Model Studies on the ELFA wiggler

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Abstract

In this paper we present the experimental apparata used for model studies on the ELFA wiggler (λ_w = 12 cm, B_w = 3600 Gauss, total length L = 6-7 m). Two full-scale models, each one period long, have been built for the hybrid and the electromagnetic configurations. The main characteristics of the models and the high precision apparata for magnetic measurements are described. In addition the model performances are resumed and compared to the ones needed for the ELFA FEL operations.

1 INTRODUCTION

1.1 *The ELFA project*

ELFA [1] is a single-pass high-gain Compton Free Electron Laser (FEL), designed to generate high peak power of microwave radiation, in the 30-100 GHz range. The electron beam will be provided by a LINAC in short pulses ($L_b \lesssim 6$ cm) with a maximum energy around 10 MeV and a maximum peak current of 400 A. ELFA will explore different FEL regimes, determined by the relative difference between electron and radiation velocity. In order to control the group velocity of the radiation, different waveguides will be inserted into the wiggler gap achieving either steady state conditions ($v_e = v_g$) or the theoretically predicted and never experimentally observed superradiant regime.

1.2 *The ELFA wiggler*

The ELFA wiggler has a period of 12 cm and a design peak field value B_w = 3600 Gauss, to be obtained with a nominal gap of 36 mm. The wiggler must have focusing properties in both planes and must allow field tapering in the last two meters, in order to enhance the energy extraction efficency in the steady state regime. Two different construction schemes are under study: a totally electromagnetic wiggler, and a composite wiggler [2], in which the first part is hybrid (permanent magnets and iron poles) and the second part (taperable) is electromagnetic. The latter solution should result less expensive both for construction and operation, but presents some problems in the coupling of the two sections. On the other hand, the greater flexibility of the first solution allows a simple method of evaluating the exponential growth of the field along the wiggler by detuning the magnetic field at different locations inside the wiggler [3], and will enable us to test the two-wiggler scheme of harmonic production recently proposed for XUV FEL generation [4]. Two full-scale one λ_w models have been built, one hybrid and the other electromagnetic. These models have allowed us to compare the relative performances and costs, and to define the proper transverse profile of the iron poles needed for horizontal focusing.

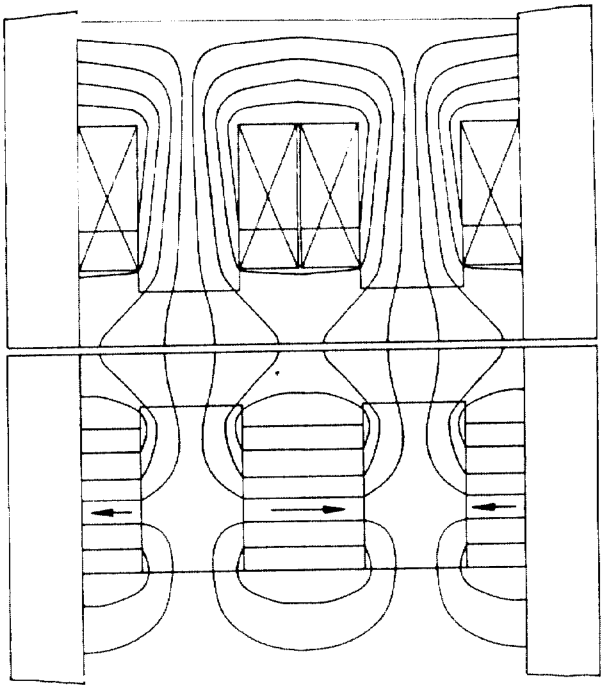
Figure 1: Models conceptual design, longitudinal cross-section of electromagnet (upper) and hybrid (lower).

2 EXPERIMENTAL SETUP FOR MODEL STUDIES

2.1 *Wiggler models*

The two models can be alternatively mounted on the same support structure, whose vertical iron walls act as magnetic mirrors, to simulate a periodic array of poles. Fig. 1 shows a cross-section of the em (upper half) and hybrid (lower half) models; also visible is the field lines pattern evaluated with the POISSON and PANDIRA codes. It can be noted that, in spite of the difference between the two schemes, the field pattern in the gap region is practically the same. Two sets of poles have been used on the model, flat and curved in the transverse direction. The curved poles have been designed to obtain a ratio between horizontal and vertical betatron wavelength of $\lambda_{\beta_x}/\lambda_{\beta_y} = 3$, in order to achieve the maximum superposition between the electron beam spot and the radiation mode in the waveguide. The central part of the poles has been machined with a circular arc approximating (deviations $\leq 50\mu$m) the exact needed curvature, evaluated according to ref. [5]. The pole dimensions are the same for both models; the length (wiggler axis direction) and the width (transverse direction) have been respectively chosen to obtain the minimum harmonic contents in the on-axis field and to ensure a sufficiently large good field region. For the hybrid model the vertical dimensions of the poles and the permanent magnet blocks needed to achieve the desired peak field level have been studied with a 3D semi-analytical treatment [6]. The resulting pole height was essentially the same needed on the em model to minimize power consumption. The material we used is ARMCO iron, since the expected maximum field in the iron is sufficiently low, making the use of special materials like Vanadium Permendur unnecessary. The machining and positioning tolerances for the poles were less than 0.1 mm.

Table 1: ELFA Model Parameters

Design peak on-axis field	3600 gauss
Wiggler period	120 mm
Poles length	27 mm
Curved poles height (on-axis)	43 mm
Poles width	120 mm

The coils of the em model have been optimized for a current of 400 A. Each coil is composed of 24 turns of a square section Cu OFHC conductor, insulated with DAGLAS. The coils have been couple casted with F-class epoxy resin; cooling is assured by forced water circulation (water temperature increase 20 ° C, $\Delta p \simeq 1.5$ bar).

For the hybrid we have used blocks of NdFeB, with a remanent field $B_r \simeq 1.21$ Tesla. The blocks were of two different dimensions in longitudinal direction, as can be noted in fig. 1; there are three identical blocks in transverse direction. All the blocks have the width equal to the height to lower costs and improve block sorting.

2.2 *PM blocks calibration*

The dipole moment of each block was measured, both in intensity and in angle, with a Helmholtz coil magnetometer, and the blocks were sorted to minimize field errors. The Helmholtz coils have a mean radius of 250 mm, with 300 turns for each coil. The estimated error is ≤ 0.1 % in a 100 mm × 80 mm region at coil center. The measurements are performed rotating the PM blocks of 180°; each component of the magnetic moment is measured twice (with two different orientations of each block) to eliminate systematic errors. Blocks movement and data aquisition is PC controlled. The temperature in vicinity of the sample has been recorded and the temperature coefficient experimentally determined; the temperature effects on the measurements have been corrected via software. Repeatibility of the system, evaluated on a 33 mm × 40 mm ×40 mm NdFeB block, was of 0.05 % for the main component and of 0.1 ° for the angle.

Table 2: EM Model Parameters

Gap height (on-axis)	40 mm
Nominal current/turn	300 A
Excitation turns/pole	24
Total nominal power	4.4 kW
Copper conductor cross-section	22 mm^2
Cooling hole diameter	3 mm
Yoke thickness	30 mm

Table 3: Hybrid Model Parameters

Variable on-axis gap	34–46 mm
PM material	NdFeB
Average remanent Field	1.212 T
Coercitive force	≥ 1.06 T
Temperature coefficient	-0.1 % / ° K
Blocks width	40 mm
Blocks height	40 mm
Blocks length	33 - 16.5 mm

The dipole moment variation of the measured blocks was less than ±0.7%, and the error in angle with respect to the blocks surface was less than ±3°.

2.3 *Model measurement apparatus*

The wiggler field measurements have been performed using a 1 mm^2 Hall probe (Bell BH-701). Probe calibration was done by confrontation with a NMR probe over the whole working range of the probe (from -6000 to $+6000$ gauss). The measured sensitivity constant was of 6.686 mV kgauss^{-1} at a control current of 100 mA. The probe linearity of the voltage vs. the magnetic field was found to be better than ±0.25% in this range of operation. The deviations from linearity have been corrected via software, using the non-linearity curve experimentally recorded during calibration. The rms repeatibility of the probe was found to be of about 0.1 %, mainly due to temperature variations during probe calibration (the nominal temperature coefficient of the probe is $-0.04\%^\circ C^{-1}$). The measurements have not been corrected for temperature effects nor the probe has been thermostated. In future we will decide which option to adopt to increase further precision.

Due to the strong gradient of the wiggler field, a crucial factor for determining the precision of the measurement is the probe positioning system. We have obtained a three-axis independent motion using one DC motor for each axis, controlled via a loop with optical bars with a resolution of 0.5 μm. Actual precision for the probe position, evaluated indirectly by field measurements, seems to be quite good for single-axis scans ($< 10\mu$m); the exact value is difficult to assess, since in this case measurement errors due to misplacements are equal to or less than the probe accuracy. When performing three-axis motion we have found quasi-systematic errors of the order of 100–150 μm. The probable source of these errors have been identified and will hopefully be eliminated by an accurate mechanical calibration of the positioning system. Movement ranges are 250 mm, 40 mm and 1200 mm for transverse, vertical and axial direction, respectively. The axial movement is clearly oversized for the present needs, but is necessary in view of the use of the measurement system on the full wiggler sections.

The entire system is monitored through a PC; movement is controlled via RS-232, whereas data acquisition is done through IEEE-448 bus.

3 FIELD MEASUREMENTS AND MODEL PERFORMANCES

3.1 *Field Measurements*

Maps have been taken of the main (vertical) field component at three different vertical positions inside the gap (including midplane), on a grid of 55 × 15 points (axial × transverse) with steps of 2 mm. In the axial direction it was not possible to explore the whole 120 mm due to Hall probe dimensions constraint; the transverse measured region spans the entire region occupied by the electron beam and is symmetric with respect to the longitudinal wiggler axis. Field mapping was performed at different excitation currents for the em model and at three different gap values for the hybrid. Further measurements have been made at fixed probe position and with variable excitation current, to determine the magnetization curve of the em model, with and without PM assisting [7]. Different field error correction systems have been tested on the models: active PM correctors mounted on the pole sides and additional correction coils for hybrid and em models, respectively.

3.2 *Model performances*

The design values for peak level, harmonic contents and transverse profile of the field were substantially achieved for both models.

In particular, the desired peak field level of 3600 gauss was easily achieved for the em wiggler with curved poles while for the hybrid the necessary on-axis gap (39 mm) resulted slightly smaller than the design value. The dependence of the peak field from current (em model) and gap variation (hybrid) was found to be with good approximation linear over the whole desired operating range (3000 to 3600 gauss). The harmonic contents is very small ($\leq$ 0.5 % of the fundamental) on both models, according to theoretical predictions. The value of horizontal focusing parameter [5] k_x determined by least-squares fit of transverse field profile was found to be equal to 0.157 cm^{-1}, while the design value is 0.166 cm^{-1}. The value of the field integral was evaluated to be $\approx$ 70 gauss cm, but due to forced periodicity of the model and errors typical of points measurement like Hall probe ones, its value is only an indication of what we can expect on the full wiggler; in any case this value seems to be compatible with ELFA FEL operation. A more detailed data presentation and analysis, together with a confrontation with theoretical predictions, can be found in ref. [8], also presented at this conference.

4 CONCLUSIONS

In this paper we have presented the experimental apparata used for model studies on the ELFA wiggler, and the characteristics of the models. Main design parameters have been achieved on the models and the proper transverse profile to ensure horizontal focusing has been identified. The critical point in preparing the measuring apparatus and assembling the hybrid model is, respectively, the mechanical calibration of the probe positioning system and the rather long time and specific mechanical apparatus needed.

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