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RADIATION SAFETY INTERLOCKS AT THE NSLS

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RADIATION SAFETY INTERLOCKS AT THE NSLS

The NSLS is a dedicated synchrotron radiation facility consisting of two electron storage rings with associated synchrotron radiation beam lines, and an injector which provides electrons for the rings. These devices produce ionizing radiation, and interlock systems are required for personnel protection.

The injector consists of an electron linac which operates at 80 MeV, and a booster synchrotron which accelerates the electrons to 750 MeV for injection into either storage ring. The normal repetition rate is once per second and the circulating current in the booster is about 20 mA for a total accelerated charge of 2×10^{-9} coulomb each cycle. It is possible to operate the linac at substantially higher pulse rates and currents. The radiation levels inside the enclosure could exceed 50 R/hr, so this area is classified as a high hazard radiation area.

The VUV ring operates at 750 MeV and the design current is one ampere. The ring is surrounded by lead and concrete shielding placed close to the beam chamber. This shielding keeps the average levels of radiation on the experimental floor well below 1 mR/hr. The shielding on the inside of the ring is less complete, so radiation levels up to one hundred mR/hr can be encountered. An interlock system covers the central region of the ring, and this is used to control access to this area.

The design energy of the X-ray ring is 2.5 GeV with a current of 500 mA, or 2.0 GeV with a design current of 1 ampere. The ring is located in a concrete tunnel, and there is lead strategically placed as shielding to keep the radiation level outside the tunnel well below 1 mR/hr. The radiation levels inside the tunnel can exceed 50 R/hr, so the X-ray tunnel is also a high hazard radiation area.

The synchrotron radiation from the X-ray ring is carried through beam pipes tangential to the ring into hutches where the experiments are located. The spectrum of the synchrotron radiation includes photons with energies up to several tens of kilovolts and the radiation flux can be extremely high: in the order of 10^{10} R/hr in the beam. In addition, high energy bremsstrahlung radiation is produced if the electron beam accidentally strikes something in the ring near the beam lines. Therefore the X-ray beam lines are high hazard radiation areas and are treated accordingly. There are approximately 36 X-ray beam lines under construction and a potential for 50 lines in total.

In the VUV area, the hazard from synchrotron radiation does not presently exist because there are no windows which can let the beam come out of the machine vacuum. The windows which are installed are too thin to support atmospheric pressure and are used to segregate regions inside the experimental apparatus. There are currently 16 beam lines in operation on the VUV ring.

PHILOSOPHY

The function of the NSLS interlock systems is to insure that no one is in an area where there is hazardous radiation, and to turn off the radiation source if a person somehow gains access to such an area.

The interlock systems for the high hazard areas meet the following design requirements.

1. The system is redundant, that is no single failure can render the system unsafe. This is done by providing 2 independent systems or circuits.

2. In so far as possible, the two circuits are physically different. This minimizes the possibility of related coincident failures.

3. The design is fail safe. This means that the most likely failure modes leave the system in a safe condition. For example, the following failures are safe: Loss of power in any part of the system, any combination of shorts to ground, and any combination of open circuits.

4. The interlock system must be testable. Redundancy sometimes makes testing difficult, but testing schemes must be worked out, since an untested interlock is undependable.

INTERLOCK SYSTEM DETAILS

A logic diagram of the interlock systems is shown in Figure 1. It should be noted that there are many more relays than there are logic gates on the diagram, since some functions, for example the search sequence, require several relays, and there are a number of auxiliary functions which do not appear on the diagram.

The interrelation of the different areas can be seen on the diagram. The extent of the action of a given interlock function is determined by the various shutters. Consider an X-ray beam line ready for operation with the hutch interlocks secured, but the safety shutter closed. If the interlock is broken, by opening the hutch door for example, the X-ray ring is not affected. When the safety shutter is open, however, breaking the interlock interrupts the RF and magnet power supplies in the X-ray ring, dumping the stored beam. If the transfer shutter between the injector and the X-ray ring is open, the linac is turned off as well.

The system is designed to avoid these inconvenient shutdowns; a shutter cannot be opened unless the area downstream of it is properly interlocked. For the same reason, the key to a hutch door is captured, and cannot be released unless the shutter is closed.

INJECTION AREA INTERLOCK

The floor plan of the linac-booster area is shown in Figure 2. Before the linac can be operated, the area must be searched to insure that no one remains inside. This search is enforced by the three check stations which are buttons which must be pushed in the proper order. There is a three minute time limit on the search process which insures that the system is never left in a partially searched condition. When the last button at the exit is pushed, there is a thirty second audible alarm period after which the linac may be turned on. On the logic diagram (Figure 1) this search and warning function is denoted by "search sequence". There are limit switches on the doors, and if a door is opened linac operation is stopped and the search is dumped. Six prominently labeled emergency stop buttons are placed around the area. Pressing any of these stops linac operation and dumps the search. Finally, the doors are locked by a transfer key system: when a door is unlocked the key is captured in the door lock; the key cannot be removed unless the door is closed and locked. The keys must be in a holding unit in the control rack in order to satisfy the injector interlock.

The two independent interlock conditions for the injector consist of the key-transfer door locks on the one hand, and the search sequence, door switch, and emergency stop requirements on the other. The relationship of these elements can be seen on the logic diagram. The door-search-emergency stop interlock chain enables the "external interlock" inputs on the two linac modulators. The external interlock on each modulator controls a contactor in the input power line of the high voltage power supply, thus controlling power to the accelerator. The key-transfer

interlock directly operates a second contactor in each modulator which independently controls the high voltage.

The injector interlock also serves to protect against electrical hazards, since the high voltage, high current connections to the booster magnets are not insulated. The power supplies for these magnets are interlocked to the injector area.

VUV RING INTERLOCK

The layout of the VUV ring is shown in Figure 3. The center of the ring is searched by touring the area, pressing the check stations in turn, within a 2 minute time limit. When the last check station is pressed, a 30 second audible warning is sounded and the entrance guard is activated. This consists of light beam detectors mounted on the stairway. The transfer shutter may then be opened and beam injected into the VUV ring.

If the interlock is broken by an emergency stop button or by interrupting the light beams while the shutter is open, three actions will occur: the linac turns off, the shutter closes, and the VUV RF turns off momentarily. If the shutter is closed at the time the interlock is broken, the only effect is to interrupt the RF. The effect of these actions is to stop injection if it is occurring, and to dump any stored beam.

The potential radiation levels in the VUV ring are far below those which define a high hazard radiation area so this interlock system serves to minimize exposures to personnel, not to protect against life threatening levels. Although most of the components are duplicated, the system is not completely redundant.

X-RAY RING INTERLOCK

The layout of the X-ray ring is shown in Figure 4. The logic of this system is similar to that of the injector interlock, although the search required is more extensive. The search is started by pressing check station 4 (CS-4) which lights a "DO-NOT ENTER" sign near the door. CS-5 is just inside the door, and pressing it sets the guard on the door so that if it is opened, the search is dumped and must be started over. A timer is also started which allows a maximum of three minutes to complete the search. Two searchers proceed in opposite directions around the tunnel searching for and noting any people inside but not forcing them to leave. At the 90° and 270° points they press CS-1 and CS-2 in either order. They meet at the 180° point, press CS-3 and continue in their original directions. From this point on, the searchers must insist that any people they encounter must move toward the exit ahead of them. At the exit the searchers compare notes and insure that every person seen during the search is present. CS-5 is pressed which initiates a 10 second period during which the door may be opened for exit. The door is closed and locked, and CS-4 is pressed which sets off the 30 second audible warning. The key is removed from the door and placed in the switch at the security rack. When this is done and the warning period is complete, the interlock system is satisfied and the RF and magnet power may be turned on, the injection shutter opened and injection commenced. As with the injection area interlock, the key-transfer door lock forms one branch of the interlock requirement, and the search sequence, door switch, and emergency stop features provide an independent branch.

If the X-ray interlock chains are broken when the injection shutter is open, the X-ray magnets and RF are turned off, the linac is turned off, and the shutter is closed. If the X-ray interlock is broken when the shutter is closed, the linac is unaffected, but the X-ray RF and magnets are turned off to dump any stored beam in the ring. The logical pathways for these actions are illustrated in Figure 1.

The electrical connections to the X-ray magnets are exposed inside the tunnel, and the power supplies are interlocked to the X-ray ring to provide electrical safety.

X-RAY BEAM LINE INTERLOCKS

Most X-ray experiments using synchrotron radiation require frequent access to the sample and the equipment. The hutch interlock systems are designed to permit a properly trained experimenter to gain access to the hutch, then restore the system to a safe condition and continue the experiment, all without intervention from NSLS operations.

The layout of a typical beam line is shown in Figure 5. The hutch comprises a small interlocked exclusion area complete with door switches, search sequence, emergency stop, and key-transfer door lock. Some beam lines have a monochromator, mirror box, or other component which also requires frequent access. These may be equipped with key transfer locks and limit switches on the access cover. Because access to such beam line components upstream of the hutch conveys the possibility of changing the beam optics or shielding, the interlock logic for these accesses is different than for a hutch. A beam line component access may be made anytime that the safety shutter is closed, but this action sets a latch which prevents the safety shutter from being reopened until the beam line

is inspected by the Safety Operator. The latch is reset with a key carried by the Safety Operator.

Since the transfer key system plays more than one role in beam line operation, the keys and locks have not been used as an independent chain of the interlock as was done in the X-ray ring and injector systems. Instead, the safety devices (door limits, emergency stop switches, key switches, and safety shutter position switches) all come in pairs, and are used to form two independent chains. In one chain, each switch operates one or more relays to provide sequencing and latching functions and extra contacts for status indication, as well as the logic connections. In the other interlock chain, the switches are simply connected together to form the necessary logic. Thus the two circuits are quite different, even though the logic is similar, and the possibility of related coincident failures is minimized.

Because of the extremely high radiation levels inside the X-ray beam-lines, access to these lines must be controlled as carefully as it is to the hutches. One method consists of constructing the beamline without any thin windows or vacuum valves upstream of the hatch. The beam pipe prevents dangerous levels of radiation from getting out, and if the pipe is opened the storage ring vacuum is lost and the radiation goes away.

Most beamlines do have windows or valves, and padlocks are used to lock the flanges on these lines so they are not opened in an uncontrolled way. This provides protection against the situation where a worker dismantles the wrong beamline due to confusion or misdirection. Obtaining the key to the padlocks has two results: it brings a safety operator to the scene who is familiar with the implications of opening a beamline, and

the padlock key is attached to another key which disables the beamline interlock. The padlocks are provided in sets which are keyed the same, with a given set confined to a beamline.

There are four latches built into the interlock logic:

1. the safety person approval latch which must be reset following a beam line access upstream of the hutch.
2. the emergency stop circuit,
3. interlock chain A, and
4. interlock chain B.

In normal operation these last three circuits should always be satisfied. If they trip, the latches force an inspection of the situation by operations personnel, and may help identify equipment or or procedural problems.

The beam line logic is arranged so mistakes which cause the storage ring to dump should not occur. The shutter cannot be opened unless the hutch and beam line interlocks are satisfied, and on the other hand, the key to open the hutch door or beam line component is captive and cannot be released unless the shutter is closed.

The beam line interlock logic is outlined in Figure 1.

VUV BEAM LINE SAFETY CONTROLS

The synchrotron radiation from the 750 MeV beam in the VUV ring is of much lower energy than that from the X-ray ring, and it has little penetrating power. However, it has been demonstrated that there can be hazardous radiation close to a thin beryllium window which admits the beam to air. At present there are none of these windows on the VUV beam lines, and permission to install such a window will not be granted unless a suitable personnel protection system is provided.

There is a potential hazard from bremsstrahlung radiation which will occur if the electron beam targets near the source point of a beam line. This is controlled by shielding collimators which confine the cone of potential bremsstrahlung, and by exclusion zones, consisting mainly of the beam pipes, which prevent access to that cone. If it is necessary to remove shielding or to move the beam pipes, the safety shutter is locked closed before this is permitted.

INTERLOCK TESTING

A personnel protection system which has been inadequately tested is not reliable. It is not possible to completely eliminate errors in construction (or in design) nor to be certain that components are not faulty. The best insurance against these problems is a comprehensive, functional test of the system. The various protective elements: door switches, emergency stop switches and the like, should be operated, and the resulting action observed. This test should also verify that each protective feature is redundant. Thus requires careful design, otherwise the action of one element may mask the effect of the redundant element. The test must be designed not only to verify that the system works as expected but also that improperly executed operations do not lead to an unsafe condition. For example, it should be checked that short cut search sequences do not work. In designing tests and interpreting the results it is important not to rely too heavily on the system logic, since this is one of the things being tested. In some cases it is necessary to defeat part of the protection to test another part. For example, the door lock must be circumvented in order to test the door limit switches. At the NSLS we use a spare "latch device" (the part of the lock assembly which is

attached to the door frame) to allow the key to be removed with the door open. The door cannot be closed completely when the latch device is in place, so the system is not in an operational state when the lock is defeated. This is safer than using a spare key or an electrical jumper, either of which might inadvertently be left in place.

An interlock system must be tested before it is put in service after any work has been done on the system, after any fault is reported, after any bypass or jumper is installed, after the bypass or jumper is removed, and after 6 months have elapsed since the last test. In the case when a fault is reported, the test should be done as soon as possible

The interlock tests are carried out using check sheets which list the test actions and have check spaces where the results are verified. The check sheets for a representative interlock system, the X-ray ring, are in Appendix A.

NON-FUNCTIONING INTERLOCKS

If an interlock system is not in an operational state, the source of radiation to that area must be disabled, either by locking a shutter or red-tagging the source. For example, if the interlock for an X-ray beam line is out of service the shutter must be padlocked, or the X-ray ring interlock turned off and red-tagged.

An exception to this practice occurs when the initial alignment of a beamline is undertaken. The beam pipe and shielding are necessarily incomplete when this is done, and frequently the interlock system is also not operational. When such an operation is undertaken, agreement is reached between the Safety Officer and the users as to exactly what will be done, and shielding, backstops, and personnel barriers are worked out. The shutter lock or beamline lockout is not removed until all shielding

and barriers are in place, and a representative of safety operations is in attendance whenever the shutter is unlocked.

ADMINISTRATIVE CONTROLS

The most straight-forward way to defeat a key transfer system, and indeed an entire personnel interlock system, is to arrange to be locked into an exclusion area by a confederate. The fact is, that it is not possible to prevent by mechanical means a determined effort to defeat the interlock system. This must be done administratively, with training, rules and sanctions.

A twenty minute video tape has been prepared which outlines the use of the beamline interlock systems and covers other safety matters at the NSLS. All new NSLS users and staff must view this presentation before they begin work at the Light Source.

The rules covering safety systems are listed in a memo which is given out with the video tape. In particular, attempts to defeat or bypass the personnel protection systems are absolutely forbidden. Any user who violates this will be banned from the NSLS for a period determined by the Department Chairman. Each user must sign this paper to indicate understanding and acceptance of these rules.

DOCUMENTATION

The primary record of interlock system matters is the "NSLS Personnel Interlock Maintenance Log" a bound laboratory notebook kept by the Safety Officer. Entries are made in this log whenever the system is tested, and include the reasons for the test and the result. These entries are handwritten, dated, and signed. Other material may also be included in the log, especially if it helps to establish an historical record of develop-

ment and operation. The completed interlock test checksheets are also signed and placed on file.

A complete set of "master prints" of the electrical schematics of the interlock systems is kept by the electrical engineer in charge of the systems. All corrections and modifications to the systems are entered on these prints, and periodically the original drawings are updated from these master prints.

NOTES ON FIGURE 1

The interlock logic diagram is drawn with logical symbols, or gates, which show the relationship of the various interlock conditions and actions. With an **AND** gate, all inputs must be true for the output to be true. The output of an **OR** gate is true if any of the inputs is true.

In the sample below, three conditions must be true; gate detector OK (no intrusion), **AND** search sequence complete, **AND** emergency stop OK (buttons not pushed) in order for the "ring OK" condition to be true. The ring OK condition allows the VUV RF to operate without interruption. The interlock line to the linac is satisfied if either the injection shutter is closed, **OR** the ring is OK (or both).

FIGURE 1 INTERLOCK LOGIC

Figure 2. Linac Booster Area

Figure 3. VUV Area

Figure 4. X-Ray Ring

Figure 5

NOTES ON APPENDIX A

A number of abbreviations have been used on the check sheets in order to make them as compact as possible CS-1, CS-2, etc. are check stations. Refer to the X-ray ring layout in Figure 4 for the location of the various check stations. ES-1, ES-2, etc. are the emergency stop buttons, which are also depicted on Figure 4.

A number of items referred to on the list are in the security rack located in the X-ray power supply area; the emergency door light, the emergency door reset button, the emergency stop light, the allow beam light, and the Red Tag switch.

Steps 5 through 12 on the check list verify that short-cut search sequences do not work. Steps 13 through 25 check that the various switches and timers perform the intended functions. Steps 26, 27 and 28 verify that the two independent interlocks each provide protection all the way to the radiation source.

Date _____
Lead Person _____
Assistant _____
Time Started _____
Time Ended _____

APPENDIX A

X-RAY RING INTERLOCK CHECK

1. Inform Control Room operator that test is in progress. Turn off linac low level RF at back of chassis and red tag. Insert lollypop and red tag.
2. Do a normal search of the X-ray ring to check that the system works. (This step not necessary if the system has been in recent use with no reported problems, and no rewiring or other work has been done.)
3. Dump the search.
4. Press CS-4.
The red sign outside the door comes on _____
5. Press CS-5. Press CS-4.
The pilot light on CS-4 does not stay on _____
6. Press CS-5. Press CS-1. Press CS-4.
The CS-4 pilot does not stay on _____
7. Open Exit Door.
Pilot on CS-1 goes out _____
8. Press CS-5. Press CS-2. Press CS-4.
Pilot on CS-4 does not stay on _____
9. Open Exit Door.
Pilot on CS-2 goes out _____
10. Press CS-5. Press CS-3.
Pilot on CS-3 does not stay on _____
11. Press CS-5. Press CS-1. Press CS-3.
Pilot on CS-3 does not stay on _____
12. Open Exit Door. Press CS-5, Press CS-2, Press CS-3.
Pilot on CS-3 does not stay on _____
13. Press CS-1. Press CS-3.
Pilot on CS-3 stays on _____

14. Open and close Emergency door.

Pilot on CS-3 goes out
Emergency door light comes on

Press Emergency Door - Reset button

15. Press CS-1. Press and release an emergency stop button.

Pilot on CS-1 goes out

16. Press CS-1. Turn off Red Tag switch, then turn it back on.

Pilot on CS-1 goes out

17. Press CS-1. Note the elapsed time until the pilot light goes out.

Time-out not more than 6 minutes

18. Press CS-1. Turn "kicker jumper #1" from "normal" to "jumper" and back to normal.

Pilot on CS-1 goes out

19. Press CS-1. Turn "kicker jumper #2" from normal to jumper and back.

Pilot on CS-1 goes out

20. Press CS-1. Prop Exit door open.

Press CS-5. Note elapsed time until pilot on CS-1 goes out.
Time delay not more than 10 seconds

21. Close Exit door. Press CS-5, CS-1, CS-2, CS-3, CS-5, one person go out the exit and press CS-4. One person stays inside. Open and close the Emergency door.

The audible alarm stops
The red sign goes out
The Emergency door light goes out

Press the Emergency door reset button.

22. Press CS-5, CS-1, CS-2, CS-3, CS-5, CS-4. Press an emergency stop button and release.

The emergency stop light goes out
Audible alarm stops
Red sign goes out

23. Press CS-5, CS-1, CS-2, CS-3, CS-5, CS-4.

The person inside notes that all
four audible alarms are sounding

Alarm interval not less than 30 seconds

The "allow beam" light does not come on
until the end of alarm interval

24. Open Exit door.

The "allow beam" light goes out
The red sign goes out

25. Press and release each emergency stop switch. In each case, the emergency stop light goes out.

ES 1
ES 2
ES 3
ES 4
ES 5
ES 6
ES 7
ES 8

26. Place the latch device on the exit door lock so the key can be removed with the door open. Put a holder on the exit door limit switch. Press CS-5, CS-1, CS-2, CS-3, CS-5, CS-4. Replace and turn the Kirk key in the Kirk switch. After the alarm period, open the booster-to-X-ray shutter. Turn the Kirk key.

The shutter closes

27. Turn the Kirk key on. Turn on the power supplies for the X-ray dipole QA, QB, QC, QD and the sextupole. Turn off the Kirk key.

Dipole goes off
QA goes off
QB goes off
QC goes off
QD goes off
Sextupole goes off

28. Turn the Kirk key back on. Search and secure the linac booster. Turn on both linac modulators. Turn on the X-ray dipole, QA, QB, QC, QD, sextupole, and injection kickers. Turn on the X-ray RF and display the RF output on an oscilloscope or other monitor. Open the booster to X-ray shutter.

One person observes the RF output and the state of the X-ray magnet power supplies. Another person observes the shutter indicator, the linac modulators and the X-ray injection kickers, and a third person removes the exit door switch holder when all is ready.

The RF output goes away
Both modulators turn off
The shutter closes
The kickers turn off
Dipole off
QA off
QB off
QC off
QD off
Sextupole off

29. Remove latch device and switch holder from exit door. Check that exit door operates properly. Remove red tags and turn on linac low level drive and withdraw lollypop. Inform operators that test is complete and have them make an entry in the Control Room shift log. Make an entry in the Personnel Interlock Maintenance Log.

Appendix B

KEYS AND KEY CONTROL

There are eight different types of keys associated with the personnel interlock systems:

- A. Kirk keys, used on the injector and X-ray tunnel doors.
- B. Kirk keys, used on the X-ray hutch doors.
- C. Kirk keys, used on the X-ray beam line components.
- D. Kirk keys, used as beam line lock-out keys.
- E. Control Room shutter enable keys.
- F. Beam line flange padlock keys.
- G. Safety shutter padlock keys.
- H. Beam line reset keys.

With the exception of the last, which are portable keys, there are specified locations for each of these keys for each set of circumstances.

The first three Kirk keys are always in one lock or another, as different access states of the interlock systems are defined. The control of these keys is defined by the mechanical and electrical features of the Kirk system.

There is a beam line lockout key at each X-ray beam line which disables the beam line interlock when it is removed from its lock. This is done whenever the beam pipe is opened, shielding is removed, or other condition makes it unsafe to open the safety shutter. The Control Room shutter enable key is also removed from its lock in this situation to provide redundant protection.

There is a Control Room shutter enable key for each X-ray beam line, located in an array of key switches near the NSLS Control Room. When a shutter is to be disabled, the key is removed from the switch and placed in a nearby rack, to provide clear indication that the shutter is disabled and to reduce the chance that the switch is turned on inadvertently. If

the beam line is shut down for safety reasons such as missing shielding, then the beamline lockout key is attached to the shutter disable key and placed with it on the rack.

The beam line flange padlock keys are always fastened to the corresponding shutter enable keys, and both are carried to the beam line when it is to be unlocked, then placed on the storage rack until the beam line is secure.

The beam line shutters are padlocked in the closed position whenever the associated interlock system is not operational. These keys are kept by the NSLS Safety Officer, and an entry is made in the Interlock Maintenance Log whenever a shutter is unlocked or relocked.

Each Safety Operator carries a beam line reset key, and uses it to reset the safety person approval latch after inspecting the beam line to verify that it is safe to operate. This key is also used to reset the latches on emergency stop and the two interlock chains if these should be tripped.

These keys are part of the primary radiation protection system, and are carefully controlled. The spare keys are kept in a locked cabinet and an accurate inventory is maintained. Access to these keys may occur only with authorization from the NSLS Safety Officer, the head of NSLS Operations, or the NSLS Safety Coordinator. This authorization may only be for the use of a specific spare key. Blanket authorization for the use of spare keys may not be given. If an interlock key is missing or damaged, those in a position to know the circumstances will confer and present the facts to the person who can authorize the use of a spare key. Where practical, locks shall be replaced or rekeyed when interlock keys are lost.