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INFLUENCE OF THE CORRECTION COILS ON THE ELECTRON'S BEAM FOCUSING IN FEL'S ACCELERATORS

WPŁYW CEWEK KOREKCYJNYCH NA SKUPIANIE WIĄZEK ELEKTRONÓW W AKCELERATORACH FEL

***Summary**: In this paper, the optimization of the solenoid construction in free electron lasers (FEL), modern class of accelerators used for more deep investigations of materials structure has been reviewed. The solenoid is used for magnetic focusing of the electron beam, while the efficiency of this process is dependent on magnetic induction profile of solenoid. The process of beam focusing is usually implemented by using the magnetic yoke. In the present paper the application of the correctional coils for the purposes of the magnetic induction profiling has been analyzed. The physical principle of the magnetic method of the electron beam focusing has been discussed, as well.*

***Keywords**: free electron lasers, correctional coils, magnetic induction profile, optimization*

***Streszczenie**: Artykuł poświęcony jest optymalizacji konstrukcji solenoidów w laserach na swobodnych elektronach (FEL), nowoczesnej klasie akceleratorów wykorzystywanych do precyzyjnych badań struktury materiałów. Ten solenoidalny elektromagnes służy do magnetycznego skupiania wiązki elektronów, a efektywność tego procesu zależy od profilu indukcji magnetycznej elektromagnesu. Często proces ogniskowania wiązki realizowany jest za pomocą jarzma magnetycznego. W artykule przeanalizowano zastosowanie cewek korekcyjnych do celów profilowania indukcji magnetycznej. Przedstawiono także fizyczną zasadę magnetycznej metody skupiania wiązki elektronów.*

***Słowa kluczowe**: lasery na swobodnych elektronach, cewki korekcyjne, profil indukcji magnetycznej, optymalizacja*

Introduction

The continuous progress in the scientific devices' parameters, necessary for development of basic and applied research requires more and more advanced apparatus construction. The present paper is dedicated to analysis of the optimization of the solenoids construction in modern free electron lasers (FEL) facilities.

Physical approach

The solenoid arrangement, the purpose of which is to focus the electronic beam, is an important part of the electron gun in FEL accelerators. It is shown in Fig. 1.

The process of focusing the electron beam is graphically shown in Fig. 2; it illustrates the interaction of electron bunch with fringe fields of solenoid, changing then electron movement at the opposite directions at upper and bottom part of solenoid, leading to its final shrinkage, as is indicated by green colour in the right part of Fig. 2.

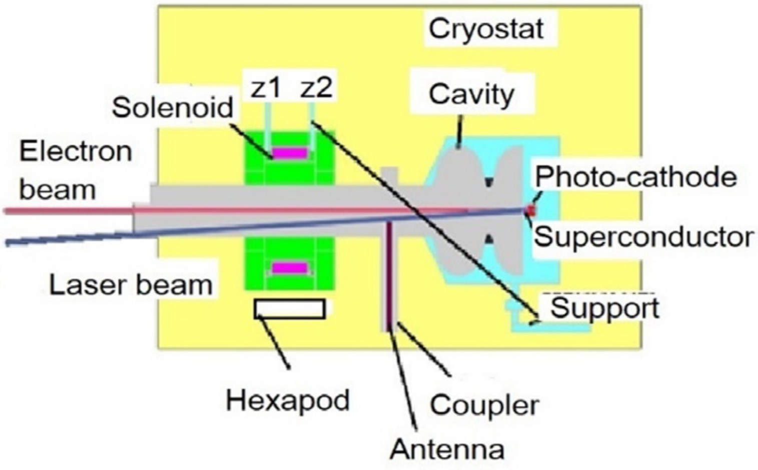

Fig. 1. Schematic view of the electron gun in modern FEL accelerator

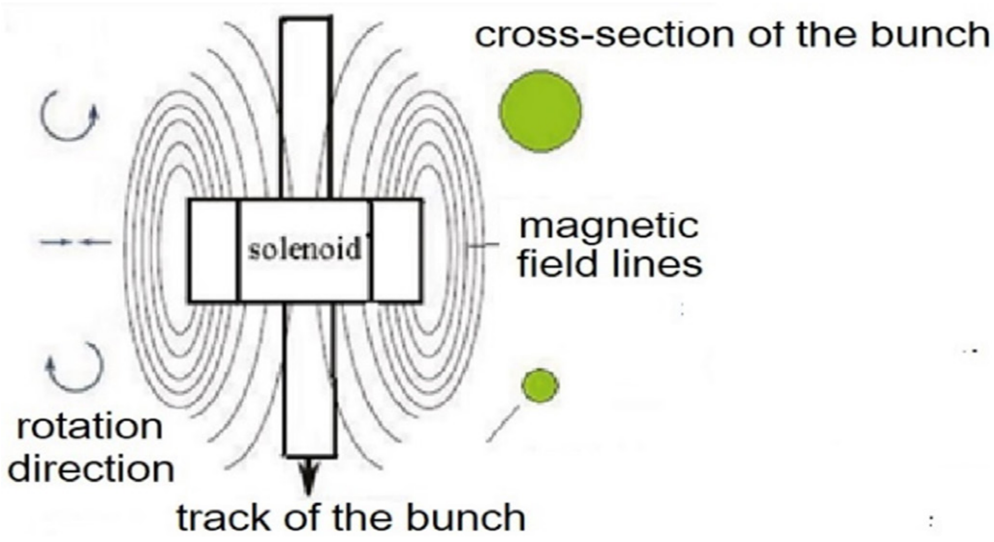

Fig. 2. The physical principle of the electron bunch movement through the solenoid

Mathematic model

Mathematical description of magnetic focusing an electron beam with envelope σ is based on the following [1] general equation:

$$\sigma'' + \frac{qE_{\mathrm{acc}}}{mc^2\beta^2\gamma}\sigma' + K_r\sigma - \frac{\kappa_s}{\beta^3\gamma^3}\frac{1}{\sigma} - \left(\frac{\varepsilon_{\mathrm{n,rms}}}{\beta\gamma}\right)^2\frac{1}{\sigma^3} = 0 \qquad (1)$$

Here σ describes the bunch size, $\varepsilon_{\mathrm{n,rms}}$ is averaged emittance, symbol ʻ denotes the derivative, m is electron mass, q electron charge, c light velocity, while β= v/c reduced electron velocity and $\gamma = 1/\sqrt{1-\beta^2}$. κ_s is beam perseverance, E_{acc} is average accelerating gradient, while the third term in Eq. 1 describes the radial focusing forces. The discussed equation has been significantly reduced in [2] in the considered case of the description of the movement of axial electrons in magnetic field of the solenoid and neglecting any other forces acting on the beam.

$$\sigma" = -\left(\frac{qB_z}{2mc\beta\gamma}\right)^2\sigma \qquad (2)$$

We integrate then Eq. 2 on the distance of solenoid length as it is between z_1 and z_2, taking into account that we are interested in the variation of the electron bunch size at the output of solenoid. Assuming then that inside of solenoid bunch envelope is approximately constant, we obtain expression 3 describing the variation on the external end of solenoid z_2 the electron beam size and then its focal length f:

$$-\frac{\sigma'(Z_2)}{\sigma} = \frac{1}{f} = \left(\frac{q}{2mc\beta\gamma}\right)^2\int_{Z_1}^{Z_2} B_Z^2\,dz \qquad (3)$$

where z_1 and z_2 are the positions of the beginning and end of the solenoid along z axis, as shows Fig. 1. So Eq. 3 allows finally explicitely to join focal length of electron beam f with integral from square value of axial magnetic induction in the solenoid according to Eq. 4, in the right side of which there have been inserted numerical values of fundamental physical parameters, such as electron mass, electron charge:

$$Int = \int_{z1}^{z2} B_z^2\,dz\;[T^2\cdot mm] = \frac{4(m_e\beta c)^2}{q^2 f(1-\beta^2)}\left[\frac{kg^2m^2}{s^4A^2\,\mathrm{m}}\right]$$
$$= 11{,}645\cdot\;10^{-6}\frac{\beta^2}{(1-\beta^2)}\cdot\frac{1}{f(m)}\left[T^2\cdot\mathrm{m}\,\right] \qquad (4)$$

The dependence of the focal length on the value of integral (Int) from Eq. 4 is shown in Fig. 3, as the function of electron velocity in the respect to the light velocity. So large values of the electron beam velocity indicate on the relativistic features of the appearing here processes, in the time scale of the femtoseconds.

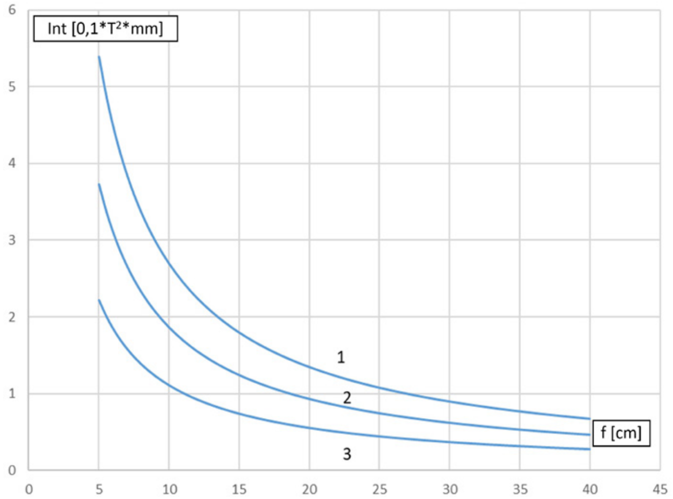

Fig. 3. The dependence of the focal length of the solenoid on the value of the integral from square of magnetic field Int, according to Eq. 4. Individual curves are dependent on the electrons velocity expressed in light velocity c units: (1) β = 0,95c, (2) β = 0,93c, (3) β = 0,89c

Results of calculations magnetic induction distribution in solenoid with correctional coils

As it follows from the curves shown in Fig. 3 the required value of the focal length of the solenoid is dependent on the value of integral Int, determined by the square of the profile of axial component of the magnetic induction along the solenoid length. Magnetic field profile should be optimized, in such a way that magnetic field profile of solenoid will be of the form of Gaussian distribution with a fast decay at the solenoid ends, in order do not exceed the limits allowable for the undisturbed operation of superconducting cavities. In FEL construction built in Helmholtz-Zentrum Berlin [3] it is suggested also that solenoid should provide integrated square of axial component of magnetic induction, according to Eq. 4 of the range 1 [$T^2 \cdot mm$].

Frequently for this aim of forming the magnetic induction profile of solenoid, the iron yoke has been employed [3]. In the present paper, the alternative method of using the internal correctional coils in common electric circuit for that purpose is analyzed.

For magnetic induction profiles calculations the finite element method (FEM) was used. In this method it is necessary to choose the boundary conditions. Three cases were considered: of the vanishing on the boundary the perpendicular to surface magnetic induction, or of appearing any barrier of magnetic field at the surface and in third case of vanishing the magnetic potential A on surface. The results of calculations of the magnetic induction distribution in solenoid with internal correction coils are presented in the considered case of ΔH = 210 [A/m] in Fig. 4 (a) and in Fig. 4 (b) of the vanishing on the boundary the perpendicular to surface magnetic induction. The results of calculations indicated that it is a large similarity between the magnetic induction lines profiles, in the both shown cases, as well as for the case of the vanishing on the surface the magnetic field potential A. Thus, in further calculations there has been applied just this third boundary condition.

The results of calculation magnetic field lines in simple solenoid of the internal diameter 3,7 cm and length 24 cm, is shown in Fig. 5, while the profile of magnetic induction distribution for that case and current density $j=10^6$ A/m^2 is given in Fig.6.

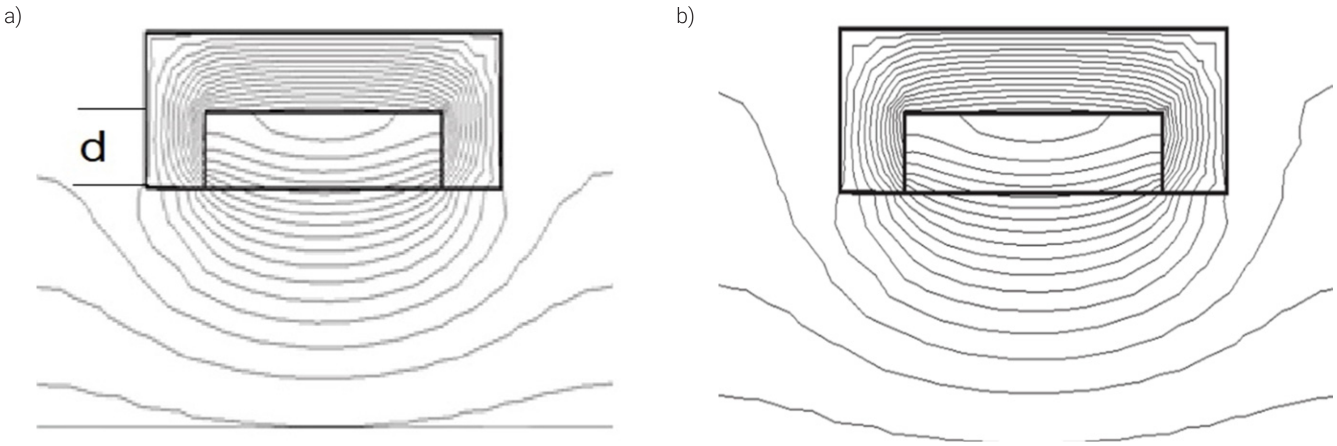

Fig. 4. Influence of the boundary conditions on magnetic induction lines in solenoidal electromagnet with internal correction coils. Part (a) ΔH = 210 [A/m], part (b) vanishing of perpendicular component of magnetic induction B_n

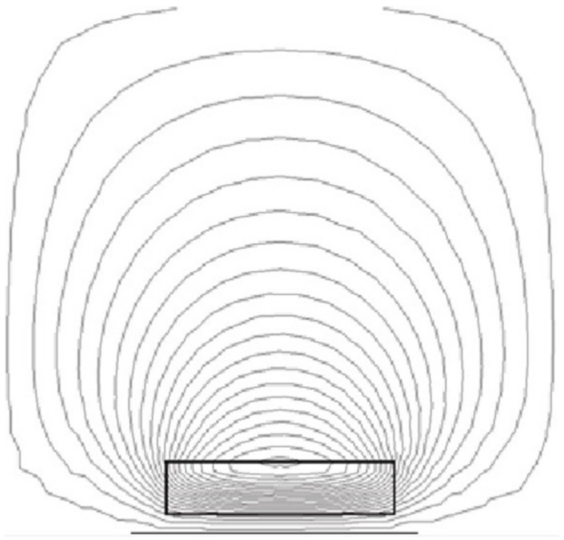

Fig. 5. Magnetic field, lines in the cross-section of the simple solenoid construction, with axis of the solenoid denoted by thin, straight line

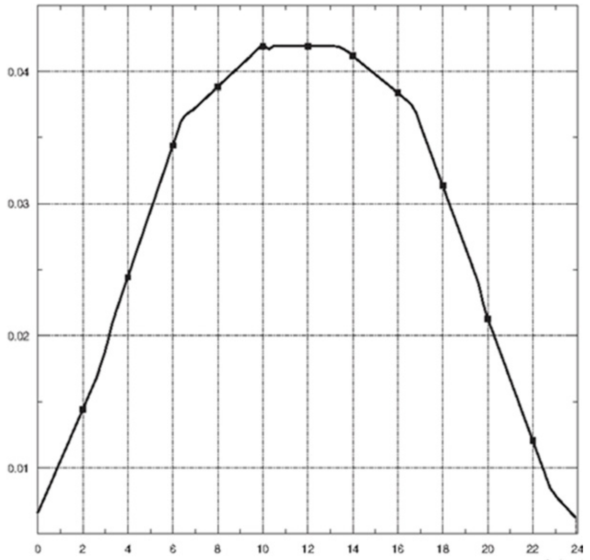

Fig. 6. Axial magnetic induction profile in [T], in simple solenoid for current density $j=10^6$ A/m^2

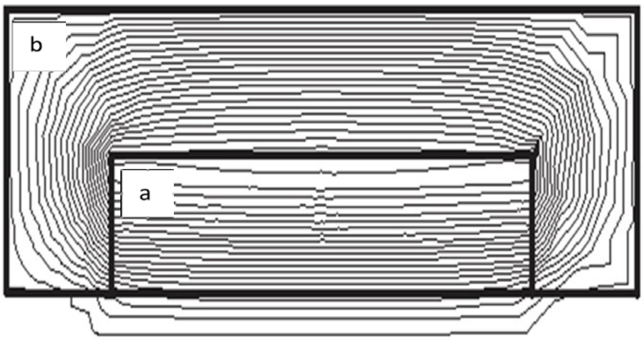

Fig. 7. Profiles of magnetic field lines in solenoid (a) with iron yoke (b), for j=10^6 A/m^2

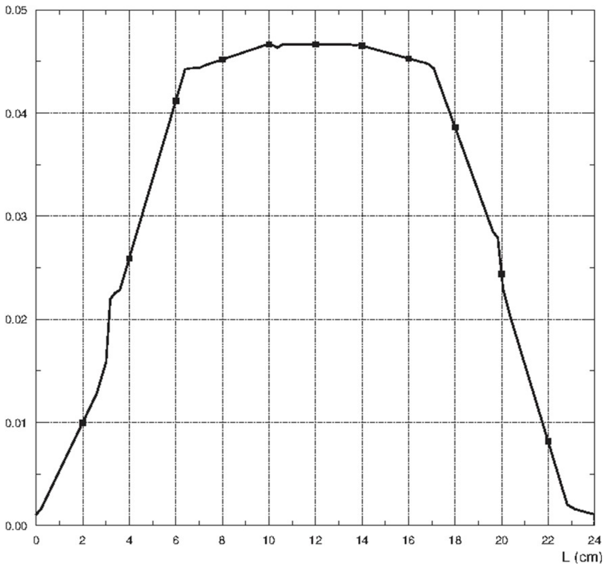

Fig. 8. Magnetic induction profile in [T], along z axis in centre of solenoid with iron yoke, for current density j=10^6 A/m^2

The value of the integral from magnetic induction distribution given by Eq. 4 is for this simple solenoid shown in Fig. 6 and current density j=10^6 A/m^2 equal to 0,0255 T^2 mm, while for the solenoid with iron yoke shown in Fig. 7 is increasing to 0,031 T^2 mm. These are smaller values than for constructed in HZB FEL accelerator and can be increased by enhancing the transport current density, for instance by using superconducting coils. The values of the focal length for that case are equal according to Fig. 3, f = 43 cm for simple solenoid and f =33 cm for solenoid with iron yoke and electrons velocity β = 0,89c.

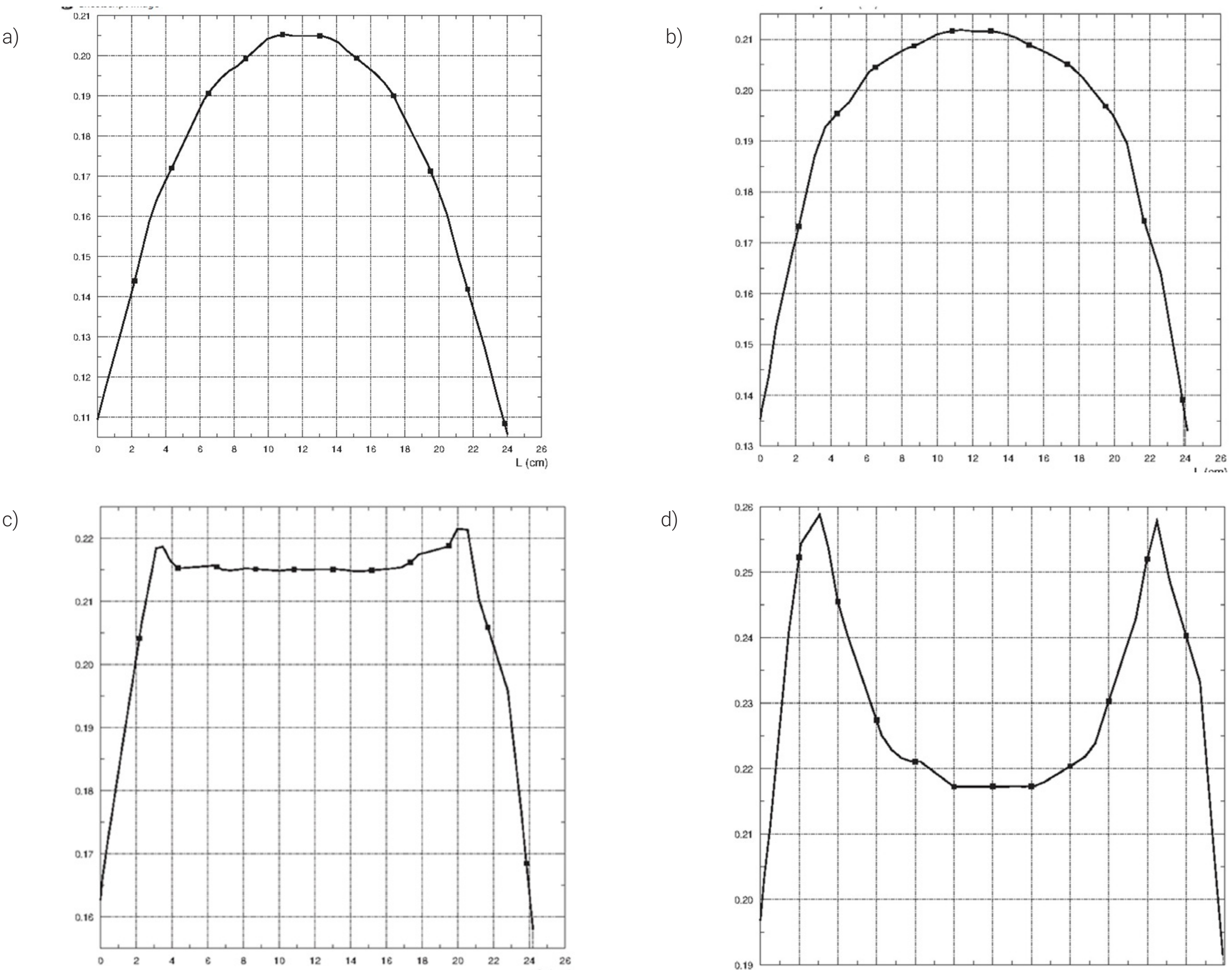

Fig. 9. Magnetic induction profile in Tesla, along z axis in centre of (a) simple solenoid, (b) for solenoid with correction coils of the thickness t = d/3, according to Fig. 4 notation, (c) t = 2d/3, (d) t = d, and current density j=5·10^6 A/m^2

As it follows from Fig. 9, the correction coils significantly influence the magnetic induction distribution in solenoidal magnet, allowing to receive this way appropriate field profile, by using much less material than in the yoke case. It is especially important for the superconducting solenoids, which require the cooling power. Comparison of Figs. 9a-c indicates that more flat induction distribution profile can be obtained along the solenoid using compensation coils. But too large correction coils create the sharp variation of magnetic induction profile, which is not a required effect from the point of view of stable flow of electron beam. Not too high values of the magnetic induction of the range 0,22 T, are connected with the current density $j = 5 \cdot 10^6$ A/m^2, which is, in fact, the maximum allowable for copper wires value.

Conclusions

In the present paper, the application of internal correctional coils in the process of focusing electron beam in FEL-s type accelerators has been investigated. The discussed method has been compared with the use of magnetic yokes, much heavier construction, the effect of which is important from the point of view of the materials' consumption and cooling power, especially for superconducting coils. It was shown that the precise profiling of correction coils is necessary at the aim to receive a smooth run of the total magnetic induction distribution.

References

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