OPTIMIZATION STUDIES FOR THE SWISSFEL RF-GUN

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Abstract

The 250 MeV SwissFEL injector test facility is in operation since August 2010. Measurements with the “CTF2 Gun 5” photocathode S-band rf-gun show promising beam parameters and satisfy the requirements of the SwissFEL project. Since the performance of the electron source is fundamental for the stability and brightness of a free electron laser, further gun optimization studies are pursued. Under investigation is currently a 3.6 cell C-band gun. First ASTRA simulations indicate that with this gun the peak-current can be increased, thanks to a shorter laser pulse and a higher initial acceleration, by almost a factor of two, at slightly better emittance values than the S-band “PSI Gun 1”. Since the beam-quality depends also on the achieved performance of the cathode, several copper cathodes had been tested in the SwissFEL injector test facility to analyze the observed rapid degradation of quantum efficiency.

INTRODUCTION

The 250 MeV SwissFEL injector test facility is in operation since August 2010, while the construction of the final SwissFEL user facility has started at the beginning of this year (2013), with the first beam being planned for 2016. The test facility is currently running with the “CTF2 Gun 5” photocathode rf-gun [1, 2]. This gun will be replaced at the end of this year by the “PSI Gun 1” [3], which is currently being manufactured at PSI. It will also be the first gun operating in the SwissFEL user facility.

The measurements performed so far with the “CTF2 Gun 5” have shown very promising beam parameters and simulations indicate that these can be improved even further by the “PSI Gun 1” [4, 5, 6]. Despite these already satisfying results, there is still potential for important improvements in the rf-design. In particular, the possibility to produce much shorter bunches employing a gun in C-band is investigated, following e.g. the example of Tsinghua university [7]. Reducing the bunch size would relax the compression factor to be achieved in the two bunch compressors and therefore have important benefits for the beam quality.

Improvements are not only possible in the rf-design but also in the photocathode performance. In fact, we present some experience gained in the SwissFEL injector test facility which demonstrate that the performance and stability of the copper photocathodes can be improved. Focusing in particular on the surface finish, a reliable, systematic preparation technique should be determined and applied.

COPPER PHOTOCATHODES

The photocathode is a crucial component of every photocathode rf-gun. Two main aspects should be taken into consideration: Performance, in terms of intrinsic emittance and quantum efficiency (QE), and reliability.

The latter aspect is considered by presenting some measurements performed at the SwissFEL injector test facility. The recent installation of a load-lock system allowed the test of several copper cathodes of the same type (Cu7, Cu8, Cu11) during the last three months. All of them have shown a very similar behaviour, characterized by a typical QE of $5 \cdot 10^{-5}$ at the operating phase and gradient of 83 MV/m at the cathode. Fig. 1 shows QE maps (top) and absolute QE measurements (bottom) for the cathode Cu7 after fifteen days of beam operation at 10 Hz (the behaviour of Cu8 and Cu11 was qualitatively identical). The lower yield measured at the center of the QE map (top left) corresponds to the area illuminated by the laser spot. Comparing the QE values from the charge versus laser energy scan (bottom) for the central region (blue) and the outer region (red), the QE in the central region is reduced by $\sim 40\%$. This degradation was already found after only three days of laser operation. Moving the laser spot to a different location for one night confirmed the short time scale of the process, as the QE map taken in the next morning (top right) clearly demonstrates.

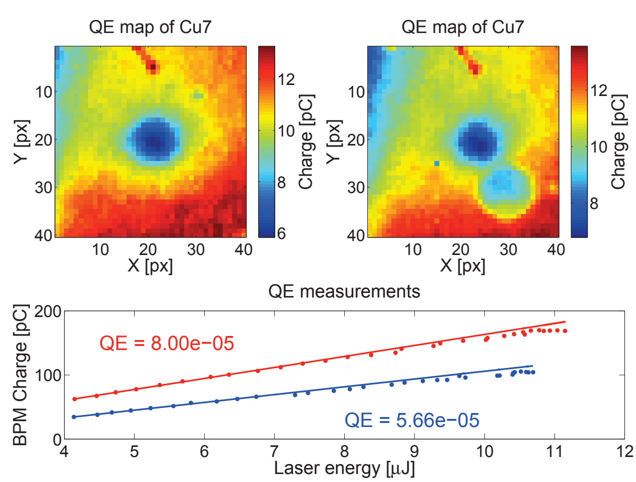

Figure 1: Top: QE maps of the copper cathode Cu7 after fifteen days of beam operation (units are arbitrary, but width of the QE hole corresponds to the laser spot size of 1 mm diameter). Bottom: Corresponding QE measurements in the central region (blue) and in the outer region (red).

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What is surprising in these observations is the fast degradation: The formation of QE holes at the laser spot location is a well-known fact but for much longer time scales which are typically in the order of several months [8], as also observed for the previous cathode Cu3.

An element analysis of the surface of Cu7 was performed to investigate the possible sources of contamination. The comparison between the relative abundances of the detected elements in the central and in the outer region are listed in Tab. 1. The only remarkable difference is the increased amount of carbon in the region of low QE. This is not surprising but rather a known phenomena when shooting a UV laser on a metallic surface on which organic substances are deposited [9]. This phenomena is however not directly visible in SEM images, as e.g. those in Fig. 2 which look very homogeneous and do not allow to distinguish between different regions or to note anything anomalous.

Table 1: EDX analysis of atomic abundances (in %) of the elements detected on the surface of Cu7 after operation.

Line	Central region	Outer region	Difference
Cu K	51.44 ± 3.01	63.78 ± 9.85	$+12.34$
C K	45.48 ± 2.83	33.01 ± 10.6	-12.47
O K	2.81 ± 0.46	2.88 ± 1.08	$+0.07$
Al K	0.19 ± 0.10	0.23 ± 0.23	$+0.04$
W K	0.07 ± 0.02	0.10 ± 0.10	$+0.03$

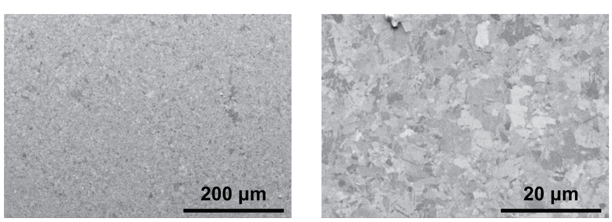

Figure 2: SEM images (BSE, 30 kV) of the central region of Cu7 after operation. The last manufacturing step for this cathode was a single-tip diamond milling, which provides mirror-like surfaces with average roughness in the range 3 - 10 nm.

Improvements in the QE could be reached either by surface cleaning treatments or by reducing the contamination rate by means of better vacuum and cathode preparation.

3.6-CELL C-BAND RF-GUN

With the aim of designing a future, optimized rf-gun for the SwissFEL project, a 3.6 cell C-band gun has been investigated as a possible but very promising option. This future rf-gun must operate at 100 Hz pulse repetition frequency, provide similar beam-emittance like the "PSI Gun 1" [4] and allow the acceleration of shorter electron bunches in the injector. Reducing the initial bunch length from 10 ps to 5 ps flat-top would relax the required compression factor.

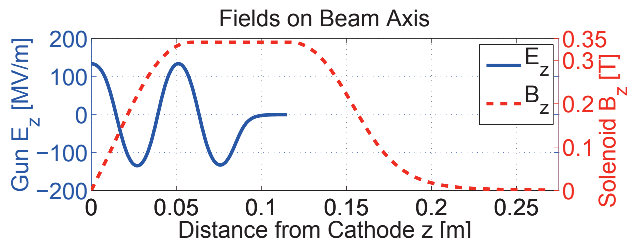

Figure 3: Electric field E_z of the gun and magnetic field B_z of the gun solenoid on the beam-axis of the gun.

An rf-gun operating at American C-band would allow to operate at a higher electric field on the cathode and to better compensate the longitudinal space-charge effects immediately after emission. Since the main accelerator of SwissFEL is operated at American C-band frequency, the synchronization for the two bunch operation would be straightforward and has also the advantage of the already available C-band technology at PSI. In order to limit the energy modulation, the travelling wave acceleration structures of the injector are kept at S-band frequency. Having a full C-band solution would require non-linear compression. The synchronization of the gun, operated at American C-band with 5.712 GHz ($40 f_b$) and "Swiss" S-band with 2.998 GHz ($21 f_b$), together with the rescaled rf-pulse-length would help to reduce the dark-current despite the higher electric field on the cathode.

For a first, preliminary analysis, the geometry of the 2.6-cells rf-gun was just rescaled from the S-band "PSI Gun 1" to C-band. In order to get comparable beam energy at the output of the gun, one additional cell was added. Fig. 3 shows the electric field distribution on the axis of the gun and the magnetic field of the gun-solenoid. The fields were calculated by the Superfish- and Poisson-solver. Similar to the design proposed by Han [10], the gun solenoid was moved close to the cathode in order to focus the electron beam immediately after emission. This design would require coaxial coupling of the rf-power to the gun, which on

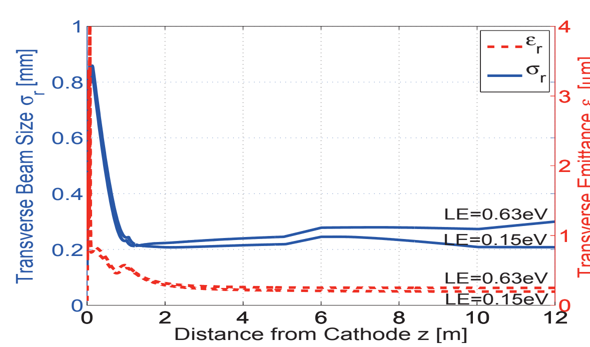

Figure 4: Transverse normalized projected emittance and beam size along the injector with C-band gun and two S-band travelling wave structures for 200 pC operation. The final energy is 180 MeV.

the other hand might make it more sensible to multipactoring.

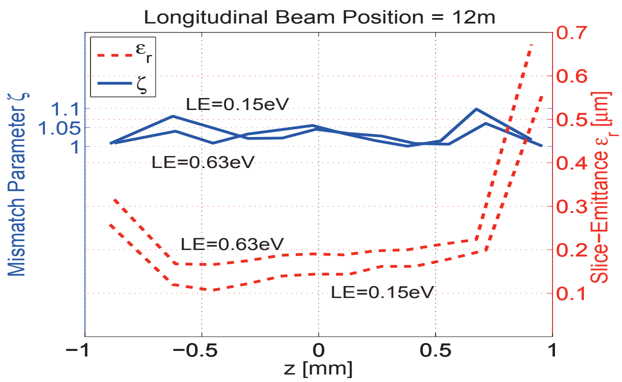

Figure 5: Slice emittance and mismatch parameter after the second travelling wave structure at 180 MeV.

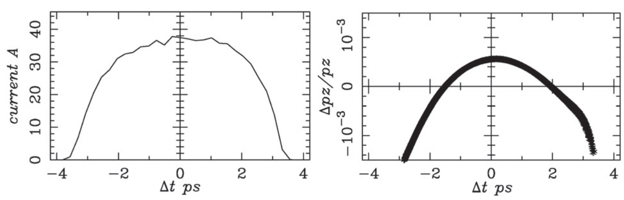

Figure 6: Longitudinal phase-space at 180 MeV for the $LE = 0.63$ eV case.

Table 2: Comparison of injector beam parameters for 200 pC operation. LE defines the width of the initial energy distribution in ASTRA. For the short bunch option, the gradient of the S-band travelling wave structures was increased by 44%.

Parameter	S-band	C-band	C-band
LE [eV]	0.63	0.63	0.15
Laser spot size [mm]	0.33	0.156	0.145
Laser pulse length [ps]	9.9	5.0	5.0
Frequency [GHz]	2.998	5.712	5.712
Gun gradient [MV/m]	100	134.8	134.9
Gun phase off crest	$-2.6°$	$-13.2°$	$-13.2°$
Pos. 1st TW struct. [m]	3.6	0.98	1.03
Gun energy [MeV]	6.6	5.6	5.6
Emittance [μm]	0.25	0.25	0.20
Slice emittance [μm]	0.21	0.19	0.15
Peak current [A]	20	38	36
Final energy [MeV]	130.4	184	185

ASTRA [11] was used for the beam-dynamics simulations with ten thousand macro particles, together with a MATLAB based optimizer [6]. In order to ease the optimization of the gun and gun-solenoid, small adjustments of the length of the gun half-cell and of the solenoid plateau-region were implemented as additional knobs in the optimizer. Figs. 4, 5 and 6 show the corresponding results of our optimizations which are summarized in Tab. 2. Since the thermal emittance depends on the initial energy distribution like $\varepsilon_{th} = \sigma_r \sqrt{2LE/(3m_e c^2)}$, simulations were performed for the base-line design with $LE = 0.63$ eV. This corresponds to the emission process on a copper cathode with a laser with a wavelength of 266.7 nm. For comparison, also a second optimization was done for a more progressive value of $LE = 0.15$ eV. Such values could be achieved in the future by increasing the wavelength of the laser or by using different cathode materials [12].

CONCLUSIONS

Our numerical simulations indicate that a C-band gun brings interesting advantages for the beam dynamics. Most of the beam parameters are very close to those which can be reached with the S-band “PSI Gun 1”, but with the advantage that the peak current is increased from 20 A to 38 A. This helps reducing the overall bunch compression factor of the FEL facility.

A reduction of the width of the initial energy distribution from $LE = 0.63$ eV to $LE = 0.15$ eV would decrease the slice emittance by 21%. This indicates that it is worth to study the problem also at the source, investigating the surface physics aspects of the emission process and trying to reduce the intrinsic emittance of the photocathodes [12, 13, 14]. On the other hand, the C-band gun and the gun-solenoid can probably also be further optimized to reach lower emittance and higher peak-current by fine tuning of the fieldmaps and beam optics.

ACKNOWLEDGEMENTS

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