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RECENT PROGRESS ON THE DESIGN OF NORMAL CONDUCTING APEX2 VHF CW ELECTRON GUN*

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Abstract

We report recent progress on the design of a normal conducting (NC) CW electron gun, APEX2 (Advanced Photo-injector Experiment2) at Lawrence Berkeley National Laboratory (LBNL). APEX2 is an upgrade of the successful APEX gun at LBNL and the LCLS-II (Linac Coherent Light Source-II) injector at SLAC, aiming at the applications for Free electron laser (FEL) such as LCLS-II High Energy upgrade, UED (Ultrafast Electron Diffraction) and UEM (Ultrafast Electron Microscopy). The APEX2 adopted a two-cell cavity design with resonant frequency of 162.5 MHz. The APEX2 gun is targeting to achieve a launching gradient at the cathode exceeding 30 MV/m and output energy above 1.5 MeV with transverse emittance of 0.1 µm at 100 pC. Advanced MOGA optimization technique has been used for both the RF cavity design and extensive beam dynamics studies, both using APEX and LCLS-II like injector layouts. Detailed RF designs, beam dynamics studies, and preliminary engineering design supported by FEA analysis will be presented, along with cavity features that were demonstrated to be crucial in the operation of the APEX gun.

INTRODUCTION

Producing high-peak and high-average brightness beams has been the R&D frontier in electron sources, a critical research path towards ultrafast atomically resolved observation and control of matter. Photo-cathode electron RF guns have been developed in a wide frequency range over the past decades and demonstrated successfully in terms of the reliability and beam quality required to drive X-ray Free Electron Lasers into hard X-ray region [1].

Due to challenges in thermal management produced by RF heating, normal conducting RF electron guns can only be operated at relatively low repetition rates (typically <1 kHz), and therefore with severe limitations to achievable beam parameters, such as the flux and brightness. Recent DOE-BES workshop on future electron sources suggested several applications would strongly benefit from high brightness beams at Megahertz (MHz) repetition rates. These applications include the LCLS-II HE, the higher energy upgrade of the SLAC FEL Project that is currently under construction. The LCLS-II HE would require a normalized transverse emittance as small as ~ 0.1 µm RMS at 100 pC bunch charge in order to extend the lasing spectrum in the hard X-ray region (>10 KeV). Moreover, the large beam coherence and high electron flux offered by a higher brightness gun would also greatly benefit compact tools for UED and UEM applications. The scientific reward for such development would be enormous, providing sub-atomic imaging capabilities to FELs, and extending the scientific reach of UED and UEM techniques to large biological samples, complex non-periodic structures in gas and liquid phases and in-situ experiments.

LBNL has a long and successful history in the development, construction and delivery of advanced normal conducting RF structures ranging from CW RFQ accelerators for ions to the recent CW APEX electron gun at LBNL and LCLS-II injector at SLAC. The strategic choice of using warm technology and accelerating fields in the Very High Frequency (VHF) range for the APEX cavity has been crucial in the successful realization of the electron gun, resulting in a solution to the long-standing problems of reliability and operation of CW high-brightness electron sources. The targeted performance of the APEX in all key parameters was achieved with the design and realization of only one prototype, with no major concept modifications. Another very important consequence of the use of warm technology is its compatibility of the structure with external magnetic fields and with delicate high quantum-efficiency (QE) semiconductor cathodes, which is essential when seeking simultaneous optimization of peak and average brightness, and bears important consequences for both FELs, UED and UEM applications.

In order to drive a MHz-class FEL with hundreds of pico-Coulombs per bunch, it is necessary to use cathodes with QE at the percent-level in order to avoid surface damage from excessive laser-heating and emittance growth from laser-induced electron heating that would dramatically decrease the beam brightness. Such degradation of the beam quality would also affect the beam lateral coherence in UED and UEM experiments, where the lower extracted charge is counterbalanced by a much smaller emission area, leading to similar fluence values at the cathode surface. Besides the APEX, only DC-guns have demonstrated reliable operation with semiconductor cathodes in CW operations, but at the expense of decreased accelerating gradient on the cathode and lower output energy.

Based on the success of the APEX gun, we propose a new RF electron gun, aimed at further increasing the

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brightness performance using proven APEX technologies in ultra-high vacuum and normal conducting CW RF in the very high frequency. The proposed effort, APEX2 promises to increase the present brightness performance of such guns by at least a four-fold factor, by targeting accelerating electric gradient at the cathode exceeding 30 MV/m and output kinetic energies at 1.5 MeV. Such a leap in electron source performance will have a tremendous scientific impact, providing high flux ultra-fast instrumentation, such as MHz-class FEL and high-repetition-rate Ultrafast Electron Diffractometers and Microscopes with smaller footprints and extended scientific capabilities.

APEX2 CONCEPT

The concept of APEX2 was first presented at FEL-2017 Conference [2], where a 2-cell cavity design was proposed by scaling from the APEX cavity to 162.5 MHz, as shown in Fig. 1 and main cavity parameters are listed in Table 1, together with APEX parameters for comparison.

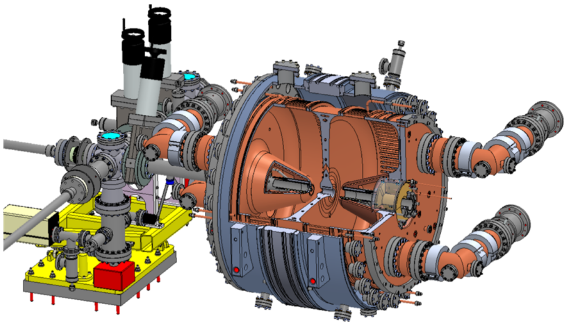

Figure 1: Originally proposed 2-cell design for APEX2 (Option 1).

Table 1: Main Cavity Parameters of APEX vs APEX2

Parameter	APEX	APEX2
Frequency [MHz]	185.7	162.5
Operation mode	CW	CW
Cathode gradient [MV/m]	19.5	34
Beam energy [MV]	0.75	2
Number of cells	1	2
RF power/cell [kW]	85	127
Power density [W/cm^2]	22	30

A preliminary beam dynamics study was conducted at the time using the APEX-like injector layout for both single and 2-cell APEX2 designs. The simulation study was carried out by MOGA optimization using ASTRA for the case of 100 pC and 10 k macro-particles. The study showed that a 2-fold reduction in the transverse emittance was obtained (~ 0.13 um at 100 pC) and hence the 4-fold brightness increase required by future applications. The high launch-accelerating gradient at the cathode (34 MV/m) has a dominant effect for transverse emittance reduction while the details of the field distribution in the cavity are less sensitive to the beam performance.

RF DESIGN OPTIONS OF APEX2

Inspired by the preliminary beam dynamics performance, we proceeded to propose APEX2 and evaluated three different cavity design options: (1) a 2-cell cavity (Fig.1), (2) a single-cell cavity with double nosecones and (3) a single-cell cavity with a drift tube in between (Fig. 2).

Option 2 is realized by removing the separation wall from the 2-cell configuration (Option 1), namely a large single-cell cavity with dual nosecones. This option obtains higher output energies for the same input RF power, but has much lower gradient on the cathode that is needed for achieving low emittance. Moreover, it also loses the flexibility of independent phase and amplitude control, compared to Option 1.

Option 3 has the best RF performance. The insertion of a drift tube in the gap restores the required high gradient on the cathode and makes the cavity more efficient with a minor decrease of the output energy. This single-cell with drift tube can easily achieve 34 MV/m on the cathode with a relatively smaller RF power increase. However it is very challenging to engineer this option with a suspended drift tube both for mechanical stability and for CW operation (thermal management).

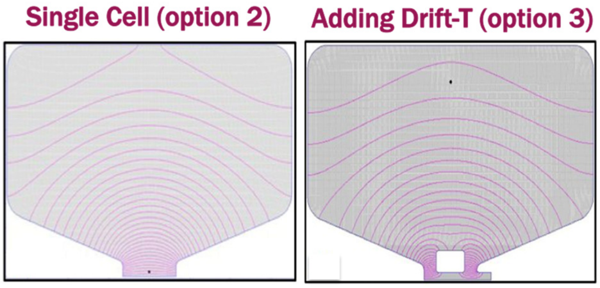

Figure 2: APEX2 cavity design options (2) and (3).

Based on considerations of beam dynamics, RF, mechanical engineering and fabrication, the 2-cell cavity design (Option 1) has obvious advantages and was chosen as the baseline design for APEX2. The 2-cell option also retains preferable independent amplitude and phase control for each cell.

RF AND BEAM DYNAMICS PERFORMANE OF APEX2

After many iterations of RF, beam dynamics and engineering studies, we have achieved a 2-cell APEX2 RF cavity design that meets all the proposed parameters and supported by good beam dynamics performance.

The 2-cell design option allows for optimization of each cell independently. For the gun cell, optimization was focused on achieving high gradient on the cathode; for cell 2, the optimization was for gaining higher energy in consideration of accommodating a focusing solenoid required by beam dynamics performance. In order to find the best possible cell profiles defined by multi-parameters, we developed a MOGA program using 2D SUPERFISH and applied it to the APEX2 cavity design [3]. The design objectives and constrains are set by performance requirements and our practical and successful experience in RF, mechanical engineering and operation in the APEX and other projects. Table 2 lists the main cavity (2D) parameters achieved using the MOGA optimization programs. We are able to attain a very high accelerating gradient of 34 MV/m on cathode while keeping an $E_{\mathrm{peak}}/E_{\mathrm{cathode}}$ ratio of only 1.09, compared with the ratio of 1.23 for the APEX gun. The cell 2 design was optimized to provide an energy boost, and at the same time allow for a long-narrow focusing solenoid to be placed in the nosecone as close as possible to the cathode, a CAD drawing with the optimized cell profiles, solenoids and cathode plug are shown in Fig. 3.

Table 2: APEX2 RF Design Parameters versus APEX

Parameters	**Gun**	**Cell 2**	**APEX**
Frequency [MHz]	162.5	162.5	185.7
Cavity radius [cm]	39.3	39.1	36.0
Cavity length [cm]	38.7	36.0	35.0
Acceleration gap [cm]	2.5	4.6	4.0
Beam Iris [cm]	1.0	1.0-1.5	1.5
Operation mode	CW	CW	CW
E_{Cathode} [MV/m]	34	N/A	19.5
Energy gain [kV]	820	820	750
E_{Peak}[MV/m]	37.0	24.7	24.0
Power [kW]	90.7	85.4	88.5
Max. P. Density [w/cm^2]	32.1	29.8	22.8

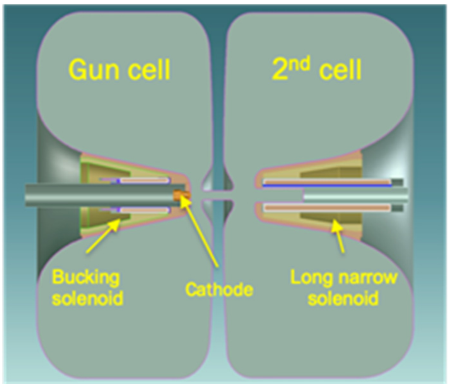

Figure 3: Optimized APEX2 guan and cell 2 profiles; the overall dimensions were kept at about the same as APEX.

Extensive beam dynamics studies have been carried out using the APEX2 RF fields to determine maximum possible spacing achievable between the gun cell and cell 2 without beam dynamics performance degradation using both APEX-like and LCLS-II injector layouts. This spacing has a major impact on engineering designs of features that can be implemented, such as watering cooling, tuning mechanisms, insertion of a small focusing solenoid etc. More detailed beam dynamics studies can be found at [4], a satisfactory beam dynamics solution has been obtained and its performance is summarized in Table 3, where the beam performance was simulated using the APEX-like injector layout with output energy of 1.5 MeV at the gun and 95% emittance below 0.09 µm and 100% emittance of 0.1 µm.

PRELIMINARY ENGINEERING DESIGNS

An ANSYS model of the APEX2 cavity was built to conduct RF, thermal and mechanical analyses. In an attempt to further improve thermal and RF tuning performance and simplify mechanical and vacuum designs, we started to explore new design concepts with support from FEA studies, a conceptual 3D CAD model is showed in Fig. 4.

For the 2-cell APEX2, the shared wall between two cells will be a solid piece with gun-drilled cooling channels. Removing the stainless-steel vessel used in APEX allows for use of the cavity equator area for vacuum and RF coupler ports. Preliminary vacuum calculations showed that adequate pumping can be achieved thru ten 10” vacuum ports per cell. Placing two RF coupler ports per cell to the equator leaves more space on end plates where the APEX RF frequency tuning schemes can be used. FEA simulations have been carried out to determine the end plate thickness with very reasonable tuning force load for a tuning range of ± 250 kHz [5].

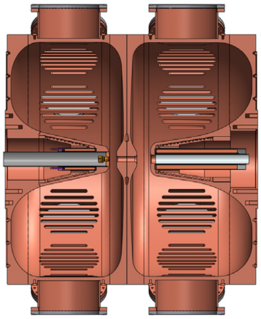

Figure 4: APEX2 3D CAD model showing evolving design concepts for RF coupler, vacuum ports, tuning and fabrication.

Table 3: Simulated Beam Performance

Parameter	**APEX**	**APEX2**
ε_{xn} (100%) [µm]	0.207	0.1032
ε_{xn} (95%) [µm]	0.180	0.0874
Peak current [A]	13.0	12.5
KE [MeV]	15.3	19.2
HOM^{+} [keV/c]	7.72	6.70

$^{+}$ Longitudinal RMS momentum spread after removing linear, quadratic correlations.

CONCLUSION

The current 2-cell APEX2 cavity design has achieved satisfactory performance in RF and beam dynamics. Preliminary engineering designs with improved features are supported by FEA simulations. More detailed 3D RF modelling and engineering design will continue.

ACKNOWLEDGEMENTS

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