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FREE ELECTRON LASERS IN 2017

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Abstract

Forty-one 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 operating and proposed FELs in the terahertz (THz), infrared (IR), visible, ultraviolet (UV), and X-ray regimes are tabulated and discussed.

LIST OF FELS IN 2017

The following tables list existing (Tables 1 and 2) and proposed (Tables 3 and 4) relativistic free electron lasers (FELs) in 2017. Some FELs in Tables 1 and 2 may not be currently operating, but are still included until we have been notified they are decommissioned. Tables 2 and 4, denoted as "Short Wavelength", contain FELs that are designed to operate in the UV and X-ray regimes (400-nm or shorter wavelength), while Tables 1 and 3, denoted as "Long Wavelength", contain all other FELs. The first column lists a location or institution, and the FEL's name in parentheses. References are listed in Tables 5 and 6; another useful reference is the following website: http://sbfel3.ucsb.edu/www/vl_fel.html.

The second 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 seven orders of magnitude of operating wavelengths indicate the flexible design characteristics of the FEL mechanism.

In the third column, t_b is the electron bunch duration (FWHM) at the beginning of the undulator, and ranges from almost continuous-wave 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, or one based on self-amplified spontaneous emission (SASE). 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 fourth and fifth columns, respectively.

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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 4.

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 2017 FEL Conference, new lasings were reported at DESY, PSI, SACLA, Pohang, and SINAP. These are all large X-ray FEL facilities, showing there is significant worldwide interest in short wavelength FEL applications. Various other facilities reported updated parameters for existing FELs, and there are several newly proposed short-wavelength FELs around the world.

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Table 1: Existing Long Wavelength Free Electron Lasers (2017)

LOCATION (NAME)	$\lambda(\mu m)$	t_b(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
Ariel (EA-FEL)	3000	5×10^7	1.4	0.5-3	26	4.44	0.8	EA,O
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
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
Novosibirsk (FEL1)	90-240	100	12	10	2x32	12	0-0.9	ERL,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)	37-85	20	22	50	32	12	0-1.1	ERL,O
Osaka (ISIR)	25-150	20-30	13-20	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)	18-250	1-25	15-34	30	38	10	0.5-2.7	RF,O
Osaka (iFEL4)	18-40	10	33	40	30	8	1.3-1.7	RF,O
Novosibirsk (FEL3)	9	10	42	100	3x28	6	0.3-1.8	ERL,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
Nijmegen (FELICE)	5-100	1	18-50	50	48	6.0	1.8	RF,O
Dresden (ELBE U37)	5-40	0.8-4	15-34	60	54	3.7	0.5-1.34	RF,O
Beijing (BFEL)	5-25	4	30	15-20	50	3	0.5-0.8	RF,O
Kyoto (KU-FEL)	5-21.5	<1	20-36	17-40	52	3.3	0.7-1.56	RF,O
Daresbury (ALICE)	5-11	~1	27.5	80	40	2.7	0.35-0.9	ERL,O
Tokyo (MIR-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Orsay (CLIO)	3-150	10	12-50	100	38	5	≤1.4	RF,O
Nijmegen (FELIX)	3-150	1	15-50	50	38	6.5	1.8	RF,O
Berlin (FHI MIR FEL)	2.9-50	1-5	15-50	200	50	4	0.5-1.5	RF,O
Hawaii (MkV)	2-10	2-5	30-45	30-60	47	2.3	0.1-1.3	RF,O
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1.0	RF,O
Nihon (LEBRA)	1.5-6.5	1	58-100	10-20	50	4.8	0.7-1.4	RF,O
JLab (IR upgrade)	0.7-10	0.35	120	300	30	5.5	3.0	ERL,O

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Table 2: Existing Short Wavelength Free Electron Lasers (2017)

LOCATION (NAME)	λ(nm)	t_b(ps)	E(GeV)	I(kA)	N	λ_0(cm)	K(rms)	Type
Osaka (iFEL3)	300-700	5	0.155	0.06	67	4	1.4	RF,O
Duke (OK-5)	250-790	5-20	0.27-0.8	0.01-0.05	2x30	12	3.18	SR,O,K
JLab (UV demo)	250-700	0.35	0.135	0.2	60	3.3	1.3	ERL,O
Okazaki (UVSOR-II)	200-800	6	0.6-0.75	0.028	2x9	11	2.6-4.5	SR,O,K
DELTA (U250)	200	100	1.5	0.04	2x7	25	7.3-10	SR,K,H
Duke (OK-4)	190-400	50	1.2	0.035	2x33	10	4.75	SR,O,K
ELETTRA (SR-FEL)	90-260	70	1	0.150	2x19	10	4.2	SR,A,K,H
Frascati (SPARC)	66-800	0.15-8	0.08-0.177	0.04-0.38	450	2.8	0.5-1.55	RF,A,S,H
DESY (sFLASH)	38	0.5	0.7	0.5-2	180 120	3.14 3.3	1.9 2.1	RF,S,H
ELETTRA (FERMI-1)	20-100	0.7-1.2	0.9-1.5	0.3-0.7	252	5.5	1-3	RF,A,H
SINAP (SXFEL-TF)	8.8	0.5	0.84	0.5	760	2.35	1.012	RF,H,E
SACLA (BL1 SX)	8-62	1	0.3-0.8	0.3	777	1.8	1.5	RF,S
DESY (FLASH2)	4-90	0.03-0.2	0.5-1.25	2.5	768	3.14	0.5-2	RF,S
DESY (FLASH1)	4-50	0.03-0.2	0.35-1.25	2.5	981	2.73	0.87	RF,S
ELETTRA (FERMI-2)	4-20	0.7-1.6	0.9-1.5	0.3-0.7	396	3.5	0.85-1.6	RF,A,H
Pohang (PAL SXFEL)	1.0-4.5	0.03-0.18	2.6-3.15	1-3	980	3.50	1.5-3.3	RF,S
DESY (European XFEL)	0.13-0.9	0.1	6-14	5	4375	4	1.65-3.9	RF,S
SLAC (LCLS)	0.12	0.07	15.4	3.5	3696	3	2.5	RF,S
PSI (SwissFEL Aramis)	0.1-0.7	0.002-0.015	2.1-5.8	1.5-2.7	3192	1.5	0.5-1.3	RF,S,SS
Pohang (PAL HXFEL)	0.06-0.7	0.02-0.09	4-10	2-4	3770	2.60	1.2-2.0	RF,S
SACLA (BL3 HX) (BL2 HX)	0.06-0.3 0.06-0.3	0.01-0.02 0.01-0.02	8.3 8.3	10 10	5817 4986	1.8 1.8	2.0 2.0	RF,S RF,S

Table 3: Proposed Long Wavelength Free Electron Lasers (2017)

LOCATION (NAME)	λ(μm)	t_b(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
KAERI (Table-top THz)	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
Ariel (THz FEL)	75-300	0.3	3-6	1000	20	2.5	0.47	RF,A
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
Beijing (PKU-FEL)	4.7-8.3	1	30	60	50	3	0.5-1.4	ERL,O
Turkey (TARLA U90) (TARLA U25)	18-250 3-20	0.4-6 0.4-6	15-40 15-40	12-155 12-155	40 60	9 2.5	0.7-2.3 0.25-0.7	RF,O
Tallahassee (Big Light)	2-1500	1-10	50	50	45	5.5	4.0	ERL,O

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Table 4: Proposed Short Wavelength Free Electron Lasers (2017)

LOCATION (NAME)	λ(nm)	t_b(ps)	E(GeV)	I(kA)	N	λ_0(cm)	K(rms)	Type
Daresbury (CLARA)	100-400	0.5	0.25	0.4	500	2.5	0.7-1.4	RF,A
Dalian (DCLS)	50-150	1	0.3	0.3	360	3.0	0.3-1.6	RF,A,H
Soleil (LUNEX 5)	4-40	1	0.4	0.4	800	1.5	<2.6	PW,H,E,SS
Glasgow (ALPHA-X)	2-300	0.001-0.005	0.10-1.0	1	200	1.5	0.5	PW,A
SINAP (SXFEL-UF)	3 2	0.35 0.35	1.5 1.5	0.7 0.7	1200 2500	2.35 1.6	1.09 1.074	RF,H,E RF,S
Groningen (ZFEL)	0.8	0.1	1-2.1	1.5	2600	1.5	0.85	RF,S,H
ASU (CXFEL)	0.15-1	0.001-0.01	0.05	0.2	300	0.0001	0.25	RF,OU,SU
PSI (SwissFEL Athos)	0.7-7	0.002-0.015	2.5-3.4	1.5-2.7	1200	4	0.7-3.5	RF,S,SS
SLAC (LCLS-II SXR) (LCLS-II HXR)	1.0-6.2 0.05-1.2	0.01-0.1 0.01-0.1	2.0-4.0 2.5-15.0	0.5-1.5 0.5-4	1827 4160	3.9 2.6	1.4-3.9 0.36-1.7	RF,S,SS RF,S,SS
DESY (European XFEL)	0.4-5 0.05-0.4	0.002-0.18	8-17.5	5	1544 4375	6.8 4	4-9 1.65-3.9	RF,S
SINAP (SCLF)	0.4-3 0.08-0.4 0.05-0.12	0.066 0.066 0.066	8 6-8 8	1.5 1.5 1.5	2352 6538 10000	6.8 2.6 1.6	1.37-4.5 0.75-1.8 0.69-1.64	RF,H,E,SS RF,S,SS RF,S,SS
LANL (MaRIE)	0.03	0.03	12	3.4	5600	1.86	0.86	RF,S,H,E

Facility type:

TF – Test Facility
UF – User Facility

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
OU – Optical Undulator
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

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Table 5: References and Websites for Existing FELs

LOCATION (NAME)	Internet Site or Reference
Ariel (EA-FEL)	http://www.ariel.ac.il/research/fel
Beijing (BFEL)	http://www.ihep.ac.cn/english/BFEL/index.htm
Berlin (FHI MIR)	http://fel.fhi-berlin.mpg.de
Bruyeres (ELSA)	P. Guimbal *et al.*, *Nucl. Inst. and Meth.* A 341, 43 (1994).
Daresbury (ALICE)	http://www.stfc.ac.uk/ASTeC/Alice/projects/36060.aspx
Darmstadt (FEL)	M. Brunken *et al.*, *Nucl. Inst. and Meth.* A 429, 21 (1999).
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, European XFEL)	http://xfel.desy.de
Dresden (ELBE)	http://www.hzdr.de/FELBE
Duke (OK-4, OK-5)	http:// https://www.phy.duke.edu/duke-free-electron-laser-laboratory
ELETTRA (SR-FEL)	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
Hawaii (MkV)	M. Hadmack, Ph.D. Dissertation, University of Hawaii, December 2012.
Himeji (LEENA)	T. Inoue *et al.*, *Nucl. Inst. and Meth.* A 528, 402 (2004).
JLab (IR upgrade)	G. R. Neil *et al.*, *Nucl. Inst. and Meth.* A 557, 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.* A 575, 58 (2007).
Kyoto (KU-FEL)	H. Zen *et al.*, *Proceedings of FEL 2013*, New York, NY, USA http:// https://accelconf.web.cern.ch/accelconf/FEL2013/papers/wepso84.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, FLARE)	http://www.ru.nl/felix
Novosibirsk (FEL1)	N. G. Gavrilov *et al.*, *Nucl. Inst. and Meth.* A 575, 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
Novosibirsk (FEL3)	G. Kulipanov *et al.*, *IEEE Trans. Terahertz Sci. Technol.* no. 5, 798 (2015).
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.* A 407, 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.* A 375, 469 (1996).
Osaka (ISIR)	R. Kato *et al.*, *Proceedings of IPAC 2010*, Kyoto, Japan. http://accelconf.web.cern.ch/accelconf/IPAC10/papers/tupe030.pdf
Pohang (PAL XFEL)	http://pal.postech.ac.kr/paleng/
PSI (SwissFEL Aramis)	http://www.psi.ch/swissfel
SACLA (BL1,2,3)	http://xfel.riken.jp/eng/users/
SINAP (SX-FEL)	Z. Zhao *et al*., Status of the SXFEL Facility. *Applied Sciences* 7(6), 607 (2017).
SLAC (LCLS)	http://lcls.slac.stanford.edu
Tokai (JAEA-FEL)	R. Hajima *et al.*, *Nucl. Inst. and Meth.* A 507, 115 (2003).
Tokyo (MIR-FEL)	http://www.rs.noda.tus.ac.jp/fel-tus/English/E-Top.html
UCSB (mm, FIR FEL)	http://sbfel3.ucsb.edu

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Table 6: References and Websites for Proposed FELs

LOCATION (NAME)	Internet Site or Reference
Ariel (THz FEL)	A. Friedman *et al.*, *Proceedings of FEL 2014*, Basel, Switzerland, http://accelconf.web.cern.ch/AccelConf/FEL2014/papers/tup081.pdf
ASU (CXFEL)	W. S. Graves *et al.*, *Proceedings of FEL 2017*, Santa Fe, NM, USA, TUB03.
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
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 (European XFEL)	http://xfel.desy.de
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
KAERI (Table-top THz)	Y. U. Jeong *et al.*, *J. Korean Phys. Soc*. 59, no. 5, 3251 (2011).
LANL (MaRIE)	http://marie.lanl.gov
PSI (SwissFEL Athos)	http://www.psi.ch/swissfel
SINAP (SCLF)	Z. Zhu *et al.*, *Proceedings of FEL 2017*, Santa Fe, NM, USA, MOP055
SINAP (SX-FEL)	Z. Zhao *et al.*, Status of the SXFEL Facility. *Applied Sciences* 7(6), 607 (2017).
SLAC (LCLS-II)	http://lcls.slac.stanford.edu
Soleil (LUNEX 5)	M. E. Couprie *et al.*, *Journal of Physics: Conference Series* **425** (2013)
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 (TARLA U25,U90)	http://www.tarla.org.tr