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A CRYOCOOLED NORMAL CONDUCTING AND SUPERCONDUCTING HYBRID CW PHOTOINJECTOR

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Abstract

Continuous wave (CW) photoinjectors have seen great progress in the last decades, such as DC gun, superconducting RF (SRF) gun and normal conducting (NC) gun. Developments of Free electron lasers and electron microscopy in the CW mode are pushing for further improvements of CW guns towards higher acceleration gradient, higher beam energy and compatibility with high QE cathodes for better beam brightness. Current SC gun gradient is limited by the cathode cell due to the complication of a cathode back plane and a normal conducting cathode plug, and R&D on SC gun improvement is ongoing. A high gradient cryocooled CW NC gun was proposed to house the high QE cathode, and a SC cavity immediately nearby gives further energy acceleration. In this paper, further RF optimization of the NC gun and ASTRA simulations of such a hybrid photoinjector are presented.

INTRODUCTION

High brightness electron guns working in CW mode are wished for a lot of advanced applications, such as free electron laser, electron microscopy and energy recovery linac [1]. Compared to pulsed guns, CW guns enable much higher average beam brightness and flexible electron bunch timing pattern. Current CW RF guns operate with a cathode gradient around 20 MV/m [2, 3], which is much lower than the 60-120 MV/m range of pulsed guns. To achieve higher beam brightness, both higher cathode gradient and beam energy are wished [1]. The next generation of normal conducting VHF-band gun with >30 MV/m cathode gradient is under study [4, 5], but it's close to the limit of the normal conducting RF technology due to both thermal loading and RF breakdown risk. Meanwhile, SC CW gun has the potential for even higher acceleration gradient and beam energy, thus better beam brightness, but its performance is still far from expectations after decades of R&D, mainly due to the technical complication of a cathode back plane and a normal conducting cathode plug. In SC gun, the contact between normal conducting cathode plug and SC cavity is avoided, and RF leak through the cathode insertion channel is stopped by a choke filter [6]. The risk of cathode pollution of the SC cavity still exists, and the SC gun gradient is usually reduced once a high QE photocathode is present inside the cavity. Moreover, the cathode cell cleaning is difficult, which is one of the keys to have low field emission and high gradient for CW mode. Besides the choke filter, two other methods are proposed to solve the cathode issue in a SC gun. DESY is working on a full SC gun with a SC lead cathode, aiming for a gradient of 40 MV/m, but the average beam current will be lower due to the low quantum efficiency of lead cathode compared to the semiconductor cathode. Peking University developed a DC-SRF hybrid gun with NC cathode plug inside the DC acceleration gap outside the SC cavity. The peak acceleration gradient inside the SC cavity reached ~30 MV/m, but the cathode gradient is low, below 5 MV/m [7]. The DC-SRF gun has demonstrated an average current of ~mA for CW operation at Peking University [7].

Inspired by the DC-SRF gun, a NC-SC hybrid gun concept was proposed in 2017 [8], and the difference from the DC-SRF gun is to replace the DC acceleration gap with a NC RF acceleration gap to increase the cathode gradient from below 5 MV/m to above 20 MV/m. In this paper, further RF optimizations of the NC cathode cell are presented, and preliminary beam dynamics based on the new cathode cell design are also reported.

NC-SC GUN CONCEPT

A high gradient NC RF cavity is proposed to house the high QE cathode and support high brightness photoemission with high cathode gradient, and the main acceleration is still in the SC cavity. The compatibility between high gradient NC RF cavity and high QE cathode has been well demonstrated in both pulsed and CW NC guns [9, 10]. Since the NC cavity voltage is low to reduce the RF heating load on the cryogenic system, the SC cavity should be as close as possible to the NC cavity to keep the beam brightness, otherwise both the beam size and emittance will blow up by the space charge effect in the low energy drift between the NC and SC cavity, as shown in Fig. 1.

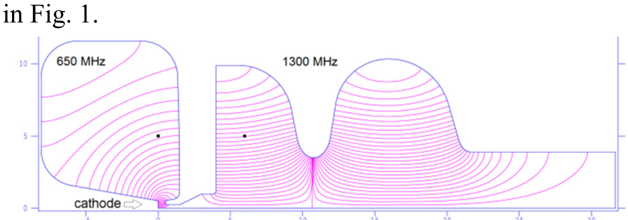

Figure 1: An example of NC-SC hybrid gun concept, which consists of a re-entrant NC cavity (0.65 GHz) and a 1.5 cell SC cavity (1.3 GHz), both coordinates are in cm.

The NC cavity and SC cavity will stay in the same cryomodule, so the NC cavity will be cryocooled. The NC cavity is high gradient but low voltage, i.e. a short acceleration gap cavity. A re-entrant cavity shape was proposed for such a cavity to make it compact and high

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shunt impedance. Scaling from the existing LBL VHF gun parameters [3], i.e. ~100 kW for 800 kV, the gun is assumed to be ~1 kW for 80 kV. Since the NC cavity will be cryocooled, the cavity quality factor will increase, and the RF heating will be reduced. Several cryocooled NC guns have been proposed for the purpose of ultrahigh gradient operation [11, 12]. Microwave measurements of a copper cavity at liquid Neon temperature has shown a RF surface resistance reduction of ~5 compared to room temperature at both S-band and C-band frequencies [13, 14]. Theory indicates the NC surface resistance is proportional to $f^{2/3}$ at low temperature limit and to $f^{1/2}$ at room temperature, so the RF heating reduction ratio from room temperature to low temperature is proportional to $f^{1/6}$, where f is the cavity resonant frequency [13]. Scaling from a factor of ~5 reduction of RF heating for 5712 MHz gives the reduction ratios of ~7 and ~8 for 650 MHz and 325 MHz. To be conservative, applying the same reduction ratio of 5 to the assumed 80 kV NC cavity, the RF heating, i.e. cryogenic load at 27 K will be reduced from ~1 kW to ~200 W. According to discussions with experts in the field of cryogenic temperature, such a cryo load is feasible, and even higher cryo load of ~500 W at 27 K was considered for another S-band cryo gun proposal at UCLA [12].

The SC cavity has various options, both in resonant frequency and cell numbers. In the paper, a 1.5 cell 1.3 GHz SC cavity, similar to the DESY SC gun [15], is considered, as shown in Fig. 1.

NC CATHODE CELL OPTIMIZATION

Since the SC cavity is 1.3 GHz, the NC cavity frequency should be a subharmonic of 1.3 GHz. In this paper, both 325 MHz and 650 MHz are considered. RF cavity scaling law shows the cavity dimension is inversely proportional to cavity frequency, and the surface RF impedance is proportional to the square root of cavity frequency. The 650 MHz cavity has relatively higher surface impedance and lower shunt impedance, but its radial size matches the 1.3 GHz cavity size better, as shown in Fig. 1. The 325 MHz cavity has the advantage of higher shunt impedance, but larger radial dimensions may not match the 1.3 GHz cavity cryomodule, as shown in Fig. 2.

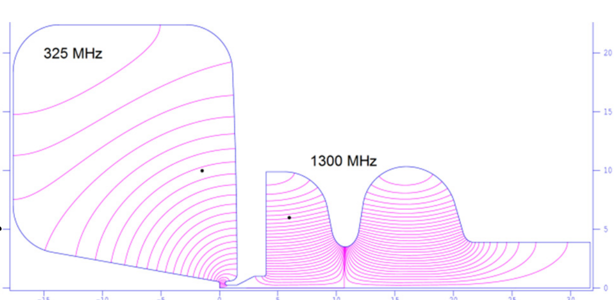

Figure 2: An example of NC-SC hybrid gun, which consists of a re-entrant NC cavity (325 MHz) and a 1.5 cell SC cavity (1.3 GHz), both coordinates are in cm.

The acceleration gap is a critical area for shunt impedance optimization. The radial dimensions of both cathode nose cone and anode nose (beam exit aperture) are minimized to concentrate the electric field inside the acceleration gap. The flat radial surface of the cathode nose cone is about 8-10 mm diameter to host a small cathode plug, and the beam exit diameter is ~5 mm. The NC cell beam exit aperture will be tapered into the size of the SC cavity beam entrance hole of 20 mm diameter to avoid beam loss in the low energy drift. In the end, the geometry optimization of the acceleration gap region is very similar between the 650 MHz cavity and 325 MHz cavity. The acceleration gap is chosen to be 5 mm, and the gun voltage is ~100 kV with a cathode gradient of 20 MV/m. The total RF heating at room temperature for such a configuration is 1300 W and 1800 W for 325 MHz cavity and 650 MHz cavity respectively. At liquid Neon temperature, the RF heating will be reduced by a factor of ~5 for both cavities to 260 W and 360 W. Both the cavity gradient and voltage can be adjusted proportionally according to the capability of the cryogenic system.

To reduce the beam degradation in the low energy drift between NC and SC cavity, the entrance of the 1.5 cell 1.3 GHz SC cavity is placed at 40 mm from the cathode surface in Fig. 1 and 2, leaving a minimum gap between NC and SC wall around 25 mm. A rough model of such a setup is built in ANSYS to check the feasibility of heat exchange from the 27 K copper cavity to the 2 K niobium cavity. With a 360 W heating load on copper cavity, a few watts are dissipated in the 2 K cavity, which is acceptable from the cryogenic point of view. Of course, a lot of engineering details of the connection between SC and NC cavity are missing in such a simulation, which can change the heat transfer between the two cavities.

Besides minimizing the distance between NC cavity and SC cavity, focusing can also be added before the entrance of the SC cavity to reduce the beam size blow up by space charge. Due to the vicinity of the SC cavity, solenoid focusing is not possible. In the DC-SRF gun from Peking University, a Pierce DC gun is used to add electric focusing near the cathode [7]. In the NC cell design, we adopted the cathode plug recession to enhance RF focusing near the plug, as shown in Fig. 3 for an example of 0.8 mm cathode recession. Meanwhile, the cathode gradient for 100 kV is reduced from 20 MV/m to 12 MV/m. The exact amount of cathode recession will be decided by beam dynamics optimization.

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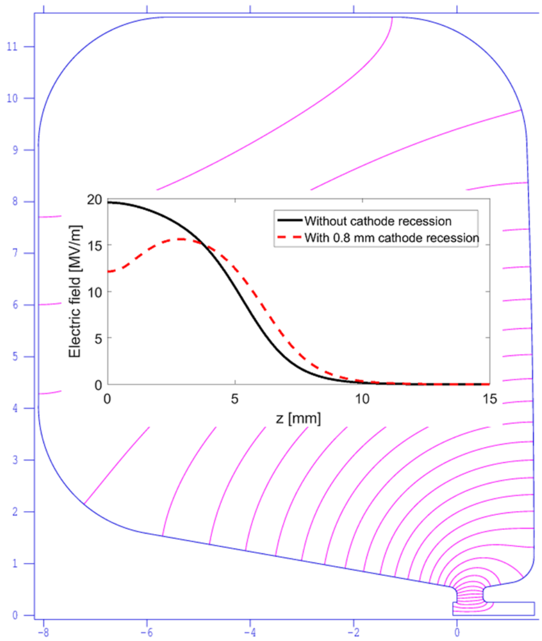

Figure 3: An example of 0.8 mm cathode recession in the 650 MHz cavity for increasing RF focusing inside the cathode cell, and the on axis electric field compares the cases with and without cathode recession.

BEAM DYNAMICS OPTIMIZATION

A photoinjector layout based on the NC-SC gun is shown in Fig. 4, consisting of the hybrid gun, a solenoid, and an 8-cavity cryomodule (CM). Only the gun without cathode recession is used in beam dynamics simulations in this paper. The gun field map between 325 MHz and 625 MHz is almost the same except the resonant frequency, so only 325 MHz gun is used in simulations. Between the gun and the 8-cavity module, there is a 1.3 GHz buncher cavity and a single cell harmonic cavity. The single cell harmonic cavity operates at the max deceleration phase to vary the 2nd order energy chirp, so that the beam temporal profile distortion during velocity compression can be improved.

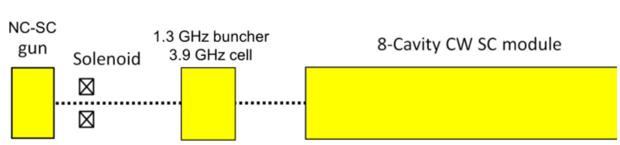

Figure 4: Preliminary injector layout.

The photoinjector is optimized using a multi objective genetic algorithm (MOGA). A code developed at LBL is used to drive ASTRA simulations for searching optimal solutions of both good emittance and short bunch length [16, 17]. The peak gradients of the NC and SC cavity are set to 20 MV/m and 25 MV/m respectively. The NC cell phase is fixed to max acceleration, and the SC cavity of the hybrid gun is variable. The buncher cavity amplitude and phase are allowed to change. The harmonic cavity amplitude is variable, but the phase is fixed for max deceleration. The harmonic cavity is located after the buncher cavity with an estimated minimum distance in between, and the buncher cavity position is variable. The position of the 8-cavity module is variable, and the first 2 cavities can individually vary their amplitudes, but the phase is fixed to max acceleration. All the other cavities in the module are set to fixed amplitudes of 32 MV/m with on-crest phases. The laser is a quasi-flattop distribution. The transverse distribution is a Gaussian distribution with 1-sigma cut, and the longitudinal distribution is a flattop with 2 ps rising and falling edges. Both the laser radius and duration are variable. The cathode thermal emittance is set to 0.5 µm.rad/mm, and bunch charge is fixed to 100 pC. In total, there are 12 variable parameters to optimize the photoinjector, as summarized in Table 1.

Two solutions with best emittance results at the end of photoinjector are found in Fig. 5, one is with harmonic cavity off (left plots), and the other is with harmonic cavity on (right plots). With harmonic cavity off, the 100% (95%) emittance of the 100 pC beam is 0.21 (0.15) mm.mrad with a peak current of ~10 A, but the longitudinal beam profile is heavily distorted with a sharp head and long tail. By increasing the harmonic cavity deceleration to ~0.47 MV, the longitudinal beam distortion is reduced, and the skewness of the beam temporal profile reduces from -0.69 to -0.29. Skewness of zero corresponds to a symmetrical distribution. The 100% (95%) emittance increases to 0.32 (0.23) µm.rad.

Table 1: Photoinjector Optimization Parameters

Parameter	**Range**	**Unit**
SC cavity phase	[-10, 10]	degree
Solenoid peak field	[0, 0.12]	T
Solenoid position	[0.45, 1.5]	m
Buncher position	[1.5, 7]	m
Buncher amplitude	[0, 32]	MV/m
Buncher phase	[-90, 0]	degree
3.9 GHz cavity amplitude	[0, 32]	MV/m
Drift between buncher and 8-cavity module	[1, 7]	m
Amplitudes of cavity 1-2 in 8 cavity module	[0, 32]	MV/m
Laser radius	[0.2, 1.2]	mm
Laser pulse duration	[10, 60]	ps

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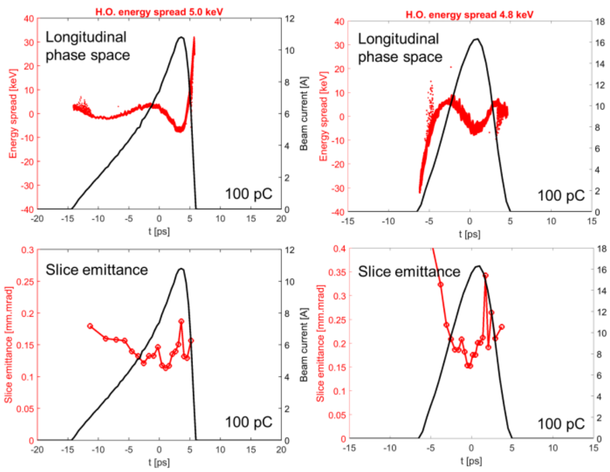

Figure 5: Slice emittance and longitudinal phase space for 100 pC beam based on the injector in Fig. 4, left: harmonic cavity off, right: harmonic cavity on.

Although the emittance values from the two optimal solutions are relatively low, but both solutions are still not thermal emittance dominated, which indicates the injector is still not fully optimized. The thermal emittances of the two solutions are 0.10 µm.rad and 0.14 µm.rad respectively, which are below 50% of the injector emittance. Further beam dynamics optimizations are still ongoing, such as the harmonic cavity position and the RF focusing effects in the cathode cell due to cathode plug recession. Moreover, beam dynamics studies are needed to check the drift tolerances between NC cell and SC cell, which is a critical point for both beam quality and engineering of the hybrid gun.

Although the injector is still not optimized, but the low thermal emittances in both solutions indicate a high transverse beam brightness from photoemission, which supports the considerations of a high gradient and low voltage cathode cell design.

CONCLUSION

In this paper, a cryocooled NC-SC gun concept is further developed. Two NC cathode cells are designed for two subharmonics of 1.3 GHz, 0.325 GHz and 0.65 GHz. The 0.65 GHz cavity has a similar radial dimension as the 1.3 GHz cavity, which can be possibly put into the same cryomodule of the TESLA cavity. RF focusing by cathode recession is also investigated, which might supress the beam blow up in the low energy drift before the entrance of the SC cavity.

Preliminary beam dynamics optimizations based on such a gun with 20 MV/m in NC cathode cell and 25 MV/m in SC cell are presented for a bunch charge of 100 pC. A 95% emittance of 0.15 mm.mrad is achieved with a 10 A peak current. By adding a harmonic cavity, the beam temporal profile distortion during velocity bunching can be improved. Further beam dynamics investigations are still ongoing.

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