PHYSICS DESIGN FOR THE ATA TAPERED WIGGLER 10.6 μ FEL AMPLIFIER EXPERIMENT*

W. M. Fawley and the Beam Research Group
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550

Abstract

We are presently designing and constructing a high-gain, tapered wiggler 10.6 μ FEL amplifier to operate with the 50 MeV ATA e-beam. The initial experiments will be done with a constant period (λ_w = 8 cm), 5 m-long linear wiggler. For an input laser power of 800 MW and electron beam brightness of 2.10^5 A/(rad-cm)^2, we hope to achieve a trapped particle fraction ~0.5 and an energy extraction efficiency of ~2% with a ~10% taper in the wiggler magnetic field. This taper corresponds to decelerating the trapped particle approximately two full ponderomotive well (i.e. bucket) heights. In this talk, we will discuss the physics motivations behind our tapered wiggler design and initial experimental diagnostics.

Introduction

There has recently been great interest in the possibilities of building ground-based, high power lasers. One leading candidate has been the Free-Electron Laser (FEL), and, in particular, the tapered wiggler amplifier variant [1]. Following the success of our microwave FEL facility (ELF) [2,3] on the 3.3 MeV Experimental Test Accelerator, we are designing a 10.6 μ high gain amplifier to operate on the 50 MeV Advanced Test Accelerator (ATA) at LLNL.

FEL operation is very similar to that of an RF linac, however, with the electron beam losing rather than gaining energy from the electromagnetic field. The transverse magnetic field of the wiggler slows down the longitudinal velocity of a relativistic electron beam such that a given transverse "slice" of electrons, when in resonance, falls back one optical wavelength for each wiggler wavelength traversed. The combination of the electromagnetic wave and static wiggler magnetic field sets up a ponderomotive potential well in which resonantly "trapped" electrons execute "synchrotron" motion as they move longitudinally down the wiggler.

In contrast to an FEL oscillator whose wiggler length (at saturation) is approximately one-half of a synchrotron wavelength long, and through which the laser beam may pass hundreds of times, a tapered wiggler FEL amplifier can be exceedingly long, but is a single pass device. The amplifier starts with a relatively high power laser beam in order to trap a significant fraction of the electron beam in the ponderomotive well during its single pass. To resonantly extract energy over distances long compared to the synchrotron wavelength, the wiggler vector potential must be continually tapered. The taper may be in either wiggler wavelength or magnetic field strength; we have opted for the latter and will use a constant period of 8 cm. The requirement of an adjustable taper leads one to use a linear, rather than helical wiggler geometry. This choice, together with a wiggler length which can be many betatron wavelengths long, necessitates a focusing mechanism in the transverse wiggle plane which causes neither steering errors nor disruption of the FEL resonance [4].

* Performed jointly under the auspices of the US DOE by LLNL under W-7405-ENG-48 and for the DOD under SDIO/BMD-ATC MIPR No. W3-RPD-53-A127.

FEL Beam Line Components

ATA nominally produces a 10 kA, 70 ns pulse whose edge emittance is too large to efficiently use in a high extraction FEL (for constant trapping fraction, the necessary input laser power scales as the seventh power of the beam emittance). We plan, instead, to use the central, high brightness ($\geq 2\times10^5$ Amps/(rad-cm)^2) 1-3 kA core of the beam current. An emittance selector, consisting of a small diameter metal pipe immersed in a variable strength solenoidal field, will separate this core from the remainder of the beam. A variable energy acceptance (1-5%), "rise time sharpener," in conjunction with the emittance selector, will permit us to inject a well-defined (in phase space) electron beam into the wiggler.

Between the emittance selector and the wiggler will be an achromatic jog to move the electron beam over 1.5 meters horizontally. At present, our design is comprised of two pairs of dipole bending electromagnets with a 2% energy acceptance. This horizontal offset allows easy insertion of the input laser beam and also the choice of sending the electron beam straight ahead into an auxilliary beam dump just beyond emittance selector instead of into the wiggler. The latter feature should prove useful during the time necessary to "tune" the accelerator and transport sections upstream of the achromatic jog.

We have decided to use an electromagnet/permanent iron magnet hybrid design (see Fig. 1) for the wiggler instead of a rare earth-iron hybrid. The latter is not easily adaptable to our desire for an easily tunable, tapered wiggler; such tunability has proven extremely useful in the ELF microwave experiment. Though our initial 5 meter long wiggler will generally be tapered 10% or less in magnetic field strength, the follow-on 25 meter experiment will need greater than 50% tunability. The pole pieces in the wiggler will be curved in order to give focusing in the direction perpendicular to B (perfectly flat pole pieces have transverse focusing only in the direction parallel to B). The proper curve (essentially a parabola near the axis) leads to equal strength focusing in both transverse directions. This permits an initially circular electron beam to remain so as it propagates down the wiggler. Since 25 meters corresponds to greater than three betatron wavelengths for our parameters, the focusing requirement is not a trivial one. Quadrupolar focusing in the wiggle plane of equivalent strength destroys the FEL resonance and reduces the net energy extraction by over a factor of ten.

Theoretical Predictions

We have exercised our two dimensional (r-z) FEL simulation code FRED [2,4] to explore the engineering requirements concerning the wiggler magnet assembly and 10μ laser driver. FRED studies the evolution of a single ponderomotive well of beam

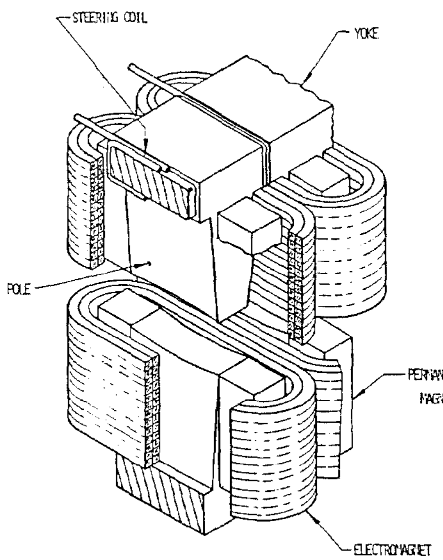

Fig. 1. An artist's depiction of one period of the 8 cm period hybrid permanent/electromagnet linear wiggler designed for the ATA 10.6μ FEL amplifier. Each two periods will be powered independently for maximum flexibility in taper tunability. The curvature visible in the iron pole piece provides focusing in the wiggle plane (left-right in this drawing).

particles as they propagate down the wiggler. Both the betatron and synchrotron motion of the particles are modelled. All quantities are assumed to be time-independent and axisymmetric at a given location. The wave equation is advanced under the paraxial approximation with the electron beam particles providing the self-consistent source term for the radiation field. In general, we load the simulation particles in a uniformly filled emittance ellipse in phase space which corresponds to a parabolic profile in the radial direction. The code can "design" its own wiggler taper by keeping a special probe particle at a constant phase in the ponderomotive well.

We have studied the sensitivity of the predicted output power and quality to various input parameters such as electron beam current and emittance; initial laser power, radius, and profile; and wiggler errors. One nice feature of the experiment is that the output power appears to be relatively insensitive to the initial laser profile (when described in either confocal cavity or Gauss-Laguerre modes). Putting all of the input laser power into a hollow mode reduces the output power by less than 10% when compared with an initially filled Gaussian profile. The predicted output Strehl ratios are quite good, generally exceeding 0.95. We attribute this high quality to the "smearing" effect of individual particle betatron motion and wave diffraction which tends to average out radially local imperfections in the gain function. We plan to make detailed spatial measurements of the output laser beam from the 5 meter experiment to verify these predictions from the simulation code, as it has important consequences for the design of much larger systems.

Another important prediction of FRED and simple linear theory [3] is the existence of exponential gain in the (relatively) low power regime. For initial laser powers of 1 MW or less, gains of 3 dB/m (see Fig. 2) should be attainable (on our microwave

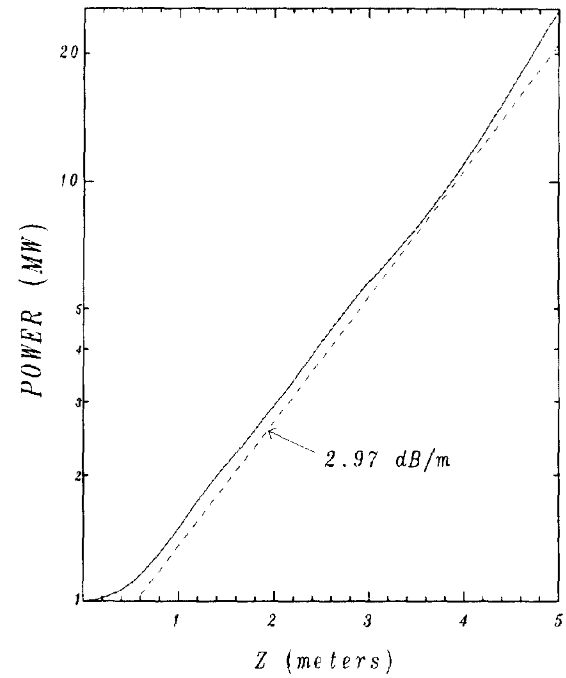

Fig. 2. A plot of output predicted 10.6μ laser power versus wiggler length showing exponential gain. The input parameters were 1 kA current, 50 MeV energy, .14 rad-cm normalized edge emittance, 1 MW initial laser power with a waist size of 0.35 cm, and 8 cm wiggler period. After an initial 50 cm necessary for the exponential growth to dominate, the laser power parallels nearly exactly to dashed line of constant exponential gain.

experiment ELF, power gains in excess of 30 dB/m have been observed over a total range of 80 dB!) If this phenomenon is verified in the "optical" regime, one should be able to use quite low input laser powers in FEL amplifiers by simply increasing the wiggler length to bring the laser power up to the point where significant energy extraction becomes possible.

Above 200 MW the relative gain predicted for the 5 meter experiment becomes smaller but the energy extraction efficiency can exceed 1%. The total taper in magnetic field strength approaches 10%; the equivalent change in resonant energy corresponds to greater than two full ponderomotive well heights. Since a short wavelength, tapered FEL amplifier will decelerate the trapped particle population many dozens of buckets heights for high extraction efficiency, it is extremely important to verify in the 5 and 25 m experiments that this can be done in a stable and controlled fashion.

Lastly, we hope to confirm the phenomenon of optical guiding predicted [5 and references therein] for high power FEL amplifiers. When a high current density electron beam is bunched sufficiently in an FEL, its effective index of refraction becomes greater than one and it begins to "guide" the laser beam, much like an optical fiber. This guiding is different than the self-focusing due to gain mentioned in [1]; it occurs solely due to the bunching and is present even in the total absence of gain. In the 6 Rayleigh length, 25 m ATA experiment, the guiding is predicted by FRED to have a strength such that the final laser beam waist is only ~twice as great as the input radius. Without such guiding, FEL amplifiers operating in the linear gain regime will be limited to a few Rayleigh lengths long.

References

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