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FELI Linac for IR– and UV–FEL Facilities

T. Tomimasu, Y. Morii, S. Abe, A. Koga, Y. Miyauchi, T. Keishi, E. Nishimura, K. Saeki, S. Sato, A. Kobayashi, A. Zakou, E. Tongu and A. Nagai

Free Electron Laser Research Institute, Inc. (FELI)
4547–44, Tsuda, Hirakata, Osaka, 573–01, Japan
TEL:0720–96–0414 FAX:0720–96–0421

FELI linac and IR–FEL facilities are now under construction and electron beams of 30–75MeV will be used for FIR– and IR–FEL experiments in this summer. It is composed of a 5–MeV electron injector and seven ETL type accelerating waveguides with a length of 2.93m ($2\pi/3$ mode, linearly tapered type). The injector consists of a 150–kV DC thermoionic triode gun operated by a 178.5–MHz and 500–ps pulser, a 714–MHz prebuncher (SHB), and a 2856–MHz standing wave type buncher (SWB). The linac is operated in three modes of 24 μs, 12.5 μs and 0.5 μs. With a choice of three modes, the maximum beam loaded energy can be changed from 165 MeV to 288 MeV.

The linac beam is sent to four vertical type undulators using S–type BT systems installed at 30–MeV, 75–MeV, 120–MeV, and 165–MeV sections at a 24–μs pulse beam load. The beam, once used for lasing at 30–MeV section or at 75–MeV section, can be bent back to the following accelerating waveguide and is reaccelerated and reused for lasing. Parameters of four undulators and intended FEL applications are shown.

FEL spectral widths and wavelength limitations are also reviewed and discussed for 0.3 μm FEL oscillations FELI is aiming at by the end of 1996.

Keywords: FEL, electron injector, 500–ps grid pulser, linear accelerator, S–type beam transport system, reacceleration, spectral width, wavelength limitation

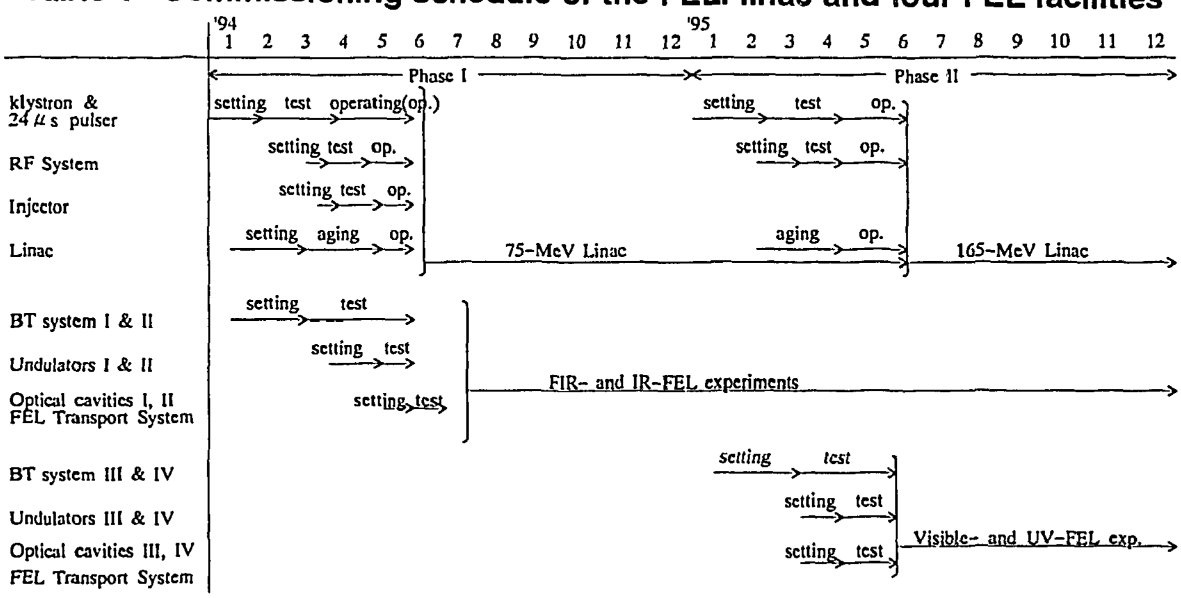
1. Introduction

A number of approaches have been proposed for the generation of UV and short wavelength FELs[1,2,3]. One of the key technologies is preserving the emittance of high–current and long–pulse electron beam low from a gun to the end of the linac, and further to an undulator. Of several candidate electron guns at the present time, a high DC voltage thermoionic triode gun is the best choice for the capability of emitting intense microbunches with a low emittance of several mm•mrad at a repetition rate of 1 GHz, during a macropulse of 20 μs[4].

Another technology keeping the high-current and long-pulse electron beam in the smaller-energy spread depends on the development of stably operable long-pulsed klystrons and their modulators being capable of driving them very stably. Since the FEL gain is getting smaller for the shorter wavelength FELs, a considerably long-pulse beam is necessary to reach saturation of UV-FELs and further to improve the FEL generation efficiency.

Therefore, we have tried several attempts for the FELI linac; the first one is 0.5-ns bunched beam injection from the gun, the second one is 24-μs beam acceleration using 24-μs flat top RF pulses, the third one is S-type beam transport systems for four vertical type undulators, and the fourth one is reacceleration of beams once used for lasing and reusing for lasing. These attempts are also reported in this paper. The commissioning schedule of the FELI linac and four FEL facilities is shown in Table 1.

Table 1 Commissioning schedule of the FELI linac and four FEL facilities



2. 5-MeV Electron Injector

The layout of a 5-MeV electron injector is shown in Fig. 1. The injector has been installed at FELI this March. It is composed of a 150-kV thermoionic triode gun, a 714-MHz prebuncher, and a 2856-MHz standing wave type buncher. The gun is a Pierce type gridded gun with a thermoelectronic dispenser cathode (EIMAC Y646B model). A cathode voltage of 150 kV for the gun was chosen because of easy operation in air without a tank filled with SF_6 gas. The gun is triggered by a 178.5-MHz and 500-ps pulser (Kentech Instruments, Ltd., England). In the subnano-pulse operation, it can be expected that an emittance of pulsed beam from the gun is less than 5π mm•mrad at 1.6A[4]. The characteristics of the gun emission recently measured is shown in Fig. 2. The emittance of the 0.5-ns beam from the gun is not measured yet but the emission current is 2.3A at the anode voltage of 117kV.

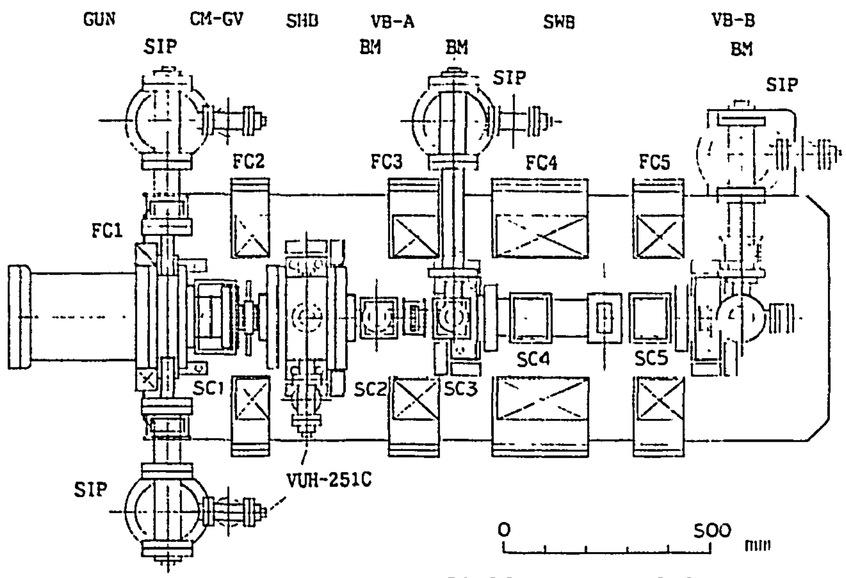


Fig. 1 A 5-MeV electron Injector

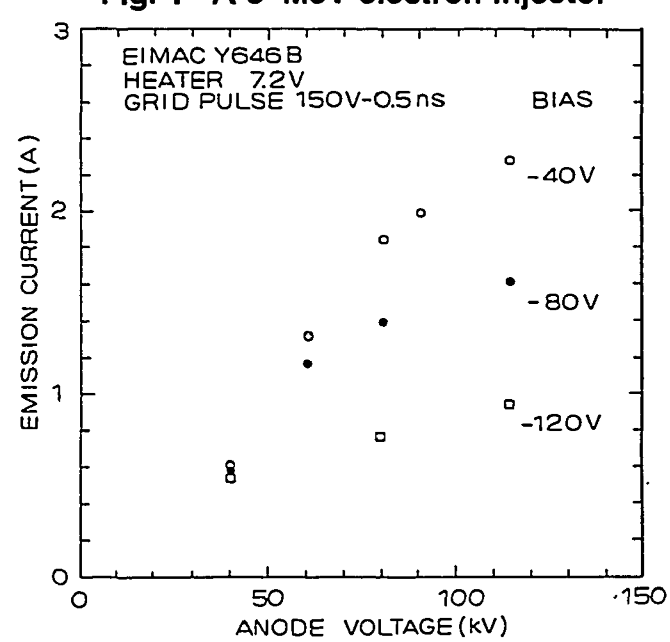


Fig. 2 Anode voltage - emission current characteristics of a gun triggered by a 500-ps grid pulser

The 714-MHz prebuncher acts as a subharmonic buncher (SHB) and is made from stainless steel to reduce the influence of a substantial rf field introduced in the cavity by the subnano-beam current from the gun. The rf frequency of 714 MHz is chosen 1) to make the cavity as compact as possible, 2) to meet the short bunch (<0.5ns) mode operation of the gun, and 3) to coincide the micropulse FEL beam with a micropulse YLF laser generated with a frequency of 2856 MHz/2^n(n is an integer). The SHB will be powered

Table 2 Main Parameters of the FELI linac injector

Gun	*Type*	*Thermoionic triode*
	Energy	*≦150 keV*
	Micropulse	*0.4~0.5 ns*
	Microcharge	*1.2 nC*
	Normalized emittance	*<10 π mm mrad*
	Macropulse	*≦24 μs*
	Repetition frequency	*1~10 Hz*
Prebuncher	*Type*	*Re–entrant cavity*
	Frequency	*714 MHz*
	Q–Value	*~2000*
	Peak field	*~50 kV*
Buncher	*Type*	*Standing wave*
	Length	*~49 cm*
	Energy	*~5 MeV for 2–MW rf*
	Energy spread (FWHM)	*<130 keV*

3. Linac and FEL Facilities

The regular sections of the FELI linac are composed of seven ETL type accelerating waveguides with a length of 2.93m ($2\pi/3$ mode, linearly tapered type)[6]. A set of steering coils, focusing coils, quadrupole magnets, optical and core monitors for beam diagnosis, and a sputter ion pump, are installed at each accelerating waveguide. The length of the injector and regular sections including bending sections for BT systems is 46m. The buncher and these accelerating waveguides will be powered by two klystrons (E3729, 2856MHz, total 48MW, 24-μs flat top rf pulses). Fig. 4 shows a schematic layout of the FELI linac including rf systems and four vertical type undulators.

The klystron used here is a klystron E3729 manufactured by Toshiba Corp. E3729 is a modified version of E3712. Since the latter is usually used in the short pulse mode (4 μs-80MW, 50pps), the test operation has been done at a long pulse mode of 24μs last December. The linac will be operated in the following modes, that is, 1) 24-μs mode, 2) 12.5-μs mode, and 3) 0.5-μs mode, in which the beam is used for the injection to storage rings and slow positron generations. With a choice of three modes, the maximum accelerated energy of a loaded beam can be changed from 165MeV (185MeV) to 288MeV

(310 MeV). The energy in parenthesis is the maximum energy at no beam load.

The klystron is powered by a pulse-forming-network (pfn) modulator including a stack of thirty optical thyristors (Toshiba SL1500GX22) combined with a saturable inductor, and a pulse transformer. The pfn consists of four-parallel lines to optimize the pulse flatness like FELIX[7]. The pfn signal is fed to the klystron cathode by means of a 1:15 pulse transformer. The cathode voltage stability of the order of 0.1% has been realized for keeping an rf power level to be 0.2%. Details of the rf system for the FELI linac is presented in this symposium.

KLYSTRON POWER

pulse length	KLY1, KLY2	P1	P2	Ea	Eb	Ec	Ed
24.0 μs	24MW	12.0MW	6.0 MW	30MeV	75MeV	120MeV	165MeV
12.5 μs	34MW	17.0MW	8.5 MW	39MeV	90MeV	142MeV	195MeV
0.5 μs	70MW	35.0MW	17.5 MW	55MeV	132MeV	208MeV	288MeV

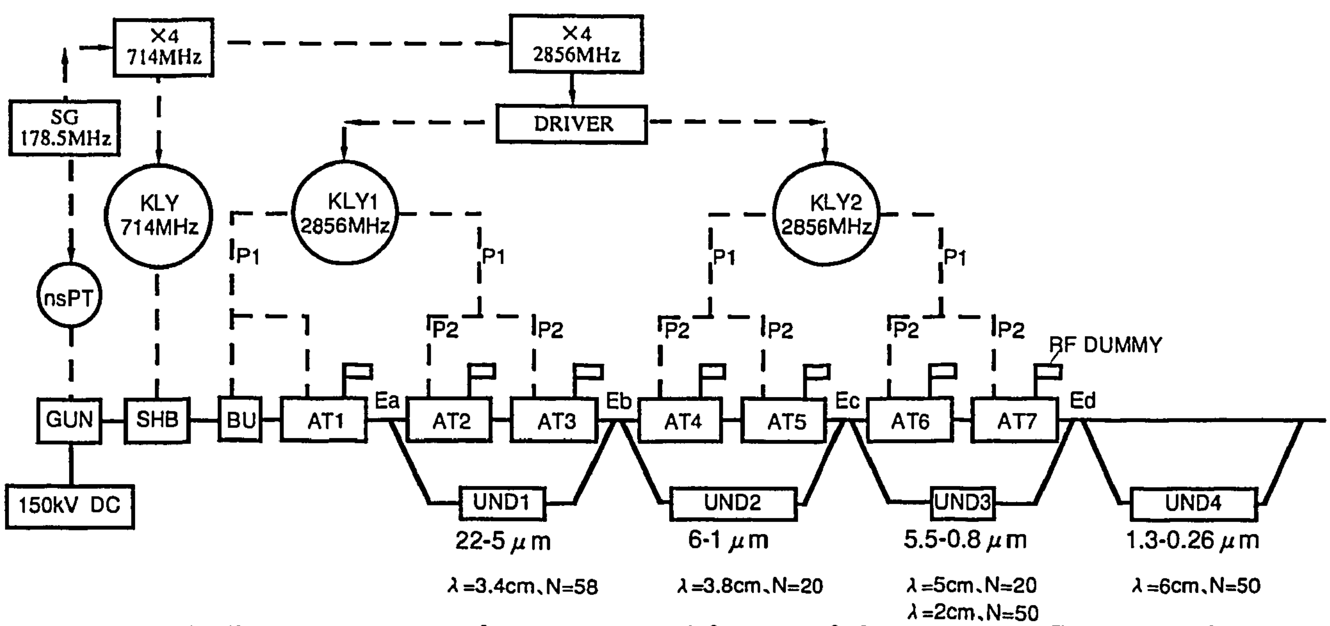


Fig. 4 FELI linac including rf systems and four undulator sites. Beam loaded energies at each site and parameters of undulators are shown.

The BT system for the linac has a quadrupole doublet every 2m on average as shown in Fig. 5 to keep the emittance and position of the accelerated beam small and on the axis of the accelerated waveguide, respectively, from the injector to the end of the linac. Beam position monitors installed at the inlet and outlet of each accelerating waveguide are used for the beam diagnosis.

The four S-type BT systems for the corresponding undulators have been designed as an achromatic and nearly isochronous (22.5° bend x 2) BT systems. The bending angle (α) of 22.5° was chosen to reduce the residual non-isochronicity $c\Delta t$ (c is the light velosity), since $c\Delta t$ is proportional to $\alpha^3 R\, \Delta P/P$, where $\Delta P/P$ is the relative momentum by a modified klystron 1AV88R manufactured by Toshiba Corp. The klystron is oeprated by a long pulse mode of 30 μs, using MOS FET modules. Its maximum rf power is 15kW (714MHz).

The 2856-MHz buncher is of a standing wave type (SWB) and its total length is around 49cm. The peak electric field will be around 10 MV/m for the rf input of 2MW. In order to reduce the influence of space-charge fields as much as possible, the distance from the gun cathode to the first cavity of the buncher is designed to be less than 80cm for the 0.5 ns-pulse injection mode.

From the Kapchinsky-Vladimirsky equation[5], an axial field Bs of a focusing solenoid keeping a beam radius r constant from the SHB to the SWB is given by

$$Bs=2\sqrt{2}\ m_0c/(e\sqrt{I_a})\cdot\sqrt{I/\beta\gamma}/r, \qquad (1)$$

where m_0 is the electron rest mass, c is the light velocity, I_a is the Alfven current (~ 17000A). I is the peak current, β=v/c is the nominal particle velocity, and γ is the Lorentz factor. The maximum focusing field is designed to be about 0.19T near the entrance of SWB. The field distribution obtained by five focusing coils is shown in Fig. 3. It is expected that a 0.5-ns injection beam of 120 keV electrons (the corresponding bunch length is 8.7cm) is bunched in a bunched length less than 1.5cm at the entrance of SWB by the bunching system of SHB and a drift space. Two beam position monitors are installed in the drift space to control the position, size and direction of bunched beam incident to the SWB, since its iris diameter is of the order of 10mm. Main parameters of the injector are shown in Table 2.

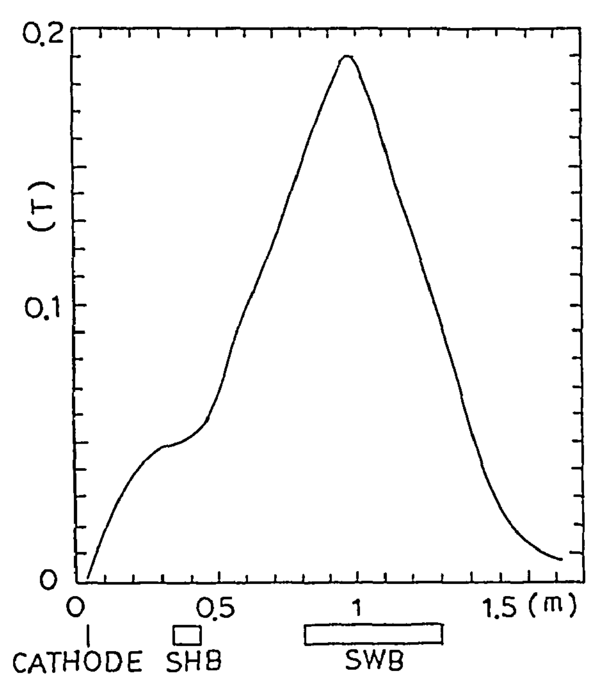
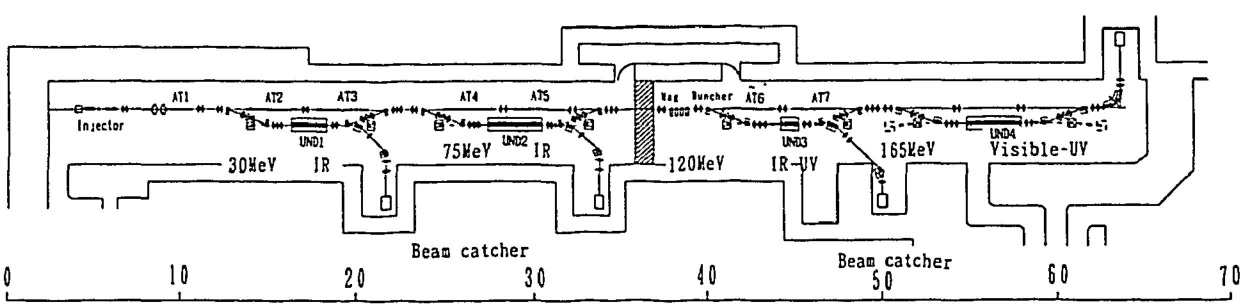


Fig. 3 Magnetic field distribution

spread. The first bending magnet (α=22.5°) of each S-type BT system is horizontally movable from the linac beam path to make a residual magnetic field at the beam path zero, when the linac beam passes straight without bending at the first magnet.

The beam passed through the undulator at 30-MeV and 75-MeV sections can be bent back to the following accelerating waveguide using the BT (22.5° bend x 2) system and can be reaccelerated, since an energy loss due to lasing is less than 1% and the residual non-isochronicity due to the two BT systems (22.5° bend x 4) is less than 0.6ps at the first and second BT systems for a beam with an energy spread of 0.5%. The reaccelerated beam is reused for lasing at the following undulator and bent back again for injection to storage rings and slow positron generations. A lattice design of the BT system of FELI has been published in elsewhere[9]. Details on IR-FEL facilities including vertical undulators [10], optical cavities and FEL transport systems[11] are presented in this symposium.



Layout of IR and UV FEL Facilities of FELI

Fig. 5 Layout of IR and UV-FEL facilities of FELI

Table 3 shows expected values of linac beams and FELs and intended FEL applications at FELI.

The FEL spectral width is one of important qualities of FELs, although it is not shown in Table 3. Fig. 6 shows relationships between spectral width and FEL wavelength. These are taken from the experimental data succeeded in FEL oscillations. Spectral widths of storage Ring-FELs are narrower than those of Linac-FELs, and those of L-band Linac-FELs are the widest. The solid lines indicate wavelength dependence of spectral widths calculated from the equation (2) for the parameters of period N of the used undulators and electron bunch length σ_z shown in parentheses.

$$\Delta\lambda/\lambda \simeq (1/\pi)|\lambda/N\sigma_z|^{1/2} \qquad (2)$$

Table 3 Expected values of linac beams and FELs and intended FEL applications at FELI

Electron energy	≦30MeV	≦75MeV	≦120MeV	≦165MeV
Peak current		≧100 A		≧100 A
Normalized emittance		≦20 π mm mrad		≦20 π mm mrad
Energy spread (FWHM)		≦0.5 %		≦0.3 %
Micropulse duration		≦6 ps		≦5 ps
Micropulse repetition frequency		178.5 MHz		178.5 MHz
Macropulse dulation		≦24 μs		≦24 μs
Macropulse repetition frequency		≦10 Hz		≦10 Hz
Average beam power		≦2.0 kW		≦3.7 kW
FEL wavelength	20−7 μm	≧1.0 μm	≧0.54 μm	≧0.25 μm
FEL average power	3 W	8 W	12 W	5 W
FEL applications	Separation Bio Science	FEL−CT Ablation	Purification Ablation	Photosynthesis

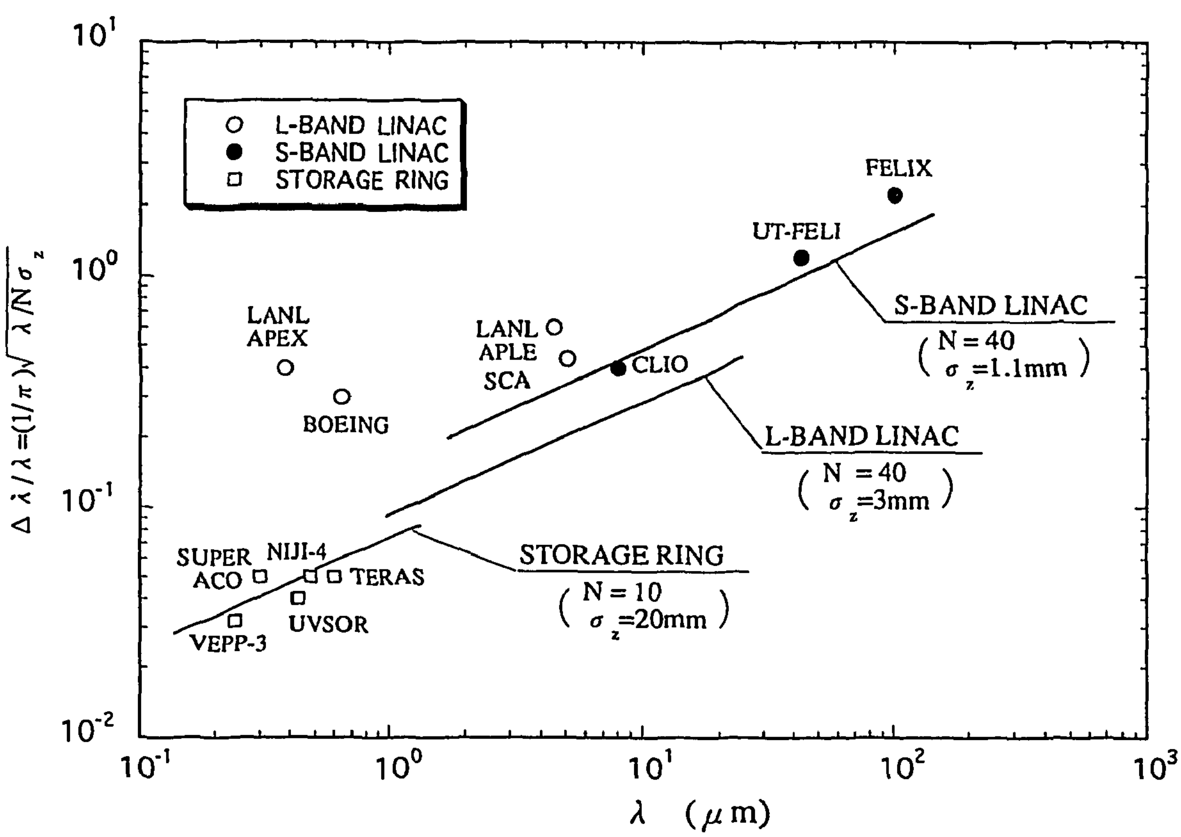


Fig. 6 Relationships between spectral width and FEL wavelength

In the previous papers[3,12] we have discussed relations between the relative energy spread $\Delta E/E$ and the normalized emittance ε_n of accelerated beam in rf linacs and stored beam in storage rings which succeeded in FEL oscillations or are planned to do so, as shown in Fig. 7. The beam quality of stored beam in storage rings in quite excellent in the energy spread and beam emittance by one figure and three figures, respectively, compared with those of the accelerated beam in conventional rf linacs. Since the latter emittance ε varies inversely with the linac energy as $\varepsilon = \varepsilon_n/\gamma$, the three figures between storage rings and rf linacs can be overcome by using high energy beam of around 200 MeV. The solid lines in Fig. 7 indicates wavelength limitations calculated for $L_u = Z_R$ (Rayleigh length), filling factor $f = 2r_b^2/r_o^2 = 1$, where r_b (the radius of the matched electron beam) = 4×10^{-4} m and r_o (the minimum spot size of the Gaussian beam), and r = 392(320) according to the inequality given by Sprangle, et al.[13]. Considering from the wavelength limitations calculated from the inequality in eq.(3), our target ($\Delta E/E = 0.3\%$, $\varepsilon_n = 20\pi$ mm•mrad, γ = 320~392) of the beam quality is reasonable for 0.3 μm FEL oscillations with an undulator of λ_o = 4–6cm and K = 1.

$$\lambda > (2\pi)^{1/2}[1+1.024\times10^{-13}(\Delta E/E/\varepsilon_n^2)^2]^{1/4}(\varepsilon_n/\gamma) \qquad (3)$$

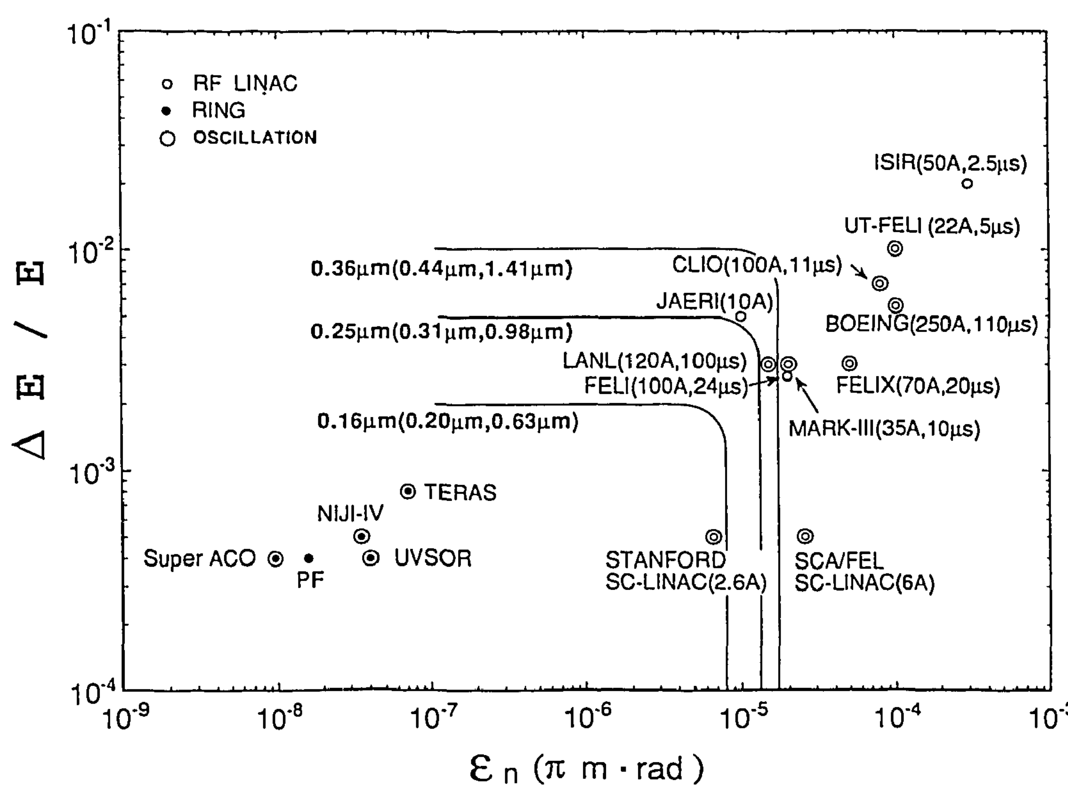


Fig. 7 Energy spread and emittance of the electron beam achieved and planned FEL oscillations.
Solid lines show wavelength limitations for γ =392 and 320.
Wavelengths for γ =320 is shown in parentheses.

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