Proposal for a Beam Test of a Superconducting Thin Film Strip Particle Detector

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October 3, 1990

Abstract

A total of 24 hours of beam time in the M-Test area is requested in three 8-hour shifts for the purpose of testing the sensitivity of a thin film superconducting particle detector to minimum ionizing energy deposits. An additional 8-hour period of open access to the test beam area is requested before each run to install the experimental equipment and prepare the cryostat for operation at 1.4K. The detection principle, previous experimental work, and the motivation for requesting test beam time are discussed.

1 Introduction

This is a request for running time in a test beam at FNAL during the FY1991 fixed target run for the purpose of attempting to detect minimum ionizing particles with a superconducting thin film strip detector. This work would be part of a program of study to determine the feasibility of a superconducting thin film tracking detector for use near the interaction region in high luminosity colliding beam environments.

Very high spatial resolution particle tracking near the interaction region at colliding beam accelerators has become an important technique used in general purpose 4π detectors. Such devices have proven to be useful for a variety of tasks:

- Identification of secondary vertices from decays of c- and b-quarks and τ leptons
- Precision location of the primary interaction vertex for an event of interest in order to eliminate tracks from other interactions occuring in the same crossing
- Improvement in momentum determination by additionally constraining tracks reconstructed by large central tracking chambers

In a high luminosity collider environment such as that anticipated for the SSC, there are stringent requirements for candidate "close-in" tracking detectors. These include radiation hardness, fast time response, and micron spatial resolution. Although development projects using silicon pads/strips or wire chambers are underway, no detector has been shown to withstand the high radiation doses expected at the SSC near the beam interaction region.

Superconducting thin film strips are attractive as possible alternatives to silicon strips or pads because of their superior radiation hardness, their simplicity of fabrication, and the ability of the films to achieve very fine spatial resolution and fast response time. Their overriding limitation at present is simply that it is unknown whether it is possible or not to detect minimum ionizing particles traversing the film. Here, we elaborate briefly on their virtues. Materials are known that suffer no significant change in their superconducting characteristics for radiation doses with fast neutrons of greater than 1 GRad [1]. The fabrication of the detector films is much simpler than that of semiconductor devices in that they are a single layer device; the film is either etched using standard photolithographic techniques or is deposited on a masked substrate. In either case no doping or overlaying one layer with another is necessary. The difficulty that does exist is that strips of a few centimeters length and $1-2\mu$m width are fairly hard to fabricate with sufficient spatial and physical uniformity. Of course, once the proper technique is discovered, the process can very reliably be repeated as a recipe. The fine spatial resolution arises naturally as strip widths $< 2\mu$m are required for the device to work. Finally, the time scale over which the initial normal zone is formed is the order of tens of picoseconds and a complete normal cross section is created in the film in a few nanoseconds. The recovery of the normal strip to its superconducting state can probably be accomplished is less than 100 ns.

The superconducting-to-normal transition is sensed by observation of the development of a voltage across the strip. Detection of the voltage pulse produced by a normal zone that is formed by ionization energy deposition, grows to a maximum size and then collapses requires a high gain, high bandwidth, low noise amplifier. In our development work we have chosen the easier method of using strips in which the normal zone propagates along the length of the film. This produces voltage drops that have slewing rates of tens to hundreds of mV/ns. These are easily detected, the bias current is zeroed, and the strip returned to the superconducting state.

The idea of using superconductors as particle detectors is not new. Experiments in which heavily ionizing alpha particles were observed to induce transitions to the normal state in superconducting films of tin and indium were carried out twenty five years ago [2]. In addition to our group at Argonne, a similar development effort is in progress by a CERN group using NbN [3].

In the ensuing sections, we briefly describe our previous work on Nb and granular aluminum (g-Al) films that has motivated this proposal, present a work plan for the test beam at FNAL, discuss issues of cryogenic safety, and give our beam and scheduling requests.

2 Summary of Previous Work

2.1 Details of Normal Zone Formation

The superconducting strip detector works as a bolometer, but rather than giving a measure of the energy deposited it functions as a binary detector, i.e. on (switched to the normal state) or off. In a tracking detector the strip would have dimensions of $\sim 1\mu$m width, $\sim 0.5\mu$m thickness, and several centimeters length. The strip is immersed in a cryogenic bath and held within a few tenths of a degree of its critical temperature. A bias current density very near the critical value serves to facilitate the switching of the strip upon any energy deposit and to create a detectable voltage drop across the normal zone created by the incident particle. A high energy charged particle traversing the strip will deposit energy in the strip in a volume approximating a cylinder. Absorption of an x-ray photon will also lead to a superconducting-to-normal transition, but produces a spherical-like initial normal zone. In either case the normal state temperature can initially be much greater than the critical value. On a nanosecond time-scale diffusion of the heat causes the normal region to grow to a significant fraction of the film cross section at a temperature comparable but greater than the critical value. The physical and geometrical properties of the strip are designed to allow either propagation of the normal zone across the full width of the strip or to at least a size that causes the current density in the remaining superconducting cross section to exceed the critical value. The normal cross section in the strip then propagates along the length of the detector. Depending on the characteristics of the film the normal zone can either spread along the entire length of the strip or collapse and allow the film to return to the superconducting state.

As part of designing our test strips and analyzing the experimental results we have obtained, we have performed numerical solutions of the heat diffusion equation on a computer and achieved agreement between our modelling and the experimental data. The best condition to detect minimum ionizing particles can be reached if low T_c superconducting materials are used. At the present time we are using granular aluminum films with $T_c \sim 1.5$K operated in a liquid helium bath pumped down to $T = 1.3 - 1.4$K. With these films, hotspots of radius a few tenths of a micron will be produced by minimum ionizing particles.

2.2 History of Strip Fabrication and Testing

The initial tests of the detection principle were attempted using NbN strips since this material has a demonstrated extreme radiation hardness. The T_c of NbN can be "tuned " in the range $11 - 15$K by varying the temperature at which the substrate is held during sputtering. Our test films had $T_c \simeq 12$K and were put in a liquid helium bath at ambient pressure ($T_{\rm bath} = 4.2$K). Testing was performed using a 20 MeV electron beam at the Argonne Chemistry Division electron linac and an ^{55}Fe x-ray source. The studies performed with the radioactive source showed us that switching will not occur for such large differences between bath and critical temperature. From our experience at the linac we realized that bremsstrahlung from electrons can cause false indications of minimum ionizing particle induced switching. The latter occurs since the full energy of the x-ray is usually deposited in the film.

We next moved on to niobium, which has the lower T_c of 9K, and observed switching induced by ^{55}Fe x-rays for the first time [4]. Again, we used a liquid helium bath at 4.2K. The switching efficiency was studied as a function of the bias current carried in the film with the intention of observing a plateau in the efficiency at sufficiently large bias currents. However, the large $T_c, T_{\rm bath}$ difference required films of width 0.2μm to be sensitive to the x-rays. The geometrical effects inherent in such narrow film widths caused inefficiencies since the x-ray was frequently absorbed near the edge of the film.

By finally, choosing granular aluminum with $T_c = 1.5 - 2.0$K and operating in pumped helium at $T = 1.3 - 1.4$K we were able to see a clear plateau in the response to ^{55}Fe x-rays as the bias current was increased [5]. Moreover, we observed transitions induced by electrons from beta decays in ^{90}Sr for the first time. Although, we used a specially designed source mounted in a low density polyethylene matrix to eliminate spurious transitions from bremsstrahlung x-rays that can be produced by the electrons, the continuous energy spectrum of the beta particles meant that electrons with dE/dx much above minimum ionizing were also traversing the film. This motivates our wish to repeat the experiment with a high energy hadron test beam so as to guarantee a source of only minimum ionizing particles with no bremsstrahlung present.

3 Work Plan for the Test Beam

The goal of our test beam work will be to perform the following measurements:

- Attempt to observe superconducting-to-normal transitions in coincidence with the incident beam
  - The initial and simplest indication of transitions will be provided by their occurence during the beam spill and lack of same between spills.
  - Beyond this we will count coincidences of transitions with signals from beam defining scintillation counters as a measure of the relative efficiency of the detector.
- When the occurence of beam induced transitions has been established, we can measure the transition rate versus bias current at various bath temperatures and search for a plateau in the counting rate.

Because of the small area of our test strips ($1000\mu m^2$), a high flux beam is needed to obtain a reasonable counting rate. For a goal of one transition per second we would require a beam flux of $100,000\ cm^{-2}s^{-1}$. While this may not be obtainable in any of the test beams at FNAL, we would like to be able to receive a few 100K pions per accelerator beam extraction period.

The equipment necessary for the experimental setup is quite modest and consists of

1. the cryogenic system and strip sample holder,
2. the biasing and transition detection electronics,
3. the beam defining logic and associated electronics,
4. and the alignment equipment needed to accurately position a micron feature size strip on the beam line.

While the alignment can, in principle, be done with a ruler and plumb bob, we would like to purchase and install a small laser to accomplish this task.

The cryogenic system consists of a glass dewar helium cryostat and a 50 cfm vacuum pump. The cryostat is fitted with a brass cover plate to permit vacuum sealing of the system. The sample holder, temperature measuring and heater lines, and pump ports project through the plate. The glass cryostat construction has an outer dewar for containing liquid nitrogen and an inner dewar for the liquid helium that is surrounded by an insulating glass vacuum shell. Alignment of the strip on the beam must be done by viewing the sample holder through four thicknesses of glass plus the inevitable frost formed on the walls of the glass. While we have actually successfully done this in the past, we have also had the fortune to use the Argonne Chemistry Division laser for alignment at the electron linac and much prefer this method. The floor space required for the cryosystem is about $1m^2$ for the cryostat and $2 \times 2m^2$ for the vacuum pump and cooling fan.

From FNAL we would request the following services and equipment:

- 220 or 440V. 3-phase power for the vacuum pump,
- a small utility vacuum pump for pumping out the helium insulating vacuum
- electronics from PREP
  - Discriminator for beam scintillators
  - Coincidence logic unit
  - Phototube amplifier unit for scintillator signals
- Surveying for aligning the laser or cryostat

4 Safety Issues

We intend to comply fully with all FNAL safety regulations. We anticipate that the main safety concern will be with operation of the cryostat. Therefore, we describe its construction and operation in more detail here.

As mentioned above, the glass cryostat consists of an outer nitrogen dewar and an inner helium dewar. The capacity of the inner dewar is about 4 liters of liquid helium. It is a standard commercial cryostat manufactured by Pope Scientific Inc. The glass walls are 2mm thick each.

The vacuum space surrounding the liquid nitrogen is permanently sealed while the helium insulating vacuum space is fitted with a pumpout port. During normal operation of the cryostat, diffusion of helium gas through the glass walls into the insulating vacuum eventually spoils the vacuum and increases the helium boil-off rate. For this reason, we restore the insulating vacuum space before each use of the cryostat. This is accomplished by pumping a vacuum on the space and backfilling with dry nitrogen to purge any remaining helium gas. This cycle is repeated a few times and finally a small volume of dry nitrogen is injected into the space. This serves as an exchange gas for cooling the helium dewar internals when liquid nitrogen is put in the outer dewar. When liquid helium is transferred into the inner dewar, the residual nitrogen in the vacuum space immediately freezes out and a good insulating vacuum is realized.

This cryostat has been used extensively in the past in connection with our studies using superconducting strips and radioactive sources. The entire glass cryostat is surrounded with a 1/2" thick aluminum cylinder that has slots milled into it to allow one to view the sample inside the cryostat. The cylinder would provide adequate containment of the cryostat should the glass be broken by an external impact. The construction of the dewar, the small amount of working cryogen involved, and the fitting of the sample holder with a pressure relief valve make it highly unlikely that pressure from boiling helium could break the cryostat walls were we to lose the insulating vacuum.

Since the test beams at FNAL tend to be several feet above the experimental floor, it will be necessary to lift the cryostat in order to get the sample into the beam. This could be accomplished by a mechanical lift. However, it is much more convenient to build a stand for the cryostat and lift it onto the stand. This permits us to have a platform for the cryostat that can be made suitably rigid to eliminate external mechanical vibration, e.g. transferred from the pump. We have, in fact, constructed such a stand, have gone through the procedure for placing the system on the stand, and verified that the procedure can be safely performed.

The authors listed on this proposal all have adequate experience with cryogenics to insure the safe completion of our work. K. Gray has extensive experience in the operation of cryosystems including patented work on cryostats. A. Gabutti and R. Wagner have a few years of experience in working on the superconducting strip development project plus previous involvement in cryogenic experiments.

In summary, we would assert that the cryosystem is designed safely and will be operated by experienced personnel in a safe manner.

5 Beam and Scheduling

The beam time necessary for carrying out the work to observe superconducting-to-normal transitions in the granular aluminum test strips is three 8-hour shifts. We would need to use the time in three different runs since one 8-hour period is the typical working time available without additional transfers of helium to the cryostat. This would also allow us to analyze our results and make any necessary modifications before further beam work.

We would like to request the work be performed in the M-Test beam line using either the CDF test beam area or the RF house downstream of it. Since the use of one area precludes use of the other area, the decision about which to use can be deferred. The reasons for the choice of the M-Test area are R. Wagner's familiarity with the CDF test beam through his collaboration on CDF and the availability of a high flux 225 GeV pion beam.

In addition to the beam time, an additional 8-hour setup time will be required before each run during which we have open access to the beam enclosure area. This amount of time is adequate to install the cryostat stand, the beam scintillation counters, all cabling, and the pumping system. During the last two hours of setup time the cryostat is pre-cooled with liquid nitrogen and helium is transferred. In order to not waste beam time it is best to schedule our beam use after a scheduled open access period in the M-Test area. Removal of our equipment from the beam area after the run will require less than two hours.

Finally, we would like to request that our running time be scheduled as early as possible in the FY1991 fixed target run. This is due to the fact that A. Gabutti will be finishing his post-doctoral appointment at Argonne in December 1990. As we would very much like to have his expertise for the tests, we would like to run in December, 1990, if possible. An extension of his appointment for a month is probably possible if it were necessary to schedule the beam time in January, 1991.

References

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