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HIGHER FIELDS AND BEAM ENERGIES IN CONTINUOUS-WAVE ROOM-TEMPERATURE VHF RF GUNS*

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Abstract

The development/proposal in the last decade of MHz-class repetition rate free electron lasers (FELs), inverse Compton scattering sources, and ultrafast electron diffraction and microscopy (UED/UEM), required the development of new gun schemes capable of generating high brightness beams at such high rates. The VHF-Gun, a 186 MHz room-temperature continuous wave RF photogun developed at the Lawrence Berkeley Lab (LBNL) was one of the answer to that need. The VHF-Gun was constructed and tested in the APEX facility at LBNL successfully demonstrating all design parameters and the generation of high brightness electron beams. A close version of the APEX VHF-Gun is in the final phase of fabrication at LBNL to operate as the electron source for the LCLS-II, the new SLAC X-ray FEL. The recently approved upgrade of the LCLS-II towards higher energies (LCLS-II HE), and the always brightness-starving UED and UEM applications, would greatly benefit from an increased brightness of the electron source. Such performance upgrade can be obtained by raising the electric field at the cathode and the beam energy at the gun exit. In this paper, we present and discuss possible upgrade options that would allow to extend the VHF-Gun performance towards these new goals.

INTRODUCTION

The last decade has been characterized by the formidable and successful development of several X-ray free electron laser (FEL) facilities capable to generate peak brightness of up to 9 orders of magnitude higher than the ones generated by 3rd generation light sources based on storage rings. More recently, a number of new FEL facilities were proposed targeting a similar dramatic performance increase also in terms of average brightness using superconducting RF (SRF) linacs operating in continuous wave (CW) mode. These facilities are designed to increase the repetition rate of the original FELs from hundreds of Hz to MHz. Among those, the LCLS-2 at SLAC was funded and it is now in the construction phase [1], and very recently, the Shanghai Coherent Light Facility (SCLF) project was approved in China [2].

The electron source is a key component in linac-based applications where it ultimately determines the maximum electron beam brightness and the facility overall performance. A high-repetition rate, high-brightness electron source was not readily available and several groups around the world started to propose and develop new schemes or upgrades for electron guns that could address that need.

It is worth to remark that the availability of such a high-repetition rate, high-brightness source would also dramatically benefit other electron beam applications such as inverse Compton Scattering sources and ultrafast electron diffraction and microscopy (UED/UEM).

In response to that need, our group at the Lawrence Berkeley Laboratory (LBNL) developed in the framework of the Advanced Photoinjector EXperiment (APEX), the VHF-Gun, a room-temperature RF photo-gun resonating at 186MHz in the VHF frequency range and designed to operate in CW mode [3, 4]. During its commissioning, the gun successfully demonstrated reliable continuous wave RF operation at the design parameters [5] generating MHz electron beams with transverse emittances, longitudinal phase space and charge suitable for the operation of a high-repetition rate X-ray FEL such as the LCLS-II [6]. Also importantly, the APEX VHF-gun also demonstrated the low vacuum pressures required to operate high quantum efficiency semiconductor cathodes (Cs_2Te and CsK_2Sb) with acceptable lifetimes [7, 8].

At the present time, a close version of the APEX gun is in the final phase of fabrication at LBNL to serve in the LCLS-II injector, while the original APEX gun is now in operation as the electron source for HiRES, the LBNL high repetition-rate UED experiment [9].

In spite of these positive developments, there are already several high repetition-rate applications that would strongly benefit from an even further increase in beam brightness at high repetition rates. A notable example is the LCLS-II HE, the higher energy upgrade of the SLAC FEL [10], which already received CD-0 (the 1st approval level by the US Department of Energy. LCLS-II HE would require for its main mode of operation at 100 pC bunch charge, a normalized transverse emittance approaching 0.1 μm rms for further extending its lasing spectrum in the hard X-ray region. This is an about two-fold reduction with respect to the present LCLS-II emittance requirement. The additional electron beam coherence offered by the higher brightness would also greatly benefit UED/UEM applications.

The successful performance of the APEX VHF-Gun pushed our group to investigate the possibility of extending the VHF technology towards higher beam brightness while maintaining the operational functionality and reliability demonstrated by the present VHF-gun. In this paper, we present several concepts for possible gun configurations with the capability of achieving the desired enhanced performance. We will refer to these upgraded gun versions as the APEX-2.

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FROM APEX TO APEX-2

In upgrading the APEX gun to the APEX-2 evolution, we want to increase the brightness and the energy of the beam at the gun while adopting as much as possible the mechanical, vacuum and RF solutions that ensured the successful performance of APEX.

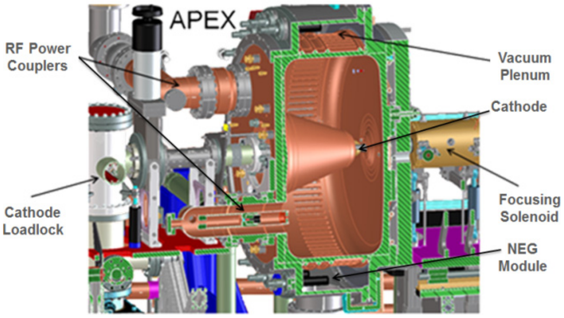

Figure 1: CAD cross-section view of the existing APEX VHF-Gun with main components in evidence. The two main RF couplers, the pumping slots on the cavity wall, and the vacuum plenum where up to 20 NEG modules can be located are visible. The photo-cathode plug is located on the tip of the nosecone and is inserted and removed without breaking vacuum by the loadlock system located in the back of the gun.

The brightness augmentation requires the increase of the accelerating electric field at the cathode during the electron emission [11, 12], and of the beam energies at the gun exit to reduce space charge forces that can degrade the quality of the beam phase space.

In order to preserve the APEX reliability, the APEX-2 design effort to maximize the cathode peak field and beam energy, is done maintaining the RF thermal heating at manageable levels by minimizing the power density on the cavity walls. This can be done by lowering the frequency of the gun from the 186 MHz (1/7th of 1.3 GHz) of APEX to the 162.5 MHz (1/8th of 1.3 GHz) of APEX-2. The lower frequency decreases the surface resistivity of the cavity copper wall, allowing for higher fields at the cathode for same surface power density. The new frequency is also convenient for the availability of commercial RF sources, and for its compatibility with existing superconducting linac cavities at 325 MHz, 650 MHz, and 1.3 GHz.

Table 1 shows a comparison between the present APEX gun parameters and the target values for APEX-2. The significantly higher field targeted at the cathode is justified by the operational experience at APEX, where no evidence of voltage breakdown was observed (with fields at the cathode of up to ~22 MV/m), and extremely low dark current values were measured (less than a nA at the nominal field). The maximum RF power choice for APEX-2 allows using four APEX-type RF couplers and RF waveguide configurations used and demonstrated at APEX. The value is also compatible with existing commercially available solid state RF sources.

Table 1: APEX vs. APEX-2 main design parameters

Parameter	**APEX**	**APEX-2**
Frequency [MHz]	186.7 (1300/7)	162.5 (1300/8)
Mode of operation	CW	CW
Technology	Room-temp. Cu	Room-temp. Cu
Number of cells	1	1 or 2
Peak power density [W/cm^2]	22	< 35
Max RF power [kW]	120	< ~250
Launching field at photocathode [MV/m]	20	~35
Beam energy [MV]	0.75	1.5-2.0

Several upgrade configurations for APEX-2 were considered. In one case, two APEX-like re-entrant-nose RF cavities are put back-to-back to create a two-cell structure where the cathode is inserted into the nosecone of one cell and the beam is extracted from the nosecone of the other cell. In this design, visible in Fig. 2, most of the APEX mechanical, RF and vacuum solutions are directly adopted. The two cells are extremely weakly coupled and can be operated with arbitrary RF phase difference enabling a flexible control over the beam exit energy and emittance preservation. This design uses about 250 kW of RF power divided between the 4 couplers to generate ~34 MV/m field at the cathode and ~2 MeV beams at the gun exit. The peak wall power density assumes a moderate value of 30 W/cm^2, and the cell inner radius increases from the 35 cm of APEX to 47.5 cm.

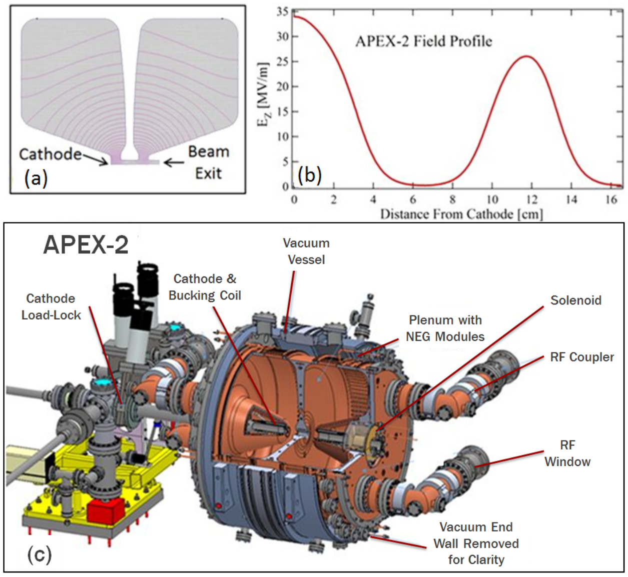

Figure 2: (a): Superfish [13] calculation showing the electric field geometry in (half) the cavity for the two-cell geometry of APEX-2. (b): accelerating field intensity along the gun axis. (c): 3-D CAD view of a preliminary mechanical design for the two-cell geometry with main components in evidence.

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Alternate configurations were also studied. By removing the central wall between the two cells visible in Fig. 2, the cavity assumes a single-cell dual-nose re-entrant geometry. Removing the wall reduces the overall heating losses (no more losses on the removed wall) increasing the beam energy for fixed RF power, but also decreasing the peak electric field at the cathode. A third geometry, which recovers the field at the cathode and at the same time allows for a higher RF efficiency, is obtained by inserting a drift tube in the middle of the gap. Initial design indicates that fields at the cathode of up to 35 MV/m can be reached with ~200 kW of RF power. The preliminary electric field configurations for both these single-cell options are visible in Fig. 3.

Cryogenic operation for APEX-2 could be also considered to alleviate thermal loading and improve efficiency. Recent experiments also showed that at cryo temperatures the increased copper rigidity can reduce the RF breakdown rate [14].

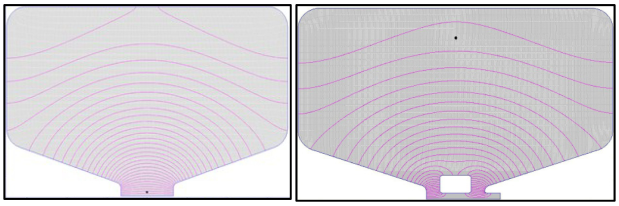

Figure 3: Superfish calculations showing the electric field geometry inside (half of) the cavity. Left: case of a single-cell dual-re-entrant nose geometry. Right: same design with the addition of a drift tube in the center of the gap.

INITIAL BEAM DYNAMICS STUDIES

Beam dynamics simulations using the ASTRA code [15] were done to evaluate the beam dynamics performance of two of the different APEX-2 geometries, the dual-cell and the single-cell dual-re-entrant nose without drift tube. An APEX-like injector layout [6] was used replacing the original APEX gun with the two different versions of the APEX-2 gun.

Figure 4 shows the preliminary results of a genetic algorithm optimization for 100 pC charge per bunch minimizing normalized emittance and rms bunch length at the end of the injector for the two gun configurations. The field at the cathode was kept fixed at 34 MV/M for both cases. The very similar solution fronts indicate that for fixed field at the cathode, the performance is essentially independent on the gun geometry. In order to keep computing time reasonable, the simulations shown in Fig. 4 used 10k macro-particles. Accurate simulations (with 250k macro-particles) using several solutions taken from the fronts systematically showed emittances ~15-20% smaller than the ones in the figure. In the bunch length range of interest for an FEL like the LCLS-II (0.8 to 1.2 mm rms), the simulated emittances for 100% of the beam are between ~0.12 to 0.144 µm. This is about a factor 2 better than in APEX approaching the desired 0.1 µm goal for 95% of the particles.

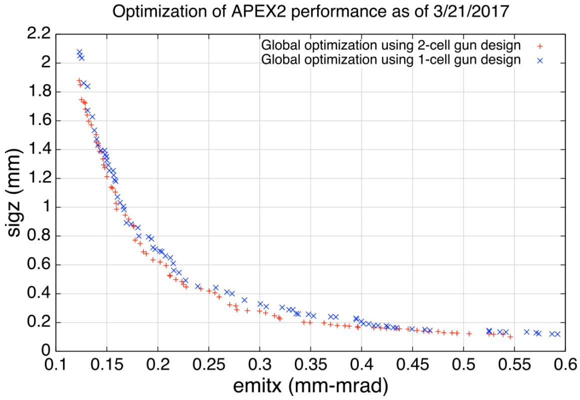

Figure 4. Fronts of solutions (trading between emittance and rms bunch length) for injector layouts using two of the APEX-2 gun geometries. See text for more details.

CONCLUSIONS

Demand from existing/proposed high-repetition rate facilities for higher brightness electron beams is pushing the design/upgrade of CW guns with higher fields and beam energies. Preliminary studies indicated the possibility of upgrading the successful room-temperature VHF-gun technology to higher fields at the cathode and beam energies, while preserving the reliability and vacuum performance demonstrated by the VHF-gun at the APEX project at LBNL. Several possible upgrade options were studied at the conceptual level and no show-stoppers were found. Initial simulations showed a brightness performance very close to the desired goal.

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