# LONGITUDINAL BEAM DYNAMICS AT THE ALICE ACCLERATOR R&D FACILITY

F. Jackson, D. Angal-Kalinin, S. P. Jamison, J. W. McKenzie, T. T. Ng, Y. M. Saveliev, P. H. Williams, STFC Daresbury Laboratory, ASTeC & Cockcroft Institute, UK

*Abstract*

The ALICE facility is an energy recovery test accelerator whose applications include an IR-FEL and THz generation. Of primary importance to the performance of the main ALICE applications is the understanding and control of the longitudinal dynamics, which are less amenable to measurement than the transverse. The longitudinal dynamics of the beam are studied in simulation and experiment in several areas of the machine. Simulations of the low energy injector where space charge and velocity bunching may occur are presented. Path length measurement using time-of-arrival monitors are carried out.

## INTRODUCTION

The ALICE facility is an energy recovery test accelerator described in detail elsewhere [1][2]. ALICE comprises a photoinjector consisting of DC gun (up to 350 keV), buncher and superconducting booster (typically 6.5 MeV beam energy); and a main energy-recovery loop (typically 26 MeV beam energy) containing a superconducting linac module, a bunch compressor, and an undulator. ALICE is a test facility which has pursued several different goals and applications including an infra-red free-electron laser (IR-FEL) and a terahertz (THz) research programme. The main demands on the ALICE beam dynamics and beam quality comes from the IR-FEL [3] which demands small energy spread and a small compressed bunch length.

Recent studies aimed to investigate the beam dynamics in a more systematic way [4], and this paper seeks to advance those studies. Recently a significant change to the ALICE injector was made with the installation of a new gun ceramic allowing a much higher voltage to be used [2]. The changes to the beam dynamics resulting from the higher gun voltage are discussed in a dedicated paper [5] focussing on observations of bunch sub-structure. This paper discusses more general aspects of longitudinal dynamics.

## LONGITIDUNAL INJECTOR DYNAMICS

The ALICE injector has a buncher and a 2-cavity booster which accelerates the beam to typically 6.5 MeV before injecting into the main linac through a transfer line of ~ 13 m length. The injector longitudinal dynamics are very sensitive to the buncher and booster settings.

First measurements of longitudinal dynamics from the ALICE gun were carried out in 2007/2008 at the time of HV DC gun commissioning [6] at 350 kV. More recently, a program of bunch length measurements in the injector and post-linac were carried out at the lower operating voltage of 230 kV which has been used since 2008 and preliminary measurements were presented in [4]. Recently a new HV gun ceramic insulator was installed and the gun currently operates at 325 kV. The differences in beam dynamics at the higher voltage are the subject of a separate paper [5].

The bunch length measurements presented in [4] were continued and developed later in 2011/2012. The majority of measurements of the injector bunch length were carried out using machine set-ups optimised for THz production in the compression chicane. In the injector, the bunch length was measured using the RF-zero crossing method while immediately post-linac the bunch length was measured by the energy spread vs. linac phase method (see [4] for a description of these methods).

Both methods described above suffer from limitations due to the diagnostic apparatus available. In addition, long term drifts in machine performance and the ability to restore the machine accurately over an extended period make conclusive measurements difficult to obtain. Fig. 1 shows bunch length measurements taken for a single machine set-up over a 5 month period in 2011 (from shift numbers #2422 in April 2011 to #2624 in August 2011) with considerable variation in the results.

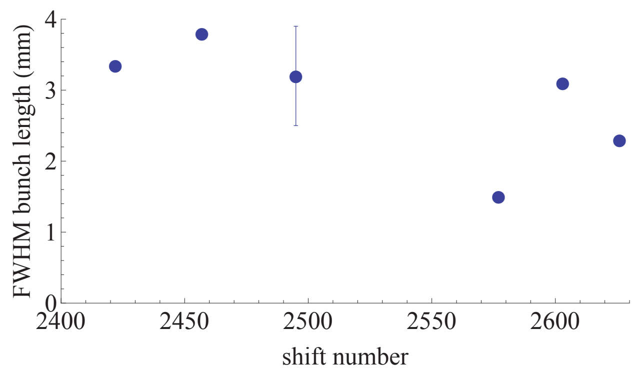


Figure 1: Injector bunch length measurements for a single machine set-up over a 5-month period. The injector bunch length is inferred at the exit of the first of the two booster cavities. The error was estimated on one measurement and is indicated by the error bar.

In the RF zero-crossing method in the injector, the energy spread of the beam with the second booster cavity on zero-crossing must be measured. On one zero-crossing the energy spread can be very large and must be reconstructed by scanning the beam with a dipole over a YAG screen. This leads to significant error, estimated during one measurement to be ~20%.

Despite the difficulties in the bunch length measurement, the dependence of bunch length on the first booster cavity phase was measured and compared with ASTRA [7] simulations, see Fig. 2. The measurements were performed in a single shift, thus the systematic and statistical errors involved may be correlated between successive measurements in the scan and make the trend discernible. Some agreement between simulation and measurement, both in absolute value and trend, is observed.

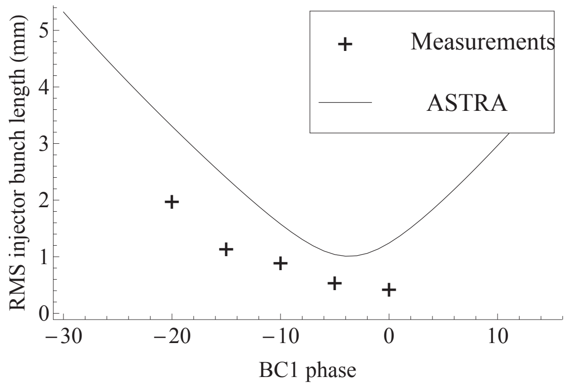


Figure 2: Injector bunch length measurement and simulation as a function of the first booster cavity (BC1) phase.

The bunch length immediately post linac (and by implication at the linac entrance) was derived by measuring the energy spread vs. linac phase (see [4] for method details). This was performed on several occasions simultaneously with the RF zero-crossing bunch length measurement at the booster. On all occasions the bunch length at the linac was found to be ~2-6 times smaller than the bunch length at the booster, indicating significant bunching in the transfer line between the booster and the linac.

Bunching is possible in the injector through both ballistic effects and magnetic compression, since the injector transfer line is not isochronous. In typical machine set-ups the bunch is chirped as it exits the booster, with the bunch head at higher energy than the tail. This would lead to ballistic de-bunching; but the $R_{56}$ of the injector is positive, meaning particles at the head of the bunch (at positive $\delta p/p$) take longer to traverse the injector line than particles at the tail resulting in compression (this is of course the same situation as in the post linac bunch compressor, except there the $R_{56}$ is negative and the head of the bunch is lower energy than the tail).

Simulations using ASTRA [7] and ELEGANT [8] have proved useful in exploring these effects. Gun-to-booster-exit simulations in ASTRA were constructed to vary the final chirp of the bunch at the booster exit, which were then transported to the linac using ELEGANT (which does not include ballistic effects). Significant bunching was observed for chirped bunches due to the non-isochronous injector transfer line, see Fig. 3. Ballistic de-bunching in the transfer line was estimated using ASTRA and was observed to be much smaller than the magnetic compression for the parameters used in these cases, see Fig. 4.

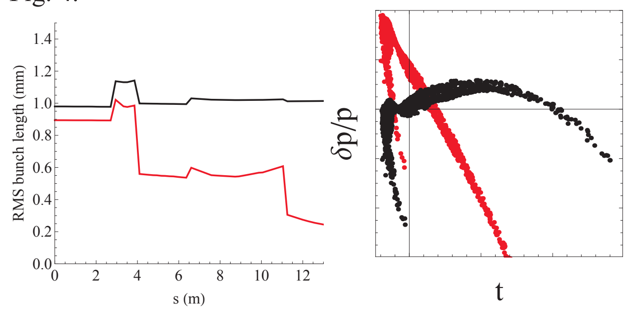


Figure 3: ELEGANT simulation of bunch length evolution in injector (left) for different longitudinal chirps at booster exit (right). The booster exit is located at s = 0 m.

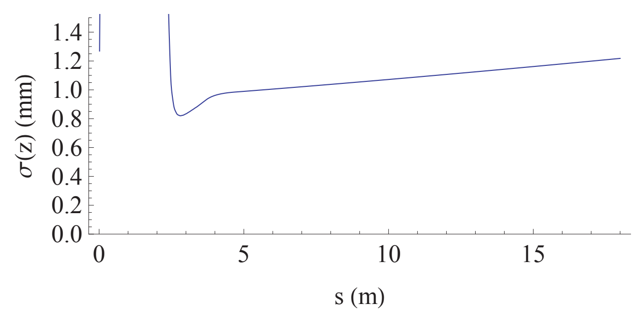


Figure 4: ASTRA simulation of bunch length evolution in a long drift space post-booster, for the larger chirped distribution in Fig 3. The booster exit is located at s ~ 5 m.

## COMPRESSED BUNCH LENGTH MEASUREMENTS

After acceleration in the main linac, the bunch is transported through an triple bend achromat arc (ideally isochronous) then a compressor chicane to the IR-FEL undulator before passing through a second arc to return to the linac for energy recovery. Sextupoles are positioned in the arcs to linearise the RF curvature and improve the bunch compression.

The THz coherent synchrotron radiation (CSR) power from the compression chicane is most frequently used to indicate maximum compression of the bunch while scanning the linac phase [9]. The ALICE IR-FEL is also highly sensitive to the compressed bunch. The width of the spectrum of the IR-FEL radiation has been used to infer the compressed bunch length [3]. In addition an electro-optic (EO) bunch length monitor has been used to directly measure the single-shot bunch length profile at the exit of the compression chicane [10][11]. This was first used in low-resolution ‘spectral decoding’ mode during IR-FEL commissioning in 2010 when it confirmed the compressed bunch length under normal conditions to be 1-2 ps (3-6 mm). More recently improvements to the experimental set-up have been made and the high resolution ‘temporal decoding’ method has been used.


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Preliminary attempts have been made to judge the variation in longitudinal bunch profile with machine lattice tuning, see Fig. 5. In this measurement the first sextupole of the first arc was turned on (to 30% of its maximum value) and off to judge the effect on bunch compression (the CSR THz power has been found to be sensitive to this magnet). The resulting observed bunch profiles indicated significant jitter in measured bunch length, which may be due to real jitter in the longitudinal bunch profile as well as experimental artefacts; however the effect of the sextupole on the bunch length is discernible.

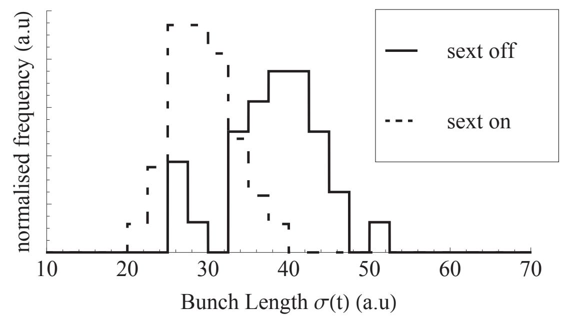


Figure 5: ALICE compressed bunch length measured by electro-optic technique, with the first sextupole in the first arc turned on and off. The horizontal scale is arbitrary units, an indicative scaling is 50 units/ps or 150 units/mm.

The EO method in combination with the THz spectral investigations are being pursued to improve understanding of the longitudinal bunch profile, since sensitivity to lattice parameters is still not fully understood.

## PATH LENGTH AND $R_{56}$ MEASUREMENTS

As mentioned above, the longitudinal dynamics effects in ALICE and deviations in the real machine from the design are not fully understood. The (iso)chronicity of the first arc is highly sensitive to the arc quadrupoles, which was indicated by previous measurements [4], and is also affected by cases of mis-steered beam in the arc sextupoles.

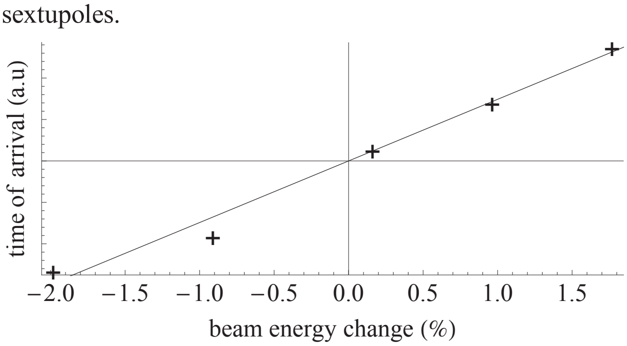


Figure 6: ALICE post-compression beam time of arrival (TOA) vs. beam energy. The TOA is displayed in arbitrary units but an indicative scaling is ~20 pS for the full range of measurements shown here.

To investigate these effects path length measurements have recently been attempted from which $R_{56}$ values can be deduced. The bunch time-of-arrival (TOA) was measured as a function of the beam energy using a post-compression BPM and a high resolution oscilloscope. Preliminary measurements of the path length vs. beam energy are shown in Fig. 6, indicating a linear dependence. This demonstrates the feasibility of the method in extracting path length measurements. The repeatability of these measurements is currently being studied along with comparisons with trajectory simulations to extract values of $R_{56}$.

## CONCLUSION

Longitudinal beam dynamics studies in ALICE continue in order to further understand and refine machine performance. Bunch length studies in the injector have highlighted and elucidated ballistic and magnetic compression effects. The electo-optic diagnostic at the bunch compressor has demonstrated useful results in judging the effect of lattice tuning on the compressed bunch. Path length measurements using BPMs as time of arrival monitors have demonstrated a feasible method of determining $R_{56}$.

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