# LASER ACCELERATION OF ELECTRONS

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## *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-loaded Waveguide structure (OILS). 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.

## 1 INTRODUCTION

There has been a concerted effort to find alternate mechanisms that can provide higher accelerating gradient. These involve acceleration by fields induced in plasmas and acceleration by focused short laser pulses [1-4].

All the laser acceleration schemes must provide a longitudinal component of the field and remain in synchronization 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].

## 2 OILS AND PHASE MATCHING

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

The parameters of accelerating structure are specified in Table 1.

Table 1: Structure Parameters

| **Parameter** | **Value** |
|---|---|
| Length | $\Lambda$=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 $\alpha_T$ greater than diffraction divergence angle $\theta_d=\lambda/a$, so that the light sees it as infinitely thin iris [Fig. 1].

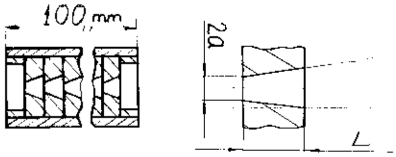

Figure 1: OILS Wavegide.

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

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

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

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: $J_1(\nu_{11})=0$,

$$\nu_{11}\approx 3.832;\ \eta=-\zeta(0.5)/\pi^{1/2},$$

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

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

Theoretical losses over a length $\Lambda$=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 $\beta$=v/$c$, $n$ is the refraction index or

$$(n-1)\approx 0.5m^2/E^2,$$

where $m$ and $E$ are the rest mass and the energy of an electron respectively;
for Xe at atmospheric pressure

$$(n\text{-}1) = 7\times10^{-4},$$

and for an electron with energy of 15 MeV

$$0.5m^2/E^2 \approx 5\times10^{-4}.$$

For high-energy electrons (greater than 1 GeV) He at 0.2 atm can fully compensate for the phase velocity of the structure:

$$v_p \approx c[1+0.75\times10^{-5}].$$

Note that the refractive index of He at 1 atm is

$$(n\text{-}1) = 3.5\times10^{-5}.$$

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.

## 3 RESULTS OBTAINED SO FAR

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

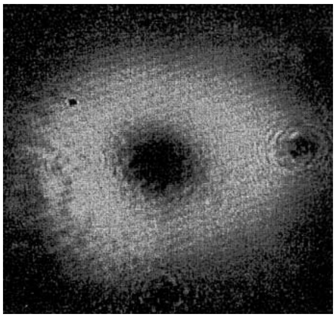

Figure 2: $TEM_{01}$* mode.

One method for obtaining the $TEM_{01}$* mode is shown in Fig. 3. 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 *Per.*, and the two beams are then recombined (in beam cube *CC*) with the proper phase relationship; to compensate for the height difference of the two arms of the interferometer a second periscope 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 (*M*).

We have successfully built the interferometer and obtained the doughnut-shape mode in the pulse regime; we have also tested it for phase matching using a polarizer turned to different angles.

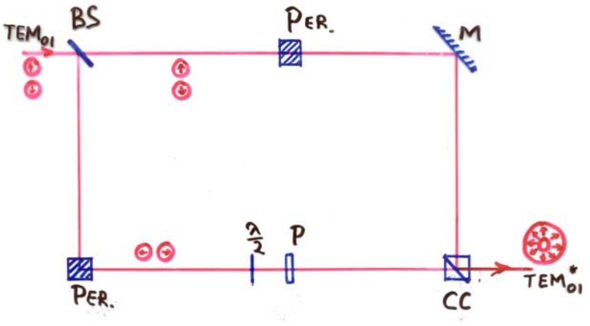

Figure 3: Mach-Zehnder interferometer.

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 waveguide. In fact there is no divergence of the beam associated with the structure—it acts like a weakly focusing lens focusing enough to overcome natural divergence of the Gaussian beam.

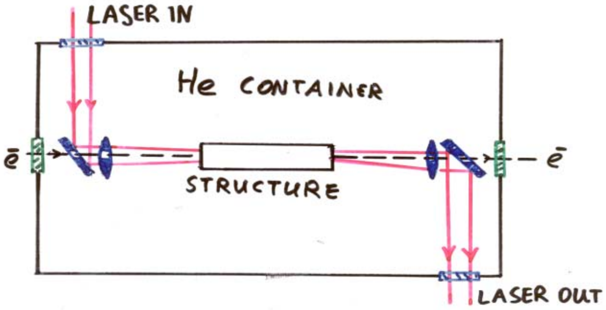

Figure 4: Chamber.

## 4 EXPECTED RESULTS

The chamber will be built and put into the beam line of the A0 electron source at Fermilab (Fig.4). Aluminum or titanium foil will be used as windows of the chamber (being able to withstand up to 2 atm of inert gas). Uncompressed electron beam (2 ps) will be used. The e-beam will be focused (to 200µm) and collimated to 50µm. The expected accelerating field is of the order of 10 MV/m for the 20 mJ laser pulse and 90 MV/m for 2 J.

## 5 REFERENCES

[1] R. Pantell, talk presented at FEL conference, 1996.
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[4] M. Xie, Proc. Of 1997 Part. Accel. Conf., 660 (1997).