AN ULTRA-HIGH BRIGHTNESS, HIGH DUTY FACTOR, SUPERCONDUCTING RF PHOTOINJECTOR

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Abstract

Recent advances in superconducting rf technology and a better understanding of rf photoinjector design make possible to propose a superconducting rf gun producing beams with ultra-high peak brightness and high average current. The superconducting rf photoinjector presented here providing such high quality beam is scaled from the present state-of-the-art design of the normal conducting rf photoinjector that has been studied for LCLS SASE FEL.

INTRODUCTION

With the advent of proposed [1, 2] superconducting radio-frequency (SRF) electron linear accelerators dedicated to production of radiation or to high energy physics that operate at high average current (high duty factor), the demand for high quality beams, *i.e.* high peak brightness[*], pushes one to consider the possibility of using a SRF photoinjector. Usually, to enhance brightness one has to expose emitting cathode to a very high electric field, and also to introduce magnetic solenoid fields within the photoinjector gun region. These focusing fields allow control and mitigation of space-charge effects, a process termed emittance compensation. Operation with high average beam current requires photocathodes having enhanced quantum efficiency (η). When superconductor is used as a photoemitter, high η minimizes the thermal load on the superconducting surface. More generally, high η implies that one may keep the size and cost of the high duty cycle laser system used to illuminate the photocathode within reasonable limits.

In the past, for an implementation of SRF guns it was always assumed that one needs strong focusing inside the gun, near the photocathode. This assumption has been partially driven by relatively low achievable gradient in SRF guns in the past. An interesting solution which avoids use of solenoid fields in transverse beam control near the cathode, so-called "rf focusing", has been proposed in [3]. Unfortunately this method requires a deformation of the cathode plane, causing nonlinear field perturbations that may cause significant emittance growth in the injector. We discuss in the following sections an alternative scheme in which rf focusing is not required. This optimized SRF gun is based on the scaling of existing normal conducting high brightness sources to lower frequency and lower rf field.

[*] Peak Brightness: $B = 2I_p / \varepsilon_n^2$ where I_p is the peak current and ε_n is the normalized transverse emittance.

Concerning the choice of the cathode material, it has been shown experimentally [11] that with various treatments of a Nb surface (mechanical diamond polishing or/and laser polishing), one can increase the Nb η from $2 \cdot 10^{-7}$ to $5 \cdot 10^{-5}$. Further increase of η is possible when emitting spot is exposed to high electric fields, through the Schottky effect. Since η scales proportional with electric field applied at the emitting spot one may expect that at gradients of 60 MV/m quantum efficiency will increase to 10^{-4}, or above if higher energy photons can be used to illuminate Nb wall. An improvement in η is of great importance. Even with $\eta = 10^4$ the laser-deposited power in the Nb wall needed accompanying cw, few MHz 1 nC/bunch beam photoemission, would be to high to keep the illuminated spot superconducting [12]. In addition, the illuminating laser itself would be technically very challenging.

More recently, a new approach to the generation of high-current, high-brightness electron beams has been proposed by the BNL group [4]. In this scheme, primary electrons are produced by a photocathode and are accelerated to several keV. At that energy they strike a specially prepared diamond window. The large secondary electron yield (SEY) of diamond multiplies the number of secondary electrons by about two orders of magnitude. These electrons drift through the diamond under an electric field and emerge into the rf accelerating field in the gun through the diamond's negative electron affinity surface. The advantages of this approach are evident in the context of SRF photoinjectors.

BASIC DESIGN PARAMETERS

It is often remarked that production of a very high brightness beam from an rf photoinjector implies the use of a large accelerating gradient. For example, the design for the LCLS photoinjector, which is presently the highest brightness source proposed, utilizes a peak on-axis electric field of between 120 and 140 MV/m at an operating rf frequency of 2.856 GHz [5]. 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 [6]. As the longitudinal beam dynamics are preserved in this case by scaling the fields as $E_0 \propto \lambda_{rf}^{-1}$, 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 within the current state-of-the-art in superconducting cavities [7].

The working point of the LCLS photoinjector is predicted to have a very high brightness, with a peak current at 1 nC charge of 100 A (10 psec flat-top pulse), and an emittance of 0.7 mm-mrad [8]. With these beam parameters, obtained from detailed PARMELA simulation, the calculated B is $5.6 \cdot 10^{14}$ A/m^2. One may scale the space-charge dominated beam dynamics naturally and exactly in rf wavelength, scaling the beam dimensions by the rf wavelength $\sigma_i \propto \lambda_{rf}$ the solenoid field as $B_z \propto \lambda_{rf}^{-1}$, and the beam charge by $Q \propto \lambda_{rf}$ [6]. Under these assumptions, the current is independent of λ_{rf}, and the emittance scales as λ_{rf} — thus the brightness scales as $B \propto \lambda_{rf}^{-2}$. Fortunately, if we scale back the charge at L-band from 2.2 nC (natural scaling), to 1 nC, we do not pay a strong penalty in brightness. For scaling of charge, we must keep the beam plasma frequency constant, which requires that $\sigma_i \propto Q^{1/3}$. Under these conditions of both charge and wavelength scaling, it can be shown that the brightness scales as

$$B\left(A/m^2\right) = \frac{2 \times 10^{12}}{a_1 \lambda_{rf}^2(m) + a_2 Q^{4/3}(nC)\lambda_{rf}^{2/3}(m) + a_3 Q^2(nC)}$$

where the constants a_i are deduced from simulation scans. These constants have physical meaning: a_1 indicates 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 design "family" [9], these constants are determined to be $a_1 = 1.5$, $a_2 = 0.81$, $a_3 = 0.052$.

For our L-band scaled design at 1 nC charge, we obtain a current of 50 A, and an emittance, as before, of 0.7 mm-mrad, for a peak brightness of $B = 2 \times 10^{14}$ 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,
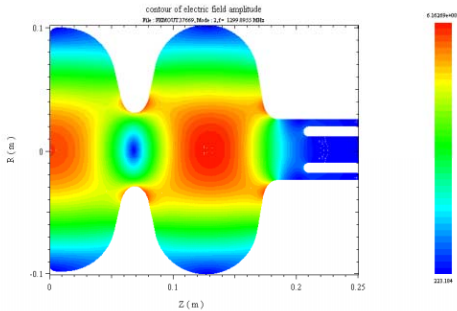

at average repetition rates well in excess of the present state of the art.

Figure 2: 1.3 GHz 1.6 cell Nb SRF gun design

SRF CAVITY AND SOLENOID DESIGN

The proposed 1.3 GHz 1.6 cell Nb cavity, used here to design the injector is shown in Fig. 2. The full cell dimensions are the similar to an inner cell of a TESLA cavity, while the first cell is longer than a half cell $(0.6\,\lambda_{rf}/2)$ in order to compensate for phase slippage occurring during the early, non-relativistic phase of beam acceleration. A coaxial input power coupler has been considered as in the normal conducting TESLA gun design [1], in order to avoid any asymmetry in the accelerating field and transverse RF kicks. The HOM coupler is located on the beam tube close to full cell iris.
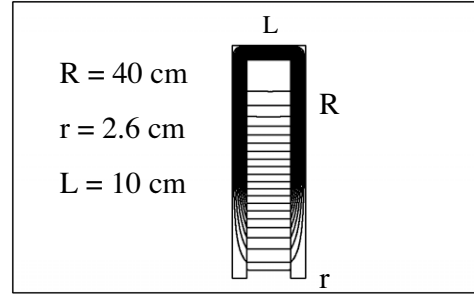

R = 40 cm

r = 2.6 cm

L = 10 cm

Figure 3: design of the solenoid coils

Further, this nearly scaled configuration has a focusing solenoid geometry that keeps most of the magnetic field outside the cavity. In fact in the frequency-scaled, superconducting case, we have further constraints. The magnetic field must not penetrate the super-conducting cavity to avoid thermal breaks down when the critical field of 200 mT is exceeded. The residual fringing field (4 Gauss on the cavity iris see Fig. 4) is tolerable in that the focusing is applied only after cool down and the small field is excluded from the superconducting cavity through the Meissner effect, thus avoiding any residual flux trapping that may cause cavity Q_0 degradation. In Fig. 3 a schematic design of the solenoid coils and iron screen is shown and in Fig. 4 the on-axis E_z component of the RF field and solenoid B_z are displayed.

A more detailed study including the laser system and cryostat design will be discussed in a future work.
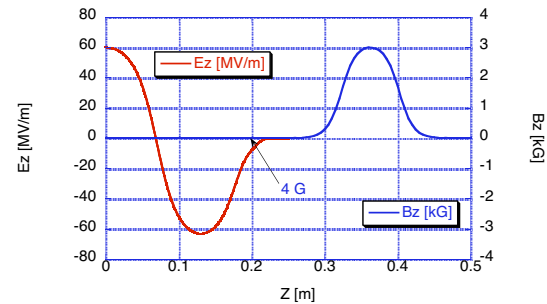
Figure 4: On-axis profiles of the RF field E_z, and B_z

BEAM DYNAMICS SIMULATIONS

PARMELA simulations performed with 50,000 macro-particles are shown in Fig. 5 and 6 up to the 1 mm-mrad emittance threshold. Longer distances have been studied by the fast running code HOMDYN and the results are shown in Fig 7.
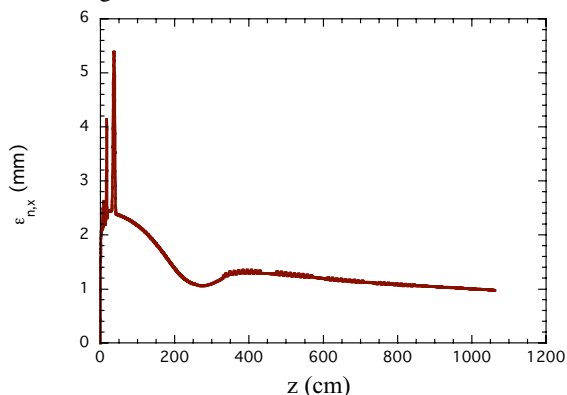

Figure 5: Rms normalized emittance evolution in SC photoinjector, from PARMELA simulations

According to the scaling philosophy discussed in the previous section, in our simulation we consider a uniform density 1 nC bunch 19.8 ps long and 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 deg. 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.
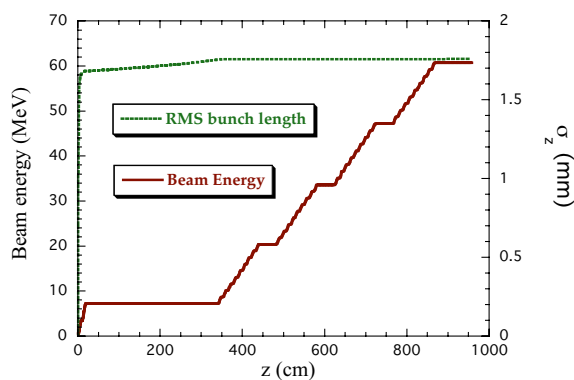

Figure 6: Rms bunch length and energy evolution, in SC photoinjector, from PARMELA simulations.

As shown in Fig. 5 the emittance compensation process is clearly visible in the drift until the bunch is injected at $z=3.3$ m in a cryomodule housing 8 L-band superconducting cavities of the TESLA type. Matching conditions for optimum emittance compensation [10] 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 (see Fig. 7). The final emittance is lower than 1 mm-mrad (with a thermal emittance contribution of 0.5 mm-mrad). A minor bunch elongation (see Fig 6.) in the drift results in a final peak current of 50 A. The total length of the injector system is 14 m.
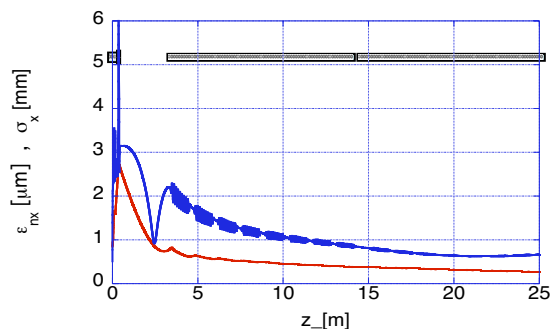

Figure 7: Rms normalized emittance and rms envelope evolution up to the exit of the second cryomodule, HOMDYN simulations.

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