Proceedings of the 6th International Symposium
on
Advanced Nuclear Energy Research
—INNOVATIVE LASER TECHNOLOGIES IN NUCLEAR ENERGY—

# PERMANENT-MAGNET HELICAL UNDULATOR FOR A MILLIMETER-WAVE FREE ELECTRON LASER

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Permanent-magnet helical undulator for a millimeter-wave free-electron laser was designed and constructed. The configuration of the undulator is based on bifilar-type permanent-magnet helical undulator and Halbach-type planar undulator. This new configuration shows enhanced magnetic field and low field error. Period, total length and peak magetic-field amplitude of the undulator is 36 mm, 900 mm and 1.44 kG, respectively. Adiabatic tapering of the magnetic field in end sides of the undulator was achieved using stepped soft-iron tubes.

Keywords : Permanent-magnet helical undulator, Free-electron laser

## 1. Introduction

In electrostatic-type free-electron lasers (FELs) operating in long pulse or cw mode, electron beam recirculation method is adopted to overcome the limited power of charging power supplies [1-3]. The required ratio of the collected electrons to generated electrons on a electron-gun is usually more than 99 %. Electron beam optics during the whole system is carefully considered to minimize a electron-beam loss. The most serious part for a electron-beam transportation is undulator. Undulator makes electron beam quality worse during interaction with radiation.

Korea Atomic Energy Research Institute (KAERI) has developed a recirculation-type FEL with a electrostatic accelerator. The energy and current of the electron beam are 430 keV and 2 A, respectively. Low-energy electron beam passing through planar undulator feels diverging force to the normal direction of the undulator field by space-charge effect and drift motion. To compress the diverging electrons, strong axial magnetic field or gradient magnetic field are necessary.

Helical undulator is another solution for the transportation of the low-energy electron beam. The field of the helical undulator intrinsically focuses the electron beam without external magnetic field. For the cw operation of the FEL, electromagnetic-type bifilar helical undulator has several problems. High-power energy supply is needed for the enough field strength of the undulator and cooling unit makes whole system large and complex. Halbach proposed a permanent-magnet (P.M.) helical undulator [4]. However, the undulator was difficult to be realized. Ashkenazy *et al.* proposed a bifilar-type P.M. helical undulator, referred to hereafter as M-2 helical undulator because one period of one channel is composed of 2 magnets with 180-degree difference of magnetization [5]. They showed that the undulator had strong magnetic field and low field error by analytical consideration and experiment using prototype undulator.

With the undulator scheme as a basis we developed a better performance P.M. helical undulator using Halbach's planar-undulator structure. The newly developed undulator, referred to hereafter as M-4 helical undulator, shows higher magnetic field and lower field error rather than those of M-2 helical undulator. The constructed undulator is extremely compact and cost for construction is more than 5 times lower than that of planar undulator. Using a 3-dimensional (3-D) simulation code, we confirmed that the helical undulator could transport the low-energy electron beam without loss.

## 2. Undulator design and construction

The most basic parameters for designing a undulator are peak amplitude of the magnetic field, period and total length. These parameters are determined by considering radiation frequency, gain, and electron-beam transportation. If we increase magnetic-field strength and undulator length to get a sufficient gain of the oscillation, electron-beam transportation becomes worse. Therefore, we must find optimum parameters to satisfy all conditions.

Simulation codes for 3-D electron-beam trajectory and 1-D FEL oscillation in a helical undulator are used for finding the optimum magnetic field and total undulator length. Central frequency of the radiation is determined to be 24 GHz. When the undulator length is 900 mm and the magnetic field is between 1.2 kG and 1.5 kG, the gain and the electron-beam transportation are simultaneously satisfied. The period and number of period are 36 mm and 25, respectively.

M-2 helical undulator was used as a basis scheme. When we tested the undulator using a prototype with period of 36 mm, the magnetic field at the end sides of the undulator showed higher amplitude than that of center, and overall field error was not so good. To overcome such a problem, a new scheme was proposed as shown in Fig. 1. Each period is composed of 4 magnets with 90-degree change of the field direction during a undulator axis. Magnet length is one-fourth of the period. The undulator is composed of 12 channels and each channel has 3-mm difference in starting position with adjacent one using nonmagnetic spacers. In this new structure of the P.M. helical undulator, M-4 helical undulator, magnetic field amplitudes at the end sides of the undulator were reduced to that of the center part, which was caused by one-fourth reduction of the magnets at the end sides compared with M-2 helical undulator. The magnetic field of the undulator was stronger and field error was lower than those of the M-2 helical undulator. When we tested the M-4 and M-2 helical undulator with a prototype of the same undulator frame, same field error of individual magnet, and same period of 36 mm, the measured magnetic field of the M-4 structure was about 20 % stronger and measured r.m.s field error was 50 % lower than those of M-2 helical undulator.

The magnetic field amplitude of the first and final few undulator periods has to be tapered smoothly to enable adiabatic electron beam injection and to transport into a deccelerating tube without loss. The adiabatic tapering of the magnetic field was easily obtained by using the stepped soft-iron tubes. The magnets in the grooves of the undulator frame are fixed mechanically by bolts in an outer tube. All of these are settled in a stainless steel tube and flanged to cavity mirrors. The main parameters of the constructed undulator are listed in Table 1.

## 3. Measurement of the magnetic field

The magnetic field measurements were performed with a transverse Hall probe gaussmeter (F.W. Bell series 9600). The Hall probe is mounted on the center of a nonmagnetic tube, which fits to inner diameter of the undulator frame, and guided by a linear motion system. Accuracy of the whole measurement system is about ±0.2 %. Figure 2 shows measured magnetic field trace of a fixed azimuthal orientation. It shows very smooth increasing of the tapering magnetic field and uniform field amplitudes in the interaction region.

The peak amplitudes of the undulator magnetic field with different azimuthal orientations are shown in Fig. 3. The average of the peak amplitudes is 1.44 kG and overall r.m.s error is 1.8 %. The r.m.s errors of the first 13 periods and more than 14-th period are 1 % and 2 %, respectively. The larger field error of more than 14-th period is caused by mislocation of the magnets. These results are obtained without sorting or odering of the magnets. We are now developing a more advanced scheme, which is capable of fine adjusting of the magnetic field to reduce r.m.s field error within 1 %.

## 4. Electron beam trajectory

The tpransportation of the electron beam in the helical undulator is carried by 3-D simulation code. Electron beam trajectories are closely related to the incident conditions of the electron beam. The acceptance angle of the incident electrons which can transport the undulator is 2 degree with respect to the undulator axis. When the diameter of the incident electron beam increases, evenif the electron beam can transport whole undulator, the electron beam trajectory after exiting the undulator becomes worse.

Figure 4 shows optimum electron beam trajectories with the condition of 430 keV energy and 2 A current. The diameter and angle of the incident electron beam are 2 mm and 0 degree, respectivrly, and the magnetic field of the helical undulator is 1.44 kG. In this case; the electron beam can transport whole undulator and enter the decelerating tube without loss of electrons.

## 5. Conclusion

Permanent-magnet helical undulator was designed and constructed for a millimeter-wave free-electron laser. The configuration of the undulator is based on bifilar-type permanent-magnet helical undulator and Halbach-type planar undulator. This new configuration shows 20 % enhanced magnetic field (Bw=1.44 kG) compared with M-2 helical undulator (Bw=1.2 kG). The field error of the undulator is low and smooth adiabatic taperings of the both end side of the undulator field are easily obtained by using stepped soft-iron tube. Period and total length of the undulator are 36 mm and 900 mm, respectively. The bifilar-type P.M. helical undulator can transport low-energy electron beam without loss, which is confirmed by 3-D simulation code. The constructed undulator is extremly compact (diameter 60 mm, length 900 mm) and cost for the construction is more than 5 times lower than planar undulator.

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## Figure captions

Fig. 1. Schematic diagram of the bifilar-type P.M. helical undulator of M-4 configuration.

Fig. 2. Measured magnetic field trace of a fixed azimuthal orientation on the axis of the undulator.

Fig. 3. Measured peak amplitudes of the undulator magnetic field with different azimuthal orientations.

Fig. 4. Electron beam trajectories in the helical undulator calculated by the 3-dimensional simulation code.

## List of Tables

Table 1. Parameters of the constructed undulator.

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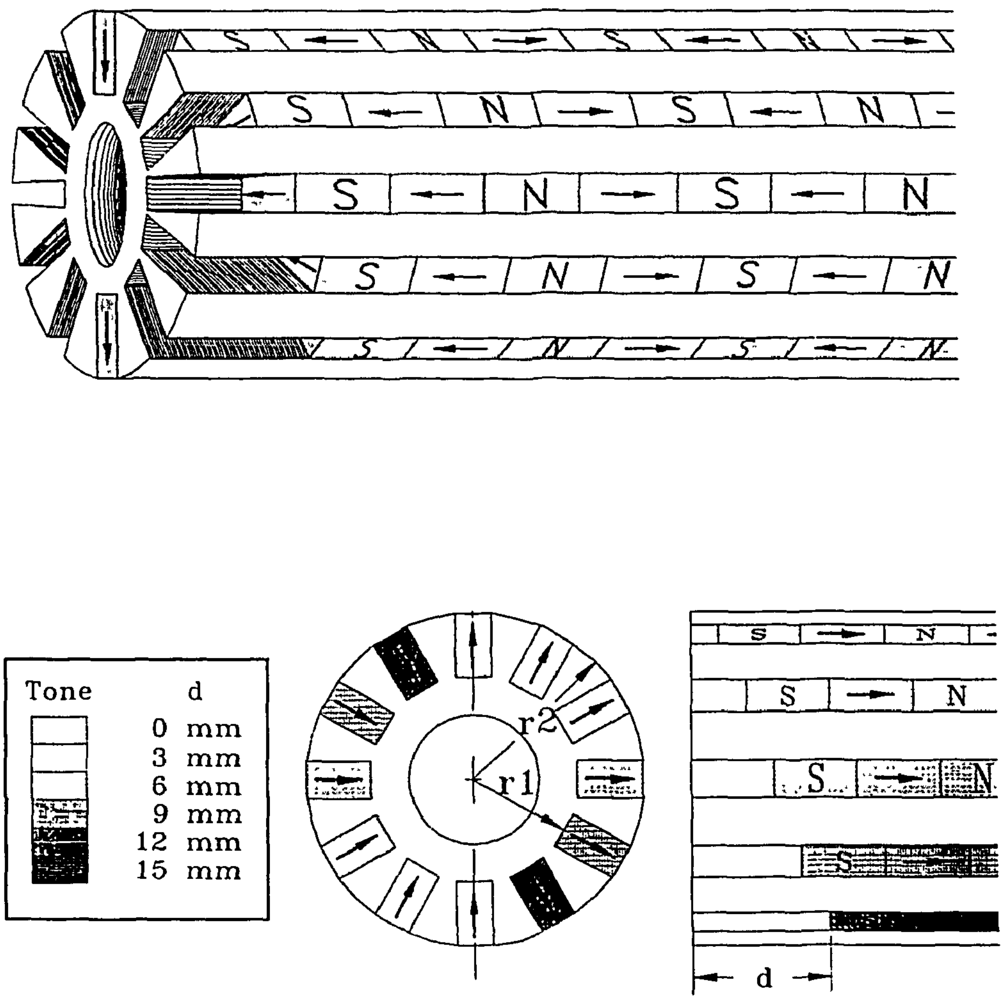
| | |
|---|---|
| Scheme | M-4, bifilar-type P.M. helical undulator |
| Magnetic field | 1.44 kG ± 1.8 % |
| Period | 36 mm |
| Number of periods | 25<br>adiabatic region : 3.5 × 2<br>interaction region : 17 |
| Total length | 900 mm |
| Magnet | Nd-Fe-B<br>size : 4 × 7 × 9 $mm^3$<br>Br : 11 kG ± 1.5 % |
| $R_1$ | 10.7 mm |
| $R_2$ | 18.0 mm |

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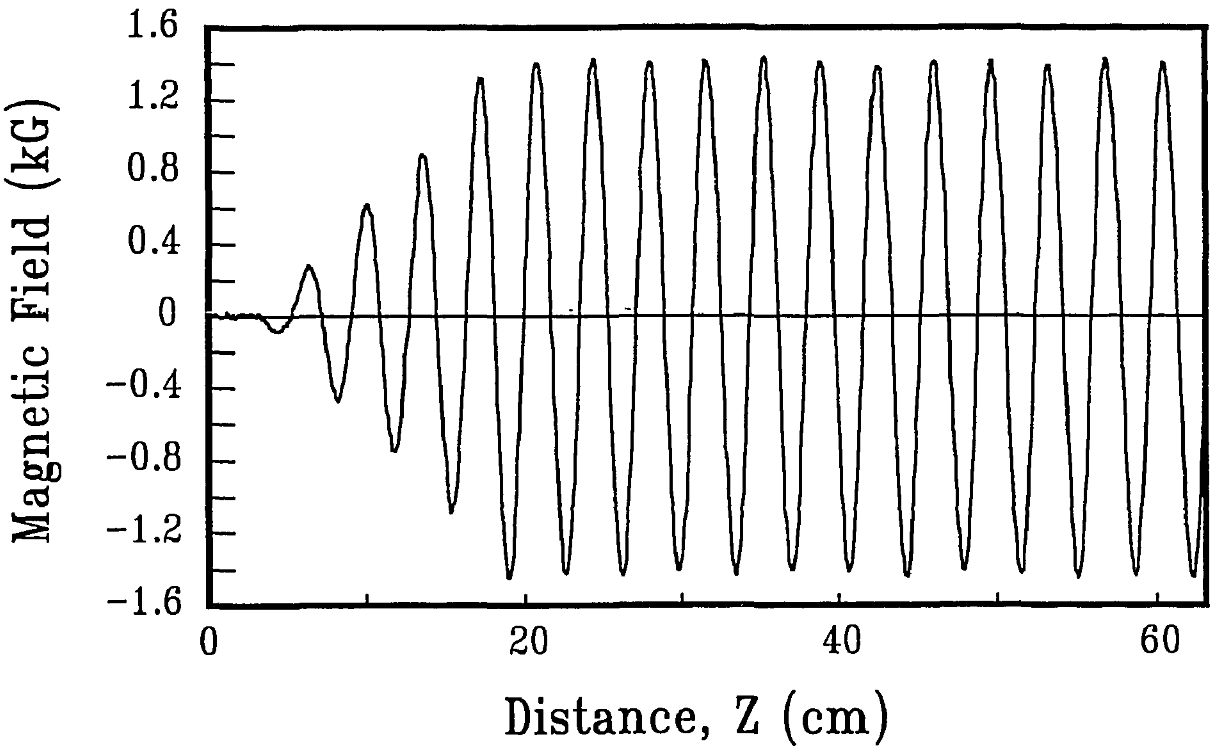
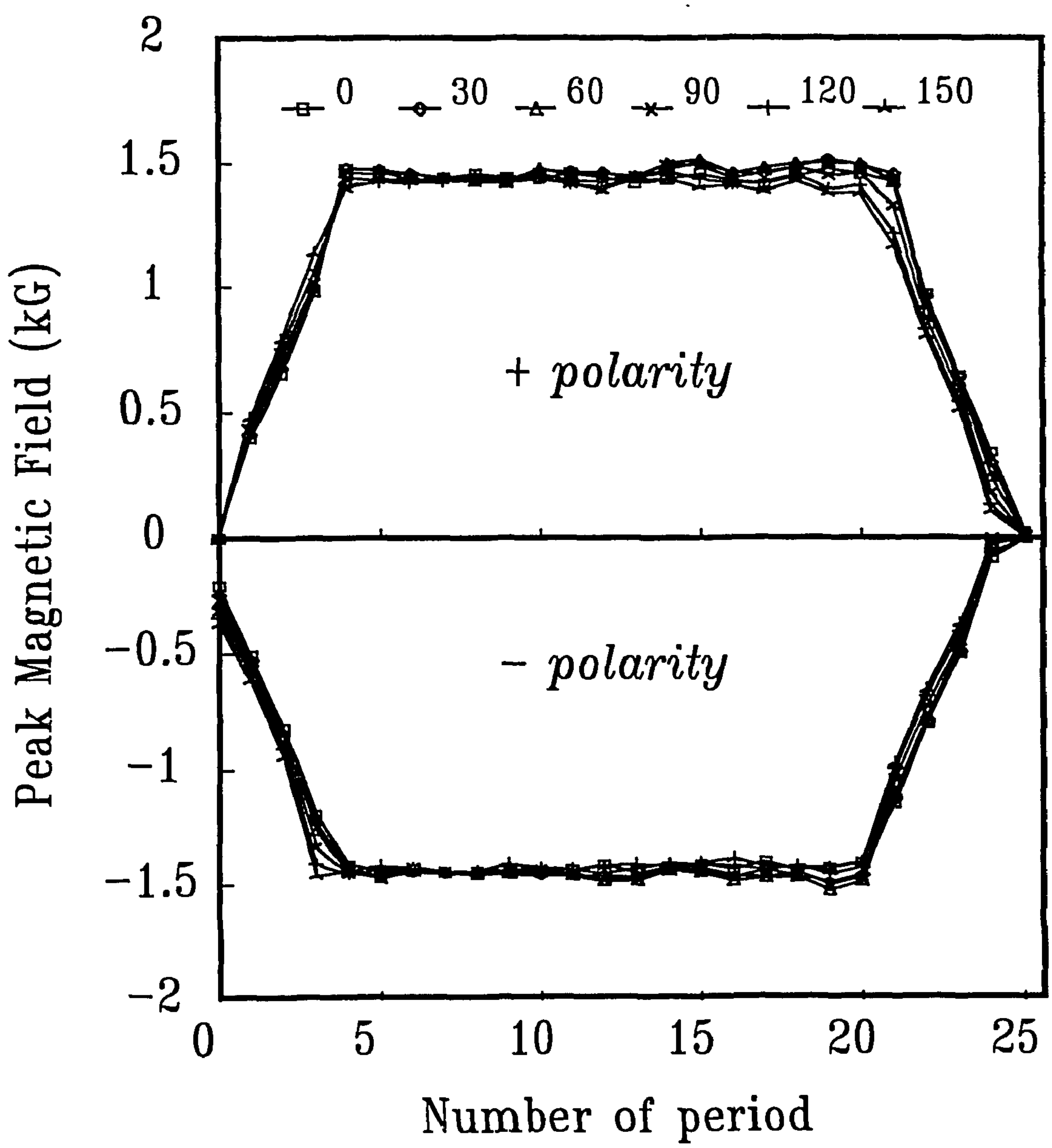



Fig. 2. Measured magnetic field trace of a fixed azimuthal orientation on the axis of the undulator.

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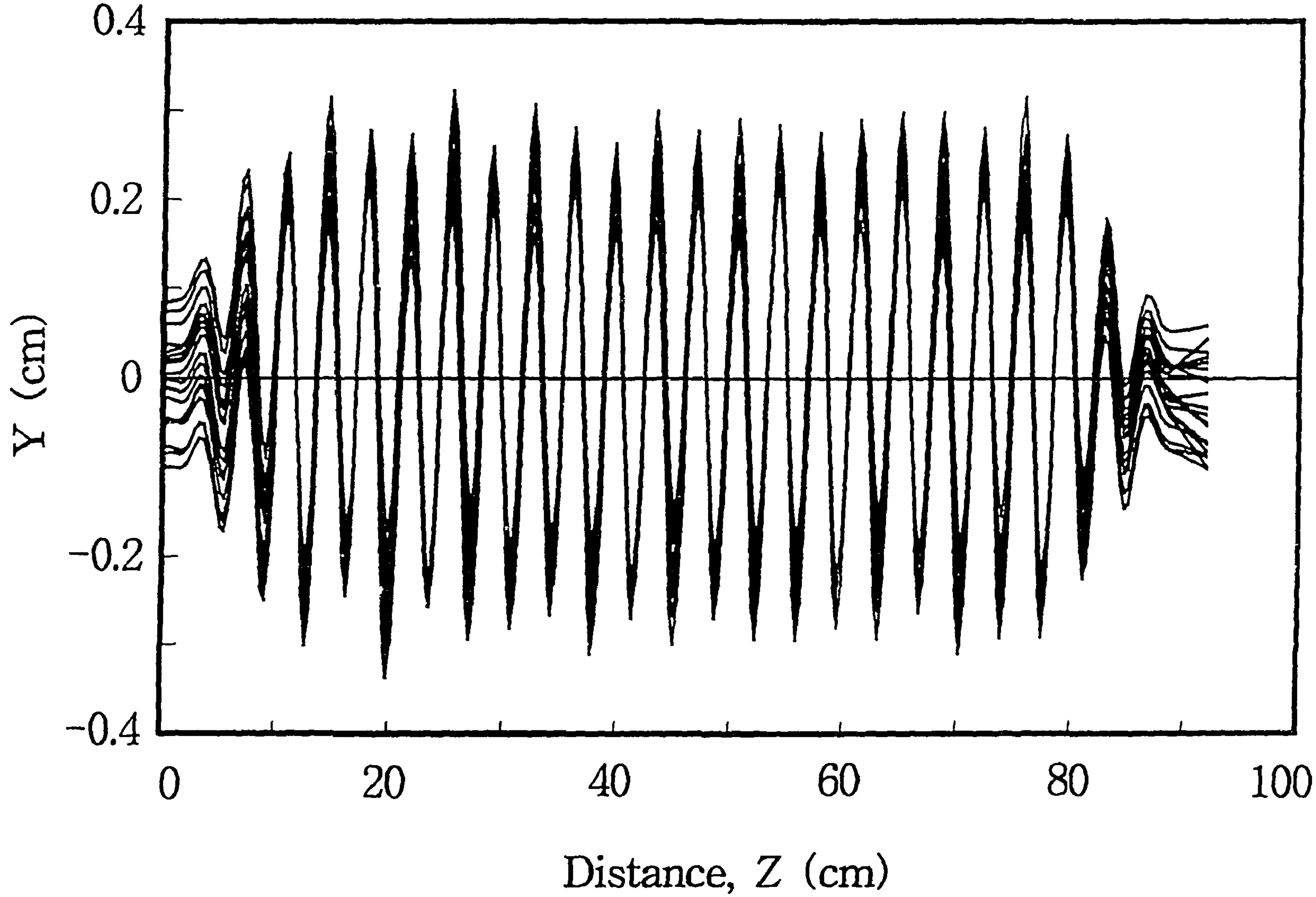


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