ARDB Technical Note 128

Toward a 1 GeV/m x 1 meter Linac

David H. Whittum

In this note we summarize the practical accomplishments required to design and layout a 1 GeV - 1 meter linac facility in End Station B. The motivation is to take stock of how far we have to go to arrive at a sensible design.

Introduction

The design of a $1\,\mathrm{GeV/m} \times 1\,\mathrm{m}$ W-Band linac requires enormous technological progress. We won't even try to discuss construction, and commissioning here. Let us instead sketch the research activities and accomplishments that would be required to conceive of a sensible design. Developing this level of detail is helpful in forming a realistic idea of a timeline. There are five somewhat independent lines of basic theoretical and experimental research.

Tube Development

We require four 50 MW, 1 μs tubes. These require drivers putting out 50 kW or so. This appears to be the critical path at present.

Injector Concept and Design

We require one 60 pC bunch, with 30 μm bunch length and rms normalized emittance of 10^{-7} m-rad.

Magnet Development

We require a quadrupole lattice filling the linac, providing quadrupole gradients of 200 T/m, with beam aperture diameter of 2 mm.

Structure Design

We require a structure capable of accepting a 10 ns, 400 MW pulse, and delivering 1 GeV/m to the beam without structure damage. The concept we are pursuing is the "active matrix linac", and this is still in the design stage.

Active W-Band Circuit Development

We require an active rf switching medium, most likely plasma or diamond, and a switch activator, most likely a short-pulse laser. A significant step in the tests of active switching will be compression of a 1 μs 50 MW pulse to 10 ns.

There are three facilities for experimental tests that would play an important role in the engineering and physics studies preceding linac design.

W-Band Test-Stand in the Klystron Dept.

To facilitate high-power studies, assessment of breakdown thresholds, field emission properties, and other damage mechanisms, it will be helpful to have a dedicated W-Band tube station in the klystron department.

Structure Tests in ASTA

To facilitate study of resonant devices, the shielded vault composing the ASTA facility will be helpful.

Structure Tests in NLCTA

Theoretical assessment of wakefields, and bench measurements must be confirmed experimentally with beam. These tests could take place at the NLCTA, following or as part of the subharmonic drive experiments currently being planned. These tests could also make use of the ASSET facility at a lower level.

Part of linac design would consist of conventional facilities design and would require a site. The best site for this purpose is End Station B. Next we elaborate on each of these items.

Tube Development

Possible lines of tube development have been discussed in broad detail in a previous technical note.[1] This note also outlines specific physics concerns and challenges for the only candidate 50 MW amplifier, a planar ubitron. Here let us concentrate on a specific listing of goals, and a possible timeline. Major lines of research and development are

Klystrino
(1) fabrication studies of the 100 kW klystrino
(2) power combining studies for the klystrino
(3) engineering design of the Caryotakis 100 kW klystrino
(4) first test of a single klystrino
(5) first test of high-power combining

Ubitron
(1) gun design for a planar ubitron
(2) wiggler design for a planar ubitron
(3) first elliptical gun test
(4) wiggler assembly
(5) wiggler field characterization
(6) tube assembly
(7) first tube test at 5 MW
(8) studies of tapering
(9) second tube assembly
(10) first tube test in excess of 10 MW

For the klystrino line of development, steps (1)-(3) are in progress. The ubitron line of development remains at a the level of theoretical and simulation work, as reported in previous tech. notes.[2]

Injector Concept & Design

At present little work has taken place on the W-Band linac injector.

Magnet Development

At present the only work reported on magnet design for a W-Band linac consists of the tech. note by Marc Hill on planar electromagnets. Additional work on permanent magnets is being pursued by Spencer and Siemann. For reasons of site-power consumption, a high-energy collider would benefit greatly from permanent magnet design for W-Band, so this subject will remain of great interest. It is possible though that a 1 GeV linac would employ electromagnets.

Structure Design

Structure design work is by far the most advanced line of research at W-Band. A 7-cell structure has been fabricated, and a measurement program is underway. A 25-cell structure has been designed and is being fabricated by Ron Witherspoon, Inc. Theoretical work has been

[1] D. Whittum, “mm-Wave Power Sources for Linear Colliders” , ARDB Tech. Note.
[2] D. Whittum, “Low-Voltage Corrections in a Planar Ubitron Amplifier” ARDB TN110, “Space-Charge Corrections in a Planar Ubitron Amplifier” ARDB TN111, “Beam Envelope in a Planar Ubitron Amplifier” ARDB TN112, “Realistic Magnet Models for a Planar Ubitron Amplifier” ARDB TN 116, “Considerations for Gun Design for a Planar Ubitron Amplifier” ARDB TN118.

performed on anomalous loss due to poor rf contact, coupler design, and alternative structures. Much theoretical work remains to be performed, particularly with attention to wakefields, and active structures. A functioning accelerator structure will require bonding, and diffusion bonding is currently thought to be the solution here.

Active W-Band Circuit Development

Active circuit elements (plasma or diamond switches) are of great interest to control pulsed heating in a W-Band accelerator structure, as well as a W-Band pulse compression system. This work is also of interest in X-Band research in the Klystron Dept. Work with silicon has been underway for some years.[3] Research with diamond is just beginning. We are helped here by the circumstance that the gyrotron community (with interest in plasma heating for fusion) has been developing high power CVD diamond windows for D-Band (140 GHz) and thus has developed quite a lot of data on diamond. Requirements on the diamond switching elements may be found in previous technical notes.[4]

W-Band Test Stand in the Klystron Department

To perform high-power studies of resonant structures at W-Band, it will be essential to have a dedicated test-stand. This test-stand would arise naturally in the course of the klystrino line of development.

Let us add though some arguments in favor of a shielded area, rather than an open test-stand, as there are certain advantages that deserve consideration. (It is possible that they could in fact be obtained on a test-stand, for that matter.) While performance and check-out of the gun, and a single-tube can be accomodated by the space-available at a klystron test-stand, more extensive studies dictate a shielded enclosure. The reason for this simply that at W-Band, powers considered "low" for work at S-Band and X-Band, can produce several MeV/m fields. Thus a 30 kW source can produce 10 MeV/m in a W-Band accelerating structure. A 10 cm structure can produce a 1 MeV beam. At the 5 MW level contemplated in a first high-power tube test, or a later stage power-combined klystrino test, a 10 cm structure can produce a 10 MeV beam. Thus the following studies require shielding appropriate to a linac: powering of a single travelling-wave structure, powering of a demountable resonant ring, pulse compression with mode conversion to fundamental mode guide, studies of a demountable tube. The demountable items require the shielded area simply because the amount of integral shielding required in the absence of a housing would make the device effectively undemountable.

For this reason one may wish to plan for the use of a shielded area in End Station B for tube studies, prior to linac design. Given the time and effort involved in such a facility, one should plan for a footprint to accomodate a 1GeV/m x 1m linac housing, four W-Band tubes, possibly four modulators, and the pulse compression system. Space should also be left also for the eventual development of an rf-photocathode gun. Footprint external to the housing should be adequate for a control room housed in a shelter within ESB, and sundries.

Structure Tests in ASTA

Assuming that a shielded tube test-facility is not provided for in ESB, one will require a shielded area for structure tests, and this would be ASTA. Given attenuation at W-Band, this would imply that the W-Band test-stand would in fact be test-stand #8. The arguments given in the previous section, in favor of a shielded area also apply to ASTA---except that W-Band use of

[3] S. G. Tantawi, R. D. Ruth, A. E. Vlieks, and M. Zolotorev "Active High Power RF Pulse Compression Using Optically Switched Resonant Delay Lines", *Advanced Accelerator Concepts*, Proceedings of the Seventh Workshop, AIP Conf. Proc. **398** (AIP, New York, 1997) pp. 813-821.

[4] D. Whittum, "RF Circuit and Resonator Scalings for a W-Band Active RF System" ARDB TN 82, "Switched Matrix Accelerator " ARDB TN.

ASTA would likely occupy most of the facility schedule.

Structure Tests in the NLCTA

The work toward W-Band structure tests in the NLCTA is well underway, and discussed in numerous technical notes.[5]

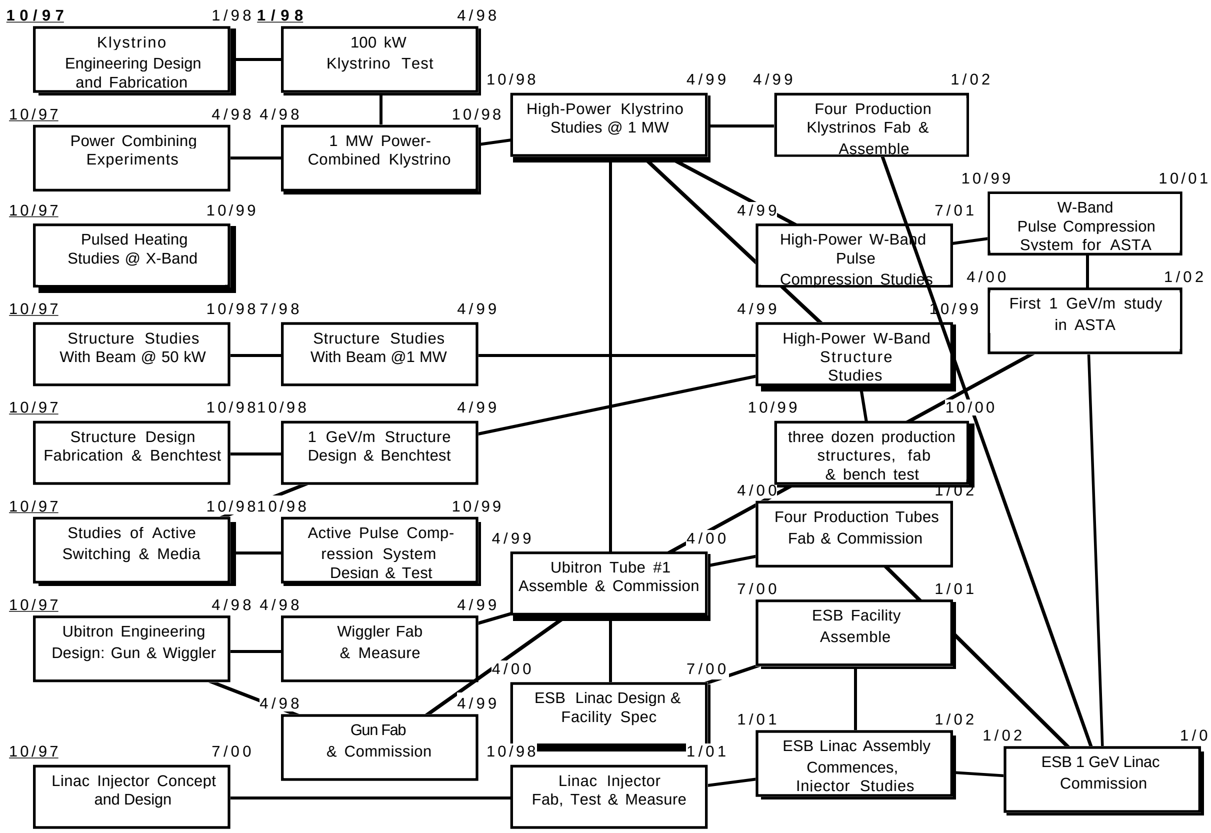

FIGURE 1. Task list for a 1 GeV - 1 meter W-Band linac and *SWAG* estimates of time required.

Conclusions: Time-Table for W-Band Development

The time-table for development of a W-Band accelerator is still the subject of discussion. Nevertheless, it is helpful to have a realistic view of what is possible. Depicted in Fig. 1 is a hypothetical time-line. According to this timeline, the earliest start of a 1 GeV/m x mm study would be in the summer of 2000. The earliest start for the linac injector commissioning would be Spring of 2001.

[5] M. Seidel and D. Whittum, “Scalings for the Ring-Linac “ ARDB TN 63, D. Whittum, “Subharmonic Drive Experiment Without Resonant Ring” ARDB TN, M. Seidel, M. Hill and D. Whittum, “Subharmonic drive experiment at the NLCTA” ARDB TN,

Appendix A - Outline for W-Band GeV Linac Design Report

(based on the NLCTA CDR, and borrowing the outline and some boiler plate language)

Abstract

When complete, this document will serve as a description of a high-gradient W-Band accelerator design, for construction in End Station B. The facility will serve as a 1 GeV linac test-bed for research toward a 5 TeV W-Band collider. In the meantime, this Appendix serves to outline what basic research remains to be pursued before we can contemplate such a design.

Preface

The goal of Advanced Accelerator Research at SLAC has been to identify an acceleration technology that could eventually be extended to a functioning 5 TeV collider for high energy physics, operating at an effective gradient of at least 1 GeV/m over a substantial length, of order a meter, and a significant charge per bunch, approaching 100 pC. In light of scalings for pulsed heating, trapping and breakdown, it was judged that this required a short rf wavelength, and the decision was made to focus attention at the 32nd multiple of the SLC frequency, 2.856 GHz. The constraint on this research was that technologies with severe intrinsic limits to efficiency or for other reasons not scalable to a high-energy collider were not of interest.

The collider concept itself, and the technologies involved are described in the ARDB publications of the last years, and the ARDB technical note library. In the remainder of this document we concentrate on outlining the design considerations for a W-Band collider test facility, for siting in ESB.

1. Introduction

This document outlines the design of a high-gradient, low-emittance test-stand. The goals for this test-stand are to develop and test experimentally a 1 GeV linac technology scalable to a high-energy collider. This research is to be carried out as a joint project between SLAC and collaborators:

Universities: Berlin Technical University, University of California at Davis, University of California at Los Angeles , University of Southern California, Departments of Applied Physics and Electrical Engineering at Stanford University.

Government Labs: Argonne National Laboratory, Lawrence Livermore National Lab, Lawrence Berkeley National Laboratory, The National Laboratory for High Energy Physics in Japan (KEK), The Naval Research Laboratory

Companies: Fusion and Accelerator Research, DULY Research, Ron Witherspoon Inc.

1.1 Overview

High energy physics today is limited by the accelerator, and little else. The most severe limit arises due to accelerating gradient, for machines of great dimension (hundreds of kilometers) are not supportable by society. The goal for research in ARDB is an advanced accelerator capable of gradients in excess of 1 GeV/m with a technology employable for a 5 TeV collider. Our immediate goal for the forseeable future is to design, build and commission a 1 GeV/meter x 1 meter accelerator. This report briefly outline the considerations that would be part of such a design.

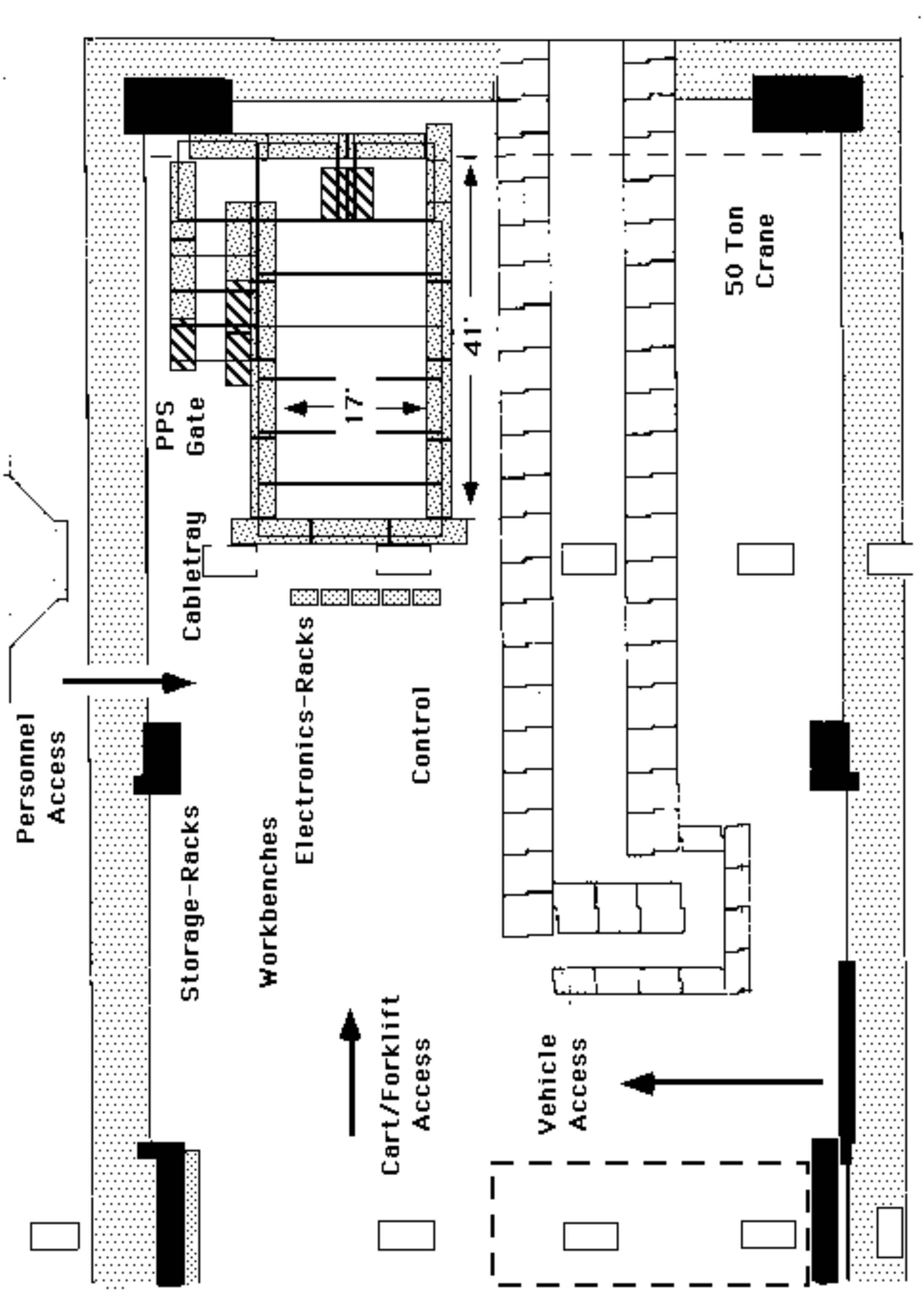

FIGURE A1. Layout of a shielded area for W-Band accelerator research in End Station B.

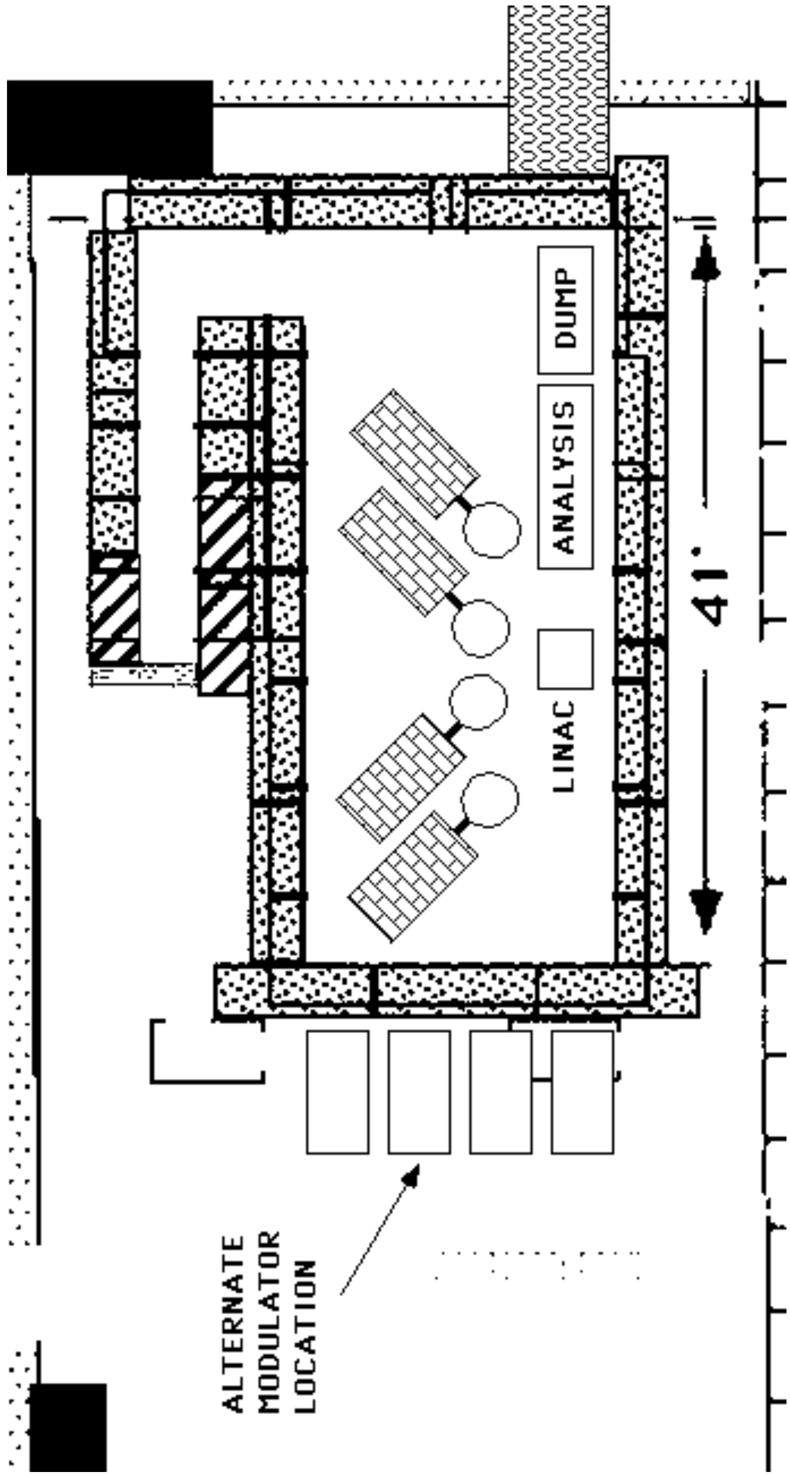

FIGURE A2. Layout of components within the accelerator housing.

1.2 Present State of Accelerator Research

The work of the advanced accelerator community is well-illustrated in the bi-annual proceedings of the Advanced Accelerator Workshop. A summary of possible lines of research and development for a 5 TeV collider may be found in the proceedings of the Snowmass workshop.[6] At present there are five such lines of research corresponding to high-gradient acceleration (1 GeV/m gradient or larger). These are mm-wave acceleration, THz acceleration, beam-driven plasma acceleration, laser-driven plasma acceleration, and laser-microstructure acceleration. Research on THz acceleration is largely dormant, world-wide. Research on laser-driven plasma acceleration is being pursued at LBL and other institutions.[6] In ARDB at SLAC we are: (1) pursuing mm-wave acceleration as our primary emphasis, (2) collaborating on E157, a test of beam-driven plasma acceleration,[7] (3) collaborating on a laser-microstructure acceleration experiment.[8] The W-Band accelerator facility described here is the goal of our research efforts at W-Band, and a route to development of a 5 TeV collider.

1.3 The W-Band Test Facility

A dedicated test-stand for studies of high-gradient acceleration and low-emittance beams

2. Subsystems

In this chapter we descibe the major subsystems of the test-stand, their specifications, equipment requirements, cost, and development time.

2.1 Overview of Subsystems

The major subsystems are: the Control System, RF, Laser, Magnets, Power Supplies, Vacuum, Instrumentation, Test & Measurement.

2.2 Control System

The control system will be based on the Solo Control Program (SCP), augmented with HP VEE for control and acquisition from VXI modules.

2.3 Microwave & Structures

The microwave power system will be based on four SLAC modulators, modified to power four high-power W-Band ubitron amplifiers, operating at 480 kV and 300 A. The low-level rf system will begin with an HP synthesizing signal generator, driving four 50 kW W-Band amplifiers, one per high-power tube. An alternative scheme, employing one 400 kW amplifier, and power spliiting is being considered.

Two possibilities are being considered for siting of the tubes and modulators. Due to high attenuation in fundamental mode guide at W-Band, a fundamental mode microwave network would require siting of the tubes within the accelerator housing. In this case, the triax feed from the modulators to the tubes wouldlikely require siting of the modulators themselves in the housing, although a feed through the housing could probably be arranged. The second alternative is an overmoded microwave network, and siting of tubes and modulators outside the housing. This would seem to be most convenient.

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[6] S. Chattopadhyay, D. Whittum, and J. Wurtele, “Advanced Accelerator Technologies, A Snowmass '96 Subgroup Summary”, *New Directions for High Energy Physics*, Proceedings of the 1996 DPF/DPB Summer Study on High Energy Physics, Snowmass '96 (SLAC, 1997, Menlo Park) pp. 356-369.

[7] R. Assmann, *et al.*, “Proposal for a One GeV Plasma Wakefield Acceleration Experiment at SLAC”, SLAC E-157.

[8] Y. C. Huang and R. L. Byer, “A Proposed Dielectric-based Laser-driven Electron Accelerator using Crossed Cylindrical Laser Focusing” *Advanced Accelerator Concepts*, Proceedings of the Seventh Workshop, AIP Conf. Proc. **398** (AIP, New York, 1997) pp. 538 - 546.

2.4 Laser

Laser requirements for the injector, if any, have yet to be determined. Laser requirements for switching elements have yet to be determined. It is possible that two laser systems will be required, one typical of an rf photocathode test-stand, the other, a short pulse, high fluence uv laser.

2.5 Instrumentation

Due to the short time-scales typically considered in W-Band studies, it is likely that diagnostics development will be a significant research activity in itself. We won't try here to guess the outcome. However, one can expect an assortment of toroids, bpms, faraday cups, screens, and a spectrometer.

2.6 Magnet

Injector requirements remain to be determined, but will likely include two solenoids. A 1-meter quadrupole lattice remains to be designed. Correctors will be required. A bend magnet is required for the spectrometer. Possibly a second bend if a separate dumpline is used. It remains to be determined if the 30 μm bunch length requirement will necessitate additional bunch compression optics.

2.7 Power Supplies

This section will include an enumeration of all magnet and miscellaneous power supplies, including specifications for regulation.

2.8 Vacuum

Requirements for vacuum will be set at 10^{-9} torr. The vacuum plan remains at a very rudimentary stage.

2.9 Water, Compressed Air, Electrical

The water system will include cooling for the tubes, structures, magnets, and the dumps.

2.10 Test, Measurement

It remains to be determined whether there is a significant advantage to siting a new W-Band test & measurement lab adjacent to the linac.

3. Experimental Program

The experimental program would consist of commissioning and operation. This includes tube commissioning after receipt from the W-Band tube-station in the Klystron Dept. Following commissioning of the first tube would be gun commissioning and beam characterization. Following each tube commissioning, beam characterization and acceleration studies would follow.

4. Administration

4.1 Personnel Requirements

One full-time technician/facilitator, one group secretary, two postdoctoral assistants, one microwave engineer, many opportunities for graduate students (four, easily) and undergraduates.

5. Conventional Facilities

The test-stand will require the construction of a shielded area within End Station B, as well as outfitting with utilities such as LCW, electrical, compressed air and HVAC. All conventional facilities will conform to applicable DOE, national, and state codes and regulations, including those portions of DOE 6430.1A that pertain to the test-stand.

The test-stand conventional facilities comprise the End Station, AC power, mechanical utilities, sewers, and drainage facilities (see Fig. 5.1). The changes to these facilities that will be needed are: none.

An Environmental Impact Statement for ESB was issued by the Energy Research and Development Administration in ____. No modifications to this statement will be required to comply with current regulations.

The fact that ESB lies in close proximity to known earthquake faults requires a conservative seismic design. For above-ground structures, equipment and components the basis for seismic design was a modification of the Uniform Building Code (1976 Edition), Section 2321, such that it equals or exceeds current seismic design practices.

5.1 Beam Housings

The beam housing for the test-stand is limited to the shielded vault depicted in Fig. A1. The housing is concrete-lined, painted white, and has controlled ventilation. Telephone service is to be provided. The vault is protected by a fire detection system. Fire extinguishers are on-hand in lieu of an automatic sprinkler system.

5.2 Support Buildings

Support buildings for the test-stand consist of temporary shelters housed within ESB.

5.3 Mechanical Facilities

Cooling needs for the test-stand are limited to cooling of the beam-dump, and temperature stabilization of the microwave structures. Cooling needs for the beam dump are minimal since the beam power is below 5W. The temperature-stabilization system consists of a closed loop.

5.4 Electrical Facilities

The power needs of the test-stand will be less than 500 kW, and are easily fit within the overhead on the existing 5MW substation employed by the NLCTA.

5.5 Beam Dump

Beam dump requirements are minimal since the beam power is less than 5W.

5.6 Space Requirements

Construction of the test-stand will be facilitated by the removal of debris, unused magnets and beamline components, and other remnants from previous operations in ESB. Alternatively, but less optimally, these items could be stacked elsewhere in ESB to clear an area for the test-stand.

5.7 Disassembly and Removals

Items consist totally of ___ tons, the heaviest item of which is ____ tons. Sufficient space is available in the magnet yard and the salvage yard for these items. No special disassembly is required. Removal requires use of the 50 ton crane at ESB and a flat-bed truck, and will take approximately one-week. All item must be surveyed.

5.8 Installation

Major items to be installed include: shielding block, the laser room and equipment, the klystron and microwave system, and the laser-tables for the experimental hall. Two cable trays will be required, two water lines, and two raceways.

6. Environment, Safety, Health, and Quality Assurance

SLAC has numerous environment, safety and health (ES&H) and quality assurance (QA) programs already in place. From the ES&H and QA standpoints, the test-stand does not present any significant new challenges. The SLAC programs in ES&H and QA will ensure that all aspects of the design installation, testing and operational phases of the project are properly managed. As appropriate, the cognizant SLAC safety committees, including

Safety Overview Committee
Hazardous Experimental Equipment Committee
Radiation Safety Committee
Fire Protection Safety Committee
Hoisting and Rigging Committee
ALARA Committee
Electrical Safety Committee
Non-Ionizing Radiation Safety Committee
Earthquake Safety Committee

will review and approve various aspects of the project. All aspects of the project will conform to the applicable DOE, national, and state codes, and regulations, including those aspects of DOE 6430.1A that pertain to the test-stand.

6.1 Fire Safety

The existing fire safety system in ESB will remain operational throughout the construction and operation of the test-stand. All areas are classified as Ordinary Hazard, Group I (?).

6.2 Radiation Safety

The design criterion will be 1 rem/yr at 30 cm from the shield surface for normal beam losses. This assumes a 2000-hr working year and an occupancy factor of 1. In addition SLAC internal design criteria require that (i) the boundary dose be limited to 5 mrem/yr for 7200-hr beam operation and (ii) the maximum radiation dose at 30c m from the outer surface of the shield from an accidental beam loss not exceed 3 rem.

The Personnel Protection System currently is designed to protect personnel from radiation, electrical and RF hazards. This is accomplished through a system of electronically interlocked gates, lights, alarms and operator displays and controls.

The PPS system will include a single entry module, with keybank, video camera and direct voice communications via intercom and telephone. The access states are as indicated in Table 5.1.

Beam containment will be monitored using two BSOICS.

All non-escorted personnel working at the test-stand during periods of beam-on will be trained at the level of RWT with the high and very-high radiation training module.

Table 5.1 Access States for the Test-Stand.

NO ACCESS
Beam on or potential for beam on.

RESTRICTED ACCESS
Similar to CONTROLLED ACCESS but electrical hazards and X-Ray hazards from RF may be present.

CONTROLLED ACCESS
Beam off. Electrical and RF hazards off. Vault has been searched. Persons are identified, are logged in and out, and must carry a key from the keybank.

IN SEARCH
Beam off. Electrical and RF hazards off. Doors are electrically locked until search completed.

PERMITTED ACCESS
Assurance that beam and RF hazards cannot come on. All door releases are enabled.

6.3 Non-Ionizing Radiation Safety

The RF-system for the test-stand will incorporate all safety measurements that are currently standard for SLC operations.

An intact and signed label on each waveguide joint is always a prerequisite to operational transmission of RF through a waveguide network.

Test-stand operations staff will conduct RF radiation hazard surveys periodically to ensure that the RF leakage level is less than $1 mW/cm^2$.

6.4 Electrical Safety

The provisions for locking of electrical systems for service will utilize SLAC's established procedures for lockout and tagout. Energized equipment will be worked on only under very limited and controlled conditions and only qualified employees will perform such work. All work will be performed in accordance with safe work practices and in accordance with OSHA 1910, Subpart. S. Special procedures are in place to permit authorize personnel to occupy areas adjacent to energize hazardous magnets. These procedures are called RASK, for Restricted Access Safety Key. Under these procedures, a special RASK authorization form must be filled out to obtain a key that enables the hazardous supply under test. Testing is done in accordance with written procedures. The emrgency-off buttons remain active and will crash off the power supply when pushed.

6.5 Construction

The line organization acting through the subcontract administrator has primary responsibility for overseeing safety compliance by construction subcontractors. This responsibility includes:

- Apprising subcontractors of SLAC and DOE safety criteria prior to construction
- Conducting periodic inspections of subcontractor construction areas to evaluate the quality of the subcontractor's safety compliance program.
- Receiving subcontractor accident reports and compiling information for reporting to DOE.

The Quality Assurance and Compliance Department of the ES&H Division oversees the QACD Subcontractor Oversight Program (Reference Document SLAC-I-770-0A17A-001-R001).

6.6 Emergency Preparedness

In the event of any abnormal condition the interlock system will automatically shut the machine down until the situation is diagnosed and corrected. The formal emergency planning system described in the SLAC Emergency Preparedness Plan (Reference Document SLAC-I-720-70000-105) will help to ensure a logical, organized, and efficient response to any emergency.

6.7 Environmental Protection

The test-stand is expected to have no impact on groundwater.

6.8 Hazardous Material Issues

In accordance with 29 CR 1910.1200 (the OSHA hazard communication standard) SLAC has developed a SLAC Hazard Communication Program (Reference Document SLAC-I-720-0A06Z-001, 1992). Under this program, SLAC directs Department Heads and Group Leaders to conduct regular inventories of hazardous materials, to make Material Safety Data Sheets (MSDSs) available to all employees, to ensure appropriate labelling of hazardous materials to train employees to identify and control hazards in the workplace, and to inform users, subcontractors, and temporary employees of the hazards that may be encountered at SLAC.

6.9 Quality Assurance

Component specifications remain to be developed.

7. Summary

This Appendix should be helpful in outlining how much remains to be done to formulate an actual design report!

Acknowledgments

Thanks to the authors of the NLCTA CDR, from which certain boiler plate language (earthquake safety, etc.) has been duplicated.