A RESCUE MODE FOR THE DIAMOND LIGHT SOURCE PRE-INJECTOR LINAC

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Abstract

The Diamond Light Source injector consists of a 100 MeV linac and a 3 GeV full-energy booster. The linac contains two S-band accelerating structures driven by two high-power klystrons. Details are presented in this paper of a new switching network in the linac waveguide, allowing either of the klystrons to drive the low-energy section of the linac while the other is repaired and run into a dummy load. This allows limited operation of the linac in the event of a failure in either klystron or modulator.

THE NEED FOR A RESCUE MODE

High power RF for the Diamond linac is generated by two Thales TH2100 S-band klystrons, each delivering 5 μs pulses of up to 20 MW at a repetition rate of 5 Hz. Since the start of Diamond operation in 2007 one klystron has powered bunchers and an accelerating structure, and the other has fed a second accelerating structure [1]. With the klystrons feeding the two structures independently, a failure of the klystron or modulator feeding the lower energy structure and bunchers renders the linac, and hence the injection system as a whole, inoperable. In the event of a failure of the higher-energy klystron or modulator, linac operation is still possible at a reduced energy.

There have been several short-term interruptions to linac operation, including failure of a modulator thyratron and faults in several minor electronic components, but the greatest linac disruption so far has been the exchange of the two original klystrons for new tubes. Routine monitoring of tube perveance enabled one klystron to be replaced before failure during a scheduled machine shutdown after 19,600 hours of operation. Perveances of both klystrons in the months leading up to the exchange of klystron 2 are shown in Fig. 1.

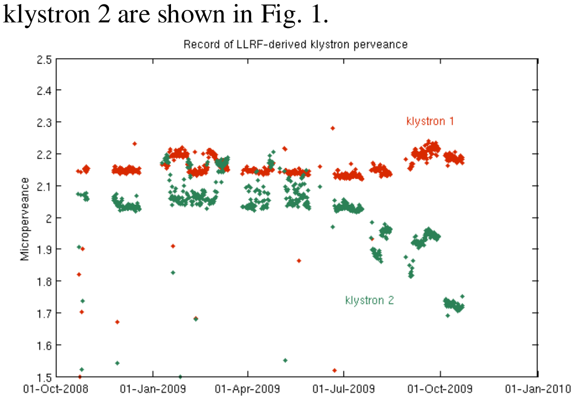

Figure 1: Perveance record of klystrons through 2009.

The perveance log is noisy, but the trend is clear. A higher precision direct measurement of tube current and voltage using an oscilloscope connected to pick-ups mounted within the klystron tank confirmed the perveance drop and so the klystron was changed.

Klystron 1 failed after 17,200 hours without warning during the preparation for a user run. The cause of failure was a broken heater filament. For both klystron exchanges, the total linac down time was approximately 20 hours; this includes fault finding, dismantling and rebuilding of lead shielding, clearance of safety procedures, installation of the new tube, a full radiation survey of the new klystron and retuning of the linac for operation with the new klystron. Had the klystron filament failed during user beam time, the injection system as a whole would have been down for 20 hours, putting Diamond operation at risk. In order to address this risk, the RF feed to the linac has been reconfigured to enable either klystron to power the first structure and bunchers; this has involved a rebuild of the waveguide network in the linac vault to include two four-way S-band switches, and the development of a lower energy operating mode for the linac, booster and linac-to-booster transfer line.

MODIFICATIONS TO THE WAVEGUIDE NETWORK

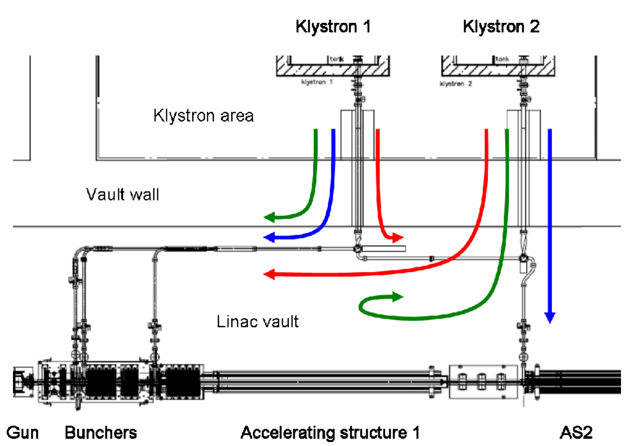

Figure 2: The new waveguide configuration.

A drawing of the modified waveguide network is shown in Fig. 2. The switches allow three different modes of operation, indicated by the coloured arrows: blue indicates normal operation, with klystron 1 feeding the low energy stage and klystron 2 the high energy stage; red is the klystron 1 test mode, in which klystron 1 is run into the dummy load and klystron 2 feeds the low energy stage; green is klystron 2 test mode, with klystron 2 running into the dummy load and klystron 1 feeding the low energy stage.

The waveguide switches, manufactured by Sector Microwave, are similar to those tested at SLAC [2] and installed at APS [3]. Operational parameters of the new switches are listed in Table 1.

Table 1: Waveguide Switch Parameters

Frequency range	2.60 GHz to 3.95 GHz
VSWR	1.05 : 1 maximum
Isolation	80 dB minimum
Insertion loss	0.1 dB maximum
Lifetime operations	100,000 minimum

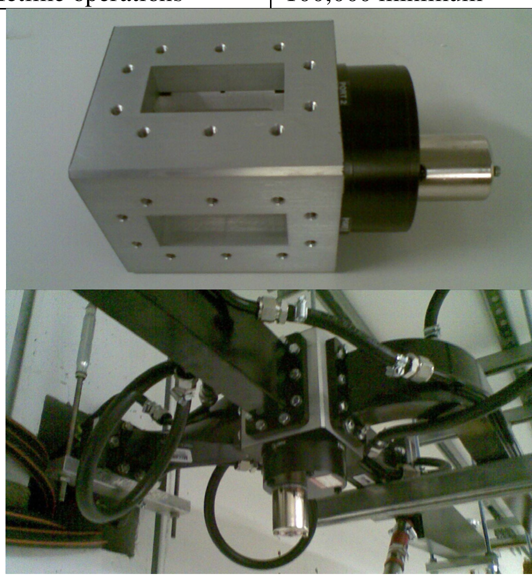

Figure 3: WR284 waveguide switch (above) and switch assembly in situ (below).

As the RF path is not intended to be switched in normal operation, the switches are manually operated and mounted within the linac vault. Photographs of a switch and of one of the two switch assemblies are shown in Fig. 3. The water-cooled Thales TH4077B dummy load is mounted directly on the switch and leads off into the background of the picture. The waveguide run in the foreground leads towards the first accelerating structure. The new waveguide network was manufactured by Mega Industries and includes a mixture of LIL and CPR flanges to couple the switches to existing linac components. Waveguide, switch and water load are all filled with 2 BarG SF_6 and the new waveguide is water-cooled.

The new waveguide network was installed in June 2010. A total insertion loss of 0.165 dB was measured across both switches and the new waveguide bridge between them. No transmission of power was measured across the switch, but nevertheless, the LLRF has been configured to shut down both modulators in the event of a high reverse-power reading at the exit of either klystron. High-power conditioning was completed over two days, by gradually increasing RF power and pulse length. Some arcing was observed initially at powers above 16 MW, but with closely controlled conditioning and after two SF_6 purge and refill cycles, power could be ramped to the operational values for both klystrons 1 and 2 operating in normal mode and in switched modes.

BEAM PROPERTIES IN RESCUE MODE

Table 2 shows parameters of beams generated using one klystron compared with standard two-klystron operation in 0.3 nC single bunch mode. Normalised emittance and Twiss parameters are similar in both modes, and beam size measured in a dispersive region is dominated by emittance rather than energy spread in both cases. Stability is unaffected by the energy reduction.

Table 2: Comparison of One- and Two-klystron Operation

	One klystron		**Two klystrons**	
Energy	44.9 MeV		99.9 MeV	
Energy spread	< 0.3 %		< 0.3 %	
	x	y	x	y
ε_N [mm.mrad]	42.7	45.0	39.6	39.2
α	-0.64	0.18	-1.11	-0.50
β [m/rad]	2.91	1.54	2.47	2.60

For rescue mode operation, the two dipoles of the linac to booster (LTB) transfer line were scaled according to the reduced beam energy and new settings for the eight quadrupoles were calculated with the LTBQg tool, which performs a least-squares minimisation of the beam size along the transfer line whilst constraining the Twiss parameters at the LTB entrance and exit [4]. Booster magnet settings for low energy injection were scaled with beam energy. Some empirical optimisation was necessary to achieve injection into the booster.

Initial experiments with the 45 MeV rescue-mode beam have demonstrated transmission along the LTB of greater than 80%, similar to 100 MeV transmission, but reduced injection efficiency into the booster. Figure 4 shows a typical booster current trace obtained in rescue mode with multibunch operation, showing a rapid loss of beam in the first few milliseconds of the booster ramp and then acceleration of the remainder of the beam to 3 GeV. In the plot shown, beam is lost at 3 GeV before much of the beam is decelerated back down to 45 MeV. There are minimal losses at 3 GeV when beam is extracted; booster efficiency is dominated by injection losses.

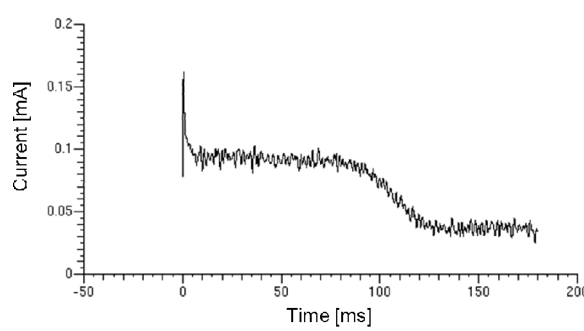

Figure 4: Beam current in the booster.

Injection efficiency into the booster is lower for single bunch operation than for multibunch operation, in which a similar charge is spread over a train of 120 bunches. Transverse emittance is shown in Fig. 5, illustrating the much higher emittance in single bunch mode. It is likely that the reduced transmission into the booster in rescue mode is a consequence of the increased geometric emittance at the lower linac energy. Emittance also increases with bunch charge, although a trend of injection efficiency with charge is not yet clear. Experience with standard 100 MeV beam shows the same increase of emittance in single bunch mode, with injection efficiency reducing as charge increases in single bunch mode. Emittance can be degraded by mis-steering of the drifting beam through the non-powered accelerating structure.

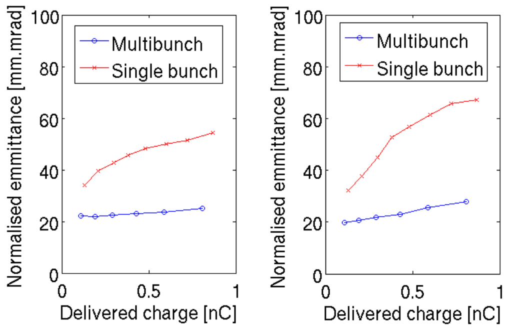

Figure 5: Beam emittance as a function of charge for single klystron operation: horizontal emittance on left, vertical emittance on right.

The TH2100 klystrons operate at 20 MW but are rated at 37 MW peak pulse power, and so there is scope for increasing beam energy in single klystron mode, but at this early stage of investigation it has been decided not to stress linac components more than necessary.

Shot-to-shot injection efficiency into the booster has been variable, for example Fig. 6 shows a histogram of injection efficiencies over a 5 minute period of 0.16 nC multibunch operation. Efficiency is strongly periodic, with an oscillation frequency just below 0.8 Hz. This oscillation was traced to the booster quadrupole magnets, as can be seen in Fig. 6, which shows a strong 0.8 Hz ripple on booster quadrupole current when held at the low current required for rescue mode injection.

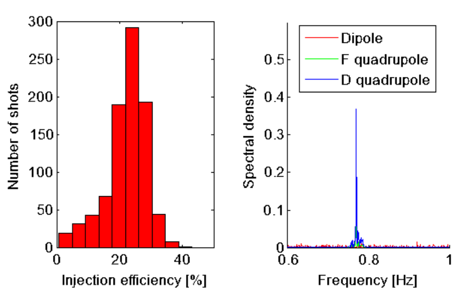

Figure 6: Injection efficiency and magnet stability.

The booster quadrupole power supply is a digital type which operates at fixed frequency with control of the output current by pulse width modulation (PWM). The 0.8 Hz ripple was removed in August 2010 by synchronising the PWM switching frequency of all of the modules. Machine availability has prevented further injection tests since this improvement to magnet stability.

OPERATIONAL EXPERIENCE

There has been one 8-week run of user beam since the installation of the new waveguide network. In this period the linac has run in normal mode, shown blue in Fig. 2. There have been no arcs or faults in the new waveguide or switches, and no measureable changes in power loss along the waveguide or reflected power at the klystrons. The switches are undamaged and operate freely. The only fault has been a slow leak of SF_6 through a damaged seal in the CPR flange at the switch which was repaired in the first week of the current scheduled machine shutdown.

Minimisation of beam losses on injection into the booster and storage ring is continuing, and a second window is to be installed at the klystron to allow the klystron to be removed without venting SF_6. The new window is the same size as the linac-to-waveguide window and so also be used as an emergency spare. Space is limited between the klystron and the vault wall, and so a new LIL to CPR adaptor has been built that includes arc detectors viewing the klystron window and the new window. The design is shown in Fig. 7. Installation is planned for the next scheduled klystron change.

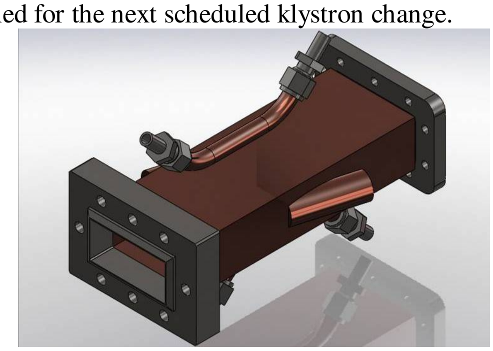

Figure 7: Design for a new arc detector viewport.

It is also planned to use the waveguide switching network to test high-power S-band components during shutdowns with minimal disruption to the linac network. A test of an S-band RF gun is planned for 2011 [5].

CONCLUSIONS

A new switched waveguide network has been installed in the Diamond linac, allowing injector operation to continue in the event of a total failure of either of the two linac RF stations. Injection through a full energy booster into the storage ring has been demonstrated although losses are currently higher than normal. Work is continuing to optimise injection efficiency in this new rescue mode.

ACKNOWLEDGEMENTS

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REFERENCES

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