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ARBITRARY LONGITUDINAL PULSE SHAPING WITH A MULTI-LEAF COLLIMATOR AND EMITTANCE EXCHANGE

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Abstract

Drive and witness beams with variable current profiles and bunch spacing can be generated using an emittance exchange beamline (EEX) in conjunction with transverse masks. Recently, this approach was used to create advanced driver profiles and demonstrate record-breaking plasma wakefield transformer ratios [1], a crucial advancement for effective witness acceleration. Presently, these transverse masks are individually laser cut, making the refinement of beam profiles a slow process. Instead, we have proposed the used of a UHV compatible multileaf collimator (MLC) to replace these masks. An MLC permits real-time adjustment of the beam masking, permitting faster optimization in a manner highly synergistic with machine learning. Beam dynamics simulations have shown that practical MLCs offer resolution that is functionally equivalent to that offered by the laser cut masks. In this work, the engineering considerations and practical implementation of such a system at the AWA facility are discussed and the results of benchtop tests are presented.

INTRODUCTION

Beam-driven wakefield accelerators have demonstrated impressive, many GV/m accelerating gradients [2, 3]. But the gradient alone does not dictate the usefulness of such an acceleration scheme due to the depletion of energy from the driver bunch, limiting the maximum energy which can be gained by the witness bunch. The *transformer ratio*, $\mathcal{R} \equiv |W_+/W_-|$ [4], expresses the ratio of the maximum accelerating field experienced by the witness bunch to the maximum decelerating field experienced by the driver bunch. This value sets an upper bound on the amount of energy which the witness can gain before the driver has been depleted. For temporally symmetric bunches, the transformer ratio cannot exceed two [5]. But by using a drive bunch with an asymmetric current profile, it is possible to achieve transformer ratios greater than two [6], increasing the maximal energy gain by a witness bunch for a given driver energy. Examples of transformer ratios above two have been demonstrated for dielectric wakefield accelerators, *e.g.* $\mathcal{R} = 4.8$ [7], as well as in plasma wakefield accelerators (PWFA). A record-setting transformer ratio of 7.8 was recently measured in a PWFA experiment [1]. Both of these examples used highly asymmetric drive beam current profiles to more effectively couple energy from the drive beam into the witness beam.

There are a variety of options for creating these shaped current profiles including combining wakefield chirping [8] or higher order multipole magnets [9] with a dispersive element, laser pulse stacking [10], or emittance exchange (EEX) [1,7]. EEX is one of the most versatile options for controlling the current profiles of high charge bunches. It works by exchanging the transverse phase space of a beam with its longitudinal phase space, possibly by placing a transverse deflecting cavity between two dog legs [4], although other beamline layouts are possible. By passing the beam through a mask prior to EEX, the beam's transverse profile is shaped, thus shaping the post-EEX current profile. This approach can generate high charge current profiles which would be difficult or impossible to achieve using other longitudinal shaping techniques. The EEX beamline at the Argonne Wakefield Accelerator Facility (AWA) [11] generated the beams used to demonstrate the record-setting transformer ratio of [1].

At AWA's EEX beamline, this transverse masking is currently done using laser-cut tungsten masks. Changing the mask shape requires installing newly cut masks into the UHV beamline, a process which can take days. The latency of this process makes it challenging to quickly iterate and refine the current profile. Our previous work in [12] described a proposal to replace these laser cut masks with a multileaf collimator (MLC), a device with dozens of independently actuated leaves which mask the beam to create a custom aperture [13–15]. A common application for MLCs is their use in radiotherapy where they can be used to clip the radiation beam to precisely match the shape of the tumor from any angle, delivering an effective dose while reducing damage to healthy tissue nearby.

For an EEX beamline, an MLC will enable real-time, nearly arbitrary control over the drive and witness spacing and current profiles. Due to the high number of free variables available for tuning and optimization, the MLC is expected to be highly synergistic with machine learning. In [12], start-to-end beam dynamics simulations were performed, comparing the beams produced by a practical MLC versus the existing laser cut masks, illustrating that the results were functionally equivalent. A UHV compatible design for an MLC consisting of forty, 2 mm wide leaves was presented as the basis for future work. In this paper, we discuss the benchtop testing of this design as a proof-of-concept of the magnetic coupling and actuation scheme while under realistic load.

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BENCHTOP TESTS

In [12] we presented the results of the first proof-of-concept test, establishing that there is sufficient magnetic coupling through the vacuum vessel wall to overcome the friction of motion. In this work, we present the next benchtop test to demonstrate three channels of the MLC operating in atmosphere (Fig. 1). The drive train, magnets, leaves, and surrogate vacuum vessel thickness are all representative of an MLC design consisting of forty, 2 mm wide leaves (shown in [12]). Each of the leaf pusher rods is 0.9 mm thick and held in alignment by a pair of "combs". To test the highest load that will be present in the full MLC, the leaves have been made from stainless steel (instead of aluminum) and are representative of the longest leaves in the 40 leaf design. The surrugate vacuum vessel walls are 1.5 mm thick, 304 stainless steel with a bright surface finish. The internal and external coupling magnets for each channel are 1/4" diameter, 1/2" long N52 neodymium cylinder magnets. No lubricants were used.

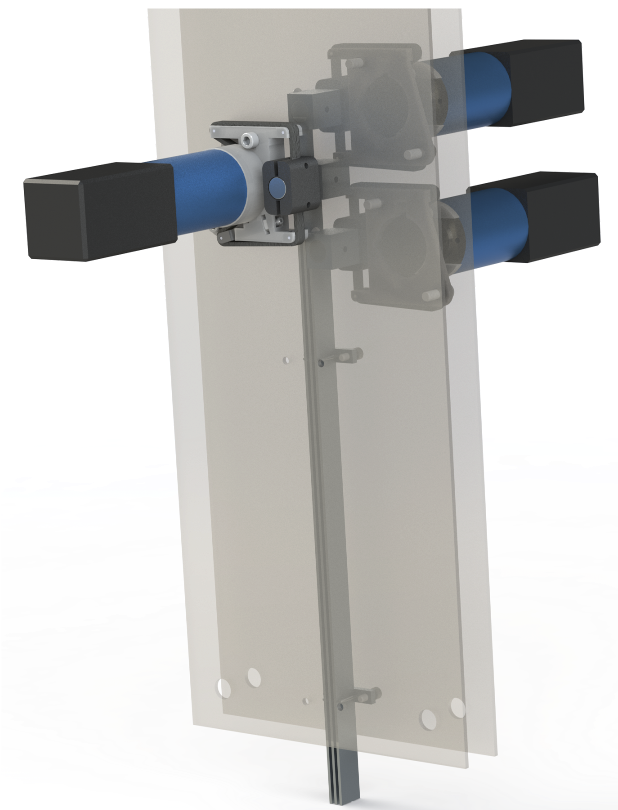

Figure 1: Render of the three channel, belt actuated benchtop test. The stainless steel front and back vacuum wall surrogate plates are semi-transparent to show additional operational details. The center leaf is actuated by the drivetrain module on the near side while the left and right leaves are actuated from the back.

These tests serve several purposes. First is to validate the magnetic coupling concept under realistic loads and ensure that the internal and external magnets do not appreciably slip. By laying out the three channels on both sides of the surrogate vacuum vessel, as will be the case in the real MLC, the worst case scenarios of magnetic coupling between channels can be checked. The next purpose is to test the cable actuation scheme. Finally, the practical experience of building these elements will give insight into the fabrication process and the tolerancing requirements for these components.

Cable Actuated

The original design of the MLC called for the actuation of the leaves using a cable driven by a stepper motor and using a spring for return motion. In order to tile effectively, this cable needed to be routed through a 90 degree turn and the spring needed to be compact. This compounded the issue of the friction at the interface of the wall from the magnet force by adding friction at the turn and requiring a strong spring which, again, increased the force that needed to be applied by the stepper motor. When this was assembled and tested, it was found that the motion was unreliable due to the stick-slip nature of the spring return when a practical spring force was used. Further, the individual routing and assembly of the drivetrain on a per-channel basis resulted in inconsistent responses. Although this test revealed important design problems, it did confirm that the magnetic coupling was sufficient for reliable actuation.

Belt Actuated

The actuation scheme was entirely overhauled with the new design shown in Fig. 2. This new approach is driven bidirectionally by a micro timing belt, eliminating the reliability and reproducibility issues arising from the spring return. Further, the new design is modular: each of the 40 channels has an identical drivetrain which can be individually assembled and dropped into place, eliminating the bespoke routing required by the old design, further improving consistency between channels. By incorporating a belt tensioning arm and using ball bearings rather than static surfaces, the motion should be consistent over time as well.

The new design is heavily leveraged off of 3D printing which provides precise and economical components. This, combined with the serpentine belt layout and other design choices, ensures that the new drivetrain module can be tightly tiled while still driving all 40 MLC leaves. This is a crucial consideration since inefficient tilings would increase the required vacuum vessel size, leading to added expense and complications.

A drivetrain module of the new design is shown installed on the testbed in Fig. 3. This new design has successfully demonstrated the reliable driving of leaves in any orientation relative to gravity, paving the way to the full MLC implementation.

DISCUSSION

Benchtop tests of a UHV compatible multileaf collimator, intended to replace laser-cut tungsten masks presently used in an EEX beamline, have been presented. Such a replacement will permit real-time control over driver and witness

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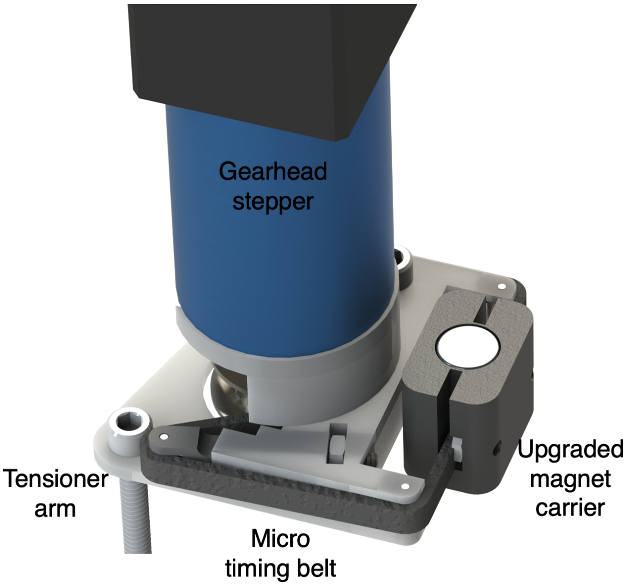

Figure 2: Annotated render of a single, belt actuated drivetrain module. The body is a single 3D printed component.

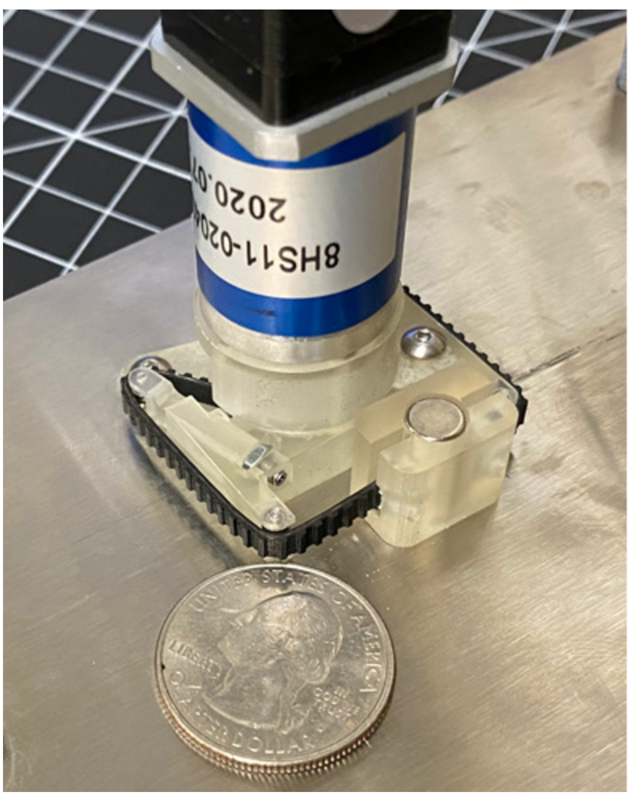

Figure 3: An assembled and installed belt actuated drivetrain module with a US quarter (24 mm diameter) for scale.

current profiles allowing for iterative refinement that is not possible with a fixed mask system. The MLC has a large number of variables for tuning, making it highly synergistic with machine learning for the optimization of beam shaping for applications including high transformer ratio wakefield acceleration.

The originally intended cable actuation scheme with spring return has been ruled out in favor of a bidirectional, micro timing belt driven design. This new design has demonstrated reliable actuation under realistic load conditions. Design and fabrication of the full, UHV compatible MLC for use at AWA is underway. After a successful demonstration of the MLC, the concept could find use in other accelerator beamlines that rely on transverse masking and require strict UHV levels, for example at BNL's ATF [16] or at SLAC FACET [17].

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