Radiation Protection Considerations in the Design of Accelerated Radioactive Beam Facilities

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There has been a steadily growing worldwide interest in generating accelerated beams of unstable nuclei for use in a variety of applications such as nuclear physics, nuclear astrophysics, atomic and condensed matter physics, and medicine. A number of facilities, either planned or under construction, will couple an intense production source of unstable elements to an efficient accelerator in order to produce accelerated ion beams of a wide range of nuclei far from stability. This paper examines the radiological safety constraints placed on the design of such radioactive ion beam facilities. The deliberate generation of volatile species of radioactivity leads to problems not usually encountered at other high-intensity accelerator projects. The need to contain the loose radioactivity compounds the difficulty of handling the target/ion source and mass separator and puts tight constraints on the reliable control of the ion beams. The use of targets of atomic number up to and including 92 leads to the production of alpha-emitting radioactivity. The high biological hazard of this radioactivity requires that its dispersion be closely controlled both in the working environment and off-site. The success of the radioactive ion beam facilities will depend on cost-effective solutions to these problems.

1 Introduction

There are two methods of generating beams of radioactive ions of high energy. One of these is the 'projectile fragmentation method' where heavy ions are accelerated to high energy and then made to impinge on a thin target. The ensuing reactions generate nuclear fragments that may then be energy- and mass-analyzed to provide beams of exotic nuclei. The energy of these is controlled by the energy of the projectile and the angle at which the fragments are collected.

The second is the 'Isotope Separator on Line' (ISOL) method followed by a high-efficiency accelerator. In this method a beam of high-energy particles (usually protons) bombards a thick target while at the same time the target is heated to high temperature. The radioactive atoms produced in the target either diffuse or are driven out into an ion source and accelerated to a low energy. This undifferentiated beam of ions is mass-analyzed to select a specific species, which is then accelerated. The latter method has the advantage of better energy resolution for the accelerated ions and higher maximum intensity of the ion beams. This paper will discuss only the ISOL method as most high intensity facilities presently under construction or planned (Table 1) are of this type.

2 Radiation Protection Concerns

Some of the radiation protection issues at the radioactive beam facilities are of the same kind as those encountered at high-intensity proton or heavy ion accelerators in general. But the deliberate generation and transport of volatile species of radioactivity and the perceived need for frequent servicing of the target/ion source system introduce a new dimension not usually encountered at accelerator research facilities. A not necessarily exclusive list of the main radiological issues is:

1. radiation from intense proton beams
2. radioactivity induced in targets and structures
3. loose radioactivity containment
4. environmental impact
5. radioactivity deposition by ion beams
6. internal exposure of workers

Before we discuss these in detail it is perhaps useful to review some principles of radiation protection.

3 Some Principles of Radiation Protection

The last thirty years has seen a number of refinements in the philosophy of radiation protection. The elements of this philosophy have been summarized and codified by the International Commission on Radiological Protection [1] and have been integrated into the national regulatory systems of many countries. The basic principles may be paraphrased as follows:

- The justification of practice: the benefits to individual or society must outweigh harm caused by exposure to radiation;
- The optimization of protection: the magnitude of dose, the number of people exposed and the probability of exposure must all be as low as reasonably

Table 1: ISOL/post-accelerator RIB facilities ([a]existing, [b]under construction, [c]planned).

Location	Project	Projectile	Driver	Post-accelerator
UCL (Belgium)	ARENAS[a]	p	K=30 cyclotron	K=44 cyclotron
ORNL (USA)	HRIBF[a]	p	K=105 cyclotron	25 MV tandem
GANIL (France)	SPIRAL[b]	heavy ions	2 K=380 cyclotrons	K=256 cyclotron
TRIUMF (Canada)	ISAC[b]	p	500 MeV $^-$H cyclotron	RFQ-DTLinac
CERN (Europe)	REX-ISOLDE[b]	p	1 GeV synchrotron	RFQ-DTLinac
INFN-LNS (Italy)	EXCYT[b]	p	K=800 cyclotron	15 MV tandem
KEK (Japan)	E-Arena[c]	p	3 GeV synchrotron	RFQs

achievable social and economic factors being taken into account (ALARA principle);

- Dose and risk limits: there must be upper limits to the individual dose and risk so as to limit any inequities due to social and economic judgments.

The limit on the individual dose for workers is set at 100 mSv during any 5 year period with a maximum of 50 mSv in any given year and at 1 mSv per year for any member of the public. It should be noted that not all countries have accepted these limits as part of their regulations.

When designing a new facility it is prudent (and common practice) to set design constraints on the allowable or expected dose which are well below the dose limits. This is because operating at the dose limits is usually considered to be just tolerable and not consistent with the ALARA principle. It is also possible that there may be exposures to the workers and to the public, which do not originate from the facility under consideration. It is also prudent to allow for contingencies so that if unplanned modes of operation arise there will not be a need for over-exposure of any workers. For the ISAC facility at TRIUMF we have adopted design constraints for chronic exposures of 2 mSv per year for workers and 0.05 mSv per year for any member of the public. A third design constraint is needed for radiation damage to equipment. This depends to some extent on what materials are to be used in the high radiation fields but a limit of 10^6 Gy per year would be adequate for most organic materials.

4 Risk-based Constraints

For some design issues a dose constraint does not adequately address the complexity of the situation [2]. In these cases the hazard may have to be assessed based on the risk. This requires that an acceptable level of risk be defined. For radiation exposures below the threshold of lethality the risk of mortality is due to fatal cancers induced by the radiation. The 'risk coefficient' for the induction of fatal cancers is generally accepted to be of the order of 10^{-2} per Sv. The public is generally willing to accept mortality risks if they are less than 10^{-6} per year. 'Safe' industries are those where the risk of death is less than about 10^{-4} per year. If we accept these as risk constraints then we can write for low probability, high-dose events:

$$\begin{aligned} Risk &= P_m \\ &= P_{oc}\ H\ r \end{aligned} \qquad (1)$$

Where P_m is the probability of mortality, P_{oc} is the probability of occurrence of the event, H is the dose incurred and r is the risk coefficient. This risk must then meet the constraints set for the public or for workers. For chronic exposures the probability of occurrence is 1.0 and hence the risk is simply the dose multiplied by the risk coefficient.

5 Radiation from Intense Proton Beams

The intense proton beams used to bombard the production targets in an ISOL-type facility may give rise to high radiation fields that require massive shielding. A number of well-developed tools exist for estimating the

shielding required even for complex geometries. If the beam transport system is highly efficient the shielding is however only needed in those rare instances when there are unexpected beam losses. It is therefore tempting to minimize the thickness of shielding and to design a beam shut-off system that will interrupt the beam whenever high losses occur.

The reliability required for such a system may be estimated from the above relationship. If the radiation field outside the shielding for a maximum beam loss is H_m Sv h^{-1} then

$$\begin{aligned} P_m &= P_{oc} f_{oc} H_m \Delta t \times 10^{-2} \\ &< 10^{-4} \text{ per year} \end{aligned} \quad (2)$$

So that $P_{oc} < \frac{10^{-2}}{f_{oc} H_m \Delta t}$ where Δt is the duration of the beam loss in hours and f_{oc} is the fraction of the time that this area is occupied. An example at ISAC is a particularly thin section of shielding where a full beam loss would result in a dose rate of 30 Sv h^{-1} outside the shielding. A full beam loss lasting 1 second may therefore not occur more than about once per year. Although it is possible to design and build beam shut-off systems that have this sort of reliability, the designer may wish to examine the relative cost of increasing the shielding versus the cost of a highly reliable system. The cost estimate must include the cost of the reliability analysis, the cost of building in sufficient redundancy and the continuing costs for verification of the reliability specifications. The cost involved in creating convincing documentation in order to persuade the regulators to accept such a beam shut-off system may also not be trivial.

6 Radioactivity Induced in Targets and Structures

The total number of inelastic interactions produced by a high-energy proton is very nearly independent of the target material and is approximately proportional to the incident proton energy. There are approximately 3 inelastic interactions per GeV produced per proton of which about one third give rise to a radioactive isotope with half-life between several tens of minutes and a few years. Thus a convenient rule of thumb is that the saturation activity for incident proton energies of more than a GeV is approximately 1 Bq/GeV per proton or 6 TBq/kW. This may be compared to the $\sim$ 50 TBq/kW inventory in a typical nuclear fission reactor. At the present time accelerators do not exceed a sustained power level of more than $\sim$ 1 MW and hence their radioactivity inventory is $< 6 \times 10^3$ TBq. For comparison fission reactors of 2000-3000 MW with radioactivity inventories $\sim 10^8$ TBq are common.

The number of spallation interactions per second in a target of thickness 1 g cm^{-2} irradiated in a high energy proton beam will be equal to the beam intensity divided by the interaction mean free path in g cm^{-2}. An average value for the mean free path in medium atomic mass materials is approximately 130 g cm^{-2} and hence the activity per unit target thickness is 1.5×10^9 I_p Bq, where I_p is the beam intensity in μA. For a 100 g cm^{-2} target bombarded by a 100 μA proton beam (the ISAC design value) this yields 15 TBq. The dose rate from such a target would be approximately 3 Sv/h at a distance of 1 m.

Servicing of these targets therefore requires some remote handling capability. This may be obtained either through the use of general-purpose robots as has been done at ISOLDE and HRIBF or by the use of purpose-built robotic devices as has been done at TRIUMF and ISAC. Fig. 1 is a vertical cross section through the ISAC Target Maintenance Hall showing the remotely driven crane used to move the target modules.

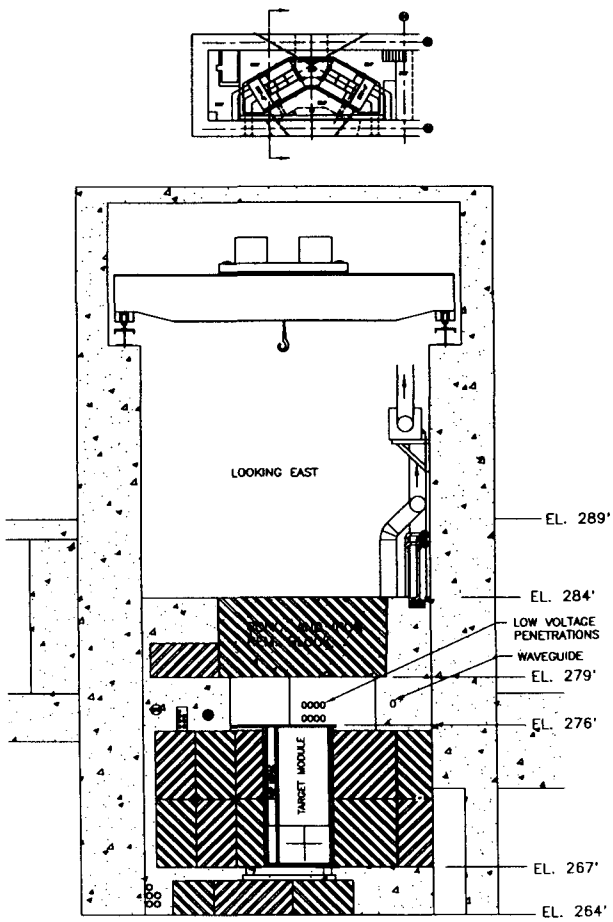

Figure 1: Cross section through the heavily shielded ISAC Target Maintenance Hall showing the remotely driven crane used to transport radioactive components of the target/ion source.

7 Loose Radioactivity Containment

The desire to operate highly efficient target/ion sources and the need to contain all loose radioactivity are contradictory objectives. Typically targets consist of an 'oven' made of a refractory material such as tantalum, filled with the target material which may be heated to temperatures up to 3000° C during bombardment. Optimizing such a target/ion source to yield the maximum ion beam intensity for a particular elemental species will also optimize it for chemically and physically similar species. The most severe problems will be encountered for targets of high atomic number such as Th and U because they are capable of producing the greatest variety of radioactivity.

As an example we have calculated the 'unwanted' radioactivity for the case of the production of a ^{210}Fr beam from a UC_2 target. Optimizing the target/ion source for Fr will also optimize it for the other alkali elements and to a lesser extent the elements in the adjacent columns of the periodic table. The neutral refractory atoms will plate out on the nearest cool surface. The volatile neutrals will be pumped away by the vacuum system. But all ionized species will be transported to the first stage of the magnetic mass analyzing system. At ISAC this 'pre-separator' passes all species with a mass ±15% that of the selected mass. All others are stopped within the vaccum chamber of the magnet. Those with mass within ±15% of $A = 210$ are stopped on slits downstream of the magnet. Fig. 2 shows the expected gamma-ray fields from these two loss points as a function of time after a one week irradiation of a 50 g cm^{-2} UC_2 target with 100 μA of 0.5 GeV protons. The fields are sufficiently high that for the first week after end of bombardment (EOB) servicing these components cannot be 'hands on'. It is expected that the ions, at an extraction potential of ~ 60 kV, will have sufficient energy to be implanted into the surface of any material they may encounter. An energy of 60 keV is very similar to that of recoil nuclei produced during alpha decay and it is known that such nuclei are to some degree immobilized when injected into a surface [3].

The volatile species generated present a more severe problem. For high-mass targets all noble gas, iodine and radon isotopes may be produced. Of these the radioiodines and radon progeny are the most radiologically significant. The radio-toxicity of alpha-emitting radioactivities is generally two orders of magnitude greater than that of the radioactivities usually encountered at accelerators, e.g. ^{60}Co (Table 2). The most severe problem is presented by ^{210}Po which can be produced both directly and by many precursors, among them several species of radon. The production and release of ^{210}Po may thus continue even after the end of target bombardment as the precursors decay via a radon channel.

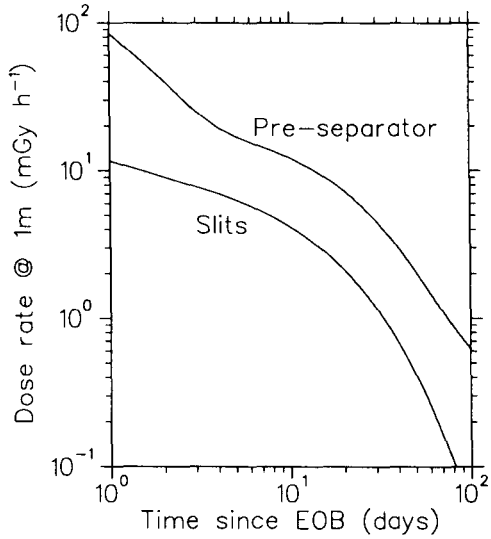

Figure 2: The γ-dose rate at 1 m from the ISAC pre-separator loss point and slits (^{210}Fr ion production).

Table 2: Relative radiological significance of Po. The Annual Limit on Intake (ALI) is that quantity of radioactivity which if taken into the body will produce an effective dose of 20 mSv.

Nuclide	Half-life	ALI (Bq)	
		(ingestion)	(inhalation)
^{206}Po	8.8 d	1.5×10^6	5.6×10^5
^{208}Po	2.9 y	1.3×10^4	4.9×10^3
^{209}Po	102 y	1.3×10^4	4.9×10^3
^{210}Po	138 d	1.7×10^4	6.1×10^3
^{60}Co	5.3 y	5.9×10^6	2.0×10^6

The production cross sections for many of the products of most interest are not very well known and different methods of calculating them disagree. Fig. 3 [4] shows the production cross sections, summed over atomic number for 0.5 GeV proton reactions in ^{238}U as a function of the product mass calculated using both the semi-empirical formulae due to Silberberg and Tsao [5] [6] as well as the LAHET Monte Carlo code [7]. The Monte Carlo code does not do well at predicting the low-mass products as it does not have a good model for the fragmentation process. More serious is the fairly large discrepancy in the spallation region near mass 180. There is no good data available for products in this mass region and thus there is a large uncertainty in the estimates of

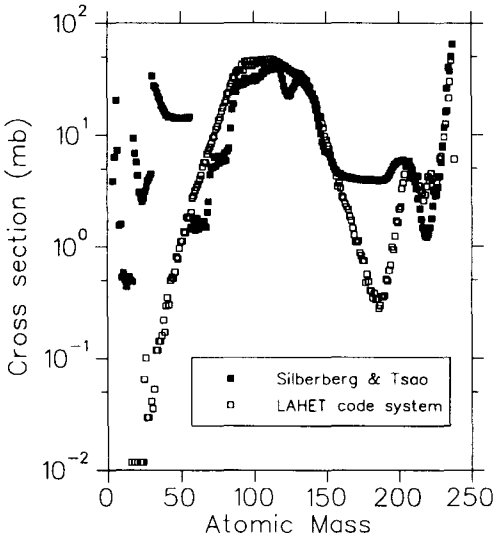

Figure 3: Production cross section for 0.5 GeV proton reactions in ^{238}U summed over atomic number.

the production of some of the most radiologically significant radioactivities.

The solution both at ISOLDE and at ISAC has been to capture and hold all the gases exhausted from the vacuum system during operation. During transport and storage the targets and front-end electrodes are contained in sealed boxes. However, how well the emissions can be controlled during the servicing of the targets may be a critical issue in determine the maximum proton beam intensity with which high-mass targets may be bombarded. At ISOLDE inadvertent release of alpha radioactivity during servicing has at times led to prohibitions on the use of high mass targets [8].

8 Environmental Impact

For most accelerator facilities the dose to the public due to the prompt radiation emitted during operation is not a significant problem. However, at the radioactive ion beam facilities substantial inventories of radioactivity will be accumulated in the spent targets and stored in the vacuum exhaust holding tanks. Accidental release of these could have potentially serious consequences.

The radiological consequences of chronic releases of radioactivity to the atmosphere are usually estimated using standard models prescribed by the regulatory authorities of individual countries. These follow more or less closely those described in an IAEA Safety Guide [9]. For ISAC we have estimated the dose to the 'critical group', occupants of a residential area located at approximately 1 km from TRIUMF, using the Canadian National Standard [10]. Table 3 shows the dose to this group if all the volatiles, including all Po species produced in a one week bombardment of a 50 g cm^{-2} UC_2 target are released both without a delay and a delay of one week. The total dose for this one week production

Table 3: Dose to critical group from a 1 week run of 100 μA, 0.5 GeV protons on a 50 g cm^{-2} UC_2 ISAC target.

Species	(Dose (μSv)	
	(no delay)	(1 week delay)
All Po species	40	40
Radio-iodines	3	1
Others	0.8	0.4

approaches very nearly the design constraint set for the public and hence necessitates the hold-up of this radioactivity for much longer times. We have used the average atmospheric conditions prevailing at the site for making this estimate.

However, in order to evaluate the accidental release of not just a week's production but some fraction of the equilibrium inventory, we must factor in the probability that the atmospheric conditions would be such as to produce the largest possible dose. This means that the wind is blowing in the direction where the population is likely to receive the largest dose and that the atmospheric stability is such as to produce the least dispersion. The probability for these conditions to occur is $\sim$ 10% per year for ISAC. A 'bounding analysis', assuming that the entire equilibrium inventory of 35 GBq of ^{210}Po is released, results in a dose of 0.17 Sv to the critical group. Hence

$$\begin{aligned} Risk &= P_{oc} \times 0.1 \times 0.17 \times 10^{-2} \\ &= P_{oc} \times 1.7 \times 10^{-4} \\ &< 10^{-6} \end{aligned} \quad (3)$$

and therefore $P_{oc} < 6 \times 10^{-3}$ or less than once in 170 years. In practical terms this means that such a release at any time during the life of the facility is not acceptable to the public and the probability must be vanishingly small. Establishing this level of reliability may require that the most noxious radionuclides will have to be 'scrubbed' from the exhaust stream and more effectively immobilized.

9 Radioactivity Deposited by Ion Beams

Although the number of radioactive ions in transit at any given time is insufficient to constitute a significant source of radiation, points where either a fraction or all of the

beam are intercepted will build up a source equivalent to 50% of the ion beam rate in a time equal to the half-life of the ion being transported. This may be only a fraction of a second for ions of the shortest half-lives.

Known losses are due to neutralization by residual atoms in the beam line vacuum, interception by limiting apertures and beam monitors, and deliberate stripping to increase the charge to mass ratio. At lower intensities the known chronic loss points may be shielded locally and unexpected losses monitored with an active beam shut-off system analogous to that used for proton beam losses.

Such a system should have a large dynamic range so as to be able to quickly stop a sudden large increase in the radiation field due to the fast build-up of short-lived ions but also to detect at an early stage the slow build-up of long-lived species that may contaminate the beam.

At higher levels it may be required to shield the entire ion beam line and experimental stations. The evaluation of whether a beam shut-off system is more cost effective than shielding is, *mutatis mutandis*, the same as for proton beams.

10 Internal Exposure of Workers

The threshold for the need to monitor the internal exposure of workers is usually defined by the national regulatory authorities. Useful guidance is provided by the ICRP Publication 54 [11]. Bioassay monitoring for a given radio-nuclide is required if the intake is likely to be greater than 0.3 times the annual limit on intake (ALI). ICRP further defines an 'investigation level' at 0.3 times the ALI pro-rated over the number of monitoring periods per year. Although it is possible to monitor the *intake* of radioactivity, dosimeters that can do this with sufficient reliability to comply with the requirements for permanent dose records are not generally available . It is much easier to monitor the *uptake*, that is the fraction of the intake which remains in the body or a specified organ. This may be done by measuring the radioactivity in vivo (e.g. thyroid monitoring) or in excreta. One therefore defines a 'derived' limit on the uptake called the 'derived investigation level' given by

$$DIL = \frac{T}{365}\frac{3}{10} ALI\, m(T/2) \qquad (4)$$

where $m(t)$ is the radioactivity in the organ or excreted per unit intake and T is the monitoring interval in days. Fig. 4 shows the rate at which some relevant α-emitters are excreted with the urine as a function of time after intake. It is clear that ^{210}Po is the most significant radiologically and can be used to estimate the dose due to the other radio-nuclides if the proportions in the work environment are known. Table 4 shows the sensitivity

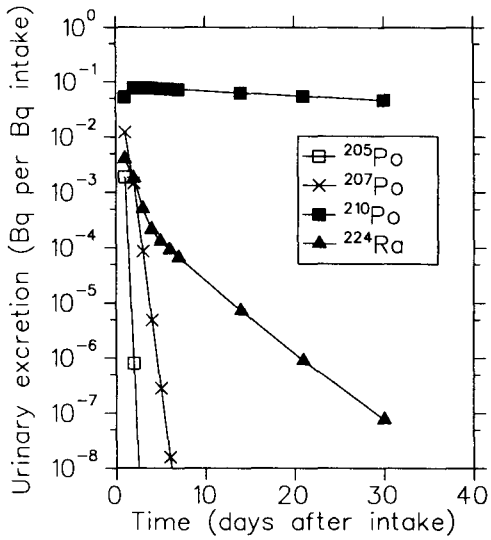

Figure 4: Urinary excretion rates for some relevant α-emitters.

required for ^{210}Po monitoring in urine for different monitoring intervals [12]. A sensitivity sufficient to detect several 10's of Bq of ^{210}Po in a day's urine is achievable but monitoring of a large number of people will require significant investment in time and resources. At ISAC the equilibrium inventory of ^{210}Po in the facility is expected to be $\sim$ 35 GBq. The ALI of 3.3×10^4 Bq represents only $\sim 10^{-6}$ of this inventory. Bioassay monitoring will certainly be required for the maintenance personnel whenever high-Z targets are used.

Table 4: α-in-urine monitoring requirements for ^{210}Po (ALI = 3.3×10^4 Bq).

Monitor Period (days)	IL (Bq, intake)	DIL (Bq d^{-1}, excreted)
7	1.9×10^2	1.4×10^1
14	3.8×10^2	2.4×10^1
21	5.7×10^2	3.1×10^1
30	8.1×10^2	3.7×10^1

11 Conclusion

The construction and operation of accelerated radioactive beam facilities pose new challenges in the design of radiological safety systems and procedures. Many of these have solutions that are extensions of the principles that have been used for existing high-intensity accelera-

tors. The most significant new requirement is the secure containment of loose radioactivity to protect both the environment from chronic and accidental releases and the workers during servicing of the target/ion source components. This requirement is most severe for the bombardment of high-Z targets which may result in the production of α-emitting radioactivity. Cost effective solutions to these problems will be determining factors for the ultimate ion beam intensities.

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