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FIRST RESULTS FROM A MULTILEAF COLLIMATOR AND EMITTANCE EXCHANGE BEAMLINE

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Abstract

By shaping the transverse profile of a particle beam prior to an emittance exchange (EEX) beamline, drive and witness beams with variable current profiles and bunch spacing can be produced. Presently at AWA, this transverse shaping is accomplished with individually laser-cut tungsten masks, making the refinement of beam profiles a slow process. In contrast, a multileaf collimator (MLC) is a device that can selectively mask the profile of a beam using many independently actuated leaves. Since an MLC permits real-time adjustment of the beam shape, its use as a beam mask would permit much faster optimization in a manner highly synergistic with machine learning. Beam dynamics simulations have shown that such an approach is functionally equivalent to that offered by the laser cut masks. In this work, the construction and first results from a 40-leaf, UHV compatible MLC are discussed.

INTRODUCTION

In the context of beam-driven wakefield accelerators, the *transformer ratio*, $\mathcal{R} \equiv |W_+/W_-|$ [1], is the ratio of the maximum accelerating field experienced by the witness bunch to the maximum decelerating field experienced by the driver bunch. Increasing this ratio is a crucial consideration for the effective acceleration of a witness beam since this ratio sets a limit on how much energy can be coupled into the witness before the drive beam is depleted. For longitudinally symmetric bunches, the transformer ratio cannot exceed two [2]. But by using a drive bunch with an asymmetric longitudinal profile, it is possible to achieve transformer ratios greater than two [3], increasing the achievable energy gain by a witness bunch for a given driver energy. When coupled with the large, GV/m accelerating gradients demonstrated in wakefield accelerators [4, 5], a high transformer ratio, beam-driven accelerator is appealing.

Transformer ratios above two have been demonstrated for dielectric wakefield accelerators, *e.g.* $\mathcal{R} = 4.8$ [6], and plasma wakefield accelerators (PWFA). A record-setting transformer ratio of 7.8 was recently demonstrated in a PWFA experiment [7]. Both of these examples used asymmetric drive beam current profiles to more effectively couple energy into the witness beam from the drive beam.

There are a variety of options for creating shaped current profiles including combining wakefield chirping [8] or higher order multipole magnets [9] with a dispersive element, laser pulse stacking [10], or transverse masking combined with emittance exchange (EEX) [6, 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, often by placing a transverse deflecting cavity between two dog legs [1], 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 ratios of Refs. [6] and [7].

At AWA's EEX beamline, this transverse masking was previously done using laser-cut tungsten masks. Changing the mask shape required installing newly cut masks into the UHV beamline, a process which could take days. The latency of this process made it challenging to quickly iterate and refine the current profile. Our previous work in Refs. [12, 13] 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 [14–16]. A common application for MLCs is their use in radiotherapy where they can be used to shape 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, our MLC enables 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 Ref. [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. In Ref. [13] a revised design philosophy was introduced and benchtop tests were performed. Here, we discuss the final design and fabrication of a forty leaf, UHV compatible MLC and its first results from AWA's EEX beamline.

DESIGN AND FABRICATION

Based on our benchtop tests [12, 13], we settled on a 40 leaf MLC design. Each leaf is 2 mm wide with a tungsten tip which masks the beam. These tips are connected via

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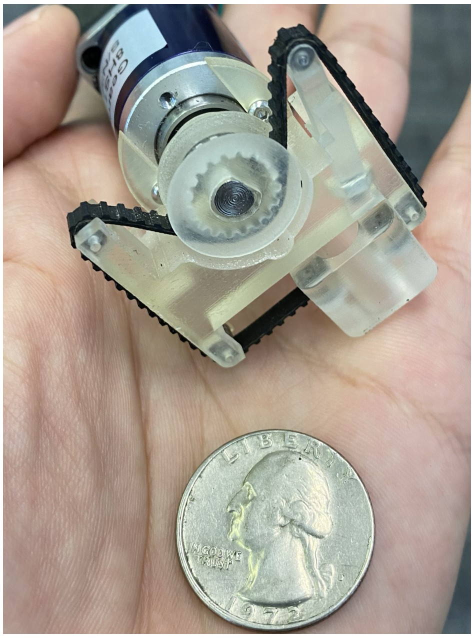

Figure 1: An assembled, belt-actuated drivetrain module with a US quarter (24 mm diameter) for scale.

an aluminum rod to a magnet inside the vacuum chamber which couples to an exterior magnet. All 40 leaves are held together as a "cassette" which can be installed as a single unit into the vacuum chamber. The vacuum chamber was purpose built for this experiment; a long slot (~600 mm) was cut through the length of the chamber for the cassette using a high aspect ratio, wire EDM. Each of the 40 channels has an identical, 3D printed drivetrain module (Fig. 1) that supports a stepper motor, gearhead, serpentine micro timing belt, and tensioning arm. This design can be compactly tiled to reduced the required size of the vacuum vessel, as shown in Fig. 2. Due to the stringent vacuum requirements of the AWA beamline, no lubricants were used in the vacuum chamber.

PRELIMINARY RESULTS

After cleaning, the MLC was installed in AWA's EEX beamline [11]. For this preliminary test, we sought to demonstrate the creation of masks and their transformation into current profiles via EEX. First, a mask corresponding to a ramped drive beam and a witness beam has been formed using the MLC. An electron beam was passed through this mask and imaged by a YAG screen 28 cm downstream, with no intervening optics. This screen image is shown in Fig. 3. This masked beam was then propagated through the EEX beamline and then streaked using an additional transverse deflecting cavity to reveal the current profile of the beam in Fig. 4.

As a further demonstration, the MLC leaves were configured to represent a bunch train and witness, as may be used for resonant wakefield excitation [17–19] or resonant excitation of coherent Cerenkov radiation [20]. Figure 5

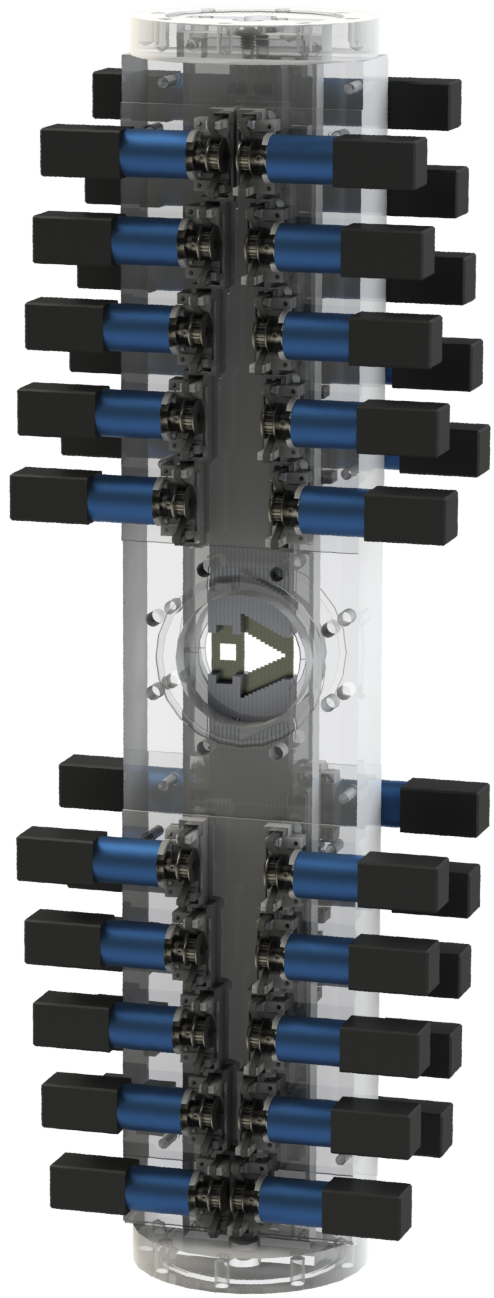

Figure 2: A render of the multileaf collimator with the vacuum chamber and some support structures made translucent for clarity, shown here creating a mask for a ramped drive beam and witness beam.

shows the masked beam, imaged on a YAG screen directly downstream of the MLC while Fig. 6 shows the streaked beam after EEX, revealing the train of bunches in the current profile.

DISCUSSION

A UHV compatible, multileaf collimator has been designed, fabricated, and integrated into AWA's EEX beamline,

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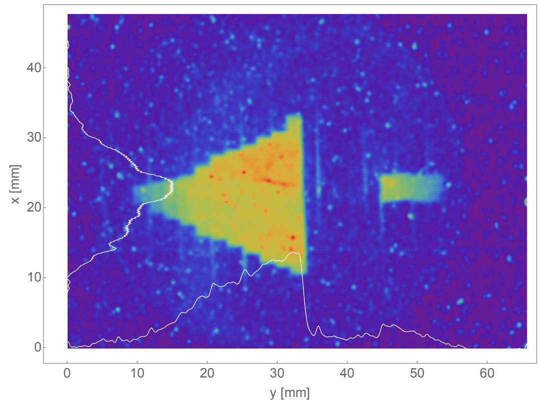

Figure 3: A YAG image immediately downstream of the MLC, showing the beam "shadow" corresponding to a ramped driver and witness.

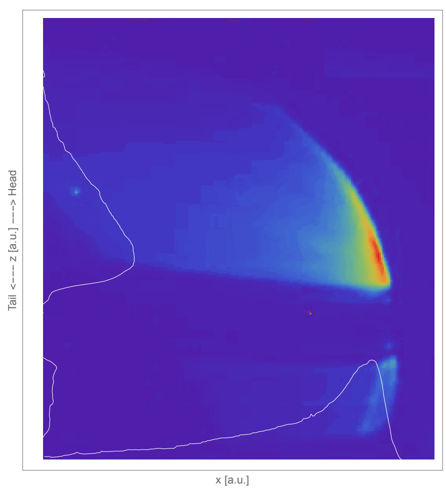

Figure 4: After EEX and the TDC, the longitudinal profile of the beam is revealed in the vertical direction. The transversely masked beam has been transformed into a ramped driver and witness current profile.

replacing the laser-cut tungsten masks previously used. This upgrade permits real-time control over driver and witness 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 first results from the MLC, including the masked beams and their resultant current profiles, have been shown, including examples corresponding to ramped, high transformer ratio drive beams with trailing witness beams and resonant bunch trains. Further work will continue to improve the MLC, including efforts to use machine learning to enhance the beamline performance. The concept may find use in other accelerator beamlines that rely on transverse masking and require strict UHV levels, for example at BNL's ATF [18] or at SLAC FACET [21].

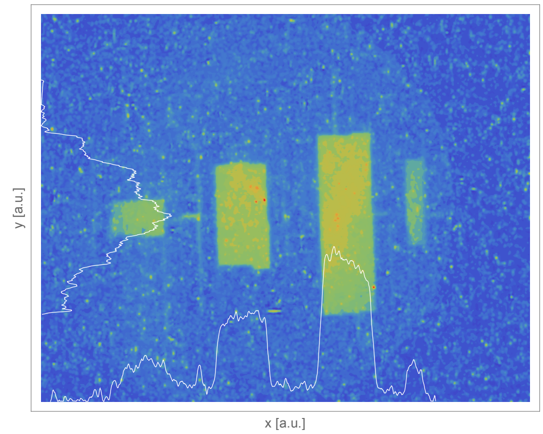

Figure 5: A YAG image immediately downstream of the MLC, showing the beam "shadow" corresponding three pulse resonant bunch train and witness.

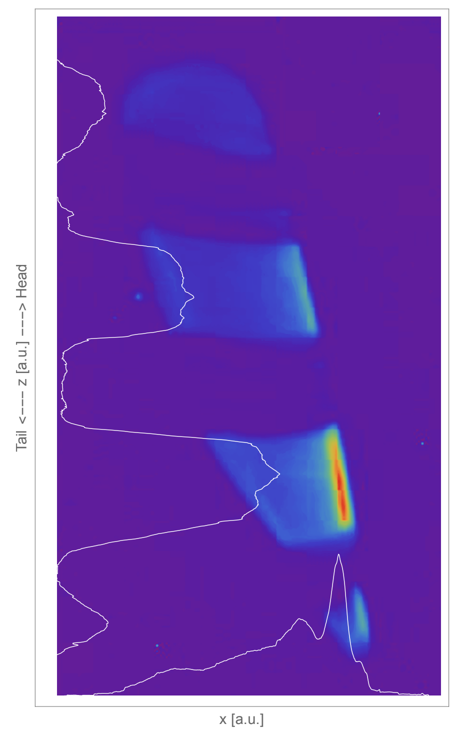

Figure 6: After EEX and the TDC, the longitudinal profile of the beam is revealed in the vertical direction. The transversely masked beam has been transformed into a three pulse resonant bunch train and witness current profile.

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