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ARGONNE'S WAKEFIELD ACCELERATOR PROGRAM

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Abstract Experimental and theoretical studies of wake field accelerator concepts have been the focus of Argonne's HEP Advanced Accelerator R&D Group for several years. The Advanced Accelerator Test Facility (AATF) has enabled the group to measure directly the wake field of a beam bunch as it traverses structures and media. Based upon its research, the group is designing a demonstration wake field accelerator of more than 1 GeV final energy. A summary of work to date, including experimental results of wake field studies in plasma and dielectric wave guides, plus a description of the proposed new machine are presented.

INTRODUCTION

For the past few years our Accelerator R&D Group at Argonne has studied wakefield acceleration through theory, simulation, and experiments. The purpose of this research has been to better understand the physics of wakefield phenomena with the goal of determining what role, if any, wakefield acceleration techniques can realistically have in future high energy linear colliders. A special test facility, the Advanced Accelerator Test Facility (AATF), was designed and constructed to enable us to conduct premier wakefield acceleration experiments.

This has proven to be an interesting and fruitful endeavor. Our research has involved wakefields in resonant structures, in plasmas, and in dielectrically loaded slow wave structures. We have accelerated injected beams by the wakefield method in all of the devices listed above. Self focussing in a plasma, a possible final focus lens for linear colliders, was also experimentally demonstrated and compared with theoretical work on the subject.

The AATF program has also led to unexpected insights into wakefield phenomena. We believe that these may soon qualify the technique as a practical approach for future linear colliders and other applications.

In this paper I will briefly review highlights of the AATF program, summarize the implications of each, and will describe a new project now in the proposal stage. This new initiative will permit further development of wakefield acceleration technology with a goal of demonstrating a practical, working accelerator based on the technique.

HIGHLIGHTS OF THE AATF PROGRAM

The AATF and its research program has been described in a number of articles and papers.[1] With the AATF it became possible for the first time to measure directly the wakefields of short bunches of relativistic particles as they travel through various media and structures. The AATF represents a new kind of experimental tool which can be used in studies of accelerator technology, plasma physics, and several other fields.

The initial AATF experiments measured wakefields in iris loaded waveguides.[2] For the first time, theory, simulations, and experiments on wakefields in structures could be compared, and the results validated the AATF design. These tests were followed by plasma wakefield experiments. Electrostatic plasma waves produced by bunched beam-plasma interactions were measured as functions of pulse and plasma parameters. Longitudinal wakefields of several MeV/m were measured in these experiments, and for the first time ever, acceleration of injected beam by a plasma was demonstrated.[3]

During some plasma wakefield experiments we observed harmonic contents in plasma waves which indicated that non-linear waves were present. Later, we showed that this resulted from the driver beam being compressed by self-pinch forces to a diameter roughly one third that which it would have had in the absence of the plasma. This pinching mechanism is the same as that used in plasma lenses.[4]

We recently performed an experiment which measured the time-resolved beam width as it exited the plasma cell used in the wakefield acceleration tests. Some of this data is shown in Figs. 1a-1b. The observed focussing is consistent with analytical estimates and with with results of PIC code simulations[5,6] which predict that a quasi-stable phase space distribution is obtained.

Perhaps the most significant experiments (related to high gradient, high energy accelerator at least) are those concerning Cherenkov Wakefield Acceleration (CWFA). Wakefields in dielectric loaded circular guides were measured and compared to analytical predictions and numerical simulation results. Figure 2a-2b shows typical predicted and measured wakefields as measured in the AATF. Of particular importance was the recognition and experimental confirmation that the CWFA configuration studied by us produces no transverse wake forces (to order $1/\gamma^2$) on either the driver or the accelerated bunch.[7,8]

What can we conclude from our work to date? One thing, and this will make some "I told you so" people happy, is that neither cavity structure nor plasma wakefield accelerating schemes are likely to find uses as high energy accelerators. The problem has to do with transverse wakefields. For cavity structures, prevention of serious deflecting mode excitation will require exacting alignment of the beams -- to about the same extent as will be required in cm wave length rf linac concepts. In the plasma wakefield accelerator not only must the co-linearity of the driver and driven pulses must be extremely accurate, but the inherent focussing forces are nonlinear. As a result, preservation of accelerated beam quality in either of these schemes is probably not possible over distances needed for acceleration to high energy. There may be, however, other applications for these devices -- wigglers or low energy machines, for example.

THE CWFA CONCEPT

The geometry of a CWFA is shown in Fig. 3. It consists of little more than a tube of suitable dielectric material through which the pass the driver and driven beam pulses. Wake fields with a phase velocity equal to that of the drive pulse are generated and used to accelerate the second bunch. The mode frequencies are determined by eigensolutions of field boundary conditions, and mode excitation depends upon the bunch length relative to the eigenmode wavelengths. Figure 4 shows how the frequency of the lowest mode depends upon the geometry and dielectric constant.

Mathematical analyses which predict the absence of deflection forces as $\beta \to 1$ do not provide a simple physical picture as to why it is so. A concise argument can be made that it is a consequence of translational invariance in the CWFA structure. Experiments at the AATF detected no transverse deflections in CWFA experiments, whereas beam alignments in structure and plasma wakefield tests were critical, and transverse wakes were actually measured analyzed -- confirming our predictions.

For a driver beam of about 10 ps, a dielectric constant of 4, an inner radius of 4 mm, and a fundamental mode of 10 Ghz, coupling to the beam is such that the wake amplitude is about 2 MeV/nC. It is possible, therefore, to obtain high accelerating gradients with reasonable beam intensities.

Potential problems posed by a CWFA include flashover on the inner surface of the dielectric at high fields and bulk charging of the dielectric as the driver beam develops a large energy spread and loses particles in the dielectric. Information we have been able to obtain thus far suggests that flashover will not be a problem up to 150-200 MeV/m at the high characteristic frequencies of the wake. Several ideas are under consideration to prevent bulk charging problems. One is to have the CWFA dielectric composed of a thin walled quartz tube surrounded by a thin flowing layer of, for example, silicon oil. The fluid could be circulated through a porous conducting material to remove charges which were deposited in it. Another possibility is to fabricate electrically conducting ceramics of suitable dielectric constant. The wake field device need not have a large Q because only the transient response will be used to accelerate beam.

An intriguing idea which might increase the transformer ratio is to use a non-linear dielectric, such as a ferroelectric.[9] Wavefront sharpening, not unlike that used in radial transmission line for induction linacs, will create a substantial increase in wake amplitude. On the other hand, such material will invalidate the conditions which produce no transverse forces for off-center beams. This needs to be investigated in more detail.

Thus the CWFA offers a technique to obtain high acceleration gradients while avoiding most of the transverse force problems that conventional structure based linacs will have. We recently have developed a plan of research designed to further demonstrate the feasibility and practicality of a CWFA. The goal of this plan is to build a 1 GeV CWFA with a gradient of at least 100 MeV/m.

THE PROPOSED ARGONNE WAKEFIELD ACCELERATOR (AWA)

Figure 5 shows the elements of the CWFA based accelerator we propose. The key ingredients are:

1. a source of intense, short electron bunches
2. a "conventional" rf powered linac to accelerate the electron bunches to modest energy
3. wakefield sections comprising the CWFA
4. beam optics to provide staging -- bringing a new driver pulse into proper position to replace an expanded pulse, thereby extending the CWFA process in stages.

Several particularly interesting design aspects are presented here.

We have developed a design for a 100 nC, 10 ps (4σ), photo--cathode based source. Several criteria make such a source feasible. One is that we do not require a small emittance drive beam. Our design will provide a beam of $\varepsilon_r \simeq 150$ π-mm-mrad after acceleration to 150 MeV. The designed beam brightness is therefore an order of magnitude less than already demonstrated at LANL or proposed at BNL. The specified short pulse results from having a short laser pulse (about 2 ps) whose front is specially shaped such that the outer edge of the illuminated photo-cathode emits first. The electrons emerge from the cathode in a concave disk. There is a strong correlation between radius and divergence as the beam emerges, and hence the disk "flattens out" as it drifts. A prototype cavity has been machined and is being tested at this time at low rf power. Specifications for the laser system have been prepared and purchasing will proceed upon availability of funds. Figure 6 shows a PARMELA simulated pulse distribution about half a meter after the beam leaves the cavity and has been focussed by a solenoid.

Beam loading is a serious concern in the conventional rf structures of the preaccelerator and drive linac. Large energy spreads and potentially serious beam break-up modes must be minimized. Our designs use very large aperture iris loaded L-band guides. The preaccelerator is a standing wave cavity, and the main accelerator (150 MeV) will probably have high group velocity guides in ring resonator configurations. By using ring resonators, the effective useful power flow in the guides will be several times that delivered by the rf power source.

Even with large aperture irises, wakefields will produce undesirably large energy spreads within each drive bunch. To substantially reduce this spread, we propose to use a special dielectric loaded guide at the linac exit, much like that proposed for CWFAs but of higher characteristic frequency.[10] By passing the linac beam through a relatively short section of this CWFA tube the net, superposed wakefields seen by a bunch produce considerably less energy spread in a bunch than would normally be the case. We plan to incorporate such a device, in our case a quartz tube of about one third meter in length, at the end of the 150 MeV drive linac.

Staging will use magnetic separation of the individual drive beam pulses to place each into its proper beam transport for delivery to a CWFA section. Isochronicity in these transports is important. Beam elements will be adjusted to provide nearly correct pulse timing, but fine tuning of pulse timing will involve laser pulse timing adjustments via optical elements.

The AWA will also provide an opportunity to extend AATF type measurements to new levels. Several stages of the project -- 12 MeV beam from the preaccelerator and higher energy beams as the drive linac becomes operational, for examples -- will provide platforms for interesting experiments and for training experience by young scientists and engineers.

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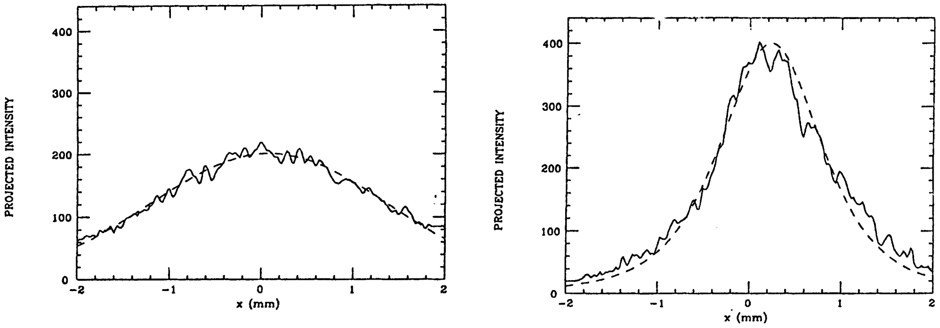


FIGURE 1. Beam width at exit of plasma cell (a) plasma off (b) plasma on.

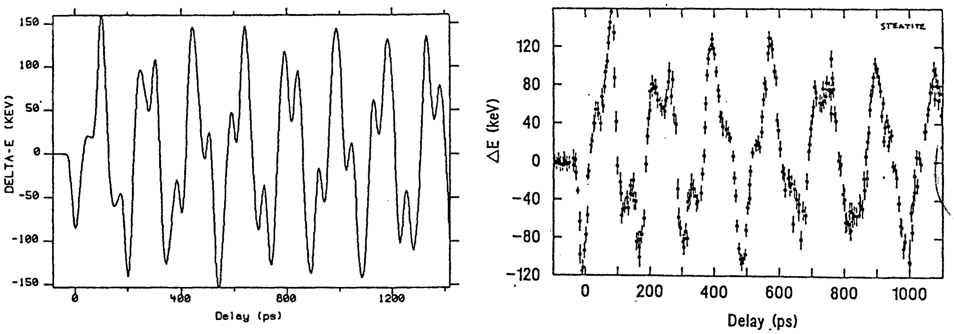
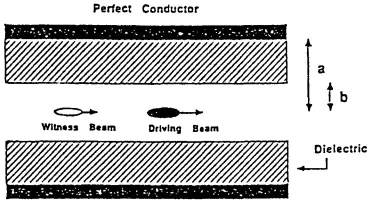


FIGURE 2. Cherenkov wakefields. Vertical axis is the shift in energy by the center of charge of the witness beam. Horizontal scale is separation between driver and witness beam pulse (a) predicted (b) AATF measurement.



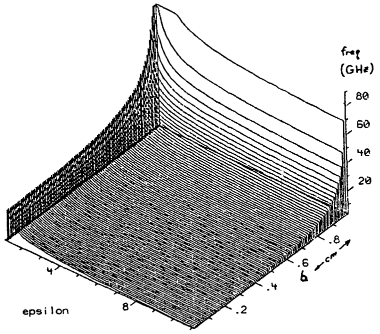
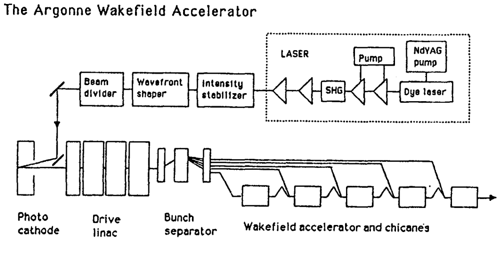


FIGURE 3. Geometry of a Cherenkov wakefield structure.

FIGURE 4. Relationship between inner diameter b, dielectric constant, and lowest mode frequency for a 1 cm outer diameter CWFA tube



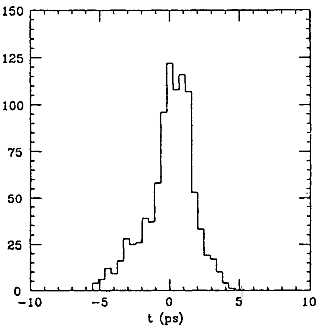


FIGURE 5. Elements of Argonne's proposed wakefield accelerator (AATF)

FIGURE 6. PARMELA simulated pulse distribution for a 100 nC beam pulse from the Argonne design source