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Spectra Technology

Inverse Cerenkov Laser Accelerator Experiment Annual Report

1990 Annual Report

Submitted to
Department of Energy

Submitted by
Spectra Technology, Inc.

29 March 1991

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**INVERSE CERENKOV LASER ACCELERATOR EXPERIMENT
ANNUAL REPORT**

Submitted to

Department of Energy
Office of High Energy Physics
Dept. of Energy
HEP/ER224/GTN
Washington, DC 20585

by

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29 March 1991

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Section 1

EXECUTIVE SUMMARY

During the past year further progress was made on preparations for the Spectra Technology, Inc. (STI) inverse γ Cerenkov acceleration (ICA) experiment to be performed on the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. Major progress was made in the design and fabrication of the experimental apparatus. This includes the gas cell, where the ICA process occurs, and the optical system that converts the CO_2 laser beam into a radially polarized beam.

During the summer, Dr. Igor Pogorelsky joined the STI ICA team. He is stationed at the ATF and is responsible for the psec CO_2 laser. Since joining us he has finished assembling the oscillator and psec slicer systems. He also performed preliminary tests on the CO_2 amplifier.

In terms of progress on theoretical work, we finished optimizing the ATF ICA design parameters using our Monte Carlo computer simulation. Our optimized design predicts for the ATF conditions that over 50% energy gain should be observed. We published a paper on an improved method of performing ICA by operating near the resonance of a gas. We also began analysis of a method of accelerating particles in a vacuum using a radially polarized beam and axicon focusing. Although this new method can no longer be considered ICA, it has the potential of high acceleration gradients without the drawbacks of gas scattering and gas breakdown. Three papers were published and two conference papers were presented during 1990.

Section 2

BACKGROUND

2.1 BRIEF REVIEW OF INVERSE ČERENKOV ACCELERATION (ICA)

Figure 2-1 shows the basic arrangement of the ICA configuration that is being investigated during this program. A radially polarized laser beam is sent through an axicon optic (either a lens or mirror) that "focuses" the laser beam onto the e-beam traveling through a hole in the optic. (The axicon in reality bends the light onto the e-beam axis rather than focuses it.) The laser light accelerates the electrons over the interaction length L . Within this region there is a gas (e.g. H_2) whose pressure is adjusted such that the phase matching condition, $n\beta\cos\theta_c = 1$, is satisfied (n is the index of refraction of the gas, β is the ratio of the velocity of the electron to the speed of light, and θ_c is the Čerenkov angle).

It has been shown that the maximum energy gain in this configuration is given by

$$\Delta W \propto \sin\theta_c \left(\frac{PL}{\lambda} \right)^{1/2},$$

where P is the laser peak power and λ is the laser wavelength.

Significant focusing of the e-beam is also possible in the geometry shown in Fig. 2-1. The ATF ICA experiment will be primarily examining the acceleration process. Observing e-beam focusing will be difficult for the ATF conditions.

2.2 PROGRAM GOALS

The primary goal of this program is to build upon the earlier ICA experiments performed at Stanford University by demonstrating ICA using the improved design of a radially polarized laser beam and axicon focusing. This is the geometry developed by Fontana and Pantell [J. R. Fontana and R. H. Pantell, J. Appl. Phys. 54, 4285 (1983)]. It has the advantage over the Gaussian

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Fig. 2-1. Basic optical configuration to be used during the inverse Čerenkov acceleration experiments.

laser beam geometry used during the earlier Stanford ICA experiments by providing enhanced acceleration and less potential problems with gas breakdown. Also focusing of the e-beam is possible. As part of this goal, we will be verifying the accuracy of our computer model prediction.

A secondary goal is to investigate other novel operating regimes and/or configurations. For example, acceleration in a vacuum (see Sec. 3.2.3). We will also attempt to investigate any e-beam guiding or focusing effects if the conditions permit. [The relatively low energy of the e-beam (50 MeV) means that scattering of the electrons by the gas is expected to mask any focusing effects during the experiment. This would not be the situation if the e-beam energy were higher (say 1 GeV)]

2.3 GENERAL PROGRAM PLAN

We will be performing the ICA experiment using the 50 MeV linac and psec CO₂ laser at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL). The goal for the CO₂ laser is 100 mJ/pulse in a 10 psec pulse length.

We have been approved for Phase I experiments by the ATF Review Committee. These experiments will use only the CO₂ laser. The primary objectives are to demonstrate the creation of the radially polarized laser beam and to investigate any possible nonlinear effects (e.g. gas breakdown). Analysis performed during this past period indicate that these nonlinear effects are unlikely to occur for the anticipated conditions of the psec CO₂ laser.

The Phase II experiments will demonstrate the ICA process by integrating the e-beam with the Phase I experimental hardware. We plan to use the ATF e-beam diagnostics extensively during this phase.

Section 3

REVIEW OF PROGRESS

3.1 PROGRESS ON EXPERIMENTAL HARDWARE PREPARATIONS

3.1.1 Basic Experiment

Figure 3-1 is a schematic plan view of the ICA experiment located on top of a 4' x 8' optical table. During the Phase I experiment only the optical system and gas cell will be used. The beamline pipe for the e-beam and the associated screens and cameras will be used during the Phase II experiments. Hence, these latter items are not being prepared at this time.

The psec CO₂ laser beam enters from the upper right-hand corner of the table. It then is directed into the radial polarization converter system where the linearly polarized input beam is converted into an annular beam with radial polarization (See Sec. 3.1.3). This annular beam is sent into the gas cell where the ICA process occurs. A cw CO₂ laser is located on the table to help align the optics.

A photograph of the basic experiment is shown in Fig. 3-2. The gas cell is the metal box on the right of the picture. An acrylic enclosure surrounds the top of the table to provide eye protection from the CO₂ laser beam and to prevent dust from settling on the optics.

The basic experiment for Phase I will be located in the ATF Experimental Area as shown in Fig. 3-3. The 4' x 8' optical table will be positioned next to the psec CO₂ laser table for easy access to the CO₂ laser beam. For Phase II the 4' x 8' optical table will be moved through the concrete shielding via a wall portal that has been already built into the shielding. Tentatively, for the Phase II experiments, the plans are to position the table downstream of the grating accelerator experiment.

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Fig. 3-1. Plan view schematic of the inverse Čerenkov acceleration experiment.

Fig. 3-2. Photograph of the Phase I experimental system being assembled at STI.

Fig. 3-3. Plan view of the ATF Experimental Area showing the locations of the ICA Phase I and II experiments.

3.1.2 Gas Cell

The gas cell was designed and fabricated during this past time period. A plan view of it is given in Fig. 3-4. The e-beam enters from the right and travels through a 4- μ m thick diamond film e-beam window. It passes through the central hole of the axicon mirror positioned on the axicon stage. The e-beam traverses through the interaction region and then exits through a hole in the 45° mirror positioned on the mirror stage. From there the e-beam leaves the gas cell through the output e-beam window and goes to the e-beam diagnostics downstream from the gas cell. Since the Phase I experiments will not use the e-beam, during these experiments the e-beam window ports will be sealed with dummy plugs.

The CO₂ laser beam enters the gas cell through the window on the upper left-hand side of the cell. The laser beam reflects off the 45° mirror and goes to the axicon mirror. When the beam reflects off the axicon mirror it is focused down onto the e-beam. The spent laser beam then exits the gas cell by reflecting off the 45° mirror and going through the same gas cell window it entered originally. Of course, the spent beam is still diverging when it leaves the cell. This divergence is advantageous because it minimizes possible feedback problems with the laser beam reflecting back into the CO₂ oscillator/amplifier system.

On the side and top of the gas cell are observation ports. These will be useful for aligning the laser beam to the e-beam, and for detecting any nonlinear effects that may occur within the gas when the psec laser beam passes through it.

3.1.3 Radial Polarization Converter System

The basic principle underlying our converter system is depicted in Fig. 3-5. Two laser beams with intensity profiles given by $I_0 \sin^2 \theta$ and $I_0 \cos^2 \theta$ are combined coherently. The result is a radially polarized annular laser beam.

Figure 3-6 shows a schematic of the radial polarization system that was assembled during this past year. Except for the θ -phase plate, all the optics

Fig. 3-4. Plan view of the gas cell.

$$I = I_0 \sin^2 \theta$$

$$I = I_0 \cos^2 \theta$$

+

=

=

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Fig. 3-5. The coherent combination of $\sin^2 \theta$ and $\cos^2 \theta$ beams yields a radially polarized beam.

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Fig. 3-6. Schematic of the radial polarization converter optical system.

have been received. The linearly polarized input beam passes through a 50/50 beam-splitter. One beam goes through a θ -phase plate, which uniformly retards the beam as a function of azimuthal angle; the other beam passes through a delay plate to match the gross delay caused by the θ -phase plate. The two beams are then sent through a second 50/50 beam-splitter with the result that each beam now has a $\cos^2\theta$ intensity distribution. To make one of the beams have a $\sin^2\theta$ intensity distribution, it is sent through a half-wave plate. The other beam is sent through an appropriate delay plate to match the gross delay of the half-wave plate. Finally, the beams are recombined on a polarizing beam-splitter to create a radially polarized beam. The polarizing beam-splitter is designed to combine most of the energy of the two beams into one beam.

3.1.4 Psec CO₂ Laser System

As mentioned earlier, Dr. Igor Pogorelsky was hired during this past year to work full-time for STI at BNL. His primary responsibility is the psec CO₂ laser system. He has also performed analysis to examine potential nonlinear effects that may occur in the gas cell when the high peak power CO₂ laser beam is sent through it during the Phase I experiments. His initial findings are that these effects, such as stimulated Raman generation and gas breakdown, should not be a problem.

Extensive work has been required on the psec CO₂ laser system because it was delivered to the ATF incomplete and not fully tested. The psec slicing system had to be constructed; amplification of psec pulses had not been performed; and the isotopic mixture and gas reprocessor had not been tested. By hiring Dr. Pogorelsky, the STI ICA program has helped carry part of the cost burden to get the psec CO₂ laser operational. The laser is critical to our program as well as all the other laser acceleration programs planned for the ATF. Without Dr. Pogorelsky, the ATF staff would have had a very difficult time finding the manpower needed to get the CO₂ laser working. Although hiring Dr. Pogorelsky was not originally planned, our program plan was modified and approved by DOE in order satisfy this very important need.

Figure 3-7 shows the psec slicing system constructed by Dr. Pogorelsky for the CO₂ laser system. Two Brewster angle germanium plates are used to slice

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Fig. 3-7. ATF CO₂ laser psec pulse slicing system.

the front and back ends of the laser pulse from the CO_2 oscillator. The reflectance and transmittance of these plates is controlled by laser light from the Nd:YAG laser. This same laser is used to drive the photocathode for the ATF linac.

The CO_2 oscillator is a hybrid single mode grating tuned laser shown in Fig. 3-8. A low pressure "smoothing" tube is switched on before the main discharge. This tube ensures the output is a clean 100 ns pulse with an output energy of ≈ 100 mJ.

Figure 3-9 is a schematic of the multipass mirror system for the CO_2 amplifier. This design should yield 10^5 times amplification of 10 ps pulses with minimal parasitic oscillation. A telescope lens system will transform the Gaussian beam into a super-Gaussian spatial distribution.

3.2 PROGRESS ON THEORETICAL WORK

3.2.1 Model Predictions for ATF ICA Experiment

A Monte Carlo computer simulation of the ICA interaction, which was developed earlier during the STI ICA program, was used to find the optimum design for the ATF ICA experiment. This model was based upon earlier models developed at Stanford University and the University of California, Santa Barbara. It includes all the relevant physics for the ICA interaction such as Rutherford scattering (caused by the gas and e-beam windows), straggling and other inelastic losses, axicon or Gaussian beam focusing, optical beam propagation with diffraction and interference effects, and e-beam emittance, energy spread, and width. The model was validated using available experimental data.

Figure 3-10 shows the model predictions for the final design of the ATF ICA experiment. The actual gas cell dimensions were used, including the "dead" gas space between the e-beam entrance and exit windows, and the axicon and 45° mirrors (see Fig. 3-4). The other parameters were: $\theta_c = 20$ mrad, $L = 20$ cm, laser beam OD = 1 cm, e-beam focused to $r = 0.18$ mm, $P = 1.71$ atm H_2 , and $4\text{-}\mu\text{m}$ thick diamond windows. The left histogram is with the laser off; the right one is with 25 GW of laser peak power delivered to the interaction region.

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Fig. 3-8. Schematic of the hybrid single mode grating tuned CO_2 oscillator. The oscillator produces 100 ns pulses with 100 mJ/pulse in a zero-transverse, single-longitudinal mode and on one selected rotational line.

Fig. 3-9. Schematic of the multipass mirror configuration for the CO_2 amplifier.

- Actual Gas Cell Dimensions Used, Including “Dead” Gas Space
- $\theta_c = 20$ mrad, $L=20$ cm, laser beam OD=1 cm, e-beam focused to $r=0.18$ mm, $P=1.71$ atm H_2 , 4- μ m thick diamond windows

No Laser

Laser Power = 25 GW (Delivered)

Number of Particles = 1000

Fig. 3-10. Model predictions for the final design of the ATF ICA experiment.

(This peak power is 4x less than the planned output from the psec CO₂ laser system and it is meant to be a very conservative estimate of optical losses between the laser and the gas cell.) As can be seen, >25 MeV energy gain on the 50 MeV e-beam is expected, which represents an increase of over 50% and an acceleration gradient of >125 MeV/m.

3.2.2 Analysis of Near-Resonance ICA

One important issue concerning ICA is e-beam emittance growth caused by electron scattering off the gas molecules. Previous analysis has shown that ICA works best in this regards when high- γ e-beams are used (>1 GeV). Still it is desirable to find ways to further reduce gas scattering. Two novel approaches have been examined. The first is to operate with a laser whose wavelength is near the natural resonance of the gas molecule. The second is to operate in a vacuum, but limit the phase slippage of the electron. (This latter idea originated from Dr. David Sutter at DOE. It is no longer an ICA process, but it uses the same optical system as ICA.)

Details of the near-resonance ICA can be found in the reprint in Appendix A of the paper we published this past year. Briefly summarizing the results, we found that significant acceleration gradients (>5 GeV/m) are possible using gas pressures of ≤ 0.01 atm. These results are very encouraging and warrant further experimental verification sometime in the future.

3.2.3 Laser Acceleration in a Vacuum

The idea of accelerating electrons in a vacuum is not new. What is new is using a radially polarized beam focused by an axicon. This basic geometry is shown in Fig. 3-11. At the entrance to the axicon focus region the electron is on the forward part of the EM wave phase. At the end of the focus region the electron has slipped to the back part of the phase, but it has still maintained positive acceleration during this time. What differentiates the axicon focusing system from previous optical systems proposed to accelerate electrons in vacuum is the ability to control this slippage distance. Optimum interaction lengths of order 1 cm are predicted with acceleration gradients of ≈ 2.7 GeV/m assuming a 10^{12} W laser peak power.

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Fig. 3-11. Vacuum accelerator concept. The upper right-hand drawing depicts the basic optical configuration with a radially polarized beam being focused by an axicon mirror onto the e-beam in a vacuum. The lower graphs show the phase relationship of the electron with respect to the EM wave.

We are currently in the process of writing a paper on our analysis. We will also be presenting our results at the upcoming 1991 IEEE Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991. Thus far the results appear very encouraging and could lead to some exciting new possibilities in the field of laser acceleration.

Section 4

FUTURE PLANS

Figure 4-1 is an update of the ATF ICA program schedule. Assembly and pretesting of the hardware to be used for the Phase I ATF ICA experiments will continue into the spring of '90. When the ATF is ready to accept our equipment for the Phase I experiments, it will be shipped and set up at the ATF. It is not certain at this time when the ATF will be ready. Assuming that they are ready by this summer, then the Phase I experiments can be performed. Depending on the results of the Phase I experiments, plans for Phase II will be modified accordingly. The schedule shown in Fig. 4-1 for the Phase II preparations and experiments assumes the Phase I experiments run on schedule.

Our theoretical work will continue during this time. As mentioned we are currently preparing a paper on our vacuum acceleration analysis. We also plan to examine the possibility of performing some type of vacuum acceleration experiment on the ATF ICA system. Options include operating the experiment without gas or e-beam windows using an interaction length of 20 cm. This interaction length is $\approx 20\times$ longer than desired, which significantly reduces the amount of acceleration. However, it may be still possible to detect some nonzero acceleration, which would be evidence that the vacuum acceleration is occurring. Another option would be to modify the gas cell to reduce the interaction length.

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Fig. 4-1. Schedule update for the ATF ICA program.

Appendix A

PAPERS WRITTEN DURING THIS PAST PERIOD

This appendix contains reprints of papers published during this past year. Their citations are listed below:

- 1) S. C. Tidwell, D. H. Ford, and W. D. Kimura, "Generating Radially Polarized Beams Interferometrically," Appl. Optics 29, 2234 (1990).
- 2) R. D. Romea and W. D. Kimura, "Modeling of Inverse Čerenkov Laser Acceleration With Axicon Laser-Beam Focusing," Phys. Rev. D 42, 1807 (1990).
- 3) L. C. Steinhauer and W. D. Kimura, "High- γ Inverse Čerenkov Acceleration in Resonant Media," J. Appl. Phys. 68, 4929 (1990).

In addition to these papers we also presented during this past year the following conference papers:

- 1) J. R. Fontana, W. D. Kimura, and R. D. Romea, "Emittance Considerations in Inverse Čerenkov Accelerators," APS Spring Meeting, Washington DC, Apr. 16-19, 1990.
- 2) L. C. Steinhauer, R. D. Romea, and W. D. Kimura, "Design Factors for a High Gamma Inverse Čerenkov Accelerator," APS Spring Meeting, Washington DC, Apr. 16-19, 1990.

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