RESONANCE, PARTICLE STABILITY, AND ACCELERATION IN THE MICRO-ACCELERATOR PLATFORM*

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Abstract

A micron-scale dielectric-based slab-symmetric accelerator is currently being designed and fabricated at UCLA. This Micro-Accelerator Platforn (MAP) accelerates electrons in a 800 nm wide vacuum gap via a resonant accelerating mode excited by a side-coupled optical-wavelength laser. Detailed results of particle dynamics and field simulations are presented. In particular, we examine various methods of achieving net acceleration and particle stability. Additionally, structural designs that produce accelerating fields synchronous with relativistic and subrelativistic electrons are discussed.

INTRODUCTION

The Micro-Accelerator Platform (MAP) is a resonant cavity that accelerates injected electrons with a gradient on the order of 1 GeV/m. It can potentially be attached to a micro-scale electron source so that it becomes a compact monolithic electron source and accelerator with industrial and medical applications.

To study this structure via simulations, we have considered a model that consists of only the accelerating section of the MAP. Two Distributed Bragg Reflectors (DBRs) composed of two distinct dielectrics surround the vacuum gap through which the electrons travel. These DBRs serve as dielectric mirrors meant to confine the resonant fields to the surrounded vacuum gap. A near-infrared finite-bandwidth laser couples into the structure via periodic diffractive optical elements composed of dielectric slots (see Figure 1). This incident laser powers a standing wave accelerating mode (periodic in the *z*-direction as oriented in Figure 1) within the cavity. While the structure is 1mm long in the direction of propagation and can be as long 1 mm long in the *x*-direction, it is on the order of 1μm thick in the *y*-direction.

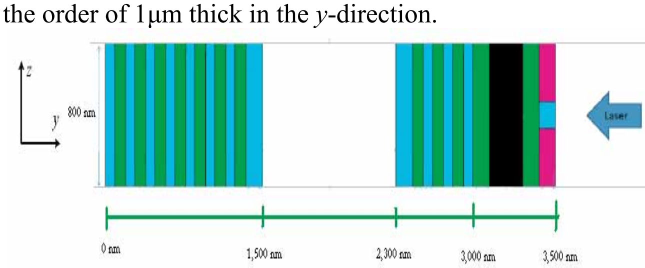

Fig. 1: One period of the MAP. The incident NIR laser propagates from right to left and electrons are accelerated along the *z*-axis. The structure is invariant in the *x* direction.

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To guarantee that the injected electrons are accelerated synchronously, the periodicity of the coupling slots ensures that electrons travel one period of the structure during one period of the incident laser. This yields a resonant standing wave field in the accelerating gap with a wave number and analytical form given in Equation 1. [1]

$$k_z = \frac{\omega}{\beta c}\text{; and}$$
$$E_z = E_0 \cosh\left(\frac{k_z y}{\gamma}\right)\cos(k_z z). \tag{1}$$

Here, k_z is the wave number of the standing wave, ω is the radial frequency of the incident laser, and γ and β have their usual relativistic definitions. This proposed structure provides many advantages. The invariance of the structure in the x-direction minimizes the effects of wakefields on electron bunches travelling through the structure and the dielectric composition allows for the use of high power lasers without having to worry about the low breakdown thresholds typically seen in metals.

Designing the MAP still faces challenges. Although standing wave resonances have been discovered for electron velocities ranging from the speed of light to 7/8ths of the speed of light, finding resonances designed to accelerate slower electrons has proven difficult. Furthermore, for lower velocity electrons, transverse defocusing is a hurdle to be overcome. These challenges will be discussed in later sections of this paper.

RELATIVISTIC RESONANCE

The relativistic version of the MAP (with a structure period matching the central wavelength of the incident laser) has been extensively studied [1]. Various dielectric combinations have been used in these simulations, with many of these combinations yielding strong resonances. In particular, those combinations which included materials whose indices of refraction differed greatly had resonances with very high field amplitudes relative to the incident laser.

Motivated by fabrication considerations [2], we have decided to compose our relativistic structure with SiO_2, HfO_2, and ZrO_2. In simulations, we define these materials to accurately reflect their optical properties as measured in the lab. Strong resonances with quality factors between 200 and 300 have been found. One period of such a resonance is displayed in Figure 2.

Finding such a high quality resonance is promising insofar as it enables efficient high-gradient acceleration. This will be discussed further below.

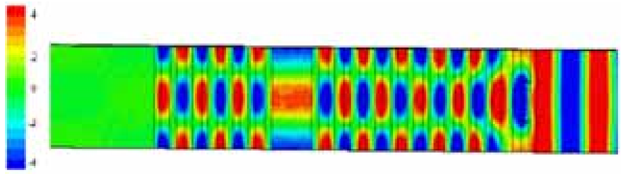

Fig. 2: Color field map of E_z in the relativistic MAP exhibiting strong resonance, normalized to the drive laser amplitude. Materials used are zirconia, silica, and hafnia. The laser propagates from right to left and electrons travel vertically through the cavity.

SUBRELATIVISTIC RESONANCE

In the full MAP structure, electrons are injected into the structure via an field enhanced emitter driven by a pyroelectric crystal.[3] The injection energy of these electrons is expected to be approximately 25 KeV. To synchronously accelerate electrons at this energy, the standing wave resonance of the MAP needs to have a periodicity of $\beta\lambda$, where λ is the central wavelength of the incident laser. To excite accelerating modes meant to accelerate lower energy electrons, one often needs to change the thickness of the dielectric "matching layer" adjacent to the vacuum gap.

After appropriately tapering the matching layer in the one period MAP model, we have been able find resonance with a period of 700 nm (meant to synchronously accelerate electrons with β=0.875). This resonance is displayed in Figure 3.

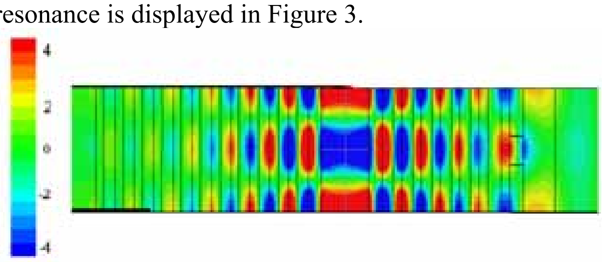

Fig. 3: Color field map of E_z in the β=0.875 MAP exhibiting strong resonance, normalized to the drive laser amplitude. The laser propagates from right to left and electrons travel vertically through the cavity.

To find an accelerating mode for lower energy electrons, we first considered a simplified MAP that consisted of a perfectly conducting metal with periodic coupling slots (whose periodicity is dictated by the electron velocity), a high dielectric constant material (Ge – ignoring the fact that Ge is not transparent in the NIR), a dielectric matching layer, and a small accelerating gap. The easily defined boundary conditions and strong diffractive qualities of this model made it significantly easier to find resonance than in the fully dielectric MAP. After striking the simplified MAP with 2 counter-propagating lasers we were able to excite a standing wave with a 240 nm period, appropriate for synchronously accelerating electrons with an energy of 25 KeV.

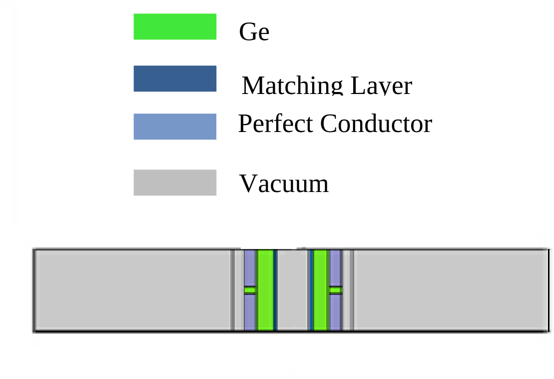

Fig. 4: Simplified version of the MAP. Particles are accelerated vertically and lasers are incident on the structure from both the left and right.

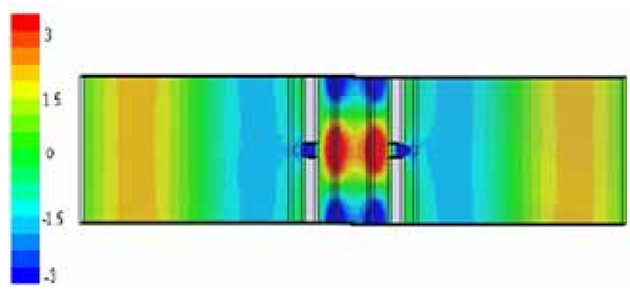

Fig. 5: Resonance in low beta simplified MAP due to two incident oppositely propagating lasers, normalized to the drive laser amplitude.

This simplified approach cannot be translated to the actual MAP structure, as the Fabry Perot modes dominate. If we naively look for resonance in the MAP with 240 nm periodicity, we only excite Fabry-Perot modes. We have also attempted to find a 240nm periodicity standing wave resonance in a MAP structure with 2 couplers on opposite sides of the vacuum gap and 2 counter-propagating lasers, but once again only found Fabry-Perot modes. When we constructed a model that combined elements of the metallic MAP with the all-dielectric MAP, we found similar results.

We may be able to achieve net acceleration of low energy electrons without having to excite standing wave resonances with unattainably small wavelengths. We can instead achieve this by sending electrons through a MAP structure that consists of periods with 2 distinct lengths (e.g. 700 nm and 800 nm). This approach could potentially achieve net acceleration as well as particle stability and will be discussed in the following section.

PARTICLE DYNAMICS

Using the simulation software VORPAL [4], we have been able to successfully simulate the dynamics of electrons travelling through the 2D relativistic MAP. In VORPAL, resonance is established by sending a laser pulse with a central wavelength of 800 nm and a Gaussian envelope in time at the coupling slots of the MAP structure. After the vacuum cavity has had sufficient time to fill (~2 ps), the accelerating mode resonance is established and particles are injected into the cavity.

In simulations in which the periodicity of the coupling slots matches the central wavelength, we have observed sustained high gradient acceleration of electron bunches injected with highly relativistic velocities. In Figure 6, we see that a relativistic electron bunch with an injection energy of 59.4 MeV gains 0.3 MeV over 300 microns, corresponding to an accelerating gradient of 1 GeV/m. Achieving such a high gradient of acceleration enables us to design a MAP structure that has a small length along the direction of acceleration but nevertheless achieves significant energy gain.

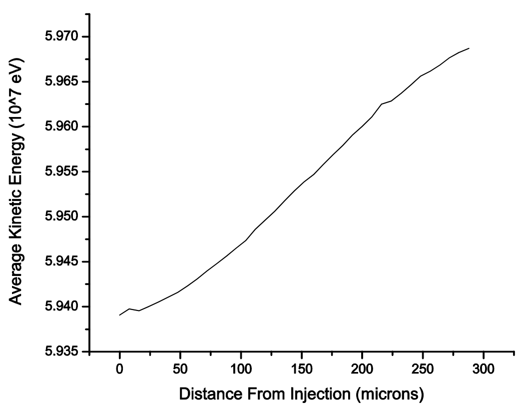

Fig. 6: Average bunch energy versus longitudinal distance from the location of injection.

In addition to creating a structure that accelerates relativistic electrons, we hope to design a structure that can accelerate low energy electrons. However, as is described above, we have not been able to excite a standing wave resonance with a wavelength small enough to accelerate electrons at subrelativistic energies. If a subrelativistic electron is injected into a structure that has a periodicity designed for a relativistic electron, it will travel a distance less than one period of the structure during one period of the incident laser. Thus, synchronicity is not achieved and phase slippage occurs.

An approach, motivated by the work of Ming Xie, in which two different period lengths coexist in the same model (for instance, a 700 nm period adjacent to a 800 nm period) can potentially set up a standing wave resonance whose periodicity changes along the length of the structure. In this structure, low energy electrons will experience continuous phase slippage, but the standing wave resonance can be designed in such a way that more energy is gained while the electron slips through "accelerating phases" than is lost when it slips through "decelerating phases."[5] Studies of this alternating gradient structure are underway.

In addition to achieving net acceleration, we also need to ensure that the electrons travelling through the accelerating cavity remain transversely focused and longitudinally stable. Equation 2 shows the forces experienced by the electrons travelling along through the accelerating mode resonance [1].

$$F_z = qE_0 \cosh\left(\frac{\omega y}{\beta c \gamma}\right)\cos\left(\frac{\omega z}{\beta c}\right);$$
$$F_y = \frac{qE_0}{\gamma}\sinh\left(\frac{\omega y}{\beta c \gamma}\right)\sin\left(\frac{\omega z}{\beta c}\right). \qquad (2)$$

Here, q is the electron charge and E_0 is the electric field amplitude of the incident laser. Clearly, if an electron is in a phase such that it is longitudinally stable and accelerated, it experiences forces that are transversely defocusing. However, this defocusing force approaches zero as the electron velocity approaches the speed of light and correspondingly, transverse defocusing does not occur in simulations of relativistic electron bunches. On the other hand, for subrelativistic electrons, the transverse defocusing force is non-negligible. Ming Xie's phase slippage approach has provided for transverse focusing in other linac-type structures [5] and its applicability to the MAP is under investigation.

CONCLUSIONS

Using HFSS and VORPAL, we have developed a full understanding of the relativistic MAP structure and have successfully simulated particle acceleration of relativistic electrons. Efforts to develop a similar understanding of the subrelativistic MAP structure are underway.

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