RESULTS FROM THE NOCIBUR EXPERIMENT AT BROOKHAVEN NATIONAL LABORATORY'S ACCELERATOR TEST FACILITY*

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Abstract

Conversion efficiencies of electrical to optical power in a Free Electron Laser are typically limited by their Pierce parameter, ρ ~0.1%. Introducing strong undulator tapering can increase this efficiency greatly, with simulations showing possible conversion efficiencies of ~40%. Recent experiments performed with the Rubicon Inverse Free Electron Laser have demonstrated acceleration gradients of ~ 100 MeV/m and high particle trapping efficiency by coupling a pre-bunched electron beam to a high power CO2 laser pulse in a strongly tapered helical undulator [1,2]. By reversing the undulator period tapering and re-optimizing the field strength along the Rubicon undulator, we obtain an Inverse Free Electron Laser decelerator, which we have aptly renamed Nocibur. This tapering profile is chosen so that the change in beam energy defined by the ponderomotive decelerating gradient matches the change in resonant energy defined by the undulator parameters, allowing the conversion of a large fraction of the electron beam power into coherent narrow-band radiation [3]. We discuss this mechanism as well as results from a recent experiment performed with the Nocibur undulator at Brookhaven National Laboratory's Accelerator Test Facility.

INTRODUCTION

The UCLA Particle Beam Physics Laboratory, in collaboration with Brookhaven National Laboratory's Accelerator Test Facility (ATF), has recently utilized the Inverse Free Electron Laser (IFEL) mechanism to use optical energy from a high power CO2 laser to accelerate a 52 MeV electron beam to 92 MeV in ~0.5 m [1]. These experiments utilized the strongly tapered helical Rubicon undulator to demonstrate highly efficient conversion between optical and electrical energy. This process in reverse, electro-optical conversion, represents a potentially attractive source for high peak power and high average power radiation source.

The Nocibur experiment at ATF utilizes a strongly tapered helical undulator to couple a pre-bunched electron beam to a high power CO2 laser, using the Inverse Free Electron Laser mechanism to now decelerate the electrons (Fig. 1). By designing the undulator tapering such that the FEL resonance condition is maintained as the beam decelerates, energy lost by the beam is converted into coherent radiation by way of stimulated emission [3]. By decelerating large fractions of the beam to ~50% the initial beam energy, electro-optical conversion efficiencies of up to ~40% are attainable.

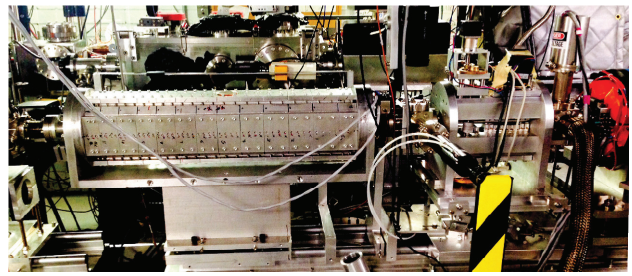

Figure 1: Nocibur undulator and pre-buncher installed in ATF beamline.

DESIGN OF UNDULATOR TAPERING

The undualtor tapering is designed to match the ponderomotive gradient set by the undulator and laser parameters to the FEL resonance condition, chosen such that the resonant phase remains constant throughout the deceleration (Fig. 2). In the case of this experiment we choose the resonant phase to be Ψr = -π/4.

Description	Definition
Undulator wavelength	$k_w = 2\pi/\lambda_w$
Laser wavelength	$k = 2\pi/\lambda$
Normalized laser vector potential	$K_l = \frac{eE_0}{m_0 c^2 k}$
Normalized undulator vector potential	$K = \frac{eB}{m_0 c k_w}$
Decelerating Gradient	$\frac{d\gamma}{dz} = \frac{e}{mc^2} E \cdot \beta \rightarrow \frac{d\gamma^2}{dz} = 2kK_l K \operatorname{Sin}(\psi_r)$
Resonance Condition $\left(\frac{d\psi}{dz} = 0\right)$	$\gamma^2 = \frac{\lambda_w}{2\lambda}(1+K^2)$
Undulator Tapering Differential Equation	$\frac{dK}{dz} = \frac{2kKK_l \operatorname{Sin}[\psi_r] - \frac{d\lambda_w}{dz}\frac{1+K^2}{2\lambda}}{\lambda_w K/\lambda}$

Figure 2: Derivation of differential equation determining K tapering.

The Nocibur undulator was previously used in the Rubicon IFEL acceleration experiments. To create the necessary decelerating gradient the Rubicon undulator period tapering was reversed and the field strength was re-tuned to match the K tapering solution to the differential equation (Fig. 3). The undulator was modeled in Radia, tuned and measured with a hall probe and the second integral was zeroed using pulse wire measurements (Fig. 3).

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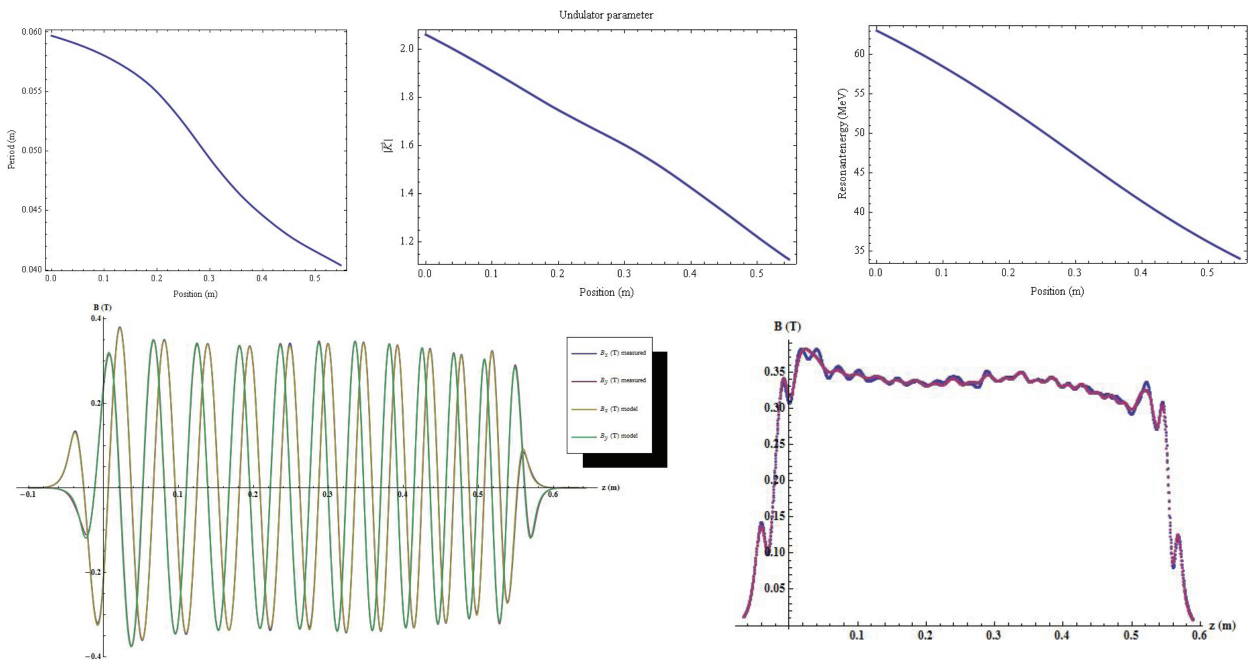

Figure 3: (Top) Design parameters for period tapering, K tapering and resonant energy along undulator. (Bottom) Actual field measurements compared with Radia model field maps.

EXPERIMENTAL PROCEDURE

The deceleration mechanism requires a strong seed to support the desired gradient. For this we copropagate the electron beam with a laser pulse from ATF's high power CO2 laser, parameters described in Table 1.

Table 1: Experimental Laser and E-Beam Parameters

Parameters	Values
E-Beam Energy	65 MeV → 35 MeV
E-Beam Current	100 A
Laser Focal Intensity	4 TW/cm²
Laser Wavelength	10.3 μm
Rayleigh Range	0.3 m
Laser Waist	1 mm
Peak Power	200 GW

Rough overlap between the laser and e-beam was achieved using a Germanium switch inserted into the beamline. Fine timing to place the E-beam at peak laser intensity was then done by varying a delay stage in the laser transport path and observing the increase or decrease in the amount of charge decelerated.

To maximize the amount of charge captured we control the injection into the ponderomotive bucket defined by the undulator and laser parameters using a pre-buncher.

The pre-buncher consists of a planar modulator section and a variable gap chicane. The modulator section creates a sinusoidal modulation at the resonant wavelength. The chicane dispersion serves to increase the bunching and also introduce a small delay such that the bunched beam enters the bucket at the decelerating resonant phase chosen in the design.

As seen in Fig. 2, the decelerating gradient depends on the laser vector potential. Taking diffraction into account, the tapering equations were solved considering the laser focal point to be at the center of the undulator. To focus the laser, a NaCl lens was placed outside of vacuum, upstream of a NaCl window that served to couple the CO2 laser into vacuum. By moving this lens and observing the laser spot on a pyrocamera located at an equivalent distance to the undulator center, we were able to set the waist position as desired.

RESULTS

Seeding the undulator with ~ 1 J of laser we were able to observe consistent full deceleration from 65 MeV to 35 MeV. Varying the pre-buncher chicane gap we were able to increase the fraction of electrons fully decelerated from ~5-10% with no pre-buncher installed, to ~30%, corresponding to ~100 pC (Fig. 4). We expect this to contribute ~3 mJ of laser energy to the seed and ~ 1 GW of power, demonstrating an electro-optical conversion efficiency of ~15 %.

RADIATION MEASUREMENTS

Using the FEL simulation code, Genesis 1.3, we were able to simulate the radiation growth, showing a direct correlation between the energy extracted from the electron beam and the growth of the radiation field [4]. Figure 5 shows results from a Genesis simulation showing 80% of a 1 kA beam decelerated by 30 MeV, producing 25 GW of radiation on top of a 100 GW seed

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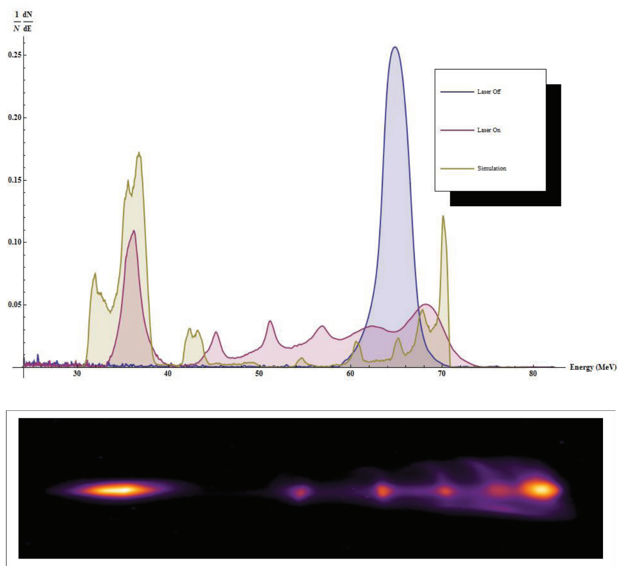

Figure 4: (Above) Deceleration data from Nocibur experiment showing 30% trapping compared with simulation and no laser shot. (Below) Spectrometer image of E-Beam energy spectrum corresponding to the spectra plotted above.

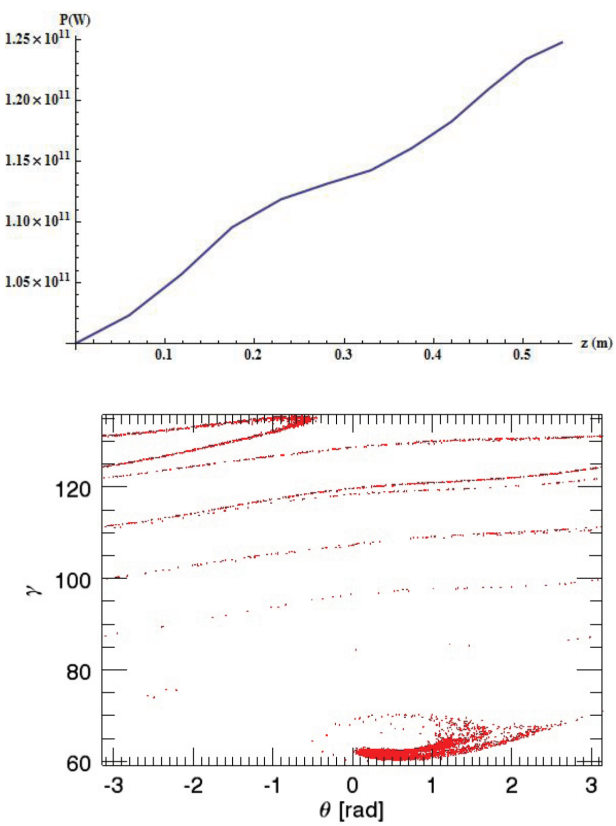

Figure 5: Genesis simulation results showing 25 GW radiation growth and deceleration using 1 kA peak current electron beam.

through the process of stimulated emission [5]. Experimental limitations forced us to run at 100 A, decreasing the radiation power generated to ~1 GW. Observing this radiation growth above the 100 GW seed is nontrivial. Increasing the peak current would not only increase the generated radiation power, but also increase the spectral bandwidth of the generated radiation allowing us to potentially use spectral filtering to observe the produced radiation. Efforts to increase the peak current at ATF are under way for future experimental runs.

CONCLUSIONS

High electro-optical conversion efficiencies (~40%) have been demonstrated at long wavelengths (35 GHz) where a waveguide could be utilized to maintain high laser intensities [6]. The Nocibur experiment serves as an important proof of principle experiment for short wavelength, highly efficient lasing utilizing strong tapering. The demonstration of a potential 15% conversion efficiency is a large step forward, and can be improved by increasing the peak current of the electron beam, and better optimization of the pre-buncher.

Future plans for measuring the produced radiation are being considered, potentially taking advantage of the spectral broadening when lasing with a short bunch or increased diffraction of the produced radiation.Extending this technology such that the signal becomes comparable to the seed or larger can be realized in an oscillator configuration or a longer tapered section FEL after burner. This high gain regime is an attractive solution for high average power, high peak power radiation sources, and these results from the recent Nocibur experiment affirm the practicality of pursuing these schemes.

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