Design Analysis for a 100-MeV Inverse Čerenkov Laser Accelerator*

J. R. Fontana
University of California, Santa Barbara
Santa Barbara, CA 93106

W. D. Kimura and L. C. Steinhauer
STI Optronics, Inc.
2755 Northup Way, Bellevue, WA 98004

I. Pogorelsky
Brookhaven National Laboratory/STI Optronics, Inc.
ATF/Bldg. 820, Brookhaven National Laboratory, Upton, NY 11973

Abstract

The analysis of a 100-MeV demonstration experiment based upon inverse Čerenkov acceleration (ICA) is presented. This experiment would use the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. With 50-GW of delivered laser peak power from the ATF CO_2 laser, our analysis indicates the 65-MeV ATF *e*-beam can be accelerated to >165 MeV using three stages of acceleration in ~1 m of total length. The number of electrons accelerated can be raised to $\sim 10^9$ by prebunching the *e*-beam using an already available device.

I. INTRODUCTION

Laser particle acceleration research has been making steady progress. A number of experiments are in progress. The Accelerator Test Facility (ATF) has been constructed at Brookhaven National Laboratory and is available for laser acceleration experiments. This new facility features a 50-MeV linac, which will be upgraded to 65-MeV, and a high peak power (~10 GW) CO_2 laser, which also can be upgraded to generate 100-GW of peak power.

The US Department of Energy (DOE) is interested in a near-term 100-MeV laser acceleration demonstration experiment. The DOE is also interested in the design for a 1-GeV linac based upon laser acceleration.

This paper describes the design of a 100-MeV demonstration experiment that is based upon inverse Čerenkov acceleration (ICA) and can be performed at the ATF using much of the existing equipment.

II. EXISTING ICA EXPERIMENT

An inverse Čerenkov laser acceleration experiment is currently being performed at the ATF [1]. Hydrogen gas (P = 1.7 atm) is used in a gas cell to slow the phase velocity of the laser light to match the electron velocity. The beams intersect at a Čerenkov angle of θ_c = 20 mrad with an interaction length of 20 cm.

The ATF ICA experiments are testing an improved geometry [2] that focuses a radially polarized laser beam onto the *e*-beam. Assuming 5-GW of laser peak power delivered to the interaction region (for a 10-GW input into a 50% efficient optical system), an energy gain of ~12 MeV is predicted. This gain scales as the square root of laser peak power. Thus, a peak power of 50-GW delivered will result in 38-MeV energy gain.

The present gas cell design is already near optimum for the ATF conditions and can be used as the basis for a multistaged 100-MeV ICA demonstration experiment. Since one stage gives 38-MeV energy gain (assuming 50-GW delivered laser peak power), three stages will yield >100 MeV energy gain. The only major changes to the existing ICA experiment needed are upgrading the ATF CO_2 laser to produce 100-GW peak power and modifying the gas cell system to recycle the laser beam. This latter issue is discussed in more detail next.

* Supported by US DOE Contract Nos. DE-AC06-83ER40128 and DE-FG03-90ER40545.

0-7803-1203-1/93$03.00 © 1993 IEEE

III. CONCEPTUAL DESIGN FOR 100-MeV DEMONSTRATION EXPERIMENT

Figure 1 is the simplified conceptual arrangement for the 100-MeV ICA demonstration experiment. A small portion of the drive laser power (~120 MW) is sent to a prebuncher; the rest of the power (~100 GW) is sent to the 3-stage accelerator.

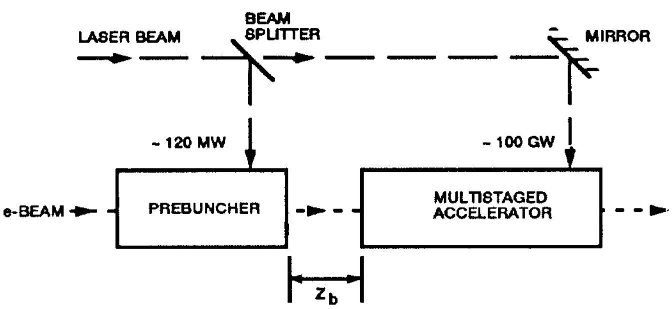

Figure 1. Conceptual arrangement for the 100-MeV demonstration experiment.

Prebunching the *e*-beam before it enters the multistaged accelerator will significantly enhance the experiment. Without prebunching the electrons enter the multistaged accelerator at all phases resulting in only a small fraction of electrons being accelerated to the full 100-MeV energy gain. The existing gas cell being used in the current ICA experiments can be used as a prebuncher. Only ~120 MW of laser peak power is needed to drive the prebuncher and will give an optimum bunching distance $z_b \approx 20$ cm. At this point the prebunched *e*-beam will enter the multistaged accelerator.

A. 3-Stage ICA Accelerator Concepts

Two possible arrangements for the multistaged accelerator are shown in Figures 2 and 3. In the first concept (Figure 2), the incoming radially polarized laser beam reflects off a 45° mirror, which has a small hole in its center for passage of the *e*-beam. The laser beam then reflects off a curved axicon and is focused down onto the *e*-beam. (The purpose for using a curved axicon will be explained later in Section III.B.) After intersecting the *e*-beam in the first stage, the spent laser beam reflects off a slightly conical cylindrical mirror tube. This tube functions the same as the curved axicon and focuses the laser light back onto the *e*-beam in the second stage. The process repeats itself for the third stage. This first concept is very similar in arrangement to the existing ATF ICA experiment [1], which uses a flat axicon rather than a curved one, has only one stage of acceleration, and does not use cylindrical mirror tubes.

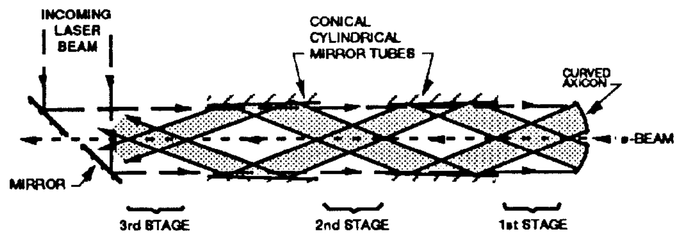

Figure 2. Concept for a 3-stage ICA accelerator.

One disadvantage of the first concept is the length of gas-filled space between the acceleration stages, which leads to additional scattering of the electrons by the gas molecules. Similar to the present ICA experiment, each interaction region is 20-cm long. This means the space between the stages must be >20 cm. Hence, for this first concept the total 3-stage accelerator length is ≈110 cm.

Figure 3 depicts an alternative concept for the 3-stage accelerator that minimizes the distance between stages. The incoming radially polarized laser beam travels through a 45° mirror with a large hole in its center. The laser beam reflects off a waxicon, which converts the beam into a hollow one while maintaining its radial polarization characteristics. This hollow beam is directed off the 45° mirror to the curved axicon where it is focused onto the *e*-beam. The spent laser beam then immediately reflects off the slightly conical cylindrical mirror tube towards the second stage, and the process repeats itself for the third stage. Since the incoming laser beam

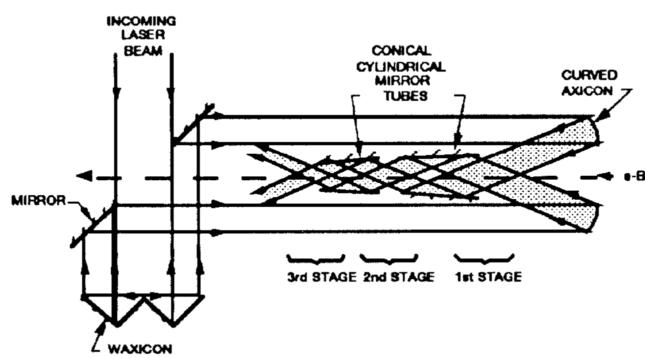

Figure 3. Alternative concept for 3-stage ICA accelerator.

does not need to travel through the mirror tubes as in Figure 2, the diameter of the tubes can be reduced thereby decreasing the space between acceleration stages. The total accelerator length of this second concept is ≈70 cm.

B. β-Slippage Compensation

In the preceding concepts, the curved axicon helps compensate for phase slippage between the electrons and light wave as the electrons gain energy within each interaction region. The Čerenkov angle θ_c, given by $\cos\theta_c = (1/n\beta)$, where n is the index of refraction of the gas and β is the ratio of electron velocity to the velocity of light, changes as the electrons gain energy. By varying the Čerenkov angle within the interaction region it will be possible to maintain near optimum phase matching as the β of the electrons increases. This can be done by using a slightly concave axicon such that the angle of intersection is slightly larger (~1 mrad for the ATF conditions) at the end of the interaction region than at the beginning. The slightly conical shape of the cylindrical mirror tubes also accomplishes this same effect. An alternative method for β-slippage compensation is to use a slightly converging laser beam reflecting off a flat axicon and straight cylindrical mirror tubes.

C. Recycling Laser Beam

Another issue implied in the preceding concepts is being able to reintersect the laser pulse with the electron bunch in the second and third stages. Due to differences in the electron drift velocity relative to the effective group velocity of the laser pulse, the relative drift distance between the electrons and light pulse over a distance L is

$$\Delta z_{drift} = \theta_c^2 L . \quad (1)$$

The laser pulse length in space is $\Delta z_l = c\tau_l$, where τ_l is the laser pulse width in time. Thus, the ratio of these two distances is

$$\frac{\Delta z_{drift}}{\Delta z_l} = \frac{\theta_c^2 L}{c\tau_l} . \quad (2)$$

Hence, if for example, θ_c = 20 mrad, τ_l = 100 ps, and L = 110 cm (see Figure 2), then the amount of slippage is 1.5% of the laser pulse length. Therefore, recycling the laser pulse should not be an issue.

IV. SUMMARY

Table 1 summaries the estimated performance for the 100-MeV ICA demonstration experiment.

Table 1
Estimated Performance of 100-MeV ICA Demonstration Experiment.

ATF Parameter	*Assumed Value*
Injector	65 MeV *e*-beam
CO_2 Laser Peak Power	50 GW (delivered)
ICA Parameter	*Estimated Performance*
Energy Gain	95 to 125 MeV (net)
# of Accelerated Electrons/Pulse	>5 × 10^8
Energy Gradient	1st Concept: >92 MeV/m 2nd Concept: >143 MeV/m

The effect on *e*-beam emittance requires additional analysis to extract emittance information from the models. Emittance growth is less of an issue for high-γ *e*-beams; however, the ATF *e*-beam energy is relatively low which will impact the emittance growth of the accelerated *e*-beam.

V. REFERENCES

[1] W. Kimura, I. Pogorelsky, G. Kim, L. Steinhauer, S. Tidwell, and K. Kusche, "Update on the ATF Inverse Čerenkov Laser Acceleration Experiment," see *Conference Record of the 1992 IEEE Particle Accelerator Conference.*

[2] J. R. Fontana and R. H. Pantell, *J. Appl. Phys.* 54, No. 8, 4285 (1983).