

Design considerations for the IBM X-ray lithography facility

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Synchrotrons, like other large particle accelerators, have historically been the tools of universities and national laboratories for research. Moving this technology to industry presents many challenges which do not exist in an academic environment. One major challenge is to develop a facility to house and support the ring in a manufacturing-like mode where operator, customer, and public concern for radiation and industrial safety is of extreme importance. This paper describes IBM's efforts to design and build a facility to address these safety concerns.

Introduction

Other papers in this issue describe IBM's entry into X-ray lithography and the need for a dedicated X-ray facility [1]. It was decided that the X-ray facility should be located at the IBM plant site in East Fishkill, New York. East Fishkill is close to the IBM Thomas J. Watson Research Center in Yorktown Heights, New York; it is also the location of the Advanced Semiconductor Technology

Center (ASTC), which is the corporation's new pilot line development center for semiconductor devices. The X-ray lithography project is a joint program between the Research Division and the former General Technology Division (now Technology Products Group). In addition, in 1992, the IBM Federal Systems Company became a member of the joint operating team.

The X-ray facility, dubbed ALF for Advanced Lithography Facility, houses the Helios 1 electron synchrotron and its support equipment, as well as clean and nonclean (house) condition research areas. This means supporting limited wet-process tooling in a clean environment. An additional requirement is to have the exposure tools located on a vibration-resistant floor equivalent to the one in the ASTC. A major consideration is shielding for the secondary radiation produced by the operation of the linear accelerator (linac), the electron storage ring (ESR), and the radio frequency (rf) equipment. Because of public concern with respect to the safety of radiation and radiation facilities, a primary requirement for the shielding is that it allow ALF to be run as a nonradiation facility. This means that general access to the facility (excluding the linac, ESR, and rf areas) will not be

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restricted for radiation-protection purposes under all anticipated operating conditions.

The technical requirements for the facility were developed in planning sessions with the participating IBM divisions and Oxford Instruments, the synchrotron supplier. Soon thereafter Bechtel National was selected to be the general contractor and joined the planning team. The plans developed included specialized requirements for supporting the synchrotron, the usual support for photolithographic processing, and special considerations due to the high-voltage and radiation sources in the building.

In this paper, we describe the design, implementation, and subsequent testing of the radiation shielding. Finally, we give a brief discussion of the implementation of the ALF safety and security systems. Since the perception of hazards was as important in our considerations as the hazards themselves, it was our goal to design and construct a state-of-the-art facility with respect to all aspects of safety. Realizing that we did not have enough in-house expertise in this area, the authors contracted with the Columbus, Ohio laboratories of Battelle Memorial Institute for engineering and consulting services on radiation shielding as well as other aspects of safety and security.

General description of ALF

ALF was designed as an addition to the ASTC building providing two immediate advantages:

1. It permitted the direct clean connection of the process areas of the two buildings to facilitate the flow of wafers from the exposure areas in ALF to the process areas in the ASTC.
2. It allowed ALF to use the chemical distribution and waste-handling facilities of the ASTC. Details of the building design and construction have been published elsewhere by the authors [2, 3].

Briefly, ALF contains about 20 000 square feet of process space in a gross area of about 50 000 square feet. The process area is constructed on a 5-micro-inch maximum displacement antivibration slab, which is isolated from the rest of the structure. A three-story south utilities wing houses the air-conditioning units for the building, and a two-story north wing contains the electrical substation, exhaust, cooling water, heating water, and chemical transfer systems. As shown in **Figure 1**, the electron synchrotron is located in the center of the building. The power supplies and cryogenic systems that support the synchrotron are located in the northwest quadrant of the building along with the control room. The class 1000 clean room is located on the east side adjacent to the ASTC, to which it is connected at the second story

via a class 10 000 corridor. The clean room holds the wet-process tools and the metrology equipment of ALF. The steppers are also in the clean room but in class 1 mini-environments. Wafers are handled by the SMIF (Standard Manufacturing InterFace™) system.

The research laboratory on the west side of the building is a high-ceiling house-conditions laboratory for experiments that do not require clean conditions, such as beam characterization, beamline hardware development, radiation damage studies, and photoresist characterization. Primarily because of the detailed planning and close cooperation of all the parties involved in the design and construction of ALF, it was finished on schedule and under budget. The installation of Helios also went smoothly [4].

While radiation was the main safety concern in the design of the facility, the high-voltage sources for the klystrons and the rf transmitter are a more serious potential hazard. Also used in the plant room are significant quantities of liquid nitrogen and liquid helium, which potentially pose both asphyxiation and cryogenic hazards. To be sure that all aspects of safety were well covered, the authors formed a safety review committee at the start of the program. This group included representatives from the working laboratory sites, from Corporate safety organizations, and, later, from Battelle Columbus. The scope of the contract with Battelle Columbus included radiation safety and shielding design, physical security, employee and user training, cryogenics use and training, and general safety. This was later expanded to include the design, fabrication, and installation supervision of the primary (lead) shielding.

Radiation sources in ALF

As with any high-energy accelerator facility, there are sources of ionizing radiation which must be controlled. In ALF the major sources are the linear accelerator (linac) injector, the electron storage ring (ESR), and klystrons that provide radio frequency power to the linac. Some details are provided for each in order of increasing concern.

The klystrons themselves are a minor generator of radiation. They are very large, high-current vacuum tubes producing up to 37 MW of rf energy, operating at about 20 kV. Whenever electrons move in a vacuum, the potential for X-ray generation exists. Unshielded, the klystrons can produce measurable radiation fields when in operation; however, the X-rays are low-energy and are easily eliminated with thin lead shielding. Preliminary tests at Oxford showed that about 1/16 inch of lead would be required to provide adequate shielding. While the klystron shielding eliminated the need to control the rf room (see **Figure 1**) as a radiation area, strict access control is maintained to protect personnel from electrical hazards.

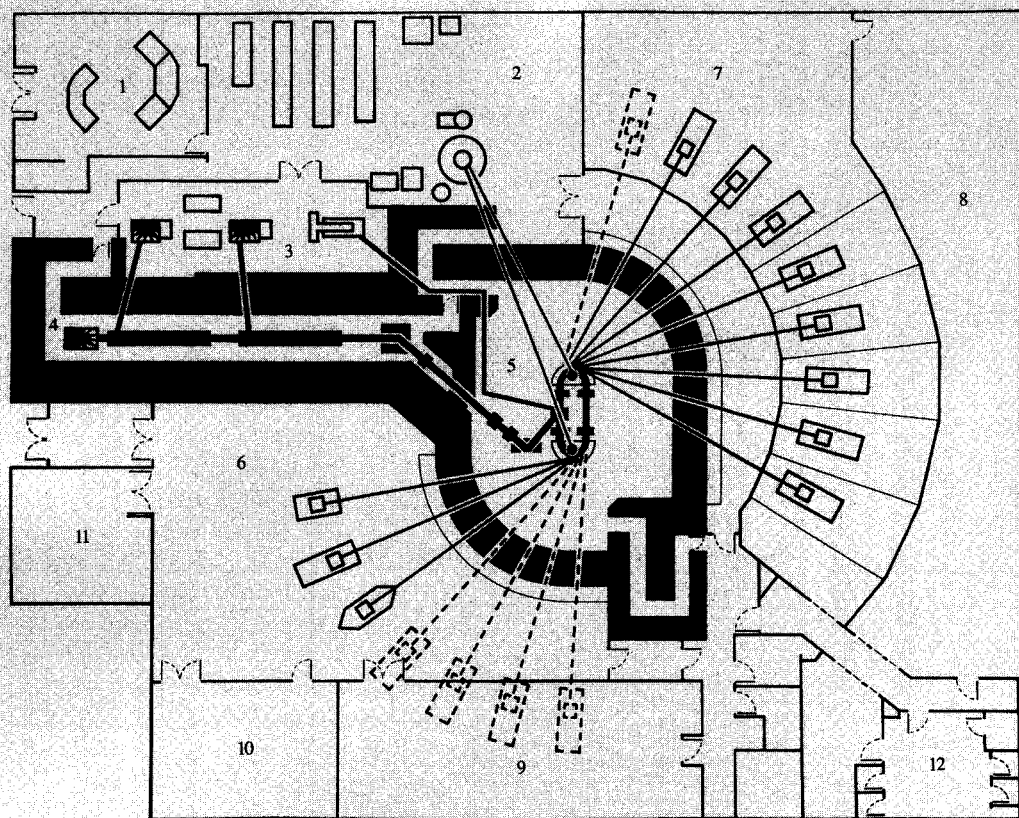


Figure 1

General layout of ALF building: 1, control room; 2, plant room housing power supplies and cryogenic equipment; 3, rf equipment room housing klystrons for linac and TV transmitter; 4, linac room; 5, ESR room; 6, research area; 7, process area (class 1000); 8, tool core (class 10000); 9, Laboratory 1; 10, Laboratory 2; 11, Laboratory 3; 12, change area and lockers.

The ESR is the next most prolific source of radiation. Although the ESR operates at a beam energy of 700 million electron volts (MeV) (much greater than the 200-MeV linac), the ultrahigh vacuum and great beam stability prevent large electron losses from occurring. Instead, the ESR beam is lost gradually over many hours of operation, thus reducing the radiation dose rate to a very small value. The two main electron loss mechanisms which generate radiation are total beam loss and residual gas scattering.

In a total beam loss situation, some unexpected event upsets beam stability and causes the entire beam to be quickly lost. Electrons striking some component of the ESR generate high-energy X-rays, which creates an electromagnetic cascade that also produces neutrons. Lead shielding is strategically placed to stop the electromagnetic cascade as close to the electron loss point as possible. This

produces neutrons which are shielded by the concrete and other hydrogenous materials (e.g., polyethylene). The second mechanism results from the fact that a perfect vacuum does not exist inside the ESR. At some point an orbiting electron will interact with a residual gas molecule and be scattered out of the beam. The lost electron(s) then create the same radiation cascade as the total beam loss mechanism, but to a much smaller degree.

The greatest radiation source in ALF is the linac. Although it operates at 200 MeV (compared to the ESR at 700 MeV), the linac and transport line have many more loss points. First, between the two linac sections is a focusing magnet, called the triplet, which acts as an aperture. This is a very high loss point. At this location the electrons have 100 MeV of energy, which is still great enough to create the same cascade described above. After

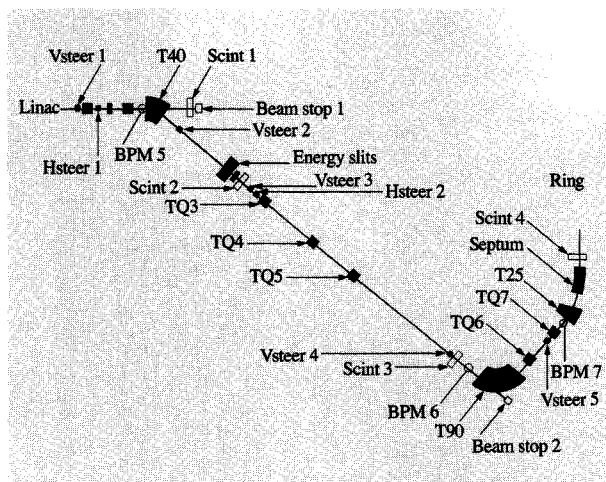


Figure 2

Components of the Helios 1 200-MeV injection transport line.

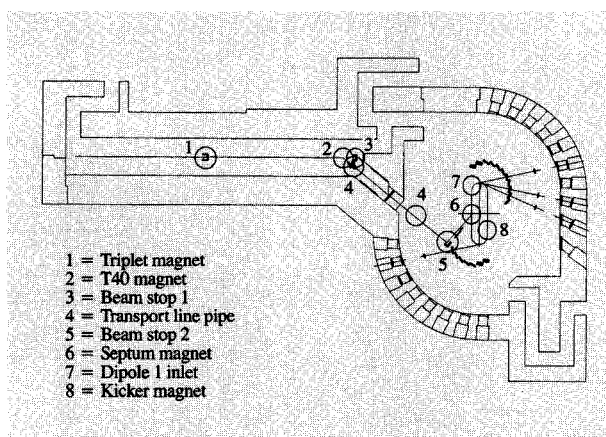


Figure 3

Known radiation activation locations.

passing through linac section 2, the electrons have about 200 MeV of energy and reach the first bending magnet, called T40 (see **Figure 2**). Because the beam is not exactly monoenergetic, some electrons will be bent too much or too little through T40 and will strike the transport beam pipe. The next loss point is the energy-analyzing slit, where electrons of specific energy are allowed to pass while others are removed (also creating a radiation cascade). The final loss point is the septum magnet, where the injected beam is merged with stored beam in the ESR.

Wherever electrons are lost and an electromagnetic cascade is produced, materials close to the loss point

become radioactive. Fortunately, the isotopes produced are all relatively short-lived and are not a long-term concern. However, immediately after shutdown significant radiation levels exist at the triplet, at the transport line pipe immediately behind T40, at the energy slits, and at the transport line pipe just inside the ESR vault (see **Figure 3**). Local lead shielding has been installed and these areas are no longer an exposure concern.

ALF radiation shielding design

The decision was made very early in the project that ALF would NOT restrict access to the facility for radiation protection reasons. To reach this goal, a target dose had to be specified so that shielding of the rf equipment, the ESR, and the linac could be appropriately designed. After much discussion at many levels, a consensus was reached that the target should be some small fraction of the average annual background radiation dose everyone receives. To that end, a target of 20 mrem/yr was chosen, representing about 10% of the average annual U.S. background dose.* Further, the target dose would apply to a person standing at the outside of the shielding for ten hours a day, five days a week, 50 weeks a year. In reality, actual personnel exposures would be well below this target limit.

Once the target dose limit was decided, all three of the project contractors (Battelle, Bechtel, and Oxford) were asked to produce independent shielding designs. When all proposals were ready, the teams were brought together at Yorktown to compare results and produce a single design. The final design used the most conservative specifications from each proposal.

• ESR/linac shielding design

Bechtel and Oxford used empirical shielding data to derive their shielding estimates. Battelle was asked to perform an analysis on the basis of Monte Carlo and first-principle calculations. We describe only the Battelle calculations here.

The first step involved setting the design basis for the calculations. For ALF, information was needed on electron losses in kilojoules (kJ) per year. It was assumed that the ESR stored current was 500 mA (the actual value was 250 mA) and that workers would be present ten hours a day, five days a week, 50 weeks a year. The operational modes were also broken into a "first-year commissioning" period and a "normal operating" year. For comparison, the first-year period assumed a fill/dump cycle about every

*Millirem per hour (mrem/hr) is a unit of radiation dose rate. For comparison, the average annual background dose rate to which everyone in the U.S. is exposed is about 200 mrem/yr. Of this amount, about half is from natural terrestrial and cosmic origin. The remainder is from manmade sources such as medical and dental X-rays and consumer products. The radiation level where access control is required is 5 mrem/hr. At this level, the area must be posted as a radiation area and access controlled to allow only authorized personnel to enter. In addition, personnel radiation-monitoring badges might be required. This environment clearly is not desired for ALF.

15–30 minutes, while normal operation assumed a two-hour cycle (actually about 8–12 hr).

Assumed electron losses used were as follows:

- First year
 1. linac – 2.34×10^4 kJ/yr.
 2. ESR – 33.4 kJ/yr.
- Normal year
 1. linac – 1.38×10^4 kJ/yr.
 2. ESR – 13.1 kJ/yr.

The electromagnetic cascade mentioned above generates three major types of radiation: photons, neutrons, and pions. Photons (X-rays and gamma rays) are generated primarily by bremsstrahlung, pair production, and neutron inelastic collisions. Bremsstrahlung is a photon field with a broad energy spectrum generated when electrons scatter from a positively charged nucleus. The electron energy and radius of the electron trajectory after the interaction determine the energy of the photons generated; the higher the energy and smaller the radius, the greater the photon energy. Pair production is the generation of an electron and positron by the interaction of a high-energy photon with the fields near a nucleus. The positron and electron annihilate to produce two 0.511-MeV photons. Neutron inelastic collisions generate photons when a neutron–nucleus scatter event leaves the nucleus excited. The excess energy of the nucleus is radiated as a photon.

Most of the neutrons generated are from photon interactions with nuclei in the shielding material. A photon with sufficient energy (generally 8–10 MeV) colliding with the nucleus of an atom may impart enough energy to the nucleus to knock out a neutron. Photoneutrons tend to be isotropic and affect shielding design in all directions. Secondary neutron sources are quasideuteron reactions. These are also photoneutrons, but originate from a different, high-energy mechanism; the nucleus is assumed to be a collection of deuterons with their own neutron production rate. Quasideuteron neutrons are high-energy (greater than about 150 MeV) and forward-directed.

Figure 4 shows the expected neutron spectrum for the ESR. Most neutrons generated in ALF are about 10 MeV, although a significant fraction of the neutrons are present at higher energies.

For photons greater than about 150 MeV, bombardment of nuclei can produce positive, negative, and neutral π mesons (π^+ , π^- , and π^0). The π^0 meson decays into two photons that add little to the overall radiation production. The π^+ meson decays by the reaction

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

followed by

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,$$

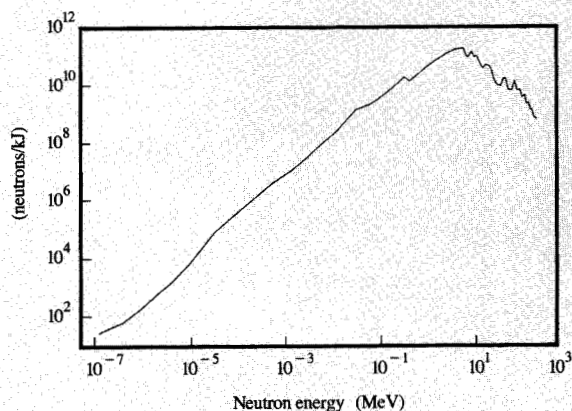


Figure 4

ANISN calculated neutron spectrum; isotropic neutron source from 700-MeV electrons.

where ν_μ and $\bar{\nu}_\mu$ represent a neutrino and an antineutrino associated with the muon decay, and ν_e is the electron neutrino. The positron adds negligible radiation via annihilation. Only the π^- adds to the overall radiation levels via neutron production from

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

followed by

$$\mu^- + p \rightarrow n + \nu,$$

where the p is a proton in the nucleus. The quantity of neutrons generated is about an order of magnitude less than that from the other processes, but it was included in the calculations.

The calculation employed the ANISN one-dimensional discrete-ordinate transport code [5] to simulate the source $\rightarrow$ lead $\rightarrow$ concrete geometry by assuming a one-inch-radius spherical source surrounded by a six-inch-thick sphere of lead with various thicknesses (0.2, 1.9, 4.37, and 6.56 feet) of concrete located at different distances beyond the lead (starting at 16.4 feet, the distance from the ESR to the inside of the ESR shielding wall). Because the quasideuteron neutrons are forward-directed (not isotropic, as assumed by ANISN), the shielding in the forward direction will be underestimated. However, using pessimistic operating conditions and loss fractions more than compensates for the error.

• Shielding design results

The ANISN results are shown in Table 1 for both the first-year and the normal-year assumed operating conditions.

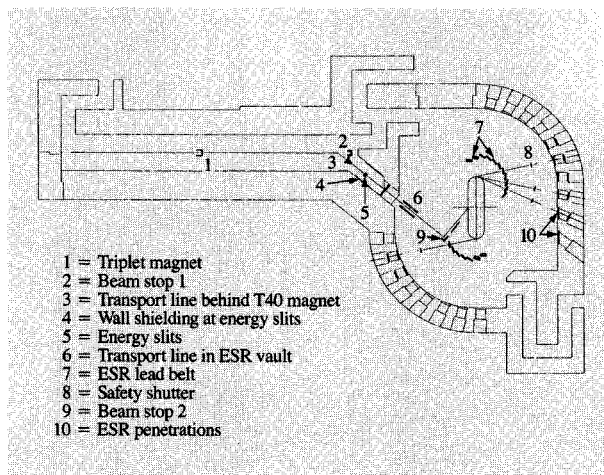


Figure 5

Lead shielding locations.

Table 1 Calculated concrete shielding requirements—combined annual exposures from injection and operation (in mrem per year).

<i>First-year operating conditions</i>				
<i>Distance from center</i>		<i>Concrete thickness</i>		
(ft)	(cm)	0.67 m	1.33 m	2.0 m
18.6	567	1895	—	—
20.8	633	—	33.4	—
23.0	700	—	—	2.05
32.8	1000	354.0	9.7	0.75

<i>Normal-year operating conditions</i>				
<i>Distance from center</i>		<i>Concrete thickness</i>		
(ft)	(cm)	0.67 m	1.33 m	2.0 m
18.6	567	1115	—	—
20.8	633	—	19.6	—
23.0	700	—	—	1.18
32.8	1000	208.0	5.7	0.43

The normal-year target of 20 mrem/yr is met by 4.37 feet (1.33 meters) of concrete, but exceeds the target for the first year (33.4 mrem/yr vs. 19.6 mrem/yr). It was agreed by those involved that the first-year operating conditions really were overly pessimistic, and the decision was made to use the normal-year results. Battelle also recommended that a safety factor be added to their results. For comparison, the Oxford calculations ranged between 5.25 and 6.5 feet (1.3–2 meters) of concrete. Bechtel also estimated the same general amount of shielding.

Overall, the final thickness was set at 5.5 feet (1.68 meters) of concrete with a three-foot-thick roof for both the ESR and linac vaults. The ALF project staff felt very comfortable with the final shielding design, not only because the contractors worked independently, but also because they used different calculation techniques. In all cases, the contractors were instructed to use pessimistic assumptions concerning operating conditions, loss locations and percentages, beam currents, equipment-on time, etc. In fact, electron losses greater than 100% were used to ensure that the shielding would be adequate even at maximum linac output.

One assumption that was difficult to deal with involved specific loss locations and percentages. While known locations were accounted for, unknown or floating locations were a challenge. To obtain better data, two tests were performed by Battelle and IBM—one at the Brookhaven National Laboratories National Synchrotron Light Source (NSLS), and the other at Oxford on Helios 1. Both tests involved measuring radiation production during various phases of operation and testing of radiation-monitoring equipment in a high-energy accelerator environment. When the data were factored back into Battelle's calculations, slightly less concrete was found to be needed, but the change was not cost-effective.

After many months of operating experience with ALF, the actual operating conditions have been found to be much better than originally assumed for the shielding design. The shielding is indeed overdesigned.

ALF shielding construction

As described above, an electromagnetic cascade is started when high-energy electrons are lost from the beam. Neutrons are also generated as the cascade photon radiation interacts with nearby materials. Because the photons and neutrons behave quite differently, the shielding required for each is also different.

The photon radiation generated is forward-directed, generally along the original path of the electrons. In order to terminate the cascade quickly, lead is placed in discrete locations as close as possible to the loss points: around the triplet, beam stops, transport line pipe loss points, and energy slits, and in a six-inch-tall belt around the ESR (see Figure 5). Stopping the photon radiation in lead creates photoneutrons that are not forward-directed, but are emitted isotropically. The concrete walls and roof of the ESR and linac vaults are the neutron shielding.

In order for the X-ray beamlines to pass through the shielding, 18 penetrations were provided through the ESR vault wall. Other penetrations were also made for wiring, plumbing, and equipment and personnel access. All penetrations were either backfilled with concrete and polyethylene or were designed as labyrinths (e.g., personnel access passages) in order to prevent radiation

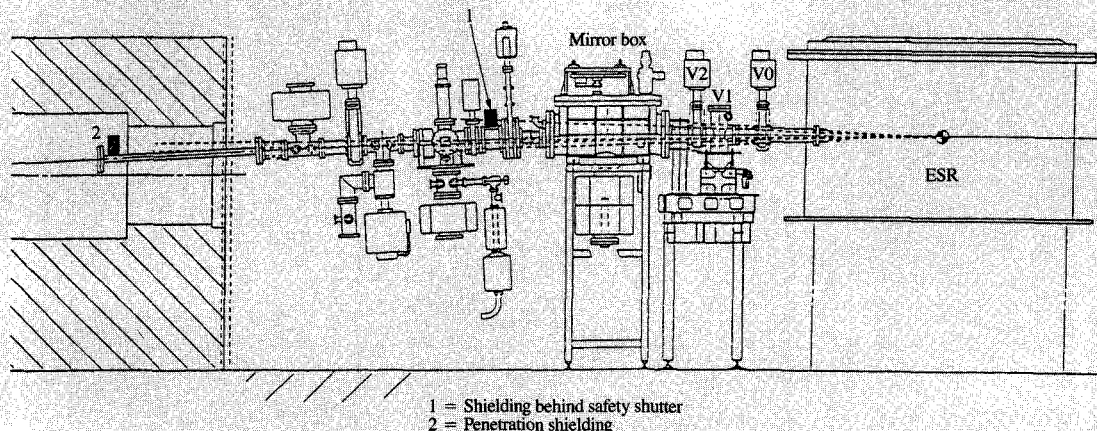


Figure 6

IBM beamline configuration and lead shielding.

leakage. Polyethylene was used because neutron shielding is most effective with hydrogenous materials.

Three labyrinths were provided for personnel access to the ESR and linac vaults. For safety reasons, two means of egress are required from each vault, so a labyrinth was placed at each end of the linac vault and at opposite sides of the ESR vault (see Figure 1).

Late in the design of the ESR lead belt, ray tracing of the beamlines disclosed a small amount of leakage through the safety shutter (see Figure 6). The leakage was stopped by installing a tungsten and lead shield behind the shutter on top of the beamline. A final lead shield also had to be placed in the concrete wall penetration to intercept the last bit of leakage.

Even though the additional lead and tungsten were required to maintain shielding integrity, the use of a beamline X-ray mirror is also extremely useful for radiation protection. The mirror deflects the low-energy X-rays of interest downward about 3 degrees, while the unwanted high-energy radiation continues straight through the beamline to be stopped by the lead. If mirrors were not used, level, straight-through beamlines would be needed, and both low- and high-energy radiation would reach the stepper or end station. The low-energy X-rays would not escape, but the high-energy radiation would create a serious personnel exposure concern directly behind any end station. Substantial shielding at the stepper or end station would be required, or the equipment would have to be located in the ESR vault and operated remotely. Either solution would greatly affect the operation of the facility. The mirrors allow the low-energy X-rays to be used safely

while allowing the high-energy radiation to be readily shielded.

ALF shielding test results

After the ESR was installed and made operational, a test of the shielding effectiveness was performed in the fall of 1991 by Battelle and IBM. The test consisted of placing 200 thermoluminescent dosimeters (TLDs) and neutron track etch detectors (TEDs) at selected locations inside and outside the ESR and linac vaults and at various locations around ALF. An estimate was made of the expected dose rates using the QAD Combinatorial Geometry Neutron and Gamma-Ray Shielding computer code [6] with updated operating conditions (basically, more accurate duty cycles for the linac and ESR). The locations showing significant results are presented in Figure 7. Clearly, the results at locations 12, 13, 14 and 8, 9, 10 were higher than expected. The photon doses at locations 12 to 14 are caused by previously unknown electron losses in the transport line as it first enters the ESR vault. The reason for the elevated neutron levels at locations 8 to 10 is unknown, although it could be artifacts from the TED processing. In both cases, the resulting doses outside the shielding would certainly exceed the 20-mrem/yr limit.

To eliminate the transport line problem, a new shield was fabricated by Battelle (see Shield No. 6 in Figure 5). The addition of four inches of lead reduced the radiation levels to normal. Further testing in July 1992 verified the effectiveness of this new shielding and showed that the earlier neutron results at locations 8 to 10 were indeed artifacts.

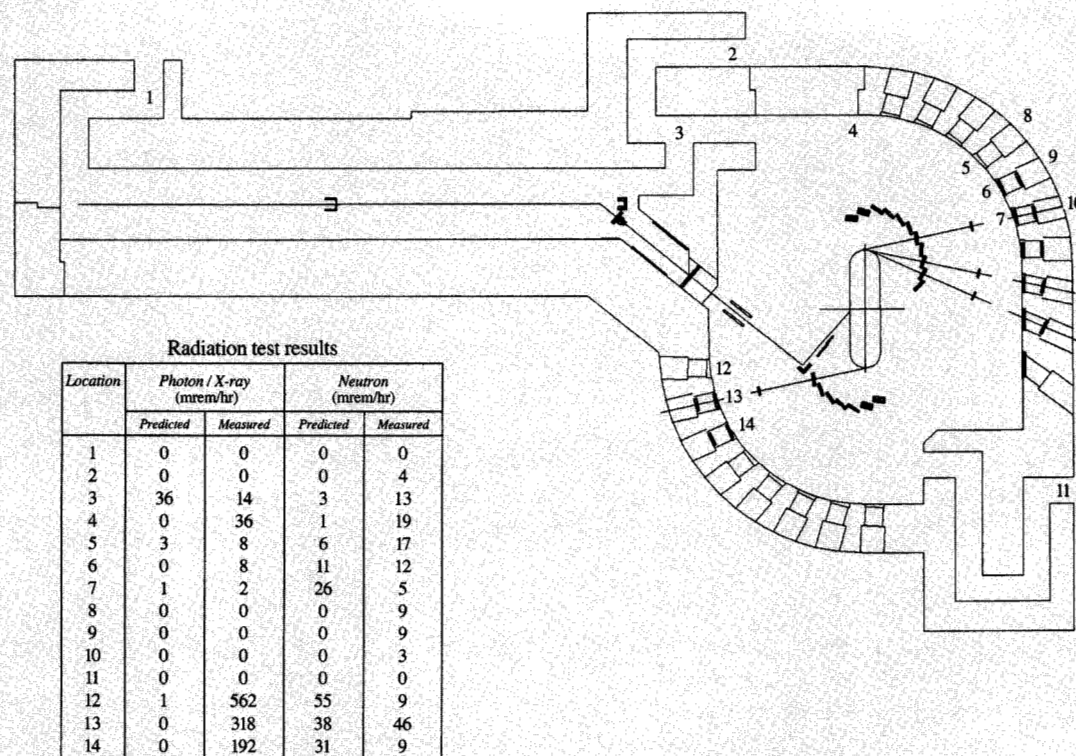


Figure 7

Selected radiation test result locations.

Test runs were performed specifically to measure the actual electron loss locations and quantities. Up to this point, only estimates were available for calculations. When the measurement results are ready, they will be fed back into QAD and the earlier calculations to see how much they deviate from the true shielding needs.

To verify the dosimetry work done by Battelle and to provide monthly TLD services, another contractor was retained to provide monitoring outside the concrete shielding. The measured background radiation dose in ALF is about 20 mrem/month (240 mrem/yr). Doses outside the shielding at all monitored locations are not statistically different from background. While the 20-mrem/yr limit is impossible to measure directly, the monthly monitoring data combined with conservative shielding design will ensure that no person will receive even a significant fraction of the dose limit.

Security and personnel safety at ALF

Security and safety at ALF are monitored by the Security and Personnel Safety System (SPSS), which consists of two PS/2[®] computers that monitor facility, beamline, radiation, and system status. Before Helios is allowed to operate, the ESR and linac vaults must be searched. An operator informs the SPSS that a search is needed and then proceeds to walk through the vaults checking for other people and for equipment problems. The operator must activate check-station buttons as he/she progresses to inform the SPSS that all areas of the vaults have been searched. A second operator monitors several TV cameras to ensure that the first operator does not run into trouble.

When the searches are complete, the SPSS allows Helios to operate. During operation, if the SPSS detects any faults, permission to operate is withdrawn from Helios and the beam is dumped. Operation is not permitted until

the fault is investigated and corrected. Examples of faults monitored include vault access doors, rf room access doors, ESR/beamline vacuum and equipment-cooling water flow for machine protection, and safety shutter and vacuum valve position status. The SPSS also provides a data log feature that can help in reconstructing fault conditions.

Summary and conclusions

ALF was designed to be operated as a nonradiation facility and, in fact, is being operated in that manner. After a careful and conservative design process, the radiation shielding and monitoring instruments were carefully installed according to the plan. A two-phase testing strategy was implemented. Some areas needing additional shielding to meet our very tight criteria were identified, and the additional shielding was designed and installed. The total safety and security installation now exceeds all of our expectations. A significant database has been developed for future comparisons and to evaluate engineering changes.

It is the conclusion of the authors that with proper planning and careful installation, a tool as complex as an electron synchrotron—formerly limited to national laboratories and major universities—can be installed and operated in an industrial setting safely and without major concern to the staff.

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