Tolerances and Uncertainties Versus Magnetic Performance in MECO Magnet System

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***Abstract*—MECO, the muon-to-electron conversion experiment, requires a total of 96 superconducting solenoids designed for construction by industry and assembly into 4 separate cryostats following completion of final design. The magnet system has a 12 × 26 m installation footprint.**

The objective of the tolerances and uncertainties sensitivity studies was to demonstrate the feasibility of building a MECO magnet system around the conceptual design that meets the performance requirements in the presence of expected material property variances, realistic manufacturing tolerances, and manufacturing and design uncertainties. The study also presents a method for minimizing manufacturing costs by setting adequate tolerances and using the most appropriate manufacturing and assembly procedures.

Monte-Carlo magnetic modeling was used to introduce field errors from various possible deviations of the structure from the nominal design, and correlate them with the field performance.

The conclusion from the study is that the design is robust. Field requirements are met in the presence of material property uncertainties and modest machining and assembly tolerances.

This implies that the project may be able to accept field quality risk and ask the fabricator to accept only the responsibility for placing the coils with correct turn counts in their warm positions at reasonable tolerances.

***Index Terms*—Detector magnets, superconducting magnets.**

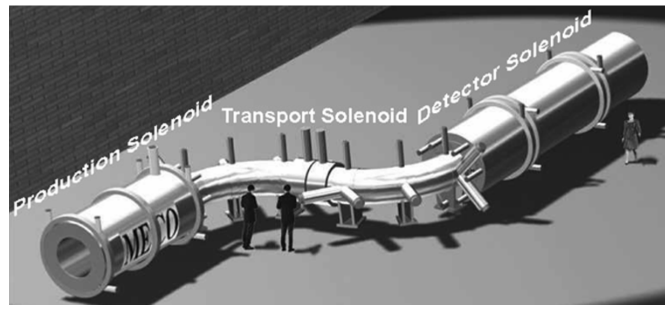

Fig. 1. MECO magnet system. Iron boxes around PS and DS removed.

I. Introduction

THE Muon-Electron Conversion Experiment (MECO) seeks to detect direct muon to electron conversion, which would provide evidence for a process that violates muon and electron lepton number conservation, implying physics that cannot be explained by the Standard Model.

The central part of the MECO experiment is a superconducting magnet system depicted in Fig. 1. A high energy proton beam is directed onto a heavy target to produce pions inside the 4-m-long by 1.5-m-diameter bore of the Production Solenoid (PS). A fraction of the muons resulting from pion decay are captured in the PS and guided into a 1 m bore diameter S-shaped Transport Solenoid (TS). The TS has a developed axial length of about 13 m and provides sign and momentum selection with collimators. The muons are brought to rest in a stopping target inside the 10 m long by 1.9 m bore Detector Solenoid (DS). MIT Plasma Science and Fusion Center has completed a conceptual design [1] for these solenoids. The major engineering challenge of the project is to provide overall magnet performance that accomplishes the goals of the experiment. To a large extent the success of the experiment is defined by the field quality of the as-built MECO magnet system. A magnetic field specification [2] was developed defining the field as well as tolerances on the field and its spatial derivatives, which vary as a function of location. The magnet design defined in the Conceptual Design Report (CDR) [1] was a point design having a magnetic field well within the limits defined by the field specification. Transition to construction requires analyzing the feasibility of actual implementation of this design, with account of all manufacturing tolerances and design uncertainties that might affect the final physical performance of the magnet system. The methods and results of such analyses provide a convincing argument that each step is neither excessive nor insufficient. This reduces technical risk to the manufacturer and can save cost. These studies lead to better formulated construction specifications and better defined cost and schedule paths.

II. Methods and Analyzes

A. Approach Considerations and Comparisons

The implications of a field-specification vs. a physics driven approach is better appreciated with the aid of the Venn diagrams in Fig. 2. The top portion of the diagram contains the legend. The field specification is designed to match the required physical performance as shown in R0. The magnet CDR is a point design meeting the performance defined by the field specification, as in any of the diagrams R1, R2 or R3. R1, R2 and R3 show different actual performances relative to both the field specification and

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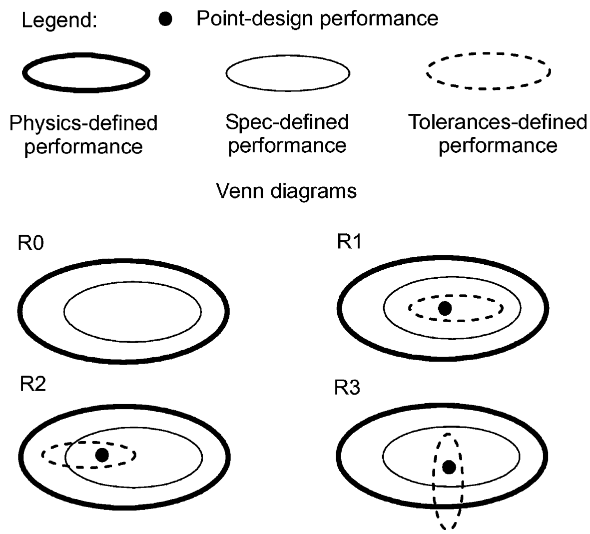

Fig. 2. Venn diagrams of MECO performance possibilities.

the physics requirements when tolerances and uncertainties are considered.

The R1 figure shows a situation where a reasonable set of manufacturing and materials tolerances have been applied to the point design, and the field specification is met at the extremes of these tolerances. This situation is the best possible, and R1 depicts success.

If the field specifications are not met we have to deal with one of two situations, R2 or R3.

In the case of R2, the magnetic field performance with reasonable tolerance assumptions may lie outside the field specification, but still meet the physics requirements for the experiment. This is unfortunate, as it follows that there are likely some magnet designs which meet the physics requirements, but not the field specification. The cost consequences to the project for this condition are unknown.

If reasonable tolerance perturbations to the point design result in field performance that is outside the acceptable physics basis for the experiment as is depicted in R3, then the point design is unacceptable. Changes to the magnet design or the manufacturing methods may be possible to bring the performance within the acceptable range, but success is not guaranteed a priori. Such a condition raises a serious question of feasibility, which needs to be resolved prior to proceeding with the magnet procurement.

Detecting which of the situations, R2 or R3, actually occurs requires extensive physical simulations, which are both labor intensive and time consuming, particularly when stochastic methods such as Monte Carlo are involved. Thus, in this project, we first examined possible engineering solutions in order to maintain the projected performance within the R1 environment. To handle situations of the class depicted in R2, and discovered at the time of the CDR, the field specification was loosened.

B. Importance of Tolerances Studies

At the start of the tolerance studies we anticipated that we

- May find that the field specifications can be met with available commercial capabilities.
- May reduce the need for cold alignment and extensive field mapping by showing that a limited set of measurements, many of them dimensional and when the magnet is warm, will guarantee that the specification is met.
- May find that a limited set of magnetic measurements is sufficient to ensure the spec is met throughout the field volume.
- Will reduce the risk perceived by manufacturing vendors and reviewers (for whom the field specifications may seem unusual and possibly difficult to meet) by demonstrating that reasonable manufacturing tolerances result in field specifications being met.
- May show that we can accept field quality risk and ask the vendor to accept only the responsibility for locating warm coils with correct turn counts at tolerance-specified positions. Such requirements are familiar to manufacturers.

C. Contributions to Field Deviations From Nominal

The following is the list of potential contributors to the field errors grouped by the nature of the errors and by the way they are applied to the model.

Non-cumulative (coil to coil) errors in positioning the current result from errors on mandrel interior dimensions, positioning of the winding within the mandrel, tolerances on the winding pack density (insulation thickness, winding compression, etc.) and conductor dimensions, as well as positioning of turns in incomplete outer layers, and turn-count-induced deviations, including intentionally dropping turns in outer layers having small turn counts by design.

Cumulative errors in warm coil placement include machining tolerances on axial, transverse, and angular dimensions of outer mandrel surfaces, errors on alignment of mandrels at cold mass assembly, errors in support rod lengths due to the uncertainties of their cold-to-warm temperature distribution, and warm survey, and alignment errors.

Structural uncertainties group uncertainties of mechanical material properties (20% variations of Young's modulus, and coefficient of thermal expansion), as well as errors in modeling shape change from cooldown, energizing, and gravity loads, and positions of support rod ends. Uncertainties related to the evaluation of sagging of the foundation support structures were also assessed as part of this study.

Effects due to return yokes, pole pieces, other magnets, and other magnetic materials include positioning of return yokes and pole pieces, errors in magnetic properties of steel, tolerances on gaps in pieces of return yokes, and effects of holes (seen and unforeseen) in return yokes.

Errors and tolerance on operating current complete this list.

D. Computational Procedures

Vector Fields OPERA computer program is used to model field, including effects of iron return yokes, pole pieces, and coils. Coils are treated as constant current density distributions. The contribution of the iron to the field is saved and not recalculated when only coil perturbations are studied.

To test the adequacy of the coil model the coils are modeled as filament loops. Effects of filament modeling are checked by varying the number of filaments per turn. Non-integral turns per layer are handled by using a fractional current filament with fractional spacing. Layer to layer transitions are handled by using a fractional (~0.5) current filament with correct spacing since current density is ~0.5 nominal in the transition. Field due to current is calculated using Biot-Savart. The nominal field of the iron is added to current-generated field to get the total field.

Structural uncertainties and uncertainties related to material properties are simulated using the ANSYS computer program. Various 2D and 3D models of parts of the MECO magnet system are created for modeling local effects. A global 3D structural model is used for modeling the nominal behavior of the system during cooldown, and electromagnetic loading. It also includes gravitational loads.

The following procedure describes the general methodology of the tolerance study. Modify coil placements and current distribution in coil, with or without accumulating placement errors. Coil placement errors are introduced randomly by uniform probability distribution within a tolerance-defined range. Add cumulative errors in compliance with the magnet assembly procedure. Apply a magnet alignment procedure during installation as appropriate; this procedure is described below. Check field specifications along a set of paths defined at the extremes of the specification volume in a coordinate system fixed with respect to the nominal magnet centerline. Meeting the field spec along these paths ensures that the spec is met in the full volume. In the case of stochastic errors (cumulative or noncumulative coil placement errors), multiple configurations (typically >100) with stochastically chosen errors are run; passing means all configurations pass. Error distribution width is increased until cases fail, to determine if tolerances are overly tight. Generally we were not close to failing the spec.

As a detailed example, we present the effect of cumulative errors due to machining tolerances on dimensions of the outer mandrel surfaces. First we developed a detailed manufacturing procedure for typical coil mandrels of the PS, the TS, and the DS magnet. Nominal machining tolerances on axial, transverse, and angular dimensions of the outer mandrel surfaces are shown in the Table I. These are based on standard ANSI [3] machining grades.

The first step of the analysis was to apply random errors to each coil, modifying its position, (x, y), and the angle, α according to the following formulae

$$\begin{aligned} x_{error(i)} =& x_{error(i-1)} + \sigma_{axl}\cos\alpha_i + \sigma_{trans}\sin\alpha_i \\ &+ (\cos(\alpha_i + \sigma_{angle}) - \cos\alpha_i) \\ &\times \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \\ y_{error(i)} =& y_{error(i-1)} + \sigma_{axl}\sin\alpha_i + \sigma_{trans}\cos\alpha_i \\ &+ (\sin(\alpha_i + \sigma_{angle}) - \sin\alpha_i) \\ &\times \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \end{aligned}$$

Here $\sigma_{axl} = \delta * \Delta_{axl}$, $\sigma_{trans} = \delta * \Delta_{transl}$, $\sigma_{angle} = \delta * \Delta_{angle}$ represent the uncertainties in the position and angle of a coil, δ is a random floating-point number between ± 1.

Each configuration uses a different set of random numbers to generate the modified coil positions. Fields from each configuration are evaluated along four different extreme paths and are compared with the field specification. Fig. 3 shows the passing rate for 6 sets of delta variables starting from the nominal tolerances and doubling for each subsequent set. In this simulation each grouping was run for 100 configurations. (In some simulations up to 500 configurations were analyzed.) We started registering some failures at 4 times chosen tolerances.

TABLE I
COIL MANDREL TOLERANCES

Magnet / Deviation	PS, TS Grade 7-9	DS Grade 9
Δ_{axl} (mm)	0.14	1
Δ_{trans} (mm)	1	1.6
Δ_{angle} (μrad)	70	170

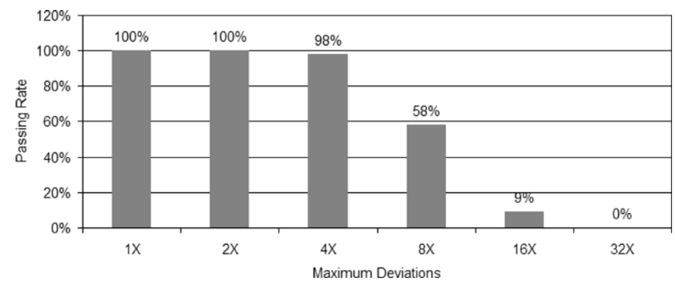

Fig. 3. Field spec passing rate for the cumulative errors due to machining tolerances on dimensions of outer mandrel surfaces.

E. Tolerance Study Results

Testing the field of the perturbed magnet system showed that most of the deviations from the nominal design do not violate the field spec even at the maximum expected deviations from design parameters. However, some factors required making adjustments to the manufacturing, assembly and operating procedures, and these are discussed here.

The upper limit on coil current is set so that a half turn can be added or subtracted from anywhere in the coil without violating field spec. This enables alignment of coil-to-coil conductor joints, and simplifies their cooling scheme.

The requirement of exact turn count was applied to all coils, except the PS. In the PS coils with a small number of outer layer turns were modified, removing these turns, and field specifications are still met.

Conductor definitions were extended to include the tolerances on the dimensions of the channel. The accepted tolerances were defined in such a way that their accumulation will not change the coil layer count or result in any critical violations of the field spec.

Field specifications were checked with the last-layer turns concentrated at one end of the mandrel. Uniform distribution of the last-layer turns is required only in the DS.

The base pedestals of the TS support system were too narrow and produced unnecessarily large embedment loads. The bases were widened. In addition to the widened pedestals a floor frame shown in Fig. 4 was conceived. It is placed above the slab and requires minimal connections to the slab. The frame minimizes issues of nonuniform floor settlement.

Stochastic analyses of cumulative errors due to dimensional tolerances on machining exterior surfaces of mandrels justified

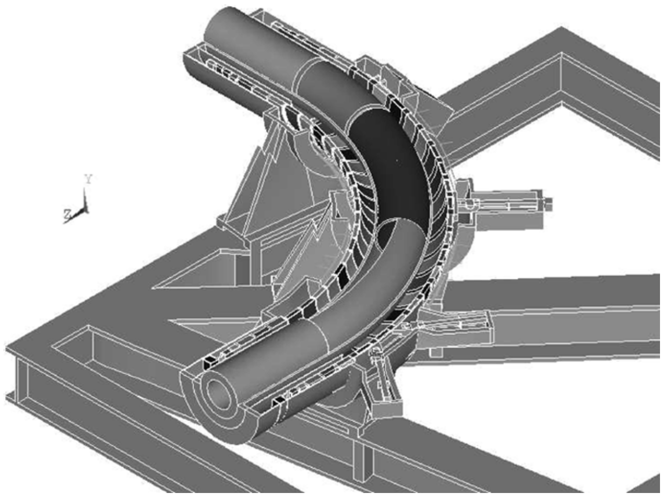

Fig. 4. Global TS model with shields. The upper halve of the magnets and cryostat shells are shown removed.

using standard ANSI [3] machining grades in the range of 7–9 for different parts of subassemblies. Based on current results for field variations, we may not need to do better than grade 8 or even 9. Typical tolerance-related accumulated deviations of the ends of cold mass are of order $+/-1$ mm. This is potentially harmful to the field spec but can be aligned out during the magnet installation in the hall.

The warm magnet installation and alignment procedure requires the end coils of each magnet to be centered on the nominal magnet system centerline. The axial gap to adjacent magnets adjusted for cooldown and energizing errors will be held to the nominal. The field specification defines the field properties in an absolute coordinate system. Thus, the field specification is still met even though coils positioned according to the above procedure may not be in their nominal position.

Another source of errors having design implications is the uncertainty of thermal contractions of the cold mass support rods. In the CDR we used stainless steel support rods with an intermediate LN2 intercept. Safety demanded elimination of nitrogen in the radiation environment. This led to replacing LN2 by GHe as the intermediate cooling agent. To avoid the uncertainty in the temperature distribution along the support rods their material was changed to G11 and the intercept between cold and warm ends was eliminated.

A possibility of reducing the coil count recommended by the Magnet Oversight Group in pursuit of cost reduction was evaluated with respect to its effect on the field quality. The conclusion was that the only part of the magnet system where coil count reduction may be considered is in the bends of the TS magnets. This study was interrupted by the termination of the project in August 2005.

III. Conclusion

From the composite of all the analyses, we concluded that the magnet design is acceptably tolerant to the many sources of field errors, which were considered. In addition, the field specification has matured to better reflect the conditions we can achieve, but without degradation to the physics requirements of the experiment. We have chosen physical dimensions and operating parameters such that we have some contingency (e.g. for extra radiation shielding if necessary). Easily achievable material properties and machining and assembly tolerances result in the magnetic field meeting specification. We have lowered the risk of not meeting the field specification. We believe we can accept that risk and ask the vendor to accept only the responsibility for warm placement of coils of the correct turn count. A few studies, such as the effects of steel property variations, remained open at the time of project termination, but these were not foreseen to pose any difficulties. In addition, we were evaluating possible ways of measuring cold, energized coil positions, although additional study may have shown this to be unnecessary.

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