

DEVELOPMENT OF A MAGNET SYSTEM TO CANCEL THE ATTRACTIVE FORCE TOWARD STRUCTURAL REFORM OF UNDULATORS

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Abstract

Toward realization of a new undulator concept based on a much more compact and lightweight structure than conventional ones, cancellation of a magnetic attractive force is being studied, which significantly relaxes the requirements for the undulator mechanical design and reduces the cost and lead time of construction and installation. We have proposed to add periodically-magnetized monolithic magnets beside the main magnets generating the undulator field and attractive force, which are expected to generate a repulsive force having the same gap-dependency as the attractive force in a cost-effective way. The present status of the development of the force cancellation system is presented, with a focus on the result of preliminary experiments using the periodically-magnetized magnets. Also introduced is a development plan for the compact and lightweight undulator based on the cancellation system.

INTRODUCTION

It is well known that a large attractive force is generated between the top and bottom magnetic arrays of undulators, if the gap in between is relatively narrow. For example, a typical undulator in SPring-8 having the Halbach configuration with the period of 32 mm and the total length of 4.5 m has the attractive force of about 3 tons at the gap of 8 mm. The undulator in SACLA having the hybrid configuration with the period of 18 mm and the total length of 5 m has the attractive force of around 9 tons at the gap of 3 mm. To control the magnet gap precisely against the large attractive force, the undulators usually require rigid mechanical components and frames. Moreover, a large number of components are necessary to distribute the mechanical load along the undulator axis and avoid deformation of the magnetic arrays. Such a conventional undulator design gives rise to structural issues that most of the weight, dimension and cost of the undulator are attributable to the auxiliary apparatus but not to the core part, i.e. the magnetic arrays.

The above discussion in turn gives us a new concept of undulator design; if the attractive force is cancelled out, the heavy and large base frame is no longer required, and then the undulator can be much more lightweight and compact. As a result, the cost and lead time of construction, transportation and installation are significantly reduced.

Up to now, two different methods have been developed to cancel the attractive force. One is the mechanical system composed of a number of springs having different

lengths and coefficients attached to the both sides of the main magnets, which was applied to an in-vacuum wiggler developed at Synchrotron SOLEIL [1]. The other is the magnetic system composed of two rows of magnet array generating a repulsive force attached to the both sides of the main magnets, which is applied to the in-vacuum revolver undulator (IVRU) developed at SPring-8 [2]. Although both systems worked well for their own purposes, they may not be applicable to the new undulator concept.

In the former method, the precise magnetic measurement indispensable for undulator field correction is not possible with the conventional instrument, and the gap-dependency of the repulsive force generated by the springs is somewhat different from that of the attractive force. In the latter method, the number of magnets and magnet holders is three times as large as that of the main magnetic array, which increases the cost and time and effort for manufacturing.

As an alternative to the above two methods, R&Ds are under progress in SPring-8, toward realization of a cost-effective force cancellation system, which are reported in this paper.

BASIC CONCEPT

The cancellation system under development is based on the magnetic system applied to IVRU, which is schematically illustrated in Fig. 1. The point is that to generate repulsive force the magnets arrays which has the same structure with the main magnets are used in IVRU, while multipole monolithic magnets (MMMs) are discussed in this paper, which may be more cost-effective and easier fabricable than the IVRU type.

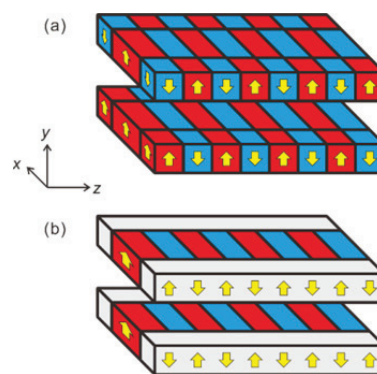


Figure 1: Conceptual drawing of force cancellation system (a) by normal magnets applied to IVRU and (b) by MMMs discussed in this paper.

ISBN 978-3-95450-133-5

The magnetic system to cancel the attractive force is required to generate the repulsive force having the gap dependence identical to the attractive force. It is well known that the magnetic field of the undulator, and thus the attractive force F , depend exponentially on the gap,

$$F \propto \left[\sum_n \alpha_n \exp\left(-n\pi \frac{g}{\lambda_u}\right) \right]^2.$$

i.e., where n is an integer indicating the harmonic number of the undulator field and α_n indicates the coefficient depending on the period and the remanent magnetic field, and so on.

In order to reduce the cost and effort for construction of the repulsive array, we are exploring the applicability of the multi-pole magnetizing method, which has been originally proposed by one of the authors (S. Y.) to facilitate the construction of extremely short-period undulators [3,4]. By using this method, the repulsive force having the same gap-dependence will be generated in a cost-effective way.

PRELIMINARY EXPERIMENT

Outline

The goal of the preliminary experiment is to demonstrate that the repulsive force by the MMMs has the same gap-dependence as the attractive force by the main magnets, and to acquire the data necessary to design the force cancellation system in the prototype of the compact and lightweight undulator.

Measurement of Field on Multipole Monolithic Magnet

The monolithic blocks are magnetized by the pulse magnetization and feed system shown in Fig. 2. The specification of the monolithic block and the system are listed in Table 1. The monolithic blocks have the length of 150 mm, the width of 30 mm, and the thickness of 4 or 8 mm. The pulse current and duration are 15 kA and 0.3 ms (FWHM), respectively. The pulse magnetic field were 2.49 T and 1.13 T at the gap of $G = 4$ mm and $G = 8$ mm, respectively, which were measured by the air-core pickup coil. The magnetization heads are for 15 mm period. The block are magnetized and fed by the stroke of 15 mm, iteratively.

The measured magnetic field on MMM are shown in Fig. 3. In the upper figure, the z -direction distributions of B_y at $x = 0$ mm and $y = 2$ mm are shown. The blue and red lines indicate the field distributions of 4 mm-thick and 8 mm-thick MMM, respectively. In the middle figure, the x -direction distribution of B_y at $z = 3.75$ mm (at the peak position) and $y = 2$ mm is shown. The maximum deviation of the peak amplitude along z except the both ends was less than 0.2%, which shows that a good-quality sinusoidal field was obtained. The lower figure shows the y -direction distributions of B_y , which corresponds to the gap-dependence of the peak field.

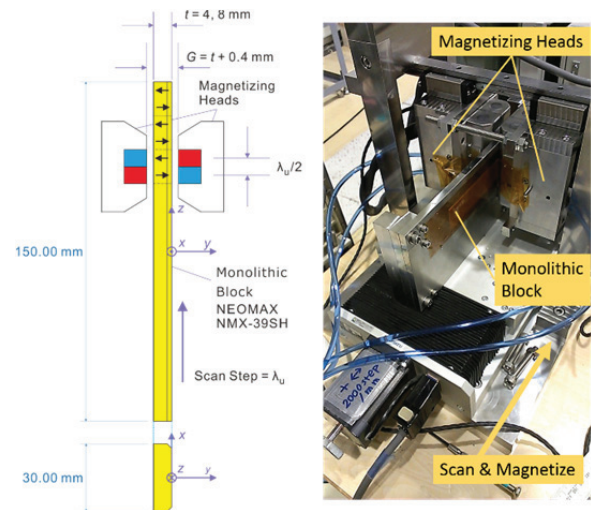


Figure 2: Magnetization system for MMM.

The above measurement results show that the magnetic field generated by the 8 mm-thick MMM was higher than that by the 4 mm-thick MMM. This sounds plausible if we assume that both MMMs were magnetized with the same pulse field. In practice, however, this is not true: the pulse field with $G = 8$ mm is much lower than that with $G = 4$ mm. We thus need to investigate the magnetization of the both MMMs to examine if all the experimental results are consistent.

Estimation of Magnetization in Multipole Monolithic Magnet

To estimate the magnetization in the MMM, the numerical results using the magnetization model as shown in the upper figure of Fig. 4 were compared with the experimental results. In the model, we have assumed that the magnetization profile is trapezoidal along the longitudinal axis and is composed of the flat-top region with the height of M_{top} and the transition domain with the length of d .

After numerical trials, it has been found that $M_{top} = 1.15$ T and $d = 1$ mm reproduces the experimental results for the 4 mm-thick MMM, and $M_{top} = 1.11$ T and $d = 1.25$ mm reproduces those for the 8 mm-thick MMM. The difference between the two conditions comes from the difference in the gap between the magnetization heads.

Table 1. Magnetization Experiment Setup

Period	15 mm
Periodic Number	10
Block Size	L150 mm, W30 mm, 4mmt / 8 mmt
Block Material	NMX-39SH (Hitachi Metals, Ltd.) ($B_r = 1.2 - 1.28$ T)
Pulse Current	15 kA, 0.3 ms (FWHM)
Pulse Field (Gap Center)	2.49 T (4 mm), 1.13 T (8 mm)

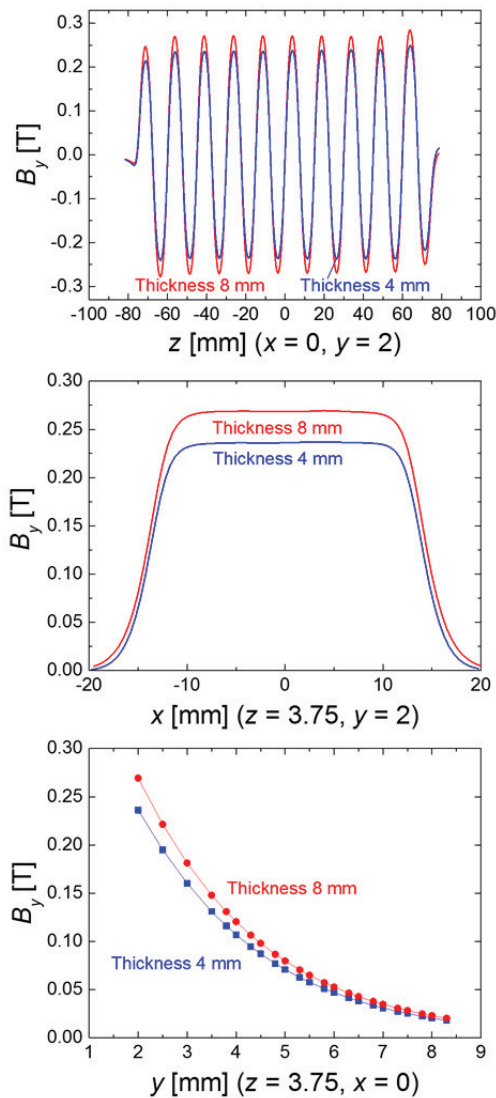


Figure 3: Field distribution of MMM.

The above values of M_{top} are almost the same as the magnetization including the diamagnetic effect for the magnets having $B_r = 1.2$ T and $B_r = 1.13$ T, respectively. Although M_{top} for the 4 mm-thick MMM reaches B_r of NMX-39SH (block material), that for the 8 mm-thick MMM is limited by the strength of the pulse field, 1.13 T, at the gap of the magnetization heads of 8 mm. If a cooling capacity of the magnetization heads is enhanced and the pulse current is increased, the 8 mm-thick MMM will be fully magnetized as well as the 4 mm-thick MMM.

Measurement of Attractive / Repulsive Force

Having verified that the MMM generate the sinusoidal field as expected, the repulsive force created by them, as well as the attractive force created by the main undulator magnets, have been measured with the measurement setup shown in Fig. 5. The main magnets having the Halbach configuration with the period of 15 mm, width of 20 – 25 mm, height of 8 mm and total length of 600 mm,

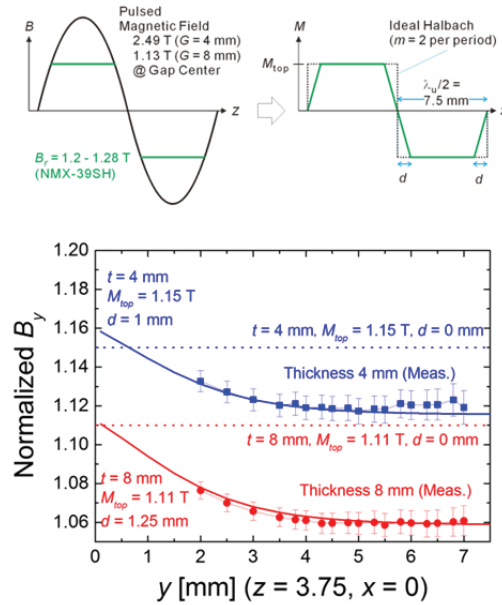


Figure 4. Modelling and numerical computation of magnetization in MMM.

were mounted on the copper magnet beams. Each magnet block is made of NMX-50BH (Hitachi Metals, Ltd.) which has a high remanent field of 1.36 T. Each magnet beam was connected to the undulator base frame using 4 load cells, which were calibrated for both the forces of compression and tension within an accuracy of 0.5 kg. The gap between the magnetic arrays was measured by several linear gauges.

The MMMs are attached on both sides of the main magnets using the stainless-steel supports. The gap between the MMMs was adjusted to coincide with the gap

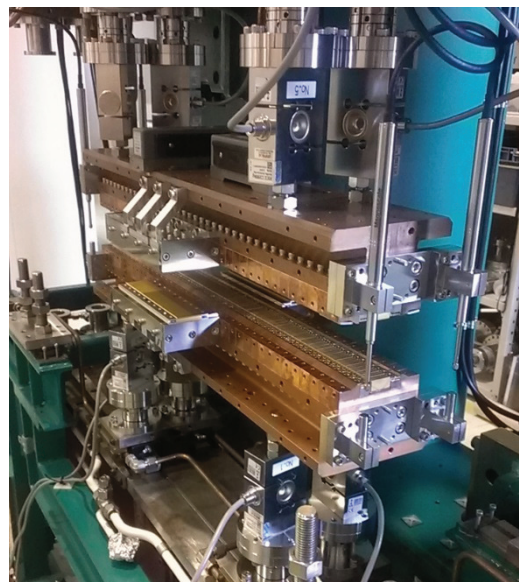


Figure 5: Gap-force measurement system. The force between the upper and lower magnets is measured by 8 strain-gauge-type load cells which supports the magnets. The real gap between them is measured by 4 linear gauges.

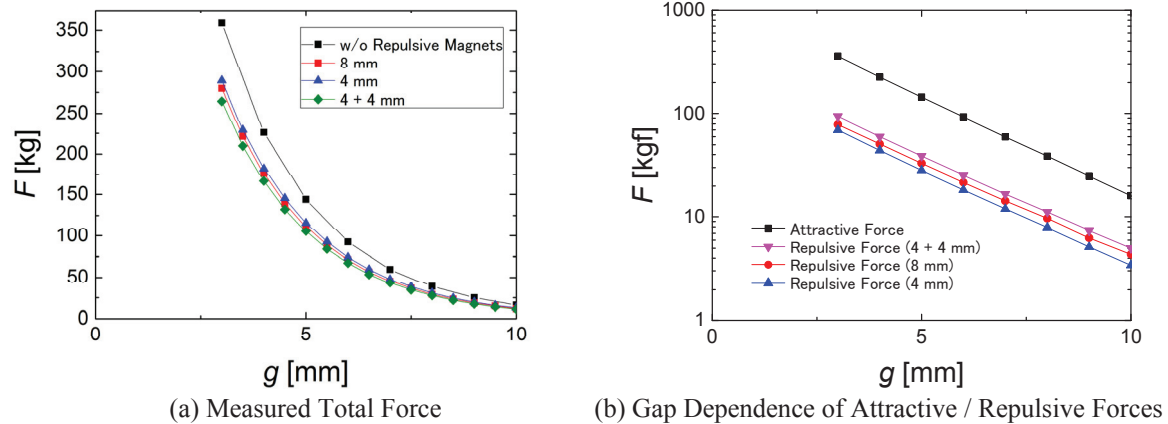


Figure 6. Measured force in preliminary experiment. The force is measured (1) without MMM (black square line), (2) with 4 mm-thick MMM (red circle line), (3) with 8 mm-thick (blue upper triangle line), (4) with two-ply 4 mm-thick (pink lower triangle line).

between the main magnets. Measurements were performed in the conditions (1) without the MMMs, (2) with the 4 mm-thick MMMs, (3) with the 8 mm-thick MMMs, (4) with the two-ply 4 mm-thick MMMs.

Results and Discussions for Force Measurement

The attractive forces measured as a function of the gap are shown in Fig. 6 (a) for various conditions. The black square line, the red circle line, the blue upper triangle line, and the pink lower triangle line indicate the measured forces at the conditions (1) – (4) mentioned above, respectively. The repulsive forces generated by the MMMs, which are retrieved from the experimental results, are plotted as a semi-logarithmic scale in Fig. 6 (b) as well as the attractive force. The gradients of the repulsive force in the all conditions were the same as that of the attractive force, which means that the gap-dependence of the repulsive force is coincident with the attractive force by the Halbach array. This is an encouraging result, because the absolute value of the repulsive force is adjustable by designing the size and B_r of the MMMs. Then we conclude that the attractive force can be fully cancelled out by the scheme presented in this paper.

Note that the repulsive forces are much smaller than the attractive force even though the repulsive magnets are twice wider than the main magnets. Of course, there is a difference in the lengths of the main magnets ($L = 600$ mm) and the MMMs ($L = 150$ mm). The remains is quantitatively explicable by the differences in B_r , height (thickness), the number of magnets in one period, and the distribution of the magnetization. To compensate those disadvantage in the MMMs, one can make the width or B_r of the multipole monolithic magnet large, or make the gap between the multipole monolithic magnets small.

Comparison of Experiment and Calculation

In Fig. 7, the experimental and calculated data are compared under an assumption that the total length of the MMMs is the same as that of the main magnets (600 mm).

Namely, the experimental data were reconstructed by subtracting 4 times (= 600 mm/150 mm) the repulsive force from the attractive force. In the numerical calculation, the values of M_{top} and d derived above were used.

The calculation well reproduced the experiment data for condition (1). However, from the results for conditions (2) – (4), we found non-negligible discrepancies between the experimental and numerical data of the repulsive forces. More detailed data showed that within the gap from 3 mm to 10 mm, there are around 20% differences in conditions (2) and (4), and around 15% difference in condition (3). This means that the numerical model of the MMM does not reflect the reality well. Not only z -direction distribution of the magnetization in multipole monolithic magnets, but also the y -direction distribution should be introduced in the future work.

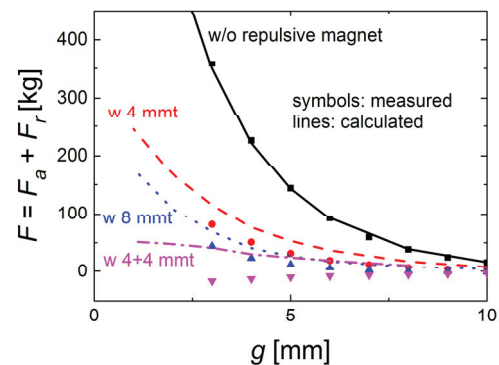


Figure 7: Measured and calculated force. The force is measured and numerically calculated (1) without MMM (black square, solid line), (2) with 4 mm-thick MMM (red circle, dashed line), (3) with 8 mm-thick (blue upper triangle, dotted line), (4) with two-ply 4 mm-thick (pink lower triangle, chain line).

DEVELOPMENT PLAN FOR COMPACT AND LIGHTWEIGHT UNDULATOR

In parallel to the development of the force cancellation system, the prototype of a compact and lightweight undulator based on the force cancellation system is being developed in SPring-8. The conceptual drawing of the prototype is introduced in Fig. 8.

We plan to measure the field distribution in the prototype at the gap of around 1 mm and check the suppression of the phase errors in the undulator field caused by the deflection of the magnet beam due to large attractive force. To measure the field at the very narrow gap, the gap between the multipole monolithic magnets is designed to be the same as the gap of main magnets. Two types of monolithic magnet with two different B_r are selected. The repulsive forces are mainly tuned by the width of the multipole monolithic magnets.

Because the numerical calculation have not reproduced the experimental repulsive forces well, the experimental data is also used to design the prototype. The adjustment mechanism for the repulsive force by means of phasing the multipole monolithic magnets is under discussion.

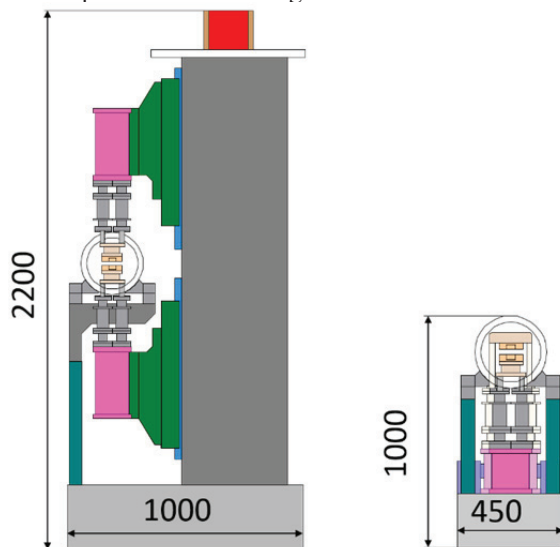


Figure 8: Conceptual drawing of conventional (LEFT) and lightweight compact & cost-effective (RIGHT) undulator.

CONCLUSION

Activities in SPring-8/SACLA toward a new undulator concept were introduced. To achieve the cost-effective force cancellation system which can generate the repulsive force having the same gap-dependence as the attractive force, we discussed the usage of the multipole monolithic magnets as the repulsive magnet. The preliminary experimental results showed that the multipole monolithic magnet can generate the repulsive force having the same gap-dependence with the attractive force by the main magnets. The development plan for the prototype of the lightweight and compact undulator based on the cancellation system was introduced.

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