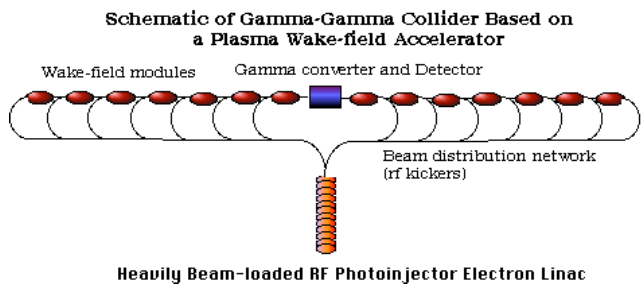

Figure 3. Schematic of a γ–γ collider using a hardware transformer scheme. A large number of bunches are created in heavily beam-loaded linac fed by an rf photoinjector based on a compressor. Separate wake modules are driven by the beams, which are fanned out in a binary rf splitting scheme.

It was originally pointed out by W. Gai[12] that one could mitigate concerns about the transformer ratio of wake-field accelerators by driving a large number of wake-field modules from one work-horse linac. A schematic of a variation on this "hardware transformer" is shown in Figure 7. The single linac which feeds both sides of the collider must then have as many bunches in a single rf fill as the total number of modules, and in this geometry, they must be separated by the time-of-flight through a single module section, including drift. This heavily beam-loaded linac is fed by an rf photoinjector employing one or more magnetic compressors. The separate wake modules are driven by the beams, which are fanned out in a binary rf splitting scheme which is driven at the half-sub-harmonic of the linac rf frequency. These drive bunches must also be combined with the accelerating bunch, which because it will be over a TeV in energy at peak, must not see bend fields or they will radiate large amounts of energy through synchrotron photons. Thus the recombining sections must also be based on (very high frequency ~ 50 GHz) rf kickers. The stability of these rf splitting and combining systems is of course critical in determining the performance of the collider.

The first quantitative step in constructing this straw-man design is to self-consistently determine the length of a module, by setting the decelerating gradient of the beam in the module, and the energy of the beam exiting the drive linac. The decelerating gradient is of course dependent on the beam charge, emittance, bunch length and plasma density. These parameters are determined by simulation of the plasma wake-field interaction (detailed simulations with similar parameter sets are given in a following section), and are given in Table 1. Once the decelerating gradient is chosen, the accelerating gradient and plasma wavelength are also known; it remains to choose the length of the module, which sets the linac energy, as we will take the length of the module to be such that the trailing edge of the drive beam loses 95% of its energy in the plasma. The energy in turn is chosen partially by geometric considerations and partially by beam-loading considerations, the results of which are displayed in Table 2. Note that the stored energy per pulse is quite large (60 J). This compares quite favorably with laser sources of similar repetition rates.

The length of the intermodule drift in the collider is chosen to give sufficient space to bring in a new drive beam and remove the spent one, match the accelerating beam optics from one module to the next, but keeping the dead (non-accelerating) space to a minimum. The total accelerating module plus dead space length is finally chosen to be commensurate with a subharmonic of the drive linac rf wavelength.

TABLE 1. Nominal drive beam and accelerating module parameters for the plasma wake-field accelerator-based collider shown in Figure 4.

Beam Energy	3 GeV
Beam Charge	20 nC
Stored Energy/Bunch	60 J
Bunch Length	0.8 mm
Norm. Emittance	50 mm-mrad
Plasma Density	2×10^{14} cm^{-3}
Plasma Wavelength	2.2 mm
Deceleration Wake	500 MeV/m
Accelerating Wake	1 GeV/m
Wake Module Length	5.7 m
Intermodule Drift	2.66 m

Table 2 shows a set of design parameters for the heavily beam-loaded drive linac based on a normal conducting TESLA-like 1300 MHz structure; by heavily beam-loaded, we mean that the beam power is well in excess of dissipated rf power. The accelerating gradient is chosen to be relatively low (6 MeV/m), in order to mitigate the rf power dissipation and related issues. These issues in this case include the peak and average power per cavity at the chosen 5% duty cycle; the peak power of 5.9 MW at a pulse length of 14.5 µsec (78% of this power goes into accelerating the drive bunches) is easily achievable. The nominal average dissipated rf power is 66 kW, which is a similar power to the TTF photoinjector power, but with nearly an order of magnitude more total mass. The cooling of this cavity should therefore be a straightforward design problem.

TABLE 2. Design parameters of heavily beam-loaded 1300 MHz drive linac for plasma wake-field collider. Parameters chosen based on Table 1 parameters, optimized for high level of beam-loading (beam power well in excess of dissipated rf power).

Avg. accel. gradient	6 MeV/m
Shunt impedance ZT^2	30 MW/m
Active length	500 m
Cavity length	1.1 m
Peak rf power (cavity)	5.9 MW
Number of bunches	2 x 250
Beam current (in fill)	690 mA
RF flat top	14.5 msec
Duty cycle	5%
Avg. bunch rep. rate	865 kHz
Avg. diss. rf power/cavity	66 kW
Total ave. diss. RF power	30 MW
Total avg. beam power	104 MW

Table 3 shows the parameters associated with the accelerated beam and the total system performance. The efficiency of energy extraction from the wake is kept to 20%, in order to load the beam at 91% of the peak amplitude (transformer ratio of approximately 1.8 per module). This gives a center-of-mass energy at the collision point of 2.5 TeV, with collisions occurring at an average rate of 3.5 kHz. Assuming a wall-plug efficiency associated with the 1300 MHz rf system of 40%, we obtain an average power of 335 MW to run the collider. This is within the range of acceptable powers for this type of third-generation (post-NLC) collider.

TABLE 3. Accelerated beam, system collider performance.

Accelerated charge	2 nC
Wake efficiency	20%
Length of Collider	2 x 2.16 km
Accel. beam energy	1.25 TeV
Avg. collision rate	3.5 kHz
Drive linac/wall effic.	40%
Total wall power	335 MW
Total efficiency	7.6%

No luminosity estimates will be attempted at this point, as there are many issues associated with the emittance dynamics in the collider, as well as the detailed design of the (γ-γ, e^--γ or e^--e^-) collider final focus and interaction point. The interaction point is a complex subject well beyond the scope of present consideration; let us examine only the relevant issue of emittance.

There are two fundamental physical mechanisms which give rise to emittance variation in this type of accelerator - emittance damping due to dipole radiative decay of the betatron oscillation amplitude, and emittance growth due to multiple scattering off of the plasma ions. Of course, there are many other sources of emittance growth, including higher focusing multipole moments, chromatic and collective transverse instability. The damping of oscillations in a uniform focusing channel such as the plasma ion-focusing column we are considering has been analyzed in detail by Huang, Chen and Ruth[13]. The equation for emittance damping derivable from this work is

$$\frac{d\varepsilon_n^2}{dz} = -\frac{2\pi r_e^2 n_0}{3}\varepsilon_n^2, \qquad (3.1)$$

which yields exponential damping with characteristic length $z_d = 3/2\pi r_e^2 n_0$. For the plasma densities of interest here this damping length is enormous, on the order of 10^8 m, and thus we can ignore this effect henceforth; only in the case of a nearly solid state plasma density would this effect be strong enough to consider.

On the other hand, the excitation of the emittance growth due to multiple scattering can be quantified by the following expression, based on the familiar angular growth formula due to Bethe,

$$\frac{d\varepsilon_n^2}{dz} \cong 9.13\left(\frac{n_0 r_e^3}{\gamma}\right)^{1/2} \frac{Z^2 \ln\left(184/Z^{1/3}\right)}{A}\varepsilon_n. \qquad (3.2)$$

This can be integrated, assuming small emittance growth,

$$\Delta\varepsilon_n^2 \cong 18.25\left(n_0 r_e^3 \gamma_f\right)^{1/2} \frac{Z^2 \ln\left(184/Z^{1/3}\right)}{A}\frac{\varepsilon_n m_e c^2}{eE_{acc}}. \qquad (3.2)$$

For the parameters of this collider design the rms normalized emittance increase, assuming a hydrogen plasma and beginning with an rms normalized emittance of $\varepsilon_n = 10^{-8}$ m-rad (the vertical emittance from a state of the art damping ring), is $\sqrt{\Delta\varepsilon_n^2} \cong 1.33\times10^{-9}$ m-rad, consistent with the assumption of small growth.

It should be noted at this point that the laser-driven variations on plasma acceleration, generally demand a higher plasma density in order to guide the laser, in analogy to the ion-focusing considered here. This is because the effective emittance of the laser beam, $\varepsilon_l = \lambda_l/4\pi$, is much larger than that of the mult-MeV electron beam considered in our straw-man design. The laser divergence must be controlled by a strongly focusing channel, which implies a high density. Thus, unless a completely evacuated channel is used (which has the additional advantage of uniform acceleration), the multiple scattering driven emittance growth will be a larger, perhaps non-negligible issue for laser-plasma accelerators.

IV. PROPOSED STAGING EXPERIMENT

A state-of-the-art, high charge, low emittance rf photoinjector, with chicane compressor[8], termed the Fermilab Test Facility[14], is now under construction at Fermilab. This injector is a prototype for the TESLA Test Facility Injector to be installed in 1998 at DESY, and also will serve as a test bed for research into new ideas in particle beam physics. Among the formally proposed experiments is a collaboration (FNAL P890) between UCLA, Univ. of Rochester, and FNAL, to perform a first test of staging in plasma accelerators.

The predictions of the wake-fields driven by a 20 nC, 0.8 mm bunch length beam (same as the straw-man design) are shown in Figure 4. In this PIC simulation, the initial particle distribution is derived from PARMELA.

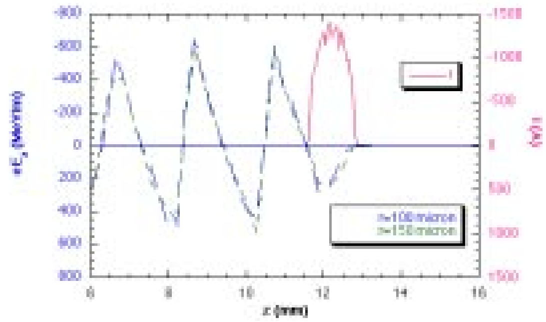

Figure 4. PIC simulation of the proposed PWFA experiments at the FTF.

Figure 5 shows a schematic of the proposed configuration for a two-stage PWFA experiment at the FTF. Two sets of witness and drive beams are split by use of a one-half subharmonic deflection mode cavity. The first witness beam is accelerated in the intial stage, and is then reinjected into the second stage for further acceleration. While this experiment will be technically challenging, we believe that it is important for the future of high energy physics accelerators.

Figure 5. Schematic of two-stage PWFA experiment.

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