Inverse Cerenkov Laser Acceleration Experiment at ATF

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Abstract

Inverse Cerenkov laser acceleration was demonstrated using an axicon optical system at the Brookhaven Accelerator Test Facility (ATF). The ATF S-band linac and a high power 10.6 μm CO_2 laser were used for the experiment. Experimental arrangement and the laser and the electron beams synchronization are discussed. The electrons were accelerated more than 0.7 MeV for a 34 MW CO_2 laser power. More than 3.7 MeV acceleration was measured with 0.7 GW CO_2 laser power, which is more than 20 times of the previous ICA experiment. The experimental results are compared with computer program TRANSPORT simulations.

Introduction

After more than a decade of theoretical and conceptual studies, many advanced acceleration schemes have entered a new age of experimental demonstration. [1] The Brookhaven Accelerator Test facility is a dedicated laser linac complex for laser acceleration and coherent radiation generation experiments. One of the laser acceleration experiments at ATF is the Inverse Cerenkov Acceleration (ICA) experiment.[2]

Inverse Cerenkov acceleration occurs when an electromagnetic wave and electron beam travel in a medium satisfying the condition,

$$n\beta \cos\theta_c = 1. \tag{1}$$

where n is refraction index of the medium, β is the the ratio of electron velocity to the speed of light, and θ_c is the angle between the electron beam and EM wave propagation direction. The earlier Stanford experiments[3] demonstrated the ICA effect. But the arrangement employed in those experiments has the deficiencies that, the coupling between the laser and e-beam is inefficient, and interaction length is limited. A much more attractive scheme was proposed later by Fontana and Pantell[4] for ICAusing an axicon optical system (Fig.1). The electron beam is cylindrically centered on the z-axis. Hydrogen gas provides phase matching between the laser and electron beam. A radially polarized laser beam is focused onto the z-axis at the Cerenkov angle θ_c by the axicon lens. The longitudinal electric field component E_z at the axicon lens focus accelerates electrons. The ideal maximum energy gain for the axicon lens ICA can be estimated by,[4]

$$\Delta W \approx 68.8 \left(\frac{PL}{\lambda}\right)^{1/2} sin\theta_c. \tag{2}$$

where P is the laser power, L is the interaction length, and λ is the laser wavelength.

The potential and advantage of the axicon ICA has been further studied,[5] and the first experimental demonstration of axicon ICA was carried out at the ATF. We will first briefly describe the experimental setup of the ICA experiment, then the experimental results will be presented. Finally computer program TRANSPORT was used to explained the experimental observations.

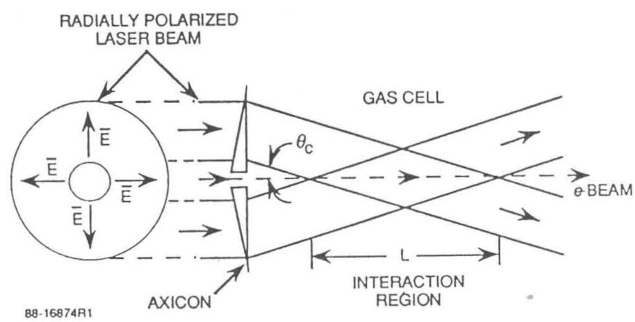

Figure 1: Axicon ICA schematic.

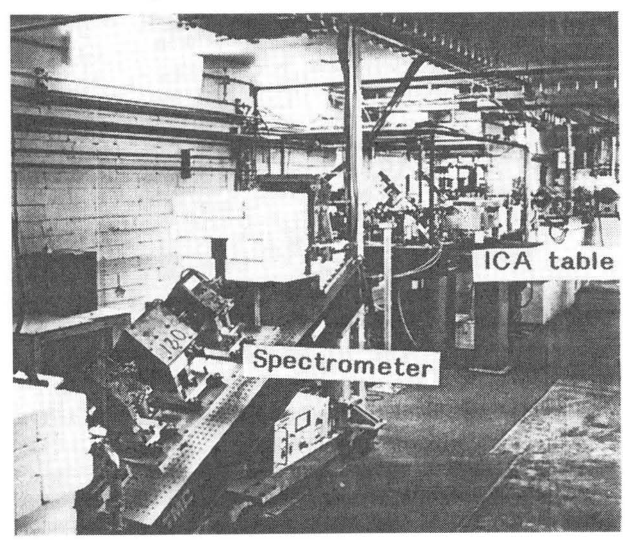

Figure 2: Inverse Cerenkov acceleration beam line.

Experiment arrangement

The ATF consists of a one-and-half cell photocathode RF gun, two sections of S-band SLAC type linac, experimental area, a Nd:YAG laser system and a CO_2 laser. The

Nd:YAG laser is phase locked with the linac RF system, and is used to drive the photocathode RF gun and switch the short CO_2 laser pulses. The ATF CO_2 laser[6] is used as drive source for the ICA and other laser acceleration experiments. The photocathode RF gun and the linac is capable of producing a 50 MeV bright electron beam.

There are three experimental beam lines at the ATF, the ICA experiment is located on the laser acceleration beam line (Fig.2).[7] The main components of the ICA experiment are, a double interferometer to convert linearly polarized CO_2 pulses into radially polarized ones,[8] a hydrogen gas cell, an axicon optical system (Fig.3), and laser and electron beam diagnostics. A spectrometer consisting of a dipole, a quadrupole triplet and a beam profile monitor (BPM) was used to analyze the electron beam energy. The axicon angle of the axicon mirror is 10 mrad, which is half of the Cerenkov angle θ_c. The interaction length during the ICA is about 12 cm.

Since ICA is the first experiment utilizing the ATF 50-MeV beam line, a large amount of the effort was devoted to commissioning the ATF linac and electron beam transport line. The ATF laser acceleration line is made up of a emittance selection line, a quasi-telescope achromatic transport line, a final focusing system and spectrometer. Most quadrupole magnets used for these lines are surplus SLAC quadrupoles designed for much higher beams energy. The remanence field and hysteresis made their usage difficult. A strategy was adopted to simplify the electron beam optics and to use as little as possible those quadrupoles. We also designed an automatic degaussing program for the electron beam line commissioning.

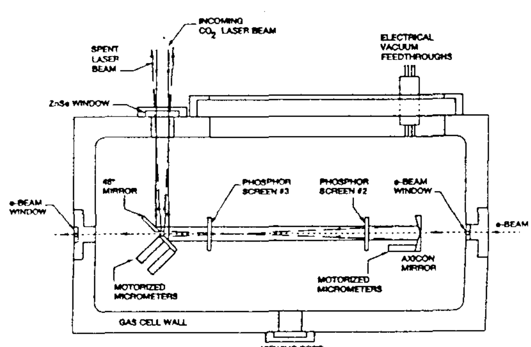

Figure 3: Inverse Cerenkov acceleration gas cell.

The most basic requirement for the success of the ICA experiment is the synchronization between the electron beam(bunchlength$\approx$ 10 ps) and CO_2 laser pulses(from ns to couple hundreds ps). This includes both spatial and temporal overlap. The Spacial alignment was aided through the usage of a HeNe laser aligned with the electron beam, and an IR camera was used to view the CO_2 laser beam. The CO_2 laser pulses were detected by a fast photodiode with a couple hundreds ps rising time. The electron beam timing was determined by a Hamamatsu photomultiplier tube R1635. The PMT was inserted into a hole of a lead brick. The small opening for x-ray detection was covered by aluminum foil. The PMT detected x-rays generated by the electron beam when it passed through the gas cell output window. The delay time of the PMT was calibrated with a stripline monitor which had a rise time of 100 ps. The accuracy of the PMT was measured to be a 150 ps with an electron pulse train with exact time interval of 24.5 ns.

Inverse Cerenkov Acceleration

The first ICA experiment at ATF was performed using modest CO_2 laser power. This enabled us to use Pockels cell to generate 10-ns CO_2 laser pulses, and to test the laser and electron beams synchronization. Another important advantage of this configuration was that all accelerated electrons felled within our spectrometer acceptance.

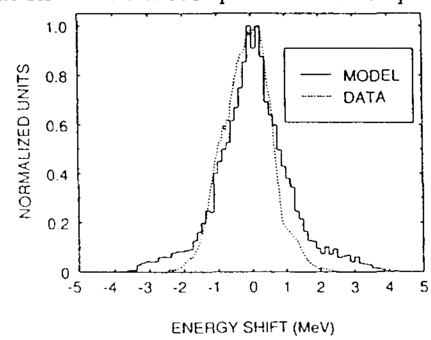

Figure 4: Electron energy spectrum for 0.7 GW laser power.

To further increase the electron acceleration, the CO_2 laser power was increased to about 1 GW using a Nd:YAG laser stimulated semiconductor switch. The pulse length of the CO_2 laser was about 300 ps. Since more than 5% electron beam energy change was expected, the intensity of the accelerated electron signal was two orders of magnitude smaller than without acceleration. We adjusted two quadruples used in the spectrometer to reduced the electron beam spot size and dispersion. A remote controllable image intensifier was installed with the BPM of the spectrometer to increase the sensitivity of the detection.

Instead of observing the spread electron beam filled the BPM screen, we only observed the electron beam signal reduction and the beam profile distortion. To fully measure the energy change in the electron beam due to ICA, we scaled the dipole and the quadrupole magnets simultaneously, while keeping the gain of BPM image intensifier constant. Fig.4 plots the reconstructed experimental data against computer model predictions.[5] The maximum electron acceleration was measured to be 3.7 MeV at the maximum gain of the BPM image intensifier. This corresponds to 31 MV/m acceleration gradient.

To understand the experimental observation, a charge particle beam optics code TRANSPORT was used to study the electron beam transport and the ICA process. For the cylindrical symmetric axicon lens employed in ICA experiment, the laser field in the interaction region can be described by TM_{0n} modes,[4]

$$E_z(r) = E_0 J_0(k_c r)$$
$$E_r(r) = -i\left(\left(\frac{\omega}{\omega_c}\right)^2 - 1\right)^{1/2} E_0 J_0'(k_c r) \qquad (3)$$
$$H_\phi(r) = -i\frac{n\omega}{\omega_c}\sqrt{\frac{\epsilon_0}{\mu_0}} E_0 J_0'(k_c r).$$

where E_0 is a constant, ω_c is the cut-off angular frequency for the mode, and J_0 and J_0' are the Bessel function of the first kind and its derivative. The acceleration element in TRANSPORT represents a travelling wave linac, which is dominated by the TM_{01} mode. So to first order, the TRANSPORT acceleration element behaves similar to the ICA from a beam dynamics point of view. The approximation used in TRANSPORT is not valid for electron bunch length much longer than the acceleration wavelength. For a 10 ps electron beam, the effect of ICA is equivalent to increasing in the energy spread while keeping the reference particle energy constant. We simulate this ICA effect by setting the phase of TRANSPORT acceleration element to 90 degree from peak acceleration while using the same interaction length and total energy gain as of that of the ICA. By varying the wavelength of the TRANSPORT acceleration element, we can produce an electron beam that had the same energy spread as the ICA. We can also simulate the edge focusing of TM_{0n} modes by using the following equation,[9]

$$\frac{1}{f_0} = \frac{1}{2}\frac{\gamma'}{\gamma}. \qquad (4)$$

where f_0 is the focal length of the thin lens, γ' is the average acceleration gradient and γ is the beam energy. We also can simulate the focusing (or defocusing) effect during the ICA using equation given in reference.[5]

Figure 5 plots vertical electron beam profile from the entrance of the vertical bending magnet of the spectrometer to the BPM. It can be seen that any electrons with energy spread larger than 1% will be collimated by the beam pipe (ID 2 cm). The distortion observed is caused by the asymmetry in ICA focusing (for deaccelerated particles) and defocusing (accelerated particles). The only correct way to detect the ICA effect for this beam optics is to scale all magnets in the spectrometer as we did it in the experiment.

Conclusion

We have successfully demonstrated an axicon optical system Inverse Cerenkov laser accelerator. The highest laser acceleration was observed at 3.7 MeV, corresponding to 31 MV/m. We are now in the process of upgrading ATF CO2 laser system, preparing for a 100 MeV inverse Cerenkov laser acceleration demonstration experiment.

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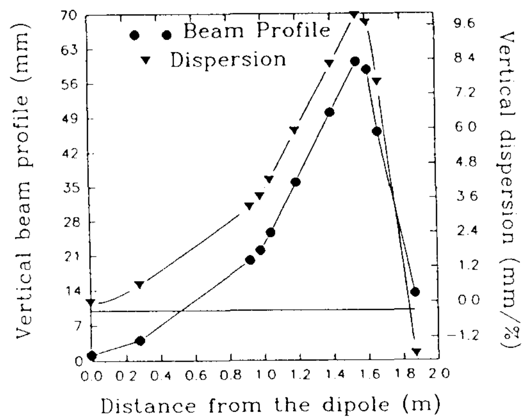

Figure 5: Vertical electron beam profile and dispersion in the spectrometer.

References

1. Advanced Accelerator Concepts, Ed. by J.S. Wurtele, AIP Conf. Proc. 279(1993).
2. W.D. Kimura, "Inverse Cerenkov Acceleration Experiment", p.135 -154, BNL - 47000 ed. by H.G. Kirk(1991).
3. J.A. Edighoffer et al, Phys. Rev. **A23**, 1848(1981).
4. J.R. Fontana and R.H. Pantell, J. Appl. Phys. **54**(8), 4285(1983).
5. R.D. Romea and W.D. Kimura, Phys. Rev. **D(42)**, 1807(1990).
6. I. Pogorelsky, " High Power Picosecond CO_2 laser system for ATF Electron Accelerator Project", AIP Conf. Proc. 279, p608(1993).
7. X.J. Wang and H.G. Kirk, "The Brookhaven ATF Low-Emittance Beam Line", Proc. of 1991 Part. Accel. Conf, p604(1991).
8. S.C. Tidwell et al, Appl. Optics **32**, p.5222(1993).
9. R.H. Helm et al, "Beam Dynamics", The Stanford Two-Mile Accelerator, Ed. by R.B. Neal(1968).