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German G.A. Shneerson, Alexander A.S. Nemov, Anna A.D. Lagutkina

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German G.A. Shneerson, Alexander A.S. Nemov, Anna A.D. Lagutkina. Designing Quasi-Force-Free Configurations of Non-Destructive Megagauss Magnets. 8th Euro-Asian Pulsed Power Conference (EAPPC 2020), Aug 2021, Biarritz, France. hal-04021029

**HAL Id: hal-04021029**

**<https://univ-pau.hal.science/hal-04021029>**

Submitted on 9 Mar 2023

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DESIGNING QUASI-FORCE-FREE CONFIGURATIONS  
OF NON-DESTRUCTIVE MEGAGAUSS MAGNETSDesigning Quasi-Force-Free Configurations of  
Non-Destructive Megagauss Magnets

G.A. Shneerson, A.S. Nemov, A.D. Lagutkina  
Peter the Great St. Petersburg Polytechnic University  
St. Petersburg, Russian Federation  
gashneerson@mail.ru

**Abstract**— An approach to designing quasi-force-free configurations of non-destructive magnets aimed at achieving pulsed megagauss fields above 100 T is presented. Axisymmetric configurations of magnets that are characterized by a low ratio of the mechanical stresses in the windings to the magnetic pressure of the generated field are presented. The characteristic feature of new variable-radius configurations is the reduced magnetic field in the area close to the coil end, which allows to overcome limitations caused by mechanical stresses in the end area. Further development of this approach may lead to megagauss-level research magnets.

**Keywords**— *quasi-force-free windings; non-destructive magnets, strong pulsed magnetic fields; variable-radius configurations*

## I. INTRODUCTION

The concept of quasi-force-free magnets is based on the idea of designing conductors in which vectors of current density and magnetic induction are parallel, and, therefore, no Lorentz force is generated. In practice, that can be realized only to a certain extent [1] and requires magnets of special geometry that generate both poloidal and toroidal fields, which can be also referred to as “tilted windings concept” [2]. One of the possible configurations is a quasi-force-free pulsed non-destructive magnet is a winding in a coaxial screen [3], a schematic representation of which is shown in Fig. 1. The slope of the conductors in a quasi-force-free winding should be chosen so as to satisfy everywhere the equilibrium condition that requires that the magnetic pressure of the poloidal field on the one side of the winding equals to the magnetic pressure of the toroidal field on the other side:

$$\frac{B_p^2}{2\mu_0} \approx \frac{B_\phi^2}{2\mu_0} \quad (1)$$

The performance of a quasi-force-free configuration can be characterized by a dimensionless parameter  $\eta$  which is defined as the ratio of the von Mises stress at a certain point of the winding to the magnetic pressure of the generated magnetic field:

$$\eta = \frac{\sigma_{max}}{\frac{B_0^2}{2\mu_0}} \quad (2)$$

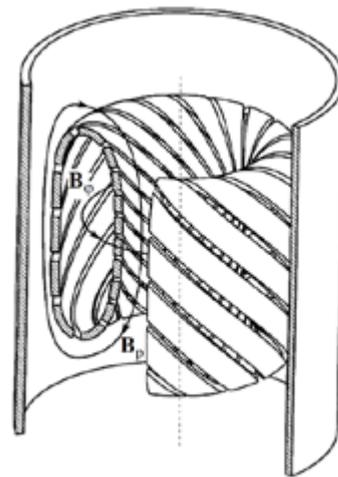


Fig. 1. A quasi-force-free winding in a coaxial screen [3]

For an idealized infinite-length quasi-force-free winding, the dimensionless strength parameter takes the maximum value  $\eta \approx 0.2$ . In a finite-length system because of the presence of the curved end zones, maximum values of  $\eta$  are higher, but can be ensured below 0.5 [1]. Taking into account finite thickness of a real winding allows to satisfy (1) only approximately, and additional measures are required to decrease maximum values of  $\eta$  and ensure strength of the winding.

One of the ways to decrease mechanical stresses is using multi-layer coils – theoretically an  $n$ -layered quasi-force-free coil stresses may be up to  $n^2$  times lower than in the single-layer one. A number of various quasi-force-free configurations of a two-layer system in a coaxial screen was developed [4],[5]. Fig. 2 shows an axisymmetric representation of a two-layer configuration developed in [4], and the distribution of the dimensionless strength parameter in it. Only top half of the structure is shown due to the symmetry of the magnetic system. The maximum value 0.24 for  $\eta$  was ensured in this configuration by means of manual correction of the poloidal current in coils. The latter means that physical implementation of such a structure requires additional conductors for taking away part of the current from the winding, which presents

This work was supported by the Russian Science Foundation, project No. 18-19-00230.

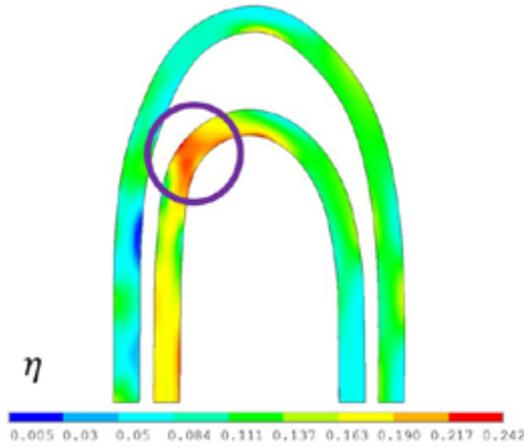


Fig. 2. The dimensionless strength parameter in a two-layer quasi-force-free magnet (an axisymmetric approximation) [4].

certain technical difficulties and also may disturb the magnetic field and influence mechanical stresses as a result.

It can be seen from Fig. 2 that the end part of the inner coil (the circled area) is among critical areas where higher stresses are observed. Designing end parts of the coils appears to be one of the general problems in developing quasi-force-free magnets. That problem becomes especially acute for multilayer windings. In this research we propose a method for mitigating the mentioned difficulty of designing end parts of quasi-force-free configurations by means of weakening the magnetic field in that area.

## II. VARIABLE-RADIUS CONFIGURATIONS

The difficulties in designing end parts of the windings may be significantly reduced by weakening the magnetic field in these areas. One obvious way is increasing the internal radius of the magnet in the areas close to its ends. However, for a single-layered winding, that is not possible without breaking the equilibrium conditions (1), which require the magnetic pressure of the poloidal field inside to be equal to the magnetic pressure of the toroidal field outside. In a single-layer system the first one is inversely proportional to  $k$  squared, whereas the second one is inversely proportional to  $k$ , which means that increase in the internal radius results in breaching the equilibrium – see Fig. 3.

In two- and multilayer windings that problem, however, can be solved by varying internal and external radii of the individual windings. Fig. 4 presents an axisymmetric finite element model of a two-layer winding of variable radius with the ratio of internal radii in two parts  $k = \sqrt{2}$ , as well as results of magnetic and stress analysis for this configuration. The dimensions of the windings and toroidal currents in them were chosen so as to ensure approximate equilibrium of the parts of the windings of constant radius. Between those parts, a linear change of the winding radius was implemented (a transitional variable-radius part). Poloidal current remains unchanged within each layer, which means that, unlike the configuration shown in Fig. 2, this distribution of current densities can be ensured by appropriate

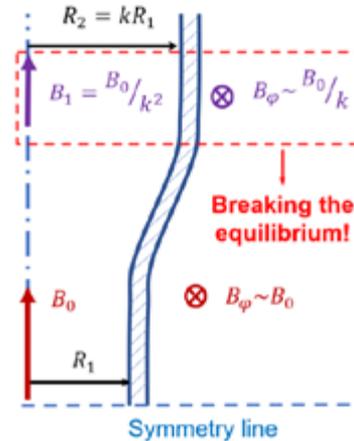


Fig. 3. Breaking the equilibrium in a single-layer variable-radius quasi-force-free winding.

shape of the conductors – a method for constructing 3D configurations on the basis of axisymmetric ones was proposed earlier in [5].

Plots of components of the dimensionless body force indicate that for path 1 and path 3 (parts of the windings of constant radius) toroidal and axial components of the body force are negligible, and radial components change its sign within each winding, ensuring small resultant (approximate equilibrium). The equilibrium, however, is not ensured in the transitional variable-radius part of the windings, which is especially true for the outer winding – plots of forces along path 2 in Fig. 4 indicate existence of considerable toroidal and axial components of the body force in the windings. These forces evidently influence stresses in all parts of the winding. As a result, the dimensionless strength parameter  $\eta$  takes values up to 0.25 in path 1 and path 3 (constant-radius parts of the winding) and up to 0.32 in path 2 (the intermediate part). Plots of magnetic flux density components in Fig. 4 illustrate that axial field in the upper part of the system (path 3) was reduced at least 1.5 times in comparison to that in the middle part of the system (path 1). That is less than factor 2, which could be expected for  $k = \sqrt{2}$ , because of the fact that the distribution of toroidal current in the winding was modified so as to achieve approximate equilibrium in the considered cross-sections. Factor 1.5 of the field reduction provides 2.25 times decrease in the magnetic pressure in the upper part of the winding, which can be used for designing a finite-length two-layer configuration similar to presented in Fig. 2, but with reduced stresses in the end part of the windings.

In the presented configuration, the relatively high values of  $\eta$  up to 0.25 were observed in the second layer of the winding, while the strength parameter in the first one does not exceed 0.17. It is reasonable, therefore, to apply additional measures aimed at reducing stresses in the second layer. One of the possible ways may be varying the shape of that part and the distribution of toroidal currents in it. A more significant correction might be achieved by correcting the poloidal current in the second layer, i.e., removing part of the current at a certain

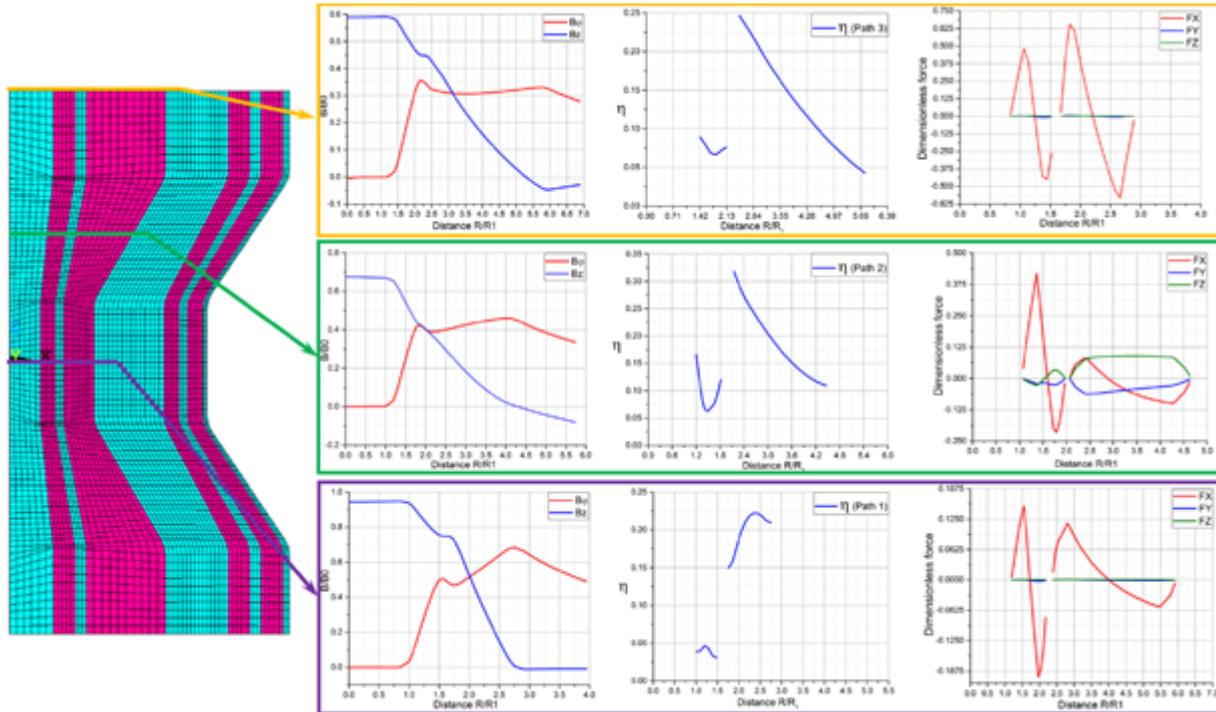


Fig. 4. Axisymmetric finite element model of a two-layer variable-radius configuration of a quasi-force-free coil. Results of the analysis: components of magnetic flux density  $B_\phi$ ,  $B_z$ ; dimensionless strength parameter  $\eta$ ; components of the dimensionless force:  $\frac{F}{B_0^2 / 2\mu_0 R_1}$ .

point of the winding. Additionally, as it was demonstrated in [4], stresses in a winding may be considerably reduced by dielectric reinforcements in the system.

Achieved values of the dimensionless strength parameter in the constant-radius parts below 0.25 indicate the possibility to generate the magnetic field with flux density 100 T by a winding of a material with the strength 1 GPa. The discussed possibilities of further decreasing mechanical stresses in the windings gives reasons to expect moderate stresses in finite-length systems developed according to the proposed idea of variable-radius windings.

### III. CONCLUSIONS

The presented example of a two-layer infinite-length magnetic system illustrates the possibility to reduce the magnetic field in the parts of windings that are distant from the central area with the strongest field. The reduction of the field by factor 1.5 was achieved while keeping mechanical stresses at a moderate level, characterized by the dimensionless stress parameter below 0.25. These results demonstrate a possibility to create a finite-length variable-radius two-layer winding with significantly reduced magnetic flux density in its end parts. Unlike the configurations shown in Fig. 2, such variable-radius

configurations may be characterized by significantly reduced mechanical stresses in the end parts without a need for poloidal current correction. That gives grounds for the development of an axisymmetric conceptual model of a non-destructive magnet with the field beyond 1 megagauss.

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