Top-Up at Diamond Light Source: preparation and initial practical experience

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Abstract

Diamond Light Source is a 3 GeV electron storage ring, which has been successfully operating in top-up mode since October 2008, having previously operated in decay mode only. Although in the UK there is no legal requirement to submit a safety case to the relevant authority (the Health and Safety Executive) when implementing top-up operation for the first time, it is required to keep doses ALARP and within the 1 mSv annual dose limit which Diamond has set for all staff, users and visitors. Prior to operating Diamond in top-up mode, a study of the radiological safety implications was carried out to ensure that these requirements could be met. The study involved calculation using FLUKA of dose rates arising from accidental beam losses. These losses took the form of either continuous losses in a front end arising from poor injection, or loss of a single injected electron pulse into a beamline optics hutch. In addition to the calculations, dose rate measurements were made outside beamline hutches under conditions of deliberately engineered beam losses in front ends, intended to compare as closely as possible with those modelled. As a result of this study, a number of changes to Diamond's radiation monitoring regime were proposed and implemented before top-up operation was permitted. The study also helped to define the limits within which top-up would be permitted to operate.

1. Radiological hazards of Top-Up operation

Top-up operation introduces additional radiation hazards which are not present when injection takes place with shutters closed, as it exposes the beamlines to the injected electron beam and to the gamma and neutron radiation generated inside the storage ring during injection. Beam losses from top-up were not considered when the shielding for DLS was designed, so it was especially important to verify that the existing shielding was adequate to cope with the increased injection losses. The side wall of a typical optics hutch is constructed from 30 mm lead, which has been specified to protect against scattered gas bremsstrahlung and synchrotron radiation, not the high energy products of the initial scattering of an electron beam.

2. Modelling and Measurements

2.1. Beam loss scenarios

The results of electron tracking studies for top-up beam losses [1] led to three generic scenarios being considered for dose calculations using Fluka [2], [3].

- Electrons could be injected directly through the open shutters into the optics hutch of a beamline, scattering from the tungsten gas bremsstrahlung collimator and giving rise to elevated gamma and photoneutron doses outside the hutch.
- Injected electrons could reach and scatter from components in the Front End of a beamline. The cascade products would enter the optics hutch, and scatter from the gas bremsstrahlung collimator.
- Injected electrons could be lost in the storage ring (the expected location is the insertion device, as the aperture here is smallest) and the cascade products enter the optics hutch, where they scatter from the gas bremsstrahlung collimator.

For electrons to be injected directly into a beamline due to a single fault, the dipole immediately before the beamline must be at less than 20 % of nominal field. All 48 dipoles in the DLS storage ring are wired in series so this fault has a very low probability of occurring. There are more complex faults which could cause this type of loss, involving errors in multiple magnets combined with energy offsets between stored and injected beams. It has been shown that, although interlocks can be set to prevent such losses occurring continuously, they may not act quickly enough to prevent a single pulse from being injected into the storage ring and through an open beamline shutter.

Losses in the front end may occur under certain fault conditions which cannot be excluded by the stored beam and energy interlocks. The particle tracking studies showed that, depending on the design of the front end, electrons would either strike the first fixed aperture or pass through it and strike the vacuum vessel wall. No electrons reached the second limiting aperture. A combination of magnet and trajectory errors were required for electrons to be lost in this manner.

The third category of electron losses – those which occur continuously in the storage ring – will occur under normal operation in both decay and top-up modes. The difference in top-up mode is that it is injected electrons rather than stored beam which are lost.

2.2. FLUKA modelling

The FLUKA geometry model consisted of a section of ratchet wall and a generic optics hutch. Tracking studies [1] showed that beamline I20 has a front end acceptance closest to the beam centre line, and that if top-up is demonstrated to be 'safe' (in terms of injection directly into the hutch being impossible) for this beamline, all other beamlines will also be safe. I20 also has canted undulators. Since this reduces the amount of gas bremsstrahlung entering the optics hutch, the side walls are shielded with 22 mm lead rather than the 30 mm which is used on most of the existing DLS beamlines. It is therefore also a good beamline to use for radiation shielding calculations. The front end limiting apertures, which are copper absorbers, were modelled in a simplified form.

FLUKA was run for each beam loss scenario using 5 x 10^6 primary electrons per calculation cycle. Biasing techniques were used to reduce the run times and to increase the probability of photonuclear interactions. The results of 10 such cycles were used to determine the average dose and the statistical error. Doses were scored outside the side walls of the hutch, using rectangular 'bins' of size 10 cm x 10 cm x 10 cm. The scoring regions were set to cover the areas of interest and a range of ± 50 cm from beam height in the vertical direction. The scoring area was not extended outside the ratchet side walls of the storage ring, as the electron losses were not expected to significantly challenge the bulk storage ring shielding. For continuous losses in the storage ring, electron transport thresholds were set so that the primary electrons did not enter the hutch. In practice, this is achieved by the dipole magnet.

FLUKA scores particle fluence in the region of interest, and a user routine [4] containing fluence-to-dose conversion coefficients for the appropriate energy and particle type was used to convert to ambient dose equivalent, H*(10). In order to make a comparison with the measurements described in the following section, an electron loss rate of 5 mA min^{-1} was assumed in the calculation of dose rates. This is equivalent to a power loss of 0.47 W at 3 GeV, and is at least 100 times greater than the loss which would be expected in normal operation.

The loss of a single injected pulse of electrons on the gas bremsstrahlung collimator in the optics hutch resulted in maximum doses of 1.4 µSv nC^{-1} ± 8 % gamma, and 24 µSv nC^{-1} ± 0.6 % neutron outside the shielding, as shown in Figure 1. Typically, top-up will be operated with 0.1 nC per pulse. As discussed above, interlocks on stored beam and injected beam energy will prevent losses of more than one pulse of electrons in this manner.

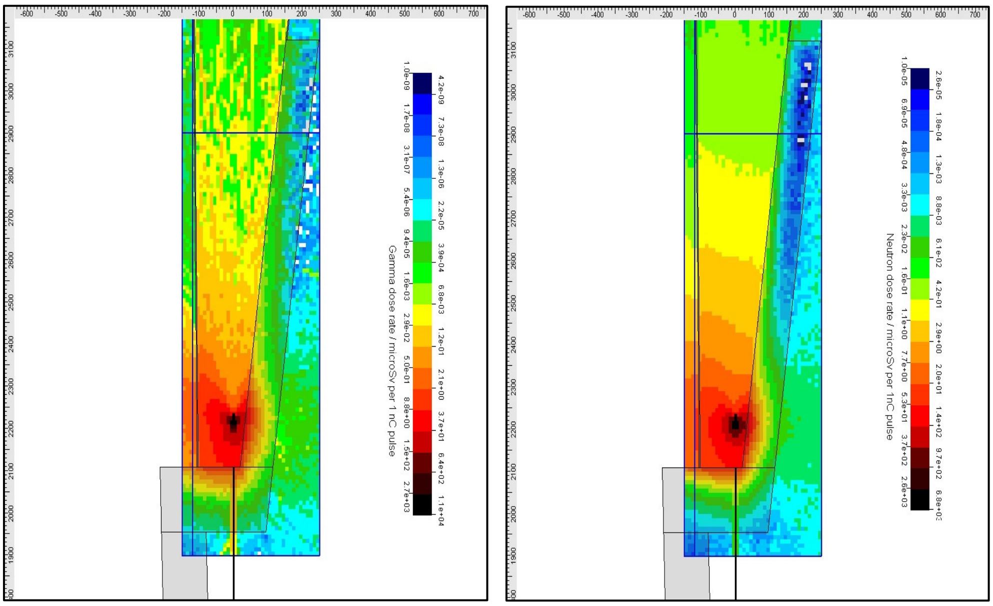

Fig.1 - Gamma and neutron dose rates from injection of single 1 nC electron pulse into beamline hutch.

Various possibilities exist for losses in the front end. Considering a loss at a grazing angle of 0.1° on the vacuum vessel between the first and second fixed apertures, maximum dose rates outside the hutch for a loss rate of 5 mA min^{-1} were 44 µSv h^{-1} ± 33 % gamma and 133 µSv h^{-1} ± 7 % neutron, as shown in Figure 2.

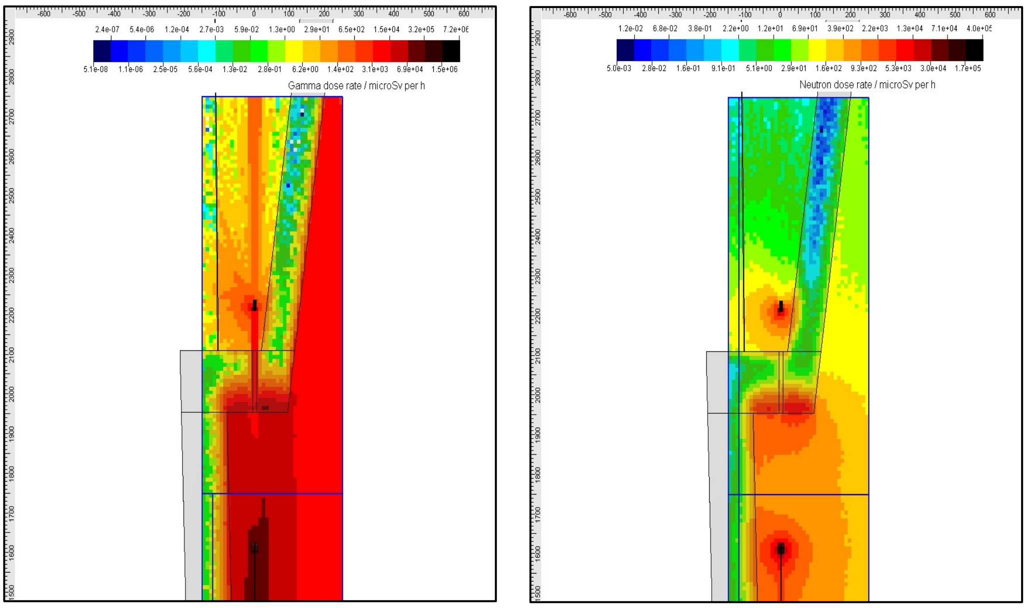

Fig.2 - Gamma and neutron dose rates from grazing incidence beam loss in front end.

Losses in the storage ring ID straight were modelled by considering a mis-steered electron beam striking the vacuum vessel at the location of the insertion device, 20 m upstream of the ratchet end wall. At a grazing angle of 0.1°, maximum dose rates outside the hutch for a loss rate of 5 mA min^{-1} were 45 µSv h^{-1} ± 50 % gamma and 56 µSv h^{-1} ± 8 % neutron, as shown in Figure 3.

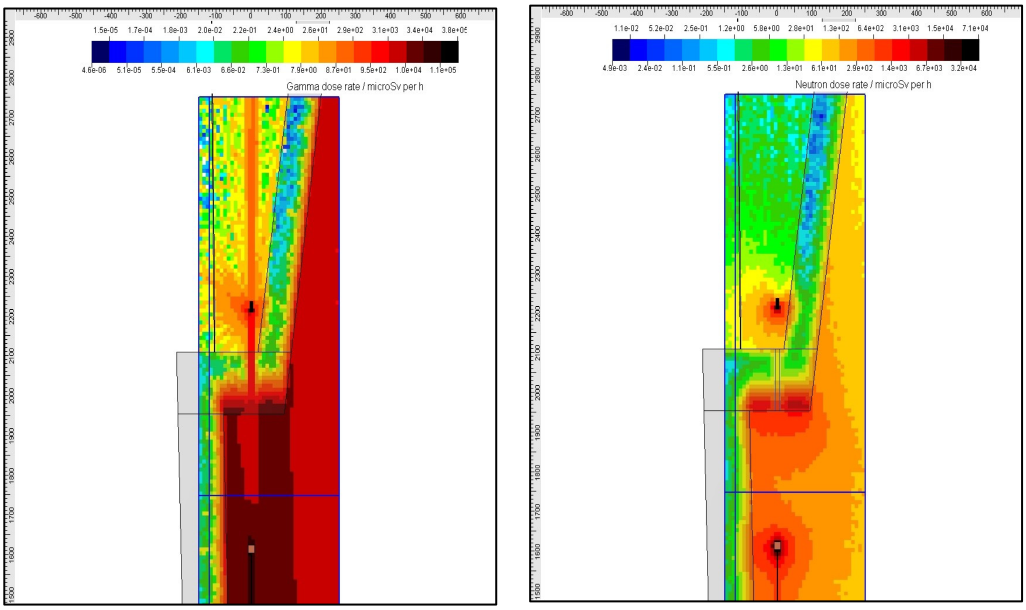

Fig.3 - Gamma and neutron dose rates from grazing incidence beam loss at insertion device.

Whilst there is nothing to prevent losses in the ID straight occurring at a shallow grazing angle, the tracking studies suggested that losses in the front end would actually be at grazing angles greater than 1°. Dose rates when the grazing angle is increased are significantly lower, as under these conditions most of the cascade is stopped by the ratchet end wall rather than entering the hutch through the beam port.

2.3. Measurements

As noted above, the continuous loss of injected electrons in the storage ring does not require fault conditions to occur. It was therefore possible to carry out a series of measurements in which these losses were arranged to take place preferentially at a nominated location in the ring. This was achieved by putting bumps on the injected beam as it passed through the machine cell of interest, which caused it to scrape somewhere upstream of the front end. With an injection rate of 10 mA to 20 mA per minute, it was assumed that up to 5 mA min^{-1} would be lost in the cell of interest. This was found to be the minimum loss which allowed dose rates above background to be detected outside the beamline. Gamma and neutron dose rate measurements were taken outside the hutches of all operational beamlines, using hand-held radiation monitors and also the neutron-sensitive Centronics IG5 ion chamber. Measurements were made with insertion devices fully out and at minimum gap. For all beamlines except I02, which is immediately downstream of the injection region, it was necessary to inject with no stored beam and lose the charge locally. For I02, it was possible to set up poor injection on top of a stored beam.

Typical measured dose rates on insertion device (ID) beamlines were less than 1 μSv h^{-1} gamma and less than 10 μSv h^{-1} neutron. No significant difference was found between different ID beamlines, and it did not appear to matter whether the ID gap was open or closed. A ‘hot spot’ on the hutch wall opposite the gas bremsstrahlung collimator was identified as scattered solid target bremsstrahlung, as gas bremsstrahlung will pass through the collimator and scatter from the first optical element. Later tests without beam bumps confirmed this. Slightly elevated dose rates were also measured along the storage ring ratchet wall, next to the insertion device. At the time of the measurements, only one dipole beamline, B16, was operational. On this beamline, radiation measurements detected no evidence of the beam losses taking place near the dipole.

3. Conclusions

3.1. Analysis of measurement and model results

It was not possible to quantify precisely the beam loss location and angle used for the measurements, which meant that a direct comparison with the results of the Fluka calculations was of limited value. The dose rates predicted by the model tend to be higher than those which are observed. This is possibly because the local electron losses during the measurements were not as great as had been assumed, or because the simple geometry of the model does not include many large machine components between the scattering point and the ratchet wall aperture which can intercept the shower of scattered radiation prior to it reaching the beamline.

On this basis, it was concluded that the model represented the worst case dose rates which would be observed during poor top-up injection. It was apparent from both measurements and modelling that neutrons would be the dominant factor in dose rates outside the beamline. Consequently, the IG1 gamma ion chambers which had been initially installed on beamlines were replaced with IG5 neutron-sensitive chambers. These chambers were tested inside the linac vault to ensure that they responded in a pulsed radiation field. The identification of 'hot spots' led to some installed monitors being re-located, and an increased number of moderated TLDs have been included in the existing environmental dosimetry programme around the beamlines.

Given that the loss rates assumed for the measurements and the modelling are artificially high, it can be concluded that none of the beam loss scenarios considered above will result in dose rates which are a cause for concern outside the beamline hutches.

3.2. Changes to hardware interlocks and software limits

In order to prevent the accident scenarios discussed in this paper, a number of additional hardware interlocks were implemented in the Personnel Safety System (PSS):

- A 'top-up key' must be turned in the machine control panel before top-up injection can commence.
- A stored beam in excess of 50 mA is required before top-up injection can start, as an inability to store beam is indicative of dipole failure. This interlock was over-ridden for the top-up measurements, where injection took place without stored beam.
- The storage ring dipole current must be within ± 1 % of its nominal value before top-up injection can start.
- The current in dipoles 2 and 3 of the booster-to-storage ring (BTS) transfer line must be within ± 1 % of nominal. This sets limits on injected beam energy within ± 5 %, and ensures that injected electrons cannot be transmitted directly into a beamline optics hutch.

To support the hardware interlocks, and act as an early warning of potential fault conditions, a set of software limits have also been implemented in the top-up control program. These are designed to inhibit injection if stored beam does not exist or if its lifetime is too low, if the storage ring injection efficiency is too low, or if the storage ring or BTS dipole currents are out of range. These limits should prevent excessive loss of injected beam in the storage ring or front ends.

3.3. Installed radiation monitors

The installed radiation monitors are part of the PSS and will close shutters or dump the beam if they detect elevated levels of radiation. Until top-up operation was implemented, the monitors had been set to alarm based on dose rate, with a threshold of 4 μSv h^{-1}. For top-up, an alarm on integrated dose was introduced (whilst maintaining the dose rate alarm), which sets a limit of 2 μSv per 4 hour period. In the event that this limit is exceeded, injection is inhibited for the remainder of the 4 hour period, and the machine goes into decay mode operation. The machine operator receives a warning when the monitors are approaching their integrated dose threshold, which allows them to take preventative measures.

Practical experience to date has revealed instantaneous dose rates up to 15 μSv h^{-1}, but only during the brief injection periods. The integrated dose threshold has never been reached during user beam shifts, and has only been approached closely during certain periods of machine development work when there may be unusual injection patterns.

4. Current operation and future work

As of June 2009, DLS has been operating in top-up mode with a maximum stored beam of 250 mA. Injection takes place every 10 minutes, maintaining a stored beam current between 248 mA and 250 mA.

A separate top-up related issue regards increased losses in the storage ring itself and in particular concerns about possible radiation damage to insertion devices. Efforts are therefore being made to understand and reduce beam losses at the insertion devices. Some experiments have also been carried out with TLDs to help in quantifying the doses delivered, although with the majority of insertion devices being in-vacuum, this makes it difficult to relate the measured dose to that received by the magnetic arrays.

Developments in other areas at DLS will see the commissioning of four more beamlines and the completion of an RF cavity test facility by the end of 2009. The stored beam will also be increased to reach the design current of 300 mA once both RF cavities are fully conditioned.

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