DEVELOPEMENT OF 10-T SUPERCONDUCTING WIGGLER FOR ANGIOGRAPHY AT TERAS

S. Sugiyama, H. Ohgaki, M. Mikado, T. Noguchi, K. Yamada,
M. Chiwaki, R. Suzuki, M. Koike, T. Yamazaki, and T. Tomimasu[a)]
Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba City, Ibaraki 305
T. Keishi, H. Usami and Y. Hosoda
Sumitomo Electric Industries,Ltd., 1-1-3,Shimaya, Konohana-ku, Osaka 554

Abstract

The design of a 10-T superconducting wiggler as synchotron radiation source for angiography has been carried out to be installed in a 800-MeV electron storage ring, TERAS, at Electrotechnical Laboratory (ETL). The magnet of the wiggler consists of three pairs of iron-cored superconducting coiles designed to provide a peak field of 10.5 T on the beam trajectory. The effect of the wiggler on the storage ring has been investigated and a pair of quadrupole doublet on both sides of the wiggler can compensate large deviation of betatron tune.

Introduction

Digital subtraction angiography (DSA) with synchrotron radiation has become a powerful and non-inversive method to investigate heart disease.[1-3] So far, high energy storage rings are required to produce hard X-rays at 33 keV in sufficient intensity. For a dedicated synchrotron radiation source a smaller storage ring at reduced cost would be desirable. In this case, a powering superconducting wiggler leads the problem of intent effects on stored electron beams and stable operations become difficult.[4]

The development of a 10-T superconducting wiggler has been proposed as a 33.17-keV photon source for DSA. The 10-T wiggler is going to be installed at a straight section of ETL 800-MeV storage ring, TERAS, with the diameter of about 10 m.[5] The length of straight section is 1.8 m. The critical photon energy of synchrotron radiation generated with the wiggler is 4.47 keV. The present paper, the construction of the wiggler magnet is described, and the influence of the wiggler on stored beams is discussed.

Construction of a superconducting wiggler magnet

Main design concepts of the superconducting wiggler magnet have been a central field of 10 T, a periodicity around 500 mm, a total length of the system less than 800 mm, and accepted value of the field integral less than 10^{-3} Tm. Iron-cored coiles and relatively small pole gap are needed in order to meet these specifications.

Table I. The parameters of 10-T wiggler magnet

Maximum field on the beam axis	main coil 1	10.5	T
	auxiliary coil	5.5	T
Critical photon energy (E=0.8GeV)		4.57	keV
K parameter (Kmax)		352	
Period length		228	mm
Effective length		386	mm
Full gap	Magnetic pole	37	mm
	Vacuum chamber	25	mm
Horizontal aperture (vacuum chamber)		181	mm
Wiggler length	Magnet	684	mm
	Overall length	790	mm
Iron core		no carbon steel	

Coil	Coil name	main	aux.
	Maximal field(T)	10.5	5.5
	Density (A/mm^2)	301	-152.8
	Overall current(A)	370	-187.5

The wiggler magnet consists of three pairs of superconducting coil in which the central pair of coil produces a high magnetic field, and the auxiliary pairs prove the cancellation necessary to satisfy the beam stability of the storage ring. The overall view of the magnet assembly and the longitudinal cross-section can be seen in Figure 1. Three pairs of coils have coil straight section and racetrack end turn arrangements. They are arranged in parallel perpendicular to the electron beam axis.

The coils are wound onto bobbin frames that are made of stainless-steel. These modules are inserted to soft iron pole pieces with reasonable magnetic and mechanical property. The coils are also surrounded by iron yoke to pass magnetic flux and to support the coils. The iron yoke also works for a screening of stray field.

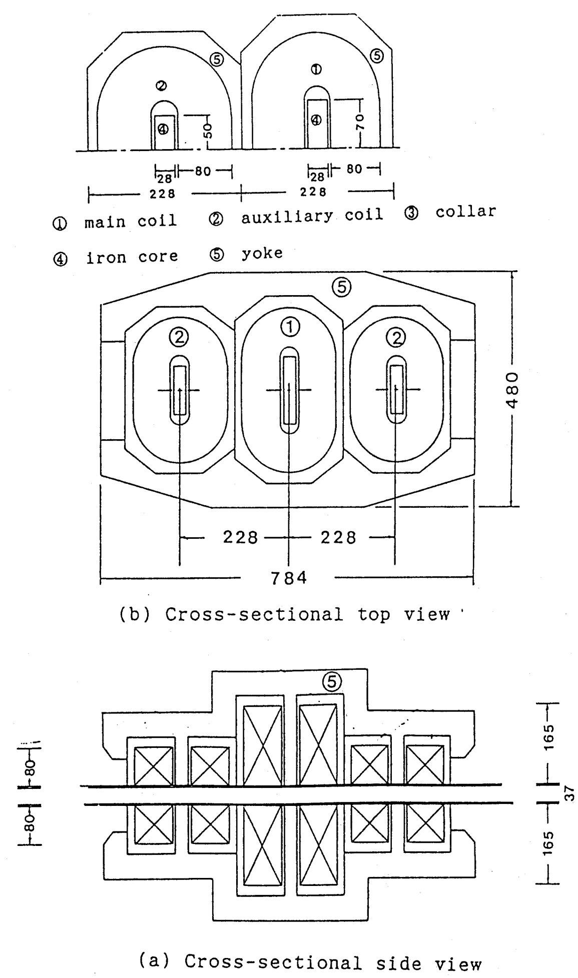

Fig. 1. Structure of the wiggler magnet

The winding coils are made of Nb_3Sn superconductor with the diameter of 1.25 mm and with critical current of nominal 900 A/mm^2 at magnetic field of 10 T. Current density can be determined in order to optimize the field/current characteristic of the conductor. The safety margin between the operating current and the conductor short sample value at the maximum field in the winding is limited under 40 %. In this way, the maximum overall current is determined to be 380 A. The turn numbers of main and auxiliary coils are 7500 and 3800, respectively. The cross-sections of these coils are 80 mm wide and 165 mm high, and also 80 mm wide and 80 mm high, respectively. The lower and upper poles of the coiles are joined with a separated gap of 37 mm to form the dipole block of superconducting magnets.

The use of the iron poles and yoke makes it possible to produce the peak magnetic field of 10.5 T that is higher than the corresponding value when no iron is used. The two auxiliary coils can produce nominal field strength of 6.5 T. In order to minimize the focusing effect on the electron beam, the wiggler period length is limited to 456 mm, a total length of the wiggler less than 800 mm. A sufficient field homogeneity over the beam aperture is attained by making the coil straight section long and wide enough. The straight sections of main coil and auxiliary coil are 140 mm and 100 mm, respectively.

The parameters of 10-T wiggler magnet are shown in Table I.

Effects on the electron beams

The trajectory of electron beam under the magnetic field was calculated. The vertical component of magnetic field is obtained for the case that no iron is used and magnetic field is produced only by coil winding. Figure 2 shows the electron beam trajectory and vertical magnetic field on the electron trajectory for 800 MeV electron beams. The forth order Runge-Kutta method is used in the calculation of the electron trajectory. The field strength along the beam trajectory has been adjusted to make the integrated value given by the following equations (a) and (b) nearly equal to zero. The value obtained from the curve B(s) of Fig.4 is given as follows:

$$\int B(S)\,ds = 3.3\times10^{-6}\ (\mathrm{Tm}) \qquad (a)$$

$$\int \int^{s} B(s')\,ds'ds = 5.4\times10^{-5}\ (\mathrm{Tm}) \qquad (b)$$

where the integrand is taken all over the length of the wiggler, s is the distance along the electron beam axis, B(s) is vertical magnetic field in T. These values are considered to be small enough not to affect the electron dynamics in the storage ring.

The radius of curvature of an electron at the middle of main coil (where the field strength is 10.5 T) can be obtained from the following equation:

$$\rho = 3.36E/B = 0.256\ (\mathrm{m})\ \text{for}\ E=0.8\ (\mathrm{GeV}),\quad B=10.5\ (\mathrm{T})$$

where ρ is radius of curvature in m, E is electron energy in GeV, B is vertical magnetic field in T.

The influence of the wiggler on particle motion in the storage ring is the appearance of the shift of betatron tune. The wiggler introduces vertical focusing effect on the electron beam and therefore changes the vertical tune. If the wiggler field were perfectly dipole, the tune shift would be given by:

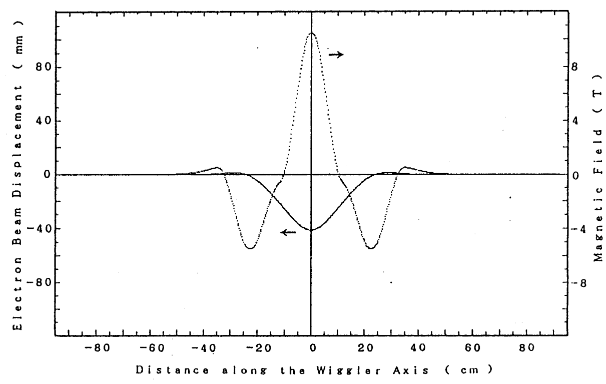

Fig. 2. Beam trajectory at electron energy of 800 MeV and vertical distribution of magnetic field along the beam axis at the peak field strength of 10.5 T in the main magnet

$\Delta\nu_x = 0$, and

$$\Delta\nu_y = (1/4\pi)\langle\beta_y\rangle(0.3/E)^2 \int_{L/2}^{L/2} B(s)^2 ds$$

where the symbol < > represents the average in the wiggler, E is the electron energy in GeV, B(s) magnetic field in T, L the length of the wiggler.[6] At 800 MeV this equation gives a tune shift of about 0.43 that implies the strong influence of the wiggler on the operation of the storage ring. Large magnitude deviation of the betatron tune requires quadrupole lens triplets adjustments all over the storage ring and a new couple of quadrupole doublet on the both sides of the wiggler.

Figure 3 shows some of the tune-diagrams of the storage ring. Here the two-dimensional (s-x) wiggler central plane is divided into small rectangular elements of width of 48.0 mm along the longitudinal axis. Within each element, the strength of the magnetic field is assumed to be uniform. Incidence-angle and deflection-angle of an electron upon passing through each element are obtained from the electron trajectory shown in Fig. 3. The tune shift due to the wiggler is calculated from the transfer matrix of all lattice elements of the storage ring.

In this calculation, it is found that the stable region of the tune diagram almost vanishes when the wiggler works. To overcome this problem, a pair of a quadrupole doublet, Q1 and Q2, are installed on the both sides of the wiggler. Figure 4 shows the tune diagrams and the scheme for spacing the wiggler and a pair of quadrupole doublet to correct beam orbit. Fig. 4 (a) shows the tune diagram on no operation of the wiggler. Fig. 4 (b) and (c) display the diagrams at the wiggler magnetic field of 10.5 T, the focusing strengths of quadrupole doublet (Q1: 0.3, Q2: -0.1) and (Q1: 0.77, Q2: 0), respectively, at beam energy of 800 MeV. It should be noted that the wiggler causes the collapse of the tune diagram of the storage ring and forms the stop-band along the resonance line in the diagram. Fig. 4 shows also that the adjustment of focusing strength of the quadrupole magnets is effective to enlarge the stable region of the tune diagram.

The betatron functions β_x and β_y and the dispersion function η are calculated with the use of the computer code MAGIC[7]. Figure 5 shows the these functions when the wiggler is powered and not powered. It should be noted that the vertical amplitude of electron beam increases at the center of the central magnet on the operation of the wiggler. This beam blow-up can be reduced by a joint action of the magnet field of the wiggler and quadrupole gradient being changed.

Conclision

The 10-T superconducting wiggler provides the SR with the critical photon energy of 4.47 keV. The wiggler strongly affects the electron beam of the storage ring. The intense effect of the wiggler on the storage ring can be reduced by using a set of quadrupole magnets installed in both sides of the wiggler.

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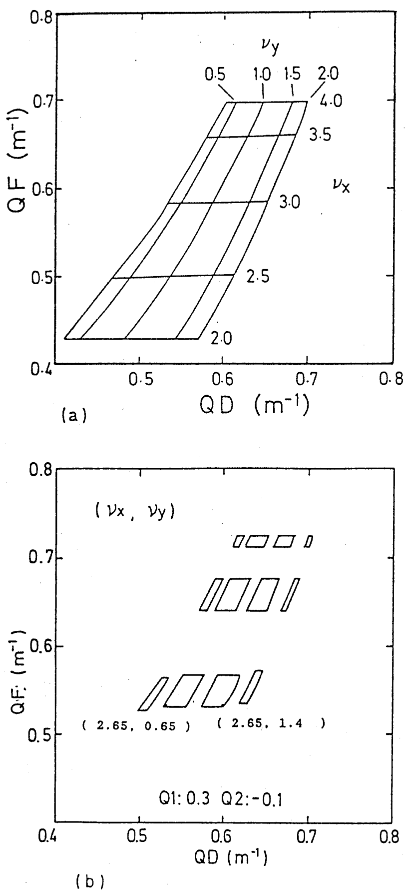

Fig. 3. The tune diagrams of the storage ring and the arrangement of the wiggler.The tune diagram (a) is obtained on no operation of the wiggler, the diagrams (b) wiggler magnetic field of 10.5 T, the focusing strength of (Q1: 0.3, Q2: -.1).

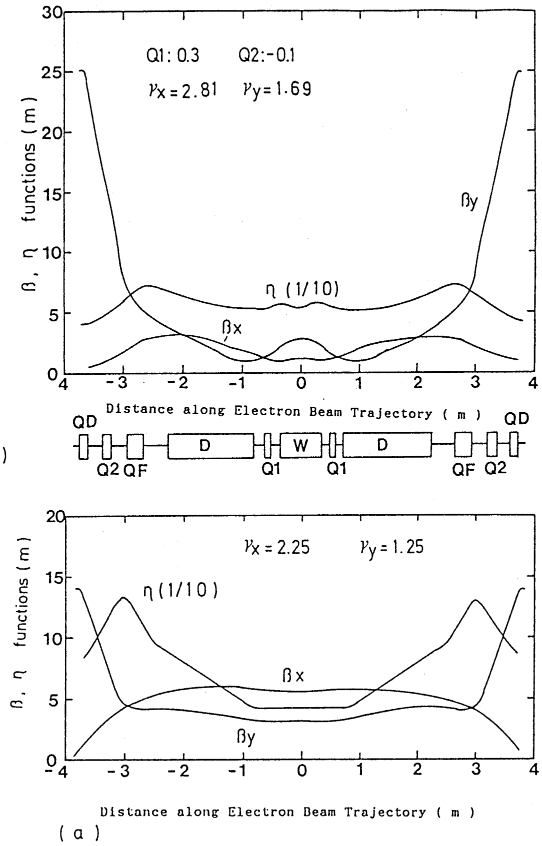

Fig. 4 The betatron functions and the dispersion functions,(a): when the wiggler is not powered, (b): at the wiggler magnet field of 10.5 T and the focusing strength of the quadrupole magnets (Q1: 0.3, Q2:-0.1).

References

a)Present address: FEL Engineering Co., 2-7-4 Kyomachibori, Nishi-ku, Osaka City, 550 Japan

1 T. Tomimasu, SPIE, Vol.1140 X-Ray Instrumention, 207 (1989)

2 A. C. Thompson, R. Hofstadter, J. N. Otis, H. D.Zeman, R. S. Kernoff, E. Rubenstein, J. C. Giacomini, H. J. Gordon, G. S. Brown, and W. Thomlinson, Nucl. Instrum. Methods A266 252 (1988)

3 R. K. Smither and E. M. Westbrook, Nucl. Istrum. Methods A266 260 (1988)

4 G. Kulipanov, "First ICFA School on Beam Dynamics and Engineering of Synchrotron Light Sources", (7-18 May 1990)

5 T. Tomimasu, "TELL-TERAS Activity Report 1987 -1990,"ElectrotechnicalLaboratory,p.19, (December 1990)

6 M. W. Poole and R. P. Walker, IEEE Trans. Nucl. Sci.NS-32 3374 (1985)

7 A. S. King, M. J. Lee and W. W. Lee, SLAC-183 (1975)