Radiation Control Group Note 94-2

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Beam Loss Considerations

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Introduction

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Normal Beam Loss

Accelerator shielding is usually designed for expected beam losses which will occur during normal operation. In general, beam losses result from halo scraping (gas scattering or emittance/acceptance inadequacies etc) and also from other factors including tune up, beam physics experiments and beam injection/extraction mismatching Taking all these "normal" losses into account results in an estimated overall average loss of some 0.001% to 0.01% in the case of CEBAF. This resulted in a derived design postulate of 0.1% loss for personnel protection as a conservative measure. Because this loss was not identified with any particular region in the accelerator it was averaged out (in both time and length) around the whole machine resulting in a line source of 1W per meter during normal operations. Using this power loss the shielding required was calculated to achieve an hourly dose rate which when multiplied by a working year of 2000 hours was approximately 250 mrem. The 250 mrem/year is the design goal for controlled areas.

It is important to understand the amount of conservatism included in all design goals; people will not necessarily be working only when the accelerator is working; neither will they remain in the highest radiation regions for the whole of their working year. In these circumstances even if the accelerator operates less efficiently than expected the average personnel dose generally trends toward a log normal distribution based on an upper limit or highest dose. Thus designing shielding for 250 mrem per year could well result in average doses being some 10% to 20% of this. Because most radiation exposure is from work on activated components (usually the major contributor to personnel dose equivalent) the additional small increment from prompt radiation is not likely to result in unduly hindering such radiation work, because of the need to keep personnel doses below the CEBAF Action Level for annual exposure (1.0 rem/y).

Accidental Beam Loss

Now we must ask is what will happen if something occurs to spill all the beam at a point (inadvertent insertion of a disc or magnet failure or RF pattern shift etc)? It is difficult to answer this question in a quantitative way because one is dealing with the probability of an event occurring and also the probability of failure of any routine remedial measures that are required (either automatic or manual) to terminate the fault and the probable length of time needed to detect and correct either fault condition. This problem was discussed at a LANL workshop and the conclusion was reached that in default of firm understanding on the reliability of any automatic beam terminating equipment, the maximum dose that could be received by any person should be a few tens of rem if the fault condition should last for one hour. It was felt that one hour was a conservative number because there was much anecdotal evidence to suggest that such fault conditions had been sustained for substantial fractions of one hour at existing accelerator facilities. The one hour would also provide safety margins for those losses at less than a maximum beam loss, but still at much higher than normal beam loss, for example, when running at reduced intensity; under such conditions the loss condition might not be noticed for some time. This judgment of technical experts has now found its place in the accelerator safety order (guidance).

In translating this condition to the CEBAF case, the fault condition has been set at 15 rem. **The definition is therefore " should the worst credible accident occur no person would receive more than 15 rem", the worst credible accident (WCA) is defined as full beam loss at a point for one hour.** In effect this is also the maximum hourly dose rate; **no-one shall be in a position where the passive shielding is such that they can receive more than 15 rem in one hour by an accidental beam loss.**

The implication of the above definition is that should any accidental beam loss occur the usual automatic instrumental techniques for termination of the loss condition will operate in time scales of less than one second so that the actual dose to any exposed person will be minimal (4.2 mrem/second). But should the safety system not function and should other administrative provisions for determining and correcting the faults take one hour then the maximum possible dose to any maximally exposed individual will be 15 rem.

It is also important to make clear that the intention of this requirement is to accommodate any possible fault in the automatic shut-down system, **thus the 15 rem in one hour cannot be translated into a higher dose rate for a shorter period defined by the time scales for shut-off devices to operate.**

It is easy to see that shielding designed for normal point losses of a few watts to give 0.125 m rem per hour average can result in a dose of 10 to 20 rem per hour for a one megawatt WCA.

A further point of possible confusion arises because of the one-shot machines which only operate over time scales of hours per capacitance discharge. A recent amending paragraph in the DOE Accelerator order redefines an accident as the maximum dose that could be received in any one hour. Now this definition does not alter the CEBAF condition where the accident condition dose received in any one hour is the same as the hourly dose rate but there could be some argument under this definition for reduced shield thicknesses for accelerators that can be shown by calculation to destroy themselves in very short time at modest levels of beam loss. However, this cannot apply to CEBAF which is designed to run continuously at various energies and intensities.

<u>Instrument trip settings</u>

One of the major problems in the past of using radiation monitors to trip off accelerator beams is the use of a dose rate trip. Accelerators typically produce radiation spikes with high initial dose rates but which are transient and are trivial in contributing to personnel dose equivalent. Radiation monitors which terminate the beam under such transient conditions are at best a nuisance and at worst become discredited. For this reason the Continuous Area Radiation Monitors (CARM) were specified to incorporate a different method of determining a fault condition. This method relies on the generation of dose weighted digital pulses produced from the radiation monitor which makes it rather easy to integrate dose over a reasonably long time scale. This technique was used at the Rutherford Laboratory's spallation neutron source facility and also at the LLNL tandem user facility. For the CEBAF CARMs, the integration time chosen was 10 minutes. Thus for example, choosing an alarm trip setting of 25 mrem/h, the CARM will trip the beam if the **dose exceeds 4.2 mrem in a 10 minutes interval** but not if the dose rate is say 0.42 mrem/minute for less than 10 minutes. The reader will be interested in comparing the

WCA dose rate (15 rem/h - 4.2 mrem/second) with the trip dose rate (25 mrem/h - 4.2 mrem/10 minutes), so it is easy to see that the CARM will trip **in one second** for a WCA condition. This method of defining accident conditions and the radiation monitor techniques for terminating beam loss pioneered at CEBAF is unique to accelerators and is rapidly becoming an industry standard.

In addition to the trip level there is an alert setting that doesn't trip the beam but merely warns of elevated dose levels. This normally would be set at 2.5 mrem/hour or 0.42 mrem in the 10 minute integration period.

At present the approach to defining trip and warn settings is to adopt a much lower threshold because the radiation instruments are being used to monitor general radiation levels resulting from point like sources whereby one instrument monitors more than one source. Thus each instrument will read less than the maximum level when sited at a distance from the source. For this reason the current settings are 2.5 mrem/hour for trip and 1 mrem/hour for warning. This flexible approach which takes into account the nature of the radiation source and other factors such as occupancy will be used in practice for setting CEBAF trip and warn settings.

Consequences of deliberately losing beam at points not equipped with a beam stop

During set up periods there is the possibility of losing beam at low intensity and whether this can be considered part of normal practice or otherwise. Remembering that the accelerator is shielded for some 5W point loss (1W per meter line) and that 5W is 5nA at 1 GeV thus, depending on energy, the accelerator is normally shielded for a few nano-amps of beam loss at a point. Assume we deliberately lose beam for a short period of time but at levels that will not actuate our warn alert. The maximum we can lose is given by:

$$2.5 \times 5 / 0.125 = 100 \text{ nA}$$

where 2.5 mrem/h is warn set level
0.125 mrem/h average design dose rate
5 nA is approximately normal design beam loss current

Thus occasional and brief losses at the 100 nA level should not result in excessive exposure of personnel provided that such activity is kept in control by good discipline by the ops crew.

Other consequences of such beam losses are:

1. production of increased radio activation of nearby components
2. increased environmental radioactivity
3. radiation damage to sensitive components

Let us examine each of these consequences at the 100 nA beam loss level.

1. We will ignore the photo produced radio nuclides because they will only be generated within the main core of the photon shower which is finely pointed in the forward beam direction and will probably occur inside some solid chunk of metal and hence not contribute greatly to the general levels of radiation exposure. Considering neutron production, a simple calculation be performed which will give an order of magnitude result based on the use M. Barbier's danger parameter data (Bar 69). Thus, high energy neutron production is approximately 10^{11} n /(s.kW). At 1 meter the flux will be (assuming isotropy):

$$\phi = 10^{11}/(4\pi 100^2) = 8\ 10^5 \text{ n cm}^2 \text{ s}^{-1} \text{ kW}^{-1}$$

For 100 nA the power lost would be about 100W to 400W so this activating flux must be reduced to say 10^5 n cm^{-2} s^{-1}.

Inspection of Barbier's DP curve for iron (Fig B2) and aluminum (Fig B1) the DP for one day irradiation at the calculated flux followed by one day cool down results in a DP for iron of 0.1 mrem/hour and 2 mrem/h for aluminum. For a block of material we can take half the DP value to be equal to the surface dose rate. So we see that under the conditions specified the surface dose rate on material at 1 m distance from the loss point would be approximately 0.05 mrem/h for iron and 1 mrem/h for aluminum. So for very brief irradiations of a few minutes and rather long cool down periods the remanent radiation levels would be trivial and could be tolerated.

2. The environmental effects of the irradiation are mainly to do with activation of tunnel air. This will result in a significant increase in activated air in the tunnel but this air will not be discharged to the environment until the beam has been terminated and the short lived products have been allowed to cool down. Furthermore, the 100nA loss is less than the source term taken for the radioactive air production in the accelerator tunnel under normal operational conditions. The production of Na-22 and H-3 in the ground water are also likely to be trivial because of their long half lives and the brief time of the irradiation period.

3. Radiation damage effects to nearby radiation sensitive components. The dose rate near targeted electron beams can be approximated by the expression (Sul 92):

$$D = 2.7\times10^{5}\sqrt{E}\,\theta^{-1.5} \quad \text{rad/(h.kW) at 1m}$$

where E electron energy (MeV)

θ emission angle in degrees (>20)

This expression gives a dose rate of about 10^4 rads per hour for 100 nA (at 1 GeV) at 1 m from the target. In the forward spike of the bremsstrahlung shower the dose rate will be very much higher. It is of interest that for GeV beams, the dose rate lateral to the bremsstrahlung spike can be reduced by some two orders by rather thin shielding (2 g cm^{-2}). Therefore any sensitive components near to such beam loss points should be shielded with rather modest thicknesses material and certainly kept away from the forward bremsstrahlung spike. **The possibility of damaging electronic devices installed in the tunnel could well be the main reason for not permitting such beam loss to occur.**

Conclusions

This note discusses the operational basis for radiation shielding for normal and accidental beam loss. Also considered are the design considerations for the installed radiation monitors and the consequences of losing beam at low intensity around the accelerator without using an appropriate beam dump.

References

Bar 69 M Barbier,"Induced Radioactivity", North-Holland Pub Co., (1969)

Sul 92 A Sullivan,"A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators", Nuclear Technical Publishing, (1992).