USING SIMULATIONS TO UNDERSTAND PARTICLE DYNAMICS AND RESONANCE IN THE MICRO-ACCELERATOR PLATFORM*

J. McNeur†, G. Travish, UCLA, Los Angeles, CA 90095, USA
H. Yin, UESTC, Chengdu, China
R. Yoder, Manhattanville College, Purchase, NY 10577, USA

Abstract

The Micro-Accelerator Platform (MAP) is a slab-symmetric micron-scale electron accelerator. Electrons gain energy via a standing wave electromagnetic resonance powered by a side coupled Ti:Sapphire laser. In this paper, we will discuss simulations of resonance and particle dynamics in this structure. Three-dimensional simulations showing evidence of stable 1 GeV/m acceleration are detailed along with simulations studying defocusing and wakefield effects in the MAP. Additionally, optimization of the structure and the coupling of laser power into the cavity will be explored.

INTRODUCTION

The Micro-Accelerator Platform (MAP) is designed to accelerate electrons at an energy gradient of 1 GeV/m. Composed of dielectrics in order to avoid material breakdown due to the high electromagnetic fields present, the MAP is periodic in the direction of propagation. The period length of the structure matches the wavelength of the incident optical laser. The electromagnetic field is confined in the MAP by 2 Bragg stacks surrounding the vacuum channel in which electrons travel. The accelerator is approximately 1 mm in the direction of propagation (z), 5 microns in the direction parallel to the propagation of the incident laser (y), and 1 mm in the remaining direction (x). A cross section is shown in Fig. 1.

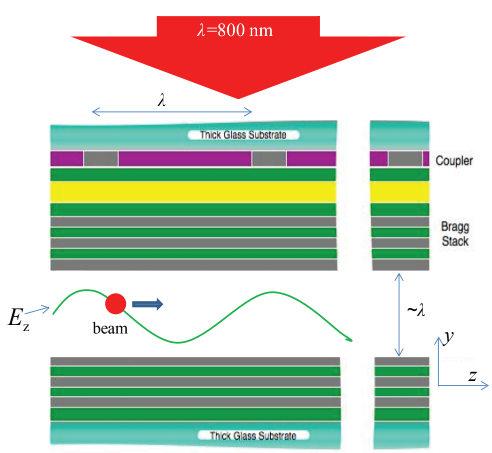

Figure 1: Cross section of MAP.

* Work supported by DTRA grant HDTRA1-09-1-0043
† jmcneur@physics.ucla.edu

The electrons are accelerated as they synchronously travel along the standing wave resonance. The wavelength of this standing wave is engineered to match the distance the electrons travel in one optical cycle of the Ti:Sapphire laser, thus guaranteeing the synchronicity of the laser and the electron beam. Although the excitation of the electromagnetic resonance is well understood both computationally [1] and analytically [2], recent studies have used powerful simulation tools to study detailed particle dynamics, including acceleration and wakefield generation. These are discussed in later sections. The aforementioned analysis has been conducted using a relatively simple version of coupling slots. In order to maximize the energy gained by the electrons as they traverse the MAP, however, energy needs to be coupled efficiently into the vacuum gap of the structure. Recent developments in optimizing the design of the MAP have resulted in coupling efficiencies greater than 70 percent and beam loading percentages close to 100. These results will also be discussed below.

SIMULATION MODEL

The structure, which is effectively 2 dimensional as it is invariant in the x direction, is composed of Hafnia, Zirconia, and Fused Silica. Both HFSS and VORPAL have been used to model the standing wave resonance in this MAP model. Although these results have been discussed extensively in past publications [1], an example resonance is shown in Fig. 2.

The standing wave resonance is well understood analytically [2] and is given in Eq. 1. Here, ω is the radial frequency of the incident laser, β and γ have their usual relativistic definitions, E_0 is the field amplitude and E_z is the z component of the electric field:

$$E_z = E_0 \cos\left(\frac{\omega z}{\beta c}\right) \cosh\left(\frac{\omega y}{\beta \gamma c}\right) \cos(\omega t). \quad (1)$$

Since these results are so well understood, we will focus on the use of simulation tools to understand phenomena particular to the MAP that are not yet fully understood, including the acceleration of and wakefields generated by a flat beam traversing the vacuum cavity of the MAP as well as the maximization energy coupling into the structure by optimizing the design.

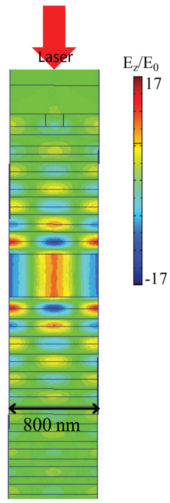

Figure 2: Colored field overlay of accelerating mode of the one period of the MAP.

ACCELERATION

The standing wave resonance shown above can accelerate electrons at an energy gradient of 1 GeV/m. Using the PIC code VORPAL [3], we have been able to simulate such an energy gain. In VORPAL, a 800 nm long electron bunch is injected into a structure, illuminated with a 0.4 GV/m gaussian pulse laser, at a time after the structure has been filled with the accelerating mode. As the bunch length is equal to the optical wavelength of the resonance, only a fraction of the bunch is accelerated, while much of the electron bunch phase slips and does not gain full energy. The initial kinetic energy distribution of this bunch as well as the energy distribution of the bunch after traveling 1 mm is shown in Fig. 3. Evidently, the bunch gains 1 MeV of kinetic energy over 1mm of travel, equating to an energy gain of 1 GeV/m, as expected.

WAKEFIELDS

As mentioned above, Wakefield-induced beam breakup and energy loss is also expected to hamper acceleration in the MAP. Recently, studies to quantize these effects have been conducted. The fields generated by a 2-dimensional 1pC ribbon beam with an energy of 60 MeV are shown in Fig. 4. The beam is 30nm tall vertically and 1 micron long horizontally.

These fields, on the order of 0.2 GV/m, result in an energy loss of at most 8 keV over 80 microns of travel, as shown in Fig. 5. This extrapolates to a maximum energy loss of .1 MeV over 1mm of travel, which is an order of magnitude less than the simulated energy gain of 1 MeV over the same distance. In the near future, the interplay between acceleration due to the laser fields and deceleration due to the wakefields will be studied extensively for beams that have the same parameters we expect to encounter experimentally [4]. Furthermore, the spatial modulation of the beam and associated emittance growth will also be studied extensively.

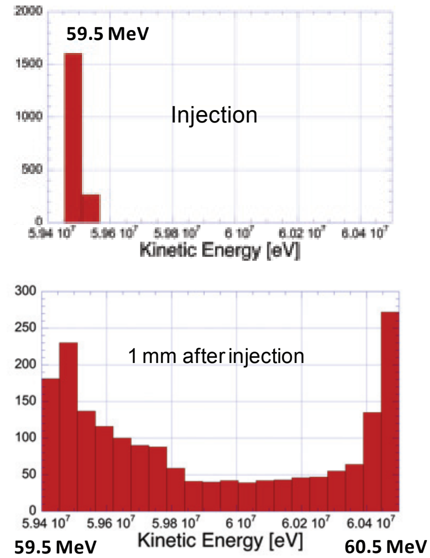

Figure 3: Acceleration of electron bunch over 1mm of propagation.

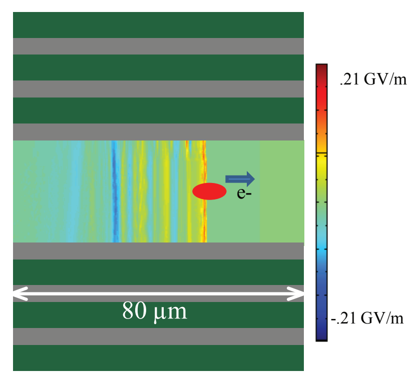

Figure 4: Wakefields generated by a 2 dimensional ribbon beam.

COUPLING

We have also used CST Microwave Studio and HFSS to study how to efficiently couple laser power into the accelerating cavity of the MAP. In the time-domain solver of Microwave Studio, by isolating the maximum reflected electromagnetic field signal while the structure is filling with the accelerating mode, we can calculate the energy stored in the structure during this time. By calculating the ratio of the stored power to the incident power, we can calculate the coupling efficiency of the structure. In the frequency domain solver in HFSS, this calculation is performed using the usual S-parameters.

ISBN 978-3-95450-115-1

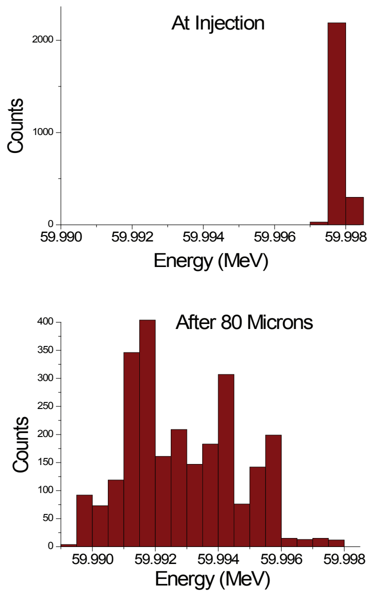

Figure 5: Energy histogram of the electron beam before (top) and after (bottom) deceleration due to wakefields.

When this calculation is performed on the usual MAP structure shown in Fig. 1, a coupling efficiency of approximately 10 percent is found. In light of this poor result, a new design for a more efficient MAP has been proposed that consists of 2 distinct Bragg stacks on each side of the accelerating gap. The two Bragg stacks are engineered to reflect different wavelengths so that in combination they confine a larger bandwidth of wavelengths than the original MAP design did. Additionally, two distinct coupling layers are used in the new design. Figure 6 shows this new design.

As the wavelengths of the fields reflected out of the accelerating cavity vary with the dielectric constants of the surrounding materials and the angles of the reflected fields vary due to diffraction from the coupling layers, a broadband DBR such as that in Fig. 6 can be expected to confine more electromagnetic energy than the original MAP design. Indeed, the coupling efficiency of the new model has been computed to be approximately 75 percent in both HFSS and Microwave studio. An example of resonance in this structure is shown in Fig. 6. Further work will include optimizing the coupler design and fabricating this new structure.

CONCLUSIONS

Achieving resonance in the Micro-Accelerator Platform has been extensively studied and is well understood in both a computational and general analytic sense. Recent work has focused on using powerful computational tools such as VORPAL, HFSS, and CST Microwave Studio to understand problems specific to the MAP, such as achieving

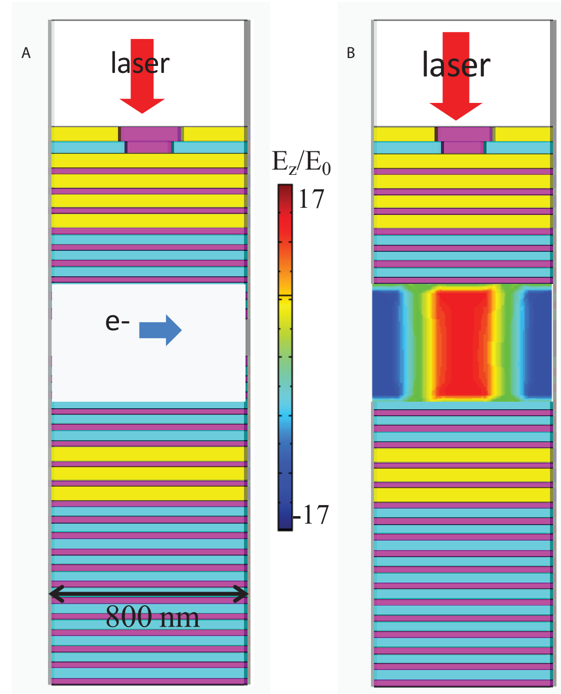

Figure 6: a) Modified MAP with distinct DBRs and coupling ; b)Resonance generated in Modified MAP.

acceleration and minimizing the negative effects of wakefields under realistic experimental conditions and maximizing energy coupling into the MAP's accelerating cavity.

REFERENCES

[1] J. McNeur et al., in *Advanced Acceleration Concepts, 2010,* (AIP Conf. Proc. 1299), pp. 427-432.

[2] A. Mizrahi and L. Schachter, Optical Bragg accelerators, Phys. Rev. E 70, 016505 (2004).

[3] C. Nieter and J.R. Cary, "VORPAL: a versatile plasma simulation code", J. Comp. Phys. 196, 448-472 (2004).

[4] G. Travish et al., "Experimental Progress Towards a Resonant Slab-Symmetric Dielectric Laser Accelerator," WEPPP009, these proceedings.