STATUS AND UPGRADES OF THE NLCTA FOR STUDIES OF ADVANCED BEAM ACCELERATION, DYNAMICS, AND MANIPULATION*

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Abstract

The Next Linear Collider Test Accelerator (NLCTA) is a low-energy electron accelerator (120 MeV) at SLAC that is used for ultra-high gradient X-band RF structure testing and advanced accelerator research. Here we give an overview of the current program at the facility, including the E-163 direct laser acceleration experiment, the echo-enabled harmonic generation (EEHG) FEL experiment, narrow-band THz generation, coherent optical transition radiation (COTR) studies, microbunching instability studies, and X-band structure testing. We also present the upgrades that are currently underway and some future programs utilizing these upgrades, including extension of the EEHG experiments to higher harmonics, and an emittance exchange experiment.

INTRODUCTION

The NLCTA is a low-energy electron accelerator (120 MeV) at SLAC used for ultra-high gradient X-band RF structure testing and advanced accelerator research. The layout of the NLCTA facility is shown in Fig. 1. At the NLCTA, the electron beam is generated in a 1.6 cell BNL/SLAC/UCLA S-band photocathode rf gun and is boosted to 60 MeV in an X-band linac (X1). After passing through a large chicane (C-1), the beam can be either transported into a separate experimental hall for the E163 laser acceleration experiments [1], or used for X-band rf structure testing and other advanced beam dynamics and beam manipulation studies. Recently, a new beam line which in-

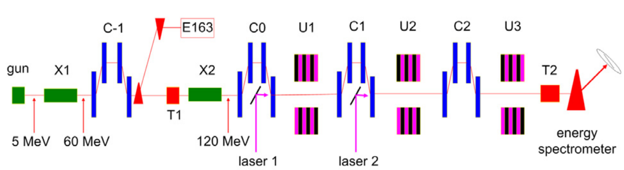

Figure 1: Layout of the NLCTA facility

cludes three undulators (U1, U2, and U3) and three chicanes (C0, C1, and C2) has been constructed to test the EEHG [2, 3] technique. The facility is currently undergoing various upgrades, including redesign of the beam energy spectrometer for higher energy resolution, and installation of two X-band transverse cavities (T1 and T2) for beam heating and measurement of beam slice parameters. After the upgrades, the NLCTA will provide an excellent base for the benchmarking of EEHG theory. It also offers much of the required infrastructure for studies of other advanced accelerator concepts. Below we give an overview of the status and detail the upgrades to the NLCTA, and present some future programs that can benefit from the unique capability of this facility.

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NLCTA CURRENT PROGRAM

E-163 Laser Acceleration

E-163 experiments aim at replacing microwave power from klystrons with laser-generated visible light to boost the energy of particles. The NLCTA beam after chicane C-1 (60 MeV) is transported to a separate experimental hall for laser acceleration studies.

Phase stable net acceleration of electrons from a two-stage optical accelerator has been demonstrated [1]; currently the E163 group is seeking to demonstrate that particles can be accelerated in photonic crystals [4].

ECHO-7

ECHO-7 is a generic proof-of-principle experiment to demonstrate the EEHG technique for seeding short-wavelength FELs. In the EEHG scheme, the beam is energy modulated by a laser with wave number k_1 in the first modulator and then sent through a chicane with strong dispersion, after which complicated fine structure is introduced into the longitudinal phase space. A second laser with wave number k_2 is used to further modulate the beam energy in the second modulator. After passing through a second chicane, the echo signal then occurs at the wave number $k_E = nk_1 + mk_2$ as a recoherence effect, where n and m are integers. The main advantage of EEHG is that the bunching factor is a very slowly decaying function of the harmonic number, thus allowing the generation of coherent soft x-ray radiation directly from a UV seed laser in a single stage.

To test the EEHG technique, an additional X-band structure (X2) was installed to boost beam energy to 120 MeV, and a new beam line including three undulators and three chicanes was constructed. In the ECHO-7 experiment, the laser wavelength in U1 is 795 nm and that in U2 is 1590 nm. The echo signal at harmonic frequencies of the second laser will be generated in U3 and reflected out with an OTR screen to a UV spectrometer.

To date, the 5th harmonic of the second laser has been observed and the basic physics of EEHG has been verified [5]. The ECHO-7 team is working to extend the harmonic number to higher values and to fully benchmark the EEHG theory to confirm that it can be scaled to x-ray wavelengths.

Narrow-Band THz Generation

Narrow-band THz radiation is routinely obtained through difference frequency generation of two lasers in crystals. Researches are now trying to demonstrate that a relativistic charged particle beam can be used as a nonlinear medium for this purpose as well [6]. At the NLCTA, this experiment will make use of the EEHG beamline. The only modifications necessary are to reduce the R_{56} of C1 to a miniumum value, and to tune the wavelength of the seed laser in U2 to 1550 nm. This generates a beat-wave energy modulation in the electron beam at 10 THz, which is then converted to density modulation in C2. Narrow-band THz radiation is generated at a CTR foil, and is measured with a standard Michelson interferometer and a bolometer. A transverse cavity (T2) will be used to directly resolve the density-modulation in the beam at THz frequencies. The laser wavelength and beam energy chirp will be varied to demonstrate the flexibility of this scheme in generating tunable narrow-band THz radiation.

Studies of Microbunching Instabilities

During the commissioning of the ECHO-7 experiment, unexpected COTR was observed during off-crest acceleration in X2 and subsequent compression in C0. Simulations show that the compressed bunch length is about 30 fs, which is too long to generate coherent radiation at optical wavelengths. It is likely that the initial ripples in the temporal profile of the drive laser were compressed and amplified through the microbunching instability to generate COTR. Note, NLCTA has four chicanes, so the microbunching gain can potentially be very high.

A typical beam image and wavelength spectrum of the radiation measured with the presence of COTR is shown in Fig. 2. Instead of a regular Gaussian shape, a donut-like distribution was observed. This is consistent with the theoretical prediction that when electron beam is transversely coherent, the OTR image of the beam will show the gradient of the transverse distribution, which is a donut for a Gaussian distribution [7]. The presence of spectral lines is a strong indication that the beam temporal profile has fine structure. The details of the studies are presented in a companion paper of these proceedings [8].

X-Band RF Structure Testing

The rf sources at the NLCTA also allow ultrahigh gradient X-band structure testing, where there are two X-band rf

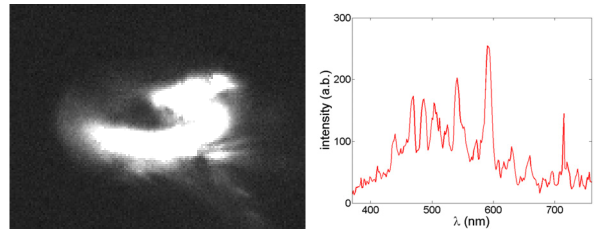

Figure 2: Typical COTR image (left) and wavelength spectrum (right).

stations available that produce up to 300 MW, 250 ns pulses at 60 Hz. The X-band structure testing program can be run in parallel with beam operations. The latest structures, part of a SLAC-CERN-KEK collaboration, have been reliably operated at 100 MV/m [9].

NLCTA UPGRADES

The NLCTA facility is undergoing many upgrades, which will greatly enhance its capabilities. Specifically, the beam energy spectrometer was redesigned for higher energy resolution (with dispersion increased from 0.5 to 1.5 m) and was installed in March 2011. Two X-band transverse deflecting cavities (Fig. 3), one for heating beam slice energy spread (T1) and the other for measurement of beam slice parameters and laser-induced beam energy modulation amplitudes (T2), have been fabricated and will be installed in late March 2011. Furthermore, the laser system has been upgraded to provide more power and greater stability, and an in-vacuum UV spectrometer has been installed to allow extension of the EEHG experiment to the VUV range. The control system is being upgraded to an all EPICS based system as well. While the first stage of

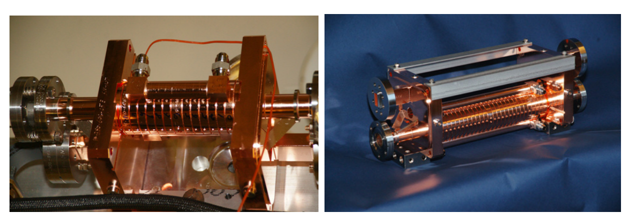

Figure 3: Photograph of the transverse cavities T1 (left) and T2 (right).

the ECHO-7 experiment has demonstrated that the long-term memory of phase space correlations in the EEHG scheme can be preserved, the key advantage of EEHG—that high harmonics can be generated with small energy modulation—has not been demonstrated because of the low slice energy spread (∼1 keV). To make the energy modulation comparable to the beam slice energy spread while limiting the chicane size to a reasonable level, the beam slice energy spread will be increased to ∼10 keV using a small transverse cavity. In a transverse cavity, the beam slice energy spread increases by $\sigma_\delta = K\sigma_x$, where

$K = 2\pi eV/\lambda_{rf}E$ is the dimensionless strength of the transverse cavity, V is the voltage of the cavity, and E is beam energy. Analysis shows that a small cavity with a voltage of ~ 100 kV is able to heat the beam slice energy spread to ~10 keV while limiting the transverse emittance growth to below a permissible level.

Another transverse cavity (T2) with a maximum deflecting voltage of 6 MV will be installed for measuring the slice emittance. The cavity, together with the upgraded energy spectrometer, allow the measurement of slice energy spread and laser energy modulation as well. It should be pointed out that the slice energy spread growth in T2, if not controlled, is on the order of ~ 100 keV, which makes it difficult to measure initial slice energy spread and laser energy modulation. To circumvent this issue, a series of insertable collimators with various apertures have been installed just before T2 to reduce the energy spread growth. Simulation shows that with a 100 μm collimator, 30 keV laser energy modulation can be readily resolved, as can be seen in Fig. 4.

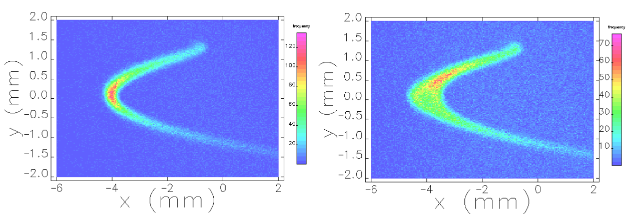

Figure 4: Beam image after the energy spectrometer with laser off (left) and on (right), from simulation. The peak energy modulation is 30 keV.

Once the laser energy modulation amplitudes and beam slice energy spread are known, a full benchmark of EEHG theory becomes feasible.

NLCTA FUTURE PROGRAM

After demonstration of the key advantage of the EEHG technique, that high harmonics (7th in present experimental setup) can be generated with small energy modulation, we plan to pursue EEHG at even higher harmonics to confirm the scaling and identify possible risks in implementing it in x-ray wavelengths.

The NLCTA also offers an excellent base for studies of microbunching instabilities. We plan to imprint a well-defined modulation in the cathode laser, and study the microbunching gain through the beamline. The transverse cavity T1 may be used to Landau damp the microbunching instability by increasing the beam slice energy spread. The transverse cavity T2 together with the upgraded energy spectrometer may allow us to visualize the modulations in beam longitudinal phase space when strong microbunching instability is present.

The transverse cavity T1 will be installed in the center of chicane C-1 to test emittance exchange (EEX) and phase space exchange with a chicane-type beam line [10]. The first beam line proposed for EEX consists of a simple 4-bend chicane and a transverse cavity in the center of the chicane [11]. However, only partial EEX can be achieved with such a beam line. However, recently it was pointed out that the chicane scheme can achieve exact EEX as well, by adding (at least two) quadrupoles before the transverse cavity[10]. Two quadrupoles together with three drifts are used to form a negative unity transfer matrix for the transverse plane, which reverses the dispersion of the first half of the chicane and is optically equivalent to flipping the sign of a dogleg. At the NLCTA the chicane C-1 has 12 integrated quadrupoles, of which three can be easily tuned to provide a negative transfer matrix. Future plans are to test the chicane-type EEX at the NLCTA.

An X-band gun test area (XTA) is currently being constructed in the NLCTA tunnel to test high gradient (~200MV/m) photoinjectors [12]. Several injectors will be tested, including a modified version of the 5.6 cell gun which was originally developed for the SLAC Compton scattering experiment; a new version of the gun developed in collaboration with LLNL for the MEGa-ray project; and the UCLA Hybrid gun. The XTA will also incorporate an X-band structure to accelerate the beam to 100 MeV, and a diagnostic station with an X-band deflecting cavity and a beam energy spectrometer. High power rf tests are scheduled to start in the summer of 2011, with photoelectrons expected in late 2011.

SUMMARY

The NLCTA is a dedicated facility for ultra-high gradient X-band RF structure testing and advanced accelerator research. Its capabilities will be greatly enhanced after current upgrades, and can have a strong impact on emerging studies of advanced beam acceleration, dynamics, diagnostics, and manipulation.

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