QUALITY CONTROL OF HIGH TEMPERATURE SUPER-CONDUCTING BULK MATERIAL BY NONDESTRUCTIVE METHODS

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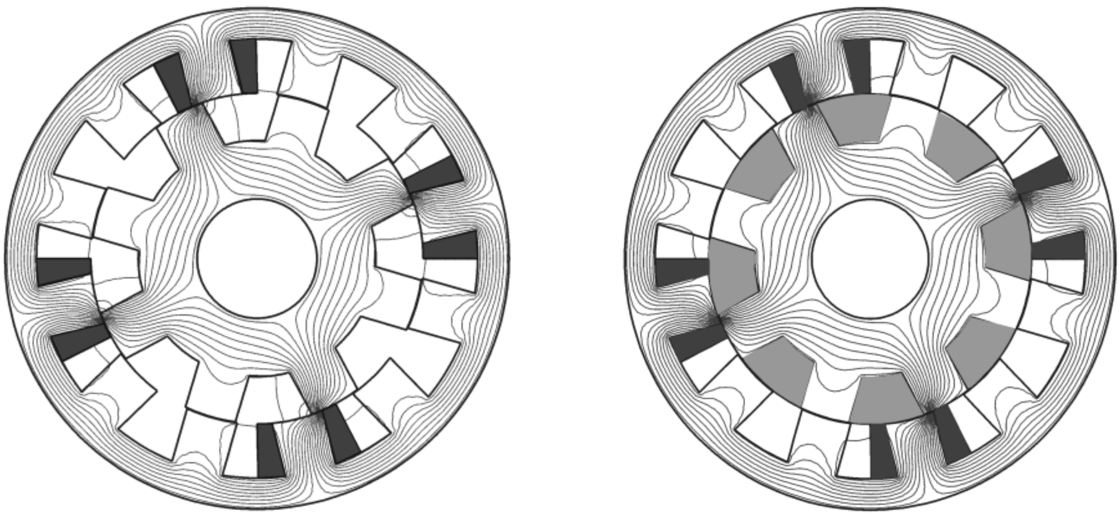
1 APPLICATION OF HTSC'S IN ELECTRICAL MACHINES

The use of HTSC material to improve the performance of electrical machines has been described in many papers [1,2,4,5]. For the excitation coils of direct-current (DC) and synchronous (SM) machines as well as for the armature windings of all types of electrical machines the use of HTSC-conductors (strands) contribute to the reduction of the machine losses. Using their field trapping capability HTSC-bulks can be considered for the improvement of the excitation of DC-machines and SM's as well. Furthermore HTSC-clusters arrangements are of favourable utilisation for hysteresis and mixed-μ reluctance motors [5]. The excellent data of all types of these "Superconducting Machines" have been achieved by assuming ideal states of the HTSC's with infinite J_c's surrounding the surface of the HTSC-block in form of a current sheet (Meissner phase) or trapping the excitation field perfectly [1]. Under the conditions of real applications of HTSC's for energy converters, they are exposed high counter flux densities resulting in field dependent finite J_c's (Shubnikov phase). Furthermore the processing of the HTSC bulks suffers from the achievable sizes (cross section and thickness) and their in-homogeneity (multi-domains). Thus it has been of a great importance to develop methods and calculation codes capable to identify all these imperfections of today's manufactured HTSC-blocks. This is necessary for the development of the proposed energy converters with improved performances.

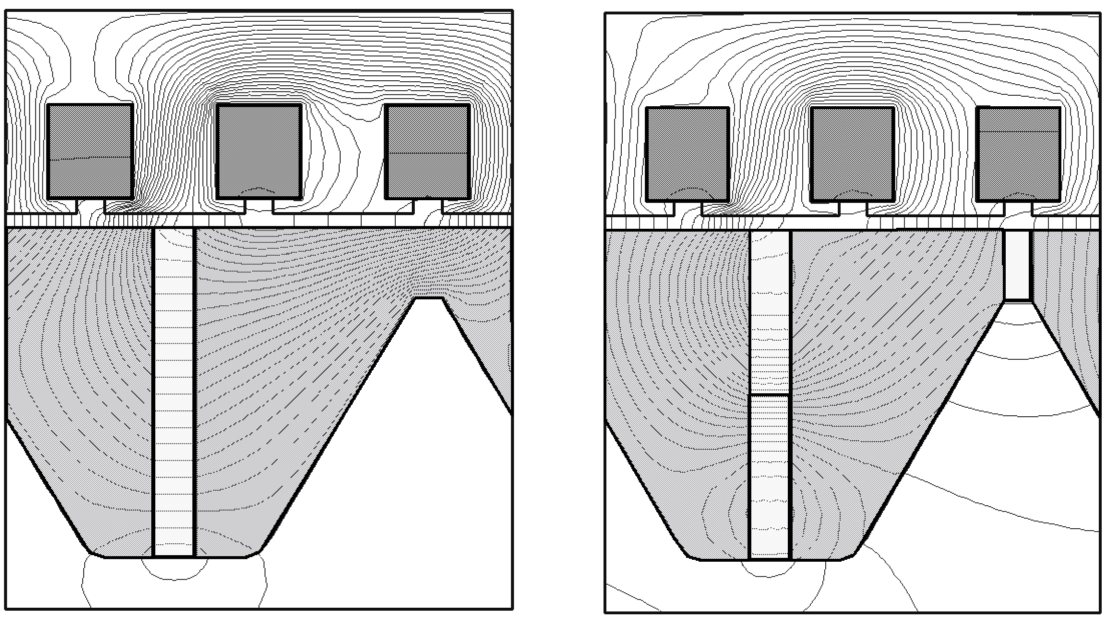
Following figures illustrate different applications of HTSC-bulks in electrical machines as for excitation (trapped field) or for parasitic field reduction (magnetic screens). **Fig. 1** shows the classical rotating switched reluctance machine used for high speed applications e.g. To achieve remarkable force densities, this machine type has to be operated at very high flux densities (1.8-2.0T). A portion of this flux penetrates into the slot region (stray-flux) thus considerably reducing the force output. If an ideal HTSC is placed in the rotor slot (**Fig. 2**), the screening effect will expel the field completely from this region and thus increasing the force and power.



a) Rotor without HTSC screens b) Rotor with HTSC screens

Fig. 1. Magnetic field distribution of a switched reluctance machine

The flux concentrating arrangement shown in **Fig. 2** is known as a further superconducting permanent magnet (SPM) excited SM design. The excitation system generates a horizontal directed flux, which is collected by the iron poles adjacent on both sides of the SPM and guided to the air gap of the machine. **Fig. 2a** shows the field plot of a SPM in the Meissner state (loaded case, one pole pitch). As a further improvement feasibility a HTSC bulk is placed as a magnetic screen in the centre of the iron-pole thus reducing the armature reaction. This simple measure leads to a remarkable increased power output (**Fig. 2b**).



a) SPM in the Meissner state b) SPM in the saturated Shubnikov state (additional HTSC-screens)

Fig. 2. Comparison of SM's with HTSC's in a flux concentrating arrangement (one pole-pitch, linear representation)

If a SPM in the trapped flux state is used as the field excitation for a synchronous machine in a gap oriented arrangement (**Fig. 3**), the effects of the saturation state (Shubnikov phase) on the field distribution influence the performance of the converter drastically. Furthermore it has to be noticed that only three dimensional field calculations are able to take the effects of the inhomogeneous flux distribution in the air-gap (plane A) into account (**Fig. 4**). Only in the Meissner state the excitation field distribution is fairly constant within the machine width (x-direction) and can thus be determined by a 2-D field calculation code [1] in plane B of **Fig. 3**.

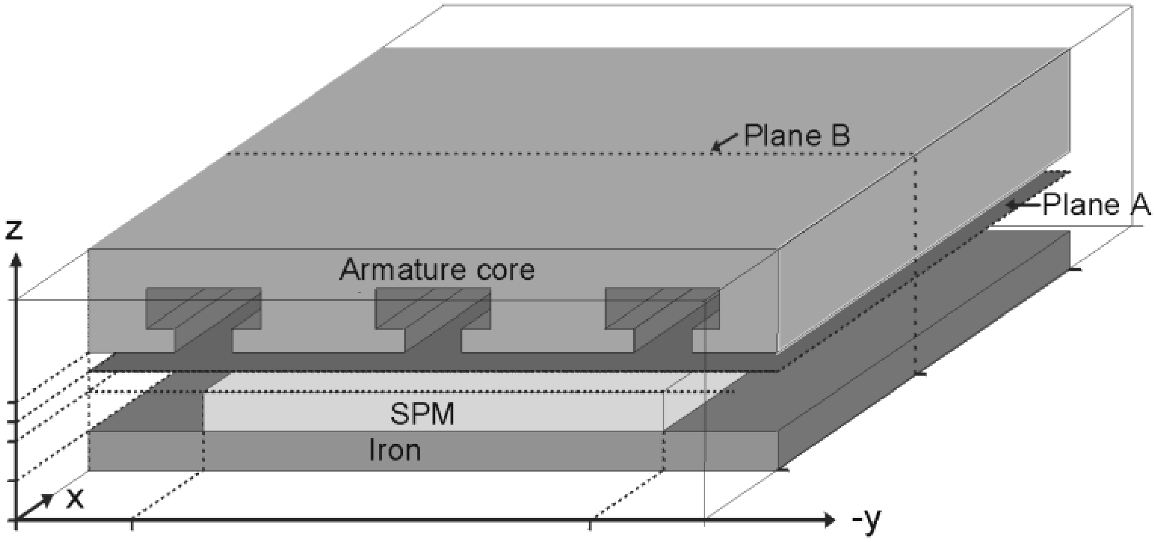
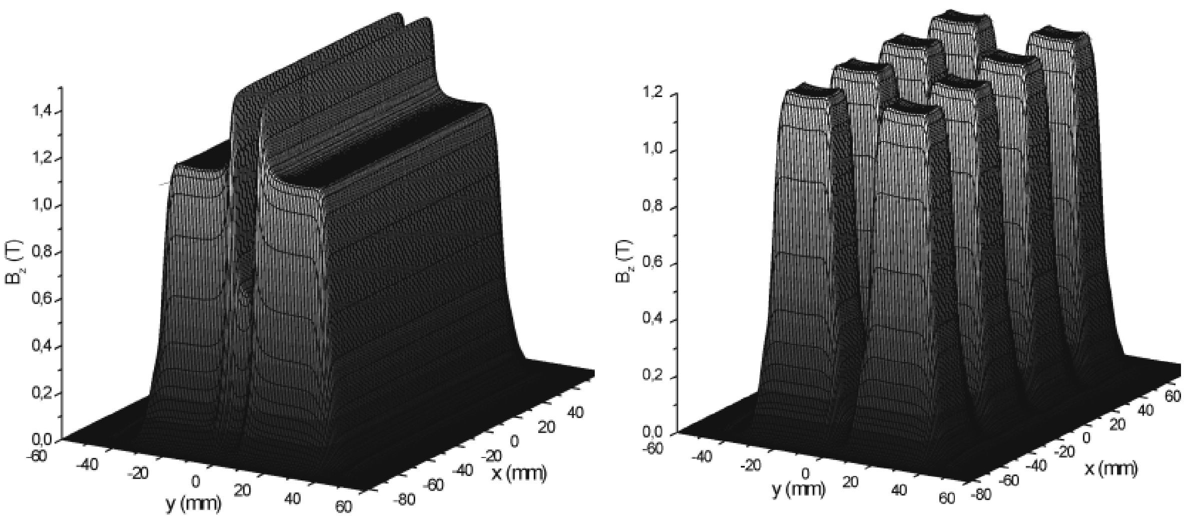


Fig. 3. 3D-Calculation model for a HTSC-excited SM (linear representation, one pole-pitch). Gap oriented excitation by “Superconducting Permanent Magnets”

The results of the field calculation for two different HTSC arrangements are shown in **Fig. 4**.



a) HTSC in the Shubnikov state (one single HTSC block per pole)

b) HTSC in the Shubnikov state (cluster arrangement)

Fig. 4. Flux density distribution in plane A of **Fig. 3** (normal component)

Finally it may be concluded, that manufacturers of HTSC-bulk material are faced with two major demands. At first for SPM applications the critical current has to be increased as high as possible so that surfaces of adjacent HTSC-bulks with currents in an opposite direction compensate each other with the effect of a more or less homogenous excitation field distribution (neglecting slotting effects). A second demand on the HTSC-quality is related to the producible block-size without internal sub-domains. With respect to the total flux -that means the power of a machine- an increased block size with reduced current densities may be replaced by a cluster of several high quality SPM-blocks of minor size. The knowledge of the material parameters e.g. domain sizes and critical current densities are of a maximum importance for the design of above mentioned machines.

2 PROPERTIES OF REAL HTSC-BULKS

In large volumes manufactured HTSC-bulk's may exhibit a more or less non-homogeneous internal structure with unknown J_c's (distribution and value) and with unknown positions and orientations of superconducting sub-domains. To control the quality the HTSC's will be inserted into the warm bore of a high field magnet of several Tesla and then cooled below the critical temperature T_c. Thus magnetically saturated (Shubnikov state) the magnetic flux will be trapped within the HTSC by internal currents after the switch-off of the external field. To scan the trapped field distribution in the proximity of the HTSC surface, the measurement set-up shown in **Fig. 5** with a 3D-Hall probe has been applied. The values of all three flux density components will be used for the determination of the J_c's (distribution and value) and thus for the quality control of the HTSC-bulks.

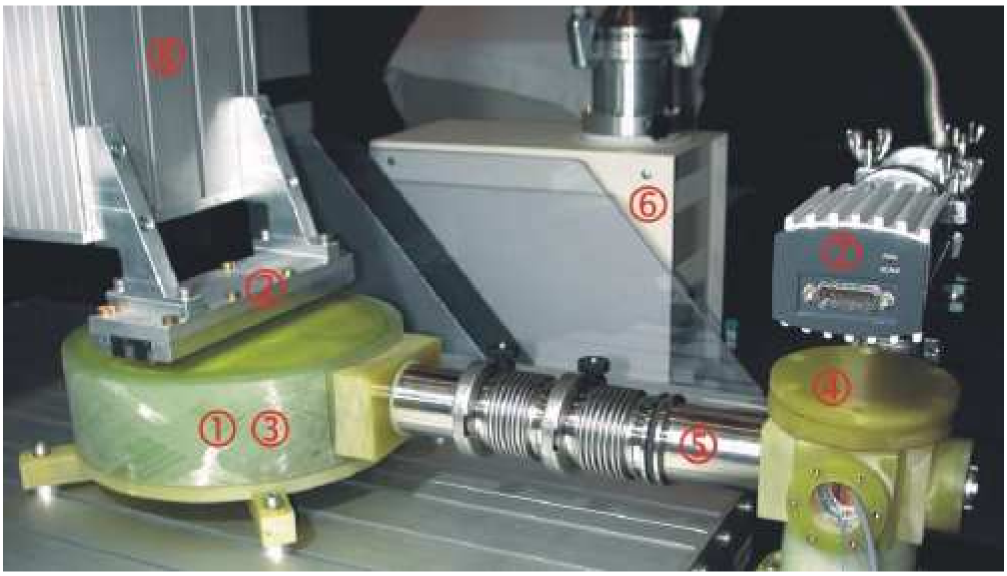
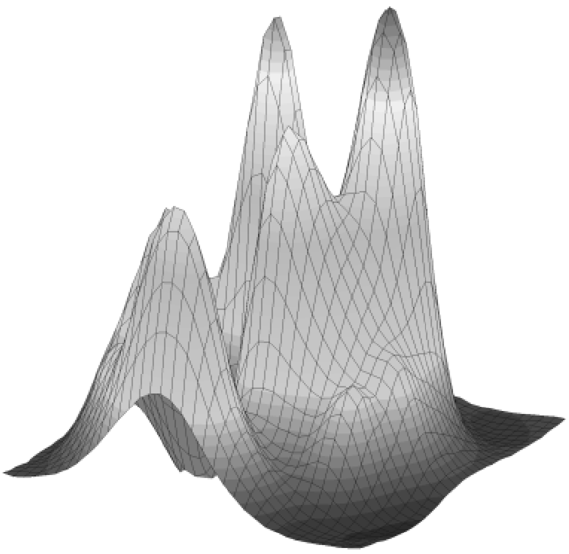
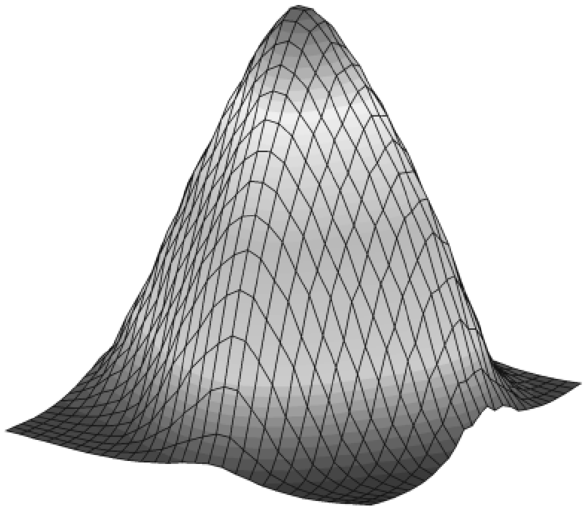


Fig. 5. Magnetic field measurement set up (3D-co-ordinate table) with a 3D-Hall probe



a) HTSC-bulk composed of several sub-domains



b) Single grain HTSC-bulk

Fig. 6. Distribution of the magnetic field (normal component at 2 mm above the surface) trapped by HTSC-bulks of different quality in the saturated Shubnikov state

The two field distributions shown in **Figs. 6a and b** differ markedly as the left HTSC-bulk consists of several small sub-domains whereas the right one exhibits the trapped field of a perfect single domain high quality HTSC. Only these bulks can react on external magnetic fields in such a way as it is shown in **Figs. 7a and b** for an inherently stable magnetic bearing for high speed applications.

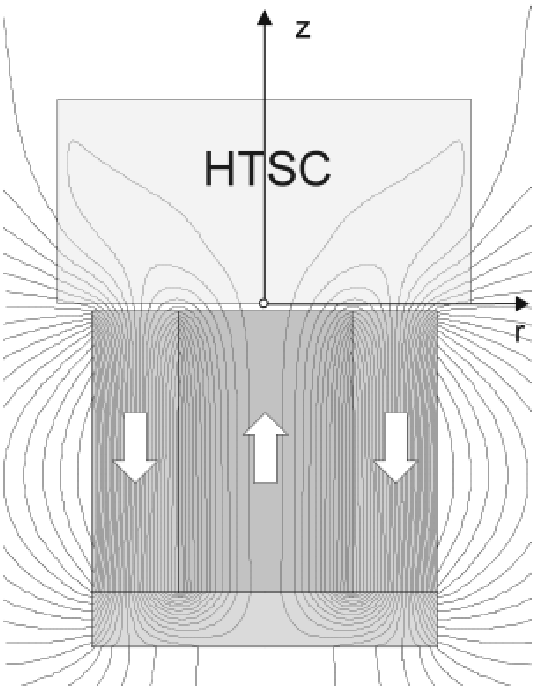


Fig. 7a. Interaction between a multi-pole permanent magnet and a perfect single domain HTSC-bulk

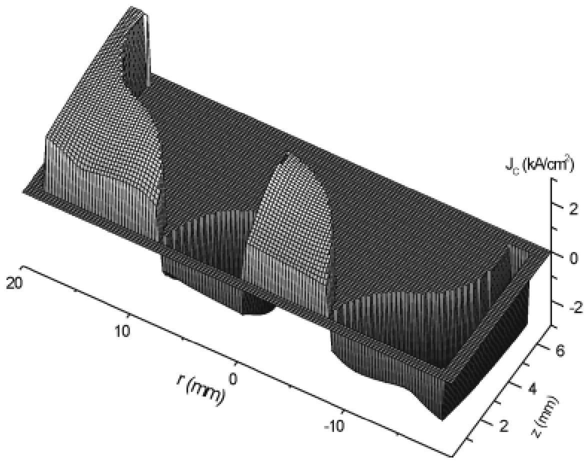


Fig. 7b. Current density distribution within the HTSC from **Fig. 7a** (approach and retreat movement)

The goal of the proposed quality control is to distinguish the manufactured HTSC-bulks with respect to an increased reaction on external fields. This property is required by the optimal design of electrical machines (excitation magnets or magnetic screens **Figs. 1-4**), levitation systems (attractive or repulsive) and inherently stable contact-free magnetic bearings for high speed rotating shafts.

3 QUALITY ESTIMATION AS AN INVERSE FIELD PROBLEM

As mentioned before, the internal structure of commercially available superconducting bulk samples is strongly related with the manufacturing process (top-seeded melting), implicating that the orientation of the crystallographic a-b planes can not be ensured for arbitrarily large pellets. At a certain distance from the seed, the planes may loose their orientations and the material solidifies in disoriented directions of the original a-b-planes. As mentioned above the identification of the positions, dimensions and orientations of the superconducting domains together with the values of their internal J_c's is of a great importance. By the use of all three components of the external field in the close neighbourhood of the HTSC known from scanning measurements (**Fig. 6**), the current distribution within the sample can be identified. Such procedure constitutes a typical inverse problem and belongs to the class of the improperly posed tasks. That is, its solution may not be unique nor continuous to the input data thus the standard numerical field calculations can not be applied directly to the identification of the current density distribution within HTSC's.

To solve this problem the fundamental finite element equation set has to be extended by equation's describing the magnetic field in regions of measurements (**Fig. 8**). This leads to the following over-determined, linear and ill-conditioned set of equations with two unknowns: the vector potential values in the whole region and the current density values within the superconductor (in matrix representation):

$$\mathbf{MA} = \mathbf{U}. \tag{1}$$

Since the coefficient matrix **M** is of the size m×n (with m>n), the solution of the equation set exists in the sense of the least squares:

$$\mathbf{A_0} = \min\left\|\mathbf{U} - \mathbf{MA}\right\|^2 . \tag{2}$$

This solution can be written as

$$\mathbf{A_0} = \mathbf{RU}, \tag{3}$$

where **R** denotes the Moore-Penrose pseudo-inverse [3,6]. If the matrix **M** is of the rank n, the least squares solution of Eq. 1 can be obtained by using the modified Gramm-Schmidt or Householder method. On the other hand, under the condition of rank **M**<n, a least squares solution exists, but it is not unique. In this situation it is possible to obtain the minimal least squares solution, i.e. the vector of minimum Euclidean length which minimises Eq. 2. This can be computed by the singular values decomposition of **M** that enables the calculation of the

appropriate Moore-Penrose pseudo-inverse. The method consists of two steps: at first the sparse matrix **M** is reduced to the tri-diagonal form by the aid of Lanczos transformations. In the second step the singular values of this matrix are computed by the use of the QR algorithm [3]. This enables to determine the matrix **R** in the Eq. 3 and the minimal least squares solution $\mathbf{A_0}$ of the problem. It should be noted here, that -because of the possible numerical instabilities- the implementation of the above algorithm is very difficult. Therefore it is necessary do define several accuracy criterion to prevent convergence to solutions with unacceptable values. Additionally the matrix **M** should be scaled with the effect that the relative errors in its elements are all of comparable size. Such a scaling procedure helps to prevent the least squares problem from being unnecessarily sensitive to both measurement and numerical calculation inaccuracies.

At first –for testing of the proposed method– an arbitrary J_c distribution within the HTSC has been assumed and the external magnetic field has been calculated. **Fig. 8** shows the magnetised HTSC (radius 30 mm, height 15 mm) under the consideration, that the external flux densities can be measured (area of measurements $\mathbf{G_0}$ indicated in **Fig. 8**). Using these field values the current density distribution within the HTSC has been identified and compared with the assumed one. The number of nodes in the whole area (equal to the number of unknown vector potentials) has been equal to 14153. The discretisation of the HTSC into small rings with square cross-sections (0.25 x 0.25 mm) leads to additional 3600 unknown current density values. To obtain an over-determined equation set with advantageously much more equations than unknowns, it is necessary to take into account extended regions where all components of the magnetic field have to be measured.

The real superconductor is usually composed by some sub-domains which can carry the current of high magnitude and others with decayed properties with respect to their internal J_c's (drastically shown in **Fig. 6a**). As the knowledge of the continuous J_c distribution is not so essential for the force determination, thus from the practical point of view it is necessary to define the average current density values for some bigger sub-regions of the HTSC only. This simplifies the calculation process and gives the required information about the distribution of superconducting domains within the HTSC together with the individual J_c. Thus, according to the required accuracy, the superconducting region has been artificially divided into more or less separated parts (rings) with identical cross-sections and the individual mean J_c value for each individual part has been determined. By this approach the number of unknown J_c values has been advantageously reduced to a small number (e.g. 16, 25 or 36). This cuts down at the same time the extension of the measurement area leading finally to much smaller equation sets and stabilising the calculation process. The identification of the J_c distribution within the HTSC of **Fig. 8** has been performed for different sizes, positions and dimensions of the measurement region $\mathbf{G_0}$. For the above example the matrix **M** has finally the following dimensions: the number of equations m =48969 and –depending on the partitioning of the HTSC– the number of unknowns n=14169, 14178 or 14189 respectively. The following error function ρ acts as the convergence criterion for the calculations:

$$\rho = \|\mathbf{U} - \mathbf{MA}\| \leq tol\|\mathbf{M}\| * \|\mathbf{A}\|, \quad (4)$$

where *tol* denotes the required tolerance.

Additionally the difference between the defined (measured) A_m and calculated vector potentials A in the measurement area $\mathbf{G_0}$ was estimated:

$$\varepsilon = \iint_{G_0} (A_m - A)\, dz\, dr. \tag{5}$$

Typical values of the accuracy parameter for the above example have been: tol=10^{-11}, ρ=10^{-8}, ε=10^{-7} Vsm. It has been necessary to perform about of 75000 Lanczos iteration steps in order to obtain the above postulated accuracy. The field plot in the region under investigation is shown in **Fig. 8** and the J_c distributions in the cross section of the HTSC are shown in **Figs. 9a, b and c** respectively for different fragmentations.

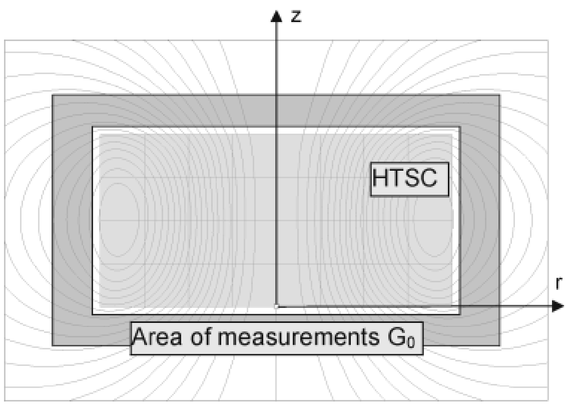


Fig. 8. Field distribution of a cylindrical HTSC (HTSC subdivided into 4×4 rings)

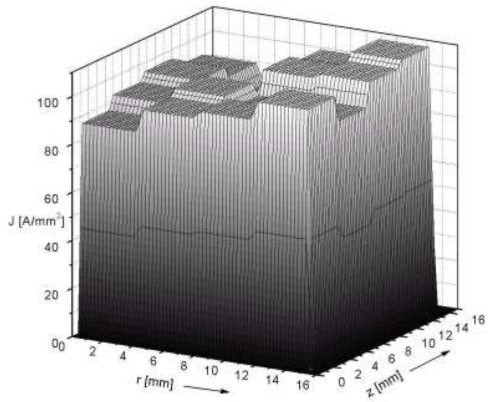


Fig. 9a. Identified current density within one half of the HTSC ring. (J_c distribution in case of 4×4 subdivisions)

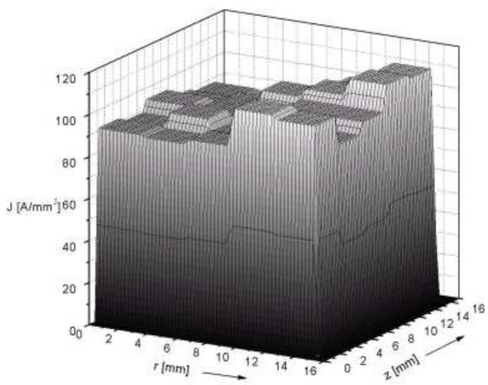


Fig. 9b. J_c distribution in case of 5×5 subdivisions

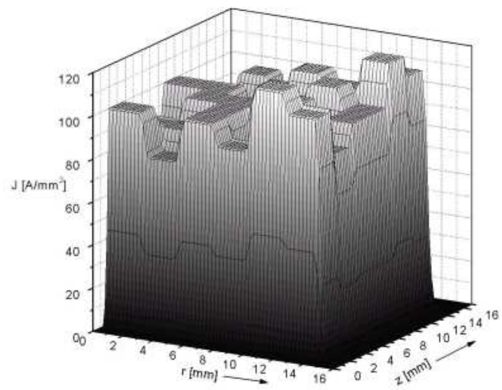


Fig. 9c. J_c distribution in case of 6×6 subdivisions

As can be deduced from the J_c-distributions shown above, the proposed algorithm enables a stable and physically correct solution of the analysed inverse problem (determination of the current density distribution within the HTSC), thus it can be applied for the detection of flaws eventually existing within the HTSC's (regions with small J_c values). The solution of the problem differs strongly according to the number of assumed subdivisions of the HTSC region. For practical applications it is sufficient to examine the mean J_c distribution in maximum 36 HTSC rings.

The mean value of the determined J_c in each sub-region can be called the "engineering current density", as only this value is responsible for the force interaction between the HTSC and any external magnetic field. The final solution depends furthermore on the size and position of the measurement regions. It can be stated, that the measurements have to be performed at the points where the magnetic field possesses high values and gradients.

For the application of HTSC's as field excitation units within electrical machines the knowledge of the mean value of the J_c is only necessary in a reduced number of sub-domains, whereas for screening applications (reluctance machines, magnetic bearings) the current density distribution has to be determined more precisely. It should be noted here that the different current density distributions within the HTSC (**Fig. 9**) generate practically the same field distribution in the measurement area G_0. This non-uniqueness of the obtained solutions is very typical for such inverse problems.

CONCLUSION

A non-destructive quality control of HTSC-bulks based on measurements of the field distribution trapped by the HTSC has been developed. The proposed method is based on the determination of the current density within the HTSC. This identification code has been validated by many experiences and thus may serve as a non-destructive quality evaluation algorithm for single HTSC bulk pieces and clusters used for magnetic bearings and the excitation of electrical machines e.g.

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