High gradient ultra-high brightness C-band photoinjector optimization

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Abstract. Cathode, laser system, high RF peak field, and gun solenoid are fundamental aspects that have to be optimized to produce high brightness beam in photoinjectors. In order to produce ultra-high brightness beams of about one order of magnitude more than the present devices, new studies have been done in the last years. One promising approach is to increase the peak field on the cathode surface. In this paper we will present a study on a C-band gun using a cathode peak field of 240 MV/m. A first RF study to reach such very high field was done, by means of shortening the RF pulse duration. A first design of the RF structures and solenoid was carried out. If we will not reach exactly the predicted gradient during the RF tests, the impact on the beam dynamics have been simulated reducing the peak field on the cathode up to the value of 130 MV/m, maintaining the same geometry. The convenience of such gun also at a lower gradient, opened the way to possible applications on light production devices. For example, this C-band injector is one of the main options to guide the X-band linac in the CompactLight design study, where an X-ray FEL is foreseen.

1. Introduction
To produce very high brightness \( B = 2I/\epsilon^2 \) beams, the photoinjector optimization has to minimize every possible non reducible contribution to the final beam transverse emittance, while increasing the final peak current. The main emittance contributions in a photoinjector are well known [1, 2, 3], starting from the electron generation at the cathode up to the injector exit. In the following we will focus on these contributions.

Reducing the residual magnetic field on the cathode it is possible to reduce the so-called magnetization emittance:

\[
\epsilon_{n,magn} = \sigma_x^2 \frac{eB_0}{2mc}
\]

(1)

avoiding a transverse momentum in the particles during the emission process.

The contribution due to the photo-electric emission linearly depends on the laser spot size \( \sigma_x \) that can be reduced increasing the cathode peak field:

\[
\epsilon_{photo} = \sigma_x \sqrt{\frac{2(h\omega - \phi_{eff})}{3mc^2}}
\]

(2)

Due to the space charge forces after the emission, the emittance starts to increase and in general this contribution decreases with the inverse of the cathode peak field and, for fixed bunch dimensions (\( \sigma_r \) and \( \sigma_z \)), increases with the beam charge:
This contribution can be divided in a linear and in a non-linear ones. To quickly stop the space charge contribution to the total beam emittance, after the cathode are located RF cavities in which resonates an high accelerating field that usually exceeds the 100 MV/m. The RF contribution to the beam emittance is not zero, but can be minimized properly tuning the launch phase \([4]\):

\[
\epsilon_{RF} = \frac{\alpha k^3 \sigma_x^2 \sigma_z^2}{\sqrt{2}}
\]  

where \(k = 2\pi/\lambda\) with \(\lambda\) the RF wavelength and \(\alpha = \frac{eE}{2mc^2}\) is the dimensionless parameter that describes the accelerating strength of the RF field. The linear part of the space charge contribution to the total emittance can be properly compensated using a solenoid after the RF \([5]\) and properly matching the slice rotation in the phase space to the position of the first accelerating structure \([6, 7]\). The use of a solenoid on the contrary generates a contribution to the final beam emittance due to the non-zero energy spread that is:

\[
\epsilon_{sol} \propto \frac{\sigma_x^2}{f_{sol}}
\]  

where \(f_{sol}\) is the solenoid focal length. The simultaneously optimization of all these parameters is challenging and needs a remarkable amount of simulation time. The use of a code that includes all these effects (especially the space charge, that typically plays a key role in a photoinjector) is mandatory.

2. **C-band gun scaling approach**

In this work we optimized the beam dynamics and the layout of a full C-band photoinjector made up of a 1.6 cells photo-gun and two TW structures with \(f_{RF} = 5.712\ \text{GHz}\). The basic idea of this gun is to maintain the same geometry of the 1.6 cells S-band gun (including the solenoid), shrinking of a factor 2 the longitudinal lengths, while doubling the electric and magnetic fields. Also the drift between the cathode and the first section was properly scaled and then re-optimized. Taking into account the higher peak field and properly reducing the laser spot size \(\sigma_x\) and the duration \(\sigma_z\) using the well known scaling laws \([8]\), it is possible to reduce the cathode emittance, and due to the higher peak field the space charge emittance too.

3. **Injector layout optimization**

The schematic layout of the optimized photoinjector is represented in Figure 1. On the left side, it is represented the 1.6 cells C-band gun, downstream there is the solenoid to compensate
the emittance and finally two 2 meters long C-band TW structures operating at 40 MV/m. Because the first structure can work both on crest and using an RF compression (velocity bunching) [9, 10], the two structures are surrounded by solenoids to keep under control the beam transverse shape and the emittance during the compression process. Considering the on crest working point with this injector it is possible to reach 165 MeV in about 5 meters. Using the GPT code [11] the launch phase, the magnetic fields along the machine and the sections positions were optimized. Fast scans with GPT were performed using 20k particles while the final one was done using 500k particles. In Table 1 are reported the main beam parameters at the exit of the injector, considering the two C-band structures operating on crest and the solenoids around the structures are switched off.

Table 1. Beam parameters at the end of the second C-band section in the on crest working point.

| Beam Parameter               | Value  |
|------------------------------|--------|
| Charge (µC)                  | 75     |
| Beam Energy (MeV)            | 165    |
| Relative Energy Spread       | 0.06%  |
| RMS Bunch Length (µm)        | 296    |
| Beam Emittance (µm)          | 0.15   |
| Current slice (A)            | 25     |

4. C-band injector RF and magnetic design
The design of the gun was focused to achieve such a high gradient keeping under control all known quantities that drive the breakdown phenomena [12], [13]. The two C-band TW structures were designed and scaled, as a first approach, by those developed for the SwissFEL [14] and that can operate with a single klystron and a pulse compressor at the level of 40 MV/m. Main results about the RF design (including different options for the RF couplers) have been reported in [15]. Main parameters of the C-band gun are shown in Table 2.

Table 2. Main parameters of the C-band gun (the values in parenthesis are referred to the TM020-type coupler).

| Parameter                        | Value                     |
|----------------------------------|---------------------------|
| Resonant frequency [GHz]         | 5.712                     |
| $\frac{E_{\text{cath}}}{\sqrt{P_{\text{dis}}}}$ [MV/(m·MW$^{0.5}$)] | 65 (55)                   |
| RF input power [MW]              | 40 (70)                   |
| Cathode peak field [MV/m]        | 200-240                   |
| Rep. rate [Hz]                   | 100-1000                  |
| Quality factor                   | 11000 (14000)             |
| Filling time [ns]                | 150                       |
| Coupling coefficient             | 3                         |
| RF pulse length [ns]             | 180                       |
| Mode separation 0-π [MHz]        | ~90                       |
| $\frac{E_{\text{surf}}}{E_{\text{cath}}}$ | 0.9                      |
| Pulsed heating [°C]              | < 40                      |
| Average diss. Power [W]          | 200-2000                  |
For the gun solenoid, axial symmetric 2D simulations have been performed using Poisson Superfish, reaching an integrated magnetic field that is the same of the SPARC_LAB S-band gun solenoid. We are evaluating the possibility to insert a bucking coil for the cancellation of the residual field on the cathode surface. By simulations the bucking coil is able to reduce the residual magnetic field from almost 360 G to \( \approx 1 \) G.

5. Soft velocity bunching for CompactLight

CompactLight [16] is a design study for a compact hard X-ray FEL facility beyond today’s state of the art, using the latest concepts for high brightness electron photo-injector, very high gradient X-band structures at 12 GHz and innovative compact short-period undulators. The possibility to produce very high brightness beams in a very reduced space opened the way to the application of the C-band injector to CompactLight. To match the CompactLight injector requests the first section phase is optimized to perform a soft velocity bunching with a compression factor of about 3. To take under control the beam spot size and the beam emittance the solenoid S around the sections are switched on. Furthermore the energy request for the injector are about 300 MeV, so at the end of the injector four X-band structures, each 0.9 meter long and operated at 65 MV/m, are added. Because the side effect of the velocity bunching is to accumulate the charge in the bunch head, a correction of this effect was performed by the introduction of Ka-band \((f_{RF} = 34.272 \text{ GHz})\) cavity (0.1 meter long) before the first C-band structure. It operates at 180°respect to the crest and decelerates the beam of about 2 MeV, in this way the effect is an accumulation of the charge on the tail. The gradient of these structures was searched to have a final beam with a flat current profile and \( \epsilon_{n,rms} \leq 0.2 \) \( \mu \)m, that is the upper limit of the emittance for the CompactLight injector. In Figures 2–4 are reported trends of the main beam parameters along the injector. In Figure 5 are reported: the slice beam current distribution, the slice emittance and the slice energy spread.

In Table 3 are reported the main beam parameters at the end of the X-band structures.
Figure 4. Energy and bunch duration along the linac. The RF compression is in the first C-band section.

Figure 5. Slice parameter analysis. It was used a rolling slice to analyze the beam parameter. The slice \( L_{\text{slice}} = 5 \mu m \) moves along the bunch distribution and the parameters are calculated in the slice. Due to the combined effects of the Ka-band cavity and the velocity bunching the final current distribution is symmetrical.

Table 3. Beam parameters at the end of the second C-band section in the on crest working point.

| Beam Parameter          | Value |
|------------------------|-------|
| Charge (pC)            | 75    |
| Beam Energy (MeV)      | 344   |
| Relative Energy Spread | 0.4%  |
| RMS Bunch Length (fs)  | 307   |
| Beam Emittance (µm)    | 0.16  |
| Current slice (A)      | 80    |

6. Injector comparison for different cathode peak fields

In the case the final cathode peak field will not reach the expected value of 240 MV/m, we explored the beam dynamics also for lower cathode peak field. With GPT, different scenarios have been studied, decreasing the cathode peak field. In particular the scan was performed...
Figure 6. Final brightness and final emittance for a beam exiting by four different C-band injectors with different cathode peak fields in the gun. To make a comparison, the simulation results for a beam exiting from a S-band injector with 110 MV/m cathode peak field are reported.

re-optimizing the entire line (launch phase, magnetic fields, structure positions) for each case. This comparison focused on four cases with $E_{\text{peak}} = [240, 220, 160, 130]$ MV/m on cathode, and two C-band structures on crest. Also the laser on cathode dimensions were properly scaled according with the peak fields on the cathode and the cathode emittances were re-calculated for each case according with the eq.2. To perform a comparison between these four C-band cases and a S-band gun, it has been optimized with GPT a S-band injector layout made by a 1.6 cells S-band gun, operating at 110 MV/m, a solenoid to compensate the emittance and three 3 meters long S-band structures operating at 20 MV/m. In Figure 6 the final results for the beam emittance and brightness for the four C-band injectors and the S-band injector are summarized. It is clear that for a fixed frequency, increasing the cathode peak field it is possible to improve the beam emittance and brightness. According with RF calculation reducing the peak field up to 160 MV/m, it will be possible to increase the repetition rate toward the kHz regime, as required by COMPACTLIGHT. This working point can represent also an improvement in the beam brightness compared to the S-band gun at low repetition rate.

7. Conclusions
The beam dynamics and the layout for the C-band injector have been optimized. This device is very compact and allows the production of ultra-high quality beams. The application of this injector on CompactLight is very promising due to the reduced longitudinal size and the very high quality beams ($\epsilon_{n,rms} \approx 0.15 \mu m$ with a $I_{\text{slice}} \approx 80$ A). The design criteria of the gun and the solenoid have been discussed.
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