INJECTOR DESIGN FOR THE 4GLS ENERGY RECOVERY LINAC PROTOTYPE

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Abstract

Daresbury Laboratory has been given funding for the construction of an Energy Recovery Linac Prototype (ERLP) that operates at an electron beam energy of up to 35 MeV and drives an infra-red FEL. The ERLP serves as a test-bed for the study of beam dynamics and accelerator technology important for the design and construction of the proposed 4th Generation Light Source (4GLS). A key component of the ERLP is the high-brightness injector. The injector consists of a DC photocathode gun, a single-cell buncher cavity, a super-conducting booster and a transfer line to the main linac. In this paper, the design of the ERLP injector from the DC photocathode gun to the exit of the booster is discussed. The performance of the injector has been studied using the particle tracking code ASTRA.

INTRODUCTION

There is growing interest in the development of free-electron laser (FEL) and synchrotron radiation facilities based on the Energy Recovery Linac concept. However, before the construction of a full-scale facility can be considered many accelerator physics issues need to be studied and resolved. Daresbury Laboratory has been given funding to build an Energy Recovery Linac Prototype (ERLP) [1] which will operate at a beam energy of 35 MeV and drive an infra-red oscillator FEL. The performance of the FEL will depend crucially on the electron beam properties from the injector and the transport of the electron beam to the FEL.

The injector must be capable of producing a high-average current beam with a small transverse and longitudinal emittance at the same time. In the low energy section of the injector (350 keV) the effect of space charge on the beam dynamics cannot be neglected and, hence, this section can only be modelled accurately with multi-particle tracking codes that include space charge effects. The code ASTRA [2] has been used for the modelling of the ERLP injector from the cathode to the exit of the booster for various parameter settings. Emittance degradation in the transfer line from the booster to the main linac due to space charge effects has been studied in Ref. [3].

INJECTOR LAYOUT

The layout of the ERLP injector is shown in Fig. 1. A replica of the DC photocathode gun [4] used at the Jefferson Lab IR-Demo FEL is currently being built at Daresbury Laboratory. The gun will be operated with a negative electron affinity GaAs photocathode which will be illuminated by frequency-doubled light (532 nm) from a mode-locked $Nd{:}YVO_4$ laser with an oscillator frequency of 81.25 MHz. The emitted electrons will be accelerated to a kinetic energy of 350 keV in the gun.

A large-bore solenoid is attached to the gun exit with the centre located 23.6 cm downstream of the cathode. The solenoid is followed by an RF shielded valve, a light box for steering the cathode laser beam onto the cathode, an electron beam position monitor, steerers and a pumping unit.

A single-cell, normal-conducting buncher cavity is then employed for velocity bunching before the electrons enter the booster. The buncher is operated at the fundamental linac frequency of 1.3 GHz and located at z = 1.3 m. Three different buncher designs were investigated [5] and the buncher design employed at the ELBE facility was found to be the most promising in terms of RF power requirements and manufacturing simplicity. The buncher is followed by a viewer, equipped with a YAG screen, and a second solenoid, which is located at z = 1.67 m and used to focus the beam at the entrance of the booster.

The booster consists of two super-conducting 9-cell TESLA-type cavities operated at 1.3 GHz. The cryomodule design is based on the design of the ELBE linac [6] at the Forschungszentrum Rossendorf. The electron bunches are accelerated to an energy of 8.35 MeV and then transported by a transfer line containing 4 dipole magnets to the straight of the main linac and merged with the full energy (35 MeV) single-pass recirculated beam.

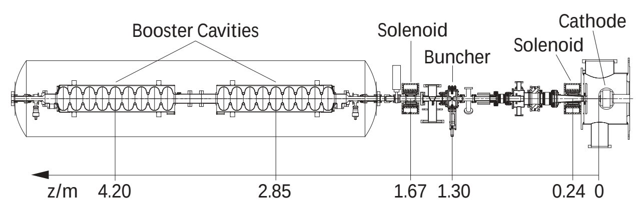

Figure 1: Layout of the ERLP injector.

INJECTOR MODELLING

The photocathode gun, the two solenoids, the buncher and the two 9-cell TESLA-type cavities were included in the beam modelling with ASTRA. The on-axis field distributions of these components generated by either POISSON or CSTs Microwave Studio have been used as input files for ASTRA. The placing of the components has been broadly

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optimised in terms of beam dynamics but was constrained by the necessity of inserting other equipment (steerers, diagnostics, vacuum ports, etc.); the overall philosophy was to keep the distance from the gun to the booster as short as possible. The operating parameters of the injector components have been optimised in order to achieve small transverse and longitudinal emittances, reasonable Twiss parameters at the beginning of the transfer line, and to preserve a linear energy chirp along the bunch which is required for magnetic bunch compression. The aim was to demonstrate a modelled performance significantly better than the required parameters needed for ERLP operation. Initially, 5000 macro particles were used to scan the parameter space and the final modelling was made with 10^5 particles.

The electron bunch properties at the cathode are determined mainly by the cathode laser parameters. However, GaAs will normally dominate the bunch length for very short laser pulses, as it has a rather long decay time due to the absorption and diffusion lengths in GaAs [7]. The response behaviour of GaAs is not easy to model and only a very limited amount of experimental data is available. A longitudinal Gaussian distribution with an rms length of 20 ps has been assumed for the beam modelling. Refractive optics in the laser beam path will be used to produce a near flat top transverse distribution at the cathode. For the ASTRA simulations, a flat top transverse beam profile was chosen which is ideal in terms of space charge effects and yields the smallest emittances. The diameter of the laser spot size at the cathode was varied between 4 and 5 mm which corresponds to a rms beam size of 1.0 and 1.25 mm, respectively.

Table 1: Injector parameters used in ASTRA.

Parameter	Unit	Case 1	Case2
Laser spot size	mm	4.0	5.0
Laser pulse length	ps	20	20
Bunch charge	pC	80	80
Gun voltage	kV	350	350
1^{st} Solenoid	G	300	292
Buncher	MV/m	1.75	1.76
Phase	deg	-90	-90
2^{nd} Solenoid	G	210	210
1^{st} Cavity	MV/m	9.0	9.0
Phase	deg	20	20
2^{nd} Cavity	MV/m	7.0	7.0
Phase	deg	-30	-30

The evolution of the rms values of the beam size, transverse normalised emittance, bunch length and longitudinal emittance is shown in Fig. 2 for laser spot sizes of 4 and 5 mm, and the corresponding operating parameters are summarised in Table 1. It can be seen that a difference in the laser spot size can be compensated by a slight adjustment of the operating parameters. At the beginning of the transfer line (end of tracking), a normalised transverse emittance of $1.4\ \mu$m, a normalised longitudinal

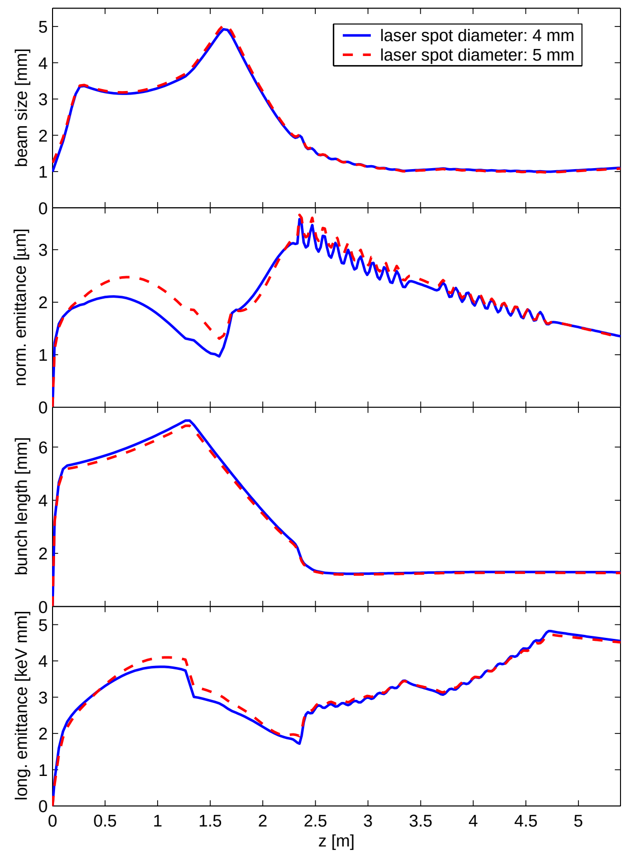

Figure 2: Evolution of the rms values of the transverse beam size, normalized emittance, bunch length and longitudinal emittance.

emittance of 4.5 keV mm and a bunch length of 1.2 mm (4 ps) is predicted. The corresponding Twiss parameters are $\alpha_x, \alpha_y \simeq -2$ and $\beta_x, \beta_y \simeq 15$ m, for which a matching solution for the transfer line is straight forward [8].

The buncher phase was set to zero-crossing phase ($-90°$) to keep non-linearities induced by the sinusoidal shape of the RF to a minimum. It has been found from the simulations that it is advantageous to locate the second solenoid as close as possible to the booster. However, the minimum distance between the centre of the second solenoid and the centre of the first cell of the first TESLA cavity is restricted to 0.75 m due to physical constraints (cryostat, bellows, valve, etc.).

Matching into the booster was found to be the most critical part of the injector – especially at 350 keV where the beam energy is not relativistic – as the TESLA cavities are not β-matched. As β is 0.8 at 350 keV, the electrons slip back with respect to the RF phase. This leads to the counter-intuitive situation where the beam is slightly decelerated in the first cell of the first TESLA-type cavity at optimum phase.

The electron beam from the injector has to be merged with the recirculated beam in the straight upstream of the main linac. The range of injection energies is defined by

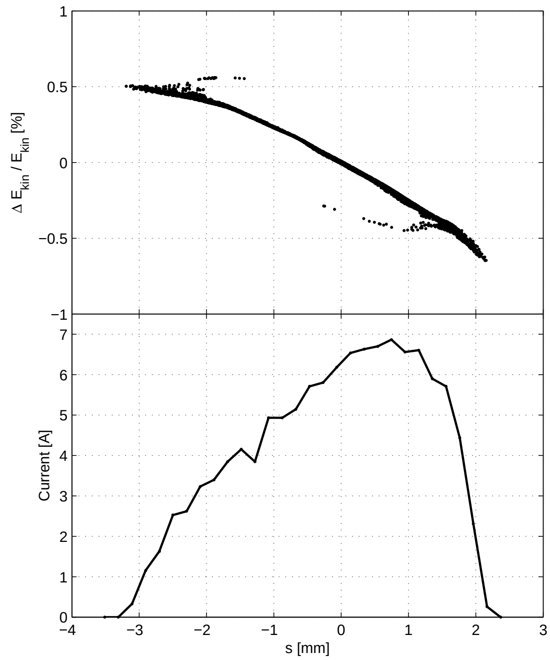

Figure 3: Longitudinal phase space distribution and profile at z = 5.4 m (cf. case 1 in Table 1).

the injection angle and the energy of the recirculated beam. The gradients of both booster cavities were set to give a beam energy of 8.35 MeV at the exit of the booster. As the electrons have relativistic energies downstream of the first cavity, the second cavity has no influence on the bunch length but can be used to introduce an energy chirp. The longitudinal phase space distribution at the beginning of the transfer line (z = 5.4 m) is shown in Fig. 3 (case 1 in Table 1).

As the initial bunch length from the cathode cannot be predicted precisely the beam dynamics have been studied for initial bunch lengths of 15, 20 and 25 ps. The results are shown in Fig. 4. As can be seen, similar beam parameters can be produced at the end of the tracking by adjusting the operating parameters. The phase space distributions are also very similar to that shown in Fig. 3.

SUMMARY AND OUTLOOK

From the ASTRA simulations it can be concluded that the injector layout is capable of delivering the required beam parameters for ERLP operation. The most critical part of the injector design is the matching into the first booster cavity. A booster for non-relativistic beam energies would favour a series of short cavities with independently adjustable phases [9] instead of one long 9-cell cavity with one fixed phase for all cells. This would improve the adjustability of the longitudinal phase space.

As the initial bunch length from the cathode is the least known parameter in the modelling we intend to measure the bunch length with a transverse deflecting cavity during commissioning of the ERLP injector.

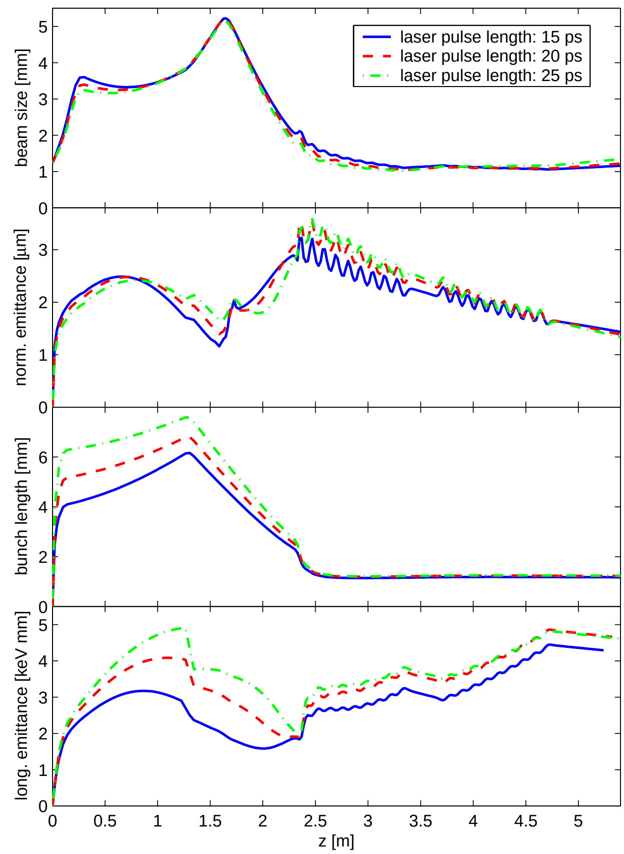

Figure 4: Evolution of the rms values of the transverse beam size, normalized emittance, bunch length and longitudinal emittance for different laser pulse lengths.

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