BEAM DYNAMICS AT THE ALICE ACCELERATOR R&D FACILITY

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Abstract

ALICE is an energy recovery accelerator which drives an infrared free electron laser (IR FEL), based at STFC Daresbury Laboratory. Beam dynamics are of primary importance for the operation of the IR-FEL, to ensure sufficient peak current with minimal energy spread and transverse emittance. Measurements of beam parameters presented and compared with particle tracking simulations. Of particular interest in the ALICE machine is the relatively long injection line where space charge and velocity bunching effects can be significant.

INTRODUCTION

The ALICE accelerator at Daresbury laboratory is an energy recovery test accelerator whose main application an IR-FEL, but which also operates as a THz source and as an injector to the EMMA non-scaling FFAG accelerator. The current status and more details of ALICE can be found in [1].

The main components of ALICE are an injector consisting of a DC electron gun (230 kV); a superconducting booster module; and a main energy-recovery loop containing a superconducting linac module, a bunch compressor chicane and an undulator. The beam is injected into the linac at energies up to 7 MeV and accelerated up to 30 MeV. Bunch charges of up to 100 pC are used.

The main demands on beam quality in the ALICE machine come from the IR-FEL requirements. The bunches must be compressed to around 1 ps to provide a high peak current, while the single bunch energy spread should be less than 200 keV (0.7%). Transverse emittance requirement are less stringent, with < 20 mm mrad (normalised) being acceptable.

The injector dynamics are optimised by use of focussing solenoids, an RF buncher, and a booster module containing 2 cavities (BC1 and BC2) whose phases can be set independently to minimise energy spread. The linac module also consists of two cavities (LC1 and LC2) whose phases are set to provide a longitudinal chirp to the bunch for chicane compression. The first arc of the main loop contains sextupoles to linearise the longitudinal phase space.

Previous ALICE beam dynamics studies include start-to-end-simulations[2], dedicated injector design studies [3] , and injector measurements[4].

Some of the original ALICE machine design parameters have not yet been achieved, resulting in more challenging tuning of the beam dynamics. Operating the DC gun at the full design field of 350 kV, after an initially successful demonstration[4], eventually proved problematic[5] and since 2009 a maximum voltage of only 250 kV has been possible (230 kV is used in practice), increasing the effects of space charge at the gun. Beam loading effects in the RF cavities have not permitted the simultaneous use of high charge and high repetition rate bunches. Until recently only 40 pC bunch charge was used (rather than the nominal 80 pC), and FEL operation was not achieved until the repetition rate was substantially reduced, allowing higher charge bunches to be accelerated with low beam loading. The layout of the ALICE accelerator is shown in Figure 1.

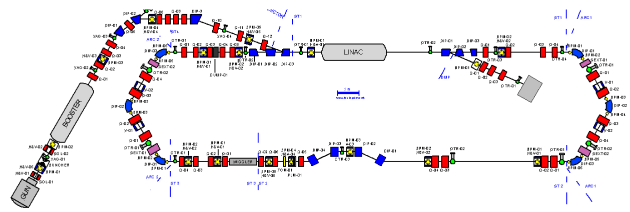

Figure 1: ALICE Layout.

INJECTOR DYNAMICS

The ALICE injector dynamics are complicated by space charge causing transverse and longitudinal emittance blow-up, and the varying accelerating phase seen by the non-relativistic beam in the first cells of the booster causing introducing non-Gaussian and non-linear effects in the phase space. The initial ALICE injector configuration was guided by the optimisation studies in [3], and detailed injector measurements were taken when the gun operated at 350 kV [4]. Since the reduction of the gun voltage to 230 kV, a re-optimisation of the injector set-up resulted in a baseline set of parameters from which to start operation. Finally, adjustments were made for what worked best in practice.

The injector diagnostic line measurements in [4] did not always match ASTRA simulations well in all regards. Non-ideal effects on the beam dynamics, especially in the 230 keV beam transport section include stray fields, imperfect steering, field inhomogeneities, cathode and laser imperfections.

FEL Requirements on Injector Longitudinal Dynamics

The minimum bunch length (and thus highest peak current) achievable at the FEL is determined by the intrinsic (i.e. uncorrelated) energy spread of the beam. The minimum bunch length is estimated by $\delta p/p.R_{56}.E_0/E_m$ (see for example[6]), where $\delta p/p$ is the uncorrelated fractional energy spread at the entrance to the linac, R_{56} is the linac-to-undulator momentum compaction (280 mm design value for ALICE), E_0 is the injector beam energy (7 MeV) and E_m is the post-linac beam energy (28 MeV). Thus a minimum bunch length of

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1 ps (0.30 mm) would require an uncorrelated energy spread of δp = 0.5% (30 keV) at the linac entrance.

The energy spread at the FEL is crucial for the FEL gain and is determined by the bunch length at the linac entrance. The energy spread as a function of the bunch length Δz is estimated by

$$\Delta E = \sqrt{\Delta E_0^2 + h^2 \Delta z^2} \quad (1)$$

where ΔE_0 is the uncorrelated energy spread and the chirp h is given by $E_L \frac{2\pi}{\lambda}\sin(\phi - \phi_0)$ where E_L is the on-crest linac energy gain (around 21 MeV), λ is the RF wavelength (231 mm), ϕ_0 is the linac phase at which the energy spread is minimised ($\phi_0 = 0$ if the bunch enters the linac with zero chirp), and ϕ is the off-crest phase. At the design off-crest phase of 10°, and for an typical intrinsic energy spread of 30 keV, an energy spread ΔE = 200 keV at the FEL requires a bunch length in the injector of around Δz = 2.0 mm (7 ps).

Injector Longitudinal Dynamics Measurements and Simulation

To ascertain whether the FEL requirements were fulfilled, several measurements of the longitudinal phase space were performed. Simulations indicated that the bunch length and intrinsic energy spread are most strongly affected by the the buncher power and phase of the first buncher cavity (BC1).

The energy spread and bunch length as a function of buncher power were measured at 40 pC bunch charge and are shown in Figure 1.

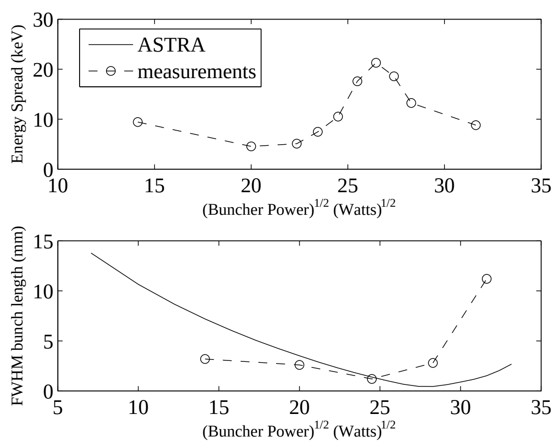

Figure 2: ALICE injector measurements (Top) Uncorrelated energy spread in the ALICE injector as a function buncher power. (Bottom) Bunch length in the ALICE injector as a function buncher power, points are measurements and the line is the ASTRA simulation. The booster cavity BC1 is set to baseline value of -10° and the bunch charge is 40 pC.

For these measurements BC1 phase set to the baseline value (-10°), and the uncorrelated energy spread was measured using a YAG screen at high dispersion, using the BC2 as zero-cross cavity to minimise the energy spread for each buncher power. The bunch length was also measured at various buncher powers, using the zero-crossing RF method[7]. The energy spread and bunch length were found to be sufficient for FEL requirements for buncher power of around 600 W.

The measurements above were performed at fixed BC1 phase. However, the BC1 phase is seen to clearly affect the linearity of the longitudinal phase space in simulations, creating a trade-off between bunch length and intrinsic energy spread. As the BC1 phase moves closer to crest, the bunch length decreases but a 'hook' in the longitudinal phase space develops, limiting the uncorrelated energy spread of the bunch (see Figure 2).

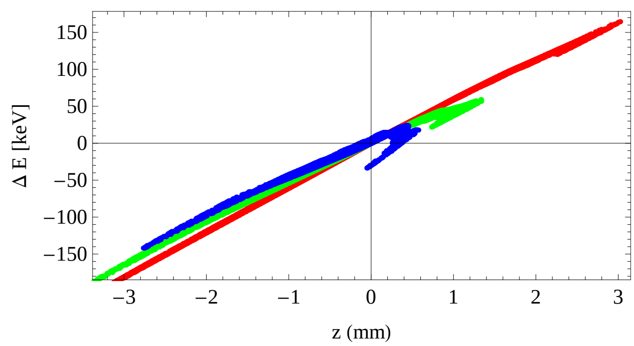

Figure 3: ALICE simulated injector longitudinal phase space as a function of BC1 phases. BC1=-20° (red), -10° (green), -5° (blue).

Preliminary injector bunch length measurements as a function of BC1 phase have been recently been carried out at the higher bunch charge of 60 pC, the results are shown in Figure 3.

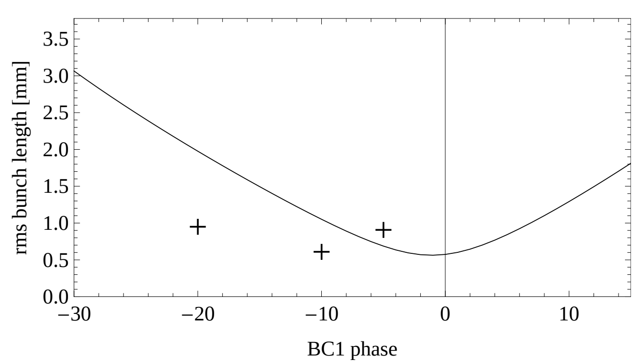

Figure 4: Preliminary ALICE bunch length measurements as a function of BC1 phase (crosses) and ASTRA simulation (line). The bunch charge is 60 pC and the buncher power is 0.53 kW.

POST-LINAC DYNAMICS

The linac is operated off-crest to chirp the bunch for longitudinal compression. In an ideal scenario with the post linac R_{56} = 280 mm from the chicane and zero longitudinal chirp from the injector, the predicted off-crest phase for maximum compression is approximately

10°, for injector energy of 7 MeV and post-linac energy of 28 MeV.

In practice, the amount of bunch compression in ALICE is indicated by the emission of coherent THz radiation from the chicane. The maximum THz signal in ALICE is observed at around 15-18°, since in reality the bunch from the injector arrives at the linac entrance chirped in the opposite direction to that required for post-linac bunch compression.

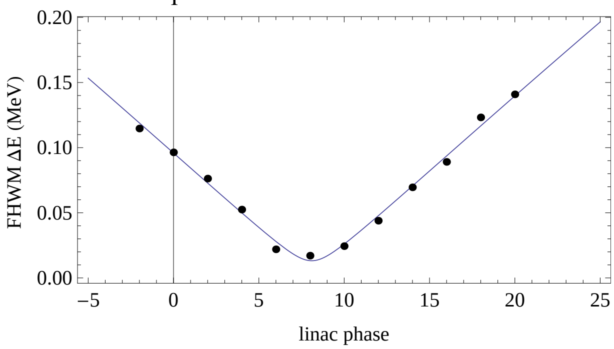

Figure 5: ALICE post-linac energy spread vs linac phase. The points are measurements, the line is a fit of Equation (1) where the free parameters are bunch length and minimum energy spread. A bunch length of 1.3 mm FWHM is extracted.

The bunch length at the linac entrance can be inferred from the post-linac energy spread measured on a screen in a dispersive region. The energy spread as a function of the bunch length is given by equation (1). A preliminary measurement has been carried using a standard machine set-up, and the bunch length extracted by fitting equation (1) to the data (see Figure 4). Although the model fits the data quite well, the extracted bunch length (FWHM 1.3 mm) is around half the value measured simultaneously in the injector using the RF zero cross method (FWHM 2.3 mm). This indicates longitudinal bunch development in the transfer line between the booster and the linac (see discussion below).

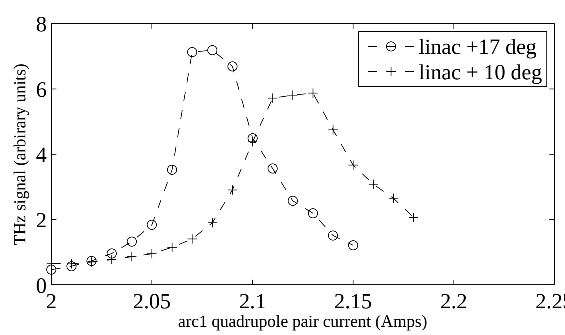

Figure 6: ALICE THz signal vs first arc quadrupole strength, for two fixed linac off-crest phases. Two quadrupoles (symmetrically positioned about the central arc dipole) are varied together to vary the post-linac R_{56}.

The bunch length at the entrance to the FEL has been measured with an electro-optic device at 1-2 ps[1], coinciding with the maximum chicane THz signal. The momentum compaction R_{56} has not been measured in the post-linac lattice, however it is suspected that there is a non-zero R_{56} from the first arc. The arc design is nominally isochronous but is quite sensitive to the arc quadrupole strengths, which has been verified in recent measurements of the THz signal (see Figure 5). The arc sextupoles are observed to affect the THz signal, however it is suspected that the imperfectly steered beam in the arc means the sextupoles may effectively be acting as quadrupoles, rather than providing linearisation of the chirp.

CONCLUSION

The ALICE beam dynamics have been measured in various locations of the beam transport system. The measured bunch length and uncorrelated energy spread are sufficient for operation of a IR-FEL[1], even though the original machine specifications have not yet been fully achieved. It is planned in the next year to install a new ceramic insulator on the DC gun which should enable 350 kV operation as in the original design.

It is suspected that the longitudinal phase space may be evolving in the long transfer line between the booster and the linac (around 13 m length). Usually, the BC2 cavity is set such that it does not completely minimise the energy spread, thus the beam is chirped on exit of the booster, with the head of the bunch at higher energy. The R_{56} of the injector lattice is of the sign that would cause momentum compaction of the bunch for this kind of chirp. In addition, the R_{51}, R_{52} of the injector are non-zero, which may also lead to bunching effects. On the other hand, the bunch chirp at the booster exit would be expected to cause velocity de-bunching in drift spaces. This interplay of bunching and de-bunching effects is currently being studied in simulation.

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