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Simulations of the 100 kW TJNAF FEL using a step-tapered undulator

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Abstract

The Thomas Jefferson National Accelerator Facility (TJNAF) free electron laser (FEL) can be upgraded to operate at 100 kW average power in the near future using a configuration that recirculates the electron beam to recover energy. It is important to extract the maximum energy from the electron beam in a pass through the undulator while inducing the minimum amount of exhaust energy spread. A larger energy extraction reduces the requirement for a large recirculating current, while a smaller exhaust energy spread allows the intense electron beam to be recirculated without damaging components. To improve FEL performance, we explore the use of the step-tapered undulator, which alters the resonance condition halfway through the undulator. Short pulses complicate the desired interaction. Comparisons are made to the conventional periodic and linearly-tapered undulators. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Thomas Jefferson National Accelerator Facility (TJNAF) free electron laser [1] can be upgraded to operate at increased power of 100 kW by increasing the kinetic energy of the electron beam to $E_e = 210$ MeV and the pulse repetition rate to $\Omega = 750$ MHz. The average electron beam power would then be $P_e = E_e \hat{I} \ell_e \Omega / c = 14$ MW, where $\hat{I} = 270$ A is the peak current, $\ell_e = 0.1$ mm is the electron pulse length and c is the speed of light. An output power of 100 kW requires an extraction efficiency of $\eta \approx 0.7\%$. The undulator period is $\lambda_0 = 8.0$ cm over $N = 36$ periods with rms undulator parameter $K = 1.7$. The conventional undulator has a periodic field and wavelength, but a linearly tapered undulator gradually changes the undulator parameter K by modifying the gap between the undulator magnets. A step-tapered undulator abruptly changes the value of the field halfway through the undulator. The tapered undulator [2–7] is described by the

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modified pendulum equation

$$\frac{\mathrm{d}v}{\mathrm{d}\tau} = \frac{\mathrm{d}^2\zeta}{\mathrm{d}\tau^2} = \delta + \theta\left(\tau - \frac{1}{2}\right)\Delta + a\cos(\zeta + \varphi),$$

where

$$\theta(z) = \begin{cases} 0 & \text{for } z<0 \\ 1 & \text{for } z>0 \end{cases} \quad \text{is the step function,} \qquad (1)$$

ζ is the electron phase, v is the electron phase velocity, φ is the optical phase, a is the dimensionless optical field amplitude, $\delta = -[4\pi N K^2/(1+K^2)](\Delta K/K)$ is the phase acceleration caused by the linear tapering of the undulator, and $\Delta = -[4\pi N K^2/(1+K^2)](\Delta K/K)$ is the step-taper at $\tau = z/N\lambda_0 = \frac{1}{2}$ along the undulator.

Previously published results showed as much as a 75% efficiency enhancement with a negative step-tapered undulator, based on simulations and experimental results from CLIO and FELIX [4–6]. In contrast, we found only a slight improvement in efficiency with a small negative taper for the parameters investigated. The results of this research show that step-taper cannot always be as effective as found earlier, and that an FEL must be far into strong-field saturation before tapering can extend the saturation limit. We also show how step-tapering affects the shape of desynchronism curves which is useful in designing for peak power and for more stable FEL operation.

2. Weak field gain

The 100 kW TJNAF FEL is described by dimensionless peak current $j = 5$, pulse length $\sigma_z = 3$ and resonator $Q = 4.2$ [2]. To study FEL gain, we use weak optical fields, where the dimensionless field is $a < \pi$. Desynchronism $d = -\Delta S/N\lambda$ measures the shortening of the resonator cavity length by ΔS compared to the slippage distance $N\lambda\cdot$ The desynchronism between optical pulse and electron pulse was varied from $d = 0$–0.3. The gain results from many simulations at different values of desynchronism d with a step-tapered undulator are plotted in Fig. 1. The conventional non-tapered case ($\Delta = \delta = 0$) produces the highest gain of 60%. At small and large values of desynchronism the gain decreases for all the undulators away from peak values around $d = 0.1$. Gain for small step-taper of $\Delta = \pm\pi$ ($\delta = 0$) is only slightly reduced from the conventional case. Larger step-taper $\Delta = \pm 2\pi$ causes a significant reduction in gain around 40% peaking at lower values of $d \sim 0.05$. The FEL still works beyond the losses ($Q = 4.2$) for larger values of $d < 0.2$.

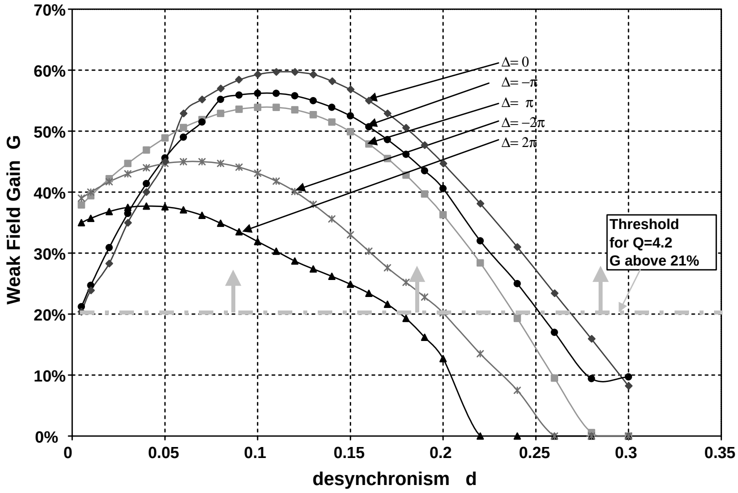

Fig. 1. Weak field gain G versus desynchronism d for step taper with $Q = 4.2$. Gain above threshold for all cases, optimum gain with no taper ($\Delta = 0$).

3. Steady state power

Fig. 2 shows the efficiency plotted versus desynchronism d for different values of $\varDelta$. For a conventional undulator with no taper ($\varDelta = 0$), the desynchronism was varied from $d = 0.005$ up to 0.3 to study pulse slippage effects. We found the best results for desynchronism $d = 0.04$, which gave efficiency $\eta \approx 0.8\%$, above the requirement for 100 kW, as shown in Fig. 2. At that value of desynchronism, the induced energy spread was $\Delta\gamma/\gamma = 3\%$, well below the 15% limit for recirculation. Fig. 2 shows that slight increases of desynchronism to $d > 0.06$ makes the efficiency marginal ($\eta < 0.7\%$).

For linear taper ($\varDelta = 0$), we considered different values of $\delta = \pm\pi,\ \pm 2\pi,\ \pm 4\pi$ corresponding to a change $\Delta K/K = \pm 0.9\%,\ \pm 1.9\%,\ \pm 3.8\%$, respectively. We found that negative taper, $\delta = -\pi,\ -2\pi$ gave the highest efficiency $\eta \approx 0.9\%$ at desynchronism $d = 0.04$. This is similar to our simulations of the TJNAF 10 kW FEL [8]. For these cases, the full-width induced energy spread was $\Delta\gamma/\gamma = 3\%$, which is below the limit for safe recirculation.

For a step-taper undulator ($\delta = 0$), the results of longitudinal multimode simulations are also

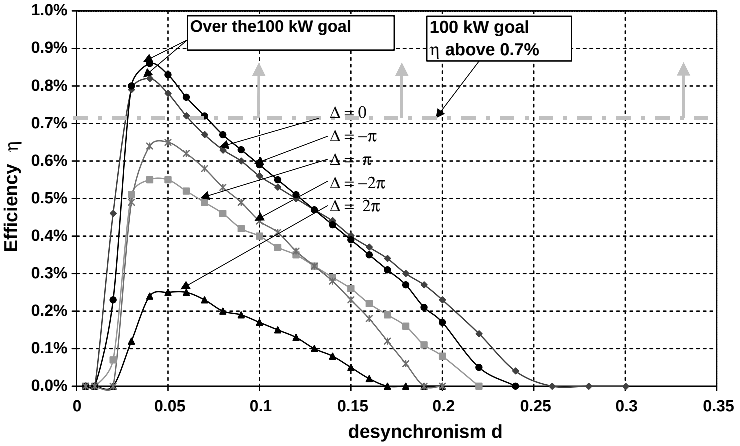

Fig. 2. Efficiency η versus desynchronism d for step taper with $Q = 4.2$. Power above 100 kW for $\varDelta = 0, -\pi$.

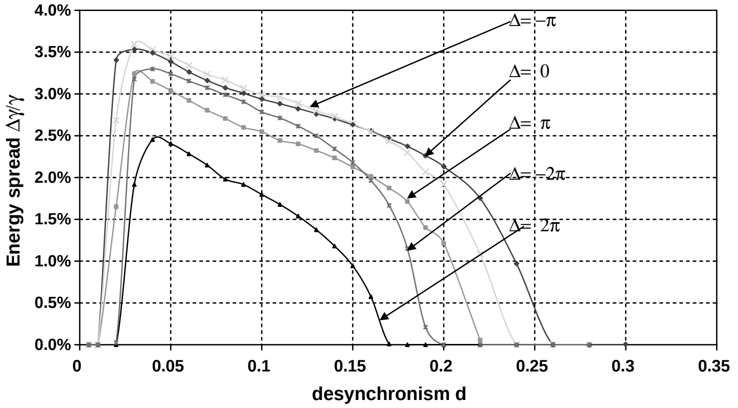

Fig. 3. Energy spread $\Delta\gamma/\gamma$ versus desynchronism d for step taper with $Q = 4.2$. Lower power reduces energy spread for all undulator designs.

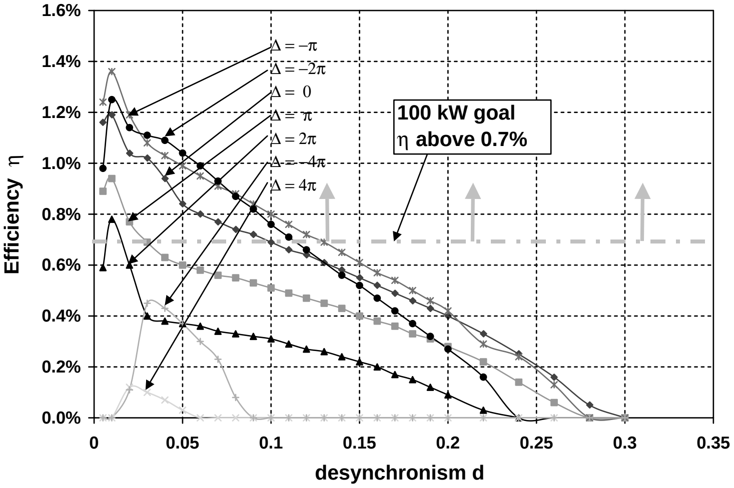

Fig. 4. Efficiency η versus desynchronism d for step taper with $Q = 10$. Power above 100 kW for a larger range of tapers $\Delta = 0, \pm\pi, \pm 2\pi$.

shown in Fig. 2. We found that for the same value of $d = 0.04$, a negative step-taper $\Delta = -\pi$ again gave the best results and the efficiency was increased to 0.9%. Larger values of tapering, $\Delta < -2\pi$, and larger desynchronism, $d > 0.06$, did not work.

With both the linear and step taper a slight increase in efficiency over the conventional undulator was observed for small negative taper. The induced energy spread did not change significantly with any undulator design.

4. Higher Q experiments

Fig. 4 shows the result of simulations, with a larger quality factor $Q = 10$. In this case, the extraction efficiency, for some values of Δ and d, exceeds 1%. Specifically in the $\Delta = -\pi$ case the efficiency increased from 0.9% to 1.4%. For values of $\Delta = \pm 4\pi$ and $d > 1.2$, the FEL failed to exceed the efficiency limit. Compared to the $Q = 4.2$ case, there is a larger range of desynchronism in which the FEL operates above the power requirement (Figs. 3 and 4).

Acknowledgements

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