WAKEFIELD ACCELERATORS*

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Abstract

The search for new methods to accelerate particle beams to high energy using high gradients has resulted in a number of candidate schemes. One of these, wakefield acceleration, has been the subject of considerable R&D in recent years. This effort has resulted in successful proof of principle experiments and in increased understanding of many of the practical aspects of the technique. Some wakefield basics plus the status of existing and proposed experimental work is discussed, along with speculations on the future of wake field acceleration.

Introduction

The motivation for the development of new acceleration methods is well documented [1]. In response to this need the accelerator community has responded with a large number of imaginative and (in some cases) clever ideas. Most of these ideas have been presented in the series of proceedings [2] generally referred to as "advanced accelerator conferences". Examination of these proceedings suggests certain trends in this field of research. One is that the number of new ideas (but hopefully not enthusiasm and effort) seemed to peak several years ago. The other is that there has been a weeding out of ideas under critical examination by the community.

Acceleration techniques may generally be classified as plasma based, near field, or far field. Plasma based schemes usually rely upon acceleration by fields which result when the charges in a plasma are redistributed, either by excitation of plasma waves by lasers as in plasma beat wave acceleration or by direct beam-plasma interaction as in plasma wakefield acceleration. The most attractive features of plasma wave based accelerators are immunity from electrical breakdown and the potential for extremely large accelerating gradients. This gradient is usually defined by the wave-breaking limit at $\approx \sqrt{n_e(cm^{-3})}$ eV/cm where n_e is the plasma electron density. Gradients of a few GeV/m are in principle obtainable for modest plasma densities.

Near field schemes use fields whose properties are determined by local boundary conditions. Conventional linac structures, grating structures, switched power devices, and non-plasma based wakefield structures are examples of near field devices. Excitation of these fields can be either from external rf power sources or, in a wakefield (WF) device, from direct interaction with an energetic beam.

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Far field acceleration uses free radiation fields. Examples of this include inverse free electron lasers (IFEL) and methods based on the inverse Cherenkov effect. IFEL acceleration has been demonstrated at low level [3], and efforts are proceeding to experimentally study inverse Cherenkov acceleration [4].

Wakefield acceleration stands out as a technique which has attracted considerable interest in recent years and is the focus of several experimental programs. Possibly because the technique represents in many ways an extrapolation of well understood principles, it has also undergone relatively close examination. Its potentials and pitfalls are better understood than those of the more exotic schemes.

Wakefield Issues

If wakefield acceleration is to become a viable candidate for future accelerators, several interrelated key issues must be addressed.

- what are attainable gradients with "real" drive beams?
- are the drive beam dynamics tenable?
- can accelerated beam quality be preserved to provide useful luminosity for a linear collider?
- can it be acceptably efficient?

A wakefield accelerator is by definition a "two step" device. A more or less conventional linac is used to accelerate drive beam bunches. These in turn are used to excite EM fields in wakefield structures which accelerate "witness" bunches to high energy. In light of the fact the wall plug efficiency of a conventional linac is only marginally acceptable for a TeV collider, designing a wakefield based TeV machine with comparable efficiency is not easy.

One frequently discussed parameter of WF accelerators is the "transformer ratio", R, defined as the ratio of the peak of the accelerating wake field to the average decelerating field felt by the drive bunch. It would seem that R is therefore a handle on the efficiency, and that with some sort of transformer scheme it should be possible to obtain high gradients efficiently. Unfortunately, R, the drive bunch charge N, and the accelerating gradient G are related:

$$RG \propto N$$

Efforts to substantially increase R usually require unreasonable N if a gradient in excess of 100 MeV/m is sought.

Beam dynamics problems differ between plasma wakefield and other wakefield schemes. In plasma, a two-stream type instability within the drive bunch can cause serious deterioration of the bunch. The wake, even for the case of perfect azimuthal symmetry, has strong (de)focussing effects on the accelerated beam depending upon the phase of the wake. While these forces can, in principle, provide all the desired focussing of the accelerated beam, they also place stringent requirements on the relative alignment of the driver and accelerated bunches. Any nonlinear components of the plasma wave, not unexpected if high gradients are present, will further complicate beam control.

Structure or dielectric wake devices introduce potentially serious single bunch beam break up (BBU) instabilities to the drive beam. Increasing the aperture of the device reduces BBU effects, but also reduces the gradient for a given drive bunch charge. The same wakes which produce BBU in the driver also result in effective emittance increase in the accelerated beam. Fortunately, mode damping can be designed into the devices to decouple the accelerated bunch from the deflecting modes generated by the drive beam.

The following section describes several wakefield acceleration research programs, attempting to highlight the specific ways that the above mentioned concerns are addressed.

Wakefield Experiments

The DESY/Darmstadt Wake Field Transformer- The first serious wakefield accelerator experiment was started at DESY in the early 1980s [5]. It had as one of its goals the demonstration of a wakefield transformer, schematically shown in figure 1. The underlying principle is that the energy deposited by a ring shaped drive bunch at the outer radius of the device is compressed as the wake pulse travels inward to the center. Transformer ratios of about ten are typical in the experiments to date. This experiment required the development of a hollow driving beam, pulse compression and acceleration systems, novel diagnostic devices, and the transformer itself ...each by itself a noteworthy accomplishment.

The transformer concept has been successfully demonstrated at modest levels. As an outgrowth of this work, efforts are now directed toward developing the resonant wake field transformer (RWT) as a basis for a linear collider. The RWT scheme uses a series of equally spaced hollow ring pulses to resonantly excite and "build up" fields in a wake field transformer. It is much easier to supply the requisite charge in several bunches than in a single bunch. Initial experiments with five bunches confirm the "build up" and produced a gradient of ≈ 1.5 MeV/m at a gun current of only 5-10 A. (The gun has delivered up to 80 A). The effect of azimuthal asymmetry in the drive beam charge density has been observed, and the experimenters acknowledge that strong transverse fields must somehow be dealt with.

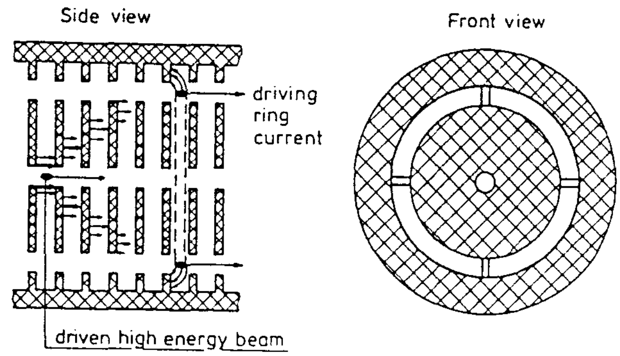


Figure 1: The wake field transformer.

Design parameters of a RWT based high energy linac suitable for high energy physics use have recently been outlined [6]. Superconducting cavities would provide the drive beam acceleration, with energy recover of drive beam energy employed to increase the overall efficiency (Figure 2). It is claimed that a TeV RWT based based collider would require only 4 km of driver cavity length.

The KEK plasma wakefield experiment- A PWFA experiment was performed at KEK [7] using a train of five 250 MeV bunches from a linac normally used by the KEK photon factory. The actual bunch separation was about 350 psec, the plasma wave period. The bunch train passed through a 1 m long plasma cell, after which the energy of each bunch in the train was measured using an innovative combination of a magnetic analyzer and a streak camera to observe Cherenkov radiation in air from the beam.

Because the interbunch spacing was fixed, resonance was established by tuning the plasma density. A 4 MeV energy shift of the fifth bunch, consistent with theory, was measured in this experiment. More experiments are possible using this apparatus such as the use of a positron witness bunch. Some of the experimental results are shown in Figure 3.

The Argonne Wakefield Program- Argonne has supported an active research program in wakefield and related effects [8]. A special facility with which wakefields could be directly measured (AATF) has permitted detailed measurements of wakefields in plasma (linear and nonlinear), in pillbox cavity arrays, and in dielectric loaded wave guides. Some of these results are shown in Figure 4.

During the past year the Argonne group has placed extensive effort on the study of dielectric loaded wave guides as wakefield devices. The attractiveness of this particular wake field scheme lies in its simplicity and potential performance characteristics. Moreover, several extensions to this technique appear to overcome some of the potentially seri-

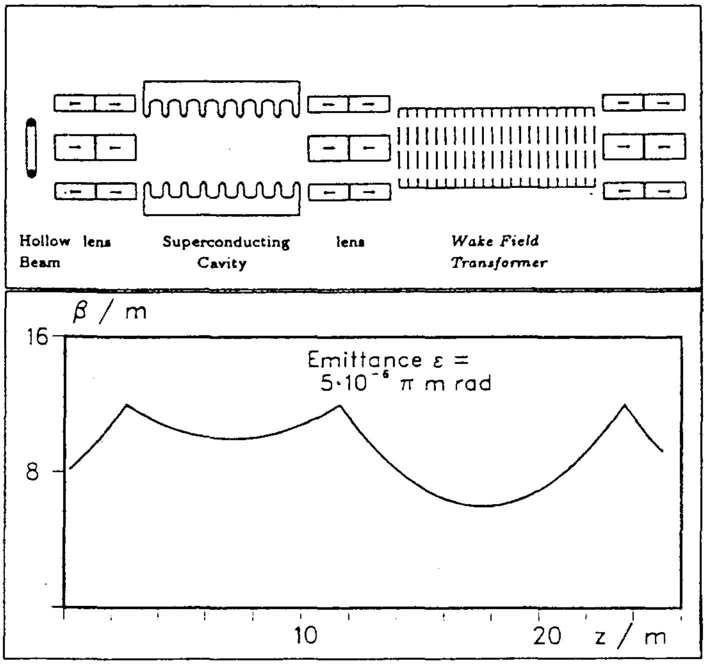


Figure 2: A RWT based cell of a high energy linac.

ous transverse wake effects. One of these is schematically shown in Figure 5. This configuration rapidly damps all but $m = 0$ modes. The longitudinal wire boundary does not affect the TM_0 accelerating mode but permits the higher order hybrid modes to leak out into the absorbing material [9]. A bunch to be accelerated need only be placed a few cycles behind the drive bunch to be "insulated" from emittance increasing deflection modes produced by the driver.

Another use of dielectric wakefield structures is in the (infelicitously named) coupled wake tube accelerator (CWTA) configuration (see Figure 6). Here the drive bunch and accelerated bunch travel along separate but parallel paths. rf energy produced in the dominant TM_{oo} mode in the relatively large aperture drive section is coupled into a smaller cross section acceleration tube. Both tubes are designed to have the same luminal ($v_{ph} = c$) TM_{oo} frequency. The HEM mode damping described previously can be used to suppress deflecting modes if desired.

The gradient step up ratio and length through which the bunch is accelerated (group velocity dependent) can be varied in this arrangement to adjust the transformer ratio and energy transfer efficiency. One of the more important advantages of a CWTA is that BBU in the driver can be reduced to tolerable levels while maintaining large accelerating gradients. The fact that dielectric loaded guides have an additional parameter, dielectric constant, makes them attractive for CWTA use.

Power efficiency in Argonne's wakefield accelerator concept is increased by extracting as much energy as possible from the drive linac by accelerating several pulses from a single

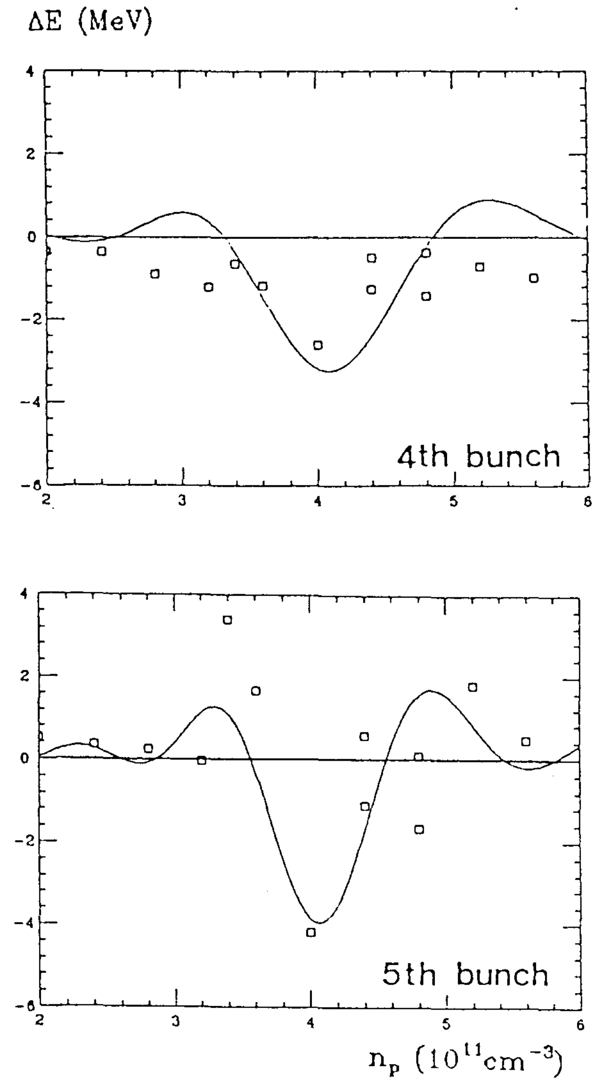
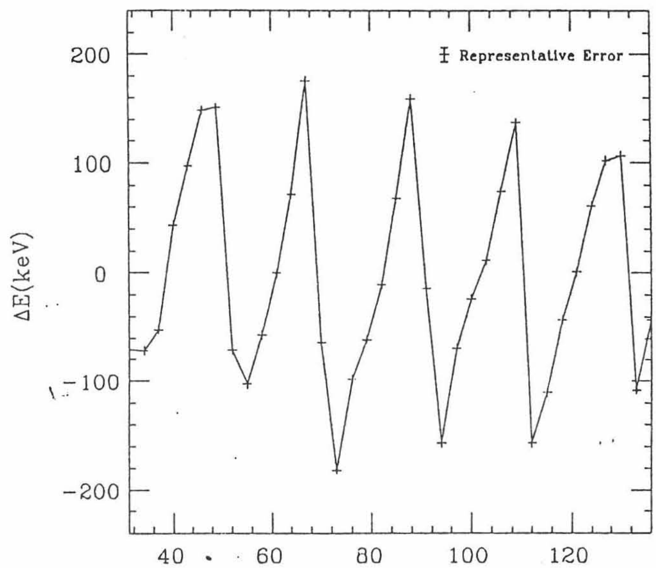


Figure 3: Observed energy shifts of the 4th and 5th bunches as functions of plasma density in the KEK PWFA experiment.



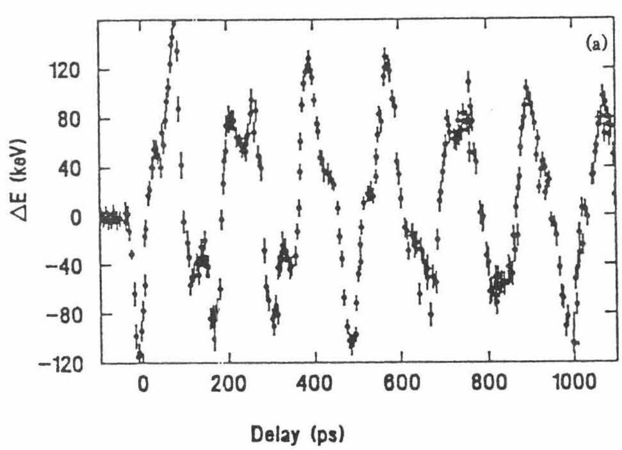


Figure 4: Examples of measured wakefields in- (a)plasma (non linear regime), (b)dielectric loaded guide

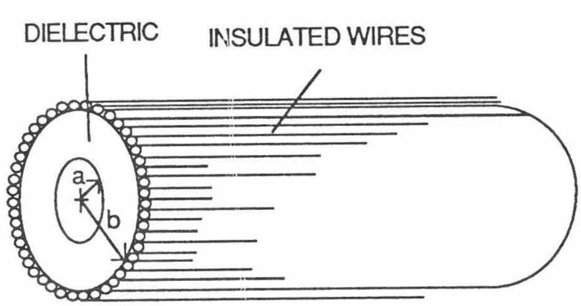


Figure 5: Deflection mode damping dielectric WF tube

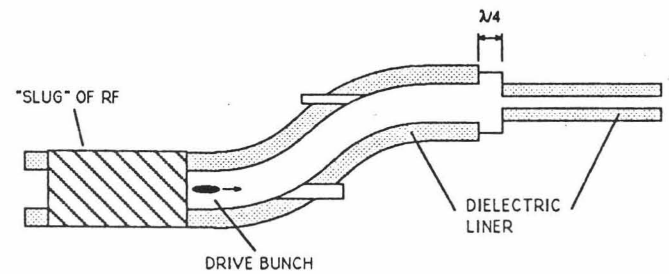


Figure 6: Schematic CWFA section

rf fill. Re-acceleration of drive pulses is not presently being considered in this design.

A new facility is being constructed at Argonne to extend wakefield and related technologies to significantly higher levels of performance than are currently possible. The new Argonne Wakefield Accelerator (AWA) facility will use a new photocathode based, intense (100 nC, 10 psec fw) electron source and a specially designed L-band linac to produce drive pulses. Research on devices with gradients in the 100 -1000 MeV/m range will be possible at the AWA in about two years.

Comments and Conclusions

Wakefield acceleration research is being carried out in a growing number of locations. Besides the programs outlined above there are also proposals to study wakefield acceleration in the USSR at Novosibirsk and Yerevan.

Because wakefield acceleration is in some ways better understood than some of the more exotic advanced schemes, it is held to more stringent standards at this time. While accelerators based on this technique appear feasible, more research is clearly required before a credible high energy linac design can be made.

It is also interesting to note that except for plasma based devices, wakefield accelerator concepts are tending to adopt the look of the so called two beam accelerator (TBA), perhaps best represented by CERN's developing CLIC [10] scheme. It may be hoped that this research will soon define the role (if any) of wake field techniques in future high energy accelerator technology.

References

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