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Compact RF-Linac Free-Electron Lasers*

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ABSTRACT

Design studies using the INEX simulation method are presented for an infrared compact rf-linac-driven FEL. The possibility of such a device relies upon two technological advances: a very bright electron beam from a linac with a photocathode injector, and a short-period, high-field wiggler.

I. Introduction

The free-electron laser (FEL) appears to be a device with very many potential applications in scientific research and modern technology [1]. Present day FELs are quite large, complex, and costly devices which are housed in laboratories comparable in size with synchrotron radiation facilities. Hence, their accessibility to users is rather restricted. If the size and complexity of FELs could be substantially reduced, it is expected that these devices could be made available to a much broader community of users.

The accelerator, in its well shielded enclosure, is usually the largest component of an FEL. The size of the accelerator is largely determined by the requirement for relatively high energy (≥ 40 Mev) electrons in order that an FEL generate short ($\leq 3\mu\text{m}$) optical wavelengths with conventional wiggler magnets. If the period of the wiggler could be reduced by a factor of 10, from 3 cm to 3 mm, the electron beam energy could be reduced by about $\sqrt{10}$. This would of course reduce considerably the size of the accelerator. If the electron energy is kept below about 15 Mev, one benefits additionally in that one is below the threshold for neutron production via giant dipoles resonances in carbon and oxygen (concrete). This in turn reduces the required amount of shielding for safe operation.

We believe that a factor of ten reduction in the period of the wiggler field is possible with the pulsed wire technique [2]. This technique is unique in that it also maintains

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the dimensionless vector potential $a_w = e B_w \lambda_w / 2\pi mc^2$ about equal to one. This is essential to maintain the optical gain at reasonably large values. The penalty for achieving such microwiggler fields is that the gap decreases roughly in proportion to the wiggler's wavelength. In order to propagate the electron beam through such a small-gap wiggler, the transverse normalized emittance must decrease also roughly in proportion to the wiggler's wavelength.

We believe that the required reduction in transverse emittance is possible through the use of a photocathode injector for the linac [3, 4]. Besides producing very low emittance beams the photoinjector also eliminates a significant part of the linac's front end - buncher cavities - and therefore also reduces the overall size of the accelerator. Thus, the combination of two technological advances, the photoinjector for very bright electron beams and the short period, high-field, pulsed-wire wiggler, form the basis for a significant reduction in the size and complexity of an FEL. The resulting compact device can be very efficient if energy recovery [5] is used to convert most of the energy left in the electron beam after its interaction in the FEL into rf fields in the accelerator. Energy recovery can be used with either room temperature or superconducting pulsed linacs.

This paper presents a preliminary design for a compact rf-linac-driven FEL and an evaluation of its performance derived from the 3-D FEL simulation code FELEX and the INEX (Integrated Numerical Experiment) method. Accelerator and beam transport calculations assume a laser-driven photocathode injector and show that a very bright beam can be generated. The FEL calculations investigate the properties of two short-period wigglers, with periods of 9 mm and 3 mm, both of which maintain the dimensionless vector potential $a_w = 1$. The maximum energy of the linac is limited to about 15 Mev, partly to reduce shielding requirements. We mention, but do not study in this paper, the possibility of reaching shorter optical wavelengths by operation on a higher harmonic [6, 7].

II. Simulation of Compact FEL Performance.

In the simulation results presented in this section, fully 3 D FEL calculations were performed with the code FELEX [8, 9, 10]. The calculations include the 3 D motion of electrons including energy spread and emittance, optical diffraction and mode overlap with the electron beam, etc. However, the results of this section do not include any pulse effects; that is, only single wave front (single frequency) calculations were done. Single pass optical gains were calculated to determine small signal gain and saturated gain as

a function of optical wavelength and the wiggler parameters. Multiple-pass single wave front calculations were performed to determine the self-consistently-calculated steady-state resonator solutions.

The optics parameter values used in the simulations included a simple two-mirror stable near-concentric optical resonator of fixed length equal to 277.778 cm. The Rayleigh range was always chosen to be equal to one-half of the wiggler's length: this is the condition for minimum vignetting losses at the ends of the wiggler. The center of the wiggler was taken to coincide with the central focus of the resonator. Output coupling was taken to be 10% mirror transmission (total for both mirrors). The mirrors were much larger than the optical spot sizes on them so that no losses (besides transmission losses) occurred on these elements. Vignetting losses at the ends of the wiggler were included by putting apertures into FELEX of a size equal to the gap of the wiggler at the ends of the wiggler. Wigglers with two different wavelengths were considered; since the same electron beam was used to drive each wiggler, two different optical radiation wavelengths - about 8 μm and about 2.7 μm - arose in these simulations.

The electron beam characteristics were determined from PARMELA simulations of the photoinjector-accelerator and beam transport system. The electron beam properties used in the FEL simulations of this section were: peak current $I = 300$ A (some cases with $I = 150$ A were also studied); "90%" normalized transverse emittance $\epsilon_n = 25\pi$ mm² mr; mean electron energy 15 Mev ($\gamma = 29.354$); and fractional energy spread $\Delta\gamma/\gamma = 0.5\%$ (FWHM).

A complete discussion of the pulsed-wire technique for short-period, high-field wigglers can be found in [2]. Figure 1 shows a photograph of such a wiggler. It is built of hollow copper tubing wound on a hollow stainless steel mandrel. The period is $\lambda_w = 0.8$ cm, the bore is 0.2 cm, and it is 25 periods long. Fields of 1-2 T can easily be generated and sustained for times of 100 μs or longer. More advanced designs with shorter periods are presently being pursued. Table 1 shows the properties of the two different wigglers considered in the compact FEL simulations. Different lengths of these two wigglers were used.

II. Simulation Results for Wiggler 1.

We first present single pass gain results for different wiggler length L_w . For $L_w = 33.3$ cm (37 periods), we obtained a maximum small signal gain (at 300 A) of $G_{ss}(300) = 142.7$ at an optical wavelength $\lambda = 8.2$ μm . Obviously, that far exceeds expected resonator

losses, so we reduced L_w and obtained the small-signal and large-signal results shown in Table 2. In the table, P is the input power at the wiggler's entrance, and η is the extraction efficiency. All of these values should be interpreted as peak micropulse values.

In Fig. 2 we show the results of a multiple pass simulation for the $L_w = 9$ cm wiggler. The optical wavelength is $9.0 \mu\text{m}$, the total round-trip mirror transmission loss is 10%, and a maximum steady-state intensity loading on the downstream mirror is $1.275 \text{ GW}/\text{cm}^2$. Note that a peak power in excess of 2GW is reached, and an extraction efficiency of about 5% is achieved.

IV. Simulation Results for Wiggler 2.

Table 3 shows single-pass results for the shorter period wiggler with $\lambda_w = 0.3$ cm for various wiggler lengths. Sufficient gain appears even in a wiggler whose total length is about one inch! Figure 3 shows the results of a multiple-pass calculation at an optical wavelength of $2.82 \mu\text{m}$ for the $L_w = 4.2$ cm wiggler. Once again, the total cavity loss due to mirror transmission was taken to be 10%. The maximum steady-state intensity loading on the down-stream mirror was found to be $1.1 \text{ GW}/\text{cm}^2$. Recall that in all calculations we fix the Rayleigh range of the resonator to equal one half of L_w . Hence, the shorter the wiggler, the larger the spot size on the cavity mirrors. If the assumed electron-beam and wiggler properties can be achieved experimentally, mirror damage problems may limit the size of the laser resonator. The present compact FEL design assumes that the linac produces electron pulses at the rate of 108 Mhz. This means that there are two optical pulses circulating at the same time in the resonator.

V. INEX Simulation of a Compact FEL.

A complete PARMELA simulation of the photoinjector/linac/beam transport system was done to generate an electron micropulse. The accelerator frequency is 1300 Mhz, and the beam transport includes a dogleg bend magnet (two 10° bends) which displaces the beam and focuses it into the wiggler. Properties of the resulting electron micropulse are shown in Fig. 4. The pulse length is about 14 ps, the peak current is in excess of 350 A, the energy spread is about 0.5%, and the transverse emittances are in the range of $8\text{-}10\pi$ mm-mr over most of the pulse (xz is the wiggle plane; yz is the betatron plane; a plane-polarized wiggler has been assumed).

The PARMELA electron micropulse is used in a multipass FELEX FEL simulation in the INEX (Integrated Numerical Experiment) method. The same wiggler and resonator conditions as used to generate the results of Fig. 2 (wiggler 1 with $L_w = 9$ cm) were used

in the INEX simulation. The results are shown in Fig. 5. The upper two graphs show the evolution of the average power and extraction efficiency vs. pass number. The lower two graphs show the optical micropulse, and the extraction through the electron micropulse, at steady-state. The optical wavelength is about $8.4\text{ }\mu\text{m}$.

VI. Summary and Conclusions.

We have presented a preliminary design, and performance calculations, for a compact infrared FEL which is based upon the realization of two technological advances: a very bright electron beam generated by a linac with a photoinjector [3, 4], and a short period, high field, microwiggler built with pulsed-wire techniques [2]. A schematic layout of the device is shown in Fig. 6. The accelerator frequency is 1300 Mhz. Electron pulses are produced at a 108 Mhz rate during a $10\text{ }\mu\text{s}$ macropulse. If the device operates at a repetition frequency of 1 hz, the results of an INEX simulation show that a time-averaged laser power output (over minutes or hours) of about 3 watts can be achieved at an optical wavelength of $8.4\text{ }\mu\text{m}$. Similar power levels at a wavelength near $2.9\text{ }\mu\text{m}$ could be achieved with a wiggler with a 0.3 cm period. The excellent beam quality is conducive to operating the FEL in a higher harmonic to achieve shorter wavelength operation, but we have not explored quantitatively that possibility in this study.

We believe that our results, which rely upon the experimentally demonstrated photocathode device and the as yet undemonstrated pulsed-wire microwiggler technology, portend a new generation of compact FELs which might allow a much wider community of users than has been possible so far to access the benefits of FEL technology.

Figure captions:

- Figure 1: Pulsed-wire miniwiggler with $\lambda_w = 0.8$ cm and $L_w = 20$ cm.
- Figure 2: Results of a multiple-pass single wavefront simulation using the $\lambda_w = 0.9$ cm wiggler with $L_w = 9$ cm.
- Figure 3: Results of a multiple-pass single wavefront simulation using the $\lambda_w = 0.3$ cm wiggler with $L_w = 4.2$ cm.
- Figure 4: Properties of the electron micropulse from the PARMELA simulation of the photoinjector/linac/beam transport system.
- Figure 5: Results of a finite pulse 3-D FEL simulation of a compact FEL using the 9 cm long $\lambda_w = 0.9$ cm wiggler.
- Figure 6: Schematic layout of a compact FEL showing the photoinjector drive laser, the linac, and the FEL.

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Table 1: Parameters of the two different wigglers used in the FEL simulations.

Wiggler	Wavelength, cm	Magnetic field, T	a_w	Full gap, cm
1	0.9	1.1911872	1	0.3
2	0.3	3.5735616	1	0.1

Table 2. Single-pass results for wiggler 1.

L_w , cm	L_w/λ_w	G(300)	λ , μm	P, MW	η , %
18.0	20	9.019	8.12	0	0
		1.127	8.5	768	2.163
		3.561*	8.14	0	0
		1.100*	8.26	370	1.653
9.0	10	1.797	8.4	0	0
		1.115	9.0	2000	5.0

*These values are for $I = 150$ A

Table 3. Single-pass results for wiggler 2.

L_w, cm	L_w/λ_w	G(300)	λ, μm	P, GW	η, %
6.0	20	4.09	2.72	0	0
		1.116	2.92	0.576	2.1
4.2	14	2.133	2.76	0	0
		1.116	2.82	1.23	3.16
3.0	10	1.453	2.82	0	0

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

COMPACT FEL DESIGN USING PHOTOINJECTOR

Figure 6