STUDY OF A C-BAND TW ELECTRON GUN FOR SwissFEL

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Abstract

For a future upgrade of the SwissFEL facility, the replacement of the S-band standing wave electron gun by a C-band standing wave, or traveling wave gun is investigated. The full model of the C-band TW gun is calculated with HFSS and is characterized by an almost vanishing group velocity in the first cell to increase the field at the cathode. ASTRA simulations predict that in the case of the C-band SW gun, a two times higher peak current of ~ 40 A can be generated while still preserving the low normalized slice emittance of ~ 0.2 μm at 200 pC, due to the higher electric field on cathode and improved magnetic focusing. This would help to halve the overall beam compression factor, relax the phase stability requirement of S- and X-band systems operated off-crest for compression and decrease the gain curve in the micro bunch instability. Compared to the SW gun, a TW gun provides a more homogeneous acceleration and does not require any circulator. In this study, the preliminary RF design and beam performance of a C-band TW gun is presented and compared to a pure C-band SW gun presently under design at Paul Scherrer Institut and to the operating S-band SW gun.

INTRODUCTION

The baseline design of the SwissFEL injector [1] foresees a 2.6-cell S-band standing wave (SW) gun as electron source. Recent studies [2] have shown the potential of a 5.6-cell C-band SW gun to double the transverse brightness at the end of the injector. One drawback of SW guns is the need for a high power circulator in order to protect the klystron from the reflected power. Unfortunately, such C-band circulators are commercially not available yet and their design can not be solved with a straightforward rescaling of the device [3]. However, if a traveling wave (TW) gun with a similar performance as that of a conventional SW gun can be designed, the need for a circulator is eliminated, representing an important advantage for the technical realization of the device.

In this paper the feasibility and several advantages of this approach are demonstrated by presenting a preliminary RF design with the corresponding beam dynamics simulations. In particular, the presented design shows the potential of having a very short filling time in the order of 40 ns. Considering in addition that the maximum surface electric field at the iris is smaller than that at the cathode due to the TW nature of this design, the maximum achievable accelerating gradient at the cathode can potentially increase compared to a SW solution.

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RF DESIGN

The main motivations for designing a gun in C-band for the SwissFEL injector are the confidence with the C-band technology being developed at PSI and the higher gradient which can be achieved at higher frequencies.

In this paper, the feasibility of an injector based on a photo-cathode RF TW gun is adressed. Fig. 2 shows the electric field computed by HFSS for the full cavity model composed by one coaxial input coupling cell containing the cathode, 18 regular cells with 60° phase advance and one coaxial output coupling cell. The main RF parameters of the cavity are summarized in Tab. 1. The on-axis longitudinal electric field $|E_z|$ of this TW gun as compared to that of a SW gun [2] is also plotted (Fig. 2, bottom). Furthermore, a zoom of the cathode region is provided (top right) to show an off-axis field enhancement at the cathode of 20 %, which still represents an open issue to be improved.

Table 1: RF Cavity Parameters.

Frequency f_0	5.712 GHz
Phase advance / cell $\Delta\phi$	60°
Regular cell length L_c (1)	8.7 mm
# of cells	20
RF Length L	~ 180 mm
Filling time τ_L	39 ns
Group velocity v_g	$0.015 \cdot c$
Q (2)	5720
R/Q (2)	9128 Ω/m
Nominal cathode gradient	135 MV/m
Nominal input power	120 MW
Cavity attenuation S_{21}	1.06 dB

(1) $\lambda_0 = c/f = 52.485$ mm.
(2) From the eigenmode solution with losses of the regular cell.

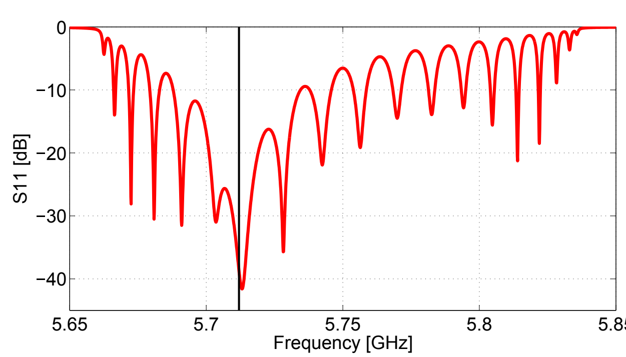

Figure 1: RF frequency spectrum of the TW gun of Fig. 2. The operating American C-band (5.712 GHz) is indicated.

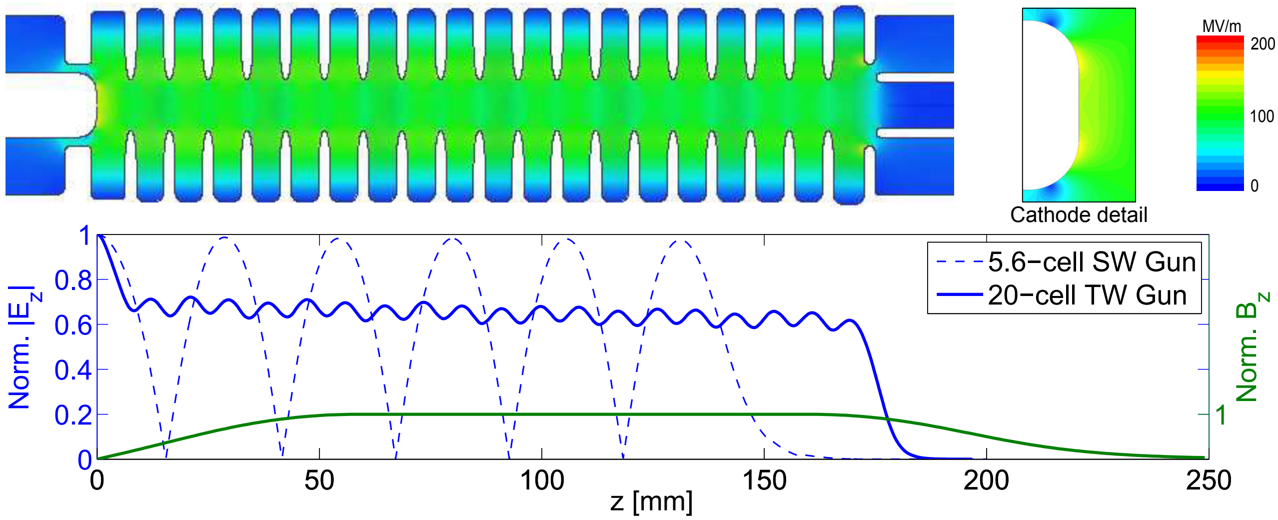

Figure 2: Magnitude of the electric field on a longitudinal slice of the TW gun normalized to 135 MV/m at the cathode (top), detail of the cathode region (top right), magnitude of the longitudinal electric field on-axis $|E_z|$ and longitudinal magnetic field B_z of the gun solenoid (bottom). For comparison, the electric field profile of the SW gun is also plotted.

The RF frequency spectrum of the proposed traveling wave gun is plotted in Fig.1 and confirms that a circulator is not necessary since the reflection coefficient S_{11} is smaller than −25 dB in the frequency range 5712 ± 5 MHz corresponding to the klystron pass band.

The very short filling time enables two different RF feeding approaches. A first option is a recirculation scheme [4] based on a 180° hybrid. Here a rectangular RF pulse of 0.3 μs length and 40 MW amplitude can provide the nominal 135 MV/m at the cathode by generating a power multiplication factor of 3.6. A second scheme, more flexible because of the straightforward implementation of phase and/or amplitude modulation, foresees the use of a BOC pulse compressor [5]. Fig. 3 shows a configuration based on this scheme, where the nominal cathode gradient of 135 MV/m is reached. A rectangular RF pulse of 3 μs length and 24.6 MW amplitude from the klystron is compressed by a factor 6 in the BOC and provides 120 MW for 50 ns at the gun input (20% waveguide losses accounted for). The phase is modulated to obtain a flat output amplitude over a 50 ns time interval, as shown in the inset. The BOC output phase during this time interval has a peak-to-peak variation smaller than 5°, justifying the assumption of steady-state in the beam dynamics simulations.

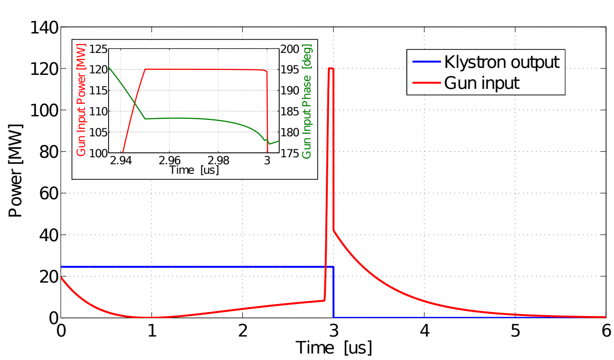

Figure 3: Rectangular RF pulse output from the klystron and corresponding RF input pulse to the gun after the BOC pulse compressor (20% waveguide losses accounted for). The inset provides a zoom of the 50 ns time interval for beam operation.

BEAM DYNAMICS

The beam dynamics has been optimized with the same tools as described in [2]. In the first phase, the most influential parameters tuned that improved beam quality were the input and output coupling cell lengths. These two parameters were initially defined as free parameters within the MATLAB optimization routine for beam dynamics which optimizes the transverse beam brightness at the end of the injector. The requested cell length changes were automatically achieved by stretching a default on-axis fieldmap. Once a good working point was found, a HFSS simulation of the full gun model with the optimized lengths was performed (Fig. 2) and the beam dynamics fine tuned again.

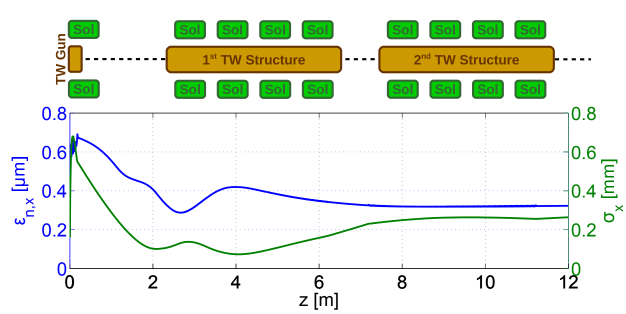

Figure 4: Normalized projected transverse emittance $\varepsilon_{n,x}$ and rms beamsize σ_x along the beamline sketched on top.

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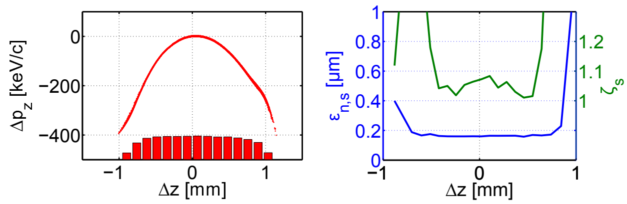

Figure 5: Longitudinal phase space and corresponding charge distribution of the 200 pC bunch (left), normalized slice emittance $\varepsilon_{n,s}$ and mismatch parameter ζ_s (right) after the second TW structure (z = 12 m and E = 130 MeV).

The evolution of the transverse projected emittance and the rms beam size along the first part of the SwissFEL injector for a 200 pC bunch are shown in Fig. 4, while the resulting slice emittance and mismatch parameter at the end of the simulated section are shown in Fig. 5. Compared to the solution with a C-band SW gun (see Tab. 2), the normalized slice emittance decreases from 0.21 μm to 0.16 μm at a beam energy $E > 100$ MeV preserving a good mismatch parameter.

Three additional important setups were also simulated and gave promising results. First, lowering the cathode intrinsic emittance from 0.91 μm/mm-rms (conservative value) to 0.60 μm/mm-rms (value measured at the SwissFEL Injector Test Facility [6]) further reduced the normalized slice emittance at $E > 100$ MeV to 0.14 μm without spoiling the peak current of 34 A. In the second case, even using a Gaussian longitudinal laser pulse it was possible to achieve a normalized slice emittance of 0.19 μm and a peak current of 38 A, slightly better than the C-band SW case with flat-top longitudinal pulse. Finally, an increased nominal gradient at the cathode of 150 MV/m provided a peak current of 35 A and a normalized slice emittance of ~ 0.15 μm.

Table 2: Comparison of SwissFEL injector layout parameters and simulated beam quality at $E > 100$ MeV for the S-band SW (SSW), the C-band standing wave (CSW) and the C-band traveling wave (CTW) guns.

SwissFEL injector	SSW	CSW	CTW
Laser pulse FWHM [ps] [(1)]	9.9	5.0	5.4
Laser transv. sigma [mm] [(1)]	0.200	0.174	0.163
Bunch charge [pC]	200	200	200
Gun frequency [GHz]	2.998	5.712	5.712
Gun design gradient [MV/m]	100	135	135
Gun phase [deg] [(2)]	−2.6	−9.3	−1.1
Solenoid max. field [T]	0.2080	0.3549	0.4527
Solenoid max. field pos. [m]	0.300	0.139	0.110
1st TW struct. pos. (Fig. 4) [m]	3.3	2.274	2.152
1st TW struct. avg. grad. [MV/m]	13.8	18.2	9.539
Gun output energy [MeV]	6.6	9.5	15.5
Peak current I_{peak} [A]	20.0	37.4	34.7
Projected transv. emit. $\varepsilon_{n,x}$ [μm]	0.25	0.26	0.32
Mean slice emit. $\bar{\varepsilon}_{n,s}$ [μm] [(3)]	0.21	0.21	0.16
Mean mismatch $\bar{\zeta}_s$ [(3,4)]	1.03	1.05	1.08
Transv. brightness [TA/m]^2 [(5)]	36	69	104

(1) Flat-top transverse and temporal distribution of the laser pulse assumed.

(2) With respect to maximum energy gain.

(3) Mean over 20 slices, neglecting the 3 most external at the head and tail of the bunch.

(4) Definition used: $\zeta_s \equiv 1/2 \cdot (\beta_0\gamma_s - 2\alpha_0\alpha_s + \gamma_0\beta_s)$, where α, β, γ are the Twiss parameters for the whole bunch (index 0) and the single slice (index s).

(5) Definition used: $B_\perp \equiv 1/(4\pi) \cdot I_{peak}/\bar{\varepsilon}^2_{n,s}$.

CONCLUSION

This preliminary study demonstrates the feasibility of a photo-cathode C-band traveling wave gun as electron source for the SwissFEL injector. The direct advantage of using a TW cavity is the elimination of any high power circulator from the RF network. This was demonstrated to be possible without spoiling the beam quality compared to the SW case.

Even better, with a nominal gradient of 135 MV/m at the cathode, the transverse beam brightness is increased by 50% compared to the C-band SW design, which corresponds to a factor of ~ 3 with respect to the baseline design of SwissFEL. Due to the very short filling time of 40 ns, there is still potential to go beyond this “nominal” gradient, which further improves the beam quality.

Further studies will be carried out to optimize the RF design (number and length of cells, phase advance per cell, undesired field enhancement at the cathode, coupling) and the magnet design. The RF pulse shape (phase and/or amplitude modulations) can provide an additional degree of freedom for the optimization of the beam dynamics.

ACKNOWLEDGMENTS

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