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X-RAY INSTRUMENTATION IN THE LLL LASER-FUSION PROGRAM

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ABSTRACT

The LLL Laser-Fusion Program includes an active experimental effort to measure the distributions in energy, space and time of pulses of soft X-rays (1.2-10 keV) radiated by laser-induced plasmas. Requirements for high resolution in these measurements clearly preclude the use of conventional X-ray diagnostic techniques. We will describe the following as examples from our program of advanced X-ray instrument development.

1. Wavelength-dispersive spectrographs with fractional-electron volt resolution at several keV and imaging systems with 3 micron resolution over a 100 micron source.
2. Advanced solid state X-ray sensors that recover data from these instruments in a more expedient manner than photographic film.
3. Microcomputer-controlled stand-alone spectrograph data systems and minicomputer-based integrated systems that can deal with the large array of data generated by the high resolution instruments.
4. An electrostatically-deflected X-ray streak camera with moderate spectral and spatial resolution and a timing resolution of better than 15 ps.

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INTRODUCTION

The LLL Laser-Fusion Program supports an active experimental plasma diagnostics effort. High resolution X-ray spectral and imaging measurements are an integral part of this program. The unconventional nature of the X-ray source, a hot, dense, very short-lived plasma created by laser irradiation of a glass fusion-fuel pellet, has required the development of unique instruments. These instruments must have high spectral and spatial resolution to be of value in the characterization of the plasma. We will describe a low energy X-ray crystal spectrometer with several electron-volt resolution at 2 keV, and an imaging instrument known as the X-ray microscope with 3 μm resolution over a 100 μm object. The use of photographic film as a detector in these instruments produces incumbent losses in quantitative accuracy and expediency in the recovery of data. We have therefore investigated as replacements for the film several advanced self-scanning solid-state detectors. Each detector measures the X-ray dose in silicon at a large number of discrete photosensors, whose responses are serially-organized and read out by integral (on-chip) scanning circuits. They include a linear self-scanning photodiode array (SSPA) for the crystal spectrometer, and CCD and windowless silicon-target vidicon (S-TV) two-dimensional sensors for the X-ray microscope. Our work to date has shown these detectors to be competent as the primary sensors for the two instruments.

Digital data retrieval systems have been developed to handle the large volume of data generated by the SSPA sensor after a transient laser event. A stand-alone system in place with the crystal spectrometer uses a microcomputer to mediate the loading of the SSPA signal levels into solid-state memories and to provide versatility in data I/O operations. An advanced system, under development, will be CAMAC-implemented. Elementary arithmetic required to normalize the laser event data by predetermined sensitivity factors is performed by the CPU of each system.

As we plan for a digital system for the two-dimensional sensors, we must contend with an array of data at least a hundred times greater than that for the SSPA. The loading of digitized levels into solid-state memories may not be cost effective, and direct loading into minicomputer core would be an unacceptable burden on the system. We have considered semi-permanent analog storage with magnetic discs or TV scan conversion memories.

We will briefly introduce another unique X-ray diagnostic instrument, the X-ray streak camera, which is thoroughly discussed by L. Coleman elsewhere in these proceedings. The streak camera has moderate spectral and spatial resolution and a timing resolution less than 15 ps.

LASER-FUSION EXPERIMENTS

The aim of the LLL Laser-Fusion Program is to extract energy from an inertially-confined thermonuclear reaction. In current experiments a small amount of fuel, consisting of an equimolar mixture of deuterium and tritium gases encapsulated in a glass microsphere like that shown in Figure 1, is compressed and heated by a high brightness laser beam with intensities in the target plane exceeding 10^{15} w/cm². If electron densities of the order of 10^{22} e/cm³ and temperatures near 1 keV are achieved, D-T fusion reactions proceed, releasing energy in the form of fast neutrons and alpha particles.

The diameter of the fuel-bearing microsphere shell is typically 80 μ m and its wall thickness is about 3/4 μ m. The D-T gas load has a density of 2 to 5 mg/cm³. A series of large-aperture Nd/yag glass lasers has been developed to irradiate the fusion targets with short, bright beams of 1.06 μ m light. For example, the CYCLOPS facility laser, shown in Figure 2, nominally delivers 60 joules of energy to the target in a single 80 ps (FWHM) pulse ¹.

The condition of the plasma generated at the fusion target and the efficiency of the thermonuclear burn are diagnosed by a wide variety of instruments. These include scattered-light detectors, fast ion calorimeters, and neutron and alpha particle detectors that measure the number of reactions and ion temperatures associated with the thermonuclear burn. The laser-produced plasma is an intense source of X-rays, with 5% or greater of the absorbed energy appearing as X-rays with energies above 100 eV. Figure 3 is an example of a measured spectrum. Components of the spectrum include thermal and non-thermal bremsstrahlung at high energies, free-bound continua and line spectra radiated by the heavier elements (such as silicon in the glass microshell) at lower energies ². The distribution of the thermal bremsstrahlung, which is routinely measured by broad-band absorption edge detectors, leads directly to an estimate of the plasma time-averaged electron temperature ³.

Due to their high resolution in the middle region of the spectrum, crystal spectrometers are used in our laboratory to obtain information about the line spectra from which inferences about the plasma conditions may be made. The relative

intensities of principal diagram lines due to different ionization species of the same element (silicon, for example) are sensitive to the plasma ionization-recombination equilibrium and hence the electron temperature. The intensity ratios of various satellite lines provide a check on the extent to which equilibrium is achieved. Finally, the electron density can be inferred from the correlation of line width measurements to elaborate models for broadening mechanisms in the plasma ⁴.

While the data obtained with the crystal spectrometer on the microscopic condition of the plasma can eventually lead to an improvement in the laser-fusion technique, the X-ray microscope yields more immediate information about the impact of target parameters and laser irradiation conditions. Figure 4 is a microscope image of a target in an energy band centered at 2.5 keV showing the initial outline of the shell where it was heated by the laser beams and the imploded remnants at the time of maximum compression. This picture indicates the degree of compression of the D-T fuel and whether the necessary symmetry of implosion was obtained. The measurement of compression obviously requires as fine a spatial resolution as possible.

CRYSTAL SPECTROMETER

Due to the short duration of the X-ray pulse from a laser-produced plasma, counting techniques and solid state detectors cannot be used to obtain high resolution spectra. We must rely instead on wavelength-dispersive instruments such as grating and crystal spectrometers. Figure 5 is a schematic of a spectrometer designed to observe the line spectra of ionized silicon in the energy region from 1.8 to 2.3 keV ⁵. Photon energy discrimination is obtained by using a flat potassium acid phthalate (KAP) analyzing crystal. A 2" long crystal is inclined at an angle of 13.2° with respect to the line of sight to the laser target, located 5" forward of the crystal. Radiation diverging from the target can fall on the crystal at angles of grazing incident varying from 11.6° to 15.0°. At each point on the crystal the local angle of incidence and the Bragg diffraction condition determine a unique small range of photon energies that will be reflected with high efficiency to a detector plane containing either film or the SSPA detector.

The range of photon energies that can reach a point in the detector plane, a measure of the spectrometer resolution, is determined by the acceptance angle of the point for rays diffracted from the crystal. For a given spectrometer geometry the factors that control the resolution are the crystal diffraction profile width and the angular extent of the X-ray source in the plane of dispersion. At 2 keV

the limiting resolution imposed by the KAP profile width is about 3/4 eV. High dispersion instruments with large source-to-crystal and crystal-to-detector distances have been used in our laboratory to obviate the effect of an extended source and to obtain the crystal-limited resolution. For the SSPA-equipped spectrometer, however, these distances are so short that a limit of about 1.8 eV is imposed by the extent of the 100 μm -diameter source.

SSPA DETECTOR

The radiation diffracted by the crystal is monitored by the SSPA detector. The SSPA is a planar silicon device that incorporates a linear array of photodiodes and a scanning circuit on a single chip of silicon. There are 512 photodiodes on the array, spaced on 25.4 μm centers. The width of the photodiodes normal to the centerline of the array is 432 μm . We place a slotted tantalum shield over the SSPA to prevent ionizing radiation from reaching all components of the chip except the array of photodiodes.

The scanning circuit is a digital shift register consisting of a network of MOS transistors. Periodically it causes a reverse-bias voltage to be applied to the photodiodes, one after another, after which the photodiodes are left isolated until next addressed by the scanning circuit. The depletion layer produced at each diode junction accumulates photocharge created by photon absorption in the silicon near it. The frequencies at which the scanning is performed are much too slow to allow time dissection of the radiation pulse from a laser-induced plasma.

The SSPA is a usefully-sensitive detector of low energy X-rays⁶. Figure 6 illustrates measured and calculated sensitivities in the region from 1 to 10 keV. Above 4 keV much of the signal is due to charge that diffuses to the diodes for collection from generation sites well below the PN junctions. We have also found that the SSPA is a linear detector and that a dynamic range of 100:1 can be achieved. Figure 7 is an example of a spectrum of silicon line radiation obtained for a glass-microsphere experiment at the CYCLOPS facility.

X-RAY MICROSCOPE

Prior to the development of reflecting focusing optical elements like those used in the X-ray microscope, the only satisfactory way to form an X-ray image of a small, self-luminous source was with a pinhole collimator. A pinhole camera involves a trade-off between through-put and spatial resolution that did not prove acceptable for the measurement of fusion-fuel compression in our laboratory. The more sophisticated reflecting lens achieves both large detector solid-angle and high resolution⁷.

A beam of soft X-rays striking a polished mirror at a grazing angle will be reflected with high efficiency for photon energies less than a critical value. This critical value is a function of the index of refraction of the mirror surface and the angle of incidence. Above the critical energy the reflection efficiency decreases abruptly, providing a mechanism for obtaining energy-discriminated images. The most recently developed X-ray microscope lens is a cylinder incorporating two conic sections in tandem, a paraboloid and a hyperboloid that are confocal and coaxial. Focusing requires a reflection off first one conic surface and then another.

Figure 8 is a photograph of an X-ray microscope lens designed for an image magnification of nine at an object-to-lens distance of 300 mm. The solid angle subtended by the reflecting surfaces of the lens is 4.2×10^{-6} steradians, with an anticipated transmission of about 50%. For comparison, a pinhole camera fitted with a 5 μm diameter pinhole has a solid angle of 2.2×10^{-10} steradians and a transmission of 100%. A Monte Carlo ray tracing computer calculation predicts a spatial resolution for the X-ray lens of less than 1 μm over a 100 μm field of view.

Stringent tolerances were required of the in-house fabrication of the X-ray lens. To obtain the submicron resolution it was necessary to hold slope errors to less than 2 microradians, surface figure accuracy to 100 Å, and surface finish to 50 Å r.m.s. The figure surface was machined into a copper-coated beryllium cylindrical blank by a numerically-controlled diamond-turning machine. A thin coating of nickel was then laid down over the copper and polished to the required tolerance.

The evaluation of the conic microscope lens is not yet complete, but its use in plasma experiments is anticipated in the near future.

2-d X-RAY SENSORS

To expedite the recovery of data from the X-ray microscope we are evaluating two types of high resolution X-ray-sensitive video sensors. We will use them to assist in the set-up and alignment of the microscope lens and, if the sensors prove to be adequate, to recover plasma data.

The first video sensor is an RCA-4804 SIT vidicon with the intensifier and faceplate assembly replaced by a 1" vacuum valve. In the early development of the silicon-target vidicon, low energy X-ray measurements were made with thin-windowed vidicons with good results⁸. We are expanding on this work with a tube that is now commercially available and easily modified.

The sensitive component of the vidicon is a 15 μm thick silicon wafer. Secondary electrons generated by the absorption of X-rays in the silicon are collected on the elements of a rectangular matrix of diffused PN diodes formed on the electron gun side of the wafer. The diode sampling sites, which are periodically read-out by the scanning electron beam, are spaced on 13 μm centers. The vacuum integrity of the electron gun of the valve-equipped vidicon is preserved by a 0.3 mil thick beryllium window set across the aperture of the tube forward of the silicon wafer. This device should achieve its highest sensitivity in the photon energy region from 1 to 4 keV, in which the radiation is hard enough to penetrate the beryllium window but soft enough to be stopped in the silicon wafer.

The second sensor we are evaluating is the RCA SID51232 charge-coupled device. This detector is a significant advance in the technology of CCD imagers, particularly in that it is the first CCD to provide commercial television spatial resolution and to use vertical frame transfer sensor organization⁹. This latter attribute implies that the sensor can be used to detect short pulses of penetrating radiation in a more straightforward way than an imager built with the previous CCD architecture, known as interline transfer organization.

For the RCA device the ccd cell size, the basic measure of the spatial resolution of the detector, is 30 x 30 μm . To reach the sensitive silicon an X-ray beam must penetrate about 1.5 μm of polycrystalline silicon and silicon dioxide, putting a lower limit on the range of detectable photon energies at 1.5 keV. We expect the high energy response to roll off in the neighborhood of 8 keV due to a finite charge carrier diffusion length in the sensitive silicon. An X-ray calibration of this detector and the modified vidicon tube is in progress.

DIGITAL DATA SYSTEMS

The spatially-resolving silicon detectors we have described read their signal levels out in a serial format that permits digitization in a straightforward way. We have built two digital data systems for the crystal spectrometer, one as a stand-alone system with a microcomputer as the central processor unit (CPU) and the other with a CAMAC interface to a multi-purpose minicomputer CPU. The processor in each system monitors the timing and triggering of the spectrometer measurement, controls the loading of the digitized signal levels into solid-state memories, and provides experimenter access to the data through high-level software.

The first system uses an Intel 8080 microprocessor programmed in the PL/M language¹⁰. Figure 9 is a block diagram of the system as implemented at the CYCLOPS facility. Since this facility does not provide pre-fire trigger signals, synchronization of the scanning of the SSPA with the laser event is not possible and it is necessary to run the SSPA in a continuous scanning mode. If the laser event occurs in the middle of a scan, a portion of the SSPA signals are loaded into memory immediately during the remainder of the scan, while the rest of the data appears in the following scan. A counter circuit in the data system terminates the loading at the proper point to prevent overwriting of the early data. Two other arrays of numbers are stored in the system and used by the microprocessor to normalize the shot data. One of these arrays consists of SSPA levels measured while the detector was in the dark and the other contains predetermined factors that account for the variation in sensitivity from one photodiode element to another.

Under the control of the experimenter, the microprocessor can send the reduced data to any of several output devices. These consist of a CRT display, X-Y recorder, and a teletype fitted for punched paper tape operations. The data records are labeled with the time of occurrence of the laser event as monitored by an IRIG clock in the system. Figure 10 is a photograph of the microprocessor system tucked away into a corner at the CYCLOPS facility.

A second digital data system is being built for a crystal spectrometer at the new ARGUS laser facility. This system is a CAMAC module containing solid state memories and control circuits that interfaces with a PDP 11/40 minicomputer programmed in a modified BASIC language¹¹. Since accurate pre-fire trigger signals are available at ARGUS, the module will control the frequency of occurrence of the SSPA read-out scans in a predetermined sequence. The successful completion of the sequence will be indicated in a 10-bit status word that will be available to the CAMAC dataway.

The memory contains two sections, one for shot data and the other for dark level data. The levels can be brought out along the dataway in blocks or in an addressed point-by-point format, depending on the software implemented by the experimenter. The options available for processing and displaying the data are much more numerous than for the stand-alone system.

The development of a digital data system for the high-resolution 2-dimensional sensors is in an early stage. The system design must anticipate that there will be an arbitrary number of sensors, each producing of the order of a million digital bits of data, competing for the resources of the system at the same time. None of the sensors have a useful inherent signal storage capability and it thus appears necessary to write the data into semi-permanent analog or digital storage devices that are dedicated one-for-one to each sensor. Analog storage devices are available at fairly reasonable cost in the form of magnetic discs and solid-state scan conversion memories. One option for the design of a system calls for digitizing the record of each sensor at a microprocessor-controlled central station that stands apart from a CPU. The system could transport the records to a general purpose computer such as the CDC7600 available at our laboratory via modem, or could write the records onto portable media such as floppy discs.

X-RAY STREAK CAMERA

The most sophisticated X-ray diagnostic instrument used in the laser program is the X-ray streak camera. This instrument has been used to obtain the time history of the spectral or spatial distributions of X-rays emitted by laser targets with resolutions of the order of 15 ps¹².

The heart of the camera is an RCA streak tube modified to obtain X-ray sensitivity. As shown in Figure 11, photons passing through a 100 μm X 1 cm rectangular slit at the front of the tube are converted in a thin (100 Å) gold photocathode. The rectangular pattern of slow photoelectrons that emerge from the back of the gold are then accelerated to the electrostatic deflection section. This section sweeps the pattern across a phosphor screen at a controllable rate to produce a record of the time history of X-ray fluence at the entrance slit. The geometric resolution of the tube is limited by space charge spreading to 100 μm .

To obtain a spectral measurement, K-edge absorption filters of various elements and thicknesses are arrayed across the entrance slit of the streak tube. For example, filters of chlorine, titanium, and cobalt form broad bands with mean energies of 2.6, 4.0, and 5.3 keV, respectively. Figure 12 is an example of data obtained with this measurement for a glass microsphere target. The records show two peaks in X-ray emission, the first due to the initial heating of the glass by the 80 ps laser pulse, and the second due to the high temperatures developed in the compressed fuel volume. The period between the two peaks is the implosion time, during which the compression is achieved.

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LNK:dj

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FIGURE CAPTIONS

1. Glass Microsphere Laser-Fusion Target.
2. CYCLOPS Facility High-Brightness N₂/yag Laser.
3. X-Ray Spectrum Radiated by Irradiated Laser-Fusion Target, a Composite Due to Several Different Instruments.
4. X-Ray Microscope Picture of Irradiated Laser-Fusion Target, for Polar Illumination by CYCLOPS Laser.
5. Isometric Projection of the Active-Recording X-Ray Crystal Spectrometer.
6. X-Ray Sensitivity of the Self-Scanning Photodiode Array.
7. Typical Spectrometer Data for Laser-Irradiated Glass Microspheres. Recovered at the CYCLOPS Laser Facility.
8. Photograph of the 9x Cylindrical X-Ray Microscope Lens.
9. Block Diagram of the Microprocessor-Based Digital Data System.
10. Photograph of the Microprocessor-Based Digital Data System at the CYCLOPS Laser Facility.
11. Schematic of the X-Ray Streak Camera Tube.
12. Time-Resolved X-Ray Spectral Measurements Obtained for a Glass-Microsphere Target by the X-Ray Streak Camera.

Figure one

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Figure two

This is figure 1-3 of NCRI 50021-79

Figure three

This is figure 9-25 of UCRL 50021-74

Figure Four

This is figure 7-60 of HCRL 50021-79

Figure five

Koppel - Fig. 1

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Figure six

Koppel - Fig. 4

Photo figure 4 figure 6 - 77541

Figure seven

Koppel - Fig. 7

There is figure 7 of UCL-77541

Figure Eight

Figure nine

Koppel - Fig. 6

Also figure 6 of NCR-77591

Figure 1

Figure eleven

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Figure 12