FREE ELECTRON LASERS IN 2010

J. Blau#, Y. H. Bae, K. Cohn, W. B. Colson, and J. M. Wittrock
Physics Department, Naval Postgraduate School, Monterey CA 93943 USA

Abstract

Thirty-four 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 and 3) relativistic free electron lasers (FELs) in 2010. A location or institution, followed by the FEL's name in parentheses, identifies each FEL; references are listed in Tables 4 and 5. Another good reference is http://sbfel3.ucsb.edu/www/vl_fel.html.

The first column of the table lists the operating wavelength λ, or wavelength range. The longer wavelengths are listed at the top with short x-ray wavelength FELs at the bottom of the table. The large range of operating wavelengths, seven orders of magnitude, indicates the flexible design characteristics of the FEL mechanism.

In the second column, σ_z is the electron pulse length divided by the speed of light *c*, and ranges from almost CW to short sub-picosecond pulse 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 up to many times shorter in the 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 third and fourth 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, and m is the electron mass. For an FEL klystron undulator, there are multiple undulator sections as listed in the N-column; for example 2x33. Some undulators used for harmonic generation have multiple sections with varying N, λ_0, and K values as shown. Most undulators are configured to have linear polarization. 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, $\lambda = \lambda_0(1+K^2)/2\gamma^2$, provides a relationship that can be used to relate the fundamental wavelength λ to K, λ_0, and $E=(\gamma-1)mc^2$, 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 at the bottom of the tables.

The FEL optical power is determined by the fraction of the electron beam energy extracted and the pulse repetition frequency. For the conventional oscillator in 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. The JLab infrared FEL operating at 75 MHz has demonstrated an average power of 14 kW, with the recovery of the electron beam energy in superconducting accelerator cavities.

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 $z_0 \approx L/12^{1/2}$ and has a fundamental mode waist radius of $w_0 \approx (z_0\lambda/\pi)^{1/2}$. The FEL typically has more than 90% of the power in the fundamental mode.

Progress in FELs continues; at the 2010 FEL Conference, there were 5 new lasings reported worldwide, and many laboratories are proposing new short wavelength facilities.

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#blau@nps.edu

Table 1: Demonstrated Free Electron Lasers (2010)

LOCATION (NAME)	$\lambda(\mu m)$	$\sigma_z(ps)$	E(MeV)	I(A)	N	$\lambda_0(cm)$	K(rms)	
Frascati (FEL-CAT)	760	15-20	1.8	5	16	2.5	0.75	RF,O
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA,O
Novosibirsk (RTM)	120-230	70	12	10	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
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	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	2.0	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
BNL (HGHG)	5.3	6	40	120	60	3.3	1.44	RF,A
Beijing (BFEL)	5-25	4	30	15-20	50	3	1.0	RF,O
Dresden (U100-FELBE)	18-280	1-25	18-34	15	38	10	0.5-2.7	RF,O,K
(U27-FELBE)	4-21	0.5-4	15-34	15	2x34	2.73	0.3-0.7	RF,O,K
Tokyo (KHI-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Nieuwegein (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
Nieuwegein (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)	0.9-6.5	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
BNL (ATF)	0.6	6	50	100	70	0.88	0.4	RF,O
Dortmund (FELICITAI)	0.42	50	450	90	17	25	2.0	SR,O
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 upgrade)	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
Trieste (ELETTRA)	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	6x75	2.8	2.2	RF,A,S,H
RIKEN (SCSS Prototype)	0.03-0.06	1	250	300	600	1.5	0.3-1.5	RF,S
DESY (FLASH)	0.0045	0.15	1200	2000	984	2.73	1.23	RF,S
SLAC (LCLS)	0.00015	0.07	13600	3500	33x112	3	2.5	RF,S

MA - Microtron Accelerator
EA - Electrostatic Accelerator
SR - Electron Storage Ring
A - FEL Amplifier
K - FEL Klystron
O - FEL Oscillator

ERL - Energy Recovery Linear Accelerator
RF - Radio-Frequency Linear Accelerator
PW- Laser Plasma Wakefield Accelerator

S - Self-Amplified Spontaneous Emission (SASE)
H - High-Gain Harmonic Generation (HGHG)

Table 2: Proposed Free Electron Lasers (2010)

PROPOSED FELs	$\lambda(\mu m)$	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	
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 (RTM1)	5-100	10	50	20-100	3x33	6	2.0	ERL,O
Daresbury (ALICE)	4-12	0.6	35	53	40	2.7	0.7-1	RF,ERL
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
Novosibirsk (RTM)	2-11	20	98	100	4x36	9	1.6	ERL,O
Shanghai (SDUV-FEL)	0.35	2-8	100-140	100	360	2.5	1.0	RF,H
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 (2010)

PROPOSED FELs	λ(nm)	σ_z(ps)	E(GeV)	I(kA)	N	λ_0(cm)	K(rms)	
Shanghai (SUV-FEL)	88	2	0.28	0.40	360	2.5	1.025	RF,S
Glasgow (ALPHA-X)	30-850	0.1-0.3	0.10-1.0	1	200	1.5	0.5	PW,A
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	0.2-2.32	RF,S
ARC-EN-CIEL (LEL3)	8-40	0.1	1	0.2-1	350	3.0	2.4	RF,O
DESY (FLASH II)	4-80	0.15	0.5-1.2	2.5	12x64	3.14	0.5-2	RF,S,H
Trieste (FERMI-I)	4-80	0.5	0.9-1.5	0.5-0.8	1140	3.5	1.4	RF,H
Wisconsin (WiFEL)	2.3-6.9	0.1	1.7	1	788	3.3	0.74-1.9	RF,H
ARC-EN-CIEL (LEL1)	1.5-200 1.5-200	0.1-0.03 0.1-0.03	0.22-1 0.22-1	1.5 1.5	200 700	2.6 3	2.3 1.6	RF,H
BESSY (Soft X-ray)	1.2	0.08	2.3	3.5	1450	2.75	0.9	RF,S
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
Netherlands (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
ARC-EN-CIEL (LEL2)	0.5-1	0.1-0.03	0.8-1.2	2	500 500	2.6 1.8	2.3 2.2	RF,H
DESY (Euro XFEL)	0.4-1.6	0.08	17.5	5	4700	3.6	3.2	RF,S
ARC-EN-CIEL (LEL4)	0.2-2	0.05-0.03	3	1	700 1000	3.5 1.8	3.4 2.2	RF,H
Swiss (FEL-Athos) (FEL-Aramis)	0.7-7 0.1-0.7	0.02 0.02	2.1-3.5 2.1-5.8	3 3	1500 3000	4 1.5	0.7-2.7 0.85	RF,H RF,S
RIKEN (SPring8SCSS)	0.1	0.5	6-8	2	1500	1.5	1.3	RF,S
Pohang (PAL X-FEL)	0.06-0.1	0.05	10	3	4500	2	1.662	RF,S

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H - High-Gain Harmonic Generation (HGHG)

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 (ATF)	K. Batchelor et al., Nucl. Inst. and Meth. **A318**, 159 (1992).
BNL (HGHG)	A. Doyuran et al., Nucl. Inst. and Meth. **A475**, 260 (2001).
BNL (SDL FEL)	http://sdl.nsls.bnl.gov/
Bruyeres (ELSA)	P. Guimbal et al., Nucl. Inst. and Meth. **A341**, 43 (1994).
Darmstadt (FEL)	http://www.ikp.physik.tu-darmstadt.de/richter/fel/
DESY(FLASH)	http://flash.desy.de
Dortmund (FELICITAI)	http://www.delta.uni-dortmund.de/index.php?id=2&L=1
Dresden (U27-FELBE) (U100-FELBE)	http://www.fzd.de
Duke (OK-4, OK-5)	http://www.fel.duke.edu
Frascati (SPARC)	http://www.sparc.it
Himeji (LEENA)	T. Inoue et al., Nucl. Inst. and Meth. **A528**, 402 (2004).
JLab (IR, UV upgrade)	http://www.jlab.org/FEL
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)	http://accelconf.web.cern.ch/AccelConf/l00/papers/TH301.pdf
Nieuwegein (FELICE)	http://www.rijnhuizen.nl/felix
Nieuwegein (FELIX)	http://www.rijnhuizen.nl/felix
Nihon (LEBRA)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/MOPPH046.PDF http://www.lebra.nihon-u.ac.jp/ (Japanese Page)
Novosibirsk (RTM)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
Okazaki (UVSOR- II)	http://accelconf.web.cern.ch/AccelConf/a01/PDF/WEP014.pdf
Orsay (CLIO)	http://clio.lcp.u-psud.fr/
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)	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)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/FRAAU04.PDF
RIKEN (SCSS Prototype)	http://www.riken.jp/XFEL/eng/index.html
SLAC (LCLS)	http://www-ssrl.slac.stanford.edu/lcls/commissioning/documents/th3pbi01
Tallahassee (Big Light)	http://www.magnet.fsu.edu/usershub/scientificdivisions/emr/facilities/fel.html
Tokai (JAEA-FEL)	R. Hajima et al., Nucl. Inst. and Meth. **A507**, 115 (2003).
Tokyo (KHI-FEL)	M. Yokoyama et al., Nucl. Inst. and Meth. **A475**, 38 (2001).
Trieste (ELETTRA)	http://www.elettra.trieste.it/projects/euprog/fel
Tsukuba (ETLOK-II)	K.Yamada et al., Nucl. Inst. and Meth. **A528**, 268 (2004).
Tsukuba (ETLOK-III)	N. Sei et al., Optics Letters **34**, 1843 (2009).
UCLA-BNL (VISA)	A. Tremaine et al., Nucl. Inst. and Meth. **A483**, 24 (2002).
UCSB (FIR FEL)	http://sbfel3.ucsb.edu
UCSB (mm FEL)	http://sbfel3.ucsb.edu

Table 5: References and Websites for Proposed FELs

LOCATION (NAME)	Internet Site or Reference
ARC-EN-CIEL FEL	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/FRAAU01.PDF
Beijing (PKU-FEL)	http://accelconf.web.cern.ch/AccelConf/f06/PAPERS/TUAAU05.PDF
Berlin (Fritz Haber Inst.)	H. Bluem, Proceedings of FEL 2010. http://www.jacow.org
BESSY (Soft X-ray)	M. Abo-Bakr et al., Nucl. Inst. and Meth. **A483**, 470 (2002).
Daresbury (ALICE)	http://accelconf.web.cern.ch/AccelConf/FEL2009/papers/wepc39.pdf
DESY (FLASH II)	http://accelconf.web.cern.ch/accelconf/IPAC10/papers/tupe005.pdf
DESY (XFEL)	http://www.xfel.net
Glasgow (ALPHA-X)	http://phys.strath.ac.uk/alpha-x/
Harima (SUBARU)	http://epaper.kek.jp/a98/APAC98/6A004.PDF
India (CUTE-FEL)	http://www.rrcat.gov.in/technology/accel/maascd/abpl; http://accelconf.web.cern.ch/accelconf/f07/PAPERS/MOPPH074.PDF
JLab (JLAMP)	http://www.jlab.org/FEL
LBNL (NGLS)	http://accelconf.web.cern.ch/accelconf/IPAC10/papers/wepea067.pdf
Netherlands (ZFEL)	J. P. M. Beijers, Proceedings of FEL 2010. http://www.jacow.org
Nijmegen (THz-FEL)	http://accelconf.web.cern.ch/accelconf/FEL2009/papers/tupc84.pdf
Novosibirsk (RTM)	N. G. Gavrilov et al., Nucl. Inst. and Meth. **A575**, 54 (2007).
Novosibirsk (RTM1)	V. P. Bolotin et al., Nucl. Inst. and Meth. **A475**, II-37 (2001).
Pohang (PAL X-FEL)	http://accelconf.web.cern.ch/AccelConf/FEL2008/papers/tubau05.pdf
RIKEN (SPring8 SCSS)	http://www.riken.jp/XFEL/eng/index.html
Rome (SPARX 1)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/MOPPH058.PDF
Shanghai (SDUV-FEL)	Z. T. Zhao et al., Nucl. Inst. and Meth. **A528**, 591 (2004).
Swiss (FEL-Athos,Aramis)	http://fel.web.psi.ch/
Tokyo (FIR-FEL)	H. Koike et al., Nucl. Inst. and Meth. **A483**, II-15 (2002).
Trieste (FERMI I)	http://accelconf.web.cern.ch/accelconf/FEL2009/papers/mopc02.pdf http://www. elettra.trieste.it/FERMI
Turkey (TACIR I & II)	http://accelconf.web.cern.ch/AccelConf/e08/papers/mopc001.pdf; http://thm.ankara.edu.tr
Wisconsin (WiFEL)	www.wifel.wisc.edu