STATUS, PLANS AND RECENT RESULTS FROM THE APEX PROJECT AT LBNL*

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Abstract

The Advanced Photo-injector EXperiment (APEX) at the Lawrence Berkeley National Laboratory (LBNL) is dedicated to the demonstration of the capability of an electron injector based on the VHF-gun, the new concept RF gun developed at LBNL, of delivering the beam quality required by MHz-class repetition rate X-Ray free electron lasers. Project status, plans, and recent results are presented.

INTRODUCTION

APEX, the Advanced Photo-injector EXperiment at the Lawrence Berkeley National Laboratory (LBNL) is dedicated to the development and test of an injector based on the VHF-Gun [1-3], a new concept high repetition rate high-brightness electron gun. The successful development of such an injector will critically impact the performance of future 4th generation light sources when MHz-class repetition rates are required. In particular, the baseline of the SLAC LCLS-II project [4] includes an injector based on such a gun.

The VHF-Gun is a normal-conducting continuous wave (CW) RF gun where electrons are generated by laser-induced photo-emission on high quantum efficiency (QE) cathodes and accelerated up to the nominal energy of 750 keV. The gun cavity resonates at 186 MHz, the 7th sub-harmonic of 1.3 GHz or the 8th sub-harmonic of 1.5 GHz, the two dominant superconducting linac technologies. The low frequency makes the resonator size large enough to lower the power density on the cavity walls at 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. A second advantage of the low frequency is the long wavelength that allows for large apertures on the cavity walls with negligible field distortion. Such apertures provide the vacuum conductance necessary to achieve the low pressures required to operate the sensitive QE cathodes with acceptable lifetime. A last advantage of such a scheme is that it is based on mature and reliable RF and mechanical technology, an important characteristic to achieve the reliability required to operate in a user facility.

The APEX project was initiated at the end of 2009 and was organized in 3 stages (Phase 0, I and II), with the first two (now completed) dedicated to the development and testing of the gun, cathode testing and electron beam characterization at the gun energy. In Phase II, presently in its very final installation phase, a buncher and a linac are added to the VHF-Gun to compress and accelerate the beam up to 20-30 MeV reducing space charge forces in order to perform a reliable characterization of the gun/injector brightness and compression performance.

The commissioning of the VHF-Gun and the demonstration of all its major design goals are reported elsewhere [5], here we concentrate on the status of the installation of Phase-II of APEX and on the more recent commissioning results.

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PHASE-II DESCRIPTION

Figure 1 shows the CAD layout of APEX Phase-II. The vacuum loadlock that allows replacing the reactive high quantum efficiency (QE) without breaking vacuum, and the VHF-Gun are visible in the left-bottom corner of the figure.

In Phase-II a 1.3 GHz CW buncher is inserted downstream the gun followed by a linac composed by three 1.3 GHz pulsed accelerating section. A suite of beam diagnostics systems capable of 6D beam phase-space characterization completes the accelerator layout.

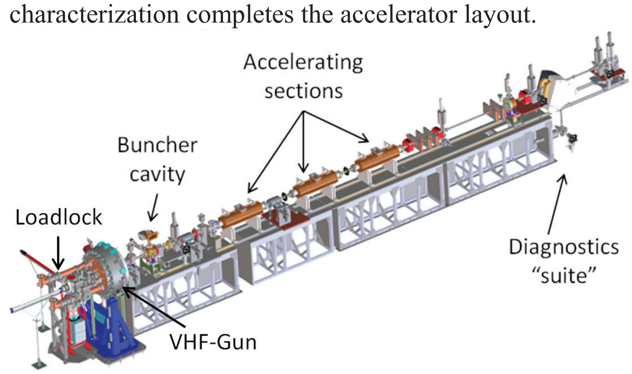

Figure 1: APEX Phase-II Layout.

The buncher, shown in Fig. 2, uses a two-cell design optimized for high shunt impedance and for being multipacting free over the whole range of power [6]. The main parameters for the buncher are shown in Table 1. The RF power is fed in each cell by two coaxial couplers terminated with a loop that couples the magnetic field in the cell. Two additional flanges in each of the cells are

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used to connect a vacuum pump (combined NEG-Ion pumps- NEXTorr type from SAES) and an RF probe.

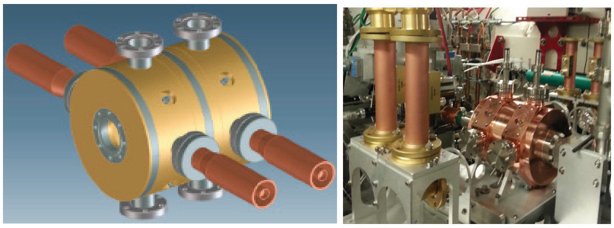

Figure 2. Left: APEX buncher CAD view. Right: a picture of the buncher installed in the Phase-II beamline.

The couplers ports and the additional two flanges were optimized to minimize dipolar and quadrupolar field components induced by the ports themselves and that could degrade beam emittance. The buncher resonance frequency is controlled by the cooling water temperature.

The fabrication of the buncher is completed, the two cells have been frequency tuned and their field balanced using the four dimples in each cell, and the unit is now installed in the beamline. A picture of the buncher is visible in the right part of Fig. 2, while in the left part a CAD view that includes also the four RF couplers is shown.

The buncher coupler, an LBNL design, is a coaxial structure with a bandpass response centered at 1.3 GHz and with few MHz bandwidth. The design incorporates a custom RF window to separate the vacuum in the buncher from the air side. The RF power from four CW 1.3 GHz 2.5 kW solid state amplifiers (from TOMCO) is fed to the four couplers by individual semi-rigid 1-5/8" heliax-type HCA158-50J cables.

Figure 3: APEX Buncher RF coupler.

Figure 3 shows a picture of one of the buncher couplers. In the right part of the figure, the copper loop that magnetically couples the field inside the buncher, is visible. The rotatable flange on the right, allows clocking the coupler to obtain the desired coupling factor.

Both the buncher and its couplers were completely designed and fabricated at LBNL with the only exception of the brazing operations that were performed by California Brazing (Newark, CA).

The Phase-II linac is composed by three 1m-long 1.3-GHz normal-conducting standing-wave accelerating sections. At the moment only two sections are installed, the third one, delivered with some delay, will be installed sometime later this year. The sections are a modified version of the 7-cell sections designed and used by the Argonne AWA group [7]. The central cell, where the RF power is fed, was modified to include two opposite located RF power couplers (only one in the original design) and two dummy couplers (perpendicularly to the real ones) to effectively minimize dipolar and quadrupolar field distortions that could affect the beam emittance.

Table 1: Buncher Main Parameters

Parameter	Value	Units
Frequency	1.3	GHz
Mode of operation	CW	
Mode separation	1.2	MHz
Ideal conductor Q_0	23500	
Nominal Voltage	240	kV
Nominal power	8	kW
Power per cell	4	kW
Power per coupler	2	kW
Resonant mode	π	
Shunt impedance	7.2	MΩ

Figure 4 shows the two accelerating sections installed in the Phase-II beamline. The two RF couplers and one of the dummies on top of the section are visible.

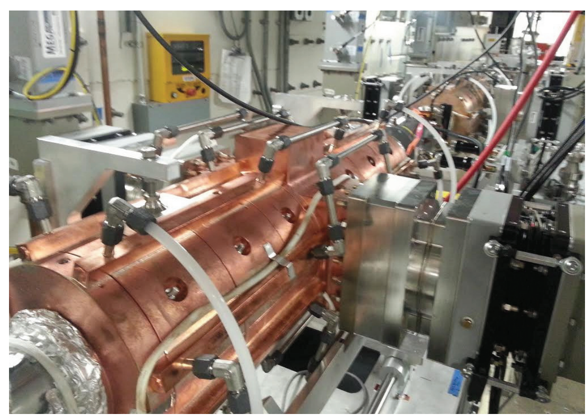

Figure 4: The modified AWA accelerating sections installed in the Phase-II beamline.

A single klystron (THALES TV 2022F) generates 25-MW peak power over a 10 µs pulses at 10 Hz for the 3 accelerating sections and for the 1.3 GHz transverse deflecting cavity used for beam diagnostics. The power from the klystron is delivered to the 4 devices by a complex network of SF_6 filled L-Band rectangular waveguides that includes a 4-port RF circulator and high power phase-shifters/attenuators for each of the branches.

While the VHF-Gun and the buncher run in CW mode, the linac operates in pulsed mode at 10 Hz repetition rate. The rationale behind this configuration is based on the fact that electron beam brightness (the main of the APEX Phase-II goals) is a single bunch property of the beam that is not affected by the repetition rate. This permitted using

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a room temperature copper linac with a strong cost reduction and system simplification.

Downstream of the linac, a beam diagnostics suite 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 transverse deflecting cavity. More details on the diagnostics can be found elsewhere [8].

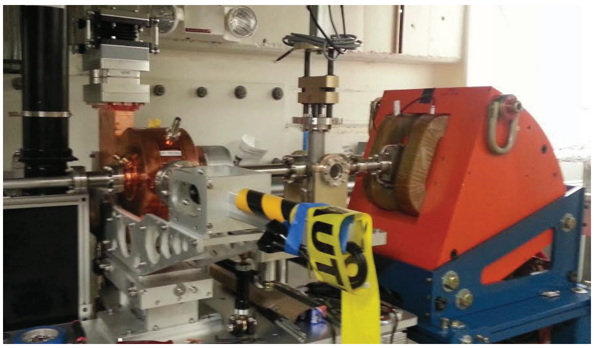

Figure 5: Part of the Phase-II diagnostics beamline. The 1.3-GHz single-cell transverse deflecting copper cavity is visible in the left of the picture followed downstream by the large orange spectrometer (vertical) bending magnet.

PHASE-II INSTALLATION STATUS

Phase-II beamline installation is close to completion and subsystem check-outs already started. High power RF conditioning of the linac sections and of the buncher will start as soon as the check-out is completed, and will be followed by beam commissioning.

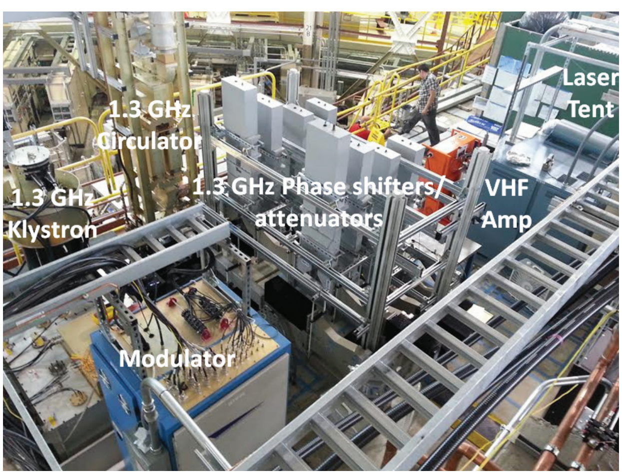

Figure 6: Several APEX subsystems on the BTF roof.

Figure 6 shows the Beam Test Facility (BTF) roof where all the RF power sources and the cathode driver laser are located.

Figure 7 shows the Phase-II beamline installed inside the BTF.

Figure 7: APEX Phase-II beamline installed in the BTF.

RECENT RESULTS

In April 2015 the beam tests were suspended to allow the installation of the Phase-II beamline. Before that, a number of beam measurements at the beam energy using the Phase-I beamline were performed.

Cs_2Te photocatode characterization campaign

Cesium-Telluride (Cs_2Te) photocathodes, produced by INFN/LASA in Milan, Italy, were extensively tested during a many days campaign.

The results demonstrated the capability of such a cathode to perform at the challenging unprecedented regime imposed by high repetition rate x-ray FELs such as the LCLS-II.

Multiple runs at 1 MHz repetition rate with constant charges per bunch of 20, 100 and 300 pC were performed to characterize the QE and the QE lifetime of such a cathode. Figure 8 shows an example of such runs.

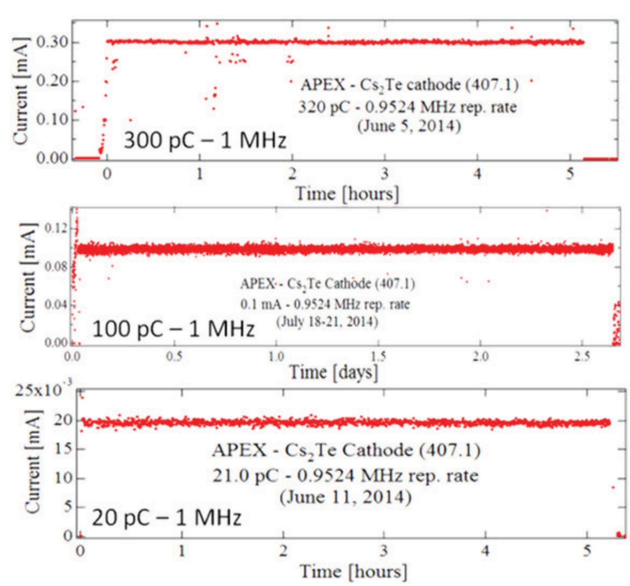

Figure 8: Example of constant current tests with Cs_2Te.

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The measurements showed an extremely high QE with long lifetimes well beyond LCLS-II requirements. The reason for the slow QE lifetime was identified as a progressive oxidation of the photo-emitting material due to the residual oxygen that shows in the gun when the RF is ON (~10^{-11} Torr partial pressure). Figure 9 shows a summary of the QE lifetime measurements with the fit indicating the clear correlation between the integrated amount of oxygen and the QE value. More details on such measurements can be found elsewhere [9, 10].

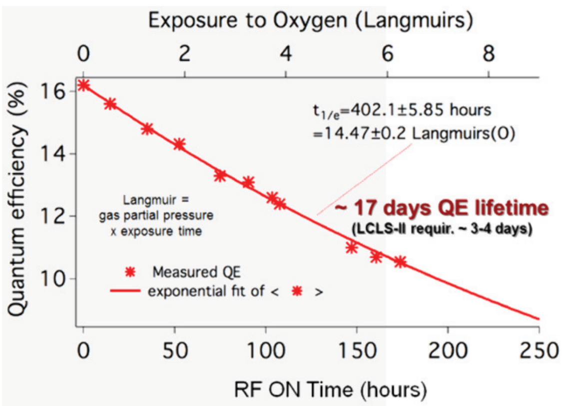

Figure 9: Cs_2Te QE vs. time and integrated Oxygen exposure.

Dark characterization and reduction

Dark current in high duty cycle accelerators can represent a serious issue. If not properly controlled, it can induce quench of superconducting RF structures and additional radiation dose that can degrade the performance of permanent magnet-based devices.

An extensive dark current characterization campaign was performed at APEX that allowed to quantify the current intensity as function of the beam energy (Fowler-Nordheim analysis) as well as to identify the location in the gun of the field emitters responsible for most of the dark current generation (around the copper area just outside of the cathode plug). These findings make it possible to define an effective multi-point strategy to reduce photoemission from the gun. Details of the measurements and the analysis can be found in [11].

On August 2014, a failure of one of the RF waveguides that bring the power to the VHF-Gun contaminated the gun and forced us to open the gun cavity for the necessary cleaning. Such a situation offered the possibility of actuating some of the points in our dark current reduction strategy. In particular, we carefully re-polished the area where the field emitters were located, and performed a dry-ice cleaning cycle of the whole cavity wall followed by an additional cleaning cycle of the cathode area.

When we restarted later in January 2015, the dark current intensity showed an impressive decrease by more than 3-orders of magnitude going from ~350 nA down to ~0.1 nA. Figure 10 shows the Fowler-Nordheim analysis before (top) and after (bottom) the cleaning/re-polishing operation.

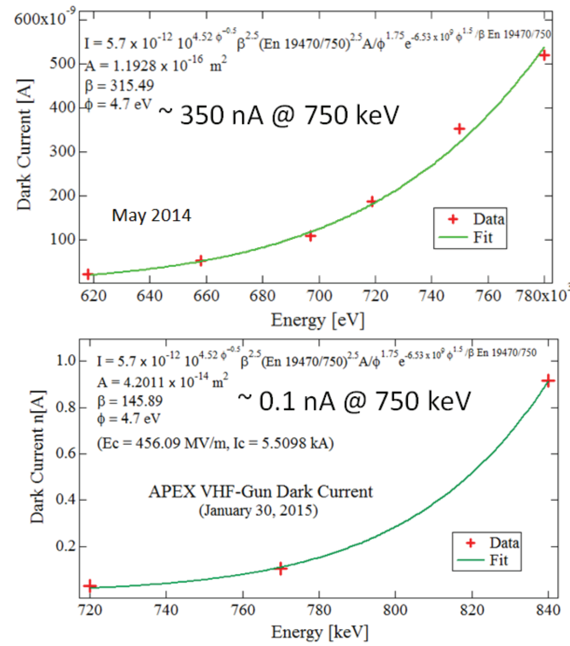

Figure 10: Dark-current Fowler-Nordheim analysis before (top) and after (bottom) the cleaning/re-polishing operation.

PLANS AND CONCLUSIONS

Plans for the near future include the beam commissioning of Phase-II beamline, and in particular the demonstration of the compression and emittance required by the different modes of operation of LCLS-II.

In addition, APEX will operate in support of HIRES, the high repetition rate ultrafast electron diffraction program at APEX funded by DOE-BES [12].

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