ALICE (ERLP) INJECTOR DESIGN

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Abstract

In this paper we look at how the ALICE (formerly ERLP) injector has been re-designed to meet more realistic criteria from the previous design. A key component of ALICE is the high brightness injector. The ALICE injector consists of a DC photocathode gun generating 80 pC electron bunches at 350 keV. These bunches are then matched into a booster cavity which accelerates them to an energy of 8.35 MeV. In order to do this, two solenoids and a single-cell buncher cavity are used, together with off-crest injection into the first booster cavity, where the beam is still far from being relativistic. The performance of the injector has been studied using the particle tracking code ASTRA.

INTRODUCTION

The injector for the Daresbury Energy Recovery Linac, now called ALICE, was designed some time ago [1], however, due to certain space and aperture constraints, a redesign was required. Another influence was a better knowledge of the laser spot size on the cathode and this precise aspect is dealt with in [2] in more detail.

The injector must be capable of producing a high bunch charge beam with a small transverse and longitudinal emittance at the same time. In the low energy part of the injector, electrons have an energy of 350 keV after emission and so space charge is a very important effect. In order to take this into account, modelling must be performed with multi-particle tracking codes. The code ASTRA [3] has been used for the modelling from the cathode to the exit of the booster for various parameter settings. Tracking with space charge from the booster to the main linac was already studied in [4].

The emphasis of this paper will be on practical and achievable parameters - the aim being to have a set of parameters which can be subsequently perfected through diagnostic measurements rather than a set of ideal parameters which are unlikely ever to be reached.

We also attempted to use a logical approach to injector optimisation as opposed to a 'mechanistic' method of finding an optimum through numerous parameter variations. This should give a better physical insight together with the possibility to make practical compromises whenever needed.

INJECTOR DESCRIPTION

The layout of the ALICE injector is identical to that shown in [1]. The gun used is almost identical to the DC photocathode gun [5] used at the Jefferson Lab IR-Demo FEL. The gun is operated with a negative electron affinity GaAs photocathode, illuminated by frequency-doubled light (532 nm) from a mode-locked $\mathrm{Nd:YVO_4}$ laser with an oscillator frequency of 81.25 MHz. The emitted electrons are then accelerated to a kinetic energy of 350 keV. A solenoid is attached to the gun exit, with the centre at 23.6 cm downstream of the cathode, for emittance compensation. A single-cell, normal-conducting buncher cavity is then used for velocity bunching of the bunch before it enters the booster. The buncher is operated at the fundamental frequency of 1.3 GHz and located at $z = 1.3$ m. The buncher is followed by a viewer with a YAG screen and followed by a second solenoid located at $z = 1.67$ m to focus the bunch at the entrance of the booster.

The booster consists of two super-conducting 9-cell TESLA-type cavities operated at 1.3 GHz. Bunches are accelerated to an energy of 8.35 MeV and subsequently transported by a transfer line to the main ALICE linac where the beam is further accelerated to its nominal energy of 35 MeV.

INJECTOR MODELLING

Because all distances had been already determined, the parameters which could be varied were restricted to both solenoids and the first and second booster cavity injection phases. The buncher gradient could also be varied, but this tends to affect only the final bunch length, however, variations of this were also examined. A script was written to make an initial exploration of the entire parameter space and then, once the most promising area had been identified, the surrounding solution space was examined. The constraints imposed were a good transverse and longitudinal emittance as well as an acceptable energy spread and reasonable Twiss parameters at the beginning of the transfer line to the main ALICE linac. A critical requirement was to have a minimum beam size at the buncher, despite the fact that this would not help the transverse emittance, so as to avoid aperture problems. The initial modelling was done with 1000 macro-particles and for the final runs, this was increased to $10,000$.

The electron bunch properties at the cathode are determined mainly by the cathode laser parameters. The response behaviour of GaAs is not easy to model, however, experimentally it was found that the bunch length leaving the cathode is roughly 28 ps, indeed this was further found to be closer to a double peak as modelled in [2], but shall be taken to be temporally uniform for the purposes of this article. The laser spot size was measured at a 4 mm FWHM, corresponding to an rms beam size of 1 mm.

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To have adequate focusing into the buncher, initial scans of the first section of the injector line, up to the second solenoid, showed that the first solenoid should be set at around 330 G. This left three main parameters to be varied, namely the strength of the second solenoid and the injection phases of the two cavities in the booster. These three parameters were looked at and only the best cases are shown here. Because one of the requirements was to avoid an excessively large energy spread, the cavity injection phases were set in the range of -15° to 15° and were varied in 5° steps resulting in $7 \times 7 = 49$ separate runs. Further, it rapidly became apparent that the second solenoid should be set at around 230 G so only three separate settings for this were considered, those of $220, 230$ and 240 G. Similarly, in order to have the desired bunch length by the time one reaches the booster, it can be shown analytically that the buncher should be set at around 2 MV/m, therefore, different settings were looked at ranging from 1.6 MV/m to 2.2 MV/m. A plot of a scaled version of all the six main parameters at the exit of the booster was then made versus run number in sets of 49 each and the best case is shown in Fig. 1 below. Now, from Fig. 1, it is easy to see which run is the most favourable. However, this has to be balanced against existing aperture restrictions in the injector line after the booster. Here it was found difficult to find an easy match which kept the transverse beam size at a reasonable value throughout the remainder of the lattice if the Twiss parameters, $\beta_{x,y}$ and $\alpha_{x,y}$ were below and above the bounds of 60 m and -6, respectively as can be seen from Fig. 1. This restricts the runs shown to those on the right hand side of the graph. Here the trade-off between a good transverse emittance and beam size, and a good longitudinal emittance and energy spread, can clearly be seen. Therefore, the best settings given the constraints can be quickly found and are summarised in Table 1 below. The main parameters are illustrated in the remaining figures below. Fig. 2 shows the transverse emittance whereas Fig. 3 shows the longitudinal. Fig. 4 shows the transverse beam size and bunch length and the energy spread at the exit of the booster is given in Fig. 5 together with its spectrum in Fig. 6. The achieved design parameters at the exit of the booster are summarised in Table 2. These parameters should ensure good operation of the ALICE injector and are considerably better than those required for lasing in the FEL.

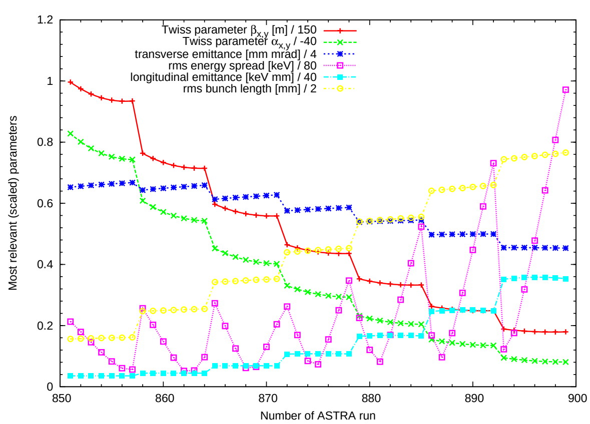

Figure 1: Multi-parameter plot at the exit of the booster.

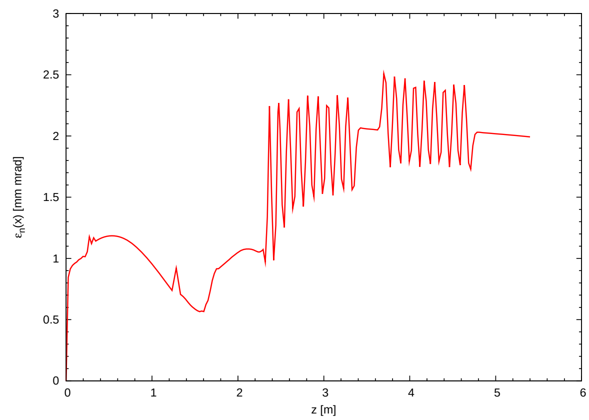

Figure 2: Transverse emittance.

CONCLUSIONS

From the ASTRA models it can be seen that the injector layout together with the settings summarised in Table 2 should be capable of delivering the required beam parameters for ALICE operation. The most problematic part in the injector modelling was the matching into the first booster cavity when the beam is still far from being relativistic. This is because the first cell actually decelerates the beam slightly.

Further modelling, which includes an estimate of thermal emittance also needs to be done as this has, so far, been neglected, and also for a possible extended injector line. This line would include space for a special diagnostic line consisting of a transverse kicker, a dipole and a YAG

Table 1: Main ALICE injector parameters.

Parameter	Units	Value
Laser spot size	mm	4.0
Laser pulse length	ps	28
Bunch charge	pC	80
Gun voltage	kV	350
1^{st} Solenoid	G	330
Buncher gradient	MV/m	2.2
Buncher phase	deg.	-90
2^{nd} Solenoid	G	230
1^{st} Cavity gradient	MV/m	9.0
1^{st} Cavity phase	deg.	10
2^{nd} Cavity gradient	MV/m	7.0
2^{nd} Cavity phase	deg.	-10

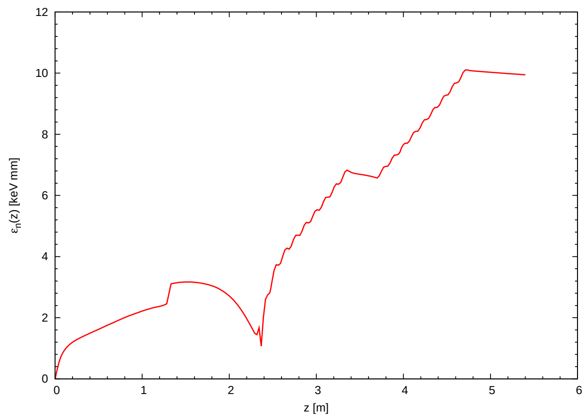

Figure 3: Longitudinal emittance.

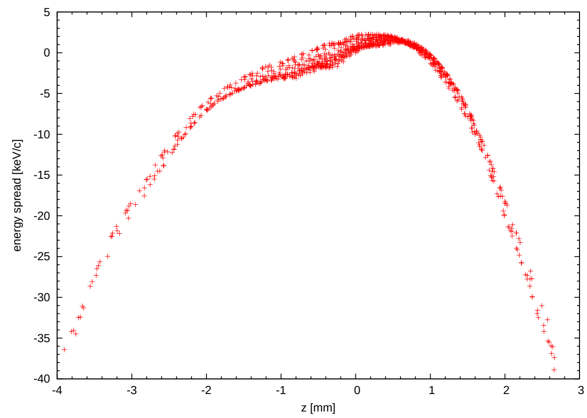

Figure 5: Energy spread at booster exit.

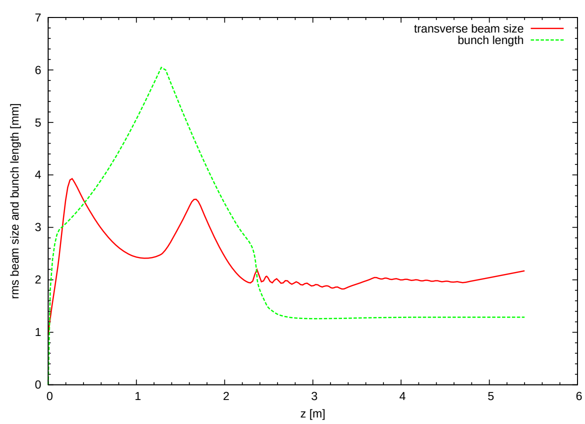

Figure 4: Beam size (x, y) and bunch length at the exit of the booster

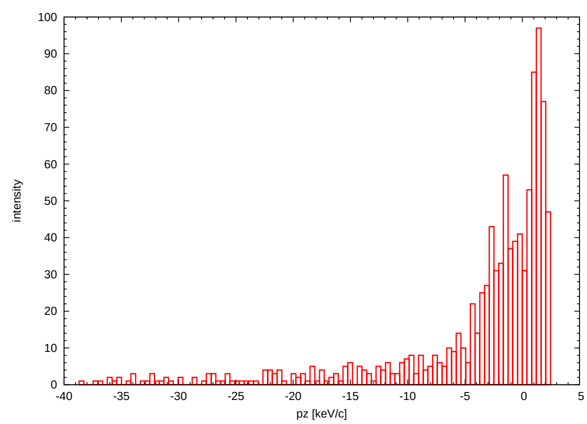

Figure 6: Spectrum at booster exit.

screen. While this diagnostic line did indeed exist, it has had to be taken out to make room for the booster.

A separate model also needs to be looked at so as to be able to tune ALICE as an injector for the non-scaling FFAG, EMMA [6, 7], which shall run at energies of 10 to 20 MeV.

Table 2: Design parameters at the exit of the booster.

Parameter	Units	Value
Transverse beam size	mm	2.2
Transverse divergence	mrad	0.4
Transverse emittance	mm mrad	2.0
Bunch length	mm	1.3
Energy spread (rms)	keV	7.7
Longitudinal emittance	keV mm	10
$\beta_{x,y}$	m	39
$\alpha_{x,y}$		-5.9

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