

# THE ELLIPTICAL MULTIPOLE WIGGLER PROJECT

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## ABSTRACT

The elliptical multipole wiggler (EMW) has been designed, constructed, and installed in the X13 straight section of the NSLS X-ray Ring. The EMW generates circularly polarized photons in the energy range of 0.1-10 keV with AC modulation of polarization helicity. The vertical magnetic field of 0.8 T is produced by a hybrid permanent magnet structure with a period of 16 cm. The horizontal magnetic field of 0.22 T is generated by an electromagnet, the core of which is fabricated from laminated iron to operate with a switching frequency up to 100 Hz. There are dynamic compensation trim magnets at the wiggler ends to control the first and second field integrals with very high accuracy throughout the AC cycle. The residual closed orbit motion due to the electromagnet AC operation is discussed.

## I. INTRODUCTION

An elliptical multipole wiggler with an AC electromagnet has been selected for the NSLS X-Ray Ring to generate x-ray radiation in the energy range of 0.1-10 keV with time-dependent polarization [1,2]. The AC elliptically polarized wiggler will make it possible to detect the very weak signatures of circular dichroism and other effects associated with right- vs. left-handedness of some physical systems. In order to generate polarized photons near the upper limit of the energy spectrum, the vertical deflection parameter  $K_y$  should approach a value of about 12, corresponding to a hybrid wiggler peak field of 0.8 T. Since there is a trade-off between the on-axis photon flux and degree of circular polarization, the horizontal parameter  $K_x$  should be optimized for each specific experiment. For this electromagnet, the maximum design value of  $K_x$  is about 2.5 at a current of 1 kA.

Originally, the EMW as a source of circularly polarized photons was proposed by Yamamoto and Kitamura [3]. Their device consisted of permanent magnet wigglers with crossed fields capable of generating circularly polarized radiation with higher harmonics on the wiggler axis. The next step in the development of EMW design was made by Walker and Diviacco [4] who suggested replacing the horizontal permanent magnet structure by an AC electromagnetic wiggler to modulate in time the helicity of the on-axis circularly polarized radiation.\*\*

To increase the measurement accuracy of the asymmetry between the effect of left and right circularly polarized radiation, the modulation frequencies should be located in the

\*\* The first proposal to use an electromagnet to vary the helicity of undulator polarized radiation was made by Onuki [5].

ranges with the minimum spectrum power density of closed orbit noise. From this point of view, for the NSLS X-ray Ring, the preferable modulation frequencies are:

$$0 < f_{\text{mod}} < 10 \text{ Hz and } f_{\text{mod}} \sim 100 \text{ Hz.}$$

Great care has been taken in the design of the EMW to minimize the orbit disturbance generated by its operation. The following requirements for field integrals of the electromagnetic structure have been imposed:

$$\int_0^{L_w} B_x(z, t) \cdot dz \leq \pm 1 \text{ Gauss} \cdot \text{cm} \quad (1)$$

$$\int_0^{L_w} d\tilde{z} \int_0^{\tilde{z}} B_x(z, t) \cdot dz \leq \pm 100 \text{ Gauss} \cdot \text{cm}^2 \quad (2)$$

Where  $B_x(z, t)$  is the AC horizontal magnetic field,  $z, \tilde{z}$  are longitudinal coordinates, and  $L_w$  is the wiggler length.

In the X-Ray Ring, these field integral limitations restrict the vertical closed orbit motion to be less than 1.5 micron. These requirements are applied for the modulation frequency range up to 100 Hz and must hold throughout the AC cycle. Both wiggler magnetic structures were optimized in a magnetostatic approximation by means of the 3-D code TOSCA. The computer simulations of power dissipation due to eddy currents induced in the design elements of EMW were carried out with the 3-D code ELECTRA.

## II. HYBRID STRUCTURE

The vertical magnetic field is produced by a hybrid wedge-pole configuration consisting of Nd-Fe-B rectangular magnetic blocks and vanadium-permendum wedge poles. One pole and two permanent magnets form a half-period block, each of which is mounted on an iron backing beam between iron "neutral" poles having zero scalar potential (Figure 1.)

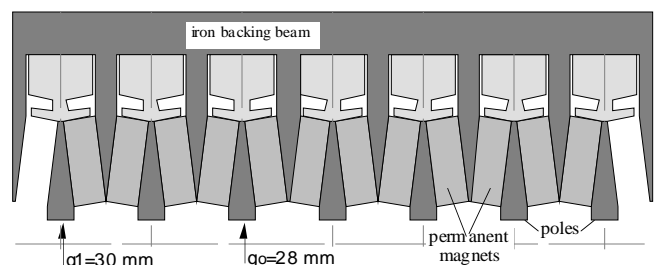


Figure 1. The wedge-pole hybrid configuration

Five full-field and two half-field poles produce a mirror-symmetric magnetic field distribution with a period length of 16.0 cm. A peak field magnitude of 0.8 T at a minimum gap  $g_0$  of 28.0 mm was achieved. The nonsteering termination was realized with the magnetic gap  $g_1$  increasing by 2 mm at the half-field poles. The upper and lower hybrid assemblies are attached to independent drive trains, providing a continuously variable gap motion from a minimum of 28.0 mm to a maximum of 160 mm. At an extreme AC regime, when the electromagnet is energized with 100 Hz alternating current with an amplitude of 550 A, the computed total losses due to eddy currents induced in the vanadium-permendum poles, the permanent magnets, and the iron "neutral" poles can reach about 60 W per wiggler period.

### III. ELECTROMAGNETIC STRUCTURE

The electromagnetic structure generates a periodic alternating horizontal magnetic field of antisymmetric configuration in order to provide the periodic vertical beam trajectory deflection along the wiggler. The electromagnet includes six uniform poles with a magnetic gap of 54 mm and end structures consisting of two poles at each side. The current excitation is provided by means of two water-cooled, "snake-type" coils [6] with a copper cross section of about 140 mm<sup>2</sup>. The magnetic gaps of the end structure poles and number of turns around the first and last poles are different from those in the main periodic structure. This end structure performance was designed to attain a nonsteering {first field integral, Eq. (1)} and a displacement-free {second field integral, Eq. (2)} termination provided that the pole strength pattern is close to theoretical 1/4 : 3/4 : 1. The iron cores of the first and last poles are separated from the main yoke and are provided with adjusting systems to vary their magnetic gaps. To reduce the generation of eddy currents, the yoke of the electromagnet was constructed from 0.5-mm-thick laminations of transformer iron with a silicon content of 3.5%. At the extreme regime ( $I=0.55$  kA and  $f_{\text{mod}}=100$  Hz), the computed power loss does not exceed about 5 W per wiggler period.

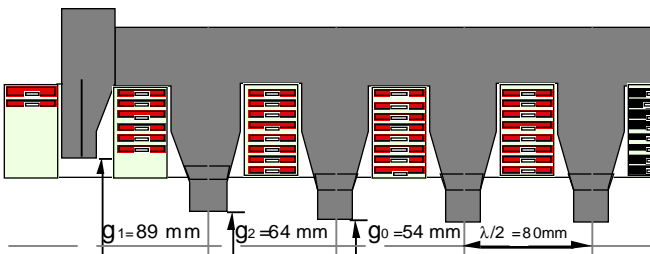


Figure 2. Electromagnetic structure design.

### IV. VACUUM CHAMBER

The vacuum chamber of the EMW was manufactured by the deformation of a stainless steel circular pipe to an elliptical cross section of inner dimensions: major axis of 50 mm and minor axis of 25 mm. To decrease the eddy current losses in the vacuum chamber, a wall thickness of 0.6 mm was chosen as the minimum possible from a mechanical collapse point of view. The power dissipation computed by ELECTRA does not exceed 0.8 W per wiggler period at the extreme AC regime.

### V. POWER SUPPLY FOR ELECTROMAGNET

The principle of forced DC current commutation is used in the power supply for the electromagnetic structure. It consists of a thyristor-stabilized DC power supply as an initial current source and a commutator based on the fast thyristor bridge-inverter. The bridge-inverter output is connected to the electromagnet coil in parallel with capacitor. This scheme is designed to supply the electromagnet by direct current or by trapezoidal shape alternating current with a switching frequency range from 0 up to 100 Hz. The switching time (current polarity reversing time) does not exceed 2 msec, and it retains the same duration up to the upper limit of switching frequencies. The power supply can provide an output current range of 0.2 - 1.2 kA with the current magnitude difference between both polarities less than 0.5%.

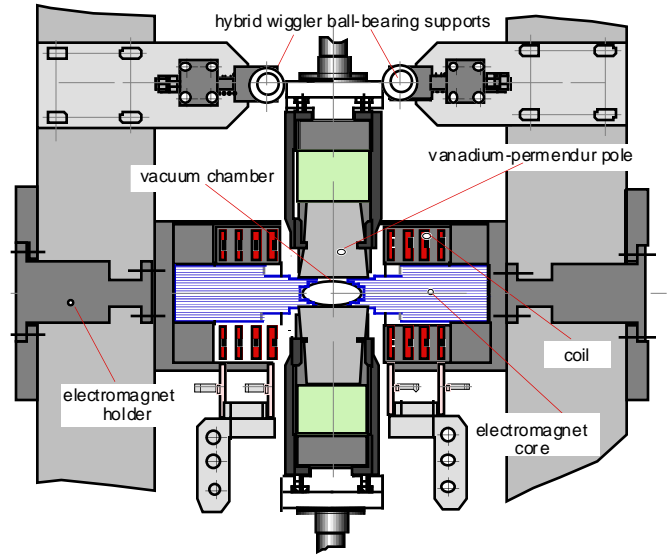


Fig. 2. Side sectional view of the elliptical multipole wiggler.

### VI. TIME-DEPENDENT WIGGLER FIELD INTEGRALS

The electromagnet design includes some nonuniformities related mostly to anti-symmetric locations of the coil current leads. In turn, these nonuniformities give rise to a disturbance of the ideal antisymmetric magnetic field configuration at both ends of the electromagnetic structure. This effect has been corrected easily for DC operation by means of the passive gap adjusting systems at the end poles. However, during switching, periodic time-dependent components arise for both the first and second field integrals. Due to the slightly different geometry of the electromagnet ends, the eddy currents induced in the copper turns, the iron elements of hybrid structure, and the vacuum chamber lead to different magnetic field time delays along the wiggler, hence, to different conditions of field integral compensation at each time moment.

On the other hand, the surroundings of the electromagnet include some conductive elements with a thickness a few times the skin depth at frequencies corresponding to the switching time (0.5 kHz). As the switching frequency is increased, the time of magnetic field diffusion through these materials becomes comparable or greater than a half-period of current pulse. It is obvious that the time-dependent

components of integrated fields should have different behaviors and magnitudes for each range of switching frequencies. Besides, there is a relatively weak saturation in periodic structure poles that can cause a nonlinear behavior of the time-dependent field integral components at the higher current amplitudes (above 0.6 kA).

Moreover, a strong magnetic coupling between both magnetic structures leads to time modulation of the field integrals in the hybrid wiggler. This effect was experimentally observed during magnetic field measurements. Because electromagnetic poles are arranged directly opposite to the "neutral" poles of hybrid structure, some part of the magnetic flux shunts into the adjacent iron. The magnetization of the thin "neutral" pole tips alternates periodically with the horizontal field. Consequently, in the areas of the tip that are magnetically saturated, there is a time modulation of the magnetic conductivity in the perpendicular direction. This, in turn, leads to a time variation of the integrated field in the hybrid structure. The magnitude of the vertical field time-dependent component has a complicated nonlinear dependence on the magnetization amplitude but its sign does not depend on the sign of alternating magnetization field. Results of magnetic field measurements for both structures at the DC and AC electromagnet modes are presented in detail in [8]. The above mentioned reasons forced us to develop an active system for dynamic compensation of the time-dependent integrated field components.

## VII. DYNAMIC COMPENSATING SYSTEM

The active system consists of two trim magnets mounted at each side of the EMW and separately powered by computer-controlled special bipolar power supplies (BPS). The sum of the electromagnet shunt signal and synchronous arbitrary function generator (AFG) signal is used as a reference voltage for the BPS. As a result, the current of each trim magnet follows the current shape in the electromagnet main coil during the entire AC cycle. Since the time-dependent components of field integrals are periodic in time and rigidly connected to switching frequency, the trim magnet current wave form can be corrected by a synchronous pulse with a programmed shape (AF). The AF technique was originally developed for the APS synchrotron correction magnets [7] and has been incorporated in this active system. The shape of the AF is based on magnetic measurement data but can be programmed using the information from storage ring BPMs. Results of the compensation of the time-dependent integrated field by the active system obtained at the magnetic measurement stage are described in [8].

## VIII. BEAM STUDIES AT NSLS X-RAY RING

The first beam studies have been carried out at modulation frequencies of 2 and 100 Hz. The effect of the EMW on the tune shift and beta-function distortion is negligibly small. For the beam orbit distortion studies, a number of tools, such as the NSLS X-ray Ring BPMs, spectrum analyzer, and photon beam monitor, were used. Dynamic compensation of the time-dependent integrated field of electromagnetic structure has been attained within the requirements expressed by Eqs. (1) and (2) at the 2 Hz AC mode and current amplitude of 0.4 kA. With the active system switched off, the initial rms amplitudes of the closed orbit oscillation reached:

$$a_y \approx 13\mu \text{ and } a_x \approx 4.9\mu.$$

Using the compensation current feedback additionally corrected by the AFG, the vertical orbit motion was suppressed down to an rms amplitude of 1.1 micron. After turning on the storage ring global feedback, the residual rms amplitudes of the beam orbit noise corresponding to modulation frequency of 2 Hz were reduced and did not exceed:

$$a_y \leq 0.2\mu \text{ and } a_x \leq 0.5\mu.$$

These spectrum amplitudes correspond to the beam orbit angle rms errors at the straight section within the angles of:

$$\Delta y' \leq \pm 0.75 \cdot 10^{-7} \text{ rad} \text{ and } \Delta x' \leq \pm 2 \cdot 10^{-7} \text{ rad}.$$

It is necessary to note that the horizontal orbit motion caused by the time-dependent field component of the hybrid wiggler was suppressed only by means of global feedback. At the 100 Hz AC mode, the compensation of the horizontal time-dependent component related to the second field integral is in good agreement with the magnetic measurement data. The corresponding residual spectrum amplitude of beam noise did not exceed 1.1 micron. However, there were some difficulties in compensating the time-dependent first integral component. The beam orbit motion measurement synchronized with the switching frequency showed a phase misalignment between the AF and current pulses. Probably, this effect was due to a lengthening of transmission line between the EMW and power supply that caused changing of the current pulse rise rate. Since the global feedback is not effective at frequencies as high as 100 Hz, a new 2-D compensation active system is being developed to suppress the time-dependent field integral components of both the electromagnetic and hybrid structures. A 2-D Panofsky's-type dipole has been chosen as an optimal trim magnet for the new active system. This system is under construction, and it will be installed in the EMW in the near future. After its adaptation, the beam studies at the frequency of 100 Hz will be continued to attain the restrictions for orbit motion specified by Eqs. (1) and (2) for both the horizontal and vertical betatron plane.

## IX. ACKNOWLEDGMENTS

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