SINGLE BUNCH AND MULTI BUNCH OPERATION WITH SINGLE KLYSTRON USING A PROGRAMMABLE SLED SYSTEM

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Abstract

The Linac for Diamond Light Source has been running with two 3 GHz klystrons, powering two 5.2m-long accelerating structures to deliver 100 MeV electron beam since the start of operation. By introducing a SLED RF pulse compressor system to generate a pulse capable to power both structures from one klystron, redundancy and reliability will be improved. With a 5 µs total pulse, it is possible to charge the SLED cavities for 4 µs and generate a high peak pulse for the last 1 µs able to power both structures. An arbitrary waveform generator function was implemented in digital low-level RF to generate a flat top pulse, which can be utilized for both single bunch and multi bunch operation. Details of the waveguide network, low-level RF design and high-power operation will be described. Results from full energy operation will also be shown.

LINAC MODIFICATIONS

Diamonds original Linac configuration can be seen in Fig. 1 on the left. To use both klystrons to power the RF pulse compressor, a new configuration of the waveguide had to be designed. The first design with SLED did not use compressed RF pulse for the bunching structures as can be seen in the middle configuration layout in Fig. 1. This was later changed, and the final design layout was made, shown on the right side of Fig. 1.
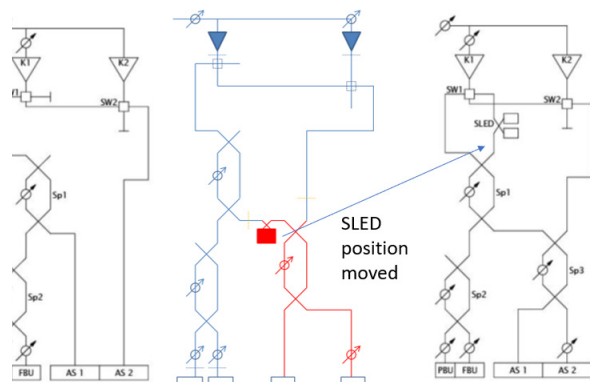

Figure 1: Linac configurations from start to finish of project. Initial without SLED (left), Intermediate (middle), final design (right).

This design allows either of the klystrons to power the pulse compressor by using two RF switches SW1 and SW2. After the pulse compressor the power will first be split to the bunching structures FBU and PBU. After this the remaining power goes through a splitter SP3 which

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splits the power between the two accelerating structures AS1 and AS2. By changing the switches both klystrons can also be used as in the old configuration.

A High-power RF window capable of withstanding a peak power of 70 MW was also installed directly after the SLED, see Fig. 2. This window is based on the PAL design [1], and the design change from 2856 MHz to 2998 MHz lowered the power limit slightly.

The final installation was done in March 2024 and allowed carrying out high power tests.
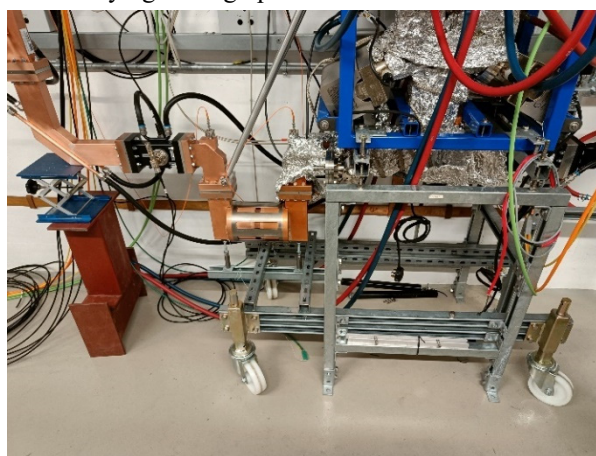

Figure 2: SLED and window assembly inside Linac.

DIGITAL LOW-LEVEL RF

The DLLRF is based on the Micro Telecommunications Computing Architecture (MicroTCA) standard. It was chosen for its reliability, modularity and scalability. The DLLRF consists of a 2U MTCA.4 chassis, a MCH, an AMC computer board, a Struck SIS8300-KU card and a Struck DWC8VM1 RTM with supporting clock/local oscillator (LO)/reference generation RF circuits, see Fig. 3.
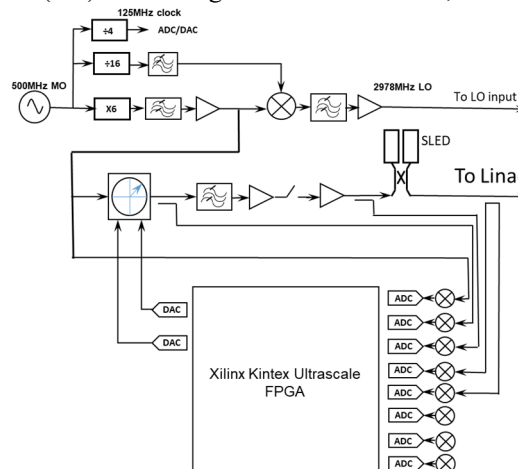

Figure 3: Schematic for the digital low-level RF.

The AMC computer board is AM G64 from Concurrent. It is a double module with an Intel Xeon CPU and supporting PCIe Gen3. It communicates with the FPGA through PCIe bus. It will run Linux and EPICS. It will be the interface to the Diamond control system. NAT-MCH-PHYS MCH is used for the chassis management. The Struck SIS8300-KU has a Xilinx Kintex Ultrascale FPGA, 10 channels 16-bit ADC and 2 channels 16-bit DAC. It has a 4 lane PCIe Gen3 interface. The Struck DWC8VM1 has 8 channels downconverter and one vector modulator. IF signals are transferred through ZONE3 connector to FPGA.

IF and clock signal are generated from the 500MHz master oscillator. A frequency divider is used. Clock frequency is four times the IF frequency, as IQ demodulation is used in the firmware. The 3GHz signal is generated from the master oscillator (MO) using a frequency multiplier. This method was chosen due to its simplicity. The number of components in the clock and LO generation were minimized to avoid introducing additional phase noise.

The DLLRF works in pulsed mode. An external trigger is provided by the timing system through one of the two ADC channels. The 3GHz signal is down-converted to IF signal in RTM and sampled by ADCs. The sampled IF signal is demultiplexed into IQ components. The CORDIC algorithm is used to translate IQ components to amplitude and phase.

SLED operation requires the DLLRF to generate a pulse with phase and amplitude modulation capability. Phase and amplitude feedback will be needed to correct the pulse-to-pulse variation and long term drift. Phase and amplitude modulation is required in the final 1 µs. Three working modes were implemented in the firmware, namely standard mode with a simple phase switch, waveform mode (arbitrary waveform generation in the last 1 µs pulse) and full waveform mode (arbitrary waveform generation for the full 5 µs pulse). Full waveform mode provides the maximum flexible control to the output signal and is what is used to generate the outputs we see in this paper, see Fig. 4.
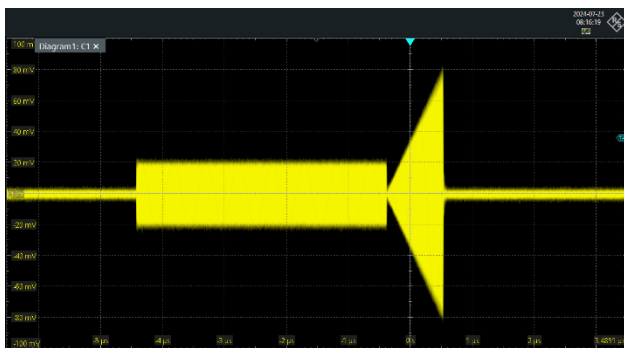

Figure 4: Amplitude modulated output signal from DLLRF in full waveform mode.

POWER TESTS

Prior to final installation, high power test had been done into a single structure [2]. After final installation all structures can now be powered. Initially tests were only done

using klystron 1 to find a position of phase and power that could generate a beam through the Linac and into the Booster. Changeover from klystron 1 to 2 would thereafter be simple as only a phase adjustment of the individual structures would be required. Figure 5 shows the end 1 µs of the modulated signal seen in Fig. 4. Figure 6 shows the last 1 µs of an effort in full waveform mode to flatten the top, this based on the modulation shown in Fig. 7. Flat top has been proven in waveform mode before, see [2].
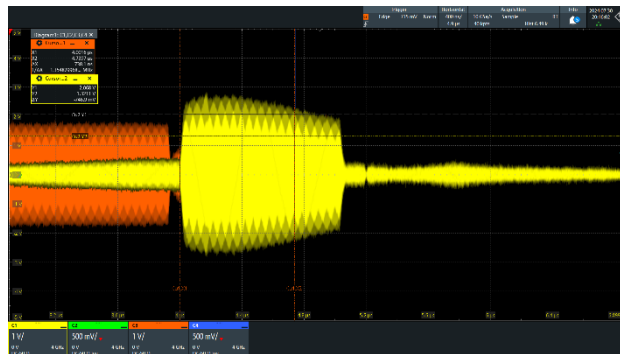

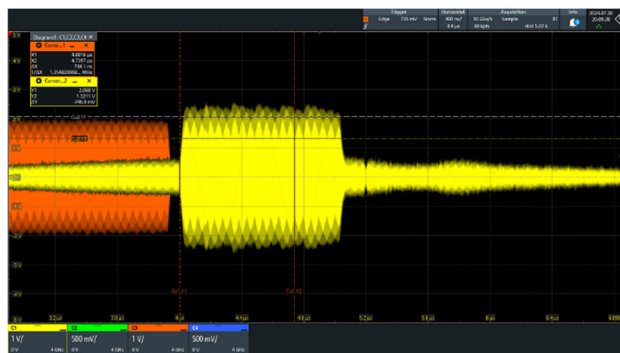Figure 5: Modulated non-flat SLED pulse (Yellow), klystron signal (Orange).

Figure 6: Modulated flat SLED pulse (Yellow), klystron signal (Orange).
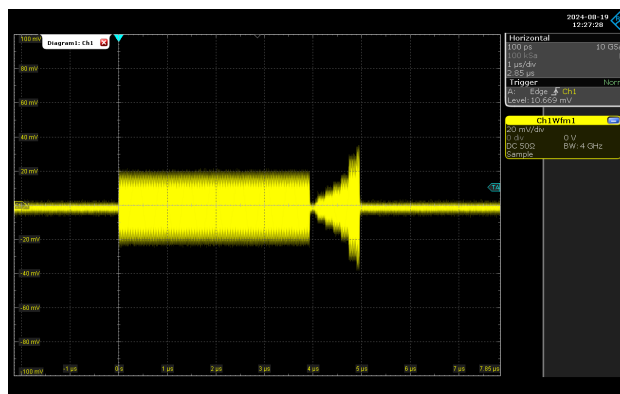

Figure 7: Modulation waveform of SLED pulse in Fig. 6.

Waveforms to all structures can be seen in Fig. 8, which shows all structures having the same modulated SLED signal.
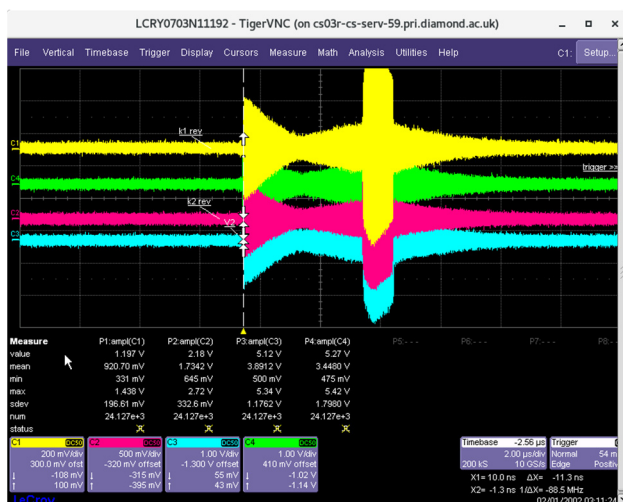
Figure 8: Modulated SLED waveforms of all four Linac structures.

INJECTION

Injection into the Booster was tuned up by initially testing Linac throughput with the same parameters as normal operation with two klystrons, with single bunch shots. As expected, the injection into the Booster was not successful, so phase, power and magnets had to be adjusted. Power could be set by using the signals from directional couplers located at the structures' inputs. By connecting these signals to an oscilloscope and measuring them with and without SLED in operation, the required power levels for the structures could be calculated. After estimating the required power, it was observed that the bunching profile was changed. This change comes from the slight discrepancy of the estimated power and was shown to be very hard to correct without affecting Linac transfer. Therefore, it was better to optimise for a new bunching profile.

After phase and power setup it was possible to measure a 100 MeV electron beam in the Linac to Booster transfer line after the 1st dipole magnet, see Fig. 9.
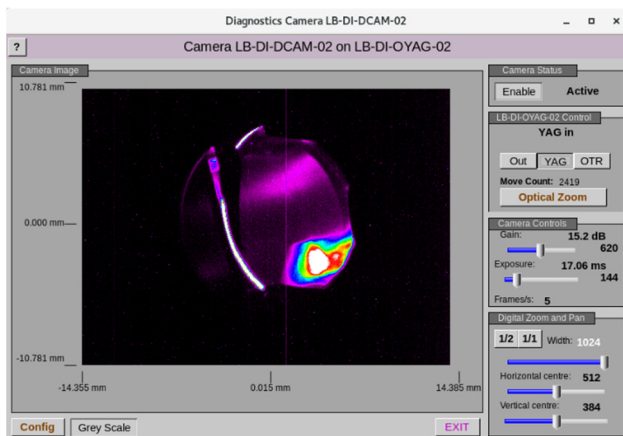

Figure 9: 100 MeV beam in Linac to Booster transfer line, measured after dipole.

Beam also needed large adjustment on the vertical trajectory for injection to be achieved. This is due to the difference in the bunching profile changing the trajectory for the beam into the transfer line, completely changing the effect of the steering and quadrupole magnets.

SUMMARY AND ONGOING WORK

Diamond's Linac has been modified to incorporate a SLED cavity to inject 100 MeV beam with one single klystron instead of using two. By using amplitude and phase modulation from a digital low-level RF a flat peak has been generated. This will allow both single bunch and multi bunch to be accelerated and injected into the Diamond Booster. Single bunch has successfully been injected into the Diamond Booster. Demonstrating injection of a 100 MeV single bunch beam into the Booster with only one Linac klystron in operation has proved the SLED systems' functionality. What remains to be done is to achieve multi bunch injection and for procedures to be developed to handover to the Operations group.

Ongoing work will improve the generated SLED pulse by adding phase modulation in addition to the amplitude modulation. This will provide additional optimisation parameters that will make it possible to allow the amplitude of the klystron to be optimised around the saturation point.

REFERENCES

[1] Y. Joo *et al.*, "Development of new S-band RF window for stable high-power operation in linear accelerator RF system," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 866, pp. 1–8, Sep. 2017. doi:10.1016/j.nima.2017.05.031

[2] C. Christou, P. Gu, and A. Tropp, "Programmable SLED System for Single Bunch and Multibunch Linac Operation," in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 73-75. doi:10.18429/JACoW-LINAC2022-MOPOJ019