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RF PERFORMANCE OF A NEXT-GENERATION L-BAND RF GUN AT PITZ

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Abstract

A new generation of high-gradient normal conducting 1.3 GHz RF gun with 1% duty factor was developed to provide a high-quality electron source for superconducting linac driven free-electron lasers like FLASH and European XFEL. Compared to the Gun4 series, Gun5 aims for a ~50% longer RF pulse length (RF pulse duration of up to 1 ms at 10 Hz repetition rate) combined with high gradients (up to ~60 MV/m at the cathode). In addition to the improved cell geometry and cooling concept, the new cavity is equipped with an RF probe to measure and control the amplitude and phase of the RF field inside the gun. The first characterization of Gun5.1 included measurements of RF amplitude and phase stability (pulse-to-pulse and along 1 ms RF pulse). The dark current was measured at various peak power levels. The results of this characterization will be reported.

INTRODUCTION

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) develops, tests and characterizes high brightness electron sources for FLASH and European XFEL for more than 20 years. Since these user facilities operate superconducting accelerators in pulsed mode, the corresponding normal-conducting L-band RF gun also has to operate with long RF pulses at 10 Hz repetition rate. To obtain high electron beam quality from a photocathode RF gun, a high acceleration gradient at the cathode is required. The peak RF electric field of 60 MV/m at the cathode is considered as a goal parameter for a high brightness L-band photogun. Therefore, the RF gun has to provide stable and reliable operation at high average RF power. The previous gun cavity generation (Gun4) had a maximum RF pulse length of 650 μs, which implies a maximum of 27000 electron bunches per second. Growing interest from the FEL user community for even longer pulse trains motivated developments of the next generation of normal conducting L-band gun cavity (Gun5), which aims for 1 ms RF pulses. Combined with 6.5 MW of peak RF power, this results in a very high average power of ~65 kW. In addition to the improved resonator shape and cooling, Gun5 has a built-in RF probe to directly control the phase and amplitude of the RF field in the cavity. RF conditioning faces issues of stability and reliability. Aspects of pulsed heating and dark current should also be considered.

GUN5.1 SETUP AT PITZ

The RF gun cavity is a 1½-cell normal conducting copper cavity operating in a π-mode standing wave at 1.3 GHz. The Gun5 design includes several major improvements over the Gun4-generation, which are aimed at improving the performance of the gun. An elliptical shape of the internal geometry was applied in order to optimize the distribution of the peak electric field over the cavity surface [1]. Detailed studies to reduce the dark current resulted in an elliptical shape of the cathode hole at the back wall of the cavity [2]. In order to control the RF field in the cavity directly, an RF probe has been integrated in the front wall of the full cell. An optimized cavity cooling system and improved rigidity [1] should mitigate the challenges associated with the 1% duty cycle.

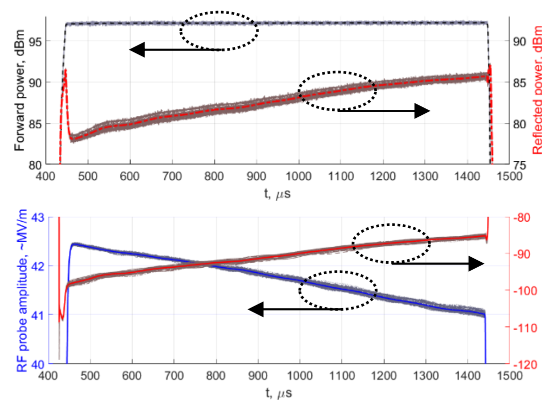

Figure 1: RF signals from 1 ms pulses. Top plot – directional coupler signals. Bottom plot: corresponding RF probe (pickup) signals.

The Gun5.1 RF feed setup was taken over from the waveguide distribution system of the previous generation of guns (Gun4.x) [3], including two waveguides (WG1,2) with two 5MW directional couplers (WG1,2 5 MW), followed by RF windows and a T-combiner in vacuum. The combined RF feed can be controlled by the 10 MW directional coupler (as was the case in recent Gun4.x generation setups) or by the newly installed RF pickup in the cavity. Typical RF signals for 1 ms RF pulses are shown in Fig. 1,

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where average pulse profiles are shown over the statistics of 50 subsequent shots (grey traces).

RF GUN CHARACTERIZATION

The standard PITZ procedure for the RF gun conditioning [3] was applied to Gun5.1. Conditioning started on 18th of October 2021 with a repetition rate of 1 Hz, after 10 days the repetition rate was increased to 5 Hz, and then after additional 21 days it was set to 10 Hz. The RF pulse length was increased from 10 µs to 100 µs / 1 ms for 5 Hz / 10 Hz with the peak power slowly ramped for each pulse duration.

Beam Momentum and Dark Current

For beam-based RF calibration, the photoelectron beam momentum was measured as a function of the RF gun launch phase for various levels of peak RF power. The cathode gradient was estimated from the field profile of the π-mode obtained from bead-pull measurements. The measured peak RF power scales as $P_{RF}[MW] \cong 0.00192 \cdot (1 \pm 0.037) \cdot (E_{cath}[MV/m])^2$. The results of the beam measurements are shown in Fig. 2 (left graph), where the calculated cathode gradient and corresponding phases of the maximum mean momentum gain (MMMG) are plotted versus measured maximum beam momentum together with simulated curves.

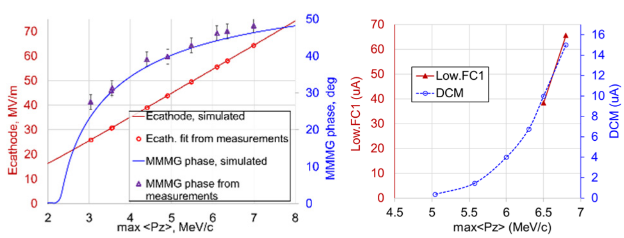

Figure 2: Gun gradient and the mean momentum gain (MMMG) phase (left plot) and the measured dark current (right plot) vs. maximum beam mean momentum.

The dark current measured by the first Faraday cup (LOW.FC1 at z=0.8 m from the cathode) and by the dark current monitor (DCM at z=2.1 m) is shown at the right plot of Fig. 2 as a function of the measured maximum beam momentum as the RF peak power varies. Comparison with the corresponding dark current measurements for Gun4.2 demonstrates a reduction of a factor 3 to 5.

Gun Resonance Temperature and Pulsed Heating

The gun cavity resonance is maintained by thorough water temperature control of the resonator body. The controlling temperature sensor is placed in the copper cavity body at the iris between the half and the full cell and is in between the cooling water and the inner cavity surface. Since the beginning of conditioning, an overall resonance temperature increase of ~5°C was observed. Most of the change occurred within the first 6 weeks, the resonance temperature stabilized 12 weeks after the start of conditioning. The dependences of the resonance temperature on the peak RF power and pulse duration are shown in Fig. 3. The slope of the resonance temperature was measured as ~0.5ºC/5 MW (left plot) at 200 µs RF pulse length, which corresponds to a change in heating by ~10 kW (average power). A resonance temperature growth of ~1.8ºC for ~7 MW peak RF power was observed by increasing the RF pulse length from 10 to 400 µs (right plot).

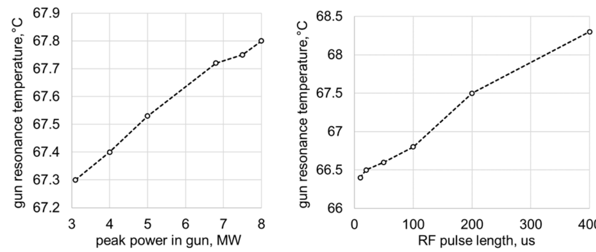

Figure 3: Gun resonance temperature versus peak power for 200 µs RF pulse length (left) and versus pulse length for 7 MW peak power in the gun (right).

Stability

To control the RF gun amplitude and phase, PITZ employs a µTCA-based low level RF (LLRF) system [4], which has large commonalities to those used at the European XFEL and FLASH. The control system allows lossless RF signals acquisition. The LLRF feedback has been tuned at PITZ for 1 ms pulse duration and 6.4 MW peak power in the gun. The results of stability monitoring of 500 subsequent shots are shown in Fig. 4, where the relative amplitude and absolute phase rms jitters along the pulse are plotted. Generally, the shot-to-shot rms jitter is ~0.02% for the amplitude and ~0.02 deg (~40 fs) for the phase.

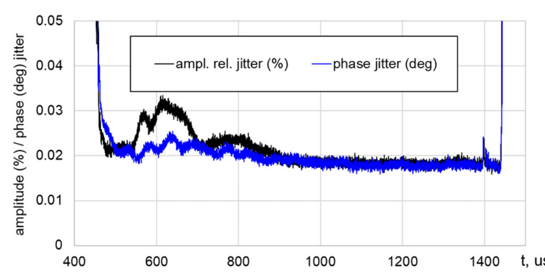

Figure 4: Relative amplitude and absolute phase rms jitters along the RF pulse.

The Gun5.1 cavity detuning due to pulsed heating was measured as 15.6 kHz for 1 ms RF pulse length at E_{cath}~60 MV/m and 11 kHz for 1 ms RF pulse length at E_{cath}~50 MV/m. The latter detuning per pulse length is 24% lower than the detuning measured for Gun4 at 450 µs pulse length.

To check the beam stability along the RF pulse, beam momentum has been measured for 1 ms pulses while scanning the photocathode laser timing position w.r.t. to RF gun pulse while maintaining the same launch phase (MMMG). The LLRF system at PITZ can use either the virtual probe (based on 10 MW directional coupler forward and reflected power signals) or the direct field measurements from the newly implemented RF pickup (real probe). The momentum distribution of electron bunches was

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measured in the first dispersive section, yielding mean momentum $\langle P_z \rangle$ and rms momentum spread. The results are plotted in Fig. 5 for both available options of the controlling sensor (virtual and real probe). The linear slope of the mean momentum profile $\frac{1}{\langle P_z \rangle_0}\left|\frac{d\langle P_z \rangle}{dt}\right|$ is a factor of 7 smaller for the real probe case compared to the virtual one (0.0016 $(\text{ms})^{-1}$ versus 0.011 $(\text{ms})^{-1}$, respectively). This is significantly better than the result obtained in 2021 for Gun4.1 with a virtual probe: 0.021 $(\text{ms})^{-1}$ within a 200 µs pulse.

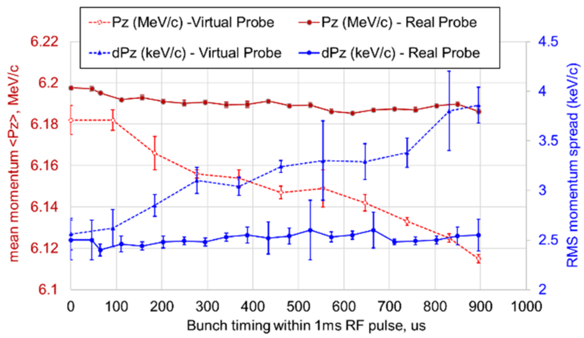

Figure 5: Beam mean momentum and rms momentum spread along the 1 ms RF pulse.

Mini-breakdown Events

Currently, the RF performance of Gun5.1 is limited by what are called as mini-breakdowns within RF pulses detected by the gun cavity pickup and by all directional couplers for reflected power signals. A typical mini-breakdown (mBD) is a short (~10…15 µs) interruption within the first part of an RF pulse (usually the first 30 µs of the flattop), then the amplitude is restored within the characteristic cavity filling time to the nominal amplitude (Fig. 6). The mini-breakdown rate (the ratio of number of "broken" pulses to the total pulse number) was measured to be ~0.05…0.2% at various RF pulse length and peak power levels. It starts to be detectable at an RF pulse length of ~350…400 µs and increases as the peak power increases. All mBD events are always accompanied by a small vacuum pressure spike (from ~$2 \cdot 10^{-9}$ mbar to 5…$8 \cdot 10^{-9}$ mbar), which is well below the vacuum interlock threshold. No correlation was found between mBD events and the static magnetic field configuration around the gun and the RF feed system. It is remarkable that the aforementioned location of a mBD within the RF pulse remains approximately the same for various pulse durations and peak power levels. The reason and nature of this distortion in the gun operation is still under investigation. Despite the rather low rate, mBD events could impact the efficiency of the LLRF feedback. This is a probable reason for irregular behaviour of the rms jitter in the first part of the RF pulse measured during 1 ms LLRF tests (Fig. 4).

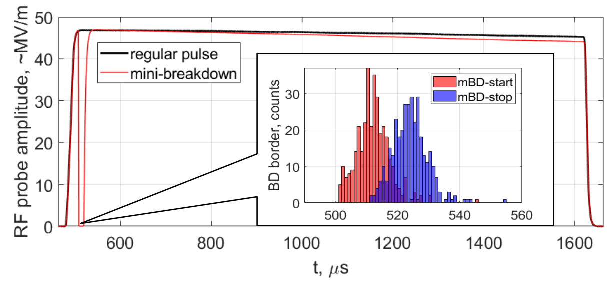

Figure 6: Typical mini-breakdown (mBD) event over regular RF probe 1 ms signal. Inset: 4.5-hour statistics of the mBD event start and end time locations within the RF pulse; the mBD rate over this period was 0.21%.

CONCLUSION

The first prototype of a new generation high-gradient normal conducting 1.3 GHz RF gun (Gun5.1), developed for 1 ms RF pulse operation at the European XFEL and FLASH, has been installed at PITZ for RF conditioning and characterization. The goal of high average RF power of up to 65 kW was achieved. The new cavity is equipped with an RF probe to measure and control the amplitude and phase of the RF field inside the gun cavity. The probe has been put into operation and employed for the LLRF regulation, yielding very good performance (pulse-to-pulse and along 1 ms RF pulse), exceeding that provided by the previously used virtual probe based on directional coupler signals. The measured detuning due to the pulse heating within the RF pulse was measured to be by ~24% lower than for the case of Gun4. The Gun5.1 peak power has been calibrated with electron beam longitudinal momentum measurements. The dark current from Gun5.1 was measured to be 3-5 times lower than the typical values of Gun4.2. A detailed investigation of the mini-breakdown events preventing Gun5.1 from its full performance is currently ongoing.

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