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# STATUS OF THE APEX PROJECT AT LBNL*

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*Abstract*

The Advanced Photo-injector Experiment (APEX) at the Lawrence Berkeley National Laboratory is focused on the development of a high-brightness high-repetition rate (MHz-class) electron injector for X-ray FEL applications. The injector is based on a new concept gun, utilizing a normal conducting 186 MHz RF cavity operating in CW mode in conjunction with high quantum efficiency photocathodes capable of delivering the required repetition rates with available laser technology. The APEX activities are staged in 3 main phases. In Phases 0 and I, the gun is tested at its nominal energy of 750 keV and several different photocathodes are tested at full repetition rate. In Phase II, a pulsed linac is added for accelerating the beam at several tens of MeV to reduce space charge effects and measure the high-brightness performance of the gun when integrated in an injector scheme. At Phase II energies, the radiation shielding configuration of the bunker where APEX is located limits the repetition rate to a maximum of several Hz. Phase 0 is under commissioning, Phase I components under fabrication, and initial activities for Phase II are underway. This paper presents an update on the status of all these activities.

## INTRODUCTION

APEX (the Advanced Photo-injector EXperiment) is an electron injector based on a normal-conducting (NC) continuous-wave (CW) RF photo-gun under construction at the Lawrence Berkeley National Laboratory (LBNL) [1-3]. The project is part of the R&D activities promoting the development of the Next Generation Light Source (NGLS), a soft x-ray light source based on an array of up to ten independently tunable free electron laser (FEL) beamlines [4, 5]. The NGLS design addresses the interest of a large scientific community in the XUV and soft x-rays requiring extremely high brightness sources with photon energies ranging from about few hundreds eV to few keV at repetition rates as high as ~ 100 kHz per beamline [6, 7]. Particularly challenging are the requirements for the electron injector to operate in a facility such as the NGLS [8]. Indeed, it must deliver beams at MHz repetition rate with the required high brightness over a broad range of charges per bunch. Such an injector presently does not exist, and APEX has been designed to address such a need.

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APEX electron photogun is based on reliable and mature mechanical and RF technologies. The core of the gun, see Figure 1, is a NC copper RF cavity operating in CW mode in the VHF band at 186 MHz (7th sub-harmonic of 1.3 GHz). The cavity, when fed by ~ 100 kW of RF power, creates a field on the cathode of ~19.5 MV/m that accelerates the beam through the 4 cm gap at ~750 keV. The two major goals targeted by the gun design were the CW operation capability, and the low vacuum pressure performance ($10^{-11}$ – $10^{-9}$ Torr) necessary to operate the sensitive high quantum efficiency (QE) semiconductor photo-cathodes required at those repetition rates. The relatively low RF frequency choice allowed addressing both of these needs. Indeed, the larger resonating structure associated with the VHF frequency decreased the heat load on the cavity wall at a level small enough to permit CW operation with conventional cooling techniques. Additionally, the long wavelength allowed opening significantly large slots on the cavity walls with negligible field distortion and creating the high conductance vacuum path required by the low pressure operation.

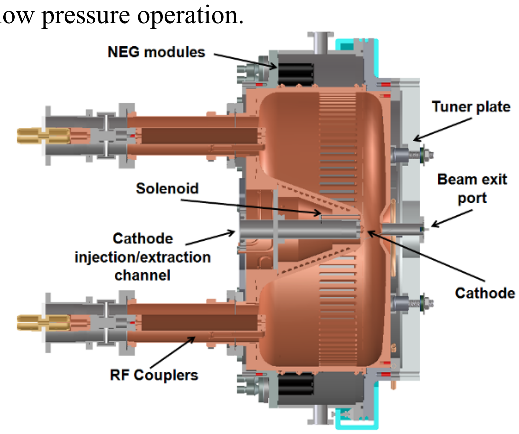


Figure 1: The VHF gun cross-section.

APEX is staged in 3 phases. In Phase 0 the VHF gun and a diagnostic beamline for cathode characterization are installed. Different photocathodes are tested at MHz repetition rate at the gun energy to define the best choice for a high repetition rate X-ray FEL. Before testing cathodes, several important milestones need to be demonstrated in this phase, including full RF condition of the gun cavity, measurement of the beam energy at the gun exit, and vacuum performance demonstration.

In Phase I, an electron beam diagnostic suite is added to the Phase 0 layout, to allow a full 6D characterization at full repetition rate of the beam phase space at the gun energy. The suite includes among others, a Cornell-like two-slit emittance measurement system (to measure the emittance in the space charge dominated regime) [9], a spectrometer and a transverse deflecting cavity (modified Cornell design) [10] for slice emittance and energy spread measurements and full longitudinal phase space characterization. At the relatively low energy of the gun, space charge forces are still dominant and the emittance compensation process is not completed yet. Because of this, in Phase I it will not be possible to prove the final brightness performance of the gun; nevertheless, it will permit comparing measurements with simulation results and the continuation of photocathode studies.

In Phase II, the last of the project, a room temperature pulsed linac (based on ANL-AWA accelerating sections [11]) is added to the Phase I layout. The electron beam diagnostic suite of Phase I after some modification is moved downstream the linac. The linac accelerates the beam up to about 30 MeV making space charge forces sufficiently small to perform reliable measurements of beam brightness. The radiation shielding configuration of the bunker housing APEX will limits the high energy operation of APEX at few Hz repetition rate. Nevertheless, the ultimate task of Phase II is to demonstrate the capability of an injector based on the VHF gun to deliver the required beam brightness, and being brightness a single bunch property, the limited repetition rate will not affect the scope of this phase.

## APEX INSTALLATION STATUS

At the present time, all Phase 0 hardware (with the only exception of the vacuum loadlock system) has been installed. Figure 2 shows a 3D CAD view of the system with the major components in evidence, while Figure 3 shows the real hardware as installed in the test area.

The beam diagnostics included in the present layout allows for the measurement of beam current, energy and transverse profile, and for cathode QE maps, intrinsic emittance and lifetime [12].

The photocathode drive laser, developed in collaboration with Lawrence Livermore National Laboratory and UC Berkeley, has been installed and fully commissioned. The IR pulses generated at 1064 nm by the Yb-doped fiber laser are frequency converted to generate 532 and 266 nm in 2$^{nd}$ and 4$^{th}$ harmonic. This photon energy flexibility allows driving photoemission in various different cathode materials. The two main cathodes to be tested in the next future include $CsK_2Sb$ produced at LBNL [13] and $Cs_2Te$ [14]. The laser power at both harmonics is sufficient to drive photoemission in the cathodes at the required charge level (300 pC/bunch). A copper photocathode in conjunction with a hydrogenated diamond amplifier will be tested as well [15].

The 120 kW 186 MHz CW RF source for the gun is fully operational reliably delivering the required power to the gun through two branches equipped with RF circulators. The measured relative power stability of the system is ~ $10^{-3}$ rms when controlled by a high level software feedback.

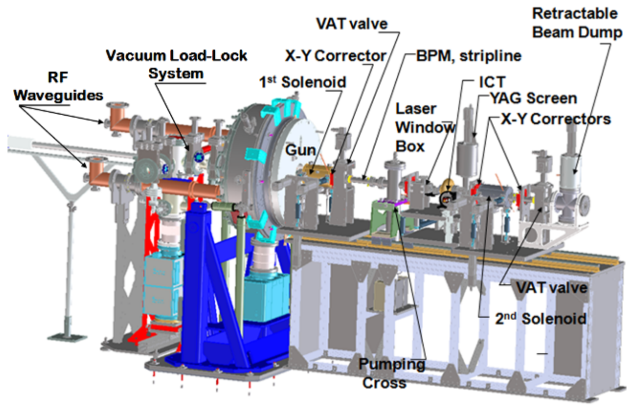


Figure 2: APEX Phase 0 layout.

The EPICS based control system is in advanced stage of implementation and permits the full control of most of the beamline components. High level macros developed in MatLab on linux platforms allow for the system operation and for fairly complex measurements.

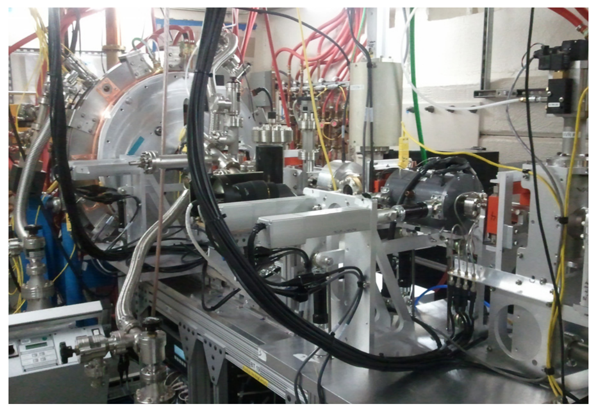

Figure 3: The APEX Phase 0 inside the LBNL test area.

The FPGA-based low level RF system (developed at LBNL) that allow controlling the RF system, synchronizing it with the laser and to tune the frequency of the RF source to follow the cavity frequency, is installed and fully operational [16].

## INITIAL COMMISSIONING RESULTS

The first important commissioning result for the project was achieved on December 15, 2011 when the gun cavity was conditioned at the nominal power of 100 kW in CW mode after only ~ 150 integrated hours of conditioning. This important milestone confirmed the capability of the gun of operating at the required fields without breakdown issues. Continuous runs of more than 30 hours duration with no faults showed a solid RF reliability of the system. As predicted by simulations, evidence of multipacting resonances in the cavity was detected at low power, and a wide multipacting-free region around the nominal operation point was confirmed. Multipacting in the RF feeder coaxial lines downstream the RF windows was cured by adding ~50 Gauss solenoidal field to the region.

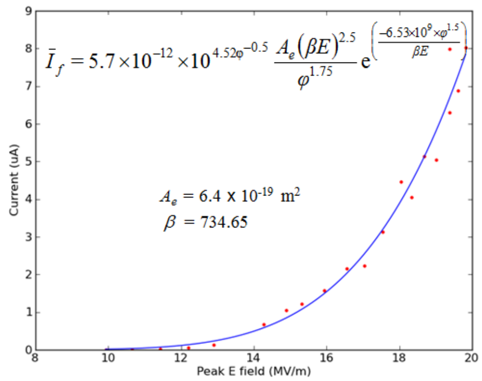


Figure 4: Example of dark current measurement.

Initial dark current characterization was performed in two phases. First, a coaxial Faraday cup was installed right at the beam exit pipe of the gun. Figure 4 shows an example of such a measurement and the Fowler-Nordheim fit of the data. A value of ~8 µA average current was measured at the nominal power. Later, the Faraday cup was moved in its present position at the end of the Phase 0 beamline. In this configuration, the dark current at nominal power dropped down to ~ 100 nA.

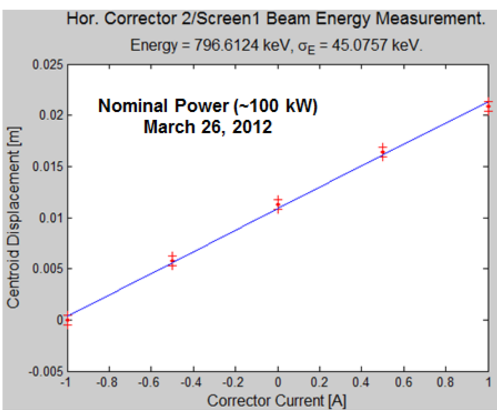


Figure 5: Beam energy measurement using dark current.

By imaging the dark current on a YAG screen using a solenoid it was observed that the field emission is generated by few point-like sources on the cathode plane. In the present configuration a “dummy” molybdenum plug is installed instead of a real cathode. The better polishing level of a real cathode plug, jointly with better cleaning techniques to remove particulates could potentially reduce dark current intensity.

Dark current was also used to measure the maximum energy at which the electron can be accelerated when the nominal power is applied to the cavity. The dark current beam was focused on a YAG screen and a horizontal corrector upstream of the screen was energized at several different values. An example of such measurement is shown in Figure 5. The slope of the fit is proportional to the particle momentum and the measured energy value was 800 keV with a standard deviation of 45 keV. Such a value is slightly higher than the expected 750 keV mainly due to the limited accuracy in the RF power measurement. This important result confirmed again the capability of the gun to generate the required fields.

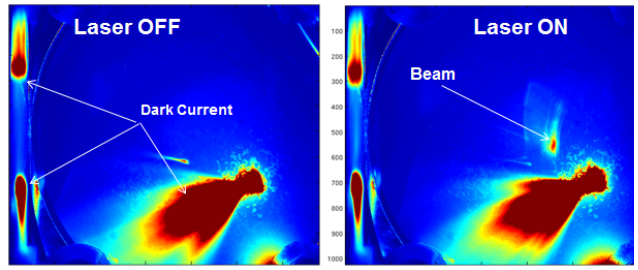


Figure 6: First evidence of photoemitted beam on a dummy cathode.

The dummy molybdenum cathode plug ensures the proper RF contact but presents a very poor estimated QE in the UV of ~ $10^{-6}$. With the present laser power and that QE, the expected photoemitted charge per bunch is ~ 6 fC that, with the MHz repetition rate, would generate an average current of ~ 6 nA. Despite of such very small numbers, on March 30, 2012 we synchronized the laser with the gun RF and visualized an image of the photoemitted beam on a YAG screen (see Figure 6). In an another shift, by using a lock-in amplifier with the laser trigger as reference, we measured at the Faraday cup at the end of the beamline an average current of ~10 nA. These results represented a successful cross-check of the photogun in all of its functionality. Tests with real cathodes are scheduled in the next future.

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