INVERSE ČERENKOV EXPERIMENT

Final Report

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CONTENTS

SECTION		PAGE
1	EXECUTIVE SUMMARY	1-1
2	DESCRIPTION OF EXPERIMENT	2-1
2.1	INTRODUCTION	2-1
2.2	COMPUTER MODEL DEVELOPMENT AND PREDICTIONS	2-4
2.2.1	Brief Description of Model	2-4
2.2.2	Model Predictions for Phase II Experiments	2-4
2.3	DESCRIPTION OF EXPERIMENTAL APPARATUS	2-7
2.3.1	Optical System	2-7
2.3.2	Electron Beamline System	2-17
2.3.3	Diagnostics	2-21
2.3.4	Spatial and Temporal Alignment of the Beams	2-23
2.4	EXPERIMENTAL RESULTS OF PHASE I EXPERIMENTS	2-26
2.4.1	Optical System Tests	2-26
2.4.2	Nonlinear Effects	2-27
2.4.3	Electron Beam Window Lifetime Tests	2-27
2.5	PHASE II EXPERIMENTS	2-28
2.5.1	Results of Run #1	2-28
2.5.2	Preparations for Run #2	2-29
	REFERENCES	2-30
3	THEORETICAL ANALYSIS AND SUPPORT	3-1
3.1	INTRODUCTION	3-1
3.2	FREE SPACE LASER ACCELERATION	3-1
3.2.1	Additional Theoretical Optimization	3-2
3.2.2	Optimum Interaction Length	3-8
	REFERENCES	3-9
4	SUMMARY OF PAPERS AND PRESENTATIONS DURING PRESENT AND PAST PROGRAMS	4-1
4.1	PAPERS WRITTEN DURING PRESENT PROGRAM	4-1
4.2	PRESENTATIONS GIVEN DURING PRESENT PROGRAM	4-2
4.3	PAPERS WRITTEN DURING PAST PROGRAMS	4-4
4.4	PRESENTATIONS GIVEN DURING PAST PROGRAMS	4-5
APPENDIX	PAPERS WRITTEN DURING CURRENT PROGRAM	A-1

FIGURES

FIGURE		PAGE
2-1	Arrangement for inverse Čerenkov interaction.	2-2
2-2	Monte Carlo model predictions for the ATF ICA experiment of the e -beam energy spectrum (50 GW).	2-6
2-3	Monte Carlo model predictions for the ATF ICA experiment of the e -beam energy spectrum (5 GW).	2-8
2-4	Schematic plan view of the ICA experiment optical system.	2-9
2-5	Photograph of ICA experimental hardware.	2-10
2-6	Photograph of radial polarization converter system.	2-11
2-7	Plan view of gas cell.	2-13
2-8	Photograph of gas cell.	2-14
2-9	Location of ICA experiment in ATF experimental hall.	2-15
2-10	Photograph of ICA experiment in ATF experimental hall.	2-16
2-11	Schematic drawings of the plan and side views of the ICA electron beamline system.	2-18
2-12	(a) Schematic drawing of diamond film e -beam window. (b) Basic design for entrance e -beam window holder.	2-19
2-13	Preliminary simulation of electron energy spectrometer output.	2-22
2-14	Schematic plan view of ICA relay imaging system for gas cell internal screens.	2-24
2-15	Schematic side view of ICA relay imaging system for gas cell internal screens.	2-25
3-1	Maximum energy gain as a function of crossing angle and parameterized in a for a free-space laser accelerator.	3-4
3-2	Maximum energy gain as a function of crossing angle and parameterized in the e -beam energy γ for a free-space laser accelerator.	3-6
3-3	Maximum energy gain as a function of crossing angle and parameterized in L , the interaction length for a free-space laser accelerator.	3-10

TABLES

TABLE		PAGE
2-1	ATF RF <i>e</i> -Gun Characteristics	2-3
2-2	ATF ICA Experiment Parameters	2-5
2-3	Electron Beam Window Pressure Test Parameters	2-20
3-1	Predicted Free-Space Laser Accelerator Performance	3-8

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SECTION 1

EXECUTIVE SUMMARY

This final report describes the work performed at STI Optronics, Inc. (STI) to investigate inverse Čerenkov acceleration (ICA) as a promising method for laser particle acceleration. In particular, an improved configuration for ICA is being tested in a experiment presently underway on the Accelerator Test Facility (ATF) located at Brookhaven National Laboratory (BNL). In the experiment, the high peak power (~10 GW) linearly polarized ATF CO₂ laser beam is converted to a radially polarized beam. This beam is focused with an axicon at the Čerenkov angle onto the ATF 50-MeV *e*-beam inside a hydrogen gas cell, where the gas acts as the phase matching medium for the interaction. An energy gain of ~12 MeV is predicted assuming a delivered laser peak power of 5 GW.

The experiment is divided into two phases. The Phase I experiments, which were completed in the spring of 1992, were conducted before the ATF *e*-beam was available and involved several successful tests of our optical system. Phase II experiments are with the *e*-beam and laser beam, and are still in progress. The ATF demonstrated delivery of the *e*-beam to our experiment in Dec. 1992. A preliminary "debugging" run (Run #1) with the *e*-beam and laser beam occurred in May 1993. This revealed the need for some experimental modifications, which have been implemented. Our second run is tentatively scheduled for October or November 1993. The ATF has given our experiment top priority as one of the first users of their facility.

In parallel to the experimental efforts has been ongoing theoretical work to support the experiment and investigate improvements and/or offshoots. One exciting offshoot has been theoretical work showing that free-space laser acceleration of electrons is possible using a radially-polarized, axicon-focused laser beam, but without any phase-matching gas. The Monte Carlo code used to model the ICA process has been upgraded and expanded to handle different types of laser beam input profiles.

We have been collaborating with Prof. Jorge Fontana, University of California, Santa Barbara, Prof. Richard Pantell, Stanford University, and Prof. Thomas Katsouleas, University of Southern California. We have also begun discussions with Dr. Alexander Varfolomeev, Kurchatov Institute of Atomic Energy, on possible collaborative work.

The next section of this report reviews the status of the present experiment. Section 3 presents additional theoretical results besides the ones given in our published papers. A summary of papers and presentations produced during this current program are listed in Section 4. The Appendix contains copies of the papers written during this current program.

SECTION 2

DESCRIPTION OF EXPERIMENT

2.1 INTRODUCTION

The acceleration of relativistic electrons using the inverse Čerenkov effect was first demonstrated at Stanford University in 1981.²⁻¹ Later, Fontana and Pantell²⁻² developed an improved configuration for the inverse Čerenkov acceleration (ICA) process. Their basic scheme is shown in Figure 2-1. A radially polarized laser beam is focused by an axicon onto the e -beam traveling through a gas-filled interaction region. The light intersects the e -beam at the Čerenkov angle θ_c , where $\theta_c = \cos^{-1}(1/n\beta)$, n is the index of refraction of the gas, and β is the ratio of the electron velocity to the speed of light.

This configuration has several important advantages over the geometry used during the Stanford experiments. First, it produces a more efficient coupling of the laser energy into the e -beam. Second, the transverse electric field components from the laser beam are focused axisymmetric about the e -beam. This helps mitigate some of the detrimental effects of gas scattering by channeling the electrons in the longitudinal direction.²⁻³ This same effect can also focus the e -beam using the inverse Čerenkov effect. Third, the potential problem of laser-induced gas breakdown may be less of an issue. This is because when the radially polarized laser beam is focused by the axicon, its profile in the interaction region follows a $J_1(r)$ Bessel pattern, where r is the radial distance away from the longitudinal z -axis. The $J_1(r)$ Bessel function is zero at $r = 0$ and maximum at a finite distance away from the z -axis. Hence, gas breakdown, if it should occur, will tend to be located in a circular region away from the e -beam. (The situation is actually much better than this because the laser energy in this circular region is also distributed along the entire interaction length, thereby lessening the chance for gas breakdown.) As will be discussed later, a radially polarized laser beam focused by an axicon also has important advantages for laser acceleration of electrons in a vacuum.

The goal of our program is to demonstrate improved laser acceleration using the Fontana and Pantell configuration. Our experiments are being performed on the new Accelerator Test Facility (ATF) located at Brookhaven National Laboratory (BNL). This facility features a 50 MeV linac fed by a Nd:YAG (4 ω) laser-driven photocathode e -gun. The ATF also has a high peak power CO₂ laser, which was developed for laser

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Figure 2-1. Arrangement for the inverse Čerenkov interaction. The electrons travel parallel to the z-axis and the laser beam consists of a radially polarized field that passes through an axicon and converges at an angle θ_c onto the z-axis. L is the interaction region length.

acceleration studies. The scientist responsible for the ATF CO₂ laser, Dr. Igor Pogorelsky, is actually a member of our ICA experiment team and was supported through funds from our program.

The ICA experiment is one of the first users of the ATF. Both the Nd:YAG and CO₂ lasers are operational, with the Nd:YAG laser being used regularly to drive the photocathode. This same laser is also used to slice out the variable pulse lengths (10 ps - 100 ps) from the CO₂ laser oscillator.

The ATF RF *e*-gun has surpassed several of its original design goals. Its design and achieved characteristics are listed in Table 2-1.

Table 2-1. ATF RF *e*-Gun Characteristics

Parameter	Design	Achieved
Energy, MeV	4.6	4.6
Repetition rate, Hz	6	6
Electron pulse charge, nC	1.0	2.0
Electron pulse length (rms), ps	2.5	4.9
Peak current, A	160	106
Energy spread (rms), %	0.3	0.4
Emittance ($\gamma\sigma_x\sigma_{x'}$), mrad	7×10^{-6}	4×10^{-6}
Beam brightness, A/m ²	3×10^{12}	7×10^{12}

The *e*-beam requirements for the ICA experiment are not stringent so that the *e*-gun characteristics listed in Table 2-1 are well within the needs of our experiment. (This is one advantage of ICA over some of the other laser acceleration approaches which have more stringent *e*-beam requirements.)

The ICA experiment was divided into two phases. Phase I was to examine certain experimental issues in preparation for Phase II. Phase I was successfully completed in the spring of 1992. Phase II is to perform the actual laser acceleration experiments on the ATF *e*-beam. We are still in the process of conducting Phase II. Delays in the ATF schedule prevented us from completing Phase II during the present contract.

In this section, the theory and experimental hardware for the present program are described. The results of the Phase I experiments are presented, and an update on the Phase II results thus far is given.

2.2 COMPUTER MODEL DEVELOPMENT AND PREDICTIONS

2.2.1 Brief Description of Model

A Monte Carlo computer simulation of the ICA process was developed²⁻³ based upon earlier models developed at the University of California, Santa Barbara and at Stanford University. The model includes all the relevant physics and is more versatile than the earlier models in its ability to simulate many different experimental conditions. It also uses a more accurate characterization of the optical field as the laser beam propagates through the interaction region.

The model includes Rutherford scattering caused by the gas and *e*-beam windows, straggling, and other inelastic losses suffered by the electrons. It is designed to model axicon focusing and can handle any arbitrary optical field distribution coming into the axicon. Thus, it can analyze the affects of experimentally measured beam profiles. Diffraction and interference effects of the laser beam are included using a fast Fourier transform (FFT) technique. Electron beam characteristics such as emittance, energy spread, and width are also included.

Another distinguishing feature of our model development was the amount of validation performed on it. Wherever possible, the model was checked against available experimental data. In particular, the accuracy of its scattering predictions was verified by comparing with empirical-based scattering formulas and with experimental data obtained by Pantell at Stanford.²⁻⁴ The model was also run to see if it could predict the Stanford ICA experiment. Its predictions are in excellent agreement with the Stanford results.

2.2.2 Model Predictions for Phase II Experiments

The basic parameters for the ATF ICA experiment are listed in Table 2-2.

Table 2-2. ATF ICA Experiment Parameters

Electron beam mean energy	50 MeV
Electron beam energy spread	0.2 MeV
Electron beam angular divergence	1.2 mrad
Electron beam diameter in gas cell	0.18 mm
Čerenkov angle	20 mrad
Hydrogen gas pressure	1.7 atm
Gas cell window thickness	2.1 μm diamond
Laser wavelength	10.2 μm
Laser peak power	5 -50 GW delivered
Laser pulse duration	30-100 ps
Laser beam outer diameter	1 cm
Axicon inner hole diameter	0.05 cm
Interaction length, L	20 cm
Distance between gas cell mirrors	30 cm

For our simulations of the experiment we assume, conservatively, that various optical losses and inefficiencies will result in 1/2 of the laser output power being delivered into the interaction region. Thus, if the laser peak output power is 100 GW, then the simulation is run at a value of 50 GW for the laser input parameter. For the other conditions listed in Table 2-2, this results in a prediction of nearly 80% energy gain over the 50 MeV *e*-beam (i.e. ~ 38 MeV). This prediction is shown in Figure 2-2. For our interaction length of 20 cm this corresponds to an acceleration gradient of ~ 190 MeV/m.

Note in Figure 2-2 that because the electrons are uniformly distributed in phase over the light wave, the spectrum displays a full range of particle energies. For efficient acceleration a prebunched *e*-beam would be used whose phase is selected for optimum acceleration only.

The present ATF CO₂ laser system output power is limited to ~ 10 GW. Theory predicts that the maximum energy gain is simply proportional to the square-root of the laser peak power. Hence, if we assume only 5 GW of laser peak power is delivered to the

(a)

(b)

Figure 2-2. Monte Carlo model predictions for the ATF ICA experiment of the e -beam energy spectrum. (a) Laser off. (b) Laser on, 50 GW delivered to interaction region. The rest of the parameters are: e -beam energy = 50 MeV, $\theta_c = 20$ mrad, $L = 20$ cm, laser beam OD = 1 cm, e -beam focused to $r = 0.18$ mm, $P = 1.71$ atm hydrogen, and the e -beam windows are $2.1 \mu\text{m}$ thick diamond.

interaction region (i.e., 0.5×10 GW), then the maximum acceleration is reduced by $10^{1/2}$ or from ~ 38 MeV to ~ 12 MeV. Our model results confirm this case in Figure 2-3. As can be seen, this still results in significant energy gain that can be easily detected by an electron energy spectrometer.

2.3 DESCRIPTION OF EXPERIMENTAL APPARATUS

2.3.1 Optical System

Figure 2-4 shows a schematic layout of the Phase I optical system. The ATF CO₂ laser beam is transported along the ceiling of the experimental hall to our 4'x8' optical table where it is directed downward to the surface of the table as shown in the upper right-hand corner of Figure 2-4. It is then sent through a 2X expansion telescope that increases the beam diameter to ≈ 2 cm. Next, it is directed into the radial polarization converter optical system.²⁻⁵ This is an improved version of the techniques developed earlier during this program.²⁻⁶ After leaving the converter system, the radially polarized laser beam goes through a beam reduction telescope, which reduces its diameter to ≈ 1 cm. Finally, the beam is sent into the gas cell where the ICA process occurs (details of the gas cell are shown later).

Also depicted in Figure 2-4 are the cw CO₂, GaAlAs diode, and HeNe lasers used for aligning our optical system. The cw CO₂ laser (Synrad, Model 48G-1-115W) is grating tunable. The diode laser (GALA, Model 078-04-1) lases at 780 nm. It has a much shorter coherence length than the cw CO₂ laser and, therefore, mimics the short coherence length of the short pulse ATF CO₂ laser. This is very important when adjusting the optical path lengths of the radial polarization converter system.²⁻⁷

A photograph of the Phase I experimental hardware is shown in Figure 2-5. A separate panel contains the gas manifold system for filling and evacuating the gas cell. This specially designed system is portable for remote control of the gas system (necessary during the Phase II experiments) and has built-in safety features to ensure safe handling of the hydrogen gas.

Data acquisition is done using a personal computer (PC). Contained within the PC is a video data acquisition system which features a frame grabber board that can be connected to either a regular CCD camera or an IR-sensitive camera. The IR camera is

(a)

(b)

Figure 2-3. Monte Carlo model predictions for the ATF ICA experiment of the e -beam energy spectrum. This simulation assumes 1/10 the delivered laser peak power as assumed in Figure 2-2. (a) Laser off. (b) Laser on, 50 GW delivered to interaction region. The rest of the parameters are the same as in Figure 2-2.

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Figure 2-4. Schematic plan view of the ICA experiment optical system. The entire system is located on a 4' x 8' optical table. Not shown is the electron beamline hardware that is connected to the gas cell (see Figure 2-10).

used extensively when diagnosing the radially polarized CO₂ laser beam. The software, written in C, is capable of acquiring single shot data and analyzing the stored image.

Figure 2-6 is a photograph of the radial polarization converter system. It is based upon a double-interferometer. A detailed explanation of the system is given in Ref. 2-5 (see the Appendix).

A plan view and photograph of the gas cell is shown in Figures 2-7 and 2-8, respectively. The cell is fabricated from a single piece of aluminum and, therefore, has no welds. The walls are 1" thick and both the lid and bottom are 1.25" thick. This type of construction was used for two reasons. First, it provides maximum safety (the cell was hydrostatically tested to 70 psi) and eliminates possible gas leaks through aluminum welds. Second, it provides an optically rigid platform for the optics inside the cell and the gas cell *e*-beam windows, which must all be precision aligned to each other to ensure good spatial overlap of the focused laser beam and *e*-beam. There is also a large observation port along the top of the cell.

As can be seen in Figure 2-7, the laser beam enters the cell through a ZnSe window. It reflects off a 45° mirror and is sent to the axicon mirror. This 45° mirror has a 1.0 mm diameter hole drilled through it at 45° to its surface for the *e*-beam to travel through. The axicon mirror also has a 1.0 mm diameter hole drilled through its center normal to its surface. An axicon mirror rather than a lens (as shown earlier in Figure 2-1) is used because of the higher damage threshold (approximately 10X better) of reflective metal optics rather than transmissive optics. The axicon is cut with a 10 mrad apex angle, which will result in a Čerenkov angle of $\theta_c = 20$ mrad.

The laser beam reflects off the axicon and is focused down onto the *e*-beam traveling from right to left in the Figure 2-7. After interacting with the *e*-beam, the spent laser beam reflects off the 45° mirror and exits the gas cell. This spent beam can then be further analyzed using optical detectors located outside the gas cell (see Section 2.3.4). The *e*-beam windows consist of a 2.1 μm thick diamond film deposited on a silicon substrate. Details of the *e*-beam windows are described in Section 2.3.2.

Figures 2-9 and 2-10 show the location and a photograph of the ICA experiment in the ATF experimental hall, respectively. Our optical table, which contains the entire optical system, is positioned just downstream from the Grating Accelerator experiment. The small rectangular box in the lower left-hand corner of our table in Fig. 2-9 represents

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Figure 2-7. Schematic plan view of the gas cell where the ICA interaction occurs. The laser beam focusing angles are exaggerated for clarity.

Figure 2-2.

Figure 2-9. Schematic plan view of the ATF experimental hall showing the location of the ICA experiment on Beamline #1 and relative to the ATF CO₂ laser.

the gas cell (c.f. Figure 2-4). The laser beam from the ATF CO₂ laser is delivered to our experiment through a portal hole near the ceiling in the concrete shielding that separates the experimental hall from the CO₂ laser room. Downstream from our table is located the electron energy spectrometer (see Fig. 2-10).

2.3.2 Electron Beamline System

Figure 2-11 is a drawing of the ICA electron beamline system attached to the gas cell. The gas cell position relative to the beamline is surveyed in with the aid of special surveyor's targets attached to the cell body. On both ends of the cell are a bellows and pop-in phosphor screen. Gate valves on the ends of the beamline permit breaking into the bellows in order to access the *e*-beam windows. The design of the *e*-beam window holders actually enables replacement of the entrance *e*-beam window from inside the gas cell rather than needing to open up the beamline. For changing the exit *e*-beam window it will still be necessary to break into the beamline; however, experience during the Stanford ICA experiments showed that it is the entrance window which is most susceptible to radiation damage from the *e*-beam. Thus, being able to change the entrance window without breaking into the beamline will help expedite matters. Fortunately, as explained later, our *e*-beam window holder design protects the window seals from direct electron impact, thereby making the windows much less susceptible to radiation damage.

Upstream of the gas cell are a pair of steering magnets for control of the *e*-beam transverse position. We are using a standard BNL trim magnet design (BNL Drawing No. SLS-17.17-1-5). A photograph of the beamline system was shown earlier in Figure 2-5.

Figure 2-12(a) is a schematic drawing of the gas cell window manufactured for us by Crystallume, Menlo Park, CA. It consists of a 2.1 μm thick diamond film deposited on a 0.36 mm thick silicon substrate sealed to a stainless steel holder with C7-W Armstrong epoxy. A <1 mm x 1 mm portion of the silicon substrate has been etched away in the center leaving only the diamond film through which the electrons pass. The window was pressure and vacuum tested at the manufacturer to verify its ability to withstand the required pressure differentials. The results are summarized in Table 2-3.

Figure 2-11. Schematic drawings of the plan and side views of the ICA electron beamline system. The electrons are traveling from left to right.

(a)

(b)

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Figure 2-12. (a) Schematic drawing of the diamond film *e*-beam window. The diamond film is 2.1 μm thick. (b) Basic design for the entrance *e*-beam window holder. This holder is inserted into the end of the gas cell (see Figure 2-7).

Table 2-3. Electron Beam Window Pressure Test Parameters

Test	Pressure (psid)*	Number of cycles
Proof pressure	47.9	5
Pressure cycle	32.3	5000

*Note, the nominal operating pressure during the ICA experiments is 25 psi.

Even at nearly 2 times the nominal operating pressure, the window did not break. (It is not known how high of pressure is required to break the window.) After the preceding pressure cycling tests, the window was leak checked and had no measurable leak. Thus, these diamond windows have demonstrated the required mechanical strength.

The only weak point of this particular window design is the use of epoxy for sealing the silicon substrate to the stainless steel holder. Past experience at Stanford showed that organic adhesives, such as epoxy, have severely limited lifetimes if the *e*-beam strikes the adhesive. For this reason a metal seal is preferred; however, the Crystallume window design cannot be easily modified to accommodate a metal seal. Fortunately, during normal ICA operation the *e*-beam will be traveling through the center of the window, roughly 6 mm away from the epoxy. However, during alignment of the *e*-beam through the gas cell, the beam can easily strike the epoxy if the adhesive is unprotected. Fortunately, there are straightforward methods for protecting the epoxy from direct impact by the *e*-beam.

Figure 2-12(b) shows a drawing of the gas cell *e*-beam input window holder which holds the window and is inserted into the end of the gas cell as shown in Figure 2-7. The epoxy is protected by a lead iris plug positioned in front of the *e*-beam window. The length of the lead iris (2.5 cm) is chosen to not only stop most of the 50 MeV electrons, but also to attenuate the secondary radiation produced when the electrons are stopped by the lead.

Some secondary radiation (*x*-rays and *γ*-rays) will still reach the epoxy. Fortunately, similar diamond windows manufactured by Crystallume using the same epoxy have been successfully used at BNL under high radiation environments.²⁻⁸ These windows were constantly irradiated for 14 days with *γ*-rays from a Co-60 source for a total absorbed dose of 1×10^5 rad. The window remained leak-tight after this exposure.

During Phase I the e -beam window durability was successfully tested and the results are discussed in Section 2.4.3.

2.3.3 Diagnostics

With regard to the optical system, there are a number of different diagnostics being used. As mentioned earlier, an IR video camera is used to obtain images of the CO₂ laser beam. This is used for verifying the proper alignment of the radial polarization converter and, as explained in Section 2.3.4, for aligning the spatial overlap of the laser and electron beams.

The output pulse energy of the ATF CO₂ laser beam is sampled using a Molelectron J25 pyroelectric joulemeter. Its output is sent into a Molelectron JD501 joulemeter digitizer that sends the pulse energy information directly to our PC. Hence, the laser peak power delivered to the gas cell can be automatically measured during each shot.

With regard to the electron beam diagnostics, the e -beam position within the interaction region is determined using phosphor screens inside the gas cell (see Section 2.3.4). The electron beam energy will be measured using a spectrometer magnet system specifically design for the ATF.²⁻⁹ It features a video output that can be directly stored and analyzed by our PC.

An example result of a code simulation for the spectrometer output under the conditions of the ICA experiment is shown in Figure 2-13. The bottom distribution is for the laser off with energy dispersion oriented along the horizontal direction. The spectrometer quadrupoles have been adjusted to give the narrowest spectrum in the horizontal direction to help compensate for scattering of the e -beam caused by the e -beam windows and phase matching gas. (Scattering effects are included in the simulation.) This makes the vertical distribution large, but the width in the vertical direction is not important for the ICA experiment.

The top distribution in Figure 2-13 is with the laser on (laser peak power = 5 GW delivered). There is a dramatic change in the distribution, which should be easily measured. Note the resolution of the spectrometer is roughly 25 keV. This is much higher than needed for our experiment; hence, even less than perfect ICA interactions should be observable. Thus, the spectrometer will also be a useful tool when fine tuning the experimental parameters (see below).

Figure 2-13. Preliminary simulation of the electron energy spectrometer output for the ICA experiment. This does not represent an optimized case. Top figure is with the laser on; bottom figure is with the laser off. Energy dispersion is in the horizontal plane with each symbol representing roughly 25 keV.

2.3.4 Spatial and Temporal Alignment of the Beams

Ensuring that the laser and electron beams are spatially and temporally overlapped inside the gas cell is a critical task during the Phase II experiments. Within the interaction region, the laser focal spot is ~ 0.4 mm in diameter. The e -beam will be focused down to this size or slightly less inside the gas cell. It is important that the beams remain overlapped over the 20-cm interaction region.

Spatial overlap of the beams is detected using the optical imaging system shown in Figures 2-14 (plan view) and 2-15 (side view). Two remote-controlled phosphor-coated screens are located inside the gas cell. One is near the axicon mirror; the other is near the 45° mirror. Light emission from these screens is relay-imaged to video cameras via a remote-controlled translating lens system. When imaging the upstream screen (Screen #2), the lens is farthest from the gas cell. When imaging the downstream screen (Screen #3), the lens is closest to the gas cell. Note that a periscope system is used to direct the light to the relay lens positioned 8 inches above the table top (see Figure 2-15). This is to avoid interference with the radial polarization converter system (see Figure 2-4).

Unfortunately, the light emission from the phosphor screen is not bright enough to be sensed by the IR video camera. Thus two cameras are used, an IR and a standard CCD, to visualize the laser and e -beam images, respectively. The phosphor emission from Screens #2 and #3 are detected by the CCD camera whose output is stored in our PC. Thus, the position of the e -beam within the gas cell is known at two points. The IR camera is used to detect the CO_2 laser beam spatial distribution within the axicon focal region. When imaging the laser light, the phosphor screens are swung out of the laser beam path; however, the relay lens still images the laser light at the screen's position along the e -beam path. In order to compare the CO_2 laser beam position at these two locations with the e -beam positions stored in the PC, a HeNe laser (see Figure 2-14) that can be seen by both cameras is used as a common reference image. By adjusting the remotely controlled micrometers on the axicon and 45° mirrors inside the gas cell, the laser beam position can be made to overlap the e -beam position at the two locations, thereby ensuring the beams are overlapped over the entire interaction region.

The HeNe alignment laser shown in Figure 2-14 and its associated mirrors is also used to align the gas cell, the optics inside the cell, and the beamline. Some of the mirrors are on kinematic mounts that permit the mirrors to be positioned where the beamline

Figure 2-14. Schematic plan view of the ICA relay imaging system for the gas cell internal screens.

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Figure 2-15. Schematic side view of the ICA relay imaging system for the gas cell internal screens.

bellows are located (see Figure 2-11). This HeNe laser system is also used to calibrate images seen by the CCD and IR video cameras.

Temporal synchronization will be performed in two steps. First, various detectors are available at the ATF to sense the passage of the e -beam pulse. These will be used to estimate its arrival time in the gas cell. (Recall the e -beam pulse is 6 ps long.) A fast HgCdTe photodetector will be used to detect the ATF CO₂ laser pulse at a location on our optical table. With careful measurements of the path lengths for both beams from their respective temporal detectors to the center of the gas cell, the time delay needed to obtain temporal overlap can be estimated. Fortunately, for this initial synchronization it is only necessary for the 6-ps e -beam pulse to lie somewhere within the 1 to 3-cm long (i.e., 30 to 100-ps) laser pulse. Once this occurs a change in the electron energy spectrum should be detected by the sensitive spectrometer magnet (see Section 2.3.3). The second step is to use the spectrometer output to help fine tune the temporal overlap by optimizing the signal seen by the spectrometer.

2.4 EXPERIMENTAL RESULTS OF PHASE I EXPERIMENTS

A summary of the accomplishments during the Phase I experiments are listed below.

2.4.1 Optical System Tests

- 1) Demonstrated conversion of the linearly polarized ATF CO₂ laser beam into a radially polarized beam using the double-interferometer system. Because of the short coherence length of the laser beam, it was important to show that the phase of the double-interferometer system could be adjusted properly.
- 2) Determined that the radially polarized laser beam focused by the axicon inside the gas cell is stable, and has acceptable position and angle tolerances.
- 3) Measured the $J_1(r)$ Bessel pattern in the axicon focal region and found it agreed with theory (see Ref. 2-5 in Appendix).
- 4) Performed optical damage tests on the spiral-phase-delay plate (see Ref. 2-5), which is the optic in our system most sensitive to laser damage, and

determined that its damage threshold for 100-ps laser pulses is $>190 \text{ mJ/cm}^2$. This value corresponds to the same fluence on the optic if the laser were to produce 100 GW of peak power. Thus, damage of optical components should not be a problem during the ICA experiments. (Note, damage thresholds tend to increase with shorter laser pulse lengths, so that a 10-ps laser pulse will have a higher damage threshold than the 100-ps pulse.)

2.4.2 Nonlinear Effects

Possible nonlinear effects, such as gas breakdown and stimulated Raman generation, caused by the high peak power laser beam being focused by the axicon in the hydrogen gas are estimated not to be an issue for the conditions of the ATF ICA experiment. During Phase I we observed no laser-induced gas breakdown in hydrogen gas for laser peak powers at the $\sim 2 \text{ GW}$ level for a laser pulse length 100 ps. Although this does not represent the 50 GW case, we do not expect problems with gas breakdown during the Phase II experiments.

In summary, during the Phase I experiments we did not observe any unusual phenomena when the ATF CO_2 laser beam was focused inside the gas cell.

2.4.3 Electron Beam Window Lifetime Tests

As mentioned earlier, the durability of the diamond film *e*-beam window seals during exposure to the *e*-beam was of concern. To verify that our window holder design (see Figure 2-12) protects the window adequately, during Phase I we performed *e*-beam exposure tests of a sample window. The window was sealed in a holder similar in design to the holder shown in Figure 2-12(b) with a lead plug shielding the window from direct *e*-beam impact. The window was held under vacuum during the tests with a 1-atm pressure differential across the window.

Since the ATF 50-MeV *e*-beam was not ready yet, we exposed the sample window to the National Synchrotron Light Source (NSLS) 70-MeV *e*-beam for a total of 12 hours. This corresponded to roughly 100X more exposure than expected during the ATF ICA experiments. The sample window was still leak-tight after this test. Therefore, we are confident that the *e*-beam windows will survive exposure to the ATF *e*-beam allowing us to perform the ICA experiments without worry of window failures.

2.5 PHASE II EXPERIMENTS

2.5.1 Results of Run #1

As mentioned earlier, we are currently performing the Phase II experiments. Our experiment is the first major laser acceleration experiment to use the e -beam.

The main objectives of the Phase II experiments are to: 1) verify the timing and spatial overlap between the electron and laser pulses; 2) examine the e -beam energy spectrum as a function of laser peak power, gas pressure, and timing between the electron and laser pulses; and 3) compare the experimental results with model predictions.

In May 1993 we had an opportunity to perform our first run with both the laser and e -beam. Both the laser and e -beam were not fully optimized yet; however, their performance were adequate enough for debugging the ICA experimental apparatus. The e -beam energy was 50 MeV, but due to various problems could not be focused to a tight focus inside the gas cell. Consequently, only a relatively small amount of electrons made it through the gas cell.

We estimate that approximately >4 GW of laser peak power in a ~ 60 ps pulse length was delivered to the gas cell interaction region. This estimation includes losses incurred by the laser beam in going through the radial polarization converter system.

Most of the experimental hardware functioned as planned; however, several problems were uncovered. First, the gold-coated axicon and 45° mirrors inside the gas cell suffered some optical damage when exposed to the 4 GW laser beam. (Recall this laser peak power was higher than the tests during the Phase I experiments.) Second, some laser light passed through the 1.0 mm diameter hole in the axicon mirror and struck the back of the gas cell input e -beam window. The laser power was high enough to damage the window and broke its vacuum seal. Third, the performance of the imaging system described in Sec. 2.3.4 was not entirely satisfactory, primarily because the phosphor emission from the internal gas cell screens could not be seen by the IR camera and the HeNe laser light was also barely visible. These were the only major problems encountered during the first run; the other problems were minor in nature.

2.5.2 Preparations for Run #2

The current contract ended on August 31, 1993; a new contract has begun to finish the ICA experiments at the ATF. Between the first run and the writing of this final report, we have made changes to the ICA experimental apparatus to correct the problems encountered during the first run. These are listed below.

- 1) The gold-coated axicon and 45° mirrors inside the gas cell have been replaced with bare copper mirrors. We know from experience with bare copper mirrors in the rest of the ICA optical system that they can tolerate the high laser peak power. Copper mirrors were not originally used inside the gas cell because of activation problems when exposed to the *e*-beam. Although the mirrors will become more radioactive than the gold-coated aluminum mirrors, we believe they can be safely handled.
- 2) The holes in the copper axicon and 45° mirrors was reduced to 0.5 mm. There are three reasons. First, this will reduce the amount of laser light that travels through the hole to the gas cell input *e*-beam window. Second, this will reduce the amount of laser light in the center of the beam that is lost when reflecting off the 45° mirror. Third, the smaller holes more tightly define the position of the *e*-beam within the cell. As discussed later, a HeNe laser beam will be directed through the gas cell in order to indicate the position of the *e*-beam. Hence, smaller holes in the mirrors will reduce the uncertainty in the overlap of the *e*-beam and HeNe laser beam.
- 3) The laser beam entering the radial polarization converter system has a Gaussian profile. This means there is significant laser energy in the center of the beam, which strikes the holes in the gas cell mirrors and can pass through to strike the gas cell input *e*-beam window. An axicon telescope is being installed before the input to the radial polarization converter system. This telescope will convert the Gaussian beam into an annular one, thereby creating a small hole in the center of the radially polarized beam. This should dramatically reduce the amount of laser energy that strikes the holes in the gas cell mirrors and that can pass through to the *e*-beam window.

- 4) A laser shield is being positioned between the input *e*-beam window and the back side of the axicon mirror. This brass shield has a 0.6 mm diameter hole in its center to permit passage of the *e*-beam. Being made of brass it is highly reflective in the infrared and will prevent any laser light from striking the silicon substrate of the *e*-beam window.
- 5) A pop-in mirror was installed in the beamline at the position of the kinematic mirror labeled KM1 in Fig. 2-14. This will allow the HeNe laser beam to be directed down the beamline through the gas cell without breaking the vacuum of the beamline. The pop-in mirror can also be activated remotely. This HeNe laser beam will be used to indicate the position of the *e*-beam inside the gas cell as seen by the IR camera. The kinematic mirror labeled KM2 in Fig. 2-14 is no longer needed.
- 6) Both the *e*-beam and ATF CO₂ laser systems are being improved. The problems with focusing the *e*-beam will be corrected before the second run. The laser peak power should also be higher.

Tentatively, the second run will occur in October or November 1993. The primary goals of the second run are to test the improvements to the experimental apparatus and obtain *e*-beam energy spectra from the spectrometer magnet. If all goes as planned, preliminary data showing acceleration of the electrons should be obtained. We expect that more extensive data collection will occur during the third and fourth runs later next year.

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SECTION 3

THEORETICAL ANALYSIS AND SUPPORT

3.1 INTRODUCTION

During the ICA program theoretical studies focused on two areas: construction of the basic tools for modeling ICA physics, and preliminary consideration of new ideas for enhanced laser acceleration.

The tools which have been developed under the present program are the following. (1) An electron beam dynamics code²⁻³ which uses a full Fourier-transform description of the electromagnetic fields and computes the evolution (acceleration and focusing) of a finite emittance electron beam using a Monte-Carlo description of scattering in the gas medium. This code accepts imperfect (nonaxisymmetric) input lasers. (2) An "outer-boundary" method code³⁻¹ which resolves electromagnetic fields into Bessel modes and computes the acceleration and focusing of a finite-emittance electron beam in non-scattering media. This code accepts any axisymmetric laser beam and operates efficiently on a 386 PC. (3) A multistage code³⁻² which computes finite-emittance beam evolution through a multiple-stage acceleration system assuming a simplified description of the electromagnetic fields. This code also runs efficiently on a 386 PC.

The advanced acceleration ideas given preliminary consideration in the present program include the use of near-resonant media for phase matching in an ICA,³⁻³ free-space acceleration,³⁻¹ and various ideas for controlling the electromagnetic field intensity and phase in the electron beam path, e.g., curved axicon surface, axicon with a grating or stepped surface,³⁻⁴ and use of a shaped conducting wall surrounding the interaction region.

Details of the code work in support of the ICA experiment are covered in the reprints of our papers given in the Appendix that were published during this program. In this section we present some additional theoretical analysis that was not included in those reprints.

3.2 FREE SPACE LASER ACCELERATION

One of the most exciting theoretical developments that occurred during the present program is an analysis showing that laser acceleration in free-space can occur using the

same radially-polarized, axicon-focused laser beam geometry as in ICA, but without any phase matching gas (see Ref. 3-1 in Appendix). Free-space laser acceleration is attractive because it completely eliminates the problems with gas scattering and the need to have e -beam windows.

The ICA focusing geometry has important advantages relative to free space laser acceleration. All of this is explained in detail in Ref. 3-1 and will not be repeated here. Instead we present the results of additional analysis that was performed to optimize the design for a free space laser accelerator experiment. Multistaging, which has important ramifications for free-space laser accelerators, has also been analyzed and is discussed in Ref. 3-2. in the Appendix.

3.2.1 Additional Theoretical Optimization

The theory of free space laser particle acceleration developed Ref. 3-1 was used to predict maximum electron energy gain under the conditions of the ATF. This analysis summarizes the results of further calculations and suggests experimental designs for testing this scheme. The designs are slight modifications to the current ICA experimental design, and all are for one interaction region. (Multistaging is certainly possible, but was not considered in this analysis.)

Using the expression for the axial electric field on the z -axis in the paraxial approximation, the energy gain ΔW of an electron in the axicon-focused geometry is given by

$$\Delta W = \frac{4\theta ka}{\sqrt{2\pi}} q \left(\frac{P_l}{\epsilon c} \right)^{1/2} \int_0^2 \frac{du Q(\xi)}{(u + i\theta ka)^2} \exp \left[i \frac{ka}{2\theta \gamma^2} u \right], \quad 3.1$$

where q is the electron charge, P_l is the peak laser power, ϵ is the permittivity of free space, c is the speed of light, $u = z/L$, and $Q(\xi)$ is the function defined in the analysis of Ref. 3-1. Here, a is the radius of the peak intensity point incident on the axicon, L is the location where the ray emanating from $r = a$ crosses the z -axis in a geometrical optics description, θ is the crossing angle ($\theta = a/L$), and $\lambda = 2\pi/k$ is the laser wavelength. (Note, θ is not the Čerenkov angle!) The interaction length has been arbitrarily chosen to be $2L$. The exponential in the integrand of Eq. 3.1 represents the phase slippage between the electron and the electric field in the highly relativistic limit $\gamma \gg 1$. This slippage is

due to the mismatch between the particle speed and the phase velocity of the wave and is present regardless of the crossing angle θ . There is also an additional phase slippage (proportional to θ^2) because the electric field and electrons are not traveling in the same direction, and this is contained in the function $Q(\xi)$. The energy gain of an optimally-phased electron is given by the absolute value of Eq. 3.1 as discussed in Ref. 3-1.

The above analysis shows that four parameters determine the maximum energy gain: the peak laser power P_L , the crossing angle θ , the product ka , and the relativistic factor γ . The energy gain is proportional to the square root of the peak laser power. The functional dependence of the energy gain on θ , ka , and γ is not as straightforward, but can be obtained numerically. Assuming that γ and λ are fixed by the current ATF conditions, then the three parameters P_L , a , and θ are all that is necessary to determine the energy gain in a single interaction region.

Equation 3.1 was numerically solved for values of ka , θ , and γ . An analytical expression was also obtained for the solution of Eq. 3.1 in the limit when $\theta ka \gg 1$, using the method of stationary phase to obtain an expression for the axial electric field and by taking the leading term in an asymptotic expansion of the integral over the interaction length. This approximate expression, which is given below, is useful for understanding the basic trends observed in the numerical solutions using the paraxial approximation for the electric field.

Figure 3-1 shows the energy gain of an optimally phased electron computed from Eq. 3.1 as a function of the crossing angle θ for three values of the beam size a . The energy gain is expressed in dimensionless form. From Ref. 3-1

$$q \left(\frac{P_L}{ec} \right)^{1/2} = 19.4 [P_L (\text{Watts})]^{1/2} \text{ eV.} \quad 3.2$$

Thus, at a laser peak power of 50 GW, the top of the scale shown in Figure 3-1, (i.e., Maximum Energy Gain = 0.7), corresponds to an energy gain of about 3 MeV. The wavelength is 10.2 μm and $\gamma = 100$, which are the conditions for the current ICA experiments. The largest beam size is slightly smaller than the beam size being used in the current experiments. As the beam size is decreased, the energy gain increases due to the increase in the field intensity.

Two effects are observed for lower crossing angle: (1) a decline in $|\Delta W|$ so that there is an optimum value at some intermediate θ , and (2) the emergence of an oscillatory

Figure 3-1. Maximum energy gain as a function of crossing angle and parameterized in a for a free-space laser accelerator. For this analysis, the diameter of the laser beam is equal to $4a$.

dependence of $|\Delta W|$ on θ . The first effect, an overall decline in $|\Delta W|$ as the crossing angle decreases, arises due to the combination of a decrease in the axial field strength and from a finite γ , i.e., as the crossing angle decreases, the interaction length increases and the velocity mismatch between the particle and the electric field effectively cancels out any net acceleration, since the electron alternately experiences accelerating and decelerating forces. In fact, as $\theta \rightarrow 0$, there will be no energy gain. The second effect, the oscillatory dependence of $|\Delta W|$ on θ , is due to the rapidly increasing phase slippage experienced by the electron as θ becomes small and γ is finite coupled with the interaction length terminated at $z = 2L$. For large values of the crossing angle, the energy gain decreases as $(1/\theta)^{1/2}$ due to the angular phase slippage, i.e., the larger the angle, the greater the phase mismatch between the electric field and the electron, because the component of the phase velocity of the field along the direction of electron motion increases. For the beam sizes considered in Figure 3-1, an optimum crossing angle can be found which maximizes the maximum energy gain.

The effect of increasing γ on the energy gain is shown in Figure 3-2 for the conditions shown. As γ is increased, the phase slippage due to velocity mismatch is smaller. Thus, at smaller crossing angles, where this phase slippage is important, this results in a larger energy gain, and the oscillations at small θ have disappeared. The maximum occurs at a smaller crossing angle.

Also shown in Figures 3-1 and 3-2 is the analytical results obtained using Eq. (13) of Ref. 3-1 for the axial electric field, which is an approximate expression obtained from the method of stationary phase, and approximating the integral for ΔW over the interaction length by taking the leading term in an asymptotic expansion for $\theta ka \gg 1$. This results in an approximate expression for the energy gain of an optimally phased electron given by

$$|\Delta W| \approx q \left(\frac{P_l}{\epsilon c} \right)^{1/2} \frac{8 \sqrt{2}}{e^2 \sqrt{\theta k a}} \frac{1}{\left(1 + \frac{1}{(\theta \gamma^2)} \right)}. \quad 3.3$$

Figure 3-1 shows that this is a good approximation for large a , and becomes less accurate as a decreases as expected. For small values of θ , we also expect this expression to break down. Interestingly, this expression has a maximum when

Figure 3-2. Maximum energy gain as a function of crossing angle and parameterized in the e -beam energy γ for a free-space laser accelerator.

$$\theta_m = \frac{\sqrt{3}}{\gamma}, \quad 3.4$$

regardless of the beam size a . Thus, Eq. 3.3 can be used to determine, to a good approximation, the desired crossing angle for maximum energy gain. Note that as $\gamma \rightarrow \infty$, θ_m goes to zero, which violates the assumption $\theta ka \gg 1$ that went into the derivation of Eq. 3.2. At this optimum crossing angle, Eq. 3.3 becomes

$$|\Delta W|_m = 6.75 \left[\frac{\gamma \lambda P_I(W)}{a} \right]^{1/2} \text{ eV}. \quad 3.5$$

A qualitative understanding of why $|\Delta W|$ has a maximum as a function of θ can be obtained by considering the phase slippage between the electron and the electric field over a given interaction length. In the highly relativistic limit and assuming θ is small, the phase slippage over a length z is

$$\Delta \phi = \frac{ka u}{2} \left(\theta + \frac{1}{\theta \gamma^2} \right), \quad 3.6$$

where $u = z/L$. The first term in the parenthesis is due to the angular phase slippage and the second term to a finite γ . For a fixed value of ka , $\Delta \phi$ becomes large as θ goes to zero and when θ is large. The minimum phase slippage occurs when $\theta = 1/\gamma$, which is smaller by a factor of $\sqrt{3}$ than the optimum crossing angle for the energy gain given in Eq. 3.4. The reason for this is because the electric field strength on axis increases with increasing crossing angle roughly by $\theta^{3/2}$. Thus, the optimum crossing angle for energy gain is larger than the minimum phase slippage point.

From the above analysis, we see that to obtain the maximum energy gain, the beam size a should be made as small as possible subject to optical damage. From Eq. 3.2 we can estimate how the maximum energy gain scales with increasing laser power keeping the laser intensity on the axicon fixed at some value below the optical damage. The intensity scales as P_I/a^2 and the maximum energy gain scales as $(P_I/a)^{1/2}$; therefore, increasing the laser power and the beam size to keep the laser intensity fixed results in an increase in the maximum energy gain of the electron which scales as $P_I^{1/4}$.

Table 3-1 lists some predicted maximum energy gains for experimental parameters of interest. The energy gains are those calculated from Eq. 3.1. Examples 1 and 2 are for experimental parameters near those of the current ICA experiments. Examples 3-6 are

for smaller beam sizes on the axicon. Note that for $\gamma = 100$, the crossing angle from Eq. 3.3 is 17.3 mrad. This is close to the optimum computed from Eq. 3.1 and listed in Table 3-1.

Table 3-1. Predicted Free-Space Laser Accelerator Performance for $\gamma = 100$ and $\lambda = 10.2 \mu\text{m}$.

Example #	Laser Power P_l (GW)	Crossing Angle θ (mrad)	Axicon Diameter $4a$ (mm)	Interaction Length L (cm)	Maximum Energy Gain $ \Delta W $ (MeV)
1	5	20	5.2	6.5	0.419
2	50	20	5.2	6.5	1.32
3	5	19.6	4	5.1	0.505
4	50	19.6	4	5.1	1.60
5	5	13.9	3	5.4	0.617
6	50	13.9	3	5.4	1.95

3.2.2 Optimum Interaction Length

The analysis above and the results given in Ref. 3-1 assumed that the interaction length was terminated at $2L$, where $L = a/\theta$, a is the beam size, and θ is the crossing angle. This may not be the optimum length. Obviously, the energy gain will be zero when the length is zero, and it also will approach zero when the interaction length tends to infinity. Thus, if there is to be any net electron acceleration at all, there must be an optimum interaction length. An analysis of the choice of the optimum interaction length is given in this section.

The analysis given above was modified to include the effects of truncating the interaction region to a length bL . In the previous analysis, b is kept fixed at 2. A simple estimate of the effect of varying the interaction length can be obtained by including this in the approximate expression for the energy gain Eq. 3.3. This results in

$$|\Delta W| \approx q \left(\frac{P_l}{\epsilon c} \right)^{1/2} \frac{4 b^{3/2}}{\sqrt{\theta k a}} \frac{\exp\left(-\frac{1}{2} b^2\right)}{\left(1 + \frac{1}{(\theta \gamma^2)}\right)}. \quad 3.1$$

From this expression, we find that the value of b which maximizes this function is for $b = \sqrt{1.5} = 1.225$. To check whether a smaller value of b would indeed result in an increased energy gain, Eq. 3.1 was numerically solved for different values of b (which is just the upper limit in the integral). The results are shown in Figure 3-3. An enhancement of about 40% in the energy gain of an optimally phased electron is estimated in decreasing the interaction length from $2L$ to $1.22L$. Notice that as the interaction length is increased, the energy gain exhibits more oscillations. This is most likely due to the rapidly increasing total phase slippage between the electron and the electric field as the interaction length increases. From Eq. 3.6 we see that as the interaction length is increased (larger value of u in Eq. 3.6), the phase slippage increases more rapidly as θ increases.

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- 3-3. L.C. Steinhauer and W.D. Kimura, J. Appl. Phys. **68**, 4929 (1990).
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Figure 3-3. Maximum energy gain as a function of crossing angle and parameterized in L , the interaction length for a free-space laser accelerator.

SECTION 4
SUMMARY OF PAPERS AND PRESENTATIONS
DURING PRESENT AND PAST PROGRAMS

4.1 PAPERS WRITTEN DURING PRESENT PROGRAM

The following is a listing of papers written during the present program.

1. W.D. Kimura, R.D. Romea, S.C. Tidwell, and D.H. Ford, "Progress on Inverse Čerenkov Laser Accelerator Experiment," in Advanced Accelerator Concepts, AIP Conference Proceedings No. 193, C. Joshi, Editor, (American Institute of Physics, New York, 1989), pp. 203.
2. S.C. Tidwell, D.H. Ford, and W.D. Kimura, "Generating Radially Polarized Beams Interferometrically," Appl. Optics **29**, 2234 (1990).
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5. I. Pogorelsky and P. Russell, "Preliminary Tests and Modeling of the 10.6 μm Picosecond Pulse-Formation System," BNL Publication: CAP-ATF-Tech. Note #7.
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7. I. Pogorelsky, A.S. Fisher, J. Veligdan, and P. Russell, "Spatial Dynamics of Picosecond CO₂ Laser Pulses Produced by Optical Switching in Ge," in SPIE Conference Proceedings, Vol. 1413, 21 (1991).
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9. L.C. Steinhauer and W.D. Kimura, "A New Approach for Laser Particle Acceleration in Vacuum," J. Appl. Phys. **72**, 3237 (1992).
10. W.D. Kimura, I. Pogorelsky, L.C. Steinhauer, S.C. Tidwell, G.H. Kim, and K.P. Kusche, "Inverse Čerenkov Acceleration Experiment," to be published in Advanced

Accelerator Concepts, AIP Conference Proceedings (American Institute of Physics, New York).

11. L.C. Steinhauer and W.D. Kimura, "Multistaging and e -Beam Trapping in Laser Particle Accelerators," to be published in Advanced Accelerator Concepts, AIP Conference Proceedings (American Institute of Physics, New York).
12. S.C. Tidwell, G.H. Kim, and W.D. Kimura, "Efficient Radially Polarized Laser Beam Generation Using a Double-Interferometer," to be published in Applied Optics.
13. L.C. Steinhauer and W.D. Kimura, "Multistaging in Free Space Laser Particle Accelerators," to be published in Journal of Applied Physics, Oct. 15, 1993.

4.2 PRESENTATIONS GIVEN DURING PRESENT PROGRAM

The following is a listing of presentations given at conferences, workshops, and other meetings during this present program.

1. J.R. Fontana, W.D. Kimura, and R.D. Romea, "Emittance Considerations in Inverse Čerenkov Accelerators," Spring Meeting of the American Physical Society, Apr. 16-19, 1990, Washington, DC, Paper A11-9.
2. L.C. Steinhauer, R.D. Romea, and W.D. Kimura, "Design Factors for a High-Gamma Inverse Čerenkov Accelerator," Spring Meeting of the American Physical Society, Apr. 16-19, 1990, Washington, DC, Paper A11-10.
3. I. Pogorelsky, A.S. Fisher, J. Veligdan, and P. Russell, "Spatial Dynamics of Picosecond CO₂ Laser Pulses Produced by Optical Switching in Ge," SPIE OE/LASE '91, Los Angeles, CA, Jan. 20-25, 1991.
4. L.C. Steinhauer, W.D. Kimura, and R.D. Romea, "A New Look at Inverse Čerenkov Acceleration and Vacuum Laser Acceleration," 1991 Particle Accelerator Conference, San Francisco, CA May 6-9, 1991, Paper FGR-8.
5. W.D. Kimura, "Radially Polarized Laser Beams and Their Applications," invited seminar presented at University of Southern California, Los Angeles, CA, Nov. 13, 1991.

6. W.D. Kimura, "Inverse Čerenkov Laser Acceleration of Electron Beams," invited seminar presented to Center for Accelerator Physics, Brookhaven National Laboratory, Upton, NY, Feb. 4, 1992.
7. W.D. Kimura and J.R. Fontana, "Inverse Čerenkov Laser Acceleration of Relativistic Electrons," invited seminar presented to University of New Mexico, Albuquerque, NM, Apr. 16, 1992.
8. W.D. Kimura, I. Pogorelsky, L.C. Steinhauer, S.C. Tidwell, G.H. Kim, and K.P. Kusche, "Inverse Čerenkov Acceleration Experiment," Advanced Accelerator Concepts Workshop, Port Jefferson, Long Island, NY, Jun. 14-20, 1992.
9. L.C. Steinhauer and W.D. Kimura, "Multistaging and ϵ -Beam Trapping in Laser Particle Accelerators," Advanced Accelerator Concepts Workshop, Port Jefferson, Long Island, NY, Jun. 14-20, 1992.
10. I. Pogorelsky, "High Power Picosecond CO₂ Laser System for ATF Electron Acceleration Project," Advanced Accelerator Concepts Workshop, Port Jefferson, Long Island, NY, Jun. 14-20, 1992.
11. I. Pogorelsky and I. Ben-Zvi, "Laser Diagnostics for Picosecond e -Beams," Advanced Accelerator Concepts Workshop, Port Jefferson, Long Island, NY, Jun. 14-20, 1992.
12. J. Fontana, W. Kimura, I. Pogorelsky, and L. Steinhauer, "Latest Developments in Inverse Čerenkov Laser Acceleration Experiments and Theory," XVth International Conference on High Energy Accelerators, Hamburg, Germany, Jul. 20-24, 1992, Paper TUE045P.
13. W. Kimura, I. Pogorelsky, G. Kim, K. Kusche, L. Steinhauer, and S. Tidwell, "Latest Results on Inverse Čerenkov Acceleration Experiment," to be submitted to 1993 Particle Accelerator Conference, Washington, DC, May 17-20, 1993.
14. J. Fontana, W. Kimura, and L. Steinhauer, "Design of a 100 MeV Laser Accelerator Based Upon Inverse Čerenkov Acceleration," to be submitted to 1993 Particle Accelerator Conference, Washington, DC, May 17-20, 1993.
15. L. Steinhauer and W. Kimura, "Phase Control in High-Gradient Laser Particle Accelerators," 1993 Particle Accelerator Conference, Washington, DC, May 17-20, 1993, Paper L10.

4.3 PAPERS WRITTEN DURING PAST PROGRAMS

Research related to laser acceleration has been performed at STI since 1983. The work during those earlier years concentrated on examining issues related to scaling high power lasers for laser acceleration applications and on the issue of avoiding optical damage problems by using glancing (grazing) incidence optics. This latter experimental work demonstrated that low absorptance optics (i.e. very high reflectivity) can be fabricated to transport high power laser beams. The results of this work will be very useful in designing multistaged laser acceleration systems.

For completeness, we list here papers written during those past programs.

1. W.D. Kimura and D.H. Ford, "Absorptance Measurements of Metal Mirrors at Glancing Incidence," *Appl. Optics* **25**, 3740 (1986).
2. W.D. Kimura and D.H. Ford, "Photoacoustic Calorimetry System for Glancing Incidence Mirror Absorptance Measurements," *Rev. Sci. Instrum.* **57**, 2754 (1986).
3. W.D. Kimura and T.T. Saito, "Glancing Incidence Measurements of Diamond Turned Copper Mirrors," *Appl. Optics* **26**, 723 (1987).
4. W.D. Kimura, "Absorptance Characteristics of Silver and Silver-on-Copper Mirrors," *Appl. Optics* **26**, 2450 (1987).
5. W.D. Kimura and T.T. Saito, "Measurements of Diamond-Turned Copper Mirrors at Glancing Incidence," in *Reflective Optics*, Dietrich Korsch, Editor, *Proceedings of SPIE*, Vol. 751, 88 (1987).
6. W.D. Kimura, "Measurements of Multilayer Dielectric Mirrors Designed for Glancing Incidence Operation," in *Laser Optics for Intracavity and Extracavity Applications*, P.M. Fauchet and K.H. Guenther, Editors, *Proceedings of SPIE*, Vol. 895, 230 (1988).
7. W.D. Kimura and D.H. Ford, "Glancing Incidence Absorption Measurements in Metal Mirrors," *Laser Induced Damage in Optical Materials: 1985*, Natl. Bur. Stand., Spec. Publ. 746, 227 (1988).
8. W.D. Kimura, F.J. Woodberry, and L.F. DeSandre, "Model Comparisons With Glancing Incidence Measurements of Overcoated Metal Mirrors," *Laser Induced*

Damage in Optical Materials: 1986, Natl. Inst. Stand. and Tech., Spec. Publ. 752, 684 (1988).

9. W.D. Kimura, "Performance of Overcoated Mirrors Designed for Glancing Incidence Operation," in Mirrors and Windows for High Power/High Energy Laser Systems, C.A. Klein, Editor, Proceedings of SPIE, Vol. 1047, 10 (1989).
10. W.D. Kimura, Q.D. Appert, P.N. Arendt, V.E. Sanders, and M.L. Scott, "Tarnishing Measurements of Al_2O_3 Overcoated Silver Mirrors," Laser Induced Damage in Optical Materials: 1988, Natl. Inst. Stand. and Tech., Spec. Publ. 775, 267 (1989).

4.4 PRESENTATIONS GIVEN DURING PAST PROGRAMS

The following is a listing of presentations given at conferences, workshops, and other meetings during the past programs.

1. W.D. Kimura and D.H. Ford, "Glancing Incidence Absorption Measurements of Metal Mirrors," 17th Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, Oct. 28-30, 1985, Session B.
2. W.D. Kimura, "Comparison of Bare Silver and Bare Silver on Copper Mirrors," OSA Workshop on Optical Fabrication and Testing, Seattle, WA, Oct. 21-23, 1986, Paper IV-WB8.
3. W.D. Kimura, F.J. Woodberry, and L.F. DeSandre, "Model Comparisons With Glancing Incidence Measurements of Overcoated Metal Mirrors," 18th Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, Nov. 3-5, 1986, Session D.
4. W.D. Kimura and T.T. Saito, "Measurements of Diamond Turned Copper Mirrors at Glancing Incidence," Society of Photo-Optical Instrumentation Engineers (SPIE) O-E/LASE '87 Reflective Optics Conference, Los Angeles, CA, Jan 11-16, 1987, Paper 751-11.
5. W.D. Kimura, "Measurements of Multi-Layer Dielectric Mirrors Designed for Glancing Incidence Operation," O-E/LASE '88, Laser Optics for Intracavity and Extracavity Applications, Los Angeles, CA, Jan 10-15, 1988, Paper 895-23.

6. R.G. Berger and W.D. Kimura, "Maintaining Phase Matching in Multi-Staged Laser Accelerators," Conference on Lasers and Electro-Optics (CLEO), Anaheim, CA, Apr. 25-29, 1988, Paper WC2.
7. W.D. Kimura, "Laser Accelerators and Glancing Incidence Optics," Keio University Spring Colloquium, Tokyo, Japan, Apr. 2-4, 1988.
8. W.D. Kimura, Q.D. Appert, P. Arendt, V.E. Sanders, and M.L. Scott, "Tarnishing Measurements of Al_2O_3 Overcoated Silver Mirrors," 20th Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, Oct. 26-28, 1988.
9. W.D. Kimura, "Performance of Overcoated Mirrors Designed for Glancing Incidence Operation," O-E/LASE '89, Mirrors and Windows for High Power/High Energy Laser Systems, Los Angeles, CA, Jan. 15-20, 1989, Paper 1047-02.

APPENDIX
PAPERS WRITTEN DURING CURRENT PROGRAM

This appendix contains copies of the papers written during this current program. These papers are referenced elsewhere within this final report.

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