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High Temperature Superconducting Current Lead Test Facility with Heat Pipe Intercepts

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Abstract—A high temperature superconducting (HTS) current lead test facility using heat pipe thermal intercepts is under development at the Superconducting Technology Center at Los Alamos National Laboratory. The facility can be configured for tests at currents up to 1000 A. Mechanical cryocoolers provide refrigeration to the leads. Electrical isolation is maintained by intercepting thermal energy from the leads through cryogenic heat pipes. HST lead warm end temperature is variable from 65 K to over 90 K by controlling heat pipe evaporator temperature. Cold end temperature is variable up to 30 K. Performance predictions in terms of heat pipe evaporator temperature as a function of lead current are presented for the initial facility configuration, which supports testing up to 200 A. Measurements are to include temperature and voltage gradient in the conventional and HTS lead sections, temperature and heat transfer rate in the heat pipes, as well as optimum and off-optimum performance of the conventional lead sections.

I. INTRODUCTION

Work has begun at Los Alamos National Laboratory’s (LANL’s) Superconductivity Technology Center (STC) on a Current Lead Test Facility (CLTF). The facility will provide the STC with the ability to evaluate the thermal and electrical performance of High Temperature Superconducting (HTS) current leads.

A. Motivation

Current leads for cryogenically cooled electrical devices transfer electrical energy as desired, but also transfer thermal energy from the ambient environment to the refrigerated device. The price paid for this unwanted heat transfer can be high as the refrigeration cycle required to offset it must operate at the low efficiency associated with low temperature cooling.

When normally conducting (conventional) current leads are considered, the limited range of Lorenz ratios for materials available to the designer means that a current lead with high electrical conductivity (and thus a low heat generation rate) will always have a high thermal conductivity (and thus a high heat conduction rate). Heat transfer at the cold end of a conventional current lead can be minimized by optimizing the geometry of the lead for a given material, current, and temperatures at the ends of the lead [1]. Even lower cold end heat transfer rates are achieved via a counterflow arrangement with vapor-state cryogen flowing from the cold to the warm ends of the leads [2]. For helium bath-cooled systems this is convenient but many HTS devices operate at temperatures above that of liquid helium. Conduction cooling by means of mechanical refrigerators is often desirable for these applications, and another means of reducing current lead heat transfer is sought.

A solution to the problem is found in a binary current lead configuration, with a warmer, conventional section joined to a colder section built from HTS material. Refrigeration is provided at the junction to intercept the thermal energy carried by the conventional section, and to maintain the temperature of the HTS section below its critical temperature.

The unique properties of HTS materials break the conventional Lorenz relationship and greatly reduce cold end heat transfer rates for a given current [3]. While it has been shown that HTS lead performance is improved by counterflow cooling [4], these materials also perform well in purely conductive configurations.

A disadvantage of HTS leads has been their fragility: bulk HTS materials can be quite brittle and difficult to handle and install into devices. Recent developments in materials fabrication have improved this situation, however, and current densities up to 280 A/cm² have been reported for YBCO coated conductor materials in the form of thin, flexible metallic/ceramic tapes [5].

There is thus motivation for development of conduction-cooled current leads built from these new materials and from bulk HTS materials as well. LANL’s CLTF will provide a laboratory facility to support this development.

B. Facility Features

1) General. The CLTF is designed to accommodate a variety of HTS lead configurations and materials, and will operate over a range of currents up to 1000 A. Conventional lead sections will provide electrical current to the HTS sections. Refrigeration will be provided by mechanical cryocoolers. The warm end temperature of the HTS sections will be controlled and variable from 65 K to over 90 K. The cold end temperature will be controlled and variable at less than 30 K. HTS lead sections (with appropriate junctions) will bolt into the facility, simplifying assembly and focusing effort on HTS experimentation rather than on facility configuration.

2) Heat pipe thermal intercepts. Cryogenic heat pipes will be used as thermal intercepts between the conventional and HTS sections and are a unique feature of the CLTF. These heat pipes, also under development at LANL, combine high electrical resistance with high thermal conductance over a temperature range from 65 K to 120 K. Previous test results for these devices are found in [6].
II. DEVELOPMENT AND CONFIGURATION

A. Development Plans and Progress

The facility is planned in two phases: phase one will support tests at currents up to 200 A, and phase two will increase current capacity to 1000 A. Both phases will support testing at low voltage (less than 10 V). Phase one development to date has included design and construction of a vacuum vessel and top plate; cryocooler installation and characterization; design, construction, and characterization of conventional lead sections, design and construction of cryogenic heat pipes; and design of junctions for HTS lead sections.

B. Internal Components

1) Component layout: Fig. 1 identifies the internal components of the CLTF and shows their locations.

2) Component descriptions. The facility is built around a two-stage Gifford-McMahon cryocooler. Phase one configuration uses a cryocooler with 17 W of cooling capacity at 77 K to the heat pipe intercepts, with up to 9 W of cooling capacity at less than 20 K at the cold end of the HTS leads.

The conventional lead sections, formed from flexible copper braids, are connected from the top plate to the upper thermal/electrical connections on the heat pipes. This braid material is mechanically flexible and is available in a wide range of cross-sectional areas, thus the aspect ratio (length per unit area) required for optimal performance is easily satisfied for a given lead length. The heat pipes are clamped into a copper block which is in turn bolted to the first stage of the cryocooler. Fig. 2 is a photograph of the top plate, coldhead, conventional leads, heat pipe mockups used for configuration, and the heat pipe clamp block.

The HTS leads will be connected between a junction on the lower thermal/electrical connections on the heat pipes and a junction on the second stage of the cryocooler. The lower junction will complete the current leads’ electrical circuit and will provide a thermal intercept at the cold end of the HTS leads.

A section of a prototype heat pipe is shown in Fig. 3. The working fluid is nitrogen, pressurized to 2000 psig at room temperature. The central evaporator rod is electrically isolated from the condenser case by a layer of epoxy. The epoxy layer also seals the pressurized nitrogen charge within the chamber. When the condenser is between the critical and the triple point temperatures of nitrogen (65 K and 120 K), the nitrogen condenses and accumulates as liquid in the lower portion of the chamber. Heat applied to the evaporator rod evaporates some of the liquid, and a convective cell forms within the chamber. Boiling and condensing heat transfer provide a high heat flux relative to the temperature differential between the evaporator and the condenser, resulting in a high thermal conductance for the device.

Electric heaters mounted on the first and second coldhead stages will control temperature at both ends of the HTS leads.

C. External Components
1) **Current.** Two current supplies are available to the facility: an AMI model 10100PS-412 supports testing up to 100 A and a Hewlett Packard model 6464C provides up to 1200 A. Current feedthroughs into the vacuum vessel are water cooled for temperature control at the warm end of the conventional leads.

2) **Diagnostics and data acquisition.** Cryogenic temperature controllers will be used to monitor and control first and second stage cryocooler temperatures. Voltage drop across a calibrated resistive shunt in series with the current leads will indicate lead current. Temperatures will be measured at the warm and cold ends of the conventional and HTS lead sections, on the evaporator rod and condenser body of the heat pipes, and on both stages of the cryocooler. The heater power required to control temperatures on the coldhead stages will be monitored. Voltage taps on the HTS lead sections will monitor their performance; voltage signals from these taps will also be used to control lead current in an active protection system. These signals will be read by a scanning digital voltmeter and multiplexed into a computerized data acquisition system.

### III. MODELING AND PERFORMANCE PREDICTION

#### A. General

The performance of the CLTF has been predicted by means of mathematical models of the system components chosen for the first phase (200 A maximum) of the facility. These were combined to predict system performance in terms of heat pipe evaporator temperature as a function of lead current. Evaporator temperature controls the warm end temperature of the HTS lead section, thus it was chosen as the parameter of interest in the performance analysis. Fig. 4 presents the results of this analysis.

Models for five components were combined to generate Fig. 3. These components include 1) the conventional lead sections, 2) the coldhead's first stage, 3) the heat pipes, 4) the interface between the heat pipes and the coldhead's first stage, and 5) the radiation shield.

#### B. Conventional Lead Modeling

The conventional lead sections were modeled via finite differencing of the heat conduction equation. Equations were written representing thermal generation and conduction in the leads with temperature-dependent properties. 14 nodes were used in the solution and the results show close agreement with well-known analytical solutions for conductively cooled current leads [7]. To optimize a lead design at a given current for minimum cold end heat transfer rate, warm and cold end temperatures, and zero warm end temperature gradient were specified. The model was then used to calculate the lead's aspect ratio (length per unit area). Off-optimum solutions were obtained by specifying the aspect ratio and three of the other boundary conditions, and solving for the remaining parameter.

#### C. Other Component Models

1) **Coldhead.** The coldhead's first stage was modeled by fitting a second-order curve to manufacturer's performance data. First-stage performance was affected by second-stage heat load; a constant second-stage load of 3.0 W was assumed. Data were available up to 70 K; the curve fit was extrapolated to 90 K.

2) **Heat Pipe.** Previous work has characterized the performance of a heat pipe design similar to that used in the CLTF [8]. This work has shown an almost linear dependence of thermal conductance on heat transfer rate in the heat pipe at a condenser temperature of 80K. This dependence was assumed valid over a range of temperatures from 65 K to 90 K.
3) Interface and shield. A constant interface resistance of 0.2 K/W was assumed to exist between the heat pipe condenser bodies and the coldhead’s first stage. Experimentation indicates that a constant parasitic heat load of 2 W may be assumed to be transferred from the radiation shield to the first stage.

D. Performance Prediction Results

Fig. 4 shows that the heat pipe evaporator temperature is minimized by optimizing the conventional lead sections for a given current. Thus it seems desirable to optimize a conventional lead for the maximum anticipated current for a series of tests. Note, however, that the heat pipes will not function below the triple point of nitrogen, thus 65 K is the lowest desired evaporator temperature. Further, an upper limit on evaporator temperature is defined by the critical temperature of typical HTS materials, taken here to be 90 K. Fig. 4 shows that conventional lead sections optimized for currents less than about 190 A allow the evaporator to run colder than desired while limiting the maximum current. Thus a conventional lead optimized for currents near 200 A is desirable for tests at lower currents as well. Fig. 4 also shows that, given the assumptions and limits mentioned above, and with an optimized lead, the maximum operating current for the CLTF in this configuration is 211 A.

Fig. 4 predicts performance for phase one development; a similar set of calculations has been made for phase two (1000 A maximum) configuration. These calculations indicate that the first stage cooling capacity of the phase two cryocooler must be at least 90 W at 77 K to support a maximum current of 1000 A.

IV. EXPERIMENTAL RESULTS

A. Conventional Lead Sections

Conventional lead sections formed from tinned copper braids have been installed into the facility. The performance of these leads is compared against the model described above (section III, B) in Fig. 5. Good agreement with the model is shown. Error bars on the plot indicate the range of uncertainty in heat transfer rate measurement. Spread in the heat transfer rate data at a given current was caused by unsteady temperature conditions.

B. Phase Two

Much of the work done and experience gained in phase one development is directly applicable to the higher current levels planned for phase two. Components that interface with the cryocooler cold stages will be redesigned for the larger cryocooler, but components such as the heat pipes and sensors will be reused. The higher heat transfer rates associated with phase two testing will allow the heat pipes to be driven to their performance limits. Data from these tests will support the design of a new generation of more powerful cryogenic heat pipes.

C. Expanded Electrical Testing

With the DC current capacity of the facility expanded to 1000 A, attention will turn to increased voltage isolation for facility components to support tests at higher voltages. Alternating current testing for evaluation of AC losses in HTS leads is also anticipated.