RECENT RESULTS FROM THE APEX PROJECT AT LBNL*

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Abstract

The commissioning at the Lawrence Berkeley National Laboratory (LBNL) of a high-brightness high-repetition rate (MHz-class) photo-gun, based on a normal conducting 186 MHz (VHF-band) RF cavity operating in CW mode, is now completed. The gun has been designed to satisfy the requirements for operating high-repetition rate 4th generation light sources. Test of high quantum efficiency photocathodes with bunches of hundreds pC at MHz repetition rate are now underway. They include, Cs_2Te cathodes developed in collaboration with INFN-LASA and multialkali antimonides (CsK_2Sb), prepared by a collaborating group at LBNL. The present experimental results and the plan for future activities are presented.

INTRODUCTION

This paper describes the recent progress and experimental results obtained by the Advanced Photo-injector EXperiment (APEX) at the Lawrence Berkeley National Laboratory (LBNL).

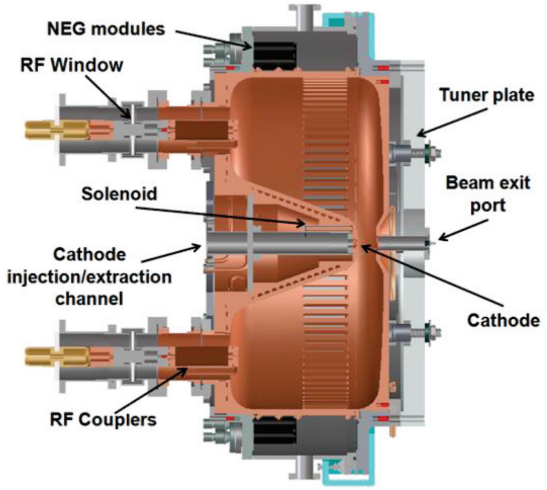

Figure 1: The VHF Gun cross sections.

The project main goal consists in the development and test of a new concept high-repetition rate high-brightness electron injector capable to operate in high-repetition rate free electron laser (FEL) and energy recovery linac (ERL) applications. The successful development of such an injector will critically impact the performance of future 4th generation light sources when high-repetition rates (> 10 kHz) are required, and of high repetition rate ultrafast electron diffraction (UED) and inverse Compton scattering (ICS) applications.

The core of the system is represented by a normal-conducting (NC) continuous wave (CW) RF gun [1, 2] (see Fig. 1) where the electrons are generated by laser-induced photo-emission on high quantum efficiency (QE) photo-cathodes and accelerated by the cavity fields (~20 MV/m) to up to ~750 keV energy. The gun cavity has been designed to resonate at about 186 MHz (7th subharmonic of 1.3 GHz) in the VHF frequency region. The low frequency choice makes the resonator size large enough to lower the power density on the structure walls at a level that conventional cooling techniques can be used when the cavity is run in CW mode.

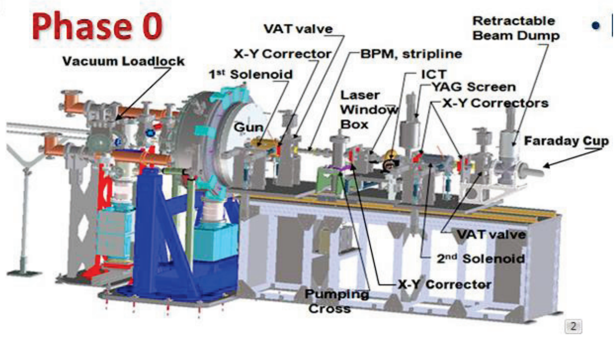

Figure 2: APEX Phase 0 CAD view.

A second advantage of the low frequency is the relatively long wavelength that allows for large apertures on the cavity walls with negligible distortion of the electromagnetic fields. Such apertures create the proper high-vacuum conductance path paving the way for the achievement of the very low pressures required by high-QE semiconductor cathodes (minimizing contamination and damage and hence ensuring longer QE lifetimes).

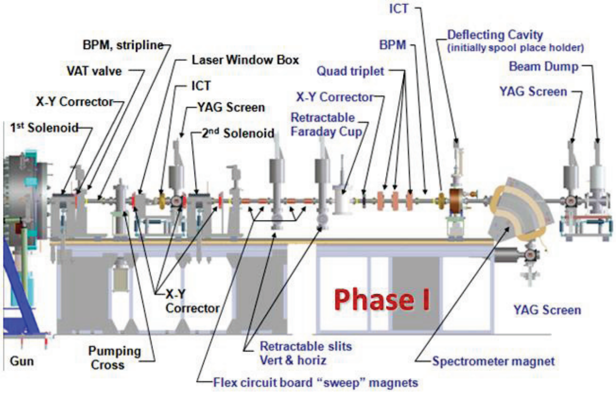

Figure 3: APEX Phase I CAD view.

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A last advantage of the VHF scheme is that it is based on mature and reliable RF and mechanical technology, a very important characteristic to achieve the reliability required to operate in a user facility.

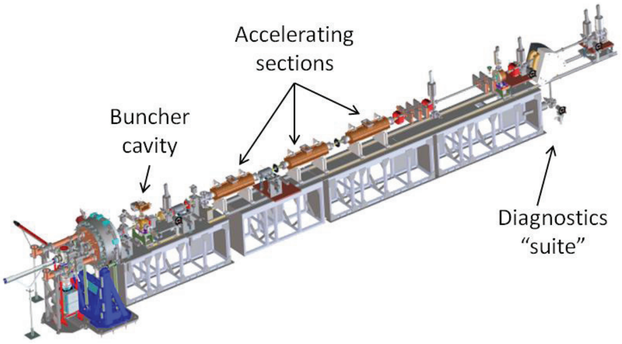


Figure 4: APEX Phase II CAD view.

The APEX project is organized in 3 main stages: Phases 0, I and II. Phase 0, shown in Fig. 2, is dedicated to the development and characterization performance of the gun, and to the testing and characterization of different types of cathodes. In Phase I, visible in Fig. 3, a complete suite of diagnostics [3] allows for the full 6D phase-space characterization of the electron beam at the gun energy. Beams of several hundreds of pC per bunch at MHz repetition rate will be characterized and compared with expected results from simulations. In Phase II, shown in Fig. 4, three pulsed NC 1.3 GHz accelerating sections [4] (a modified version of the AWA cavities at Argonne National Laboratory) and one 1.3 GHz buncher cavity are added to accelerate the beam up to about 30 MeV and compress it to the required lengths. Phase II configuration allows to reduce space charge forces at the level necessary to perform meaningful emittance measurements and be able to demonstrate the brightness performance of the gun. Due to cost and shielding limitations, Phase II operates in pulsed mode with 10 Hz repetition rate. Testing of different photocathodes will continue also during Phases I and II.

STATUS OF THE INSTALLATION

Phase 0 has been completely installed, and Figure 5 shows a picture of it inside the Beam Test Facility (BTF) at LBNL where the APEX project is located.

The vacuum loadlock system, which allows replacing cathodes without breaking the vacuum, is a clone of the system developed by INFN-LASA for PITZ and FLASH in Germany. The system is fully installed and successfully commissioned. The geometry of the extractable molybdenum cathode "plug", which supports the photo-emitting material, has been modified to allow for a smoother insertion in the gun and for minimizing the stress on the RF contact spring (see Fig. 6).

A vacuum leak in one of the two gun RF magnetic loop type couplers, revealed a design weakness in the part. The electrical contact between the coupler inner conductor and the loop cap, both copper parts, was ensured by the mechanical pressure created by two titanium screws. Due to the thermal stress generated when the cavity is switched on and off, the two copper parts gradually lost contact and all the current associated with the RF fields started to flow through the titanium screw creating overheating of the parts (see left part of Fig. 7).

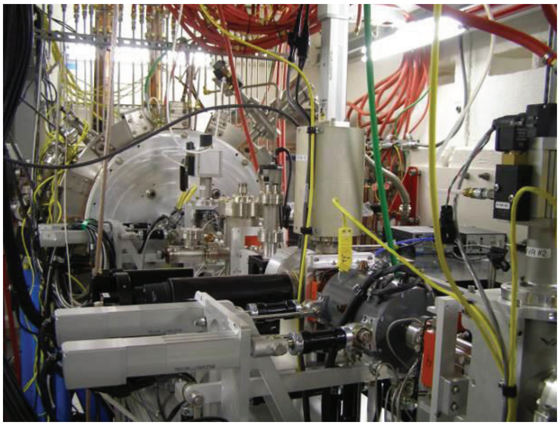


Figure 5: APEX Phase 0 installed in the BTF at LBNL.

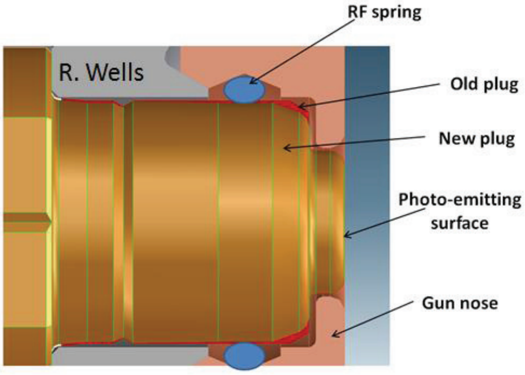


Figure 6: Comparison between the geometry of the previous (red) and new (gold color) cathode plugs.

The issue was serious enough that it was decided to completely redesign the couplers. The new design removed the screws, the copper parts were electron-beam welded together, and the copper cooling line cross section was enlarged for an increased flow of water.

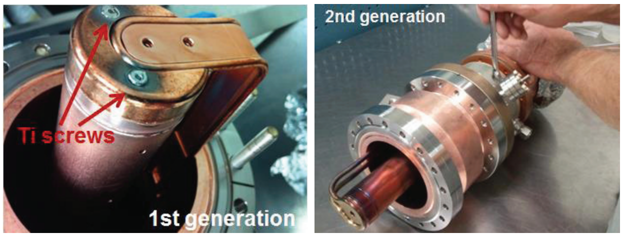


Figure 7: Left: 1st generation gun RF coupler. Right: the newly fabricated 2nd generation coupler being assembled.

The new design also addressed the presence of multipacting in the in vacuum coaxial line between the coupler loop and the RF window. The vacuum part of the coaxial was significantly shortened and all couplers components were coated with titanium nitride. In mid-

February 2013, the two new couplers were installed and smoothly RF conditioned at full power in a few days. No evidence of multipacting was detected. Since then, the couplers have been reliably working at the nominal power.

The installation of the diagnostics suite components of Phase I is undergoing (in parallel with cathode tests) and systems as the double-slit emittance meter (based on a Cornell design), and the spectrometer are in advanced phase of installation (see Fig. 8). The 1.3 GHz deflecting cavity, a modified version of the Cornell design, required for “slice” transverse emittance and longitudinal phase space measurements is under fabrication at the LBNL mechanical shops.

Figure 8: Phase I diagnostics systems in the BTF. Left: the 2-slit emittance meter. Right: the spectrometer dipole.

Phase II long delivery items, such as the klystron (Thales TV 2022F) and the related modulator (by DTI), have been ordered, and the complex RF distribution system, which distributes the 1.3 GHz RF power from the single klystron to the 3 accelerating sections, the buncher and the deflecting cavity, is fully designed (see Fig. 9), and parts are ready to be ordered.

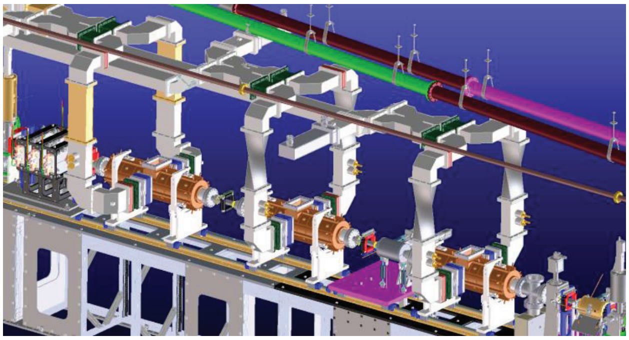


Figure 9: CAD view of part of the RF distribution system for APEX Phase II.

EXPERIMENTAL RESULTS

The VHF gun has been fully commissioned and demonstrated all major nominal parameters such as CW operation, accelerating field, beam energy, and vacuum performance. Detailed results of the gun commissioning have been reported elsewhere [5].

The photo-cathode drive laser, a ~1 W 1064 nm Yb-doped fiber-laser developed in collaboration with University of California Berkeley and Lawrence Livermore National Laboratory, is fully commissioned and in operation. The system, capable of MHz repetition rate operation with the required energies per pulse at the different wavelengths, includes 2nd and 4th harmonic generation, longitudinal and transverse pulse shaping, and pulse picking capabilities [6]. An additional commercial laser (Calmar) with higher power (~ 2 W in the infrared) is presently under installation.

The reliability of the VHF gun system, after almost 2 years of high power RF operation experience, revealed to be excellent. The large majority of the faults that rarely affect the system (once every few days) are due to cooling water supply fluctuations that trigger the interlock protection system.

The overall system performance stability is being tested. Figure 10 shows a relative RF power fluctuation in the VHF gun cavity of ~ 0.14% rms, indicating an accelerating field fluctuation of ~ 0.07%. Such result has been obtained by using a high-level MatLab feedback which reads the power in the cavity from the FPGA based LLRF system [7], and controls the RF power input to the RF amplifier for maintaining the power in cavity constant. The stability performance figure will be probably improved in the next future when the feedback will be implemented completely at the LLRF system level.

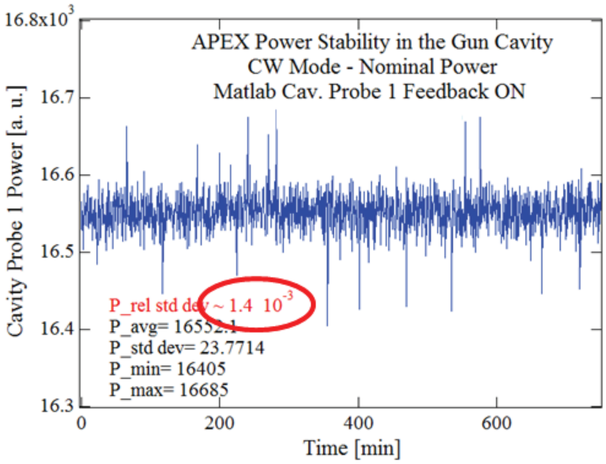


Figure 10: VHF Gun RF power fluctuation measurement.

The synchronization between the gun RF and the photocathode driving laser oscillator is performed by the LLRF system [7], and presently shows a measured time jitter of ~ 2 ps rms. Such a figure corresponds to a RF phase jitter (at the gun frequency) of ~ 0.15 degrees, and is dominated by the contribution of the non-ideally designed piezo/picomotor actuator controlling the position of one of mirrors in the laser oscillator cavity. Although the present jitter value is sufficiently small for the operation and tests to be performed at APEX, the near future upgrade to the new laser system (the Calmar laser mentioned above) should significantly decrease the jitter value.

The two main high-QE semiconductor photocathodes planned for testing include Cs_2Te produced by INFN/LASA (the same material used at the FLASH FEL in Germany), and the multi-alkali CsK_2Sb produced by a partner group at LBNL. Additional cathode materials are under consideration for future tests.

The completion of the vacuum loadlock system allowed to start the beam tests with the high-QE cathodes. After the activation of the 20 NEG modules in the gun (400 l/s pumping speed each, from SAES Getters), and several days of baking of the cavity [4], a vacuum pressure in the gun of ~ 1.0 10^{-11} Torr was obtained with no RF and of ~ 8.0 10^{-10} Torr when the RF is on at the nominal power. Partial pressures for "dangerous" molecules (H_2O, O, ...) are always 2 orders of magnitude smaller than the actual absolute pressure.

On March 18, 2013, the cathode tests initiated with one of the 3 available Cs_2Te cathodes prepared by LASA. Figure 11 shows the image of the very first beam from Cs_2Te on the YAG screen in the Phase 0 beamline (on March 18, 2013). The repetition rate was limited to 100 Hz to avoid damaging the screen, and because the fast equipment protection system (FEPS), required for high-current operation, was not commissioned yet. The charge monitors were not calibrated but the estimated charge per bunch was of several hundreds of pC.

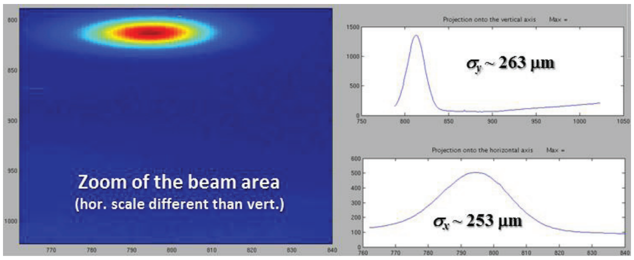
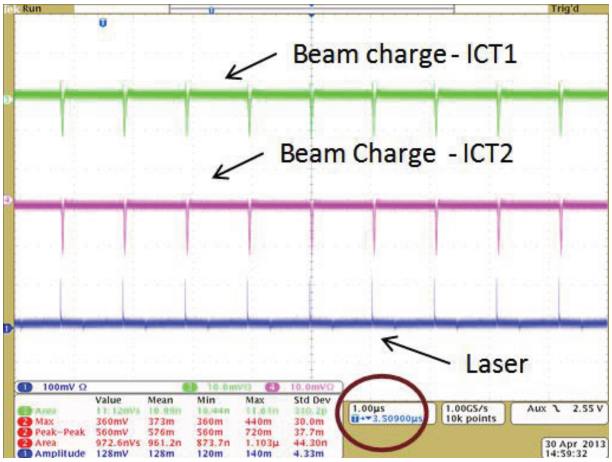


Figure 11: First high-charge beam from a Cs_2Te cathode.

In the subsequent days, following the successful commissioning of the FEPS and calibration of the current monitors, we started to operate at 1 MHz repetition rate. Figure 12 shows scope traces with 2 charge monitors (Bergoz ICTs) and a driving laser photodiode during one of these MHz runs.

At the end of April 2013, an almost continuous 1 MHz run of ~ 4 days integrated an extracted charge of ~ 40 C, roughly equivalent to the charge extracted from the same type of cathode during 3 months of FLASH operation. The top part of Fig. 13, shows the QE values measured during the run, and indicates a decrease of such a quantity from an initial ~ 10% to a final ~ 4%. Although preliminary, this is remarkably important result because it indicates a QE lifetime compatible with the operation of a MHz-class repetition rate x-ray FEL. Indeed, in a typical user facility scenario, the operation schedule includes a maintenance day for every week of user shifts. If the QE of the cathode stays higher than ~ 1% during such a period, then cathodes can be replaced (a ~20 minute operation) during the maintenance day with no impact on the user time.

The QE variations visible in the Figure are due to the fact that no laser pulse amplitude feedback was installed at the time, and the photon energy per pulse was drifting following the temperature variations associated with the alternating days and nights during the run, as visible in the bottom part of Fig. 13. The correlated charge-per-bunch variation is evident in the central part of the Figure.



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1 100mV Ω                 3 10.0mV Ω   4 10.0mV Ω
              Value      Mean    Min     Max     Std Dev
3 Area        11.12nVs   10.99n  10.44n  11.61n  330.2p
2 Max         360mV      373m    360m    440m    30.0m
2 Peak-Peak   560mV      576m    560m    720m    37.7m
2 Area        972.6nVs   961.2n  873.7n  1.103µ  44.30n
1 Amplitude   128mV      128m    120m    140m    4.33m
1.00µs   T→▾3.50900µs   1.00GS/s 10k points   Aux ⤥ 2.55 V
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Figure 12: Scope traces from 2 charge monitors (ICTs) and a driving laser photodiode showing the 1 MHz time structure of the pulses.

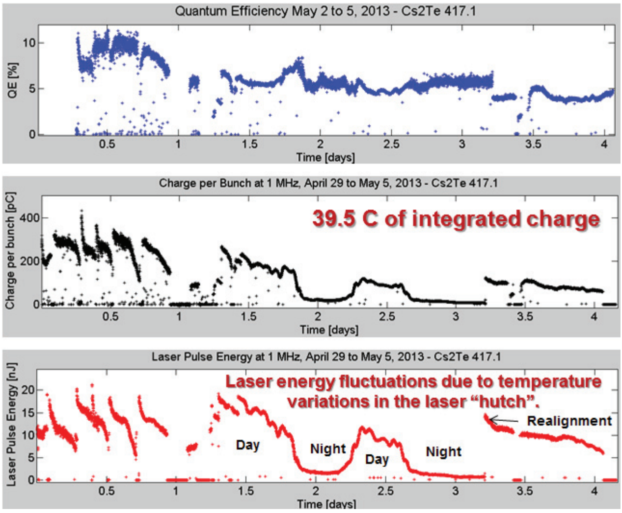

Figure 13: Results of a 4-day run with a Cs_2Te cathode at 1 MHz repetition rate. Top: QE values during the run. Center: charge per bunch, Bottom: laser energy per pulse

To stabilize the laser performance, we recently developed and installed two feedback systems to control the laser pulse energy and pointing. The systems use the image of the laser beam on the virtual cathode and the reading from a power meter to respectively control the horizontal and vertical angles of a mirror and a variable neutral density attenuator installed on a stage. The feedbacks have been successfully commissioned and the results of a 16 hour test are shown in Figure 14. With the laser stability now ensured by the new feedbacks, more systematic QE lifetime tests with the Cs_2Te will restart soon.

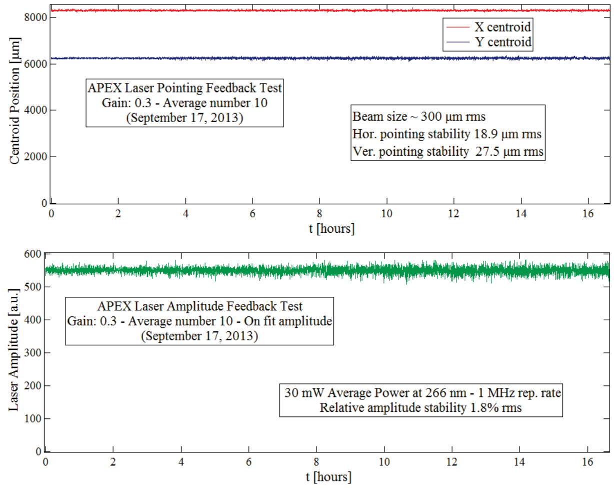

Figure 14: Test of the laser feedback systems. Top: pointing stability results. Bottom: energy per pulse results.

An initial preliminary thermal emittance measurement of the Cs_2Te cathode was performed by a solenoid scan at low charge per bunch (~900 fC) and at a beam energy of ~ 800 keV.

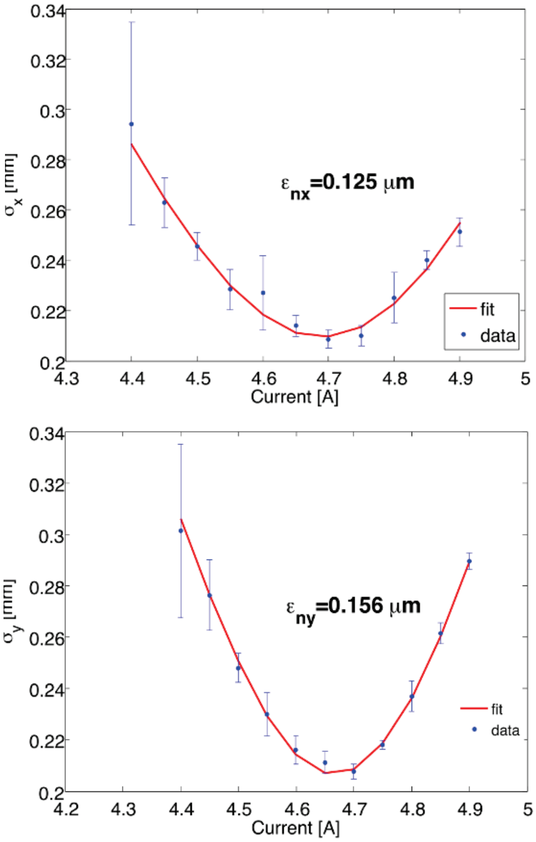

Figure 15: Cs_2Te cathode thermal emittance measurement by the solenoid scan technique. Top: horizontal plane result. Bottom: vertical plane result.

Figure 15 shows the results of the scan for both horizontal and vertical planes. For each of the solenoid current values, the average rms transverse size and standard deviation were calculated over ten individual beam images. The beam sizes at the virtual cathode during the measurements were of ~ 250 µm rms for the horizontal plane and of ~ 265 µm rms for the vertical one. The resulting normalized thermal emittance value for this preliminary measurement is:

$$\varepsilon_n/\sigma_R = 0.54 \pm 0.05\ \mu\text{m/mm}_{\text{rms}}$$

Such result is consistent with values measured by other groups. Additional more systematic measurements varying the laser transverse beam size at the cathode are scheduled for the near future.

FUTURE PLANS

After the completion of the tests with the presently installed Cs_2Te cathodes, CsK_2Sb multialkali cathodes will be inserted in the gun and characterized. One of such photocathodes, has been already successfully produced by our LBNL partner group and is ready for testing.

The installation (in the first half of 2014) of all the beam diagnostics systems included in APEX Phase I, will allow for the full 6D phase space characterization of beam at the gun energy, and for the comparison of the experimental results with the expected values predicted by the simulations.

Finally, in about 18 months from now (assuming the reception of the required funds), the completion of the installation of the Phase II components will allow for the final characterization of the brightness performance of the VHF gun.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Staples, F.Sannibale, and S. Virostek, VHF Band Injector, CBP Technical Note No. 366, LBNL October 2006.
[2] K. Baptiste et al., NIM A 599 (2009) 9.
[3] D. Filippetto et al., Proceedings of IPAC2012, New Orleans, Louisiana, p. 963 (2012).
[4] H. Qiang et al., NA-PAC13, to be published.
[5] F. Sannibale et al., PRST-AB 15 (2012) 103501.
[6] D. Filippetto et al., to appear in the Proceedings of 2013 Free Electron Laser Conference, New York, NY (2013).
[7] G. Huang et al., Proceedings of IPAC2012, New Orleans, Louisiana, p. 3488 (2012).