FREE ELECTRON LASERS IN 2015

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Abstract

Thirty-nine 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 terahertz (THz) infrared (IR), visible, ultraviolet (UV), and X-ray wavelength regimes are tabulated and discussed.

LIST OF FELS IN 2015

The following tables list existing (Table 1) and proposed (Tables 2, 3) relativistic free electron lasers (FELs) in 2015. 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 seven orders of magnitude of operating wavelengths indicate 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 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 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 2015 FEL Conference, there were three new lasings reported: the mid-IR FEL oscillator at Kyoto University was operated with a photocathode, the 3rd stage of the Novosibirsk THz FEL operated at 9 µm, and the XUV FEL at DESY (FLASH) demonstrated cascaded SASE operation. Progress continues on many other existing and proposed FELs around the world; several large X-ray FEL facilities are scheduled to come online over the next couple of years.

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Table 1: Existing Free Electron Lasers (2015)

LOCATION (NAME)	λ(μm)	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	1-4	15-34	30	40	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
Kyoto (KU-FEL)	5-21.5	<1	20-36	17-40	52	3.3	0.7-1.56	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)	5-11	~1	27.5	80	40	2.7	0.35-0.9	ERL,O
Dresden (ELBE U27)	4-21	1-4	15-34	30	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
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
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
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
Okazaki (UVSOR-II)	0.2-0.8	6	600-750	28.3	2x9	11	2.6-4.5	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	2x33	10	4.75	SR,O,K
ELETTRA (SR-FEL)	0.09-0.26	70	1000	150	2x19	10	4.2	SR,A,K,H
PSI (SwissFEL Test)	0.07-0.8	0.5-3	100-220	20-160	265	1.5	0.5-1.3	RF,S
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	3.14 3.3	1.9 2.1	RF,S,H
ELETTRA (FERMI-1)	0.02-0.1	0.7-1.2	900-1500	300-700	252	5.5	1-3	RF,A,H
ELETTRA (FERMI-2)	0.004-0.0144	0.7-1.6	900-1500	300-700	396	3.5	0.85-1.6	RF,A,H
DESY (FLASH2)	0.004-0.08	0.05-0.5	500-1250	2500	768	3.14	0.5-2	RF,S
DESY (FLASH1)	0.004-0.05	0.05-0.5	350-1250	2500	981	2.73	0.87	RF,S
SLAC (LCLS)	0.12 nm	0.07	15400	3500	3696	3	2.5	RF,S
SPring-8 (SACLA)	0.06-0.25 nm	0.02-0.03	8300	3000-4000	6300	1.8	1.52	RF,S

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Table 2: Proposed Free Electron Lasers (2015)

PROPOSED FELs	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
Colorado State University	200-800	5-15	6	100	50	2.5	1.0	RF,O
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
Ariel (THz FEL)	75-300	0.3	3-6	1000	20	2.5	0.47	RF,A
Beijing (PKU-FEL)	4.7-8.3	1	30	60	50	3	0.5-1.4	ERL,O
Turkey (TARLA U25) (TARLA U90)	3-20 18-250	0.4-6 0.4-6	15-40 15-40	12-155 12-155	60 40	2.5 9	0.25-0.7 0.7-2.3	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 (2015)

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
SINAP (SXFEL)	8.8	0.26	0.84	0.6	720	2.5	0.95	RF,H,E
Glasgow (ALPHA-X)	2-300	0.001-0.005	0.10-1.0	1	200	1.5	0.5	PW,A
Groningen (ZFEL)	0.8	0.1	1-2.1	1.5	2600	1.5	0.85	RF,S,H
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	0.7-3.5 0.5-1.3	RF,S,SS 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
Pohang (PAL SXFEL) (PAL HXFEL)	1-4.5 0.06-1	0.06-0.18 0.045-0.09	2.6-3.2 4-10	1-3 2-4	1300 4100	3.43 2.44	1.6-3.4 1.3-2.1	RF,S
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
LANL (MaRIE)	0.03	0.03	12	3.4	5600	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

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Table 4: 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. **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 (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 (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. **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)	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)	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
Novosibirsk (FEL3)	G. Kulipanov et. al., IEEE Trans. Terahertz Sci. Technol. **5**, 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. **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 IPAC 2010, Kyoto, Japan. http://accelconf.web.cern.ch/accelconf/IPAC10/papers/tupe030.pdf
PSI (SwissFEL Test)	S. Reiche, Proceedings of FEL2014, Basel, Switzerland.
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
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
UCLA-BNL (VISA)	A. Tremaine et al., Nucl. Inst. and Meth. **A483**, 24 (2002).
UCSB (mm, FIR FEL)	http://sbfel3.ucsb.edu

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Table 5: 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
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 IPAC 2014, Dresden, Germany. http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/thpri074.pdf
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 (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 (Table-top THz)	Y. U. Jeong et al., J. Korean Phys. Soc., Vol. **59**, No. 5, 3251 (2011).
LANL (MaRIE)	http://marie.lanl.gov
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
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 (TARLA U25,U90)	http://www.tarla.org.tr

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