Title

High Temperature Superconductor Cable Test Facility Specifications

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1. INTRODUCTION

The US DOE Office of Science High Energy Physics (HEP) and Fusion Energy Sciences (FES) programs are collaborating on the development of High Temperature Superconductors, and are exploring various possibilities for a future cable testing facility. This document provides a first review of the technical requirements such a facility should meet to be competitive internationally, from the perspective of Fusion Energy Sciences stakeholders. Additional requirements should be determined from HEP stakeholders if this is to be a shared facility. We note that there is significant overlap with needs of the HEP community as well as the high-field solenoid community; there are areas of joint interest as well as areas where requirements or preferences differ. A systematic review of synergies and differences is beyond the scope of this report.

The document is structured around a suite of driving considerations for a user test facility:

- Applied magnetic field
- Sample characteristics
- Facility support requirements
- Facility usage

For each element, we provide draft requirements for a facility; furthermore, we provide additional guidance that should be considered prior to deciding on final facility specifications. We note that much of the input is based on experience from users and operators of facilities such as the SULTAN and EDIPO facilities at CRPP in Villigen, Switzerland, and the high field solenoids operated by the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida.

2. APPLIED MAGNETIC FIELD

There is a strong preference for a dipole field configuration for the testing of large, high-current cables that are typically envisioned for FES applications, and the information presented below is largely based on this assumption. However a solenoid configuration, i.e. with a large central bore in which bent samples can be placed, is also a possibility and can satisfy the needs of some experiments envisioned for FES. Note that a higher field on sample can be attained in solenoidal configuration. An important clarification is that a solenoid configuration is not compatible with HEP HTS dipole insert testing, but is essential for high-field HTS solenoid insert testing.

Specification 2.1. *A field of 15 T is a minimum to make the new facility an attractive option; envisioning a path towards 20-25T in the future would be important for the long-term viability/competitiveness of the facility.*

> It must be recognized that in dipole configuration 15 T is at the limit of today's technology; fields of 20 – 25 T are beyond state-of-the-art and serve as long term goals of HEP's US Magnet Development Program.

Specification 2.2. *The homogeneous field region should be at least* $500-600$ *mm (within* $0.5-1\%$*), but preferably* $900-1000$ *mm.*

The primary consideration is to allow multiple twist pitches of the HTS cable samples to be in the high-field region. The space below the high-field region for making the joint should be at least 600 mm, but preferably at least 1000 mm long. This would provide enough length to have the joint located in the low-field region.

Specification 2.3. *An AC "ripple" field (* ~ 10 *Hz,* $+/-500$ *A) transverse to the sample is important to measure local AC losses. Separately, larger field excursions are important to evaluate ramping losses that will be incurred in magnets and to support quench performance analysis, and are best performed using the main magnet itself at the level of* ~ 1 *T over* ~ 1 *s. Both capabilities are secondary to the primary background field, but the facility should be designed with the goal of accommodating some level of AC field production for AC loss measurements.*

AC loss measurements are important to understand and predict quench behavior, and to quantify thermal loads associated with initial magnet ramping and dB/dt associated, for example, with plasma current induction using the central solenoid in Tokamaks.

Specification 2.4. *A distance of* ~ 800 *mm (or more) should be provided from the good field region to the low-field joint region.*

Together with Spec 2.2, this implies that sample lengths can be on the order of $2-3$ m; the magnet cryostat will need to accommodate sample lengths at this scale.

3. Sample Characteristics

This section discusses sample characteristics, including sample space dimensions, powering of the sample current, sample temperature control, and AC loss measurements. The sample space must have its own vacuum well. A larger well facilitates cable experiment design and enables a broader suite of experiments to be performed. On the other hand the cost, complexity, and risk associated with producing high field grows with aperture size.

Specification 3.1. *The well dimensions must be at least* 90 *mm* $\times$ 140 *mm (dimensions of the original EDIPO facility), and preferably* 100 *mm* $\times$ 150 *mm to be compatible with experiments in the FRESCA-II facility at CERN. Larger well size enables unique experiments.*

We note that the specification above identifies a rectangular well; this is consistent with existing facilities used by the fusion community. Round wells can of course be envisioned, e.g. but a more detailed look at existing and planned experiments will be required to determine the minimal requirement.

Specification 3.2. 100 *kA to sample is highly preferred. A superconducting transformer with total loop resistance of* ~ 100 *n-Ohm is a fine option, although a DC power supply would be ideal. The supply must be capable of holding current for* ~ 30 *minutes. A DC supply capable of at least* 30 *kA must be available to provide the needed experimental flexibility. Current must be measured either with a temperature controlled shunt or via current transducers (preferred).*

We note that if a superconducting transformer option is pursued to provide the 100 kA sample current, more detailed evaluation of possible samples is needed to properly specify the transformer characteristics. In particular the potential range of sample inductance and joint resistance needs to be understood before defining the transformer size and turn ratio.

Specification 3.3. *Variable temperature range from* 4.2 – 50 *K is essential; increasing upper temperature to* 60 *K or* 77 *K is preferable. The sample cooling system must be able to handle the anticipated loads at temperature (e.g.* > 10 *W at* 20 *K).*

The method for cooling the samples must have the requisite flexibility to handle varying thermal loads and cable architectures, and accommodate both pressurized flow and conduction cooled sample configurations. The possibility of using different cryogens for different samples should be considered, at least as a possible future upgrade scenario for the facility. There is some interest in accessing temperatures down to 1.9 K (superfluid Helium) as well as 77 K (liquid Nitrogen).

Specification 3.4. *Provide flexible space around the facility for users to come with their own support systems such as flows, instrumentation, etc.*

Due to the broad spectrum of potential engineering solutions for fusion using HTS materials, users should have the flexibility to apply their own coolant systems to feed the sample, and their own diagnostics to measure critical parameters unique to their experiments. This flexibility is particularly important due to the strong interest in such a facility coming from the private sector.

Specification 3.5. *Test sample calorimetry and VI (Voltage-current) measurements, both with sufficient signal to noise resolution, should be provided to enable AC loss measurements.*

As mentioned under Spec. 2.3, loss measurements on cables serve multiple purposes, including evaluation of operational heat loads and evaluation of cable and magnet quench behavior, which provide critical information for proper magnet protection design. The facility must be designed to provide some level of AC loss measurements, although more sophisticated measurements may require the user to provide additional specific experimental equipment.

Specification 3.6. *The ability to apply (separately) axial and transverse mechanical loads using facility-supplied systems would be ideal, but is not essential for most users.*

The ability to apply axial tension/compression and transverse pressure to samples is complicated by the diversity of sample geometries that are envisioned, and the intrinsic constraints associated with a dipole magnet configuration. Some level of applied load capability should be provided, but for many experiments the load may need to be applied through judicious experiment design leveraging, for example, differential thermal contraction of sample support materials to impart the desired load.

4. Facility Support

A facility designed to support experiments for fusion energy sciences must provide a breadth of user support services. Here we summarize critical elements needed to properly support HTS cable measurements in a facility.

Specification 4.1. *Versatile, re-configurable, and comprehensive feedthrough system(s) to support a broad range of experimental sensors and signals. Anticipate a breadth of novel diagnostics, including voltage, optical, and acoustic signals with broad frequency range requirements (*$1-10^7$ *Hz or greater). Some voltage signals require high precision (sub-*μ*V). Current measurement at the* 10 *ppm level.*

It is likely that, due to the rapidly evolving state of HTS conductor and cable development, the suite of diagnostics that will be requested and/or applied to samples will be highly variable from test to test, and that new diagnostics will be developed and applied based on new physical concepts not yet explored.

Specification 4.2. *Support for sample preparation, with a suite of nominal sample holders / adapters and associated diagnostics that serve as a baseline for measurements.*

An important role for cable test facility is to provide a baseline for experiments, both in terms of scope and measurement quality, that support technology development. Quality measurements, taken over time on a breadth of samples, provide both measurement statistics and experience (both for the facility and its technical staff) that are critical to the community. Without a reliable baseline for experiments the community risks having tests performed that lack proper rigor and quality with possible severe consequences - we note that cable sample measurements serve as building blocks to the development of magnet technology and ultimately to fusion systems.

Specification 4.3. *Access to an operational team with requisite expertise in sample preparation, system operation, and experimental data reduction to serve as a baseline for cable measurements.*

As a user facility dedicated to a spectrum of users from Industry, Laboratories, and Universities, it is essential that some level of expertise is maintained by the facility to support experiments. The operational team serves multiple critical roles for users and for the community: they maintain facility readiness, review and guide planned experiments to maintain standards for high quality measurements, provide oversight of experiment design and readiness, and support users in performing sample measurements. Expertise in sample preparation, test protocols, facility operation and safety, and data management are critical.

Due to the varied nature of anticipated HTS cable samples and the diversity of expected users, the facility should anticipate having more interaction with the users than in the ITER era.

Specification 4.4. *The facility needs to be a centralized repository of raw data and overseer of operations for all users. Best practice should be shared with the community at large.*

Specification 4.5. *The facility must be responsive to a broad spectrum of users, including importantly from the private sector. In particular, procedures to handle issues of schedule and access, intellectual property, publications, etc. must all be established.*

Collaboration models between facility operations staff, government-funded investigators, and private-funded investigators need to be encouraged as part of the facilities operational model. Models of well-functioning user facilities exist, for example in the light source community, that balance the public-funded and private funded work.

5. Facility usage

Specification 5.1. *Typical research groups working on HTS cables, both private and public, envision* 2 – 3 *R&D samples per year. A conservative usage estimate under current funding conditions would be* ∼ 6 – 9 *samples per year, but that number would likely double with increased funding from DOE and the private sector in HTS technology development for fusion. The facility and its supporting staff must have the flexibility to accommodate a diverse and variable set of clients and collaborators.*

Anticipating usage is difficult due to the many interconnected factors that play a role. First, facility capabilities and flexibility to handle various samples dictates the pool of candidate samples. Second, access to the facility, both in terms of schedule availability and cost of performing an experiment, weigh heavily on a potential users decision to use the facility. For some potential users, a third driving factor is the availability of expertise in sample preparation and testing to support efficient and effective experiments. Finally, and most importantly, the usage will depend on the communities investment in HTS for fusion, both in the commercial and in the public sector.

Facility availability and usage are intrinsically linked - access to a test facility will spur further need for the facility as cable technology advances.

6. Final Comments and Summary

We have summarized key issues/elements that an HTS cable test facility will need to address in order to serve the fusion community. We note that investing in such a facility will only prove valuable if it is part of a larger program with a broader research portfolio in HTS development, either within FES or jointly by FES and HEP. This is needed to support the technology development and to develop the expertise that will bring it to fruition. Investing in the people who develop the samples, work to identify and resolve HTS issues, develop and refine simulation tools, and explore applications is the vital role of the academic and public sector. If left to industry alone the facility will not be highly utilized due to time pressures.

Although not directly a specification, we note that the size of the external cryostat and support systems should be designed with some margin to enable future upgrades to the magnet. The lessons from SULTAN and EDIPO are that the infrastructure is very valuable long-term, and some forethought will pay dividends in the future to facilitate upgrades.

The field is rapidly changing and the need for such a facility is acute now. High-profile and high-impact work is likely to occur in the near term; the window for US leadership here is narrow and if the program is slow to be defined and executed other nations will field such a test facility and the US will lose what lead it has.

Finally, we note that the specifications defined here are only a first draft of critical elements that need to be considered for a facility for FES applications, and should serve simply to aid in preliminary scoping studies for such a facility. Many of these elements deserve more detailed and refined analysis for final specifications, and additional considerations should be taken into account to properly support the needs of the HEP community if this is to be a shared facility. Furthermore, the funding paradigm for facility operations needs careful consideration to enable efficient use of expertise and infrastructure, and to enable cost-effective access to users from DOE laboratories, universities and the private sector. Before designing and building a facility, we recommend a working group be established by FES and HEP to define the priorities/goals for the program and how best to achieve them.

Appendices

A. Cable Test Facility Requirements Questionnaire

The following questionnaire was used to request input from the stakeholders associated with this document:

Questionnaire I: Draft facility capabilities and functional requirements

The intent is to focus on a dipole magnet providing field on cable samples. Please weigh in on the following areas:

- *Applied magnetic field:*

  1) Magnetic field strength the facility can provide on sample. The intent is to focus on capabilities beyond those currently available to the international community. What is the minimum field strength required? What field strength would make the facility particularly attractive? Over what length is the field required, and with what level of uniformity? What is the minimum distance from the low field joint region to the test field region?

  2) Additional AC field production. Is there motivation for additional AC field superposition on the sample? If so, what are the characteristics that are most valuable, e.g. AC field modulation frequency and amplitude?

  3) Weigh in on other considerations related to the applied magnetic field.

- *Sample characteristics:*

  4) Sample space requirements. We assume the sample will have its own vacuum space (well). How large an aperture is needed, and over what length? Weigh in on issues / concerns related to sample access.

  5) Sample power supply requirements. What are the characteristics needed of the sample current supply? Is current from a superconducting transformer acceptable, or is their need/preference for a power supply? What voltage/current ripple can be tolerated for measurements envisioned? Is there a preference for current measurement via a shunt or via a current transducer? How long must current be maintained on the sample? What range of sample inductance should be assumed?

  6) Sample temperature control. What range of temperature is required on the sample? What level of temperature control is required? What range of cooling power is required, i.e. what is the maximum sample power loss that must be compensated for in steady state? Is there a particular sample cooling design that should be incorporated, or that should be avoided?

  7) Weigh in on the need for AC loss measurements. What measurement techniques should be included, e.g. calorimetry, VI, magnetization? What level of accuracy is needed?

8) Sample mechanical considerations. What capabilities should a facility supply in terms of mechanical loading of the sample, e.g. longitudinal tension / compression, transverse pressure, etc.? What level of accuracy and control is needed, and over what range?

9) Weigh in on other considerations that a facility should take into account / accommodate to support your possible needs.

- *Facility support:*

  10) Measurement equipment. What measurement equipment should be provided by a facility? What type and number of sensors should be anticipated? What is a minimum, and a preferred, data acquisition frequency for the various sensors? Do you envision new/future sensors that might influence a new facilities specifications?

  11) Describe the level of support required / preferred from a test facility, e.g. sample preparation support, test support, data analysis and reduction support, etc.

  12) Weigh in on other facility support requirements that should be documented.

- *Facility usage:*

  13) Anticipated number of samples. How many samples do you envision you or your group to test annually? What are the driving considerations that impact the number of samples to be tested?