USE OF RE-ACCELERATION AND TAPERING IN HIGH GAIN FREE ELECTRON LASERS TO ENHANCE POWER AND ENERGY EXTRACTION

Ritika Dusad[#] and Gil Travish
UCLA Department of Physics and Astronomy, Los Angeles CA 90095, U.S.A.

Abstract

In high gain Free Electron Lasers (FELs), it is possible to use undulator tapering to increase power and energy extraction beyond saturation. For some applications, however, tapering is not sufficient or results in excessively long structures. Here we study the use of tapered undulators interrupted by short accelerator sections to increase the power extracted per unit length. Re-acceleration restores nominal energy to the beam with minimal disruption to bunching, and allows repeated use of a single undulator-taper profile. We show that for suitable parameter sets this approach can perform better than ideal tapering alone, and may serve to greatly improve and simplify high peak and average power FELs. Based on these findings, we propose a first experiment to test the re-acceleration with tapering concept.

INTRODUCTION

High-Gain Free Electron Lasers [1] employ high current and long undulators to achieve exponential gain in power. However this power extraction eventually saturates when the beam is fully bunched. Tapering [2] the undulator allows the extraction of more power from the beam, but this scheme has a limit of about 10% of the initial beam power. Here we examine a new technique to increase the power extraction per unit length of the structure. Instead of having a very long tapered undulator, we propose to cut that taper into shorter sections that are interrupted by short re-accelerator sections which put nominal energy back into the beam allowing repeated use of a single taper profile. Re-acceleration has already been considered in low-gain FELs as a means to increase power extraction efficiency [3,4]. The Tapered Undulator Re-accelerated Free electron laser (TURF) promises a higher power extraction per unit length than a linearly tapered FEL of the same length. In some particular cases, it has been observed that the power output from TURF exceeded that from a maximally linear tapered (90% taper) FEL by a factor of three. For more realistic taper and length limits, the scheme proposed here exceeds converted FEL power output significantly.

CONCEPT

The synchronous condition that governs FEL dynamics between the undulator parameter, a_u, and period, λ_u, energy of the beam, with Lorentz factor γ, and radiation wavelength, λ_r, is

$$\lambda_r = \frac{\lambda_u}{\gamma^2}\left(1+\frac{a_u^2}{2}\right). \quad (1)$$

Tapering changes the undulator parameter or undulator period dynamically with the change in energy of the beam to maintain a constant FEL radiation wavelength according to equation (1). After some 10% of the original electron beam energy has been depleted, a short accelerator section can restore nominal energy to the beam. Subsequent tapered undulator sections and re-acceleration sections can be used to generate more optical power. Figure 2 gives a basic layout of the TURF scheme.

Simulations show (Figure 1) that significantly more power can be generated in TURF than in a linearly tapered FEL of the same length. This result can be used to construct a more compact FEL and at possibly at a lower cost than that of a conventional FEL.

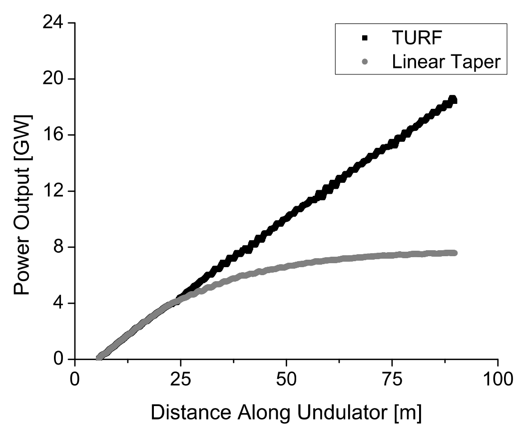

Figure 1: Peak power output as a function of device length after saturation of the FEL for TURF (black), and linear undulator tapering alone (grey), for a typical optical wavelength FEL.

TURF requires short structures with high accelerating gradients. The length of the accelerator module is minimized to avoid de-bunching of the electron beam by using a gap length formula given by KJ Kim et al [5]. In order for the particles to arrive at the appropriate optical phase, the allowed distance, d, between undulator sections is given by

$$d = n\lambda_u\left(1+a_u^2\right). \quad (2)$$

[#] ritikadusad@ucla.edu

ISBN 978-3-95450-117-5

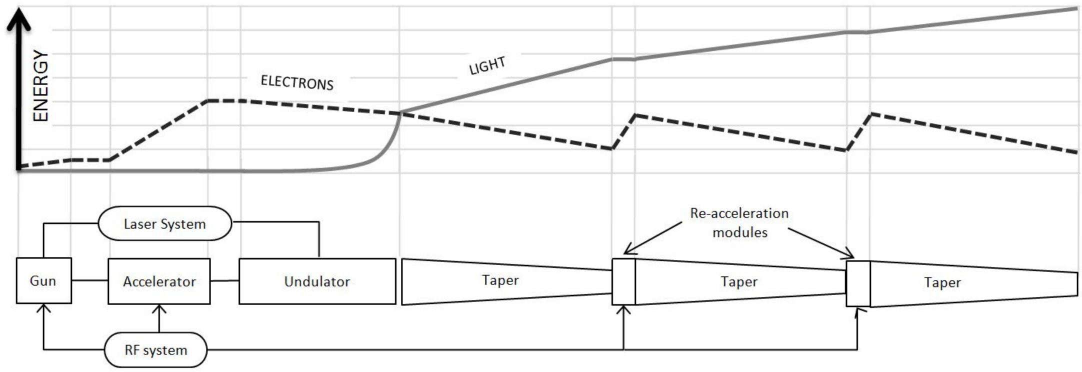

Figure 2: Schematic representation of a Tapered Undulator Free Electron Laser. The energy of electrons (dashed line) and light (bold line) are represented conceptually.

This gap length d only depends on the undulator parameter and period, and an integer multiple, n. Figure 3 represents a case study of variation of λ_r for an FEL with undulator parameters $a_u \approx 1.2$, and λ_u=2.73 cm. A smaller λ_r, corresponding to higher beam energy, implies that more energy is available for extraction, but demands higher gradients to restore the depleted energy in a given length.

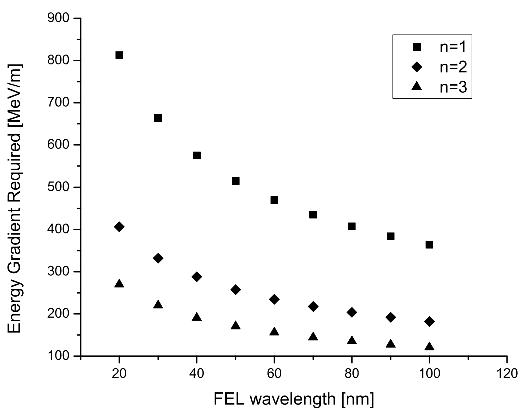

Figure 3: Energy gradient of re-accelerator section required to put 10% of the original beam energy back into the beam vs. the FEL wavelength.

Electron Beam Admittance

Long tapered undulators that allow a power extraction efficiency of more than 10% of the beam power input require complex beam optics to manage the broad energy range of the beam. It is desirable to have a narrow energy range electron beams to reduce beamline optics and undulator complexity. Although TURF causes fillamentation of the beam, as described in the next section, it also maintains the energy range of the core electrons within a narrow range (e.g. 10%) of the original synchronous value by restoring small amounts at regular intervals. The reduced energy range allows for the use of simpler beam optics and re-use of the same undulator taper-profile. The energy profile of the beam and the optical radiation is shown schematically in Figure 2.

SIMULATION RESULTS

A Ming Xie-like model [6] was used to arrive at base values for initial simulations. A fully 3-dimensional FEL code, GENESIS 1.3 [7], was used to study and optimize FEL parameters, and simulate the performance of the TURF concept in comparison with straight taper and other optimal taper schemes.

A simple Δγ/γ routine was written to incorporate the energy gain through the short re-accelerator sections. Later a PIC code can be used to simulate the non-linear effects of the phase space evolution.

A few general comments on the simulation results are worth considering before an example case is examined.

Filamentation

Due to re-acceleration in TURF, a large fraction of electrons gain sufficient energy to escape the pondermotive bucket (separatrix) and therefore stop participating in the undulator gain process. However, the beam still maintains a central core of bunched electrons (Figure 4, left) that are tightly bunched together to produce FEL radiation.

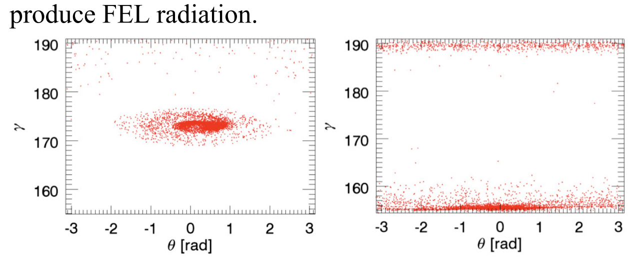

Figure 4: The phase space of the electron beam at the end of the undulator line for TURF showing filamentation (left) and a linear stepped tapering showing debunching (right). Particles in the TURF case that have very high energies (γ >191) have been omitted in this figure.

Debunching

In linear tapering, electrons spread out (Figure 4, right) within the pondermotive separatrix and therefore the electrons that are not at the correct phase with respect to the radiation field do not radiate at the resonant wavelength. This reduces the intensity of radiation. The

ISBN 978-3-95450-117-5

modest taper required by the TURF scheme causes far less debunching than that found in a long linear-taper case.

EXAMPLES

Power Beaming

The concept of transmitting power from earth to space and visa-versa has been considered at least since the Sixties [8, 9]. A coherent optical source provides an effective method of directing power through the atmosphere for conversion to electricity via photovoltaic panels. A compromise between good atmospheric transmission and photovoltaic efficiency yields an ideal wavelength around 840 nm [10]. Production of megawatt to gigawatts of electrical power on earth is straightforward; and, if the direction of such power to space could be achieved, the access costs to space could be reduced and the sustained utilization of space could be expanded.

The application of FELs to the problem of power beaming has been examined previously [10, 11], but here we study this problem using the TURF approach. Table 1 shows a preliminary parameter study for an FEL that incorporates TURF. The power output from a piecewise-linear taper (stepped), and that from TURF has been compared in Figure 1. The linear scheme saturates at ~8 GW whereas, power from TURF goes up to 18 GW, which is almost 2.5 times that from the other cases. In addition, the linear trend of the power curve corresponding to TURF suggests that in principle, more power can be extracted from the beam till saturation is reached or the structure becomes impractically long to construct any further.

Table 1: Undulator Parameters for a Power Beaming FEL

Parameter	**Value**
Energy	96.6 MeV
Energy Spread	0.1%
Current (peak)	500 Amps
Norm. Emittance (rms)	1.2 mm mrad
Undulator Period	4 cm
Undulator Parameter (a_u)	1
Radiation Wavelength	840 nm
FEL Parameter (ρ)	~0.011
Gain Length	20.5 cm
Re-acceleration Section Length	32 cm
Re-acceleration Energy Gain	10%

The preservation of phase space of the beam through the various sections of the FEL, most importantly, the re-acceleration module in the TURF model is validated as shown in Figure 4. Under the simplified acceleration scheme modeled, the TURF shows preservation of bunching and tolerable filamentation. At the energies of the interest here, it is not anticipated that a more complete simulation (including RF effects on the beam) would result in appreciably different FEL performance.

Proof-of-principle Experiment

Based on encouraging simulation results, a first experiment can be considered to test a simple TURF layout: two tapered (adjustable) undulators, and one re-acceleration section that can be switched on or off to test the concept of TURF. An existing facility would be used to reduce the effort required for such a test. As an example, the Next Linear Collider Test Facility (NLCTA) at SLAC offers suitable beam parameters [12], accelerator sections and RF power along the beamline, as would be required by the re-acceleration section.

REFERENCES

[1] D. Prosnitz, et al., Phys. Rev. A 24 3, 1436 (1981).
[2] T. Orzechowski, et al. Phys. Rev. Lett. 57 2172 (1986)
[3] G. Saxon. NIM A418 (1998).
[4] R. H. Pantell et al., NIM A331 (1993).
[5] K.-J. Kim, M. Xiea and C. Pellegrini. NIM A 375 (1996).
[6] M. Xie, LBL-36038, Berkeley, CA (1994).
[7] S. Reiche, NIM A429, 243 (1999).
[8] P. Glaser, Science, 162 3856, pp 857-861 (1968).
[9] G. A. Landis, IEEE Aerospace and Electronics Systems, 6 6 (1991).
[10] C. Muller and G. Travish. Proc. of FEL'03 conference Tsukuba, Japan. (2003) .
[11] K.-J. Kim et al., Proc. FEL Conf. (1997).
[12] M. Dunning et al., Proc. of PAC. (2009).

ISBN 978-3-95450-117-5