PREPARATION FOR TOP-UP OPERATION AT DIAMOND

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Abstract

It is planned to start top-up operation in Diamond in the near future. In this report we summarise the various activities that have led up to this point, including radiation safety considerations, preparation of hardware interlocks and control software, and injection optimisation.

INTRODUCTION

It has always been a goal to operate Diamond in top-up mode after a period of initial operation in standard "decay mode". Some basic requirements were therefore incorporated in the design from the beginning, in some cases for other reasons also:

- Single bunch operation of the linac.
- Switched-mode power supplies for the booster.
- Flexible timing system to allow arbitrary filling patterns to be set up.
- Top-up mode of the Personnel Safety System (PSS), interlocked via the stored beam current.

With Diamond now in routine operation since January 2007 the machine has been well characterised and it is planned to start top-up operation in the near future, initially on a trial basis to evaluate performance including any effects on beamlines.

SAFETY CONSIDERATIONS

Before top-up can be implemented at Diamond, the risk of radiation doses being produced which could exceed our adopted dose limit of 1 mSv/year for staff, users and visitors, needed to be carefully assessed. The additional hazard that can arise in top-up mode compared to standard decay mode results from the fact that injection occurs with beamport shutters open. We can distinguish three possible scenarios that could give rise to an increased radiation dose outside a beamline hutch due to injection with shutters open. In order of decreasing severity these are:

i/ Injected electrons are transmitted through the first part of the beamline within the storage ring shielding, the "front-end", through the open shutter into the optics hutch, where they scatter directly on the gas bremsstrahlung collimator within the hutch, creating a large dose outside the hutch.

ii/ Injected electrons are lost within the front-end on the vessel walls or other components, creating a cascade which can be transmitted through the open shutter and into an optics hutch, where the radiation further scatters from the gas bremsstrahlung collimator producing a radiation dose outside of the optics hutch.

iii/ Similar to ii/ but due to loss of electrons in the storage ring in the straight section immediately upstream of the relevant beamline.

The radiation hazard, likelihood of occurring, and appropriate control mechanisms have been considered for each of these cases. Radiation doses have been investigated using the Monte-Carlo simulation code FLUKA [1], and where possible (Case iii/) also by direct measurement. Case iii/ is a likely scenario since electron losses at some level always occur during injection, and can occur predominantly at an insertion device (ID) location because of the narrow apertures at that point. Cases i/ and ii/ however can only occur under fault conditions and extensive particle tracking has been carried out to identify the circumstances under which these can arise [2].

Calculations show that in Case i/ relatively high radiation doses can be produced, up to 80 µSv h^{-1} and 1,350 µSv h^{-1} gamma and neutron doses respectively, for a 0.5 mA/min electron loss rate. Here we refer loss rates to the storage ring current, where 1 mA is equivalent to a charge of 1.9 nC. Doses are sufficiently high in this case that the possibility of it occurring must be rigorously excluded. However, they are not so large that we need to consider transitory situations that could in principle result in a single shot of electrons entering a beamline hutch e.g. after a magnet failure and before an interlock system can act to inhibit injection.

Tracking simulations show three types of situation in which Case i/ could arise:

- Single dipole magnet immediately upstream of an ID beamline at < 20 % of nominal strength.
- Single dipole magnet at < 90 % of nominal strength, in combination with several other quadrupole and sextupole errors.
- A difference in energy of injected and stored beams of at least 10 %, in combination with several other quadrupole and sextupole errors.

Simulations also show that the dipole error in the first two cases above is not compatible with the presence of a stored beam. In order to retain lattice independence, these situations will therefore be excluded by means of the stored beam interlock and additional energy interlocks, based on the dipole currents in the booster-to-storage ring transfer line (BTS) and in the storage ring.

Radiation doses are much reduced for Cases ii/ and iii/ because of the multiple scattering targets and the fact that only a fraction of the radiation cascade passes into the optics hutch. Calculations show worst case doses of 4 µSv h^{-1} gamma and 13 µSv h^{-1} neutron (at 0.5 mA/min) for Case ii/, less still for Case iii/. Experiments have also been carried out to measure the radiation levels which are generated on all beam lines due to localised injected beam losses near the respective insertion devices. The results show that even at artificially enhanced loss rates of 10 mA/min radiation is only just detectable in certain areas outside beamline hutches, and typically no more than 2 µSv h^{-1} gamma and 10 µSv h^{-1} neutron. The doses in both of these cases are therefore not large, and so can be managed essentially under standard dose control regimes.

In summary, radiation doses will be restricted by the following three levels of control:

Software Limits: The top-up control program will be the “first line of defence” against potentially hazardous situations. The program will continually monitor the progress of top-up, and will inhibit injection if either there is no stored beam, the BTS or storage ring dipole currents are out of range, the stored beam lifetime is less than a pre-determined value, or if the transfer efficiency between the BTS and the storage ring is less than a pre-determined value. In this way upper limits are set on the injected and stored beam electron loss rates.

Hardware Interlocks: In order to exclude the possibility of the highest level of doses occurring (Case i/ above) stored beam and energy interlocks have been implemented within the PSS system in hardwired, redundant and diverse circuits, consistent with the standards adopted for the PSS system as a whole.

Active Radiation Monitors: If either the beamline or storage ring radiation monitors detect an excessively high level of radiation then either the relevant beamline shutter will be closed, or injection will be inhibited, respectively.

HARDWARE PSS INTERLOCKS

Injection with shutters open is only permitted if:

- The top-up key has been inserted in the key panel.
- There is a stored beam current in excess of 50 mA.
- The BTS dipoles 2 and 3 are at the nominal current +/ 1%. Simulations show that this is sufficient to restrict the energy of the beam injected into the storage ring to the required +/- 5%.
- The storage ring dipoles are at nominal current +/- 1%.

The beam current interlock uses inputs from two independent sources, the DCCT and a beam position monitor. Window comparators detect current below threshold (50 mA) as well as above (500mA). The energy interlocks use DCCTs which are independent from those used in the power supplies for regulation, together with pairs of diverse trip level amplifiers arranged as window comparators to provide the two guard line inputs to the PSS.

DOSE CONTROL AND MONITORING

The results of the FLUKA modelling, and the measurements taken during the tests, both indicate that the radiation field outside of the beamline hutches will be dominated by neutrons, by about an order of magnitude. All beamlines have an installed radiation monitor located outside of the first (optics) hutch, which would close the beamline shutter if high radiation levels were detected. The monitors originally installed were argon ion (IG1 type) chambers which are only sensitive to high energy photons. Before top-up is implemented the monitoring system will therefore be changed to utilise hydrogen ion (IG5 type) chambers for combined neutron and gamma detection in order to enhance the sensitivity to electron loss induced radiation fields.

The dose control regime on the installed radiation monitors will also be changed so that it is based on integrated dose in addition to instantaneous dose rate, as is currently the case for decay mode operation. Dose will be integrated over 4-hour periods. The monitors will alarm and prevent injection for the remainder of the 4-hour period if the integrated dose exceeds 2 µSv. The existing alarm and interlock based on instantaneous dose rate will continue to be operational to detect any short-lived high dose rate events.

In addition to the active radiation monitoring, linked to the PSS, several passive thermoluminescence dosimeter (TLD) based monitors are deployed around each beam line optics hutch. These have been in place since 2007 in order to build up baseline data prior to top-up, and will be read out at the end of each machine run (typically 4 weeks). Although these do not offer instant feedback, the use of TLD allows multiple locations around each optics hutch to be monitored, thus providing greater confidence that dose limits are not being exceeded.

TOP-UP OPERATION

Top-up will operate using single bunches from the linac in order to fill, and maintain, any arbitrary filling pattern. The desired fill pattern is held as an EPICS waveform record which is used by both the fill pattern generator and top-up. So far only two patterns have been used in User Mode – $2/3^{rds}$ fill and hybrid fill, i.e. $2/3^{rds}$ fill plus a single bunch in the gap.

A system has been implemented on the visible synchrotron light monitor to measure the charge within each of the 936 storage ring buckets using a time-correlated single photon counting system [3]. The fill pattern is averaged over the period between top-up cycles and used to determine which buckets are to be filled on the next cycle.

A high-level application to drive top-up has been written which interfaces to the Master Timing Generator. It consists of a background process running continuously on a server which actually performs the top-up, plus a user interface process of which instances can run on the control room workstations, All the high-level application software is written in Python.

The top-up control program (see Fig. 1) initiates an injection cycle at fixed time intervals, at present set to 2 minutes. Each cycle consists of a variable number of single bunch injections at 5 Hz repetition rate. The cycle begins by warming up the booster injection and extraction magnets, firing test shots (typically 5 in number) into the beam dump in the BTS (with BTS dipole 1 off), ramping up BTS dipole 1, firing shots into the storage ring, and then finally ramping BTS dipole 1 down. Currently the SR septum power supply needs time to warm up and is brought on 5 seconds before the SR kickers. No warm up is required for the kickers, each firing being used to inject beam.

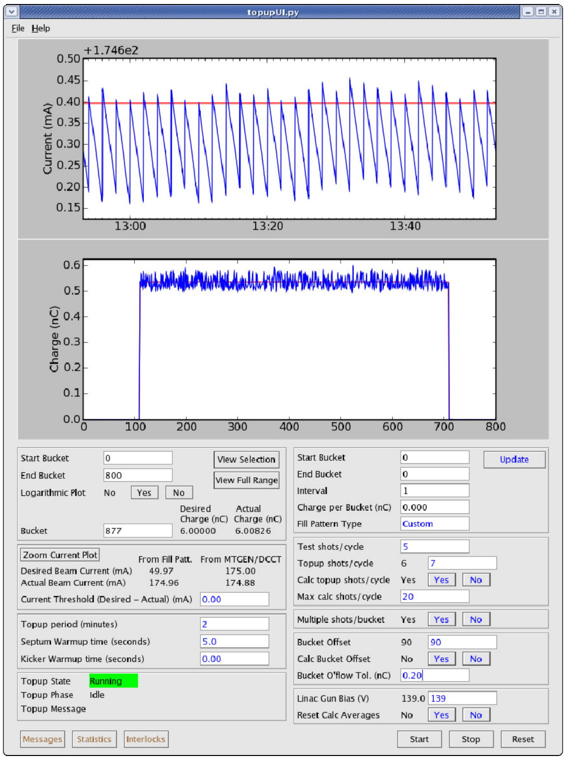

Figure 1. Top-up control panel.

The number of shots to be fired in each cycle is calculated from the loss of current during the previous cycle, using the average charge injected per shot over the last 10 cycles, to account for variations in linac charge from cycle to cycle, up to a predefined maximum number of shots. At the start of top-up the linac gun bias is adjusted manually so that the number of shots required is typically around 10, in order to reduce the variation in charge along the typical 600 bunch train to 10 % or less. Shots are fired into the buckets with the greatest deficiency of actual charge with respect to target charge. Multiple shots can be fired into one bucket during a cycle if required, for example to maintain the single bunch of a hybrid fill pattern which decays relatively quickly. The current is checked between shots and the series of injections terminated if the current exceeds the target value.

The process halts if the transfer efficiency to the BTS for the test shots is less than a pre-determined value (currently 50%). It also halts if any of the software limits discussed above are exceeded. In addition the program also checks that shots were fired into the correct buckets and that the charge in any bucket does not exceed the required value by a predefined margin. If top-up stops because a software interlock has been triggered, an audible alarm is sounded. An alarm is also sounded, but top-up continues to operate, if the beam current goes above or below the demanded beam current by more than a predefined margin.

As the injection process will always disturb the electron beam to some extent, some beamlines may wish to gate out the top-up period from experiments and so the timing system provides a hardware gate on each shot, a hardware gate on each full cycle and a software gate (EPICS PV) on each full cycle.

STORAGE RING INJECTION OPTIMISATION

To minimise radiation levels it is important that injection into the storage ring is as efficient as possible. Only limited attention was given to single bunch operation during the initial storage ring commissioning and in early 2007 single bunch injection efficiency was around 70%, whereas for multibunch it was closer to 95%. Single bunch injection has subsequently been improved and is now comparable to multibunch injection efficiency.

Another requirement of top-up is to be able to inject with IDs closed [4]. After a careful vertical centring of the devices there is now no effect on either lifetime or injection rate at the present minimum gap of 7 mm. At the reduced minimum gap of 5 mm which will be implemented in the near future, with the exception of one device, the lifetime decreases by about 20 %, but there is no significant effect on injection efficiency.

Another aspect that has received considerable attention is that of minimising the disturbance of the stored beam introduced by the injection process [5]. In early 2007 the oscillation amplitude was at the level of ±2 mm, dominated by the effect of the 4 kicker magnets, the septum having minimal effect. One of the kicker vessels was subsequently replaced, and power supplies and controls software have all been modified in an effort to minimise the effect. The differences in pulse shape are now < 2% of the peak amplitude. Relative amplitude and timings have also been optimised to minimise the effect on the beam, which currently results in oscillation amplitudes of typically ±250 μm horizontally and ±150 μm vertically. Replacement of the kicker vessels with more uniform coatings and/or further development of the kicker power supplies are under consideration to reduce this.

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