STUDIES OF UNDULATOR TAPERING FOR THE CLARA FEL

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Abstract

Undulator tapering is a well-known method for enhancing the performance of free-electron lasers [1]. It works by keeping the resonant wavelength constant, despite variation in the electron beam energy. Both the energy-extraction efficiency and the spectral brightness of the FEL can be improved using this technique. In this paper we present recent studies of undulator tapering for the CLARA FEL in both SASE and seeded modes. The methods used to optimise the taper profile are described, and the properties of the final FEL pulses are compared.

INTRODUCTION

Undulator tapering is a well-known and widely used technique for improving the performance of free-electron lasers [1]. It works by keeping the resonant wavelength matched to the bunching in the electron beam, despite the changing energy of the electrons as they travel along the length of the undulator. It was originally proposed as a way to improve the energy extraction efficiency of an FEL [2–5], but has since found many other applications. For example, when tapering is combined with self-seeding, it provides a route to coherent, high-power, hard x-ray FELs [5,6]. Alternatively, it can be used in combination with an external laser modulator to generate short, fully coherent radiation pulses by restricting high FEL-gain to the energy-chirped sections of the electron bunch [7–9]. Similarly, energy-chirps arising from velocity bunching or longitudinal space charge can be compensated using an undulator taper [10, 11]. A reverse undulator taper can also be used to *suppress* FEL power, whilst still allowing a high degree of bunching to develop within the electron bunch. This can then be used for a variety of applications, such as generating circularly polarised light in a helical undulator after-burner [12].

In view of this diverse range of applications for undulator tapering, the topic is currently one of interest for study at the CLARA FEL currently under construction [13, 14]. CLARA aims to provide a test facility at which a wide range of current and future FEL schemes can be tested experimentally, and so the suitability of the proposed layout for effective tapering needs to be established at an early stage.

In this paper we present preliminary studies of undulator tapering using the CLARA FEL. We study two cases, namely seeded and SASE operation at 266 nm, and for each case investigate the performance of undulator tapering at improving the final FEL pulse quality.

TAPER OPTIMISATION METHODS

The basic principle of undulator tapering is simple, that is, the resonant wavelength should be kept constant by matching the undulator strength parameter a_u to the changing electron energy. In practice however, establishing the optimum taper profile is not straight-forward. Here, we compare two contrasting techniques.

The first method relates to the 1D Kroll-Morton-Rosenbluth (KMR) formalism [1,3]. In this, a Hamiltonian method is used to define a fixed synchronous phase Ψ_r that relates the rate of energy-extraction to the particle energy, the field amplitude and a_u. The Ψ_r parameter also defines the ponderomotive bucket area, and so the selection of Ψ_r becomes a trade-off between capturing the greatest number of particles (small Ψ_r) and maximising the rate at which energy is extracted from the electron beam (large Ψ_r). A modification of this method was recently proposed in [15], in which Ψ_r is allowed to vary along the radiator. The problem then changes from finding the optimal fixed-value of Ψ_r to one of optimising $d\Psi_r/dz$. In this study, we investigate a linear increase of the form:

$$\Psi_r(z) = \frac{\pi}{2L_d} z \tag{1}$$

where L_d is the so-called *detrapping length* (bucket area shrinks to zero at $z = L_d$, see [15] for details). With this parameter defined, the problem reduces to one of iteratively solving the equation:

$$a_u(z+\Delta z) = a_u(z) - \frac{\sqrt{2}e}{m_e c^2}\frac{\lambda_r}{\lambda_u} f_B(z) E_0(z) \sin\Psi_r(z)\Delta z \tag{2}$$

where f_B is the Bessel factor for a planar undulator and the radiation field amplitude E_0 is found at each step from time independent GENESIS calculations [16]. Solving Eqn. 2 gives a continuous taper profile; this has been converted to a stepped taper for later analysis using full, time dependent simulations.

The second method investigated is direct optimisation of the taper profiles using time-dependent GENESIS simulations. Whilst 3D, time-dependent simulations are slow, they automatically include various limiting effects such as radiation refraction and diffraction, radial dependence of the radiation field and the growth of sidebands that are missing from the 1D, steady-state method outlined above [17].

In principle, arbitrary taper profiles can be optimised in this way. However, to simplify the problem we investigate

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a stepped taper of the form:

$$a_u(z) = \begin{cases} a_u(0), & \text{if } z \leq z_0 \\ a_u(0) - b(z - z_0)^2, & \text{otherwise} \end{cases}$$

where b and z_0 are parameters to be optimised. In this study, each of the parameters are scanned in a grid in order to identify the best values.

CLARA FEL PARAMETERS

The latest proposal for the CLARA FEL is that the radiator section should be composed of many short undulator modules interleaved in a FODO focussing channel, with space reserved for mini-chicanes, diagnostics, etc. after each undulator. This layout would bring it closer to short-wavelength FEL facilities in terms of matching the undulator length to the FEL gain length, and has been selected in order to make it suitable for demonstration of the HB-SASE [18] and Mode-Locking [19] FEL schemes. The downside is that the undulator packing-faction remains relatively low at 0.62, potentially allowing significant radiation diffraction to take place between the undulator modules. The main parameters of the FEL are given in Table 1, and a plot of the electron beam size through the first two FODO periods are shown in Fig. 1.

Table 1: Summary of CLARA Parameters

Parameter	Unit	Value
Electron energy	MeV	232
Normalised emittance	mm.mrad	0.5
Energy Spread	keV	100
Bunch charge	pC	250
RMS bunch length	fs	250
Radiator period	mm	27.5
RMS undulator parameter, a_u		1.7285
Number of periods		28
Number of undulator modules		17
FODO period	m	2.475

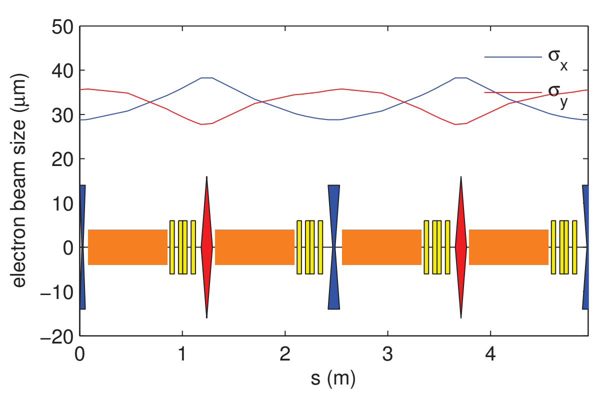

Figure 1: Electron beam size through two FODO periods of the radiator section in CLARA.

TAPERING FOR SEEDED OPERATION

Due to the limited space available for the CLARA radiators, demonstration of a full self-seeding plus tapered undulator set-up has not been considered here. Instead, these studies aim to simulate the scheme by providing an external laser seed. In the baseline design it is foreseen that an 800 nm seed-laser will be provided [13]. This could be used in combination with a chicane to provide initial bunching at 800 nm, with the radiators set to be resonant at 266 nm. For simplicity however, these studies have assumed direct seeding of the electron bunch at 266 nm. Such a seed laser could be considered as potential future upgrade of the facility.

In order to match the characteristics of self-seeding as closely as possible, it has been assumed that the seed power is ~$10^{-4} \times P_{sat}$. The length of the seed pulse has been set equal to the electron bunch at 250 fs rms, giving a pulse energy of 50 nJ at the entrance to the radiator.

Figure 2 shows the results of scanning the taper parameters z_0 and b. Two options are considered, either maximising the pulse energy or the spectral brightness (defined here as the integrated spectrum in the region 264.67 nm to 267.33 nm). Without tapering, the FEL reaches an initial saturation at 4.56 m into the radiator (4 undulator modules). The results indicates that for both options the taper should begin before this, and in order to maximise pulse energy the profile should be gradual (b = 0.0002 starting after 1 module). In contrast, maximising the spectral brightness favours a stronger reduction in a_u (b = 0.0019) starting after 3 modules.

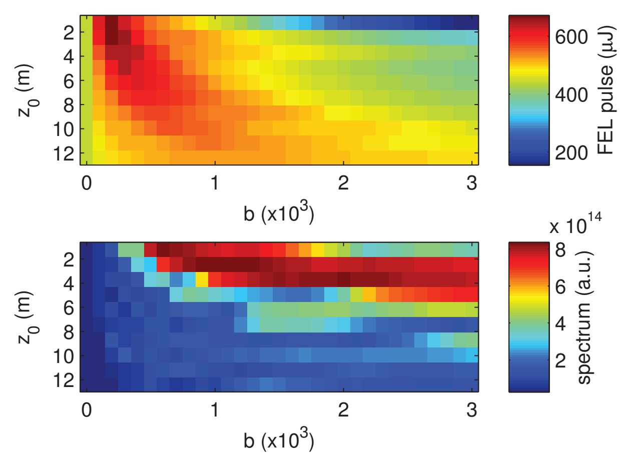

Figure 2: FEL pulse energy (top) and integrated spectrum (bottom) as a function of quadratic taper parameters.

When using the modified KMR technique to optimise the taper profile, a similar trade-off is observed. Selecting a relatively large value of L_d = 17.8 m leads to a gradual increase in Ψ_r, resulting in a larger bucket area that maximises the number of captured particles. The rate of energy extraction is slow, but the final pulse energy is maximised. Alternatively, selecting a smaller value of L_d = 8.9 m leads to more rapid energy extraction, but sacrifices the number of parti-

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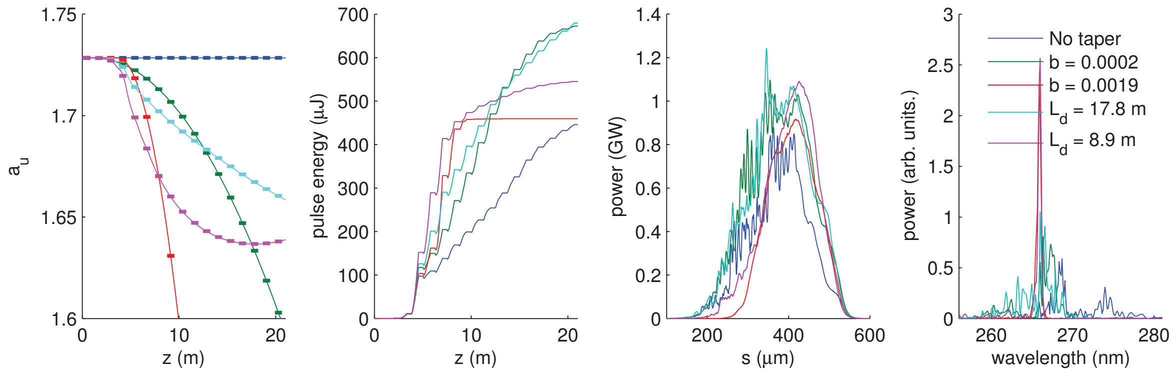

Figure 3: Comparison of optimum pulse properties found using quadratic (red and green lines) and modified KMR (cyan and magenta lines) taper profiles (seeded operation). A pulse calculated for an un-tapered FEL is also given for reference (blue lines). Far left: undulator taper profiles. Middle left: pulse energies as a function of z. Middle right: pulse profiles at $z = 21.01$ m. Far right: pulse spectra at $z = 21.01$ m.

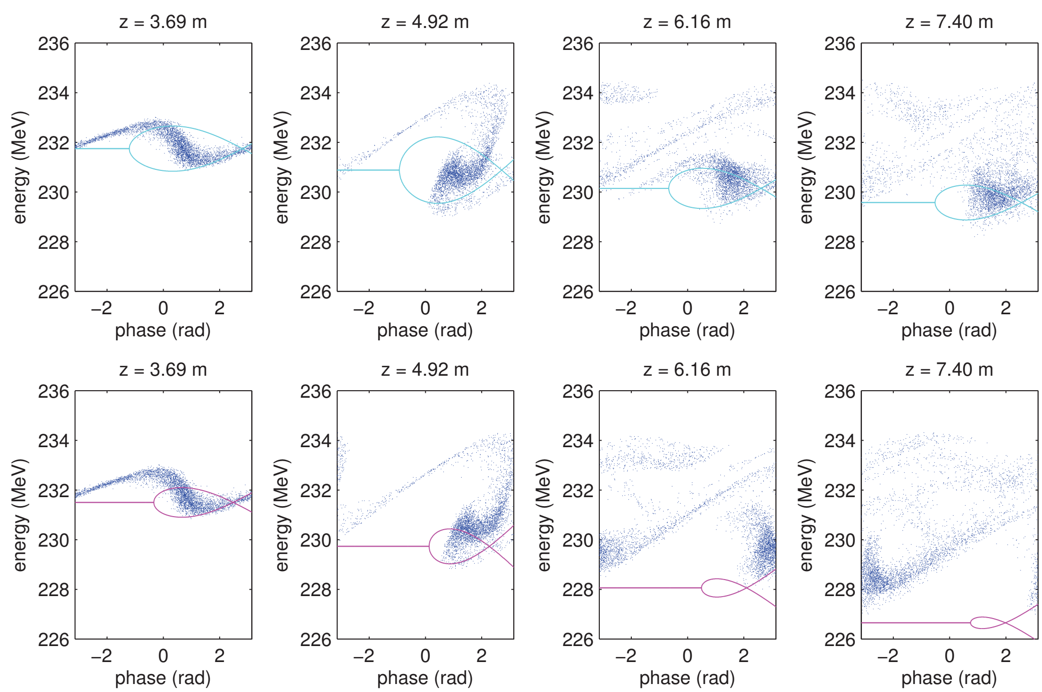

Figure 4: Electron bunch phase space at various points along the radiator for two taper profiles, each calculated using the modified KMR method. Top: $L_d = 17.8$ m. Bottom: $L_d = 8.9$ m.

cles captured in the bucket. The final pulse energy in this case is lower, but the spectral brightness is maximised.

A comparison of the FEL pulse properties is given in Fig. 3. As can be seen, the modified KMR method marginally outperforms the simple quadratic taper profile when optimising for either pulse energy or spectral brightness, despite the inherent simplifications of the 1D analysis. The taper profiles arrived at using this technique quickly deviate from quadratic, approaching a linear variation of a_u with z for $L_d = 17.8$m, and levelling off completely for $L_d = 8.9$ m.

The increase in pulse energy is modest, going from 440 μJ in the untapered case to 680 μJ for the modified KMR case with $L_d = 17.8$ m. The pulse durations are also reasonably similar, ranging from 480 fs for the modified KMR case with $L_d = 8.9$ m to 635 fs for the untapered case (FWHM). The feature that benefits the most from tapering is the line-width, which reduces by up to a factor of 10 over the non-tapered case, with a similar increase in the spectral brightness. The final FEL pulse for the modified KMR case with $L_d = 8.9$ m has a time-bandwidth product of 0.86, close to that of a transform-limited Gaussian pulse.

When optimising for pulse energy, the increase comes mainly from side-band growth rather than an increase at the target wavelength. A faster taper is clearly beneficial

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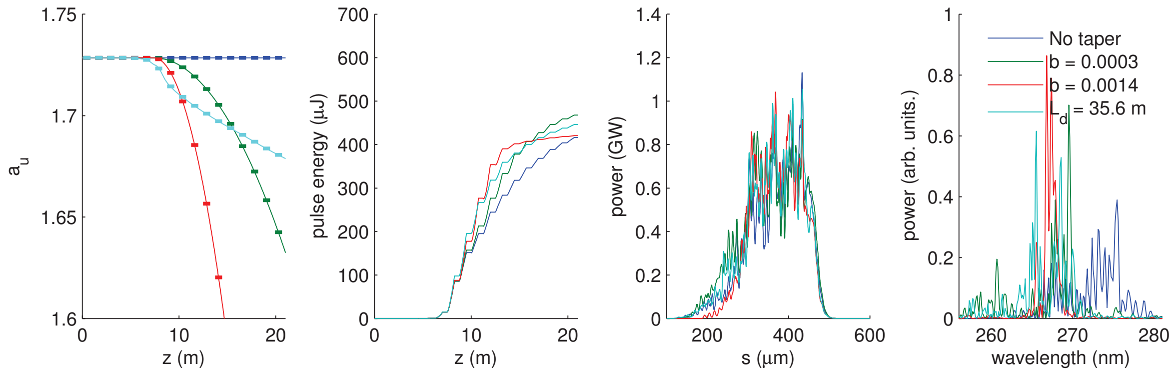

Figure 5: Comparison of optimum pulse properties found using quadratic (red and green lines) and modified KMR (cyan lines) taper profiles (SASE operation). A pulse calculated for an un-tapered FEL is also given for reference (blue lines). Far left: undulator taper profiles. Middle left: pulse energies as a function of z. Middle right: pulse profiles at z = 21.01 m. Far right: pulse spectra at z = 21.01 m.

at preventing this, as the detrapped particles are moved further from resonance, limiting their ability to form sidebands. This can be seen by examining the electron phase space (see Fig. 4). Here, the two modified KMR cases of maximum pulse energy (L_d = 17.8 m, top) and maximum spectral brightness (L_d = 8.9 m, bottom) are compared. For maximum pulse energy, the ponderomotive bucket is large, with a high fraction of particles either inside or close to the separatrix. For maximum spectral brightness, the more aggressive taper profile means that the bucket area is smaller and the number of captured particles is reduced. However, for those particles that are captured, more energy is extracted at the target wavelength, with the remaining particles left further from from resonance (thereby preventing side-band growth). In the case of a quadratic taper profile with b = 0.0019, the FEL pulse decouples completely from the electron bunch after 9.6 m.

TAPERING FOR SASE OPERATION

The impact of undulator tapering for CLARA in SASE mode has also been investigated. It is anticipated that the tapering will be less effective in this mode due to the stochastic nature of the radiation growth. In SASE mode, each radiation spike is uncorrelated in phase with respect to its neighbours, leading to a mismatch between radiation phase and electron bunching as the FEL pulse moves forward. This in turn limits the ability to maintain particle trapping simply by adjusting a_u.

For the case of no tapering, the FEL reaches an initial saturation point at 9.5 m into the radiator, although as with the seeded case the pulse energy continues to increase after this point due to sideband growth. After applying the modified KMR technique to identify the optimum taper profile, it was found that when setting L_d to 35.6 m that both the pulse energy and spectral brightness could be simultaneously maximised. When applying a quadratic taper profile starting after 6 undulator modules (z = 7.9 m), it was found that it is possible to improve on either the pulse energy or the spectral brightness over and above what could be achieved with the modified KMR technique, although not simultaneously.

The results of this analysis are shown in Fig. 5. As with the seeded FEL simulations, the pulse duration is left largely unchanged by the tapering, ranging from 450 fs FWHM for the b = 0.0014 case (maximum spectral brightness) to 580 fs for the b = 0.0003 case (maximum pulse energy). The increase in pulse energy found from tapering is ~10-15 %. The main improvement is once again observed in the integrated spectrum around the target wavelength, which in this case can be improved by more than a factor 5.

CONCLUSIONS

An investigation has been carried out into the suitability of the proposed CLARA FEL structure for improving both the final FEL pulse energy and spectral brightness via undulator tapering. Two contrasting taper optimisation techniques have been investigated, and the analytic modified KMR method was found to produce comparable, and in some cases superior, results to those given by direct 3D, time-dependent optimisation of a quadratic taper profile (despite the inherent simplifications). However, it remains a possibility that direct optimisation of an arbitrary taper profile would still be beneficial; this option is feasible given modern cluster computing resources and numerical optimisation techniques (see [20] for example).

As expected, undulator tapering has been found to be more effective for seeded operation than for SASE. Both spectral brightness and pulse energy can be significantly increased by using a tapered undulator, although indications are that the increase in pulse energy comes largely from sideband growth.

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