FREE ELECTRON LASERS IN 2011

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Abstract
Thirty-five 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.

The following tables list demonstrated (Table 1) and proposed (Tables 2, 3) relativistic free electron lasers (FELs) in 2011. The 1st column lists a location or institution, and the FEL's name in parentheses. References are listed in Tables 4 and 5; another good 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 3rdcolumn, σ_z is the electron pulse length at the beginning of the undulator, divided by the speed of light c, 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 pulse 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 pulse. 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 5thcolumns, 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 eis the electron charge magnitude, 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; 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 harmonics.

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 the conventional oscillatorin steady-state, the extraction can be estimated by 1/(2N);for the 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 the 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 $w_0 \approx (z_0\lambda/\pi)^{1/2}$. The FEL typically has more than 90% of the power in the fundamental mode.

Progress in FELs continues at the 2011 FEL Conference, there were five new lasings reported worldwide, including SACLA at SPring-8, which joins LCLS at SLAC as the world's second hard X-ray laser. Other new lasings reported were an infrared FEL at Daresbury (ALICE), a seeded soft X-ray FEL at ELETTRA (FERMI), a UV FEL at DELTA (U250), and a deep ultraviolet FEL at SINAP (SDUV-FEL). Many laboratories around the world are proposing new short wavelength facilities, some using new techniques such as echo-enabled harmonic generation (EEHG).

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Table 1: Demonstrated Free Electron Lasers (2011)

LOCATION (NAME)	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
Frascati (FEL-CATS)	760	15-20	2.5	5	16	2.5	0.75	RF,O
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA,O
Novosibirsk (NovoFEL 1)	120-240	50	12	8	2x33	12	0.71	ERL,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 (NovoFEL 2)	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
Osaka (FELI4)	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)	11-14	<1	25	17	40	4	0.99	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 (U100-FELBE)	18-280	1-10	15-34	15	38	10	0.5-2.7	RF,O,K
(U27-FELBE)	4-21	1-10	15-34	15	2x34	2.73	0.3-0.7	RF,O,K
Tokyo (MIR-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
FOM (FELIX)	3-250	1	50	50	38	6.5	1.8	RF,O
Orsay (CLIO)	3-150	10	8-50	100	38	5	1.4	RF,O
FOM (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	0.15	120	400	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
DELTA (U250)	0.39	90	1500	40	7, 7	25	10, 7.3	SR,K,H
SINAP (SDUV-FEL)	0.35	1	135	50-100	360	2.5	0.98	RF,A,H,E
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
Orsay (Super-ACO)	0.3-0.6	15	800	0.1	2x10	13	4.5	SR,O,K
JLab (UV demo)	0.25-0.7	0.2	135	270	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
ELETTRA (EUFELE)	0.2-0.4	28	1000	150	2x19	10	4.2	SR,O,K
Duke (OK-4)	0.19-0.4	50	1200	35	2x33	10	4.75	SR,O,K
Frascati (SPARC)	0.066-0.5	0.5-8	115-177	40-380	450	2.8	2.2	RF,A,S,H
SPring-8 (SCSS)	0.03-0.06	1	250	300	600	1.5	0.3-1.5	RF,S
ELETTRA (FERMI-1)	0.02-0.08	0.7-1.2	1200	300	252	5.5	1-3	RF,A,H
DESY (FLASH)	0.0041	0.05	1250	2000	984	2.73	1.23	RF,S
SLAC (LCLS)	0.00012	0.07	15400	3500	3696	3	2.5	RF,S
SPring-8 (SACLA)	0.00012	0.05	7000	3000	4986	1.8	1.3	RF,S

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Table 2: Proposed Free Electron Lasers (2011)

PROPOSED FELs	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	Type
KAERI (THz-FEL)	400-600	20	6.5	0.5	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
Nijmegen (THz-FEL)	100-1500	3	10-15	50	40	11	0.5-3.3	RF,O
India (CUTE-FEL)	50-100	1000	10-15	20	50	5	0.57	RF,O
Novosibirsk (NovoFEL 3)	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
Berlin (Fritz Haber Institute)	3-300	1-5	20-50	200	50 40	4 11	0.5-1.5 1-3	RF,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	15,30	5.5	4.0	ERL,O
Harima (SUBARU)	0.2-10	26	1500	50	33,16	16,32	8.0	SR,O,K

Table 3: Proposed Short Wavelength Free Electron Lasers (2011)

PROPOSED FELs	λ(nm)	σ_z(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
ELETTRA (FERMI-2)	10-20	0.7	1.5	0.8	396	3.5	1-1.7	RF,A,H
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)	4-80	0.15	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)	1-100	0.5	2	1	2300	1.5	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
DESY (Euro XFEL)	0.4-1.6	0.08	17.5	5	4700	3.6	3.2	RF,S
PSI (SwissFELAthos) (SwissFELAramis)	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
Pohang (PAL X-FEL)	0.06-0.1	0.05	10	3	4500	2	1.66	RF,S

Accelerator type:

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

FEL type:

A - FEL Amplifier
K - FEL Klystron
O - FEL Oscillator
S - Self-Amplified Spontaneous Emission (SASE)
H - High-Gain Harmonic Generation (HGHG)
E - Echo-Enabled Harmonic Generation (EEHG)

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Table 4: References and Websites for Demonstrated FELs

LOCATION (NAME)	Internet Site or Reference
Beijing (BFEL)	http://www.ihep.ac.cn/english/BFEL/index.htm
BNL (SDL FEL)	http://sdl.nsls.bnl.gov/
Bruyeres (ELSA)	P. Guimbal et al.,Nucl. Inst. and Meth. **A341**, 43 (1994).
Daresbury (ALICE)	http://alice.stfc.ac.uk
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://www.jacow.org.
DESY(FLASH)	http://flash.desy.de
Dresden (U27, U100)	http://www.hzdr.de/FELBE
Duke (OK-4, OK-5)	http://www.fel.duke.edu
ELETTRA (EUFELE)	http://www.elettra.trieste.it/projects/euprog/fel
ELETTRA (FERMI-1)	http://www.elettra.trieste.it/FERMI
FOM (FELICE, FELIX)	http://www.rijnhuizen.nl/felix
Frascati (FEL-CATS)	http://www.frascati.enea.it/fis/lac/fel/fel2.htm
Frascati (SPARC)	http://www.sparc.it
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://www.jacow.org
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
Novosibirsk (NovoFEL 1)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
Novosibirsk (NovoFEL 2)	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)	R. Prazeres, F. Glotin, J. M. Ortega, Proceedings of FEL 2004, Trieste, Italy. http://accelconf.web.cern.ch/AccelConf/f04/papers/THPOS06/THPOS06.pdf
Orsay (Super-ACO)	M. E. Couprie et al.,Nucl. Inst. and Meth. **A407**, 215 (1998).
Osaka (FELI4)	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

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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 (Fritz Haber Inst.)	H. Bluem et al., Proceedings of FEL 2010, Malmo, Sweden. http://accelconf.web.cern.ch/AccelConf/FEL2010/papers/mopa09.pdf
DESY (FLASH II)	B. Faatz et al., Proceedings of INAC 2010, Kyoto, Japan. http://accelconf.web.cern.ch/accelconf/IPAC10/papers/tupe005.pdf
DESY (XFEL)	http://www.xfel.net
ELETTRA (FERMI-2)	http://www.elettra.trieste.it/FERMI
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
Harima (SUBARU)	A. Ando, Proceedings of APAC 1998, Tsukuba, Japan. http://accelconf.web.cern.ch/AccelConf/a98/APAC98/6A004.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 2011, Shanghai, China. http://www.jacow.org
LBNL (NGLS)	J. N. Corlett et al., Proceedings of IPAC 2010, Kyoto, Japan. http://accelconf.web.cern.ch/accelconf/IPAC10/papers/wepea067.pdf
Nijmegen (THz-FEL)	R. T. Jongma et al., Proceedings of FEL 2010, Liverpool, UK. http://accelconf.web.cern.ch/accelconf/FEL2009/papers/tupc84.pdf
Novosibirsk (NovoFEL 3)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
Pohang (PAL X-FEL)	H. S. Kang and S. H. Nam, Proceedings of FEL 2010, Malmo, Sweden. http://accelconf.web.cern.ch/AccelConf/FEL2010/papers/mopc19.pdf
PSI (SwissFELAthos,Aramis)	http://www.psi.ch/swissfel
Rome (SPARX 1)	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)	A. Aksoy, O. Karsli and O. Yavas, Infrared Phys. Technol. **51**, 378 (2008).
Wisconsin (WiFEL)	http://www.wifel.wisc.edu

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