CONF-970231--36

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Critical Issues for High-Power FEL Based on Microtron Recuperator/Electron Out-Coupling Scheme

N.A. Vinokurov, A.A. Zholents, W.M. Fawley,
and K.-J. Kim
**Accelerator and Fusion
Research Division**

RECEIVED
JUN 12 1997
OSTI

MASTER

March 1997
Presented at
*SPIE's International
Symposia, "Photonics
West" Conference,*
San Jose, CA,
February 8-14, 1997,
and to be published in
the Proceedings

44
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory
is an equal opportunity employer.

Critical Issues for High-Power FEL Based on Microtron Recuperator / Electron Out-Coupling Scheme*

N. A. Vinokurov^a, A. A. Zholents^b, W. M. Fawley^b, and K.-J. Kim^b

^a Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia;
and Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439

^b Lawrence Berkeley National Laboratory, One Cyclotron Road, MS 71-259,
Berkeley, CA 94720, USA

March 1997

MASTER

HH
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC 03-76SF00098.

Critical issues for high-power FEL based on microtron recuperator / electron out-coupling scheme

N. A. Vinokurov^a, A. A. Zholents^b, W. M. Fawley^b, and K.-J. Kim^b

^a Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia;
and Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439

^b Lawrence Berkeley National Laboratory, One Cyclotron Road, MS 71-259, Berkeley, CA 94720, USA

ABSTRACT

The FELs based on the RF accelerator-recuperator and the electron outcoupling is promising for obtaining average output power of hundreds of kilowatts. We present basic considerations for the system stability and performance optimization for this scheme.

Keywords: free electron lasers, accelerators

1. INTRODUCTION

Optical beams with high average power could be important power source for industrial applications. Power beaming to satellite requires spatially coherent, 1 micron radiation beam with average power greater than 100 kW¹. Free electron lasers (FELs) driven by high power electron accelerator can meet these requirements.

One of the most attractive features of free electron lasers (FELs) is the possibility of generating fully transverse coherent light, having very high average power. This is due to the simplicity (in comparison with other types of lasers) of the working media—the electron beam. The average power in such a beam may be about 1 GW (in storage rings), and corresponding power density is in the order of 10 GW/mm². Such a high power is simply the consequence of the high electron velocity, the corresponding linear and volume density energy being only 3 J/m and 33 J/cm³, respectively.

On the other hand, the efficiency of the conversion of the beam power to the radiation power is rather small in an FEL, being typically not more than a few percent. For high power application, therefore, it is necessary to recover the beam power after the FEL interaction. The main reason for the energy recovery, except of simple energy saving, is the dramatic reduction of the radiation hazard at the beam dump.

One of the possible methods of beam energy recovery is to return the beam to the RF accelerating structure, which was used to accelerate it. If the length of path from the accelerator through the FEL to the accelerator is chosen properly, the deceleration of particles will occur instead of acceleration, and therefore the energy will return to the accelerating RF field (in other words, the beam will excite RF oscillations in the accelerating structure together with the RF generator). Such a mode of accelerator operation was demonstrated at the Stanford HEPL². An obvious extension of such an approach is the use of multipass recirculators instead of simple linacs. By increasing of the number of passes, cost and power consumption can be reduced. However, the threshold current of instabilities (see below) also decreases, so the "optimal" number of passes exists.

Another severe problem concerns the output of radiation from the optical resonator of the FEL. A solution is the use of the coherent undulator radiation of prebunched electron beams. The FEL itself is necessary only to provide the electron bunching in this scheme. For the high gain bunching FEL this approach is referred to as MOPA; and for the low gain FEL with optical resonator, as "electron outcoupling"³. Both these terms describe the principles of operation concerning the behavior of radiation: amplification of the input signal and "extraction" from the optical resonator. The second approach seems to be easier for reasonable peak electron currents, but the combination of the two approaches may be interesting as well.

In this paper we will discuss some theoretical aspects of the high power FEL operation based on the multipass recirculator and the electron beam outcoupling scheme. These ideas are implemented and will be tested at the Novosibirsk facility⁴, which is now under construction.

2. THE GENERAL SCHEME

Assuming a few-centimeter period for the undulator, it is easy to estimate that for the infrared FEL one needs to have electron energy in the order of 100 MeV. Assuming 1% electron efficiency of the FEL and required output power of 100 kW, one obtains the required beam current of 100 mA. As was mentioned in the introduction, we will discuss the use of the RF recirculating accelerator (the detail information on the accelerators of such a type is contained in the book⁵) in order to provide the required electron beam, and also to decelerate it after use (see Fig. 1). As the RF accelerating structure is used, the total length of each pass has to be the multiple of the RF wavelength (at least, approximately). The last path, containing an FEL, has to be about one half of a wavelength longer. Some desirable features of an accelerator-recuperator are listed below.

1. The ejection (and, correspondingly, the injection) energy is to be less than 10 MeV, to avoid neutron generation in the beam dump.
2. The electron optical system has to provide proper focusing for the accelerating and the decelerating beams. It is not so trivial, as each orbit, except for the last one, is used to transport two beams (accelerating and decelerating) with the different initial conditions simultaneously, and there are $2N$ (N is the number of passes through the linac during acceleration) beams with very different energies inside the linac.
3. Energy acceptance should be a few percents or larger to decelerate the spent electron beam. This can be achieved by employing magnetic system consisting of achromatic bends with low enough transverse dispersion function inside.
4. It is preferable to have a zero transverse dispersion function in the straight line sections to allow the optimization of the betatron phase advances at each orbit to increase the threshold current for the transverse beam breakup (see below).
5. The frequency of the RF system tends to be low to decrease the longitudinal and transverse impedances and increase the longitudinal acceptance. Another advantage of low frequencies is the possibility of using the separated (uncoupled) RF resonators with individual tunes of fundamental and asymmetric modes.
6. To preserve low transverse emittance it is preferable to have a high peak current only at high energies. So the rotation in the longitudinal phase space by $\pi/2$, $3\pi/2$, ... may be useful.

Figure 1. The scheme of the FEL with the accelerator-recuperator. 1—injector; 2—RF accelerating structure; 3—180-degree bends; 4—the FEL magnetic system; 5—beam dump; 6—mirrors; 7—the output light beam.

3. COLLECTIVE INSTABILITIES

As the average current is rather high, the issue of collective instabilities is very crucial for such projects.

The most important transverse instability is so-called regenerative beam breakup. It is caused by the excitation of the axially asymmetric modes of electromagnetic oscillations inside the linac. The regenerative beam breakup is understood fully now⁵). If the linac consists of uncoupled resonators, we may tune the most dangerous TM_{110} mode for each of them to different resonant frequencies. Then the start current for the transverse beam breakup is given by

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

$$I_s = -I_0 \frac{\lambda^2}{Q_a L_{eff} \sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{(R_{12})_{nm} \sin[\frac{c}{\lambda}(T_n - T_m)]}{\gamma_m}} \quad (1)$$

where $I_0 = \frac{mc^3}{e} \approx 17 \text{ kA}$, Q_a is the quality factor, $\tilde{\lambda} = \frac{\lambda}{2\pi}$, λ is the wavelength corresponding to the resonant frequency of the TM₁₁₀ mode, γ_m is the relativistic factor at the m -th passing through the cavity, $(R_{12})_{nm}$ is the coordinate of the sine-like trajectory at the n -th passing which begins from the m -th passing, and $T_n - T_m$ is the time difference between n -th and m -th passing. For the circular cylindrical cavity of length L ,

$$L_{eff} \approx 0.9 \left(\frac{\sin \frac{L}{2\tilde{\lambda}}}{\frac{L}{2\tilde{\lambda}}} \right)^2 L. \quad (2)$$

The physical meaning of (1) is simple. The magnetic field of the TM₁₁₀ mode deflects the beam at each pass (with number m). The deflected beam makes an addition to the mode field depending on its coordinates at later passes (with number n). The consideration of the balance between this "amplification" and the damping due to the losses (finite Q_a) leads to the expression for the start current I_s . In principle, the electron beam transport of the microtron-recuperator may be chosen to provide the positive denominator of (1), and, correspondingly, the stability at all beam currents. But, we need to satisfy this condition for each cavity of linac and also for the vertical and horizontal directions. Because of the axial asymmetry of practical RF cavities, two polarizations of the TM₁₁₀ mode have, in general, different resonant frequencies and are "skew."

According to these remarks, we may estimate the worst case by setting $\sin[\frac{c}{\lambda}(T_n - T_m)] = -1$, and the combination of

the design betatron functions $\sqrt{\beta_m \beta_n \frac{\gamma_m}{\gamma_n}}$ for $(R_{12})_{nm}$ to Eq. (1):

$$I_s > I_0 \frac{\lambda^2}{Q_a L_{eff} N(2N-1) \left\langle \frac{\beta}{\gamma} \right\rangle}, \quad (3)$$

where

$$\left\langle \frac{\beta}{\gamma} \right\rangle = \frac{1}{N(2N-1)} \sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \sqrt{\frac{\beta_m \beta_n}{\gamma_m \gamma_n}}. \quad (4)$$

Eq. (3) shows that it is preferable to use the low-frequency nonsuperconducting RF system (higher $\tilde{\lambda}$ and lower Q_a) and strong focusing at low energies. It also demonstrates the limitation to the number of passes. However, for more realistic estimates, we may assume a random phase distribution in Eq. (1), and then obtain:

$$I_s \approx I_0 \frac{\lambda^2}{Q_a L_{eff} \sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}}. \quad (5)$$

We now turn our attention to the longitudinal collective instability, which has some special features for recuperators.

To simplify the picture, consider the linac as one accelerating gap. Such a simplification works, for example, if we have the π -structure of similar RF cavities. Taking the effective voltage on the gap in the form $\text{Re}(U e^{i\omega t})$, (ω is the frequency of the RF generator), we obtain:

$$\frac{2}{\omega} \frac{dU}{dt} = \frac{i\xi - 1}{Q} U + \rho(I_b + I_g), \quad (6)$$

where $\omega_0 = (1 + \frac{\xi}{2Q})\omega$ is the resonant frequency, $Q = Q_L \omega / \omega_0$, Q_L is the loaded Q of the cavity, $\rho = R_L / Q$, and R_L is the loaded characteristic impedance for the fundamental (TM₀₁₀) mode, and I_b and I_g are the complex amplitudes of the beam and (reduced to the gap) generator currents correspondingly⁶. We are interested in the case of constant I_g . The beam current I_b , depends on U due to phase motion and beam losses. Linearization of (6) near the stationary solution

$$U_s = \frac{Q\rho}{1 - i\xi} [I_b(U_s) + I_g] \quad (7)$$

gives:

$$\frac{2}{\omega} \frac{d\delta U}{dt} = \frac{i\xi - 1}{Q} \delta U + \rho \left[\frac{\partial I_b}{\partial \text{Re}(U)}(U_s) \text{Re}(\delta U) + \frac{\partial I_b}{\partial \text{Im}(U)}(U_s) \text{Im}(\delta U) \right] \quad (8)$$

Strictly speaking, I_b depends on the values of U at previous moments of time, so Eq. (8) is valid only if the damping time Q/ω is much longer than the time of flight through the recuperator T_{2N} . Considering the system of two linear differential equations (8), it can be shown that there exist the values of ξ , which provide the system stability, when the trace of the right-hand side matrix is negative:

$$\frac{\partial \text{Re}(I_b)}{\partial \text{Re}(U)} + \frac{\partial \text{Im}(I_b)}{\partial \text{Im}(U)} < \frac{2}{\rho Q} \quad (9)$$

To proceed further, we have to specify the elements of the beam conductivity matrix in the stability condition (Eq. 9). The complex amplitude of the beam current I_b may be written in the form

$$I_b \cong -2I \sum_{n=1}^{2N} e^{i\varphi_n} (1 + i\psi_n + l_{n-1}\epsilon_{n-1} - a_{n-1}) = I_b(U_s) - 2I \sum_{n=1}^{2N} e^{i\varphi_n} (i\psi_n + l_{n-1}\epsilon_{n-1}), \quad (10)$$

where I is the average beam current, φ_n is the equilibrium phase for the n -th pass through the resonator, and a_n and l_n describe the beam losses⁸ at the n -th orbit. The small energy and phase deviations ϵ_n and ψ_n obey the linear equations:

$$\epsilon_n = \epsilon_{n-1} + e \text{Im}(U_s e^{-i\varphi_n}) \psi_n + e \text{Re}(\delta U e^{-i\varphi_n}) \quad (11)$$

$$\psi_{n+1} = \psi_n + \omega \left(\frac{dt}{dE} \right)_n \epsilon_n, \quad (12)$$

where $\left(\frac{dt}{dE}\right)_n$ is the longitudinal dispersion of the n -th orbit. The initial conditions for the system of Eqs. (11) and (12) are, certainly, $\epsilon_0 = 0$ and $\psi_1 = 0$, if we have no special devices to control them for the sake of beam stabilization, or other purposes. Then the solution may be written using the longitudinal sine-like trajectory S_{nk} and its "derivative" S'_{nk} (56 and 66 elements of the transport matrix):

$$\psi_n = e \sum_{k=1}^{n-1} S_{nk} \operatorname{Re}(\delta U e^{-i\varphi_k}) \quad (13)$$

$$\epsilon_n = e \sum_{k=1}^n S'_{nk} \operatorname{Re}(\delta U e^{-i\varphi_k}) . \quad (14)$$

Substitution of the Eqs. (10), (13) and (14) into Eq. (9) leads to the stability condition

$$\frac{1}{e I \rho Q} > - \sum_{n=1}^{2N} \sum_{k=1}^{n-1} \left[S_{nk} \sin(\varphi_k - \varphi_n) + l_{n-1} S'_{n-1,k} \cos(\varphi_k - \varphi_n) \right] . \quad (15)$$

If the recirculator does not have decelerating passes, all equilibrium phases φ_n may be equal. Then the first term into the square brackets is zero, and only the energy dependence of beam losses may cause the longitudinal instability. For the accelerator-recuperator, it needs to satisfy (at least approximately) the recuperation condition

$$\operatorname{Re} \left(U_s \sum_{n=1}^{2N} e^{-i\varphi_n} \right) = 0 . \quad (16)$$

For the longitudinal stability it also needs to have longitudinal focusing for most of passes through the linac [see Eq. (11)]:

$$e \operatorname{Im}(U_s e^{-i\varphi_n}) < 0 \quad (17)$$

(if all $(dt/dE)_n > 0$). Conditions (16) and (17) may be satisfied simultaneously, if

$$\arg(e U_s e^{-i\varphi_{N-k}}) + \arg(e U_s e^{-i\varphi_{N+k+1}}) = -\pi, \quad 0 \leq k \leq N-1 . \quad (18)$$

Condition (18) affords the equalities of beam energies after $(N-k)$ -th and $(N+k)$ -th passes through the linac, permitting the use of the same beamline for the accelerating and the decelerating beams.

To make the stability condition (15) more explicit, consider a simple example. Assume that all equilibrium phases are equal during acceleration. Conditions (17) and (18) define the equilibrium phases for deceleration:

$$\arg(e U_s e^{-i\varphi_n}) = \begin{cases} -\varphi_0 & \text{for } n \leq N \\ \varphi_0 - \pi & \text{for } n > N \end{cases} . \quad (19)$$

Then Eq. (15) may be simplified:

$$\frac{1}{eI\rho Q} > \sin(2\varphi_0) \left(\sum_{n=N+1}^{2N} \sum_{k=1}^N S_{nk} \right) + \cos(2\varphi_0) \left(\sum_{n=N+1}^{2N} \sum_{k=1}^N l_{n-1} S'_{n-1 k} - \sum_{n=1}^N \sum_{k=1}^{n-1} l_{n-1} S'_{n-1 k} - \sum_{n=N+1}^{2N} \sum_{k=N+1}^{n-1} l_{n-1} S'_{n-1 k} \right) \quad (20)$$

Typically, the first term in the right hand side of Eq. (20) is dominant, so the condition of the "absolute" (i.e., at any current) stability is:

$$\sum_{n=N+1}^{2N} \sum_{k=1}^N S_{nk} < 0. \quad (21)$$

The sum (21) may be calculated analytically, if the longitudinal dispersions $\left(\frac{dt}{dE} \right)_n$ are the same for all orbits (as it is in the classical race-track microtron). Then

$$S_{nk} \propto \sin\left(\Phi \frac{n-k}{N}\right), \quad (22)$$

where Φ is the phase advance for the longitudinal oscillations from the entrance of the accelerator to the FEL. As was already mentioned, it is preferable to have $\Phi = \pi/2 + q\pi$, q being an integer. Simple calculations transform Eq. (21) to $\sin \Phi < 0$, so $\Phi = 3\pi/2$ is preferable. Thus, the longitudinal motion is "more stable" in microtron-recuperators than in pure accelerators, due to stabilization by the interaction of the beam with the linac. This conclusion is correct in most cases, even when φ_n and $\left(\frac{dt}{dE} \right)_n$ depend on n . Another advantage of the phase advance $3\pi/2$ in comparison with $\pi/2$ are lower second order longitudinal aberrations⁹, but the disadvantage is the appearance of longitudinal crossover at lower energies. The special case, when all orbits, except the N -th, are isochronous, was considered earlier⁷.

The stability of longitudinal motion was checked with a preliminary numerical simulation code previously⁸. Recently, we have developed another code which takes advantage of the stability analysis developed above. Thus the simulation begins with a stationary initial operating condition defined analytically for a set of input parameters such as the average injector current and average current losses in the recuperator, quality factor of the cavity, mirror reflection efficiency and average radiated power, and then continue simulations allowing pulse-to-pulse jitters in the injection current, injection energy and phase. A typical result of the simulation with 10% current jitter, 10% energy jitter and 1° phase jitter is shown in Fig. 2. To demonstrate the stability, the injector current (upper plot) was switched off for ~10 microseconds. The accelerating voltage and the radiation power returned to the stationary values in few tens of microseconds.

Figure 2. Simulation results showing stability of the accelerating voltage and the output power in the presence of energy and current jitter of the injector beam. Note that the stable operation is recovered even when the current is turned off for about 10 microseconds.

The scheme of FEL with the electron outcoupling² is shown in Fig. 3. The FEL-oscillator is the optical klystron with undulators 1 and 3, dispersive section 2 and mirrors 6. The microbunched (in the FEL-oscillator and the bend 4) electron beam passes through radiator 5. As the electron beam in the radiator is deflected from the optical cavity axis, the coherent undulator radiation leaves the cavity.

Figure 3. The scheme of the FEL. 1—first undulator; 2—dispersive section; 3—second undulator; 4—achromatic bend; 5—undulator-radiator; 6—mirror; 7—electron beam; 8—coherent undulator radiation.

As the FEL is used here only to bunch the electron beam, it has to be optimized for minimal intensity of light on the mirror surfaces. To limit the intracavity power it is convenient to choose a high value of longitudinal dispersion of the dispersive section. In addition, it is preferable to have the second undulator sufficiently longer than the first one. Then the "useful" energy modulation in the second undulator, which causes the density modulation in the radiator, is significantly more than "harmful" modulation in the first undulator, which increases the effective energy spread in the radiator. To minimize this increase of the effective energy spread, the intracavity power loss must be minimized (so, the mirror reflectivity has to be good).

To demonstrate explicitly the dependence of different parameters we will obtain a simple estimate for it. Assume that the fundamental mode of the optical resonator inside the undulator can be approximated by the Gaussian beam with the Rayleigh length z_0 . The amplitude of the electric field may be expressed through the light peak power P as $2\sqrt{\frac{kP}{cz_0}}$, k being the wave number. To obtain significant beam bunching, the amplitude of the energy modulation must exceed the energy spread σ_E :

$$2\sqrt{\frac{kP}{cz_0}} e \alpha_0 z_0 > \sigma_E, \quad (23)$$

where α_0 is the amplitude of the deflection angle of the undulator, and the (effective) undulator length is assumed to be equal to $2z_0$. The maximal intensity at the large distance s from the waist (on the mirror) is

$$I_m \approx \frac{kPz_0}{\pi s^2}. \quad (24)$$

The combination of the inequality (Eq. 23), Eq.(24) and $\alpha_0^2 = 8\pi/(k\lambda_w) \cdot K^2/(2 + K^2)$ (λ_w and K are the undulator period and deflection parameter) which leads to the following limitation for the distance from the undulator to the mirror:

$$s > \frac{\sigma_E}{8\pi e} \sqrt{\frac{2ck\lambda_w}{I_m} \left(1 + \frac{2}{K^2}\right)}. \quad (25)$$

With the current technology, the average power on mirrors should be limited to a value of about 1 kW/cm². Assuming a duty factor for the radiation intensity to be about 1/2000 energy spread of about 300 keV, an undulator period of about 5 cm, a deflection parameter of about $\sqrt{2}$ and the 1 micron wavelength, one obtains 12 m for the right-hand side of Eq. 25. Therefore, it is enough to use the simplest two-mirror optical resonator with the length of about 100 m and increase its Rayleigh length to improve the tolerances for the mirror alignment.

The stationary value of the intracavity peak power can be derived from the energy conservation

$$\frac{J_1(4\pi N_D \Delta)}{2\pi N_D} G = G_{th} \quad (26)$$

Here the field amplitude is expressed through the amplitude of the relative energy modulation in the first undulator Δ ; N_D is the effective number of periods in the dispersive section (which is proportional to the longitudinal dispersion from the middle of the first undulator to the middle of the second one); and G is the small gain and G_{th} is the gain at the threshold of oscillation (which is equal to the round-trip loss). The left side of Eq. (26) describes the fractional increase of power generated by the electron beam in the cavity; and the right side describes the round trip loss. Using the approximation $J_1(x) \approx x/2 - x^3/16$, we obtain from Eq. (26):

$$\Delta \approx \frac{1}{\sqrt{2}\pi N_D} \sqrt{1 - \frac{G_{th}}{G}} \quad (27)$$

As for the optical klystron, the small signal gain depends on N_D as $N_D / \exp[2(2\pi N_D \sigma_E / E)^2]$, one can adjust the longitudinal dispersion to obtain the optimal modulation amplitude (about $2\sigma_E / E$)^{10,11}, in the second undulator. The ratio of the energy modulation amplitudes in the first and the second undulators is approximately the ratio of the corresponding undulator lengths. Moreover, the energy modulation in the first undulator will cause not the density modulation, but only the increase of the energy spread in the third undulator (as the longitudinal dispersion from the middle of the first undulator to the middle of the third one is too high). Therefore it is preferable to make the second undulator several times longer, than the first one.

For low enough emittances and energy spread, the power of the coherent undulator radiation is proportional to the number of the undulator periods. But for a very long undulator the longitudinal velocity spread will lead to debunching at long distances from the entrance; therefore only the beginning of the undulator makes a significant contribution to the total radiation power. If the effect of energy spread is dominant, the analytical estimate of the power^{10,11} gives:

$$P < 5[\Omega] \left(\frac{\sigma_E}{E} \right)^{-1} I I_p \quad (28)$$

(SI units), where I_p is the peak current. The simple way to obtain the limitation (28) is following. The power of the coherent undulator radiation for the "optimally" bunched electron beam is

$$P \equiv 100[\Omega] N I I_p \quad (29)$$

where N is the number of periods. The maximum N may be found from the condition of the conservation of bunching:

$$k c \frac{dt}{dE} \Delta E = 4\pi N \frac{\Delta E}{E} < 1 \quad (30)$$

where $\Delta E \approx 2\sigma_E$ for the optimal modulation. The inequality (Eq 26) demonstrates the necessity to have low energy spread. (However, eq. (26) is not applicable for a energy spreads significantly lower than

$$D = 4 \sqrt{\frac{I_p}{\mathcal{H}_0}} \sqrt{\frac{K^2}{4 + 2K^2}} \left[J_0 \left(\frac{K^2}{4 + 2K^2} \right) - J_1 \left(\frac{K^2}{4 + 2K^2} \right) \right],$$

as it does not take into account the bunching effect of the radiation field¹².) The computer simulation^{13,14,15} of the electron outcoupling scheme confirmed its feasibility at the discussed range of parameters.

Over the course of the past couple of years we have done a small number of numerical simulations^{15,16} with both 1-D and 2-D time-dependent PIC codes to investigate the behavior of the electron outcoupling scheme. Our results suggested that it would be necessary to reduce the net pass-to-pass reflectivity of the oscillator section and use a dispersive drift section in order that the recirculating power in the optical cavity was sufficiently small that mirror damage could be avoided. The length of the drift section was limited by the initial energy spread of the beam; too great a length led to poor bunching output at the end of the oscillator and thus poor radiator performance. It was also apparent that reducing the intramirror distance below that of exact synchronism (i.e., cavity detuning) with the electron beam micropulse repetition rate would also help reduce the intracavity power and aid the oscillator portion of the FEL in operating in a stable mode. For peak currents in the 100-400 A current range and 100 MeV beam energies, we found that at $\lambda = 1.7$ microns, intracavity powers could be limited to ~100 MW or less and beam bunching fractions at the end of the oscillator could be as large as ~0.4, averaged over the micropulse. Our radiator simulations showed that an up to 1.8% energy conversion could be achieved in a 10-m length and that larger factors would be possible for longer micropulse lengths where slippage would play so prominent a role.

A new set of 2D simulations were done with an increased beam energy of 150 MeV, peak beam current of 200 A with an output wavelength of 850 nm. For a wiggler length of 43 periods, including a drift section in the middle whose effective length for dispersion was also 43 periods, we found that the saturated intracavity power was in the 300-600 MW range depending upon details of detuning and mirror reflectivity. The peak bunching was as high as 0.6 and the output was essentially monochromatic.

We are in the process of carrying out further simulations to investigate the optimization of the transverse optical klystron as discussed in the above, as well as radiator optimization to see if the extraction efficiency could be as high as our longer wavelength study.

5. CONCLUSIONS

The consideration of the stability issues show that the use of the non-superconducting RF system is preferable for hundred-kilowatt FELs. In this case the FEL, based on the RF accelerator-recuperator, looks promising. The electron outcoupling requires energy spread to be low enough, but this limitation is within the state-of-the-art of accelerator technology. More detailed calculations would be required for the design optimization of the particular projects.

REFERENCES

1. H. Bennett, "Laser power beaming: An emerging technology for power transmission and propulsion in space," these proceedings.
2. T. I. Smith, et al., *Nucl. Instr. and Meth.* **A259**, p. 1, 1987.
3. G. N. Kulipanov, et al., *IEEE J. Quantum Electr.* **QE-27**, p. 2566, 1991.
4. N. A. Vinokurov, et al., *Nucl. Instr. and Meth.* **A375**, p. 403, 1996.
5. R. E. Rand, *Recirculating Electron Accelerators*, Harwood Academic Publishers, 1984.
6. P. B. Wilson, SLAC-PUB-2884, Feb. 1982.
7. L. Merminga, et al., *Nucl. Instr. and Meth.* **A375**, ABS39, 1996.
8. J. A. Edighoffer and K.-J. Kim, *Nucl. Instr. and Meth.* **A358**, p. 519, 1995.
9. A. S. Sokolov and N. A. Vinokurov, *Nucl. Instr. and Meth.* **A341**, p. 398, 1994.
10. G. N. Kulipanov, et al., *Nucl. Instr. and Meth.* **A375**, p. 576, 1996.
11. G. N. Kulipanov, et al., *Preprint 95-52, Budker INP*, 1995.
12. K.-J. Kim and M. Xie, *Nucl. Instr. and Meth.* **A331**, p. 359, 1993.
13. D. D. Quick, et al., *Nucl. Instr. and Meth.* **A341**, ABS92, 1994.
14. J. Blau, et al., *Nucl. Instr. and Meth.* **A341**, ABS94, 1994.
15. S. J. Hahn, et al., *Nucl. Instr. and Meth.* **A358**, p. 167, 1995.
16. S. J. Hahn and W. M. Fawley, "Multidimensional simulation studies of the SELENE FEL oscillator/buncher followed by a radiator/amplifier output scheme," *Proc. SPIE* **2376**, pp. 116-124, 1995.