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PRELIMINARY TESTS AND BEAM DYNAMICS SIMULATIONS OF A STRAIGHT-MERGER BEAMLINE*

A. Al Marzouk†, T. Xu, P. Piot[1], Northern Illinois University, DeKalb, IL, USA
S. Doran, G. Ha, J. Power, E. Wisniewski, C. Whiteford
Argonne National Laboratory, Lemont, IL, USA
S. Benson, A. Hutton, G. T. Park, K. Dietrick, J. Guo, S. Wang
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
R. Ryne, C. Mitchell, J. Qiang, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[1] also at Argonne National Laboratory, Lemont, IL, USA

Abstract

Beamlines capable of merging beams with different energies are critical to many applications related to advanced accelerator concepts and energy-recovery linacs (ERLs). In an ERL, a low-energy "fresh" bright bunch is generally injected into a superconducting linac for acceleration using the fields established by a decelerated "spent" beam traveling on the same axis. A straight-merger system composed of a selecting cavity with a superimposed dipole magnet was proposed and recently tested at AWA. This paper reports on the experimental results obtained so far along with detailed beam dynamics investigations of the merger concept and its ability to conserve the beam brightness associated with the fresh bunch.

INTRODUCTION

The straight-merger (SM) concept was originally investigated in the context of multi-species beam separation [1] and most recently proposed for electron-beam merging and separation [2] in energy-recovery linacs (ERLs). An SM, diagrammed in Fig. 1(a), consists in superimposing a time-dependent deflecting force $\mathbf{F}_c(\varphi) = \mathbf{F}_0 \sin(\varphi)$ produced by a transverse-deflecting cavity (TDC) with a magnetostatic transverse force from a dipole magnet $\mathbf{F}_d$. Choosing the TDC deflecting-force amplitude to be $\mathbf{F}_0 = \mathbf{F}_d$, the total force experienced by a bunch becomes $\mathbf{F}_t(\phi) = \mathbf{F}_d[1 + \sin(\varphi)]$; see Fig. 1(b). In the case when the merger is used in an energy-recovery linac, the recirculated bunch (once it has participated in, e.g., the electron-cooling process) passes through the SM with a phase $\varphi = \pi/2$ (maximum deflection) and experiences the transverse force $2\mathbf{F}_d$ while a fresh low-energy bunch from the injector passes through the SM at $\varphi = 3\pi/2$ so that the deflecting force vanishes. The latter mode of operation is called the transparent mode as ideally the fresh bunch phase-space quality is not affected by the SM. One of the advantages of the present SM concept compared to using only a TDC ($F_d = 0$) operated to deflect the spent bunch ($\varphi = \pi/2$) and injecting the fresh bunch at zero crossing (e.g. $\varphi = \pi$) is that the SM does not introduce any correlation to first order. However, the transparency of the SM to the fresh bunch needs to be investigated thoroughly: the field produced by the TDC is time-dependent so that the head and tail of the bunch will experience a weaker deflection force compared to the bunch center. The TDC force arises from both magnetic and electric fields while the superimposed dipole field provides a magnetostatic force. These effects could play a role in the beam dynamics that could ultimately degrade the beam eigen emittances in the case of magnetized beams such as employed in some electron-cooling schemes [3] in hadron collider [4].

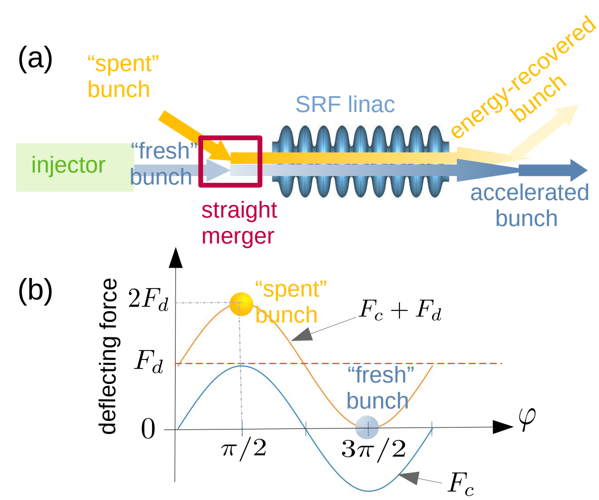

Figure 1: Overview of the SM concept for ERL application (a) and the deflecting force experience by the "fresh" and "spent" bunch (b). The dashed horizontal line represented the magnetostatic force F_d from the dc dipole magnet.

This paper presents preliminary investigation of an SM using first-principle simulation and preliminary experimental results qualitatively supporting the concept. However, it should be stressed that our beam energy is much higher than the one produced out of a typical ERL high-current photoinjector (< 10 MeV) [5].

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† afnan.almarzouk1@gmail.com

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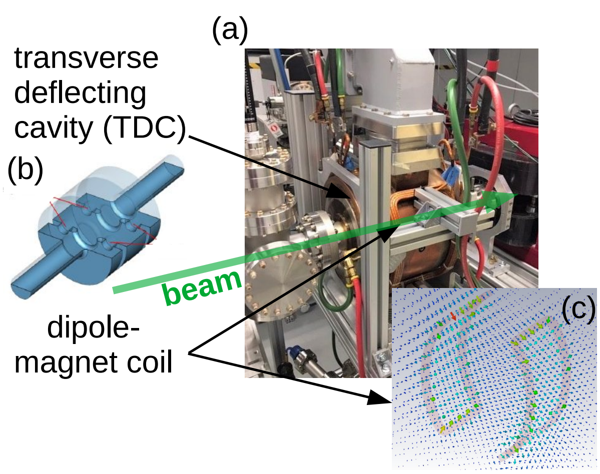

Figure 2: Photograph of the SM proof-of-principle experiment at AWA (a) with TDC geometry (b), and the dipole-coil magnet and the field map (c).

EXPERIMENTAL DEMONSTRATION

The proof-of-principle experiment of the SM concept installed at the Argonne Wakefield Accelerator (AWA) appears in Fig. 2(a). The SM beamline includes a three-cell (1/2+1+1/2-cell) TDC cavity operating on the $TM_{110,\pi}$ mode with fundamental frequency $f_0 = 1.3$ GHz [6, 7]; see Fig. 2(b). The cavity is surrounded by a dipole magnet composed of two coils producing a dipole field $\mathbf{B} = B\hat{x}$; see Fig. 2(c). The system is configured to deflect the beam vertically (i.e. $\mathbf{F}_d \parallel \mathbf{F}_c \parallel \hat{y}$). The beam produced by the AWA drive-beam photoinjector is accelerated up to 40 MeV and injected in the merger. So far, the system was successfully commissioned and some preliminary data on the merger "transparency" were acquired. Figure 3 experimentally reproduced the expected feature presented in Fig. 1(b). For this experiment, the TDC cavity was operated at low power to ensure that even with full deflection the beam does not go outside the field of view of the downstream YAG screen ("YAG1" located 1.2 m from the TDC center). In this case, a maximum deflection of 20 mrad was produced using a $\sim$ 40-MeV bunch.

In a following experiment we attempted to qualitatively demonstrate that when operated in transparent mode, the SM does not disturb the beam. We injected the beam at $\varphi = \pi/2$ and compared the transverse distribution measured on YAG1 when the SM is turned off (i.e. $F_c = F_d = 0$). The resulting distributions appear in Fig. 4(b,c) and confirm that within the shot-to-shot noise, the distributions are indiscernible as inferred from the projection appearing in Fig. 4(d). It should be noted that during this set of measurements, the AWA photoinjector was operated in the blow-out regime [8] resulting in an RMS bunch length of $\sigma_z \simeq 0.6$ mm for a 2-nC bunch corresponding to a ratio $\varrho \equiv \sigma_z/\lambda_0 \simeq 2.6 \times 10^{-3}$ (where $\lambda_0 = c/f_0$ is the RF wavelength) so that the curvature effect of the deflecting field is expected to be insignificant.

BEAM DYNAMICS MODEL

In parallel to the experiments, we have also investigated the beam dynamics of the SM via numerical simulations. Specifically, we developed a model of the SM using 3D field maps of the TDC and dipole magnet. The field maps were imported in OPAL-T [9]. An example of the simulation appears in Fig. 5 and shows how the net compensation of the kick is established. It points to large transverse oscillation occurring within the TDC due to the local interplay between the time-dependent TDC and static dipole-magnet

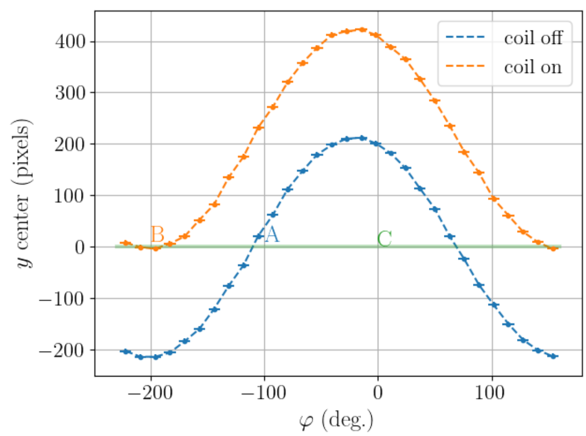

Figure 3: Measurement of the beam vertical displacement as a function of the TDC phase (with an arbitrary phase offset). The letter labels respectively indicate the cases of TDC operated at zero crossing with dipole magnet off (A) and the case of the SM operated in the transparent mode (B). The horizontal line (case "C") corresponds to both the TDC and dipole magnet being turned off.

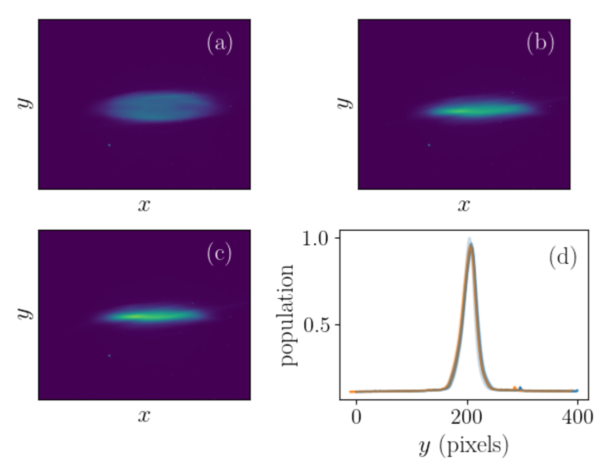

Figure 4: Measured transverse beam distributions at YAG1 associated with the three cases displayed in Fig. 3. Plots (a), (b) and (c) corresponds to cases labeled respectively as "A", "B", and "C" in Fig. 3. Plot (d) compares the peak-normalized vertical projections computed from images (b) and (c) respectively shown as blue and orange solid traces. For each cases 10 shots are superimposed.

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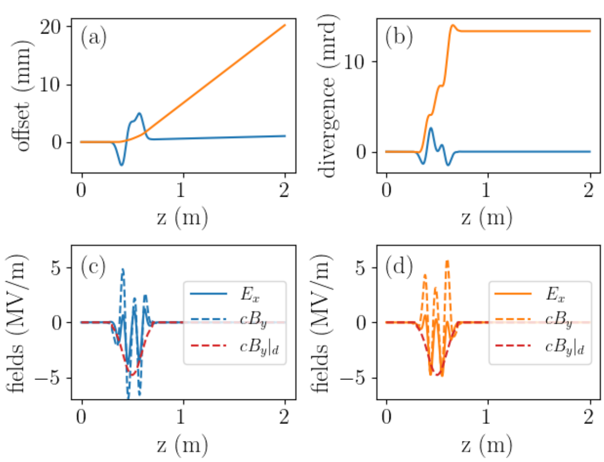

Figure 5: Simulated trajectory (a), and angle (b) experienced by a reference particle crossing the SM system operated in the transparent (blue traces) and deflecting mode (orange traces). Plots (c) and (d) give the fields experienced by the reference particle for the transparent (c) and deflecting (d) settings of the SM. In the lower plots, the red dash trace represents the field produced by the superimposed dipole magnet $B_y|_d$. These simulations are performed with OPAL-T.

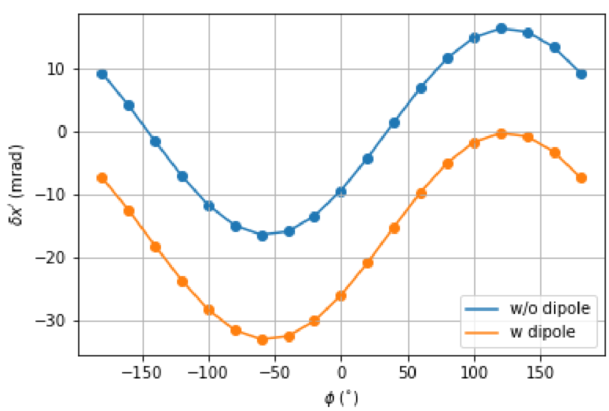

Figure 6: Simulated transverse kick received by the beam due to the TDC on (blue trace) and the SM (orange trace) as a function of phase (simulations performed with LW3D).

field. Such oscillations could be a source of beam degradation. To investigate possible phase-space degradation, including radiative effects due to coherent synchrotron radiation (CSR), the LW3D program [10] was modified to directly import 3D field maps and track macroparticles in a realistic model of the deflecting cavity. We performed the SM simulations at an energy of 60 MeV (maximum AWA energy) for a 1-nC bunch with length of $\sigma_z = 1.34$ mm corresponding to a peak current $\hat{I} \simeq 90$ A. These corresponding simulations showed in Fig. 6 indicate that a 16 mT dipole field superimposed with the TDC fields can provide the necessary compensation for the fresh bunch to remain undeflected; see Fig. 7.

Finally, the CSR wakefields computed by the LW3D program downstream of the SM for both the fresh and spent

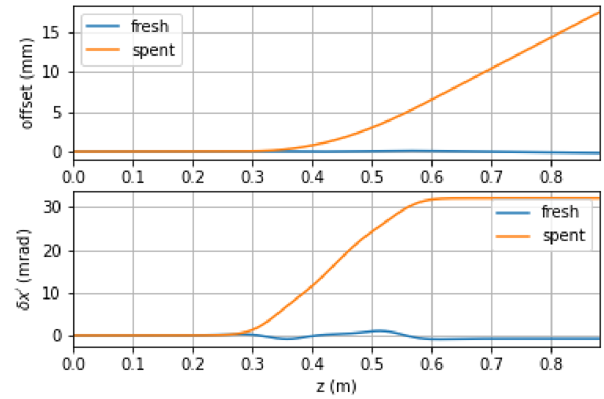

Figure 7: The trajectories and the divergence of both the fresh (blue trace) and spent (orange trace) bunch through the SM as simulated by the LW3D code.

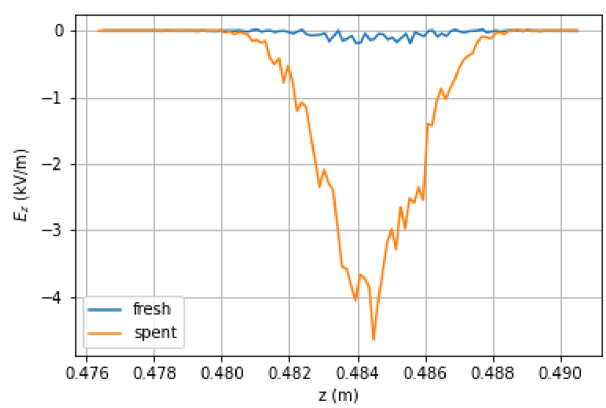

Figure 8: The CSR wakefield computed by the LW3D program downstream of the SM for the fresh (blue trace) and spent (orange trace) bunch.

bunches are illustrated in Fig. 8 where the wake of the spent bunch is one order of magnitude larger than that of the fresh bunch despite the trajectory excursion revealed in Fig. 5(a, blue trace). For the peak currents anticipated in electron coolers, CSR will be insignificant. However, it will be a major effect in beam-driven accelerators applications where the SM merges or extracts a drive bunch. Yet, using the SM could be an improvement over the proposed schemes [11].

OUTLOOK

Preliminary measurements presented in this paper confirm the capability of an SM to weakly affect an incoming bunch when operated in the "transparent" mode. Further studies will focus on quantitatively characterizing the effect of the SM on the phase space (via transverse-emittance measurement). Likewise, future experiments will focus on exploring the impact of the SM on a long incoming bunch by elongating the photocathode drive-laser temporal profile. On the simulation side, work is underway to apply the field computed in LW3D to the macroparticles to fully quantify the impact of the collective effects on the phase space.

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