1998

Short-wavelength free-electron lasers in 1997

Colson, W.B.

Nuclear Instruments and Methods in Physics Research A, Volume 407, (1998), pp. 26-29
http://hdl.handle.net/10945/44051

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 407 (1998) 26–29

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Short-wavelength free-electron lasers in 1997

W.B. Colson

Physics Department, Naval Postgraduate School, Monterey, CA 93943, USA

Table 1 lists existing and proposed relativistic free-electron lasers (FELs) in 1997. The top part of the table lists existing FELs. These are substantially complete experiments that may not be operating at the present time. The bottom part of the table lists proposed FELs. Each FEL, existing or proposed, is identified by a location, or institution, followed by the FEL's name in parentheses. The table can be found at http://www.physics.nps.navy.mil/fel.html.

Additions and corrections can be transmitted to us for inclusion on the table in the future.

The first column of the table lists the operating wavelength λ, or wavelength range, in micrometers (μm). The large range of operating wavelengths, six orders of magnitude, indicates the flexible design characteristics of the FEL mechanism. The second column describes the electron pulse length divided by the speed of light c, and ranges from CW to short picosecond pulse time scales. The expected optical pulse length can be 3 to 5 times shorter or longer than the electron pulse depending on the optical cavity Q, the FEL desynchronism, and the FEL gain. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam energy E and peak current I provided by the accelerator are listed in the third and fourth columns in units of MeV and Amperes. The accelerator type is listed as the first entry in the last column with a code such as RF for the radio-frequency linac. While there are a variety of accelerators used, most are RF with some electron storage rings, microtrons, and electrostatic accelerators. Storage rings tend to be used for the short-wavelength applications, while the electrostatic accelerators provide longer wavelengths.

The next three columns list the number of undulator periods N, the undulator wavelength λ_0 in centimeters, and the undulator parameter $K = e\bar{B}\lambda_0/2\pi mc^2$ where e is the electron charge magnitude, $\bar{B}$ is the RMS undulator field strength, and m is the electron mass. For an FEL klystron undulator, there are multiple undulator sections as listed in the N-column. Note that the range of values for N, λ_0, and K are much smaller than for the other parameters indicating that most undulators are similar. Only a few of the FELs use the klystron undulator at present, and the rest use the conventional periodic undulator. The FEL resonance condition,

$$\lambda = \frac{\lambda_0\ (1+K^2)}{2\gamma^2},$$

where γ is the relativistic Lorentz factor $\gamma = E/mc^2$, provides a relationship that can used to derive K from λ, E, and λ_0. The middle entry of the last column lists the FEL type: "O" for oscillator, "A" for amplifier, etc. Most of the FELs are oscillators, but recent interest in short-wavelength FELs have produced several proposals for amplifiers that avoid the need for mirrors. A reference describing the FEL is provided at the end of each line entry.

For the conventional undulator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator

0168-9002/98/$19.00
PII S0168-9002(97)01360-0

Table 1
Relativistic short wavelength free-electron lasers (1997)

FEL	λ (μm)	σ_z	E (MeV)	I (A)	N	λ_0 (cm)	K (rms)	Acc., Type [Ref.]
Existing FELs								
UCSB(mm FEL)	340	25 μs	6	2	42	7.1	0.7	EA,O [1]
Florida(CREOL)	355	8 μs	1.3	0.13	185	0.8	0.1	EA,O [24]
Stanford(FIRFEL)	80–200	15 ps	4	8	50	1	0.7	RF,O [2]
Himeji(LEENA)	65–75	10 ps	5.4	10	50	1.6	0.5	RF,O [3]
UCSB(FIR FEL)	60	25 μs	6	2	150	2	0.1	EA,O [1]
Osaka(ILE/ILT)	47	3 ps	8	50	50	2	0.5	RF,O [4]
Tokyo(UT-FEL)	43	10 ps	13	20	40	4	0.7	RF,O [5]
Nieuwegein(FELIX1)	5–35	5 ps	25	50	38	6.5	1.2	RF,O [6]
Osaka(ISIR)	40	30 ps	17	50	32	6	1	RF,O [7]
Bruyeres(ELSA)	20	30 ps	18	100	30	3	0.8	RF,O [8]
Nieuwegein(FELIX2)	20–110	5 ps	45	50	38	6.5	1.8	RF,O [6]
Stanford(FIREFLY)	15–65	1–5 ps	15–32	14	25	6	1	RF,O [9]
Frascati(LISA)	15	7 ps	25	5	50	4.4	1	RF,O [10]
Grumman(CIRFEL)	12–21	5 ps	9–14	100	73	1.4	0.2	RF,O [11]
Beijing(IHEP)	10	4 ps	30	14	50	3	1	RF,O [12]
Orsay(CLIO)	3–53	0.1–3 ps	21–50	80	38	5	1.4	RF,O [13]
LANL(RAFEL)	16	15 ps	17.4	300	200	2	0.9	RF,O [14]
Osaka(FELI1)	5.5	10 ps	33.2	42	58	3.4	1	RF,O [15]
Darmstadt(IR-FEL)	5	2 ps	40	2.7	80	3.2	1	RF,O [16]
Stanford(SCAFEL)	3–13	0.7–12 ps	22–45	10	72	3.1	0.8	RF,O [17]
Vanderbilt(FELI)	2.0–9.8	0.7 ps	43	50	52	2.3	1	RF,O [18]
Duke(MarkIII)	3	3 ps	44	20	47	2.3	1	RF,O [19]
Osaka(FELI)	2–6	2 ps	170	100	50	6	1.3	RF,O [4]
Osaka(FELI2)	1.88	10 ps	68	42	78	3.8	1	RF,O [15]
BNL(ATF)	0.5	6 ps	50	100	70	0.88	0.4	RF,O [20]
Tsukuba(NIJI-IV)	0.35	160 ps	300	5	2 × 42	7.2	2	SR,O [21]
Orsay(Super-ACO)	0.35	26 ps	800	0.1	2 × 10	13	4	SR,O [22]
Duke(OK-4)	0.34	2.5 ps	500	30	2 × 33	10	2.4	SR,O [39]
Okazaki(UVSOR)	0.24	6 ps	500	5	2 × 8	11	2	SR,O [23]
Proposed FELs								
Netherlands(TEUFEL)	180	20 ps	6	350	50	2.5	1	RF,O [25]
Rutgers(IRFEL)	140	25 ps	38	1.4	50	20	1	MA,O [26]
Moscow(Lebedev)	100	20 ps	30	0.25	35	3.2	0.8	MA,O [27]
Osaka(ILE/ILT)	95	3 ps	9	50	10	6	3	RF,O [46]
Tokai(SCARLET)	40	40 ps	15	10	62	3.3	1	RF,O [4]
LBL(IRFEL)	3–50	30 ps	55	60	40	5	1	RF,O [28]
TJNAF(IRFEL)	2.5–25	1.5 ps	200	36	2 × 12	20	4	RF,O [29]
Boeing(kWFEL)	0.2–4	9 ps	120	300	220	2.18	1.31	RF,O [30]
Osaka(ILE/ILT)	12	3 ps	9	50	30	0.79	0.22	RF,O [47]
Stanford(FEL)	10	4 ps	24	25	52	2.6	0.9	RF,O [31]
UCLA(IRFEL)	10	2 ps	20	200	40	1.5	1	RF,A [32]
Novosibirsk(RTM)	2–11	20 ps	98	100	4 × 36	9	1.6	RF,O [33]
BNL(HGHG)	3.4	10 ps	30	110	83	1.8	1.4	RF,A [34]
TJNAF(UVFEL)	0.16–1	0.2 ps	200	270	72	3.3	1.3	RF,O [29]
Rocketdyne(FEL)	0.84	3 ps	90	500	160	2.4	1.4	RF,MOPA [35]
Dortmund(DELTA)	0.4	50 ps	500	90	17	25	2	SR,O [36]
Harima(SUBARU)	0.2–10	26 ps	1500	50	33,65	16,32	8	SR,O [42]
BNL(DUVFEL)	0.075	6 ps	310	300	682	2.2	1.5	RF,A [37]
Frascati(COSA)	0.08	10 ps	215	200	400	1.416	1	RF,O [38]

Table 1 (*Continued*)

FEL	λ (μm)	σ_z	E (MeV)	I (A)	N	λ_0 (cm)	K (rms)	Acc., Type [Ref.]
DESY(TTF1)	0.042	0.8 ps	390	500	490	2.73	0.9	RF,A [45]
BNL(ATF-UV)	0.25	6 ps	70	100	70	0.88	0.4	RF,O [20]
Duke(VUV)	0.05–1	10 ps	1000	350	2×33	10	2	SR,O [43]
DESY(TTF2)	0.006	0.17 ps	1000	2500	981	2.73	0.9	RF,A [40]
SLAC(LCLS)	0.00015	0.08 ps	14350	3393	3312	3	3.7	RF,A [41]
DESY(TESLA)	0.0001	0.08 ps	35000	5000	1200	5	4.2	RF,A [44]

RF – RF Linac Accelerator
SR – Electron Storage Ring
A – FEL Amplifier
MOPA – Master-Oscillator Power-Amplifier
MA – Microtron Accelerator
EA – Electrostatic Accelerator
O – FEL Oscillator

spectral bandwidth, $\frac{1}{4}N$, or $P \approx EI/4eN$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially more. The average FEL power is determined by the duty cycle, or spacing between electron pulses, and is generally many orders of magnitude lower than the peak power.

In the FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L = N\lambda_0$ has Rayleigh length $z_0 \approx L/\sqrt{12}$ and has a mode waist radius of $w_0 \approx \sqrt{N\gamma\lambda/\pi}$. The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

The author is grateful for support of this work by the Naval Postgraduate School and the Directed Energy Weapons Group, SPAWAR, U.S. Navy.

References

[1] G. Ramian, Nucl. Instr. and Meth. A 318 (1992) 225–229.
[2] J.W. Lewellen et al., Nucl. Instr. and Meth. A 358 (1995) 24–26.
[3] T. Mochizuki, S. Miyamoto, S. Amano, M. Niibe, Nucl. Instr. and Meth. A 393 (1997) II-47; S. Miyamoto and T. Mochizuki, J. Jpn. Soc. Infrared Sci. Technol. 7 (1997) 73–78.
[4] M. Asakawa et al., Proc. 15th Annual Meeting of the Laser Society of Japan, Osaka, Japan, January 19–20, 1995.
[5] E. Nishimura et al., Nucl. Instr. and Meth. A 341 (1994) 39.
[6] R.J. Bakker et al., J. Appl. Phys. 74 (1993) 1501; D. Oepts et al., Infrared Phys. Technol. 36 (1995) 297.
[7] S. Okuda et al., Nucl. Instr. and Meth. A 341 (1994) 59.
[8] P. Guimbal et al., Nucl. Instr. and Meth. A 341 (1994) 43.
[9] K.W. Berryman, T.I. Smith, Nucl. Instr. and Meth. A 375 (1996) 6.
[10] M. Castellano et al., Nucl. Instr. and Meth. A 304 (1991) 204.
[11] I.S. Lehrman et al., Nucl. Instr. and Meth. A 393 (1997) 178.
[12] J. Xie et al., Nucl. Instr. and Meth. A 331 (1993) 204; Nucl. Instr. and Meth. A 341 (1994) 34.
[13] J.M. Ortega et al., Nucl. Instr. and Meth. A 375 (1996) 618.
[14] R.L. Sheffield et al., Proc. SPIE 2988 (1997) 28–37.
[15] A. Kobayashi et al., Nucl. Instr. and Meth. A 375 (1996) 317.
[16] J. Auerhammer et al., Nucl. Instr. and Meth. A 341 (1994) 63.
[17] H.A. Schwettman, T.I. Smith, R.L. Swent, Nucl. Instr. and Meth. A 375 (1996) 662.
[18] C. Brau, Nucl. Instr. and Meth. A 318 (1992) 38.
[19] S.V. Benson et al., Nucl. Instr. and Meth. A 250 (1986) 39.
[20] K. Batchelor et al., Nucl. Instr. and Meth. A 318 (1992) 159.
[21] T. Yamazaki et al., Nucl. Instr. and Meth. A 331 (1993) 27; T. Yamazaki et al., Nucl. Instr. and Meth. A 341 (1994) ABS3.
[22] T. Hara et al., Nucl. Instr. and Meth. A 341 (1994) 21.
[23] S. Takano et al., Nucl. Instr. and Meth. A 331 (1993) 20; H. Hama et al., Nucl. Instr. and Meth. A 341 (1994) 12.
[24] L.R. Elias et al., Nucl. Instr. and Meth. A 304 (1991) 219; M. Tecimen, Nucl. Instr. and Meth. A 341 (1994) 219.
[25] J.I.M. Botman et al., Nucl. Instr. and Meth. A 341 (1994) 402.

[26] E.D. Shaw et al., Nucl. Instr. and Meth. A 318 (1992) 47.
[27] K.A. Belovintsev et al., Nucl. Instr. and Meth. A 341 (1994) ABS45; A. Agafonov et al., Nucl. Instr. and Meth. A 331 (1993) 186.
[28] K.J. Kim et al., Nucl. Instr. and Meth. A 341 (1994) 280.
[29] G. Neil et al., Free Electron Lasers for Industry, vol. 2, UV Demo Conceptual Design.
[30] J.L. Adamski et al., Proc. SPIE, LASE'97, High-Power Lasers and Applications, San Jose, CA, February 13, 1997.
[31] J.F. Schmerge, R. Pantell, Nucl. Instr. and Meth. A 341 (1994) 335.
[32] G. Baranov et al., Nucl. Instr. and Meth. A 331 (1993) 228.
[33] N.G. Gavrilov et al., Status of Novosibirsk High Power FEL Project, SPIE Proc., vol. 2988 (1997) 23; N.A. Vinokurov et al., Nucl. Instr. and Meth. A 331 (1993) 3.
[34] I. Ben-Zvi et al., Nucl. Instr. and Meth. A 318 (1992) 208.
[35] R.J. Burke et al., Proc. SPIE, Laser Power Beaming, Los Angeles, January 27–28, 1994, vol. 2121.
[36] D. Nolle et al., Nucl. Instr. and Meth. A 341 (1994) ABS7; Schmidt et al., Nucl. Instr. and Meth. A 341 (1994) ABS9.
[37] S. Krinsky (Ed.), The BNL DUV FEL Report, January 1994.
[38] F. Ciocci, G. Dattoli, A. DeAngelis, B. Faatz, F. Garosi, L. Giannessi, P.L. Ottoviani, A. Torre, IEEE J. Quantum Electron 31 (1995) 1242.
[39] V.N. Litvinenko et al., Proc. SPIE 2998 (1997) 188.
[40] W. Brefeld et al., Nucl. Instr. and Meth. A 375 (1996) 295.
[41] M. Cornacchia, Proc. SPIE 2998 (1997) 2–14.
[42] S. Miyamoto et al., Report of the Spring-8 International Workshop on 30 m Long Straight Sections, Kobe, Japan, 9 August, 1997.
[43] V.N. Litvinenko et al., Nucl. Instr. and Meth. A 358 (1995) 369.
[44] R. Brinkmann et al., Nucl. Instr. and Meth. A 393 (1997) 86.
[45] W. Brefeld et al., Nucl. Instr. and Meth. A 393 (1997) 119.
[46] M. Asakawa et al., Nucl. Instr. and Meth. A 375 (1996) 416.
[47] N. Ohigashi et al., Nucl. Instr. and Meth. A 375 (1996) 469.