UPGRADE OPTIONS TOWARDS HIGHER FIELDS AND BEAM ENERGIES FOR CONTINUOUS-WAVE ROOM-TEMPERATURE VHF RF GUNS*

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Abstract

Science demand for MHz-class repetition rate electron beam applications such as free electron lasers (FELs), inverse Compton scattering sources, and ultrafast electron diffraction and microscopy (UED/UEM), pushed the development of new gun schemes that could generate high brightness beams at such high rates. Our group at the Lawrence Berkeley Laboratory (LBNL) proposed a new concept room-temperature RF gun resonating in the VHF frequency range (30-300 MHz) capable to operate in continuous wave mode with fields required for high-brightness performance. A prototype 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 advanced phase of construction at LBNL for the LCLS-II, the super-conducting X-ray FEL in construction at SLAC. Studies showed that the high-energy LCLS-II upgrade, and UED and UEM applications, would greatly benefit from a further increased gun brightness 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 technology towards these new goals.

INTRODUCTION

Experiment requirements at X-ray free electron laser (FEL) facilities, inverse Compton sources (ICS) and ultrafast electron diffraction and microscopy (UED/UEM) have been progressively and intensively pushing towards high repetition-rate operation (MHz-class) that requires linac-based accelerators capable of generating electron beams with the proper brightness. A key component for such accelerators is a high repetition-rate, high brightness electron source, which ultimately determines the beam properties and the facility overall performance.

The VHF-Gun, a room-temperature RF photo-gun developed at the Lawrence Berkeley Laboratory (LBNL) in the framework of the Advanced Photoinjector EXperiment (APEX) [1, 2], was envisioned as a path forward towards those high repetition-rates, high brightness goals. After almost a decade of development, the APEX gun succeeded in demonstrating continuous wave (CW) RF operation [3] with MHz electron beams with the emittances and charges required for operating a high-repetition rate X-ray FEL such as the LCLS-II at SLAC [4, 5]. The gun also demonstrated the low vacuum pressures required to operate high quantum efficiency semiconductor cathodes with acceptable lifetimes [6].

Based on these achievements, a new VHF-Gun, a close version of the one used at APEX, is in the final phase of fabrication at LBNL to serve in the LCLS-II injector.

Furthermore, the APEX gun is now in operation as the electron source for HiRES, the LBNL high repetition-rate UED facility [7].

As recently pointed out by a DOE-BES workshop on future electron sources [8], there are several high repetition-rate applications that would strongly benefit from an additional increase in beam brightness. For example, the LCLS-II HE, the higher energy upgrade of the SLAC FEL [9] that has already received CD0 (the first level of approval by DOE), would require for a 100 pC bunch a normalized transverse emittance as small as 0.1 μm rms for effectively extending its lasing spectrum in the hard X-ray region. The additional electron beam coherence offered by a higher brightness gun would also greatly benefit UED/UEM applications.

Leveraging on the success of APEX in terms of high brightness performance and operation reliability, our group at LBNL started to investigate new concepts that would extend the VHF-Gun technology towards higher beam brightness while maintaining the operational functionality and high reliability of the presently operating APEX gun. In this paper, the results of this initial exploration are presented. From now on, we will refer to these upgraded gun versions as the APEX-2.

APEX-2 DESIGN GOALS AND OPTIONS

In electron guns, the maximum achievable brightness depends on the accelerating electric field at the cathode during the electron emission: the higher the field the higher the achievable brightness [10, 11]. Also, higher beam energies at the exit of the gun reduce the intensity of space charge forces within the beam minimizing the degradation effects that such forces can have on the beam emittance. In other words, the path towards a higher brightness gun upgrade primarily consists in optimizing the design for higher accelerating fields at the cathode and higher beam energies at the gun exit. In the APEX-2 design studies we pursue the maximization of these two quantities while maintaining the solid mechanical and RF performance of the original APEX design.

In particular, in order to preserve the reliability and low vacuum operation pressure demonstrated by the APEX gun, the APEX-2 design effort to maximize the cathode peak field and beam energy, should be done maintaining

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the RF thermal heating at manageable levels by minimizing the power density on the RF structure walls and by the use of a proper cooling system. Table 1 shows a comparison between the present APEX gun parameters and the target values for the APEX-2 design.

Table 1: APEX and APEX-2 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 power/cell [kW]	100	< 130
Launching field at photocathode [MV/m]	20	~35
Beam energy [MV]	0.75	1.5-2.0

The frequency of the gun in APEX-2 is lowered from 186 MHz (1/7th of 1.3 GHz) to 162.5 MHz (1/8th of 1.3 GHz) to decrease the surface resistivity of the cavity copper wall, allowing for higher fields at the cathode for the same peak surface power density. This frequency is also convenient for the availability of commercial RF sources, and for its compatibility with existing superconducting linac cavities at 325 MHz and 650 MHz.

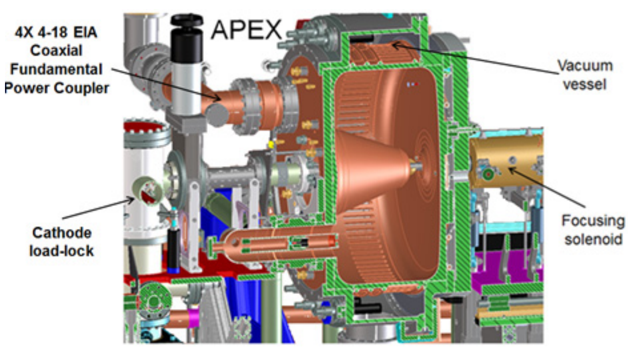

Figure 1: CAD cross-section view of the existing APEX gun with main components in evidence. The two main RF couplers and the vacuum plenum where up to 20 NEG modules can be located are visible. The photo-cathode is located on the tip of the nosecone and can be inserted/removed from the gun without breaking the vacuum by the vacuum loadlock system located in the back of the gun. The radius of the cavity is about 35 cm.

The choice for the maximum power per cell targeted with APEX-2 allows using the same main RF coupler design and waveguide configurations used and demonstrated at APEX. The value is also compatible with existing RF source options.

The significantly higher target field at the cathode is justified by the experimental experience with APEX (where no evidence of voltage breakdown was observed with fields at the cathode of up to ~22 MV/m) indicating the existence of a potentially large margin for the increase of such quantity. The choice is also justified by the extremely low dark current values measured during the APEX operation (less than a nA at the nominal field), which should ensure low values also at the targeted APEX-2 field values.

Besides exploring an upgraded version of the one-cell reentrant- nose cavity used in the original APEX, we also investigated other geometries. In one case, shown in Fig. 2, two such reentrant-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, the two cells are extremely weakly coupled and can be operated with arbitrary RF phase difference enabling a more flexible control over the beam exit energy and emittance preservation. It is worth to remark that the same successful mechanical solutions, vacuum scheme and RF distribution configuration used for APEX, are implemented in this new design minimizing the risk of additional unexpected issues.

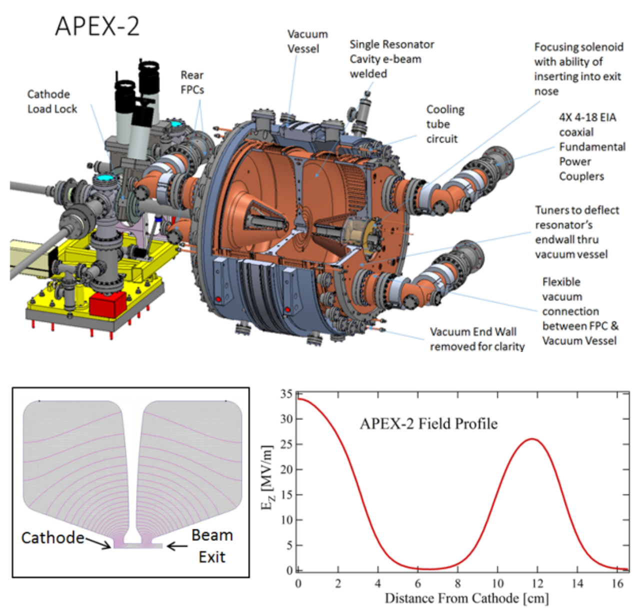

Figure 2: Top: CAD view of the conceptual design for a two-cell geometry of APEX-2 with its main components. Bottom left: Superfish calculation showing the electric field geometry in (half) the cavity. Bottom right: accelerating field intensity along the axis of the gun.

In an alternate design, for maximizing the beam exit energy, the central wall between the two cells can be removed and the cavity becomes a single cell two-nose reentrant cavity. Removing the wall reduces the overall heating loss but also slightly decreases the peak electric field on the cathode. One possible way to compensate for this is to insert a drift tube in the middle of the gap, the electric field configuration for both these options are shown in Fig.3.

The above cavity profiles are preliminary and require additional optimization to possibly increase their shunt

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impedance and to eliminate potential multipacting resonances over the power range of operation.

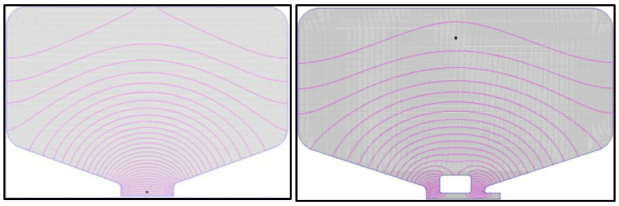

Figure 3: Superfish calculations showing the electric field geometry inside (half of) the cavity. Top: case of a single cell double reentrant nose cavity. Bottom: same design with the addition of a drift tube in the center of the gap.

We are also planning to explore the option of cryogenic operation for APEX-2. At cryogenic temperature, both the electric conductivity and thermal conductivity of the cavity copper walls increase significantly, which alleviates the thermal loading and improves the cooling efficiency. Additionally, recent experiment results show that the increase of copper rigidity at low temperature can significantly reduce the RF breakdown rate [12].

BEAM PERFORMANCE EVALUATION

In order to evaluate the beam dynamics performance of the APEX-2 VHF-guns, we performed simulations with the ASTRA code [13] using an APEX-like injector layout replacing the original APEX gun with two different versions of the APEX-2 gun: the two-cells and the single-cell dual reentrant nose geometries described above.

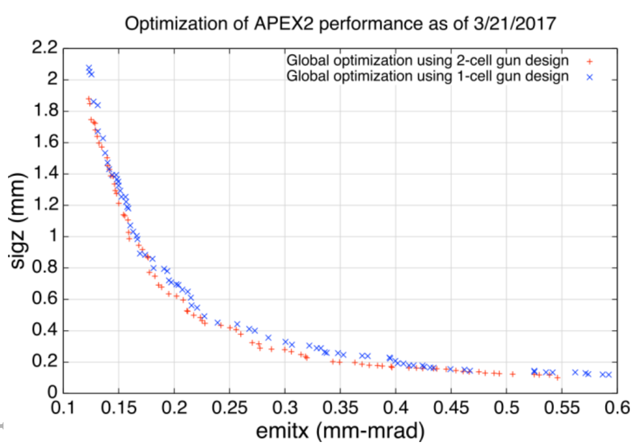

Figure 4: Pareto-optimal fronts showing the performance of APEX-2 using an injector layout based on two different gun design options.

Figure 4 shows the preliminary results of a genetic algorithm optimization for 100 pC charge per bunch minimizing normalized emittance and bunch length (and hence peak current) at the end of the injector for the two APEX-2 gun configurations. The field at the cathode was kept fixed at 34 MV/m in both cases. The two Pareto fronts show different solutions trading between low emittances and short bunch lengths. The extremely similar fronts indicate that the performance of the gun is pretty much independent on the gun geometry.

The simulations shown in the figure use 10k macro-particles in order to keep computing time reasonable. Accurate simulations using 250k particles, performed on a few characteristic solutions taken from the fronts in Fig. 4, systematically showed emittance values about 15-20% smaller than the ones in the figure.

In the bunch length range of interest for an FEL like the LCLS-II (between 0.8 and 1.2 mm rms), the simulated emittance values for 100% of the particles are between ~0.12 to 0.144 µm approaching the desired 0.1 µm value required for 95% of the particles.

CONCLUSIONS

Demand from existing and proposed high-repetition rate facilities for higher brightness electron beams is pushing to the design/upgrade of guns with higher gradients and beam energies. Preliminary studies indicated the possibility of upgrading the successful room-temperature continuous wave VHF-gun technology to higher accelerating fields at the cathode and electron beam energies while maintaining the reliability and vacuum performance already demonstrated by the original VHF-gun at the APEX project at LBNL.

Several possible options were analysed and studied at the conceptual level indicating no evident show-stoppers. Initial simulations indicated a brightness performance close to the desired target.

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