HIGH POWER RF TEST AND ANALYSIS OF DARK CURRENT IN THE SwissFEL-GUN

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Abstract

To fulfill the beam quality and operational requirements of the SwissFEL project, currently under construction at the Paul Scherrer Institut, a new RF photocathode gun for the electron source was designed and manufactured in house. A 2.6 cell S-band gun operating with near-perfect rotationally symmetric RF field was designed to operate with a 100 MV/m cathode field at a repetition rate of 100 Hz with average power dissipation of 0.9 kW with pulse duration of 1 µs. The first SwissFEL-gun is now fabricated and installed in the SwissFEL Injector Test Facility (SITF). The frequency spectrum and field balance, through bead-pulling, have been directly verified in-situ and then the gun has been operated with high-power RF. The results of bead-pull measurements and high-power tests are presented and discussed. In addition the emitted dark current was also measured during the high-power tests and the charge within the RF pulse was measured as a function of the peak cathode field. Faraday cup data were taken for cathode peak RF fields up to 100 MV/m for the case of a diamond-milled polycrystalline copper cathode.

INTRODUCTION

The SwissFEL free electron laser project currently under construction at the Paul Scherrer Institut will be composed of a 5.8 GeV accelerator and two undulator beam lines which will cover the photon energy ranges from 12.4 keV to 1.8 keV and from 1.8 keV to 0.18 keV for Aramis and Athos lines, respectively [1]. To fulfill the beam quality and operational requirements a new RF photocathode gun for the electron source was designed [2] and manufactured in house [3]. It is composed of 2.6 cell operating with a near-perfect rotationally symmetric π-mode at the S-band frequency. The middle cell is coupled to two rectangular waveguides symmetrically arranged to cancel the dipolar component of the field. The racetrack interior shape of this coupling cell is optimized to minimize the quadrupolar field component. It is designed to operate with a 100 MV/m cathode field at a repetition rate of 100 Hz with average power dissipation of 0.9 kW and a pulse duration of 1us. The first SwissFEL-gun is now fabricated and installed in the SwissFEL Injector Test Facility (SITF) [4]. In order to have the possibility to exchange cathode without breaking the vacuum the back-plane of the RF gun has a hole where a cathode plug can easily be inserted through a load-lock system [5]. Figure 1 shows a 3-D view of the SwissFEL-gun where the cathode-plug is visible in the back-plane. Measurements at room temperature in the clean room showed that the resonant frequency depends on the force with the cathode-plug is pushed into the gun and thus the frequency spectrum and field balance, through bead-pulling, have been directly verified in SITF before starting with RF conditioning. Table 1 lists a comparison between RF simulations with HFSS [6] and measurements of the SwissFEL-gun RF parameters. In addition the emitted dark current was also measured during the high-power tests. Past measurements on the previous installed CTF3 gun showed quite high value of the dark current [7], thus the charge within the RF pulse of the SwissFEL-gun was measured as a function of the peak cathode field at different pulse durations. Faraday cup data were taken for different cathode peak RF fields for the case of a diamond-milled polycrystalline copper cathode with surface roughness R_a=5 nm.

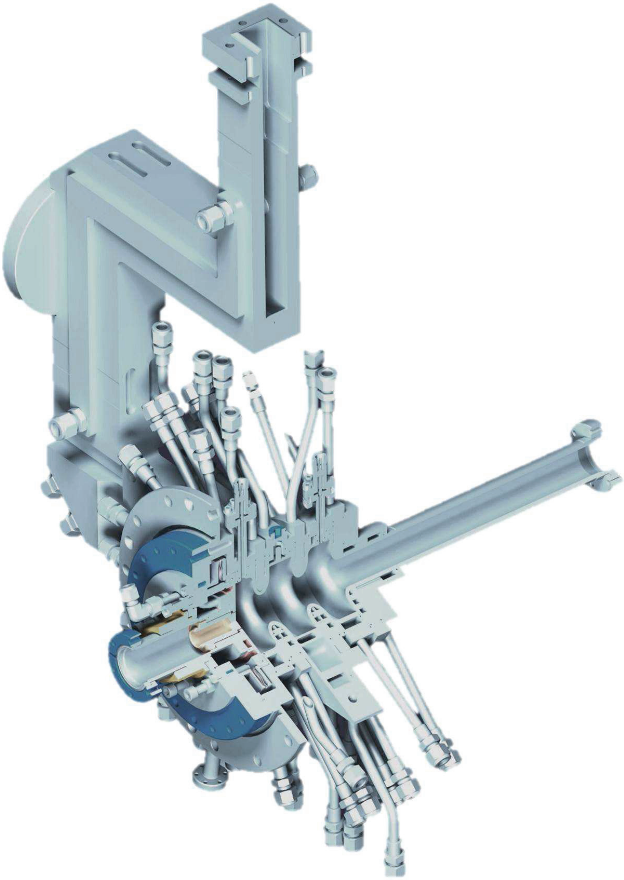

Figure 1: 3-D view of the SwissFEL-gun.

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Table 1: SwissFEL-gun RF Parameters for the SwissFEL Injector Test Facility (SITF)

Parameter	HFSS	Measured	unit
π-mode freq.	2997.912	2997.912	MHz
β-coupling	1.98	2.02	
Q_0	13630	13690±100	
Filling time	485	481	ns
Mode sep.	16.36	16.20	MHz
Field balance	>98	>98	%
Operational temp.	57.7	53.0	°C

CATHODE-PLUG TUNING

In order to perform the frequency tuning of the RF gun through the cathode-plug, the manipulator of the plug was equipped with a calibrated pressure gauge. Figure 2 reports the result of the measurements for different force. RF gun is tuned at nominal SITF frequency of 2997.912 MHz when a force of more than 600 N is applied. Figure 3 shows electric field profiles on-axis at position of the cathode-plug obtained from bead-pulling with a ceramic bead of 3 mm diameter. At nominal frequency the ratios (field balance) are $E_2/E_c = 1.02$ and $E_1/E_c = 1.01$ where E_c is the field at cathode and E_2 and E_1 are the fields in the middle and last cell, respectively. The frequency spectrum at operational conditions is shown in Fig. 4. Frequency separation with adjacent mode is 16.2 MHz, in a good agreement with the simulation result.

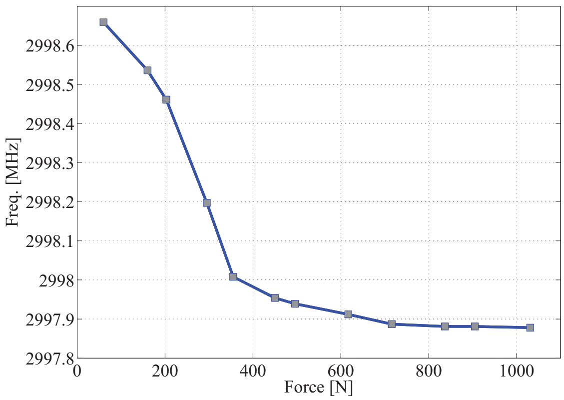

Figure 2: Resonant frequency of the π-mode as a function of the applied force on the cathode plug.

HIGH POWER RF TEST

The gun was tested at full power in the SITF bunker using actual RF distribution system of the injector with a TH2100 35 MW klytron, 35 MW peak power and 5 kW average power circulator and an active temperature control of the gun body temperature. The gun was conditioned over a period of one week and a typical processing curve to high power is given in Fig. 5. The RF conditioning process has been performed with a pulse repetition rate of 100 Hz, by gradually increasing the RF power through an automatic conditioning tool and changing the pulse width from 0.3 to 1.0 µs. After the conditioning period the vacuum level with RF power was around 1×10^{-10} mbar. It is worthwhile to note that nominal RF power of 18 MW with the RF pulse width of 1 µs in the first week of operation was reached.

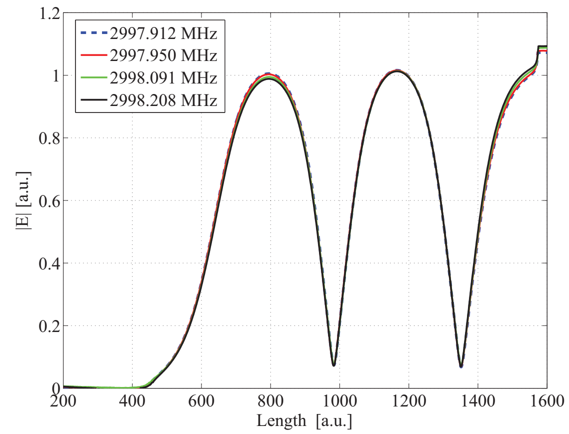

Figure 3: Electric field profile on-axis for different position of the cathode plug.

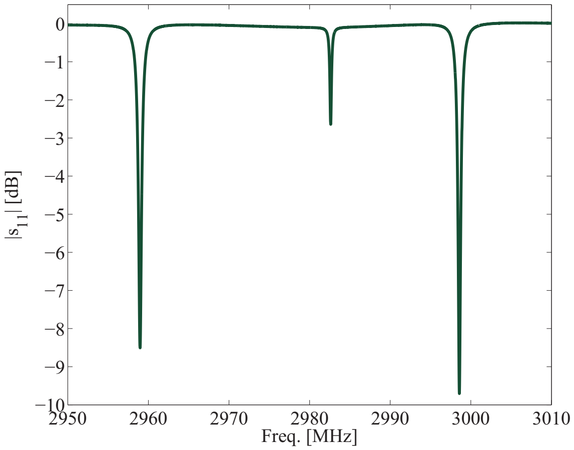

Figure 4: Frequency spectrum of the SwissFEL-gun. Operating frequency in vacuum 2997.912 MHz at 53 °C, frequency separation with adjacent mode is 16.2 MHz.

Beam Energy Jitter

The momentum and momentum spread of the electron beam can be measured through the energy spectrometer arm placed after the RF gun and before the first traveling wave structure. It consists of a 30° dipole magnet and in order to maximize the momentum resolution of the spectrometer, a quadrupole in front of the bending magnet was used to have the contribution of the dispersion to beam size larger than the contribution of the natural beam size. Energy resolution at the spectrometer was 4 keV rms and a systematic error

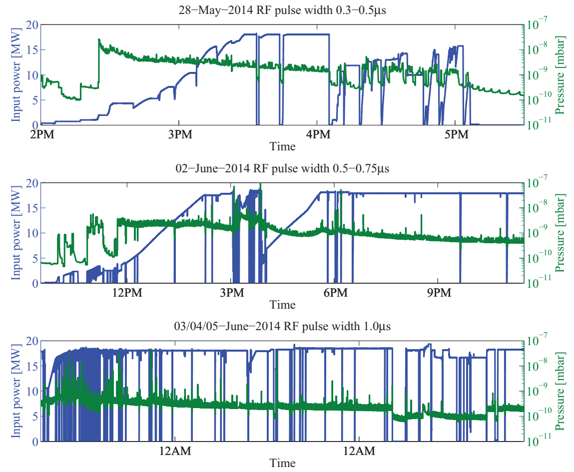

Figure 5: RF conditioning to high power.

due to uncertainties from dipole magnetic field of 1 %. Figure 6 shows an example of non-Gaussian horizontal profile at the spectrometer YAG screen which is fitted with a confi function [8]. The horizontal axis is converted in MeV according to the dipole dispersion of 0.387 m. Figure 7 shows the bunch mean energy and energy spread jitters at the gun exit measured on 49 not consecutive shots over 30 sec with laser at 10 Hz and RF repetition rate 10 Hz and 100 Hz. It is worthwhile noting that the rms relative mean energy jitters are 0.023 % and 0.020 % for 100 Hz and 10 Hz, respectively. Rms jitter of the energy spread is 0.5 keV for both repetition rates.

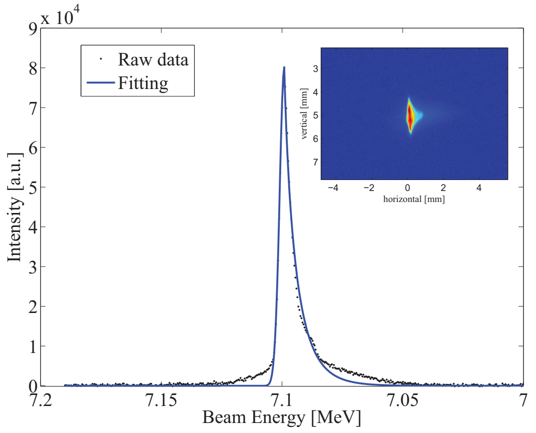

Figure 6: Example of non-Gaussian horizontal profile at the spectrometer at 7.1 MeV (black points) which is fitted with a confi function (blue line).

DARK CURRENT ANALYSIS

The low energy beam transport line between the RF gun and the first S-band accelerating structure has a length of approximately 3.3 m. At the gun exit there is a solenoid, followed by the laser ports and a coaxial Faraday cup that allows the observation and measurement of the dark current from the RF gun and cathode. Figure 8 shows the typical signals on the scope connected to the Faraday cup once the gun solenoid was adjusted to maximize charge collection in the cup itself. Dark current signals show a plateau due to the amplitude modulation of the RF input power, which will be used to maintain a constant amplitude of the accelerating field for a two-bunch operation with a 28 ns spacing in SwissFEL [1]. At nominal operating conditions with peak electric field at the cathode of 100 MV/m, the integrated dark current collected by the Faraday cup is approximately 50 pC. The dark charge was also imaged using a 200 µm thick YAG crystal scintillator placed in the same housing of the Faraday cup. Figure 9 shows a comparison between images of the dark currents in the CTF3-gun and SwissFEL-gun both focused with the gun solenoid on the same YAG screen. At nominal operating condition of the

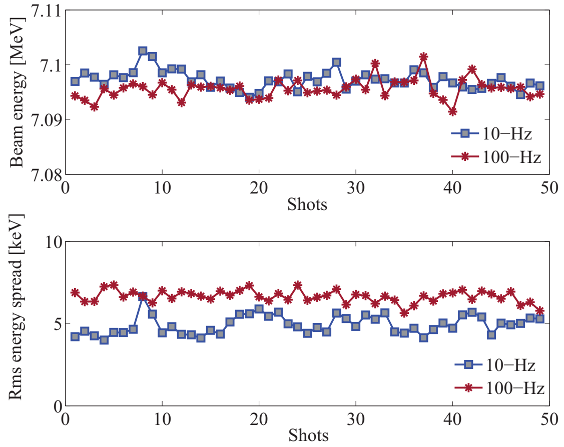

Figure 7: The bunch mean energy jitter (top) and bunch rms energy spread (bottom) at the gun exit measured on 49 not consecutive shots over 30 sec with laser repetition rate 10 Hz and RF repetition rate 10 Hz and 100 Hz.

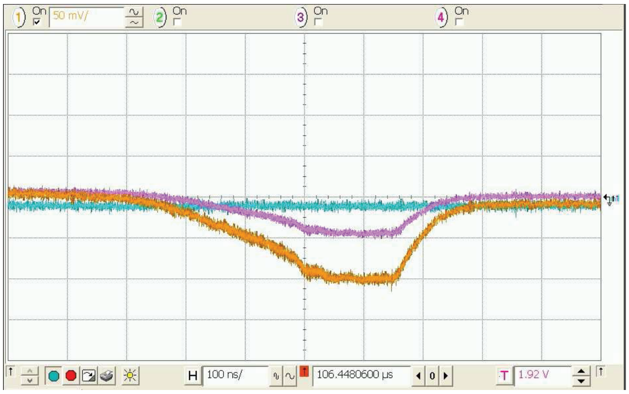

Figure 8: display on scope of signals from the Faraday cup during the measurement. Yellow trace: raw signal. Blue trace: background. Pink trace: signal after background subtraction.

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gun (85 MV/m on the cathode surface), the dark current in the CTF3 gun collected by the Faraday cup was about 1.4 nC [7]. The observed scaling of integrated dark current with cathode field is plotted in Fig. 10 before and after alignment of the solenoid and at 10 Hz and 100 Hz. Basically the emission of electrons in a period of the RF field is generated by the field emission which can be described by the well-known Fowler-Nordheim (F-N) equation. Using such equation, and taking into account the transient behavior due to the filling time of the gun, the field enhancement factor β can be estimated in the range 63-68 with the assumption

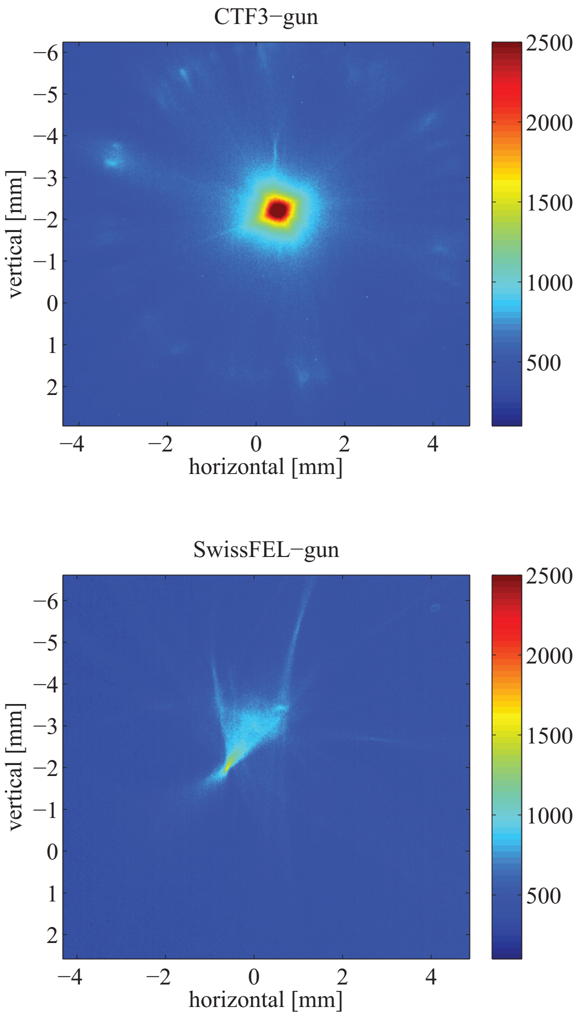

Figure 9: Reference images of dark current at nominal condition on the YAG screen in the CTF3 gun (top) and SwissFEL-gun (bottom).

CONCLUSION

The frequency tuning of the SwissFEL-gun based on the cathode-plug was possible applying a force larger than 600 N. The field imbalance was around 2 % and the frequency separation equal to 16.2 MHz, in good agreement with the simulations. The gun was smoothly conditioned to full power at 100 Hz over a period of one week and at the end the vacuum level was around 1×10^{-10} mbar. We compared the relative mean energy and energy spread jitters at the gun exit at 10 Hz and 100 Hz. Rms relative mean energy jitters were 0.023 % and 0.020 % for 100 Hz and 10 Hz respectively, while the rms jitter of the energy spread was 0.5 keV for the both cases. Furthermore, we measured the emitted dark current within the RF pulse as a function of the peak cathode fields. At nominal operating conditions of the gun, peak electric field at cathode of 100 MV/m, the integrated dark current collected by the Faraday cup was approximately 50 pC. Using F-N equation and taking into account the transient behavior due to the filling time of the gun we estimated a field enhancement factor β in the range 63-68. As conclusion the SwissFEL-gun fulfilled RF specifications and is suitable for the SwissFEL injector.

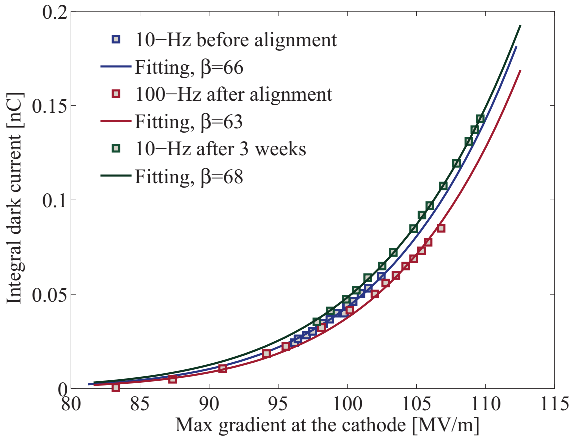

Figure 10: Integrated dark current on RF pulse as a function of the peak electric field at cathode before and after alignment of the RF gun and solenoid and at 10 Hz and 100 Hz.

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