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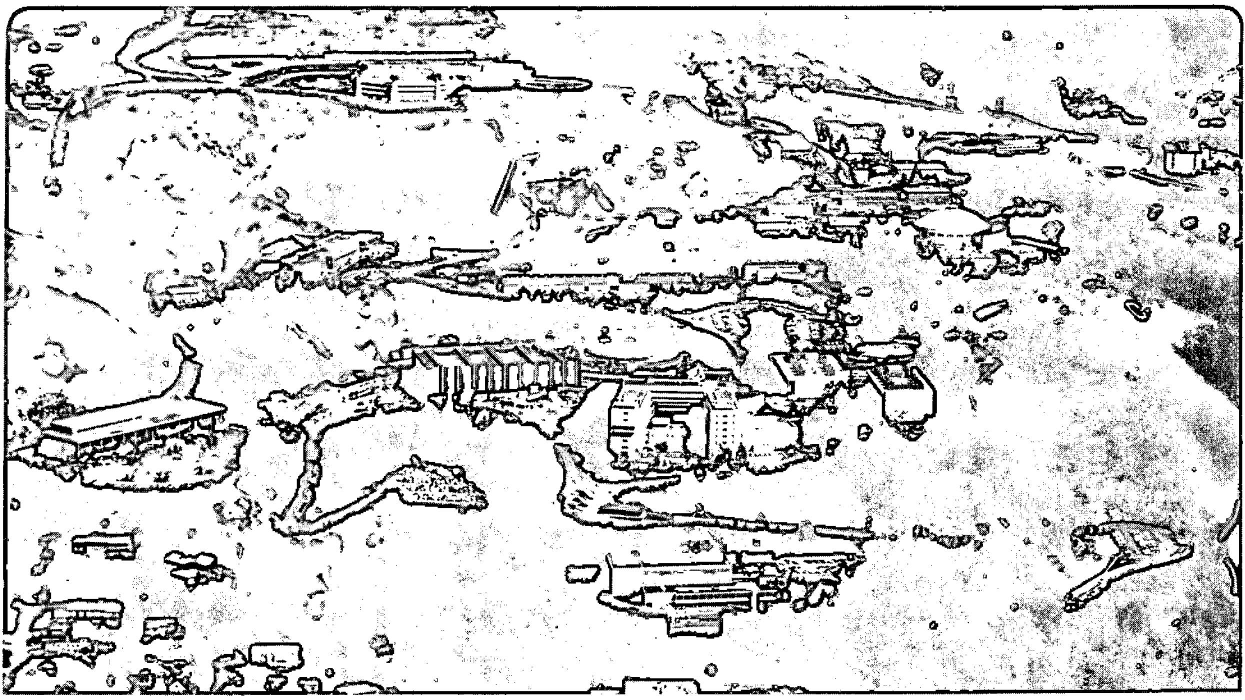
March 1991



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PROPOSAL FOR A CRYOGENIC MAGNETIC FIELD MEASUREMENT SYSTEM FOR SSC DIPOLE MAGNETS*

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ABSTRACT

This proposal describes the research and development required, and the subsequent fabrication of, a system capable of making integrated magnetic multipole measurements of cryogenic 40-mm-bore SSC dipole magnets utilizing a cryogenic probe. Our experience and some preliminary studies indicate that it is highly unlikely that a 16-meter-long probe can be fabricated that will have a twist below several milliradians at cryogenic temperatures. We would anticipate a twist of several milliradians just as a result of cooldown stresses. Consequently, this proposal describes a segmented 16-meter-long probe, for which we intend to calibrate the phase of each segment to within 0.1 milliradians. The data for all segments will be acquired simultaneously, and integrated data will be generated from the vector sums of the individual segments. The calibration techniques and instrumentation required to implement this system will be described. The duration of an integral measurement at one current is expected to be under 10 seconds. The system is based on an extrapolation of the techniques used at LBL to measure cryogenic 1-meter models of SSC magnets with a cryogenic probe.

It should be noted that the expansion of the dipole bore from 40 to 50 mm may make a warm-finger device practical at a cost of approximately one quarter of the cryogenic probe. A warm quadruple measurement system can be based upon the same principles.

INTRODUCTION

During March 2-3, 1989, the CDG, (Central Design Group) of the SSC held a workshop on "Measurements of Cold SSC Magnets." The purpose of this workshop was to compare different cold measuring systems and to identify the most promising techniques. As a result of this workshop, we were invited to submit a proposal to the SSC based upon our presentation at the workshop. This paper is an edited and condensed version of the proposal submitted to the CDG of the SSC during July of 1989. (A report that consists of the technical section of the 1989 proposal is available.)[1]

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A strong advantage of this system over the "mole" system presently being used is that the time required for an integral measurement at one current is less than 30 seconds, whereas the mole now requires a few hours. This could lead to significant savings even if only 10% of the 8000 dipoles are measured cryogenic. If 800 magnets are measured, at 2 hours per current with six currents, $200 per hour testing costs results in a saving of $1,920,000.

The expansion of the dipole bore from 40 to 50 mm will decrease the effort required to develop a cryogenic probe and will also make a warm-finger device (i.e., an insulated room temperature probe) practical at a cost of approximately one quarter of the cryogenic probe.

SELECTED CDG SPECIFICATIONS AND REQUIREMENTS[2]

1. Complete measurement system, including probe, mechanical driving units, and auxiliary electronic and computer instrumentation.

2. Operate at both 4.2-4.5 deg K and 1.8 deg K.

3. Capable of measuring multipoles between 0.3 T and 7.0 T (For example, six currents I = 0.32, 0.64, 1.5, 3.0, 5.0, and 6.5 kA on the up-ramp plus possibly the same levels on the down-ramp could comprise a measurement set).

4. The precision of the integral multipoles is as follows [in ± "units"; 1 "unit" = 1.0×10^{-4} @ 1 cm].

n	a_n		b_n	
	systematic	random	systematic	random
0	tbd	3.0	tbd	3.0
1	0.1	0.3	0.1	0.3
2	0.05	0.2	0.1	0.2
3	0.1	0.2	0.05	0.2
4	0.1	0.2	0.1	0.3
5	-	0.2	0.04	0.1
6	-	0.1	0.07	0.2
7	-	0.2	0.1	0.2
8	-	0.1	0.2	0.1

5. The equipment will be equipped with a dipole field tilt meter with an accuracy (resolution) of 0.1 mrad; the dipole tilt angle will be measured with respect to gravity.

6. The instrument has to fit the ID of magnet bore tube [32.26 mm] and must not scratch the copper plating on the inside wall of the bore tube.

7. The instrument must allow for sagitta [=3.40 mm] and fringe fields.

8. Heat generation must be under 5 watts over total magnet length.

PROPOSAL PHASES

Phase 1

An R&D phase during which mechanical methods for manipulating measurement probes in the SSC magnet bore tubes will be developed and evaluated, search coil configuration and fabrication techniques will be developed, equipment needed for testing the performance will be acquired, and the measurement system and calibration techniques will be refined.

At the completion of Phase 1, a report on the research findings, an assessment of the capabilities of a completed system based upon those findings, and an estimate of the cost to produce such a system will be provided to the SSCL. We propose that the SSCL, in cooperation with LBL, would then draw up a set of specifications appropriate to the completed system.

Phase 2

This is the construction phase to build the completed prototype system in accordance with the specifications established after Phase 1.

The following sections of this proposal describes the measurement system as it is presently conceived.

MEASUREMENT PROBE

Figure 1 illustrates the measurement probe with its associated drive and position encoders. The search coil array for these measurements will be 16 meters long and may consist, approximately, of eight two-meter-long identical segments.

Figure 2 portrays cross-sections of both radial and tangential search coil arrays. Each segment will have coils to measure the dipole strength and the higher error harmonics. The error harmonics will be measured utilizing coils connected in series opposition implementing analog bucking of the dipole signal. Additional coils have been included for mechanical symmetry in order to reduce stresses that will produce bowing of the search coil array. The gap between the ends of segments will be small in comparison to the segment length and the integrated data will be corrected for the gap. The pros and cons of both tangential and radial coils will be investigated. The actual number of segments and their length, will be dependent upon a twist tolerance of 0.1 milliradians, i.e., the longest segment for which we can be assured that the twist of that segment will always be under 0.1 milliradians.

The measurement probe will be cryogenic during data acquisition. Twist will occur from unbalanced stress changes due to cooling of the coil from room temperature to liquid helium temperature. In addition, there will be twist due to friction while turning.

CALIBRATION

Bucking Coils

Radial coils will be calibrated in a magnet that has been mapped with an NMR magnetometer. Based upon these measurements, coils will be paired to optimize the bucking ratio. The bucking ratio will be checked by flipping coil pairs (connected in series opposition) in a magnet.

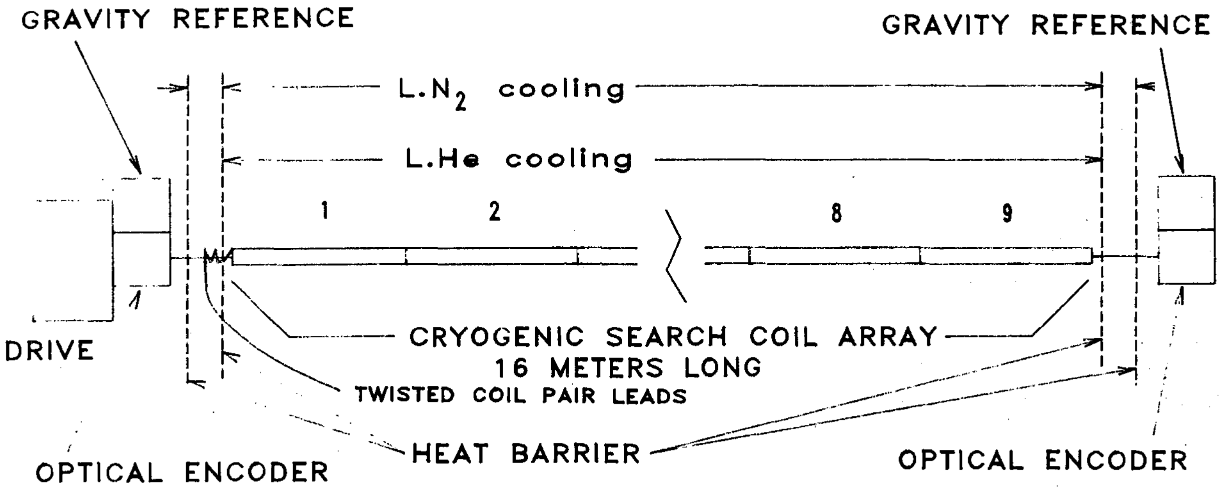


Fig.1. Measurement probe system.

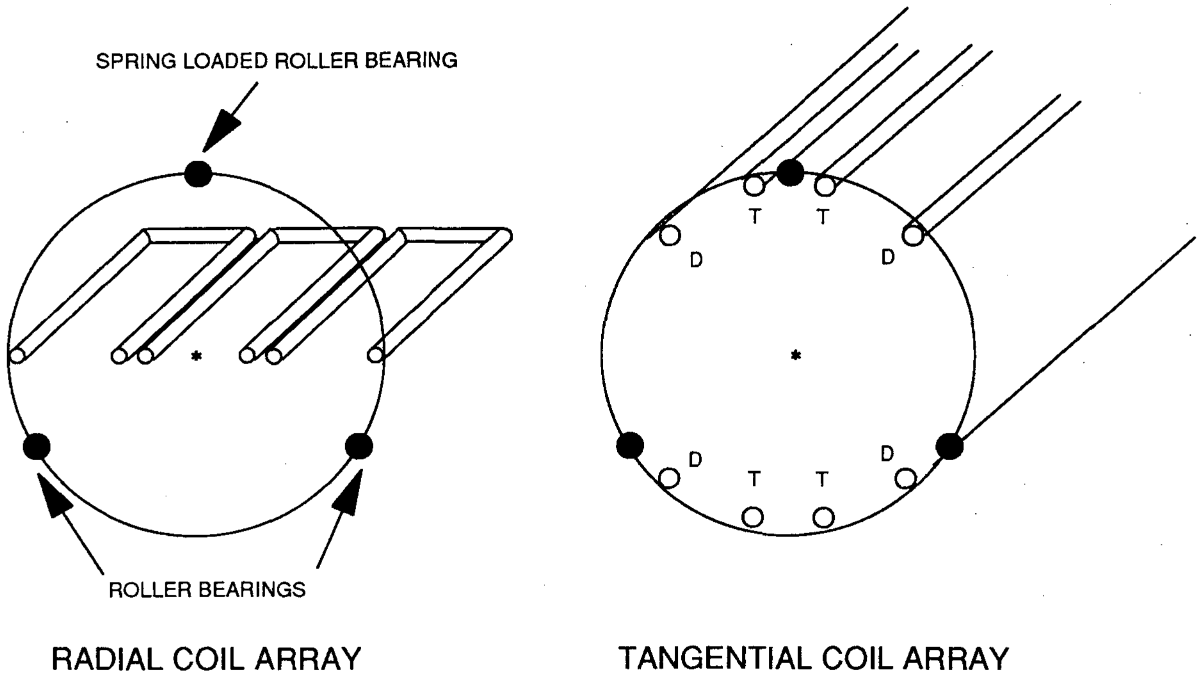


Fig. 2. Cross-section of search coil array options. Each array has the capability for bucking the dipole signal during harmonic measurements. For symmetry each array has dummy coils.

Twist Calibration System

The twist of the 16-meter-long array will be calibrated as follows:

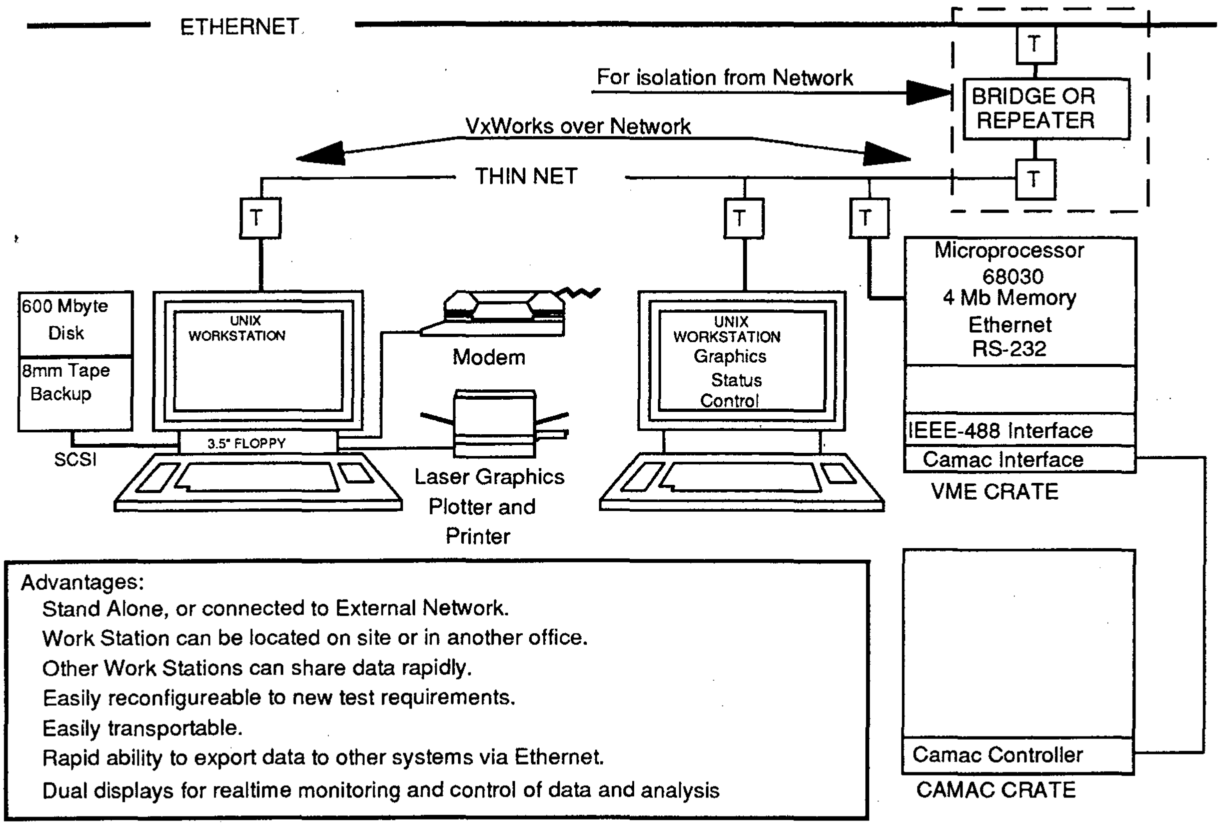
The search coil array will be cryogenic in an SSC bore tube. A dipole reference magnet (with length slightly longer than a segment) will be positioned at each coil segment along the bore tube, always keeping a constant orientation of the dipole magnet with respect to gravity.

Data will be acquired: 1) with both clockwise and counter-clockwise rotations of the probe, 2) with the probe driven from each end separately, and 3) with the dipole reference magnet rotated about its vertical axis. These eight sets of data for each position will allow the calibration of both the twist and the absolute phase of each segment of the search coil array with respect to gravity. For this proposal to be most effective, it will be necessary that the twist be reproducible. Absolute optical encoders at each end of the probe will allow monitoring of twist reproducibility. We recommend that the twist calibration system be utilized if there is a significant change in the twist characteristics of the probe.

After the twist has been calibrated, the option of making measurements continuously in one direction is viable. This would enable very rapid measurements during current ramping. It would also allow good measurements of the decay of persistent currents during an injection cycle.

Maintenance

As indicated in the previous section, the phase calibration may need to be confirmed periodically. The twist calibration system will be an essential subsystem required for this purpose. It will consist of the probe with its associated drive(s), encoders, gravity sensors, 17-meter-long cryosystem, and the nonsuperconducting reference magnet with its gravity sensors. It may be advisable to include an NMR magnetometer in the field of the calibration magnet.



Advantages:

- Stand Alone, or connected to External Network.
- Work Station can be located on site or in another office.
- Other Work Stations can share data rapidly.
- Easily reconfigureable to new test requirements.
- Easily transportable.
- Rapid ability to export data to other systems via Ethernet.
- Dual displays for realtime monitoring and control of data and analysis

Fig. 3. Stand alone computer system [T] Ethernet Transceiver.

DATA ACQUISITION SYSTEM

Computer Hardware

The computer system will consist of a UNIX workstation connected by means of ETHERNET to a VME crate. The VME crate incorporates interfaces to CAMAC and IEEE-488 bus. Figure 3 describes the components of the computer sections of the Data Acquisition System.

Computer Software

VxWorks is a real-time operating system that is down-loaded to the VME crate from the UNIX Workstation.[3] UNIX is used as a high-level software development platform to develop real-time code that will run and be debugged under VxWorks. The application code will be structured similar to the system used to make harmonic error analysis measurements of cryogenic magnets at LBL.[4]

Data Format

The output data format will be compatible with the Self-Describing Dataset software developed by the SSC CDG.

Instrumentation

Figure 4 is a representative block diagram of the instrumentation required to acquire the harmonic analysis data. Other instrumentation, such as a DVM, multiplexer, temperature monitors, power supply controller, gravity sensor monitors, etc., will also be required.

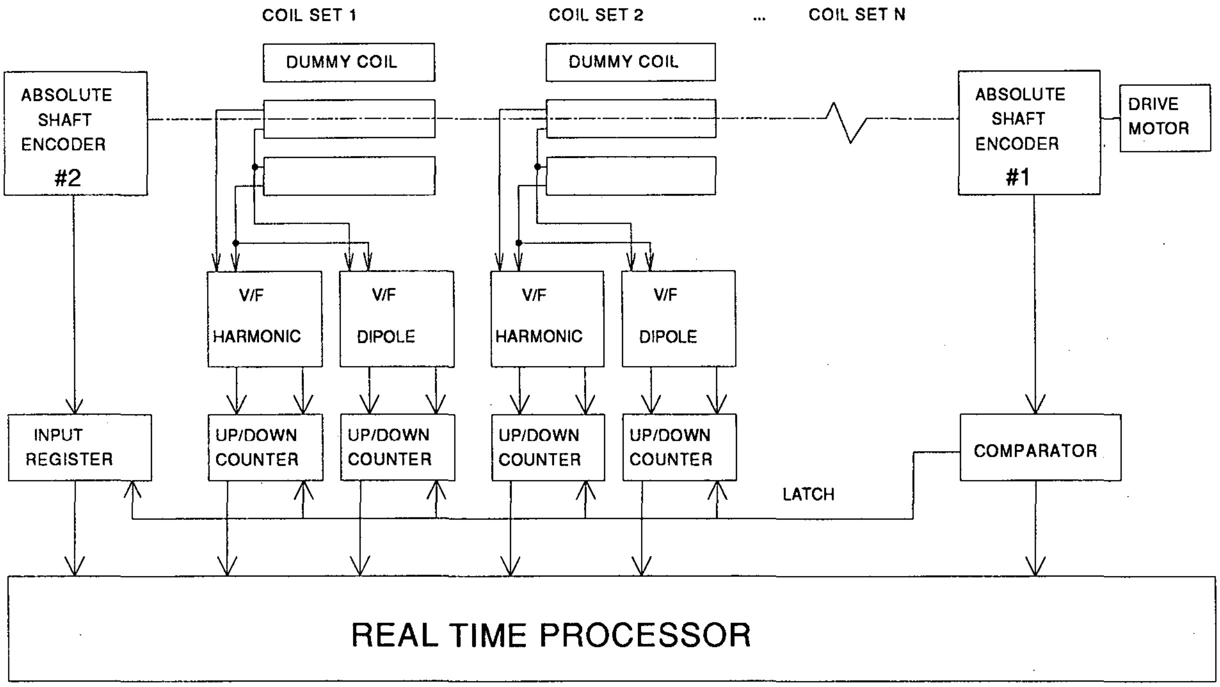


Fig. 4. Harmonic analysis electronic instrumentation.

Each probe segment will have two digital integrators enabling simultaneous acquisition of unbucked and bucked data . The digital integrators will be hardware-latched by an optical encoder at the motor end of the search coil array. An optical encoder at the other end of the array will provide information as to the total twist of the array. There will also be a gravity reference at each end. The system will have the capability of acquiring data with the probe turning both clockwise and counterclockwise. We also propose to have the capability of driving the probe at each end (one end at a time, giving further information about the twist). This redundancy will allow us to resolve the absolute phase with respect to gravity of each segment of the probe. The option of driving both ends simultaneously will also be considered.

It is anticipated that all instrumentation, including optical encoders and motor, will be at room temperature external to the cryosystem.

CRYOSYSTEM INTERFACE

The cryosystem interface would be similar to the one used at LBL for measurement of 1-meter model SSC magnets. It may be desirable to implement additional liquid helium cooling at each end to reduce heat flow to the probe.

PROBE CENTERING

It may not be possible to rely upon the bore tube to center the probe within the magnet with sufficient accuracy to measure the error harmonics to the required accuracy. If this is the case, corrections for feed down multipoles will be made.

MECHANICAL ANALYSES

The probe itself is a major mechanical engineering undertaking. Preliminary investigations show that the magnet bore tube ID and its length makes this a very difficult task. This, of course, is the reason for the requested two-stage approach.

In addition to general probe design work evaluating the merits of a number of schemes (two or three), we need to design a number–perhaps about ten–of composite material probe body test segments. They must be wound by a subcontractor or subcontractors with suitable filament winding machines. We also need to design, fabricate, and instrument two cryotest systems:

a) One horizontal system for dynamic testing of a short length of probe segment support assemblies (able to handle perhaps three connected probe segments). The test would include torsional and bending stiffness and vibration damping characteristics, as well as bearing assembly data in regard to stiffness, friction, and vibration damping.

b) One vertical system for static testing of a short length of probe tube. The tube will most likely be cantilevered, and the purpose of the testing will be to determine the size, nature, and repeatability of temperature-change-induced twisting and deformation from initial true cylindrical geometry of the tube samples. The tests may require a large number of temperature cycles to achieve a (predicted) stabilized condition.

In addition to the obvious need for testing to gather data to verify the probe design, we need the data to design (during Phase 2) a suitable probe calibration, storage, and general maintenance facility for safe handling of the probe. The probe assumes the function of a measurement standard and therefore must be assigned appropriate care.

Probe Materials

A high initial priority in the R&D effort must be the prompt search for acceptably reliable data on prospective probe materials: mechanical, thermal, electrical, and magnetic characteristics–covering temperatures from ambient down to the required 1.8 K–4.5 K probe operating temperature range. If data do not exist in the literature, we must make measurements on candidate materials.

Probe Twist Due to Friction

The single most difficult task is the achievement of less than 0.5 milliradian end-to-end twist of the full 16-meter-length probe as it turns in the magnet bore tube.[5] The present proposal takes exception to this specification in the literal sense by providing calibration of the absolute azimuthal position and twist of each of the magnetic coil segments comprising the whole probe.

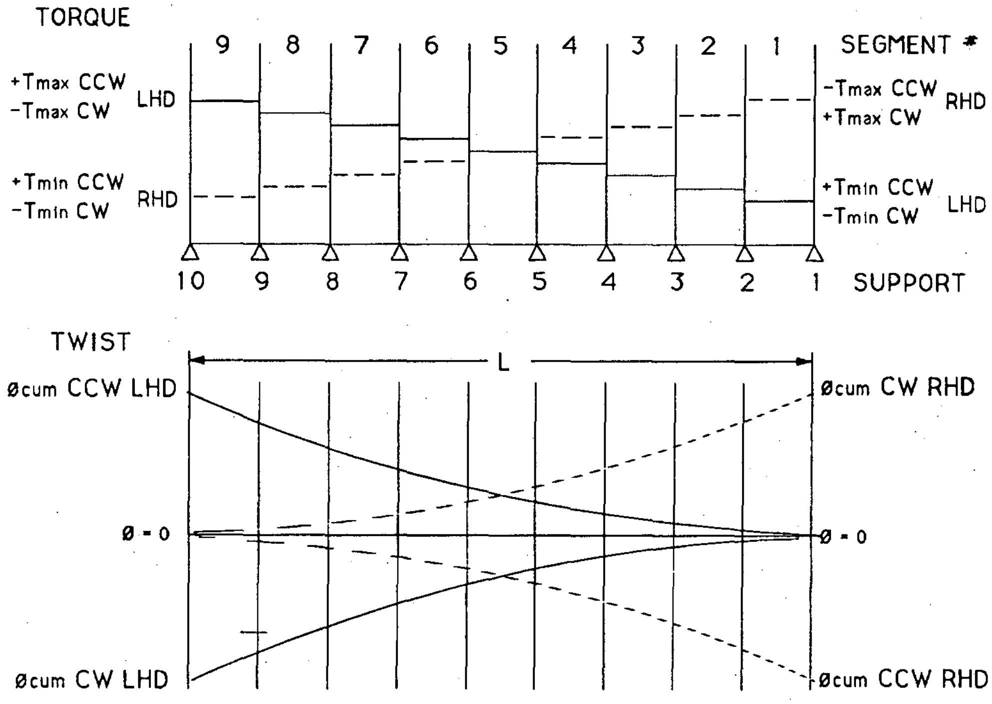


Fig. 5. Nine-segment probe characterizations of torque and twist angle.

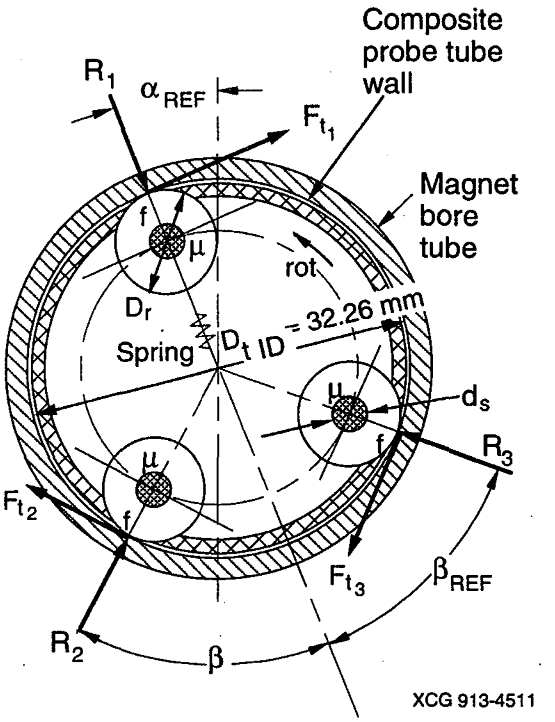


Fig. 6 Probe twist characterization model used for bearing friction calculations.

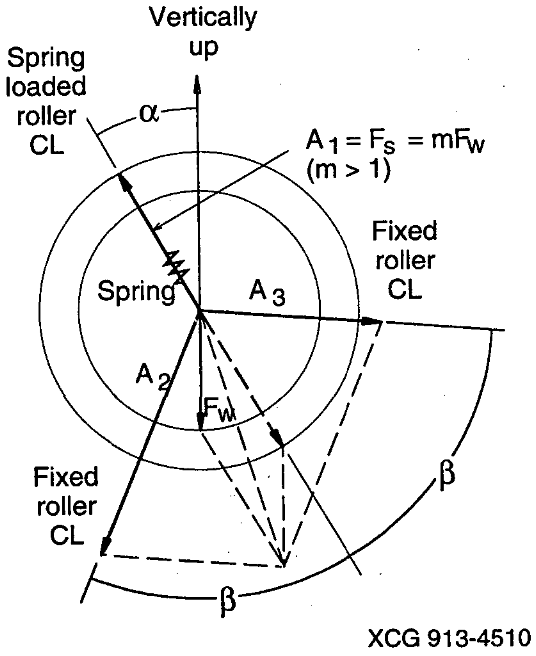


Fig. 7. Probe supports force diagram.

In the practical sense, then, we intend to keep the twist within each section to 0.1 milliradian. This can obviously be accomplished by making the coil segments sufficiently short. It now appears that the only available material that can provide the necessary extremely high modulus-to-density ratio is a carefully designed composite configuration of UHM (Ultra High Modulus) carbon fibers in an epoxy matrix with a very high fiber to volume ratio.

Figure 5 graphs the characterizations of accumulated torques and twist angles in a probe comprised of nine segments. These graphs illustrate that the probe segment closest to the driven end will experience the most twist. Figure 6 shows the model used in conjunction with Figure 7 for calculating frictional forces.

Further preliminary calculations, taking into account probe geometry, support force geometry, friction geometry, bearing materials, and the estimated physical characteristics of several candidate probe materials, resulted in Table I. This is the basis of our conclusion that UHM carbon fibers in epoxy deserve our immediate attention in this R & D phase.

Table 1. Probe material considerations, shear modulus G_{ie}, requirement.

Material Property Data				
Composite	Estimated			Require
	ρ Kgm^{-3}	E, 0°, GPa	G_{ie}, GPa	G_{ie}, GPa
S glass/epoxy	1970	53	15	69
Kevlar 49/epoxy	1380	76	22	48
Boron/epoxy	2080	208	59	72
UHM carbon/epoxy	2000	550	157	70

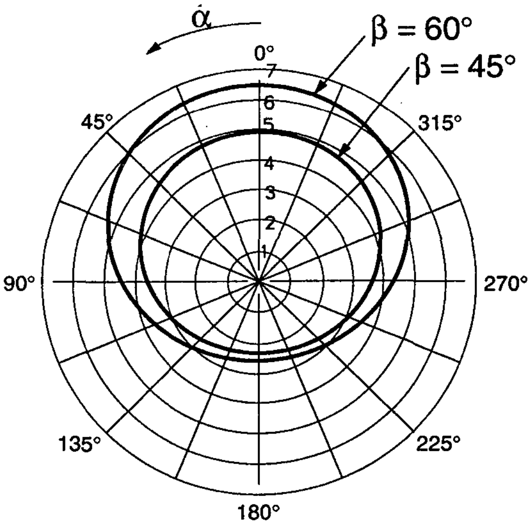


Fig. 8. Probe supports factors vs. angular rotation. å = angle of rotation of the probe within the SSC Magnet bore tube. β = angle of fixed bearing supports in relation to the force vector from the spring-loaded support bearing.

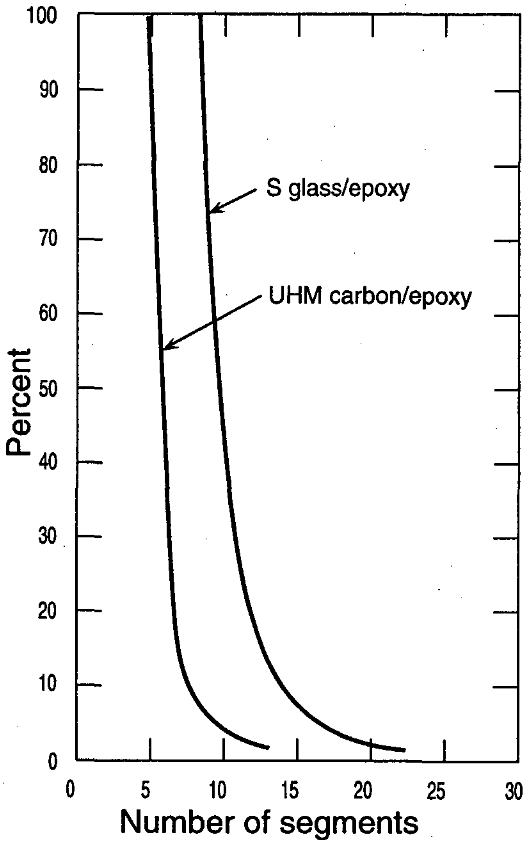


Fig. 9. Based upon allowable gravitational sag specification, this chart shows for any number of probe segments the calculated ratio of thicknesses of the longitudinal tension wall component to the torsional tension wall component, expressed in percent.

Concern has been voiced that this material may have too high an electrical conductivity to allow its use in the probe. We have reason to believe that the electrical (and thermal) resistivity of carbon increases dramatically as the liquid helium temperature is approached. This will be addressed as a first-priority R&D investigation.

Probe Support

The mechanically simplest scheme consists of three circumferentially installed shaft mounted rollers per support. Two of the rollers are fixed, and the third is radially spring loaded. The fixed rollers thus serve to center the probe in the magnet bore tube, while the spring-loaded roller provides the necessary force to accomplish this task. This scheme is inherently free of radial backlash.

Design considerations will take into account: 1) the need to avoid scratching the copper surface of the magnet bore tube, 2) concerns about "wobbling" rotation in bore tubes that may be "out of round," and 3) the need to keep frictional forces (and the resulting torsional forces on each probe section) to a minimum value.

Support-bearing analysis as depicted in Figure 7 indicates that fixed roller bearings positioned at ±45° off the force vector from the spring-loaded bearing will provide the maximum centering ability in the SSC magnet bore. Figure 8 plots the pressure of the spring-loaded support bearing against the SSC magnet bore for 45° and for 60° placements of the fixed bearings. This determination must be further considered against the preference for pure geometrical symmetry, which is best achieved with the 60° placements.

Bending of Probe Due to Gravity

In principle, the bending of the probe sections due to gravity can be reduced to an arbitrarily small value by installing enough supports. From a probe twist point of view, however, there should be as few supports as possible.

A cursory analysis of the requirement to have a "skin" with longitudinal strength to resist gravitational sag resulted in the graph of Figure 9. Again, the preference for carbon fibers in epoxy is evident.

Probe Horizontal Bow Due to Magnet Curvature

Mechanical. The probe must be compelled to follow the magnet bore tube by forces supplied through the probe bearings. The higher conformity that is needed, the more bearings that must be used. More bearings mean less structural efficiency, thus higher mass, friction, and twist. The fewer supports the better. Analysis shows that the spring-loaded contact force required on the roller bearings to overcome gravity exceeds that required to follow the curvature of the SSC magnet bore tube.

Magnetic Measurement Effects. It is possible that each segment will be nominally straight, with most of the bowing occurring at the interface between segments. We intend to model the predicted probe trajectory within the bent magnet and determine the effect upon the accuracy of the harmonic measurements.

Probe Twist Due to Temperature/Humidity Change

The hygrothermal behavior of composite materials must be considered. Potential problems start with the manufacture of the composite, i.e., fabrication of prepregs, winding, cure scheme, etc., and continue during its useful life by the influence of the environment on the composite. A fair basis of theory and available material property data exist for customary temperature environments.

In our case we will design for maximum possible laminate symmetry and test the resulting sample designs down to liquid helium temperature. For most materials the bulk of mechanical property changes will have taken place when liquid nitrogen temperature has been reached. We will establish if this is the case for our laminates.

Calibration and Maintenance of a Probe as a Standard

Our objective will be the design of a probe on which the hygroscopic twist going from room temperature to liquid helium temperature and back is repeatable within acceptable limits and of acceptable magnitude. We anticipate the need to minimize hygroscopic twist in the probe by maintaining it in a dry atmosphere at all times.

The probe is designed to be very stiff, but it may not be very strong. It must at all times be protected against damage by overstressing, even by apparently harmless handling practices. We anticipate the use of a fixture that will support the probe whenever it is out of the bore tube and that will serve as a guide for inserting the probe into the bore tube. Associated with the fixture will be a set of procedures intended to make the probe and its maintenance system as klutz-proof as possible.

Torsional Vibration of Probe

The probe will have a number of natural frequencies for torsional vibrations. To minimize exciting these, we plan to ensure smooth production of torque from the drive motor and smooth absorption of torque in the probe and drive bearings. The most likely source of excitation will be the copper plating on the magnet bore tube, if presently observed samples are typical.

Once the input amplitude of the disturbances has been minimized, we are left with the task of reducing friction. Internal friction at room temperature is about three times larger for carbon/epoxy than for stainless steel (expressed as amplitude loss factor). Glass/epoxy is about 5 times larger and Kevlar 49/epoxy is about 30 times larger. We do not know what these ratios are at liquid helium temperature. An increase in bearing friction will improve damping but will also increase probe twist. This is a tradeoff that must be evaluated.

Heat Flow Calculations

Heat flow within the probe consists almost completely of heat entering the probe from the warm ends. This flow can be reduced to very low values by liquid nitrogen and liquid helium intercepts. Heat generated within the probe is essentially limited to the heat generated by bearing friction and will be negligible.

Temperature uniformity of the probe will be essential for its accuracy. It can be facilitated by maintaining a helium atmosphere within the probe and bore, and minimizing heat flow through the probe. Material samples and actual design and test data will be required before much further progress can be achieved in this area.

Slip Rings

As continuous rotation is desirable for ramping and decay measurements, slip rings are required for the handling of lead wires to the probe coils. They will most likely decrease the torque required to turn the probe and will most likely make it more consistent.

Slip rings also introduce problems:

1. They do not eliminate lead torque. Their torque may not be uniform.
2. They require several joints in each lead wire, each of which is a source of a thermal emf.
3. The slip ring sliding contacts create electrical noise.

The slip rings may thus degrade the quality of the probe data. The torque from the slip rings at one end of the probe does not affect the probe when driven from this end, but it does affect the probe when the probe is driven from the end opposite the slip rings. Since an existing system is working well with slip rings, we do not anticipate these to be insurmountable issues.

Coils

Tangential vs. Radial. Tangential coils/coil support will weigh less and will allow a higher degree of probe symmetry than radial coils. Radial coils can be made structurally more symmetrical at the expense of added dead weight (i.e., increased probe twist). Consideration of which coil structure to use will be one of the high-priority determinations during the R&D phase of this proposal.

Fabrication Techniques. We intend to investigate conventional wire windings versus printed circuit board type and the method of attaching the coils to the measurement tube.

COST ESTIMATE

The following estimates were based upon a 32.26-mm ID bore tube for 40-mm ID dipoles. Costs for developing a system for 50-mm ID dipoles would be approximately 25% less. It is also estimated that developing a warm-finger device will reduce the cost to 25% of the estimate below.

Phase 1: R & D Effort, Equipment and Expenses (1989 Estimates)

Effort Breakdown

Discipline	Effort (Years)
Physicist	0.5
Mechanical Engineer	2.0
Mechanical Designer	1.0
Electronics Engineer	0.5
Computer Programmer	0.5
Mechanical Technician	1.5
Electronics Technician	1.5
Project Management Staff	0.3
Total	**7.8**

Equipment and Fabrication

	K$
Short Magnet System	20
Short Cryosystems	150
Gravity Sensors	40
Tube Fabrication	100
Electronic Instrumentation	80
Mechanical Instrumentation	60
Total Equip. and Fab.	**450**

Other Expense Items

Miscellaneous Expenses	30
Travel	15
Consultant Services	20
Total Other	**65**

Phase 2: Prototype System Fabrication (1989 Estimates)

The cost of this phase will have to be determined when final specifications have been established. Our present estimate of the effort, equipment, and supplies and expenses are:

Effort Breakdown

Discipline	Effort (Years)
Physicist	0.5
Mechanical Engineer	1.0
Mechanical Designer	1.5
Electronics Engineer	0.5
Computer Programmer	1.0
Mechanical Technician	1.5
Electronics Technician	1.0
Project Management Staff	0.3
Total	**7.3**

Equipment and Fabrication

	K$
Calibration Magnet System	20
Long Cryosystem	150
Gravity Sensors	20
Tube Fabrication	100
Computer System	70
Electronic Instrumentation	80
Mechanical Instrumentation	60
Total Equip. and Fab.	**560**

Other Expense Items

Miscellaneous Expenses	30
Travel	15
Consultant Services	20
Total Other	**65**

ACKNOWLEDGEMENTS

Our gracious thanks to Lee Wagner, who helped produce the original proposal to the CDG.

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