FREE ELECTRON LASERS IN 2013

J. Blau#, K. Cohn, W. B. Colson and R. Vigil
Physics Department, Naval Postgraduate School, Monterey CA 93943 USA

Abstract

Thirty-seven years after the first operation of the free electron laser (FEL) at Stanford University, there continue to be many important experiments, proposed experiments, and user facilities around the world. Properties of FELs operating in the infrared, visible, UV, and X-ray wavelength regimes are tabulated and discussed.

List of FELs in 2013

The following tables list existing (Table 1) and proposed (Tables 2, 3) relativistic free electron lasers (FELs) in 2013. The 1st column lists a location or institution, and the FEL's name in parentheses. References are listed in Tables 4 and 5; another useful reference is http://sbfel3.ucsb.edu/www/vl_fel.html.

The 2nd column of each table lists the operating wavelength λ, or wavelength range. The longer wavelength FELs are listed at the top and the shorter wavelength FELs at the bottom of each table. The large range of operating wavelengths, seven orders of magnitude, indicates the flexible design characteristics of the FEL mechanism.

In the 3rd column, t_b is the electron bunch duration (FWHM) at the beginning of the undulator, and ranges from almost CW to short sub-picosecond time scales. The expected optical pulse length in an FEL oscillator can be several times shorter or longer than the electron bunch depending on the optical cavity Q, the FEL desynchronism and gain. The optical pulse can be many times shorter in a high-gain FEL amplifier. Also, if the FEL is in an electron storage-ring, the optical pulse is typically much shorter than the electron bunch. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam kinetic energy E and peak current I are listed in the 4th and 5th columns, respectively. The next three columns list the number of undulator periods N, the undulator wavelength λ_0, and the rms undulator parameter $K=eB\lambda_0/2\pi mc^2$ (cgs units), where e is the electron charge magnitude, B is the rms undulator field strength, m is the electron mass, and c is the speed of light. For an FEL klystron undulator, there are multiple undulator sections as listed in the N-column; for example 2x7. Some undulators used for harmonic generation have multiple sections with varying N, λ_0, and K values as shown. Some FELs operate at a range of wavelengths by varying the undulator gap as indicated in the table by a range of values for K. The FEL resonance condition, $\lambda = \lambda_0(1+K^2)/2\gamma^2$, relates the fundamental wavelength λ to K, λ_0, and the electron beam energy $E=(\gamma-1)mc^2$, where γ is the relativistic Lorentz factor. Some FELs achieve shorter wavelengths by using coherent harmonic generation (CHG), high-gain harmonic generation (HGHG), or echo-enabled harmonic generation (EEHG).

The last column lists the accelerator types and FEL types, using the abbreviations listed after Table 3.

The FEL optical power is determined by the fraction of the electron beam energy extracted and the pulse repetition frequency. For a conventional FEL oscillator in steady state, the extraction can be estimated as 1/(2N); for a high-gain FEL amplifier, the extraction at saturation can be substantially greater. In a storage ring FEL, the extraction at saturation is substantially less than this estimate and depends on ring properties.

In an FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L=N\lambda_0$ has a Rayleigh length $z_0 \approx L/12^{1/2}$ and has a fundamental mode waist radius $w_0 \approx (z_0\lambda/\pi)^{1/2}$. An FEL typically has more than 90% of its power in the fundamental mode.

At the 2013 FEL Conference, there were three new lasings reported worldwide: an HGHG VUV/soft X-ray FEL at FERMI in Trieste (FERMI-2), an EEHG UV FEL at SINAP in Shanghai (SDUV-FEL), and a super-radiant THz FEL at ELBE in Dresden (TELBE). Progress continues on many other existing and proposed FELs, including several large X-ray FEL facilities around the world.

ACKNOWLEDGMENTS

The authors are grateful for support from ONR and the HEL-JTO.

#blau@nps.edu

ISBN 978-3-95450-126-7

Table 1: Existing Free Electron Lasers (2013)

LOCATION (NAME)	λ(μm)	t_b(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
Frascati (FEL-CATS)	430-760	15-20	2.5	5	16	2.5	0.5-1.4	RF
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA,O
Novosibirsk (FEL1)	120-240	50	12	8	2x33	12	0.71	ERL,O
Dresden (TELBE)	100-3000	0.15	15-34	15	8	30	≤5.7	RF,SU
Nijmegen (FLARE)	100-1400	3	10-15	50	40	11	0.5-3.3	RF,O
KAERI (THz FEL)	100-1200	20	4.5-6.7	0.5	80	2.5	1.0-1.6	MA,O
Osaka (ISIR, SASE)	70-220	20-30	11	1000	32	6	1.5	RF,S
Himeji (LEENA)	65-75	10	5.4	10	50	1.6	0.5	RF,O
UCSB (FIR FEL)	60	25000	6	2	150	2	0.1	EA,O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF,O
Novosibirsk (FEL2)	40-80	20	20	20	33	12	1.0	ERL,O
Osaka (ISIR)	32-150	20-30	13-19	50	32	6	1.5	RF,O
Tokai (JAEA-FEL)	22	2.5-5	17	200	52	3.3	0.7	RF,O
Bruyeres (ELSA)	20	30	18	100	30	3.2	0.8	RF,O
Dresden (ELBE U100)	18-280	1-4	15-34	15	40	10	0.5-2.7	RF,O
Osaka (iFEL4)	18-40	10	33	40	30	8	1.3-1.7	RF,O
LANL (RAFEL)	15.5	15	17	300	200	2	0.9	RF,O
Kyoto (KU-FEL)	5-21.5	<1	20-36	17-40	53	3.3	0.96	RF,O
Darmstadt (FEL)	6-8	2	25-50	2.7	80	3.2	1.0	RF,O
Osaka (iFEL1)	5.5	10	33.2	42	58	3.4	1.0	RF,O
Beijing (BFEL)	5-25	4	30	15-20	50	3	0.5-0.8	RF,O
Daresbury (ALICE)	5-8	~1	27.5	80	40	2.7	0.35-0.9	ERL,O
Dresden (ELBE U27)	4-21	1-4	15-34	15	68	2.73	0.3-0.7	RF,O
Berlin (FHI MIR FEL)	4-50	1-5	15-50	200	50	4	0.5-1.5	RF,O
Tokyo (MIR-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Nijmegen (FELIX)	3-250	1	50	50	38	6.5	1.8	RF,O
Orsay (CLIO)	3-150	10	12-50	100	38	5	≤1.4	RF,O
Nijmegen (FELICE)	3-40	1	60	50	48	6.0	1.8	RF,O
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1.0	RF,O
Nihon (LEBRA)	0.8-6.5	1	58-100	10-20	50	4.8	0.7-1.4	RF,O
Tsukuba (ETLOK-III)	0.85-1.45	90	310	1-3	2x7	20	1-2	SR,O,K
UCLA-BNL (VISA)	0.8	0.5	64-72	250	220	1.8	1.2	RF,S
JLab (IR upgrade)	0.7-10	0.35	120	300	30	5.5	3.0	ERL,O
DELTA (FELICITA-I)	0.42-0.47	50	450-550	90	2x7	25	1.4-1.7	SR,O,K
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
JLab (UV demo)	0.25-0.7	0.35	135	200	60	3.3	1.3	ERL,O
Duke (OK-5)	0.25-0.79	5-20	270-800	10-50	2x30	12	3.18	SR,O,K
BNL (SDL FEL)	0.2-1.0	0.5-1	100-250	300-400	256	3.9	0.8	RF,A,S,H
Okazaki (UVSOR-II)	0.2-0.8	6	600-750	28.3	2x9	11	2.6-4.5	SR,O,K
Tsukuba (ETLOK-II)	0.2-0.6	55	310	1-3	2x42	7.2	1-1.4	SR,O,K
SINAP (SDUV-FEL)	0.2-0.35	2-8	100-180	20-100	360	2.5	0.98	RF,A,H,E
DELTA (U250)	0.2	100	1500	40	2x7	25	7.3-10	SR,K,H
Duke (OK-4)	0.19-0.4	50	1200	35	2x3 3	10	4.75	SR,O,K
ELETTRA (EUFELE)	0.09-0.26	70	1000	150	2x19	10	4.2	SR,A,K,H
Frascati (SPARC)	0.066-0.8	0.15-8	80-177	40-380	450	2.8	0.5-1.55	RF,A,S,H
DESY (sFLASH)	0.038	0.5	700	1000	180 120	3.1 3.3	1.9 2.1	RF,A
SPring-8 (SCSS)	0.03-0.06	1	250	300	600	1.5	0.3-1.06	RF,S
ELETTRA (FERMI-1)	0.02-0.08	0.7-1.2	1250	300-600	252	5.5	1-3	RF,A,H
ELETTRA (FERMI-2)	0.004-0.0144	0.7-1.6	1000-1400	300-700	396	3.5	0.85-1.6	RF,A,H
DESY (FLASH I)	0.004	0.01-0.5	370-1250	2000	984	2.73	0.87	RF,S
SLAC (LCLS)	0.12 nm	0.07	15400	3500	3696	3	2.5	RF,S
SPring-8 (SACLA)	0.08-0.25 nm	0.02-0.03	8300	3000-4000	6300	1.8	1.52	RF,S

ISBN 978-3-95450-126-7

Table 2: Proposed Free Electron Lasers (2013)

PROPOSED FELs	λ(μm)	t_b (ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
KAERI (THz-FEL)	400-600	20	6.5	1	28	2.3-2.6	2.1-2.4	MA,O
Tokyo (FIR-FEL)	300-1000	5	10	30	25	7	1.5-3.4	RF,O
Colorado State University	200-1000	5-15	6	100	50	2.5	1.0	RF,O
NPS-Niowave (THz)	170-550	1-2	3-5	3-7	10	3.3	0.5-1.2	RF,SU
India (CUTE-FEL)	50-100	1000	10-15	20	50	5	0.57	RF,O
Berlin (FHI FIR FEL)	40-500	1-5	20-50	200	40	11	1-3	RF,O
Novosibirsk (FEL3)	5-30	10	40	20-100	3x33	6	2.0	ERL,O
Beijing (PKU-FEL)	4.7-8.3	1	30	60	50	3	0.5-1.4	ERL,O
Turkey (TACIR I) (TACIR II)	2.7-30 10-190	1-10 1-10	40 40	8-80 12-120	56 40	3 9	0.2-0.8 0.4-2.5	RF,O
Tallahassee (Big Light)	2-1500	1-10	50	50	45	5.5	4.0	ERL,O
Daresbury (CLARA)	0.1-0.4	0.5	250	400	500	2.9	0.7-1.5	RF,A
Dalian (DCLS)	0.05-0.15	1	300	300	360	3.0	0.3-1.6	RF,A,H

Table 3: Proposed Short Wavelength Free Electron Lasers (2013)

PROPOSED FELs	λ(nm)	t_b (ps)	E(GeV)	I(kA)	N	λ_0(cm)	K(rms)	Type
JLab (JLAMP)	10-100	0.1	0.6	1	330	3.3	1.0	ERL,O,A
Rome (SPARX 1)	10-30	0.2-0.01	0.96-1.5	1	715	3.4	0.2-2.3	RF,S
SINAP (SXFEL)	8.8	0.26	0.84	0.6	720	2.5	0.95	RF,H,E
DESY (FLASH II)	4-60	0.01-0.5	0.5-1.2	2.5	768	3.14	0.5-2	RF,S,H
Wisconsin (WiFEL)	2.3-6.9	0.1	1.7	1	788	3.3	0.74-1.9	RF,H
Glasgow (ALPHA-X)	2-300	0.001-0.005	0.10-1.0	1	200	1.5	0.5	PW,A
LBNL (NGLS)	1-5	0.5	2.4	0.6	2300	1.9	1.4	RF,S,H
Rome (SPARX 2)	1-14	0.2-0.01	0.96-2.6	1-2.3	220 900 400	4.0 2.8 2.2	3.1 1.63 1.34	RF,S
Groningen (ZFEL)	0.8	0.1	1-2.1	1.5	2600	1.5	0.85	RF,S,H
Rome (SPARX 3)	0.6-1.6	0.2-0.01	1.5-2.4	2.3	2520	1.5	0.91	RF,S
PSI (SwissFEL Athos) (SwissFEL Aramis)	0.7-7 0.1-0.7	0.002-0.015 0.002-0.015	2.5-3.4 2.1-5.8	1.5-2.7 1.5-2.7	1200 3192	4 1.5	0.7-2.5 0.85	RF,S,E RF,S
SLAC (LCLS-II SXR) (LCLS-II HXR)	1.0-6.2 0.06-1.2	0.01-0.1 0.01-0.1	2.0-4.0 7.5-13.5	1-4 1-4	2746 3138	3.9 2.6	1.5-3.7 0.41-2.2	RF,S,SS RF,S,SS
Pohang (PAL SXFEL)	1-10	0.06-0.18	2.6-3.2	1-3	1300	3.43	1.6-3.4	RF,S
(PAL HXFEL)	0.06-1	0.045-0.09	4-10	2-4	4100	2.44	1.3-2.1	RF,S
DESY (Europe XFEL)	0.05-0.1	0.1	17.5	5	4700	3.65	3.3	RF,S
LANL (MaRIE)	0.03	0.03	12	3.4	3200	1.86	0.86	RF,S,H,E

Accelerator type:
MA - Microtron Accelerator
ERL - Energy Recovery Linear Accelerator
EA - Electrostatic Accelerator
RF - Radio-Frequency Linear Accelerator
SR - Electron Storage Ring
PW- Laser Plasma Wakefield Accelerator

FEL type:
A - FEL Amplifier
K - FEL Klystron
O - FEL Oscillator
S - Self-Amplified Spontaneous Emission (SASE)
H - Harmonic Generation (CHG, HGHG)
E - Echo-Enabled Harmonic Generation (EEHG)
SS - Self-Seeded Amplifier
SU - Super-radiant FEL

ISBN 978-3-95450-126-7

Table 4: References and Websites for Existing FELs

LOCATION (NAME)	Internet Site or Reference
Beijing (BFEL)	http://www.ihep.ac.cn/english/BFEL/index.htm
Berlin (FHI MIR)	http://fel.fhi-berlin.mpg.de
BNL (SDL FEL)	http://sdl.nsls.bnl.gov
Bruyeres (ELSA)	P. Guimbal et al., Nucl. Inst. and Meth. **A341**, 43 (1994).
Daresbury (ALICE)	http://www.stfc.ac.uk/ASTeC/Alice/projects/36060.aspx
Darmstadt (FEL)	M. Brunken et al., Nucl. Inst. and Meth. **A429**, 21 (1999).
DELTA (FELICITA-I)	D. Nölle et al., Nucl. Inst. And Meth. **A445**, 128 (2000).
DELTA (U250)	H. Huck et al., Proceedings of FEL 2011, Shanghai, China. http://accelconf.web.cern.ch/AccelConf/FEL2011/papers/mooa5.pdf
DESY (FLASH, sFLASH)	http://flash.desy.de
Dresden (FELBE)	http://www.hzdr.de/FELBE
Duke (OK-4, OK-5)	http://www.fel.duke.edu
ELETTRA (EUFELE)	http://www.elettra.trieste.it/elettra-beamlines/fel.html
ELETTRA (FERMI)	http://www.elettra.trieste.it/FERMI
Frascati (FEL-CATS)	http://www.frascati.enea.it/fis/lac/fel/fel2.htm
Frascati (SPARC)	http://www.roma1.infn.it/exp/xfel
Himeji (LEENA)	T. Inoue et al., Nucl. Inst. and Meth. **A528**, 402 (2004).
JLab (IR upgrade)	G. R. Neil et al., Nucl. Inst. and Meth. **A557**, 9 (2006).
JLab (UV demo)	S. V. Benson et al., Proceedings of FEL 2011, Shanghai, China. http://accelconf.web.cern.ch/AccelConf/FEL2011/papers/weoci1.pdf
KAERI (THz FEL)	Y. U. Jeong et al., Nucl. Inst. and Meth. **A575**, 58 (2007).
Kyoto (KU-FEL)	http://wonda.iae.kyoto-u.ac.jp/index-e.html
LANL (RAFEL)	D. C. Nguyen et al., Proceedings of LINAC 2000, Monterey, CA, USA. http://accelconf.web.cern.ch/AccelConf/l00/papers/TH301.pdf
Nihon (LEBRA)	K. Hayakawa et al., Proceedings of FEL 2007, Novosibirsk, Russia. http://accelconf.web.cern.ch/AccelConf/f07/papers/MOPPH046.pdf
Nijmegen (FELICE, FELIX)	http://www.ru.nl/felix
Nijmegen (FLARE)	http://www.ru.nl/flare
Novosibirsk (FEL1)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
Novosibirsk (FEL2)	N. A. Vinokurov et al., Proceedings of FEL 2009, Liverpool, UK. http://accelconf.web.cern.ch/AccelConf/FEL2009/papers/tuod01.pdf
Okazaki (UVSOR- II)	H. Zen et al., Proceedings of FEL 2009, Liverpool, UK. http://accelconf.web.cern.ch/AccelConf/FEL2009/papers/wepc36.pdf
Orsay (CLIO)	http://clio.lcp.u-psud.fr
Osaka (iFEL4)	T. Takii et al., Nucl. Inst. and Meth. **A407**, 21 (1998).
Osaka (iFEL1,2,3)	H. Horiike et al., Proceedings of FEL 2004, Trieste, Italy. http://accelconf.web.cern.ch/AccelConf/f04/papers/THPOS17/THPOS17.pdf
Osaka (ILE/ILT)	N. Ohigashi et al., Nucl. Inst. and Meth. **A375**, 469 (1996).
Osaka (ISIR)	R. Kato et al., Proceedings of FEL 2007, Novosibirsk, Russia. http://accelconf.web.cern.ch/AccelConf/f07/papers/FRAAU04.pdf
SINAP (SDUV-FEL)	Z. T. Zhao and D. Wang, Proceedings of FEL 2010, Malmo, Sweden. http://accelconf.web.cern.ch/AccelConf/FEL2010/papers/moobi1.pdf
SLAC (LCLS)	http://lcls.slac.stanford.edu
SPring-8 (SCSS, SACLA)	http://www.riken.jp/XFEL/eng/index.html
Tokai (JAEA-FEL)	R. Hajima et al., Nucl. Inst. and Meth. **A507**, 115 (2003).
Tokyo (MIR-FEL)	http://www.rs.noda.tus.ac.jp/fel-tus/English/E-Top.html
Tsukuba (ETLOK-II)	K.Yamada et al., Nucl. Inst. and Meth. **A528**, 268 (2004).
Tsukuba (ETLOK-III)	N. Sei, H. Ogawa and K. Yamada, Optics Letters **34**, 1843 (2009).
UCLA-BNL (VISA)	A. Tremaine et al., Nucl. Inst. and Meth. **A483**, 24 (2002).
UCSB (mm, FIR FEL)	http://sbfel3.ucsb.edu

ISBN 978-3-95450-126-7

Table 5: References and Websites for Proposed FELs

LOCATION (NAME)	Internet Site or Reference
Beijing (PKU-FEL)	Z. Liu et al., Proceedings of FEL 2006, Berlin, Germany. http://accelconf.web.cern.ch/AccelConf/f06/papers/TUAAU05.pdf
Berlin (FHI FIR)	http://fel.fhi-berlin.mpg.de
Colorado State University	S. Milton et. al., Proceedings of FEL 2012, Nara, Japan. http://www.jacow.org
Dalian (DCLS)	T. Zhang et. al., Proceedings of IPAC2013, Shanghai, China http://accelconf.web.cern.ch/accelconf/IPAC2013/papers/weodb102.pdf
Daresbury (CLARA)	J. A. Clarke et. al., Proceedings of IPAC 2012, New Orleans, LA, USA. http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/tuppp066.pdf
DESY (FLASH II)	http://flash.desy.de
DESY (Europe XFEL)	http://www.xfel.eu
Glasgow (ALPHA-X)	http://phys.strath.ac.uk/alpha-x/
Groningen (ZFEL)	J. P. M. Beijers et al., Proceedings of FEL 2010, Malmo, Sweden. http://accelconf.web.cern.ch/AccelConf/FEL2010/papers/mopc22.pdf
India (CUTE-FEL)	S. Krishnagopal and V. Kumar, Proceedings of FEL 2007, Novosibirsk, Russia. http://accelconf.web.cern.ch/accelconf/f07/papers/MOPPH074.pdf
JLab (JLAMP)	S. V. Benson et al., Proceedings of FEL 2009, Liverpool, UK. http://accelconf.web.cern.ch/accelconf/FEL2009/papers/mopc70.pdf
KAERI (THz-FEL)	Y. U. Jeong et al., Proceedings of FEL 2012, Nara, Japan. http://www.jacow.org
LANL (MaRIE)	http://marie.lanl.gov
LBNL (NGLS)	J. N. Corlett et al., Proceedings of IPAC 2010, Kyoto, Japan. http://accelconf.web.cern.ch/accelconf/IPAC10/papers/wepea067.pdf
Novosibirsk (FEL3)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
NPS-Niowave (THz)	http://www.niowaveinc.com
Pohang (PAL XFEL)	J.-H. Han et. al., Proceedings of IPAC 2012, New Orleans, LA, USA. http://accelconf.web.cern.ch/accelconf/IPAC2012/papers/tuppp061.pdf
PSI (SwissFEL Athos,Aramis)	http://www.psi.ch/swissfel
Rome (SPARX 1, 2, 3)	http://www.sparx-fel.it
SINAP (SX-FEL)	Z. T. Zhao and D. Wang, Proceedings of FEL 2010, Malmo, Sweden. http://accelconf.web.cern.ch/AccelConf/FEL2010/papers/moobi1.pdf
Tallahassee (Big Light)	http://www.magnet.fsu.edu/usershub/scientificdivisions/emr/facilities/fel.html
Tokyo (FIR-FEL)	http://www.rs.noda.tus.ac.jp/fel-tus/English/E-Top.html
Turkey (TACIR I & II)	http://www.tarla-fel.org
Wisconsin (WiFEL)	http://www.wifel.wisc.edu

ISBN 978-3-95450-126-7