SIMULATIONS OF THE ALICE ERL

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Abstract

ALICE is a low-energy Energy Recovery Linac operated at Daresbury Laboratory in Cheshire, UK. The ALICE injector is based around a 350 kV DC photo-cathode electron gun. With an operating voltage of 325 keV, electron dynamics in the ALICE injector are space-charge dominated and highly non-linear, and this complicates simulations of the beam dynamics in this region. With an intermediate energy of 6.5 MeV, and a final ring energy of 27.5 MeV, the space-charge effects in the rest of the machine can also not be ignored. In this paper we summarise some of the work that has been performed to understand and optimise the simulations of the ALICE ERL, in several different operating modes, and using several different modelling codes.

ALICE

The ALICE facility is an energy recovery test accelerator at Daresbury Laboratory, Cheshire [1]. ALICE comprises a photo-injector consisting of a DC gun (up to 350 keV, but typically 325 keV), a normal-conducting buncher and a superconducting booster (typically 6.5 MeV beam energy); and a main energy-recovery loop (typically 26 MeV beam energy) containing a superconducting linac module, 2 transport arcs, a bunch compressor, and an undulator. ALICE is normally run at an operating bunch charge of 60 pC, with up-to ~4000 bunches in a 100 µs pulse train. As a test facility ALICE has pursued several different goals and applications, including an infra-red free-electron laser (IR-FEL) and a terahertz (THz) research programme. Due to its low energy design, space-charge forces play an important role in the beam evolution throughout the ALICE accelerator. This complicates the simulation and measurement of beam parameters on the machine. The use of specialised codes is required throughout the simulation chain.

INJECTOR

The extremely low electron energy at the exit of the DC photo-cathode gun along with the long transport line to the 1st SC booster means that simulation of the electron beam evolution in this area of the machine is both challenging as well as important for the determination of beam properties in the rest of the machine. Initial studies of the ALICE injector were performed in the ASTRA code [2], but have recently also been performed with the code GPT [3]. Comparisons between the two codes are excellent, and differences are mostly due to imperfect transformation of parameters between the two codes. As has been reported previously [4], the strong space-charge dominated beam properties, especially at lower gun voltages of 230 keV and 60 pC bunch charges, leads to longitudinal irregularities in the beam. Evidence of this can be seen in the ASTRA simulations of the ALICE injector.

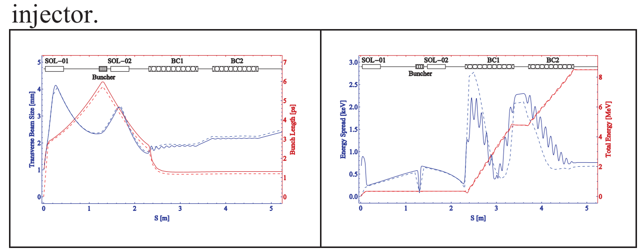

Figure 1: Comparison between ATSRA (solid) and GPT (dashed) for a 60 pC electron bunch in the ALICE injector.

Upon exiting the second SC booster cavity, the beam is at an energy of 6.5 MeV. Initial design work on ALICE had modelled the, then 8.35 MeV, beam using the MAD code [5], and it was assumed that space-charge would not be an issue at the assumed bunch charge of 80 pC. With the lowered operating energy of 6.5 MeV, space-charge is now assumed to still be relevant. Due to the relative simplicity of including dipole elements into the GPT simulations, the rest of the injector has only been adequately modelled in this code. Approximations without dipoles have previously been performed in ASTRA.

MAIN LOOP

The beam from the injector is accelerated in two SC linac cavities to a nominal working energy of 26 MeV. It is then passed through an isochronous TBA arc design, before being compressed in a 4-dipole chicane. The IR-FEL is situated almost immediately after this chicane. After the FEL, the beam is transported through a second decompressing arc, before being decelerated in the SC linac modules. The initial design of ALICE post-linacs was originally performed in MAD, again assuming that the space-charge forces could be neglected at the original design energy of 35 MeV. However, experimental results have shown that there are still noticeable space-charge effects on the electron beam in the post-linac beam transport at the lower running energy of 26 MeV. Simulations of the bunch compression mechanism with realistic bunches was also felt to be important. For this reason the entire main loop was simulated in the GPT code. This allowed for simple link up between the injector and main loop simulations, and allowed for both space-charge forces to be included as well as the modelling of realistic RF fields in the main linacs. An example full space-charge simulation, at 60 pC, comparing the

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longitudinal properties of the electron bunch for various linac phases is shown in Fig. 2.

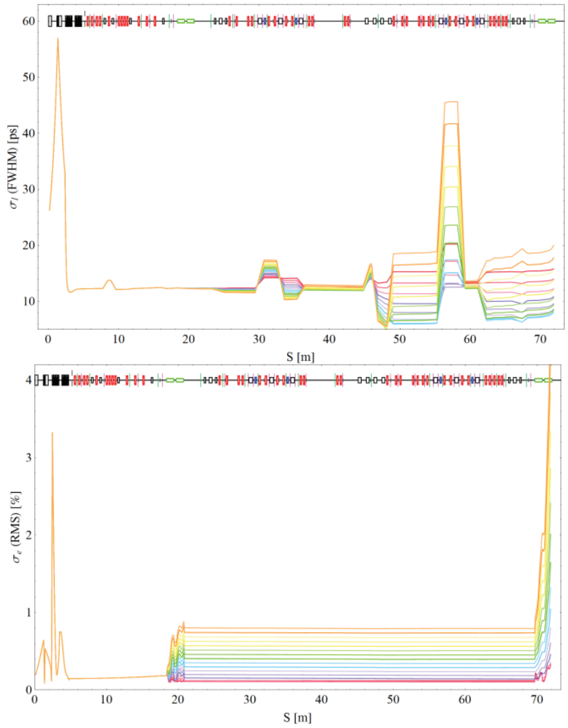

Figure 2: Longitudinal properties of the ALICE machine for various linac off-crest phases from 0° (Red) through 8° (green) to +16° (Orange), and at a 60 pC bunch charge.

FULL MACHINE SIMULATIONS

Effect of the FEL on Energy Recovery

Simulations have been performed of the effects on energy recovery of the FEL process. In this case we model the FEL as a separate process outside of GPT.

The FEL interaction is modelled by solving the scaled 1D FEL equations for the electron's change in energy and longitudinal position (see e.g. [6]):

$$\frac{d\theta_j}{d\bar{z}} = p_j; \frac{dp_j}{d\bar{z}} = Aexp(i\theta_j) + A^* exp(-i\theta_j)$$

Where p_j is the normalised particle momentum of the jth electron, θ_j is the particle phase in terms of the FEL wavelength (assumed to be 8μm) and A is the scaled complex radiation field amplitude, and is assumed not to vary here (valid for low gain FELs). Simulations of the beam effect due to the FEL process are shown in Figure 3, with the scaled phase space for one wavelength (8μm) of the full bunch. The nominal bunch length is ~40 wavelengths in total. The scaled momentum has an offset of $2.6/\bar{z}$ ($\bar{z} = 1.05$), corresponding to optimum FEL detuning, and with a radiation amplitude of $\sqrt{40}$. This roughly corresponds with the expected situation with the FEL at saturation.

We compare the change in machine length (expressed as an equivalent RF phase difference between the accelerating and decelerating linac passes), with and without the FEL process, required to minimise the energy spread at the exit of the return linacs. As the relative phase is changed, the dumped beam energy also varies, and thus we show both the relative and absolute energy spreads. The results show that as the FEL "power" is increased, the minimum energy spread occurs at greater phase offsets in the return linacs.

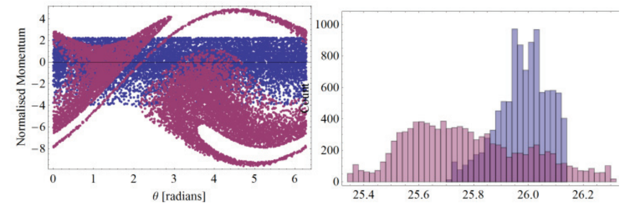

Figure 3: Normalised Phase space pre- (Blue) and post- (Purple) FEL for one 8μm wavelength bunchlet (left) and the resulting change in bunch energy spread for the entire bunch (right).

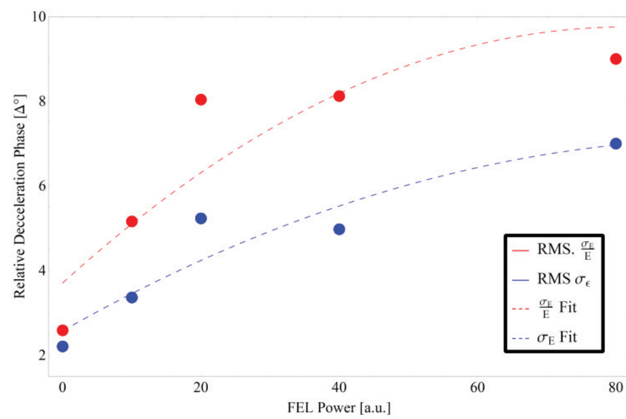

Figure 4: Variation in optimal return linac relative phase vs. increasing FEL induced energy spread.

The phase space distributions for the optimal relative phase, and for several FEL powers, are illustrated in Fig. 5.

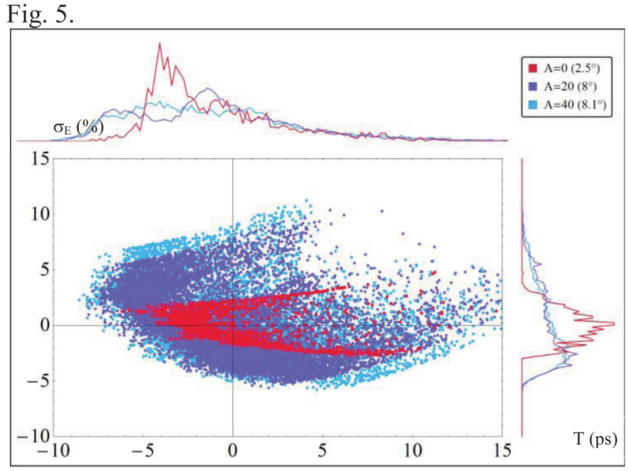

Figure 5: Bunch length (ps) vs. relative energy spread (%) distributions, after the return linac deceleration, for 3 different FEL powers.

Simulating 2-loop Mode

The possibility of running ALICE in a proof-of-principle 2-loop mode has been discussed. Here we present simulations of the ALICE ERL running the main linac cavities at phases such that the beam exercises 2-loops before being decelerated to the injection energy of 6.5MeV and then dumped. The biggest impediment to running on the real machine is the energy spread induced in the 2^{nd} pass through the linac cavities. With an "optimal" tuning of the machine, the energy spread increases from ~35 keV (~0.1%) to ~220 keV (~1%), and drives large beam-sizes in the 2 arcs of the machine, as well as the bunch compression chicane. Reducing the energy spread increase through careful tuning of the booster and linac phases, see Table 1, leads to a non-optimal chirp on the bunch during the 2^{nd} pass, which in turn leads to a bunch length increase at the nominal FEL position from ~7 ps (FWHM) to ~20 ps.

Table 1: Machine Properties for a 2-loop ALICE ERL

Machine Property	Value
BC1 Phase	-3°
BC2 Phase	+34°
LC1/2 Phase	+1°
ARC-1 Extension	+13.75mm

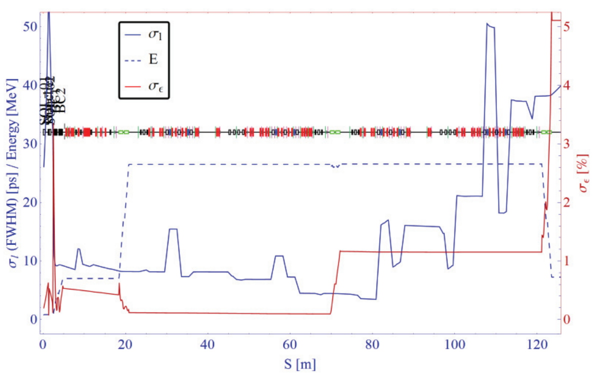

Figure 6: Longitudinal beam properties for 2-loop ALICE ERL at 60 pC.

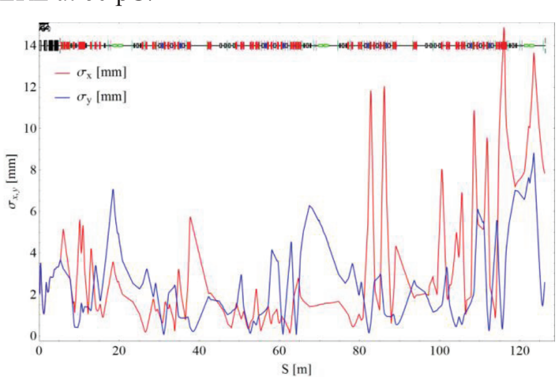

Figure 7: Transverse beam properties for the 2-loop ALICE ERL at 60 pC.

The averaged transverse and longitudinal properties around the 2-loop ERL are shown in Fig. 6 and Fig. 7 respectively. In Fig. 8 we show the longitudinal phase space at the exit of the linac cavities on each of the 3-transits. The significant chirp on the bunch at the beginning of the second pass is clear, which leads to a strong over-compression in the bunch compressor. Variation of the bunch compression chicane is not currently possible.

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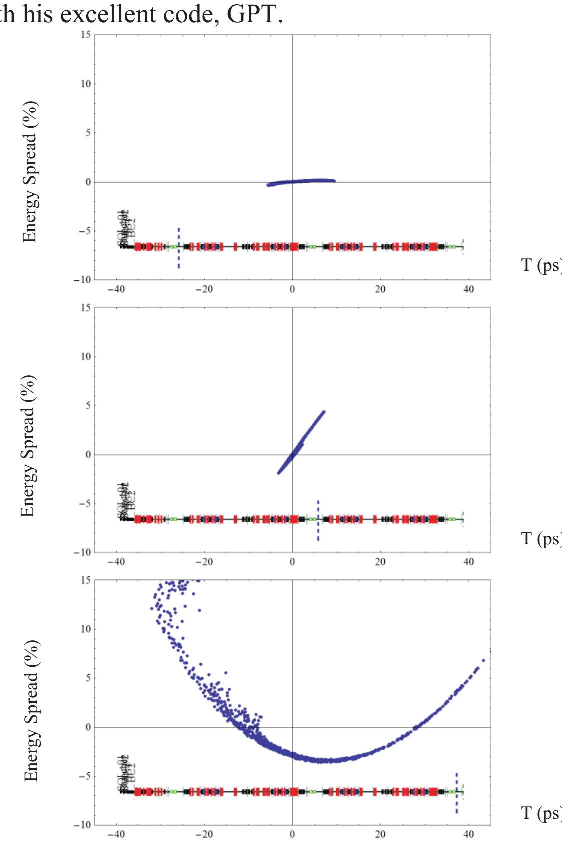

Figure 8: Longitudinal phase space at the exit of the 2^{nd} linac cavity for each of the 3-passes at 60 pC.

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