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OPTIMIZATION OF THE PERLE INJECTOR

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Abstract

The injector for PERLE, a proposed electron Energy Recovery Linac (ERL) test facility for the LHeC and FCC-eh projects, is intended to deliver 500 pC bunches at a repetition rate of 40.1 MHz for a total beam current of 20 mA. These bunches must have a bunch length of 3 mm rms and an energy of 7 MeV at the entrance to the first linac pass while simultaneously achieving a transverse emittance of less than 6 mm·mrad. The injector is based around a DC photocathode electron gun, followed by a focusing and normal conducting bunching section, a booster with 5 independently controllable SRF cavities and a merger into the main ERL. A design for this injector from the photocathode to the exit of the booster is presented. This design was simulated using ASTRA for the beam dynamics simulations and optimized using the many objective optimization algorithm NSGAIII. The use of NSGAIII allows more than three beam parameters to be optimised simultaneously and the trade-offs between them to be explored.

INTRODUCTION

PERLE is a proposed three turn 500 MeV ERL intended as a test facility for the FCC-eh/LHeC projects [1]. The bunch repetition rate of PERLE is 40.1 MHz which means that to achieve an average beam current of 20 mA a bunch charge of 500 pC is required. The specification of PERLE requires also a transverse emittance of less than 6 mm·mrad at a bunch length of 3 mm to be delivered from the injector to the main ERL loop. The specifications of the PERLE injector are summarised in Table 1.

Table 1: A Summary of the Specification for the Bunch Properties Delivered from the PERLE Injector

Beam parameter	Required value
Bunch charge, pC	500
Bunch repetition rate, MHz	40.1
Average beam current, mA	20
RMS normalised transverse emittance mm·mrad	< 6
RMS bunch length, mm	3
Beam energy, MeV	7
Uncorrelated energy spread, keV	< 10
Operation mode	CW

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The requirement of a CW operation mode and beam parameters of the injector means that there are three possible options for the electron source: a high voltage DC electron gun, an SRF CW gun or a VHF CW gun. The gun should operate with photocathode illuminated with laser light which is the only way of providing beams with the required time structure at the required quality.

The majority of pre-existing ERL projects have used DC gun based injectors. The possible operation mode with polarised electrons of PERLE would require a GaAs based photocathode. This kind of photocathode is extremely sensitive to the vacuum conditions and at the moment only DC guns are capable of achieving the vacuum quality required. Such a gun was used as electron source of ALICE ERL test facility at Daresbury Laboratory, UK [2]. In addition it has been experimentally demonstrated at Cornell University that DC gun based injectors can deliver bunches with bunch charges higher than the nominal value for PERLE and transverse emittances lower than required for the PERLE specification [3]. The history of successful use of DC electron guns on ERL projects, the possibilty of re-using the ALICE electron gun, the fact that they are the only technology which can provide polarised electron beams and their experimentally demonstrated performance at high bunch charges are all factors in why the injector for PERLE will be based on a DC electron gun.

INJECTOR LAYOUT

The PERLE injector follows the proven layout comprising of a 350 kV high voltage electron gun, focusing solenoid, a normal conducting buncher cavity, solenoid and then a superconducting booster linac. The booster linac consists of 5 SRF cavities with independently controllable phases and amplitudes. A sketch of the layout can been seen in Fig. 1.

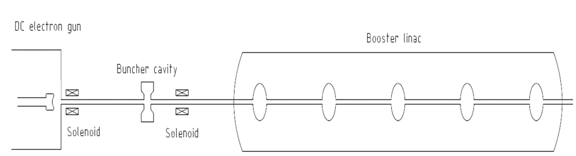

Figure 1: The layout of the PERLE injector.

The electron gun used for the PERLE injector will be an upgraded and modified ALICE electron gun operating with an antimonide based photocathode such as Cs_3Sb. The majority of the upgrade will be identical to that designed for ALICE itself [4]. However the electrode system has to

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be changed as much higher bunch charge is required. The geometry of the electrodes was obtained using a many objective optimization to minimise slice emittance and beam size at the position of the second solenoid and is a compromise design between 500 pC unpolarised operation at 350 kV and a 500 pC polarised operation at 220 kV [5]. To allow for the potential for an upgrade for polarised operation which would require operation at the lower gun voltage of 220 kV

The significant space charge forces of the 500 pC bunch cause a rapid increase in the bunch length shortly after emission. This means that irrespective of the initial laser pulse duration the bunch length at the buncher is long enough that RF induced non-linearities in the longitudinal phase space at the exit of the buncher are a concern. To mitigate this potential issue a 401 MHz subharmonic buncher is going to be used.

The booster comprises 802 MHz single cell cavities and their phases and amplitudes can be individually controlled. This allows for fine adjustment of the bunching proccess in the first two cells as well as control of the final chirp on the bunch using the last cavity of the booster.

OPTIMIZATION PROCCEDURE

The design of the PERLE injector is an optimization problem with multiple objectives, multiple constraints and a significant number of variables. The use of multi-objective optimization algorithms to optimise DC gun based injector is common. An example of this being the optimization of the Cornell University injector [6]. Multiobjective genetic algorithms are used because there are multiple competing requirements on the injector, complex space charge dominated beam dynamics and a sufficently large number of variables to make finding the optimal solution by hand challenging.

The PERLE injector optimization procedure uses 19 variables which are summarised with their permitted ranges in Table 2. There needs to be some distance between the components to allow for the placement of components such as diagnositcs, vacuum pumps and the mirror box for delivery of the photoinjector laser light. The minimum distances required for this were estimated using the distances in the ALICE injector

Four constraints were used in the optimization, one inequality and three equality. The inequality constraint was that the rms transverse beam size which must be less than 6 mm at all points along the injector beamline to ensure that the beam will fit through all of the apertures in the injector. The bunch length specification of 3 mm and the final energy of 7 MeV were both handled as equality constraints rather than objectives as a specific value is required at the injection point and consequently trading off between these parameters and the objectives is not required. The bunch length and energy constraints were handled by transforming them into inequality constraints with a variable tolerance decreasing linearly with generation from an intial tolerance of ±55% to a final tolerance of ±5%. The constraint that particle count equals zero was treated as an inequality constraint that the

Table 2: The Variables in the Optimization of the PERLE Injector with Their Permitted Ranges

Variable	Range
Laser spot diameter, mm	4 – 10
Laser pulse duration, ps	1 – 160
1st solenoid field, T	0.01 – 0.05
1st solenoid and buncher additional distance, m	0 – 0.4
Buncher amplitude, MV/m	0.5 – 4.0
Buncher phase, °	-110 – -70
Buncher and 2nd solenoid additional distance, m	0 – 0.4
2nd solenoid setting, T	0.01 – 0.05
2nd solenoid and booster addtional distance, m	0 – 0.4
1st booster cell amplitude, MV/m	0 – 25
1st booster cell phase, °	-50 – 50
2nd booster cell amplitude, MV/m	0 – 25
2nd booster cell phase, °	-50 – 50
3rd booster cell amplitude, MV/m	0 – 25
3rd booster cell phase, °	-50 – 50
4th booster cell amplitude, MV/m	0 – 25
4th booster cell phase, °	-50– 50
5th booster cell amplitude, MV/m	0 – 25
5th booster cell phase, °	-50 – 50

number of particles lost must be less than one. A summary of the constraints used in the optimization can be seen in Table 3.

Table 3: The Constraints in the Optimization of the PERLE Injector

Constraints
RMS transverse beam size < 6 mm
Final RMS bunch length = 3 mm
Final energy = 7 MeV
Number of particles lost = 0

The optimization had five objectives which are summarized in Table 4. The cylindrical symmetry of the the injector was used to reduce the number of objectives as the transverse properties are the same in both the horizontal and vertical planes so only one of the planes needs to be considered. The first two objectives were the transverse and longitundinal emittance which serve as measures of the beam quality. The RMS energy spread factors in both the correlated and uncorrelated energy spread. The uncorrelated energy spread should be as low as possible. However the desired value of the correlated energy spread, which is essentially defined by the energy chirp which, in turn, depends on the merger and the longitudinal match of the main ERL loop. The correlated energy spread value required for these is not currently well defined. As the desired chirp is not known it was decided

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to try and achieve as small a correlated energy spread as possible. The motivation for this was to try and maximize the flexibility and have an injector which didn't have a tendency towards either positive or negative chirps and which consequently should be able to achieve as wide a range as possible of both postive and negative chirps by adjusting the last cavity of the booster.

The transverse and longitudinal halo parameters as defined in [7] are used as a means to quanitfy the bunch shape. This is done as it is desirable to avoid bunches with significant temporal tails. The halo parameter has the advantage of being defined in 2d phase space which gives a more complete veiw of the behaviour of the bunch distribution.

Table 4: The Objectives in the Optimization of the PERLE Injector - the objectives are all minimised at the booster exit

Objectives
RMS transverse normalized emittance
RMS longitundinal normalized emittance
RMS energy spread
Transverse halo parameter
Longtidunal halo parameter

The number of objectives in this optimization is greater than three which means that NSGAII is no longer a suitable optimization algorithm. Above three objectives the non-dominated sorting approach used begins to lose its ability to provide selection pressure towards more optimial solutions. Consequentially a specialist many objective optimization algorithm NSGAIII was chosen. an algorithm related to the NSGAII but which changes the selection process to improve the diversity preservation and aid the search process [8] [9]. NSGAIII was implemented using the python library DEAP (Distributed Evolutionary Algorithms in Python) [10]. The algorithim parameters chosen for the optimization were those used in the original NSGAIII paper with the exception of the reference points and population size. The reference points were created with two layers using the approach described in the paper the outer layer with p=4 and the inner layer with p=3 [8]. The population size was then set to 120. This optimization was run for 100 generations.

The injector was simulated using the accelerator code ASTRA [11]. The particle count was set to 4096 which is relatively low. The requirement for 12,000 individual ASTRA runs means that the particle count and space charge grid needed to be set as a compromise between accuracy and keeping the run time of the optimization reasonable. The intial thermal emittance of the bunch was determined using the FD_300 emission model and assuming a Cs_3Sb photocathode illuminated with a 532 nm laser.

OPTIMIZATION RESULTS

The result of the optimization is a 5d pareto front of equivalently optimal solutions. This front can be used to understand how the different objectives trade off against each other and what values of the objectives are achievable. The final solution can then be selected from the pareto front using this information. Two 2d projections of the pareto front have been plotted to show how two different objectives trade off against each other. The first of these shows how transverse and longitudinal emittance trade off against each other and can be seen in Fig. 2.

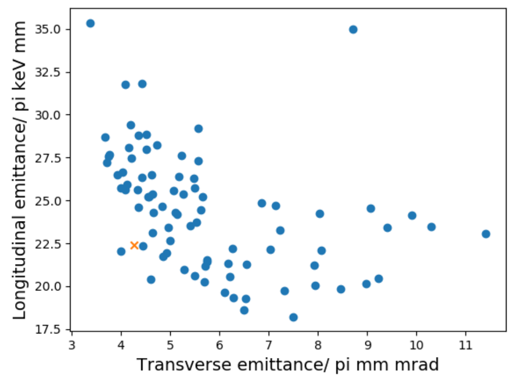

Figure 2: The 2d projection of the 5d pareto front showing how transverse emittance and longitudinal emittance trade off. The chosen solution is marked with an orange x.

The second plotted trade off shows the transverse emittance against the longitudinal halo parameter This can be seen in Fig. 3.

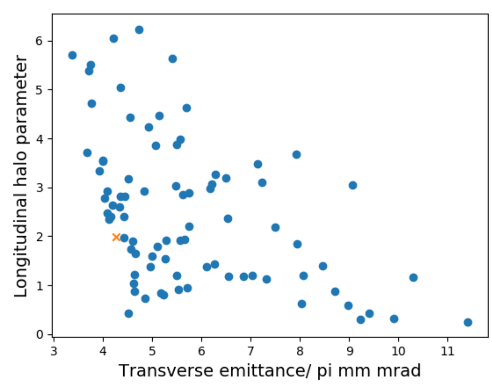

Figure 3: The 2d projection of the 5d pareto front showing how transverse emittance and longitudinal halo parameter trade off. The chosen solution is marked with an orange x.

The selected solution is not the lowest emittance solution in the pareto front. Instead the decision was made to sacrifice some performance in transverse emittance for improved longitudinal parameters. The lower transverse emittance solutions had significantly larger longitudinal halo parameters. This manifested itself in the form of significantly larger slice energy spread in the tail of the bunch. This could potentially cause problems with halo formation later in the ERL.

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CHOSEN SOLUTION

The chosen solution was adjusted by hand to achieve an exact final energy of 7 MeV and to minimise the correlated energy spread. It was then re-run at the higher particle count of 32768 to get a more accurate result.

The beam parameters at booster exit for the chosen solution can be seen in Table 5. These parameters in general meet the PERLE specification.

Table 5: The Parameters of the Chosen Solution after It Has Been Re-Run at Higher Particle Count

Parameters of the chosen solution	
RMS transverse normalized emittance, mm·mrad	4.0
RMS longitundinal normalized emittance, keV·mm	25.1
Bunch length, mm	3
Beam energy, MeV	7

The rms horizontal transverse beam size and the bunch length along the injector can be seen in Fig. 4.

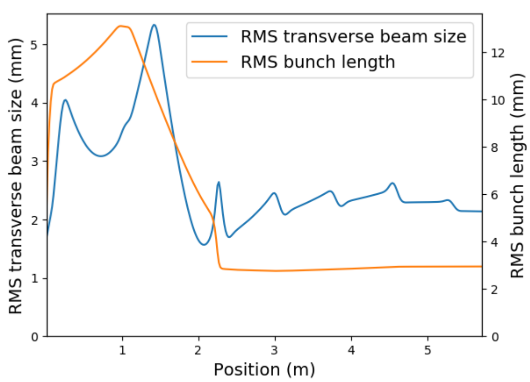

Figure 4: The variation of rms transverse beam size in blue and the rms bunch length in orange along the injector.

The transverse beam size is well controlled below the target value of 6 mm. The bunch length increases rapidly after emission due to the space charge but it never grows above the point where the 401 MHz buncher would introduce significant non-linearities. The bunching is primarly done by the buncher cavity but there is some bunching in the first cell of the booster. After that the bunch length is held constant at the target value of 3 mm rms.

The transverse and longitudinal emittances can be seen in Fig. 5. The transverse emittance is compensated down to a value of 4 mm·mrad at the booster exit which is below the required specification of less than 6 mm·mrad. This is greater than the thermal emittance indicating either imperfect compensation or some slice emittance growth.

The average bunch energy and rms energy spread can be seen in Fig. 6.

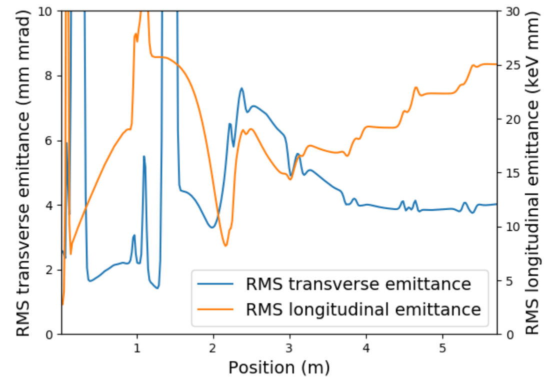

Figure 5: The variation of rms transverse normalized emittance in blue and the rms longitudinal emittance in orange along the injector.

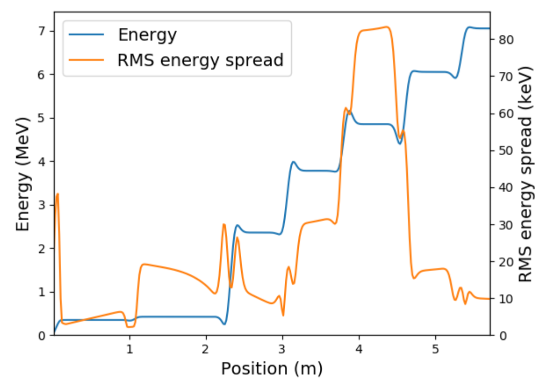

Figure 6: The variation of average beam energy in blue and the rms energy spread in orange along the injector.

The energy gain is most significant in the first booster cavity but after that is fairly consistent ending at the specified value of 7 MeV. The final cavity can be used to adjust the chirp on the beam which may important for the longitudinal match of the main ERL loop. However at present the requirements on the chirp of the injected bunch are not well defined.

The transverse phase space and bunch distributions in space and momentum can be seen in Fig. 7. From the transverse phase space it can be seen that in general the emittance is well compensated but that the tail is poorly compensated. The transverse bunch phase space may be considered as satisfactory.

The longitudinal phase space and longitundinal bunch distributions can be seen in Fig. 8. The longitundinal phase space is not as linear as would be desired. The biggest issues being at the head and tail of the bunch which is due to space charge effect at injection. Prior to the booster entrance there was a clear third order non-linearity due to space charge. The current longitudinal phase space shape began to emerge in the first cell of the booster.

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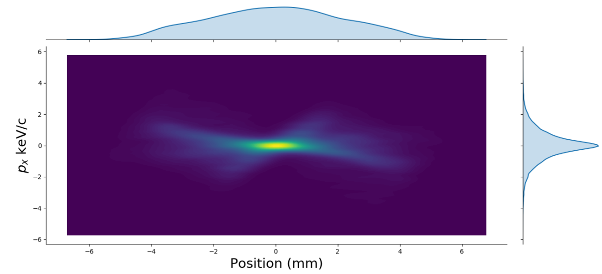

Figure 7: The transverse phase space at the exit of the booster. At the top is the bunch distribution in space while on the right is the distribution in momentum.

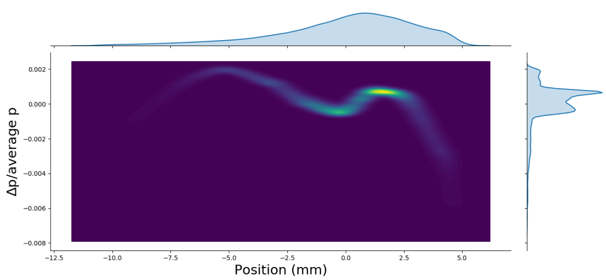

Figure 8: The longitudinal phase space at the exit of the booster. At the top is the bunch distribution in space while on the right is the distribution in momentum.

CONCLUSION

The chosen injector solution satisfies the PERLE specification at the booster exit. The longitundinal phase space may need to be improved and the possbility of linearization will be investigated. The next step towards a complete injector design is selection of the scheme and optimization of the merger. The beam dynamics will be investigated and optimised to the start of the first spreader section at the exit of the linac. Once a complete injector design has been obtained tolerance studies will need to be performed.

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