UCRL-90750
PREPRINT

Sub-Nanosecond Cinematography in Laser Fusion
Research: Current Techniques and Applications
at the Lawrence Livermore National Laboratory

L. W. Coleman

This paper was prepared for submittal to
the Proceedings of the 16th International
Congress on High Speed Photography and
Photonics, Strasbourg, France, August 27-31,
1984.

January 10, 1985

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Sub-nanosecond cinematography in laser fusion research: Current techniques and applications at the Lawrence Livermore National Laboratory*

Lamar W. Coleman

Laser Program, Lawrence Livermore National Laboratory
P.O. Box 5508, L-481, Livermore, CA 94550

Abstract

Progress in laser fusion research has increased the need for detail and precision in the diagnosis of experiments. This has spawned the development and use of sophisticated sub-nanosecond resolution diagnostic systems. These systems typically use ultrafast x-ray or optical streak cameras in combination with spatially imaging or spectrally dispersing elements. These instruments provide high resolution data essential for understanding the processes occurring in the interaction of high intensity laser light with targets. Several of these types of instruments and their capabilities will be discussed. The utilization of these kinds of diagnostics systems on the nearly completed 100 kJ Nova laser facility will be described.

During the last decade there have been significant advances in the technology and applications of ultrafast photography.¹⁻¹⁴ Driven by the need for sub-nanosecond resolution measuring capabilities for pulsed laser diagnostics and for laser-plasma interaction and laser fusion research, ultrafast streak cameras have come from the few, large, breadboard systems of the early 1970's (typified by the camera shown in Fig. 1) to easily available, widely used, compact, refined, high capability optical and x-ray cameras such as those shown in Figs. 2 and 3. Together with the developments in streak camera technology, there have been comparable developments in the design and use of integrated diagnostics systems, particularly for laser-plasma research that utilize the resolution capabilities of ultrafast cameras.¹⁵⁻²¹ Using these systems on large experimental laser facilities often imposes special, stringent requirements on the design and implementation of these diagnostic systems.

Figure 1. Ultrafast streak camera in early 1970's

Figure 2. Modern ultra fast optical streak camera

At the Lawrence Livermore National Laboratory, we make major use of and place heavy reliance on ultrafast streak camera based diagnostic instruments in our Laser Fusion Program. These diagnostic instruments have been developed and refined over several years and various ones have been prototyped and used on experiments of the Argus, Shiva, and Novette laser facilities. The target chambers in which experiments were conducted at these facilities were typically about 2 m in diameter. Although numerous systems requirements such as vacuum, interlocks, and control had to be met, the sizes of the systems were such that the instruments were relatively accessible and amenable to "hands on" tending.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Figure 3. Modern ultrafast soft x-ray streak camera

Figure 4. Artist's rendition of the 100 kilojoule Nova laser facility

The Nova laser facility, shown in Figs. 4-6, is on an entirely different scale. The Nova target chamber shown in Fig. 6 is 4.6 m in diameter. The engineering design of the diagnostic instruments and the systems requirement are much more stringent and difficult than with the previous systems. Our interests and therefore the bulk of our recent effort with time resolved diagnostics instruments and ultrafast cameras has been toward developments and improvements related to meeting these systems requirements.

Figure 5. Output of four of the Nova laser beam lines

Figure 6. Nova target chamber in early stage of assembly

Fourteen ultrafast streak cameras will initially be used at Nova; six for laser system diagnostics and eight utilized in target diagnostic instruments. The ten beam Nova laser will be operated on target at one of three wavelengths, the fundamental Nd:glass output (1.05 μm), the second harmonic (0.53 μm), or the third harmonic (0.35 μm). One of the laser diagnostics cameras is dedicated to the laser oscillator; the remaining five are located in the diagnostic packages at the outputs of the laser chains. Signals at the different wavelengths from the ten beams will be multiplexed onto the slits of the five cameras with fibre optics. All these cameras are read out with optically coupled CCD arrays which are interfaced to the Nova computer control system for data acquisition, reduction, and analysis.

Table I summarizes the ultrafast streak camera based target diagnostic instruments that will be implemented on Nova. Versions of many of these instruments are also in use at other laboratories around the world. Although these kinds of instruments have been used on experiments with earlier laser facilities at Livermore (Argus, Shiva, and Novette), each one has had to be significantly re-engineered in order to be used on Nova.

Table 1. Streak camera based Nova target diagnostics systems

• Optical pyrometer	Time resolved, absolute intensity measurement in one or more wavelength bands
• Optical spectrometer	Combines a grating spectrometer with a streak camera for time resolved measurement of spectrally dispersed optical signals
• Optical/x-ray camera	Streak camera that records both laser light and hard x-rays for absolute cross-timing
• X-ray spectrometer	Measures time resolved x-ray emission in several spectral bands that are defined by grazing incidence mirrors and absorption filters. Can be used with pinhole imaging.
• X-ray transmission grating spectrometer	Combines an x-ray streak camera with a collecting mirror and a 1000Å or 2000Å period free-standing gold transmission grating. Provides time resolved measurement with continuous x-ray spectral dispersion.
• X-ray crystal spectrometer	X-ray diffraction crystal with an x-ray streak camera. Provides time resolved high spectral resolution ($\frac{\Delta E}{E} \sim 3 \times 10^3$) measurements to study, for example, time evolution of x-ray spectral lines ($0.5 \text{ KeV} \leq h\nu \sim 10 \text{ KeV}$).
• High resolution x-ray imaging (22X)	High magnification grazing incidence x-ray microscope - streak camera combination for time resolved one dimensional images of x-ray emission. Spatial resolution is $\sim 5 \text{ m}$, limited by streak camera spatial resolution.

Because of the size of the Nova target chamber, most of these instruments are quite large, heavy, and more complex than their predecessors. Access to them for set-up, data retrieval, maintenance and servicing will be more complicated and in some cases require special fixturing and possibly removing or rearranging other systems attached to the target chamber. For these reasons, the matters of prime importance for the effective use of these instruments, including the streak cameras, are the systems related ones. Our emphasis has been on developing and using high resolution diagnostic instrument systems and on implementing modifications and improvements primarily directed at the issues of providing reliable and stable operation, ease of servicing and maintenance, but without sacrificing their inherent technical capabilities.

The Nova streaked x-ray crystal spectrometer will be discussed as a specific example of a target diagnostic instrument.²² Figure 7 shows a schematic diagram of the concept of this instrument. X-ray produced from a laser irradiated target are incident on a Bragg crystal. The diffracted spectrally dispersed x-rays are incident on the slit of a soft x-ray streak camera. In this way the time dependence of x-ray lines can be measured with a temporal resolution determined by the streak camera. The choice of crystal and the size and geometry of the instrument are determined by the range of x-ray energies of interest, by the length of the streak camera slit (photocathode size), and the spatial resolution of the camera. While being relatively simple in concept, the implementation of such an instrument on Nova must be carefully designed and engineered. Table II lists some of the crucial operational and systems related criteria that the instrument must meet. Figure 8 is a simplified outline drawing of the system as engineered to meet these criteria. The front end design allows the crystal to be positioned for an experiment or moved out of the way to provide a direct line of sight to the streak camera slit for alignment purposes. The front of the streak camera provides the necessary features for vacuum interfaces and control as well as a shutter mechanism to protect the thin photocathode when the camera is not in use. A special film holder with a shutter can be remotely decoupled from the streak camera and retracted the 2 m to the periphery of the target chamber so the film can

Figure 7. Concept of x-ray crystal spectrometer

Table 2. Nova streaked crystal spectrograph requirements

- Blast shield for crystal: 12 μm Be
- X-ray shielding for streak camera: ≥ 2.5 cm of heavy metal along direct line-of-sight
- Direct line-of-sight from target to cathode for streak camera timing
- External visual inspection of streak camera photocathode
- Tolerance for positioning of crystal and streak camera: ≤ 1 mm
- Retractable to a standby position not obstructing any other diagnostic line-of-sight
- Operating vacuum in the x-ray streak camera tube: $\leq 10^{-5}$ Torr
- Operating vacuum in front of the streak camera: $\leq 5 \times 10^{-4}$ Torr
- Streak camera front end vacuum coupled to target chamber
- Protection of streak camera photocathode during venting and pump down
- Removal of streak camera independent of target chamber vacuum
- Load/retrieve film without venting streak camera or target chamber
- The operation of the streak camera, crystal positioner, and necessary vacuum valves must be remotely controllable:
 - a) manually upon demand and
 - b) automatically via software instructions
- Streak camera power must be interlocked such that the camera cannot be removed from its functional position with power applied
- Streak camera image converter tube voltages must be interlocked to the image converter tube pressure
- Status of all valves, pressures, and camera parameters must be monitored and indicated
- The system must be automatically configured to a "stand-by" condition at all times except immediately prior to a shot and configured to the "shot" condition for the shot

Figure 8. Schematic of the Nova streaked x-ray crystal

be retrieved. The holder can be reloaded and repositioned on the back of the camera for another experiment without disturbing the vacuum, the alignment of the crystal or the streak camera. For maintenance the entire camera/film holder system can be retracted to the edge of the chamber for inspection and servicing. The entire assembly must also be mechanically stable to be able to adjust and maintain the alignment of the crystal and streak camera relative to the target of less than one millimeter.

The present capabilities of ultrafast cameras make possible a number of highly capable optical and x-ray measurement instruments. The applications of these systems on a large experimental system such as Nova requires developing and implementing unique engineering designs. As noted earlier, the operating parameters of ultrafast cameras can seriously

Table 3. Ultrafast streak cameras summary

The capabilities of our present diagnostics are often limited by streak camera parameters.

- Spatial resolution

- Very important parameter, presently $\sim 100 \mu\text{m}$ limiting spatial resolution significantly affects performance and is the factor determining the geometry (size) and design of a diagnostic system. This is particularly true for imaging and spectroscopic instruments. Improvement by a factor of $\sim 5-10$ is needed, but not at the expense of other parameters and preferably at constant photocathode size

- Systems and operational considerations

- Important for large experimental facility (Nova) (reliability, mechanical and electronic stability, serviceability, ability to provide timing fiducials, and ability to interface to control and data acquisition systems)

- Dynamic range

- Range of a few hundred we now typically have is adequate; improvement will help

- Sensitivity

- Sensitivity provided by variety of optical and x-ray photocathodes on present cameras is adequate

- Time resolution

- $\sim 20 \text{ psec}$ we have is sufficient now. Improvement to $\sim 5 \text{ psec}$ will be needed in the future, but not at the expense of other performance parameters

constrain the design of a diagnostic instrument either by limiting its capability or imposing undesirable geometric requirements on the system design. In order to meet the need for improved measurement ability in laser-plasma interaction and laser fusion research, improved ultrafast photographic capabilities will be required. Table III summarizes the types of developments and improvements, along with the constraints from our perspective. Improved spatial resolution will allow imaging systems to be smaller and maintain resolution, and spectroscopy can cover broader spectral ranges. As emphasized above, the systems and operational criteria are very important, especially with large facilities. Improved time resolution to ≤ 5 psec will eventually be needed in conjunction with the other improvements, but for the near term is the least important of our operating parameters for improvement.

There have been impressive advances in the technology and applications of ultrafast photography in ten years. We have come from a situation in which a few basic ultrafast optical streak cameras were used in simple applications to one in which sophisticated optical and x-ray cameras are becoming more and more widely used and their unique capabilities are the basis for the design of sophisticated high resolution measuring systems. Prototype framing cameras are under development and new applications of ultrafast photography are continually being explored. Research in laser-plasma interactions and laser fusion offers challenges for innovation and advancement in a number of areas in high speed photography and photonics. Progress in these research areas will depend in a significant way on how well we continue to meet those challenges.

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