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MODELLING PM DIPOLES WITH LONGITUDINAL FIELD GRADIENT FOR SILA FACILITY

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Abstract

Computational models are described which were built for parametric simulations of permanent magnet (PM) dipoles with a longitudinal field gradient. The dipoles will be used as bending magnets in the synchrotron facility SILA, a new project of the National Research Center "Kurchatov Institute". The dipoles employ a Sm-Co permanent magnet material and pure iron. The need for high magnetic performance and anticipated interference between neighbouring components is a challenge for design and construction of the magnet system. For this reason the magnet designs must rely on precision 3D simulations. The dipoles are described in detail with parameterized models. Parametric simulations are to be applied at all stages of the project till the commissioning to provide realistic prediction of the magnet behaviour.

Key words

synchrotron, storage ring, permanent magnet, dipole, mathematical model

1 Introduction

The 4^{th} generation Russian accelerating-storage facility SILA, named from a Russian acronym for "synchrotron-laser", is expected to achieve ultra-low emittance resulting in increased coherence and brilliance of the emitted light as compared to existing light sources [Kovalchuk et al.]. This implies a new compact and powerful magnet design which is now under development [Arslanova et al., 2023].

The SILA storage ring will have 40 super-periods, 34 of them being regular. Every regular super-period consists of 4 long PM dipoles with longitudinal gradient (DL). The dipoles are identified by pairs as end and middle. In each pair the dipole modules are geometrically identical. The paper is focused on numerical study and consequent design solutions for the end dipoles DL1A, DL1E. The computational model for the inner pair of dipoles DL2B, DL2D is not finalized yet.

The absence of coils makes the PM dipoles more power-efficient than conventional EM magnets but complicates the field adjustment. The field tuning is achieved with the use of magnetic and thermal shims. This necessitates a detailed and accurate description of magnetic properties of every shim, PM unit, and assembly to ensure the required tunability and field quality of $\Delta B/B \leq 2 \cdot 10^{-4}$. These data should be easily accessible, sorted, displayed, and analysed to keep a full control on the magnet production. This is a challenging problem best resolved with recent Big Data technologies [Altsybeyev, Kozynchenko, 2019].

Table 1. Field specification for PM dipole DL1A

Module	Field, T	%
DL1A5	0.4536	100%
DL1A4	0.2634	58%
DL1A3	0.1983	44%
DL1A2	0.1542	34%
DL1A1	0.1120	25%

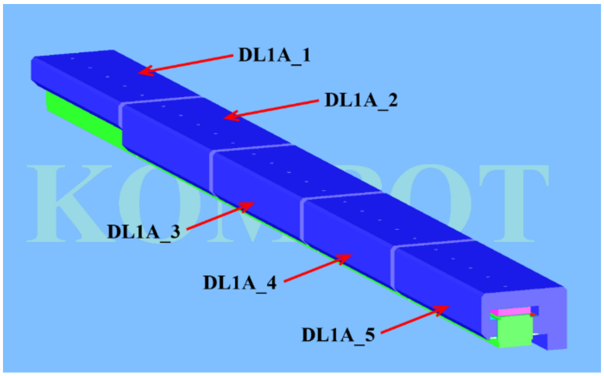

Figure 1. KOMPOT model of DL1A. Computed domain was reduced to one half of whole assembly due to symmetry.

DL1A was carefully studied in the context of the desired field distribution, and design and technology constraints. The dipole is described with parameterised 2D and 3D models. A reach set of magnetic simulations was performed in order to validate and optimize the dipole design. The code KOMPOT [Amoskov et al., 2008] developed at JSC "NIIEFA" was utilized in magnetostatic simulations. The code has proved its reliability in comparative computations including benchmarks initiated in the course of several domestic and international projects. Accuracy of simulations was validated with measurements on cyclotrons at the Flerov Laboratory of Nuclear Reactions (FLNR) and JSC "NIIEFA".

The results of simulations made it possible to justify structure materials, geometry and arrangement of PM blocks, air gaps, and poles to confirm the field requirements. Also, the thermal effect and possible magnetic cross talks were investigated as well as correction measures identified for practical construction.

2 Dipole modelling

2.1 PM dipole DL1A

In the SILA facility PM dipoles with longitudinal gradient have a modular structure. DL1A is formed with 5 PM modules placed closely to each other along the beam line. All modules consist of a different amount of PM blocks. This provides generation of a stepwise field.

Figure 1 illustrates the KOMPOT model of the DL1A dipole configured with modules DL1A5, DL1A4, DL1A3, DL1A2, DL1A1. As PM magnets are new for the Russian accelerator technology, their design was guided by the technical description of the ESRF-EBS facility [ESRF-EBS documentation], which have similar specification.

The use of PM allows reduction of power consumption and space and weight that makes the dipole more compact. However, PM dipole performance is sensitive to thermal and radiation effects and mechanical tolerances. Reasoning from these aspects, we select Sm_2Co_{17} as it demonstrates higher thermal stability and radiation resistance as compared to more common NdFeB magnets. Additionally, the Sm_2Co_{17} thermal stability will be improved with passive Fe-Ni alloy shims which magnetization depends strongly on temperature [Pyatin, 1982]. After integration of PM in the modules the magnet calibration is no longer possible, and the resultant field is tuned with the use of iron shims. The shims should be selected from magnetic measurements on every PM module.

The dipole modules are similar in shape but populated differently with PM blocks to change the longitudinal gradient by steps. Each module should provide an individual field level according to the desired field profile.

Small gaps between modules draw attention to possible magnetic cross talks. The field of a free-standing module would differ from its field in the assembly. This effect must be reflected in the computational model of DL1A.

2.2 Objectives

Magnetic simulations were carried out to accommodate the dipole design to the required performance. The following issues were studied:

- suitability of the ESRF-EBS dipole configuration to the SILA facility specification;
- modifications to be introduced in the existing design to reduce the dipole field by 1.5 times to comply with the SILA requirements;
- necessity for low carbon poles made of ARMCO or similar steel to avoid the hysteresis effect;
- effect of the modular design of PM dipoles on the longitudinal field distribution;
- assessment of cross talks of the neighbouring PM modules;
- selection of module locations and number of PM blocks in order to reach the desired stepwise variations of the longitudinal field;
- adjustment of the pole shapes to provide required homogeneity of the central field;
- selection of the material and geometry for thermal shims and assessment of their efficiency at various temperatures;
- selection of geometry of the end iron shims intended for fine adjustment of the field; assessment of the relevant correction range.

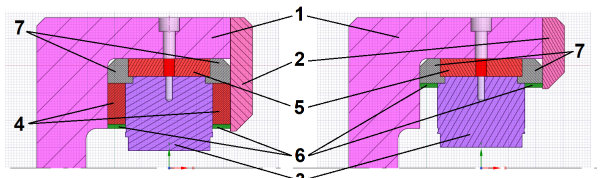

Figure 3. Components of modules DL1A2 to DL1A5 in 1/2 cross-section. 1 – iron yoke, 2 – side plate, 3 – pole, 4 – vertical PM, 5 – horizontal PM, 6 – Fe-Ni thermal shims, 7 – Al spacers.

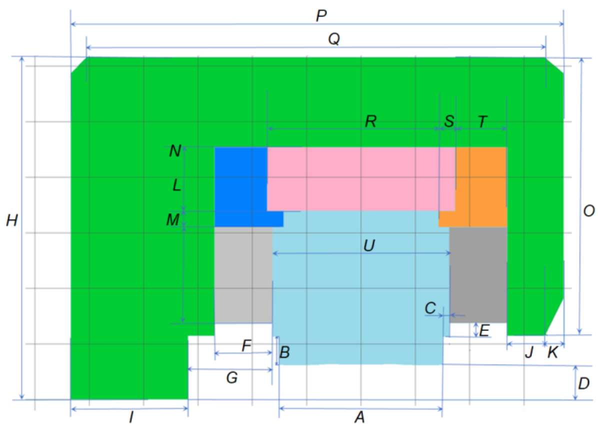

Figure 2. Parametrized DL1A5 model. Reference design.

2.3 Parametrized model

A parametrized model of DL1A was initially based on the ESRF-EBS dipole specification. Due to the symmetry the calculated domain was reduced to a 1/2 of the whole dipole. Figure 2 illustrates the reference DL1A model reflecting the basic design without shims.

More than 100 runs with variable parameters were performed using the code KOMPOT. The 2D and 3D simulations enabled check of the adopted parameters and gave course to further design optimization.

2.4 Design optimization

The data base formed from simulations with the parametrized model yielded the optimal DL1A design Opt-1. Opt-1 dictates the horizontal and vertical orientations of PM blocks in modules DL1A5, DL1A4 DL1A3, DL1A2, while DL1A1 has solely horizontal PMs. The next series of computations with Opt-1 model gave candidate materials for the yoke and poles. The simulations also detected:

• parameters of the yoke, PM blocks, and poles required to guarantee a 1.5 times reduction in the DL1A field as compared to the ESRF-EBS dipole;

• recommended gap sizes between neighbouring modules as well as the need for the end iron shims;

• the need for thermal shims and their sizes;

• the ESRF-EBS pole shapes would be affordable as the first approximation.

In the Opt-1 modules DL1A2 – DL1A5 are assumed geometrically identical but magnetized with different numbers of PM blocks. Each of these modules consists of the iron poles and the yoke with side plates, vertical PM blocks with the 1 mm wide end iron shims, horizontal PM blocks, passive thermal shims, aluminium spacers. The components of modules DL1A2 – DL1A5 are shown schematically in Figure 3 for a symmetric half of a module cross-section.

The module DL1A1 is designed differently. The vertical PM blocks and end iron shims are excluded, the side plates are shortened. The pole sizes are reduced that increased a longitudinal gap between the poles to 30.5 mm as compared with 25.5 mm in other four modules.

Every PM block of the dipole consists of 5 segments filled with unit magnets. Each segment is 80-mm long. In a vertical PM block segments are 13 mm high and 30 mm wide, while segments of the horizontal PM are twice wider.

Models with different amounts of magnetic material per block were computed. The results allowed selection of optimal sizes and locations of magnets in the assembly to ensure longitudinal field homogeneity.

The initial pole geometry for the Opt-1 model was taken the same as in ESRF-EBS. However, the simulation revealed insufficient field quality in the region of DL1A1 resulted from a larger pole gap. To reach the desired field tuning the DL1A1 pole shapes should be optimized in iterative parametric simulations.

Additionally, a DL1A design option Opt-2 with solely horizontal PM blocks was simulated. The field quality was studied with respect to the amount of the magnetic material, the pole shape, the presence of the thermal and end iron shims, and possible magnetic interaction between the components. The simulations resulted in the selection of the DL1A5 pole geometry that provides the field inhomogeneity within admissible range of $\pm 0.02\%$. Also the field sensitivity was estimated to the thickness of the Fe-Ni and iron shims and optimal shim sizes were chosen.

3 Summary

Parametrized 2D and 3D models were used to study magnet design of the PM dipoles for the SILA facility. The basic concept came from the ESRF-EBS lattice. Above hundred runs with variable geometric, magnetic, and structural parameters were made to accommodate the initial specification to the SILA requirements. The following points have been established:

• the length of the dipoles with longitudinal gradient must be enlarged as compared to the initial design to reduce the field by 1.5 times. Results of the simulation are a base to advance to the optimized practical configuration.

• The best candidate for the yoke and poles is a low-coercivity magnetic material. ARMCO or a similar steel can be employed.

• The pole shape is selected for the identical modules DL1A2 to DL1A5 assuming the design gap of 25.5mm. The pole profile ensures the longitudinal field homogeneity with the error as low as $\pm 0.02\%$. The pole for DL1A1, which is distinguished from the others by the enlarged gap of 30.5 mm, demands further optimization.

• The number and sizes of magnet units has been selected for each module. Varied amount of the magnet units within the modules affect notably the longitudinal field distribution. The filling pattern is proposed for each module with respect to typical sizes of magnet units so that to ensure discontinuity of 0.8% or less. Further optimization is recommended at the stage of prototyping.

• Magnetic interaction within the DL1A assembly has been estimated assuming a 7 mm gap between the modules.

• With the specified sizes of magnet units, the fluctuations of the integrated field in the working region are observed as +11.5% in DL1A5 and -4% in DL1A4. These fluctuations are too high to be compensated with the iron shims. The magnetic structure needs further optimization to reach the required field quality. Possible crosstalks between neighbouring magnets must be taken into account because of their close locations.

• The thickness of Fe-Ni shims is determined to compensate temperature fluctuations of the PM field with respect to the amount of the magnetic material in every module.

• Field tuning scheme is adopted and sizes of iron shims are selected for every module.

The next step will be magnetic measurements on the prototype to optimise the configuration and achieve the best field quality.

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