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Design of a high repetition rate S-band photocathode gun

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ABSTRACT

Photocathode RF guns have been developed in many laboratories for generating high quality electron beams for free-electron lasers based on linear accelerators. Such guns can generate electron beams with an exceptionally high peak current as well as a small transverse emittance. Their applications have been recently expanded for ultrafast electron diffraction, coherent terahertz radiation, and X-ray or γ-ray radiation by Compton scattering. In this paper, we design an S-band normal-conducting gun with capabilities of high quality beam generation and high repetition rate operation. The RF design and thermal analysis of the gun cavity and coupler are introduced. Optimal position of the gun focusing solenoid for low emittance beam generation is found by performing particle tracking simulations. Then, the gun system is designed to be able to afford the optimal solenoid position. The cooling-water channel surrounding the gun cavity and coupler is designed and analyzed numerically. The pressure in the gun is simulated with a vacuum model containing the detailed inner structure of the gun. An injector for a free-electron laser application is designed by using this gun and the beam dynamics simulation is shown. A cold test with a prototype gun for confirmation of the RF design is reported.

1. Introduction

Beam brightness from electron injectors has been dramatically increased with the development of photocathode RF guns for the last two decades. In many laboratories, such guns have been adopted as the injectors for free-electron lasers (FELs) based on linear accelerators (linac) [1–6], for ultrafast electron diffraction [7–11], for coherent terahertz radiation [12,13], and for X-ray or γ-ray Compton scattering [14]. In such guns, an electron beam is generated at the cathode by using a drive-laser pulse and the beam is accelerated from rest to relativistic energy by the strong RF accelerating field. By optimizing the drive-laser pulse and accelerating the emitted beam quickly, high peak current and low transverse emittance can be achieved.

When RF power is transmitted into a gun cavity, RF power dissipation takes place at the cavity surface. Then, the surface temperature rises at the location with strong surface current. Due to the local temperature rise, the temperature distribution of the cavity becomes non-uniform, cavity deformation takes place, and therefore the cavity may suffer from mechanical stress. Such a cavity deformation also affects the RF field distribution, which may result in changes of the resonant frequency and field balance. Therefore, the cavity temperature must be controlled with cooling-water in order to keep the cavity at the nominal temperature and to keep the temperature distribution as uniform as possible. As the RF duty factor increases, the problem of the non-uniformity of temperature distribution becomes more severe. This limits the maximum achievable repetition rate and also impairs stable RF operation. An optimally designed cooling-water channel is therefore required.

Another obstacle to increasing the repetition rate may come from the excessive heating at the RF coupling region. If the RF coupler is connected to the side of the cavity cell where the surface current induced by the RF field is strong, the coupling region can have high temperature and high surface stress due to the RF heating. However, if the coaxial RF coupler is instead connected to the gun front iris where RF power dissipation density is low, the coupling region can be relatively cool and does not limit the repetition rate. Furthermore, when a coaxial coupler is utilized, the entire outer tube of the cavity can be enclosed with axisymmetric cooling-water channels around the cavity cylinder. Therefore, the cooling capacity can be maximized and the cavity deformation caused by the RF heating also becomes axisymmetric. High order transverse RF modes will not exist because of the perfectly symmetric cavity inner surface as well. Such a type of RF coupler has been employed in the DESY L-band guns [15], which are operating for FLASH [4] and PITZ [16].

Even with the fast acceleration of a beam in an RF gun, the beam radially expands through the gun and the transverse emittance blows out due to the space charge force. This transverse increase can be compensated by using a focusing solenoid [17]. This process is realized by reconfiguring the beam distribution in the transverse

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phase space by using the focusing solenoid. The solenoid should be placed around the gun for an efficient transverse emittance control as will be discussed in Section 2. If the RF coupler is connected to the side of the cavity cell, the optimal location for solenoid is occupied by the coupler and therefore the solenoid must be placed downstream of the gun. In this gun design, the solenoid can be placed at the optimum location thanks to the coaxial coupler.

The resonant frequency was chosen to be 2.998 GHz, which is the European standard S-band frequency. Compared with the Eindhoven gun [18], which is another S-band gun with a coaxial RF coupler, the possibility of further cooling channel installation was considered and the coupler tube length was increased to allow solenoid installation around the gun. Compared with lower frequency band guns such as L-band guns, an S-band gun made from oxygen-free electronic (OFE) copper generates very low emittance and short pulse electron beams because of the high accelerating field at the cathode. Compared with higher frequency bands, such as C- or X-bands, an S-band gun allows enough space for the cooling-water circuit installation inside the iris and therefore temperature control of the gun against RF thermal heating can be properly performed. Their repetition rates are, however, generally limited to about 100 Hz [5]. The gun introduced here has a potential of a repetition rate as high as 1 kHz as will be discussed in Section 3. This gun will provide a possibility to operate an FEL based on normal-conducting technology at such a high repetition rate [19].

The RF design, thermal analysis, and vacuum simulation of the new gun are reported in this paper. A prototype of the gun was produced for low power RF tests with a network analyzer. The test results with the prototype are also presented.

2. Beam dynamics consideration in the gun design

The transverse beam emittance can be minimized by optimizing the gun cavity geometry and the location of the gun solenoid. The lengths of the gun cells are optimized based on the previous study in Ref. [20] and further beam dynamics simulations for this particular gun design have been carried out. The optimum location of the main solenoid is also found with beam dynamics simulation.

The length of the first cell strongly affects the beam formation and acceleration when the beam is in a non-relativistic regime. When a beam is emitted from the cathode, the velocity of the beam is almost zero. After the emission, the beam is accelerated by the RF field to become relativistic through the first cell. When the beam energy is very small, the space charge effect changes the beam properties considerably. As the beam is accelerated, the space charge effect becomes weaker. The beam dynamics also depends on the length of the second cell. The relation between the cell lengths and beam dynamics has been studied in detail elsewhere [20].

After simulations with various sets of cell lengths as carried out in Ref. [20], the lengths of the first (half) and second (full) cells were chosen to be 28 and 50 mm, respectively. This optimization was carried out at 200 pC bunch charge, 8 ps laser pulse length and 120 MV/m peak field at the cathode. Even though the effect on the beam dynamics is relatively small compared to the initial beam shape defined by the drive-laser parameters or the focusing solenoid field configuration, the gun should be carefully designed for best beam performance. Otherwise, a new manufacturing and installation of a gun will be needed to improve the beam quality later with an improved gun design. This is practically difficult because it may interrupt the operation of the entire accelerator system for quite a long time.

When an electron beam is accelerated in a photocathode RF gun, the strength of space charge effect is different for each

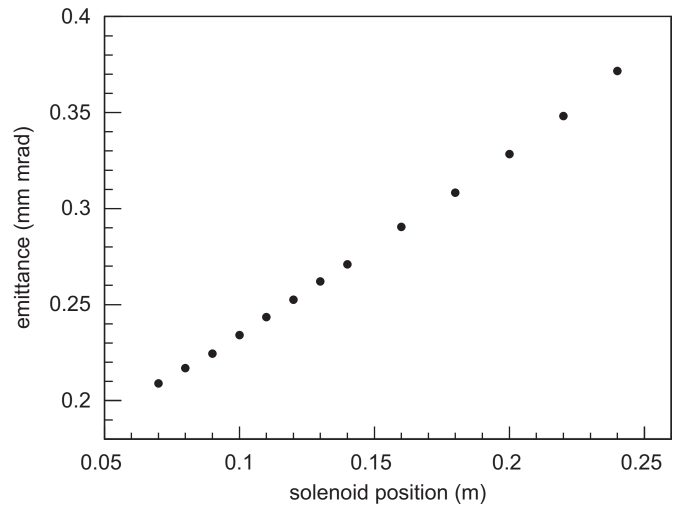

Fig. 1. Normalized transverse emittance (full rms) as a function of the distance between the center of the solenoid and the cathode. Simulations were carried out at 200 pC bunch charge and 100 MV/m peak RF field at the cathode. The drive-laser beam size and the beam launch phase at the cathode were optimized at each solenoid position.

temporal slice of a bunch. The head and tail slices experience weaker repulsive force to the radial direction, while the central slices experience stronger defocusing force. As a result, the slices show different shape and angle in transverse phase space. The area in the phase space, emittance, can be minimized under a certain condition combined with the solenoid field, the RF field, and the initial beam shape. As pointed out in Refs. [15,21], if the gun consists of two $(1/2+1)$ cells, the optimum location of the solenoid is around the cavity.

Fig. 1 shows the beam emittance at the exit of the gun for a 200 pC beam as a function of main focusing solenoid position. At the cathode, the solenoid field is compensated to zero by a bucking solenoid sitting behind the gun. For the simulations using the ASTRA code [22], 100 MV/m gun RF peak field at the cathode and 8 ps drive-laser pulse length were used. A flat-top temporal laser profile with 1 ps rise/fall time was used. The radial size of the drive-laser pulse was optimized to obtain the lowest transverse emittance for each condition. Since these simulations were carried out without further linac sections, the projected beam emittance blows up after the minimum point. The minimum projected emittance takes place when the temporal slices of the beam are aligned in the transverse phase space, and the distance from the cathode to the minimum emittance point varies depending on the solenoid position. Here, we took the minimum projected emittance value for each simulation condition. The laser full radius was in a range between 0.28 and 0.46 mm. The optimum radius for a lowest emittance increased with the solenoid position from the cathode. The launch phase of the beam at the cathode was also optimized at each solenoid position. As shown in Fig. 1, lower emittance can be achieved as the solenoid moves toward the cathode.

When the physical thickness of the solenoid, 0.135 m in the design here, is considered, the surrounding of the gun cavity should be cleared for solenoid installation in order to achieve the lowest emittance.

3. Gun cavity design

In this section, we discuss the detailed gun design. An RF design is carried out, which satisfies the requirements discussed in Section 2. Given the RF field distribution, the thermal behavior is analyzed numerically.