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Simulations of the 100 kW TJNAF FEL using a short Rayleigh length

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Abstract

The TJNAF FEL can be upgraded to operate at 100 kW average power and then explore the use of a short Rayleigh length in order to reduce the power density on the resonator mirrors. The short Rayleigh length can only work with a relatively short undulator. Multimode simulations are used to self-consistently model the optical mode interaction with the electron beam. The steady-state resonator mode is affected by the complex, non-linear electron beam evolution as well as the resonator design. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Thomas Jefferson National Accelerator Facility (TJNAF) may be able to modify their free-electron laser (FEL) [1,2] to an increased power output of 100 kW. The changes will involve increasing the electron beam energy to $E_e = 210$ MeV with a pulse repetition rate of $\Omega = 750$ MHz while maintaining a peak current of $I = 270$ A in an electron pulse length of $l_e = 0.1$ mm. The resulting electron beam power is $P_e = 14$ MW in an electron beam radius of $r_e = 0.3$ mm. An extraction efficiency of $\eta \approx 0.7\%$ is needed to reach the 100 kW optical output.

Energy spread and emittance cause only small degradation of the weak field gain and steady-state power. The undulator wavelength is $\lambda_0 = 8$ cm with $N = 36$ periods and an rms undulator parameter of $K = 1.7$. This will result in a radiation wavelength $\lambda \approx 1$ μ m in an optical resonator $S = 32$ m long with an output coupling of 21% corresponding to resonator quality factor $Q = 4.2$.

Dimensionless parameters are used to describe the physics of the FEL design. The electron pulse length l_e is three times the slippage distance $N\lambda$ so that short-pulse effects are minimal, although present. The dimensionless current density at the peak of the electron pulse is $j = 8N(e\pi KL)^2\rho/\gamma^3 mc^2 = 40$, where N is the number of undulator periods, e is the electron charge, L is the undulator length, ρ is the electron density, γ is the Lorentz

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factor, m is the mass of the electron and c is the speed of light. The dimensionless optical field amplitude is $|a| = 4\pi NeKLE/\gamma^2 mc^2$ where E is the electric field of the optical mode. The Rayleigh length is defined as $Z_0 = \pi w_0^2/\lambda$ where w_0 is the radius of the mode waist and the normalized Rayleigh length is $z_0 = Z_0/L$. The dimensionless optical beam width $w = [z_0 + (\tau - 1/2)^2/z_0]^{1/2}$ where $\tau = z/L$ is the dimensionless position along the z -axis, shows that lower values of Rayleigh length z_0 would produce a larger spot size at the mirrors. A short Rayleigh length gives a small mode waist where the optical amplitude will be much larger than at the mirrors. Fig. 1 shows the shape of the optical mode and the power density on the mirrors for Rayleigh length $z_0 = 0.1$ to 0.5 . Reducing the Rayleigh length from $z_0 = 0.3$ to 0.1 reduces the power density on the mirrors by 300% [3].

2. Transverse mode effects

Fig. 2 presents a three-dimensional simulation of the proposed laser in x , y and τ . The upper-right table presents the dimensionless parameters describing the 100 kW design, along with the gray scale for the intensity plots of the optical amplitude $|a|$. Transverse dimensions are normalized to $(L\lambda/\pi)^{1/2}$, and the longitudinal dimensions are normalized to the undulator length L . The dimensionless electron beam radius is $\sigma_{x,y} = 0.2$ in

the x and y dimensions. The betatron oscillation frequency is $\omega_\beta = 1$ over the undulator length with the electron beam focused in the middle of the undulator at $\tau_\beta = 0.5$. The beam's angular spread $\sigma_{\theta x,y} = 0.04$ is determined by the matching requirement $\sigma_{\theta x,y} = \omega_\beta^2 \sigma_{x,y}^2$. With constant emittance, the results were comparable. The mirror radius is $r_m = 7.2$, while the mirror curvature is $r_c = 1.5$ yielding a normalized Rayleigh length $z_0 = 0.1$. The quality factor $Q = 4.2$ corresponds to an approximate 21% mirror transmission, and edge losses around the mirrors are 1% per pass ($e = 0.01$).

The top-left plot, $|a(x,n)|$, presents the development of a slice through the optical mode over $n = 64$ passes showing how steady state develops. The top-center plot, $|a(x,y)|$, presents the final optical wavefront at the undulator exit $\tau = 1$ showing the electron beam centered in the mode. The center plot, $|a(x,\tau)|$, shows a section through the optical wavefront during the final pass. The mirror separation was shortened to three times the undulator length instead of 11 times the undulator for numerical convenience. The additional resonator length does not contribute to the optical field and is neglected in the simulations. The bottom-left plot, $f(v,n)$, shows the development of the electron phase velocity distribution, and next to it is the final electron phase space plot showing a spread of $\Delta v = 30$, corresponding to energy spread $\Delta\gamma/\gamma = 6.5\%$ and efficiency $\eta = 1.6\%$. In the bottom-right is the development of optical power $P(n)$ and gain $G(n)$.

Fig. 1. Optical mode shapes for various Rayleigh lengths. By reducing z_0 from 0.3 to 0.1, a 300% reduction in intensity is experienced at the mirrors.

3. Weak field gain

Simulations were conducted to estimate the weak field gain for the proposed parameters. The normalized Rayleigh length was varied from $z_0 = 0.1$ to 0.5 . For each z_0 , the phase velocity was varied from $v_0 = 3$ to 15 to determine the optimum. For each value of z_0 , the peak gain in weak fields ($|a| < \pi$) was plotted for values of $\sigma_x = 0.1$ to 0.5 in Fig. 3. In each case, the optimum phase velocity was found to be $v_0 \approx 4$. The maximum gain of 9.4 was obtained with a small electron beam radius $\sigma_{x,y} = 0.1$ and small Rayleigh

Fig. 2. Three-dimensional simulation in x , y and τ , for $z_0 = 0.1$, $v_0 = 10$, $\sigma_{x,y} = 0.1$. A small beam size implies a possible mode distortion. The weak field gain reaches $G = 900\%$, while at saturation the efficiency reaches $\eta = 1.6\%$.

Fig. 3. Weak field gain vs. electron beam radius for optimum v_0 . Small electron beam radius and small Rayleigh length was found to be beneficial. A larger electron beam is outside the optical mode thus reducing gain.

length $z_0 = 0.1$. As the electron beam radius σ_x was increased, gain decreased for all values of z_0 . Lower values of z_0 produced higher values of gain at each σ_x . This result contradicts basic FEL theory [4], where the maximum gain occurs when the electron beam size is only slightly smaller than

the optical mode, which corresponds to $z_0 = 0.3$. It appears that a short Rayleigh length and correspondingly smaller electron beam provides a higher beam density to amplify the optical mode, which enhances the gain. In some cases, the larger electron beam is outside the optical mode, which would reduce the gain. The current density is too small for optical guiding [4], however the weak field simulation results show significant mode distortion, which could enhance the gain. With larger electron beams, there is less optical mode distortion.

4. Steady-state power

Simulations were run until steady-state power was obtained for values of normalized Rayleigh length $z_0 = 0.1$ to 0.5 and electron beam radius $\sigma_{x,y} = 0.1$ to 0.5 . At each value of z_0 and $\sigma_{x,y}$, the phase velocity was varied from $v_0 = 1$ to 14 . The highest peak power for each value of z_0 was selected, and the extraction efficiency η at that power was then plotted against σ_x (Fig. 4). The results show that a smaller electron beam enhances

Fig. 4. Efficiency vs. electron beam radius at optimum electron beam phase velocity v_0 .

efficiency. It was also found that for short Rayleigh lengths, the optimum phase velocity v_0 increases, but good efficiency is maintained. Maximum efficiency was 2% with $z_0 = 0.3$, $\sigma_{x,y} = 0.1$ and $v_0 = 11$. For a small electron beam size $\sigma_{x,y} = 0.1$ and small Rayleigh length $z_0 = 0.1$, we observed multiple optical modes with power oscillating by as much as 20%. However, these multimodes could be suppressed with larger

electron beams. Multimodes seem to develop higher power and efficiency.

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References

- [1] G.R. Neil, et al., Nucl. Instr. and Meth. A 445 (2000) 192.
- [2] R.D. McGinnis, J. Blau, W.B. Colson, D. Massey, P.P. Crooker, A. Christodoulou, D. Lampiris, Simulations of the TJNAF 10 kW free electron laser, Nucl. Instr. and Meth. 445 (2000) 49.
- [3] D.W. Small, R.K. Wong, W.B. Colson, R.L. Armstead, Free electron lasers with short Rayleigh length, Nucl. Instr. and Meth. 393 (1997) 204.
- [4] W.B. Colson, C. Pellegrini, A. Renieri (Eds.), Free Electron Laser Handbook, North-Holland, Elsevier, The Netherlands, 1990 (Chapter 5).