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HIGH REPETITION RATE ULTRAFAST ELECTRON DIFFRACTION AT LBNL*

D. Filippetto, M. Mellado Munoz, H. Qian, F. Sannibale, R. Wells, W. Wan, M. Zolotorev,
Lawrence Berkeley National Laboratory, 94720 Berkeley, CA, USA

Abstract

Here we propose to use the APEX photo-gun as novel source for time-resolved electron diffraction studies. The electron source has been designed, built and successfully tested at LBNL. It combines a high accelerating field needed for bright beams, MeV electron energy essential for time resolution in gas-phase experiments and studies of bulk processes, together with continuous (CW) operations. Ultra-short electron pulses can be delivered with a maximum repetition rate of 186 MHz, enabling new science to be studied.

We report the design of a dedicated electron diffraction beamline that fits in the space constraints of the APEX tunnel. Simulations of beam properties have been carried out with a genetic optimizer, showing 100 fs time resolution. Beam jitters in energy, time and position are currently being characterized, and a mitigation strategy via fast feedback loops is discussed.

INTRODUCTION

Next revolutionary science instruments will combine high peak brightness for time and space resolution, with high average flux for high Signal-to-noise ratio (SNR) allowing the study of complex structures and probing weak phenomena. Such antagonist requirements demand for high accelerating fields and high repetition rate operations at the same time. While high fields are possible with the use of GHz frequencies (f_{rf}), the cavity wall surface resistance increases with f_{rf}, and so does the power dissipated, eventually reaching the limit of what conventional cooling techniques can handle (~100W/cm^2). Furthermore the electron beam slippage in rf guns does not allow to take full advantage of the very high peak field achievable using GHz frequencies, as the optimum injection phase can be far away from the on-crest phase, thus lowering the effective field at the cathode. The Advanced Photo-injector EXperiment (APEX) at the LBNL has been designed to demonstrate the brightness performance of an injector based on the new concept VHF RF photocathode gun developed at LBNL [1,2]. The Gun main parameters will be briefly described in the next section, while a complete description can be found in [1,3].

Although the main goal of the APEX project is the demonstration of the required performances as an injector for MHz repetition rate FELs, this source of high-flux ultrafast electron pulses can also be used for different applications. In this paper we discuss the use of APEX for ultrafast electron diffraction (UED) experiments. We describe the main parameters (see Table 1) and the foreseen transport and focusing beamline.

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THE SOURCE PARAMETERS FOR UED

The core of the APEX project is represented by the VHF gun. The design of the gun was optimized for allowing CW operations, excellent vacuum performances and high accelerating fields. In such respect, the choice of a resonant cavity resonating at VHF frequency permits higher fields than DC guns and large apertures for an increased vacuum conductance, while the large volume eases the cooling.

Table 1: APEX Parameters for UED Applications

Parameter	Value
Rep. rate [MHz]	Up to 186
Charge per bunch [fC]	1~3x10^5
Norm. emittance [µm]	~ 0.01-0.6
Gun exit energy [keV]	< =800
Max. Gradient at cathode at photoemiss. [MV/m]	21.5

A theoretical repetition rate up to 186 MHz can be achieved, though the present photocathode laser limits operations to 1 MHz. With such high repetition rate ~µA average current can be produced, keeping a very low charge per bunch. This produces a series of advantages: the average current is similar to the one used in conventional static transmission microscopes (TEMs), suggesting that very accurate and clean measurements would be possible, with excellent spatial resolution. At the same time, bunch charges <1 pC can be longitudinally compressed via rf cavities to produce ultrashort pulses that leading to sub-ps resolution. Also, depending on the particular experiment, the electron beam can be manipulated along the beamline, matching the electron beam probe phase space to the experiment requirements. Lowering the electron current at the sample would allow for smaller emittances (smaller beams at the cathode or transverse collimation), or/and very small energy spreads (energy collimation).

THE PROPOSED UED BEAMLINE

Figure 1 shows a layout of the APEX beamline. The straight line will be used for FEL studies. The beam will

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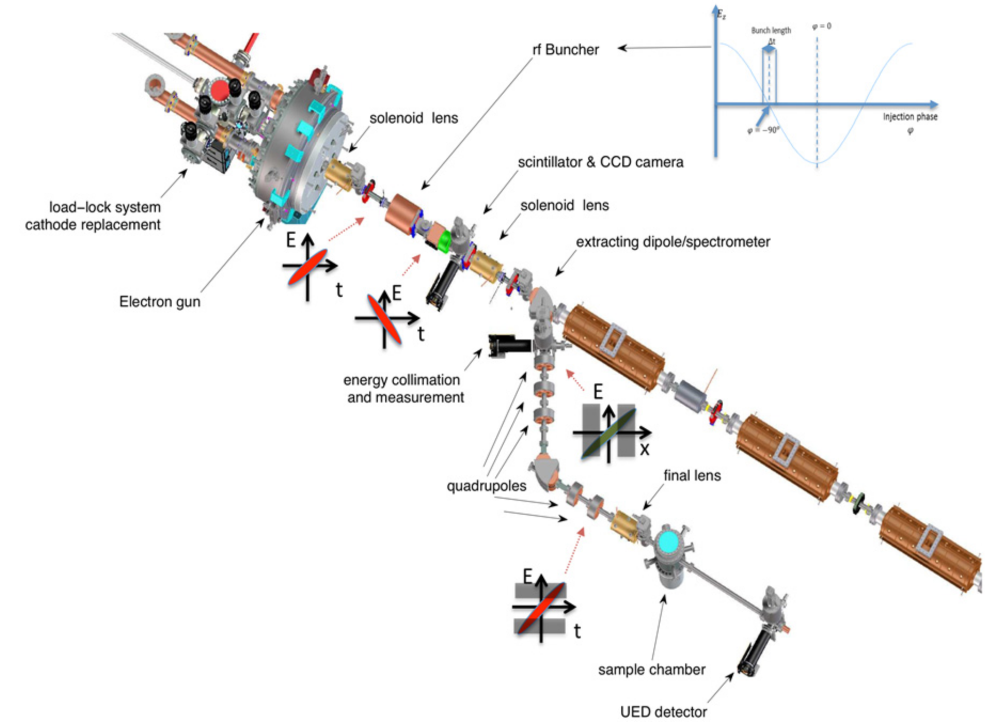

Figure 1: APEX layouts with main components in evidence. Both the FEL and the UED lines are showed.

be accelerated up to 30 MeV, studying emittance compensation and bunch compression. We also foresee a second beamline, departing from the main one right before the injection into the linac. The design of such beamline, showed in Fig. 1, is currently being finalized and will be dedicated to UED experiments.

The UED beamilne is being designed to maintain the maximum flexibility possible on the beam parameter space. Downstream the VHF gun a first solenoid focuses the electron beam in rf buncher [4]. As shown in the upper right inset of the figure, the beam is nominally injected at or close to the zero crossing of the buncher, so that no net acceleration is taking place. The strong negative chirp applied to the quasi-relativistic beam produces longitudinal compression in the following drift. The buncher here can be considered to the first order as a longitudinal lens, so that the final longitudinal waist position and size can be controlled by the initial bunch length, i.e. the laser pulse length. For a nominal peak voltage of 240 kV we found solutions with to 100 fs rms bunch length at the sample chamber (Fig. 2). A second solenoidal lens after the buncher (approx 1.7 m from the cathode plane) focus the beam on a diagnostic station placed after the first dipole magnet. The dogleg line includes two 60-deg. dipole bends and three quadrupoles for achieving overall achromaticity. The horizontal dispersion at the first viewscreen along the dogleg is about 0.15 m, allowing energy collimation using vertical apertures. Two quadrupole magnets downstream the dogleg shape the beam for final focusing by the last solenoid into the sample chamber. This setup will allow small spots on the sample, enabling diffraction of single sub-µm objects, toward ultrafast nano-diffraction experiments chemical dynamics and, eventually, biological dynamics and imaging. A high resolution imaging system downstream the sample chamber is will collect the diffraction patterns using an ultralow noise CCD detector. We are also presently studying the possibility of building an rf deflecting cavity similar to the one being installed for the APEX straight line [5], and placing it right after the sample chamber for bunch length and time resolved measurements (not in the baseline design).

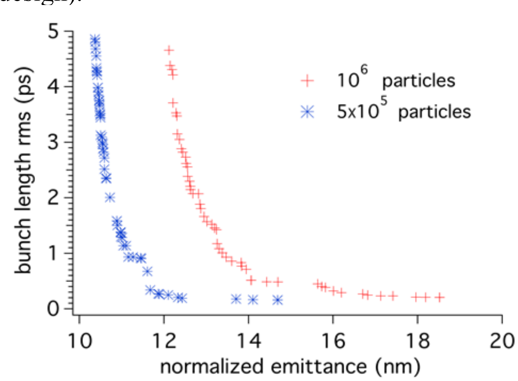

Figure 2: Preliminary ASTRA simulations for the proposed UED beamline. The plot shows results of a genetic optimization of emittance and bunch length at the sample.

Figure 2 shows the results of preliminary ASTRA [6] simulations on the beamline. The plot shows an optimum curve as result of beamline optimization for bunch length and transverse emittance at the sample chamber. A genetic algorithm was used for this, optimizing the beamline elements magnetic strength. The figure shows

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the trade-off between transverse emittance and pulse length, and suggests that a normalized emittance below 20 nm can be achieved with 100 fs beams at the sample and 10^6 particles. Such low transverse emittance is achieved by using long laser pulses for photoemission. The laser aspect ratio (Radius over Length) is indeed much smaller than 1 in all our simulations, allowing the transverse emittance to be minimized at expenses of initial beam current [7]. The electron beam is then longitudinally compressed by the rf buncher [8] downstream the gun, keeping the transverse emittance constant and maximizing the 5D brightness. Optimization of transverse emittance and current is thus performed separately, allowing to potentially reaching very high brightness [7].

Another key point of a UED beamline is minimization of jitters, in time space, and energy. In the APEX case, the very high repetition rate allows the characterization of system noise up to very high frequencies (half the repetition rate), and the consequent design of fast feedbacks to cure and minimize beam fluctuations. The characterization of the laser and electron beam jitters is already started, an rf chassis has been developed for jitter measurements, that accepts -50 dBm input signals from photodiodes, beam position monitors, or faraday cups, and, after mixing with a reference, outputs a DC signal that can be studied using an FFT analyzer.

Figure 3 shows some very preliminary results, correlating UV laser pulse energy jitter to electron beam charge jitter. The 100 kHz frequency span is limited by the instrument.

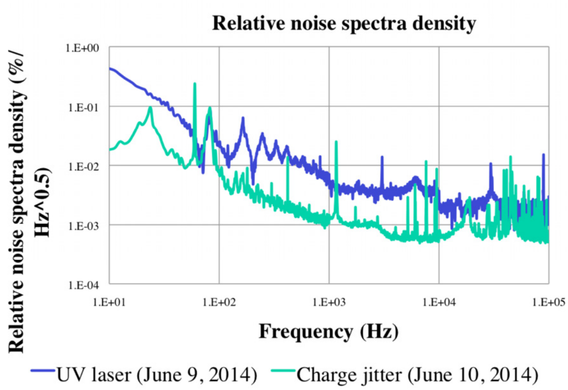

Figure 3: Noise spectral density of UV laser energy (blue), and electron beam charge (cyan), measured by taking the signal from a stripline BPM.

FUTURE ACTIVITY AND PLANS

The UED beamline has recently been founded by DOE-BES. We are now defining the magnets tolerances and will be purchasing and installing the dogleg magnets by February 2015. Jitter studies are started and will be carried out along the machine thorough the next year. Our plan is to find the dominant sources of noise and locally suppress them via fast feedback systems.

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