# LASER ACCELERATION OF ELECTRONS

Research Brief for Ph.D Qualification Examination

**Rodion Tikhoplav**

Department of Physics and Astronomy

University of Rochester, Rochester,

New York 14620

April 2001

## ABSTRACT

We study the possibilities of using a laser beam to accelerate charged particles (electrons) in a waveguide structure with dimensions much larger than the laser wavelength. The laser operates in the $TEM_{01}$ mode which provides the largest possible longitudinal component of the electric field. The laser output is transformed into radial polarization and injected into an Open Iris Waveguide structure. Such a structure allows the transfer of longitudinal momentum from the laser to the electrons. The phase velocity of the laser and of the electron beam can be matched by introducing an inert gas at low pressure into the structure. We propose to test this acceleration

scheme at the A0 electron source (15 MeV) at Fermilab. The expected accelerating field is of the order of 90 MV/m.

# I. INTRODUCTION

In the last decades particle accelerators of ever increasing energy have been built an operated. All of these machines use RF technology. However because of synchrotron radiation high energy electron colliders cannot be circular machines and this requires very high accelerating fields if the machine is to be of finite length. Thus there has been a concerted effort to find alternate acceleration mechanism that can provide these high gradients. These involve acceleration by fields induced in plasmas and acceleration by focused short laser pulses [1-5].

All the laser acceleration schemes must provide a longitudinal component of the field and remain in synchronization (phase matched) with the electron bunch. In the RF regime this is achieved by propagating the RF power in a waveguide or similar structure. Such structures have dimensions of the order of the RF wavelength. For a laser field this would imply structures of dimensions of 1 μm, which in turn, makes the tolerances on the electron beam size and position almost impossible.

In 1996 R. Pantel [1] proposed a scheme for propagating a laser beam in an open iris structure which is analogous to propagation in a Fabry-Perot resonator with flat mirrors. This scheme has been analyzed in detail by M. Xie [4] but has not as yet been tested. The phase velocity of the laser beam is only slightly in excess of the speed of light so that for a fully relativistic electron beam the phase matching length is 67 cm. Thus, for 34 TW of laser power (the maximum that that can be supported by the structure) the accelerating field $E_a$=0.54 GV/m [4].

Since our test will be carried out with low energy electrons (15 MeV) we must provide a phase matching mechanism. We propose to load the structure with an inert gas to slow down the laser phase velocity. For 1 atmosphere of Xe we have $v_L = c[1-7\times10^{-4}]$ which equals to the electron beam velocity $v_c = \beta c$.

We plan to use initially 2 J pulses of 2 ps duration $\lambda$=1054 nm focused to the area of ~1 $mm^2$ thus at peak intensity $I=10^{14}$ $W/cm^2$ resulting in an acceleration gradient of 90MV/m. For a 0.5 m structure the energy gain will be 45 MeV, which is a spectacular change in momentum for our low energy injected test beam.

## II. THE OPEN IRIS-LOADED WAVEGUIDE STRUCTURE AND PHASE MATCHING

We will use a regenerative Nd:glass laser with $\lambda$=1054 nm (Fig. 1) seeded by the oscillator used for the A0 electron source (Fig. 2) to initially generate 20 mJ pulses. These will be compressed to a 2 ps width.

The accelerating structure has the following parameters:

-length: 10 cm (25cm),

-diameter: $2a$=1mm,

-number of elements: 50 (125),

-thickness of an element: $L$=2mm.

Each element has tapered edges with the angle of tapering greater than diffraction divergence angle $\theta_d=\lambda/a$, so that the light sees it as infinitely thin iris [Fig. 3].

The structure can be visualized as an “unfolded” flat mirror Fabry-Perot resonator with Fresnel number:

$N=a^2/\lambda L=119$,

and $Q=2\pi L/\lambda\alpha_c=26\text{x}10^6$,

where $\alpha_c$ is loss per cell; $\alpha_c=8\nu_{11}{}^2(M+\eta)\eta/[(M+\eta)^2+\eta^2]^2$,

where $\nu_{11}$ is the first zero of Bessel function: $J_1(\nu_{11})=0$, $\nu_{11}\cong3.832$;

$\eta= -\zeta(0.5)/\pi^{1/2}$,

and $\zeta$ is Riemann's Zeta function;

$M=[8\pi N]^{1/2}$.

Theoretical losses over a length ☹$=10$ cm (and, later we will use 25 cm) should be less than 5% (10%). It is interesting to note that such a large $Q$ factor allows the structure to be effective for a length of up to five meters.

Intensity loss in the excluding beam loading structure is not the only problem we need to overcome. The other important problem is phase matching. For the low-energy (less than 50MeV) electrons, the structure should be filled with Xe. We wish to have $\beta=1/n$, where $\beta=\mathrm{v}/c$, $n$ is the refraction index or $(n-1)\cong 0.5m^2/E^2$, where $m$ and $E$ are the rest mass and the energy of an electron respectively; for Xe at atmospheric pressure $(n-1)=7\times10^{-4}$, and for an electron with energy of 15 MeV (10 MeV) $0.5m^2/E^2\cong 5\times10^{-4}$ ($\cong 10\times10^{-4}$). For high-energy electrons (greater than 1 GeV) He at 0.2 atm can fully compensate for the phase velocity of the structure. $\mathrm{v}_p\cong c[1+0.75\times10^{-5}]$. Note that the refractive index of He at 1 atm is $(n-1)=3.5\times10^{-5}$. Since the index of refraction depends on the gas' pressure, it can be used for fine tuning of the structure. Note however that the gas should not break down under the laser pulse.

It is interesting to note that since the velocity matching is achieved, the strong focusing for a half of the electrons occurs (and strong defocusing for the other half). This is due to the fact that longitudinal component of the electric field is 90° out of phase from the transverse (radial) electric field. So half of the accelerated electrons experience outward (focusing) radial electric field, and the other half—inward (defocusing) electric field.

## III. RESULTS OBTAINED SO FAR

For symmetry reasons and to gain a factor of $\sqrt{2}$ in accelerating field for given laser power, it is desirable to use radial polarization of the laser [5]. A radially polarized field is shown in Fig. 4a and the intensity distribution in Fig. 4b. This mode is designated as the $TEM_{01}*$ mode (doughnut-shape).

One method for obtaining the $TEM_{01}*$ mode is shown in Fig. 5. We extract a $TEM_{01}$ mode from the laser and split it into two beams (50/50 beam splitter *BS*). One beam is rotated by 90° in periscope *PS1*, and the two beams are then recombined (in beam cube *BC*) with the proper phase relationship; to compensate for the height difference of the two arms of the interferometer a second periscope *PS2* is used. To compensate for possible intensity difference, the combination of polarizer (*P*) and half-wave plate ($\lambda/2$) is used; to make sure that the beams recombine in phase we use a piezo-driven mirror (*Pz*). The failure to phase-match results in getting another (non-radial) mode (Fig. 6).

We have successfully built the interferometer and got the doughnut-shape mode (Fig. 7); we have also tested it for phase matching using a polarizer turned to different angles (Fig. 8).

The 10 cm structure also has been built and we obtained 85% (intensity) transmission through the structure. The mode-structure of the beam remains the same before and after the waveguid (Fig. 9). In fact there is no divergence of the beam associated with the structure—it acts like a weekly focusing lens focusing enough to overcome natural divergence of the Gaussian beam.

At this moment we are working on setting up a Q-switched pulsed laser (2 ns) to test the mode behavior (the interferometer plus the wave guide) in the pulse mode regime.

# BIBLIOGRAPHY

(1) R. Pantell, talk presented at FEL conference, 1996.

(2) W.D. Kimura et al., Phys. Rev. Lett. **74**, 546 (1995).

(3) Y.C. Huang al., Appl. Phys. Lett. **68** (6), 753 (1996).

(4) M. Xie, Proc. Of 1997 Part. Accel. Conf., 660 (1997).

(5)