Guiding of a Pulsed, Infrared CO_2 Laser with an Open Iris-Loaded Waveguide Structure

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Capillary waveguides are problematic for laser acceleration schemes due to the ease at which higher order modes of the laser are excited during wall interaction. The series of apertures of an Open Iris-Loaded Waveguide Structure (OILS), which are much larger than the laser wavelength and interact very little with the beam, allow little laser-wall interaction, thus there is no transfer of energy to higher order modes. We present initial designs and measurements of the OILS used to guide a plane polarized TEM_{00} mode, 10.6 micrometer, CO_2 laser pulsed at a 1 ns pulse length over a 10 cm path. The beam waist of .7 mm was optimized for optimum vacuum-guide coupling and low power loss. Initial measurements are performed at 1mJ and it was found that at least 73% laser transmission can be achieved with this open waveguide without exciting higher order modes.

Introduction

Motivation for the development and implementation of a new type of waveguide is its applications to new laser acceleration schemes such as the Inverse Free Electron Laser (IFEL) acceleration experiment at UCLA.

As higher acceleration gradients are needed for experiments in the realm of particle physics RF accelerators need to continually increase in size. While the desired gradients are achieved, from a practical point of view this solution is not desirable.

The IFEL is a new accelerator which will subject electrons that are already relativistic to an acceleration gradient up to 100 MeV/m.

This experiment requires a tightly focused (single mode), high intensity beam of radiation for the acceleration of electrons, which is difficult to maintain with a conventional hollow (capillary) waveguide whose dimensions are much larger than the wavelength of the laser. For the IFEL experiment the waveguide must be bigger than the laser wavelength in order to inject an electron beam down its axis and multiple modes won't be easily excited which drops laser intensity.

The open waveguide known as the Open Iris-Loaded waveguide Structure (OILS) is presented and studied here. Basic theory of how the structure should work and its advantages over hollow waveguides are discussed. Preliminary data on power transmission through the guide and preservation of the injected beam is also presented.

IFEL

The IFEL uses an "undulator" to cause electrons to oscillate in the same plane as the electric fields of a laser enabling them to become accelerated. An undulator, pictured in Figure 1, is a series of permanent magnets whose direction of polarity change in such a way as to make the electrons moving down the axis to oscillate at a given period transversely to their original direction of motion.

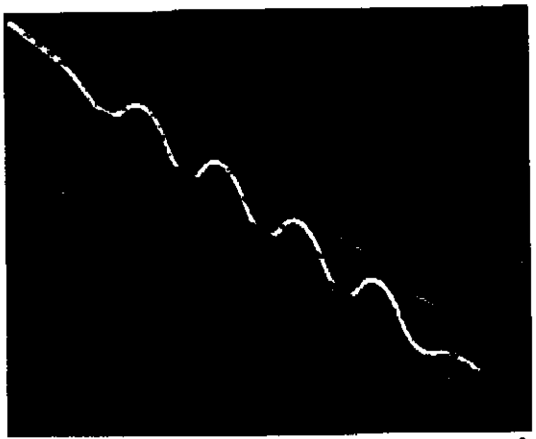

Figure 1: Undulator, a series of permanent magnets used in the IFEL experiment.

In this configuration the motion of the electrons is actually parallel to the electric fields of the injected laser beam so they can gain net acceleration if the laser wavelength λ_r and undulator period λ_u obey the relation

$$\lambda_r=(\lambda_u/\beta^2)(1+k^2), \quad (1)$$

$$\beta=U_e/mc^2$$
$$k\approx B_u\lambda_u$$

We are using a laser wavelength of 10.6 μm for the UCLA IFEL experiment, which then lets us determine what magnetic field magnitude and undulator period are required.

The radial electric field of the laser E_r is proportional to the inverse of the waste size of the beam w, or where the beam size is smallest and the wavefront is flat. At the Rayleigh length Z_r

$$Z_r=(\pi w^2)/\lambda_r \quad (2)$$

the intensity of the beam has decreased by a factor of $\frac{1}{2}$ and E_r has decreased by a factor of $\frac{1}{\sqrt{2}}$. We wish to have a focused beam with a small waist size so the Rayleigh length will be short making the beam diverge quickly at an angle

$$\theta = \lambda/\pi w \quad (3)$$

Therefore how the laser is focused and guided is crucial to laser-electron interaction.

Capillary Waveguides

To prevent an electromagnetic wave from diverging as it would in free space the wave can be injected into a hollow conductive tube known as a capillary waveguide. As with any electromagnetic wave, while within the guide the wave must obey Maxwell's equations by taking into account boundary conditions at the walls. A consequence is that only certain "modes" and wavelengths of waves can exist inside the tube, where a mode refers to a specific solution of Maxwell's equations. The TE mode is where there is no electric field in the longitudinal direction, TM mode is no magnetic field in the longitudinal direction, and the TEM mode is where both the electric and magnetic fields are only present in the transverse direction.

Theoretically the TEM mode can propagate through a capillary waveguide at any wavelength which makes it a desirable mode to use for experiments. If aligned appropriately these waveguides are very good at transmitting most of the laser power but it is very easy to excite higher order modes from laser-wall interaction destroying peak intensity and the electron acceleration scheme.

OILS

a) BACKGROUND

One of the reasons why the open waveguide structure known as OILS is a more desirable waveguide than a capillary waveguide is that higher order modes are not excited in an OILS since the irises appear infinitely thin to the laser. There is little interaction of the beam with the walls.

Also if aligned properly, very little power is lost in the guiding process which is important for the IFEL because an intensity of $5*10^{11}$ W/cm^2 is needed to "microbunch" the electrons so that they may be accelerated more efficiently.

b) THEORY

As can be seen from Figure 2 the OILS is simply a series of apertures, or irises shown in Figure 3, cut at an angle of ten degrees which is much larger than the diffraction angle of the laser

$$1.22\frac{\lambda}{2a} = 0.33^\circ \quad (4)$$

so the edges of the irises appear infinitely thin.

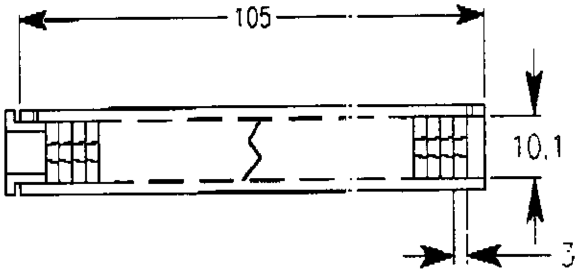

Figure 2: OILS waveguide, partially filled with guiding cells. Dimensions in mm.

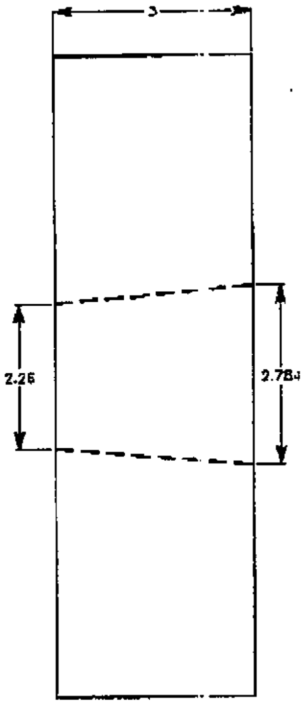

Figure 3: Individual waveguide cell with aperture cut at an angle of 10°. Dimensions in mm.

In order to lose minimal amount of power at the vacuum-aperture boundary maximum coupling for the TEM_{00} mode (single beam) has been calculated to occur at a ratio of beam radius to aperture radius (R/a) of 0.65. [1]

As the Gaussian beam of the laser passes through the series of irises the tails of the beam are cut off preventing the beam from diverging; the irises act as a weakly focusing lens. In the far-field the beam may be described by a Bessel function which has a much smaller divergence than a Gaussian.

The cornerstone of irises is even though the beam is allowed to diverge as it passes through each iris the divergence angle is so small that it is negligible. Rather than having an infinite number of irises throughout the length of the waveguide, or simply a tube, several irises may comprise the waveguide at a constant separation achieving the same effect as a hollow waveguide without much laser-wall interaction. Consequently no higher order modes are excited preserving the peak intensity in the middle of the beam. This concept is the most important aspect of the open waveguide. A capillary waveguide could easily replace the open waveguide in terms of beam power lost but it is too easy to excite different modes in a hollow waveguide which drastically reduces peak beam intensity.

It turns out that the eigenmodes of the open waveguide are identical to those of a Fabry-Perot resonator, which is simply two highly reflective panes of glass. Just as each iris in the waveguide cuts off the tails of the Gaussian creating a Bessel function in the near field each bounce of a laser in the resonator creates a Bessel intensity profile. Simply each bounce in the resonator is identical to each pass through an iris.

To calculate the power lost at each cell and to determine the exact aperture radius which should be used for maximum power transmission the following equation for power lost per cell may be used

$$\alpha_c \approx \frac{8{v_{11}}^2\eta}{(M+\eta)^3} \qquad (5)$$

v_{01} = first zero Bessel function = 2.4048

$M = \sqrt{8\pi N}$

N =Fresnel Number =$a^2/(\lambda$*cell length)

η =constant

a =aperture radius

The total transmitted power becomes

$$P = (1-\alpha_c)^N \qquad (6)$$

N =total guide length/cell length

A waveguide length of 9 cm was chosen as an appropriate length for proving that the structure was guiding the beam and will likely be an appropriate length for eventually microbunching of electrons. The power transmitted through the structure was calculated for different aperture radii and Figure 4 shows the power transmitted per cell length for a radius of 1.13 mm.

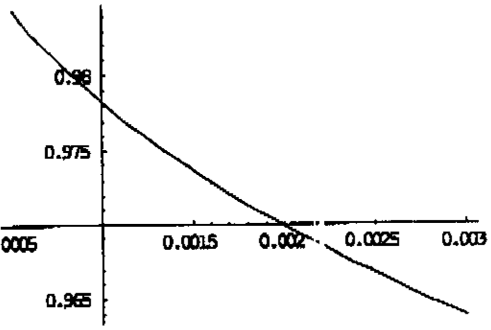

Figure 4: Cell Length (mm) vs. Power Transmitted (%) for 9 cm of waveguide.

From this calculation a cell length of 3 mm was then chosen since at least 95% transmission is expected and 3 mm is a reasonable dimension for machining of the cells.

The waveguide in Figure 2 was built by machining 30 individual aluminum disks of width 3 mm and diameter 10 mm then placing them inside an aluminum tube.

Experiment

To test the structure it was first set on multiple optical stages to have 2 degrees of freedom, pitch and yaw, given by translation stage on both ends of the waveguide for alignment ease. Shown in Figure 6.

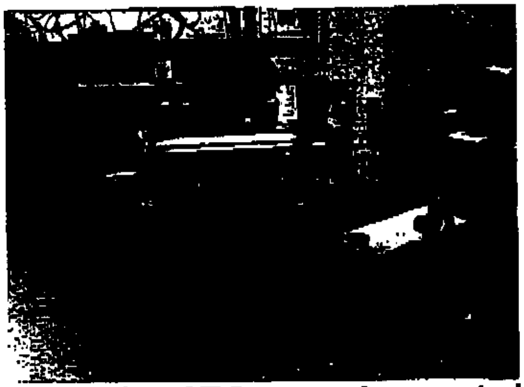

Figure 6: OILS mounted on optical stages.

The beam size and intensity was determined by directing the laser into a Pyrocam, which is simply a CCD camera capable of detecting 10 μm light, with and without the waveguide in the beam path. From the beam sizes and intensities the transmission efficiency of the waveguide can be calculated.

Even though there is little laser interaction with the walls and little laser power is expected to be lost the first tests were still conducted at a low laser energy of 1 mJ or less to make the operation of the experiment more simple. Later tests could be performed at energies as high as 100 J, where plasma formation, due to the laser removing electrons from the walls of the waveguide, will need to be taken into account. The plasma acts as a mirror for the laser drastically reducing the amount of laser power transmitted through the guide.

A copper concave mirror with a focal length of 1 m acted as a lens for the laser beam. The waist of the beam was determined by moving the camera along the length of the beam path downstream of the mirror to find where the beam size was the smallest. The waist was found to be 121.92 cm, so the beam is actually slightly divergent.

At the focal length, the beam had a waist of .7 mm which provides good coupling into the 1.13 mm radius aperture.

To determine the transmission efficiency of the waveguide the camera was kept in the same spot downstream of the waist throughout the experiment. Data was taken with the waveguide placed upstream of the waist at a beam size of 1.36 mm. The beam shown in Figure 7 is the laser without the waveguide in place and has an approximate area of 1.74 mm^2 with an intensity of 80 (a.u.).

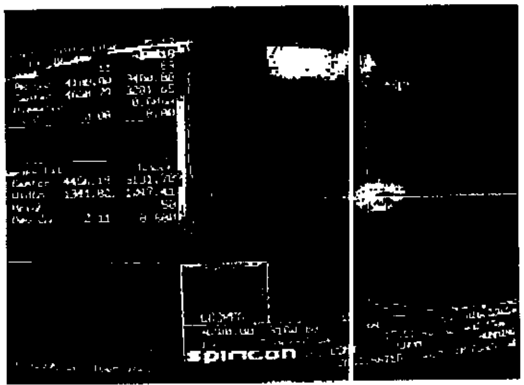

Figure 7: Picture of Pyrocam screen showing the beam shape without the waveguide in place.

Figure 8 shows the shape of the beam with the waveguide. The spot size is smaller at 1.12 mm^2 and the intensity increased to 90; also the spot is nearly circular with no diffraction patterns.

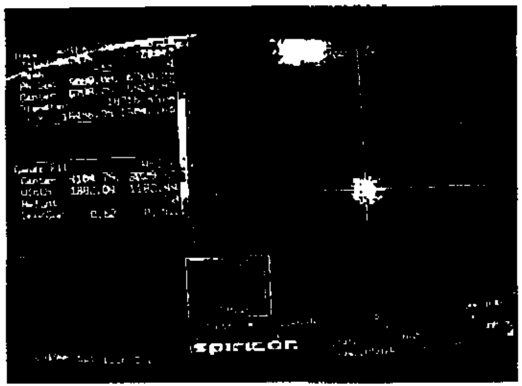

Figure 8: Picture of Pyrocam screen showing the beam shape with the waveguide in place.

This is proof that the beam was guided without exciting higher order modes. Using beam energy

$$E = IA \quad (7)$$

where I is the intensity and A is the area, the transmission efficiency was calculated to be 73%.

It should be noted that since the beam was not circular coupling was most likely not ideal in addition to the fact that data was not taken at the waist but upstream of it so the R/a coupling condition was another factor that decreased beam transmission.

Conclusion

The increase of the beam's intensity while traveling through the waveguide is promising but to be more conclusive future measurements will need to involve comparing measurements of the beam at equal distances before the structure and after it. If the waveguide is in fact acting as a reliable structure the size of the two spots should be the same since the waveguide is essentially increasing the length of the waist but leaving the rest of the beam unchanged.

References

[1] M. Xie, *Laser Acceleration in Vacuum and Gases with Capillary Waveguide*, LBNL-42733, *Phys. Rev. Lett.* (1999)