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Colson, W.B.

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## Short wavelength free electron lasers in 1996

W.B. Colson

*Physics Department, Naval Postgraduate School, Monterey, CA 93943, USA*

A list of the existing and proposed relativistic free electron lasers (FELs) in 1996 is given in Table 1. The top part of the table contains existing FELs. These are substantially complete experiments that may not be operating at the present time. The bottom part of the table lists proposed FELs. Each FEL, existing or proposed, is identified by a location, or institution, followed by the FEL's name in parentheses. The table can be found at <http://www.physics.nps.navy.mil/fel.html>. Additions and corrections can be transmitted to us for inclusion in the table in future.

The first column of the table lists the operating wavelength, or wavelength range, in micrometers ( $\mu\text{m}$ ). The large range of operating wavelengths, six orders of magnitude, indicates the flexible design characteristics of the FEL mechanism. The second column describes the electron pulse length divided by the speed of light  $c$ , and ranges from CW to short picosecond pulse time scales. The expected optical pulse length can be 3-5 times shorter or longer than the electron pulse depending on the optical cavity  $Q$ , the FEL desynchronization, and the FEL gain. Most FEL oscillators produce an optical spectrum

that is Fourier transform limited by the optical pulse length.

The electron beam energy  $E$  and peak current  $I$  provided by the accelerator are listed in the third and fourth columns in units of MeV and amperes. The accelerator type is listed as the first entry in the last column with a code such as RF for the radio-frequency linac. While there are a variety of accelerators used, about 75% are RF and about 13% are electron storage rings. Storage rings tend to be used for the short wavelength applications, while the electrostatic accelerators provide longer wavelengths.

The next three columns list the number of undulator periods  $N$ , the undulator wavelength  $\lambda_0$  in centimeters, and the undulator parameter  $K = e\bar{B}\lambda_0/2\pi mc^2$  where  $e$  is the electron charge magnitude,  $\bar{B}$  the RMS undulator field strength, and  $m$  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  $N$ ,  $\lambda_0$  and  $K$  are much smaller than for the other parameters indicating that most undulators are similar. Only about 13% of the FELs use the klystron undulator,

Table 1  
Relativistic short wavelength free electron lasers (1996)

| FEL                   | $\lambda$<br>( $\mu\text{m}$ ) | $\sigma_z$       | $E$<br>(MeV) | $I$<br>(A) | $N$ | $\lambda_0$<br>(cm) | $K$<br>(RMS) | Acc., Type [Ref.] <sup>†</sup> |
|-----------------------|--------------------------------|------------------|--------------|------------|-----|---------------------|--------------|--------------------------------|
| <i>Existing FELs:</i> |                                |                  |              |            |     |                     |              |                                |
| UCSB (mm FEL)         | 340                            | 25 $\mu\text{s}$ | 6            | 2          | 42  | 7.1                 | 0.7          | EA, O [1]                      |
| Stanford (FIRFEL)     | 80-200                         | 15 ps            | 4            | 8          | 50  | 1                   | 0.7          | RF, O [2]                      |
| Himeji (LEENA)        | 65                             | 10 ps            | 5.4          | 10         | 50  | 1.6                 | 1            | RF, O [3]                      |
| UCSB (FIR FEL)        | 60                             | 25 $\mu\text{s}$ | 6            | 2          | 150 | 2                   | 0.1          | EA, O [1]                      |
| Osaka (ILE/ILT)       | 47                             | 3 ps             | 9            | 50         | 50  | 0.66                | 0.5          | RF, O [4]                      |
| Tokyo (UT-FEL)        | 43                             | 10 ps            | 13           | 20         | 40  | 4                   | 0.7          | RF, O [5]                      |
| Nieuwegein (FELIX1)   | 5-35                           | 5 ps             | 25           | 50         | 38  | 6.5                 | 1.2          | RF, O [6]                      |
| Osaka (ISIR)          | 40                             | 30 ps            | 17           | 50         | 32  | 6                   | 1            | RF, O [7]                      |
| Bruyeres (ELSA)       | 20                             | 30 ps            | 18           | 100        | 30  | 3                   | 0.8          | RF, O [8]                      |
| Nieuwegein (FELIX2)   | 20-110                         | 5 ps             | 45           | 50         | 38  | 6.5                 | 1.8          | RF, O [6]                      |
| Stanford (FIREFLY)    | 15-65                          | 1-5 ps           | 15-32        | 14         | 25  | 6                   | 1            | RF, O [9]                      |
| Frascati (LISA)       | 15                             | 7 ps             | 25           | 5          | 50  | 4.4                 | 1            | RF, O [10]                     |
| Grumman (CIRFEL)      | 12-21                          | 5 ps             | 9-14         | 150        | 73  | 1.36                | 0.2          | RF, O [11]                     |

Table 1 (continued)

| FEL                   | $\lambda$<br>( $\mu\text{m}$ ) | $\sigma_z$ | $E$<br>(MeV) | $I$<br>(A) | $N$    | $\lambda_0$<br>(cm) | $K$<br>(RMS) | Acc., Type [Ref.] |
|-----------------------|--------------------------------|------------|--------------|------------|--------|---------------------|--------------|-------------------|
| Beijing (IHEP)        | 10                             | 4 ps       | 30           | 14         | 50     | 3                   | 1            | RF, O [12]        |
| Orsay (CLIO)          | 3–53                           | 0.2–4 ps   | 21–50        | 80         | 38     | 5                   | 1.4          | RF, O [13]        |
| LANL (AFEL)           | 4–6                            | 10 ps      | 15           | 200        | 24     | 1                   | 0.3          | RF, O [14]        |
| Osaka (FELI)          | 5.5                            | 10 ps      | 33.2         | 42         | 58     | 3.4                 | 1            | RF, O [15]        |
| Darmstadt (IR-FEL)    | 5                              | 2 ps       | 40           | 2.7        | 80     | 3.2                 | 1            | RF, O [16]        |
| Stanford (SCAFEL)     | 3–13                           | 0.7 ps     | 22–45        | 10         | 72     | 3.1                 | 0.8          | RF, O [17]        |
| Vanderbilt (FELI)     | 2.2–9.6                        | 2 ps       | 43           | 50         | 52     | 2.3                 | 1            | RF, O [18]        |
| Duke (MarkIII)        | 3                              | 3 ps       | 44           | 20         | 47     | 2.3                 | 1            | RF, O [19]        |
| Osaka (FELI)          | 2–6                            | 2 ps       | 170          | 100        | 50     | 6                   | 1.3          | RF, O [4]         |
| Osaka (FELI2)         | 1.88                           | 10 ps      | 68           | 42         | 78     | 3.8                 | 1            | RF, O [15]        |
| BNL (ATF)             | 0.5                            | 6 ps       | 50           | 100        | 70     | 0.88                | 0.4          | RF, O [20]        |
| Tsukuba (NIJI-IV)     | 0.35                           | 160 ps     | 300          | 5          | 2 × 42 | 7.2                 | 2            | SR, O [21]        |
| Orsay (Super-ACO)     | 0.35                           | 20 ps      | 20           | 0.1        | 2 × 10 | 13                  | 4            | SR, O [22]        |
| Okazaki (UVSOR)       | 0.3                            | 6 ps       | 500          | 5          | 2 × 8  | 11                  | 2            | SR, O [23]        |
| BNL (ATF-UV)          | 0.25                           | 6 ps       | 70           | 100        | 70     | 0.88                | 0.4          | RF, O [20]        |
| <i>Proposed FELs:</i> |                                |            |              |            |        |                     |              |                   |
| Florida (CREOL)       | 200–600                        | CW         | 1.7          | 0.2        | 185    | 0.8                 | 0.15         | EA, O [25]        |
| Netherlands (TEUFEL)  | 180                            | 20 ps      | 6            | 350        | 50     | 2.5                 | 1            | RF, O [26]        |
| Rutgers (IRFEL)       | 140                            | 25 ps      | 38           | 1.4        | 50     | 20                  | 1            | MA, O [27]        |
| Moscow (Lebedev)      | 100                            | 20 ps      | 30           | 0.25       | 35     | 3.2                 | 0.8          | MA, O [28]        |
| Tokai (SCARLET)       | 40                             | 40 ps      | 15           | 10         | 62     | 3.3                 | 1            | RF, O [4]         |
| LBL (IRFEL)           | 3–50                           | 30 ps      | 55           | 60         | 40     | 5                   | 1            | RF, O [29]        |
| CEBAF (IRFEL)         | 2.5–25                         | 1.5 ps     | 200          | 36         | 2 × 12 | 20                  | 4            | RF, O [30]        |
| Boeing (kWFEL)        | 0.2–4                          | 7 ps       | 120          | 500        | 220    | 2.18                | 1.31         | RF, O [31]        |
| Stanford (FEL)        | 10                             | 4 ps       | 24           | 25         | 52     | 2.6                 | 0.9          | RF, O [32]        |
| UCLA (IRFEL)          | 10                             | 2 ps       | 20           | 200        | 40     | 1.5                 | 1            | RF, A [33]        |
| Novosibirsk (RTM)     | 2–11                           | 20 ps      | 98           | 100        | 4 × 36 | 9                   | 1.6          | RF, O [34]        |
| BNL (HGHG)            | 3.4                            | 10 ps      | 30           | 110        | 83     | 1.8                 | 1.4          | RF, A [35]        |
| CEBAF (UVFEL)         | 0.16–1                         | 0.2 ps     | 200          | 270        | 72     | 3.3                 | 1.3          | RF, O [30]        |
| Rocketdyne (FEL)      | 0.84                           | 3 ps       | 90           | 500        | 160    | 2.4                 | 1.4          | RF, MOPA [36]     |
| Dortmund (DELTA)      | 0.4                            | 50 ps      | 500          | 90         | 17     | 25                  | 2            | SR, O [37]        |
| Harima (HIT)          | 0.28                           | 100 ps     | 500          | 3          | 170    | 1.8                 | 4.2          | SR, O [4]         |
| BNL (DUVFEL)          | 0.075                          | 6 ps       | 310          | 300        | 682    | 2.2                 | 1.5          | RF, A [38]        |
| Frascati (COSA)       | 0.08                           | 10 ps      | 215          | 200        | 400    | 1.416               | 1            | RF, O [39]        |
| Duke (Ring)           | 0.05                           | 10 ps      | 1000         | 350        | 2 × 33 | 10                  | 1.7          | SR, O [40]        |
| DESY (TTF1)           | 0.042                          | 0.8 ps     | 390          | 500        | 490    | 2.73                | 0.9          | RF, A [41]        |
| DESY (TTF2)           | 0.006                          | 0.15 ps    | 1000         | 2500       | 981    | 2.73                | 0.9          | RF, A [41]        |
| SLAC (LCLS1)          | 0.004                          | 0.3 ps     | 7000         | 2500       | 723    | 8.3                 | 4.4          | RF, A [42]        |
| SLAC (LCLS2)          | 0.00045                        | 0.15 ps    | 15 000       | 5000       | 1000   | 4                   | 4.5          | RF, A [42]        |
| SLAC (LCLS3)          | 0.00015                        | 0.25 ps    | 15 000       | 5000       | 1833   | 3                   | 2.7          | RF, A [42]        |
| DESY (TESLA)          | 0.0001                         | 0.08 ps    | 35 000       | 5000       | 1200   | 5                   | 4.2          | RF, A [41]        |

RF – RF Linac Accelerator; MA – Microtron Accelerator; SR – Electron Storage Ring; EA – Electrostatic Accelerator; A – FEL Amplifier; O – FEL Oscillator; MOPA – Master-Oscillator Power-Amplifier.

none use the tapered undulator at present, and the rest use the conventional periodic undulator. The FEL resonance condition,

$$\lambda = \frac{\lambda_0(1 + K^2)}{2\gamma^2},$$

where  $\gamma$  is the relativistic Lorentz factor  $\gamma = E/mc^2$ , provides a relationship that can be used to derive  $K$  from  $\lambda$ ,

$E$  and  $\lambda_0$ . The middle entry of the last column lists the FEL type: “O” for oscillator, “A” for amplifier, etc. About 17% of the FELs are amplifiers, while the rest are FEL oscillators. A reference describing the FEL is provided at the end of each line entry.

For the conventional undulator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral

bandwidth,  $1/4N$ , or  $P \approx EI/4eN$ . 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 more. The average FEL power is determined by the duty cycle, or spacing between electron pulses, and is generally many orders of magnitude lower than the peak power.

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  $z_0 \approx L/\sqrt{12}$  and has a mode waist radius of  $w_0 \approx \sqrt{N} \gamma\lambda/\pi$ . The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

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