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RF DESIGN OF APEX2 CAVITIES

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Abstract

APEX2 is a proposed high repetition rate, high brightness electron source based on continuous-wave normal conducting RF cavities, aiming to further extend the brightness performance for Free Electron Laser and Ultra-fast Electron Diffraction/Ultra-fast Electron Microscopy beyond APEX. APEX2 photo-electron gun cavity consists of two 162.5 MHz RF cells, one Gun Cell for generating photo-electrons and one 2nd Cell for further accelerating the beam. Both cells adopt the re-entrant structure similar to APEX. In this paper, we present the RF design of the APEX2 cavity. A novel cavity design method based on Multi-Objective Genetic Algorithm has been implemented. A design that fulfills the requirements of both beam dynamics and engineering feasibility has been achieved.

INTRODUCTION

The high brightness, high repetition rate electron source is the key component for several scientific applications, such as X-ray Free Electron Laser (XFEL) and Ultra-fast Electron Diffraction/Microscopy (UEM/UEM). In the Advanced Photo-injector EXperiment (APEX) at Berkeley Lab, a photo-electron gun based on a normal conducting quarter-wave RF cavity operated at Very-High-Frequency (VHF) 185.7 MHz (1/7th of 1.3 GHz), has been designed, manufactured and successfully commissioned [1]. An electron injector almost identical with APEX has been produced as the injector for the Linac Coherent Light Source II (LCLS-II).

Based on the success of APEX, a new project named APEX2 [2] has been initiated at Lawrence Berkeley National Laboratory. APEX2 aims at further extending the performance of normal conducting gun technology for high brightness high repetition rate electron source.

MULTI-OBJECTIVE GENETIC ALGORITHM FOR CAVITY DESIGN

The requirements on $E_{cathode}$ and V, along with constraints from power considerations, engineering feasibility and beam dynamics requirements, impose considerable challenges on the APEX2 cavity RF design. A novel design method based on Multi-Object Genetic Algorithm (MOGA) [3] has been developed and applied on APEX2.

The cavity geometry is described by a vector $\mathcal{G} = \{g_1, g_2, \ldots\}$, where the g_n represents the geometric parameters. Once $\mathcal{G}$ is given, we can calculate the cavity eigenmodes and the RF field properties with EM field solvers. In this case, we use 2D solver SUPERFISH [4] due to its fast speed and built-in post-processing functions. The relevant RF properties and cavity geometry parameters constitute the figure of merit vector $\mathcal{M} = \{m_1, m_2, \ldots\}$, where the m_n represent the cavity frequency f, cathode launching field $E_{cathode}$, cavity radius R, etc..

As a multi-objective optimization problem, a cavity RF design can be formatted into searching for geometries $\mathcal{G}$s that

$$\begin{aligned} \text{Minimize} \quad & o_i(\mathcal{G}), i = 1, 2, \ldots; \\ \text{while are subjected to} \quad & c_j(\mathcal{G}) \leq 0, j = 1, 2, \ldots; \\ & g_n^L < g_n < g_n^U, \end{aligned} \tag{1}$$

where the objective vector $\mathcal{O} = \{o_1, o_2, \ldots\}$ and the constraint vector $\mathcal{C} = \{c_1, c_2, \ldots\}$ are derived from $\mathcal{M}$, while the g_n^L and g_N^U are respectively the lower and upper limit of g_n.

The optimization result is a group of geometries $\mathcal{G}_1, \mathcal{G}_2, \ldots$, which are non-dominant over each other. Together they make up the Pareto front in the objective phase space. A final geometry is chosen from the Pareto front based on further considerations. Many MOGA algorithms have been developed and implemented in different applications. In this paper we use Non-dominant Sorting Genetic Algorithm II (NSGA-II) [5] for its well-tested performance and high efficiency.

MOGA is naturally suited for parallel computing. We parallelized the NSGA-II with Multiple Passage Interface and carried out the computation on a 12-core local Windows workstation. For a population of 720, it takes about 48 hours to finish the calculation of 200 generations.

DESIGN OF 162.5 MHz APEX2 RF CAVITY

A 162.5 MHz two-cell cavity is chosen as the baseline for APEX2. The choice of the frequency allows compatibility with other frequencies frequenctly used in LINAC cavities (i.e. 325 MHz and 650 MHz for XFEL). Compared to APEX (185.714 MHz), the lower frequency also helps reduce the surface resistance and therefore the power density. With high E_{cathode}, the Gun Cell generates high current, high brightness electron beam while providing an output energy similar to the APEX gun. The 2nd Cell provides further acceleration up to 1.5 MeV. Both cells are of re-entrant structure similar to APEX. The RF coupling between two cells is negligible, so they can be operated separately.

The RF design is intentionally kept similar to the APEX gun, which has already demonstrated several key operating

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parameters. The new RF field profile of the APEX2 cavity has then been applied on the extensive beam dynamics studies [6] to optimize the emittance performance. It is an iterative process involving the RF design, the beam dynamics study and the engineering considerations [7].

Design of Gun Cell

The Gun Cell geometry is described by 17 segments and 19 independent geometric parameters, as shown in Figure 1.

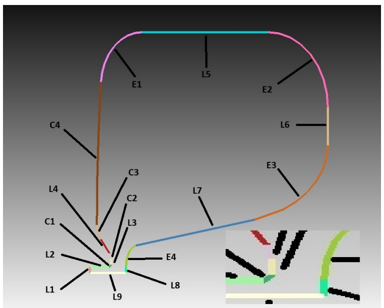

Figure 1: Geometric description of Gun Cell.The zoom-in view of the gap region is at the bottom right.

The most important optimization goal of the Gun Cell design is the high launching electric field on the cathode, which determines the beam transverse brightness [8]. The total RF power should be as small as possible. Other considerations include the RF frequency, peak power density, peak electric field, the practical cavity size limit, the accommodation of the cathode and laser system and so on. These design goals and limits are defined as objectives and constraints in MOGA, as listed in Table 1.

Table 1: MOGA Optimization Setting for Gun Cell Design

Objectives	**Constraints**
With $V = 820\,\mathrm{kV}$	$E_{\mathrm{peak}} < 37\,\mathrm{MV/m}$
1) Maximize E_{cathode}	$PD_{\mathrm{peak}} < 35\,\mathrm{W/cm^2}$
2) Minimize P_{total}	$f = 162.5{\pm}3\,\mathrm{MHz}$
	$R < 41\,\mathrm{cm}$
	Anode extrusion $K < 2\,\mathrm{cm}$

In MOGA, we chose a population $N = 720$ and calculated up to $g = 200$ generation. The Pareto fronts plotted at $g = 180, 190, 200$ are shown in Figure 2. Good convergence has been achieved at the 200th generation. The Pareto front clearly shows the trade-off between a high E_{cathode} and a low P_{total}. On the Pareto front of $g = 200$, we chose a geometry with $E_{\mathrm{cathode}} \geq 34\,\mathrm{MV/m}$ and the minimum P_{total} as the optimized solution, indicated as the dark dot in Figure 2.

The SUPERFISH field plot and main RF parameters of this optimized solution are shown in Figure 3 and Table 2. Compared with APEX gun, E_{cathode} has increased significantly from 19.5 to 34 MV/m. This improvement is mainly due to the decrease of the accelerating gap width G from 4 to 2.5 cm. Reducing the beampipe radius r_{b} from 1.5 to

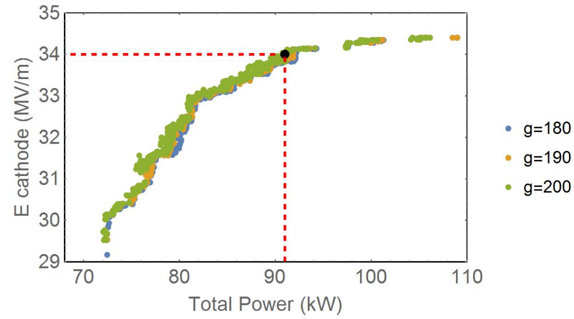

Figure 2: Pareto front for Gun Cell design.

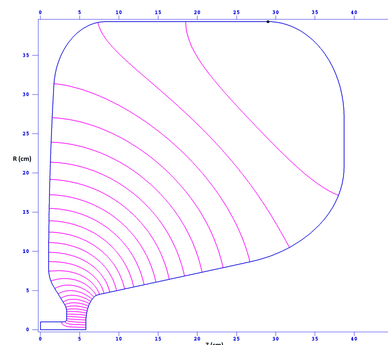

Figure 3: SUPERFISH solution of optimized Gun Cell.

1 cm also helps concentrating the E field along the beam axis. P_{total} is maintained at almost the same level as for APEX. The output energy V increases slightly from 750 to 820 kV. Due to the large enhancement of E_{cathode}, both E_{peak} and PD_{peak} are inevitably increased significantly compared to APEX.

Table 2: Main geometry and RF parameters of the optimized gun cell and 2$^{\mathrm{nd}}$ cell. APEX gun cavity parameters are also included as a reference.

RF Parameters	**Gun Cell**	**2$^{\mathrm{nd}}$ Cell**	**APEX**
R (cm)	39.3	39.1	36.0
L (cm)	38.7	36.0	35.0
G (cm)	2.5	4.6	4.0
r_{b} (cm)	1.0	1.0/1.5	1.5
f (MHz)	162.5	162.5	185.7
V (kV)	820	820	750
P_{total} (kW)	90.7	85.4	88.5
PD_{peak} (W/cm^2)	32.1	29.8	22.8
E_{cathode} (MV/m)	34.0	NA	19.5
E_{peak} (MV/m)	37.0	24.7	24.0

Design of 2nd Cell

The 2$^{\mathrm{nd}}$ Cell geometry is similar to the Gun Cell except there is no cathode plug. It is described by 20 segments and 21 independent geometric parameters.

The main function of the 2$^{\mathrm{nd}}$ Cell is to provide further acceleration. For a fixed total voltage, we chose the low

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peak surface E field and the low RF power loss as the design priorities. Other considerations include the RF frequency, peak power density, the practical size, the connection to the Gun Cell and the integration of the focusing solenoid. The beam dynamics simulation [6] shows that the focusing solenoid should be placed close to the cathode to achieve good emittance compensation, thus the accelerating gap of the 2nd Cell cannot be too large. At the same time, the gap can neither be too small considering the total RF power. The objectives and constraints in MOGA are listed in Table 3.

Table 3: MOGA Optimization Setting for 2nd Cell

Objectives	Constraints
With $V = 820\,\text{kV}$:	G+ chamfers < 5.7 cm
1) Minimize E_{peak}	$PD_{peak} < 30\,\text{W/cm}^2$
2) Minimize P_{total}	$f = 162.5 \pm 3\,\text{MHz}$
	$R < 39.3\,\text{cm}$
	Anode extrusion $K < 1.5\,\text{cm}$

Same as the Gun Cell, we chose a population $N = 720$ and carried out the calculation up to $g = 200$ generation. Good convergence has been achieved at the 200th generation, as shown in the Pareto front plot in Figure 4. The Pareto front shows a trade-off between a low E_{peak} and a low P_{total} as expected. On the Pareto front of g = 200, we chose a geometry with $E_{peak} \leq 25\,\text{MV/m}$ and the minimum P_{total} as the optimized solution, indicated as the dark dot in Figure 4.

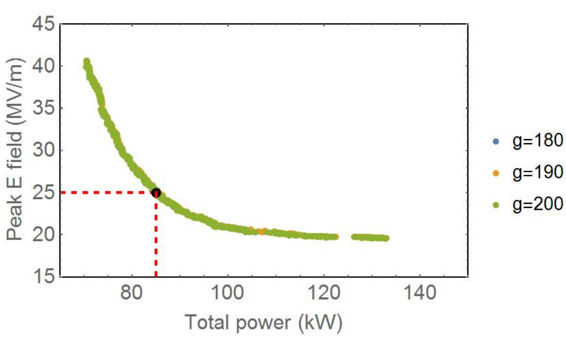

Figure 4: Pareto front for 2nd cell design.

The SUPERFISH field plot and main RF parameters of this solution are shown in Figure 5 and Table 2. Compared with the Gun Cell, the gap width G is increased to 4.6 cm to reduce E_{peak} and PD_{peak}. The radial size is close to the Gun Cell right below 40 cm. The total RF power at 85 kW is also similar to the Gun Cell.

Complete Two-Cell Structure

With the design of each cell done, they are put together to make the complete two-cell cavity, as shown in Figure 6. The distance between the cells is kept far enough to prevent RF coupling but also close enough to minimize the beam size growth along the structure, which would lead to a consequent emittance increase at the solenoid due spherical aberrations [6].

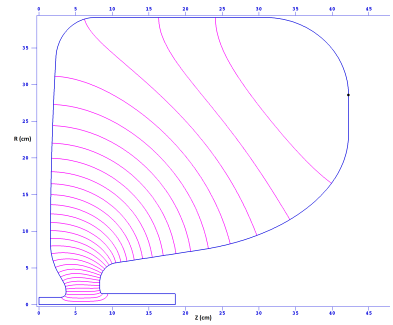

Figure 5: SUPERFISH solution of optimized 2nd Cell.

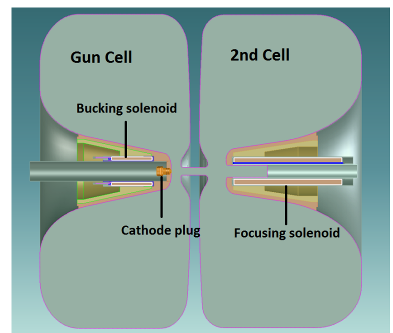

Figure 6: The 2-cell layout of APEX2 gun cavity.

CONCLUSION

The RF design of a 162.5 MHz two-cell VHF gun cavity has achieved significant increases of $E_{cathode}$ and V compared to the previous generation of CW normal-conducting guns (19.5 to 34 MV/m and 750 keV to 1.5 MeV). This improvement is likely to lead to a considerable enhancement of the injector beam brightness. A novel RF cavity design method based on MOGA has been developed and implemented in the design procedure.

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REFERENCES

[1] F. Sannibale *et al.*, "High-brightness beam tests of the very high frequency gun at the Advanced Photo-injector EXperiment test facility at the Lawrence Berkeley National Laboratory", *Rev. Sci. Instrum.*, vol. 90, p. 033304, 2019.

[2] F. Sannibale *et al.*, "Higher fields and beam energies in Continuous-Wave room-temperature VHF RF guns", *Phys. Rev. Accel. Beams*, vol. 20, p. 113402, 2017.

[3] A. Konak *et al.*, "Multi-objective optimization using genetic algorithms: A tutorial", *Reliability Engineering & System Safety*, vol. 91, pp. 992-1007, 2006.

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[4] K. Halbach and R. F. Holsinger, "SUPERFISH - a computer program for evaluation of rf cavities with cylindrical symmetry", *Part. Accel.*, vol. 7 ,pp. 213-222, 1976.

[5] K. Deb *et al.*, "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II", *Parallel Problem Solving from Nature PPSN VI*, pp. 849-858.

[6] C. Mitchell *et al.*, "Beam dynamics simulation of an APEX2-based photoinjector", presented at the 10th International Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May. 2019, paper TUPTS080, this conference.

[7] A. Lambert *et al.*, "Mechanical design and analysis of the proposed APEX-2 VHF CW electron gun", presented at the 10th International Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May. 2019, paper WEPRB084, this conference.

[8] D. Filippetto, P. Musumerci, M. Zolotorev, and G. Stupakov, *Phys. Rev. Accel. Beams*, vol. 17, p. 024201, 2014.