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OPTIMIZATION STUDIES ON ACCELERATOR SAMPLE COMPONENTS FOR ENERGY MANAGEMENT PURPOSES*

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Abstract

Over the past few years, both concerns and interests in research topics related to the large amount of energy required to operate accelerator facilities have relatively increased. This sheds light on the importance of the research field of energy management that entitles, with a view to long-term operations, the implementation of smart and sustainable technologies.

In this work, an optimization algorithm has been developed and tested on a design of a superconducting undulator magnet aiming at finding a compromise between getting the best performance for excellent science from a component with superconductivity preserved and safe operation maintained and at the same time reducing the material consumption and eventually the effective cost.

INTRODUCTION

Superconductor (SC) based designs are one of the key technologies in present accelerators. The vanishing electrical resistance together with the ability to provide field values well above those from conventional conductors are the main motivations behind exploiting superconducting wires in building coils and magnets for large-scale accelerators. However, these superconductors can also quench under certain conditions, driving the wires into the normal state and potentially allowing for overheating and destruction of the conductor material and/or the whole device.

This work will present the results obtained from developing an optimization algorithm which aims primarily at investigating some accelerator sample components from a sustainability perspective. This entitles searching for an optimal design where the amount of material used is minimized, meanwhile maintaining a desired operational condition.

Since the measure of efficiency always relates to an improvement in comparison to another solution, it is therefore important, when performing such investigations to specify also a reference component. In this study, the design of a compact SC undulator magnet has been used as a reference model. This undulator component is based on the structuring technique with laser micro pulses to produce an alternating current path. Details on the realization of this compact undulator using laser-scribed technology are described in these references [1–3]. In the next sections, the design of the reference component, specifications related to the performed optimization analysis and results obtained from the developed algorithm are presented.

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UNDULATOR MAGNET AS A TEST SAMPLE

The test component used in this investigation is the design of a compact SC undulator magnet built from the high-temperature superconductor (HTS) REBCO tapes. The reference design is realized from a built demonstrator with soldered joints where the alternating current path along individual tapes is produced with the structuring technique using laser micro pulses [1]. For the reference analysis, the following geometrical features were used for the single tape: a tape's overall thickness of 55.6 µm, a SC layer thickness of 1.6 µm, a periodic length λ of 8.05 mm and a number of periods of 12.5. The structure of layers in a single tape was based on that of a 2G HTS tape excluding the two copper stabilizer layers on the tape's surface [4]. A groove width of 25 µm and a magnetic gap of 6 mm are assumed. In addition, the number of tapes in each pole of the magnet is assumed to be 30 for the reference analysis. A 2D representation of the design of the reference tape and a 3D representation of the design of the reference undulator can be seen in Fig. 1.

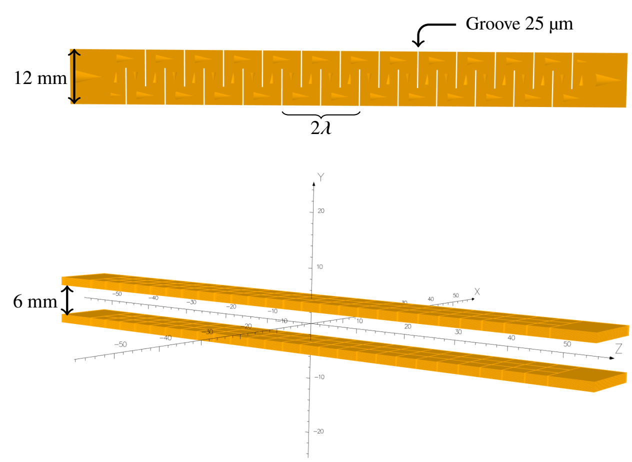

Figure 1: Two-dimensional representation of a single laser scribed REBCO tape. The annotations on the image indicate the tape's width of 12 mm, the groove, and two consecutive periods. To better visualize the groove's width, a factor of 10 was assigned (upper panel). Three-dimensional representation of the reference design of the SC undulator with two poles each having 30 SC tapes. The annotation indicates the magnetic gap of 6 mm (lower panel). The alternating current direction is represented through the arrows on the tape's surface.

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OPTIMIZATION ANALYSIS

The optimization analyses were carried out within OPERA SIMULIA 3D software [5]. These analyses aim primarily at defining a compromise between the size of a component and its performance, in an attempt to define a more sustainable design where the SC material being reduced meanwhile assuring a safe operation in the superconducting state for a desired operational field level. To this end, an initial model based on a real demonstrator magnet was defined and used as a reference analysis. Three design parameters were defined: k_1 for one third of the tape's width, k_2 for the number of periods and k_3 for the number of tapes per pole. The geometry was defined in a parameterized way such that all single parts of the magnet are defined in a variable definition (without assigning numerals). Such definition was accompanied with using the design parameters (especially k_1) as a base for assigning values of other design parts (e.g. the periodic length λ was defined as a function of k_1). Geometry constraints were defined by setting a lower and upper limit for each of the three design parameters. For the operation requirements, additional field-related constraints were defined for the desired peak level as well as for the slope estimated from the load-line of the magnet's design, such constraints help keeping safe operation based on the characteristics of the critical surface of the REBCO material [6].

Two optimization functions were defined. The first with an objective of minimization was the design's volume $f_1(k)$:

$$f_1(k) = \left[k_1(2k_2 - 1)(2k_1 + t) + k_1^2(2k_2 + 2) + 48k_1\right] 2dk_3\,,$$

where t is the groove's width and d is the thickness of the SC layer. The variable k represents the three design parameters: k_i with $i = 1, 2, 3$. The second function with an objective of maximization was the field integral per unit wavelength $f_2(k)$ defined longitudinally on the symmetry axis ($x = x_0, y = y_0, z = z$) as:

$$f_2(k) = \frac{\int_{z_i}^{z_j} |B_y(x = x_0, y = y_0, z)| dz}{\#\lambda}\,.$$

Such definition for the second objective function $f_2(k)$ comes in accordance with the goals related to the performance level. In addition, since we are not interested in the change of field's polarity itself but rather in the absolute value of the field's strength, this makes the defined field integral a good choice. Furthermore, as the number of periods is a design variable, a division by unit of $\#\lambda$ is needed. Secondary factors related to the field quality as the good field region, the roll-off and the multi-pole components were not considered while defining objective functions.

With these optimization functions and the constrains on both the design and the field, an algorithm which uses a mixture of both deterministic and stochastic optimizations was developed. Figure 2 presents a flow chart which summarizes the different solution stages of the developed algorithm. The analysis was carried out on a 64-core workstation, with 128 processors and a RAM total capacity of 512 GB. Depending on the design complexity, a computational time of up to two days was required for one optimization analysis.

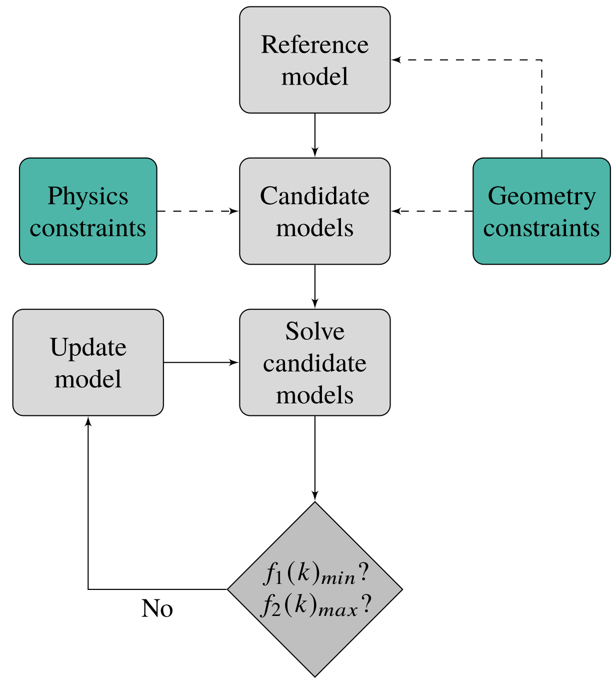

Figure 2: Flow chart summarizing the different work stages of the optimization algorithm. Starting from solving a reference model and ending with defining the optimal sustainable designs based on both geometry and physics constraints.

RESULTS

As mentioned previously, the main motivation behind developing the optimization algorithm was to define a design (or a set of designs) where both geometry and physics constraints are the criteria of sustainable component usage. Results obtained from an optimization study have proven the possibility of having 52 rank 1 solutions for a design of a SC undulator within the limits of both the geometry and field values defined in the algorithm. To better visualize the results in comparison with the reference design, a selection of feasible designs (rank $1-4$) sharing the same parameter value k_1 as in the reference model is shown in Fig. 3. The upper panel represents the component's feasible volume and the lower panel its field integral per unit wavelength plotted each as function of k_2 and k_3 parameters. The reference design was found in the rank 2 solution category. Rank 1 solutions are highlighted in red.

The graphs in Fig. 4 show how the safe operation constraints defined in the algorithm were guaranteed. On each of the figure panels the critical current (calculated assuming an operation at 4.2 K and an angle of 0 ° between the c-axis and vertical B-field) of the REBCO SC [6] is plotted together with the load-line estimated for each magnet design. The

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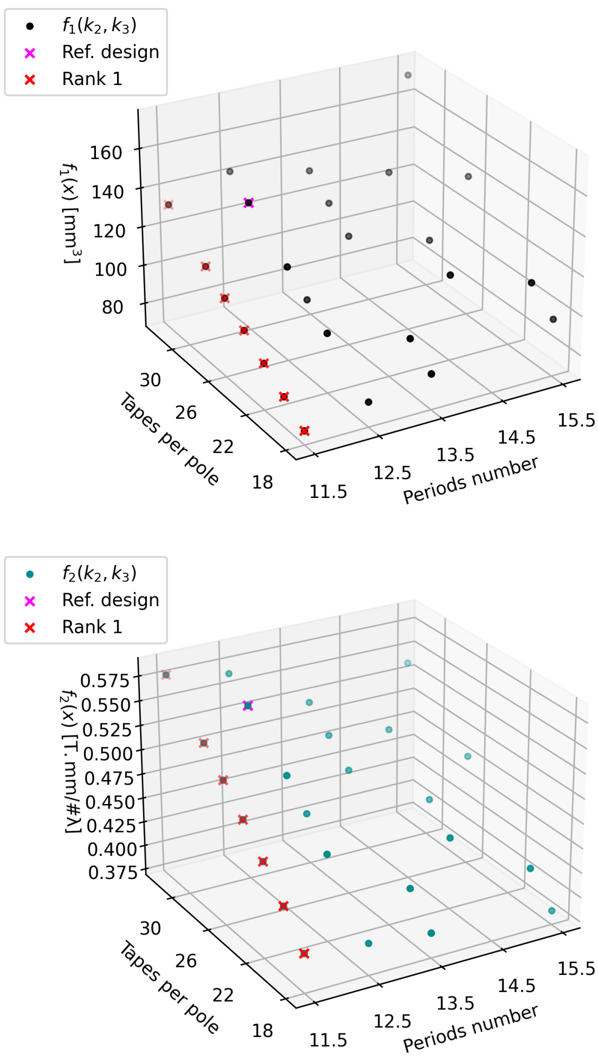

Figure 3: Selection of feasible designs (rank $1-4$) sharing the same parameter value k_1 as in the reference model of the compact undulator magnet. Feasible volumes (upper panel) and feasible field integrals per unit wavelength (lower panel) are plotted each as function of k_2 and k_3 parameters. The reference design was found in the rank 2 solution category. Rank 1 solutions are highlighted in red.

excitation point which represents the field generation source of 200 A is marked with red.

CONCLUSION

In this work, an optimization algorithm that aims at investigating the possibility of designing sustainable accelerator components has been developed and successfully tested on a reference model of a compact SC undulator. The algorithm features two main predefined groups of constraints and objective functions that are linked to the amount of used SC material and the safe operation of the component under some certain operational targets. The results have shown that there exist a possibility for further alternative good designs

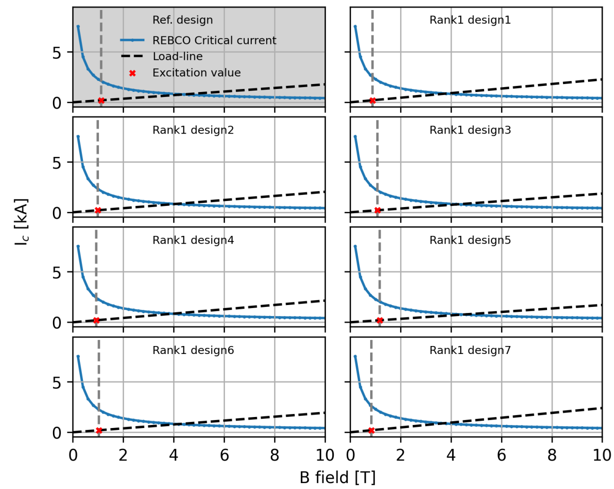

Figure 4: Safe operation for all the seven rank 1 solutions that share the same parameter value k_1 as in the reference design. The critical current I_c is plotted together with the load-line estimated for each magnet design as function of the magnetic flux density. The excitation point which represents the field generation source of 200 A is marked with red. The dashed gray line is to guide the eye for the excitation current value. The upper left panel represents the reference design and the remaining panels for the rank 1 solutions retrieved from running the algorithm.

from an energy management perspective. These designs, if compared with a reference demonstrator sample are having comparable or lesser amount of SC material. In addition they also allow a safe operation in the superconducting state for the same excitation current used in the reference model. As a follow up for the current investigation, the developed algorithm will be further expanded and tested on other magnet designs as dipoles and quadrupoles. The models of some components that are currently being used in the KARA storage ring will be used for the algorithm reference analyses.

REFERENCES

[1] A. Will *et al.*, "Design and fabrication concepts of a compact undulator with laser-structured 2G-HTS tapes," in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, SP, Brazil, May 2021. pp. 3851–3854. doi:10.18429/JACoW-IPAC2021-THPAB048

[2] B. Krasch *et al.*, "Measurement setup and magnetic field studies of a compact superconducting undulator with laser-structured HTS tapes," *IEEE Trans. Appl. Supercond*, vol. 34, no. 5, pp. 1–4, 2024. doi:10.1109/TASC.2024.3355320

[3] B. Krasch *et al.*, "Design study of a compact superconducting undulator based on laser-structured HTS tapes," presented at the 15th Int. Particle Accelerator Conf. (IPAC'24), Nashville, TN, USA, May 2024, paper THPS22, this conference.

[4] 2G HTS wire specification, https://www.superpower-inc.com/specification.aspx

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPS79

[5] Opera simulia by Dassault Systèmes, https://www.3ds.com/products-services/simulia/products/opera/

[6] C. Senatore *et al.*, "Field and temperature scaling of the critical current density in commercial REBCO coated conductors," *Supercond. Sci. Technol.*, vol. 29, no. 1, p. 014002, 2016. doi:10.1088/0953-2048/29/1/014002