Optimization and beam dynamics of a superconducting radio-frequency gun

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Abstract

Recent advances in superconducting radio-frequency (RF) technology and a better understanding of RF photoinjector design optimization make it possible to propose a specific design for a superconducting RF gun that can simultaneously produce both ultra-high peak brightness and high average current. Such a device is a critical component of next generation X-ray sources, such as self-amplified spontaneous emission free-electron lasers (SASE FEL) and energy recovery linac-based systems. The design presented in this paper is scaled from the present state-of-the-art normal conducting RF photoinjector that has been studied in the context of the linac coherent light source and SPARC SASE FEL injection schemes. Issues specific to the superconducing RF photoinjector, such as accelerating gradient limit, RF cavity and cryostat design, and compatibility with magnetic focusing and laser excitation of a photocathode are discussed.
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1. Introduction

With the advent of existing [1] and proposed [2,3] superconducting radio-frequency (SRF) electron linear accelerators dedicated to radiation production and high energy physics, the demands on the sources that supply electrons to these devices are becoming stringent. These demands run in two somewhat opposing directions: (i) the quality of each beam bunch must be very high, as measured by the peak brightness, the ratio of the peak beam current to the transverse phase space volume, $B = 2I_\mathrm{p}/\varepsilon_\mathrm{n}^2$, and (ii) the duty factor and average beam current should be as high as possible, to take full advantage of SRF-specific capabilities. As a rule, to enhance brightness one has to expose the photoemitting cathode to a very high electric field, and also to introduce magnetic solenoid fields within the photoinjector gun region. These focusing fields allow

for control and mitigation of space-charge effects, a process termed emittance compensation [4].

The demand for high duty factor logically pushes one to consider the possibility of using an SRF photoinjector gun. In fact, for some proposed sources [3], one would like to run the entire system, linac and injector, in continuous-wave mode, an operational mode which presents extreme challenges for a normal conducting radio-frequency (RF) gun.

In previous examinations of the likely implementation of a photocathode SRF gun [5], it was assumed that one needs to provide significant focusing inside the gun, near the cathode. This assumption has been partially driven by the initial relatively low estimate of the available field gradient [6]. A solution to provision of transverse beam control near the cathode that uses the so-called "RF focusing" has been proposed [7], and this requires a deformation of the cathode plane. Unfortunately, this technique provides insufficient focusing for a full control of emittance oscillations, and in addition the back wall deformation

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introduces non-linear field components that may also cause significant emittance growth in the injector.

Some experimental efforts have been made recently to investigate the feasibility of an SRF photocathode gun [8,9]. Various proposals have been made to address the photocathode issue, including the direct use of the super-conducting Nb material [10], the deposition of a thin layer of higher quantum efficiency material on the Nb substrate [11], and the introduction of a non-superconducting cathode that is thermally isolated from the rest of the SRF cavity [12]. It is crucial that a relatively high quantum efficiency (η) be obtained from the photocathode, in order to lower the needed drive laser flux impinging on the cavity. The limit on flux comes from source considerations of what a reasonable technical configuration of the laser system may be or from concerns about the thermal load on the superconducting surfaces [13].

It will be shown in this paper that a highly optimized design of an SRF photocathode gun may be now considered by simple scaling of existing high brightness sources to lower RF frequency. In the proposed 1.3 GHz configuration, the peak accelerating gradient in the gun cavity is seen to be within that demonstrated by the TESLA program at the same frequency [14]. Further, this scaled configuration adopts a focusing solenoid geometry that keeps nearly all of the magnetic field strength outside the cavity. The magnetic field in fact must not penetrate the superconducting cavity, in order to avoid thermal break-down when the critical field of 200 mT is exceeded, and to avoid any residual flux trapping that may cause cavity Q_0 degradation.

An experimental program is now under way at DESY and BNL in order to investigate quantum efficiency properties of lead that is also a superconducting material. Preliminary results show that a quantum efficiency of the order of 1.5×10^{-3} can be obtained from a Pb photocathode illuminated by a 213 nm laser pulse [11]. If these results are confirmed, a 1 nC, 1 MHz repetition rate beam (1 mA average current) could be generated by a 4 W pulsed laser source. The needed high repetition rate, high average power UV laser can be conventionally produced from a set of commercially available Ti:sapphire regenerative amplifiers (e.g., the coherent RegA at 250 KHz and about 1.2 W average power), combined to produce the repetition rate and frequency quadrupled. Alternatively, recent advanced fiber lasers [15] may soon provide the necessary pulse format and power at around 1 or 1.5 µm where a sum-frequency mixing scheme can produce the UV [16]. The former approach is available today but is expensive, whereas the later approach is still a year or two from being practical but can take advantage of extensive development work being done for UV lithography (mostly at 193 nm). With such a cathode/laser system the design of the SRF gun will be highly simplified. The drawback of this approach is thermal emittance that increases with the photon energy [17] but a convenient beam parameter set can be found in

order to keep the thermal emittance below the 1 µm threshold.

The extreme case of ampere class superconducting guns is discussed in Ref. [18]. These devices require careful control of the higher-order mode trapping and are specifically designed with wide beam tubes to facilitate damping of unwanted trapped HOM. The adoption of an external, optimized solenoid will certainly provide additional benefit for producing ultra-high brightness beams also for these high average current class guns.

Another proposed scheme is to excite a TE magnetic mode inside the cavity which focuses the electron beam and prevents the increase of the transverse emittance [19]. The HOM magnetic mode is unfortunately not a harmonic of the accelerating mode. This results in phase-dependent behavior in the focusing, and thus in the emittance compensation process.

2. Basic design approach

In a space-charge-dominated beam, i.e., when the space-charge collective force is largely dominant over the emittance pressure, the induced emittance growth in an RF gun is highly correlated. These can be reduced by a simple focusing scheme [4]. A full theoretical description of the emittance compensation process [20] has demonstrated that in this regime mismatch between the space-charge-correlated forces and the external focusing gradient produces slice envelope oscillations (or equivalently, transverse plasma oscillations) that in turn produce normalized emittance oscillations downstream the gun cavity. It has also been shown that to damp these emittance oscillations the beam must be matched properly at injection into an accelerating section to the so-called invariant envelope. This matching should be maintained until the space-charge forces are diminished by acceleration.

Following the previous matching condition a new working point suitable to damp emittance oscillations has been recently found [21,22] in the context of the linac coherent light source (LCLS) free-electron lasers project [23]. This working point can be easily scaled [24] to any other frequency, gradient [22] or charge design. In addition, in this configuration the location of the solenoid field can be shifted toward the gun cavity exit, resulting in an excellent condition for a high brightness superconducting RF gun.

The design for the LCLS photoinjector utilizes the peak electric field on-axis between 120 and 140 MV/m at an operating RF frequency of 2.856 GHz [23]. While such fields clearly exceed those achievable in superconducting RF cavities, one may easily scale the fields downward by moving to a different design frequency [24]. As the longitudinal beam dynamics are preserved in this case by scaling the fields as $E_0 \propto \lambda_{\mathrm{RF}}^{-1}$, at L-band (1.3 GHz) the needed peak on-axis field is between 54 and 64 MV/m, which is roughly equivalent to an average accelerating field between 27 and 32 MV/m. These fields are the state-of-the-art superconducting cavities

technology [14]. The working point of the LCLS photo-injector is predicted to have a very high brightness, with a peak current at 1 nC charge of 100 A (10 ps flat-top pulse), and an emittance of 0.6 μm [23]. With these beam parameters, obtained from detailed PARMELA simulation, the brightness is calculated to be $B = 5.6 \times 10^{14} \, \text{A/m}^2$.

One may scale the space-charge-dominated beam dynamics naturally and exactly in RF wavelength, by scaling the beam dimensions by the RF wavelength $\sigma_i \sim \lambda_{\text{RF}}$ the solenoid field as $B_z \lambda_{\text{RF}}^{-1}$, and the beam charge by $Q \sim \lambda_{\text{RF}}$ [24]. Under these assumptions, the current is independent of λ_{RF}, and the emittance scales as λ_{RF}, thus the brightness $B \sim \lambda_{\text{RF}}^{-2}$. Fortunately, if we scale back the charge at L-band from 2.2 nC (natural scaling) to 1 nC, we do not pay such as strong (factor of five) penalty in brightness.

For charge scaling, we must keep the beam plasma frequency constant, which dictates that $\sigma_i \sim Q^{1/3}$. Under the conditions of both charge and wavelength scaling, it can be shown that the emittance scales [24] as

$$\varepsilon_n(\mu\text{m})$$

$$= \lambda_{\text{RF}}(\text{m}) \sqrt{a_1 \left(\frac{Q(\text{nC})}{\lambda_{\text{RF}}(\text{m})} \right)^{2/3} + a_2 \left(\frac{Q(\text{nC})}{\lambda_{\text{RF}}(\text{m})} \right)^{4/3} + a_3 \left(\frac{Q(\text{nC})}{\lambda_{\text{RF}}(\text{m})} \right)^{8/3}}$$

where the constants a_i are deduced from simulation scans. These constants have physical significance: a_1 measures the contribution of thermal emittance; a_2 the component due to space charge; a_3 the emittance arising from RF and chromatic effects. For the LCLS designs "family", these constants are determined: $a_1 = 1.5$, $a_2 = 0.81$, $a_3 = 0.052$

The current can likewise be scaled as

$$I(\text{A}) = a_4 (Q(\text{nC})/\lambda(\text{m}))^{2/3}$$

($a_4 = 22.5$) to yield a brightness scaling of

$$B(\text{A/m}^2)$$

$$= \frac{2 \times 10^{12}}{a_1 \lambda_{\text{RF}}^2(\text{m}) + a_2 Q^{4/3}(\text{nC}) \lambda_{\text{RF}}^{2/3}(\text{m}) + a_3 Q^2(\text{nC})}$$

which has an interesting limit for very small charges (due to thermal effects):

$$B_{\text{max}}(\text{A/m}^2) = \frac{3 \times 10^{13}}{\lambda_{\text{RF}}^2(\text{m})}.$$

For our L-band scaled design at 1 nC charge, we obtain a current of 60 A, and an emittance, as before, of 0.6 μm, for a peak brightness of $B = 3.2 \times 10^{14} \, \text{A/m}^2$ which we expect from a potentially very high brightness *superconducting* source. The possibility is, thus, within reach that a scaled SRF version of the LCLS injector may give bunches of electrons with extremely high brightness, at average repetition rates well in excess of the present state of the art.

3. SRF cavity and solenoid design

A simple and attractive approach to cavity/cathode design has been proposed at BNL [10]. The basic idea is to illuminate the back wall of the superconducting Nb cavity with UV laser, obtaining photoemission and the electromagnetic cavity from a single integral structure. This strategy guides our cavity design as well. The proposed 1.3 GHz 1.6-cell Nb cavity, used here as a basis for studying beam dynamics in the injector, is shown in Fig. 1.

The design of the cell shape was guided by the same considerations adopted by the TESLA cavities: (i) a spherical contour near the equator with low sensitivity to multipacting, (ii) minimization of electric and magnetic fields at the cavity wall to reduce the danger of field emission and thermal breakdown, and (iii) a large iris radius to reduce wake field effects. The full cell dimensions are the same of an inner cell of a TESLA cavity, while the first is longer than a half cell ($0.6\lambda_{\text{RF}}/4$) in order to compensate for phase slippage occurring at the beginning of the non-relativistic beam acceleration. A coaxial input power coupler has been adopted, as in the normal conducting TESLA gun design, in order to prevent any asymmetry in the accelerating field and thus to diminish transverse RF kicks. The HOM coupler is placed on the beam tube close to last cell iris [25].

In Fig. 1, a schematic design of the gun/solenoid system is shown, including also the μ-metal box around the cavity already foreseen to screen the Earth magnetic field. With 1-mm thick μ-metal the residual magnetic field on the last iris surface is reduced to only 20 mG, a value that could be further reduced by increasing the screen thickness. At this level the residual fringe field is tolerable, in that the focusing field is applied only after cool down and the small field that would nominally enter the superconducting cavity is excluded by the Meissner effect. The scheme shown in Fig. 1 shows a location of the solenoid center 500 mm from the cathode. Beam dynamics simulation shows that the best location for the solenoid is 360 mm from the cathode. Additional study is under way in order to find a technical solution for placing the solenoid location inside the cryostat, including the possibility of using a superconducting solenoid.

4. Beam dynamics simulations

PARMELA simulations performed with 50,000 macroparticles are shown in Fig. 2 up to the 1 μm emittance threshold. According to the scaling approach discussed in the previous section, in our simulation, we consider a uniform density 1 nC bunch, 19.8 ps long with a radius of 1.69 mm, accelerated in the gun cavity up to an energy of 6.5 MeV, corresponding to a peak field on the cathode of 60 MV/m and an injection phase of 44.5°. Space-charge-induced beam expansion (up to $\sigma_x = 2.4$ mm) and emittance growth in the gun are compensated in a downstream drift with a solenoid located at the gun exit, 36 cm from the cathode, producing a 3 kG maximum field on the axis.

As shown in Fig. 2, the emittance compensation process is clearly visible in the drift until the bunch is injected at $z = 3.3$ m in a cryomodule housing eight L-band
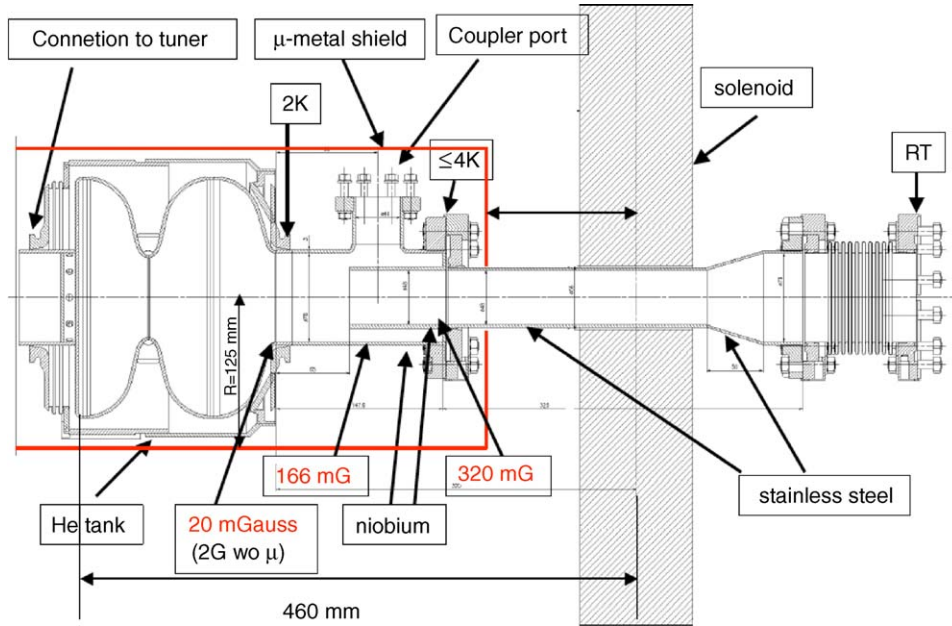
Fig. 1. Superconducting RF gun with coaxial input coupler and SC cathode, inside of cryostat assembly.
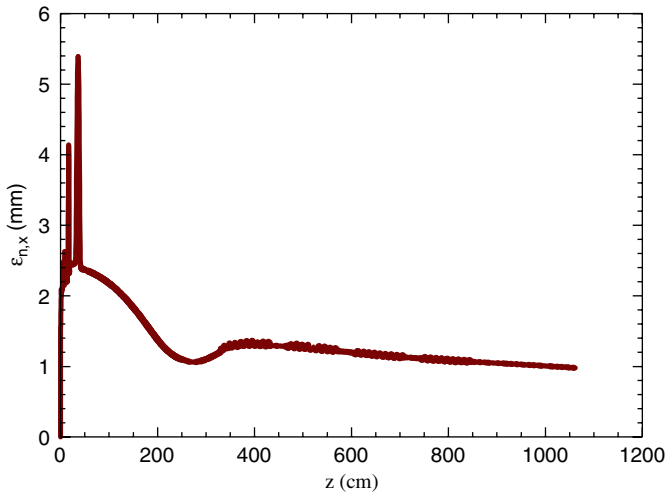

Fig. 2. RMS normalized emittance evolution in SC photoinjector, from PARMELA simulations.
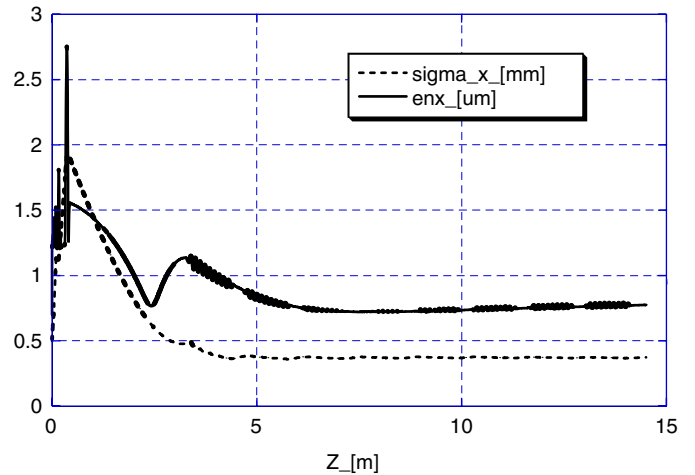

Fig. 3. RMS normalized emittance (μm) (solid line) and beam envelope (mm) (dashed line) evolution along the SC photoinjector with reduced charge (0.35 nC) parameters, HOMDYN simulations.

superconducting cavities of the TESLA type. Matching conditions for optimum emittance compensation sets the accelerating gradient to 13 MV/m. At the exit of the first cryomodule ($z = 14$ m), the bunch has been accelerated up to 117 MeV (the beam is space charge dominated up to 90 MeV) and space-charge-induced emittance oscillations are totally damped [26]. The final emittance is lower than 1 μm (with a thermal emittance contribution of 0.5 μm). A minor bunch elongation in the drift results in a final peak current of 50 A. The total length of the injector system is 14 m.

A metallic photocathode increases its quantum efficiency when illuminated by a higher energy photon beam. Unfortunately, also, the thermal emittance ε_{th} of the emitted electron beam increases [17]. A lead photocathode (work function 4.25 eV) illuminated by a 213 nm (5.82 eV) laser light has a very attractive quantum efficiency of the order of 10^{-3} that would simplify the laser system and would reduce the heat load on the cathode surface. On the other hand, a thermal emittance ε_{th} contribution of 0.7 μm/ mm would result [17]. According to the linear scaling of thermal emittance with the laser spot size on the cathode r_b, with $r_b = 1.69$ mm one has $\varepsilon_{th} = 1.1$ μm. It might be convenient to rescale the beam parameters in order to reduce the thermal emittance contribution and that is the main limitation in this design, to 0.7 μm. An $r_b = 1$ mm laser spot size would satisfy such a request. Keeping unchanged all the other parameters including the laser

pulse length ($\sigma_t = 19.8$ ps), one should scale the charge according with $Q \sim r_b^2$ resulting in a 0.35 nC beam. Simulations performed by HOMDYN, see Fig. 3, show that a final emittance of 0.76 μm can be obtained with a reduced peak current of 18 A. Nevertheless, with this scaling choice, the beam peak brightness $B \propto (Q/\varepsilon_n^2 \sigma_t) \propto (r_b^2/r_b^2 \sigma_t)$ remains approximately unchanged.

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