HIGH-GRADIENT HIGH-ENERGY-GAIN INVERSE FREE ELECTRON LASER EXPERIMENT USING A HELICAL UNDULATOR

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Abstract

Preparations for a high energy gain inverse free electron laser (IFEL) experiment using an undulator and Brookhaven National Lab's (BNL) Accelerator Test Facility's (ATF) terawatt CO2 laser are underway. 3D simulations suggest that the experiment will likely accelerate a 50 MeV beam to 117 MeV in 54 cm while maintaining a low energy spread. The helical undulator is currently under construction at UCLA's Particle Beam Physics Laboratory.

INTRODUCTION

Novel accelerator applications such as deployable gamma ray sources based on inverse Compton scattering for long range sensing of nuclear material benefit from compact accelerators, and with this motivation we conceived of an IFEL experiment using a compact helical undulator [1]. Laser based accelerators provide much higher accelerating gradients than more mature rf accelerator technology, allowing greater portability of accelerators. Furthermore, control and manipulation of beams at the optical scale becomes possible. Because the accelerating medium is vacuum, laser to electron energy transfer is efficient and beam quality output is good. Previous IFEL experiments carried out at the ATF successfully demonstrated staging and production of beams with narrow energy spreads [2]. The 2004 UCLA Neptune IFEL experiment achieved a 150 % energy gain and an accelerating gradient in excess of 70 MV/m [3].

An IFEL interaction transfers energy from a laser to an electron beam traveling collinearly in an undulator. If the IFEL resonance condition is met, energy is transferred to the electrons within a ponderomotive bucket; however, as the electrons accelerate, they dephase and lose resonance. In order to overcome this handicap, one can taper the undulator period or field strength to keep the accelerated electrons at the resonant energy. Due to the fact that in a helical trajectory the transverse velocity is never zero, helical undulators are more efficient than ones with a planar geometry. We decided on a helical design for a larger accelerating gradient which should allow for significant energy gain for an IFEL.

CONSTRUCTION

The helical undulator consists of 212 magnets arranged in 11 periods along the length of the undulator. Each undulator period has a unique wavelength and field strength. The tapering design was based on magnetostatic simulations which were validated on two previous non-tapered helical undulator devices tested at UCLA's Neptune laboratory. [4] Construction is currently underway. The magnets are rectangular with a tapered end and were wire cut from a single permanent rare earth magnet with field strength of 1.22 Tesla. An excess of magnets allows for magnet sorting. We measured the field with a hall probe at several specific points on each magnet's surface, and compiled the measurements in a database.

To ensure the most uniform field on the undulator's axis, we removed magnets with magnetization misaligned from the geometrical axis by more than 2 degrees based on the manufacturer's measurements. We then discarded magnets which differed more than 2 sigma from their similar magnets' mean values. Finally, we removed

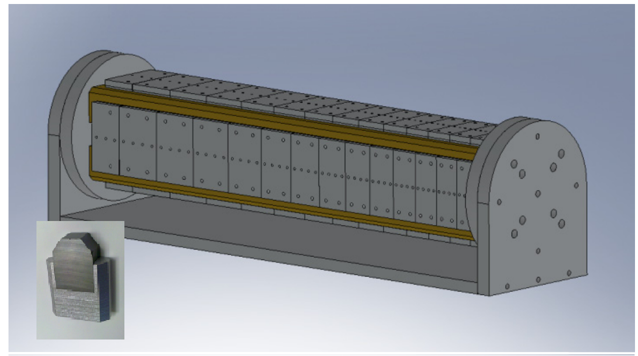

Figure 1: Assembled undulator and magnet in holder.

Table 1: 3D simulation Parameters and Results.

Parameter	Value
Input beam energy	50 Mev
Final beam energy	117 MeV
Final beam energy spread	2%
Captured fraction	>24 %
Average accelerating gradient	124 MV/m
Laser wavelength	10.6 μm
Laser power	0.6 TW
Laser spot size	550 μm
Laser Rayleigh range	9.4 cm
Undulator length	54 cm
Undulator period	4 – 6 cm
Undulator magnetic field amplitude	5.2 – 7.7 kG
Undulator gap	15 mm

magnets with the worst non uniform magnetization by comparing field measurements which should be identical given a geometrical symmetry. The magnets are then epoxied into precisely cut holders which attach to tuning plates used to adjust the undulator gap by +/- 50 μm on each side.

SIMULATIONS

Method

For full three dimensional simulations of the evolution of both the beam as well as the radiation, we adapted the free electron laser (FEL) simulation code Genesis 1.3. The software incorporates electron beams, laser radiation, and undulator fields with or without constant tapering. It also allows input and output of beam and radiation profiles for iterative simulations and takes into account the energy transfer between the particles and the radiation—both of which are useful for our IFEL simulations.

Since each consecutive period of the undulator has different wavelengths and magnetic field amplitudes, we used a novel approach to simulate the IFEL interaction whereby we segmented the undulator into its various periods and propagated the beam through each segment sequentially. We first had Genesis create initial Gaussian laser and electron distributions and then propagated them through the first undulator period. The resulting output radiation and beam profiles were then fed into the next undulator period and so on as the beam continued through the undulator. The simulations were time independent to simulate beam and laser envelopes longer than a wavelength.

Results

The parameters and results of the simulation are summarized in Table 1. The initial beam's transverse profiles were chosen to be Gaussian with an rms width of 200 μm, and the beam itself was distributed uniformly over ponderomotive phase with a normally distributed energy centered on 50 MeV and energy spread of 0.1% (fig. 2). About one fourth of the simulated beam was accelerated to a final energy of 117 MeV over the 11 periods of the 54 cm long undulator for an average accelerating gradient of 124 MeV/m (fig. 3). The accelerated fraction is well separated in energy from the rest of the beam. Although the CO_2 laser for this experiment can produce 1 TW of power, the undulator was optimized for a more conservative value of 0.6 TW to allow for a margin of error. Furthermore, the intensity can be increased further by focusing the laser spot size if needed.

Beam Loading

The iterative simulation approach allowed us to simulate the evolution of the laser radiation profile as its energy was absorbed by electrons as well as see how the system responds to heavy beam loading. As the electrons absorb the laser energy, we expect that higher beam currents should reduce the available power available for acceleration. As expected, the net surviving laser power decreases as the beam current increases (fig. 4).

Since the beam is localized within a small region of the radiation, the laser intensity close to the beam may

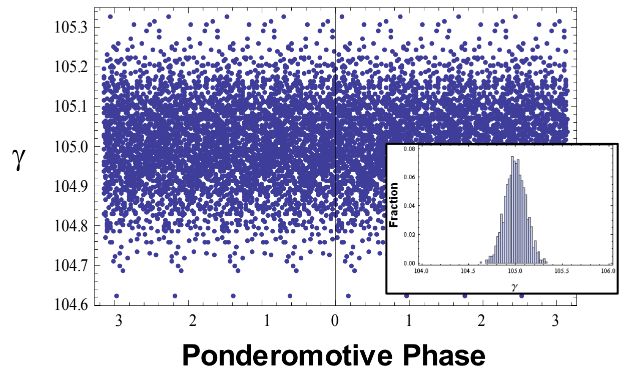

Figure 2: Initial beam phase space occupation. Inset histogram of beam energies shows a normal distribution of energy with mean of 50MeV and width of 0.1%.

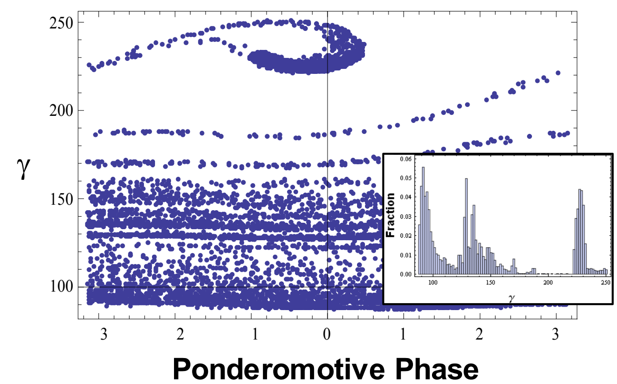

Figure 3: Final beam phase space occupation. Accelerated fraction is well separated in phase and energy.

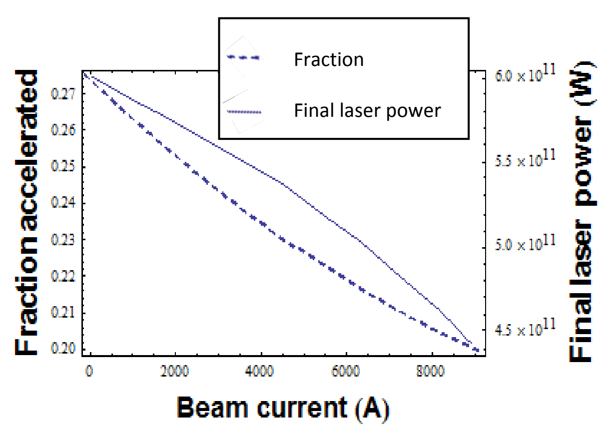

Figure 4: Both fraction accelerated and surviving laser power decrease with increasing beam current as electrons absorb the laser energy.

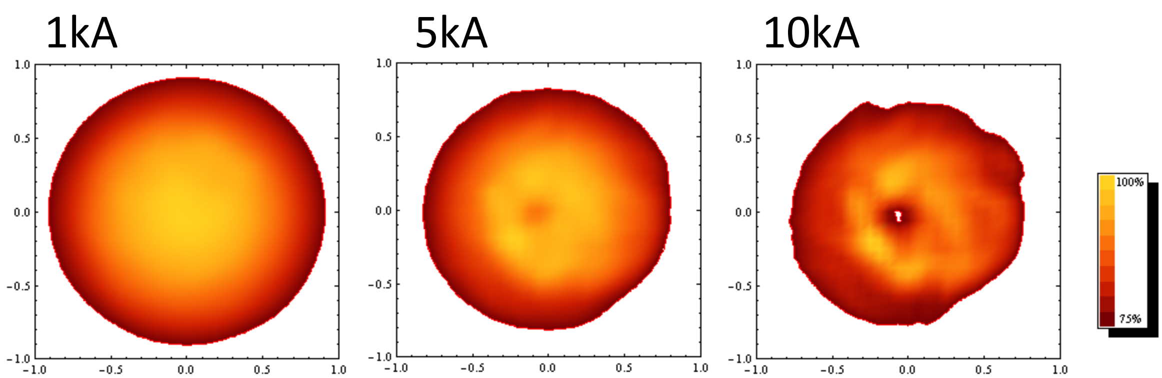

Figure 5: Transverse profile of laser intensity after IFEL interaction normalized to peak intensity. Beams with more charge erode away the intensity of the center of the laser. The electron beams' root mean square radius for each case is 100 um Transverse coordinates are measured in mm.

deplete significantly. For beam current around 1kA, no significant radiation depletion is observed; however, laser intensity near the beam may decrease by 10% for 5kA beam load and as much as 25% for 10kA (fig. 5). This causes the fraction of electrons trapped in the accelerating bucket to decrease for higher currents (fig. 4).

In order to improve the efficiency of the accelerator in the future, we are investigating ways of recycling or amplifying laser power to eliminate these depletion regions.

TESTING

As soon as the undulator's construction is complete, its on axis field will be measured with a motorized hall probe and wire pulser. After the magnets' gaps are adjusted to smooth out the on axis field on axis, the undulator will be tested at Brookhaven National Lab's Accelerator test Facility in a test beam this June.

ACKNOWLEDGEMENTS

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