Particle Wake-field Accelerators

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Abstract

A wakefield accelerator is a device which employs large amplitude electric fields generated in the wake of an intense particle beam to accelerate other trailing charged particles to high energy. The environment which the causes the beam to generate this wakefield can be any which supports the propagation of slow waves ($v_\phi < c$), e.g. plasma, dielectric-lined wave-guide, or a standard disk-loaded linac structure. In addition, the accelerating beam axis may also be either collinear or parallel to the driving beam. The typical application considered for this type of linear accelerator is a future linear collider, and therefore particular attention is paid to such issues as accelerating gradient, power efficiency, and single and multiple bunch stability. In this analysis, a unified discussion of the principles behind wakefield acceleration will be presented, and constraints on power coupling, (which places limits the accelerating gradient) and accelerating efficiency will be explored for both collinear and parallel wakefield accelerators. The effects of transverse impedances in these schemes will also be discussed, and the role of the possible beneficial effects introduced by implementation of deflection mode damping examined. Recent advances in theoretical and experimental development of wakefield accelerators will be presented, as well as prospects for future technology development and experiments at linear accelerator research facilities.

Introduction

Development of advanced high gradient radio-frequency (rf) linear accelerators requires that the problems of rf power generation and propagation in the linac structure be addressed anew. Historically, rf power for accelerators has been derived from electron tube devices such as klystrons. In these sources, high voltage electron beams interact with resonant rf cavities to produce the required electromagnetic power, which can then be coupled to an accelerating structure through a waveguide. It was recognized some years ago that this process could be simplified by allowing a high-current relativistic electron beam (the *driving beam*) to travel through the accelerating structure directly, radiating rf power into the accelerating mode which has a phase velocity $v_\phi = v_b \simeq c$. A trailing, lower current relativisitic beam can then be resonantly accelerated to high energy by this mode. This scheme is termed *wake-field acceleration*, as the coherent radiation of particles due to their passage through an accelerating structure is generally described as a wake-field.

A wake-field can be excited in structure by a beam of charged particles whenever the structure can support electromagnetic waves which have phase velocity less than c (slow waves). Seen in this light, one can in a generalized sense consider wake-fields to be coherent emission of Cerenkov radiation. Examples of wake-field structures can include linac-like periodic metallic waveguides, dielectric-lined waveguides, and (slightly expand the usage of the term structure) plasma. In these examples it is apparent that the radiation is generated by the polarization response to the beam's electromagnetic fields of resonator systems based microscopically on electronic – valence, atomic and free electrons, respectively – motion. Note that radiation generated by the interaction of of an electron beam with an externally applied magnetic field is excluded from the definition of wake-fields as we have given (*i.e.* a two-beam accelerator driven by an FEL would not be considered a wake-field accelerator).

The major advantage of wake-field acceleration over a more conventional approach is that the rf power is created inside of the accelerating structure itself, and thus considerations of how to efficiently excite the structure, which have played a dominant role in the design of high-gradient, high-frequency normal conducting linear colliders are mitigated. In a wake-field accelerator the accelerating rf is created, and then used for acceleration on time scale short compared to the power dissipation or transport in the structure. Thus the shunt impedance and group velocity of the structure have less importance in the design of a wake-field accelerator. In order for high gradients to be achieved in a wake-field accelerator, however, the longitudinal beam impedance $Z_{\|}$ should be maximized and the structure excited by a beam with very high peak current. Alternatively, one can relax the impedance requirements

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and drive the structure resonantly with a beam with current modulated at the rf frequency ω, as in a klystron.

Wake-fields: General Remarks

The wake-fields excited by a beam in a structure is generally defined to be only the field components with which a paraxial beam particle ($\mathbf{v_b} \simeq v_b\hat{z}$) interacts,[1] which are broken down into longitudinal and transverse parts,

$$W_z = E_z \quad (1)$$

$$\mathbf{W}_\perp = \mathbf{E}_\perp + v_b\hat{\mathbf{z}} \times \mathbf{B}, \quad (2)$$

respectively. The longitudinal and transverse parts of the wake-field are not independent, but are related (in the approximation that the structure is translationally invariant in z, and thus the wake-field can be written as a function of $\zeta = z - v_b t$) by the Panofsky-Wenzel theorem[1][2]

$$\frac{\partial \mathbf{W}_\perp}{\partial \zeta} = \nabla_\perp W_z. \quad (3)$$

Since we are interested in large rates of energy transfer to the structure, it is useful to examine an upper limit, the energy loss per particle of a beam of N electrons to Cerenkov radiation, in a polarizable medium with very large dielectric constant ϵ. This quantity is approximately[3]

$$eW_{z,-} \simeq \frac{1}{2}e^2 N k_0^2, \quad (4)$$

where now k_0 is the maximum wavenumber that can be excited by the beam, which is for practical purposes the inverse of the largest beam dimension, usually the rms beam length σ_z. The dependence of a single mode component of the wake-field (of wavenumber $k = \omega/v_b$) with linear response can be illustrated by writing

$$W_z(\zeta) = Z'(k)v_b \int_\zeta^\infty \lambda(\zeta')\cos\left(k(\zeta - \zeta')\right)d(k\zeta'), \quad (5)$$

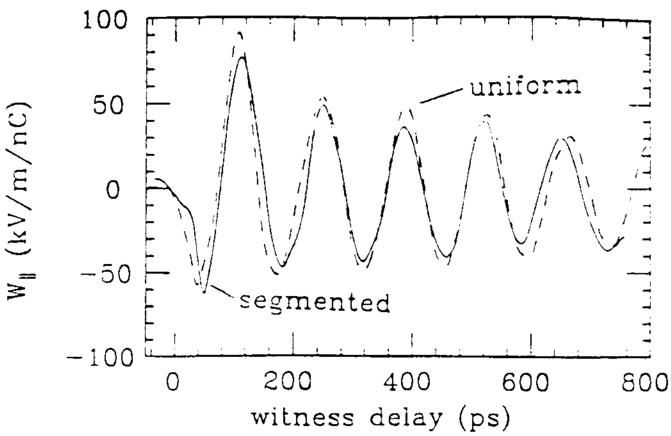
where $\lambda = I/v_b$ and $Z'(k)$ are the beam charge and the impedance per unit length of the structure at the wavenumber k, respectively. This *convolution integral, when evaluated for gaussian bunches, gives a wake-field amplitude proportional to* $Z'(k)\exp\left(-k^2\sigma_z^2/2\right)$ (*i.e.* the response is proportional to the Fourier amplitude of the current at the wave-number k). These results illustrate the need for a short, high current beam, and a high frequency, high impedance medium or structure to generate large amplitude wake-fields from one bunch. In practice, the coupling of the beam to the structure does not approach this maximum for devices with vacuum holes for the beam, and the limiting coupling is approached only in plasma. Also, the creation and transport of the high current beams needed to obtain accelerating gradients over 100 MV/m is technically challenging, and thus use of a modulated current beam or pulse train to achieve the required current spectrum may be preferable in some schemes. In particular, since the Panofsky-Wenzel theorem in the states that the transverse and longitudinal wake-field amplitudes are proportional a lower impedance structure may be necessary in order to avoid beam-breakup instability (BBU).

In many wake-field acceleration schemes the accelerating beam and the driving beam are collinear, that is they travel nominally along the symmetry axis of the structure. In this case, if the electromagnetic response of the structure is linear, both beams experience the same impedance. this places constraints on both the efficiency of the scheme and the ratio of acceleration gradient in the driving beam's wake to the deceleration gradient inside of the driver. a common statement found in wake-field literature is termed the *fundamental theorem of beam loading*. This theorem states that, for point-like beams traversing a linear structure which supports only one resonant electromagnetic mode, that the ratio of the maximum accelerating wake-field felt by the trailing beam to the decelerating field felt driving beam (the *transformer ratio* r) is less than or equal to two[1]. This factor of two arises from the fact that the driving beam, because of the causal nature of the excitation, feels only half of its own the longitudinal field. In addition, it can be shown that the energy transfer efficiency is maximized when the accelerating beam has charge equal to the driving beam, but at the price of reducing R to unity.

This theorem has a very restrictive range of applicability, however, and there are a variety of ways of making $R > 2$ if its assumptions are violated. The first method is to shape the current profile[4], to give it a long rise ($\sigma_+ \gg k^{-1}$), and a short fall ($\sigma_- < k^{-1}$). In this way one can obtain $R \simeq 2k\sigma_+$. Physically, this method is similar to stretching a spring adiabatically, and then releasing it suddenly, allowing it to go in to large amplitude oscillation Maximizing R in this way is also equivalent to minimizing the energy spread in the driving beam. Another alternative is to use a medium (*e.g.* low density plasma[5]) with a nonlinear response. In this way the impedance seen by the beam is a falling function of field amplitude, allowing the possibility of enhanced R.

Still another method of transformer ratio enhancement is to allow the driving beam and accelerating beam to traverse different paths. An example of this method is found in the radial transformer[6] studied at DESY, in which a "smoke-ring" beam excites a disk loaded structure, and the wake-field amplitudes are enhanced by the geometric compression of the electromagentic pulse as it propagates inward towards the axis. The proposed CLIC linear collider scheme[7] also uses an off-axis beam, driven efficiently by a pulse train accelerated in superconducting linac. The wake-producing "transfer structure" is relatively low impedance, since BBU instabiltiy must be suppressed over the entire length of the linear collider.

Other examples of the use of parallel driving and acclerating beam paths in wake-field accelerators are the relativistic klystron two-beam accelerator, and the dielectric



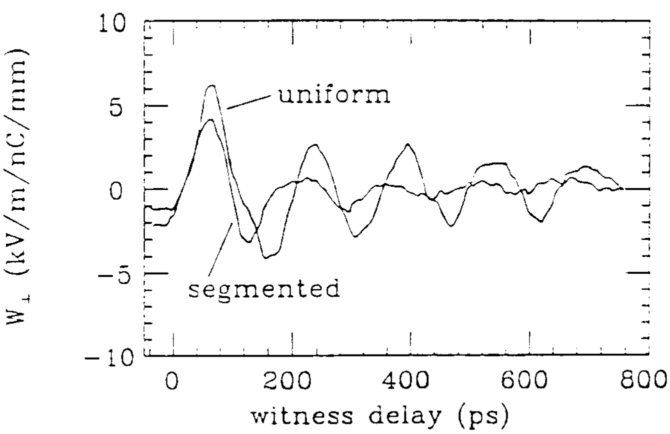


Figure 1: Longitudinal and transverse wake-fields in an undamped and damped DWA tube.

wake-field two-beam accelerator[8]-[10]. This device is discussed further below.

Wake-fields in Disk-loaded Structures

The Advanced Accelerator Test Facility (AATF) at Argonne National Laboratory was constructed to test a variety of wake-field acceleration concepts, including acceleration in a standard disk-loaded structure[11]. The AATF consists of a 21 MeV, short pulse ($\sigma_z \simeq 2$ mm) driving beam which contains up to 4 nC of charge, and a weak (pC) "witness" beam at 15 MeV, which traverses an adjustable delay transport line. When the two beams are combined to pass through a wake-field device on parallel trajectories, the witness beam may be delayed up to a nanosecond and offset transversely by several millimeters. In this way, the wake-fields due to the driving beam can be mapped out by measuring the witness beam energy changes and transverse deflections as a function of delay and offset.

The initial experiments at the AATF were performed on a disk-loaded metallic waveguide structure, and provided a good test of the standard theoretical and computational models of wake-fields in these devices. Recently, further tests were carried out on scaled SLAC structures with transverse mode damping slots. These tests showed that the Q of the dipole modes in these structures can be drastically reduced.

Dielectric Wake-field Acceleration

In the Dielectric Wake-fied Accelerator (DWA) the electromagnetic wave is slowed down in a waveguide not by undulations in the wall, but by introduction of a dielectric liner. Initial tests of this scheme at the AATF verified the basic theory of this device, measuring a multi-mode wake-field maximum accelerating gradient of 0.5 MV/m with one picosecond resolutione[8].

The simplicity and flexibility of the DWA encouraged the Argonne accelerator research group to propose an upgraded facility, to make a 1 GeV staged (using up to six drive bunches derived from a single 150 MeV linac) demonstration device, the Argonne Wake-field Accelerator (AWA). For this device it is desired to achieve up to 100 MV/m acceleration gradient, and thus a short ($\sigma_z < 1.5$ mm), high current ($Q = 100$ nC) driving beam. The desired acceleration could be obtained in a collinear device, but the short range BBU would destroy the drive beam before its energy was expended, even assuming tight alignment tolerances.

The AWA design therefore calls for using a two-beam device, in which the drive beam traverses a parallel path in a dielectric lined pipe (wake tube) with relatively large inner diameter and group velocity of the desired mode. The rf power created in this wake tube is then transferred, through a quarter wavelength matching section, to an accelerating tube with smaller cross-sectional dimensions, and a higher dielectric constant. Compression of the transverese dimensions and lowering of the group velocity allows the electromagnetic energy density to be magnified in this section. Thus the accelerating gradient can be enhanced, and large transformer ratios achieved.

The dipole mode wake-fields generated in the wake tube section can be prevented from affecting the accelerating beam in this device in two ways. First, the matching section provides some rejection of modes other than the fundamental. Second, dipole modes can be damped, as suggested by Chojnacki[10], by making the outer boundary of the wake tube, instead of a solid metal wall, out of longitudinally oriented lengths of insulated wire, backed

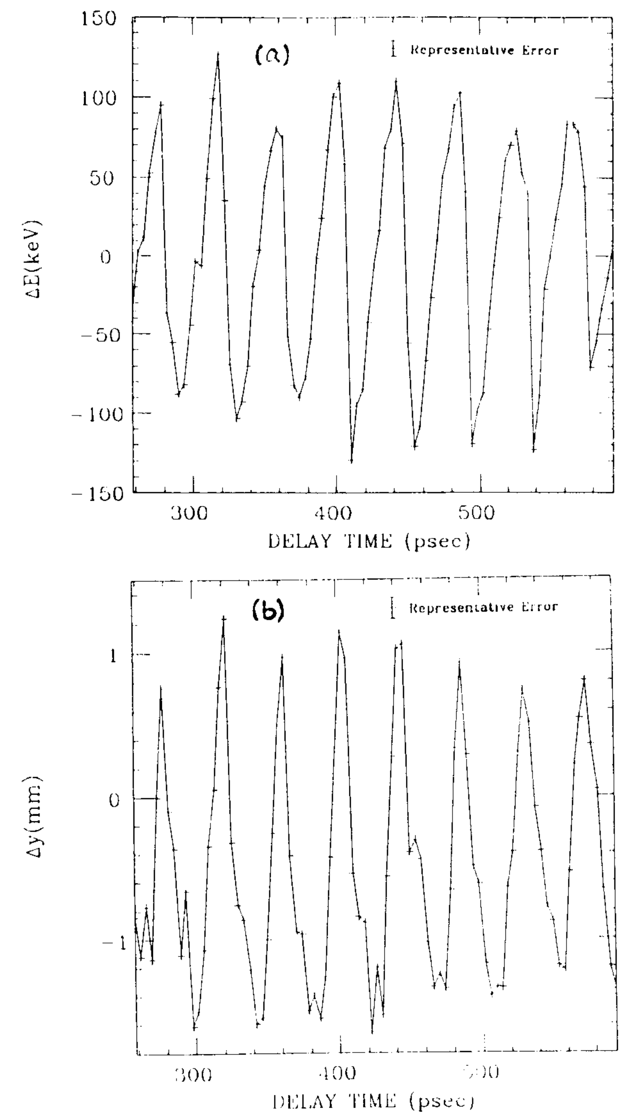


Figure 2: (a) Longitudinal and (b) transverse wake-fields in nonlinear plasma wake-fields, from Ref.14.

with microwave absorber. The wire allows the purely longitudinal currents associated with the monopole accelerating modes to travel unimpeded, while disrupting the azimuthal wall currents which support the dipole modes. The dipole modes radiate into the microwave absorber and are strongly damped. Some experimental results from the AATF are illustrated in Fig. 1, which shows damping of the dipole wake-field with almost no effect on the longitudinal wake-field.

Plasma Wake-field Acceleration

In the plasma wake-field accelerator (PWFA)[12], the beam excites the normal mode of the plasma, the electron plasma, or Langmuir, waves. These oscillations are *electrostatic* in the linear, small amplitude limit (they have no associated magnetic field), and have a frequency of $\omega_p = \sqrt{4\pi e^2 n_0/m_e}$, where n_0 is the unperturbed plasma density. Thus the plasma wake-fields are single-mode in this limit, where the perturbed electron density $n_1 \ll n_0$. Since the plasma electrons are in direct contact with the beam charge, the coupling of the beam to the plasma wave can approach the limit given by Eq. 4. The longitudinal wake-fields, unlike those in vacuum, have a strong variation in the transverse dimension. This nonlinear variation, which is very dependent on the exact configuration of the beam current, has a characteristic length scale of the beam size σ_r or the plasma skin depth c/ω_p, whichever is larger. From the Eq. 3, one can therefore deduce that the transverse wake-fields will be large and nonlinear. If the beam is long and narrow compared to c/ω_p, then the beam charge can be completely neutralized by the plasma electron response. Then the wake-fields are approximately equal to the magnetic self-fields of the beam, which is a very strong focusing force for a high current beam.

The initial tests of the PWFA were performed at the AATF, with a driving bunch of 2 nC, in a plasma of density $0.8 - 6 \times 10^{13}$ cm^{-3}. The wake-fields which were measured verified the predictions of linear theory, including the existence of strong transverse wake-fields within the driving beam[13]. Subsequent tests with twice the beam charge directly showed strong focusing of the driving beam within the plasma and concommitant enhancement of the plasma wave amplitude[14]. The amplitudes of the driven plasma waves in these experiments became nonlinear, and displayed characteristic steepened profiles. An example of an experimentally measured nonlinear plasma wake-field is shown in Fig. 2. This data provides a nice illustration of the Panofsky-Wenzel theorem, since the longitudinal derivative of the transverse wake-field is proportional to the longitudinal wake-field. The maximum wake-field in these tests was approximately 6 MV/m.

Further tests of the PWFA were perfomred in Japan at KEK[15] using a pulse train of 6 bunches to resonantly excite wake-fields in a less than 10^{12} cm^{-3} plasma. No witness beam was used in these experiments – the wake-field response was scanned in frequency by varying the plasma density, and observing the energy change in each bunch. The maximum acceleration longitudinal field was about 20 MV/m in these experiments.

Future Experiments

The staged two-beam approach to wake-field acceleration at the AWA will test systematics of the scheme, including mode damping and power transfer optimization. There are also some basic physics issues associated with maintaining high accelerating gradients in the DWA, such as dielectric breakdown and surface flashover. Examination of these problems will be the the primary goal of the AWA.

In addition, the extremely high current (10 – 20 kA) pulse that the AWA is designed to provide is an ideal driver

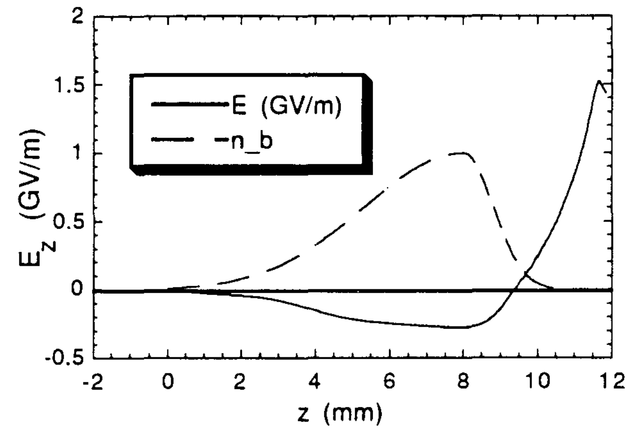


Figure 3: Plasma wake-fields the proposed Argonne nonlinear plasma wake-field acceleration experiment. Plasma density: $n_0 = 10^{14}$ cm^{-3}; beam parameters: $Q = 100$ nC, $\sigma_r = 130$ μm, rise, fall length $\sigma_{(+,-)} = 3$ mm.

for a new regime of the plasma wake-field accelerator[16], in which the plasma electrons are completely ejected from the beam channel by the rising edge of the beam. Once the beam channel is rarefied of plasma electrons, the beam is contained in a cavity like nonlinear plasma wave. In this case the electromagnetic component of the wake-field gives a longitudinal field independent of radial position, and no net transverse wake-field, just as in a linac cavity. In addition, however, the electrostatic field of the ions provides a uniform, linear focusing force which is independent of longitudinal position. The acceleration and focusing characteristics of the PWFA in this limit are excellent, and not strongly dependent on the beam profile, in contrast to the linear regime. Also, this regime allows operation at lower plasma density, meaning a longer accelerating wavelength, and easing of source requirements and beam multiple scattering.

Entry into this *ion-focusing regime* (IFR) requires that the focusing strength of the channel, the beam emittance and the current be such that the beam is self-consistently much more dense than the plasma over most of its length. This is the case for the AWA beam, which has a normalized emittance of 400 mm-mrad. In this extremely nonlinear regime of the PWFA, a ramped beam pulse can still be used to enhance the transformer ratio. An example of the expected performance of a proposed PWFA experiment which uses a ramped AWA pulse is shown in Fig. 3, for a plasma of density 10^{14} cm^{-3} and a beam rise/fall length of 3/1 mm. The transformer ratio in this case is $R > 5$, and the accelerating gradient is in excess of 1.5 GV/m, which is, remarkably, approximately the limit given by Eq. 4 assuming $k_0 = c/\omega_p$.

Further PWFA experiments using a beam extracted from the BEPC storage ring in Novosibirsk are planned[17]. In these tests the beam will be externally modulated at the plasma frequency in order to resonantly drive the plasma waves in a similar manner to the KEK experiments. Accelerating gradients of a few hundred MV/m are expected.

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