Infrared FEL lasing at Nihon University and blow up visible light

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Abstract

Laboratory for Electron Beam Research and Application (LEBRA) of Nihon University has proceeded with the development and research of the electron linear accelerator (linac) toward free electron laser (FEL). LEBRA is designed FEL to lase intense light from 5μm to 0.35μm without using of subharmonic buncher. It uses an undulator to provide flexibility for user experiments. First lasing of FEL at LEBRA succeeded in a wavelength of 1.5μm on May 26, 2001, and it was generated by energies of 83.6MeV and electron current of 100ma. During initial tests, the intensity of FEL reached about 10^8 times of light which accumulated spontaneous emission into an optical resonator at off-lasing. However, a saturation phenomenon within the lasing of FEL isn't observed yet. However, we are observing the phenomenon that visible light rises from the flash at the same time when it is made to do the lasing intensely in the wavelength of the 1.5μm. We report about the detailed progress of the development of the linac and FEL.

1. Introduction

The FEL project of Nihon University was proposed to promote research of applied science. This projectstarted in 1994, and has been requested to advance researches in physics, chemistry, biology, engineering, medical science and medical treatment [1,2,3,4]. However, a budget of project was not enough. It was planned so that the accelerator is fabricated by using the element parts supplied from the various old one to make up lack of the fund. Fabrications of accelerator and FEL system completed in March,1998. The first commissioning of linac was performed at January of 1998 [5,6,7]. At that time, it succeeded in accelerating the electron beam of 20ma in the energy of 90MeV, and then the beam current of electron reached 220ma in October,1998.

It confirmed that a spontaneous emission was accumulated by an optical resonator in March, 2001. It succeeded in a FEL lasing of 1.5μm by using the electron beam of 100ma accelerated by the energy of 83.6MeV in May, 2001. After that, the electron beam of 83.6MeV and 40ma used at the 3rd test experiment, and the laser strength reached about 6×10^7 of the accumulated light [8,20].

We sometimes observed the flash of the visible light in the test experiment of Infrared FEL. Why does such light occur? That process is being analyzed.

2. Progress to the FEL lasing

The first time, we have being tried such FEL that might produce the wavelength of from 5μm to 0.35μm by using one undulator. When the undulator was badly damaged by the radiation, we thought that the ranges of the wavelength should be covered with two undulators in order to ease its radiation damage.

The ranges of wavelength for FEL were assigned respectively from 5μm to 0.8μm and from 1.8μm to 0.35μm. The parameters of a new undulator were designed as λw = 48mm, Nw = 50 and K = 1.2. Here λw is one periodic length of the undulator, Nw is the periodic number of the undulator. K is the undulator parameter which is shown in $K = eB\lambda w/2\pi m_e c$, where B is the peak magnetic field of the undulator, m_e is the rest energy of the electron, and c is the light velocity. The lasing wavelength λp is defined as

$$\lambda p=\lambda w\ (1+K^2/2)\ /2\gamma^2, \qquad (1)$$

where γ is relativistic factor and is given as $\gamma = (E+m_e)/m_e$, and E is the kinetic energy of the electron. The optical system was set up to lase at wavelength of 1.5μm. The dielectric multilayer mirrors which have the reflectivity of 99.5% was used for the reflector of the optical resonator. For the lasing of the wavelength of 1.5μm, the value of γ is 166 from (1), therefore, the energy of the electron becomes E=84.3MeV. In this case, the accelerator of our facilities can cope with this energy fully.

On the other hand, the electron which passes through the undulator radiates energy directly to the accumulated photon. The energies transferring from the electron beam into the accumulated photon are in proportion to the energies of photon stored in the resonator. The rate of increase of the coherent light stored in the resonator is the gain of FEL. The gain G is specified by the structure of the undulator and the characteristics of the electron beam. The gain G depends on the structure of the undulator and the characteristics of the electron beam. If the characteristics of the electron beam don't take it into account, G is given as follow.

$$G \sim \lambda w^2 Nw^3 K^2/\gamma^3 \qquad (2)$$

In our case, G was 9×10^{-5}, and there was no inferiority in comparison with the example being lased by other FEL system. The high sensitivity Infrared detector (InSb:Kolmar Technologies KISDP-1-J8 40000V/Watt) was prepared for a purpose of investigating the minute action of the accumulated light into the optical resonator.

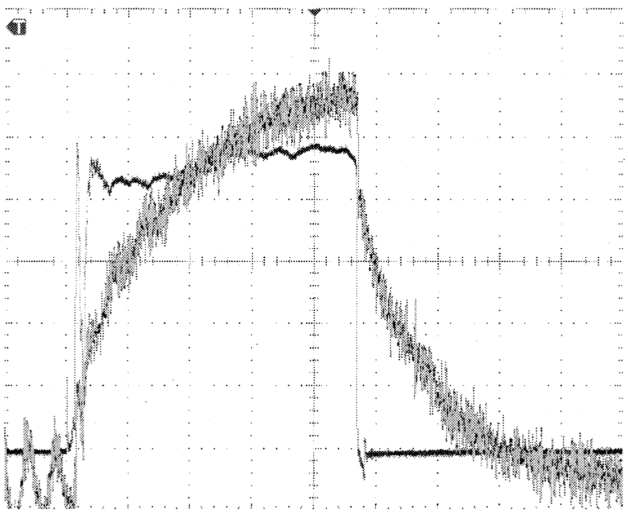

Fig.1 The shape of an intensity respond to the accumulated light into the opical resonator (V: 2mV/div, H: 4μs/div). The rectangle is the wave form of electron beam (V:20ma/div).

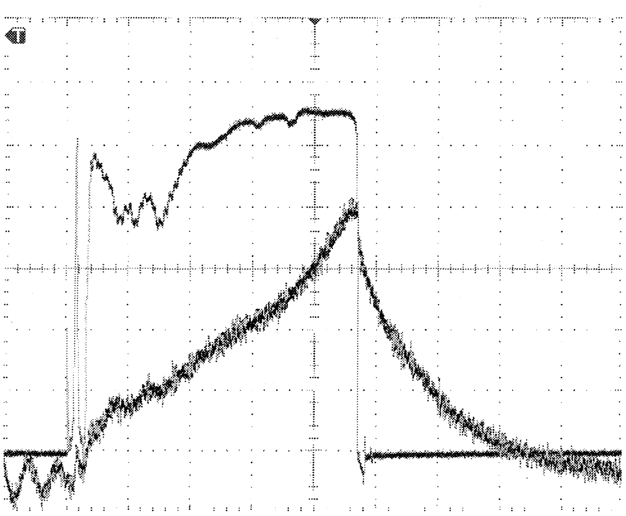

Fig.2 The shape of an intensity respond to the poor lasing light into the opical resonator (V: 5mV/div, H: 4μs/div). The rectangle is the wave form of electron beam (V:20ma/div).

3. The document of the FEL lasing

The basic experiment for the Infrared FEL was restarted again in March, 2001. The spontaneous emission was accumulated into the optical resonator as shown in the figure 1. Though we changed the length of the resonator, the symptoms of the FEL lasing was not found at all. On the other hand, it had been pointed out that the precision of the length of the optical resonator wasn't so accurate. There was such a possibility as the length of the optical resonator might deviate from the value of the design. Thus, we measured the absolute value of the distance between two mirrors into the resonator by using the primitive ruler. After that the test experiment of FEL was enforced continuously, however, the symptoms of the lasing didn't appear. We thought that the parameter contributing to the gain have greatly deviated, then doubted the setting condition of the undulator. But, there was no problem. Next, we reexamined all the devices which were set upon the beam line of FEL system. As that result, we found the difference of about 3mm in the gap interval on the entrance side of the undulator and the exit side. As for the difference of this interval, the magnetic field strength was equivalent to the difference of about 20% on the entrance of the undulator and the exit. The number of 50 period of the undulator was evaluated as about 5 from the viewpoint of actual effect. Therefore, substantial gain G decreased to less than 1/1000, and it is to be clear from (2). This accident was repaired at once. We succeeded in the first lasing of FEL at the test experiment of the next day. Then, the quantity of electron beam was the energy of 83.6MeV and the current of about 100ma.

The intensity of the spontaneous emission accumulated into the optical resonator was measured with the InSb detector with 1mm active area, and the output signal of this was displayed as an integral wave form shown in the figure 1. On changing the length of the optical resonator, the integral wave form of the intensity was changing gradually, and became a wave form shown in the figure 2.

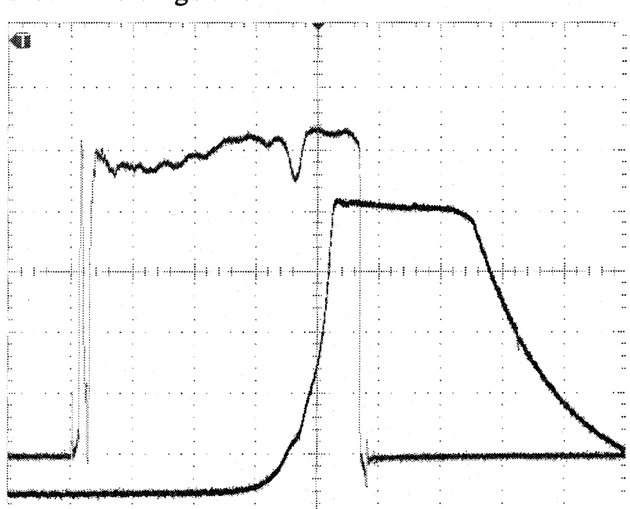

Fig.3 The shape of an intensity from the saturated detector respond to the violent lasing light into the opical resonator (V: 1V/div, H: 4μs/div). The rectangle is the wave form of electron beam (V:20ma/div).

The spontaneous emission ejected from the front electron beam was accumulated into the resonator, and the energy of the back electron beam was transferred to the accumulated light. In other words, this is the amplification of the accumulated light, and is equivalent to the phenomenon of the positive feedback in the optical amplifier which included two mirror into the feedback circuit. In the lasing, the intensity of this grew large gradually by the adjustments of the accelerator parameter such as the phase, the electron beam orbit and the focus. As the results, the output signal of the detector exceeded 4V as shown in the figure 3, and then the amplifier of this was saturated at last. The output signal was estimated to about 24V from the decay curve of it.

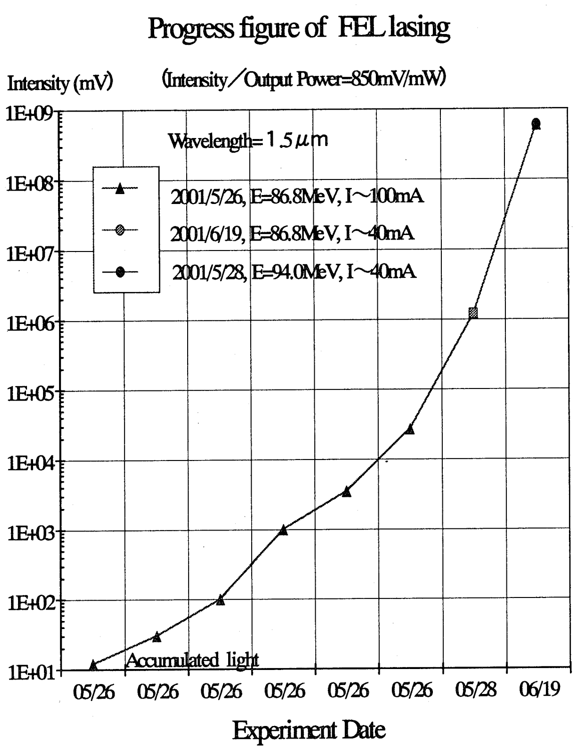

Fig.4 The progress of the intensity reinforcement in the lasing experiments. The vertical scale is the intensity of Infrared

The output signal was equivalent to about 2000 times of the accumulated light. Through the two times test experiment after this, the signal is strengthened as shown in the figure 4, and reached the intensity of about 10^8 times of the accumulated light.

When FEL is strongly lased, we sometimes observe the flash of the intense visible light as shown in the figure 5 [8,18,20]. We haven't been able to do an analysis about the rare occurrence mechanism of this light yet.

4. The FEL lasing and this meaning

The lasing experiment of the third time was tried by using of the beam current of 40ma with energy of 86.8MeV. At this time, the diameter of the electron beam in the center of an optical resonator was about 0.5mm. The detector was installed in the place to leave this point about 8m. According to the measurement of the detector, the energy of one macro-pulse reached about 0.3mJ/mm^2, and a peak power got over about 8kw/mm^2. Though FEL was lased even by a little beam current, this lasing is based on the electronic beam of the high density. In other words, we think that it is because a bunching of the electron beam is fine. That reason depends on the prebuncher that is composed of seven cavities. That has a function which makes the electron beam bunch and accelerate.

If the amount of charge of the electron beam is small, the prebuncher has such ability as have bunched the electron beam in the pulse of the subpicosecond, as shown in the figure 6.

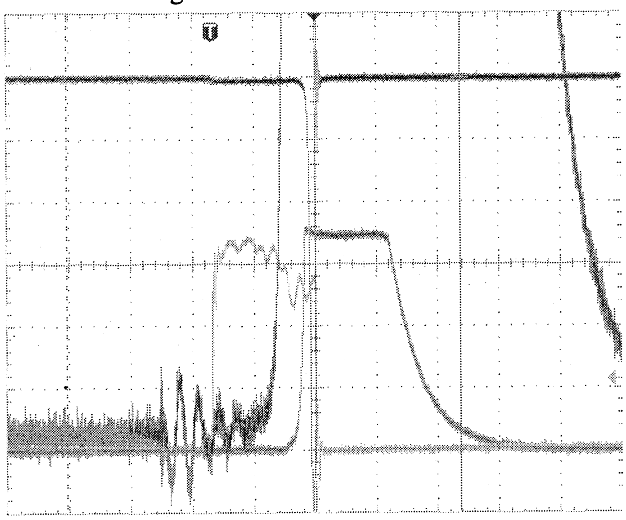

Fig.5 Upper : The shape of the intensity of the visible light (V: 500mV/div, H: 10μs/div). Lower : The shape of an intensity from the saturated detector respond to the violent lasing light into the opical resonator (V: 1V/div, H: 10μs/div). The rectangle is the wave form of electron beam (V: 20ma/div). Scale over : The shape of an intensity from the saturated detector respond to the violent lasing light into the opical resonator (V: 2mV/div, H: 10μs/div).

5. Discussion

The lasing of FEL requires the electron beam of the big peak current of the small emittance with energy of the little dispersion. Therefor, there are historical details that the high frequency electron gun was developed for the small emittance and also the subharmonic buncher was developed for the big electron current.

The gain is small when the beam current is poor. Then, the long electron beam of the duration time is necessary to make up this. In this case, a superconductive electron linear accelerator has been used for the operation of long pulse. Then, the lasing of FEL was a successful in only using of these special devices. These devices became established as a paraphernalia of the lasing of FEL. The electron linear accelerator for FEL of the Nihon University isn't using the high frequency electron gun and the subharmonic buncher as shown in the figure 7. This broke common sense until now. Then, it became the first example in the world that the ordinary electron linear accelerator was used in a lasing of Infrared FEL.

At present, the dielectric multilayer mirror is being used for the optical resonator. The reflectivity of 1.5μm wavelength of this mirror is about 99.5%. But, the reflectivity of 0.5μm wavelength which is the 3rd high harmonics is about 15%. Therefore, it can't think that the flash of the visible light is FEL lasing of the 3rd high harmonics. The forward radiated energy from the electron beam travelling in a single pass through the undulator with the strength parameter k grows exponentially. If the parameter of K depends on the magnetic nonlinear field of the undulator strongly, the 3rd high harmonics of FEL will be enhanced. The high harmonics of FEL will form microbunch structures into the electron beam. This is consistent with predictions of Self-Amplified Spontaneous Emission (SASE). At that time, we shall observe the flash into the visible light.

6. The troubles and the developments

It became clear in September, 1999 that a permanent magnet of the undulator that has sustained a radiation damage[11,12]. We determined to make the new undulator used in the wavelength in the range from 5μm to 0.8μm. A new undulator was delivered in March, 2000 [13]. The high harmonics spectrum of the spontaneous emission was measured in June, 2000 [14]. As for the time of the first operation, the output pulse of the klystron has been narrowed by the duration of less than 10μs because of the discharge of that output-window. We executed the test experiment to extend to 20μs the pulse duration of the klystron.

The output-window of the klystron was damaged into the experiment one after another. The one more high frequency window was installed in the wavegiude connected to the output window of the klystron [16].

However, this high frequency window was never damaged though the same amount of high frequency electric power passed through the output-window of the klystron and this high frequency window. We got a hint from the above mentioned fact, and installed two new ion pumps near the output-window, and tried to discharge the gas radiated from that surface rapidly.

The long pulse operation of the klystron became possible as that result [16,17]. The operation of the accelerator was stopped for five months from July, 2000 until December for an experimental hall building extensively. Accelerator operation was resumed in February, 2001. The value of G, which took an emittance, a peak current, and so on into account, have to be bigger than the loss coefficient of the reflector. The development of a low emittance and an intension of a peak current were executed in order to improve the character of electron beam [17,19]. A new cathode of a small diameter was prepared to make the emittanc of the electron beam small, and the electric power of the buncher was increased for the intension of a peak current [8].

Electron beam to be used in FEL was expected to produce high quality photon sources. We proposed such projects as spontaneous emission of ultraviolet and a parametric X-ray source in 1999 [12]. We are hoping for that challenging application research will be promoted by using these photon sources at near future.

7. Conclusion

We were proceeding with the improvement of the accelerator for the past six years. Such troubles as well as the pulse transformer, the backdiode circuit, the insulated transformer of klystron heater and the corrosion of cooling, and so on became extinct as that result. The stability of the accelerator was improved by the introduction of the stabilization power supply, the repair of strengthening of the focus system, the arrangement of the accelerator structure, the strengthening of the vacuum system around the klystron high frequency window, the improvement of the waveguid union defect, the phase compensation of the high frequency amplifier, the fine tuning of the thyratron, and so on. The long pulse operation of the klystron for the short pulse and the small emittance of electron gun were attained. The advance of the accelerator progressed steadily, and the performance of the electron beam was improved remarkably. The measurement system was prepared with the monochrome meter, the streak camera, and the high sensitivity CCD camera. It became possible that the spectrum of the spontaneous emission and a bunched electron beam were measured in real time as that result [9,10]. Because the permanent magnets sustained radiation damage, the short wavelength FEL became use impossibility [11].

So, we introduced the undulator that the length of the period was two times. The experiment environment of the FEL lasing was prepared. Then, we made the Infrared FEL be lased by the construction of the accelerator which breaks the common sense of FEL.

However, FEL is still unstable [14,16], and it can't be used for the joint use experiment. It is necessary to enhance the stability of the accelerator.

Acknowledgements

The authors would like to acknowledge helpful discussions with members of the FEL research community.

Works have been supported by Nihon University and High Energy Accelerator Research Organization and much research organization and many enterprises.

The laser lasing is the biggest research result in the joint research on the Nihon University and the high energy accelerator research organization. The authors are deeply grateful to the members of the high energy accelerator research organization who supported this project. Furthermore, this project has been supported by the Y.Sezai Nihon University president and the K.Kojima Atomic Energy Research Institute head especially strongly. The authors appreciate heartily to both leaders.

References

[1] I.Sato, et al., Proc. of 22nd LAMJ, 104-106 (1997).
[2] K.Hayakawa, et al., Nucl.Instr.and Meth. A375, ABS25-26 (1996).
[3] T.Tanaka, et al., Nucl.Instr.and Meth. A407, II 103-104 (1998).
[4] T.Tanaka, et al., KEK Proceedings 98-10 Nov. 722-724, 1998 A.(APAC98)
[5] T.Tanaka, et al., Proc. of 23rd LAMJ, 25-27 (1998).
[6] I.Sato, et al., Proc. of 23rd LAMJ, 22-24 (1998).
[7] K.Hayakawa, et al.,Proc. of 23rd LAMJ, 166-168 (1998).
[8] I.Sato, et al., Proc. of 26th LAMJ, 30-33 (2001).
[9] K.Yokoyama, et al., The 12th Sym. on Accel. Sci. and Tech., Riken,Japan, 473-475(1999).
[10] H.Nakazawa, et al., The 12th Sym. on Accel. Sci. and Tech., Riken,Japan, 394-396(1999).
[11] I.Sato, et al., The 12th Sym. on Accel. Sci. and Tech., Riken,Japan, 37-39(1999).
[12] Y.Hayakawa, et al., The 12th Sym. on Accel. Sci. and Tech., Riken,Japan, 391-394(1999).

[13] K.Hayakawa, et al., Proc. 25th LAMJ,56-58 (2000).
[14] Y.Hayakawa, et al., Proc. 25th LAMJ, 358-360 (2000).
[15] K.Hayakawa, et al., Proc. 26th LAMJ,285-287 (2001)
[16] T.Sakai, et al., Proc. 26th LAMJ, 222-224 (2001).
[17] K.Yokoyama, et al., Proc. 26th LAMJ, 231-233 (2001).
[18] T.Tanaka, et al., Proc. 26th LAMJ,246-248 (2001).
[19] K.Kanno, et al., Proc. 26th LAMJ, 73-75 (2001).
[20] Y.Hayakawa, et al., to be accepted, The 23rd International FEL Conference, Darmstadt, Germany (2001).

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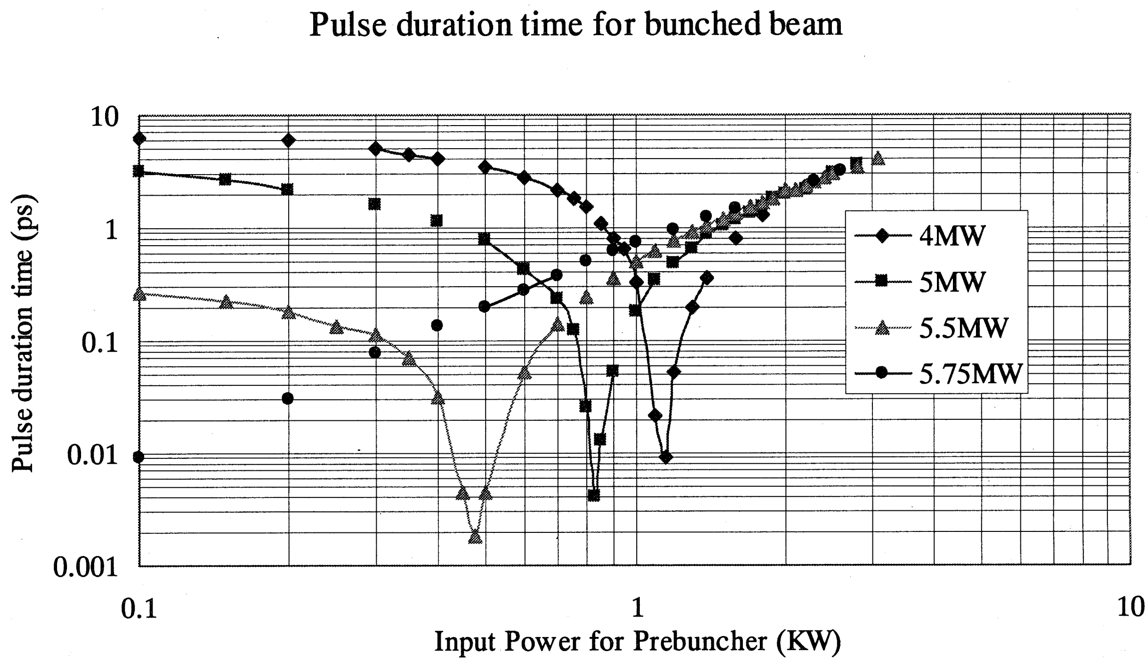
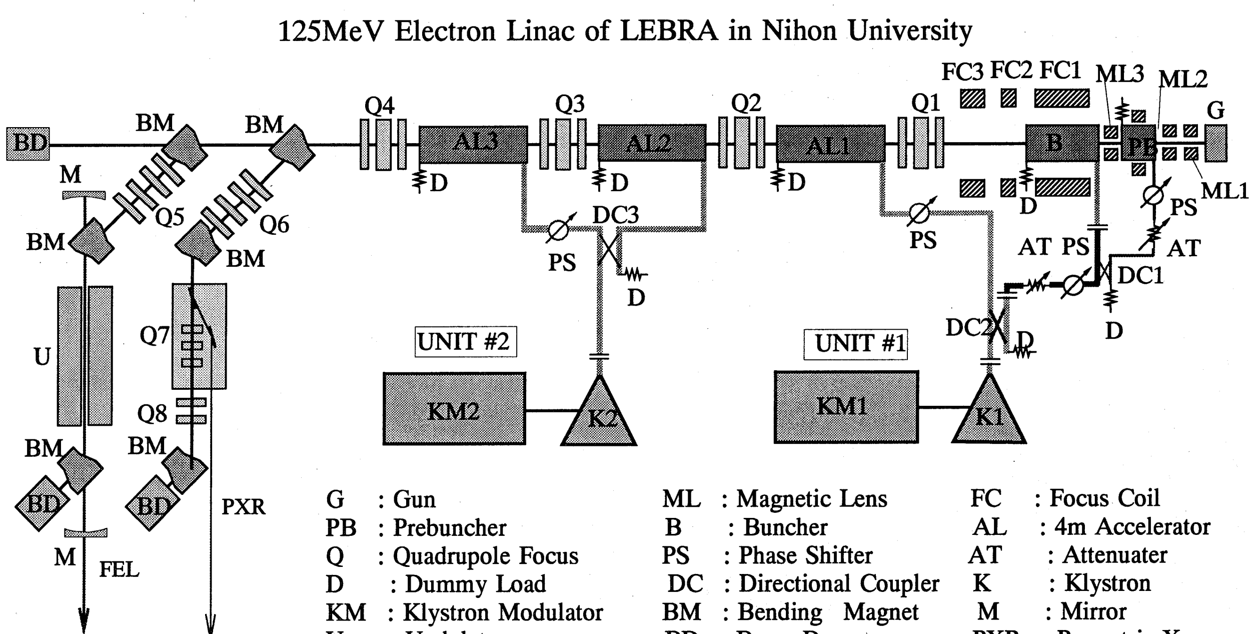


Fig. 6 The pulse duration time of the electron beam shows a result of a calculation of beam tracing which makes the both input electric power of the pre-buncher and the buncher a variable.



G	: Gun	ML	: Magnetic Lens	FC	: Focus Coil
PB	: Prebuncher	B	: Buncher	AL	: 4m Accelerator
Q	: Quadrupole Focus	PS	: Phase Shifter	AT	: Attenuater
D	: Dummy Load	DC	: Directional Coupler	K	: Klystron
KM	: Klystron Modulator	BM	: Bending Magnet	M	: Mirror
U	: Undulator	BD	: Beam Dump	PXR	: Prametric Xray

Fig.7 The layout of the 125 MeV electron linear accelerator and FEL system and Prametric Xray generator.