STATUS OF THE LBNL NORMAL-CONDUCTING CW VHF ELECTRON PHOTO-GUN*

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Abstract

The fabrication and installation at the Lawrence Berkeley National Laboratory of a high-brightness high-repetition rate photo-gun, based on a normal conducting 187 MHz (VHF) RF cavity operating in CW mode, is in an advanced phase. The cavity will generate an electric field at the cathode plane of ~ 20 MV/m to accelerate the electron bunches up to ~ 750 keV, with peak current, energy spread and transverse emittance suitable for FEL and ERL applications. The gun vacuum system has been designed for achieving pressures compatible with the use of "delicate" high quantum efficiency semiconductor cathodes to generate up to a nC bunches at MHz repetition rate with present laser technology. Several photo-cathode/laser systems are under consideration, and in particular photo-cathodes based on K_2CsSb are being developed for the gun and have already achieved a QE of 8% at 532 nm wavelength, or close to 20% including the Schottky barrier lowering. The cathode will be operated by a μJ fiber laser in conjunction with refractive transverse beam shaping to create a flat top transverse profile, as well as a birefringent pulse stacker to create a flat top temporal profile. The present status and the plan for future activities are presented.

INTRODUCTION

At the Lawrence Berkeley National Laboratory (LBNL), a normal-conducting (NC) constant-wave (CW) photo-injector is under development in the framework of a broader activity proposing the construction of a 4th generation light sourced equipped with an array of independently tunable free electron lasers (FELs) [1, 2]. The project is science driven and 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 10 eV to 1 keV at repetition rates as high as ~ 100 kHz per beamline [3, 4].

Particularly challenging are the requirements for the electron photo-injector. Indeed, high brightness electron beams with charge ranging from few pC to up to ~ 1 nC must be delivered at ~ MHz repetition rates with the reliability required to operate in a user facility.

Operating a photo-injector with that charge per bunch at high repetition rate with present laser technology requires the use of high quantum efficiency (QE) photo-cathodes. Semiconductor cathodes can offer the required QE but are typically very sensitive to ion back-bombardment damage and contamination, so in order to use such cathodes with acceptable lifetimes extremely low vacuum pressures down into the 10^{-11} Torr range are necessary.

For a number of reasons, none of the existing gun technologies, DC, super-conducting (SC) and normal-conducting high frequency (~ 1 GHz) RF guns, can presently generate the required brightness at high repetition rate [5, 6].

The scheme developed and under construction at LBNL has been designed to satisfy the above-mentioned requirements and is based on reliable and mature mechanical and RF technologies [5-7]. The core of such a gun is a normal-conducting copper RF cavity resonating at 187 MHz in the VHF band. Figure 1 shows a cross section of the VHF cavity with the main components, while Table 1 includes its main parameters.

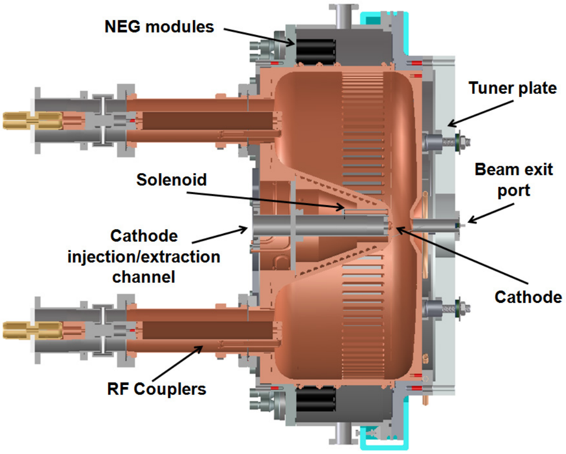

Figure 1: VHF cavity cross-section, showing the cavity main components.

Two major goals were targeted by this design, the CW operation capability and the low vacuum pressure performance. Indeed, because of the low frequency, the structure body is large enough to withstand the heat load present when operating in CW mode with the high electric fields required by a high brightness photo-

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injector. Furthermore, the long RF wavelength allows for the large high-conductance vacuum ports (the numerous slots visible along the “equator” of the cavity in Fig.1) necessary for achieving the desired vacuum pressure. Additionally, the use of a large number of NEG modules as the main pumping system allows to efficiently remove those molecules (H_2O, O_2, CO, CO_2, ...) that can be particularly dangerous for semiconductor cathodes.

A vacuum load lock system, based on the INFN design [8] used at FLASH, Germany will allow the replacement and the *in situ* conditioning of photocathodes .

Table 1: VHF CW Cavity Main Parameters

Total length [m]	0.35
Cavity internal diameter [m]	0.694
Accelerating gap [mm]	40
Frequency [MHz]	187
Q_0 (ideal copper)	30877
Gap voltage [MV]	0.75
Electric field at the cathode [MV/m]	19.5
Peak surface electric field [MV/m]	24.1
Stored energy [J]	2.3
Shunt impedance [MΩ]	6.5
RF power for 0.75 MV at Q_0 [kW]	87.5
Peak wall power density at 0.75 MV [W/cm^2]	25.0

The resonant copper structure is surrounded by a stainless steel shell (visible in Fig.1) that ensures the required mechanical rigidity and the proper vacuum sealing. No sliding tuner is present and the required frequency tuning is achieved by a mechanical system that slightly pushes or pulls the cavity wall at the beam exit port side. The RF power is supplied through two magnetic loop couplers diametrically opposed on the cathode back wall of the cavity. The 187 MHz frequency choice is compatible with both 1.3 and 1.5 GHz, the frequencies of the two presently dominant SC linac technologies.

In the first section of this paper the status of the gun fabrication is presented. The second section contains the description and status of the different photo-cathodes and laser systems being developed for operating with the VHF gun. Finally, the last section of the paper describes future plans and potential upgrades of the system. A second paper submitted to this conference is completely dedicated to the description of the beam dynamics studies performed for evaluating the performance of the VHF gun when integrated in a typical FEL injector scheme [9].

GUN FABRICATION STATUS

VHF Cavity

The VHF cavity fabrication has been completed and the first RF tests at low power have been performed. Figure 2 shows the VHF cavity cathode end plate and side wall during the final phase of fabrication, while Figure 3 shows the completed cavity during the cold RF tests. The latter included resonant frequency and quality factor measurements for the fundamental mode with the cavity in air and under rough vacuum.

Figure 2: The VHF cavity during the final phase of the fabrication.

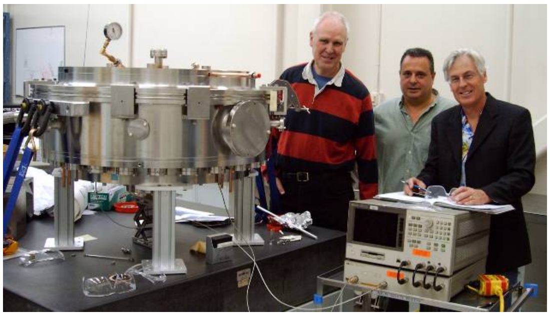

Figure 3: The completed VHF cavity during the low power RF tests.

The measured value for the quality factor Q was about 85% of the ideal copper value consistently with expectations, and the measured resonant frequency value and shift with air to vacuum transition were found in good agreement with the values predicted by the design codes. Figure 4 shows an example of Q measurement.

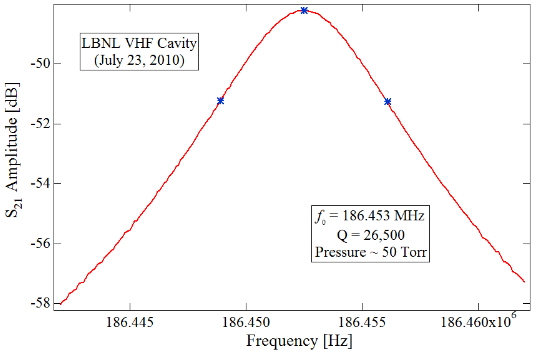

Figure 4: Example of quality factor Q measurement for the VHF cavity fundamental resonant mode.

The frequency shift induced by pulling (or pushing) the cavity wall on the beam exit side, important for calibrating the action of the mechanical tuner, was also measured and found in good agreement with predictions. Figure 5 shows three runs of measurements. After some mechanical “hysteresis” observable in the first run, the second and third runs show a linear and reproducible frequency dependence on the wall “distortion”.

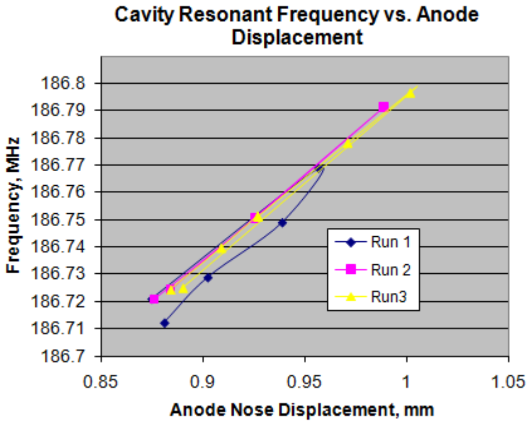

Figure 5: Fundamental mode frequency shift vs. "anode" wall cavity displacement induced by the tuner system.

Other Subsystems

The construction of the RF power source, by ETM Electromatic, is close to completion and the initial factory tests are underway. A picture of the unit is visible in Fig. 6. The 187 MHz CW RF source is based on two final amplifier branches based on tethrodes (Thales TH571B) generating up to 60 kW RF power each.

Figure 6: The 187 MHz 120kW CW RF source unit.

A number of beam diagnostic systems are also under development. Among those, a "double-slit" transverse phase space meter and a 1.3 GHz deflecting cavity for bunch length measurements, both based on the Cornell ERL gun design, and a spectrometer that in combination with the deflecting cavity will allow for longitudinal phase space measurements.

PHOTOCATHODES AND LASERS

Bunches from the gun are subjected to space charge forces. To ensure that these bunches can be fully compressed, and to control r.m.s. emittance dilution, the space charge fields within the bunch should be linear. In order to experimentally approach this situation, the beam must be shaped in space and time, in general with a constant intensity in cross section with a sharp radial cutoff, and elliptical or rectangular distribution in the longitudinal plane. In order to pursue sophisticated shaping like this, photo-cathodes are typically used in combination with lasers with pulses properly shaped to obtain the desired distribution. The requirement for 1 nC, 1 MHz bunches from the photo-injector jointly with the presently available laser power, lead directly to the need for a highly efficient photocathode. Several combinations are possible and at LBNL we are actively pursuing two different photocathode-laser systems.

In the first case, we are using K_2CsSb a multi-alkali antimonide cathode photo-emitting in the visible. The photocathodes are being developed by our group at LBNL while the laser at 532 nm is being fabricated at the Lawrence Livermore National Laboratory (LLNL). This cathode material was already used by Dowell *et al.* in the Boeing-Los Alamos Average Power Laser Experiment (APLE) [10] and yielded high average currents for relatively short pulses at high rep rate. In spite of these promising initial results, multi-alkali antimonides have been very scarcely used in high brightness electron sources because of their poor lifetime due to their sensitivity to contamination by residual gas molecules. The LBNL VHF gun has been designed to achieve pressures low enough to run such cathodes with acceptable lifetimes.

The second system includes Cs_2Te cathodes photo-emitting in the UV. This option is pursued in collaboration with INFN-LASA that is developing the photocathodes [8]. For the laser, we will use the same LLNL device used for the K_SCsSb, but now converted in 4th harmonic, or a higher power laser being developed by QPeak Inc. if higher charge bunches will be required. Cs_2Te is a relatively robust cathode that has already demonstrated reliable operation at several percent QE at the FLASH FEL in Germany.

Photocathodes emitting in the visible present two major advantages with respect to their counterparts emitting in the UV. First, the 2nd harmonic conversion from IR to generate photons in the visible is much more efficient than the 3rd or 4th harmonic conversion required by the UV case. This fact significantly reduces the power requirement for the IR laser. Secondly, pulse shaping in the visible is more effective and easier than in the UV and can benefit of relatively inexpensive commercially available shaping systems. For these reasons, our primary task will be to prove the operation capabilities of K_2CsSb in the VHF gun environment. We chose to operate this cathode at 532 nm, ie. using the LLNL frequency doubled 1064 nm fiber laser. These can easily give μJ level pulses, with ps pulse length. We also need a low energy spread, so that with our space charge limited transverse beam size, the overall intrinsic ("thermal") normalized emittance would be sufficiently low. This requires for most of the cases a photon excess energy of no more than ~ 0.5 eV, and K_2CsSb with 532 nm photons, taking into account the Schottky barrier lowering due to the high field gradient present in the gun, satisfy such a requirement. We have built a molecular beam epitaxy (MBE) style deposition system for production of this material and are investigating its properties. The system consists of 3 MBE evaporators, film thickness monitor, optical reflectivity measurement, and a sample heater/cooler. A system to measure transverse momentum is being added at this time. Yield is measured over a range of wavelengths, and are done rapidly, using a high brightness laser driven visible-UV light source.

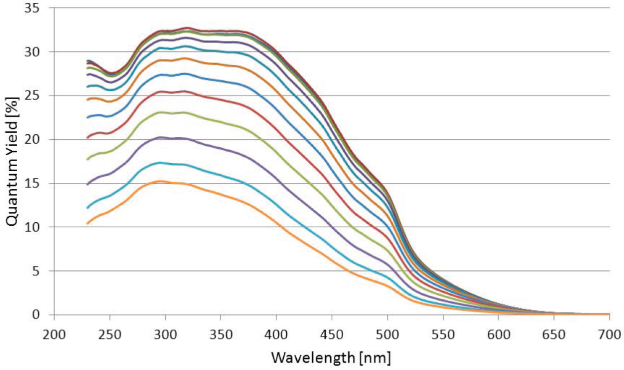

Figure 7: Quantum efficiency (QE) of K2CsSb as a function of wavelength recorded every 2 hrs for an exposure of 5x10-9 mBar of water.

This allows monitoring and optimizing the deposition as it proceeds. The top curve in Fig.7 shows a fresh film, with 6% QE at 532 nm. Including the barrier lowering caused by the high gradient field of the gun (~20 MV/m), this amounts to around 10% QE in operation. The other data are taken sequentially every 2 hrs, at a partial pressure of $5x10^{-9}$ mBar of water, and show a half life of around 20 hrs. This demonstrates that the films are surprisingly robust to water contamination. Water and oxygen are of major concern in terms of cathode lifetime, but these measurements seem to indicate that at the expected operating pressure in the VHF gun, this should not be a concern. One thing that is evident from this work is that the reactivity is very sensitive to how the cathodes are produced, and to their final 'capping', ie. how the last few monolayers of material are deposited. We have also investigated the traditional methods of making these films, ie. deposition of Sb, then K to maximize yield, then Cs [11], with co-deposition and it is clear there are many trajectories that lead to high yield films. These films were examined by an atomic force microscope (AFM) and found to have considerable roughness, with typically 20-50 nm grain height variation for grains of 0.2-1 micron in size. As these films will have considerable conductivity due to 'doping' and defects, the field will follow the surface contours and this roughness is expected to play a role in determining the electrons transverse momentum, ie. a component of the accelerating field will be transferred into the transverse direction by the inclined features in the surface. We are working on ways to reduce roughness using the deposition technique. A better way to manufacture the films is by deposition from bulk material. Bulk material can be produced by weighing materials in an Ar glove-box, then reacting using an rf heater in Ar or vacuum [12]. The great advantage of this method is that true stoichiometry can be achieved, something that is impossible for these materials using evaporation, due to the very low and unknown sticking coefficients of the alkali metals at elevated temperature. The bulk material can then be deposited by pulsed laser deposition and similar techniques. Our present work is aimed at measuring the transverse momentum from the films at using an *in-situ* measurement system as well as using a dedicated low energy ARPES (Angular Resolved Photo-Emission Spectroscopy) system for photocathode R&D, as well as understanding the growth process using synchrotron-based X-ray diffraction (XRD). We have initial results from synchrotron XRD which show the growth of competing phases of K_2CsSb and KCs_2Sb.

We also have a collaboration with Brookhaven National Laboratory for testing diamond amplified photo-cathodes in the VHF gun [13].

FUTURE PLANS

In the near future the VHF gun will be installed in the Beam Test Facility at LBNL and the experimental activity will be organized in two stages. In Phase I (fully funded), only the gun with the vacuum load lock system and a low energy beam diagnostic beamline will be installed, and the following tasks will be pursued: perform full power RF tests of the cavity; demonstrate the vacuum system performance; characterize the first generation cathode; characterize the e- beam at the gun energy at full rep-rate.

In Phase II (requires continuation funds) the following goals will be targeted: develop and install accelerating sections for achieving few tens of MeV beam energy; develop and install an high energy diagnostic beamline; characterize the beam parameters at high energy (probably at low repetition rate); perform FEL tests in the IR using new generation undulators.

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