LA-UR-94-3985

Conf-9408196--)

Title:

ADVANCED TECHNOLOGIES FOR A COMPACT RF LINAC FEL

Author(s):

D. C. Nguyen

Submitted to:

Nuclear Instrument Methods, FEL '94 Proceedings,
August 21-26, 1994, Stanford, CA

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, makes 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.

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Form No. 836 RS
ST 2629 10/91

DISCLAIMER

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

ADVANCED TECHNOLOGIES FOR A COMPACT RF LINAC FEL[†]

D. C. Nguyen

Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Advanced technologies such as the photoinjector, the short-period microwigglers, and harmonic lasing enable free-electron-laser operation in the infrared with a low-energy (~10 MeV) electron beam and thus reduce the size and cost of FELs. The next-generation, rf-linac FEL will fit in a small laboratory and produce high-power, picosecond infrared.

[†] Work supported by LANL Laboratory Directed Research and Development and performed under the auspices of the U.S. Department of Energy.

1. Introduction

FELs traditionally have been large, complex, and costly devices. The size of an FEL is determined by its electron beam energy which, for optical wavelengths, is typically tens to hundreds of MeV. Large accelerators are needed to produce the high-energy beams which in turn generate radiations that require shielding. Reducing the beam energy is thus important in keeping the FEL size and cost down. Building infrared FELs with beam energies less than 10 MeV requires using a millimeter-period wiggler or lasing at harmonic frequencies. Matching such a low-energy beam requires a low emittance. Also, because the small-signal gain is typically low for microwigglers and harmonic lasing, the beam must have a small energy spread and a high peak current.

In the past 10 years, advances in photoinjector technology have produced the beam quality needed for microwiggler and harmonic FEL operation [1]. Since its first use in 1988 [2], the photoinjector has become the electron source for many FELs [3-5]. The high-brightness beam in turn spurs further development of millimeter-period wigglers and harmonic lasing. In this paper, I will review these enabling technologies. The goal here is to compare these advanced approaches for designing the next-generation, compact FELs that produce picosecond IR pulses. Because in-depth reviews of the rf guns and wiggler technologies already exist [6, 7], I will mention only a few representative examples of these technologies.

2. Advanced technologies

2.1 Photoinjector

The photoinjector was developed at Los Alamos ca. 1986 [1]. It produces picosecond electron pulses with a small energy spread ($\sim 0.2\%$) and a peak current up to 300 A [3]. Emittance compensation with an axial solenoidal field yields normalized beam emittance as low as $1 \pi\text{-mm-mrad}$ for a 100-A peak current [5]. The low-emittance beam can be bunched in a chicane to produce peak currents up to 1 kA with minimal emittance growth. Development of L-band and S-band photoinjectors is active at Los Alamos [5] and at Brookhaven National Laboratory, respectively [8].

The major issues with photoinjectors are the photocathode and the drive laser. Multi-alkali photocathodes offer high quantum efficiencies (Q. E.), but they

are not as rugged as the low-Q. E. ($<0.1\%$) metal photocathodes. To have any appreciable lifetime, the multi-alkali cathodes need a high-vacuum environment, typically 10^{-9} torr or better. Metal photocathodes, on the other hand, require a high-power ultraviolet drive laser. Recently, Cs_2Te proved to be rugged while offering Q. E. of a few percent [9]. The drive laser has to be very stable: temporal jitter less than 0.5 ps, amplitude stability better than 1%, and spatial jitters less than $100\text{ }\mu\text{m}$ at the photocathode. Using the photoinjector increases the FEL cost and complexity, which must be weighed against its benefits.

2.2 *Short-period microwigglers*

Various designs of short-period wigglers have been studied and built. Permanent magnet microwigglers are fairly compact and require no power supply. For periods shorter than 1 cm, the magnet gap is typically less than one-third the wiggler period [10]. The small gap increases optical vignetting and requires tight fabrication tolerance to minimize field errors.

Electromagnet wigglers potentially offer very high magnetic fields with millimeter periods. Ben-Zvi et al. at Brookhaven National Laboratory fabricated and tested an 8.8-mm-period superconducting wiggler [11]. At Los Alamos, Warren built and tested a 3-mm-period slotted-tube microwiggler in which a current flowing in wiggly paths produced a strong transverse field [12]. Researchers at the Lebedev Institute and Warren at Los Alamos also built helical wigglers [13]. These helical wigglers produce a higher gain compared with their plane-polarized counterpart, and they emit circularly polarized light. Unfortunately, they do not support harmonic lasing.

Pantell and coworkers came up with a new design for a short-period wiggler that used a staggered array of iron pole pieces immersed in a longitudinal solenoidal field [14]. The transverse field component is created by redistributing the longitudinal field. Varfolomeev of the Kurchatov Institute showed that the transverse field component could be enhanced by interlacing the iron pole pieces with permanent magnets [15]. This novel scheme produced a 4.5-mm-period wiggler whose magnetic field reached 7.9 kGauss at a 1.5-mm gap.

2.3 *Harmonic lasing*

First demonstrated with thermionic guns at Stanford and at Los Alamos in 1989 [16, 17], harmonic lasing promises short-wavelength output from a relatively low beam energy. Using a 46-MeV beam, O'Shea and coworkers achieved lasing on the third harmonic at 370-nm [18]. The harmonic small-signal gain strongly depends on the wiggler dimensionless parameter a_w . To produce adequate gain in the harmonics, the wiggler must have sufficiently high a_w . Warren points out that the small-signal gains for the various harmonics peak at different a_w [19]. A complication with harmonic lasing is the need to discriminate against the unwanted harmonics. One way to select against the unwanted harmonics is to use an intracavity frequency-dependent loss element [18].

For a fixed wavelength λ , harmonic lasing can reduce the beam energy or increase the wiggler period λ_w . Working with a longer λ_w increases a_w , which is necessary for harmonic gain, but the large a_w diminishes the short-wavelength advantage of harmonic lasing. The resonant wavelength for the n^{th} harmonic is given by

$$\lambda = \frac{\lambda_w}{2 n \gamma^2} (1 + a_w^2) \quad (1)$$

where γ is the beam relativistic factor. The matching condition dictates

$$\lambda \geq \frac{\pi \epsilon_n^*}{\beta \gamma} \quad (2)$$

where $\beta = v/c$ is almost 1; ϵ_n^* is the normalized 90% emittance. Equating (1) and (2) and using $\epsilon_n^* = 4 \epsilon_n$, where ϵ_n the normalized rms emittance, we have

$$\lambda_w \geq \frac{8 \pi n \gamma \epsilon_n}{(1 + a_w^2)} \quad (3)$$

Note that both reducing the wiggler period and increasing n require a lower emittance. Also, for submillimeter periods such as in an electromagnetic wiggler, one must use a low beam energy to keep the required ϵ_n from being too small.

The small-signal gain equation for harmonic lasing, modified by Dattoli's gain reduction for finite emittance and energy spread [20], is given by

$$g_{ss}(n, \epsilon_n, \sigma_E) = \frac{n [JJ(n, \xi)]^2 \left(\frac{N_w}{\gamma}\right)^3 2 a_w^2 \pi^2 \frac{j_e \lambda_w^2}{I_A} FF\left(\frac{A_e}{A_0}\right) f_{\max}}{\left[1 + \left(\frac{8 n N_w a_w \epsilon_n}{(1 + a_w^2) \lambda_w}\right)^2\right] [1 + 1.7(4 n N_w \sigma_E)^2]} \quad (4)$$

where σ_E is the rms energy spread; $JJ(n, \xi)$ is the difference in Bessel functions defined as $JJ(n, \xi) = J_{n-1/2}(n \xi) - J_{n+1/2}(n \xi)$; ξ is $a_w^2/2(1 + a_w^2)$; N_w is the number of wiggler periods; j_e is the beam current density; I_A is the Alfven current; $FF(A_e/A_0)$ is the filling factor; and $f_{\max}$ is equal to 0.54 at the peak of the gain curve.

The saturation intensity—defined as the intensity at which the gain is one-half the small-signal gain—for lasing at the n^{th} harmonic is given by

$$I_s = \frac{1}{8 \pi} \left(\frac{\gamma}{N_w}\right)^4 \frac{m c^3}{r_0 (n JJ(n, \xi) \lambda_w a_w)^2} \quad (5)$$

where m is the electron mass; c is the speed of light; and r_0 is the classical electron radius.

To illustrate the differences of lasing at various harmonics, I estimate the performance of four operating conditions. Suppose we wish to generate 5 μm with a 10-MeV electron beam. Using a photoinjector, we could generate 2 nC in 10 ps ($I_{\text{peak}} = 200$ A) with a nominal rms emittance of 5 $\pi\text{-mm-mrad}$ and an energy spread of 0.25%. Table I lists four possible options: fundamental with a 4-mm-period wiggler, third harmonic with an 8.8-mm-period wiggler, fifth harmonic with a 11.2-mm-period wiggler, and seventh harmonic with a 13-mm-period wiggler. All

four wigglers are of Halbach type with permanent magnets whose remanent field is 1.05 Tesla. The wiggler lengths are kept constant at 10 cm and a 2% resonator round-trip loss is assumed for all cases. Note that the small-signal gains gradually go down as we go to higher harmonics because a_w is not optimized. The biggest penalty of harmonic lasing is the rapid reduction in micropulse energy at high harmonics. This is true even if the harmonic gains are as high as the fundamental gain.

3. Present status and future prospects

At present, two compact rf-linac FELs are in operation and three others are under construction. The Advanced FEL at Los Alamos has operated at 4–6 μm since 1993 [21]. It reliably generates 100–200 mJ in 10- μs macropulses. The ENEA FEL has operated in the millimeter range and is being upgraded for submillimeter operation [22]. Grumman is constructing a 14-MeV, IR FEL at Princeton [23]. The Institute for Laser Engineering in Japan is using a photoinjector and a 6.6-mm-period wiggler to build a 10- μm FEL [24]. At Stanford, Pantell and coworkers are developing a far-IR FEL with a 4-MeV rf gun and a staggered-array wiggler [25]. Fig. 1 depicts the operating wavelength and beam energy ranges of the above FELs. The UV-lasing experiment at Los Alamos is also shown for comparison [18]. The two lines correspond to the resonance conditions, assuming $a_w = 0$, for wiggler periods of 1 cm—the shortest wiggler period ever used in an FEL—and 5 cm. The region between these two lines is where most FELs operate. Note that millimeter-period wigglers and harmonic lasing allow operation below this region.

I expect the photoinjectors will become smaller and easier to operate in the near future. Progress in microwiggler design and fabrication could deliver a short-period ($\sim 3\text{-mm}$), high-field wiggler. Further efforts in miniaturizing the linac, the klystron and its modulator will be needed before we see an rf-linac FEL that fits in a small room and costs less than \$1 million. These compact FELs will probably operate in the spectral regions where no conventional tunable lasers with appreciable power exist. One such region is the 3–100- μm range, where a vast number of molecular vibrations occur. Many of these vibrational resonances can be used for detecting and mapping atmospheric constituents (e.g. LIDAR), in multiphoton molecular dissociation for isotope separation and photochemical

processing, and in the study of condensed-phase dynamics. A compact FEL operating at 3–10 μm would find use in laser surgery. In near-field microscopy, an rf-linac FEL could deliver a substantial power through the submicron aperture of a microprobe. This capability would be useful for spectrally resolved imaging.

Acknowledgment

The author is grateful to R. W. Warren, S. M. Gierman, J. Kinross-Wright and R. L. Sheffield for helpful discussion.

References

1. J. S. Fraser and R. L. Sheffield, IEEE J. Quantum Electronics QE-23 (1987) 1489
2. M. Curtin et al., Nucl. Instr. and Meth. A296 (1990) 127
3. P. G. O'Shea et al., Nucl. Instr. and Meth. A318 (1992) 52
4. S. Joly et al., Nucl. Instr. and Meth. A331 (1993) 199
5. R. L. Sheffield et al., Nucl. Instr. and Meth. A341 (1994) 371
6. C. Travier, Nucl. Instr. and Meth. A304 (1991) 285
7. R. L. Sheffield et al., LA-UR 89-2851, Los Alamos National Laboratory
8. K. Batchelor et al., Nucl. Instr. and Meth. A318 (1992) 372
9. S. Kong et al., these Proceedings, paper Mo3-20
10. K. Halbach, Nucl. Instr. and Meth. 187 (1981) 109
11. I. Ben-Zvi et al., Nucl. Instr. and Meth. A318 (1992) 781
12. R. Warren, Nucl. Instr. and Meth. A318 (1992) 789
13. V. A. Papadichev and O. A. Smith, Nucl. Instr. and Meth. A318 (1992) 803
14. A. H. Ho, J. Quantum Electron. QE-27 (1991) 2650
15. A. A. Varfolomeev et al., Nucl. Instr. and Meth. A318 (1992) 809
16. S. V. Benson and J. M. J. Madey, Phys. Rev. A39 (1989)
17. R. W. Warren et al., Nucl. Instr. and Meth. A296 (1990) 84
18. P. G. O'Shea et al., Nucl. Instr. and Meth. A341 (1994) 7
19. R. W. Warren, Nucl. Instr. and Meth. A296 (1990) 512
20. G. Dattoli et al., J. Quantum Electronics, 20 (1984) 1003
21. D. C. Nguyen et al., Nucl. Instr. and Meth. A341 (1994) 29
22. E. Giovenale et al., these Proceedings, paper We3-38
23. I. S. Lehrman et al., Nucl. Instr. and Meth. A341 (1994) ABS 31

24. M. Asakawa et al., these Proceedings, paper Mo3-43
25. J. Lewellen et al., these Proceedings, paper Mo3-76

Figure Caption

1. Plot of FEL wavelength versus energy; the two lines correspond to 1-cm and 5-cm wiggler periods. A: AFEL actual operation; B: APEX UV operation; C: Grumman-Princeton CIR-FEL projected operation; D: ILT projected microwiggler operation; E: ENEA projected submillimeter operation; and F: Stanford projected far-IR FEL operation.

Table I.
Comparison of microwiggler and harmonic lasing

λ_w (mm)	N_w	n	B_{peak} (Tesla)	a_w	g_{ss} (%)	I_{sat} GW/cm ²	E_{micro} (μ J)
4	25	1	0.58	0.15	18	43	102
8.8	11.4	3	1.1	0.65	14	36	58
11.2	10	5	1.24	0.91	12	27	37
13	7.7	7	1.3	1.12	11	21	25