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An Electron Beam Test Facility (EBTF) for TA-53

1.0 Introduction

A dedicated facility for electron-beam R&D would significantly increase the viability of the Accelerator and Electrodynamics capability at LANL. Such a facility would provide access to a high-quality source of nearly-relativistic electrons, sufficient experimental and data acquisition capabilities, and flexibility to enable a broad range of fundamental and applied accelerator and beam physics experiments. Such a facility would cost-effectively meet the needs of a broad set of projects and sponsors ranging from LANL LDRD, DOE Office of Science, NNSA Global Security, Threat Reduction, and others. Implementation of such a facility at TA-53 would allow technical resources for Accelerator and Electrodynamics capability development to remain within LANL while meeting many important mission needs that can only be met through such a facility, allowing technical capability and technical expertise to co-reside.

Many projects today are resource limited yet require significant investments in off-site facilities to be successful. Many of these facilities are significantly over-subscribed, with long queues of researchers waiting to perform experiments, and have significant constraints (technical and operational) that limit their ability to support programs related to important areas such as national security. In contrast, a dedicated small-scale electron-beam test facility (EBTF) at LANL could significantly increase project cost effectiveness and productivity by reducing or removing such limitations for LANL researchers.

Existing LANL electron accelerator capabilities and facilities would be leveraged to assemble the EBTF and several options exist. A preferred location for the EBTF has not yet been formally decided however it is assumed that the location of the decommissioned Advanced Free-Electron Laser (AFEL) project [1] in Building MPF-14 at TA-53 is one possibility. Building 14 provides space for a modest accelerator and user-support laboratories. This location also contains adequate facilities infrastructure. The EBTF electron accelerator and test beam line would be assembled using available accelerator, vacuum, and mechanical equipment to provide a reliable source of 20-MeV electrons for users at a modest cost. Upgrades to higher final beam energy could be considered later based on location and available budget.

Other options include relocating the AFEL to the former SPA [2] area in Building 14 or to Building 365, also at TA-53, which would use the LEDA tunnel which recently supported the Navy MW-FEL program. The Building-14 SPA location also contains adequate facilities infrastructure, but offers a larger space to reconfigure the beam line as needed to support an even broader range of experiments and programs. Cleanup of this area and removal of some legacy equipment would be required prior to installation of the AFEL hardware. Additionally, shielding modifications may be required to adequately shield occupants of the building from hazards associated with operating the accelerator.

Use of the LEDA tunnel in Building 365 is the likely preferred location. Although some equipment would need to be relocated, it provides adequate shielding and infrastructure for the AFEL operating at 20-

MeV as well as any envisioned upgrades to higher energy, and significant space for a variety of beam line configurations and experiments. This location supports all needed facility infrastructure, requiring only minimal facility upgrades. From a cost perspective, all three options are nearly identical.

Mission need for the EBTF exists today. This mission need is centered on a set of experiments that could be performed now at the ETBF if such a facility were made available. These experiments range from state-of-the-art proof of principle experiments, experiments and R&D that augment present programs, and new experiments and R&D to develop new programs, including technology maturation for the MaRIE x-ray free-electron laser.

2.0 Mission of the Test Facility

Transitioning the most promising technologies into viable prototypes requires linking R&D efforts to specific requirements and constraints of real-world application areas, the majority of which involve electron accelerators for the research envisioned for the EBTF. It is worth noting that most other laboratories recognized as performers in electron accelerator R&D anchor their R&D efforts around an existing electron accelerator facility at their respective site. LANL has become a recognized performer in many important areas of electron accelerator R&D (cathode development and other important disciplines) but lacks the tangible benefit of an installed and operating R&D electron accelerator. Other institutions have also reported that an operational R&D electron accelerator enhances the cycle of innovation. There are strong indications that other institutions, both industrial and academic, would likely partner or perhaps even pay to utilize a LANL electron accelerator and associated test facilities following the model of (presently oversubscribed) R&D accelerators at other DOE sites (e.g., Argonne, Cornell, Brookhaven). Implementation of the EBTF at TA-53 at LANL could enable significant and transformational R&D.

The DOE sponsored "Accelerators for America's Future" symposium and workshop [3] has highlighted key technical focus areas that can be addressed with EBTF capabilities. These key technical focus areas include:

- User facilities where industry could conduct technology demonstrations in conjunction with potential customers.
- Accelerator R&D for security and defense applications emphasizing low-cost, compact accelerator systems that are energy efficient, rugged, and highly reliable; developing these requires research in sources, accelerating cavities, RF, and beam transport systems.
- Fundamental research in ultra-high gradient, miniaturized structures, high-power RF and pulsed-power, beam phase-space optimizations that lead to high-intensity, small-emittance, high-brilliance sources of electrons. Also included is improving radiation coherence through improved control of temporal and energy quality in light sources and free-electron lasers.
- Control of beam losses and instabilities, including advanced diagnostics and analysis methods, computer models and other verification tools, and novel beam distribution control and feedback systems.

Specific R&D development areas already being considered for the EBTF that support the highlighted focus areas are described in detail below.

2.1 MaRIE technology maturation

One immediate application of the EBTF is to support technology maturation for the MaRIE XFEL. The MaRIE XFEL design uses well-established and demonstrated technology wherever possible. However, there is no question that this is an ambitious and challenging machine to build. Therefore, a technology maturation plan has been developed [4] in order to reduce the technology risk of the MaRIE XFEL by addressing key design challenges. The performance of the MaRIE electron beam source is crucial to the performance of the MaRIE XFEL as a whole. Achieving low photoinjector emittance is one of the highest-risk technology items and therefore one of the most crucial to demonstrate early. More broadly, plans to mitigate technology risks to the MaRIE project therefore include a photoinjector test at LANL, as well as supporting experiments at other facilities and enhanced modeling and simulation. Such testing could be directly supported by the EBTF, and would in fact represent one of its highest-profile early experiments.

Injector Design Test

An EBTF in MPF-14 can accommodate testing of the MaRIE XFEL photoinjector. In the proposed MaRIE Technology Maturation Plan, LANL will design, build, and test the best current design for the MaRIE XFEL photoinjector. Beam tests with the photoinjector will measure both the longitudinal and transverse electron bunch phase space as a function of axial position after the photoinjector. The bunch emittance will be measured using a pepper-pot technique to reduce the effect of its own axial evolution. The beam physics milestone of this effort is to generate and measure a normalized slice transverse RMS emittance of less than 0.2 µm and measured slice energy spread of less than 1 keV. These milestones meet the minimum MaRIE performance requirements. The photoinjector design goal is to generate a slice emittance of < 0.15 µm and slice energy spread < 300 eV. The injector tests are estimated to take 3 years to complete and will require 10 FTEs and $10M of M&S.

Timely implementation of the EBTF would allow characterization of beam diagnostics and other tests concurrent with fabrication of the MaRIE photoinjector. The present AFEL photoinjector has similar beam quality to the planned MaRIE photoinjector and could therefore serve as a useful surrogate for initial tests and troubleshooting. After completion of fabrication, the AFEL injector would be replaced with the new MaRIE prototype. The AFEL RF system is also at the MaRIE photoinjector design frequency of 1.3 GHz and is capable of operating at the desired 10-µs pulse length.

Much of the general electron accelerator and beam R&D proposed in the following sections may also have a technical impact on the MaRIE project. Also, demonstration of such an exquisitely high electron beam quality has the potential to enable new applications in other areas as well. **Customers:** DOE, DOD, DHS, NNSA, LDRD

2.2 Photocathode development and testing

Recent advances in the expanding disciplines of fundamental material science have inspired new material systems which have important properties for advancing electron source development, including modification of material parameters which influence optical absorption, quantum efficiency, effective thermal emittance, effective applied electric field, and lifetime. Some of these concepts (such as surface plasmon enhancement, band-gap engineering, quantum dots, and single-layer coatings) are in the early stages of transitioning from physics concepts to R&D models and prototypes, with much of the effort occurring at LANL and/or at our collaborative sites. Transitioning the most promising technologies into viable prototypes requires linking the R&D effort to specific requirements and constraints of real-world application areas, the majority of which involve electron accelerators to verify electron source performance. LANL has become a recognized performer in cathode development. The complete R&D cycle for transitioning new developments in material science to yield advances in photocathodes requires the eventual exposure and use of candidate cathodes in the accelerator environment. The EBTF could meet this important need. **Customers:** US Navy/Army/Air Force, DOE, DOD, DHS, NNSA, LDRD

2.3 Dielectric wake acceleration

A Dielectric Wakefield Accelerator (DWA) is formed by one or several co-axial dielectric layers surrounded by metal cladding. Wakefields in dielectric structures may reach gradients on the order of 10 GV/m, with 100 MV/m having been demonstrated in multiple experiments. These structures also have the remarkable property that the axial electric wakefield is transversely uniform and the transverse electric field is linear. This is due to the fact that the required relativistic drive beam and subsequent wakefield both travel very nearly exactly at the speed of light and the wakefield is transversely at cut-off. Achieving an axially-constant wakefield along the beam bunch would result in a minimum beam energy spread and all transverse fields on the bunch vanish, leading to an extraordinary condition of preserving the main beam brightness while providing high-gradient acceleration. The use of DWA technology may be applicable to increase the energy and luminosity of future electron accelerators, including the MaRIE XFEL. New DWA configurations, new DWA materials, and studying beam-related effects such as beam breakup and confinement mechanisms in DWA structures could all be tested at the EBTF. Additionally, other high-performance accelerator concepts such as Dielectric Laser Acceleration (DLA) can also be tested. **Customers:** DOE Office of Science, NNSA/MaRIE, LDRD

2.5 Advanced RF structures

Particle accelerators for novel applications push the requirements of RF-structures beyond the capabilities of presently existing structures. An example includes being able to transport beams of higher currents while maintaining high beam quality. Depending on the type of application, there may also be requirements to reduce structure costs and costs of support systems and operations. Some of these requirements can be addressed by improvements of traditional structures and some require the introduction of novel concepts.

LANL is undertaking a range of projects to address improvements and new developments. Cost reduction efforts are supported by very high gradient structures like dielectric wake field accelerators (DWAs) that reduce the length of an accelerator by orders of magnitude, and novel superconducting RF (SRF) structures like Photonic Band Gap structures (PBGs) and SRF spoke resonators for electron applications that basically eliminate RF-structure losses in an accelerator and reduce the power needs to essentially the beam power only. LANL also develops room-temperature PBG structures which may allow higher beam currents and better beam quality.

SRF spoke structures reduce the complexity of SRF accelerator subsystems in the operation ranges of interest at LANL. They can operate at low RF-frequencies that can be cooled by 4K liquid helium with a lower complexity cryo-plant as compared to actively pumped, multi-stage systems at 2K that are required for higher-RF-frequency operation.

PBG and spoke structures are both novel options for the provision of high-current and high-beam-quality particle beams. These provide strong damping of higher-order modes (HOMs) that introduce detrimental RF-fields that cause beam break up and increase beam emittances. Room-temperature PBGs inherently do not confine any HOMs, which in turn can be damped by removing them as they propagate to the edges of a resonator. Superconducting PBG and spoke resonators achieve the same goal by the incorporating HOM couplers directly onto the resonator volume for damping of these modes, a feature that traditional elliptical SRF resonators do not allow without significant deterioration of performance.

All types of advanced SRF structures developed at AOT would benefit from being tested on a designated beam line. There are excellent facilities at TA-53 (e.g. MPF-17) to assemble, test, and demonstrate RF performance of novel SRF structures and concepts. While this is an important part of the introduction of new capabilities, the RF-performance is only a necessary, but not a sufficient criterion for the suitability of a novel approach. The capability to transport electron beams of high charge per bunch, low emittance and low energy spread, or high average current for applications like MaRIE, high-average power FELs or inverse Compton scattering (ICS) sources requires the capability to add SRF structures to a beam line that provides relativistic electron beams. Experiments that could be performed on ETBF include demonstration of the basic acceleration properties of the novel structures, emittance measurements, measurement of wake effects and demonstration of strong HOM damping for structures like ILC-type cavities, spoke resonators, or PBG and elliptical cavity hybrid structures. **Customers:** US Navy/Army/Air Force, DOD, NA-22, NNSA

2.6 Electron source development

RF photoinjectors, consisting of a photocathode electron source embedded in a radio-frequency (RF) cavity, are the default option for many current and planned high-brightness, high-voltage, or high-average-power electron accelerators. If they are to reach their ultimate performance potential, linear accelerator-based X-ray light sources, such as LCLS, LCLS-II and MaRIE, demand source performance at or beyond the capabilities of existing photoinjectors. High-average-power electron accelerators typically require CW-average beam currents of several mA to 1 A, and also demand high quality electron beams to help mitigate potential beam-loss conditions. RF cavity-based injectors, typically referred to as "RF guns," have also been built around field-emission and thermionic cathodes.

Over the past decade there has been a proliferation of RF injector designs intended to meet the specific needs of new projects, or to address deficiencies in existing designs. Examples include superconducting and normal-conducting designs operating in the CW mode for high average current machines (LANL has on-site one of only a handful of operating superconducting RF electrons guns in the US); multi-frequency multi-mode cavities intended for use with field-emission cathodes; and cavities modified to achieve ultra-high vacuum for high-quantum-efficiency cathodes. The canonical 1.6-cell photoinjector such as in use at SLAC/BNL/UCLA, in particular, has been significantly refined to improve field symmetry and mode separation, and continues to be evolved to operate at higher gradients and longer RF pulse durations with better beam quality. The MaRIE photoinjector is a highly relevant example of this enhancement process. Finally, injector designs have been tailored to support specific beam manipulation techniques downstream from the injector, such as flat-beam transforms, which may prove critical to the feasibility of future accelerators for physics and light-source use.

In the recent past there has also been increasing emphasis on photocathode development (see above), with typical goals being higher quantum efficiency, improved lifetime, and lower thermal emittance. While this research is important, any cathode must be evaluated in the larger context of a complete injector system. In particular, the cathode properties will both influence and be influenced by the local vacuum and field conditions within a photoinjector; and the detailed cavity geometry and beam transport scheme of the injector have a profound influence upon the ultimately achievable beam quality.

There is a general, and growing, need for available facilities to test these new electron beam sources, especially in light of the reliance placed upon them for major accelerator projects to meet their design goals. The quality of an electron beam is never higher than immediately following the injector, so thoroughly characterizing the performance of new beam sources is critical to the success of the larger accelerators designed to operate with them. Understanding the interaction of the cathode with the rest of the injector is a key to developing injector systems capable of meeting not only beam quality goals, but also other performance metrics such as cathode lifetime and dark current. Effective study of these interactions requires running the beam source under its intended operating conditions and would be enabled by a facility such as the EBTF, capable of supporting electron beam source development and testing. **Customers:** US Navy/Army/Air Force, DOD, DHS, NNSA

2.7 Radiation source development

LANL has world-leading expertise in novel radiation generating technologies, and a unique cross section between those technologies and national security mission need. The main classes of radiation source studies that can be supported by the EBTF include (1) free-electron laser (FEL) based; (2) inverse Compton scattering (ICS) based; and (3) electron beam-structure based. Importantly, many other topics described in this document (e.g., in sections 2.5 Advanced RF structures and 2.9 Beam physics) have direct impact on these science and programmatic opportunities.

Two of the largest recent AOT technology development thrusts have been for a MW-class FEL weapon and for the MaRIE XFEL. These, and other FEL opportunities, would be significantly supported by an FEL test area for exploring electron beam technologies that impact FEL performance and for directly performing FEL technology demonstrations. Having this latter capability would likely require the EBTF to have a final energy range of 100 to 200 MeV. Three specific examples of novel FEL activities could include using a masked photoinjector and an emittance exchanger to seed short-wavelength FELs, an initial demonstration of the distributed seeding proposed for the MaRIE XFEL, and developing an RF undulator for an ultra-compact short wavelength FEL. Having a test bed for novel high-current RF structures for beam dynamics experiments and HOM measurements would keep LANL in the national leadership role as the MW FEL program ramps back up. Demonstrating advanced accelerator schemes that lead to practical compact accelerators would enable novel national security missions requiring compact radiation sources.

MeV gamma-ray generation from ICS is a best-in-class tool for special nuclear materials detection using nuclear resonance fluorescence. For this application, minimizing the on-axis spectral bandwidth of the radiation source while maintaining high flux is essential. LANL researchers have suggested a novel ICS/FEL hybrid approach to do this, where first the electron beam generates UV radiation through the FEL interaction and then that UV radiation is scattered off subsequent electron bunches for gamma-ray generation. With the unique parameters of the MaRIE XFEL photoinjector, the EBTF has the needed electron beam performance for demonstrating this concept.

Electron beam-structure interaction schemes can be used both as a noninvasive electron beam diagnostic and as an independent source of radiation. Examples include Smith-Purcell radiation, coherent transition radiation, and coherent diffraction radiation (It is worth noting that ICS can also be used as a noninvasive electron beam diagnostic.). Noninvasive diagnostics are general enough and of enough importance that they became one of the two priorities in the Laboratory's FY16 LDRD Strategic Investment Plan.

2.8 Isotope production concepts and testing

Several concepts for producing radioisotopes through photonuclear transmutation with electron accelerators have been proposed or are in development. Common to all of these are the need to develop and test targets able to handle high beam currents and high power densities. Other important considerations include the development of beam windows to separate the coolant and target from the beam vacuum, and beam diagnostics to monitor and steer the high-power beam throughout target irradiation. Also important is the development of target handling techniques and processes for the effective production and recovery of medial radioisotopes. An EBTF would greatly facilitate LANL's contribution to this field.

Researchers from LANL are currently supporting an NNSA project for producing the medical radioisotope Mo-99 without the use of highly enriched uranium. One of the processes LANL supports is the production of Mo-99 from the photonuclear transmutation of an enriched Mo-100 target. LANL is responsible for the high-power target design, inert gas target cooling system, target production and thermal modeling, beam optics and steering for the production system, and beam diagnostics. The beam diagnostics we are developing include an optical transition radiation technique to monitor the beam profile and position on the target window during production, beam-current monitors, capacitive beam-position monitors, and infrared camera systems to monitor beam heating of the front window.

Lacking a high-power electron beam at LANL, however, we are forced to conduct all of our accelerator experiments and demonstrations at a very old electron accelerator facility at ANL. This results in large travel costs and short time windows for development work. Radiation damage to the diagnostics is also becoming an increasingly difficult problem to solve, which is made even more difficult by the limited access to the accelerator at ANL for extensive testing. Ready access to a high-power electron accelerator at LANL for continuous testing and development, would significantly improve effectiveness in supporting NNSA and the commercial partner on this project.

Other medical isotopes which can be produced with an electron accelerator include Pd-103, Cu-64, Cu-67, Ga-67, Ac-225, and In-111, to name a few. Many of these techniques start with enriched target material, which is very expensive. The goal for cost-effective radioisotope production is therefore to minimize the target mass, which increases the power density deposited in the target and requires extensive development in the target cooling design. LANL has a long history of high-power accelerator target development and medical isotope production expertise. If we could couple this capability with testing and demonstration using an EBTF at LANL, we could significantly aid the development of these medical isotope production techniques. **Customers:** NNSA NA-21 Global Threat Reduction Initiative (GTRI), Commercial sponsors (SHINE, B&W, AMIC, Lantheus, Covidien, etc.).

2.9 Beam physics

Beam physics covers a broad range of topics, effects and techniques. Several of the most important from the standpoints of practical applications and fundamental understanding and control of electron beam propagation and evolution are highlighted below.

Emittance Exchange

Demonstration of a technique called "emittance exchange" has been proposed for some time. Beam emittance is a measure of the phase space area of a beam and is a canonically conserved quantity; however, in practice there are many mechanisms which can act to inflate the "usable" emittance of an electron beam, degrading the beam quality. There is an ongoing effort to not only understand and mitigate these effects, but also to find methods – such as emittance exchange – to "remap" the beam for improved characteristics. Several beam optics configurations have been proposed to exchange emittance between transverse and longitudinal beam phase spaces, for instance, in order to tailor the transverse properties (size and divergence) or energy and phase of a beam. To date, there has been only limited success with actual emittance exchange (EEX) systems. Recently, LANL has developed a significant basis for understanding and designing EEX systems with unique capabilities mostly applicable for the emittance reduction needs of MaRIE. However, EEX techniques can also be applied to a broad range of different accelerator needs, such as production of shaped electron bunches (needed for dielectric wakefield acceleration) or production of sub-ps bunch trains. Development of viable EEX configurations could be advanced using the EBTF, in addition to their use on the EBTF to provide desired electron bunch configurations for other experiments.

Beam Halo Formation and Emittance Degradation

A fundamental problem in accelerator physics is to understand the development of beam halo and emittance growth in high-brightness beams. Understanding and mitigating the mechanisms of beam-halo and emittance growth is of primary importance for operation of existing high-power accelerators (LANSCE at LANL or the Spallation Neutron Source at ORNL), for development of the next generation of high-power accelerators for basic scientific research (Project X, the Neutrino Factory, ESS), Accelerator-Driven Systems applications (Transmutation of Waste, Accelerator Production of Tritium, Nuclear Reactor-driver), and national security applications such as the MaRIE X-ray Free-Electron Laser (XFEL), all of which are $1B-class facilities. These mechanisms contribute to activation and materials damage that limit the lifetime and maintainability of these accelerators. Experiments performed at the EBTF can be used to further understand the physics mechanisms of halo and emittance growth, as well as to test out new techniques aimed at enabling significantly higher beam power accelerators through radical reduction of beam losses.

Nonlinear Beam Optics

Traditional linear accelerator designs utilize linear focusing elements (quadrupoles, solenoids) to provide stable particle motion. High-intensity, non-uniform beams are intrinsically mismatched with such structures, which can result in beam emittance growth and halo formation. In order to prevent halo formation and emittance growth, simple and practical (and relatively low cost) solutions that propose implementing a periodic structure of focusing–defocusing lenses (FODO lattice) with combined quadrupole and higher-order magnetic field components (duodecapole, octupole) can be used to improve beam matching and confinement of the beam distribution. In a proposed experiment that could be performed at the EBTF, the quadrupole field is kept constant along the structure while the duodecapole component gradually decreases from the nominal value to zero over a certain distance. This allows matching an initially, non-uniform beam with the non-linear focusing channel and adiabatically transforms it to a beam well matched with a quadrupole focusing structure [11]. Simulations performed for typical beam parameters show that the emittance growth could be reduced by a factor of 2, and population of the halo decreased by a factor of 3. **Customers:** DOE Office of Science, NNSA, LDRD

2.10 Non-invasive beam diagnostics development

LANL is the centralized location for nuclear materials research, including stockpile stewardship and detection capabilities. As such, LANL leverages its expertise in high-brightness beams, kilo-ampere currents, and proton and electron sources for a number of national security missions, such as megawatt laser generation, Mo-99 production, and numerous Global Security applications. Investments in LANSCE and DARHT have high reliability due to beam diagnostics that ensure beam quality for user experiments. The Laboratory is pursuing future accelerator facilities (MaRIE and others) which depend on beam brightness 1000-times higher than current facilities. These require non-invasive diagnostic technologies that can verify phase-space quality, ensuring similar reliability as existing facilities in new parameter spaces.

Accelerator R&D has advanced the beam brightness frontier, but ensuring a reliable facility for user applications creates a problem. The beam must be monitored to verify its performance, but conventional diagnostics either probe the beam invasively (for accurate measurements), or cannot scale to the ultra-high brightness at which these facilities will operate. As an example, a conventional beam-position monitor utilizes electric-field differences to determine the beam centroid. This common detector has a typical resolution of 100 microns, which is adequate for a 2-mm-diameter beam (typical for LANSCE and DARHT). However, MaRIE requirements include provisions for a 10-micron target; the same diagnostic is unsuitable.

A number of new beam-diagnostic technologies have been emerging, such as Smith-Purcell (SP), Coherent Edge Radiation (CER), Coherent Diffraction Radiation (CDR), and Inverse-Compton Scattering (ICS). Despite involving different physics, they share a critical component: the "signal" generated from each is a convolution of the six-dimensional phase-space of the beam, including higher-order moments. The deconvolution process requires complicated mathematical processing, a technical challenge that has not yet been fully solved. The more general process of deconvolution has yet to be achieved, especially for future beam parameter spaces.

Los Alamos has unique expertise in cross-cutting capabilities beyond other institutions. Los Alamos pioneered several techniques, including OTR, for high-brightness beams. The Lab possesses the leading experts in Smith-Purcell and coherent imaging techniques. Ongoing cathode studies and the Navy FEL program have provided the highest bunch densities and average-current beams in the world. The applied numerical and modeling capabilities at LANL are essential to solving the multi-dimensional diagnostics problem. Concepts and prototypical designs of these new beam diagnostic technologies could readily be tested at the EBTF. **Customers:** DOE Office of Science, NNSA/MaRIE, LDRD, US Navy/Army/Air Force, DOD, DHS

2.11 New controls concepts

The EBTF is an outstanding platform to test advanced beam controls concepts. These include new computational paradigms such as Quasi-Real-Time GPU-based simulation that promises to significantly speed up computation and control, and model-independent and adaptive control (MIAC) concepts.

MIAC approaches have the potential to extend currently achievable error bounds on desired beam properties to the precision demanded by future accelerators as well as improving the operation of existing accelerators because they are model-independent and therefore able to adapt to and track analytically unknown changes of the actual device with which they are interacting, instead of relying on initial estimates. These approaches have been studied [12] and implemented in hardware on the LANSCE proton accelerator [13]. The EBTF is an ideal platform for continued study of model-independent controls of complex systems that cannot be perfectly modeled and that have multiple components with continuously time-varying properties.

Quasi-Real Time GPU-based simulation could be used at the EBTF to develop new methods to diagnose beam properties and component performance as it would give us a very fast and accurate virtual view of the machine. By combining GPU-based simulation with beam measurements and MIAC, it is possible to adaptively tune a complex system such as an accelerator while taking into account both unknown machine variations and estimates of beam characteristics in physically inaccessible parts of the machine. Because the ETBF Test Facility is relatively small, in comparison to LANSCE for example, setting up, testing and implementing prototype global, adaptive control systems can be accomplished in a timely manner with minimal costs. **Customers:** DOE Office of Science, NNSA, LDRD

2.12 Enabling technical infrastructure

Another important aspect of the EBTF is to build and maintain the basic beam-science infrastructure within LANL by allowing hands-on testing and development of key technologies and training of technical staff. This supports the education and enhancement of the workforce today and into the future. The skills and technology developed today on the EBTF can be applied tomorrow in support of important projects such as MaRIE and new LANSCE enhancements. The AFEL-based EBTF and its reliable electron beam source is key to re-establishing other latent applied-electrodynamics and beam-science capabilities including RF testing, and on-going cathode-development and advanced-structures R&D being conducted in Building 14 supported by LDRD. The EBTF is a bridge to the future for beam science at LANL.

3.0 Performance Goals

The performance objectives of the EBTF can be summarized in terms of beam performance parameters. Table 1 below summarizes the beam parameter range to be reached. These results are directly based on AFEL specifications and supporting simulations [5]. To establish a baseline concept, the AFEL photoinjector is assumed, but other options may also be considered. For example, for effective development of radioisotope production and high-power target testing, the macropulse rate would need to be 10-100 times higher allowing ~ 150 kW average beam power. Higher final electron beam energies through upgrades to the accelerator section may also be considered.

Table 1 - Expected performance of the EBTF.

Parameter	Performance
Charge per Micropulse	Up to 5 nC
Laser Diameter on Cathode	Up to 1cm
Laser Pulse Length FWHM – uniform distribution	Up to 15 ps
Shape of the Micropulse	Single Gaussian to 4-stacked Gaussian
Micropulse Length	Physics design dependent
Peak Micropulse Current	310 A
Micropulse Frequency	108 MHz to 1300 MHz
Average Macropulse Current	Up to 0.50 A
Output Energy	13-20 MeV
Macropulse Length	Up to 15 μs
Macropulse Rate	Up to 10 Hz
Macropulse Beam Power	Up to 10 MW
Instantaneous Energy Spread	<0.1%
Cathode Thermal Energy	Cathode dependent
Instantaneous Emittance	<1 π-mm-mrad
Micropulse Energy Spread	<0.3%
RMS Micropulse Projected Emittance	1.5 π-mm-mrad @ 1 nC 0.15 π-mm-mrad @ 0.15 nC
Duty Factor	10^{-4}-10^{-3}

4.0 Accelerator Layout

4.1 Overview

The EBTF must fulfill several main purposes. It must provide a reliable source of high-quality, nearly-relativistic electrons of sufficient bunch charge and average current to be useful for a broad range of experiments. As an electron source, it will be used as a platform to develop and test different components and systems, to develop new methods of beam optimization and accelerator control, and to benchmark performance predicted by simulation codes. The EBTF must also provide the capability to easily reconfigure the injector and beam line to accommodate a variety of experiments and be sufficiently instrumented to be able to measure and diagnose the relevant beam properties.

The baseline option for EBTF builds on the Advanced Free-Electron Laser (AFEL) project accelerator and facility infrastructure [6] available in Building 14 at TA-53. Figure 1 shows a schematic layout of the AFEL beam line as presently configured in Building 14. The present infrastructure includes the AFEL photoinjector and accelerator, an optical laser room, a control room, adequate shielding for 20-MeV operation, electrical power, and cooling water, although some upgrades to these systems may be required to meet present codes. The AFEL has not been operated in over a decade. As a result, some system components may require upgrade or replacement to be returned to service. Additionally, the beam line will be reconfigured to support specific experiments for the EBTF.

In its present configuration, the AFEL consists of a 20-MeV, 50-µs average pulse, 1.3-GHz, RF-driven electron linac with a photocathode injector. The electron beam is directed by permanent magnet dipoles and focused by permanent-magnet quadrupoles to a beam spot size of 0.25-mm diameter at the entrance to the 30-cm-long wiggler. Since the EBTF will not require operation as an FEL, the wiggler will be removed to allow space for other beam experiments. Electron-beam diagnostic devices consist of current and position monitors, a spectrometer, and several optical-transition-radiation (OTR) emittance monitors. Presently all electron beam optics are mounted on a 4-m optical table. Propagation of the beam ends in a water-cooled beam dump mounted in the floor. The accelerator and beam optics is fully enclosed in a shielded vault designed to provide a high level of radiation protection during beam operations. No modifications to the shielding vault would be needed for operation of the EBTF in this location and the planned operations would be tailored to meet safety-basis and ALARA requirements.

It should be noted that the AFEL is a small-scale facility (see dimension in Fig. 1) requiring only an approximate 4m x 8.5m footprint. Figure 2 shows a plan view of the AFEL facility within Building 14. Optimum RF system operation and control mandates a short waveguide run. Because the klystron and RF system were preexisting, the vault was placed in the northeast corner of the building, as also shown in Fig. 2. The waveguide run is 25 feet, allowing excellent control of the RF system.

Previously, the cesium-potassium-antimony (CsK_2Sb) photocathodes were prepared in the staging area and transported to the vault in an evacuated chamber and then loaded into the insertion chamber. A similar process is expected for operation of the photoinjector and linac for the EBTF, although several new types of cathodes may be used. When needed for operation, the pre-prepared cathodes will be inserted into the low-energy end of the linac.

The laser room is located adjacent to the vault to minimize the optical path length required. In the present configuration, the drive-laser beam exits the laser room and passes through the concrete shield wall into the vault and into the photoinjector.

Situated on the west side of the vault and laser room is the control room. This central location allows easy access to the linac and optical system in the vault, quick coordination with the drive-laser, and interaction with the RF system when needed. The control room will contain the computer control system, data acquisition system, and most other electronics needed for operation of the EBTF.

4.2 Electron source/high-brightness accelerator

The initial accelerating structure is a copper, on-axis-coupled structure operating at 1.3 GHz. It is 1.2 m in length and consists of one half-cell followed by 10 full accelerating cells, all operating in the $\pi/2$ mode. The structure was designed to accelerate a high brightness beam to 20 MeV [7]. Figure 3 shows a cutaway view of the AFEL linac structure. We anticipate hosting the MaRIE photoinjector prototype in the EBTF; future upgrades could include both an upgraded electron gun and new accelerator structures.

The focusing solenoid provides compensation of space-charge induced emittance growth and is adjusted to give a zero magnetic field at the surface of the cathode. RF power is fed into the structure through a single waveguide and coupled to each of the accelerating cells through symmetric on-axis coupling slots. The cell-to-cell coupling configuration and accelerating gradients have been tailored to minimize effects such as multipactoring and regenerative beam breakup that would spoil the quality of the high-brightness beam. More details of the accelerator design can be found in Ref. 1 and Ref. 7.

4.3 RF systems

The RF system uses a single, 1.3-GHz, Litton Model L-3702 klystron and is designed to deliver up to 30 MW peak RF power, 30- µs pulse width and up to 100 Hz repetition rate. Average RF output power is approximately 50 kW. The system provides excellent phase and amplitude stability (±0.05 degrees, ±0.05%, respectively) needed to drive an FEL. The modulator is a thyratron-switched, line-type design which uses five large switching power supplies in parallel to charge a pulse forming network. The output of the klystron feeds a pressurized WR650 waveguide which includes optical arc detection on both vacuum windows, directional couplers, and a 4-port ferrite circulator to minimize reflected power to the klystron. The RF system is designed to be operated remotely from the control room. In its present configuration, the system uses a programmable-logic controller which communicates to a workstation running control software. A special-design timing and interlock chassis performs real-time fault protection and timing of the system. The low-level RF (LLRF) system includes a high-stability, 1.3-GHz master oscillator, a feedback system, and an 8-kW drive amplifier. More details of the RF system can be found in Ref. 8.

Although most of the RF system components are operable, the full system will need to be tested and may need to be upgraded to be fully functional. Known subsystems that will need to be upgraded include the LLRF system and safety interlocks.

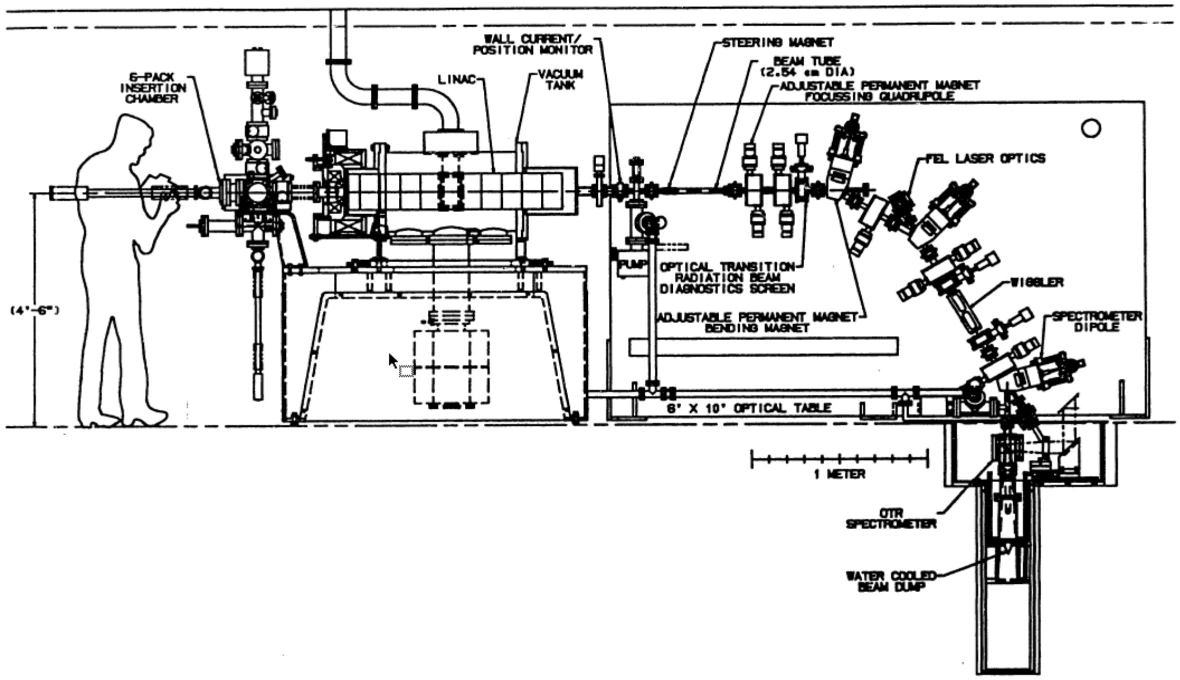

Figure 1 – Schematic layout of the AFEL beam line as configured in Building 14.

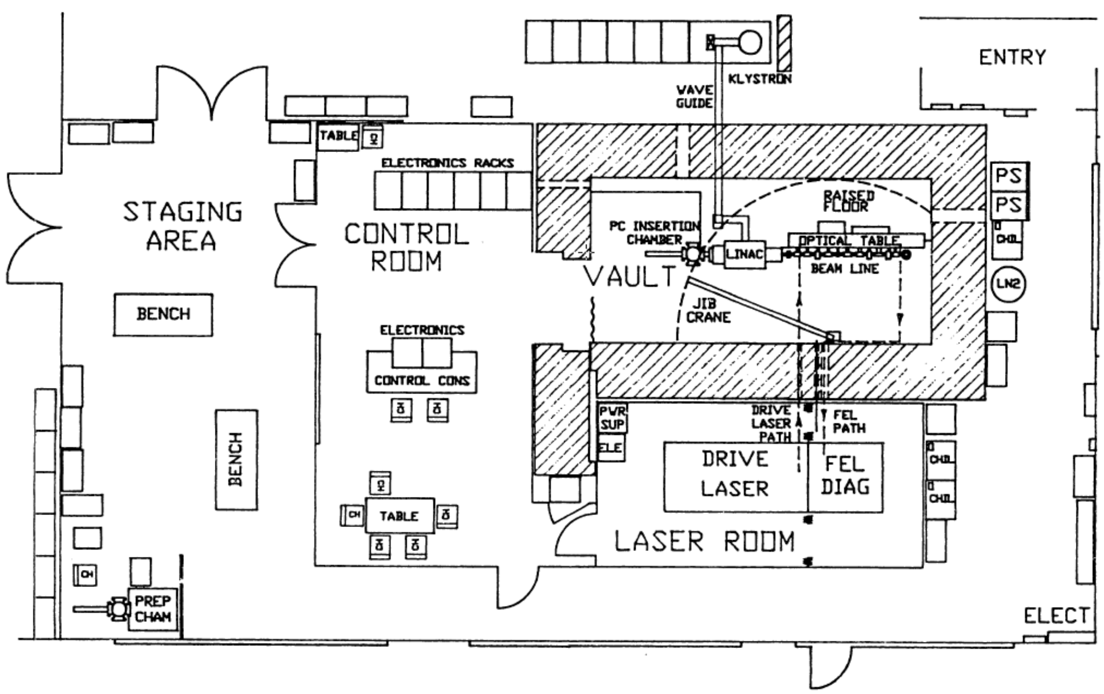

Figure 2 – Floor plan of the AFEL Facility in Building 14.

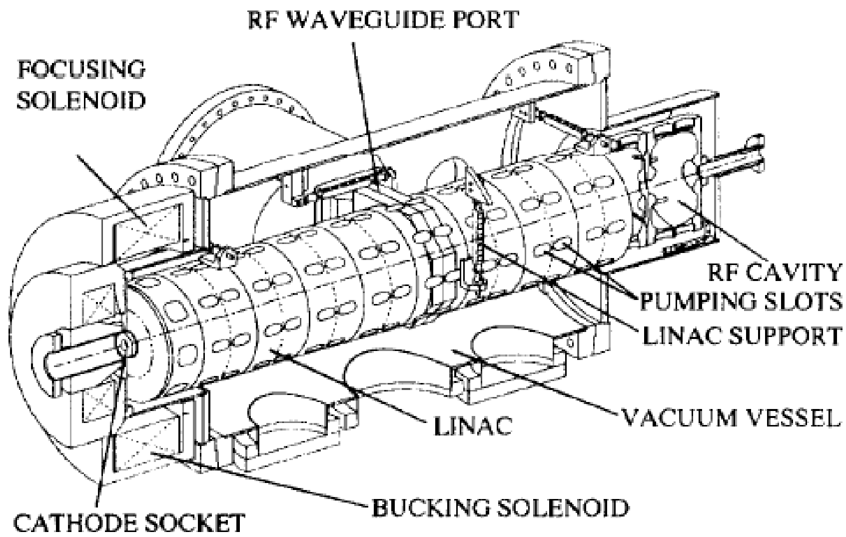

Figure 3 – Schematic cutaway view of the AFEL linac [7]. The focusing solenoid provides compensation of space-charge induced emittance growth. The linac is an eleven cell π/2-mode structure.

4.4 Diagnostics

Beam diagnostics available include current monitors, beam-position monitors, and multiple optical transition radiation (OTR) screens in the beam line. The final OTR diagnostic is integrated into the spectrometer at the end of the beam line. Interfaces of the diagnostics to a modern data acquisition and analysis system will be required.

4.5 Optical drive-laser system

The original drive laser for the photoinjector consisted of a cw mode-locked Nd:YLF oscillator operating at 1053 nm and a pulse repetition rate of 108.333 MHz, the 12th subharmonic of the 1.3-GHz RF. The nominal 60-ps oscillator output pulses were compressed and frequency-doubled to produce the final 7-ps, 10-µJ output pulse. The photoinjector drive laser phase and amplitude were stabilized and synchronized with a low-jitter master oscillator to obtain optimum photoinjector performance.

The original drive laser has been decommissioned and removed from the laser room. A new, modern drive-laser system will be required that can meet similar performance specifications to operate the AFEL linac in support of the EBTF.

5.0 Controls and Data Acquisition

A state-of-the-art controls and data acquisition system will be installed leveraging present technology used at LANSCE and will be based on the VME/cRIO standard. Also assumed is that other major system interfaces will be upgraded to support interfacing to the controls and data-acquisition system. Requirements for the system and interfaces still need to be defined.

6.0 Radiation Safety and Protective Systems

Radiation safety will be provided primarily by passive shielding and controlled access into the radiation area. The accelerator vault includes an interlocked Personnel Access System (PACS) that stops beam production when the interlocks are tripped. The system will be upgraded to meet current LANSCE PACS standards. Conduct of Operations procedures will also be drafted to provide administrative guidelines for safe operations of the EBTF.

7.0 Commissioning and Operation Plan

An initial review of safety reports, shielding requirements, and readiness review documents indicates the facility operations should meet current operating requirements. However, a new safety assessment document (SAD) may be required and formal startup of the facility will be required under the new DOE Accelerator Safety Order [9]. A detailed commissioning plan will be developed in parallel with the refurbishment activities. An AFEL operations manual/operations plan will also be developed.

Commissioning and initial operation of the EBTF is expected to be carried out by the MaRIE Photoinjector Team. This set of experiments is expected to have the highest priority and will help to establish the operations protocol for the EBTF that will be used later for future programmatic or user experiments.

8.0 Costs

A cost estimate to restart AFEL operations in Building 14 in its present configuration was completed in FY14 [10]. The costs summarized below are based on that estimate after some cost scrubbing and using FY15 labor rates. All M&S costs have been escalated 3% per year. All costs are quoted in unburdened, FY15 $. Additional implementation and cost options are based on this estimate but with modifications required to capture additional costs such as relocating the AFEL, etc. and credits for existing infrastructure that in some cases reduces costs.

The baseline cost assumptions (AFEL in its present location) include:

- All AFEL photoinjector, accelerator, and beam line components under vacuum are in working condition.
- No modifications to the AFEL shielding vault are needed.
- Only minor shielding calculations are needed to support safety basis and operating envelope reviews and approvals.
- Minimal facilities power, water, and HVAC repairs are needed.
- 1.0-1.5 years to refurbish the AFEL and to begin operations.

Option 1 – EBTF/AFEL in present location

This option assumes restarting the AFEL in its present location in Building 14. Costs include restarting or upgrading systems as specified in the FY14 cost estimate [10]. Commissioning and annual operating costs are not included. Table 2 below summarizes the costs to restart the AFEL in Building 14.

Option 2 – EBTF/AFEL moved to SPA Location

Moving the AFEL to the SPA location in Building 14 enables a broader suite of experiments beyond supporting the MaRIE XFEL development. However, additional costs include D&D of the existing SPA equipment, some lead cleanup, additional supporting radiation safety calculations, possible additional shielding required, and some system upgrades. Commissioning and annual operating costs are not included.

It is assumed that the repair and refurbishment costs of existing facilities systems used to operate the SPA will be equivalent to those of restarting the AFEL in its present location. Use of existing SPA beam line magnets and spectrometer is also assumed although some budget is allowed for magnet assembly and testing, and steering power supplies. Table 3 below summarizes total estimated costs for moving and restarting the AFEL in the SPA location.

Option 3 – EBTF/AFEL moved to LEDA

Moving the AFEL to the LEDA location in Building 365 is the likely preferred option. This option enables a broader suite of experiments including MaRIE XFEL development. Use of the LEDA tunnel in Building 365 is the preferred location because it provides adequate shielding and infrastructure for the AFEL operating at 20-MeV as well as any envisioned upgrades to higher energy or to do MaRIE cryomodule testing and RF staging, and significant space for a variety of beam line configurations and experiments. This location is supports all needed facility infrastructure, requiring only minimal facility upgrades. The potential location of the AFEL in the LEDA tunnel is shown in Fig. 4. The AFEL would replace the NCRF injector and use the existing beam line as the basis for beam transport and new experiments.

Costs associated with the required drive laser system to do photoinjector testing are reduced under the assumption that the existing laser system previously used by the Navy MW-FEL program is available. Credit is also taken for the working LEDA tunnel Personnel Access System (PACS). Additional costs have been added for relocation of the 1.3-GHz RF system from Building 14 and for engineering design labor associated with redesign of the RF waveguide. It is assumed that the repair and refurbishment costs of existing facilities systems used to operate the AFEL in Building 365 will be equivalent to those of restarting the AFEL in its present location. Use of existing beam line magnets and spectrometer from the MW-FEL program is also assumed although some budget is allowed for magnet assembly and testing, and steering power supplies. Table 4 below summarizes total estimated costs for moving and restarting the AFEL in the LEDA tunnel in Building 365.

Summary

Mission need for the EBTF exists today. This mission need is centered on a set of experiments that could be performed now at the ETBF if such a facility were made available, ranging from technology maturation for the MaRIE x-ray free-electron laser, state-of-the-art proof of principle accelerator and beam physics experiments, experiments and R&D that augment existing programs, and new experiments and R&D needed to develop new programs.

The costs to implement any of the three proposed EBTF options are nearly identical to within the errors of the estimates. However, Option 3, implementation of the EBTF in the LEDA tunnel in Building 365, will best meet all anticipated needs, including room to expand and the infrastructure to support a broad base of users. Only Option 3 supports higher beam energies and beam powers beyond the current performance specifications of the baseline AFEL.

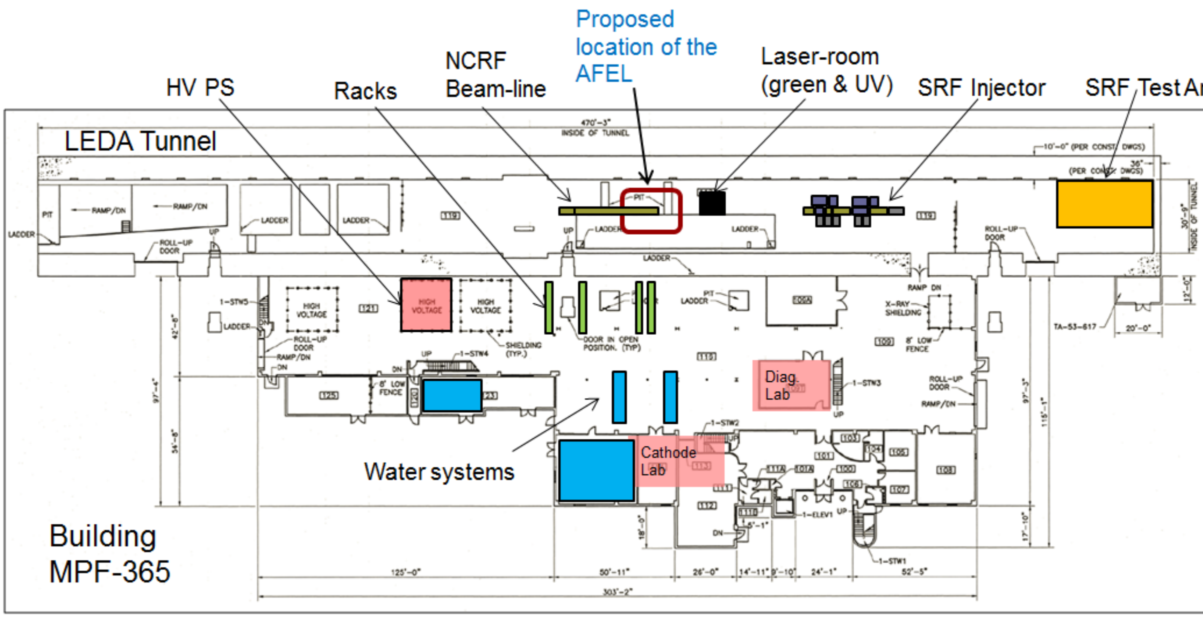

Figure 4 – Schematic cutaway view of the AFEL linac [7]. The focusing solenoid provides compensation of space-charge induced emittance growth. The linac is an eleven cell π/2-mode structure.

Table 2 - AFEL restart costs for present location in Building 14.

Scope	Labor Cost	M&S Cost
Project Lead	$108.0K	
Laser System	$161.8K	$30K
Beam Line Layout	$48.5K	
Beam Line Alignment	$17.7K	$9.3K
AFEL Water System	$51.0K	$26.7K
Facility Water Upgrades	$15.1K	$30.0K
Facility Electrical Upgrades	$15.1K	$30.0K
Facility HVAC Upgrades	$15.1K	$30.0K
Vacuum Systems	$83.9K	$38.3K
PACS System	$24.1K	$10.3K
Magnets & Magnet Power Supplies	$22.0K	$141.1K
Cathodes	$30.2K	$10.3K
Safety Basis Analysis	$66.6K	
RF Systems	$359.5K	$334.8K
Control & Data Acquisition System	$453.6K	$290.5K
Safety and Readiness Reviews	$55.3K	
Total =	$1,527.4K	$981.1K
Grand Total =	$2,508.5K ($3,135.6K with 25% contingency)	

Table 3 - AFEL restart costs for SPA location in Building 14.

Scope	Labor Cost	M&S Cost
Project Lead	$108.0K	
Laser System	$161.8K	$30K
Beam Line Layout	$48.5K	
Beam Line Alignment	$17.7K	$9.3K
AFEL Water System	$51.0K	$26.7K
Facility Water Upgrades	$15.1K	$30.0K
Facility Electrical Upgrades	$15.1K	$30.0K
Facility HVAC Upgrades	$15.1K	$30.0K
Vacuum Systems	$83.9K	$38.3K
PACS System	$24.1K	$10.3K
Magnets & Magnet Power Supplies (assumes reuse of SPA beam line magnets)	$22.0K	$45.5K
Cathodes	$30.2K	$10.3K
Safety Basis Analysis	$66.6K	
RF Systems (includes RF modifications for move to SPA)	$520.4K	$334.8K
Control & Data Acquisition System	$453.6K	$290.5K
Safety and Readiness Reviews (includes additional shielding calculations)	$60.3K	
SPA D&D	$44.0K	$30.0K
Relocate AFEL to SPA location	$44.0K	$30.0K
Total =	$1,781.3K	$954.5K
Grand Total =	$2,726.8K ($3,408.5K with 25% contingency)	

Table 4 - AFEL restart costs for LEDA location in Building 365.

Scope	Labor Cost	M&S Cost
Project Lead	$108.0K	
Laser System (assumes using NFEL drive laser system)	$30.1K	$5K
Beam Line Layout	$48.5K	
Beam Line Alignment	$17.7K	$9.3K
AFEL Water System	$51.0K	$26.7K
Facility Water Upgrades	$15.1K	$30.0K
Facility Electrical Upgrades	$15.1K	$30.0K
Facility HVAC Upgrades	$15.1K	$30.0K
Vacuum Systems	$83.9K	$38.3K
PACS System (uses existing LEDA system)		
Magnets & Magnet Power Supplies	$22.0K	$36.1K
Cathodes	$30.2K	$10.3K
Safety Basis Analysis	$55.3K	
RF Systems (includes labor to relocate RF to MPF-365)	$547.4K	$334.8K
Control & Data Acquisition System	$453.6K	$290.5K
Safety and Readiness Reviews	$55.3K	
NFEL D&D	$44.0K	
Relocate AFEL to MPF-365	$44.0K	$30K
Total =	$1,725.9K	$950K
Grand Total =	$2,675.9K ($3,344.9K with 25% contingency)	

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