FREE ELECTRON LASERS IN 2006

W. B. Colson*, J. Blau, and A. Kampouridis
Physics Department, Naval Postgraduate School, Monterey CA 93943 USA

Abstract

Twenty-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 infrared, visible, UV, and x-ray wavelength regimes are listed and discussed.

The following tables list existing (Table 1) and proposed (Table 2) relativistic free electron lasers (FELs) in 2006. A location or institution, followed by the FEL's name in parentheses, identifies each FEL; references are listed in Tables 3 and 4. Another good site for FEL references 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 FEL 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 can be 3 to 5 times shorter or longer than the electron pulse depending on the optical cavity Q, the FEL desynchronism, and the FEL gain. The optical pulse can be up to 10 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 energy E in MeV and peak current I in Amperes provided by the accelerator 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 $K = eB\lambda_0/2\pi mc^2$ in 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. Note that the range of values for N, λ_0, and K are much smaller than for the other parameters, indicating that most undulators are similar. Some exceptions are the long undulators containing many periods N that are being developed for the x-ray FEL amplifiers. Only a few of the FELs use the klystron undulator at present, and the rest use the conventional periodic undulator. Most of the undulators are configured to have linear polarization. The FEL resonance condition, $\lambda = \lambda_0(1+K^2)/2\gamma^2$ where γ is the relativistic Lorentz factor, provides a relationship that can be used to relate K to λ, E, and λ_0. The middle entry of the last column lists the accelerator type (RF for Radio Frequency Linear Accelerator, MA for Microtron Accelerator, SR for Storage Ring, EA for Electrostatic Accelerator), and the FEL type (A for FEL Amplifier, O for FEL Oscillator, S for SASE FEL, H for a high-gain high harmonic HGHG FEL). Most of the FELs are oscillators, but recent progress has resulted in short wavelength FELs using SASE (Stimulated Amplification of Spontaneous Emission) and high-gain harmonic generation (HGHG).

For the conventional undulator oscillator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral bandwidth, 1/(2N), or $P \approx EI/(8eN)$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially greater. The average FEL power is determined by the duty cycle, or spacing between the electron micropulses, and is typically many orders of magnitude lower than the peak power. The Jlab infrared FEL has now reached an average power of 10 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 mode waist radius of $w_0 \approx N^{1/2}\gamma\lambda/\pi$. The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

This year the DESY FLASH FEL has reached the shortest wavelength ever for an FEL, $\lambda \approx 0.013$ μm. There are several other new lasings: Rossendorf (U-100) at $\lambda \approx 20$-150 μm, RIKEN (SCSS Prototype) at $\lambda \approx 0.049$ μm, and BNL (SDL FEL) at $\lambda \approx 0.198$ μm. New FEL lasings are highlighted in bold in Table 1.

ACKNOWLEDGMENTS

The authors are grateful for support from ONR, NAVSEA, and the JTO.

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[*] Corresponding Author: 831-656-2765, Colson@nps.edu

Table 1: Free Electron Lasers (2006)

EXISTING FELs	**λ(μm)**	**σ_z(ps)**	**E(MeV)**	**I(A)**	**N**	**λ_0(cm)**	**K(rms)**	
Italy (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	RF,O
Korea (KAERI-FEL)	97-1200	25	4.3-6.5	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
UCLA-Kurchatov	16	3	13.5	80	40	1.5	1	RF,A
LANL (RAFEL)	15.5	15	17	300	200	2	0.9	RF,O
Stanford (FIREFLY)	15-80	1-5	15-32	14	25	6	1	RF,O
Rossendorf (U-100)	**15-150**	**0.3-10**	**15**	**240**	**38**	**10**	**2.7**	**RF,O**
UCLA-Kurchatov-LANL	12	5	18	170	100	2	0.7	RF,A
Beijing (BFEL)	5-20	4	30	15-20	50	3	1	RF,O
Dresden (ELBE)	3-22	1-10	34	30	2x34	2.73	0.3-0.7	RF,O
Korea (KAERI HP FEL)	3-20	10-20	20-40	30	30x2	3.5	0.5-0.8	RF,O
Jlab (IR upgrade)	0.7-10	0.1	120	400	29	5.5	3	RF,O
Darmstadt (FEL)	6-8	2	25-50	2.7	80	3.2	1	RF,O
BNL (HGHG)	5.3	6	40	120	60	3.3	1.44	RF,A
Osaka (iFEL1)	5.5	10	33.2	42	58	3.4	1	RF,O
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
Duke (MARKIII)	2.7-6.5	3	31-41.5	20	47	2.3	1	RF,O
Stanford (SCAFEL)	3-13	0.5-12	22-45	10	72	3.1	0.8	RF,O
Orsay (CLIO)	3-53	0.1-3	21-50	80	38	5	1.4	RF,O
Vanderbilt (FELI)	2.0-9.8	0.7	43	50	52	2.3	1.3	RF,O
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1	RF,O
Nihon (LEBRA)	0.9-6.5	<1	58-100	10-20	50	4.8	0.7-1.4	RF,O
UCLA-BNL (VISA)	0.8	0.5	70.9	250	220	1.8	1.2	RF,S
BNL (ATF)	0.6	6	50	100	70	0.88	0.4	RF,O
Duke (OK-5)	0.45	0.1-10	270-800	35	2x32	12	0-4.75	SR,O
Dortmund (FELICITAI)	0.42	50	450	90	17	25	2	SR,O
BNL (SDL FEL)	**0.2-1.0**	**0.5-1**	**100-250**	**300-400**	**256**	**3.9**	**0.8**	**RF,A,S,H**
Orsay (Super-ACO)	0.3-0.6	15	800	0.1	2x10	13	4.5	SR,O
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
Okazaki (UVSOR)	0.2-0.6	6	607	10	2x9	11	2	SR,O
Tsukuba (NIJI-IV)	0.2-0.6	14	310	10	2x42	7.2	2	SR,O
Italy (ELETTRA)	0.2-0.4	28	1000	150	2x19	10	4.2	SR,O
Duke (OK-4)	0.193-2.1	0.1-10	1200	35	2x33	10	0-4.75	SR,O
ANL (APSFEL)	0.13	0.3	399	400	648	3.3	2.2	RF,S
RIKEN(SCSS Prototype)	**0.05**	**1**	**250**	**800**	**600**	**1.5**	**1.3**	**RF,S**
DESY (FLASH)	**0.013**	**0.025**	**700**	**2000**	**984**	**2.73**	**0.81**	**RF,S**

Table 2: Proposed Free Electron Lasers (2006)

PROPOSED FELs	**λ(µm)**	**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
Netherlands (TEUFEL)	180	20	6	350	50	2.5	1	RF,O
Romania (NILPRP)	60	10	7	2	100	2	0.4	RF,O
Dresden (ELBE)	20-150	1-10	20-40	30	38	10	0.3-2.7	RF,O
Novosibirsk (RTM1)	5-100	10	50	20-100	3x33	6	2	RF,O
Daresbury (4GLS-IRFEL)	3-75	0.5-1	18-50	70	27	2.7	2	RF,O
Novosibirsk (RTM)	2-11	20	98	100	4x36	9	1.6	RF,O
Frascati (SPARC)	0.533	0.1	142	500	6x71	3	1.3	RF,S
Hawaii (FEL)	0.3-3	2	100	500	84	2.4	1.2	RF,O
Jlab (UV FEL)	0.25-1	0.2	160	270	60	3.3	1.3	RF,O
Harima (SUBARU)	0.2-10	26	1500	50	33,65	16,32	8	SR,O
Shanghai (SDUV-FEL)	0.5-0.088	1	300	400	400	2.5	1.025	RF,O
Daresbury (4GLS-VUV)	0.4-0.1	0.1-1	600	300	150	5	2	RF,O
Daresbury (4GLS-XUV)	0.1-0.01	0.1-1	750-950	1500	1000	4.5	1-3.5	RF,S
Frascati (COSA)	0.08	10	215	200	400	1.4	1	RF,O
DESY (FLASH)	0.006	0.17	1000	2500	981	2.73	0.9	RF,S
Italy (SPARX)	0.0015	0.1	2500	2500	1000	3	1.2	RF,S
BESSY (Soft X-ray)	0.0012	0.08	2300	3500	1450	2.75	0.9	RF,S
Trieste (FERMI)	0.001-0.1	0.1	1200	500-2500	1140	3.5	1.2	RF,S
Pohang (PAL X-FEL)	0.0003	0.1	3000	4000	6000	1.5	1.1	RF,S
MIT (Bates X-Ray FEL)	0.0003	0.05	4000	1000	1500	1.8	2	RF,S
SLAC (LCLS)	0.00015	0.07	14350	3400	3328	3	3.7	RF,S
DESY (XFEL)	0.0001	0.08	17500	5000	4700	3.6	3.2	RF,S
RIKEN (SPring8 SCSS)	0.0001	0.5	8000	2000	1500	1.5	1.3	RF,S

Table 3: References and Websites for Existing FELs

EXISTING FELs	**Internet Site or Reference**
ANL (APSFEL)	J. W. Lewellen et. al., NIM **A483**, 40 (2002).
Beijing (BFEL)	http://bfel.ihepa.ac.cn
BNL (SDL FEL)	http://www.nsls.bnl.gov/facility/Accelerator/DUVFEL
BNL (ATF)	K. Batchelor et. al., NIM **A318**, 159 (1992).
BNL (HGHG)	A. Doyuran et. al., NIM **A475**, 260 (2001).
BNL (VISA)	A. Tremaine et. al., NIM **A483**, 24 (2002).
Bruyeres (ELSA)	P. Guimbal et. al., NIM **A341**, 43 (1994).
Darmstadt (FEL)	http://linaxa.ikp.physik.tu-darmstadt.de/richter/fel
DESY(FLASH)	http://flash.desy.de
Dortmund (FELICITAI)	http://www.delta.uni-dortmund.de/pub/fel/FEL.html
Dresden (ELBE)	http://www.fz-rossendorf.de
Duke (MARKIII)	http://www.fel.duke.edu/lightsources/mk3.html
Duke (OK-4, OK-5)	http://www.fel.duke.edu
Himeji (LEENA)	http://www.lasti.himeji-tech.ac.jp/NS/LEENA/LEENA_HP.html
Italy (ELETTRA)	http://www.elettra.trieste.it/projects/euprog/fel
Italy (FEL-CAT)	A. Doria et. al, Phys. Rev. Lett. **80**, 2841 (1998).
Jlab (IR upgrade)	http://www.jlab.org/FEL
Korea (KAERI HP FEL)	http://www.kaeri.re.kr/fel/index.php
Korea (KAERI-FEL)	http://www.kaeri.re.kr/fel/index.php
LANL (RAFEL)	http://www.lanl.gov/orgs/ibdnew/usrfac/userfac03.html
Nieuwegein (FELIX)	http://www.rijnh.nl/n4/n3/f1234.htm
Nihon (LEBRA)	http://www.lebra.nihon-u.ac.jp
Novosibirsk (RTM)	http://www.inp.nsk.su
Okazaki (UVSOR)	http://uvsor-ntserver.ims.ac.jp
Orsay (CLIO)	http://www.lure.u-psud.fr/CLIO.HTM
Orsay (Super-ACO)	M. E. Couprie et. al., NIM **A407**, 215-220 (1998).
Osaka (FELI4)	T. Takii et. al., NIM **A407**, 21-25 (1998).
Osaka (iFEL1)	http://www.fel.eng.osaka-u.ac.jp/english/index_e.html
Osaka (iFEL2)	http://www.fel.eng.osaka-u.ac.jp/english/index_e.html
Osaka (iFEL3)	http://www.fel.eng.osaka-u.ac.jp/english/index_e.html
Osaka (ILE/ILT)	N. Ohigashi et. al., NIM **A375**, 469 (1996).
Osaka (ISIR)	http://www.ei.sanken.osaka-u.ac.jp
RIKEN(SCSS Prototype)	http://www-xfel.spring8.or.jp
Rossendorf (U-100)	http://www.fz-rossendorf.de
Stanford (FIREFLY)	K. W. Berryman and T. I. Smith, NIM **A375**, 6 (1996).
Stanford (SCAFEL)	H. A. Schwettman et. al., NIM **A375**, 662 (1996).
Tokai (JAEA-FEL)	R. Hajima et. al., NIM **A507**, 115 (2003).
Tokyo (KHI-FEL)	M. Yokoyama et. al., NIM **A475**, 38 (2001).
Tsukuba (NIJI-IV)	K.Yamada et. al., NIM **A475**, 205 (2001).
UCLA-Kurchatov	http://pbpl.physics.ucla.edu
UCLA-Kurchatov-LANL	http://pbpl.physics.ucla.edu
UCSB (FIR FEL)	http://sbfel3.ucsb.edu
UCSB (mm FEL)	http://sbfel3.ucsb.edu
Vanderbilt (FELI)	http://www.vanderbilt.edu/fel

Table 4: References for Proposed FELs

PROPOSED FELs	**References for Proposed FELs**
BESSY (Soft X-ray)	M. Abo-Bakr et. al., Nucl. Inst. and Meth. **A483**, 470 (2002); Tsukuba Mo-P-07,Mo-P-08,We-P-51 (Sept 2003).
Daresbury (4GLS)	M. W. Poole and B. W. J. McNeil, Nucl. Inst. and Meth. **A507**, 489 (2003).
DESY (XFEL)	http://xfel.desy.de
DESY (FLASH)	http://flash.desy.de
Dresden (ELBE)	http://www.fz-rossendorf.de
Dresden (ELBE)	P. Michel et. al., FEL2004 (2004) p. 8, http://www.JACoW.org.
Frascati (COSA)	F. Ciocci et. al., A. Torre, IEEE J.Q.E. **31**, 1242 (1995).
Frascati (SPARC)	A. Renieri et. al., Nucl. Inst. and Meth. **A507**, 507 (2003).
Harima (SUBARU)	S. Miyamoto et. al., Report of the Spring-8 International Workshop on 30 m Long Straight Sections, Kobe, Japan (August 9, 1997).
Italy (SPARX)	A. Renieri et. al., Nucl. Inst. and Meth. **A507**, 507 (2003).
Jlab (UV FEL)	S. Benson et. al., Nucl. Inst. and Meth. **A429**, 27-32 (1999).
MIT (Bates X-Ray FEL)	http://filburt.lns.mit.edu/xfel
Netherlands (TEUFEL)	J. I. M. Botman et. al., Nucl. Inst. and Meth. **A341**, 402 (1994).
Novosibirsk (RTM)	N. G. Gavrilov et. al., Status of Novosibirsk High Power FEL Project, SPIE Proceedings, vol. **2988**, 23 (1997); N. A. Vinokurov et. al., Nucl. Inst. and Meth. **A331**, 3 (1993).
Novosibirsk (RTM1)	V. P. Bolotin et. al., Nucl. Inst. and Meth. **A475**, II-37 (2001).
Pohang (PAL X-FEL)	pal.postech.ac.kr/kor
RIKEN (SPring8 SCSS)	T. Shintake et. al., Nucl. Inst. and Meth. A507, 382 (2003); http://www-xfel.spring8.or.jp
Rocketdyne/Hawaii (FEL)	R. J. Burke et al, Proc. SPIE: Laser Power Beaming, Los Angeles, Jan. 27-28, 1994, Vol **2121**.
Romania (NILPRP)	Proceedings of FEL 2006; www.jacow.org
Shanghai (SDUV-FEL)	Z. T. Zhao et. al, Nucl. Inst. and Meth. **A528**, 591 (2004).
SLAC (LCLS)	M. Cornacchia, Proc. SPIE 2998, 2-14 (1997); LCLS Design Study Report, SLAC R-521 (1998).
Tokyo (FIR-FEL)	H. Koike et. al., Nucl. Inst. and Meth. **A483**, II-15 (2002).
Trieste (FERMI)	C. J. Bocchetta et. al., Nucl. Inst. and Meth. **A507**, 484 (2003); Tsukuba We-P-53 (Sept 2003).