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ANALYSIS OF RF SYSTEM STABILITY ON CLARA

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Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) facility at STFC Daresbury Laboratory will test underpinning concepts and technology for a next generation X-ray free electron laser (FEL). CLARA will use four S-band normal conducting traveling wave linacs to accelerate electron bunches to a maximum energy of 250 MeV. The amplitude and phase stability of the collected RF systems is critical in enabling CLARA to achieve low (10 fs) shot-to-shot timing jitter of the photon output. Here we present initial measurements and model of the amplitude and phase jitter of the CLARA RF systems, achieved by experimentally correlating the klystron output with controls from modulator, driver, and other environment parameters. The effect of the RF jitter on the CLARA beam momentum is also integrated in the model.

INTRODUCTION

Compact Linear Accelerator for Research and Application (CLARA) is an electron accelerator, being built in phases, to serve as a platform to test novel concepts and technologies for next generation FEL machines and other suitable applications [1, 2]. CLARA uses a photo injector gun with a normal conducting copper two and half cells standing wave cavity, which provides the initial acceleration up to 6.5 MeV. A Scandinova-Thales modulator-klystron system feeds 2.5 µs long RF pulses of 10 MW at 2998.5 MHz, through pressurised wave-guides. Linac-1 is a two meter long normal conducting traveling wave structure with 61 cells and phase advance of 2π/3, which is fed by a DTI-Thales modulator-klystron system generating 0.7 µs long pulses of 20 MW at 2998.5 MHz [1, 3]. The gun and linac structures are temperature stabilised using cooling water feedback loops and relevant parameters are monitored during machine operation. The laser and RF systems are all locked to a master oscillator (MO) which provides a stable reference clock signal.Both the RF systems are controlled by Libera low level RF (LLRF) systems in conjunction with EPICS and synchronised using a Micro Research timing system [4, 5].

MEASUREMENT SETUP AND PREDICTION METHOD

Performance of different RF sub-systems are monitored using pickup signals, such as: forward and reflected power signals along the wave-guides, probe and load signals, modulator voltage and current, cooling water temperature, solenoid current, etc. Two RF front end systems have been developed to down-convert various 2998.5 MHz RF signals, by mixing them with a Local Oscillator (LO) signal derived from MO, to an intermediate frequency (IF) of 30 MHz. CLARA Fast Acquisition Box (CFAB) system has two RF channels used to record the klystron output forward signal and output signal of the driver amplifier going in to the klystron. It also records modulator voltage, current and AC mains. All channels are recorded using 14-bit ADCs at 125 mega samples per second (MSPS). The second system, CLARA RF Stability Test System (CRF-STS), has eight RF channels, used for signals extracted from Linac-1 waveguide transmission line, probe, load and input signal from driver amplifier. Both systems also record the stable MO signal, which is used to normalise and remove any variations introduced due to LO paths. CRF-STS records the IF signals using 16 bit ADCs at 256 MSPS, while the slow modulator voltage and current signals are recorded with 14 bit ADCs at 125 MSPS. Various RF signals from Libera LLRF and other diagnostics systems are also simultaneously recorded through Epics.

Software libraries are developed in Python to record and analyse data. Every pulse record is stamped with Epoch time and different systems are synchronised using Network Timing Protocol (NTP). To expedite the analysis, a multiprocessing framework is developed, which benefits from multi-core CPU and large server RAM. The amplitude and phase of recorded IF waveforms are calculated using quadrature phase (IQ) digital down conversion process [6]. Processed data from different systems are synchronised and correlated to derive a data based plant model of the RF systems.

Dependence of RF power P_{RF} and phase ϕ_{RF} of a klystron on various control inputs can be described in their simple form [7], as

$$P_{RF} \simeq I_M V_M J_1 \left(\frac{A\omega l}{2V_M} \sqrt{\frac{P_d Z_d}{2V_M} \frac{m_e}{e}} \right), \quad (1)$$

where, V_M and I_M are cathode modulator voltage and current respectively, J_1 is a Bessel's function of first kind, A is a coupling factor controlled by solenoids and transit time factor, ω is RF frequency, l is drift tube length, P_d is the klystron input driver power, Z_d is an equivalent impedance for bunching driver cavity, e and m_e are the charge and mass of electron respectively. The RF phase ϕ_{RF} is controlled by changing driver signal phase, but is also dependent on the

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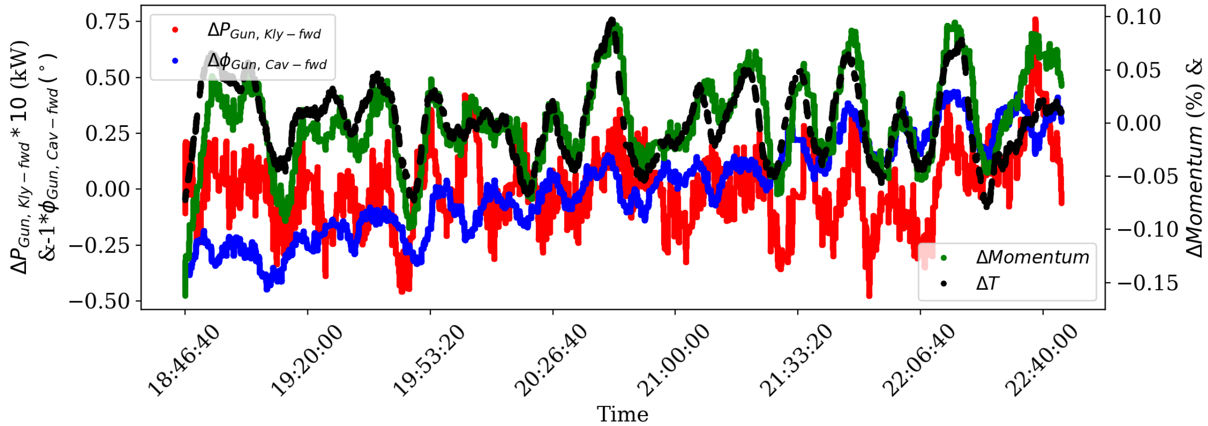

Figure 1: Drift in power and phase of Gun RF system, correlated to temperature and beam momentum.

modulator voltage as,

$$\phi_{RF} = \omega l \sqrt{\frac{m_e}{2eV_M}}. \quad (2)$$

Prediction of klystron power and phase is a nonlinear multivariate minimization problem, which can be expressed in matrix notation as,

$$\mathbf{R_k} = \mathbf{R} \cdot \mathbf{C}, \quad (3)$$

where $\mathbf{R_k}$ is a is $(N \times 1)$ column vector made from N pulse observations of the output parameter to predict, $\mathbf{R}$ is a $(N \times M)$ matrix of which each raw values are from a single pulse, and columns are various power values of relevant control input parameters. $\mathbf{C}$ is a $(M \times 1)$ column vector of coefficients to be determined. The matrix $\mathbf{R}$ is inverted using singular value dispersion (SVD) technique [8] to calculate $\mathbf{C}$. This data driven minimisation process using limited power values is similar to fitting data to selected terms of equivalent series expansions of Eqs. (1) and (2), which should be accurate over a limited input parameter range.

PREDICTION OF OBSERVED DRIFTS AND JITTER

CLARA was operated at 10 Hz during these measurements. The data was recorded for short duration at regular intervals, such as for thirty seconds every minute, and each dot on the plots in this paper represents a derived labeled parameter value for single pulse, unless specified. To study stability of Gun RF system, it was operated on crest for three and half hours, with Linac-1 off. RF power and phase had RMS jitter of 0.09% and 0.04° respectively. To highlight slower drifts, data smoothed using a two second wide moving Gaussian window are plotted in Fig. 1. Klystron power and phase drifted between ±0.075% and ±0.35 ° peak to peak. The beam momentum fluctuated over ±0.15%, and detailed analysis identified strong correlation with gun cooling water temperature variations of 0.15 °C peak to peak. The observed fluctuations overriding the linear drift in cavity forward phase also correlated with the gun water temperature, while showing weaker correlation with fluctuations in driver signal. An intuitive explanation is that the klystron power is fluctuating, which changes the beam momentum and temperature of the Gun, which changes cavity and coupler dimensions. The changes in dimensions also alter the amount of power coupled in to and reflected from the cavity, resulting in beam momentum variations. The other possible explanations is that, the fluctuation in Gun temperature is the driving factor, and variation in the part of reflected power cross-coupled in to the "forward" signal appears as a phase shift. Unfortunately the actual reflected power signals were not recorded during the experiment and can not be verified. Various possible explanations are being investigated in detail.

The correlation and prediction algorithm described in the previous section was used to predict jitter and drifts in Gun RF. Small data segments when the input controls were changed were selected to form a training data set. Appropriate power terms of modulator voltage, driver power and phase were used to form a training matrix. The predicted RF power and phase are compared to the measured in Fig. 2 with their prediction error plotted in Fig. 3. With only two and half hour of combined training data, the algorithm was able to predict the trend in klystron power and phase with 1% and 0.5° accuracy respectively. The amplitude jitter dominates beam jitter when operated on crest. The correlation study showed that the contribution from modulator voltage to RF amplitude was smaller, and the driver signal was the limiting factor for amplitude jitter.

To study stability of Linac-1 RF, the Gun and Linac-1 were set on crest and the machine was left to run without any change. As plotted in Fig. 4, linac power $P_{L01\ Kly-Fwd}$ spiked up to 400 kW (2.7%), which resulted in beam momentum spikes up to 1.2% . Modulator voltage and driver signal did not show any spikes, and wider correlation including solenoid current, various temperatures and other recorded parameters did not identify any primary reason. The spikes were removed by changing driver path and operating klystron

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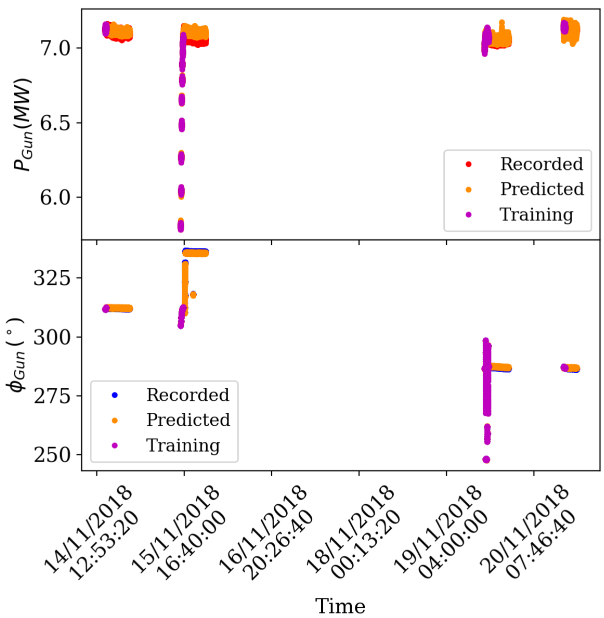

Figure 2: Gun klystron RF power and phase recorded over a week, along with the data segments used to train algorithm, and predicted RF power and phase.

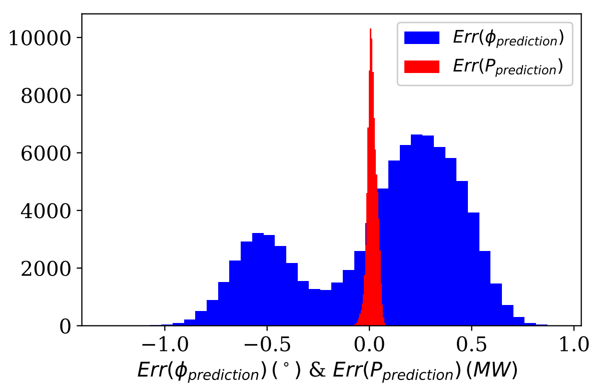

Figure 3: Error in prediction of Gun klystron RF power and phase over a week span.

in different parameter regime, which reduced power jitter to 0.038%. All observations to date point to the klystron tube as the source of the power spikes, which will be examined in detail during a shutdown.

The prediction code was extended to include beam jitter using different order terms of Gun and Linac-1 RF power and phase. The predicted beam momentum and training data span are also plotted in Fig. 4. A Gaussian fit to the prediction error showed prediction accuracy of 0.1%.

A summary of the RF stability measurements is given in Table 1.

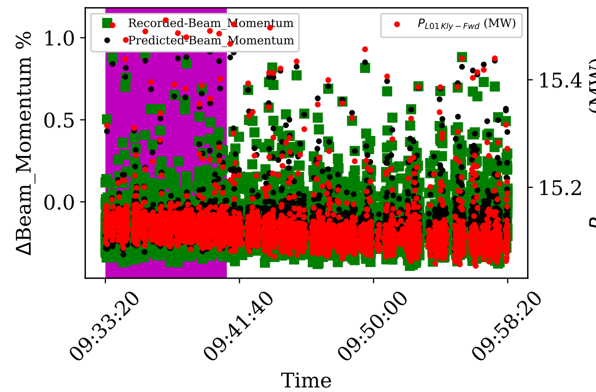

Figure 4: Linac-1 RF power and beam momentum observed during stability test, along with predicted beam momentum and training data span highlighted with magenta background.

Table 1: RF Stability Measurements

Parameter	**Value**	**Stability**	**Limiting factors**
	Gun RF system		
RF Power	6.5 MW	0.09 %	Driver signal, Temperature
RF Phase	on crest	0.04°	Driver signal
	Linac-1 RF system		
RF Power	15.2 MW	0.038 %	Driver signal, Unexplained spikes

SUMMARY AND FUTURE WORK

A study to measure and understand jitter and drifts in RF systems and beam momentum on CLARA is underway, with a goal to develop a plant model to predict them and ultimately minimise their effects. Over three and half hours of unperturbed run, Gun klystron power and phase drifted by ±0.09% and 0.5°, while temperature drifted by 0.15°C, which together caused beam energy fluctuation of ±0.15%. Gun klystron power and phase had jitter of 0.09% and 0.04° respectively. Measurements of Linac-1 RF systems were dominated by power fluctuations of the order of 2.7%. With modifications in klystron driver path, the power jitter was reduced to 0.038%. The plant model was able to predict Gun power and phase over a period of a week with accuracy of 1% and 0.5°, using combined training data set of only two an half hour. An extended version of the model also predicted beam momentum jitter with 0.1% accuracy.

The power spikes in Linac-1 klystron output will be studied in detail, by running klystron on a dummy load. The plant model will be improved by including additional control and environmental parameters.

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