CHARACTERIZATION OF PURE PERMANENT MAGNET BLOCKS FOR UNDULATORS IN 4TH-GENERATION LIGHT SOURCES

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Abstract

Permanent magnet undulators are key components in the realization of state of-the-art free-electron laser (FEL) systems. In FEL-based fourth-generation light sources long chains of undulators are used, with characteristics that are increasingly demanding in terms of magnetic field and mechanical tolerances.

The characteristics and performance of the magnetic material used in undulators is pushed to the limit of the available technology. In spite of the high accuracy of the manufacturing process, these magnet blocks must be further characterized one by one and appropriately coupled in order to achieve optimum uniformity of magnetic characteristics of the finished undulator.

This paper outlines the results obtained at the Elettra Laboratory of Sincrotrone Trieste SCpA (ST) and at Kyma Srl (a spin-off company of ST) in order to characterize the pure permanent magnet blocks used in the manufacturing of undulators for the next 4th-generation facility "FERMI@Elettra", currently being built by ST in Basovizza (Trieste).

Particular reference will be made to the software application (Kyma ID Builder) developed in order to optimize the sequence of magnet blocks. The results obtained to date show that in this way undulators can be assembled that require little or no shimming in order to meet the specifications required by the final users.

UNDULATOR MANUFACTURING PROCESS

The undulator production process at Kyma is organized in two major geographic areas. Mechanical parts manufacturing and assembling is carried out at Euromisure Srl in Pieve San Giacomo, Cremona, Italy. Euromisure is a partner of Kyma, together with Sincrotrone Trieste and Cosylab d.d. (Ljubljana). Magnetic assembling and characterization of the undulators is carried out by Kyma Tehnologija d.o.o., a daughter company of Kyma Srl, based in Sežana, Slovenia.

Magnetic assembling and characterization, which is the focus of the present paper, includes the following relevant processes:

- Undulator Magnet Block Acceptance and Characterization;
- Undulator Magnet Module Assembling and Characterization;
- Undulator Magnet Final Assembling and Characterization.

The above processes have been defined and optimized from an industrial point of view for series production.

Undulator Magnet Block Acceptance and Characterization

This process takes as input the magnet blocks coming from the manufacturer, together with the relevant production and measurement data and gives as output the same blocks, fully characterized and properly sequenced.

After a general quality control inspection, the magnetic characterization of the blocks is carried out using an Helmholtz Coil Bench, realized in-house by Kyma, starting from the original ST design. The actual bench is shown in Fig. 1.

Figure 1: The Kyma Helmholtz Coil Bench.

The characteristics of the bench are given in next table:

Table 1: Helmholtz Coil Bench characteristics.

Coil diameter	600 mm
Number of wire turns	2400
Overall dimensions	50 x 60 x 105 cm^3
Weight	40 kg
Max. acceptable magnet size	50 x 50 x 50 mm^3

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In order to ensure the maximum level of reliability of the performance of each individual magnet, a correlation is made between the measurements provided by the magnet manufacturer and measurements carried out using the Kyma Helmholtz Coil Bench. The graph in Fig. 2 shows the results of the measurements at Kyma as a function of the values provided by the manufacturer. Each dot in the graph refers to one individual magnet block.

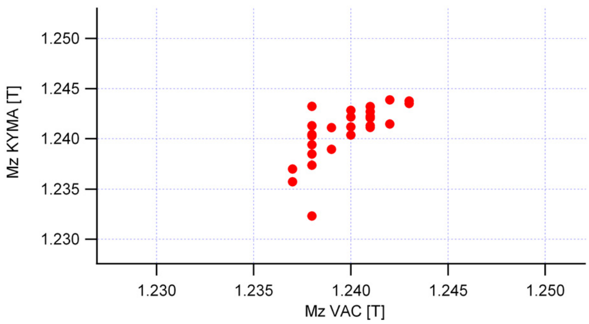

Figure 2: Correlation between magnetization (M_z) values of a subset of permanent magnet blocks.

As it can be seen, the agreement between the values measured at Kyma and those provided by the manufacturer is well below 1%, the resolution of the Kyma system being considerably higher (0.05%). These data, properly validated, represent an optimized input for the magnet sorting.

Undulator Magnet Module Assembling and Characterization

An important innovation in undulator magnetic assembling is the two-step magnet sorting and characterization. This approach, originally developed by the Insertion Device Group at Sincrotrone Trieste, became a standard production method at Kyma.

This process is then relevant to pre-assembling the single blocks into modules of three and five magnets. It takes into input the characterized blocks and gives as output the assembled modules, properly characterized and sequenced for their final assembling onto the undulator.

Once mechanically assembled, the modules are characterized using a Stretched Wire Bench, fully developed in-house at Kyma. The main characteristics of this equipment are given in next table.

Table 2: Stretched Wire Bench characteristics.

Wire length / Number of turns	1120 mm / 20
Overall dimensions	360 x 210 x 1030 cm^3
Weight	~ 500 kg
Length of sliding table	1500 mm
Motion control and data acquisition	National Instruments PXI
Software environment and HMI	LabVIEW 7.2

With this bench the magnetic field integral is measured on each module along the z direction (vertical) and computed along the x direction (transverse horizontal direction with respect to the beam axis (s) in the undulator). See Fig. 3 as a reference, where the schematics of the module measurement is shown, together with the co-ordinate system and the relevant expressions of the field integrals.

In Fig. 4 the actual Stretched Wire Bench equipment is shown. The equipment presents considerable reliability and reproducibility of measurement. In Fig. 5 the plot of the I_z and I_x field integrals is shown as measured on the same module in the four different positions available on the sliding plate. As can be appreciated a reproducibility better than 0.1 Gm is obtained. Moreover the equipment has been validated comparing the measurement with the same measurement carried out on the final characterization benches (see next paragraph). An example of such a comparison is given in Fig. 6.

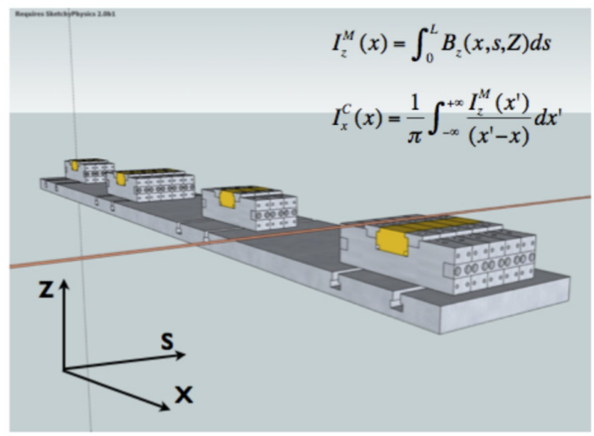

Figure 3: Schematics of the module characterization, using the Stretched Wire bench of Fig. 4.

Figure 4: The Kyma Stretched Wire Bench.

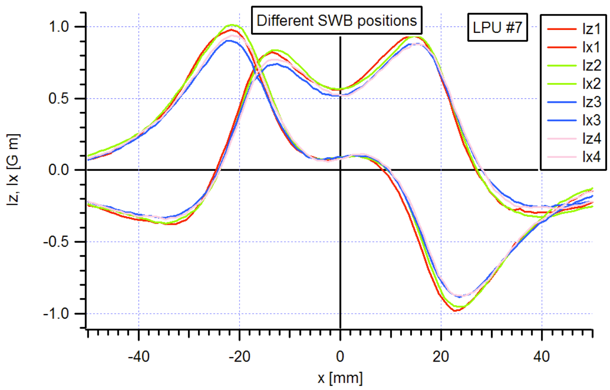

Figure 5: Assessment of the reproducibility of measurements of the same module in the different positions of the sliding plate (cfr. Fig. 3).

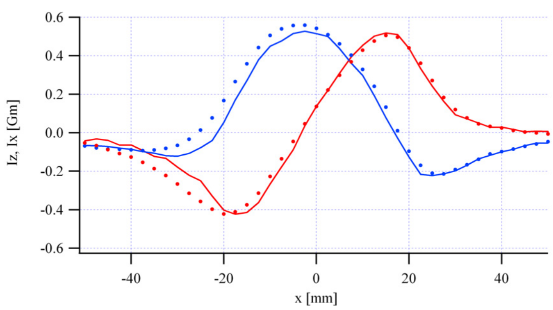

Figure 6: Comparison of field integral measurements on the Stretched Wire Bench (solid line) and the final characterization bench (dots).

Undulator Magnet Final Assembling and Characterization

Two benches realized by ACCEL are available at Kyma magnetic characterization lab. The two benches, respectively 3.5 and 5.5 m long, are a combined measuring systems made up of flip coil and three axis Hall probe.

All magnetic measurements are carried out in a temperature-controlled environment with temperature stability better than 0.5°C.

The measurements software provided by ACCEL was improved and optimized for serial production of undulators.

The final assembling of magnetic modules is made with the undulator directly placed on one of the two benches. This is done in order to follow step-by-step the final magnetic configuration of the undulator. More in detail, once a module has been assembled an optimization is launched using the Kyma ID Builder application, that chooses, among all the remaining modules, the one giving the best coupling with the modules already assembled.

This recursive assembling process is providing excellent results from an industrial point of view. In fact the undulators assembled with this process need little or no shimming.

An example of the final characterization report is given in Fig. 7. This kind of report is automatically generated for each measurement carried out on the undulator.

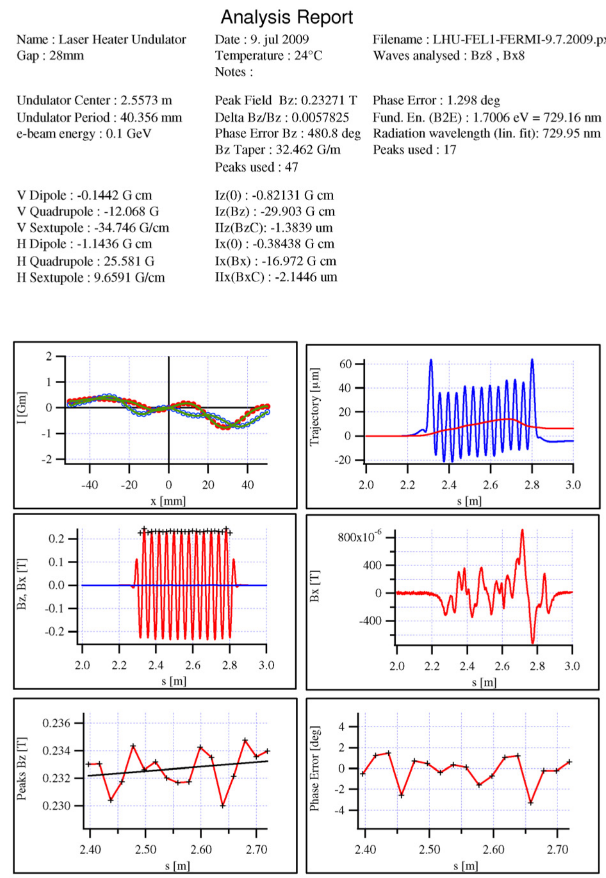

Figure 7: Example of an automatically generated final characterization report.

UNDULATOR PRODUCTION

At the time of this writing the manufacturing of undulators for the FERMI@Elettra project is well under way. Two undulators have been completed and fully characterized: the Laser Heater Undulator (LHU) and the modulator for the first undulator chain (LPU@FEL1) [1]. Eight segments of the radiator (EPUs@FEL1) are at present being realized. The first one is now in the final assembling and characterization stage.

The production process described in the previous paragraphs is giving excellent results. Just as an example, Figs. 8 and 9 give respectively the electron beam trajectory and the phase error in the LPU@FEL1. The electron beam trajectory in Fig. 8 is at 1.2 GeV energy without shimming. Only the kick in the vertical trajectory needed correction. This shows that it is possible to achieve the required specifications solely through appropriate characterization and sorting of the modules.

The phase error in Fig. 9 shows an overall RMS value of 1 deg, again with no shimming.

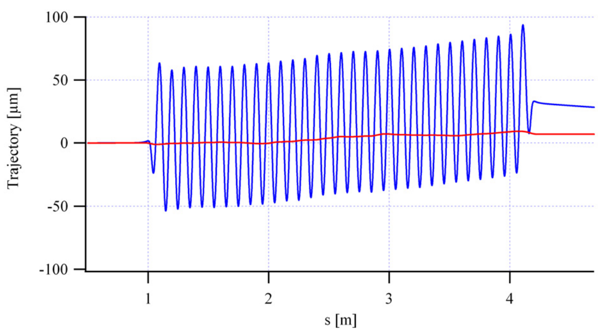

Figure 8: Electron beam trajectory in the LPU@FEL1, at 1.2 GeV without shimming.

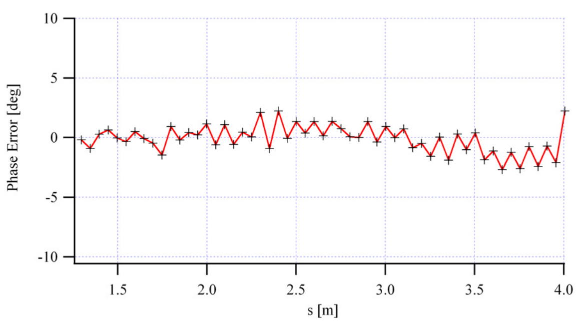

Figure 9: Phase error in the LPU@FEL1 modulator, without shimming.

KYMA ID BUILDER

Kyma ID Builder is a specific software application that has been developed at Kyma using a genetic algorithm framework adapted for the problems of magnet fields and integrals optimization involving different caching techniques.

Atop of the genetic algorithm framework four optimization packages have been developed:

- Magnet block to magnet module
- Magnet module to assembled undulator
- Virtual shimming
- Magic finger shimming

In the context of the present paper the first two will be summarized and discussed as follows.

Magnet block to magnet module

Module optimization finds the best possible arrangement of magnet blocks in sub-arrays (modules) of 3 and 5 blocks each. The goal is to obtain modules with the minimum possible field integrals. This will later allow for a more controlled assembly process.

The input data for the optimization are the magnetic field components of each single block, as previously measured with the Helmholtz coil bench. From the data of single blocks, field integrals are being computed. These integrals are then being summed together to give the predicted module integrals, which are then minimized during the optimization process. The result of this optimization is the module assembly sequence. The finished modules present field integrals below 20 G cm.

Figure 10 shows the computed field integrals of each module during the optimization process.

Magnet module to assembled undulator

The undulator assembly process is computer assisted in the sense that between every step of fixing a module on the undulator a measurement on the bench is executed. The actual integrals values are sent to Kyma ID Builder. The program takes this measurement as input data in an optimization procedure that determines the best next modules to be mounted so that the actual situation is corrected to obtain a finished undulator with a very small integral. At each step the computation is made by summing together the measured integrals of the partially assembled undulator and of the remaining un-mounted modules and gradually progressing towards an optimal configuration.

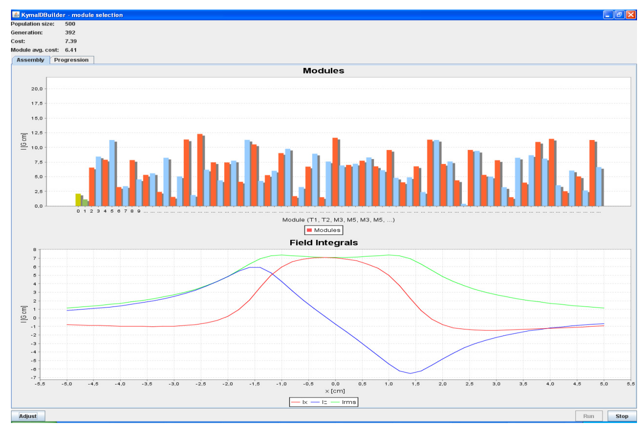

Figure 10: Field integrals computation during the optimization process with Kyma ID Builder.

CONCLUSIONS

The undulators for the FERMI@Elettra FEL are now in production at Kyma. The manufacturing process has been optimized using industrial series production concepts, with particular reference to the magnetic assembling and characterization.

The results obtained on the first undulators realized show excellent performances even in absence of any shimming.

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