MEASUREMENT OF FEL UNDULATOR AND PARTICLE TRACKING

C.TSUKISHIMA and S.NAKATA

Central Research Laboratory, MITSUBISHI ELECTRIC CORP.
Tsukaguchi-honmachi, Amagasaki, Hyogo, Japan

Abstract

An undulator for FEL experiments was constructed and the magnetic field was measured. The profiles of the electron beam at the undulator were measured and position resolution was 0.2mm, which was less than permissble misalignment calculated by beam tracking calculations in the undulator.

Introduction

Free-Electron-Lasers(FEL) was first proposed as an optical device at Stanford in 1970 [1] and offers a variety of advantages over conventional lasers. For example, it is possible to operate FEL from the far infra-red to the vacuum ultra-violet by changing the electron beam energy. By using the intermediate beam energy (several tens of MeV), FEL could become the high power far infra-red light source, whereas there are few conventional high power lasers in that wavelength region. The gain of FEL is calculated using theoretical formula [2]. In a real FEL system, however, there are many effects to reduce the gain. In this paper, we present the characteristics of our undulator and the estimation of the gain using the results of numerically calculated trajectories of the electrons through the actual magnetic field, taking into account the effects of field errors, field inhomogeneity, beam misalignment, finite beam emittance and energy spread.

Undulator

The undulator[3][4] is 1.64m long and has a linearly polarized magnetic field. The undulator period is 60mm and the number of the periods is 28. The permanent magnet configuration is similar to the one first proposed by Halbach[4]. The schematic drawing of the undulator is shown in Fig.1. In Fig.1 the x-,y-,z-axis are transverse direction, vertical direction, and beam direction respectively. About 250 magnets of nominal field Br=1.2T (NEOMAX-35) were made by the Sumitomo-Tokushu-Kinzoku Corp.. The cross section of the block was 15mmx15mm wide for the magnet and 7.5mmx15mm for the half magnet at the both sides of the undulator and the length of the block was 100mm to obtain the large good field region in the x-direction. The permanent magnet blocks, held in the pole holder, were placed on the two holders and the holders were mounted in the the vertical translational stage with two guides. The magnet gap was remotely variable from about 30mm to about 70mm. By using only one of the guides, the magnet gap of each side of the undulator could be changed independently and the undulator is used as the tapered-undulator with some field gradient.

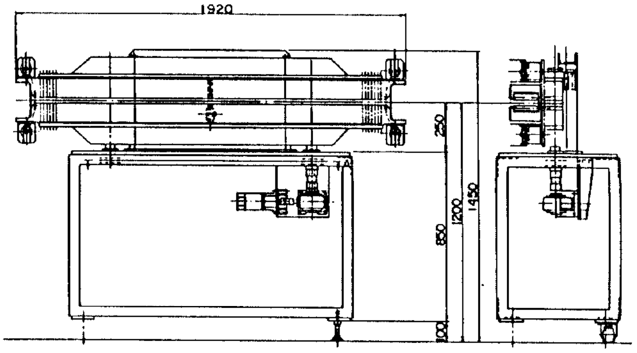

Fig.1 Schematic drawing of the undulator.

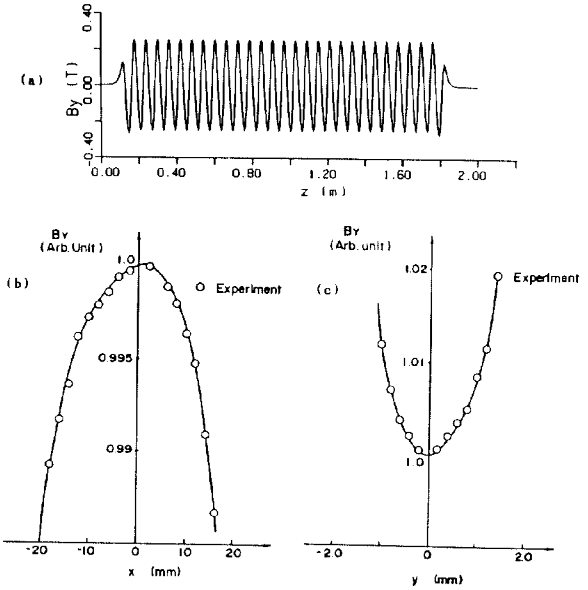

Fig.2 Measured magnetic field (By) along the z-axis (a), field profile in the x-direction (b), and in the y direction (c).

The magnets did not all have the same characteristics, i.e., magnetization, block sizes, and etc., and they caused the undulator field error. To reduce the field error, the pole holders could be moved independently; the accuracy was about 10 micro-meters. The magnetic field was measured and some results will be presented in the following paragraph. The magnetic field distribution was measured by sweeping the hole-probe. The error of the periods was less than 0.14% and was limited by the dimension of the probe (1.0mm) and the sweeping step(0.5mm).

The magnetic field was 2.5kG, at the magnet gap of 35mm and the K-value was 1.4, the gain was maximized at this value. The r.m.s. field error of 0.06% was obtained. The magnetic field(By) distribution in the x-,y- and z-axis are shown in Fig.2 (a),(b) and (c). The vertical axis of Fig.2 (a) and (b) is field strength in an arbitrary unit. The

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good field region (99% homogeneity) was about 2cm in the x-direction and was large enough for the electron wiggling radius (about 0.8mm) in the undulator. The good field region in the y-direction, however, is not so large. The effect of this field inhomogeneity to the FEL gain was calculated and the results will be presented later.

Beam Line

The experimental set-up is shown in Fig.3. The main parameters of the system are summarized in Table 1.

Table1. Main parameters of our Linac, Undulator and FEL.

Linac	
Energy	20MeV
Current	100mA
Pulse width	3.5micro-sec
Emittance (x)	1.04 pai-mm*mrad(90%)
Emittance (y)	1.14 pai-mm*mrad(90%)
Energy spread	1%(FWHM)
Repetition rate	3Hz
Undulator magnet	
Period	6cm
Length	168cm
Magnet gap	35mm
Magnetic field	2.5kG
K-value	1.4
Number of periods	28
r.m.s. field error	0.06%
FEL parameter	
Wave length	40micro-meter
Theoretical gain	42.7 %/A

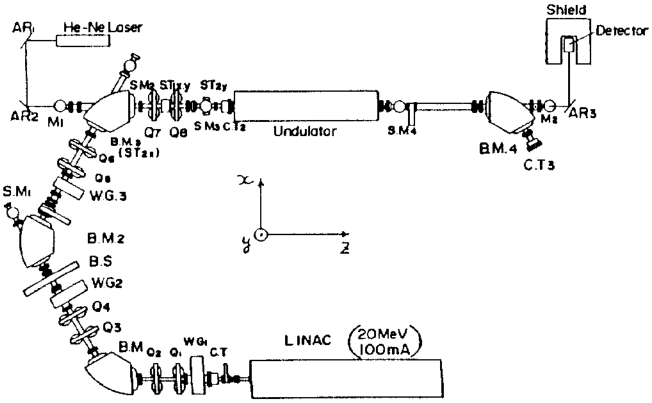

Fig.3 The layout of the beam transport line for the FEL experiment.

The RF-linac of 2.8GHz was used in our experiment. The beam energy was 20 MeV and the current was 100mA of 3.5micro-sec. The repetition rate was 3Hz. The emittances of the electron beam and the energy spread were measured by WG_1 and WG_2 and were 1.04 pai-mmmrad in the x-direction and 1.14 pai-mmmrad in the y-direction (90% of the beam) and 1% (FWHM) including energy fluctuation, respectively.

The beam line had three bending magnets (BM_1, BM_2, BM_3), eight quadrupole magnets (QM_1-QM_8) and four steering magnets ($ST_{1x,y}$ and $ST_{2x,y}$). The layout of the magnets is shown in Fig.3. In the beam line, several kinds of monitors were installed to measure the beam parameter in order to align the electron beam in the undulator. There are three wire-grid monitors(WG_1-WG_3) for beam profile monitor, four screen monitors (SM_1-SM_4) for beam position monitor, three current transformers (CT_1-CT_3) for current monitor. Furthermore one beam-scraper was installed to control the beam energy spread in the undulator. The dispersion function at the beam-scraper in the x-direction is about 1.48m. On the other hand, the beta function is 28.4m and the beam size without energy spread is 5.43mm, which is small compared with the displacement of the off-momentum electrons, hence the control of the energy spread would be easily performed.

The optical cavity consisted of two Au coated spherical mirrors with a central pin-hole of 1mm for output coupling. The curvature of the spherical mirror was 2.5m and the radius was 40mm. The diffraction loss for a confocal cavity depends on the Fresnel number, N_F, where $N_F=a^2/L$ (a=radius of the mirror, L=cavity length). For L=5m and a=20mm gives $N_F=2$ at the wavelength of 40 micro-meter,. and the diffraction loss per pass less than 0.01% was negligibly small compared with the FEL gain. The mirrors were installed in the vacuum chambers to avoid the loss caused by a vacuum window. The position of the mirrors was remotely controlled in three directions (x-, y-, and z-axis) by stepping motors, whose accuracy was about 5 micro-meter. Mirrors were also rotated along the x- and y-axis by micro-meters for course alignment and piezo-stacks for fine alignment. The course alignment of the cavity was performed using He-Ne laser.

The alignment of the electron beam axis and the light beam axis was done by using the two screen monitors (SM_3 and SM_4). The accurate position of He-Ne laser and the electron beam were measured by using the TV camera, image processor and the personal computer. The beam position was adjusted by the four steering magnets (ST1x,y and ST2x,y) according to the data obtained from the above system. Fig.4(a),4(b) shows the electron beam profiles obtained on SM_3 and SM_4. The half beam extents at the entrance of the undulator is 6mm in the x direction and 2mm in the y direction. And that at the exit of the undulator was 5mm and 5mm respectively. The position resoluton of this measurement was less than 0.2mm.

The energy spread of the beam transmited through the undulator is measured using BM_4 and the beam dump. The result is 0.25% in FWHM, which is much smaller than that of the Linac exit.

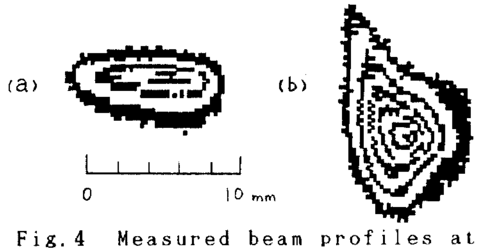

Fig.4 Measured beam profiles at the entrance of the undulator (a), and at the exit (b).

Particle Tracking

As shown in Fig.2(c), the field had small good field region in the y-direction. Due to this effect, the field for off axis electrons is different from that for on axis electrons. Thus the spectrum of the spontaneous emission from off axis electrons, is shifted from the emission from the later electron. Hence, if the electron has a large beam diameter, especially in the y-direction, the spectrum of the spontaneous emission from the total electron become broad and the FEL gain decreases. Furthermore an electron beam with a finite divergence angle faces a different field strength as well as the periods of the magnetic field from an electron beam without divergence angle.

Considering these effects, the beam motion in the actual undulator was calculated from tracking electron orbit through the measured field. The longitudinal field (Bz) was estimated from By to satisfy the Maxwell equations ($\nabla \times B=0$). In the linearly polalized undulator there is no coupling between the motion in the xz-plane and in the yz-plane. Therefore, we can treat the distribution on the phase space independently. The distribution of the electron beam in the phase space was assumed to be Gaussian having an elliptical contour and also we assumed that there was no correlation between x and y.

$$f_x(x,x') = \frac{1}{\sqrt{2\pi}\,\varepsilon} \exp\{-(\gamma x^2+2\alpha x x'+\beta x'^2)/2\varepsilon\} \tag{1}$$

For the distribution function of the energy, the Gaussian distribution was also assumed as follows.

$$f_e(E) = \frac{1}{\sqrt{2\pi}\,\sigma_E} \exp\{-(E-E_0)^2/2\sigma_E^2\} \tag{2}$$

In our beam line, the undulator was located in the dispersive section Therefore, the effects of the coupling between x-x'phase space and the beam energy for the off-momentum electron should be considered. Fig.5(a). shows the electron trajectory in the xz-plane and Fig.5(b) shows that in the yz-plane. The wiggling radius on the xz-plane ia about 0.8mm and there is no large drift in the x-direction. In the y-direction, there is a weak focusing because of the Bz field.

To evaluate the effects of actual magnetic field and the finite beam emittance on the FEL gain, the small signal gain was calculated. As a function of the relativistic Lorentz factor g , the stimulated enegy loss of the beam is

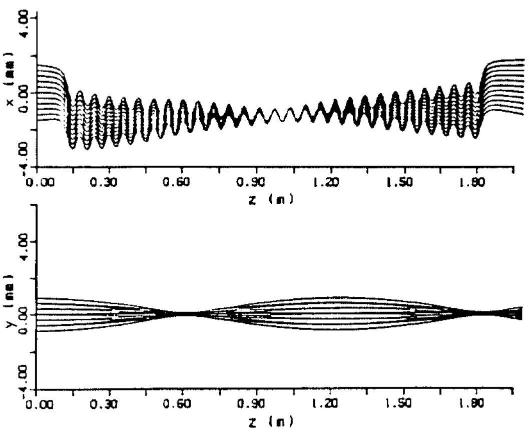

Fig.5 Electron beam trajectories in the actual undulator on the xz-plane (a), and on the yz-plane.

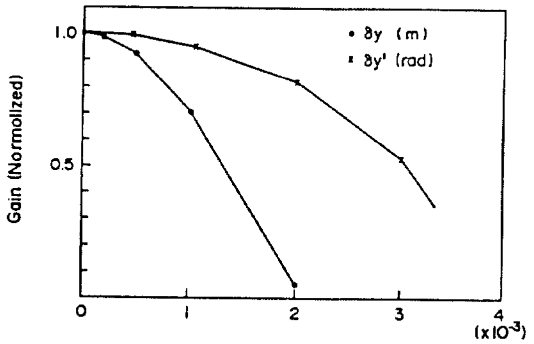

Fig.6 The gain reduction by the beam misalignment.

$$\langle \gamma_f - \gamma_i \rangle = \frac{e^2 E_0^2}{4m^2c^4} \frac{d}{d\gamma_i} \left| \int_{-L/2}^{L/2} \frac{dz}{\beta_\parallel^i} \beta_\perp^i \exp\{i(\omega t - kz)\} dz \right|^2 \tag{3}$$

Subscripts i and f represent relativistic lorentz factors of initial and final beam energies. β is the 3-dimensional vector representing the beam velocity in relativistic unit, and L is the undulator length. Then the small signal gain is

$$Gain = \frac{2mc^2 |\langle \gamma_f - \gamma_i \rangle| I_{beam}/e}{\varepsilon E_0^2 c} \tag{4}$$

The effects of the beam misalignment on the gain was estimated by this program. Fig.6 shows the dependence on the beam shift and beam divergence shift when the wavelength of the optical field is fixed to 40 micrometers. From Fig.6, the accuracy of beam positioning is obtained. The beam misalignments, especially in the vertical direction, should be less than 0.3mm and 1.0mrad not to degrade the gain more than 5%. Although the value of 0.3mm is about one-tenth of the beam size, beam positioning may be possible by using the beam positioning system.

Conclusions

We presented some characteristics of the constructed undulator with a small field error, about 0.06%, and designed beam line for FEL experiments. For the estimation of the gain in the accurate system, we calculated the beam orbits in the undulator and obtained small signal gain in our system. The effect of the vertical beam alignment errors were estimated and the error of the beam position should be less than 0.3mm and that of divergence should be less than 1mrad at the entrance of the undulator. The resolution of the beam monitoring system was far less than the value mentioned above.

Acknowledgments

We thanks Drs. T.Tomimasu, T.Yamazaki and T.Nakamura of E.T.L. for their valuable advices , and the other members of our laboratory for their useful discussions.

References

[1]J.M.J Madey, J.Appl.Phys., 42, 1906 (1971)
[2]W.B.Colson, Phys. Lett., 29, 187- (1976)
[3]S.Nakata and C.tsukishima, in Proc.of Int. Simp.on Appl.Electromagnetics in JAPAN (1988)
[4]C.Tsukishima, and S.Nakata, in Proc. of The LINEA ACCERELATOR MEETING IN JAPAN, 168 (1988)
[5]K.Halbach, Nucl.Instr.& Meth., 187, 109(1981)
[6]J.M.J.Madey, IL NUOVO CIMENTO, 50, 64(1979)