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A TUNABLE, LINAC BASED, INTENSE, BROAD-BAND THz SOURCE FOR PUMP-PROBE EXPERIMENTS

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A tunable, linac based, intense, broad-band THz source for pump-probe experiments

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THz Motivation

We propose an intense THz source with tunable frequency and bandwidth that can directly interact with the degrees of freedom that determine the properties of materials and thus provides a new tool for controlling and directing these ultrafast processes as well as aiding synthesis of new materials with new functional properties. This THz source will broadly impact our understanding of dynamical processes in matter at the atomic-scale and in real time. Established optical pumping schemes using femtosecond visible frequency laser pulses for excitation are extended into the THz frequency regime thereby enabling resonant excitation of bonds in correlated solid state materials (phonon pumping), to drive low energy electronic excitations, to trigger surface chemistry reactions, and to all-optically bias a material with ultrashort electric fields or magnetic fields. A linac-based THz source can supply stand-alone experiments with peak intensities two orders of magnitude stronger than existing laser-based sources, but when coupled with atomic-scale sensitive femtosecond x-ray probes it opens a new frontier in ultrafast science with broad applications to correlated materials, interfacial and liquid phase chemistry, and materials in extreme conditions.

Such experiments become accessible using intense THz fields that are approaching atomic bonding strength in matter. To reach this ambitious goal, peak electric field strengths of 10MV/cm (0.1V/Å) are required. For such high intensities laser-based sources are limited in their frequency range (<5THz or >20THz), pulse repetition rates of ~1kHz and lack ways for adjusting the bandwidth. Linear accelerator-based THz light sources, which have been pioneered at SLAC, can overcome these limitations. Filling the gap of laser-based intense THz sources we aim for: (i) an electric field of 10MV/cm for single cycle pulses and 1MV/cm for 10-cycle pulses as shown in figure 1, (ii) a frequency range of 5-15THz to cover many relevant phonon modes in correlated materials, and (iii) a repetition rate of 10kHz for high statistics. Changing the bandwidth allows impulsive excitation of the system with a single-cycle pulse or resonant pumping a certain mode with a 10-cycle pulse. Multi-kHz repetition rates enable averaging mode experiments such as photoemission probes but require equidistant pulses to give the excited systems time to relax to the ground state. The timing jitter between the THz accelerator and external probes (such as x-rays from LCLS) of <100fs allows to sample transients within the THz waveform and can be achieved using established techniques. Using post-processing timing corrections we aim at pushing the overall time resolution down to 10fs. Coupling this novel THz light source with femtosecond x-rays from LCLS-I/II presents a unique opportunity to dramatically expand the scope and breadth of time-resolved x-ray science at SLAC. The specifications for the photon beam to achieve the science described above are shown in Table 1.

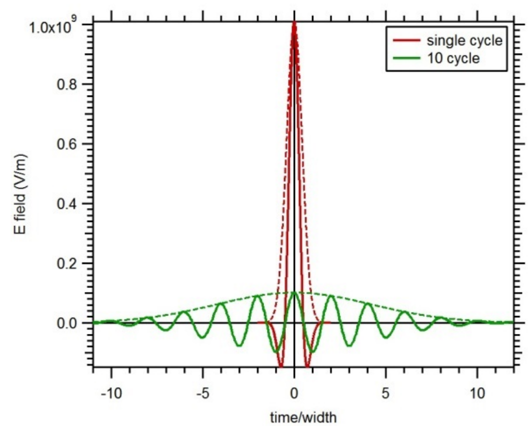

Figure 1: Electric field vs time for single cycle and 10 cycle THz pulses

THz Generation

Preliminary estimates indicate that a low power linear accelerator can generate the electron beam parameters (seeTable 2) necessary to meet the photon specifications. The transverse emittance is quite relaxed compared to state of the art high brightness sources but the pulse length is challenging at <100 MeV which is chosen to reduce the size and cost of the accelerator and associated conventional facilities.

The single-cycle pulses are generated by coherent transition radiation (CTR) from a thin metal foil inserted into the beam; an electromagnet wiggler emits the multi-cycle pulses. Estimates of the wiggler's energy per pulse exceed the desired parameters for narrow-band multi-cycle pulses. Intense lower-frequency pulses (< 1 THz) may be produced with the compact corrugated-pipe structure recently demonstrated by Karl Bane (SLAC) *et al*. Even more powerful broadband single-cycle pulses may be possible by tapering and chirping the wiggler's electromagnets in conjunction with chirp-compensating THz optics.

Three linac options are proposed that use different rf technology to meet the electron specifications. The parameters for the three options are listed in Table 3 and the basic layouts are shown in figures 2-4 and described in more detail below.

Table 1: Photon beam parameters

P-beam Parameters	Single Optical Cycle		10 Optical Cycles	
	5 THz	15 THz	5 THz	15 THz
Pulse Energy (µJ)	4.2	0.37	0.42	0.037
E-Field (MV/cm)	10	10	1	1
Spot Size	200	100	200	100
Pulse Duration (fs FWHM)	100	33	1000	330
Minimum separation (µs)	1	1	1	1
Pulses per second (Hz)	10800	10800	10800	10800
Synchronization to LCLS (fs)	10	10	10	10

Table 2: Electron beam parameters

E-beam Parameters	Single Optical Cycle		10 Optical Cycles	
	5 THz	15 THz	5 THz	15 THz
Charge (pC)	500	100	500	100
Pulse Length (fs)	150	50	150	50
Normalized emittance (µm)	50	50	50	50
Beam Size (µm)	200	150	200	150
Beam Energy (MeV)	60	60	60	60
Energy Spread %	0.4	0.1	0.4	0.1
Pulses rate (kHz)	10.8	10.8	10.8	10.8
Beam Power (kW)	0.32	0.06	0.32	0.06

Table 3: Linac options

Linac Parameters	Option 1	Option 2	Option 3
Bunches per macropulse	10	1	1
Macropulse rate (kHz)	1.08	10.8-1000	10.8
Micropulse separation (µs)	1	NA	NA
Gun Frequency (GHz)	1.3	0.187	11.4
Linac Frequency (GHz)	1.3	1.3	11.4
Linac Gradient (MV/m)	8	18	25
Linac Length (m)	20	15	2.5
Number of Klystrons	4	11	3
Klystron power (MW)	10	0.12	11

Pulsed NC L-band Option

This option is proposed to exploit the L-band (1.3 GHz), normal-conducting (NC) rf technology that was designed, developed or tested during the past eight years at SLAC for the ILC Main Linac rf system development program. In particular, it uses 120 kV Marx Modulators, 10 MW Toshiba Multiple Beam Klystrons and 5 m long TW Accelerator L-band Accelerators. It also uses a high duty, high Q NC rf gun that DESY developed for the E-XFEL project, which has been extensively characterized at PITZ. These or similar components have been operated at the required field and gradient levels with long (1-1.5 ms) pulses at low rate (5-10 Hz). For this application, they would be run with a similar duty factor with short pulses (10-15 μs) at high (1080 Hz) rate, which with their short (< 5 μs) fill times, would allow up to 10 bunches to be generated per pulse that are spaced by at least 1 μs as required for the SLAC THz source. The main concern with the higher pulse rate is the increased transient turn-on and turn-off rate, which will increase the average heat loss in the modulators and the average beam loss in the klystrons.

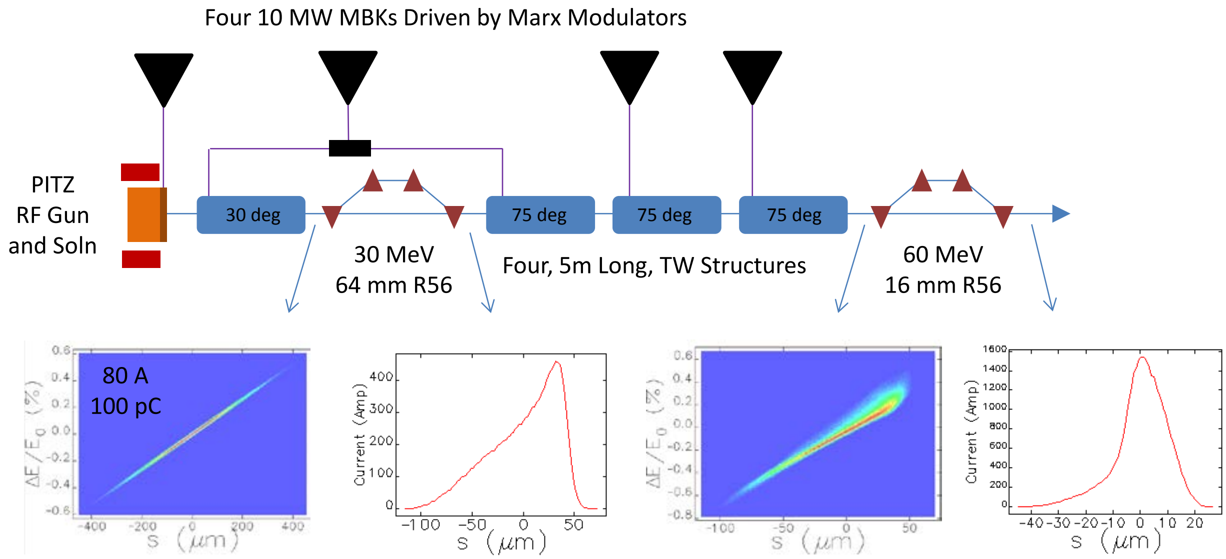

Figure 2: Normal conducting L-band accelerator option relies on tested technology but requires > 30 m long tunnel.

To generate the short electron bunches, this option uses only magnetic compression, which should allow for much easier tuning than the other options that use velocity bunching. Although the PITZ rf gun is nominally designed to generate 'flat' 20 ps pulses at low emittance, it should be able to generate ~ 1 ps rms bunches at higher, but acceptable emittances for the THz application. Shown at the bottom of Figure 2 is the longitudinal phase space evolution of a 80 A, 100 pC bunch from the gun through two stages of compression to produce a ~ 50 fs FWHM electron bunch. The second stage bunch compression requires the use of a low R56 chicane to avoid a large CSR induced energy spread as the bunch is compressed. As a result, a significant linear energy spread along the bunch (i.e. energy chirp) is required, which given the short bunch length after the first bunch compression, means running far off-crest (75 degrees) in the subsequent L-band structures.

To minimize the number of rf sources and the structure average heating, an 8 MV/m gradient is assumed, and to achieve the 60 MeV bunch energy, four, 5-m-long structures are required, which if run on-crest, would produce an energy gain of about 150 MeV.

CW SC L-band Option

This option, which uses CW, L-band (1.3 GHz), superconducting (SC) technology developed for E-XFEL and ILC allows for very high rate operation. It assumes up to 0.3 mA beam currents, which could be configured in various ways, for example, 100 pC bunches at 3 MHz or 500 pC bunches at 0.6 MHz. Its 187 MHz NC gun is of the same design as that being developed for NGLS - a prototype at the LBNL APEX facility has already been operated CW at a 1 MHz bunch rate. The gun is followed by a single cell, NC, L-band buncher cavity of a design developed for the Cornell ERL, and would be powered by a commercially available klystron or IOT, or perhaps two, 10 kW solid state amplifiers (SSAs), such as those made by Bruker. The SC cavities are the 1 m long TESLA style but operated CW as proposed for NGLS, that is, at 1.8 K with a gradient of 16 MV/m where the cavity Qo's should be least 2e10 (vs 1e10 for E-XFEL). The cryogenic system could be similar to that for the 1.5 GHz upgrade cavities at CEBAF, which run CW up to 19 MV/m. Each cavity is driven by a 7 kW SSA to allow for precise phase and amplitude control, which in particular is needed in the upstream, velocity bunching cavities. Such individual control allows for full compensation of the detuning effects of microphonics, which is an issue as the cavities would have narrow BW (around 30 Hz).

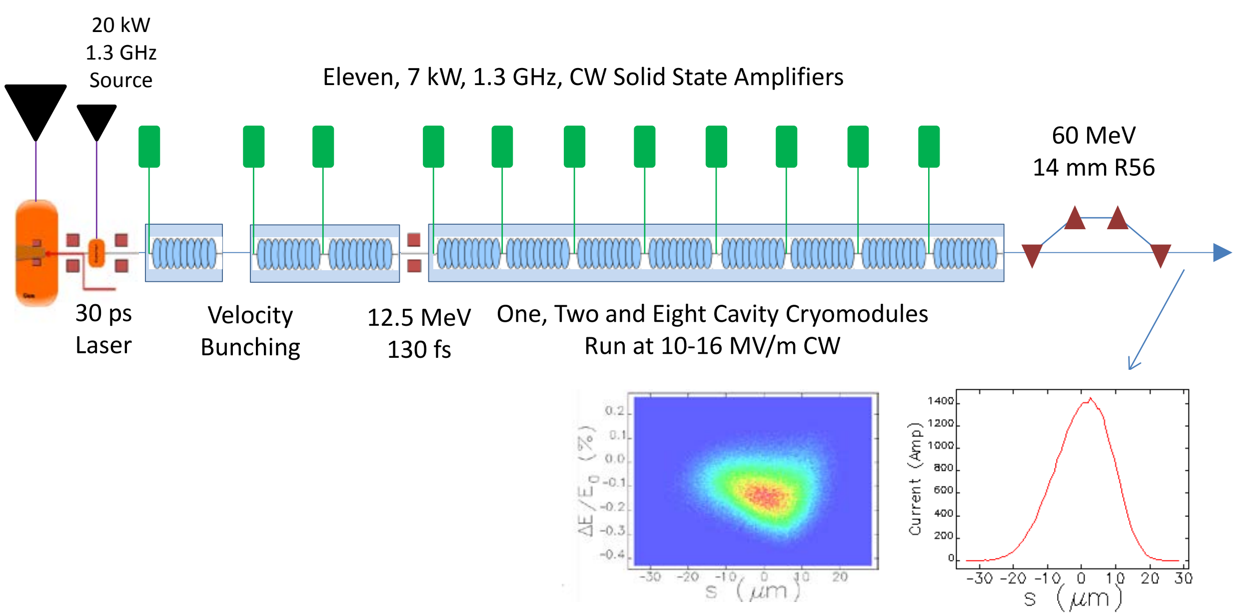

Figure 3: Superconducting L-band accelerator requires an expensive cryoplant but can operate at 1 MHz.

Short bunches are achieved through a combination of velocity bunching and magnetic compression. Simulations of the APEX gun run with 200 pC bunches achieve 130 fs FWHM at 12 MeV after velocity bunching through three SC cavities running at 10 MV/m. As for the NC L-band option, a low R56 chicane is used for the second stage compression. Again, this requires running far off crest, in this case 70 degrees in eight, 1 m cavities operating at 16 MV/m.

Pulsed NC X-band Option

The X-band option exploits the short rf pulses that are possible at high frequency and the very short bunch lengths that can be achieved in a high gradient rf gun when the associated increase in bunch transverse emittance can be largely ignored. To reduce the average heating at the required 10.8 kHz pulse rate, however, the cathode field has to be lowered from the 200 MV/m gradient used in the 5.5 cell XTA X-band gun, and a shorter (2.5 cell), tapered gradient gun design used. A 130 MV/m cathode surface field is assumed, for which ~ 3 MeV bunches of 100 μm rms at 500 pC and 50 μm rms at 100 pC should be achievable with short laser pulses. However, the temperature rise of the cathode cell from average heating will likely be over 50 degC, which will make phase regulation at X-band difficult and may introduce stress problems from thermal cycling. Also, instead of copper, a higher QE cathode material (e.g., CsTe as in the other two options) would likely be needed to reduce the average laser power.

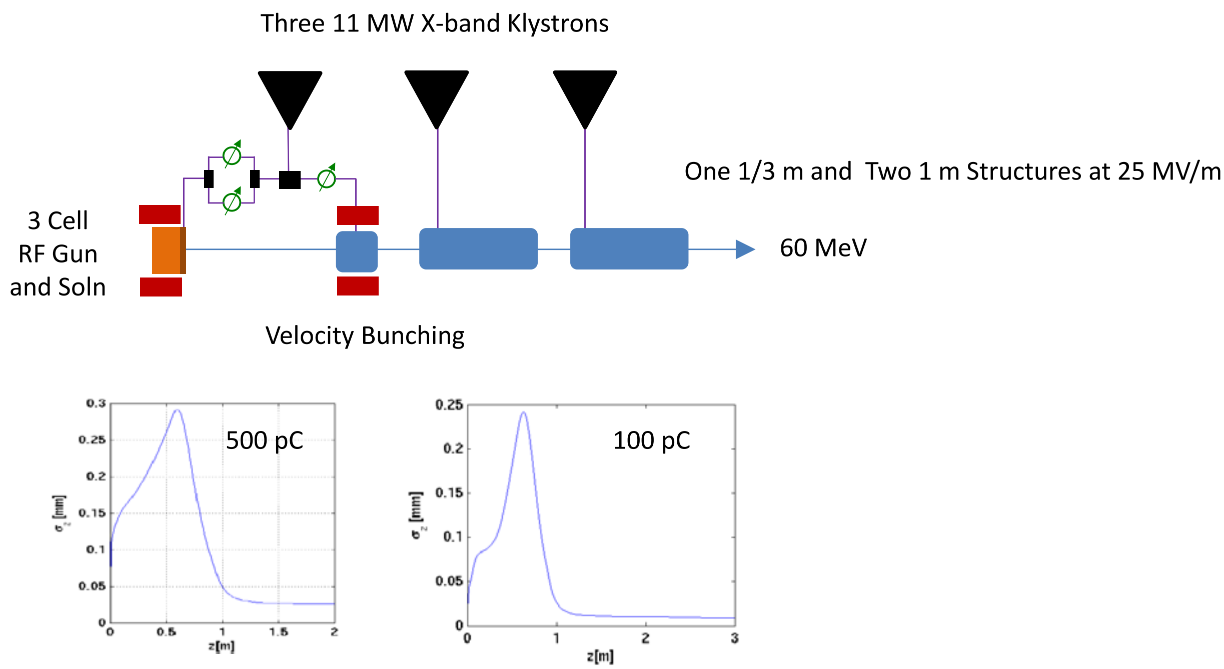

Figure 4: Normal conducting X-band accelerator option offers the most compact and inexpensive solution but requires extensive R&D.

With velocity bunching in a 33 cm long, 25 MV/m structure following the gun, the bunch lengths are further reduced to the desired values, although fairly long 'tails' are produced. To "lock in" the bunch lengths and accelerate up to 60 MeV, at minimum two, 1 m long X-band structures running at 25 MV/m are needed. For the 500 pC case, there may an issue with bunch transmission given the large bunch emittances that result and the small apertures (6 mm diameter cut-off tube) of the X-band structures. Also, the final energy spread of 1% will be significantly larger than those for the other two options.

The accelerators could be comprised of 'short' SW or 'long' TW designs (e.g. like the T105 structures at XTA), and are assumed to be powered from 11 MW klystrons with 150 ns pulses to achieve 25 MV/m gradients. At the required pulse rate, this would produce large (15 kW/m) structure heat loads, at least 8 times that in the high gradient X-band structures that have been operated at SLAC. Currently, X-band klystrons above 10 MW at the required duty factor (0.2 %) do not exist and would have to be developed along with high pulse rate modulators (with 2-4 times the the average power of the SLAC 50 MW XL4 klystrons and modulators) - alternatively, several lower peak power sources could be used.

In summary, this option provides a much more compact design with an overall length of about 5 m (< 1/4 of the other options), and does not use magnetic compression, but it requires much development to reliably achieve the high pulse rate. At 120 Hz, the current XTA design could likely be used for this application.

R&D

There are a number of items for the accelerator and photon beam handling that will require R&D. Most of the accelerator R&D is related to the development of the X-band accelerator structures and power sources as the components in the other two options already exist. However, as all of these schemes rely on a high-charge, well-compressed electron beam, improvements to injector performance offer a direct path to a brighter THz source.

In addition to the accelerator R&D additional work is necessary in the THz generation and diagnostics. Target damage is a real concern for OTR foils especially at high repetition rates and challenges in detectors and efficient transport remain to be solved. Finally the requirement of < 10 fs jitter between the X-rays and the THz photons is beyond state of the art. We propose R&D to develop a method to measure the relative photon arrival time with 10 fs resolution to time-stamp the experiments. The required R&D is listed below along with the estimated cost and time to complete with a total cost of 11 M$.

- X-band Gun/Compression 3 M$ over 2 years
- X-band klystron 2 M$ over 2 years
- APEX gun performed at LBNL
- OTR target damage 1 M$ over 1 year
- Detectors and Transport 3 M$ over 2 years
- 10 fs time stamp (THz relative to X-rays) 2 M$ over 2 years

Technical Risks and Mitigation

Generation of intense THz pulses is predicated on high-charge, ultra-short electron beams from a compact, moderate-energy accelerator. Beam loading requires further simulation, particularly for the proposed X-band gun, even at the minimum charge of 100 pC. The high compression required appears feasible, though more detailed simulations of velocity bunching (X-band case), space charge, and coherent synchrotron radiation (CSR) in the compressor chicanes are necessary.

For single-cycle generation, damage to the radiating thin foil target for CTR is likely at the smallest transverse beam sizes and at maximum compression. Edge radiation or bend radiation in principle provide similar pulse energies without need for a target, though optics need to be reevaluated for isolating the desired pulse. This source will benefit from experience with CTR from different materials at the existing THz sources on LCLS and FACET and from collaborative studies of foils with the THz facility at the Helmholtz Center in Dresden, Germany (HZDR).

Synchronization to LCLS sources on the fs scale also needs to be addressed. Existing RF and laser synchronization solutions at SLAC limit drift to 1 ps, with jitter on the order of 100 fs. Further improvement requires post-installation R&D. Since the jitter is comparable to the pulse duration, we will use demonstrated methods to adapt the “timing tools” employed at LCLS to the THz regime. This approach will measure the relative time of arrival of THz and x-ray pulses at the experiment, providing time-stamps for the data for analysis and correction.

Where direct optical mixing of x-rays and THz pulses is restricted by lack of a medium, methods based on mixing with a common, split IR pulse can instead be used. Development of robust, repeatable solutions using these techniques is mandatory to meet user needs.

There are at present no accepted standards for absolute calibration of THz energy detectors. Measurements now rely on comparing detectors and assume a good knowledge of the source. The German standards agency Physikalisch-Technische Bundesanstalt (PTB) in Berlin has recently developed calibrations to 5 THz and is working to span the gap to the infrared. The collaboration with HZDR will include comparisons of detectors, including those tested by the PTB.

Finally, the optical transport systems needed to image pulses over the ~200 m distance from the THz facility to the LCLS experimental areas also need further elaboration. DESY has already demonstrated >80% transmission over 20 m for $f > 0.3$ THz. The greater distance proposed requires a study of diffraction-limited imaging with the tight optomechanical tolerances in a vacuum sufficient to prevent atmospheric absorption. A proposed 40-m transport line from the FACET THz table to the laser room above the tunnel can serve as a testbed.

Schedule and Impact to Operations

A conservative estimate for facility construction (18 months), accelerator design/ fabrication (24 months) and installation/commissioning (12 months) is approximately three years. The impact to SLAC operations is minimal since much of the construction work is done at a site completely independent of LCLS. Parts of the construction that do impact operation such as digging or compacting that may cause significant vibrations and tunneling into the LCLS experimental halls as well as photon transport system installation would need to be scheduled during shut down periods. The majority of the building construction and all of the accelerator installation and commissioning would not impact LCLS operations and could continue during LCLS runs.

Location on the SLAC Site and layout

A proposed layout of the facility is shown in Figure 5 along with the location at SLAC relative to LCLS I and II. A 40 m long accelerator enclosure supports the full length of all *e*-beam components for any of the three options, including final radiators. Space for supporting RF and magnet power and a local control room is included.

To facilitate THz pump, x-ray probe experiments, the facility must be reasonably close to the LCLS Near Experimental Hall (NEH) and LCLS-II Experimental Hall (EH), with a transport line to both. Experimenters in these Halls are expected to be the primary users of THz with x rays. An extension to the LCLS Far Experimental Hall (FEH) is possible but has not been considered. THz diagnostics and experiments not requiring x-rays, would be located adjacent to the linac enclosure. Light from the drive-laser room, inherently synchronized with the THz, is also available for experimenters.

Figure 5: Layout of the proposed THz facility. The facility would be located adjacent to LCLS I and II. The accelerator enclosure could be much more compact for the X-band accelerator option.

The cost estimate is based on the construction of a new building, 40 m by 15 m, as shown in Figure 5. The land is relatively flat and open, and adjacent to PEP Ring Road. An interesting alternative is the end of the SLC South Arc as it enters the Collider Hall (750). This existing tunnel passes under the LCLS X-Ray Tunnel between the NEH and FEH and under the EH. The accelerator, THz sources and transport could be housed in the tunnel, while the SLC pit offers ample space for support hardware (power, RF, laser). However, the extensive decommissioning and repurposing is beyond the scope of this proposal.

The Costing Methodology and Summary

Introduction

Costing of the three options is based on LCLS-II costs (civil construction and technical), cost estimates for high-repetition-rate linac options listed elsewhere in this document (linac RF), and engineers estimates (special transport and diagnostic equipment).

Table 4: THz option components

THz Source Equipment	Option 1 (NC L Band)	Option 2 (SC L Band)	Option 3 (X Band)
Total Length (m)	35	30	20
Linac Length (m)	20	15	2.5
Number of Klystrons	4	11	3
Klystron power (MW)	10	0.12	11
Injector RF source	1 Klystron	UHF source	½ Klystron
Accelerator AC Power (MW)	2	2	2

Injector

Option 1 uses an L-band photocathode RF gun ('Pitz/XFEL'-type) and Option 3 uses an X-band RF gun ('XTA'). Option 2 uses a low frequency (100 MHz) APEX gun (LBNL). Following the LCLS-II scheme, the injector system includes the laser, RF gun, high-level RF for the gun and RF and /or magnet systems up to the end of the first buncher. For Option 1, this is to the end of the magnetic buncher at 30 MeV, for Option 2, this is to the end of the velocity buncher after the capture cavity, and for Option 3, this is to the end of the velocity buncher. Since each option thus includes the gun and a single RF structure (roughly half of LCLS-II). The injector RF structure, the RF structure, Controls and Installation cost for options 1 and 3 is assumed one half of the cost of the LCLS-II injector system. Other costs: Power Conversion, Laser, Supports, Vacuum and Other are assumed to be the same. Diagnostics are accounted for the linac and are not included here.

Linac

The linac cost estimate is based on the LCLS-II L1 cost estimate for all items except for the RF system. The linac extends from the end of the injector through to the end of 'BC1'.

The Option 1 linac uses three 5-meter long L-band structures powered by three ILC-type 10 MW L-band klystrons. The structure and waveguide costs are from engineering estimates. The HLRF costs are from the ILC TDR cost estimate

The Option 2 linac uses two cryomodules, one with two cavities and one with eight cavities. The cost for this system, including cryogenics, is adapted from the 'superconducting linac cost' table in an earlier section in this document. Each linac cavity is powered by a small solid state amplifier. This cost is from engineering estimates.

The Option 3 linac uses two 1 meter X-band structures powered by two 11 MW X-band klystrons. These costs are adapted from the X-band high-repetition rate linac in an earlier section in this document.

Terahertz Source

The single-cycle terahertz source is expected to be a small thin foil target. R&D costs for developing magnet-based sources are not included.

The terahertz radiation transport is a 200 m long vacuum chamber installed in conduit. No transmissive elements are included, steering and focusing is done with mirrors.

Civil Construction

The civil construction cost for the terahertz source enclosure (44x14 meters) is scaled (area) from the similar LCLS-II Central Utility Plant (12x21 meters). The terahertz source accelerator concrete enclosure cost (40 meters long) is scaled (length) from the LCLS-II beam transport hall (160m) cost.

The terahertz radiation transport conduit cost has been provided by engineering estimate.

Utilities

The electrical service to be installed for LCLS-II (fed from PEP IR-4) has enough capacity to power any one of the three options. Costs to connect the THz source to the LCLS-II CUP are included. It is not clear if LCLS-II water cooling will be able provide the additional needed capacity. The cost of increasing the capacity of CT-1701 is not included. Further work is needed to estimate water cooling system costs.

Cryogenics

Option 2 includes 11 CW SRF cavities operating at 16 MV/m with $Q_0 \sim 2^{10}$. These are estimated to dissipate 20 W at 2K; requiring roughly 250 kW of AC power for cryogenics.

Cost Basis summary

Option 1

		TOTAL
		47,770,350
System - Level 2		TOTAL
1.02 - Injector System		**13,033,410**
1.03 - Linac System		**13,507,342**
	Linac and Bunch Compressor	
	1.03.02 - L1	**7,984,303**
	1.03.03 - BC1	**4,153,800**
	Beamlines	
	1.03.08 - Linac to Undulator (LTU)	1,055,863
	1.03.09 - Electron Dump (EBD)	313,376
1.07 - Global Interface Systems (GIS)		**973,822**
1.09 - Conventional Facilities		**18,855,776**
	1.09.02 - A&E Professional Services	3,142,629
	1.09.04 - Beam Transport Hall (BTH)	2,200,733
	1.09.11 - Central Utility Plant (CUP)	13,512,413
1.10 - ACD, Spares, & Commissioning		**1,000,000**
1.12 - THz transport		**400,000**
	1.12.02 - Conduit Installation	100,000
	1.12.03 - Vacuum and diagnostics	300,000

Option 2

		TOTAL
		67,794,081
System - Level 2		TOTAL
1.02 - Injector System		**11,441,371**
1.03 - Linac System		**20,694,482**
	1.03.02 - L1	11,724,303
	1.03.03 - BC1	4,153,800
	1.03.08 - Linac to Undulator (LTU)	1,055,863
	1.03.09 - Electron Dump (EBD)	3,760,516
1.07 - Global Interface Systems (GIS)		**973,822**

1.09 - Conventional Facilities		**18,855,776**
	1.09.02 - A&E Professional Services	3,142,629
	1.09.04 - Beam Transport Hall (BTH)	2,200,733
	1.09.11 - Central Utility Plant (CUP)	13,512,413
1.10 - ACD, Spares, & Commissioning		**1,000,000**
1.11 - Cryogenics		**14,428,631**
	1.11.02 SC Linac Cryogenics	14,428,631
	1.11.03 - Undulator Cryogenics	
1.12 - THz transport		**400,000**
	1.12.02 - Conduit Installation	100,000
	1.12.03 - Vacuum and diagnostics	300,000

Option 3		**TOTAL**
		42,510,350
System - Level 2		TOTAL
1.02 - Injector System		**13,033,410**
1.03 - Linac System		**8,247,342**
	1.03.02 - L1	**2,724,303**
	1.03.03 - BC1	**4,153,800**
	1.03.08 - Linac to Undulator (LTU)	1,055,863
	1.03.09 - Electron Dump (EBD)	313,376
1.07 - Global Interface Systems (GIS)		**973,822**
1.09 - Conventional Facilities		**18,855,776**
	1.09.02 - A&E Professional Services	3,142,629
	1.09.04 - Beam Transport Hall (BTH)	2,200,733
	1.09.11 - Central Utility Plant (CUP)	13,512,413
1.10 - ACD, Spares, & Commissioning		**1,000,000**
1.12 - THz transport		**400,000**
	1.12.02 - Conduit Installation	100,000
	1.12.03 - Vacuum and diagnostics	300,000