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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Short-period equipotential-bus electromagnetic undulator for a far infrared free-electron laser

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Abstract

An equipotential-bus electromagnetic undulator has been developed for a far infrared compact free-electron laser. It has 2 m length, 5.6 mm gap, and 12.5 mm period. The field distribution along the undulator is formed by 2.25 mm thick poles of low-carbon steel with 4 mm thick Nd–Fe–B permanent magnets between them. The amplitude of the magnetic field is up to 6 kG. The variation of current allows us to vary the field amplitude within 10% in a constant gap. For the distribution of the peak amplitude along the undulator we obtained random r.m.s. deviation less than 0.5% without further field correction or individual adjustment of each iron pole or magnet.

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1. Introduction

The Korea Atomic Energy Research Institute has developed a compact far infrared (FIR, 30–50 μm) FEL on the base of 8 MeV, 50 mA microtron [1]. An undulator with a short period, high amplitude of magnetic field, and large number of the periods is required to obtain the FIR radiation with the system. There are strict limitations on the first, second integrals and phase shift in the undulator. It is clear from the following example: 1 G field error at the length of 2 m results in 7.5 mm beam horizontal offset from the center axis of the undulator. However, the beam should meet the following coherence requirements on the deviation and angle of the electron trajectories from center axis [2],

$$\sigma_e < \sqrt{\frac{L\lambda_R}{4\pi}} = 0.6\,\text{mm},$$

$$\sigma'_e < \sqrt{\frac{\lambda_R}{L}} = 4\,\text{mrad},$$

where L (= 2 m) is the total length of the undulator and λ_R (= 30 μm) is the wavelength of the radiation.

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The strict requirements have determined the choice of equipotential bus undulator [3] which is least sensitive to the deviation of permanent magnet (PM) magnetization as compared to any other type of undulator. Only the equipotential bus undulator allows us to obtain the required parameters as it combines the major advantages of both hybrid and electromagnetic (EM) undulators, including high amplitude of magnetic field and short period of the hybrid undulator, as well as low field errors (i.e. deviation of the field amplitude from pole to pole along the undulator) and possibility of the field variation of the electromagnetic undulator.

2. Design of the undulator

Fig. 1 shows schematic drawings of the undulator, its main parameters are listed in Table 1.

To provide the low field errors in the equipotential bus undulator, magnetic induction in the poles should be limited by $B_{\rm pole}^{\rm max} \div 14$–$15\,{\rm kG}$ so that magnetic permeability μ, is larger than 1000. In this case the deviation of the PM magnetization does not practically affect the field errors which are basically determined by the non-homogeneity of the gap along the undulator. The major part of magnetic flux between the adjacent poles is compensated with the help of Nd–Fe–B magnets. For the complete compensation, magnetic induction of the magnets should be zero ($B_{\rm PM} = 0$), and therefore $H_{\rm PM} = H_{\rm cB}$. From this condition, the excitation current in the EM coils is determined as follows:

$$IN = H_{\rm cB} l_{\rm PM}$$

where I is the current, $N = 2$ the number of turns, $l_{\rm PM} = 4\,{\rm mm}$ is the thickness of the magnets, and $H_{\rm cB}$ is coercive force of the PM material.

We shall note that at $H_{\rm PM} = H_{\rm cB}$ the field amplitude is maximum possible for the chosen thickness of the magnets as the raise of the current over this value results in saturation of the poles by the flux through the magnets. The pole width is chosen so as to obtain the maximum field amplitude for the particular period and gap under the limitation on the magnetic induction in the poles.

Besides, the third harmonic of the longitudinal field distribution is also one of the parameters to be minimized. In order to find the optimal ratio between the period and the pole width minimizing the amplitude of the third harmonic, we should analyze the distribution of the scalar magnetic potential along the axis $\psi(z)$ shown in Fig. 2.

Assuming this distribution as a sequence of trapezoids for simplicity, we may write the Fourier expansion for it as follows:

$$\psi(z) = \frac{4\psi_0}{\alpha\pi}\left(\sin\alpha\sin\frac{2\pi z}{\lambda_{\rm u}} + \frac{1}{3^2}\sin 3\alpha\sin\frac{3\cdot 2\pi z}{\lambda_{\rm u}} + \cdots\right), \quad \alpha = \frac{\pi p}{\lambda_{\rm u}},$$

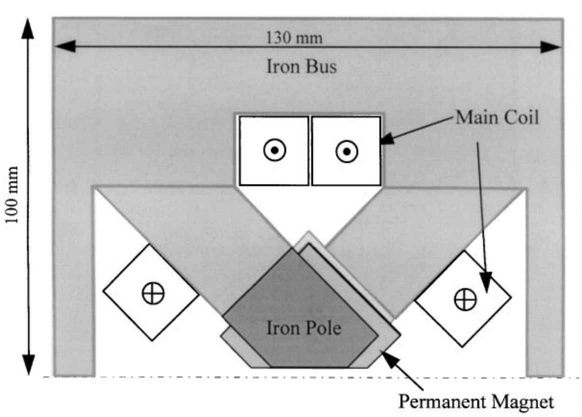

Fig. 1. Upper part drawing of the equipotential-bus EM undulator.

Table 1
Parameters of the undulator

Scheme	Equipotential-bus, electromagnet type
Magnetic field	4.8–5.3 kG
Period	12.5 mm
Number of periods	160
Gap	5.6 mm
Tuning range	10%
Total length	2000 mm
Iron pole	Soft iron Thickness: 2.25 mm
Permanent magnet	Nd–Fe–B Thickness: 4 mm $B_{\rm r}$: 10.5 kG

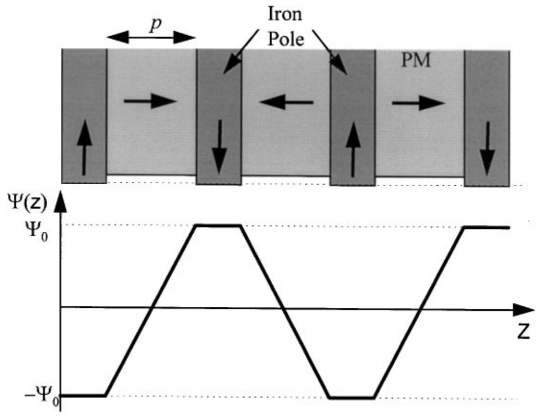

Fig. 2. Distribution of the scalar magnetic potential along the axis through the end surface of the iron pole.

where ψ_0 is the amplitude of magnetic potential at the surface of the poles, λ_u is the period of the undulator, p is the width of the PM, and 2α is the relative PM width in degrees.

Therefore, for the optimal PM width zeroing the third harmonic α should be $p/3$. In this case, omitting the higher harmonics, the magnetic potential may be written as follows:

$$\psi(z) \approx \frac{4\psi_0}{\alpha\pi}\sin\alpha\sin\frac{2\pi z}{\lambda_u}.$$

Defining the distribution of the scalar potential as

$$\psi(y,z) = \sum_{k=1}^{\infty} B_k\frac{\lambda_u}{2\pi k}\sin\frac{2\pi kz}{\lambda_u}\sinh\frac{2\pi ky}{\lambda_u},$$

we may find the amplitude of the first harmonic as follows:

$$B_1 = \frac{(24\psi_0/\pi\lambda_u)\sin(\pi/3)}{\sinh(2\pi y/\lambda_u)}, \quad y = \frac{\text{gap}}{2}.$$

Substituting $y = 2.8\,\text{mm}$, $\lambda_u = 12.5\,\text{mm}$, $\psi_0 = H_{cB}l_{PM}/2$, $H_{cB} = 10.5\,\text{kG}$, we may finally find $B_1 = 5.8\,\text{kG}$. 3D calculation of the undulator on MERMAID 3D code [4] with the use of vanadium permendure as a material of the poles gave the amplitude of magnetic field $B = 5.5\,\text{kG}$.

To determine the range of the field variation with the current in the EM coils, we will consider the dependence of the magnetic flux in the poles on the value of the current. Lowering of the current causes the linear decrease of the field amplitude and raise of the magnetic induction in the PMs which is no longer zero ($B_{PM} > 0$). These effects both result in the rapid drop of the magnetic induction in the poles B_{pole} down to zero with following raise of it but in the direction opposite to the initial. Now we define as $B_{PM} = B_{PM}^{max}$ the maximum value of the magnetic induction in the magnets for which the poles are still not saturated. Therefore, the range of the field variation may be determined from the following condition,

$$B_{pole}^{max}S_{pole} \approx B_{PM}^{max}S_{PM},$$

where S_{pole} is the pole cross-section, S_{PM} is the surface area of the magnet. From this equation, the maximum variation of the current when the poles are still not saturated is found as follows:

$$\Delta I \approx \frac{S_{pole}B_{pole}^{max}l_{PM}}{S_{PM}\,\mu_0\mu_{PM}N},$$

where μ_{PM} is the relative magnetic permeability of PM material which has a value of 1.05 for high coercive Nd–Fe–B. In the case of the short period undulator, the small value of S_{pole}/S_{PM} is inevitable and the 10% change of driving current causes the saturation in iron poles, which limits the tuning range of the undulator field in a constant gap.

3. Measurement results and discussion

The distribution of magnetic field along the undulator was measured by three Hall probes distanced by 5 mm in the transverse direction. The accuracy of the measurements was better than 0.5 G for the field range 0–5 kG and 10^{-4} for the field range 5–21.5 kG. The array of the Hall probes was moved along the axis by a drive mechanism with relative accuracy better than 0.01 mm.

Fig. 3 shows the measured and calculated peak magnetic field on axis of undulator gap as a function of applied current on the main coil. The peak magnetic field on axis of the hybrid configuration can be calculated with $B_r = 10.5\,\text{kG}$, gap of 5.6 mm, and period of 12.5 mm [5]. The value of 4.8 kG is in good agreement with the level of hybrid mode in

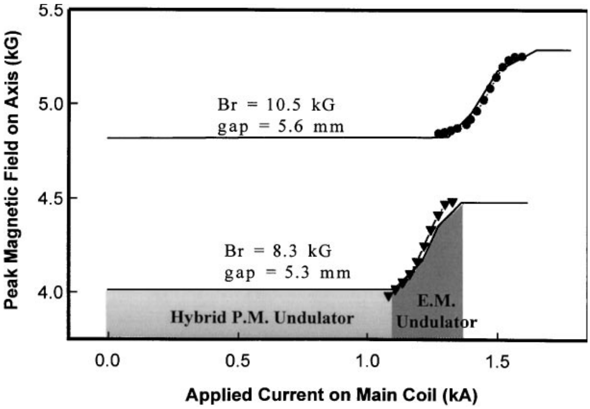

Fig. 3. Calculated (line) and measured (solid circle and triangle) peak magnetic field on axis as a function of applied current on the main coil.

the figure. When the undulator is working in the equipotential bus EM mode, the magnetic field is changed within 10% of the average value above the hybrid limitation.

For the construction of the undulator, we used magnetic blocks having $B_r = 10.5$ kG with magnetization error of $\pm 2.5\%$. To get the higher quality of the field, the end surfaces of the iron poles faced to the gap and spacers were ground to have a gap accuracy of 0.01 mm before positioning the magnets. Deviation of the field amplitude from pole to pole all along the undulator was measured to be less than 0.5% in r.m.s. value without further field correction or individual adjustment of each iron pole or magnet. Fig. 4 shows distribution of the field and the first integral along the axis measured by the central probe. Fig. 5 plots the calculated beam trajectory obtained from the results of the measurements without corrections and after correction. The field was corrected with the help of 8 correction coils equidistantly located all along the undulator so as to minimize the magnitude of the beam deviation from the axis. As a result, the maximum deviation of the beam was reduced almost tenfold from more than 3 mm down to 0.2 mm as shown in Fig. 5.

The field error from the gap accuracy of 0.01 mm is estimated to be 0.25% of the field amplitude. The measured r.m.s. deviation of the field amplitude is

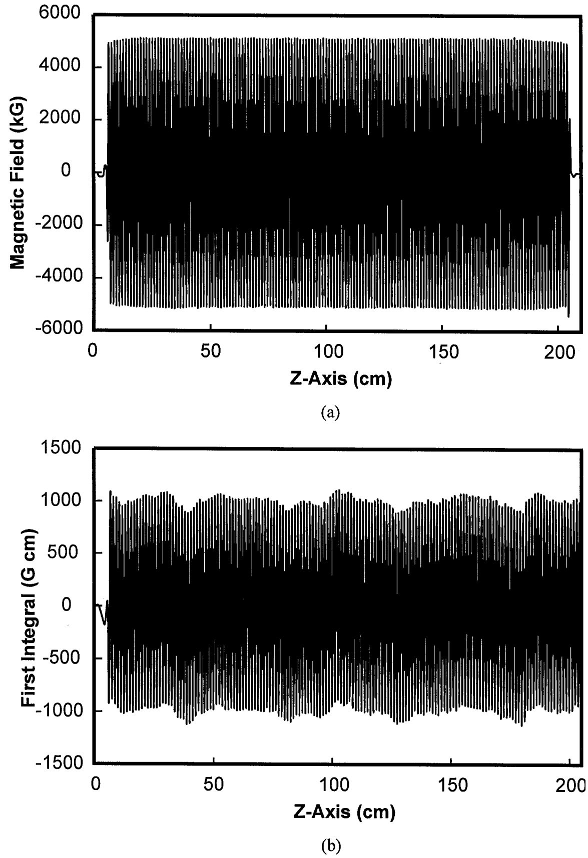

Fig. 4. (a) Measured magnetic field trace of the constructed undulator and (b) the first integral of the field.

higher than that caused by the deviation of the gap. This discrepancy is basically associated with the small thickness of the poles so that the magnetic induction in them is approximately 16 kG which slightly exceeds the reasonable limit. As a result, the magnetic potential at the surface of the poles depends on both magnetization of the magnets and their vertical position relative to the poles. The ends of the magnets are located slightly inside comparing with those of iron pole by 0.2 mm and the accuracy is approximately 0.2 mm. The small region of iron pole uncovered with PM suffers saturation with the strong magnetic induction and the magnetic error can be induced by the differences in distance through the saturation region. The deviation of the field due to the different area of local

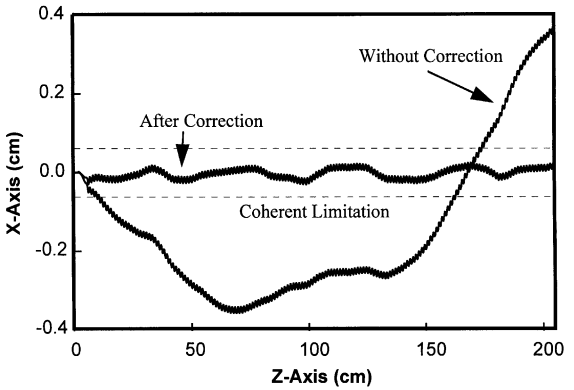

Fig. 5. Calculated electron trajectory obtained from the results of magnetic measurement without correction and with the help of eight correction coils.

saturation can be evaluated as follows:

$$\Delta B_0 \approx B_{i,\mathrm{sat}} \frac{\mu_0}{\mu_{i,\mathrm{sat}}} \frac{\Delta d_{i,\mathrm{sat}}}{g},$$

where g is the gap distance, and $B_{i,\mathrm{sat}}$, $\mu_{i,\mathrm{sat}}$, and $\Delta d_{i,\mathrm{sat}}$ are magnetic induction, relative permeability, and distance deviation of the saturated region, respectively. With the values of saturated iron, $B_{i,\mathrm{sat}} = 20\,\mathrm{kG}$, and $\mu_{i,\mathrm{sat}} = 100$, the field error due to the level deviation between the end of pole and magnets is estimated to be 0.2%. The error can be reduced significantly by using a pole made of high er permeability material such as vanadium permendur.

4. Conclusion

We have developed a short-period equipotential-bus EM undulator for a compact FIR free-electron laser. We obtained 0.45% of the r.m.s. deviation in the magnetic field amplitude from pole to pole all along the undulator for 0.01 mm mechanical accuracy of the gap. The first and second integrals were zeroed with the help of correction coils so as to keep the deviation of the beam trajectory from the axis and the beam angle far within the coherent conditions.

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