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NOVEL "STRAIGHT" MERGER FOR ENERGY RECOVERY LINACS*

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Abstract

One of the most critical design considerations for an energy recovery linac (ERL) is how to merge the injected bunch onto the linac axis with minimal beam degradation. All merger designs in established and upcoming machines involve significant bending of the injected beam – even using a so-called straight merger bends the injected beam several degrees. We propose a merger which reduces the bending of the injected beam by an order of magnitude. By passing both beams through a septum magnet followed by an rf separator cavity with a superimposed dipole magnetic field, the injected beam bends minimally within the cavity, while the recirculated beam bends to align with the linac axis. Here we describe the concept in detail and present simulation results to demonstrate the advantages of such a design, particularly for magnetized beams or minimal energy separation between the injected and recirculated beams. Measurements from an experiment at CBETA evaluating the beam dynamics of the rf separator are presented and compared with simulation results.

INTRODUCTION

Mergers remain one of the most challenging design aspects of ERLs to date. While significant effort has gone into minimizing the beam degradation due to mergers over the years, all merger designs in established and upcoming machines bend the beam significantly, which is problematic when dealing with beams sensitive to transport asymmetries, such as magnetized beams [1]. As one of the components of the Jefferson Lab Electron Ion Collider (JLEIC) design is a magnetized electron beam to cool the ion beam, driven by an ERL, this is a critical topic in future design work [2]. Additionally, this merger concept works well for ERLs without significant energy separation between injected and recirculated beams, which is traditionally a challenging design prospect.

"STRAIGHT" MERGER

The layout of the "straight" merger concept is shown in Fig. 1. Both the injected and recirculated beams pass through a septum followed by an rf separator with a superimposed magnetic dipole field. The injected beam passes through the zero-field aperture of the septum before passing through the rf separator and magnetic dipole field assembly. When the injected beam passes through this assembly, the separator is on-crest and the dipole field is set to buck, or compensate, for the kick provided by the separator. To first order, the injected bunch is undeflected. The recirculated beam, on the other hand, is deflected by the septum magnet before passing through the cavity and coils assembly. As a consequence of the required 180° phase separation in an ERL between the bunches of the injected and recirculated beams, the separator cavity and dipole field deflect the recirculated beam in the same direction - leading to a deflection twice what either the cavity or magnetic field would provide alone. The combination of the fields in the cavity coil assembly is seen in Fig. 2.

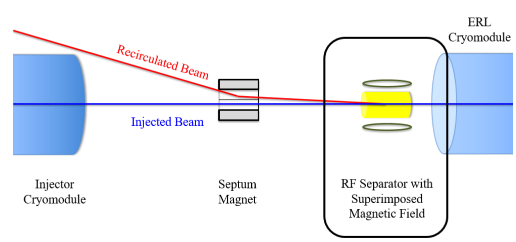

Figure 1: Layout of the "straight" merger concept, Fig. 1 from [3].

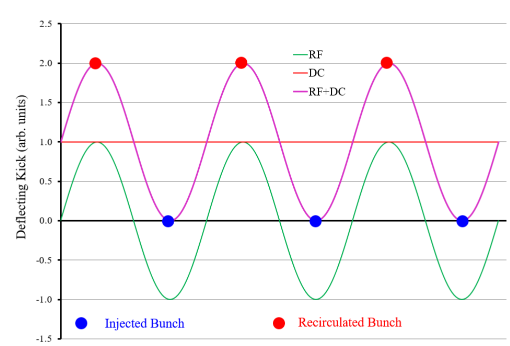

Figure 2: Kick in the rf separator with superimposed magnetic dipole, Fig. 2 from [3].

One of the anticipated higher order effects of this merger design is the "banana" effect. This effect is the deflection

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of the head and tail of the injected bunches due to the rf curvature. Fundamentally, different longitudinal slices of the bunch experience different fields from the separator cavity, while experiencing the same fields from the magnetic dipole field. Consequently, the bunch as a whole experiences no net deflection, but the head and tail of the bunch do experience some deflection and a change in energy.

The "banana" effect increases with the rf frequency of the separator cavity, so the 1.3 GHz separator at CBETA allows for this effect to be clearly demonstrated. Ideally, a machine would be designed so that the rf separator cavity has a significantly lower frequency, making this effect relatively negligible [3].

EXPERIMENTAL SETUP

The goal of the first "straight" merger experiment at CBETA was to evaluate the difference between the undisturbed beam, which passes through a drift, and the kicked beam, which passes through the combined rf separator cavity on-crest and coils, with the coil current set so that the centroid of the kicked beam matched the centroid of the undisturbed beam on screens downstream of the separator. In addition, measurements were also taken at phases off-crest, again setting the coil current so that the kicked beam centroid matched the undisturbed beam centroid. This was achieved by setting the CBETA injector to produce a 2.4 MeV electron beam, which traveled through a merger to the diagnostic line. The diagnostic line consists of two pairs of slits, one horizontal and one vertical, and the 1.3 GHz rf separator cavity, followed by a dipole and two screens. Without the dipole, the downstream viewer shows the beam spot. When the dipole is turned on, it is possible to evaluate the longitudinal phase space of the beam [4]. A labeled CAD model of the diagnostic line, with inserts of the cavity and coil assembly and picture of the actual cavity and coil assembly, is shown in Fig. 3.

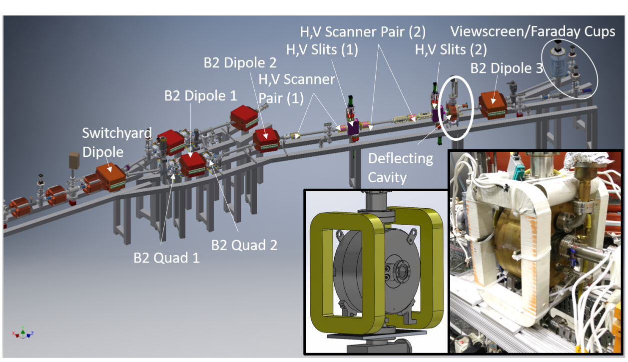

Figure 3: Labeled CAD model of diagnostic line at CBETA, with bottom center insert CAD model of cavity and coil assembly (courtesy of Joe Gubeli), and bottom right insert picture of cavity and coil assembly in the beamline.

While the slits were used during this experiment, this paper focuses primarily on the results obtained using the entire beam, comparing them to simulation results of the experiment, performed by General Particle Tracer (GPT) [5]. One exception to this is the discussion of the banana effect. Unfortunately, there is conflicting calibration data on the deflecting voltage of the cavity - one piece of data indicates 53 kV, while another indicates 113 kV. Fortunately, simulations have shown that the qualitative behavior of the beam, specifically σ_y, the *rms* vertical beam size, as a function of ϕ, the cavity phase, is independent of the deflecting voltage in this regime - this independence breaks down once the deflecting voltage is high enough. Our results show a strong agreement with the simulated qualitative behavior, justifying future experiments of this novel merger concept.

RESULTS

Operating Point

The most "straight"-forward evaluation of the results is the comparison of the undisturbed and kicked beams in terms of beam spot and longitudinal phase space at the operating point, $\phi = 0°$. These four viewscreens are shown in Fig. 4. The top row is the beam spot, while the bottom row is the longitudinal phase space; the undisturbed beam is shown in the left column, while the kicked beam is shown in the right. Looking at these results, it is clear that the kicked beam does not differ significantly from the undisturbed, which matches simulation results and our goal for this concept.

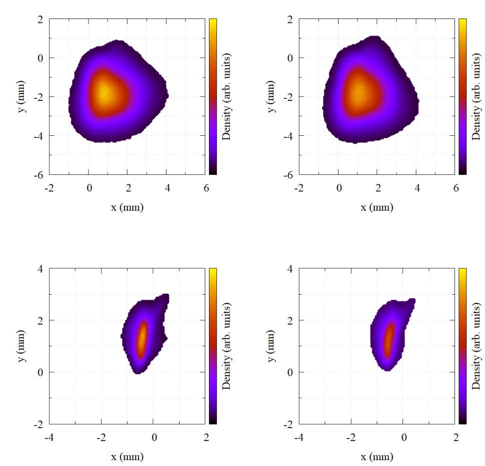

Figure 4: Measurements at the beam spot (top row) and longitudinal (bottom row) screens, for the undisturbed (left column) and kicked (right column) beams.

As a Function of Phase

In order to have more points of comparison than the four measurements shown in Fig. 4, data was also taken while varying the phase of the separator and adjusting the coil current appropriately. The *rms* vertical beam size, being the most impacted, is plotted as a function of phase in Fig. 5 at a number of thresholds for the longitudinal phase space screen. The thresholds applied in the figure are a cleaning

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mechanism - for a given measurement, beam signal is discarded if it falls below a given percentage of the maximum signal in the measurement. While the measurements shown are given for the longitudinal screen, a similar curve exists for the data taken on the beam spot screen.

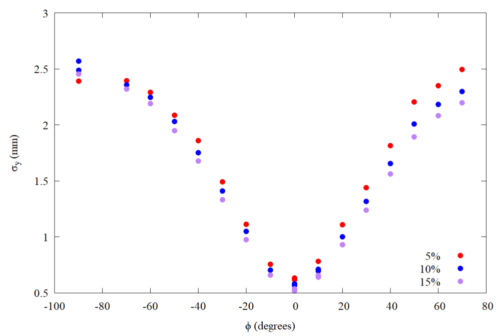

Figure 5: Measured *rms* vertical size, σ_y, on the longitudinal screen plotted as a function of degrees off-crest, ϕ, for different thresholds.

The simulated results of σ_y as a function of ϕ is shown in Fig. 6, for both the longitudinal and beam spot screens. Additional phases have been added to produce a smoother curve. Comparing this to the previous figure, there is significant agreement in the qualitative behavior of the plots. This is emphasized by plotting the longitudinal measurements and simulated curve together in Fig. 7, with the simulated curve scaled and shifted to produce the closest match, showing a strong agreement between the qualitative behavior of measured and simulated results.

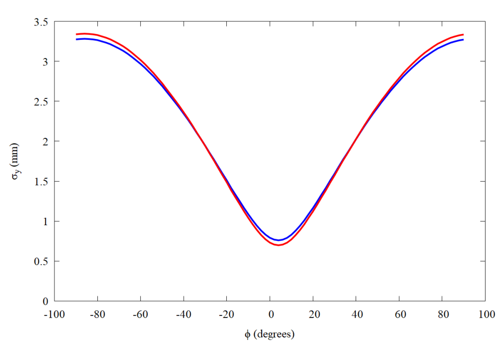

Figure 6: Simulated *rms* vertical size, σ_y, on the longitudinal (red) and beam spot (blue) screens plotted as a function of degrees off-crest.

"Banana" Effect

As mentioned previously, the "banana" effect is the residual kick experienced by the beam at the head and tail of the bunch. While this does occur in the full beam, it is easier and clearer to observe this effect on a beamlet which has passed through horizontal slits prior to passing through the cavity and coils assembly. This effect was observed during the course of our experiment and these measurements are shown in Fig. 8. This figure shows the undisturbed beamlet

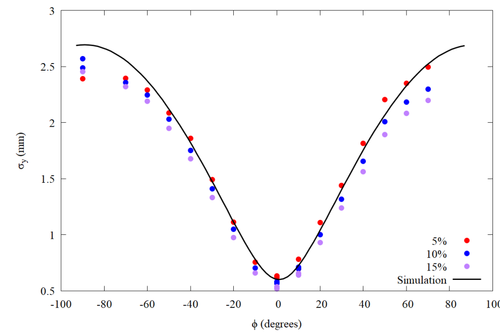

Figure 7: Longitudinal measurements plotted with the simulated curve, which has been shifted and scaled for best agreement.

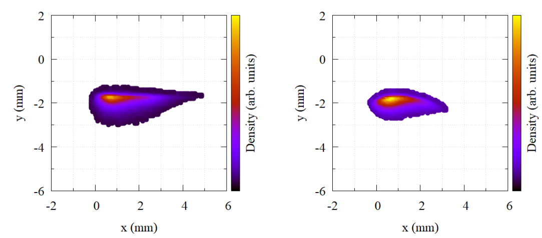

Figure 8: The undisturbed beamlet (left) and kicked beamlet (right), taken at the beam spot screen.

on the left, while the kicked beamlet on the right has the anticipated banana shape clearly visible.

CONCLUSION

Overall, the results of this initial "straight" merger experiment have shown substantial agreement with simulation and provide a strong justification for further exploring this concept as a novel "straight" merger for ERLs.

ACKNOWLEDGEMENTS

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