BEAM DYNAMICS STUDY FOR AN UPGRADED LOW-EMITTANCE RF GUN

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Abstract

High-brightness and low-emittance beams generated in RF gun based accelerators are essential for a number of applications, such as Free-Electron Lasers (FELs), Ultrafast Electron Diffraction (UED) facilities and THz radiation sources. In these accelerators, the final beam characteristics are determined both, by the properties of the electron gun and by the influence of the electromagnetic system along the beamline. To meet the requirements imposed on the beam characteristics, it is essential to identify the optimal parameters of the RF gun and the magnetic system. In this paper, beam dynamics studies of a modified RF gun for the AREAL and the REGAE accelerators are presented, with emphasis on transverse emittance compensation. Simulations were conducted by adjusting the parameters of the focusing and RF systems to identify the optimal configuration of the modified RF gun geometry.

INTRODUCTION

Advanced accelerator-based light sources such as Free Electron Lasers (FEL), THz radiation sources, and Ultrafast Electron Diffraction (UED) systems require electron beams with high brightness and low emittance [1-3]. The most effective way to generate such high-quality electron beams is by using RF-based photocathode guns [4]. In this type of electron source, a high current density beam is generated at the cathode by means of photoemission, which is then immediately accelerated in a high gradient accelerating RF field. The high accelerating field, reachable in an RF cavity allows, on the one hand, to extract a beam with a high phase space density from the cathode, because it compensates the space charge induce retraction field during emission. The rapid acceleration to near relativistic energies, on the other hand, reduces space charge induced emittance growth in the acceleration process and the following beam transport.

In addition, the use of laser pulses allows better control of beam parameters such as charge, transverse and longitudinal bunch sizes, and their distributions. All these factors strongly influence the desired final beam parameters.

Therefore, the development and optimization of photoinjectors is one of the key directions for producing electron beams with improved characteristics in linear accelerators. Efficient operation of an RF gun requires optimization from both the technical and beam dynamics perspectives. From the technical side, this includes an efficient cavity cooling, general RF parameters and the adaptation to geometrical constrains, e.g. for the integration of the solenoid magnet. Concerning the beam dynamics aspects the optimization of the focusing parameters and the length of the half-cell in dependence on the targeted beam parameters are of relevance. Optimization of all parameters within the technical constrains enables an efficient emittance compensation and a precise beam envelope control.

Currently, the AREAL linear accelerator at CANDLE and the REGAE linear accelerator at DESY are operated with the same S-band RF gun design. However, for electron diffraction used in pump-probe experiments and imaging applications at REGAE, and for low energy applications as the planned THz FEL at AREAL, an improved beam quality is required, particularly in terms of emittance compensation and beam envelope control. To overcome these challenges and to extend the application range, an upgraded RF gun is being developed for both facilities. In this design, the focusing solenoid magnet is integrated directly with the gun, and the RF cavity half-cell length is optimized. In addition, the cavity cooling will be upgraded. The aim is to achieve lower emittance beams and increase the repetition rate to the kHz range [5], thereby enhancing the average beam current.

This paper concentrates on the optimization of the half-cell length and studies emittance compensation for ~250 pC electron beams generated at AREAL, with an RF gun half-cell length reduced from 0.57 to 0.45 times half the RF wavelength λ_{RF}.

RF GUN DESIGN OF AREAL AND REGAE

Currently, the RF guns of the AREAL and REGAE accelerators consist of a 1.57 cell resonator operating at 3 GHz (S-band) (Fig. 1). The maximum accelerating gradient reaches 110 MV/m, and electron beams with energies up to 5 MeV [6, 7] are generated.

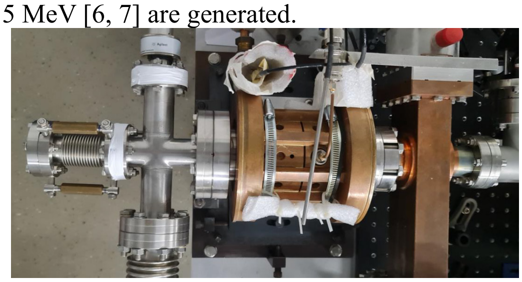

Figure 1: The S-band RF gun installed at the AREAL accelerator. A polished copper cathode is installed in the half-cell of the gun. Left of the copper body an in-vacuum spring mechanism to hold the cathode in place is visible, while on the right side the coaxial RF coupler can be seen.

The gun is a based on the L-band guns (1.3 GHz) developed for the European XFEL and the FLASH FEL. During the design of the S-band guns, the inner geometry of the cavities has been scaled with the wavelength, but no attempt to optimize the half-cell length for new working points has been made back then.

OPTIMIZATION OF THE HALF-CELL LENGTH

Since the emission phase in an RF resonator is variable, the proper choice of the emission phase is crucial. The optimal emittance is typically reached, when the emission phase is close to the phase of maximal energy gain of the gun.

However, the phase of maximum energy gain depends on the half-cell length of the gun cavity [8], as displayed in (Fig. 2).

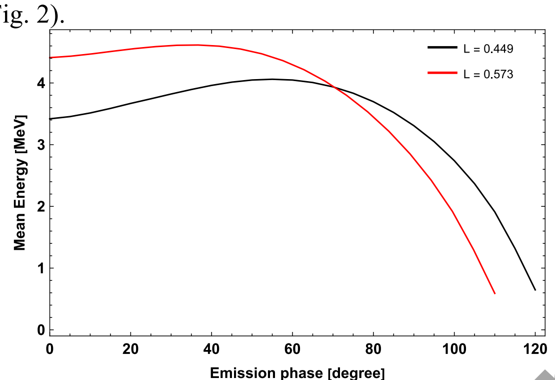

Figure 2: Energy gain as function of the emission phase for an accelerating gradient of 100 MV/m in gun cavities with elongated ($0.57\ {}^{\lambda_{RF}}/_{2}$, red) and shortened ($0.45\ {}^{\lambda_{RF}}/_{2}$, black) half-cell.

When the half-cell length of the cavity is reduced, the optimal RF phase shifts toward higher values, here from 36.7° for a half-cell length of 0.57 to 55° for a half-cell length of 0.45. At the same time the maximum exit energy is reduced from 4.6 MeV to 4.1 MeV.

For a short-pulse electron beam at the cathode surface, the maximum charge density defining the space charge limit, is determined by the available accelerating field [9].

$$\frac{d^2q}{dxdy} \approx \epsilon_0 E_{cath} \qquad (1)$$

where ϵ_0 is the vacuum permittivity, E_{cath} is the accelerating gradient on the cathode and $\frac{d^2q}{dxdy}$ is the local charge density. To achieve the minimum emittance, the maximum charge density must remain close to, but below the limit given by Eq. (1). Thus, the emittance depends on the transverse pulse shape of the laser and its duration, the transverse size, as well as the electric field at the cathode surface during emission.

For a uniform distribution of photoelectrons emitted from the photocathode, the space charge limit is reached when

$$\frac{q}{\epsilon_0 \pi R^2} = E_{cath.max} \sin\varphi$$

where $E_{cath.max}$ is the extraction field, R is the radius of the charge distribution and φ is the emission phase.

For a given charge the radius at the cathode can thus be reduced, leading to a smaller initial emittance, when the emission phase is increased. For the example displayed in (Fig. 2) the initial emittance can thus potentially be reduced by a factor

$$\sqrt{\frac{\sin(36.7)}{\sin(55)}} = 0.85.$$

However, also the exit energy is reduced, which influences the following dynamics.

Characteristic for the beam dynamics downstream of the cathode is the build-up of correlated emittance contributions, especially when higher bunch charges are generated. The origin of these correlations is found in the variation of the defocusing space charge field over the longitudinal extension of the bunch. Thus, when considering longitudinal slices of the bunch, these slices rotate differently in phase space, so that the projected emittance is increased. Applying a proper focusing allows to correct these correlated emittance contributions, so that the emittance decreases again in the drift space behind the gun [10, 11].

This so-called emittance compensation process can be described by a superposition of longitudinal slices with different space charge terms in the envelope equation given by

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \frac{K}{\gamma^2}\sigma - \frac{K_s}{\gamma^3\sigma} - \frac{\varepsilon_n^2}{\gamma^2\sigma^3} = 0. \qquad (2)$$

Here, σ is the rms beam size, with primes representing derivative w.r.t the longitudinal coordinate, γ is the ratio of total beam energy to the rest energy, and the term $\frac{\gamma'}{\gamma}\sigma'$ accounts for the reduction of the angular spread due to the increase in longitudinal momentum, i.e., the so-called adiabatic damping. The term $\frac{K}{\gamma^2}\sigma$ with $K = \left(\frac{eB_z}{2m_ec}\right)^2 + \frac{\gamma'^2}{8sin^2\varphi}$ describes the combined contribution of the focusing solenoid magnetic field B_z and the RF ponderomotive force due to the energy gain γ' and the last two terms represent the linear defocusing space charge term and the emittance term, represented by the normalized emittance ε_n, respectively. The parameter K_s is energy independent, varies with the longitudinal position in the bunch, and depends on the total bunch charge. The geometric emittance is defined as the ratio of the normalized emittance $\varepsilon_n$to the relativistic factor as $\varepsilon = \frac{\varepsilon_n}{\gamma}$.

Equation 2 assumes relativistic particle energies and displays a strong energy dependence; especially the $\frac{1}{\gamma^3}$ dependence of the space charge term is noteworthy. Of course, also the beam size is energy and emittance dependent.

The described build-up of emittance correlations and the following emittance compensation process are pronounced when high bunch charges in the nC range are extracted, as in case of FEL applications, while in UED applications – which operate with very low bunch charges in the sub pC range – it is basically absent. The higher energy gain of elongated half-cell lengths appears to be preferably when higher bunch charges are required [12, 13], while for UED applications, a shorter half-cell length and the correspondingly higher emission phase have been favored [14,15].

The AREAL accelerator, on the other hand, requests bunch charges in an intermediate range of about 250 pC. Here emittance compensation remains relevant, but it is not as well expressed as in the case of higher charges. Thus, the question of the optimized half-cell length for this charge range needs to be addressed.

At present, in the AREAL accelerator, the focusing solenoid magnet is positioned downstream of the RF gun, which limits the achievable beam parameters. A focusing solenoid magnet directly at the gun can significantly improve the accelerator performance and, thus, it is included in the upgraded gun design. The technical layout of this solenoid is not in the scope of this paper, but it is assumed that a suitable solenoid is installed directly at the exit of the gun cavity.

The following optimization has been performed with the tracking program ASTRA. A 250 pC bunch with transversely uniform and longitudinally gaussian distribution has been launched. The initial thermal emittance was modeled through a radius independent transverse momentum distribution of the emitted electrons at the cathode. The pulse length is 0.45 ps and the accelerating gradient in the RF gun cavity is 100 MV/m. The emission phase, the radius of the beam on the cathode and the maximal focusing field of the solenoid have been optimized, all other parameters remain constant. The development of the transverse beam emittance, from the cathode up to 2 m downstream, is compared for two gun cavities with different half-cell lengths in (Fig. 3). No further accelerating structure is included at this point, so the gun is followed by a drift.

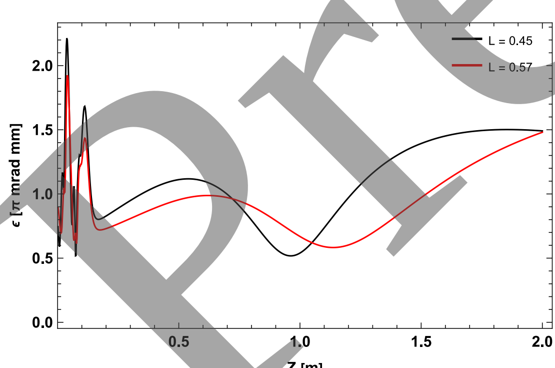

Figure 3: Transverse emittance evolution for two RF gun cavities with different length of the half-cell. The emittance minimum is shifted upward when the half-cell length is reduced.

In both cases a clear oscillation of the emittance is achieved when all parameters are optimized, indicating that the emittance compensation process works as expected. The Table 1 shows the optimized parameters and the main results of the optimization.

Table 1: Optimized Parameters for Gun Cavities With Elongated ($0.57\ \lambda_{RF}/2$) and Shortened ($0.45\ \lambda_{RF}/2$) Half-Cell.

Length of half-cell	$0.57\ \lambda_{RF}/2$	$0.45\ \lambda_{RF}/2$
Maximum solenoid field strength	0.403 T	0.367 T
Radius of the beam on cathode	0.4 mm	0.34 mm
Phase of the RF field	35°	52°
Beam energy	4.65 MeV	4.05 MeV
Minimum transverse emittance	0.58 π mrad mm	0.51 π mrad mm
Position of emittance minimum	1.14 m	0.96 m

While the initial spot size is reduced by the expected factor of 0.85, the emittance is reduced only by a factor of 0.88, indicating a somewhat increased emittance growth due to the space charge at the lower beam energy. Still the emittance is improved for the shortened half-cell length at the specified charge of 250 pC. An interesting side effect is, that the position of the emittance minimum shifts upward for the shorter half-cell length.

CONCLUSION

In summary, the study shows that optimizing the length of the RF gun half-cells is relevant for generating low-emittance electron beams in the intermediate charge region generated in the AREAL accelerator. While extended half-cell geometries provide higher output energy and, therefore, stronger suppression of space charge effects, shortened half-cell geometries enable operation at significantly higher emission phase, increasing the extraction field at the cathode and allowing the use of a smaller laser spot size. As a result, the thermal emittance during the emission time is decreased.

ASTRA simulations show that despite the lower output energy of the cavity with shortened half-cell length, the emittance compensation remains quite effective for the 250 pC beam, when the focusing solenoid is placed directly on the gun. Under optimized conditions, the $0.45\ \lambda_{RF}/2$ half-cell cavity achieves a minimum normalized transverse emittance of 0.51 π mm mrad, compared to 0.58 π mm mrad for the $0.57\ \lambda_{RF}/2$ configuration. In addition, the minimum of the emittance along the beamline is observed earlier when the half-cell length is reduced.

Thus, the study highlights the importance of the emission phase, extraction field strength, space charge effects, and emittance compensation when optimizing the photoinjector geometries. The results obtained provide a basis for the development of the RF gun in the AREAL upgrade project and confirm that optimizing the gun geometry can significantly improve the beam quality.

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