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AN EXPERIMENT ON FEL EFFICIENCY ENHANCEMENT WITH A VARIABLE WIGGLER

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Summary. At TRW, an experiment is in progress to deomonstrate efficiency enhancement on a FEL. This is accomplished by trapping the electrons in the ponderomotive potential well generated by a linearly polarized CO_2 laser beam and a tapered magnetic wiggler. An adiabatic reduction in the wiggler amplitude and/or wavelength results in an electron beam energy loss which is transformed into radiation. In the TRW experiment, the electron beam is generated by an rf linac with an energy of 25 MeV and 40 A in the microbunch. The CO_2 laser driver is a 1 Joule injection mode locked TEA laser delivering 100 MW in the interaction region. The 3 kG wiggler field is generated by SmCo permanent magnets with a magnet gap of 1.45 cm and a wavelength of λ_w = 3.56 cm. The interaction region is 300 cm long. The system is operated at a high repetition rate to facilitate diagnostics. A trapped electron extraction of approximately 3% is expected based on theoretical predictions.

A Free Electron Laser (FEL) device generates stimulated radiation by the interaction of a relativistic electron beam and an external electromagnetic wave or pump.(1) The intensity of the emission increases with the pump amplitude(2) and it is advantageous to use an external ripple magnetic field ("wiggler") as the external pump. The stimulated radiation wavelength λ_s is proportional to the wiggler wavelength λ_w downshifted by a factor proportional to the square of the relativistic electron beam energy ($E_b = \gamma mc^2$). For example, for a sinusoidal wiggler of amplitude B_w,

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + 1/2\, a_w^2\right) \tag{1}$$

where

$$a_w = \frac{qB_w}{mc}\,\frac{\lambda_w}{2\pi}$$

Recently(3), it has been suggested that the FEL efficiency can be dramatically enhanced by adiabatically tapering the wiggler field amplitude and/or wavelength. In this manner, the energy and shape of the ponderomotive potential well ("bucket") formed by the interaction of the wiggler field with the electrons and the amplified laser signal can be spatially varied (cf. Figure 1). The electrons that are initially trapped in the bucket tend to remain trapped if the motion is sufficiently adiabatic. As the bucket energy decreases, the mean energy of the trapped electrons is reduced. The energy is extracted as amplification of the input laser power. This concept has been discussed in References 3 and 4. The total efficiency of the process depends on: the number of electrons trapped in the bucket (trapping efficiency = $\eta_t \simeq J_t/J$) and the deceleration efficiency of the trapped electrons, η_D, which is approximately equal to the deceleration efficiency of the "resonant" or synchronous particle (cf. Figure 1)

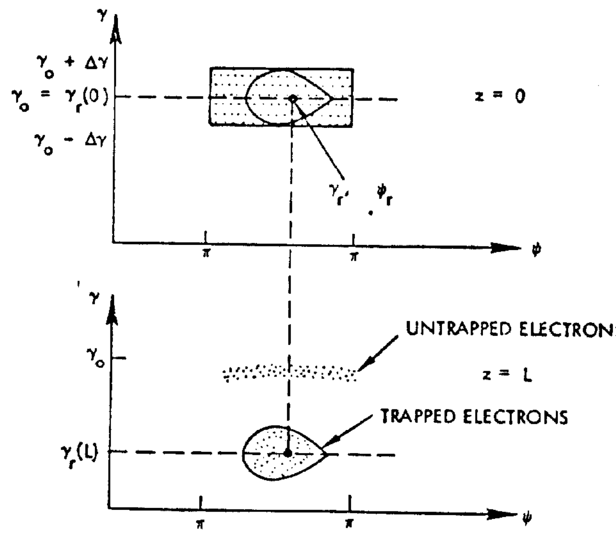

Figure 1. Adiabatic Decrease in Energy of Bucket and Trapped Electrons.

thus,

$$\eta_D = \frac{\gamma_r(z) - \gamma_r(0)}{\gamma_r(0)} \tag{2}$$

The total energy spread is mainly determined by the "longitudinal" energy spread due to the variation of the rf cycle, the d.c. longitudinal space charge of the microbunch and the "effective" transverse energy spread. This transverse energy spread is due to the random transverse motion of the electrons(5) (a consequence of the finite electron beam emittance) and the radial nonuniformity of the wiggler field that is seen by a finite radius electron beam.

Maximum trapping efficiency requires that the bucket height (h_B) (amplitude of the potential well) be equal or larger than the total energy spread $\left(\frac{\Delta\gamma}{\gamma}\right)_T$. Hence, a possible optimization of the FEL system is obtained by choosing the external parameters in such a way that the following relations are satisfied;

$$\left.\frac{\Delta\gamma}{\gamma}\right|_{long} \simeq \left.\frac{\Delta\gamma}{\gamma}\right|_{\varepsilon} \simeq \left.\frac{\Delta\gamma}{\gamma}\right|_{\nabla B} \tag{3}$$

$$h_B \geq \left.\frac{\Delta\gamma}{\gamma}\right|_{total} = \left.\frac{\Delta\gamma}{\gamma}\right|_{long} + \left.\frac{\Delta\gamma}{\gamma}\right|_{\varepsilon} + \left.\frac{\Delta\gamma}{\gamma}\right|_{\nabla B} \tag{4}$$

where the subscript ε and ∇B refer to emittance and wiggler gradient respectively. In addition the envelope of a finite emittance electron beam in the

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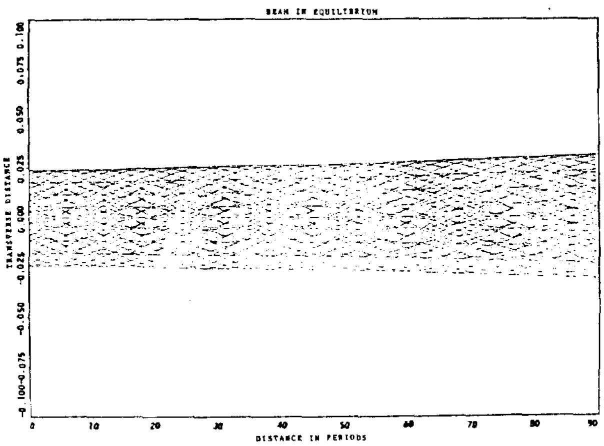
presence of a wiggler field will execute "betatron oscillations" unless the initial radius is chosen in such a way that the defocusing due to the emittance is exactly balanced by the focusing due to the wiggler field. This is the "equilibrium radius" (r_o) of the electron beam. Thus, the parameters are also chosen in such a way that the electron beam radius at the entrance of the wiggler field is the "equilibrium radius". For a tapered wiggler, the equilibrium radius will slowly increase as shown in Figure 2. It should be noted that the condition for the equilibrium radius in a constant wiggler is identical to the requirement imposed by eq. (3).

Figure 2. Transverse Motion of Electrons Including Taper in Wiggler Field



For the experiment described in this paper, $\epsilon \leq 5$ mm mrad and $r_o \simeq 3$ kG. The maximum wiggler field can be determined from the requirement that the radius of the photon beam at the entrance be sufficiently smaller than the wiggler radius to avoid edge diffraction. Further, maximum efficiency is obtained by also requiring a minimum filling factor, defined as the area of the photon beam to the electron beam.

Another design consideration regarding the wiggler parameters is given by the design choice of a_w = constant, or B_w = constant, or λ_w = constant, etc. These choices have been discussed in Ref. 3. Numerically, it is found that for low gain systems, the final efficiencies are not very sensitive to the design choice (a_w = constant or B_w = constant, etc). However, the choice λ_w = constant where the magnetic field amplitude is adiabatically decreased, is experimentally simpler and was therefore chosen for the design. It should be noted that by keeping λ_w= constant and varying B_w, the longitudinal phase velocity v_{ph} of the bucket remains approximately constant $(\omega_s/k_w + k_s)$ = constant. The decrease in total energy is due to the reduction in "effective electron mass" or "perpendicular energy" denoted by the term a_w^2 in Equation (1).

The input laser signal (driver) power density is chosen as the maximum experimentally available that can be produced by high repetition rate. In addition it must satisfy the following conditions: 1) Its magnitude should be sufficiently high to produce an energy extraction efficiency from the trapped electrons larger than 5%. 2) When it interacts with the wiggler field it should produce a "bucket" such that the bucket height is larger or equal than the total experimental electron energy spread.

The following system parameters were chosen for the experiment:

Electron beam: E_b = 25 MeV; γ = 50
$\epsilon \leq 5$ mm mrad; $\Delta\gamma/\gamma$ = .01
$I \leq 40$A peak

Laser: $\lambda_s = 10.6\mu$m; $P_{in}^{(1)} \simeq 200$ MW/cm^2
$P_{in}^{(2)} \simeq 800$ MW/cm^2

Wiggler: λ_w = 3.56 cm
initial field $B_{wi}^{(2)}$ = 2.95 kG
final field $B_{wf}^{(2)}$ = 2.55 kG

where (1) and (2) indicate different input powers experiments. The theoretically predicted gain for the system is 17% at Z = 3m for an electron beam peak current density of 2.55 A/mm^2. The extraction efficiency from the trapped electrons is predicted to be 4.5%. For system (1) the gain is predicted to be 35%.

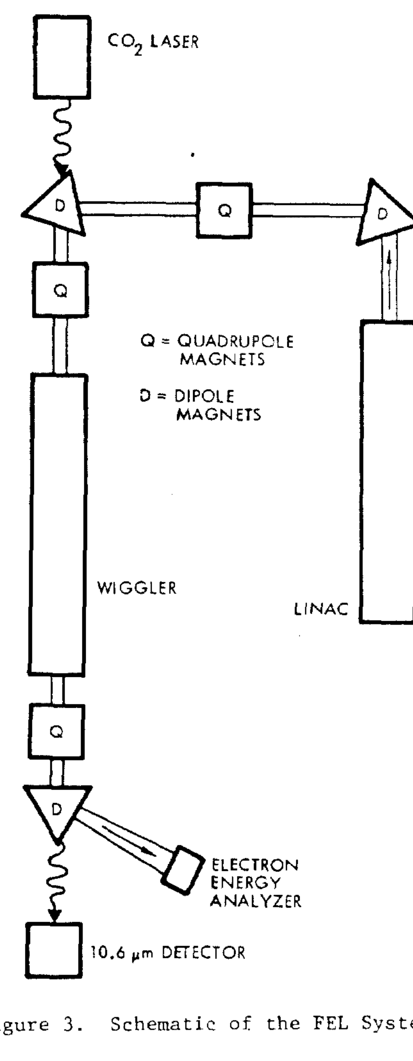


Figure 3. Schematic of the FEL System

Figure 3 shows schematically the arrangement of the experimental setup. The RF linac located at EG&G in Santa Barbara, California, has an energy range of 1 - 30 MeV with 25 MeV nominal operating point. The maximum current is 40A in a 50 psec micropulse. The emittance was measured to be 4.0 mm mrad for an energy width of 1% and peak current of approximately 16A; and 1.8 mm mrad for $\Delta E/E$ = .5% and $I_p \simeq$ 6A. Quadrupole, driver and steering magnets have been designed to focus the beam into the magnetic wiggler with a 2x8 mm elliptical waist, the smaller dimension being in the direction of the wiggler field. This focal spot has been produced successfully with the 25 MeV beam. The electron beam analyzer separates the output electron beam from the output optical radiation and will be used to determine the electron beam energy lost in the FEL interaction.

The wiggler chosen is a pair of linear permanent magnet arrays which produce a sinusoidal field on axis. The arrangement of the magnetic field vectors is shown in Figure 4. The arrows in each magnet indicates the magnet polarization. The field at the symmetry axis is given by:

$$B = 2B_s \sum_m A_m \cos(nkz) \exp(\frac{nkd}{2})$$

where B_s is the magnet surface field of 8.5 kG, n = 1 + 4 m, d the separation between the arrays, and A a factor that depends on the numbers of magnets per wavelength, the filling factor and the length of the magnets. The field strength (B) that can be produced by this arrangement depends on the wavelength of the field desired and the spacing between the planes plus a factor depending on the spacing between the magnets. The magnetic field strength and the wavelength must also self-consistently satisfy the resonant condition for 10.6 μm. Away from the midplane the magnetic field rises according to a hyperbolic cosine off axis. Non-uniformities off axis in the central plane have been determined to be less than .5% over the ID of the beam line (1.5 cm) by computer calculations using the measured field values on axis as input.

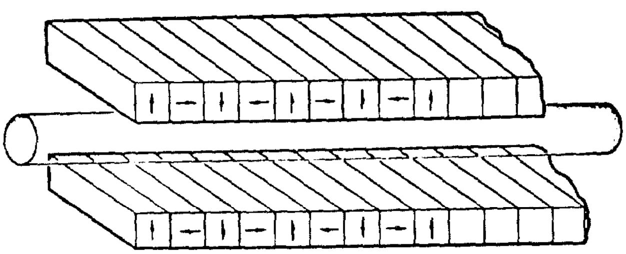
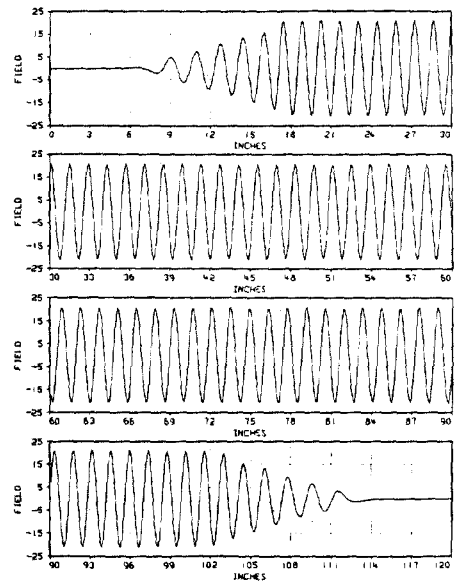


Figure 4. Permanent Magnet Wiggler

The electron beam optics of the wiggler requires careful consideration. The entrance and exit of the wiggler are tapered to provide undisturbed beam propagation. The alternating gradient focusing action of the wiggler field is used to confine the beam in the direction of the wiggler field as described above. Transverse to the field, the beam is focused in the midplane of the wiggler by a set of quadrupoles.

The wiggler has been assembled in sections of 15 wavelengths each, using proper spacers between the parallel magnet arrays. The wiggler has either constant amplitude or can be tapered. Figure 5 shows the measured constant amplitude field distribution. The performance has been checked by calculating the beam orbit through the wiggler and adjusting individual magnets for undisturbed beam propagation.

Figure 5. Measured Constant Amplitude Field Distribution



The optical system consists of a laser driver, beam propagating optics and diagnostics. The laser driver makes use of a commercial CO_2 TEA laser, Gen-Tec model DD300, capable of delivering 1 Joule per pulse at a repetition rate greater than 100Hz. This laser is used as an injection mode locked oscillator, delivering the output energy as a number of sharp pulses with peak power of 100 MW. The injection mode locking is achieved by injecting into the laser a short pulse, chopped from the output of a low power quasi-cw laser, using an electro-optic switch. The low power laser delivers 20W single line and a fast CdTe Pockets cell between crossed polarizer is the optical switch. In the initial test of the system, using a 4.5ns FWMM electrical pulse on the Pockets cell, 15 MW peak power was extracted from the laser, corresponding to a power of 60 MW/cm^2 in the interaction regime. We are in the process of improving the system, including reducing the width of the injected signal to 1 ns to make full use of the TEA laser bandwidth, and expect to achieve 200 MW/cm^2 shortly. The higher 800 MW/cm^2 power will be produced by the addition of a Lumonics amplifier.

The optical diagnostics include measurement of the gain and beam quality. Measuring the gain is difficult, since the fastest detector available for 10.6 m is a pyroelectric detector with a rise time of 500 ps, whereas the amplification of the 1ns input laser beam occurs only during the 50 ps duration of the electron beam. For a gain of 17% the amplified signal is only 2% larger than the unamplified signal. Several different techniques have been developed to overcome this problem. The most promising technique makes use of crossed polarizers to selectively reject the input radiation in favor of the amplitude radiation. This technique makes use of the fact that the gain itself is linearly polarized. If the input radiation is linearly polarized at an angle of 45^{o} to the gain axis then the effect of the gain is a net rotation of the output polarization which can be observed through crossed polarizers. Using this technique, the gain signal can be increased from a 2% effect to a 25% effect using the parameter from our experiment.

Another technique makes use of Michelson's interferometer to perform an autocorrelation measurement of the output to increase the time resolution of the measurement.

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