OPTIMIZING THE CEBAF INJECTOR FOR BEAM OPERATION WITH A HIGHER VOLTAGE ELECTRON GUN

Fay Elizabeth Hannon, Alicia Hofler, Reza Kazimi, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

Abstract

Recent developments in the DC gun technology used at CEBAF have allowed an increase in operational voltage from 100kV to 130kV. In the near future this will be extended further to 200kV with the purchase of a new power supply. The injector components and layout at this time have been designed specifically for 100kV operation. It is anticipated that with an increase in gun voltage and optimization of the layout and components for 200kV operation, that the electron bunch length and beam brightness can be improved upon. This paper explores some upgrade possibilities for a 200kV gun CEBAF injector through beam dynamic simulations.

INTRODUCTION

The CEBAF accelerator has been operational at JLab since 1995 nominally delivering 150uA of polarized electrons to three experimental halls. Historically CEBAF has been run at 6GeV, but is now undergoing an upgrade to raise the energy to 12GeV and introduce a new experimental hall [1]. The electron injector is also being upgraded to improve beam quality and operational reliability.

The injector consists of the following main components in order from the photocathode: 1) A DC electron source, 2) RF pre-buncher cavity, 3) beam chopper, 4) RF buncher cavity, 5) RF capture cavity, and 6) SRF booster cavity. There are numerous magnetic focusing elements and diagnostics positioned between each of the above components.

The CEBAF injector operates with some known issues. Those with the greatest impact are the reliability of the capture cavity (as there is no replacement) and the transverse kicks imparted to the electron beam from the couplers in the SRF booster. In order to provide the beam quality required for future CEBAF programs, some improvement to the injector is required. Of particular note is that the booster should be replaced. The unit presently has two 5-cell cavities (at 1.497GHz), but a new design is not limited to this configuration. It would also be desirable to operate without the capture cavity for improved reliability. Finally, it is anticipated that the DC gun which nominally runs at 100kV and 130kV, will be able to operate at full voltage of 200kV [2].

This paper reports on the beam dynamics simulations of the injector under the present operating conditions, and compares these to measurement for benchmarking of the code. The simulations are then extended to find the best operating conditions for the injector with a 200kV gun by using a multi-objective optimization tool. Finally, the various layout options for the booster cavity are explored, such that a suggestion can be made for an upgrade path.

CEBAF operates in two bunch charge modes simultaneously, one at 0.2pC and the other at 0.004pC. The high and low charge bunches are interleaved and a RF switchyard is used to direct them to the appropriate hall. The beamline setup must therefore work for both cases at the same time. As the setup for the high charge case is more demanding because of the space charge forces involved this was used for the optimization. The setup was then later checked at low charge to ensure beam quality was acceptable.

BENCHMARK EXPERIMENT

The nominal set up of the CEBAF injector with a 130kV gun was modelled using ASTRA [3], which is designed to track macro-particles through user defined external fields whilst including the effects of the space charge forces on the particle cloud. Simple on-axis field maps were used to represent electric and magnetic field components, and as such any asymmetric fields were ignored. The laser on the photocathode was also an ideal 'beer-can' distribution, assumed to be radially uniform with 0.25mm rms and longitudinally uniform with a FWHM of 55ps. However, the expected thermal emittance [4] from the GaAs:Cs photocathode was included in the simulations.

A simple benchmarking experiment was to set all the components to nominal settings, vary the electron bunch charge with the pre-buncher off and measure the bunch length using the beam chopper. The results of the measurement compared with simulation are shown in figure 1.

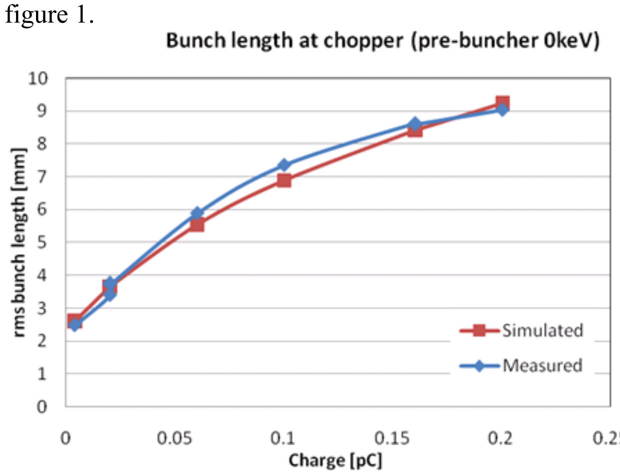

Figure 1: Comparison of bunch length, measured using the beam chopper, with simulation.

The good agreement between simulation and measurement show that the gun and solenoid settings and locations in ASTRA represent the CEBAF injector well. A second measurement was made to verify that the simulation could represent the beam dynamics for the buncher and capture cavities. A bunch profile measurement was made at the bunch-length cavity downstream of the capture cavity, with the pre-buncher off and the buncher and capture at nominal settings. Figure 2 shows the results of simulation versus measurement.

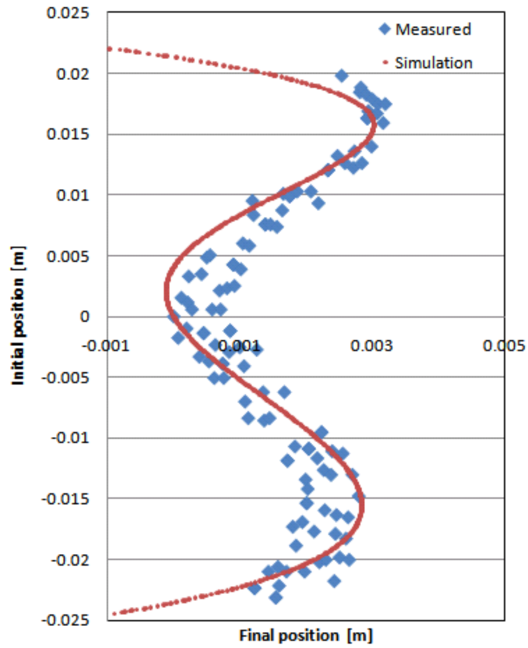

Figure 2: Arrival position of the electron bunch (0.2pC) as a function of initial longitudinal position.

OPTIMIZATION

Evolutionary or genetic algorithms are so called because of their close parallels with the theory of biological evolution, using techniques inspired by crossover, mutation, selection, and inheritance. In this way, from a population, those members that are better in some way are more likely to be selected and preserved to the next generation (inheritance). Ultimately an optimum set is reached after a number of generations; where all members of the population are equally good (Pareto-optimum set). The genetic algorithm used in this instance executes many generations of ASTRA simulations; using the output to define which solutions best meet the objectives [5]. The ASTRA model used in this study simulates the electron beam dynamics from the cathode to 15.09m (the entrance to the first linac after the booster).

Problem Definition

The optimization problem is defined by three sets of variables; those from the output that are constrained, those of the input which can be varied within some range, and those which are to be optimized for. The genetic algorithm can optimize for any number of variables, but this is a relatively simple scenario. The primary goal is to reduce the bunch length at the end of the booster whilst maintaining usable transverse properties. A selection of output variables are constrained to ensure that the optimization produces sensible solutions.

Not all the components in the injector can be varied in the optimization process. For example, the first three solenoid settings (after the gun) are excluded as these are used for spin control of the polarized electron bunches. The properties of the laser are also assumed to be fixed, so the transverse spot size on the cathode and emission time do not change. All other components were included in the optimization. In the following optimizations, there were only two objectives; to minimize the rms bunch length and the transverse emittance simultaneously. By having an objective for both transverse and longitudinal aspects of the electron bunch it will result in solutions that don't come at the expense of the other. In addition to the objectives further constraints were added, such that a minimal beam energy and maximum energy spread would be achieved, for example.

RESULTS

First the optimization was applied to the present layout with the gun at 100, 130 and 200kV to see if any improvements can be made by changing the component set-points. The result is shown in figure 3, where the optimal front of the optimization is compared against the nominal operation.

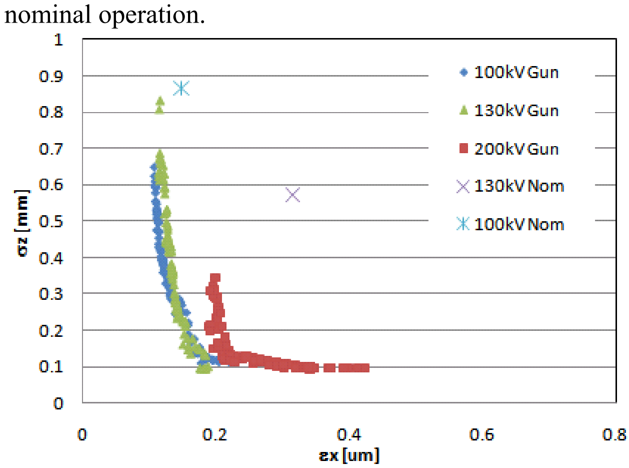

Figure 3: Optimal front for varying gun voltage using the present injector layout.

For both the 100kV and 130kV gun cases, there is some improvement to be made by operating the injector with different settings. When the gun voltage was increased to 200kV, a reduction in the beam brightness was predicted. This is due to the behaviour of the beam in the capture cavity. The capture cavity is a series of 5 connected beta-matched cells that was designed specifically to 'capture' the 100keV electron beam from the gun and accelerate to 500keV. Because the phasing between cells can't be adjusted, this results in degradation of the transverse beam quality that can't be recovered by the booster.

The 200kV optimal front cannot be improved upon by removing the capture from the optimization. The energy of the beam going into the first 5 cells of the booster cavity is too low, and slips in phase resulting in the energy being reduced in the first cell before being accelerated further. To mitigate this effect it would be advantageous to have either a single or double cell cavity that was beta-matched to gradually increase the energy of the beam before it was accelerated to around 5MeV in a subsequent 5 or 7 cell cavity.

To minimize costs it would be desirable to have the new booster cavities be contained in the existing cryomodule. This limits the number of cells that can be accommodated. Additionally, there is only room for two waveguide couplers. This means that either 2 cavities can be used, or if there are more cavities, that the power consumption is low enough to be provided by solid state devices rather than klystrons. Therefore the options investigated were 1+7, 1+1+7, 2+7, and 2+5, where each number represents the number of cells in each cavity (all at 1.497GHz). The capture cavity was omitted in the optimization, but otherwise the position of all components and laser properties remained the same.

The results of the optimization are shown in figure 4 where all optimal fronts are an improvement on the 100kV layout using the capture cavity.

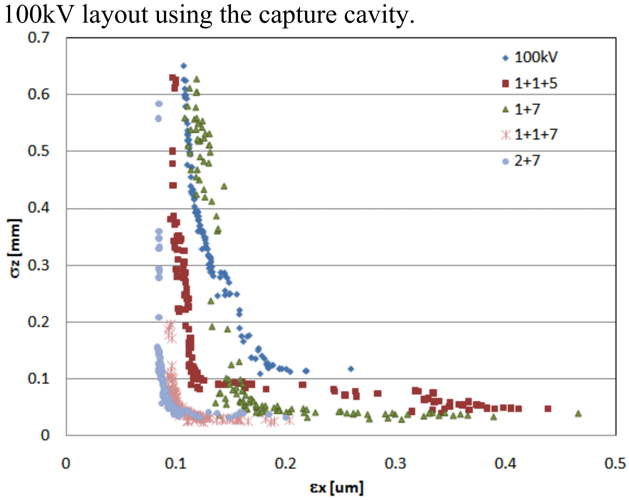

Figure 4: Optimal front for different booster configurations.

There is not much difference between the two single cell and the 2-cell followed by 7-cells cases. There is slightly more flexibility with the two single cells in terms of managing the bunch length through phasing the cavities correctly. However, given the cost saving implications of housing only two cavities inside the cryomodule, the 2+7 option is most desirable.

Figure 5. shows the beam evolution of a sample solution chosen from the optimal front of the 2+7 case. The resulting 6MeV beam has a bunch length of 0.13 mm (rms) and normalized transverse emittance of 0.94µm (rms).

OUTLOOK

Before manufacture of the booster cavity, a sensitivity study will be performed to assess the stability of the suggested operating point when errors are introduced. The booster cavities will be manufactured, tested and installed into the cryomodule at JLab during 2012. The injector upgrade is due to be ready for commissioning in 2013.

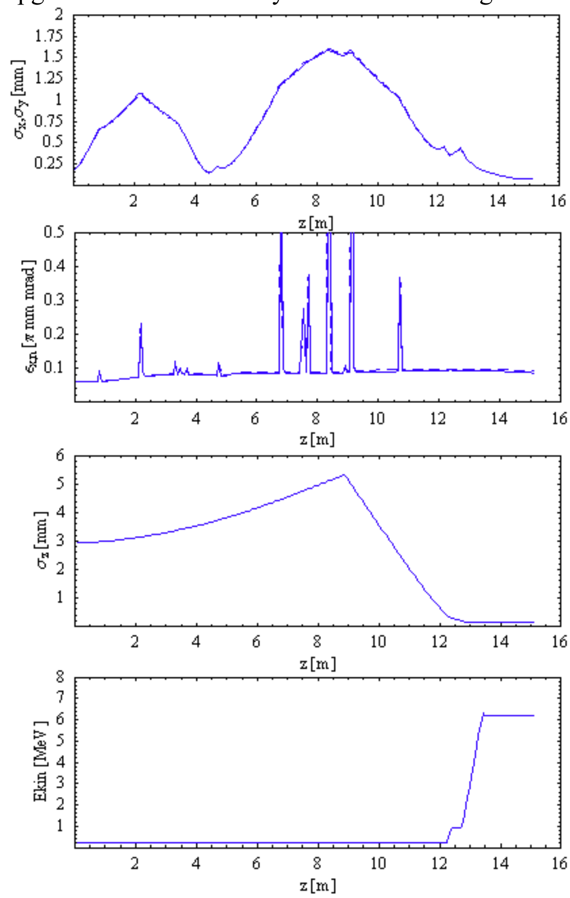

Figure 5: Beam evolution through the injector

ACKNOWLEDGEMENTS

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