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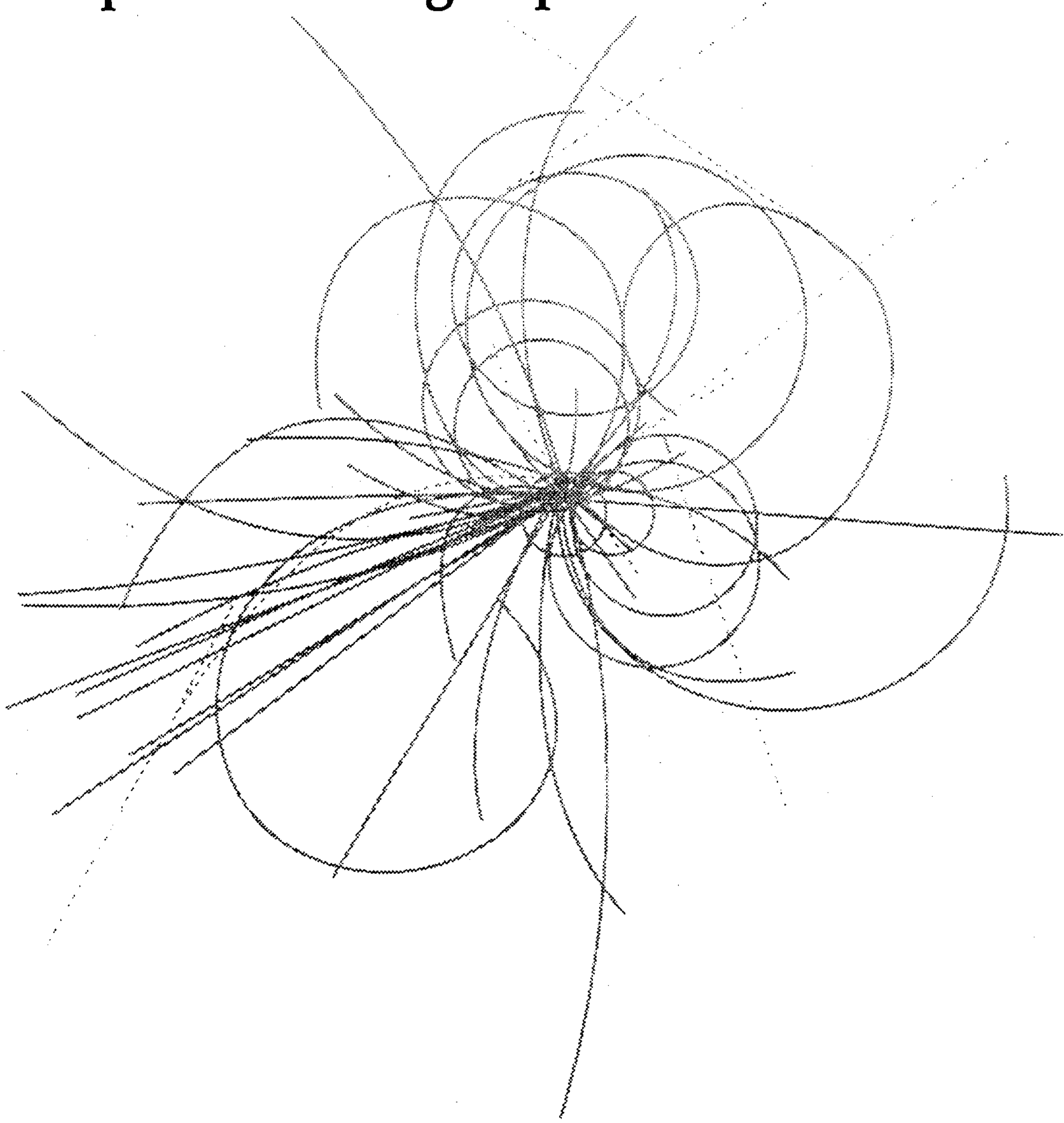
Superconducting Super Collider Laboratory



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DESIGN AND USE OF A MECHANICAL GAGE FOR MEASURING ALIGNMENT OF CRITICAL FEATURES OF STRING TEST MAGNETS

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ABSTRACT

Tight mechanical tolerances must be held for each magnet being fabricated for the Accelerator Systems String Test (ASST) of the Superconducting Super Collider (SSC) Particle Accelerator. The beam tube, single phase pipes, liquid and gaseous helium return pipes, liquid nitrogen pipes, radiation shields, and vacuum vessel must be checked with a tightly toleranced alignment gage to assure that they are installed in their intended locations at the ends of each individual magnet. The proper alignment of these critical features within each magnet will permit a series of several magnets to be successfully connected for the ASST.

This paper documents the design and use of the mechanical alignment gage, verifies its adequacy to perform the necessary measurements within tightly specified tolerances, and presents recommendations for a second generation of gages to be used with future production run magnets.

INTRODUCTION

The principle of the gage (Figures 1 and 2) is straightforward: If the gage can simultaneously fit over the beam tube flange and all the other pipe flanges, then the pipes are accurately positioned (within their allowable tolerances) in the x and y coordinates (Figure 3). If the gage cannot fit in this manner, then at least one of the pipe flanges is out of tolerance from its assigned position. The gage is *not* designed for direct measurement of the

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out-of-tolerance amounts, nor the angular orientations of the pipe flanges, nor their axial (z) locations, although an estimate can be made by the operator. The gage can be used during magnet assembly to accurately position the ends of the coldmass, pipes, and shields in the vacuum vessel. It can also be used as a go/no-go final inspection device. Just as the ASST Magnets are prototypes, this gage is also a prototype. The design, fabrication, and early trial uses of the gage focused valuable attention on the alignment of critical features of the magnet interconnect region.

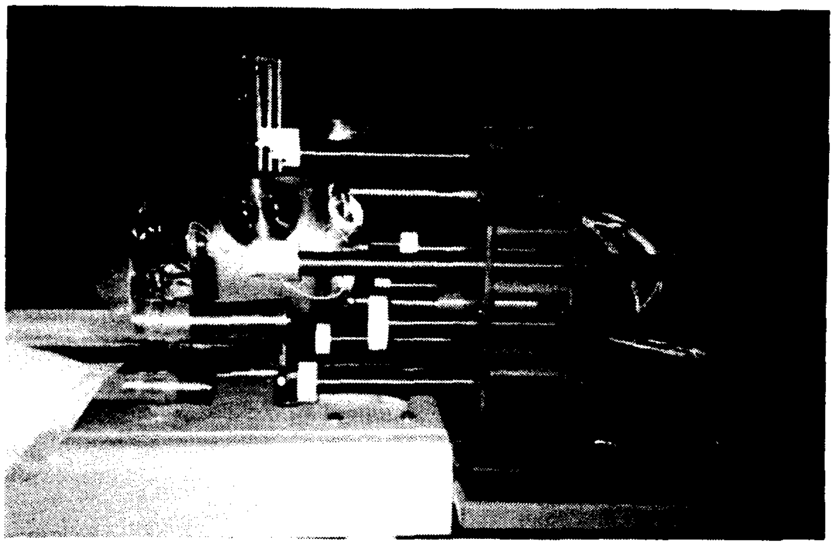

Figure 1. The gage being prepared to measure features on a magnet subassembly. The tubes of the gage will be brought forward until the (white) plastic end pieces contact their assigned features, such as pipe flanges and the end of the 20-K shield.

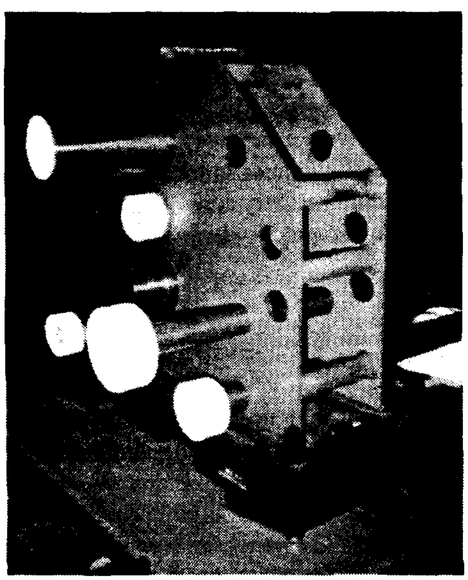

Figure 2. Closeup of the gage. Some of the sliding tubes and plastic end pieces have been installed in this view.

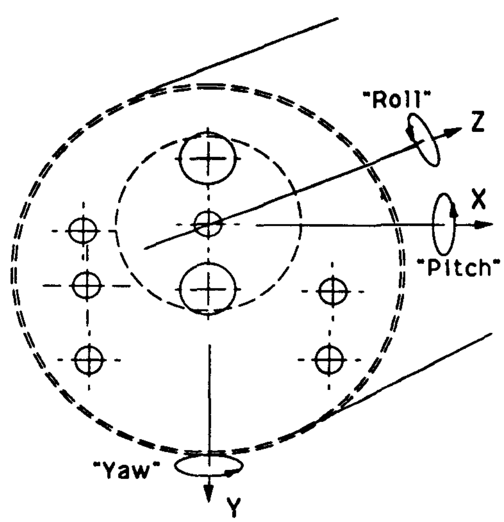

Figure 3. Coordinate system and terminology.

The gage is capable of measuring the positions of the single phase pipes, the LHe and GHe pipes, the 20-K pipe, and both 80-K pipes at both ends of the magnet. It is also capable of measuring the positions of the 20-K shield, 80-K shield, and vacuum vessel end rings. This paper focuses on the piping alignment only, not shields and vessel alignment.

DESIGN

Drawings and Components

The structural core of the gage (Figure 2) is a pair of identical vertical plates welded to a common baseplate. Stiffeners are welded between the two plates for rigidity. This welded assembly sits atop a lower baseplate connected by three bolts with spherical washers, which allows the gage to be oriented with respect to "pitch," "roll," and "yaw," as shown in Figure 3. Aluminum tubes with precisely machined ODs are inserted into the precisely machined IDs of holes drilled in the two vertical plates. This allows the aluminum tubes to slide smoothly and with a minimum of "play." Locations of these sliding tubes in the vertical plates correspond to the nominal locations of the pipes at the ends of the magnets.

Drawings of component parts of the gage were toleranced in accordance with ANSI Standard Y14.5-1982.[1] The ANSI datum structure was intended to provide clarity for fabrication and to produce well-defined inspection surfaces.

Materials

The plates and sliding tubes are 6061 aluminum alloy. All aluminum weldments were solution heat-treated and aged to the T6 condition prior to final machining. Solution heat treatment is needed to relieve internal stresses due to welding, thus stabilizing the structure. The anodizing process was controlled to assure that dimensions specified on the drawings were met *after* anodizing. Hard anodized aluminum was considered the best material choice for local plate stiffness, overall weight, and minimum fabrication cost. Wear of sliding aluminum tubes was not a major concern due to the limited number of uses (several hundred at most) during the ASST program.

Each sliding tube was fitted with a plastic (acetal resin) end piece that was custom-designed to fit over a corresponding pipe flange at the magnet's interconnect region. Plastic end pieces were used on the gage to avoid scratching the pipe or vessel flanges, particularly any polished demountable flanges planned in the early designs of the ASST Magnets. Acetal resin polymer was chosen due to the stability of its structural, thermal, and moisture-resistant characteristics.[2]

Error Analysis of the Gage

Error analysis of the gage is based upon the accumulated tolerances of its component parts. For this gage, primary considerations are the in-line accuracy of the IDs of the holes in the vertical plates and any "play" between the tube ODs and the IDs of the holes. The individual errors due to component tolerances may be treated as mutually independent and totaled as the square root of the sum of the squares (SRSS), *or* may be treated as strictly additive (worst possible case) and totaled as absolute values.

Accumulated errors built into the gage are shown in Table 1. Note that the size of each error is small at its source (*i.e.*, at the two vertical plates), but the resulting error (at the end of the fully extended tube) is about 5 times larger. The predicted SRSS error of ± 0.5 mm compares favorably with the actual errors measured on a coordinate measuring machine (see below). The accuracy of ± 0.5 mm is sufficient for measurements of the ASST Magnets.

Table 1. Sources and Magnitudes of Errors in the Gage.

Error Source (Description)	Max. Size of Error at its Source (mm)	Max. Resulting Error in Gage (mm)
Tube OD vs. hole ID at front plate	0.06	0.29
Tube OD vs. hole ID at rear plate	0.06	0.29
In-line tolerance of matched holes in plate	0.06	0.29
Total Accumulated Error (SRSS)	0.10	0.50
Total Accumulated Error (Abs. Value)	0.18	0.87

INSPECTION AND ACCEPTANCE OF THE GAGE

The gages were inspected on a coordinate measuring machine (CMM) to verify compliance with drawing specifications and to gather actual measurements of the assembled gage. A CMM of sufficient size was used to ensure accurate measuring without repositioning the gage. Aluminum extension tubes and plastic end pieces were installed, and measurements were taken with respect to the nominal beam tube centerline. Locations of each of these tubes were measured in the fully extended position, just as they would be during actual use. To measure any "play" between the installed tubes and the IDs of holes in the vertical plates, the tubes' positions were measured first under their own deadweight, then sequentially with a small force upward, right, and left. These configurations correspond to the worst case position errors to be expected in actual use. After first checking the gage in its lead end configuration, all tubes and end pieces were removed, the gage was rotated 180° on the horizontal plane to the return end configuration, and measurements (under deadweight only) were repeated.

In each configuration the diameter of the end of the tube was measured using four approximately equally spaced positions. This approach provided both the diameter of the end of the tube and a location for the center of the tube. The diameter should be constant for all positions, and any variations from the known value would have provided an indication of possible measurement errors. The measured diameter error was typically less than 0.03 mm, and the X and Y positions for the tube centers can be expected to be accurately measured to approximately this value.

Results of CMM measurements on the first gage were evaluated numerically. The errors (deviations from nominal) for all tubes were consistent, with the maximum deviation being 0.442 mm in the X direction and 0.533 mm in the Y direction. The standard deviations were 0.182 mm in the X direction and 0.249 mm in the Y direction, with an approximately normal distribution. These errors are comparable with the predicted values.

CONSIDERATIONS FOR "REFERENCE CENTERLINE" OF THE GAGE

The reference centerline for piping alignment[3] at each end of the ASST Magnet was located at the center of the beam tube flange. For straight ASST Magnets (no sagitta) this line should ideally be the same as the geometric centerline of the cold mass and the geometric centerline of the beam tube ID, and should be parallel to the geometric centerline of the vacuum vessel. However, this ideal condition was not generally achieved, so various interpretations of the reference line were used. One very detailed plan[4] was developed for possible use based upon a methodology[5] referencing the geometric centerline of the cold mass. The matter of reference centerlines for piping alignment will receive further attention during design of the production magnets for the SSC.

RESULTS OF GAGE MEASUREMENTS OF ASST MAGNETS

None of the ASST Magnets measured (to date) with the interface check gage has proven to be fully in tolerance. Typically, two or more pipes have been outside their allowable range. Estimates of the out-of-tolerance amounts range from 1 mm to 8 mm. These errors are not surprising given the prototypal nature of the ASST Magnet program; improvement of piping alignment performance is clearly expected for future (production) magnets.

The inherent accuracy of the present gage was clearly shown by the CMM measurements, but none of the magnet assembly areas had a dedicated, precisely positioned inspection stand on which to place the gage. Therefore, the *positioning and orientation* of the gage relied upon the judgement and care of the operator. Under these circumstances it is difficult to repeatedly position and orient the gage. Interpretation of the results was further dependent upon the choice of reference centerline (see above). The detailed plan[4] for positioning the gage rigidly on a precisely positioned, dedicated stand was judged to be a reliable method of alleviating the repeatability problems; however, this plan was not executed due to schedule restraints.

Based upon lessons learned, two gages will be installed on dedicated, precisely positioned inspection stands adjacent to the cryostat assembly bench (lead and return ends) at SSCL to facilitate in-process checking of piping, shield, and vessel alignment.

REVIEW OF THE MAGNET INTERFACES AND GAGES BY NWAC

Background

SSCL Magnet Systems Division (MSD) requested the Naval Warfare Assessment Center (NWAC) to review specific MSD designs relating to ASST Magnet interfaces and gaging. NWAC was consulted because the requirements and problems anticipated for magnet assemblies parallel in many aspects the complexity and scope of Naval weapons systems. NWAC was asked first to review and comment on drawings of the MSD-designed ASST Magnet gage. Secondly, NWAC was asked to recommend methods of assuring mechanical interchangeability of completed production magnets as they come together in the field.

Review of the ASST Magnet Gage

The ASST Magnet gage design is appropriate only for the limited number of units it will inspect. Sliding surfaces are not hardened and ground, so frequent checks of gage dimensional integrity are recommended. Position and orientation of the gage to contact datum surfaces of the beam tube are accomplished by means of adjustments to the gage mounting bolts. This time-consuming procedure would not meet production phase inspection rates, but is adequate for ASST units.

The ASST gage, being a "go/no-go" type, does not gather inspection data that could be used to supply a Statistical Process Control (SPC) program. At the ASST stage of magnet development, however, processes have not matured sufficiently to call for inspection data beyond basic go/no-go information.

As shown in the error analysis above, the expected (SRSS) accumulation of individual component part tolerances is ± 0.5 mm. However, the potential worst-case accumulation (sum of absolute values) is nearly ± 1 mm, which is unacceptable. Thus, final assembly requirements of the gage rely on the integrity of the gage manufacturer and the careful surveillance of Magnet Division representatives. This risk can be avoided by placing tolerance requirements at the assembly level of the gage.

Recommendations to Achieve Interchangeability for Future (Production) Magnets

NWAC recommends creation of a complete drawing package based upon the principle of interchangeability, and suggests a thorough dimensional (worst case) analysis of the lead and return end tolerances. Further, interface surfaces of major components and subassemblies within the magnet assembly should be examined to assure mechanical and functional interchangeability at worst case. This interface analysis should be independent of and concurrent with drawing package development. It should be conducted under the guidance of an SSCL interface control working group. The result of this effort would be to build quality into the drawing package; that is, if built to the tolerance *extremes* allowed by design, mating components and subassemblies would successfully assemble.

As the production phase approaches, control of manufacturing processes will become a major concern. NWAC suggests that interface gages offer a cost-effective and technically advanced means to derive feedback from many of the manufacturing processes. Such gages, instrumented with transducers to collect data and linked to a computer to process the data, provide the quality assurance organization with important options. These include inspection reports (electronic and hard copy) produced at the time of inspection, electronic storage and retrieval of reports, and data analysis by means of Statistical Process Control (SPC) software.

OTHER METHODS OF INSPECTING INTERFACE FEATURES

Several alternatives were considered prior to the decision to develop the gage in its present form. One alternative considered was the use of several smaller and simpler gages to check relative locations of different sets of components. However, this inspection method was judged to be too labor-intensive and uneconomical for ASST inspections.

Development of a customized, dedicated coordinate-measuring machine was considered. While technology was available to develop such an apparatus, and it would have the advantages of quantified measurement for data collection and analysis, the cost involved for equipment with such severely limited application prohibited this approach.

Use of an optical measuring system was also investigated. Such a system would also have been capable of quantifying measurements. Not only was this method considered too expensive, but there was considerable concern as to whether such an instrument could be made sufficiently robust for the environment in which it must function. The same observations also applied to considerations of laser measurement of ASST Magnet features.

One option not considered because of its state of development and the lack of detailed information at the time was the Portable 3D Measuring Machine. Considerable progress has been made recently in the development of these systems, and such a system is under consideration as a possible alternative approach to end configuration gaging.

The present type of mechanical gage was selected for ASST over these other inspection options because it was judged to be straightforward to build, test, and use. In addition, as a prototype gage checking a prototype magnet, it has the benefit of providing intuitive (visual) evaluation of assembly operations, even at intermediate stages of magnet assembly.

SUMMARY

A mechanical interface check gage for use with the SSCL ASST Magnets has been designed, built, and used for both in-process evaluation of subassemblies and for final inspection. The gage has permitted assembly and inspection teams to visually assess the condition of magnet piping alignment. Though not intended primarily for quantitative data retrieval, it has nonetheless permitted estimates of individual piping misalignments. It has focused valuable attention on the alignment of critical magnet features, and lessons learned can be applied to production magnets.

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