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Spectra Technology

INVERSE CERENKOV LPA EXPERIMENTS

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PROGRESS REPORT ON CURRENT PROGRAM

2.1 COLLABORATION WITH UCSB

During this year, Spectra Technology Inc. (STI) has collaborated with Prof. Jorge Fontana, of the University of California, Santa Barbara (UCSB), to examine the technical trade-offs involved in the choice of an inverse Cerenkov (IC) demonstration experiment. Prof. Fontana's responsibilities have been to address the rationale and requirements for the demonstration experiment, including an evaluation and selection of the most attractive test site and facilities. At STI, the options available for the laser and optics, needed to satisfy these requirements, are being examined. The goals of this IC demonstration experiment are to show the applicability of the IC mechanism to electron beam focusing and acceleration.⁽²⁻¹⁾

Prof. Fontana's⁽²⁻²⁾ approach for implementing the IC mechanism is a conically-focused (axicon-type) laser beam whose electric fields are radially polarized to increase the accelerating fields at the focal spot and to confine the radial extent of the electron bunch. STI has initiated an investigation into two approaches for achieving the radial profiles; they include:

(1) Create the electric field distribution in the laser cavity

or

(2) Transform a linearly polarized beam to that desired with an appropriate optical system.

The first approach can be achieved using lasers with unstable resonator cavities that employ conical elements. These cavities have been designed and constructed by several investigators^(2-3,2-4) for annular gain laser systems. The second approach can be achieved using a discrete number

of out of plane reflections to rotate the polarization. However, the simplest implementation of this technique requires that the final beamlets each have their polarization rotated slightly, as shown in Figure 2-1. This is a cumbersome technique, and it may be difficult to match the phase front of each beamlet so that the composite beam is uniphase. As an alternative, STI is examining the possibility of finding an optical element, perhaps a set of several surfaces, that transforms linear polarization into a radially polarized beam in a uniform and continuous manner around the annular aperture. An alternative is to use polarization rotating optically active materials such as AgGaS_2 or AgGaSe_2 . At $10.6 \mu\text{m}$, these materials can rotate the polarization either through the optical activity of the material itself or by applying an electric field. An interesting possibility is the use of a spiral shaped material that would continuously rotate the polarization vector. Such a scheme may be workable if the phase front of the beam can be maintained over the full aperture.

2.2 GLANCING INCIDENCE MEASUREMENTS

With the development last year of a technique⁽²⁻⁵⁾ for measuring the glancing incidence properties of mirrors, there have been a number of successful applications of the technique during this program. Last year, the glancing incidence absorptance properties, of bare metal mirrors, were investigated.⁽²⁻⁶⁾ During those measurements, it was found there can be a significant deviation away from Fresnel theory depending on the condition of the mirror surface (e.g. new versus tarnished).

Bare silver is of great interest because of its very high reflectivity in the visible. However, once exposed to room air, the silver tends to tarnish rapidly, which degrades its performance. A novel scheme⁽²⁻⁷⁾ for reducing the tarnishing rate is to include a copper film underlayer beneath the silver. The absorptance characteristics of a bare silver and a bare silver on copper mirror were measured as a function of angle of incidence and exposure to room air.⁽²⁻⁸⁾ New and untarnished, it is found that the silver mirror tends to have lower absorptance at all

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Figure 2-1. Composite Annular Beam Made from a Number of Discrete Beam Lines with the Polarization Distribution as Shown. The phase of each beam must be matched around the annulus.

angles than the silver/copper mirror. However, the silver mirror does tarnish more rapidly than the silver/copper mirror. After 60 days, the silver/copper mirror has lower absorptance at normal incidence than the silver mirror. At glancing angles of incidence, both mirrors tend to have the same absorptance. This is because, at glancing incidence, the silver mirror tends to have lower absorptance when untarnished, but as both mirrors tarnish, the silver/copper mirror absorptance does not decrease with angle as well as the silver mirror.

Additional glancing incidence measurements were performed during a program sponsored by Lawrence Livermore National Laboratory. The measurements are of diamond turned copper mirrors.⁽²⁻⁹⁾ The interest here is the affect on the orientation of the diamond turned grooves with respect to the polarization of the laser beam. It is found there is an appreciable dependence on groove orientation, enough to recommend that the grooves be oriented parallel to the plane of incidence for s-polarized light.

The work being performed, during the current DOE program, centers around the issue of dielectric overcoats on metal mirrors. Glancing incidence measurements of multi-layer dielectric and single layer overcoated mirrors have been obtained. In addition, we have been working with Frank Woodberry of the Rockwell International Science Center, and Louis DeSandre of the Naval Weapons Center, China Lake, to compare our experimental data with their thin film codes.⁽²⁻¹⁰⁾ These results and an update on the present status of the current experimental program are given in Appendix A.

Summarizing the results to date, dielectric films can dramatically affect the absorptance characteristics of mirrors at glancing angles of incidence. For example, it has been shown that a multi-layer dielectric mirror can significantly reduce the absorptance of p-polarized light at high angles of incidence. Normally, for bare metals, p-polarized light has high absorptance due to the Brewster angle effect. This has important implications with regard to IC applications, because the IC interaction

generally requires p-polarized light reflecting off the guiding mirrors. (2-1)

It is also shown that single layer dielectric films may protect silver mirrors from tarnishing, but they also alter the absorptance characteristics of the mirror. It may be possible, using the predictions of models, to design a single layer dielectric film which not only protects the silver mirror but also enhances the reflectivity of either s or p-polarized light.

2.3 STAGING STUDIES

In any type of laser particle accelerator, regardless of the type of interaction involved between the laser and accelerated particles, careful consideration of the timing, phasing, and alignment between laser and particle beams must be incorporated in a complete system study. Analysis of these problems has been initiated and a survey of preliminary results follow.

Since there are physical limitations on the lengths of laser-particle interaction regions, a practical accelerator approach is to use staging, whereby acceleration is achieved incrementally through individual sections to accumulate the desired total energy. Each section would then consist of a laser and its power supply, the interaction medium (gas, plasma, grating, etc.), as well as the particle and laser beam transport and control devices.

The studies performed thus far have analyzed the interrelations between components in a laser particle accelerator, with emphasis on the beat wave device. Since timing, phasing, and alignment between laser and particle beams must be provided for each stage, a system of detectors, triggers, phase shifters, and alignment controls must be employed to connect the stages together for optimum total acceleration. Figure 2-2 shows a schematic of such a system, where particle and laser beam lines are

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Figure 2-2. Schematic of LPA Staging.

represented by solid lines, and control signals for adjusting timing, phase, and alignment are shown as dotted lines.

2.3.1 Timing Control

The problem of timing the particle bunches and short laser pulses so that they temporally overlap becomes quite severe when both pulse lengths are on the order of picoseconds. For instance, an expansion of 0.45 mm between two mirrors corresponds to a delay of 1 psec for a laser pulse. Thus, after adjustment of optical and particle beam path lengths to meet overlap requirements, active stabilization techniques using interferometers are needed to combat changes in path lengths due to mechanical motions, temperature induced strains, etc. Once path lengths are set to achieve proper timing, changes could be kept to less than an optical wavelength using this technique.

2.3.2 Phase Control

A technological problem, common to all particle accelerator schemes, is the requirement that particle bunches enter the accelerating region with the appropriate phase relation to the accelerating wave. Since an electron bunch, a half wavelength out of phase, will be decelerated instead of accelerated, this problem becomes more severe as the wavelength of the accelerating field becomes shorter. This problem is exacerbated when the bunches must traverse more than one accelerator stage to achieve the desired final energy, as would probably be the case for either a Beat Wave Accelerator (BWA) or Inverse Cerenkov Accelerator (ICA), which have physical limitations on individual stage lengths.

The method for achieving proper timing as described above is adequate for maintaining correct phase given a technique for determining the phase between particles and wave. One way of determining the phase is by using the information imprinted on the driving wave by the particles. In the BWA, the particle bunches leave a wake in the plasma behind them, which

interferes with the driving plasma wave in a phase dependent way. The laser radiation will have a similar imprint of this information, and the exiting laser beam can be analyzed and used to adjust optical path lengths to give the optimum phase.

Likewise, in the ICA, the particle bunch will emit Cerenkov radiation, which will interfere with that used for acceleration, so that again a phase relationship can be determined.

Since information carried on a pulse in linear motion at the speed of light can never be used to externally affect that pulse, the alternative is to use that information upstream on a later arriving pulse. Thus, given particle and laser pulses with consistent temporal spacing, information of phase mismatch downstream can be used to correct for the same mismatch that would exist upstream. That is, by detecting phase using either of the above methods at the output end of each stage, and sending a correcting signal back to the path length adjuster at the input end of the stage, optimum phase control can be maintained, provided the pulse-to-pulse timing jitter is less than the allowed phase jitter. This puts a maximum limit on the allowable timing jitter of the particle bunch which must be synchronized to less than an accelerator wave period.

Although jitter ≤ 1 psec is needed, very low jitter between the electron bunches and the accelerating laser can be obtained by optically synchronizing the accelerating laser with the laser used to drive the photocathode for the electron gun source. (2-11)

2.3.3 Alignment

A generic accelerating wave can be described by a potential energy field as in Fig. 2-3, which shows that there are both accelerating and decelerating, focusing and defocusing regions. For acceleration, the desired position of the particles is on axis, in both the accelerating and focusing region (phase between $\pi/2$ and π in the figure). For pure

Figure 2-3. Potential Energy Field of Generic Accelerating Wave.

focusing, the particle beam should be centered on the axis (of course, it has a finite width and divergence), with phase π .

Both the BWA and the ICA have a preferred axis for particle propagation, which is defined by the axis of the laser beam. Deviation from the optimum direction and position of the particle beam will result in reduced performance. Given that the phase of the particles is correct, deviations will cause the particles to execute oscillations about the axis, with period β/c , where β is the so-called beta function, or wavelength of the oscillation along the axial direction. The beta function is dependent on the field strength, particle energy, and transverse width of the potential energy field. A particle bunch will emit both coherent and incoherent radiation at frequency c/β and its harmonics. The incoherent component is caused by the finite emittance of the particle beam, and the coherent part has as its source the motion of the whole bunch as it oscillates off-axis due to poor alignment.

Misalignment is therefore detected at the end of each stage by using the resulting coherent radiation. Active stabilization of the laser optics by control signals from the radiation detectors will then maintain the juxtaposition of the laser and particle beam axes.

2.3.4 Stage Length

The stage lengths are set by the minimum of:

- 1) The "phase slip" length over which a particle will either run ahead or lag behind the accelerating wave by half a wavelength (in actuality, since both of the accelerating schemes mentioned also have transverse focusing/defocusing properties, acceleration and focusing only occur for one quarter of a wavelength, which sets the limit on the phase slip length).
- 2) The laser energy depletion length: for the BWA, corresponds

to the length the initial laser pulse transfers energy to the plasma wave as it traverses the accelerator stage coincident with the particle bunch.

- 3) The laser beam Rayleigh range or line-focus length: for the ICA, this corresponds to the fact that the converging radially polarized laser beam cannot be kept focused to sufficient intensity or with the desired polarization properties for an indefinite length.

For the BWA, if the laser intensity is above a certain threshold, ⁽²⁻¹²⁾ the laser light will self-focus due to the refracting influence of relativistic oscillating electrons in the plasma. This means that the Rayleigh range for free space propagation is not the limit on stage length, because the laser beam remains tightly focused with a radius approximately equal to the beat wavelength. Pure relativistic ... self-focusing has yet to be demonstrated, but is expected to be shown when the UCLA Mars laser is fully operational. ⁽²⁻¹³⁾

If the laser beam of two frequencies can be propagated without distortion, in its self-focused channel, then the limit on stage length is either the laser depletion length, or particle slip length, as mentioned above. These two lengths turn out to be approximately equal when analysis is made of the three wave interaction. ⁽²⁻¹⁴⁾

In general, though, the two initial laser frequencies cascade down into lower frequencies by multiples of the plasma frequency as well as upward in the "Raman cascade". Work yet to be performed may show that phase mismatches between the modes could either advance or retard the phase of the generated plasma wave so that the phase slip length, as referred to previously, needs to be respectively increased or decreased.

Regardless of the true phase slip length, a converging laser beam with a power greater than the self-focusing threshold will become trapped

in a channel until the laser energy is depleted to the extent that the self-focusing threshold will cease to be met, at which point the laser beam will start to diverge from the particle beam. The high intensity beam in the self-focusing region should also ionize the background neutral gas by multiphoton ionization or Keldish tunneling, yielding a uniform plasma of density equal to the original gas density. (2-15)

The optical system for this process must be compact in the longitudinal direction to minimize overall accelerator length, and laser fluence must not exceed damage limits on optics (including windows for the plasma chamber). Figure 2-4 shows an arrangement using glancing incidence mirrors to meet these conditions for light propagation.

Figure 2-4. Optical System for Compact BWA Section.

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