SWISSFEL U15 MAGNET ASSEMBLY: FIRST EXPERIMENTAL RESULTS

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Abstract

In the framework of the SwissFEL project, an R&D activity concerning in-vacuum undulator technology is ongoing at the Paul Scherrer Institut. The magnetic field configuration of the hard X-ray SwissFEL undulators has been designed on purpose for a single pass machine. Moreover the permanent magnet material (NdFeB) is manufactured following a novel procedure (Dy diffused in the grain boundaries) to improve the coercivity versus remanence. The assembly and tests of a 44 periods hybrid magnetic structure are presented. Procedures for the magnetic field, trajectory and phase optimization are reported versus experimental results.

INTRODUCTION

The SwissFEL is the free electron laser in construction at the Paul Scherer Institute (PSI) in Switzerland. The first beam-line planned is called Aramis and shall deliver photons with wavelengths of 0.7 down to 0.1 nm. It is driven by a linac with a maximum electron energy of 5.8 GeV followed by a chain of in-vacuum permanent magnet undulators (U15). The period length is 15 mm and the K-value can be set between 0.1 and 1.6, changing the gap from 3 up to 20 mm. To meet these requirements NdFeB magnet manufacture should be improved and this is a part of the development ongoing between industries and PSI. Additional changes in the magnetic design were introduced to take advantages from the specific requirements of a linac driven free electron laser with respect to a synchrotron light source.

The undulator line is made of 12 units, each of 4 m length and 267 periods. The design of the frame and the gap drive system is part of the R&D activity ongoing at PSI and details can be found in [1]. A technical overview of the SwissFEL undulator line can be found in [2].

SINGLE MAGNET

The magnetic material selected for the U15 is NdFeB with a remanence of 1.25 T and a coercivity higher than 2300kA/m. With the conventional manufacturing procedure it is not possible to achieve these performances, the Dy used to stabilize the material has the disadvantage to hold a momentum opposite to Nd. As more Dy is added the coercivity continues to increase while remanence decreases. Hitachi Metal Ltd developed a new technique which can be applied to thin magnets. After machining the magnets to the final geometry, they are placed inside a vacuum oven where Dy is vaporized and it diffuses along the grain boundaries. They demonstrate that this approach increases the coercivity of about 320kA/m while the remanence remains substantially invariant. The rational behind this technique is the lower amount of Dy required to stabilize the magnet. The instabilities enucleate at the level of the grains in the material, the presence of Dy in the boundaries is enough to prevent this dynamic and to stabilize the magnet. This new technique has never been applied to undulator magnets and this was one of the reason to spend more effort and build a short prototype to prove the quality and reliability of this approach.

To decrease the spread of the magnetization value and error angles among the magnet production, tighter mechanical tolerances than in the SLS undulators were specified. The results of the Helmholtz coil measurements of the first 1400 magnet produced indicated a momentum spread RMS value of 0.35% and an angular RMS error of 0.185°. The histograms representing the full magnet production are presented in Fig.1.

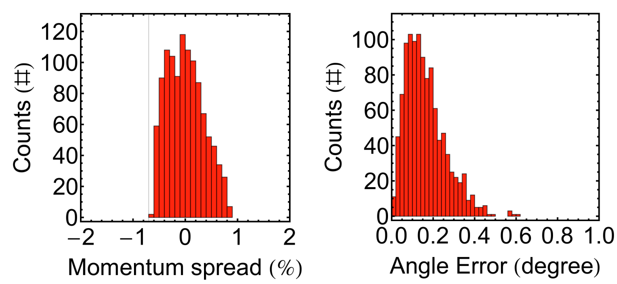

Figure 1: The statistic of the first 1400 magnets produced by Hitachi. On the left the momentum spread and on the right the magnetization angle error.

The assessment of a second magnet manufacture is ongoing to increase the offer in view of the next year production of the magnet for the full undulator line. The first batch has been received recently and a second 44 period short prototype will be assembled.

Within a Swiss program for supporting the local industries in improving their quality and innovation, an R&D activity is ongoing to demonstrate the feasibility of micro-water jet cutting applied to the high quality permanent magnet manufacturing. The first batch of magnet samples has been produced and the mechanical tolerances achieved are beyond the standard quality available on the market. The magnetic measurements of single magnets are ongoing.

MAGNETIC DESIGN

The U15 has a hybrid magnetic structure, made out of permanent magnets and iron (permendur) poles. The standard configuration which consists of one pole and two magnets have been changed into a more cost effective one consisting of a single pole and a single magnet as the

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building block of the magnetic structure. This approach has a lower degree of symmetry but reduces by half the number of magnets and substantially decreases the magnetic material wasted during the production.

The magnets and poles are arranged into block keepers, each consisting of 22 periods, see Fig. 2. The block keeper is made of extruded aluminium. Both magnets and poles have a simple shape that can be machined in principle out of a plate. The magnets are quasi rectangular with the four corners machined off. Two corners are used to fix the magnet in the keeper via two clamps which press the magnet down. The symmetry of the magnets guarantees a full rotational invariance so the magnet can be flipped in case it is required in the three angles. The poles are fixed to the keeper with two screws from the sides. This requires a more complex shape with an extra basement support.

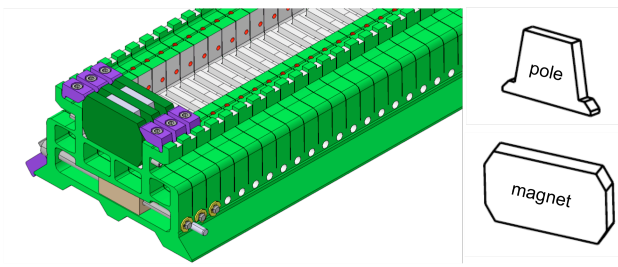

Figure 2: The aluminium extruded block keeper, design to hold 22 periods.

The pole height can be adjusted individually with a system of screws and wedges connected via a flexor, which allows for a fine-tuning in the sub-micrometer range.

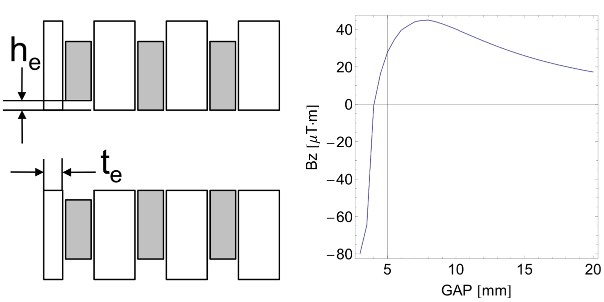

Figure 3: On the left, the schematic of the end design, where the height of the first (last) pole and the thickness of the first (last) magnet are used to march the trajectory. On the right, the kick experienced by the electron both at the entrance and at the exit of the undulator, only for one gap the match can be achieved.

The field quality requirements for a XFEL undulator are less stringent than for a synchrotron light source, because the electron shall be transported only once along the undulator line. This allows the reduction of the transversal dimension of the magnets and poles to optimize the cost and decrease the magnetic forces (<27kN). To enhance the field the pole tip has been reduced to focus more magnetic flux on axis. However this more “audacious” approach does have a draw back. It decreases the region of field homogeneity in the horizontal axis. RADIA calculation shows that the good field region (defined as a relative deviation with respect to the central field of 10^{-4}) is still large enough to allow a comfortable alignment tolerance in the horizontal plane, see Fig.4.

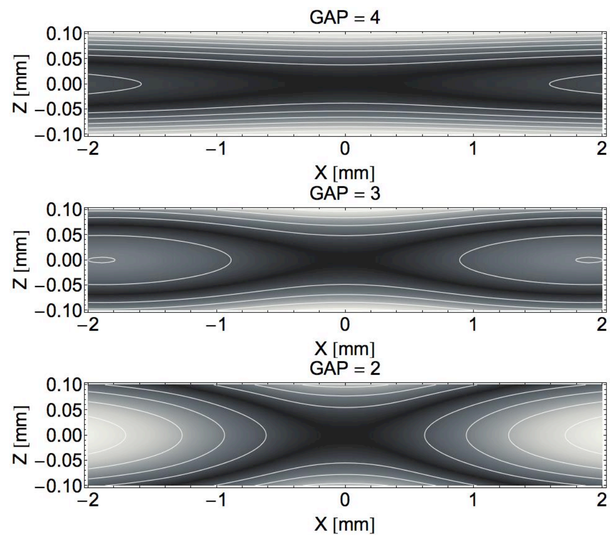

Figure 4: The field homogeneity in a U15 cross section is calculated with RADIA for different gaps. The inner most line represent relative deviation with respect to the central field of 10^{-4}, the second is $2*10^{-4}$ and so on.

Particular care has to be paid in the shaping of the end fields to match the trajectory, see Fig. 3. In a hybrid structure it is not possible to have a perfect trajectory for any gaps and in the design we chose to optimize the nominal gap (K=1.2). In the full gap range the electrons experience up to ±50 μTm both at the entrance and the exit of the undulator. The central symmetry of the structure guarantees that the two systematic kicks compensate and the result is an offset in the trajectory. This is of course not the case for the random error components.

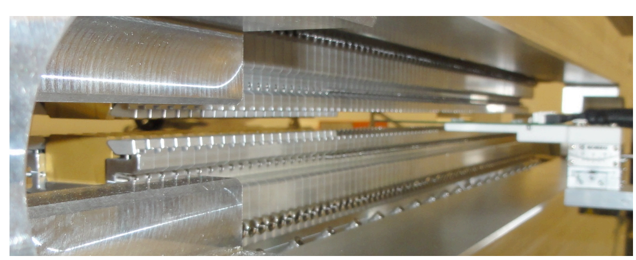

Figure 5: The short prototype undulator side view during the magnetic measurements. On the right side the hall probe head driven by a granite bench.

SHORT PROTOTYPE TEST

A first assessment of the magnetic structure (i.e. magnets, poles and block keeper design) was carried out with the help of a short stiff frame, where 44 periods (4

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block keepers) were allocated, see Fig. 5. With the help of mechanical shims the distance between the upper and the lower magnetic array (gap) can be changed. The windows on the two sides give access to the hall probe measuring head.

All the measurements presented in the following are before any optimization. The K-value versus gap was measured to validate the general magnetic design and the results are presented in Fig. 6. As expected, the agreement is very good and there is no evidence of magnet demagnetization caused eventually by the assembly procedure.

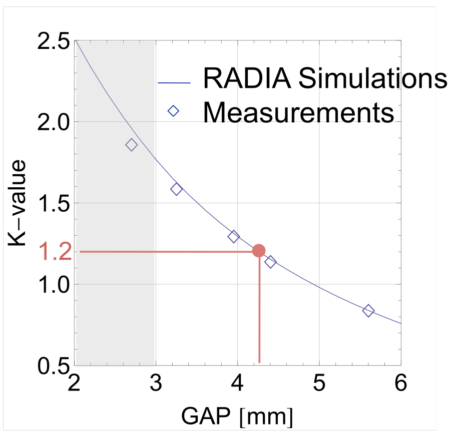

Figure 6: The K-value versus gap calculated with the computer code RADIA versus the magnetic measurements on the short prototype

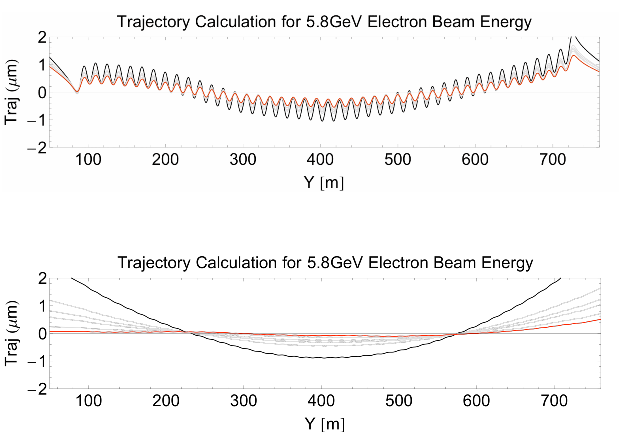

Figure 7: The horizontal (top) and vertical (bottom) trajectories calculated at 5.8 GeV before the optimization.

The trajectory has been calculated for the nominal electron beam energy of the SwissFEL (5.8 GeV) out of the data acquired for different K values. The results are presented in Fig. 7. The horizontal trajectory is within the specification for the gap range between 2.7 and 6.0 mm. On the contrary, the vertical trajectory shows a strong gap dependence and at the smallest gap it is possible to observe a large vertical parabolic trajectory. This effect can be due to the short prototype frame where the expected misalignment between the upper and lower magnetic array is larger than in the final frame. But an erroneous assembly of the poles can also induce it. These effects can be compensated by a careful adjustment of the pole transversal position in the block keeper but better tooling and procedure shall be applied for the final magnet and pole assembly in the full scale prototype to speed up the optimization procedure.

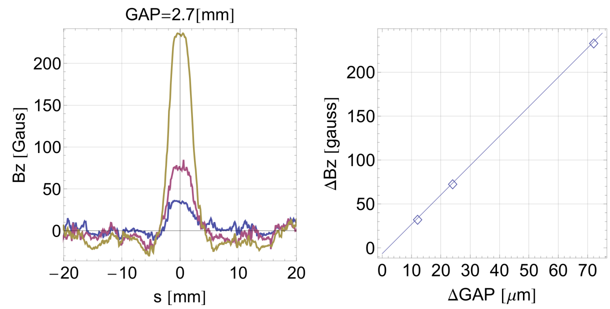

Figure 8: On the left the field profile change due to three different local gap changes, on the right their amplitude as a function of the actual gap variation.

The field changes due to the local adjustment of the gap have been measured to evaluate both the profile and the scaling of the field with the amplitude of the gap variation. An example is presented in Fig. 8 where the field profiles for three different gap changes are presented and the magnetic field amplitude plotted as a function of the local gap changes. This last result demonstrates experimentally that the field amplitude scales linearly with the local gap change in the range of interest.

Vertical and horizontal scans of the magnetic field in the undulator cross section have been made for different gaps to verify the field homogeneity calculation and they confirm the design.

FIELD OPTIMIZATION STRATEGY

In the following the field optimization before the insertion of the vacuum chamber is discussed, where the full magnetic structure is accessible and the build in option of pole height adjustment can be fully exploited.

Because of the closed frame the granite bench cannot be used. A measuring bench similar to SAFALI [1] has been developed: the Hall sensor module is mounted on a linear stage and two pinholes with a diameter of 2 mm are attached to the module. Two laser beams irradiate the pinholes and create two optical spots. During the movement along the undulator axis, the transverse position of the Hall sensor fluctuates due to mechanical errors and deflection of the stage support. Such an error is monitored by the position sensitive detectors (PSDs) as a fluctuation of the optical spot positions, and then corrected by three actuators, which can stir the probe in the transversal plane (x, y and roll).

The first correction concerns the transversal magnetic field component, which is responsible for the vertical trajectory. In a planar device the transversal magnetic field should be zero. The transversal component in phase with the main vertical component is not harmful and it may have different origins. On the contrary any random

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kick should be corrected to keep the vertical trajectory within the target of 2 micron as maximum deviation.

To adjust the vertical trajectory the pole can be moved horizontally. A relative displacement between the upper and the lower pole introduces a transversal field which can be used to compensate for vertical trajectory error. It is expected that few corrections (one every half a meter in average) should be enough to keep the vertical trajectory within the tolerances.

More critical in terms of radiation properties is the horizontal trajectory. For this purpose a more flexible mechanism has been introduced into the design of the keeper to easily change the pole height. A robot has been designed to operate the corrections following the results of an automatic data analysis. The control system will be charged with measuring the field, performing the data analysis and suggesting a correction strategy. In Fig. 9 more details are presented, where the "knobs" are highlighted together with their effect on the field profile. In the following formula the field correction Bc is expressed in terms of the single contributions:

$$B_c = a_1\xi_1 + a_2\xi_2 + \sum_{n=3}^{N-2} a_n\psi(s - \tfrac{1}{2}n\lambda_u + s_0) + a_{N-1}\xi_{N-1} + a_N\xi_N \,.$$

Each component of the formula adds up linearly and this is a good approximation in the limit of small amplitude, which corresponds to the actual mechanical limit (±60µm local gap change). The ξ and ψ functions are normalized to provide coefficients (a_n) in micron and represent the local gap change. The optimization can be applied to the magnetic field error, the trajectory error or the phase error. In the last case the problem is non linear. Even if more natural in this framework, the correction of the field has no physical relevance in the performance of the FEL. The trajectory is the parameter where more tight tolerances are required and together with the phase error has to be optimized.

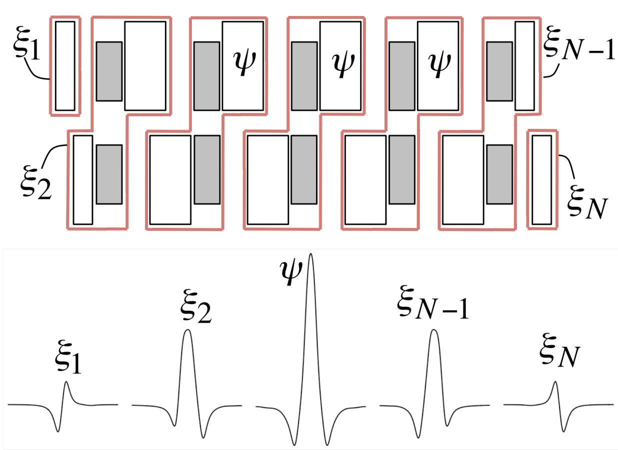

Figure 9: On the top the schematic representation of the undulator poles (grey) and magnets (white) as they are grouped in terms of local gap changes. On the bottom the impact of the local gap change on the magnetic field for the different groups.

A campaign of RADIA simulations has been carried out to verify this approach and the results are very promising. If the pole high adjustment can be carried out with an accuracy of 1 micron, only one iteration is required to optimize the horizontal trajectory within the tolerances specified by the FEL requirements.

CONCLUSION

The development of a new undulator design for the SwissFEL project is ongoing and several milestones have been already achieved. Concerning the magnetic structure, the first batch of magnets produced with the innovative Dy diffusing process have been successfully delivered by Hitachi and magnetically tested at PSI in the final block keeper design.

Two new magnetic measurement benches have been designed, assembled and commissioned. An optimization strategy has been identified and at present tested against computer simulations. In the coming months the short prototype will be used to extensively test the optimization algorithm as well as the robot for the automatic pole height adjustment.

Before the end of 2012 the full scale prototype shall be delivered and it will be measured and optimized at PSI. The magnetic measurements will be both performed without and with the vacuum chamber. This last check is essential to verify the final field configuration and eventually apply additional in situ corrections.

[1] Th. Schmidt et al. "SwissFEL U15 prototype design and first results", this conference.
[2] R. Ganter et al. "Technical overview of the SwissFEL undulator line", this conference.
[3] T. Tanaka et al. Proceedings of the 30th International Free Electron Laser Conference, Gyeongju, 2008, p. 371.

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