ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB010

FIRST DESIGN STUDIES OF A NC CW RF GUN FOR EUROPEAN XFEL

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Abstract

After the successful commissioning of the European XFEL in pulsed mode, continuous wave (CW) mode operation of European X-ray Free-Electron Laser (XFEL) is under considerations for future upgrade. DESY is pushing R&D on CW electron sources. A fully superconducting CW gun is under experimental development at DESY in Hamburg, and a normal conducting (NC) CW gun is under physics design at the Photo Injector Test facility at DESY in Zeuthen (PITZ) as a backup option. The 217 MHz NC CW gun is developed from the original LBNL 187 MHz VHF gun, with enhancement on both cathode gradient and gun voltage to further improve beam brightness. This paper presents the cavity RF design, multipacting (MP) simulations and beam dynamics studies.

INTRODUCTION

The European XFEL is driven by a 1.6 cell L-band NC RF gun in a pulse mode (650 µs RF pulse length and 10 Hz repetition rate). It provides up to 27000 pulses/sec, with a micro bunch repetition rate of 4.5 MHz. In order to further enhance user experiment capabilities, a future upgrade of the XFEL is CW operation, which enables more X-ray pulses with lower micro pulse repetition rate. For the CW gun upgrade, one option is a superconducting gun, which has the potential for highest cathode gradient and gun voltage but also higher technical risk, and is still in the R&D phase. The other option is a VHF band NC CW RF gun which has demonstrated high brightness high repetition rate (MHz-class) beam by LBNL in the APEX project [1,2]. The APEX 187 MHz gun operates at a gun voltage of 750 kV with a cathode field of 20 MV/m and average RF power of ~90 kW, and it is chosen as the electron gun for the LCLS-II project at SLAC. To further improve CW FEL performance at shortest wavelength, a next generation gun with even better beam brightness than the APEX gun is wished [3]. At LBNL, a 162.5 MHz APEX-2 gun, aiming for both higher cathode gradient and higher cavity voltage, is under design [4]. At the Photo Injector Test Facility at DESY in Zeuthen (PITZ), a 216.6 MHz NC VHF gun based on the APEX gun is under physics design as a backup option for a future CW upgrade of the European XFEL.

In this paper, RF optimization of the gun cavity is first presented, then the multipacting simulations inverstigates the MP location in the gun and MP zones. Finally, the beam dynamics studies to characterize gun performance are discussed.

RF DESIGN

Cavity RF Design

The APEX gun frequency (187 MHz) is not easily compatible with the exisiting XFEL timing system, and 162.5 MHz (8^{th} sub-harmonic of 1.3 GHz) and 216.6 MHz (6^{th} sub-harmonic of 1.3 GHz) are recommended by LLRF colleagues. To reduce RF breakdown risk of the gun at a higher gradient, 216.6 MHz was selected.

For the next generation VHF gun, although beam dynamics wishes for higher gun gradient and voltage, cavity cooling, dark current, and RF breakdown set the upper limits. Based on the APEX results, the upper limit of cathode gradient and gun average RF power are set to 30 MV/m and 100 kW, respectively, for the DESY VHF gun. To reduce the engineering difficulties, the 1^{st} DESY VHF gun will be a one cell design instead of the APEX-2 two cell design.

The cavity re-optimization based on the APEX gun profile was performed with the help of CST MWS [5]. The cavity shape is parameterized in CST, and perturbation scans on all the shape parameters find the key parameters to optimize gun frequency, shunt impedance (R_{sh}), cathode field (E_{cath}) and peak surface electric field (E_{surf}). Finally, the built-in CST optimizer optimizes the gun shapes with defined goals and constraints.

Due to the constraint on shunt impedance and 100 kW average gun power, the new gun voltage cannot be significantly higher than the APEX gun. To help achieve ~30 MV/m cathode gradient from the 20 MV/m of the APEX gun, the acceleration gap is reduced from 4 cm to 3 cm, which also slightly reduces the R_{sh}. To achieve a high cathode field and a high shunt impedance, both the cathode and anode nose should be 'shaper' to enhance the electric field in the acceleration gap, which also leads to a higher E_{surf}. In CST simulation, it is found that R_{sh} depends critically on the peak E_{surf}. Without constraining E_{surf}, the gun voltage can reach ~1 MV. The APEX gun has been operated with up to ~1.9 Kilpatrick field in the experiment without breakdown in the gun. In the following, two E_{surf} thresholds have been used in optimizations, one is more aggressive, 2.5 Kilpatrick for higher shunt impedance, and the other is 2 Kilpatrick for a more conservative approach.

Various cavity profiles have been investigated. Fig. 1(a) shows the electric field map of two typical models. The left figure shows the initial version scaled and optimized from the APEX gun with a cathode gradient of 30 MV/m and a cavity voltage of 860 kV. The peak E_{surf} on

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the cathode nose cone is 38.6 MV/m (~2.5 Kilpatrick limit). If the same cathode nose cone shape is applied with a 2 Kilpatrick limit (30.8 MV/m) on E_{surf}, both cathode gradient and gun voltage will be 20% lower. To reduce the ratio of E_{surf} to E_{cath}, the round corner of the cathode nose is replaced by a Rogowski profile (Fig. 1(a)) [6,7]. The Rogowski curve is originally used for the shaping of the electrical electrodes, with the aim of achieving a uniform electric field at the edges of the electrodes to avoid electric field enhancement and thus reduce the breakdown risk in the edge region, which can also be applied to the surface field optimization in an RF cavity. The Rogowski profile starts at the edge of the cathode plug hole, roughly 10 mm from cathode center. After optimization, the cathode gradient reached 28 MV/m with a surface peak electric field of 30.6 MV/m (~2.0 Kilpatrick limit). Compared with the round nose shape, the ratio of surface peak electric field to cathode gradient is reduced from 1.29 to 1.09. The electric field distribution on the Rogowski surface is more homogeneous than the round corner surface as shown in Fig. 1(b). The detailed RF parameters of these two models are listed in Table 1.

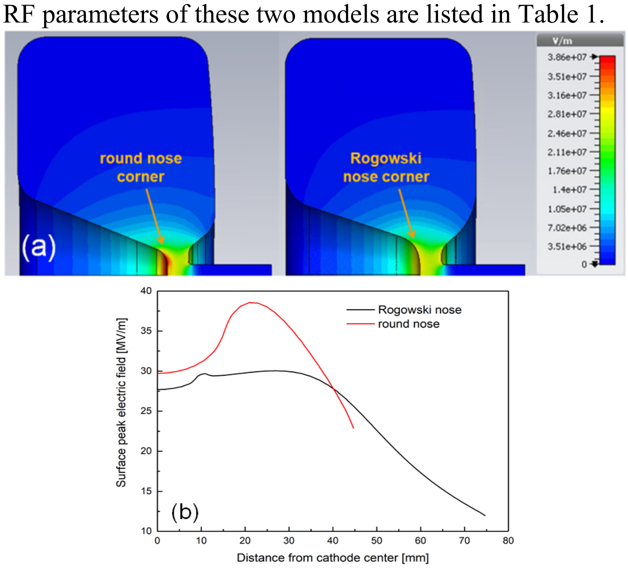

Figure 1: Electric field distribution with an input power of 100 kW. (a) Cavity with round cathode nose (left), cavity with Rogowski profile cathode nose (right); (b) surface field comparison along the cathode nose curve.

Table 1: RF parameters of the Cavities with Round Nose Shape and Rogowski Nose Shape

RF parameters	Round nose cavity	Rogowski nose cavity
Frequency, MHz	216.7	216.7
Quality factor	32160	31340
Accelerating gap, mm	30	30
Input power, kW	100	100
Shunt impendence, MΩ	7.4	6.9
Cathode gradient, MV/m	29.7	28
Peak surface E, MV/m	38.6	30.6
Cavity voltage, kV	860	830
Peak power loss density, W/cm^2	35.1	37

Cathode Plug Optimization

In Fig. 1, the cathode plug is not considered. If not properly designed, the plug vicinity may have field enhancement compared to E_{cath}, leading to more dark current and breakdown risk. Similar to the E_{surf} reduction for the cathode nose cone, applying the Rogowski surface is an effective approach to lower the E_{surf} in the plug vicinity. Figure 2 compares the field map with normal round corner and Rogowski corner. The peak surface electric field is reduced by 17%, from 35.1 MV/m to 29.2 MV/m, which is below 2 Kilpatrick limit. The field emission tracking simulations to evaluate the dark current will be carried out in the near future.

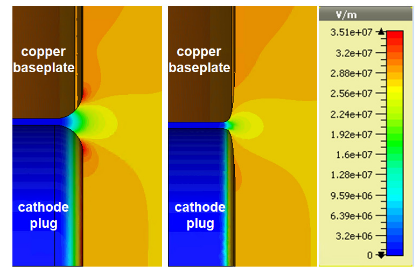

Figure 2: Field map in the cathode plug vicinity. Left: round corner; right: Rogowski corner.

MULTIPACTING ANALYSIS

The multipacting simulations were performed using the CST particle studio tracking module. The aim is to evaluate the MP zones of the cavity. At the nominal operation point, MP has to be avoided. MP is determined by the RF field distribution and surface material properties. Except for the cathode nose cone, the gun body, which is exposes to the RF field, is hard copper, indicating a stronger secondary electron yield (SEY) than annealed copper. Therefore, SEY data of the untreated copper from CERN was used in the simulations [8].

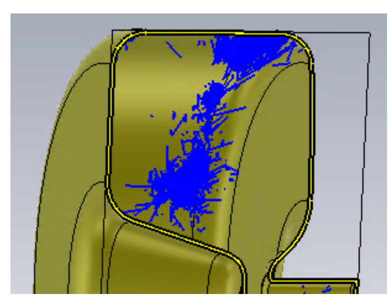

Figure 3: Stable multipacting trajectories at 400 kV cavity voltage in the gun, one point 1st order MP.

Here the cavity model with the Rogowski nose cone is simulated. Simulations show that the MP mode is one point 1st order concentrating at the outer corner of the anode plate as shown in Fig. 3. The growth rate to estimate the multipacting strength is defined as follows:

$$N(t) = N_0 e^{\alpha t}$$

where N_0 is the initial number of electrons, α is the exponential growth rate indicating the multipacting strength. The gun field is scanned with a voltage step of 20 kV and a phase step of 30°. Figure 4 shows the growth rate α as a

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function of the gun voltage, and MP exists in the range from 140 kV to 500 kV. Modification of the outer corner shape is tried to reduce the MP strength and zone, but without significant improvements. In practice, since the MP zone is relatively far from the nominal working point (830 kV), according to APEX gun experiences, the MP zone can be jumped in pulsed mode during ramping up.

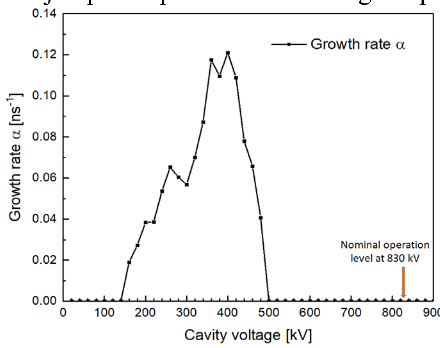

Figure 4: Exponential growth rate α as a function of the gun voltage.

BEAM DYNAMICS SIMULATIONS

Since the CW injector specs are not defined yet for the European XFEL, the LCLS-II injector setup is used to simulate the performance of the gun model as shown in Fig. 5. The on axis electric field of the gun cavity with Rogowksi nose was used for beam dynamics simulations in ASTRA [9]. Besides the gun, a 400 kV buncher is also under design at PITZ [10], which is used in the beam dynamics simulations. Two solenoids and one 8-cavity crymodule identical to the LCLS-II injector are used.

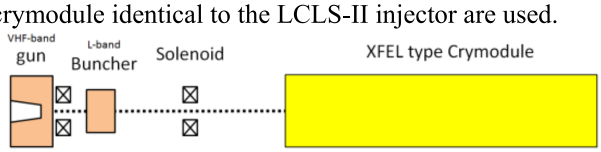

Figure 5: Schematic of the injector in the simulations.

The injector optimization is as following. The gun is operated at 830 kV with 28 MV/m cathode field, the cathode laser is temporally flattop with 2 ps edges, and spatially cut at 1-sigma of a Gaussian distribution. The peak field amplitude of the cryomodule is set to 32 MV/m with all phases on crest. The locations of the elements are identical to LCLS-II injector. The following 11 parameters are varied by a genetic optimizer to optimize both the emittance and bunch length of a 100 pC beam, laser radius and duration, gun phase, buncher voltage and phase, two solenoid strength and the field amplitude of the first four cavities of the crymodule [11, 12]. The cathode thermal emittance is set to 1 mm.mrad/mm and 0.5 mm.mrad/mm for conservative and optimistic cases, respectively.

The pareto front of the 1 mm.mrad/mm case is shown in Fig. 6. The 11 A solution is refined with 250k macro-particles, and longitudinal phase space and slice emittance are shown in Fig. 7. The 100% and 95% projected emittance at the injector exit are 0.20 and 0.15 mm.mrad, respectively. If the thermal emittance is reduced to 0.5 mm.mrad/mm, then the 100% and 95% projected emittance are reduced to 0.12 and 0.09 mm.mrad, respectively. Both the transverse and longitudinal beam qualities are improved compared to the 20 MV/m APEX gun [13].

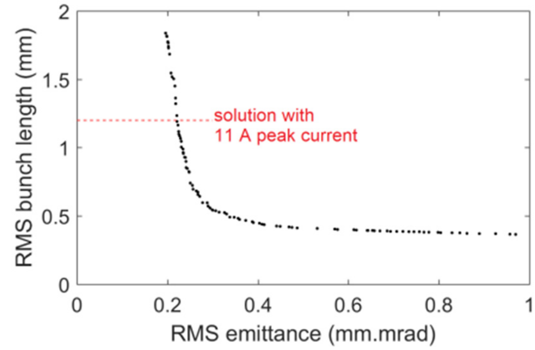

Figure 6: Pareto front of 100 pC beam with 1 mm.mrad/mm thermal emittance, 10k macro-particles simulations.

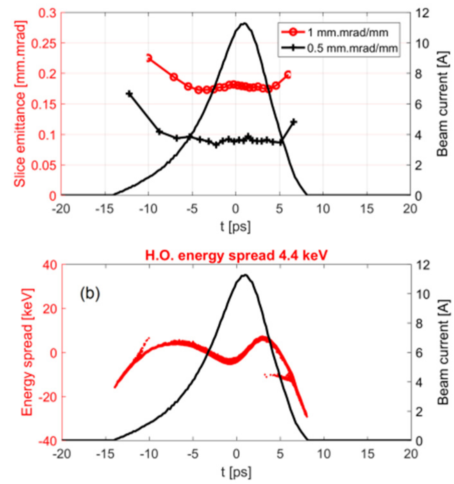

Figure 7: Refined simulation with 250k macro-particles, 100 pC with 11 A peak current, (a) slice emittance with two thermal emittance settings, (b) longitudinal phase space after removing the 1st and 2nd order chirps, the higher order energy spread is 4.4 keV.

CONCLUSION

In this paper, we report the RF design status of a NC VHF gun for the European XFEL CW upgrade. The 100 kW gun is re-optimized based on the APEX gun, with improvements on both cathode gradient (28 MV/m) and gun voltage (830 kV). By applying the Rogowski profile, the field enhancement on the anode nose and cathode plug vicinity are reduced below 2 Kilpatrick limit to lower the RF breakdown risk as well as the dark current. Simulations show that the MP zone is away from the nominal gun operation point. 100 pC beam simulations of the LCLS-II type injector show the new gun design improves the beam emittance compared to the 20 MV/m APEX gun. For thermal emittances of 1 mm.mrad/mm and 0.5 mm.mrad/mm, the 95% emittance of a 11 A beam can reach 0.15 mm.mrad and 0.09 mm.mrad, respectively.

The authors would like to acknowledge the collaborations with the APEX and APEX-2 teams at LBNL.

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