DESIGN OF GRADIENT MAGNET SYSTEM FOR CESIUM FREQUENCY STANDARD

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Abstract- The design process and the magnetic measurements on a permanent magnet asymmetric dipole to be used for magnetic selection in a Cs beam frequency standard is presented. The design target is to create a magnetic induction gradient of 50 T/m in a zone extending 10 mm in width and 50 mm in length. The computer aided design process is outlined and design predictions are compared with measurements on the manufactured units. A process of automated optimization of the magnet pole piece profile in order to increase the Cs beam optics with partcular attention to the transmission of atoms is presented and the first results obtained, leading to an increase of a factor of three in Cs transmission, are discussed.

I. INTRODUCTION

Cesium beam frequency standards require a state selection of Cs population according to the quantum state of the atoms [1]. One of the possible ways of performing this selection is to use the different values of atomic magnetic dipole moment associated with the different quantum states. If the atoms in the beam travel through a zone where a gradient of magnetic flux density is present, they experience a force whose value is proportional to the scalar product between the dipole moment of the atom and the applied gradient of magnetic flux density. If this force is directed normally to the direction of motion of the atoms a selective deflection of the atoms occurs accordingly with their magnetic dipole moment. Diaphragm or slits can then be placed on the beam trajectory to select the desired state. In the frequency standard, after the first selection, the remaining part of the beam interacts with the microwave frequency and one part of the atoms resonates. These atoms change their quantum status and consequently their magnetic dipole moment value. To quantify the share of the atoms that has resonated, a new magnetic selection can be performed (analysis) and the atoms are then conveyed towards a detector. Because the changes in magnetic dipole moment are symmetric the same magnetic gradient pattern can be used in both selection processes.

Usually the values of magnetic gradient needed to perform this process are in the order of some tens of Tesla per meter in the area interested by the beam that is usually extending some millimeter in width and some centimeter in length. These values of magnetic gradient and the need to fit the magnet inside the vacuum chamber where the beam travels, make permanent magnet systems particularly suited for this application.

Different magnet configurations can be used depending on the shape of the Cs beam. For rotationally symmetric Cs beams multipole magnets (quadrupole, hexapole) can be efficiently used, while for ribbon shaped Cs beam dipolar gradient magnets can be choosen, the last configuration was of interest in the design under analysis.

Even in this situation different solutions can be devised, as, for instance, the 'two wire magnetic field configuration' proposed in [2] and the double confocal state selector proposed in [3].

Being the central position of the beam in the vacuum chamber one of the constraints of the problem an asymmetrical permanent magnet dipole was used. This structure allowed to reach the design gradient value of 50 T/m and the shape of the pole pieces seems particularly suited for the optimization of the optical properties of the beam.

The design strategy of the magnet system was based on a two steps approach: firstly the design and the realization of a prototype not optimized magnet to be used in the first operative phase of the standard and afterwards the optimization of the optical properties of the Cs beam obtained by means of the modification of the shape of the pole pieces of the magnet.

In the following the design of the first step magnet will be outlined and comparisons between design predictions and measurements made on the manufactured magnet will be discussed. Afterwards a description of the optimization strategy used for the design of the second step gradient system will be given.

II. DESIGN OF THE GRADIENT MAGNETS

The configuration of the magnet considered most suitable for the device, as exposed in the introduction, is a dipole permanent magnet with asymmetric pole pieces. Two identical magnets can, in first instance, be used for

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the selection and the analysis phase. Even if this could be not the optimal choice it was used for the first operative phase of the frequency standard. As a consequence, only one magnet has been designed and has been produced then in two units.

One of the more stringent design constraints to be met is the external encumbrance of the magnet that should be fit in the vacuum chamber. This vacuum chamber is made of a pipe whose inner diameter is 60 mm. A circular flux return yoke was then used.

Starting from the gradient design value of 50 T/m an axial length of the magnet able to give the proper deflection to the Cs atoms turned out to be of 50 mm with a minimum gap aperture greater than 5 mm. To reach this gradient value a peak of magnetic flux density in the gap of the order of 0.8-0.9 T was required.

Once defined the magnetic design specifications, some preliminary computations were performed in order to select, accordingly with the overall dimensions of the magnets, the permanent magnet material with the coercive force able to produce this magnetic flux density value. A material belonging to the Alnico family turned out to satisfy the design requirements. As for the flux return yoke a soft iron with a saturation value of flux density of 1.8 T was used.

However, the relatively high value of magnetic flux density in the gap, calls for an analysis of the magnet able to take into account the nonlinear behaviour of the soft iron used in the yoke and in the pole piece.

In reason of the large ratio between the length of the magnet and the gap heigth, a two dimensional analysis of the device in its cross section can be performed.

A finite element magnetostatic nonlinear code (VF/OPERA2d [4]) was used to this purpose. The nonlinear characteristics used to model the ferromagnetic part and the permanent magnet one, are shown in Fig. 1.

These analyses allowed to adjust the thickness of the flux return yoke avoiding heavy local saturation that could increase the overall reluctance of the magnetic circuit and possible magnetic short circuits caused by the relative proximity between the permanent magnet and the yoke.

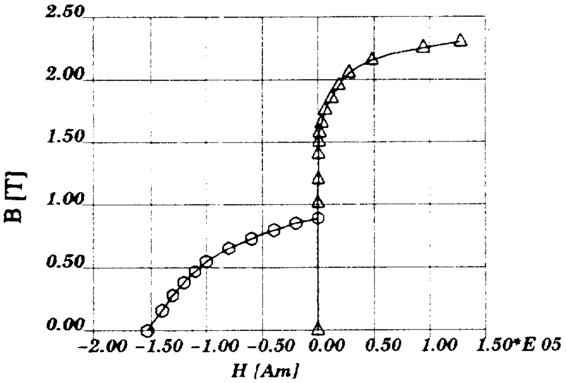

Fig. 1 Nonlinear characteristics of the permanent magnet material (o) and of the soft iron (Δ).

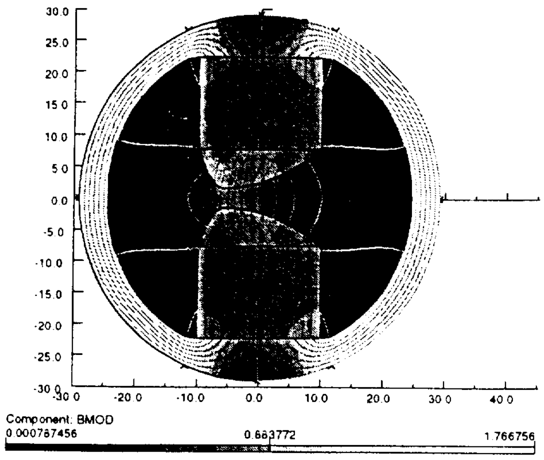

Fig. 2 Cross section of the magnet with greyscale map of absolute value of magnetic induction [T].

The result of this design process is shown in Fig. 2 together with the greyscale map of the absolute value of the magnetic flux density.

The pole piece shape, used in this first magnet, was made up of two asymmetric arcs of parabola. This profile gives, as result, a pattern of the magnetic gradient that meets, in average, the design requirement and does not raise particular difficulties in the manufacturing of the pole piece.

After the structure of the magnet in its cross section has been defined a three dimensional finite element analysis was performed in order to evaluate the fringing effects due to the finite length of the magnet and to quantify the magnetic flux density outside of the pole extensions. The three dimensional finite element code VF/TOSCA [4] was used for this analysis.

The difference between the results of the two and three dimensional analyses turned out to be less than 2 percent.

III. MAGNET REALIZATION AND MEASUREMENTS

Afterwards the completion of the magnet design its manufacture was performed. In this phase a mechanical tolerance of 0.1 mm was requested while the coordinates of pole piece profile were given in input to the numerical control machine-tool unit.

A very low vapour pressure epoxi resin was used to glue the polar expansions at the magnetic circuit. Four ISO 2 MA holes in each side are of use for securing in position the magnet.

Once the magnets were manufactured, magnetic measurements were performed on the equatorial plane of the gap, to evaluate the effective magnetic gradient value and to assess the correctness of the magnetic analyses performed. The measurement were carried out by means of an Hall probe, that ensure a relative resolution of 10^{-4}.

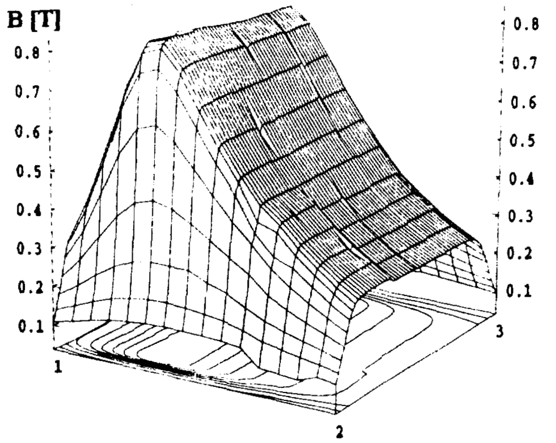

Fig. 3 Pattern of the measured magnetic flux density on the symmetry plane of the magnet [T].

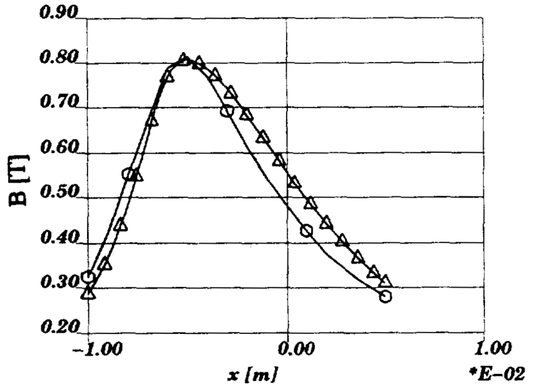

Fig. 4 Computed (o) and measured (Δ) behaviour of magnetic flux density [T], along a line normal to beam direction of motion.

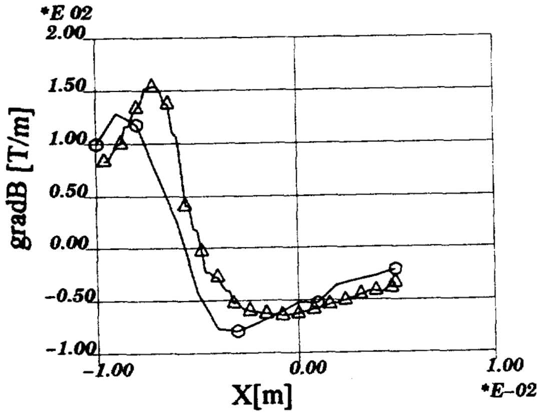

Fig. 5 Computed (o) and measured (Δ) behaviour of magnetic flux density gradient [T/m], along a line normal to beam direction of motion.

In Fig. 3 the three dimensional graphic of the magnetic flux density measured in one of the two magnet is shown. It is evident an increase of the peak value of flux density as moving in the longitudinal direction through the gap. This effect is explainable by means of a misalignment of the pole piece inside the tolerance of the manufacturing process.

In Fig. 4 the pattern of the computed and measured values of magnetic flux density are shown. The value are taken along a line tranversal to the beam axis in the middle cross section of the magnet. The line is extended fo 15 mm, but the beam extension should cover only a zone 5 mm wide across the center of the magnet. In Fig. 5 the gradient value are displayed on the same line.

As it can be seen the average value of 50 T/m is obtained in the zone where the beam travels, that is 5 mm wide across the magnet center (zero value of abscissa in graph). The differences between predicted and measured values of gradient on axis turned out to be of the 13 %. This error is relatively low especially on a quantity, like the magnetic gradient, which is not directly obtained form computations, but is obtained by means of two successive numerical differentiations.

IV. OPTICS OF THE Cs BEAM

Once the effective pattern of the magnetic gradient has been measured, the computation of the trajectory of the Cs beam was performed. The main aim of this process was the determination of the best relative position of the exit of the Cs oven and of the detector in order to maximize the number of atoms eventually collected.

The computation of the trajectories of the atoms in the beam was performed by means of the integration of the ordinary differential equation of motion on the equatorial plane of the structure. A fourth order Runge-Kutta integration method was used for the solution of the atoms motion equation.

The gradient values needed for the evaluation of the rigth hand side of the motion equation were given as input to the procedure on a regular two dimensional grid. The measured values of magnetic flux density were used for the evaluation of the optical properties of the system.

The initial coordinates of the particles are taken from the Maxwellian distribution at the temperature of the oven, giving an average velocity value around 100 m/s, and considering an angular spread of 20 mrad.

One of the most important information to be got from this procedure is the transmission of the Cs atoms, that is the ratio between the total number of atoms coming out of the oven with a given angular spread, and the number of atoms that are able to reach the detector entrance slit. The main obstacle to the transmission is given by the relatively small diameter of entrance and exit holes of the microwave cavity which has to be kept small in order not to perturb the microwave field.

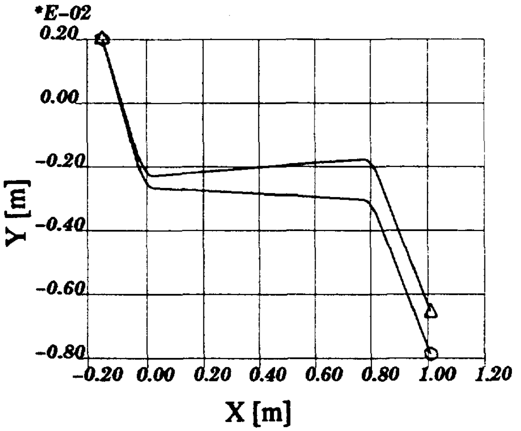

Fig. 6 Trajectories of the Cs atoms, vertical coordinates are exaggerated.

Two trajectories defining the envelope of the beam, obtained by the computations, are shown in Fig. 6.

The best transmission value achieved with the measured gradient pattern was of about 11 %.

V. OPTIMIZATION OF THE OPTICAL PROPERTIES OF THE Cs BEAM

The good correspondence obtained between computed and measured values of magnetic flux density, allows to use extensively the magnetic analysis tool for the solution of the inverse problem, that is the determination of the best magnetic gradient pattern to maximize the transmission of the Cs atoms from the oven to the detector.

The main objective of the procedure is to increase the efficiency of the magneto optical system, by focusing the trajectories of the atoms on the detector.

This process can be approached by means of an optimization procedure having as cost function of the optimization the transmission of atoms and the shape of the pole piece as design variable. The aim of this procedure is the determination of the pole profile able to give the best results in Cs transmission. Since the procedure involves both magnetic and optical analysis, every value of the cost function will require a finite element analysis of the structure to evaluate the gradient distribution and then, the computation of the trajectories in order to evaluate the transmission.

Because of the good agreement between two and three dimensional magnetic analyses, the faster of the two can be used in this procedure.

The changes of the shape of the pole piece are driven by an optimizer code, based on an implementation of the 'Pattern Search' technique. This optimization algorithm belongs to the zero-th order deterministic class of optimization algorithms [4].

Simple polynomial shapes have been used for the pole piece, taking the position of some nodal points on the profile as degrees of freedom of the optimization.

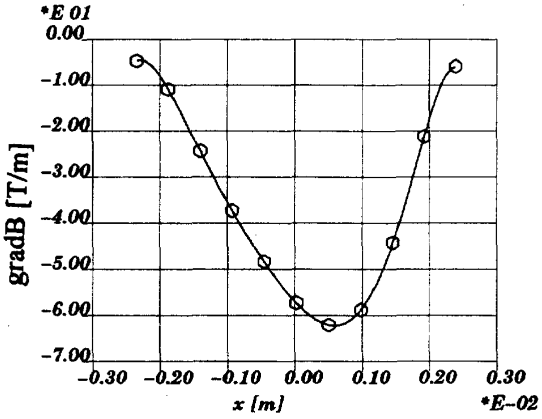

Fig. 7 Magnetic gradient pattern obtained by optimisation.

The procedure showed good convergence properties and the preliminary results seem to indicate that an improvement of a factor of three in transmission with respect to the one of the prototype magnet can be gained by a proper design of the pole piece.

Fig. 7 contains the gradient pattern corresponding to this solution, that leads to a value of transmission of 33 %.

VI. CONCLUSIONS AND WORK IN PROGRESS

The work performed confirms the validity of the magnetic analysis tools in the design process of magnetic devices, even when dealing with complex phenomena like nonlinear and permanent magnet materials.

These tools allowed to design a magnet structure able to create the desired magnetic flux density gradient and the error between predicted and measured values turned out to be in the order of the ten percent, on a quantity like the magnetic flux density gradient which is not directly retrieved by the analysis results, but has to undergo two successive numerical differentiations.

The good agreement between predicted and measured values allowed to use the magnetic analysis tools for the solution of the inverse problem, that is the definition of the "best" magnet profile able to increase Cs atoms transmission. The work is going on in this area.

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