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Advanced Accelerator Test Facility (AATF) Upgrade Plan

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ABSTRACT

We have successfully demonstrated the principles of wake-field acceleration using structures (cavity, dielectric) and plasmas as wake-field devices using the AATF at Argonne National Laboratory. Due to the limited driver electron pulse intensity and relative long pulse length, only modest accelerating gradients were observed. In order to study the wake field effects in much greater detail and demonstrate the feasibility of wake-field accelerator for high energy physics, we are considering construction of a laser photocathode injector on the existing 20 MeV Chem-Linac to produce very intense and short electron pulses.

INTRODUCTION

High accelerating gradient devices are essential for the next generation of linear colliders, and one possible method of achieving high gradients is the wake field technique. The principle of the wake field accelerator is to use an intense driving beam followed by a much less intense beam to be accelerated, with both beams passing through a wake field device such as an iris loaded structure, dielectric tube, plasma or any other kind of slow wave structure. In principle the wake field device can support very high accelerating fields. For example, a plasma can support = ~ 10 GeV/m. In the last few years, proof of principle experiments for wake field acceleration have been performed at Argonne National Laboratory using the Advanced Accelerator Test Facility (AATF).[1, 2, 3] The details of the AATF are described in great detail in reference.[1] The electron source for AATF is suppled by the ANL Chemistry Division linac, it provides 22 MeV, 30 ps long pulses with a total charge of 5 - 10 nC per pulse. Due to the limited driving beam intensity and its relatively long pulse length, a gradient of only a few MeV/m accelerating has been achieved in these initial experiments. On the other hand, as we are aware, this is the first experiment ever to accelerate an injected beam in the plasma wave. In order to study the wake field effects in great detail and achieve a few hundred MeV/m and even GeV/m acceleration gradients, we need a driving beam which supplies 50 - 100 nC charge per pulse and a pulse length of 10 ps. In this way, we can produce at least 100 MeV/m accelerating gradient in dielectric or iris loaded structures and a few hundred MeV/m and up to 1 GeV/m in plasma. We have studied the possibilities of upgrading the existing Chemistry-Linac to provide such an electron source, and we have shown that by replacing the existing thermionic gun with a laser photocathode, this goal should be achievable. In the next section we discuss the overall upgrade plan. Section 3 discusses the laser photo cathode design and computer simulation of its performance, and in the last section the experiments which will be performed using the upgraded facility.

OVERVIEW OF THE UPGRADE PLAN

The front end of the upgrade design is shown in Fig. 1. A laser RF photocathode gun is placed next to the existing thermionic cathode. An intense and short (100 nC and 10 ps) electron pulse (driver) will be produced by this specially designed photocathode. The details of the photocathode will be discussed in the next section. A short beam line transports the beam from the cathode to the main Chemistry-linac. This beam line may also be used for some magnetic pulse compression. The Chemistry-Linac will accelerate the beam up to 25 MeV. A small laser pulse following the main laser pulse from a high power laser will generate a much less intense (< 1nC) and short (< 5 ps) (witness) electron pulse. It has almost the same energy as the driver pulse and the distance between them can be adjusted over several centimeters.

Both driving and witness electron pulses will be accelerated through the linac. At the end of the linac, without bending the beam, a section of wake field structure is placed and followed by a spectrometer. Since the much larger wake fields are produced by the driving electron pulse, we will only measure the highest energy of the witness beam electrons, so the spectrometer requirements should not be demanding. A high power laser is an essential element for this photocathode gun. Based on the experimental results of J. Fischer & T. Srinivasan-Rao,[4] for a photon energy of 4.66 eV (266 nm), the quantum efficiency (electrons emitted per incident photon) is $5. \times 10^{-4}$ for Yttrium and for Samarium is 7.5×10^{-4}. For the current design, we have chosen Yttrium as our photoelectron emitter. In order to generate 100 nC pulses with less than 10 ps pulse length, a laser of 1 mJ energy per pulse at 266 nm and < 2 ps pulse length is required. The laser pulse has to be synchronized with the RF pulse, so the timing jitter requirement for the laser must be less than 10 ps. A search for this type of laser has been done, and it shows that there are currently available commercial lasers which meet our needs.

LASER PHOTOCATHODE DESIGN

The proposed laser photocathode shown in the Fig. 2 is based on the design of Frazer et al.[5] who incorporated a photo cathode in the end wall of an L band RF cavity which supports a very high standing wave field. An S band laser photocathode is also under development at Brookhaven National Lab.[6] The advantages of the photocathode over the thermionic cathode are:

1). The electron bunch length is determined by the length of the incident laser pulse plus the space charge effects.
2). The RF cavity can support an accelerating gradient of 75 MeV/m which will minimize the space charge effects.
3). The energy spread of the beam is relatively small.
4). The total charge produced is proportional to the incident laser power.

The accelerating cavity was designed using the code URMEL[7], and is shown in Fig. 1. The fields from URMEL, normalized to 3 MW input power were converted by a postprocessor to a format compatible with the beam dynamics code PARMELA.[8] Parmela was then used to simulate space charge effects in the photocathode gun. A slight modification to Parmela allows the use of an arbitrarily shaped laser wave front. A

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photocathode located in a cavity is pulsed with a laser producing a bunch of electrons. The electron bunch initially diverges with a large opening angle due to the strong space charge effects, however a solenoid located immediately after the cavity can be used to focus the beam. If all electrons leave the photocathode at the same time, the pulse length at the end of the solenoid will be quite long due to three effects: 1) the sagitta of the spherical electron bunch leaving the cavity, 2) time delay in the solenoid (since trajectories spiral around the axis, this delay increases with radius and focusing strength), and 3) space charge effects near the cathode. The total bunch length produced for a $100nC$ example would be about 15-20 psec. It is not necessary for the laser wavefront to be flat, however. If a wavefront delay element, a lens or mirror assembly with surfaces perpendicular to the direction of propagation, is inserted in the laser beam before the cathode, it is possible to delay parts of the wavefront by arbitrary amounts without deflecting or focusing it. In the example shown, a lenslike object (similar to a glass wedding cake) is used to produce a cuplike laser wavefront hitting the photocathode. Simulations with PARMELA show that when the sagitta of a 2 psec thick laser wavefront is adjusted to compensate the bunch length produced by the electron sagitta and solenoid path length effects, the bunch can be compressed to σ 1.8 psec, for the converging beam downstream of the solenoid, only slightly longer than the original laser pulse as shown in the Figs. 3 and 4. Figure 5 shows the energy spread of the beam, where E_{ref} is 2.0 MeV and Z_{ref} is 10.3 cm from the cathode. The design parameters of the cavity are listed below:

RF Gun Design Parameters

Structure type	Resonant
Structure inner diameter	160 mm
Structure length	53 mm
Number of cells	1
Operating frequency	1.303 GHz
Beam energy	1.95 MeV
Beam aperture	24 mm
Beam radius at the cathode	10 mm
Shunt impedance	1.116 M Ohm
Cavity Q	15,300
Max. surface electric field	170 MV/m
Average accelerating gradient	70 MV/m
Electric field on the cathode	120 MV/m
Cavity power	3 MW

POSSIBLE EXPERIMENTS

After completion of the linac upgrade, we will perform several experiments as follows:

Dielectric wake field experiment.

Much of the theoretical work[9, 10] has been done for the dielectric wake field device. It produces very strong longitudinal wake field but almost no any transverse wake field (focusing and deflecting). The high acceleration gradients (100 MeV/m) have yet to be achieved experimentally. We have calculated that for a 100 nC pulse and 10 ps long, the accelerating gradient is 100 MeV/m for a 30 GHz dielectric wake field structure. The properties of dielectric materials at high field (100 MV/m) and high frequency (30 GHz) are not entirely known, and this experiment will explore the possibilities of using dielectrics for accelerator applications.

Plasma wake field

Plasma can support an electric field of several GeV/m, and it has many potential applications to accelerators. For example, use the longitudinal wake field for acceleration and transverse wake fields as a plasma lens for the final focus of linear colliders. Plasma wake field effects, especially the nonlinear dynamics have not been throughly studied experimentally. The multi-dimensional nonlinear plasma wake field theory has not been developed yet. Use 100 nC driving beam and 10 ps pulse length with plasma density $n = 1.2 \times 10^{14}$, we estimate that the maximum acceleration gradient of 1 GeV/m should be achievable. Using high current beams, the plasma focusing effect (self pinching) can be studied in detail.

Iris loaded metallic structures

Wake field effects in metallic structures are very important issues for accelerator technology. The longitudinal effect is responsible for the energy spread of the beam and the transverse field (beam breakup mode) is a primary source of emittance growth. Since the wake field strength is proportional to the total charge in the beam, an intense source will be a very useful tool to study these effects.

In summary, we are currently planning to upgrade the existing AATF. This upgrade is based on a laser photocathode. Our studies have shown that a 100 nC and 10 ps electron pulse is achievable, although laser pulse shaping is required. With the upgraded facility plan, we hope that high accelerating gradient of several hundred MeV/m and even GeV/m could be achieved.

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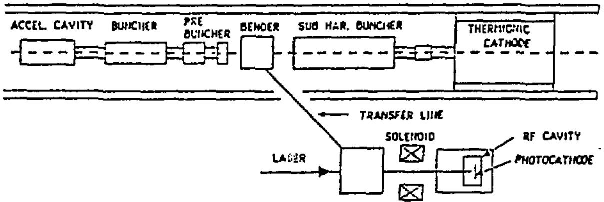

Fig. 1. Overview of upgrade plan.

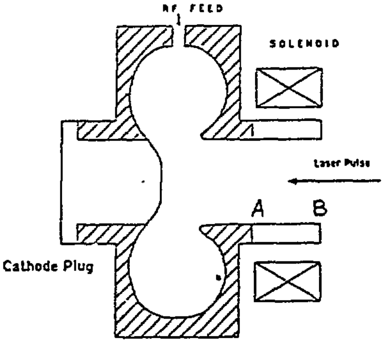

Fig. 2. RF Photocathode Design

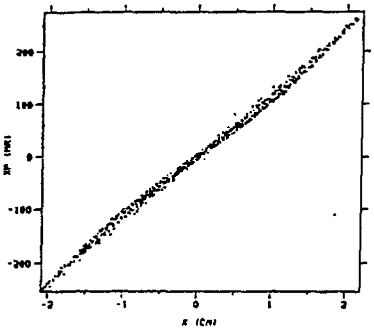

Fig. 3a. Transverse Phase Space (x, x') at A of Fig. 2.

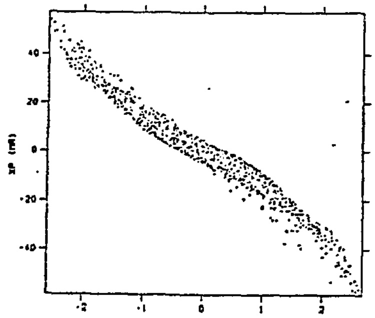

Fig. 3b. Transverse Phase Space (x,x') at B of Fig. 2.

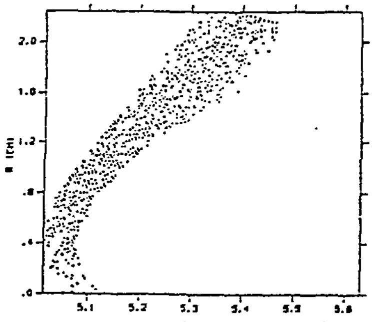

Fig. 4a. Longitudinal bunch profile (r, Z) at A.

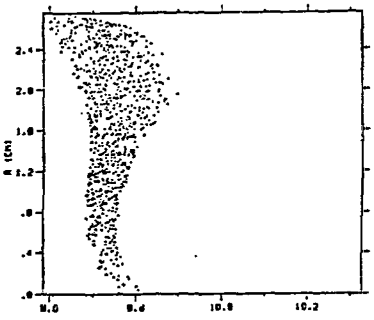

Fig. 4b. Longitudinal bunch profile (r,Z) at B.

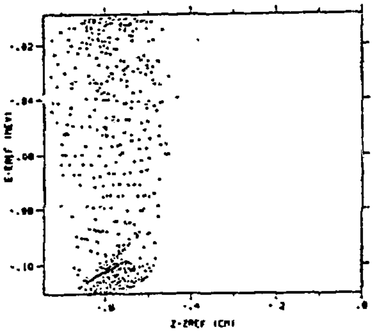

Fig. 5. Longitudinal phase space (E,Z) at B.

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