OPERATION OF THE DIAMOND LIGHT SOURCE INJECTOR

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Abstract

The Diamond Light Source (DLS) injector consists of a 100 MeV pre-injector linac and a 3 GeV full energy booster. The injection system has been reliably providing beam to the storage ring since September 2006 in both multibunch and single bunch mode, at 5 Hz repetition rate. Single bunch and hybrid modes are being developed now for users later this year. Single bunch purity has been measured in the storage ring to be better than 0.1%. The timing system can be controlled to allow a wide range of filling patterns, including complete ring fill in both single and multibunch mode, and hybrid fills with individual single bunches placed in gaps between continuous bunch trains. Top-up operation is envisaged for user operation in the future, and trials are underway to ensure safe and efficient running in this mode.

THE DIAMOND INJECTOR

Linac

The DLS pre-injector is a 3 GHz, 100 MeV electron linac operating in either long-pulse mode, in which up to 3 nC is generated in a bunch train of up to 1000 ns, or in short-pulse mode, in which a single bunch of up to 1 nC is delivered. It includes two identical accelerating structures of the DESY S Band Linear Collider Type II design, together with a three stage bunching section and a triode gun with a thermionic dispenser cathode. The linac is driven by two modulators, each with one Thales TH2100 klystron. Installation and commissioning of the linac was completed in October 2005 and specification was exceeded in both single and multi-bunch mode [1].

Booster

The booster is a missing-dipole FODO lattice with a circumference of 158.4 m. Beam is injected at 100 MeV and extracted at the full storage ring energy of 3 GeV. The booster has a single five-cell copper cavity of the PETRA design, driven by a 60 kW, 500 MHz IOT amplifier [2]. The linac and booster are cycled together at 5 Hz, and the cavity voltage is ramped during the energy ramp.

Installation of the booster was completed in December 2005, and commissioning with beam continued through 2006 as site power and cooling facilities became available. 3 GeV beam was first extracted in June 2006 and injection into the storage ring at full energy began in September 2006 [3,4,5].

Transfer Lines and Injection and Extraction Elements

Transfer lines from the linac to booster (LTB) and booster to storage ring (BTS) are 30.9 m and 68.0 m long respectively, including all injection elements. The booster has a single kicker for on-axis injection, and a preseptum, septum and fast kicker for extraction. Injection into the storage ring is through four identical kicker magnets and one septum, all mounted in a single 8.3 m straight [6].

Review of Operation

There have been four periods of user operation since the beginning of 2007, each of two to three weeks duration. During these user runs beam is delivered to the storage ring as required, usually topping up storage ring current to 125 mA twice a day at 9am and 6pm. The injection system is used more intensively during machine development shifts, normally one day per week and at the beginning and end of user runs.

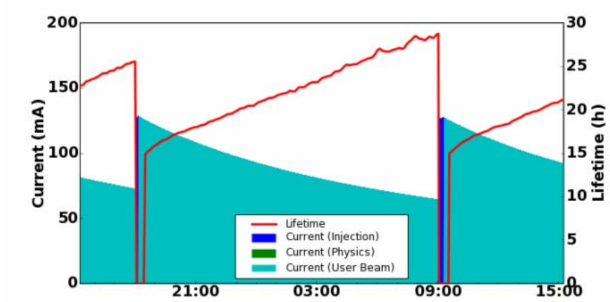

Figure 1: 24 hours of operation; refills at 6pm and 9am.

The linac and booster have been running reliably since Diamond went into operation. Linac parameters are usually optimised at the start of every user run and small corrections are made to bunching and beam energy whenever necessary. These corrections are becoming less frequent as linac stability improves. The booster has been very stable, with no retunes required since commissioning apart from phase changes following RF cabling work. No orbit corrections are needed to preserve beam ramp efficiency. A drift of tune during the booster ramp was noted during commissioning [3,4] caused by the deviation of the ramp of the defocusing quadrupoles from those of the focusing quadrupoles and the dipole over the first 40 ms. The magnet ramps can be programmed independently to keep the tune more constant, but this results in no observable reduction in beam losses.

During commissioning, the four storage ring injection kickers were found to have quite different turn on characteristics, which resulted in differences in the kicker magnet current waveforms. The problem was traced to the thyristor stacks, each of which consists of four series connected hockey puck thyristors. Individual thyristor turn on times varied between 100 ns and 600 ns. The voltage sharing resistor/capacitor networks across the thyristor stacks were modified to reduce the current in the

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thyristors at turn on. This resulted in the thyristors having a consistent turn on time of 100 ns and consequently the current waveforms became more uniform.

INJECTOR STABILITY

Linac Temperature

The linac RF preamplifiers and low-level RF system are housed in a control and instrumentation area (CIA) near to the klystron area which is maintained at a constant temperature of 22°C. Klystrons, modulators and pulse forming network racks are situated in an open area outside the CIA. Despite CIA temperature control, temperature within the LLRF rack rose by several degrees over some hours of operation, causing the output of the preamplifiers to fall slightly, with a resulting drop in high power klystron output and beam energy. Installation of an extra cooling fan in the rack rectified this problem. A linac energy drift is also evident following the start-up of the linac from cold: beam energy starts approximately 8 MeV above the nominal level and then falls to 100 MeV over the first 30 minutes of operation. This is caused by the thermalisation of the klystron gun components, and so when not in use the linac is held in a standby state in which the klystron filament current is maintained but the pulsed high voltage is not applied.

An energy-control software feedback loop has been developed to correct slow thermal drifts of the linac by controlling the voltage of the second klystron in the linac based on a beam position monitor (BPM) reading in a dispersive region of the LTB. With the improvements in the system noted above, however, this system has never been needed during user operation.

Multipacting in the Linac Prebuncher

In the first months of operation the greatest source of beam instability was multipacting in a 500 MHz subharmonic prebuncher cavity (SHPB) immediately following the gun. This was reduced by repeated conditioning of this cavity. Cavity condition is now maintained by applying power continuously during user operation, even when the linac is in standby. Single and multibunch modes have also been retuned to enable the same power to be maintained in the SHPB in both cases.

Booster Cavity Conditioning

The condition of the booster cavity has been maintained well, and cavity power can be turned off when the injector is in standby. There is minor vacuum activity in the cavity when power is applied following a long period in standby, particularly at the beginning of user runs, and so the power is introduced gradually using a similar algorithm to that used for cavity conditioning. This reconditioning algorithm imposes a threshold power level on the 45 kW sine wave input to the cavity and gradually raises the threshold to operational levels. The increase is controlled by the pressure measured in the cavity. This procedure is fully automated, and the ramp up from zero to full power can generally be achieved within two minutes.

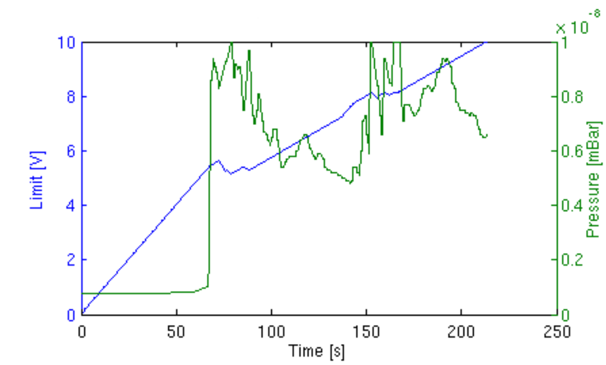

Figure 2: First booster RF ramp following a shutdown. Power limit control (left, blue) and pressure (right, green)

Drifts in Mains Frequency

During commissioning, the booster dipole 5 Hz offset sine current waveform was found to change with time. The effect was correlated with changes in the mains frequency to which the timing system was locked. By removing this lock to the mains and running at a true 5 Hz the booster dipole current achieved its specified stability. However, the electron emission from the linac gun then became highly variable as it was still locked to the mains, while the gun modulator was operating at a fixed 5 Hz to synchronize with the booster. Since the linac gun was heated via an inverter it was quite simple to modify the inverter timing to be synchronous with the timing system rather than the mains. In this configuration both the booster dipole and linac gun emission were stable. The injection system has been running in this mode to date, and injection into the booster is good. A small oscillation in capture efficiency is still apparent, resulting in variations in booster current of up to 20% over a beat period of the order of 10 seconds. This is caused by an energy oscillation of the linac driven by the beating of the mains-driven klystron filament power supplies against the fixed 5 Hz. It is planned to modify the klystron filament power supplies in the same way as the gun heater power supply to eliminate this variability in linac energy.

INJECTION CAPABILITIES

Multibunch Fill

Virtually all user operation has been carried out with a stack to 125 mA in the storage ring using a two-thirds fill pattern in which 624 of the 936 buckets are filled, shown figure 3a. The linac is operated in long pulse mode for this fill; with trains of 144 buckets injected every 120 buckets over the filled portion of the ring. The 24 bucket overlap overcompensates for the 30 ns rise-time of the linac long-pulse envelope, and results in small peaks in the storage ring fill pattern every 120 bunches. These small peaks in the fill pattern are acceptable to users.

In two-thirds fill operation, the booster current is approximately 1.3 mA and the storage ring can be filled from empty to 125 mA in less than two minutes, including orbit correction at intermediate current levels during the stack. Filling of the storage ring from empty is only carried out at the start of the user run and following unplanned beam loss: normally, the storage ring is topped up to 125mA twice a day. The top-up procedure at the moment involves closing all front-end shutters and opening insertion devices before injection of any charge. Disturbance of the beam in the storage ring during the top-up process can be measured on a storage ring BPM; this has been reduced to around 400 µm peak-to-peak following the injection kicker power supply optimisation.

Injection efficiencies are generally over 80% for linac to booster, and approach 100% for booster to storage ring. All losses in the booster occur in the first 10 ms of the 100 ms ramp, and vary according to the precise linac output energy. Booster injection efficiency is expected to rise when the linac energy is stabilised.

Single Bunch Operation

Any bucket in the storage ring can be filled using the injector single bunch mode. Fill pattern measurement using a time-correlated single photon counting technique [7] has allowed a bunch purity of 0.1% to be confirmed, i.e. 99.9% of all charge can be injected into one single bunch. Injection efficiencies are around 50% into the booster and again approach 100% into the storage ring.

Differences between multibunch and single bunch operation are largely confined to the linac, the LTB and booster sextupole ramps, and the injector can be switched between single and multibunch modes in less than 30 seconds. A BTS dipole may be de-energised to isolate the booster from the storage ring, thus enabling independent operation of the injection system, allowing the continuing optimisation of single bunch booster injection efficiency to be carried out during user beam time between refills.

Hybrid Fill

For one week in May 2007 beam was supplied to users in a hybrid mode, using a multibunch two-thirds fill followed by a single bunch fill in the mid-point of the empty third, shown in figure 3b. No new problems were encountered in hybrid fill mode; injection efficiencies were as high as in single or multibunch modes, and bunch-by-bunch lifetimes measured using the photon-counting fill monitor were consistent with those measured from current decay using the standard fill pattern.

Top-up Trials

Precise coordination of diagnostics, injection system and timing system has been demonstrated, enabling top-up trials to progress, using the single bunch capability of the injector to fill the least populated buckets of the storage ring, as identified by the photon-counting fill diagnostic. This capability can be used to top-up the fill, to smooth off the multibunch fill (figure 3c), or to inject charge into the storage ring to any arbitrary fill pattern, for example the "diamond" fill in figure 3d.

It is planned to operate Diamond in top-up mode with a two minute cycle time, and successful tests of this mode have been carried out. All top-up tests so far have been conducted in machine development shifts with the storage ring front end shutters closed, pending a thorough safety analysis of top-up operation and fault modes.

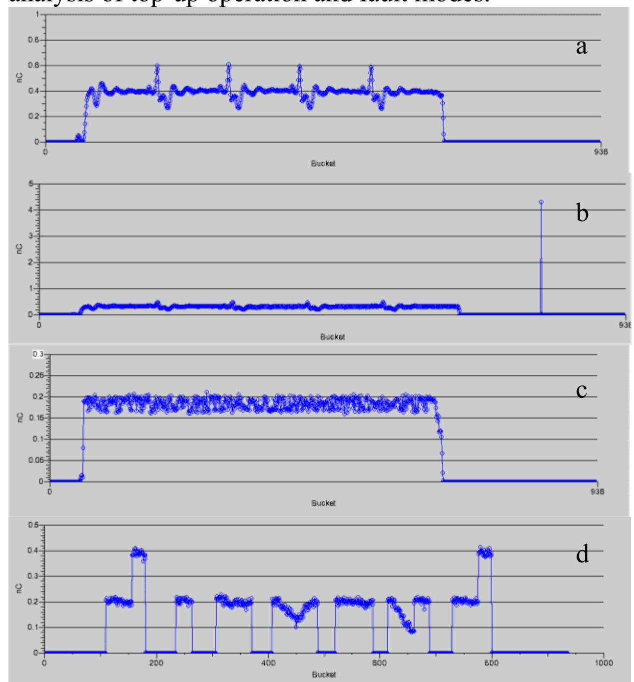

Figure 3: Storage ring fills: a) two-thirds fill, b) hybrid fill, c) smoothed two-thirds fill, d) "diamond" fill

CONCLUSIONS

Diamond Light Source has been in operation for users since January 2007, and the injection system has performed well during this time. The main sources of injector instability have been identified and eliminated, and extensive trials have been carried out of the different modes of operation. Routine operation of multibunch, single bunch and hybrid modes is now possible, and it has been shown that the injector, timing system and storage ring can be used together to allow Diamond to be operated in top-up mode.

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