Lessons Learned: Graduate Student Incurs Laser Injury to Eyes

Effective Date: **Mar 26, 2004** Point of Contact: Edward Sierra Identifier: None Provide Feedback

Lessons Learned Statement:

A Brookhaven National Laboratory (BNL) investigation team evaluated the laser incident which occurred on September 9, 2003, and identified many missed opportunities to prevent the accident. The observations and lessons described here primarily reflect the perspective of laser owners and users. The corrective actions listed at the end of this document address implementation of BNL requirements within the Chemistry Department. Discussion and lessons learned of laboratory-wide issues are addressed in Reference #3.

1. Alignment procedures which entail moving laser beams and the possibility of unanticipated reflections should be carefully worked out ahead of time with consideration of appropriate power levels, eyewear, color-shifting cards, or other beam-imaging equipment. Devising a sequence of operations to perform an alignment with minimal risk to the operator is often as challenging as performing the intended experiment once the alignment is complete. Careful analysis of the beam path should be performed before any adjustments are made. Quickly improvised procedures for alignment can lead to poor choices and unnecessary risk.

2. Reinforce the importance of laser safety eyewear. While allowances may be made for removal of safety eyewear once beam paths are defined and/or enclosed or laser intensity has been attenuated, users should view such circumstances as the exception and not the rule. Eyewear providing full protection from the beam should be worn at all times and removed only under conditions specifically and carefully addressed in Standard Operating Procedures (SOPs).

3. More quantitative understanding of laser hazards is needed among Principal Investigators (PIs) and users. Despite extensive hands-on training with the PI over several months, the student clearly did not have an adequate grasp of the threshold levels for safe viewing of indirect pulsed laser light. All laser users must appreciate that Class 3b and 4 lasers are orders of magnitude more intense than ocular damage thresholds for intrabeam viewing. In addition, users must understand that even diffuse reflections of Class 4 lasers are hazardous to view. In working with the novice user, it is imperative to reinforce safety guidelines with constant reminders of the potential hazards of working with Class 4 laser beams and provide a set of "do's" and "don'ts" that define safe working practices.

4. Vacuum chambers and other enclosures involving entrance and exit windows pose a hazard because the beam path may be altered within the chamber or enclosure in a way that is not immediately obvious. The user must assume that any and all viewports are potential laser exit ports and may pose a hazard. In this accident, the student did not correctly anticipate that moving the beam off the sample would cause the beam to propagate through the chamber and out the viewport through which he had chosen to view the sample.

5. The deceptively dim appearance of laser light on the edges of visual sensitivity must be explicitly dealt with in laser safety training. The 750 nm beam involved in this accident

is a dull red color to which the eye is not very sensitive, so that perceived brightness gives an exceedingly misleading impression of the hazard level. This fact is more broadly significant due to the rising use of Ti:Sapphire lasers and amplifiers that typically operate around 800 NM. For example, a 1 W beam of deep red light may appear similar to the familiar and much less hazardous beam from a 1 mW HeNe laser at 633 NM, thereby luring the user into a false sense of security. While bright visible light fosters a natural aversion and invisible beams may cause a "fear of the unknown," barely visible deep red and deep blue lasers fall in the gap between these two regimes and can pose a special hazard.

6. Sops should be treated as a useful educational tool and not a perfunctory exercise. Operators, in consultation with the Laser Safety Officer (LSO), should take particular care in preparing Sops to serve as a focal point for training and as a source of useful reference material regarding levels of hazard, eyewear requirements, practical "do's" and "don'ts," and specific procedures for common activities.

7. PIs must be careful about defining authorization boundaries so that students, postdocs, and even experienced researchers know which operations are permitted and which require additional planning or supervision.

8. All workers should clearly understand that they are expected to cease work when they are unsure how to proceed or how to proceed safely, or are unsure whether they are authorized to perform a task. Safe work in the laboratory requires leadership by the PI and commitment on the part of all workers regarding the establishment and maintenance of a "safety first" work culture. Time pressure should never outweigh safety concerns.

9. The LSO should provide technical guidance in the establishment of standard procedures and effective training, as well as enforcement of laser safety standards. In the case of this accident, the process of updating the SOP would have provided an opportunity for consultation with the LSO and a more careful consideration of the new hazards presented by the use of a barely visible, near-infrared pulsed laser.

10. Use of the "buddy system" can be valuable if both "buddies" are properly trained and take time to carefully discuss procedures before executing them. In the case of this accident, a thoughtful discussion of the proposed procedure could have revealed its flaws.

11. Users should be trained not to place handheld elements into a laser beam. A handheld optic directs reflected and transmitted beams in unspecified directions and is inherently unsafe.

Discussion of Activities:

On September 9, 2003, at Brookhaven National Laboratory (BNL), a second-year graduate student sustained injuries to the central vision of both eyes while working with a pulsed laser in a surface science experiment. A Class 4 alexandrite laser was being used for pulsed heating of an adsorbate-covered crystal surface in an ultrahigh vacuum chamber to induce desorption. The desorbed gas was to be ionized by a second vacuum ultraviolet probe laser and detected in a time-of-flight mass spectrometer. The alexandrite laser, which operated at 750 NM with a pulse duration of about 40 ns and a repetition rate of 20 Hz, produced the injury. At the time of the injury, the average power of the laser had been attenuated to 0.5 W (25 mJ/pulse), and the student was using a handheld inspection mirror to view the crystal sample inside the vacuum chamber while his postdoctoral coworker made adjustments to a mirror directing the laser beam into the chamber and onto the crystal surface. The student intended to observe scattered laser light and was not wearing laser protective eyewear. The window chosen for this inspection was in the direct line of the incident laser beam, but blocked by the crystal sample, so that small adjustments to the crystal position or the laser beam direction would allow a portion of the beam to exit the chamber through this window. This fact appears not to have been considered by the student prior to the accident. A drawing of the experimental chamber at the level of the laser experiment illustrates the normal beam path of the laser beam, the crystal sample, and the window ports.

Chronology of Events

The student had enrolled in a PhD program nearly two years prior to the accident, devoting much of this time to class work and spending only summers at the laboratory. The previous summer the student had worked with the Principal Investigator (PI) on a similar experiment using the same surface science chamber and the same probe laser system, but with a Nd:YAG laser as the desorption laser instead of the alexandrite laser used later. During these earlier experiments, a HeNe alignment laser coaxial with the invisible ND:YAG laser had routinely been used for the alignment of the desorption laser with the crystal. The student had been instructed on all aspects of the complex experiment and was qualified for routine operation of both laser systems and the surface science experiment.

A new, pulsed alexandrite laser was purchased and installed early in the student's second summer of laboratory work. The alexandrite laser exhibits strong thermal lensing and is designed to operate with 80º C cooling water, requiring a 30-minute warm-up time for stable operation. These conditions make the usual methods for attenuating a flashlamp-pumped, Q-switched laser to a low-power alignment mode unsuitable. Turning off the amplifier flashlamps or turning down the oscillator lamps produces a large increase in the beam size. Long pulse, un-Q-switched operation is commonly used with YAG lasers to decrease the peak power, but if the lamp energy cannot be reduced below normal operating levels, un-Q-switched average power is still too high for safe alignment procedures. Instead, the Q-switch delay can be adjusted away from the optimum timing to adjust the power. In combination with a pair of polarizers, the laser power can be controlled over a wide range without significantly affecting the quality, size, or direction of the laser beam. These characterizations and attenuation procedures were developed early in the summer, but written standard procedures for the laser laboratory were not updated and the laboratory LSO was not consulted.

The 750 NM laser light from the alexandrite laser beam poses a particular hazard due to the low sensitivity of the eye to light in the "deep red" portion of the spectrum. Even at hazardous intensities, such beams are barely visible, appearing dull red in color. At the same power, an operator would perceive a green beam as much brighter. In contrast, a 1064 NM beam from a YAG laser is truly invisible and would not tempt an operator to perform alignment by direct viewing of the beam. During the summer, the PI worked closely with the student and a postdoc preparing for this experiment. On the day before the accident, the PI, student, and postdoc worked together to perform desorption measurements similar to ones made the previous summer using a YAG desorption laser. The postdoc prepared a sample in the upper portion of the chamber and lowered it to the level of the laser experiment. A sample manipulator allows for reproducible positioning of the crystal, which can be further confirmed by line-of-sight viewing (with the laser blocked). Meanwhile, the student set up the probe laser system and the alexandrite laser for the PI, who supervised the experiment.

With the crystal dosed and properly positioned at the level of the laser experiments, the desorption laser beam was aligned through the entrance apertures, through the entrance window of the chamber, and onto the crystal. The student described the standard procedure for beam alignment through the apertures: wearing the alexandrite laser glasses with the apertures partially closed, a blue-shifted glow could be seen and centered where the outer region of the laser beam hit the apertures. The student knew that the scattered far red light from these partially closed apertures was too intense to view safely without protective eyewear when the laser was running at several W. The laser beam was collimated to illuminate about 2/3 of the area of the 12mm diameter sample crystal.

With all components of the experiment in place, the PI, student, and postdoc worked together to look for a desorption signal in the time-of-flight spectrometer. At first there was no signal, and the PI initiated a series of troubleshooting checks and adjustments. As one of these checks, the PI wanted to verify the alignment of the laser relative to the crystal. To test for light that was off-center or missing the crystal, he inserted a white card beyond the window where the beam would exit if not for the crystal. No light was observed leaving this port. With the intention of checking the centering, he asked the student to move the beam from side to side, looking for alternate edges of the beam to clear the crystal and illuminate the card. The PI quickly realized that the adjustment produced ill-defined images, and combined with the uncalibrated angle adjustment of the mirror mount, this procedure could not provide an alignment any more precise than the previous method using the adjustable apertures. The procedure was abandoned and other experimentation continued. The student had an obstructed view of this procedure from the other side of the chamber, and the postdoc did not participate. The PI could not recall which of his two junior colleagues had assisted in the procedure, or even whether it had been a crystal or a beam displacement involved. The student knew that he had assisted in a mirror adjustment to check beam centering, but did not know that a white card had been used to visualize the transmitted beam or that the procedure had been deemed useless. Troubleshooting continued and eventually led to some observed time-of-flight signals. At the end of the day, the co-workers discussed their day's results and plans were made for continued investigations the next day.

Morning preparations proceeded as on the previous day, with the postdoc preparing the sample and the student setting up the lasers. The alexandrite laser was set to deliver two W of average power by adjusting the Q-switch timing. The alexandrite laser was aligned to the crystal with the aid of adjustable diameter apertures that had previously been positioned to mark the correct path to the center of the crystal. Laser protective eyewear was worn for this alignment procedure and removed afterwards.

The student recalled the check of the crystal/laser alignment that had been performed the previous day by the PI, thought it was necessary, but was not sure how to proceed. He looked for the PI in his office, but could not find him. The prepared crystal would only last about an hour or two before the dosing would need to be replaced, so the student returned to the laboratory and proceeded to attempt the alignment on his own.

A direct view into the chamber through the window that had been used the previous day for the white card check was blocked by other hardware attached to the chamber. The crystal inside the chamber could be observed through this window, however, with the aid of the handheld mirror. The student expected to see some scattered red light from the edge of the crystal when the laser beam was steered from the center of the crystal toward the side. The laser intensity had been set to 2 W earlier by adjusting the Q-switch delay, and a polarizer in the beam path was then rotated to further attenuate the beam to 0.5 W average power for this alignment check. The student referred to this as a "low power" condition, selected for this procedure. The student developed this procedure knowing that the window provided a viewing path to the crystal, but not thinking that the line of sight was nearly along the direct beam path of the laser. The crystal normally reflected the beam away from this path to a wedged reflector and then on to a beam dump inside the chamber when correctly aligned. But only a small adjustment in the beam alignment would allow some of the direct beam to leave the chamber through the viewing window.

The power meter that was blocking the beam at the entrance of the chamber was removed and the beam was sent into the chamber, hitting the crystal, reflecting from the gold reflector and dumping inside the chamber. The student used the handheld mirror to look toward the crystal under these conditions and reported seeing a weak scatter from the wedged reflector, but no significant light from around the crystal. He instructed the postdoc to adjust the mirror to move the beam to one side, expecting to see some scattered light from the side of the crystal as the beam was moved. The student did not recall seeing any gradual beam movement prior to a bright red flash followed by persistent afterimages. He heard no sound and felt no pain associated with the flash. After a few minutes, when the afterimages did not clear he informed the postdoc who initiated procedures to get him to the clinic for evaluation.

Damage to the central vision of the right eye was evidently caused by intrabeam viewing of an undetermined fraction of the 0.5W beam (25 mJ/pulse) that missed the crystal and continued out through the window in the chamber and into the student's dominant eye, directly viewing the crystal through the inspection mirror. The exposure that led to the less severe central vision loss in the left eye is more difficult to understand. Perhaps reflection of the misdirected beam from the edge of the crystal or other metallic parts in the chamber could have produced other forward-directed beams through the same exit window, striking the other eye simultaneously. The 25 mJ pulses are many thousands of times brighter than necessary to produce retinal damage by unprotected intrabeam viewing.

The student currently has almost normal corrected vision in one eye. Damage to the vision in the other eye is greater and is still changing.

Analysis:

Direct cause: Personnel Error, Procedure Not Used or Used Incorrectly

The direct cause is personnel error because the student attempted to perform a sample alignment procedure using the Pulsed Alexandrite Laser that had been performed by the PI the previous day but for which the student had no authorization and insufficient experience. The student was normally trained in procedures by the PI via a process that involved observing a procedure, carrying out the procedure while under observation, and finally having the authorization to carry out a procedure independently. In this case, the student was attempting to carry out a procedure that was observed only once and his understanding of the procedure was faulty such that the steps the student devised were inherently unsafe.

Contributing Causes: Management Problem, Inadequate Administrative Control

The laser was installed and operated without registration and review by the LSO. The PI failed to include the Pulsed Alexandrite Laser in required postings and documentation. The BNL Standards Based Management System (SBMS) Laser Safety Subject Area requires registration of lasers and review of the space, interlocks, and laser alignment procedures by the BNL LSO. The laser was installed in a properly interlocked space but had not been reviewed by the BNL LSO or registered and the SOP was not updated to include the Pulsed Alexandrite Laser. The laser SOP had not been updated annually and signed by the Chemistry Department ES&H Coordinator or the LSO, as required. The Chemistry Department had no formal process to notify the Chemistry Department Laser Safety Coordinator (LSC) or the Chemistry Department ES&H Coordinator as to the purchase or arrival of a laser. The Chemistry Department did not have a well-documented Tier I inspection procedure for laser laboratories that would involve periodic audits of lasers, interlock records, and Sops

Management Problem, Policy Not Adequately Defined, Disseminated, or Enforced

Chemistry Department management placed a burden of documentation on the PI but did not verify completeness. The check-in form for the student was signed by the student and PI even though the required consultation with the Chemistry Department LSC that was listed on the form was not accomplished. The student had not signed the Experimental Safety Review or read and signed the laser SOP, although reading and signing both documents are clearly required in the Chemistry Department policies. The responsibility to ensure the student has read and signed both documents resides with the PI and verification of the process resides with Chemistry Department management.

The requirement that personnel update Roles, Responsibilities, Authorities, and Accountabilities (R2A2s) as needed was not adequately defined or enforced in the Chemistry Department. The R2A2 for the PI was out of date and inaccurate. No formal R2A2 existed for the LSC. Audits of R2A2s had been carried out in 2003 but involved sampling only.

Root Cause: Management Problem, Inadequate Administrative Control

Management/Supervisor failed to ensure the graduate student was completely and properly trained and understood established rules pertaining to authorization and stop work.

Management/Supervisor failed to ensure boundaries for student operations in the lab were clearly defined. At the time of the accident, the student was attempting to repeat an experimental procedure he had observed the PI perform the previous day. He sought guidance from the PI when he realized he was unsure how to proceed. Since the PI was unavailable, the student decided to continue rather than allow the sample to degrade. The student did not fully appreciate his obligations to cease work when he was not authorized to continue independently and the PI had not provided proper emphasis in this regard. The Research Associate (RA) did not recognize the student's actions as an imminent hazard and thus failed to issue a stop work order. Supervisors have the responsibility to be certain that students, Post-doctoral research associates, and even experienced researchers working under them are fully versed in the workplace hazards and appropriate control measures, particularly those involving understanding allowable boundaries for personnel that exist to ensure a safe working condition.

Recommended Actions:

1. The student shall receive specific instruction by the PI on the Pulsed Alexandrite Laser; this training shall be documented.
2. The student shall review with the PI all work planning and laser safety procedures and documentation for the Alexandrite Laser Laboratory. The Laser Safety Coordinator (LSC) shall verify this process.
3. The Chemistry Department shall define and document the Roles, Responsibilities, Accountabilities, and Authorities (R2A2) of the LSC.
4. Chemistry Department Chair shall meet with all laser users and emphasize the need to meet documentation responsibilities as required. Such responsibilities include interlock testing, updates to Standard Operating Procedures (Sops) and Experimental Safety Reviews, and system-specific training for all new users.
5. The LSC shall develop a Tier 1 type program for compliance verification in laser laboratories.
6. The Chemistry Department Chair shall emphasize to all supervisors that the link to the LSC for all new users on the facility-specific training form is required and the form must not be signed until the supervisor has ensured the new user has met with the LSC.
7. The Chemistry Department shall develop and implement a procedure to ensure that the check-in documentation for new personnel is signed and that the required training for the Experimental Safety Review designated on the check-in form has been completed.
8. The Chemistry Department shall implement a procedure to notify the LSC at the time of purchase of a new laser and again at the time of arrival of a new laser.
9. The Chemistry Department shall implement a procedure to ensure that the PI gives laser-specific training to each user and that this training is documented. This training is in addition to reading and signing the laser SOP.

Estimated Savings/Cost Avoidance:

Inadequate development and implementation of laser safety controls can result in severe/permanent eye damage.

Priority Descriptor:

Yellow - Caution

Work/Function:

- C.O.O., Procedure Following
- Human Factors
- Laboratory Experimentation
- OS&H, Personal Protective Equipment
- Safety Design

Hazard:

- Lasers

ISM Core Function:

- Analyze Hazards
- Define Work
- Develop/Implement Controls

Originator:

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Authorized Derivative Classifier:

n/a

Reviewing Official:

n/a

Keywords:

accident prevention, authorization, beam dump, laser injury, laser safety, laser safety eyewear, occupational injury, personal protective equipment, safe work practice, stop work, supervision, training

References:

1. BNL Report of the Committee charged to Investigate Laser Incident in Building 555 on September 9, 2003 (dated September 24, 2003)
2. DOE Occurrence Report Number CH-BH-BH-BNL-2003-0019, Graduate Student Incurs Laser Injury to Eyes
3. U.S. Department of Energy (DOE) Review of the Brookhaven National Laboratory (BNL) Laser Safety Program, (dated September 29 - October 10, 2003)
