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OPTIMIZATION OF A HIGH BUNCH CHARGE ERL INJECTION MERGER FOR PERLE*

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Abstract

Delivery of high charge electron bunches into the main loop of an ERL (energy recovery linac) while preserving the emittance is challenging. This is because at the typical injection momentum, space charge forces still have a significant effect on the beam dynamics. In this work we consider the design of the merger for PERLE, an ERL test facility to be based at IJCLab in France. Previous simulations have shown that the baseline DC gun based injector can achieve the required emittance at the booster linac exit. The quality of the 500 pC bunches must then be preserved with space charge through the merger at total beam energy of 7 MeV keeping the emittance below 6 mm·mrad.

The beam dynamics in the merger were simulated using the code OPAL and optimised using a genetic algorithm. Three possible merger schemes were investigated. The goal of the optimisation was to minimise the emittance growth while also achieving the required Twiss parameters to match onto the spreader at the main linac exit. A three dipole solution is then examined in more detail.

PERLE AND THE PERLE INJECTOR

PERLE is a proposed 500 MeV 3 turn ERL which is foreseen to be hosted at IJCLab in Orsay [1]. The injector for PERLE must be capable of delivering 500 pC bunches, with a RMS bunch length of 3 mm, an emittance of less than 6 mm·mrad, at a repetition rate of 40.1 MHz to give an average current of 20 mA. Table 1 shows the requirements on the beam at the exit of the main linac after the first pass.

To achieve this low emittance with high average current a DC gun based injector will be used. This injector will consist of a 350 kV photocathode electron gun, a pair of solenoids for transverse beam size control and emittance compensation, a 801.58 MHz buncher cavity, a booster linac consisting of four single cell 801.58 MHz SRF cavities and a merger to transport the beam into the main ERL loop. The Twiss matching to the optics of the main ERL loop is also done in the merger. The layout of the injector with a possible merger example can be seen in Fig. 1. After the injection line is the main linac which consists of four five cell 801.58 MHz SRF cavities.

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Table 1: PERLE Merger Specification

Parameter	Values
Bunch charge	500 pC
Emittance	< 6 mm·mrad
Total injection energy	7 MeV/c
First arc energy	89 MeV
RMS bunch length	3 mm
Maximum RMS transverse beam size	6 mm
Twiss β at 1st main linac pass exit	8.6 m
Twiss α at 1st main linac pass exit	-0.66

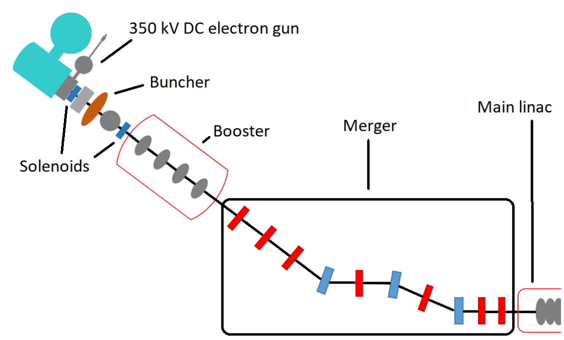

Figure 1: The layout of the injector with an example of a possible merger scheme.

SPACE CHARGE INDUCED EMITTANCE GROWTH IN MERGERS

The total beam energy in the merger is only at 7 MeV and the beam is consequently still space charge dominated. This presents the potential for significant emittance growth which must be mitigated. Three possible mechanisms by which this space charge induced degradation of the emittance can occur are:

- The variation of the space charge forces along the length of the bunch can cause emittance growth due to different transverse kicks. This can be counteracted by the process of emittance compensation [2]. However as focusing of the merger is not axially-symmetric the emittances in the vertical and horizontal planes will not necessarily be compensated at the same point.
- The space charges forces cause the longitudinal phase space of the bunch to vary as it passes through the

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merger. The head of the bunch gaining energy and the tail losing it. This can lead to imperfect cancellation of the effective dispersion leading to residual dispersion at the exit of the merger which can cause transverse emittance growth. Using the concept of generalised dispersion in some, but not all, merger schemes it is possible to restore the achromaticity of the merger [3].

- Non-linear space charge can also lead to a distortion of the phase spaces and hence emittance growth.

Some of these effects can in theory be cancelled out however doing so is challenging and it may in practice be easier to simply minimise their influence. These mechanisms also mean that the final emittances will likely be asymmetric between the transverse planes.

MERGER SCHEMES

Three different schemes are considered in this investigation. All of them use quadrupoles as their transverse focusing elements. The layouts of the schemes can be seen in Fig. 2.

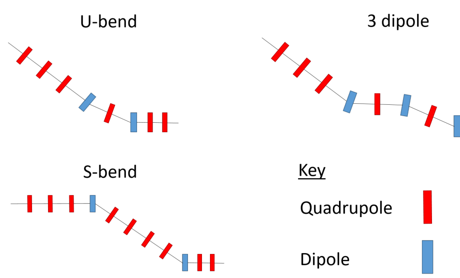

Figure 2: The merger schemes investigated in this proceeding.

The U-bend merger schemes is the minimal possible merger with the smallest number of elements. The 3 dipole scheme has been used on a number of previous ERL projects. The S-bend is the other two dipole scheme. Four quads are used here rather than three so that there are two variables for adjusting the dispersion.

OPTIMISATION PROCEDURE

The optimisation was done as a multi-step process from the cathode to the exit of the main linac. The steps of the optimisation process can be seen below. The first step was only done once and the results used for all three optimisations:

1. Gun to booster exit optimisation: This was done using OPAL [4] as the beam dynamics simulation code and the genetic algorithm NSGAII [5]. The genetic algorithm was implemented using the python library DEAP [6]. The objectives were to minimise the bunch length, transverse emittance and longitudinal emittance. The positions, solenoid strengths, buncher amplitude, booster cavity phases and all the booster cavity amplitudes except the final cavities were varied. The final booster cavity amplitude was set to get the desired output energy. The optimisation was run for 101 generations with a population size of 120 individuals. From the Pareto front a preferred solution was selected and its buncher amplitude adjusted by hand to give the correct final bunch length.

2. Space charge free merger optimisation: The output Twiss parameters at the booster exit, calculated on the basis of the first step, and the input Twiss parameters for the main linac known from OptiM were used to optimise a space charge free version of the merger using the beam dynamics code OptiM [7]. The quadrupole settings were varied in the optimisation. This was done using OptiM's inbuilt optimisation routines.

3. Cathode to main linac exit optimisation: The whole injector was then optimised with space charge using OPAL from the cathode to the end of first main linac pass, varying all the parameters varied in steps one and two. The genetic algorithm NSGAII was used. The objectives were to minimise the projected transverse emittance averaged between the two planes, the bunch length and the mismatch factor [8]. The definition of the mismatch factor can be seen in Eq. (1).

$$MMF = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta+4)}}{2}\right]^{1/2} - 1 \qquad (1)$$

Where $\Delta = \Delta\alpha^2 - \Delta\beta\Delta\gamma$ and $\Delta\alpha$, $\Delta\beta$ and $\Delta\gamma$ are the deviation of those Twiss parameters from the target matched Twiss parameters. The injector optimisation to the booster exit and the space charge free merger optimisation were used to seed the initial population of the genetic algorithm. This was done by having 40% of the initial population created with variable values close to the chosen solutions of the two previous optimisations. This biases the optimisation process towards an area of the parameter space which is known to be likely to give good solutions. The optimisation was also run for 101 generations with a population size of 120 individuals.

OPTIMISATION RESULTS

The Pareto fronts resulting from the optimisations can be seen in Fig. 3. The result of this particular optimisation seems to favour the 3 dipole scheme. However the quality of the solutions found here may be limited by the optimisation process rather than the physics of the different schemes. An example three dipole solution was chosen which provides the beam parameters shown in Table 2.

The transverse beam sizes can be seen in Fig. 4. They are currently kept below the target maximum value of 6 mm RMS. The Twiss parameter match at the end of the main linac will need to be improved.

The bunch length can be seen in Fig. 5. The majority of the bunching is done by the buncher cavity. The merger is not used as a bunch compressor.

The transverse emittances can be seen in Fig. 6. Both the the transverse emittances are within the specification. The emittance compensates down through the booster linac and then grows in the merger.

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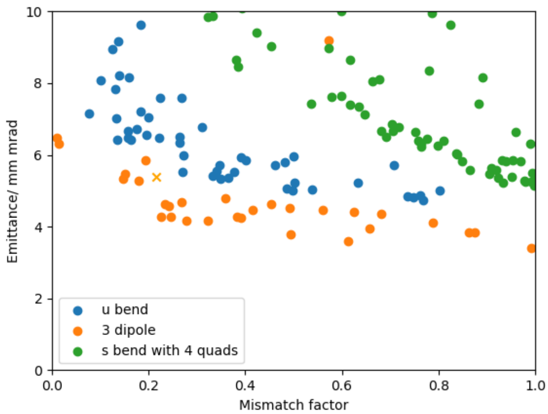

Figure 3: The Pareto fronts resulting from the optimisations. An example solution has been marked with an x. This is a 2D projection of the 3D Pareto front to show two of the variables. The bunch length is not shown. The front has been zoomed into the region of interest but extends beyond the bounds of the plot.

Table 2: Beam Properties at the End of the First Main Linac Pass for the Example Merger

Parameter	Values	Target values
Horizontal emittance ϵ_x	4.9 mm·mrad	<6 mm·mrad
Vertical emittance ϵ_y	5.8 mm·mrad	<6 mm·mrad
RMS bunch length	3.14 mm	3.0 mm
β_x/ β_y	6.93 m/ 6.48 m	8.6 m/ 8.6 m
α_x/ α_y	-0.14/ -0.72	-0.66 / -0.66

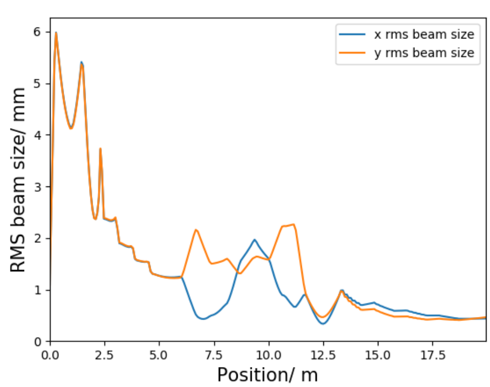

Figure 4: The rms transverse beam sizes along the example injection line.

CONCLUSIONS

An investigation of three merger schemes was presented in this work. The three dipole merger as an example of one of the three schemes was shown in more detail. The specified transverse emittance was achieved. However the Twiss matching will need further work to improve it.

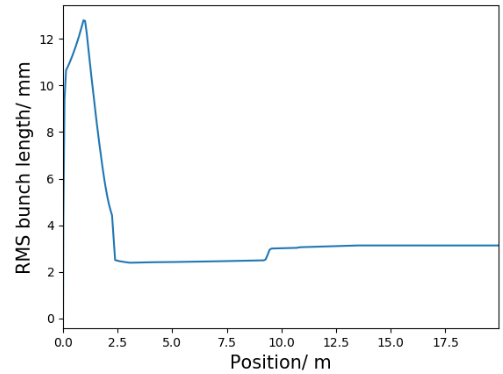

Figure 5: The RMS bunch length along the example injection line.

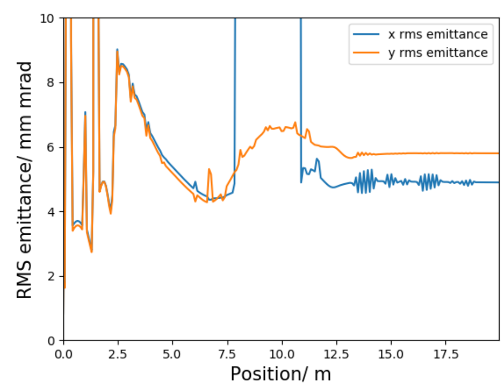

Figure 6: The transverse emittances along the the example injector.

Optimisation of these merger will continue with the optimisation process being refined. For example varying how the seeding process is carried out to ensure there is no premature convergence. The quality of the solutions being found by the optimiser may currently be limited by the optimisation process and the relative performance of the three schemes might vary with improved optimisation.

The simulations could be further refined. The effects of CSR in the merger and phase slippage in the main linac could be modelled. The main linac phase will also need to be modified based on the longitudinal match of the main ERL loop.

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