

HIGH EFFICIENCY LASING WITH A STRONGLY TAPERED UNDULATOR

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Abstract

Typical electrical to optical energy conversion efficiencies for FELs are limited by the Pierce parameter to 10^{-3} or smaller. Undulator tapering schemes have enabled extraction of as much as 1 or 2% of the electron energy. Recently, the UCLA BNL helical inverse free electron laser (IFEL) experiment at ATF demonstrated energy doubling and acceleration of 30% of an electron beam from 52 to 93 MeV with a modest 10^{11} W power CO₂ laser pulse. By reversing and retuning the undulator, the electrons may be violently decelerated, thereby transferring energy from the beam to the laser pulse. Simulations show that by sending a 1 kA, 70 MeV electron beam and 100 GW laser into a prebuncher and the reversed undulator, 41% of the electron beam energy should be converted to radiation, allowing the laser pulse power to grow to 127 GW.

INTRODUCTION

Recent results of the UCLA BNL helical IFEL experiment demonstrated the possibility of doubling the energy of an electron beam with a high-power laser. Reversing the process, one could imagine the possibility of extracting half of the e-beam power and converting it into coherent radiation. The essence of this idea is described in another paper in these proceedings as the low gain regime of tapering enhanced stimulated superradiant amplification or TESSA [1]. FELs are typically limited by the Pierce parameter ρ to less than 1 percent electro-optical power conversion and even the best lasers don't exceed efficiencies of about 30% so converting nearly half of the e-beam power to coherent radiation would be significant achievement.

Inverse free electron laser acceleration has seen progress in recent years. The STELLA experiment at ATF demonstrated efficient IFEL acceleration with gradients similar to conventional RF-accelerating cavities and captured up to 80% of electrons with the use of a prebunched beam [2]. The UCLA Neptune IFEL experiment first achieved accelerating gradients surpassing that of conventional rf-accelerators [3]. The LLNL-UCLA IFEL experiment at Lawrence Livermore National Lab used a multi-TW Ti:Sa laser and produced significant peak gradients [4].

The UCLA BNL IFEL collaboration at ATF was conceived to improve the average IFEL accelerating gradient with the use of the first strongly period- and field-tapered helical undulator. Whereas electrons propagating through a linear undulator undergo sinusoidal motion thereby reducing to zero twice per period their transverse velocity, the helical trajectories of the electrons propagating through the undulator provide continuous transverse velocity which in

turn enables continuous energy transfer. The experiment accelerated electrons from 52 to 106 MeV with a TW class CO₂ laser, averaging a 100 MeV/m accelerating gradient along the 54 cm undulator, and accelerated up to 30% of electrons from 52 MeV to a stable 93 MeV final energy with <1.8% energy spread [5].

EXPERIMENTAL DESIGN

The IFEL decelerator project builds off of the experience of the helical IFEL experiment by retuning the existing helical undulator to decelerate electrons instead of accelerating them. The experimental setup is depicted in Figure 1. In order to further increase the strength of the stimulated radiation, compression and prebunching are necessary. The peak current of the beam will be increased from 100 A to 1 kA with ATF's compressor. Furthermore, a combination prebuncher and chicane phase delay module is currently being built at UCLA with the goal of increasing the fraction of the beam accelerated to full energy. The electron beam acquires an energy modulation at the resonant wavelength while the chicane module delays the modulated beam in order to phase lock to the ponderomotive wave at the entrance of the helical IFEL undulator. 3D simulations show that 70 to 90% of the injected beam should be accelerated to high energy. With a 30 MeV change in energy, 1 kA current, and 80% capture, an estimated 24 GW e-beam power should be transferred to the radiation field.

Helical Undulator Design

The tapering of the helical undulator was previously changed [5], enabling the first demonstration of IFEL resonant energy tuning. Since the undulator period is predetermined by the dimensions of the magnets in the undulator, the gap between magnets was changed in order to manipulate the field and resonant energy along the undulator. In order to reverse the effect of the accelerator, the undulator may be reversed and the gap tapered in order to reduce the resonant energy during the interaction. The highest stable energy electron beam that may be produced at the ATF is 70 MeV, and the final energy of the decelerated electron beam is 42 MeV. The experimental parameters are summarized in Table 1.

The undulator design follows closely the methods described in [1] but differs slightly since the undulator period is fixed (see Figure 2a). Equations 1 and 2 describe the approximate longitudinal dynamics of a particle undergoing helical IFEL interaction. Here, $K_l = \frac{eE_0\lambda}{m_0c^22\pi}$ and $K = \frac{eB\lambda_w}{m_0c2\pi}$ are the laser and undulator normalized vector potentials respectively.

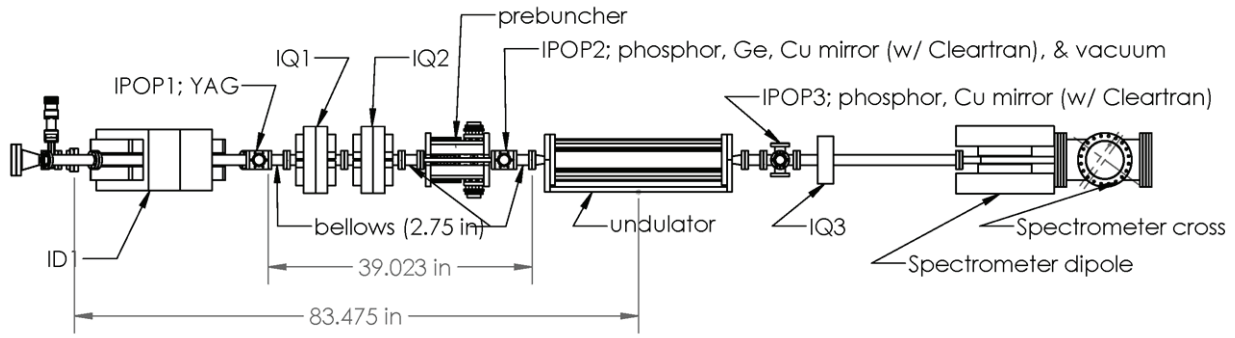


Figure 1: Diagram of the beamline setup for the IFEL decelerator project. The e-beam and laser both enter from the left side of the figure, and the dipole ID1 cancels dispersion as it kicks the electrons onto the beamline with the laser pulse. IQ1, IQ2, and IQ3 are focusing quadrupoles while IPOP1, IPOP2, and IPOP3 house beamline diagnostics. A prebuncher & phase delay stage located just upstream of the undulator prebunch and phase-lock the e-beam to the ponderomotive wave. Downstream of the undulator lies an energy spectrometer for the decelerated beam as well as a CO₂ laser pickoff for laser diagnostics (joulemeter, spectrometer, and streak camera).

$$\frac{d\gamma}{dz} = \frac{kK_l K}{\gamma} \sin \psi \quad (1a)$$

$$\frac{d\psi}{dz} = k_w - k \frac{1 + K^2}{2\gamma^2} \quad (1b)$$

Equation 1b describes the ponderomotive gradient due to the combined interaction of undulator- and laser-fields as evident by the presence of K and K_l in the equation. For a stationary resonant phase, a resonant particle's energy is determined completely by zeroing the phase advance in Equation 1b, yielding the energy of a resonant electron:

$\gamma_r = \sqrt{\frac{\lambda_w}{2\lambda} (1 + K^2)}$. Matching the gradient in the resonant energy to the ponderomotive gradient from Equation 1b results in the tapering condition, Equation 2, determining K in terms of λ_w and K_l . A positive resonant phase ψ_r yields a tapering with increasing resonant energy along the undulator while $\psi_r < 0$ results in a tapering for deceleration.

$$\frac{dK}{dz} = \frac{8\pi K K_l \sin \psi_r - \frac{d\lambda_w}{dz} (1 + K^2)}{2\lambda_w K} \quad (2)$$

When the undulator period and laser parameters are specified along with the initial condition that K at the entrance be such that the resonant energy is equal to the input beam's 70 MeV energy, the differential equation yields K which in turn determines the on-axis field strength along the undulator. An undulator builder equation can then be used to estimate the gap along the undulator needed to create the designed on-axis field.

The laser and e-beam parameters used in the tapering design are specified in Table 1, and the calculated period and resonant energy as well as the solutions to the IFEL/FEL equations are shown in Figure 2. The initial seed power was chosen to be large enough for significant deceleration but small enough to increase the ratio between the signal (stimulated power) to background (seed power). The resonant

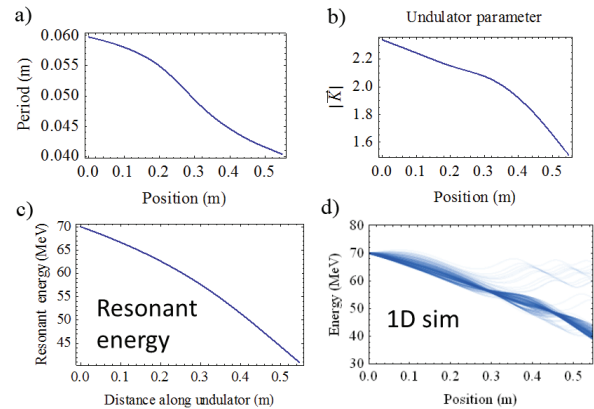


Figure 2: The a) period and b) normalized undulator vector potential decreases along the undulator causing c) the resonant energy to decrease. d) Solutions to Equation 1 describing the longitudinal IFEL dynamics were calculated with the design seed laser and undulator tapering.

phase was set to a constant $-\pi/4$ as a compromise between bucket depth and ponderomotive gradient.

Table 1: Design Parameters

E-beam energy	70 to 40 MeV
Laser focal intensity	4 TW/cm ²
Laser wavelength	10.3 μ m
Rayleigh range	30 cm
Laser waist	undulator midpoint
1/e ² spot size	0.99 mm
M ²	1.07
Resonant phase	$-\pi/4$

Time Resolved Laser Diagnostics

The setup of the beamline for the IFEL decelerator experiment is very similar to that of the IFEL accelerator experi-

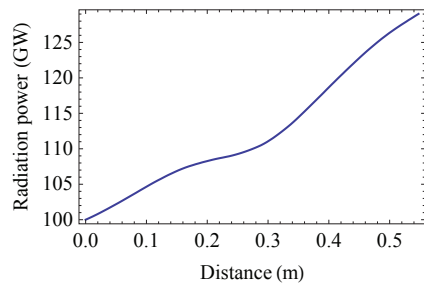


Figure 3: The radiation power grows along the undulator as the electrons are decelerated.

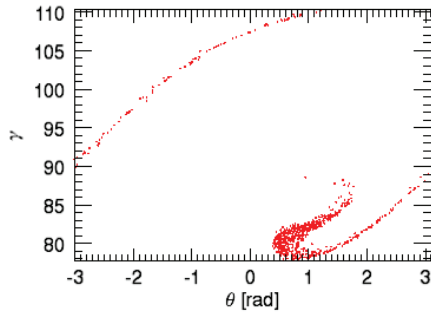


Figure 4: The e-beam longitudinal phase space is shown at the exit of the undulator. The beam loses 28 MeV as the particles are decelerated from 70 to 42 MeV.

ment with the exception of the laser diagnostics. While the peak power of the radiation is increased nearly 30% during the interaction, since the laser pulse duration of 4.5 ps is longer than the 1 ps e-beam duration, the total energy of the radiation field should only increase by a few percent, necessitating temporally resolved power measurements of the amplified pulse. In order to resolve the power gain, the amplified CO₂ laser pulse will be extracted from the beamline about 4 m from the undulator where intensities are below damage thresholds for transport optics and sent to a streak camera for time domain measurements and a grating for spectral measurements. Furthermore in order to understand better the laser evolution, small reflections from the laser will be split off up- and down-stream of the undulator and calibrated to yield relative energy measurements.

SIMULATIONS

Simulations were performed with the 3D FEL code Genesis 1.3 [6] for a 70 MeV input e-beam, laser focusing parameters listed in Table 1 and 100 GW seed laser power. The radiation power grows along the interaction as shown in Figure 3. Figure 4 shows the output beam's longitudinal phase space at the end of the undulator. Up to 43% of the beam is captured and decelerated from 70 to 42 MeV while the radiation power grows by nearly 30%. The transverse profile of the laser spot is also shown in Figure 5.

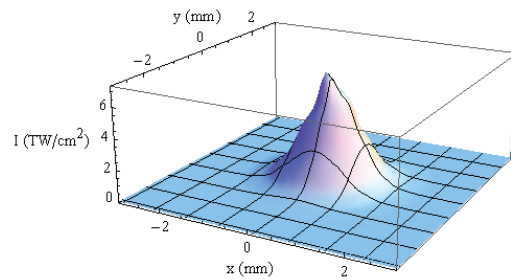


Figure 5: The transverse radiation profile is shown at the exit of the undulator. Growth of the radiation at the center of the seed is clearly visible.

CONCLUSIONS

While recent achievements in IFEL acceleration have focused on high-gradient acceleration, the UCLA-BNL helical IFEL decelerator experiment aims to achieve high-gradient deceleration in order to demonstrate high efficiency electro-optical conversion. The undulator tapering design achieves this by matching the resonant energy and ponderomotive accelerating gradients for decelerating resonant phases with the strongly tapered helical IFEL undulator. By compressing and prebunching the electron beam, significant power gain should be observable with time resolved laser measurements. For moderate laser intensities, over 40% of the e-beam energy is predicted to be converted to coherent radiation.

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