

An Injector Test Facility for the LCLS

EXECUTIVE SUMMARY

Survey advanced gun concepts and their potential impact on LCLS performance. The short time horizon (5 years) for prototyping then producing the first upgrade gun for LCLS necessarily means efforts must be directed at the most mature, compatible technology: rf guns. Longer term, different gun working frequencies, the inclusion of 3rd harmonic field shaping, and long guns (“integrated photoinjectors”) should be tested. In the next decade, technologies such as plasma-based or DC pseudospark sources will mature sufficiently that their value can be assessed, and pursued if warranted.

List the requirements that the test facility must satisfy to fulfill its goals. The test facility must provide beam acceleration, manipulation, and measurement capabilities for demonstrating fully equilibrated electron beams—that is, to demonstrate beam properties under circumstances identical to those required of the LCLS injector. The facility must also provide world-leading facilities for material science, with analytical tools specifically honed for photoemission studies, and a dedicated laser R&D laboratory not constrained by the requirement to support a running accelerator.

Describe a facility that can meet these requirements. A 150 MeV test injector, with cleanroom facilities for laser and cathode development, is required to provide the foundation for a test facility capable of addressing these goals. Significantly enhanced material science laboratories at SLAC SMS will be needed to provide expanded analytical capabilities for cathode development. Collaboration with LBNL, UCLA, and ANL will provide access to world-class talent and facilities and result in coordination and synergy of source development efforts directed at the LCLS, ERLs, and Sparc.

List potential sites for the facility, including an evaluation of pros/cons. Nine SLAC sites were considered. Two stood out based on the availability and quality of existing infrastructure. The committee recommends End Station B as the best location for the ITF, given the very extensive infrastructure and potential for growth. The Klystron Test Lab ranks a close second, requiring more extensive alteration to accommodate the ITF, but offering close coupling to the unique skills and facilities of the Klystron Department. The SLD pit and End Station A rank third and fourth, with each offering open space and some infrastructure, but significantly less hospitable conditions than ESB or KTL.

Describe relevant facilities and programs at other labs. There is just one dedicated injector lab—Sparc at INFN/Rome—that is matched in accelerator capabilities to the ITF requirements. Numerous other gun test facilities exist which can test some aspects of the gun, but none is dedicated to short-pulse gun optimization and accelerates to high enough energy to provide a direct demonstration of the full injector performance. The ERL injector effort at LBNL shares many goals with LCLS, and collaborating on cathodes, simulations, instruments, and rf design techniques provides great synergy. The gun-development efforts at UCLA and ANL similarly have significant strategic overlap, and offer facilities for gun-only testing.

Make a cost estimate with detail appropriate to the very preliminary nature of the conceptual design. Preliminary cost estimates for constructing the ITF depend on the site chosen and range from \$15.5M (ESB) to \$21.1M (SLD). Operating the facility is estimated to require approximately 16-17 FTE, \$0.7M/year in M&S, and \$0.6M/year in capital equipment funds.

Briefly assess other potential applications of the facility in support of accelerator science/technology research. The ITF will provide a unique facility suitable not only for its primary mission of advanced injector R&D, but beams of exceptional brightness that will also enable a host of electron and radiation experiments. The capability to test a variety of rf gun technologies can directly benefit ILC source development efforts. User-driven experiments in beam manipulation and radiation generation will help provide a rich environment of exciting science. Provided the essential goal of driving LCLS source development forward is not compromised, user-driven experiments that leverage portions of the infrastructure should not only be allowed, but encouraged.

Introduction

SLAC is in the privileged position of being the site for the world's first 4th generation light source as well as having a premier accelerator research staff and facilities. Operation of the world's first x-ray free electron laser (FEL) facility will require innovations in electron injectors to provide electron beams of unprecedented quality. Upgrades to provide ever shorter wavelength x-ray beams of increasing intensity will require significant advances in the state-of-the-art. The BESAC 20-Year Facilities Roadmap identifies the electron gun as "the critical enabling technology to advance linac-based light sources" and recognizes that the sources for next-generation light sources are "the highest-leveraged technology", and that "BES should strongly support and coordinate research and development in this unique and critical technology." [1]

This white paper presents an R&D plan and a description of a facility for developing the knowledge and technology required to successfully achieve these upgrades, and to coordinate efforts on short-pulse source development for linac-based light sources.

Motivation

The advancement of FEL-based light sources has been made possible in large part by the development of brighter electron sources. Beam brightness impacts light source quality both through improved coherence of the emitted radiation and decreased distance to saturation in the FEL. The importance of low emittance can be seen through the mode overlap requirement:

$$\frac{\varepsilon_N}{\gamma} < \frac{\lambda_{FEL}}{4\pi} \propto \frac{\lambda_u}{\gamma^2}$$

Where ε_N is the normalized emittance, λ_{FEL} and λ_u are the radiation and undulator wavelengths, respectively, and γ is the reduced beam energy. Reducing the emittance by a factor of two and doubling the linac length each allow operation at a factor-of-two shorter wavelength, but at very different costs.

The approximate LCLS undulator cost per unit length is \$0.35M/m, making it one of the most costly components. Operating LCLS at 0.4 angstroms would require an undulator 300 meters long with a total cost of approximately \$100M to reach saturation. Reducing the emittance by a factor of three, would allow the current LCLS 100 meter undulator to saturate at 0.4 Å, providing new science opportunities, and vital design information for next-generation XFELs [1].

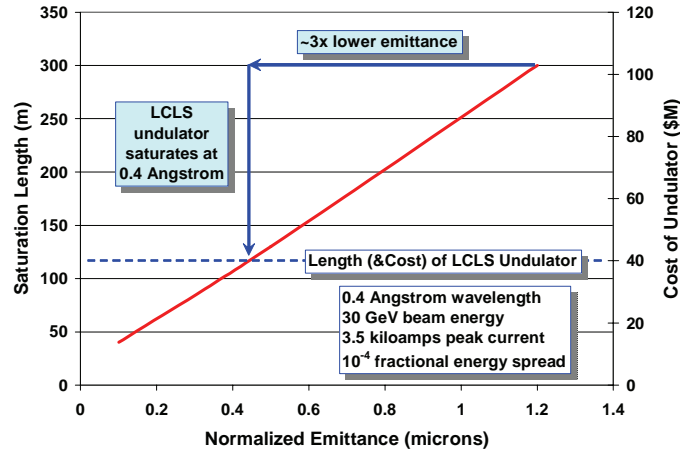


Figure 1: Lowering the current LCLS emittance a factor of three would allow LCLS to saturate at 0.4 angstroms. An undulator length of 300 meters, costing an additional \$60M, would be needed using the current LCLS-design emittance. (Calculations provided by Z. Huang, SLAC Beam Physics Dept.)

The Five Challenges

Research and development on high brightness electron sources over the last two decades has focused heavily on the rf photocathode gun. Understanding of the physics of emission, acceleration, and focusing has evolved significantly, as has the technology. Work to date has addressed most of the accessible issues impacting performance (e.g. cavity geometry, focusing configuration), and some progress has been made on the more difficult issues (cathode machining and chemical surface preparation). However, very significant challenges remain that require world-class effort in such diverse areas as laser technology, surface science, and nanofabrication to successfully solve. There are five major areas of challenge that must be addressed.

The first, and perhaps least understood, is the cathode. The cathode defines the initial electron beam distribution (through roughness, QE variation, and thermal emittance) and defines some of the key aspects of the laser system (pulse energy, wavelength). A wide variety of cathode materials and surface treatments have been investigated to date, but a cathode that efficiently makes low thermal emittance electron beams, is robust, and does not require a complex laser remains elusive.

The second challenge is the laser for the photocathode. Photoinjector performance consistently and significantly underperforms compared with design simulations. A primary reason is that the laser pulse intensity distribution is far from ideal. Significant laser development effort to approach the uniformly-filled cylinder has improved matters, but there is still room for improvement. In addition, more advanced laser pulses, such as “hollow” distributions to flatten transverse space charge forces, or the still more difficult uniformly-filled ellipsoid distribution, have not been attempted with real laser systems, but offer real promise for significant improvement in beam quality.

The third challenge is the gun itself. The initial environment that the photo emitted bunch experiences remains indelibly imprinted on the phase spaces. Techniques to flatten field profiles spatially and temporally by adding a third harmonic to the accelerating wave remain to be tested, and the latest improvements in achieving higher symmetry in the accelerating mode have yet to be fully implemented. Questions of how gun design must be altered to optimize cathode life (through more pumping or operating at a higher order mode) and permit robust load-lock operation for cathode exchange have yet to be answered.

The fourth challenge is post-acceleration beam conditioning. Beam conditioning is defined as those processes used to manipulate the transverse and/or longitudinal electron distributions or to match the beam's properties to a subsequent beamline system. An example of beam manipulation is emittance compensation where the linear space charge forces are balanced by external focusing forces. Beam conditioning is also used to match from one optical component to another, such as the transverse phase space optics for matching the beam to the undulator, or between the gun and the first accelerator. Certain type of beam conditioning must be performed after acceleration, such as chicane bunch compression, which uses non-isochronous optics to temporally compress the electron bunch.

The fifth and final challenge is accurate simulation of injector performance. High-fidelity modeling requires a fully three dimensional treatment of space charge, rf, and wakefields and is computationally very challenging. In addition, certain physics has yet to be correctly captured in the simulations, such as detailed modeling of the photoemission process that accounts for surface morphology and contamination. Simulations of beam diagnostics is also an essential step, both for understanding and expanding the limits of present diagnostic techniques, and for identifying measurement criteria that speed commissioning.

Technical Approach

These challenges are central to achieving the goals of LCLS, its upgrade to LCLS-II, and in performing R&D for the next-generation "Greenfield XFEL". Source emittance must improve a factor of two or more beyond present state-of-the-art for LCLS-II, and a factor of ten or more for the Greenfield XFEL. The difficulty of this challenge may be seen from the fact that literally dozens of photoinjectors have been built in the two decades since the invention of the rf gun[2], and yet just a factor-of-two improvement in emittance has been achieved.

Given this challenge, we divide the R&D approach into near-term and long-term tasks. The proposed Injector Test Facility (ITF), described in the subsequent sections, is designed to address the near-term objectives, while maintaining flexibility to expand the facility in the long-term.

Near-Term R&D

The initial configuration for the ITF is driven by the need to focus on electron source R&D. Technologies explored in this R&D effort should be traceable to those currently used for LCLS, in order to support upgrades like LCLS-2. Therefore the first configuration of the ITF will concentrate upon improving the RF-photocathode gun,

cathode drive laser and beam conditioning for an RF-based injector system. In this section, we describe the current status of injectors for 4th generation light sources and discuss the various options for near-term improvements in performance.

The last two decades of R&D effort on rf gun sources have yielded well-optimized designs for the electron gun and focusing geometries. The greatest improvements in beam quality can be obtained in the areas of the drive laser, photocathode, and beam conditioning. The drive laser is key to producing specially shaped electron bunches from the cathode which minimize the space-charge emittance growth. The photocathode is important in a practical sense, as one must mitigate non-ideal emission characteristics to obtain good beam performance, and in a fundamental sense, since it has an intrinsic emittance (often referred to as the thermal emittance) which is the lowest emittance achievable from the gun. Beam conditioning is relevant for manipulating beam correlations in order to control the projected emittance, increase the peak current and hence the peak brightness, and potentially to exchange the emittance from one plane to another.

The Drive Laser Requirements

The drive laser for the ITF should have the flexibility of delivering a variety of shaped pulses at IR, visible and UV wavelengths. The two extremes of pulse shapes needed are illustrated by the following proposals. The first is to use an ellipsoidal shaped laser pulse [3] to produce electron bunch with constant charge density. Simulations show the space charge forces are perfectly linear, resulting in a nearly ideal emittance compensated beam. The limiting beam emittance is now the cathode thermal emittance and the longitudinal phase space distribution (energy-time correlation) is more linear than that produced by the current LCLS cylindrical bunch shape. In this case the bunch current has a parabolic-like shape along the bunch rather than the relatively flat distribution of the cylindrical bunch.

The other extreme is to begin with a short (<400fs) laser pulse with a parabolic transverse shape[4]. In this case, the strong space charge forces drive a rapid longitudinal expansion of the bunch to the ideal ellipsoidal shape described above. It has recently been shown that the phase space errors introduced in the formation of the ellipsoidal bunch distribution in this manner may be mitigated by use of standard emittance compensation techniques[5]. An experiment by UCLA-INFN at the SPARC injector has recently begun to show promising results in operating a photoinjector in this regime, with first evidence for the ellipsoidal distribution observed.

These examples illustrate that precise shaping of the drive laser gives us the ability not only to control and minimize space charge forces, but to use them to our advantage in the production brighter beams.

Laser Development

The laser system will be designed to provide a reliable source of pulses to the photocathode while remaining flexible enough to study the impact of laser parameters on gun performance. Because initial studies will be carried out on a copper cathode RF guns,

the laser must operate in the UV at wavelengths below 270nm. The QE of copper photocathodes further implies mJ level energy in the UV. Much of the laser related R&D will explore the impact of spatial and temporal profiles on gun performance. Near term laser related R&D would focus on spectral phase and intensity control to shape the pulse in the time domain. This requires the laser to operate with enough bandwidth to support temporal features in the range of 100fs – 20ps. With today's technology, these wavelength and bandwidth requirements can only be met using a harmonically converted Ti:Sapphire laser system. This laser would be a commercially available system similar to the LCLS drive laser but would be configured in a more flexible manner. Having just purchased such a laser, we have a high degree of confidence that the cost will be approximately \$1000k. This type of broadband laser also allows investigation of wavelength tunability as well as multi-color pulse stacking techniques. These pulse stacking techniques could lead to a much simpler and more efficient drive laser in the case of time stationary spatial profiles and could provide the first experimental data with time varying spatial profiles.

The most challenging case of time varying intensity and spatial profiles are the ellipsoidal shapes proposed by C. Limborg-Deprey et al. While pulse stacking with Ti:Sapphire lasers can provide a crude approximation to the ellipsoidal shape, it is clear that generation of such pulses will require significant changes to conventional Ti:Sapphire technology or an entirely different type of laser. For example, a bundle of fiber lasers could be used to extend the pulse stacking technique to the number of pulses needed to generate smooth controllable profiles in both space and time. The challenge will then be to convert to the UV. The level of difficulty in conversion to the UV depends to a large extent on cathode advances that could lead to longer wavelength drive pulses. In any case, recent advances in integrated periodically-poled materials could mitigate this problem resulting in a very robust system with near continuous control of spatial and temporal profiles. The cost of such a system is much less certain (thus a higher contingency factor) but the cost of core components indicates that the cost of a prototype system capable of spatio-temporal control could be built for approximately \$1000k.

Diagnostics of a UV laser source with these characteristics is as challenging as producing them. Much of the laser related effort will be in the area of integrating techniques such as cross-correlation or FROG into the laser system so that we can not only control the temporal shape of the pulse but can monitor the shape and even provide automated feedback.

The Cathode

Given that the laser pulse can in principle be tailored to produce fully space charge compensated beams, the cathode (thermal) emittance becomes the limiting factor to increasing beam brightness. In addition, the quantum efficiency (QE), QE uniformity, and lifetime in the operational environment of the RF gun are important practical properties of the cathode. Therefore of the three R&D areas, cathode research is the most interdisciplinary and may require the most concentrated research. The working knowledge needed to advance cathode performance include the fields of surface and materials physics (cathode fabrication and preparation), solid state physics (electron

transport during photo-emission, quantum efficiency and thermal emittance), chemistry and vapor phase chemistry (fabrication of semi-conductor cathodes), beam dynamics (near-field image charge and current effects), vacuum technology (lifetime limit due to contamination) and laser-materials interaction (laser absorption, cleaning and damage).

The cathode R&D plan should study both metal and semi-conductor materials. However the most urgent need is for metal cathode research and how to quickly incorporate improvements into the current LCLS gun, as cathode quantum efficiency, uniformity, lifetime and thermal emittance are the greatest uncertainties for the LCLS. In this regard, some research effort has begun with the SLAC Surface and Materials Science (SMS) group, but more resources are needed. In particular the most serious limitation is the lack of a facility for performing in-situ experiments on an RF gun and a cathode load lock for the LCLS gun. The venerable GTF at SSRL is coming to an end after 10 years of operation at SSRL, and a new facility is needed soon.

With these immediate cathode needs in mind, we view near-term cathode R&D as a continuation of the present effort with SMS, in advance of the ITF. It's proposed that this effort can be done either on the LCLS Gun1 at Sector 20, or on LCLS Gun2 in the ASTA vault. The current approach assumes the R&D would be done in the ASTA vault which would be shared with the High-Gradient structures test program. The plan would be to install LCLS Gun2 at ASTA in January, 2007 and operate it with high power RF from TS1 which is currently being configured for this purpose. These studies would require a short pulse UV laser for measuring the cathode quantum efficiency with the gun operating with high power RF. Gun2 would be configured to test the following cathode processing techniques:

1. High temperature (230deg C) in-situ bake of the cathode using a hot gas flowing through the cathode water channels.
2. Plasma discharge cleaning using RF ignition of hydrogen gas.
3. Cathode cleaning using a hydrogen ion beam.
4. Laser cleaning.

A preliminary test of technique 3 was tried on the ARDB gun for the E163 experiment with an initial improvement in the QE, but later tests actually reduced the QE. Unfortunately testing could be done for only a few days due to the E163 schedule. Work on plasma discharge is being done at the GTF, but this is forced to end in August, 2006 due to both the lack of LCLS funding and the reduced viability of sharing the SPEAR injector vault with an experimental program. Therefore the task force proposes this cathode R&D be continued on Gun2 in the ASTA vault.

As mentioned above and described further below, the initial cathode R&D should concentrate on metal cathodes given their traceability to the current LCLS guns, and the greater potential for understanding emission in simple metals. The connection between QE and thermal emittance is fundamental to advancing our understanding of cathode performance. One approach to reducing the thermal emittance while maintaining good QE would involve the custom design of surface states of the metal to give the desired properties. For example, electron emission from metals at photon energies of a 4 to 5 eV are dominantly from s-wave valence states having a continuous energy spectrum.

Introducing a monolayer of Cs lowers the work function and allows excitations of narrow energy d-wave states which could reduce the thermal emittance.

Another approach would be to use structured materials to produce the desired properties. Recent advances in meta-materials having optical and electronic properties determined by their structure rather than chemistry is an attractive approach for advanced photocathodes. The intent is to begin these studies in collaboration with the LBNL group giving us access to the resources of the Molecular Foundry as well as instruments like the Photoemission Electron Microscope (PEEM). The effort can begin with PEEM measurements of electron emission from metal surfaces, prepared in the same manner as for cathodes used in the LCLS gun, to determine the angle-resolved electron spectrum near threshold. Previous work has only been done at higher photon energies. These studies will provide the thermal emittance properties of photoemission from a metal which can be compared in detail with theory and potentially used in electron beam simulations of the gun.

A second major effort should begin to design and build a load lock system for transporting cathodes between the SLAC cathode labs and LBNL as well as be capable of installing cathodes in the LCLS gun. All advanced cathodes will have to be maintained and handled in a UHV system.

Cathode Development

A copper metal photocathode was chosen for the initial LCLS configuration because of its robustness and simplicity. Because the source is not required to produce a bunch train (multiple microbunches within each pulse), the lower QE of metal cathodes compared to alkali and semiconductor photocathodes is not a major concern. The principal advantages of metal cathodes are that they are easy to fabricate and clean, and that the entire end plate of the half cell can be formed in the standard manner of Cu rf cavities thereby permitting operation at the highest field values. The photoelectric response time of metal cathodes is on the sub-picosecond level, therefore imposing no limitation on the desired temporal pulse shaping.

The QE for Cu illuminated with UV light at normal incidence depends on surface preparation, but a QE of 10^{-5} at 255 nm (the LCLS minimum) in a non-load-locked gun is achievable. In fact, recent laboratory measurements on *in vacuo* cleaning of Cu surfaces with hydrogen ions produced low-field QEs of better than 10^{-4} at 255 nm [6]. This technique non-destructively removes residual surface carbon, water, and oxides that reduce QE and is being investigated for LCLS.

Although a clean Cu cathode is sufficient for initial LCLS operation, it certainly is not the future. Beam quality and machine costs start with the cathode, e.g. in the areas of increased QE (reduced laser power), smaller thermal emittance (beam quality), longer excitation wavelength (reduced laser cost), dark current reduction (breakdown suppression, beam quality), and reduced sensitivity to contamination (longer lifetime). Little further improvement can be achieved using simple metal photocathodes. Many other materials also photo-emit, however, ranging from negative electron affinity (NEA) bulk semiconductors to nano-structured cathode architectures, each offering different advantages (and disadvantages) with regard to QE, current density, temporal response

and vacuum robustness. However, no cathode material has been developed with all the desired properties. This situation is not unlike that for SLAC/SLC injector polarized electron sources, beginning in the mid-1970's. A carefully executed SLAC R&D program, over three decades long, and based initially on the development of the first NEA bulk GaAs emitters, has led to the current multi-atomic-layer tailored cathodes that possess long lifetime, high charge and high polarization (the latter two characteristics were considered "impossible simultaneously" during the early years of development). Recognition that the NEA source (which is highly contamination-sensitive) had to be qualified in an injector, while simultaneously developing new cathode structures and a cathode load lock transfer system, led to the construction of a lab-based injector and two research surface science facilities, one dedicated to the development of cleaning and cesiation techniques, the second to fundamental measurement of polarization and QE. The combination allows rapid low-electric-field testing of new cathode structures, the best of which are qualified for lifetime high-field Shottky-enhanced charge and polarization in the injector. This successful model of separating cathode research from cathode preparation and injector testing is exactly that proposed in this white paper.

The Cathode Preparation Laboratory

For the ITF to be efficiently utilized, an onsite Cathode Preparation Laboratory (CPL) near the injector would be the transitional system into which qualified cathode structures would be deposited/cleaned, measured for QE, thermal emittance, and surface chemical composition. The cathode is then transferred to a vacuum-coupled storage chamber, awaiting vacuum load lock transfer to the injector gun. The load lock method preserves the cathode condition and ensures that a well-characterized clean cathode is installed into the gun. Used cathodes that are removed from the gun may move back to the CPL for re-measurement to correlate gun performance and cathode condition, for example changes in thermal emittance.

The CPL is a 20'x20'x10' Class 10K room, with a Class 10 Assembly Hood for cathode unpackaging/examination, and containing a set of coupled (via gate valves and transfer manipulators) chambers for (Chamber 1) measurement of surface chemical composition (x-ray photoelectron spectroscopy), surface topographical imaging (low-energy secondary electron microscopy), quantum efficiency (UV/VIS monochromator and lamp), thermal emittance (retarding field analyzer and channel plate, and (Chamber 2) deposition of semiconductor or metal cathode layers (triple reactive pulsed sputter sources), and cathode cleaning (heating and hydrogen ion sputter gun). Coupled to these chambers is a chamber for cathode storage and a load lock transfer unit. The mobile load lock connects to both the gun and to the offsite Cathode Research Laboratory.

There are cathode research programs either in operation or planned at a number of laboratories, all tailored to an onsite gun and injector. This model ensures that the cathodes developed are well-matched to their respective machines. The most efficient way to tailor cathodes for LCLS I (and II) will be to have a dedicated research facility at SLAC that will use designs developed with collaborators, such as LBNL, tailored to LCLS requirements and fabricated offsite through LBNL and SBIR collaboration.

The Cathode Research Laboratory

The proposed SLAC Cathode Research Laboratory (CRL) will concentrate its efforts in three areas: 1) Identify, evaluate and measure the suitability of new cathode structures for the LCLS, 2) Based on measurements, theoretically determine parameters for the fabrication of new LCLS-specific structure parameters and, 3) Measure the modified structures, and develop suitable *in situ* cleaning/passivation methods that ensure long cathode lifetime. A sampling of cathode types includes: Single and multi-component semiconductors (Si, CsSb, CsBr), structured metals, field emission, direct-coupled laser and rear-illuminated transmission semiconductors (diamond), diamond multi-emitter cathodes and carbon nanotubes. Some of these structures have complex nanometer-scale architectures. The CRL tools will need to be capable of making meaningful measurements on these structures.

Specific goals (and parameters) for the CRL: 1) Improve QE at the laser wavelength (materials, structures, cleaning), 2) Reduce emittance (surface lattice perfection, chemical and topographic homogeneity, complex optical constants), 3) Reduce dark current (locate “unborn” emitters) and, 4) Lengthen cathode lifetime (contamination sensitivity, surface stability, passivation). The necessary tools for these tasks are shown in the CRL layout shown in figure B-7 in Appendix B. Surface morphology is measured with a high-resolution field emission cathode SEM (FE-SEM), and Atomic Force and Scanning Tunneling Microscopes (AFM, STM); bulk structure and elemental composition with x-ray diffraction (at the SU Geballe Lab) and EDX (in the FE-SEM); complex optical constants with an *in situ* wavelength-scanning ellipsometer; surface chemical composition with XPS; and emission homogeneity with a photoelectron emission microscope (PEEM, at LBNL).

In addition, there is superb research experience on measuring photocathode band structure available at SSRL (Piero Pianetta’s group) and some cathode fabrication facilities at the Stanford NanoFab. LBNL is establishing its own terahertz-rate cathode research program, which will include the new Molecular Foundry facility for single-atom fabrication. These are programs with which SLAC could share knowledge and, possibly, resources. LBNL, in particular, proposes an active cathode program in collaboration with the CRL. The elements of this program are (extracted from a detailed contribution by H. Padmore, LBNL):

Theoretical: Use one-step models of photoemission to predict the details of the angle – energy distribution functions. Then use these models to investigate novel photocathode systems and ultimately predict and optimize transverse thermal emittance.

Experimental: LBNL will measure the angular distribution functions for a range of energies from zero to the Fermi level, using angle resolved time of flight techniques. Next comes measurements of integrated electron yield as a function of photon energy, and reflection measurements of optical constants. Measurements will be done on the uniformity of emission from cathodes, using photoemission electron microscopy (PEEM, at the ALS) [7], from both single crystal and polycrystalline materials.

Materials manufacture: LBNL will manufacture cathode materials using standard surface science techniques. Single crystals will be obtained, oriented, polished, and cleaned in

UHV, and characterized using LEED and other surface sensitive techniques. Layered systems will be produced by standard surface epitaxial growth techniques. Once we have a firm theoretical understanding of photocathode surfaces, then we can proceed to optimization of materials. It may be that use of a material such as Pd might be better as emission will be from more d-like states of higher density. Whether the result is better in the context of photocathodes is an open question as these states might be more localized, and differences in work function need to be taken into account.

The CRL effort will follow up recent work on “dark current” field emitters which showed that, even for clean particle-free surfaces, new emitters can be “born” from just below the cathode surface [8]. These, frequently dielectric, unborn emitters distort the local surface potential, forming a channel to the underlying bulk source of electrons, and act as nano-pipes of dark current. Prior to birth, they are invisible to topographic scanning, but a new technique (a rather simple modification to the Scanning Tunneling Microscope) called Scanning Kelvin Probe microscopy (SKP), samples the surface potential distortion they introduce by making the scanning tip one plate of a capacitor and the surface, the other plate. Scanning in this mode produces a surface potential map overlaid with topography [9]. Potential anomalies can then be tested for field emission characteristics, using the tunneling microscopy ability of the same instrument. Then, cleaning/processing techniques can be developed to reduce their number. Obviously, this technique is also applicable to gun electrode material (e.g., Cu) as well.

Using shared manpower, the CPL would be built immediately and the CRL in stages. The tools of immediate need in the CRL are the vacuum chambers, ellipsometer, QE monochromator, and a loadlock. The remaining items could be added in succeeding years. The combination of the SLAC CPL and CRL, LBNL collaboration, Stanford University facilities, DOE labs, and private company fabricators is a powerful, proven model [10] for steady progress in cathode capability that will contribute to improvements in LCLS I and its successors.

Beam Conditioning

The 100 to 150 MEV beam energy of the ITF provides the opportunity to study the exchange of beam properties between the transverse and longitudinal planes. Because of the rapid acceleration to relativistic energies, the transverse and longitudinal temperatures are not in equilibrium. In particular, the longitudinal temperature (hence emittance) is much lower than the transverse temperature. In general the longitudinal emittance is too small, leading to various undesirable beam instabilities driven by coherent synchrotron radiation in the bunch compressor and longitudinal space charge oscillations.

These instabilities in the LCLS are suppressed by increasing the longitudinal energy spread with an inverse FEL, aka the “laser heater”. However it would be much better to be able to move or exchange heat from the transverse to the longitudinal, thereby simultaneously achieving both the desired increased longitudinal energy spread and reduced transverse emittance. Only a few exchange schemes have been proposed in the literature, with a recent idea [11] using a flat, magnetized beam in a chicane or dogleg bend containing a transverse rf cavity to perform the exchange. The beamline layout

shown in Figure 3 incorporates both a chicane and dogleg for studying this very interesting concept, and is general enough to investigate other schemes.

Gun and Accelerator Development

With the rf photoinjector as the near-term focus of the source development effort, work to develop and test new gun geometries that offer improvements in beam quality and vacuum (for cathode lifetime) will be pursued along with improvements in reliability.

To investigate these issues, several generations of guns are envisioned. First, a higher-order-mode (HOM) gun will be built to serve as a cathode test gun (see figure 2). The open geometry—notably the lack of any disk-loading—gives clear line-of-sight access from the downstream end of the gun to the cathode, permitting analytical instruments and cathode processing instruments (e.g. an ion gun) to be mounted. The open geometry also facilitates vacuum pumping.

The design for the HOM research gun as well as other guns will be done in collaboration with John Lewellen (ANL), who is the originator of the HOM gun and has also worked with SLAC and Stanford U. on simulations of an s-band two-frequency gun [12].

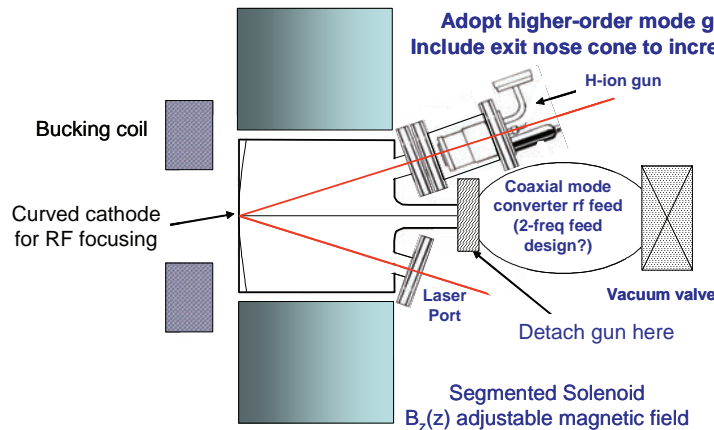


Figure 2: Proposed research rf gun utilizes a higher-order mode gun with a coaxial feed to allow flexibility in cathode and gun studies.

In general, the cathode field should be as high as possible to rapidly accelerate the electron bunch to relativistic energy. Unfortunately such high rf fields have the detrimental effect of strongly defocusing the beam at the gun exit, resulting in rf emittance growth. This defocusing can be controlled using an axial magnetic field, but for very high rf fields, the required magnetic field becomes quite strong. For example, in the LCLS gun the 120MV/m cathode field results in a rf defocusing focal length of approximately -12cm! The compensating magnetic field is likely to result in optical aberrations of the beam and increases the alignment tolerance. One solution to this problem is to continue accelerating the electrons in the gun to higher energy before exiting the gun. The higher energy beam is more weakly defocused by the rf fields.

To this end, a 5.5 cell X-band photoinjector has been built and tested at SLAC capable of generating a 7.3 MeV electron beam [13]. It would be quite useful to extend this

experience to a second gun with some modifications. These would include increasing the mode separation and the introduction of a removable cathode. Advantages of this type of gun at X-band are the increased final beam energy, inherently shorter bunch length, smaller size of components (including the later accelerating structures), and lower average RF power dissipation. Disadvantages compared to lower frequency, 1.5 cell guns are the inherently higher thermal emittance and space charge. This type of gun is a natural match for experiments requiring short bunch lengths such as in coherent transition radiation.

Unfortunately, 10-cell or so standing wave devices suffer from difficult mode separation problems, as well as challenges in dealing with the RF reflection. As such, a UCLA/Univ. Rome/INFN-LNF collaboration has recently begun aggressive R&D on a “hybrid” traveling wave/standing wave photoinjector. In this device, the RF power is coupled into the third cell, with approximately one-tenth fed back to the standing wave gun section (the first two cells), and 90% matched to a downstream traveling wave section.

In this scheme, the RF field may be much higher in the gun section than in the traveling wave section, thus simultaneously optimizing emittance performance and allowing efficient acceleration, up to 20-30 MeV in the injector alone. This geometry has also been shown to naturally lead to an RF phasing in the transition from standing to traveling wave which produces velocity bunching. Recent simulations at UCLA have shown that a kiloAmpere-class beam with 2 mm-mrad emittance is possible in the S-band version of this device. Simple scaling arguments lead to predictions of a kA, 0.5 mm-mrad beam in an X-band version.

The S-band hybrid photoinjector is now under cold-test at UCLA, and X-band version is following at INFN-LNF in Frascati. The infrastructure for high power RF does not yet exist at LNF for developing this technology yet, however. Discussions have begun between SLAC and LNF on how to proceed with collaboration in this frontier area.

Clearly moving toward higher RF frequency will necessitate the use of self-consistent Particle-in-Cell (PIC) or finite element codes like MAFIA or the new SLAC code, Pic2P developed by the Advanced Computation Department. This is because of the increased wakefields in the smaller x-band structures.

Therefore subsequent generations of guns will investigate:

1. The feasibility and efficacy of combined first- and third-harmonic frequency operation, which offers significant improvements in emittance[12,14]. The integrated photoinjector concept (a gun with significantly more cells than 1.6, yielding higher exit energy, and potentially better emittance),
2. Coaxial couplers and schemes for reducing the strong rf focusing associated with high cathode fields.
3. Self-consistent PIC simulations of guns at higher and lower frequencies to verify the simple scaling formalism and determine feasibility of x-band guns to produce high-brightness beams [15].

The beamline for the Injector Test Facility (ITF) will consist of five major components, a cathode load-lock, an RF gun, an accelerator and a chicane/dogleg and a section for user experiments. Figure 3 below shows what such a beamline might look like. This setup, or some modification of it, can be used to investigate a variety of parameter relevant to gun performance. Pre-accelerator beams can be analyzed in terms of intensity and size, while post accelerated beams can be best studied for beam quality, i.e. emittance, by reducing the complicating effects of space charge, beam spread, low intensity, $1/\gamma$ opening width of many radiative processes etc. Beam energies of 100-150 MeV, provided by two standard SLAC s-band accelerator sections, are adequate for this.

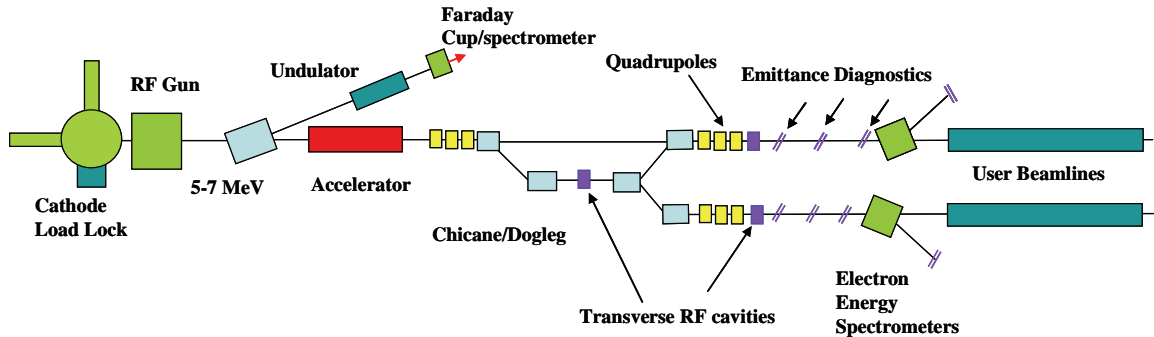


Figure 3: A proposed beamline configuration for the ITF which incorporates a cathode load-lock system, bunch compressor, emittance exchange dog leg, and a region for user experiments.

In studying cathode properties/materials it is anticipated that a load-lock system will be incorporated into the gun to permit quick changing of cathodes as well as the ability to maintain a clean vacuum environment during the change. This feature is essential if some of the more exotic cathode materials are to be studied.

The beamline will be fitted with a variety of diagnostics. Some of these will be standard devices to monitor and measure beam properties and some will be experimental devices themselves, whose properties will be investigated.

In order to study beam properties of the RF gun, an insertable scintillator will be used to view the beam exiting the gun. The scintillator can be viewed by a standard CCD camera. A Faraday cup will also be located at this location. These components are important to study bunch charge and shape as a function of parameters such as phase, magnet field strength as well as laser pulse parameters. These devices could be part of a single unit. A dipole spectrometer would also permit the measurement of beam energy and energy dispersion. A scintillator should also be located following the accelerators so that the beam profile can be viewed before entering any focusing or steering elements. In order to get an accurate estimate of beam size and emittance, OTR diagnostics will be inserted downstream of the focusing quadrupoles. A transverse cavity can be used to study beam bunch lengths and measure slice emittances. As additional, potentially non-destructive tools for measuring bunch shape and emittance, Electro-Optics and Diffraction radiation techniques can be studied and evaluated. The ability to monitor beam properties non-destructively would permit the introduction of feedback systems to optimize/stabilize

beam quality. At the end of the beamline, a spectrometer and Faraday cup should be included to measure beam energy, energy dispersion, beam charge and timing jitter.

In addition to investigating the key parameters for a high quality RF gun, the high brightness beam can be used to study beam dynamics issues such as bunch compression, emittance exchange and perhaps electron-photon collisions.

Accelerating an electron bunch to $> 100\text{MeV}$ and passing the beam through a chicane will permit the study of processes such as emittance exchange and longitudinal pulse compression. The former being a proposed technique for reducing transverse emittance and the latter being of interest in the generation of coherent transition radiation. 10 m of beamline space is called out for installing the chicane, emittance exchange doglegs, and the required diagnostic instrumentation. A chicane is also useful in studying electron-photon collisions since it permits the introduction of a laser beam into the beamline. In studies of recoiling photons it also permits the isolation of photon diagnostics from stray bremsstrahlung radiation. Electro-optic techniques can also be used to quantify bunch compression following a in addition to serving as an in-situ diagnostic for bunch length and fast timing measurements.

It is anticipated that 2 S-band SLAC-type accelerator structures will be required to accelerate a beam to 100-150 MeV. At X-band, 2 structures will also be required.

Advanced Simulation R&D with LBNL

(contributed by Ji Qiang, LBNL)

Modern photoinjectors are designed to generate a high brightness, low emittance electron beam. The phase space distribution of electrons just out of the photocathode puts a restriction on the final quality of beam that can be achieved. A number of factors can affect the phase space distribution of those electrons. These factors include mean field space-charge effects, image charge effects, collisional effects (e.g. Boersch effects), cathode material properties, surface roughness and contamination, and laser pulse spatial and temporal distribution.

Detailed numerical simulations including these mechanisms will help to understand and to optimize the electron phase space distribution from the photocathode. The process of photoemission will be simulated using Spicer's three-step model. This model uses the metal material properties such as optical density of states, work function, etc, to generate an electron energy and angular probability distribution out of the cathode at one surface location.

The space-charge effects, image-charge effects and collisional effects will be simulated using a quasi-static particle-in-cell model together with a stochastic model. The space-charge fields from the emitted electrons will also be included into the photoemission process. The non-uniformity of work function and external fields is modeled through the transverse discretization of the photocathode surface. This can also take into effects of surface roughness and contamination.

We propose to work with SLAC in development of multi-physics modeling codes to simulate in detail the emission processes, collisional, and space-charge effects that contribute to determining the electron beam emittance from photocathodes. Based on LBNL parallel beam dynamics codes such as IMPACT, we propose to develop physics

models with SLAC, and incorporate the most realistic physics descriptions available into the codes, which may then also be used in additional modeling of downstream components, leading eventually to full start-to-end simulations.

Intermediate-Term R&D

The near-term plan addresses issues related to the immediate LCLS R&D needs for approximately the next 5 to 10 years. Here we consider the longer term research requirements of the ITF, as an evolution of LCLS I technology to LCLS II. The intermediate-term R&D program goals should include:

1. Design and testing of extremely high-field guns should be studied to both increase the cathode peak field and to mitigate the strong transverse focusing associated with these high fields. The UCLA/Univ. of Rome/INFN-LNF approach is described below. In addition, the effect these extreme fields have on the cathode performance and the emission process needs to be understood. Recent work [16] shows the cathode thermal emittance grows with increased rf fields, due to a combination of the Schottky effect which lowers the emission barrier and the acceleration of the electrons inside the cathode before they escape. As the thermal emittance becomes the ultimate limit of achievable transverse beam quality, it is important to understand these high-field effects.
2. An open rf cavity geometry for efficient vacuum pumping. Most cathodes will require low vacuum pressures, especially those with sensitivities in the visible and near-IR.
3. Cathodes with high-quantum efficiency at the fundamental frequency of the drive laser. Current drive laser systems all use either frequency-doubling, -tripling or -quadrupling to produce short wavelengths needed by the cathodes. These processes are inefficient and being non-linear makes pulse shaping extremely difficult. Therefore cathodes with good sensitivity at standard laser wavelengths are needed and would help to simplify the laser shaping problem and allow the use of fiber-optics for transporting and launching the laser beam onto the cathode.
4. Cathodes with long operating lifetimes and/or cathodes which are self healing or can be rejuvenated in situ. Since the cathode is subjected a punishing environment of extremely high fields, possible arcing, back bombardment by ions and vacuum contamination, a reliable method for its restoration or replacement is needed. A cathode with great QE is worthless if it has a short operational lifetime.
5. A compact and stable drive laser based on fiber-laser technology would revolutionize the current approach to laser systems. There are two basic problems with the currently plague the operation of these laser systems: optical damage and stability. In our opinion, a major cause of these problems result from the use of discrete components with optical surfaces exposed to air, and mounted on surfaces which can move over time. The free-space propagation of the laser beam

between components allows dirt to settle on laser surfaces initiating optical damage. A hermetically sealed fiber-laser would solve these and other reliability issues.

Long-Term R&D

More exotic technologies also are under development, and offer promise in the long term. These technologies either replace the cathode, or seek to use much higher extraction field strengths, or both.

Fast-pulsed ultrahigh gradient DC photoinjectors (“DC Pseudospark” injectors) offer the prospect of significantly reduced emittance due to the extremely high quasi-DC acceleration gradients (1 GV/m, vs. ~100 MV/m in rf guns) that can be produced. As an added bonus, the extreme fields also give significant Schottky enhancement of the QE, lowering the required laser power. Electrons undergo such rapid acceleration that space charge force have very little time to heat the distribution. The quasi-DC nature of the accelerating fields means there are no time-dependent correlations induced in the beam, eliminating an important source of emittance growth, especially at high gradient. Pseudospark guns have demonstrated great promise in proof-of-principle experiments at BNL and elsewhere, but as the gun produces low energy beam (typical 1-2 MeV), it must be integrated into an accelerating cavity. Attempts to date to engineer an integrated gun have encountered significant reliability and breakdown problems. This effort should be monitored closely for future application to LCLS. The space and equipment implications for both the ITF and LCLS are modest—neither would require significant changes to accommodate a hybrid pseudospark/rf gun.

Laser-plasma based injectors (“cathodeless” or “plasma” injectors) not only offer very large accelerating gradients at the source, but eliminate the solid-state cathode with its attendant contamination and uniformity problems. These sources work by exciting plasma waves in a very dense plasma (a laser-ionized supersonic gas jet), then “kicking” a small fraction of the plasma electrons into the plasma waves with a laser. Pioneering work at LBNL’s L’Oasis lab (now copied by other laser labs worldwide) has been very promising. Very significant shot-to-shot variation in beam properties have been observed to date, requiring carefully study to improve consistency. Terawatt-class lasers capable of operating at >100 Hz repetition rates (as would be required to make an LCLS injector) are a significant R&D project unto themselves. The space and equipment implications for both the ITF and LCLS are very significant. The beamline space required for the gun would be greatly reduced, however, the laser lab space, laser system, and supporting infrastructure would grow dramatically. Siting the ITF at a location where the laser room can be greatly expanded (e.g. from the proposed 600 sf to 1800 sf) preserves the option to pursue this technology. Close collaboration with LBNL will afford the opportunity to closely monitor (and possibly participate) in this groundbreaking effort.

Existing Facilities

There are a number of facilities under construction or operating that are dedicated to injector R&D; these facilities are summarized in Table 1.

Facility	R&D Program	Inj. Type	E	Q	Emittance	Comments
			[MeV]	[nC]	[mm-mr]	
CW High Current Injectors for ERLs						
BNL-Cooling	ERL	SC Photo	50	10	30-50	under construction
LBNL	ERL	RF Photo				proposed
Cornell-ITS	ERL	DC Photo	0.75	0.8	1.6	under construction
TJNAF	ERL	DC Photo	100	0.15	15	operating
Long-Pulse Injectors for ILC or FLASH						
DESY-Zeuthen	FLASH	RF Photo	18	2	1	long-pulse, for cold line
FNPL	ILC/FLASH	RF Photo	18	8	11	long-pulse, for cold line
Short-Pulse Injectors for General R&D						
ANL-ITS	general R&D	RF Photo				operating?
BNL-ATF	general R&D	RF Photo				Users; limited R&D
UCLA-Labs	general R&D	RF Photo	18	1	?	Two rf gun labs
Short-Pulse Test Injectors for Specific Light Sources						
INFN-Sparc	Sparc	RF Photo				commissioning
SSRL GTF	LCLS	RF Photo	70	1	2	Unusable in 1-2 years

Table 1: Existing injector test facilities.

The R&D at all of these facilities is relevant to LCLS source development, as each is aimed at improved source brightness. However facilities in the first and second categories—CW and long-pulse sources—pose serious engineering challenges such as the need for a superconducting gun, or a very high average current cathode, that are not required for the LCLS. The general-purpose R&D facilities in the third category are used for a variety of experiments, and in some cases support beam users. These facilities provide excellent locations to make limited development tests, but are not suitable for injector experiments requiring very long run times (component lifespan testing) or significant disruptions of the beamline (e.g. changing the gun operating frequency).

The fourth category lists facilities that were designed as engineering tests for specific machines. INFN-Sparc (in Rome, Italy) is a very similar machine to what is proposed here, with similar research emphasis and accelerator parameters. The SSRL-GTF is specifically targeted at R&D for LCLS, but will become unusable in the next year or so, as discussed below.

Proposed Facility

In light of the substantial challenges and the LCLS need for local expertise and facilities, we propose a facility and a SLAC-centered collaborative effort to address these challenges. An Injector Test Facility (ITF) centered on a 150 MeV accelerator is the centerpiece.

High-brightness beams produced in electron sources have strong time-correlations in the transverse phase spaces that can lead to significant growth of both the projected and slice emittances if not reversed. Acceleration and focusing of the beam must be optimized as a whole system. Acceleration to ~100-150 MeV is typically enough to suppress space charge effects and approximate the final, thermalized beam state. Also, many beam diagnostic techniques for measuring beam characteristics only work in the emittance-

dominated regime. Consequently the ITF must include acceleration to 100-150 MeV to support the goals of developing optimized beam injection and diagnostics.

The ability to fabricate and perform detailed characterization of cathodes (measure QE, complex permittivity, work function, contaminant mapping) is essential. Consequently, enhancement of the existing SLAC Surface and Materials Science Laboratory with needed analytical instruments, and a dedicated cathode preparation facility are called for. The exceptional analytical facilities at LBNL will also be engaged in collaboration with the Center for Beam Physics.

Development of new laser pulse shapes, and new more efficient lasers requires a specialized laser lab. An environmentally controlled cleanroom facility housing both a “production” laser system for operating the test injector facility and a separate “development” laser for advanced R&D is called for.

Several generations of RF guns are envisioned. Facilities for assembling and testing the guns (clean vacuum assembly areas, and an RF test and measurement area) are called for. Space in the accelerator housing for both the main 150 MeV accelerator, and a separate gun-only test stand are called for, with the latter also serving for testing candidate cathodes under real-world conditions.

Testing new methods of manipulating beams, including the beam heater (for stabilization against CSR instabilities) and emittance exchange will require that significant beamline space be set aside for installing test devices. We have called for 10 m of free beamline space, including energy analysis, for such experiments.

Simulation expertise and resources currently in place for the LCLS design effort will be expanded to include collaboration with the Center for Beam Physics Accelerator Modeling and Advanced Computing group at LBNL, which shares our interest in electron source R&D.

The primary parameter goals for the Injector Test Facility are summarized in table 2 below.

Final beam energy	100 to 150 MeV
Transverse emittance goal	0.5 microns or less
Bunch charge range	0.100 nC to 2 nC
Peak current	50 to 100 amperes
Cathode	Load-locked to permit exchange
Drive Laser	Dual systems: (1) for operations (2) for development

Table 2: Primary parameter goals for the ITF

Location of the ITF

Status of the Present SSRL Gun Test Facility

The SSRL Gun Test Facility (GTF) started operation in 1996 after a 1992 LCLS review concluded that the injector was a major technical challenge for the realization of a soft x-ray linac-based FEL. SLAC and SSRL resources were used to accelerate the electron source development and thus created a facility dedicated to the development of a high brightness LCLS injector.

The facility has operated for the last 10 years with very limited budget and no dedicated personnel. The experiments conducted at the GTF have led to numerous modifications in the LCLS injector design that are expected to significantly improve the electron beam quality. However, the facility will become unusable as a test facility as soon as SPEAR3 upgrades to top-off injection. Once operating in this mode, the GTF vault will be inaccessible due to continuous operation of the SPEAR3 injector.

In 2004 an SSRL study was made to look at possible future sites and other applications in addition to the high brightness beam development. In addition to reaffirming the need for a centralized, dedicated facility for source development, this study identified several promising applications including ultrafast electron diffraction, THz radiation generation, Compton scattering and multiple accelerator physics experiments requiring high brightness beams.

SLAC Sites for the ITF

Eight potential locations for the ITF were identified and most were inspected by the committee. Each offers shielded space, support space, and some utilities.

Four of these sites were immediately rejected due to inadequate space, utilities (electricity, LCW), or both. These were PEP1B and PEP5B interaction regions, each offered ~10m of shielded tunnel length and ~220 m² of supporting space. The sector-10 off-axis injection spur offered adequate shielded tunnel space, but providing adequate support space would have required a civil construction effort comparable to the sector 20 surface building. The SLC south final focus arc tunnel offered support space in the SLC pit, but was deemed significantly less desirable than locating the test accelerator in a separate shielding vault within the pit itself.

The four remaining options offered adequate space, utilities, and crane coverage (with conditions, as noted below).

End Station A offers by far the largest space for the ITF, at approximately 40 m x 60 m. ESA has all the necessary utilities plus 15 and 50 ton cranes. There is more than adequate room to install and grow the facility as the program progresses. The A-Line and associated shielding will limit the available space to approximately 20 m X 45 m. ESA is not accessible approximately 6 weeks per year while high power beams are present in the A-Line. There is some equipment stored in the space desired for the ITF that would need to be moved.

End Station B measures approximately 20 m x 40 m with an operating 300 MeV x-band accelerator housed inside a 50 m x 3 m accelerator housing. The first 24m are occupied by the E163 injector, the latter half by the now-defunct NLC x-band accelerator. The accelerator enclosure could easily accommodate the ITF accelerator and gun test stand, provided the NLC x-band accelerator is removed. Two RF modulator stations and several racks of magnet power supply and vacuum control equipment would be freed up in the process, which could be used for the ITF. Existing SCP controls could be straightforwardly extended to cover the ITF. Since the accelerator would occupy the downstream half of the NLCTA shielded vault with the E163 accelerator, PPS and operations would be shared, resulting in the need to coordinate installation and operation schedules. The accelerator tunnel, control room, electronics and light assembly areas would be shared with other programs, resulting in significant construction cost savings in return for a modest increase in operating cost. Building 231 (adjacent to ESB to the East) could be converted into a light machine shop to support the ITF at modest cost. Impact on E163 is significant during the accelerator removal and ITF installation phases, and minor during machine operation. Impact on ILC is significant if the ITF cathode and laser labs are located within ESB. Impact on HGRF program is significant—testing of x-band components within the NLCTA housing would be halted until another solution is found.

The klystron test lab measures 22 m X 84 m of which ~950 m² is available for the ITF. There is an operating 60 MeV x-band accelerator inside a 9 m x 3 m accelerator housing. The bunker would be extended ~20 m at the expense of 10 m x 20 m space filled with existing equipment, two rf labs. The test lab has plenty of rf power available immediately adjacent to the bunker, as well as ample utilities and 10T crane coverage. This location already supports hot-testing of the LCLS guns. This location also offers close contact with the expertise of the Klystron Department and close proximity to the SMS labs. The impact on the Klystron Department Mechanical Drafting division is significant—they would be relocated to other offices. The HGRF program would also be significantly impacted during the ASTA enclosure expansion. The ITF would permanently commit 3-4 test stands of the Klystron Test Lab to fixed use.

The SLD pit measures approximately 20 m X 80 m of which a 20 m X 30 m space is available for the ITF. The facility has good utilities (electrical, water, air, phone) and even has some cryogenic capacity that could prove useful. In addition it has both elevator and 10 and 100 ton crane access. Some of the required floor space such as the cathode prep lab, electronics lab and machine shop could be moved up to the ground floor to make more space available. An accelerator housing would need to be constructed from scratch. Since all sizable equipment must enter the pit either via crane (requiring riggers), there is additional cost in constructing and operating a facility in the pit, which CEF estimates at 8% of all civil construction costs—a \$160k penalty. CEF engineers raised minor questions about the seismic stability of the pit walls. This location has minimal impact on other programs.

An alternative to building a new vault in the pit is to utilize the tunnel of the north or south arcs. The south arc was inspected but the tunnel was considered too narrow and lacked good equipment access for the injector test facility. In addition, the existing FF magnets would need to be removed, and the tunnel upgraded to correct water seepage and

other minor problems. These factors made siting the accelerator enclosure in the pit considerably more attractive.

Preliminary Cost Estimates

Construction Cost

Construction for the Injector Test Facility is expected to take 3 years, and to cost from \$15.5 million to \$21.1 million, depending on the site chosen. Construction cost estimates for each of the four candidate sites are summarized in Table 3. Civil construction estimates were provided by the SLAC CEF Site Engineering Department, while technical component cost estimates were derived from present LCLS Sector 20 cost experience. Installed equipment at each location was valued on a replacement-cost basis. Explanation of assumptions and the larger-cost items cost is provided in Appendix A-1.

Table 3. Construction cost estimate for the ITF, by site. All amounts are in k\$.

	End Station A (b. 61)	End Station B (b. 62)		Klystron Test Lab (b. 44)	SLD (b. 750)
		All Inside ⁷	External Building ⁷		
Gun and Accelerator ²	7,106	4,690	4,690	4,882	7,106
Laser System ³	2,525	2,525	2,525	2,525	2,525
Cathode Lab Equipment ⁴	1,960	1,960	1,960	1,960	1,960
Conventional Facilities ¹	2,099	984	1,194	1,454	2,240
Contingency ⁵ and Escalation ⁶	7,194	5,339	5,449	5,686	7,286
Total Construction Cost	20,884	15,498	15,818	16,507	21,100

¹Infrastructure cost estimates from CEF Site Engineering Department.

²Costs based on current LCLS injector component costs, taking 50% credit for using existing designs and drawings.

³Laser cost estimate reflects the installation of two laser systems, one for operating the ITF, the second for R&D.

⁴Costs based on upgrade of SMS equipment to support the expanded R&D effort, and construction of a new cathode preparation facility at the ITF.

⁵Contingency: 40% of total construction costs.

⁶Escalation: 3% per year for inflation.

⁷"All Inside" and "External Building" label two scenarios in which the laser and cathode cleanrooms are built either within End Station B, or in a separate, newly constructed, external building.

Operating Cost

Operation of the ITF is expected to require a core staff of trained machine operators and physicists (approx. 4 FTE), 3 lead physicists to lead the laser, cathode, and gun development efforts, 2 engineers, and a technical staff of 7-8 FTE, for a total ITF staff of 16-17 FTEs. Annual maintenance costs amounting to approximately 10% of the initial construction cost, per year, are expected, totaling ~1M\$/year. Annual M&S+CE budgets of \$300k+\$50k for injector development, \$90k+\$400k for cathode development in collaboration with LBNL, and \$75k+\$150k for laser development will permit a fast-paced R&D program. Total operating costs are anticipated to be \$2790K in effort, \$700k

in M&S, and \$600k in capital equipment purchases. Details of the operating budget may be found in Appendix A-2.

Additional R&D Opportunities

Of course, a working test facility with very high quality 150 MeV beams and key infrastructure (rf sources, laser sources) can facilitate a broad range of activities. Provided the essential goal of driving LCLS source development forward is not compromised, user-driven experiments that leverage portions of the infrastructure should not only be allowed, but encouraged. Users will make demands on the beam and the facility that will lead to the improvement of both, and will bring with them fresh ideas and unique technical skills that will benefit the ITF group. Three such collaborative R&D opportunities are described briefly below.

Development of Injector Technologies for Other Applications

The ILC currently calls for a normal-conducting rf photoinjector as the source, with similar demands on beam quality, but far more stringent demands on pulse length and gun vacuum, necessitated by the need for luminosity and polarized electrons, respectively. While long-pulse operation would require specialized rf sources not called out in this proposal, development of gun geometries that permit better vacuum and better cathode access (both for exchange and in-situ diagnosis) is needed for the ILC and LCLS alike. The ITF's provisions for a gun test stand and a full injector test would allow some of these issues to be addressed in parallel.

Ultrafast Electron Diffraction

One novel application of the high brightness beam generated by the rf gun is ultrafast electron diffraction. X-ray absorption and diffraction experiments are well suited for condensed phase samples of large size. In contrast, electrons are preferred when very few target molecules are available, such as in very small crystals of biological samples [17]. Electron diffraction has been extended to the time-domain by the use of ultrashort pulsed electron beams, which are generated by ejection of photoelectrons from metallic surfaces using pulsed lasers [18]. Very recent studies of the melting of Al thin films with electron diffraction have demonstrated 650 fs time resolution and provided insight into the melting of super-heated solids [19]. Typical electron diffraction experiments are conducted at energies in the 50-500 keV range where space charge limits the charge that can be contained in a single 100 fs long pulse. However, an S-band photocathode gun operating at a few MeV can produce 100 fs pulses with up to 10^8 electrons. Such a source has already been used in a proof of principle high-energy electron diffraction experiment at SLAC [20]. A single shot diffraction pattern from a 160 nm thick Al foil is shown in figure 4 obtained with an approximately 500 fs rms long pulse containing 2×10^7 electrons. An ultrafast single shot electron diffraction apparatus is ideally suited for a wide variety of experiments and the device will be marvelously complementary to the LCLS.

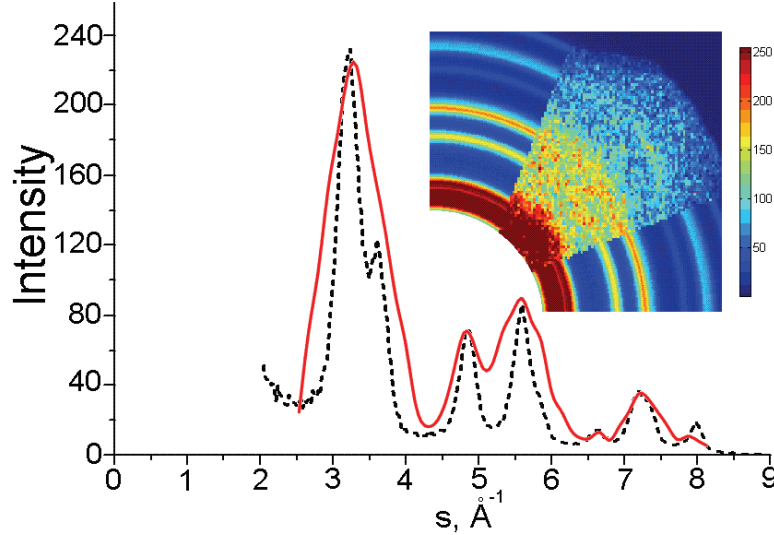


Figure 4: The measured single shot electron diffraction pattern from a 160 nm Al foil at the GTF. The theoretical intensity vs. transverse momentum is plotted as a dashed line and the measured intensity is a solid red line. The theoretical and measured diffraction pattern images are overlaid in the inset.

Terahertz Radiation

Coherent THz radiation could be produced with very high intensities from sub-picosecond electron bunches [21] through a fast process like transition radiation via metal foils generating broadband THz radiation or with an undulator or FEL [22] generating narrow band radiation. Femtosecond pulses of very high intensity FIR radiation can be used, for example, for studies of heavily absorbing samples like water or solutions of biological molecules. Using the method of dispersive Fourier transform spectroscopy chemical and biological samples have been studied [23,24] producing new results that could not have been obtained otherwise. The Terahertz frequency regime is the appropriate regime for exciting small molecules, Rydberg orbital states and gaseous and solid-state plasmas [25]. A pump-probe experiment with the THz source and the LCLS X-ray laser could be considered to study these systems.

Other Applications

There are other applications for a high brightness beam that were identified in the NGTF paper [26] including a short pulse X-ray source based on Compton scattering. A Compton source can not compete with the peak brightness of the LCLS but it could be beneficial for those experiments that do not desire the LCLS brilliance but still require the ultra-fast X-ray pulses and the necessary components for such a source, high brightness electron beam synchronized with a TW laser, are present in the ITF. Finally, it has been proposed to generate ultra-fast high intensity magnetic fields from an ultra-short electron bunch to study magnetic materials with sub ps temporal resolution [27]. Compressing the ITF electron beam could produce the desired beam with > 1 kA peak current and sub-picosecond pulse lengths.

Conclusion

While significant progress has been made in electron sources, significant challenges remain. The rapid LCLS upgrade schedule necessitates aggressive R&D on injector technologies that are substantially compatible with the existing injector and offer the highest possibility of success in a 3-5 year development time. This immediately constrains R&D efforts to rf photoinjector technology. The progress of more advanced source technologies, such as dc pseudospark or plasma-based sources, will be closely monitored, and may well provide the basis for new sources a decade or more in the future.

A test facility that can support world-class R&D in surface science, laser science, rf design, and beam diagnosis and simulations is essential for making progress consistent with the LCLS schedule and the goals of the Greenfield XFEL. A 150 MeV test injector, with facilities for laser and cathode development, would provide the foundation for a test facility capable of addressing the challenges. Enhancing the SLAC SMS laboratories to provide expanded analytical capabilities is also essential for cathode development. Collaboration with LBNL and UCLA will not only provide access to the world-class talent and facilities at the LBNL Center for Beam Physics and the Molecular Foundry, and to the agile, experienced research groups of the UCLA Neptune and Pegasus photoinjector labs, but will also result in coordination and synergy of effort directed at the LCLS, ERLs, and Sparc.

Based on the availability and quality of existing infrastructure, and compatibility with pre-existing programs, the committee recommends End Station B as the best location for the ITF, given the very extensive infrastructure and potential for growth. The Klystron Test Lab ranks a close second, requiring more extensive alteration to accommodate the ITF. The SLD pit and End Station A rank third and fourth, with each offering open space and some infrastructure, but are significantly less hospitable locations than ESB or KTL. ESB and the KTL each have active programs using portions of the space, and the ITF will have to be constructed and operated in a manner that minimally interferes with these programs.

LCLS will begin operations with the first-generation rf injector in 2007, and install an upgraded injector within the three-four years that follow, requiring the ITF to be built and functional within the next four years if it is to make a significant impact. Existing facilities at SLAC provide an excellent base upon which to build the ITF, with experimental areas that offer much of the required supporting infrastructure. Essential components of the ITF—the test accelerator, cathode, and laser labs—must be collocated with the LCLS to derive the maximum benefit from the developed expertise.

Preliminary cost estimates for constructing the ITF depend on the site chosen and range from \$15.5M (ESB) to \$21.1M (SLD). The existing infrastructure at ESB and the KTL results in very significant cost savings of \$5M over the less developed ESA and SLD sites. Construction is anticipated to take 2-3 years. Operating the facility is estimated to require approximately 16 FTE, \$0.6M/year in capital equipment funds, and \$1.7M/year in M&S.

The ITF will provide a unique facility suitable not only for its primary mission of advanced injector R&D, but the beam brightness will also enable a host of electron and

radiation experiments. The capability to test a variety of rf gun technologies can directly benefit ILC source development efforts. User-driven experiments in beam manipulation and radiation generation will help provide a rich environment of exciting science and promote a climate of inquiry and excellence required for world-class research.

Epilogue

A site and a more appropriate name have been selected since this white paper was prepared and submitted to the SLAC Directorate. The new **Center for Electron Beam Science** (CEBS) is to be built in the Klystron Test Lab.

The motivation for selecting the KTL was strong: the existing ASTA accelerator vault has since been altered to permit hot testing of LCLS Gun2. In the process, some of the essential infrastructure (s-band rf, space, etc.) required for the CEBS is already in place. While End Station B offered much in the way of existing infrastructure, existing programs are already making substantial demands of the facility and the absence of an available staff or any appreciable shop facilities make the space less attractive. The staff of the Klystron Department participated in all aspects of the LCLS Gun design, fabrication, and testing, and was indispensable in making these efforts a success. The Klystron Department has expressed serious interest in hosting the CEBS; the expertise that made Gun1 a success will be essential to making the CEBS a success.

We re-emphasize the time-urgency to get started now on injector technical issues which will affect LCLS performance, but are not funded or otherwise addressed by the LCLS construction project. Of these we feel the most serious is the photocathode. Therefore, within the context of the CEBS, effort should begin now on cathode R&D for the current LCLS gun. This early start is possible by leveraging Klystron's ASTA facility into an early version of the CEBS. The ASTA vault and RF systems are already being configured to support both LCLS gun testing and HEP high gradient (x-band) experiments. We recommend this facility be upgraded expeditiously to include a cathode R&D lab and a drive laser for the testing of cathodes in the LCLS gun. An essential component to this effort will be to form collaborations with other laboratories and universities on cathode, laser and beam dynamics research.

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Appendix A-1: Construction Cost Estimates

While the construction cost worksheet is too large to intelligibly incorporate as an appendix, highlights of the construction cost estimate can be presented, and are listed below. All costs below are stated *without* contingency (40%) or escalation (12.6% net), unless otherwise noted.

1. Civil construction estimates were made initially by the committee, and subsequently refined by CEF Site Engineering staff, based on site-by-site inspections of existing infrastructure. For the generic site (assumed simply to have a roof, and available electricity and water), the conventional facilities cost \$2.2 M. The accelerator enclosure alone is \$0.9 M. Demolition of office and lab space in the KTL added \$40 k to the cost. Seismic evaluation and other preparation costs added \$50 k to the cost for the SLD pit.
2. Beamline components and supporting power supplies, controls, and safety systems, were valued at 50% of the LCLS injector line-item costs, to take credit for reusing the designs, drawings packages, tooling, etc, for a cost of \$4.6 M. In the KTL, existing ASTA beamline components transferable to the ITF were valued at \$0.4 M. In ESB, existing NLCTA beamline components transferable to the ITF were valued at \$2.0 M.
3. RF Systems were assumed to operate at 10 Hz for accelerator structures, 120 Hz for the gun modulator. Klystrons are assumed provided if the ITF is at the KTL, otherwise new klystrons are needed, and \$0.55 M is added to the cost. Of the three modulators needed, 2 are assumed available in ESB (\$0.43 M savings), and 3 are assumed available in KTL (\$0.65 M). For the generic facility, the total RF systems cost is \$2.5 M.
4. The cathode research lab costs assume the SMS lab remains in building 40, and its equipment is upgraded for a cost of \$0.6 M.
5. The laser system costs \$2.5 M, of which \$0.5 M is supporting equipment, and the balance covers both the production laser for the ITF accelerator, and the separate R&D laser.
6. Relocating the cathode and laser labs to a new, exterior, weatherproof building was estimated by CEF to cost \$208 k, and applies to ESB scenario 2 only.
7. For comparison purposes, the conventional facilities (CF) and all other costs for Sector 20 is listed at \$2.9 M (CF) + \$20.5 M = \$23.4 M. The most comparable case in this study is ESA, less a credit for the accelerator housing: \$2.0 M (CF) + \$18.9 M = \$20.9 M (contingency and escalation have been added).

Detailed budget spreadsheets are available at:

<https://sharepoint.slac.stanford.edu/sites/guntest/pages/Whitepaper%20and%20Docs.aspx>
as the Excel document ITF_Costs_Final.xls .

Appendix A-2: Operating Cost Estimates

Operating Cost Estimate (Unburdened)

Last Rev: 28-Aug-06

Operating Assumptions

Beam Operations: 8 months per year, 5 shifts per week

Required Operator FTEs to Cover:

Maintenance: 10% of initial capital cost per year

Labor Rate, averaged over all professions

Personnel

Accelerator Operations	FTE (year)	Labor Cost (k\$)	Annual M&S (k\$)	Annual Cap Eq(k\$)	LBNL Collab?
Safety Officer/Accelerator Physicist/EOIC	1	120	50		
Facility Manager/Operations Manager/EOIC	1	120			
Operator/EOIC	1	120			
Accelerator Physicist/EOIC	1	120			
Cathode Research Lab					
Cathode Physicist	0.5	60	20	200	yes
Postdoc	1	120			
Vacuum/Mechanical Technician	0.5	60			
Cathode Preparation Lab					
Cathode Physicist	0.5	60	20	200	yes
Lead Physicist	0.25	30	50		
Vacuum/Mechanical Technician	0.5	60			
Laser Lab					
Laser Engineer	1	120	75	150	
Lead Physicist	1	120			yes
Electronics/Light Assly/Vacuum Assly					
Technician	2	240	25		
Machinist/Technician	2	240			
RF Development Engineering Support					
RF/Mechanical Engineer	1	120	250	50	
Measurement Technician	1	120			
RF Simulation/Computer Scientist	1	120			
Full-time Equivalent ITF Staff:	16.25				
Head Count (including CPE)	24				
Accelerator Maintenance (item G7 resolved as 80%/20% Effort/M&S)		840	210		
Total Effort:		1950			
Total M&S for R&D:			490		
Total Capital Equipment:				600	k\$
Total Operating Cost (Unburdened):		2790	700	600	k\$/yr
		Labor	M&S	Cap Equip	

For comparison purposes, the Brookhaven ATF has a total operating budget of \$2.1 M, with significant accelerator development support and equipment coming from outside collaborators.

Appendix B: Site-Specific Layouts for the ITF

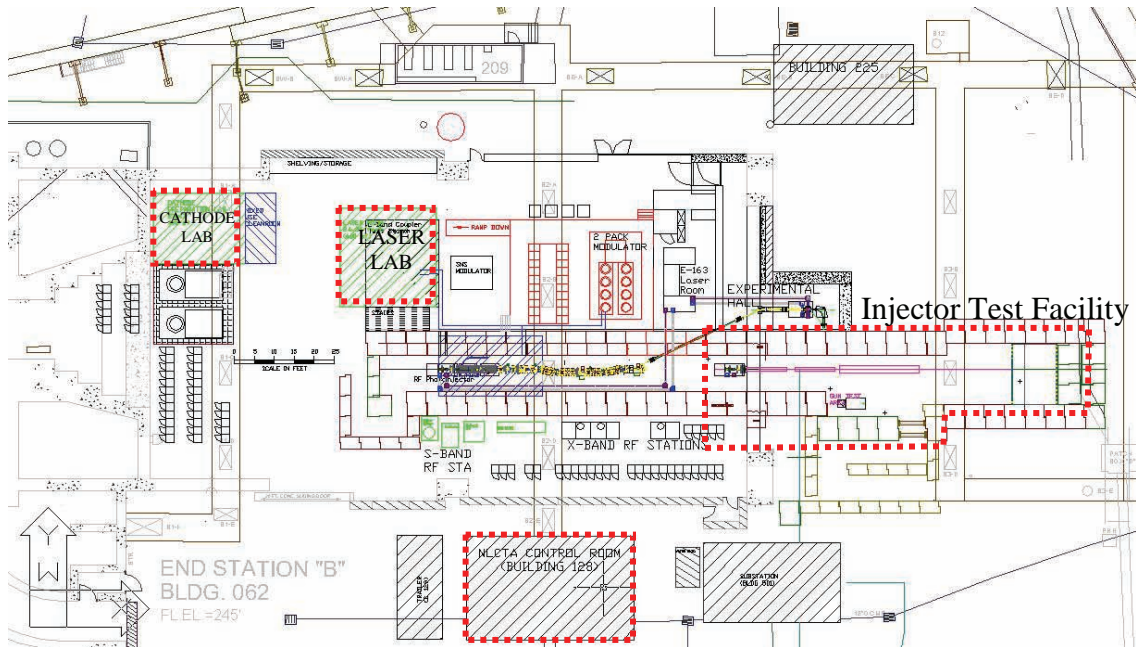


FIGURE B-1. Possible siting of the ITF in End Station B, option 1. All ITF components are within the End Station (building 62). The laser lab and machine shop are new construction. All other facilities are existing or require minor refurbishing.

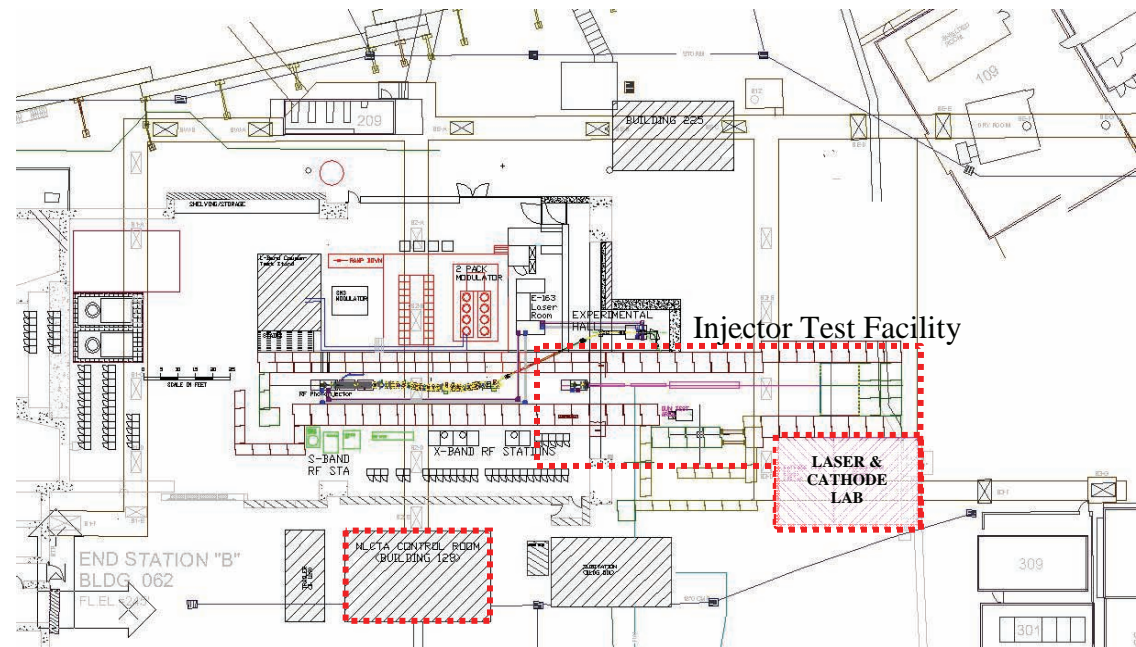


FIGURE B-2. Possible siting of the ITF in End Station B, option 2. The Laser room and cathode preparation lab are housed in a separate, new building outside the End Station. The machine shop is new construction; all other facilities are existing or require minor refurbishing.

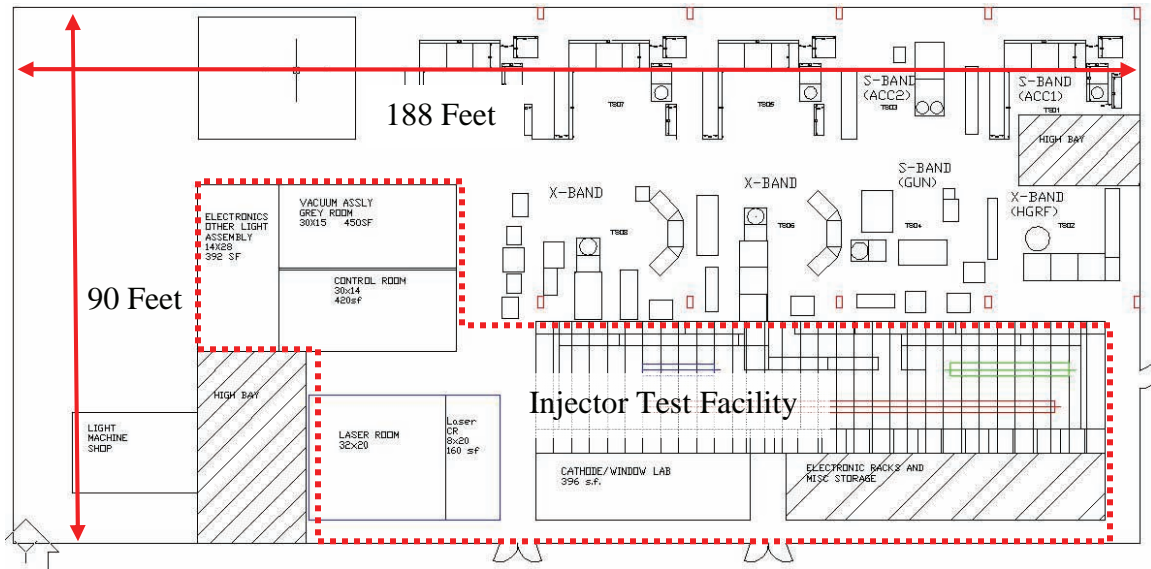


FIGURE B-3. Possible siting of the ITF at the Klystron Test Lab (building 44). Removal of offices in the southeast corner of the building to make way for the expansion of the ASTA enclosure is required. The laser room is an expansion of an existing structure.

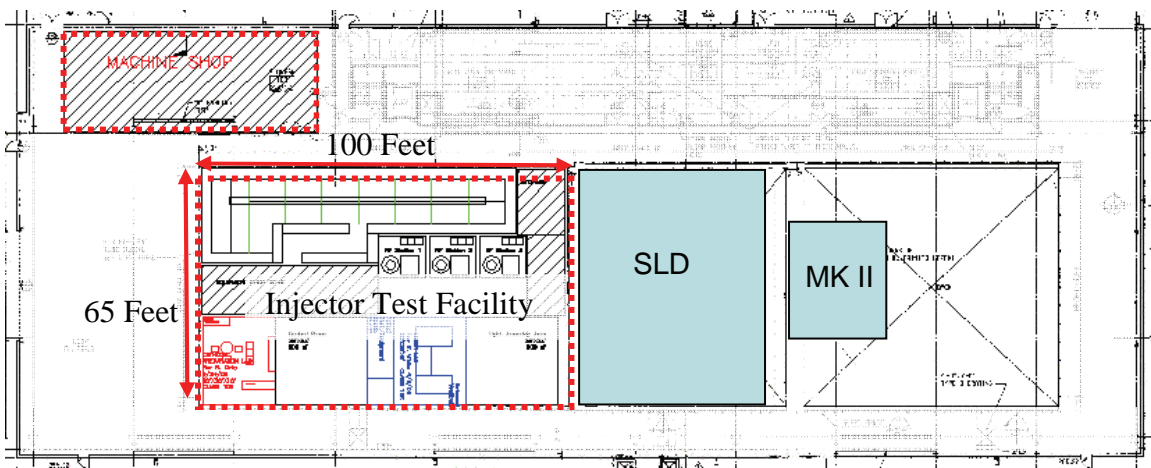


FIGURE B-4. Possible siting for the ITF in the SLD Collider Hall (building 750). Site cleanup and seismic preparation are required, as is installation of 480V service feeders and refurbishment of the LCW system. The machine shop is existing; all other ITF facilities are new construction.

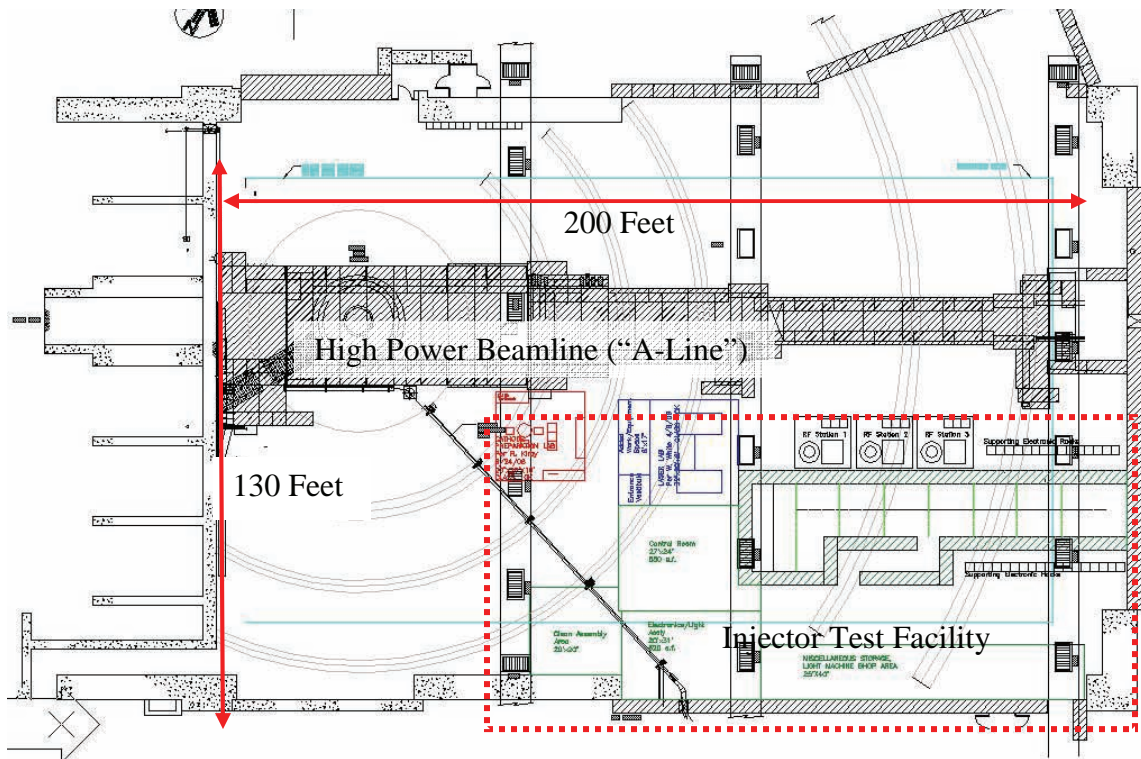


FIGURE B-5. Possible siting of the Injector Test Facility within End Station A (building 61). Minor cleanup of existing stored objects, and installation of 480V service feeders are needed for this site. The ITF facilities in this case are all new construction.

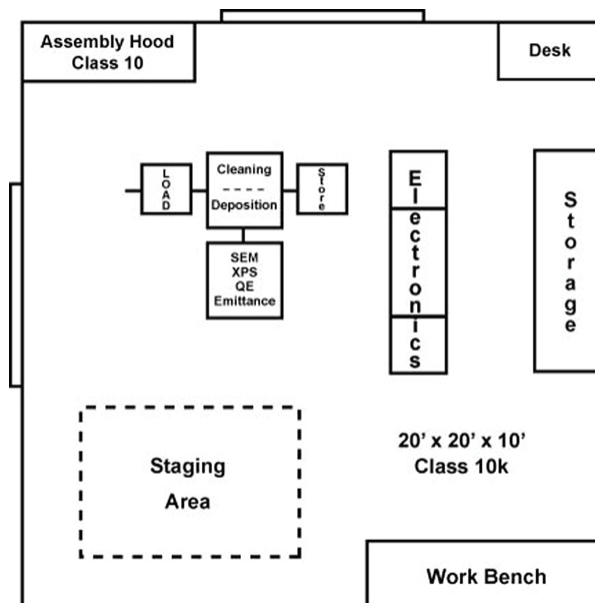


Figure B-6: Cathode Preparation Laboratory (CPL), located near the injector. Acronym list: Secondary Electron Microscopy (SEM), X-ray Photoelectron Spectroscopy (XPS), Quantum Efficiency (QE).

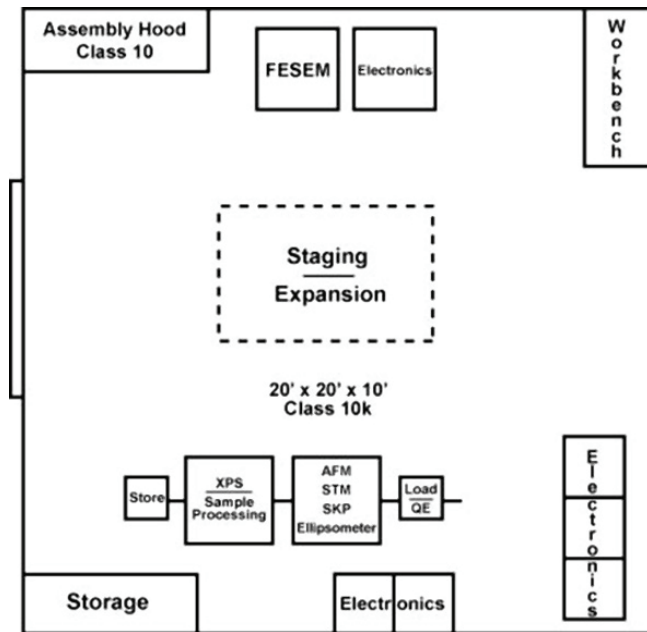


Figure B-7. Cathode Research Laboratory (CRL). Acronyms: Field Emission SEM (FESEM), Atomic Force Microscopy (AFM), Scanning Tunneling Microscopy (STM), Scanning Kelvin Probe (SKP).

Appendix C. Injector Test Facility Task Force Membership

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