# BUNCH TRAIN CHARACTERISATION FOR AN INFRA-RED FEL DRIVEN BY AN ENERGY RECOVERY LINAC

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*Abstract*

The IR-FEL on the ALICE test facility in the UK first achieved lasing in October 2010 and has since been characterised in terms of its output. In this work we make a characterisation of electron bunch properties along a complete 100 μs macropulse to characterise the lasing-induced energy change and assess the sensitivity of the FEL to oscillations in the electron beam. Measurements of bunch energy, position and timing are correlated with the FEL radiation output and discussed.

## INTRODUCTION

Since first lasing in 2010, the ALICE FEL has been producing 5-11 μm radiation for biological studies and system characterisation [1]. In this work, we extend the characterisation of the FEL by directly relating its output to beam measurements. Through synchronisation of multiple diagnostics we have tracked individual electron bunches within a macropulse in arrival time and position in the region around the FEL. Furthermore, we have been able to match the bunch-by-bunch beam measurements to the photon output emitted by each of the bunches as they traverse the FEL. This has aided the better understanding of the nature of instabilities in ALICE as well as the sensitivity of the FEL to these instabilities.

## MEASUREMENT TECHNIQUE

### *Experiment Layout*

To characterise the lasing-induced energy change from the FEL in the residual electron bunch, the FEL lasing output was compared with measurements of the electron bunch position and timing after a dispersive section in ALICE (Arc 2). The positions of the diagnostic measurements on ALICE are shown in Fig. 1.

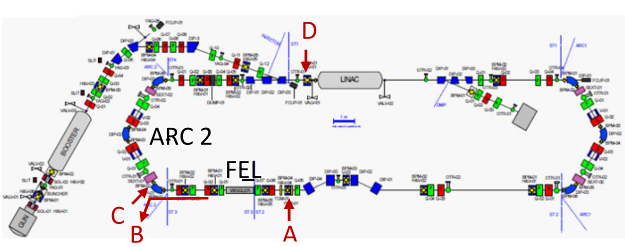


Figure 1: Layout of the ALICE accelerator and beam monitoring positions.

Bunch arrival time was measured just preceding the FEL at location A to monitor the conditions for lasing. At location B, the photon output of the FEL is measured using a fast photoelectromagnetic (PEM) detector. After the FEL, Arc 2 of ALICE was used to map energy losses in the FEL to position and timing changes. The beam position was measured after a single dipole at location C and the beam arrival time was measured at the entrance of the Linac at location D, just before the spent beam returns for energy recovery. As well as characterising Arc 2, correlation of these measurements have been used to verify the performance of the diagnostics.

Synchronisation of the diagnostics was achieved through a combination of analogue triggers and time-stamping in EPICS. The measurement is initiated with a beam signal from a pickup before the FEL, which triggers an oscilloscope to acquire of the optical pulse amplitudes from the beam arrival monitors (BAM) at locations A and D. The oscilloscope is able to sample at 40 GS/s to accurately measure all the optical pulse peaks along the 100 μs macropulse, which can be converted to arrival time with post-processsing. This first oscilloscope then sends a trigger to a second high speed oscilloscope to measure the photon output of the FEL. The measurements from both oscilloscopes are time-stamped to the local oscilloscope clock which is synchronised to the main EPICS clock of the accelerator control system. With ALICE running at 1 Hz, these BAM and FEL output measurements were able to be matched to the beam position monitor (BPM) data which is directly time-stamped into EPICS.

### *Beam Position Monitor*

The BPM in this experiment used rectangle pickups with two pairs of horizontal buttons symmetrically spaced from the $x$, y planes [2]. The beam offset is calculated using the formula $((V_{11}\text{-}V_{12}\mp V_{21}\pm V_{22}))/\Sigma$, where $V_{xy}$ is the voltage measured at each of the four buttons and $\Sigma$ is their sum which represents the total charge of the bunch. The pickups have no fiducials, so the relative positions of the BPM centres to the quadrupole centres, or the beam pipe, are unknown. Each two-plane BPM comprises two Front-Ends placed near the pickup [3]. Each of them works with two opposite button signals. It first converts them into compact 700 MHz three-period packets and then multiplexes the packets in the time domain into one channel.

The doublets are transmitted through low loss cables to a remote two-channel VME card. In each channel, the bunch-by-bunch doublets are amplified, detected, measured, and then stored in memory. After the last bunch, the card sets the number of detected bunches to be read by EPICS, and then generates a VME interrupt. Next, each memory is read by EPICS in the time between macropulses and time-stamped to EPICS time. This system is able to achieve a relative positional resolution of 30 μs.

### *Beam Arrival Monitor*

The BAM uses an optical pulse train which is synchronised to the accelerator clock to sample the relative arrival time of electron bunches in a macropulse. This is done by using an in-beamline stripline pickup to convert the passing Coulomb field of the electron bunch into an electrical signal. This is then sampled by using the electrical signal to modulate a $LiNbO_3$ crystal within a Mach-Zehnder interferometer to gate the optical sampling pulses. The time information is thus converted into an amplitude modulation which can be accurately measured on a fast oscilloscope. Individual bunches in a macropulse are thus measured in amplitude with respect to each other and with respect to unmodulated pulses to give the relative time structure within the macropulse.

Two types of pickups were used for the BAMs in this experiment, a ¾ wavelength stripline at location A and a ¼ wavelength stripline at location D. The choices of these pickups were due to the available BPMs already installed on ALICE at the desired locations, from which the pickups are borrowed for BAM measurements. These BAMs are similar in principle to those developed at DESY [4] which require a zero crossing in the pickup characteristic to reduce the charge sensitivity of the measurement. While this comes automatically when using a button pickup, we had to generate a zero crossing from the characteristic of our striplines. For the ¼ wavelength stripline this was achieved through dispersion in a short length of coax, and for the ¾ wavelength stripline, an RF filter was made to take the derivative of the signal to generate a sharp S-curve. This approach required large amplification of the pickup signal due to losses in the filter. Using these striplines we were able to measure electron bunch arrival times with a single-shot resolution of ~280 fs at location A and ~600 fs at location D.

## RESULTS

The correlated measurements taken for two machine conditions are shown in Fig. 2 with regions of non-lasing and lasing shown in blue and red respectively. Plots (b) and (c) are beam arrival measurements as a function of bunch number before and after the FEL, and have been smoothed with a 10 bunch moving average to resolve the main features. Plot (d) shows the FEL photon output and plots (e) and (f) are the x and y position offsets of the beam in Arc 2. While all of the beam position and timing measurements are have some charge dependency, this dependency has been normalised with respect to the charge measured at location C and shown in plot (a).

The first thing we notice in these measurements is that plots (c) the arrival time at energy recovery, (d) the FEL output and (e) the beam position in Arc 2, are highly correlated and show the same set of features. This confirms that the variations in FEL lasing along the train does indeed result in the energy modulation of electron bunches as expected. This is confirmed in Fig. 3 (b) and (c) which show the correlation plots of FEL output versus beam position and timing respectively. By correlating them together as in Fig. 3(a) these types of measurements we can be used to calculate the lattice parameters.

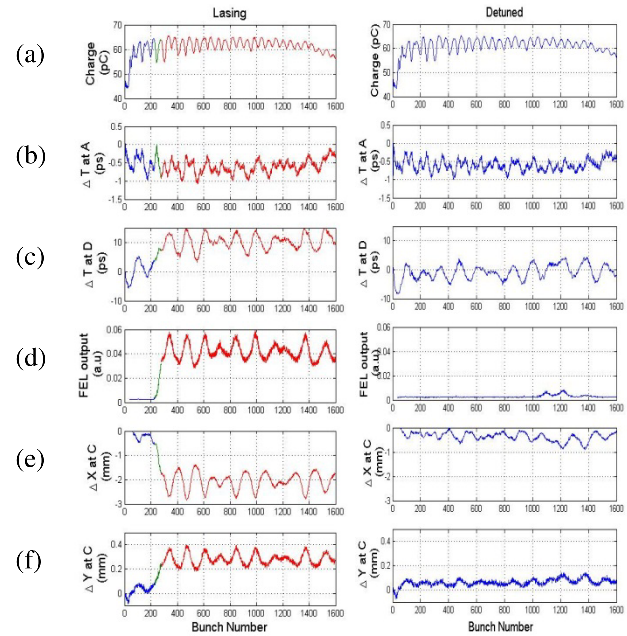


Figure 2: Measurement of macropulse train with (left) and without lasing (right).

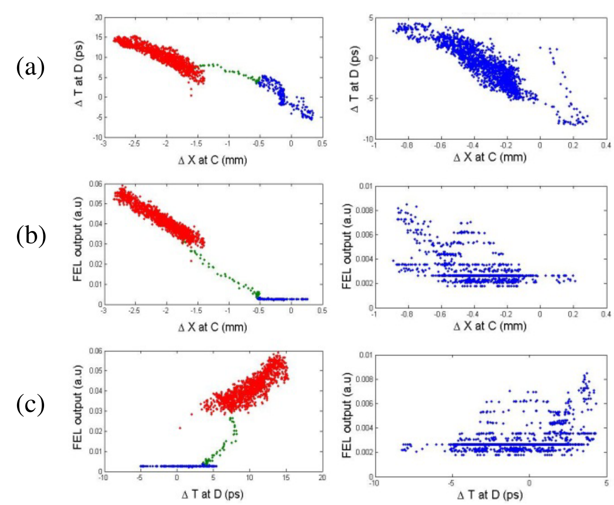


Figure 3: Correlations between BAM, BPM and FEL measurements for each bunch with (left) and without lasing (right).

Despite the fluctuations in FEL lasing causing a timing fluctuation at the point of energy recovery, we have not observed any effect on the quality of energy recovery. However, it is interesting to note that the timing fluctuations at D are not very much larger when the FEL is lasing than when it is not. This explains the insignificant effect that lasing has on energy recovery, since much of the lasing induced time changes are already present. It can also be seen from Fig. 3 that although the BAM and BPM measurements are completely decorrelated from the FEL output, they are still somewhat correlated to each other. This shows that these are not instrumental fluctuations. Instead it implies that a fair


ISBN 978-3-95450-122-9

portion of the energy fluctuations are not generated in the FEL, but further upstream and are correlated to the FEL pulse energy through its coupled time and position changes as discussed below.

What is also unexpected is the correlation between the beam arrival time before the FEL and the oscillations observed in the FEL output. In plot (b), two distinct oscillatory behaviours can be seen, a slower larger oscillation at ~100 kHz with an amplitude of ~0.5 ps and a faster oscillation at ~300 kHz with amplitude ~0.2 ps. In the FEL output and subsequent energy measurements however, only the slower oscillation is observed and not the faster. To help us understand this, the FEL output was simulated using FELO [6] for an electron bunch with a sinusoidally varying arrival time. Fig. 4 shows that for the same peak-to-peak fluctuations of 0.5 ps and 0.2 ps, oscillations at different frequencies result in different modulation depths of the FEL output. This is because the radiation from the FEL has a lifetime within the cavity has a damping effect on rapid changes. That is, for slow oscillations, the cavity has more time to lose energy as it detunes than it would if it rapidly came back into tune again, as with fast oscillations.

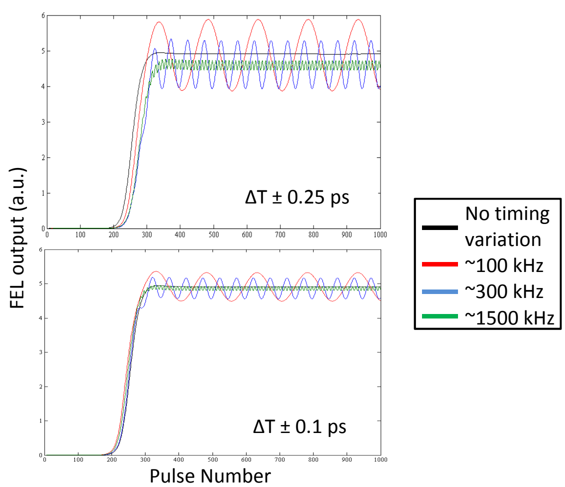


Figure 4: FELO simulation of the effect of small timing variations of 0.5ps and 0.2ps on the FEL output.

We know from previous studies of beam dynamics on ALICE, that there is a 100 kHz positional oscillation of the electron bunch in the horizontal plane [5]. This oscillation has a magnitude of ~200 µm at the entrance to the FEL and is also expected contribute to fluctuations in the FEL output. To confirm this, the effect of the position oscillation was simulated in GENESIS code as shown in Fig. 5. It can be seen that the 100 kHz, 200 µm oscillation produces a 200 kHz oscillation as the bunch swings across the nominal axes of the FEL. This converts into a 100 kHz, deeper oscillation if there is also a global offset in the mean beam position bringing the beam completely onto one side of the nominal axes.

Furthermore, the effect on the FEL output on the expected positional variation can be seen to be greater than that predicted by the measured timing variations. This indicates that although the fluctuations we observe in the FEL output is almost certainly due to a combination of the bunch position and timing error, it is clearly dominated by the position variation and the larger slow variations in the timing rather than the fast oscillations which are both smaller in magnitude and more susceptible to damping mechanisms within the FEL.

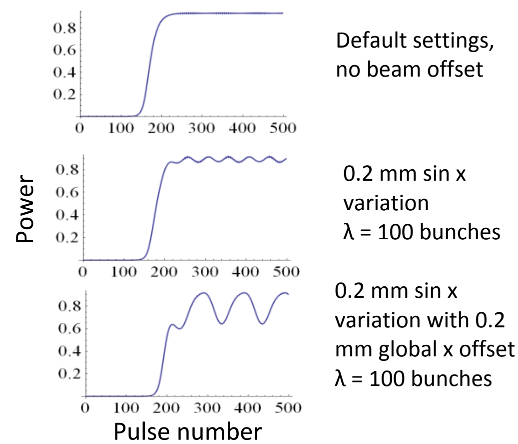


Figure 5: GENESIS simulation of the effect of small positional displacements on FEL output.

## CONCLUSIONS

We have undertaken a study of the ALICE IR-FEL, its sensitivity to input beam conditions and its effect on the residual electron beam. The study has been implemented through the synchronisation of beam arrival and beam position monitors with the FEL photon output to achieve bunch-by-bunch tracking of the beam in the region around the FEL. We have verified the diagnostics and found that the strong 100 kHz oscillation observed is likely due to both position and timing fluctuations entering the FEL, the faster oscillations being damped by the FEL cavity. Synchronised measurements of this sort can be used to enhance our understanding of dynamics within the accelerator and further analysis will aid us in tracking instabilities within ALICE.

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