APEX PHASE-II COMMISSIONING RESULTS AT THE LAWRENCE BERKELEY NATIONAL LABORATORY*

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Abstract

Science needs in the last decade have been pushing the accelerator community to the development of high repetition rates (MHz/GHz-class) linac-based schemes capable of generating high brightness electron beams. Examples include X-ray FELs; ERLs for light sources, electron cooling and IR to EUV FEL applications; inverse Compton scattering X-ray or gamma sources; and ultrafast electron diffraction and microscopy. The high repetition rate requirement has profound implications on the technology choice for most of the accelerator parts, and in particular for the electron gun. The successful performance of the GHz room-temperature RF photo-injectors running at rates <~100 Hz, cannot be scaled up to higher rates because of the excessive heat load that those regimes would generate on the gun cavity walls. In response to this gun need, we have developed at the Berkeley Lab the VHF-Gun, a lower-frequency room-temperature RF photo-gun capable of CW operation and optimized for the performance required by MHz-class X-ray FELs. The Advanced Photo-injector EXperiment (APEX) was funded and built for demonstrating the VHF gun performance, and the results of its last phase of commissioning are presented.

INTRODUCTION

APEX, the Advanced Photo-injector EXperiment [1] at the Lawrence Berkeley National Laboratory (LBNL) is an electron injector test facility dedicated to the characterization of the VHF-Gun [2-4], a new concept electron RF gun developed at LBNL for the generation of high-brightness high-repetition rate electron beams. Specifically, the VHF-Gun was the response to the need of a source capable to generate at MHz-class repetition rate the high quality beams required to operate high-duty cycle X-ray FELs [5]. Indeed, an injector based on the VHF-Gun is in the baseline of the LCLS-II project at SLAC [6].

In the VHF-Gun, the electron bunches are generated by laser-induced photo-emission on high quantum efficiency (QE) cathodes. The particles are then accelerated over a 4 cm gap up to the energy of 750 keV by the 20 MV/m electric field excited in a room-temperature continuous wave (CW) RF cavity resonating at 186 MHz (the 7th sub-harmonic of 1.3 GHz or the 8th of 1.5 GHz, the dominant superconducting linac technologies).

The low frequency choice allowed addressing the two most challenging requirements imposed by the high-repetition rate application: the capability of the gun of running in CW, and the achievement of the extremely low vacuum pressures necessary to operate reactive and delicate high QE photocathodes with acceptable lifetimes. Indeed, at this frequency, the cavity is large enough to lower the power density on the cavity walls to a level that conventional cooling techniques can be used to run in CW mode, while maintaining the high accelerating fields required for the high brightness performance. Also, the long wavelength allows for large apertures on the cavity walls with negligible field distortion. Such apertures provide the vacuum conductance necessary to achieve the desired low pressures.

The APEX project was organized in 3 stages (Phase 0, I and II), with the first two dedicated to the characterization and testing of the VHF-Gun, to cathode testing and to electron beam characterization at the gun energy. In Phase II, a buncher and a linac were added to the VHF-Gun to compress and accelerate the beam to more relativistic energies, reducing space charge forces and allowing characterizing the gun/injector brightness and compression performance.

The experimental results of the first two phases of APEX are reported elsewhere and include demonstration of the VHF-Gun performance [7], characterization of the APEX dark current [8], and demonstration of the capability of Cs_2Te cathodes to operate at the LCLS-II regime [9]. In this paper we report the results of the recent two-month beam measurement campaign to demonstrate the requirements of one of the LCLS-II modes of operation.

APEX PHASE-II DESCRIPTION

Figure 1 shows a CAD layout and a panoramic view of APEX Phase-II beamline. The vacuum loadlock that allows replacing cathodes without breaking vacuum, and the VHF-Gun are visible on the left part. Following the beam path exiting the gun, a focusing solenoid, a 1.3 GHz CW 2-cell buncher cavity [10], and a second focusing solenoid follow. A small pulsed linac composed by two 1m-long 1.3 GHz normal-conducting standing-wave accelerating sections (a modified version of the Argonne AWA structures [11]) follows.

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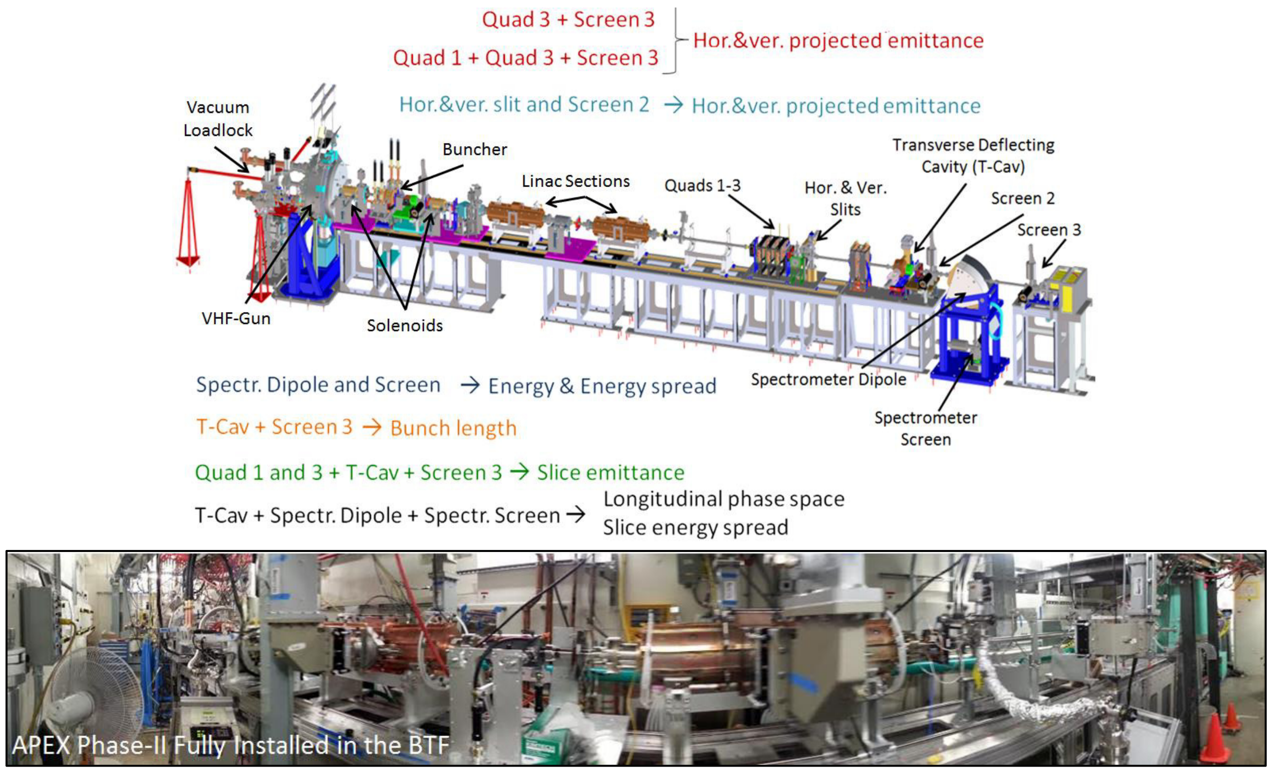

Figure 1: APEX Phase-II beamline. Top: CAD view. Bottom: panoramic photo of the beamline.

Originally the layout included a third accelerating section but due to the delayed delivery by the manufacturer this section was not installed.

As shown in Table 1, the VHF-Gun and the buncher run in CW mode, while the linac operates in pulsed mode with 10 Hz repetition rate. The rationale behind this configuration is that the electron beam 6-D brightness is a single bunch beam property that can be measured at any repetition rate. This allowed the use of a room temperature copper linac with a strong cost reduction and system simplification.

Table 1: Phase-II Beamline Main Operational Parameters

Parameter	Value	Units
Nominal beam energy	16	MeV
Nominal VHF-Gun energy	750	keV
VHF-Gun and buncher mode of operation	Continuous Wave (CW)	
Linac mode of operation	Pulsed 10	 Hz

Downstream of the linac a beam diagnostics suite [12] with 6D beam phase-space characterization capability is located. It includes emittance monitors for space charge dominated or non-dominated beams, a spectrometer, and a 1.3 GHz transverse deflecting cavity (TCav). In the top part of Fig.1, the different diagnostic system combinations used for the beam characterization are indicated. Beam position monitors, steering coils, screens, and charge monitors properly distributed along the beamline complete the diagnostic system.

EXPERIMENTAL RESULTS

The two-month beam tests initiated at the beginning of 2016 were dedicated to the demonstration of the beam performance for one of the LCLS-II modes of operation. Table-2 summarizes the main parameters to be demonstrated and the achieved results.

Table 2: Required and Demonstrated Beam Parameters

Parameter	Required	Demonstrated
Energy [MeV]	>10	15-16
Charge/bunch [pC]	>20	20-22
Peak current [A]	>5	5-9
Norm. emittance [μm]	<0.25	<~0.20*
High order rms energy spread [keV]	<15	<9**

* After accounting for space charge contribution

** Value affected by space charge. Much smaller values at LCLS-II injector energies (~100 MeV).

The measurements were performed with the gun operated in pulsed mode (18 ms RF pulses at 10 Hz repetition rate) instead of CW, and at an energy of 650 keV, instead of the nominal 750, to avoid an arcing issue that gradually developed in the RF window of one of the two gun power feeders. Measurements and simulations indicated that the arcs were associated with electron pile-up in the window ceramics induced by field emission by particulates inside the gun cavity. A window area modification was designed and implemented to eliminate the issue and is presently undergoing RF conditioning.

CsK_2Sb high QE photocathodes produced at LBNL were used for all measurements in combination with a laser pulse of 28.5 ps flat top and few hundreds of µm rms transverse size.

Figure 2 shows an example of a projected emittance measurement done with the quadrupole scan technique.

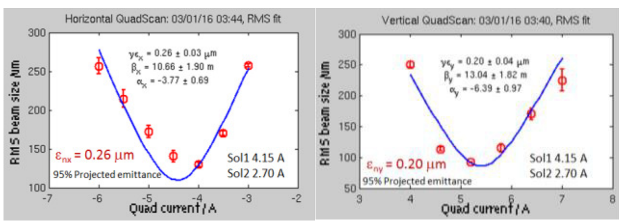

Figure 2: Example of a 95% projected emittance measurement for a 20 pC, 6.5 A peak current and 15.7 MeV beam.

Simulations indicated that space charge forces are still significant at this measurement energy and generate emittance overestimates of more than 50%.

Figure 3 shows the optimized set of solutions for 20 pC obtained by a multi-objective genetic algorithm trading between compression and emittance. The circled crosses indicate the 100% values of the measurement shown in Fig. 2 indicating that in spite of the good values measured, there is still margin for improvements.

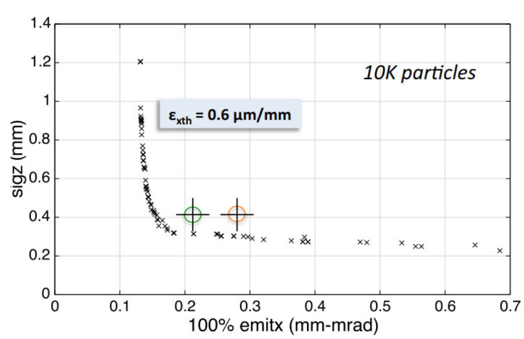

Figure 3: Simulation showing the set of optimized solutions for 20 pC. The two crosses with circles indicate the 100% values of the measurement shown in Fig. 2.

Figure 4 shows an example of longitudinal phase space measurement using the TCav in combination with the spectrometer magnet. The whole phase space and the higher-order (HO) phase space (obtained after removal of the 1st and 2nd order correlations) are shown in the left and right part of the figure respectively. In FELs with harmonic cavity linearizers, the HO phase space is the proper figure of merit for the longitudinal plane. Indeed, the linear correlation can be removed, for example by dephasing part of the downstream linac, and the quadratic term by the harmonic linearizer.

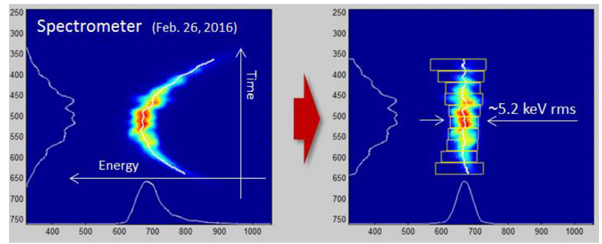

Figure 4: Example of a longitudinal phase space measurement for a 22 pC, 3.2 A peak current and 15.7 MeV beam. Left: full phase space. Right: phase space after removal of 1st and 2nd order correlations.

The 5.2 keV measured value shown in Fig.4 for the HO rms energy spread is a large overestimate of the actual value. Indeed, the measured number is convoluted with a ~ 3.6 keV spread due to the transverse deflecting cavity and also with the spectrometer resolution. Additionally, to as for the transverse case, simulations show that the effect of space charge is significant and can increase the energy spread by more than 50%. It is worth remarking that at the higher energies (~100 MeV) of actual injectors, such space charge effects become negligible.

CONCLUSIONS AND PLANS

A two-month measurement campaign at APEX successfully demonstrated all the beam requirements at 20 pC per bunch, one of the modes of operation of LCLS-II. Near future plans include beam tests for LCLS-II at higher charge per bunch, and the commissioning and first experiments at HiRES, the ultrafast electron diffraction beamline at APEX [13].

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