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) since more than 20 years develops, tests and characterizes high brightness electron sources for FLASH and European XFEL. Since these user facilities operate superconducting accelerators in pulsed mode, also the corresponding normal-conducting L-band RF gun 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 the goal parameter for the 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 0.650 ms, 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 CAVITY

The RF gun cavity is a 1½-cell normal conducting copper cavity operating in the π-mode standing wave at 1.3 GHz. The Gun5 design includes several major improvements over the Gun4-generation aiming to enhance the gun performance. The 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.

The cavity of the Gun5.1 prototype was tuned to the operation frequency and reasonable field balance of the π-mode electric field. The results of the bead-pull measurements after the last tuning step are shown in Fig. 1 together with eigenmode simulations for 0- and π-modes. Due to some technical issue a part of the π-mode measurement close to the cathode hole was corrupted, but simultaneous simulations of both modes are in a good agreement with both measurements. According to these results, the axial field distribution of the π-mode has a field balance $|E_{cath}/E_{fullcell}| \approx 1.097$.
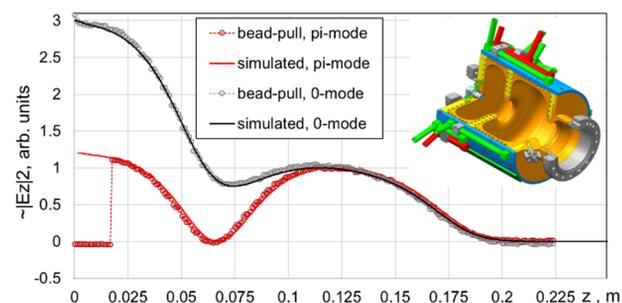

Figure 1: Results of the bead-pull measurements for 0- and π-modes after the last tuning step. The corresponding Superfish simulations are shown with solid curves. Inlet: 3D model of the Gun5.1.

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RF FEED AND INTERLOCK SYSTEM

The Gun5.1 RF feeding setup inherited the waveguide distribution system of the previous generation of guns (Gun4.x), including two RF windows and a T-combiner in vacuum. (Fig. 2).
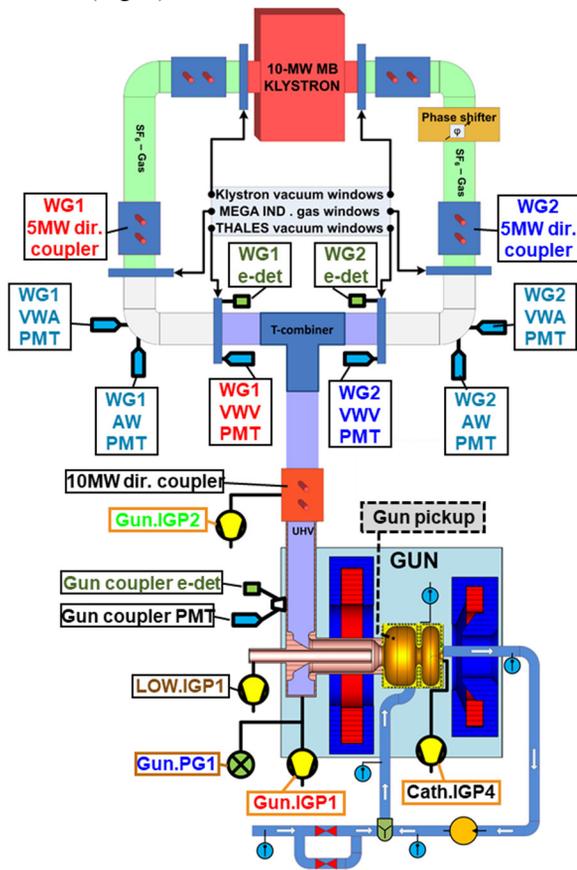

Figure 2: PITZ RF feed system for the Gun5.1 prototype.

The RF feed can be driven by the 10 MW directional coupler (as it was in the recent Gun4.x generation setups) or by a newly installed RF pickup in the cavity. Before installation at the PITZ setup two Thales vacuum RF windows were pre-conditioned at DESY in Hamburg. A short section with air under 3 bar pressure is realized between the SF6 gas and the vacuum section, to have an easy exchange between two different setups and to be as close as possible to the XFEL and FLASH setups where there is no SF6 but air waveguides. This section is also an additional safety, acting as a buffer in case of a leak in the gas vacuum windows, preventing any SF6 to reach the vacuum system. An ultra-high vacuum is provided by a differential pumping using Titanium sublimation (TSP) and ion-getter pumps (IGP), signals of ion current from the Gun.IGP1,2 (Fig. 2) are included into the interlock system with threshold of 10^{-7} mbar. The pressure gauge (Gun.PG1) is integrated for absolute vacuum pressure measurements. Each of two waveguides (WG1,2) is supplied with a set of photomultiplier tubes (PMTs) to control an RF discharge around RF vacuum and gas (air) windows. For example, WG1.VWV detects the light signal at the vacuum window of the first waveguide from the vacuum side, while WG1.VWA and WG1.AW are located in the air section and look towards the vacuum and gas window respectively. In addition, a PMT (Gun coupler PMT) is installed after the T-combiner, capturing the light signal around the 10 MW directional coupler. All in-vacuum PMTs are paired with electron detectors (e-det) to collect discharge electrons. All these sensors are included into the interlock (IL) system aiming to protect the system from sever breakdown events. Furthermore, a fast protection system based on RF reflected power pulse signals (from 10 MW and WG1, 2 5 MW directional couplers) is capable to stop the RF feed forward within a single pulse. These ILs (maximum reflected power ILs) are triggered when the reflected power threshold of ~2 MW is exceeded within a 40-µs strobe centered at the ~65th µs of each RF pulse. Details on typical RF signals from the directional couplers and RF probe as well as the beam-based calibration of the RF power in the cavity can be found in [3].

RF CONDITIONING

The standard PITZ procedure for the RF gun conditioning [4] was applied to the Gun5.1. Conditioning started on 18th of October 2021 with 1 Hz repetition rate, after 11 days the repetition rate was increased to 5 Hz, and then after 21 days the goal 10 Hz was achieved. The RF pulse length was increased from 10 µs to 1 ms for each repetition rate applying peak power slow increase for each pulse length. The conditioning history is presented in Fig. 3. The RF conditioning in the first month was performed without static magnetic field, afterwards a sweeping of the gun solenoids was applied. The history of the main solenoid current is shown in Fig. 3 together with the vacuum pressure. In the first stage of conditioning, progress was limited by vacuum trips and PMT interlocks, the second stage was dominated mainly by ILs with maximum reflected power for longer RF pulses (>400 µs). Typical signals from selected in-vacuum IL sensors are illustrated by Fig. 4. The sensors WG1 VWV PMT and WG1 e-detector showed persistent signals for the peak power in the gun exceeding 2 MW, the sensitivity for the PMT sensor was adjusted in order not produce continuous interlock. The opposite RF window IL sensors (WG2 VWV PMT and WG2 e-det) were rarely detecting a non-zero signals for much higher (~6 MW) gun power levels and were unstably persistent for short periods (tens of minutes), which was always accompanied by increased (but still under the vacuum IL threshold) vacuum level. The Gun coupler IL sensors (Fig. 2) were detecting significantly lower signals: PMT≤0.05 lux and electron-detector ≤ 0.01 mA.
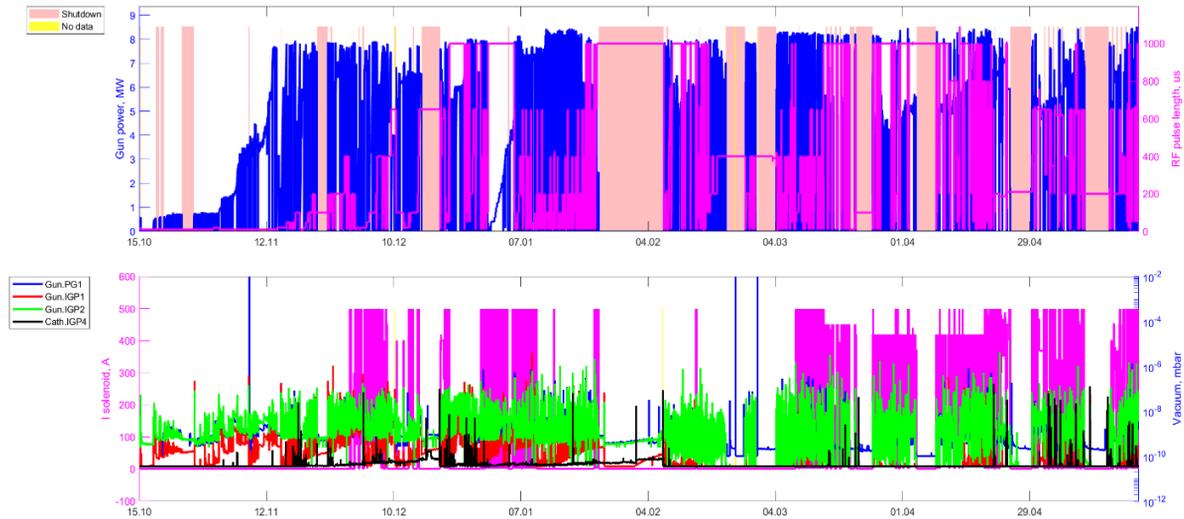
Figure 3: Top: RF peak power in the gun (blue line) and RF pulse length (pink line) during conditioning. Bottom: Current of the main solenoid (pink curve, left axis) and vacuum pressure measured by different sensors (right axis).
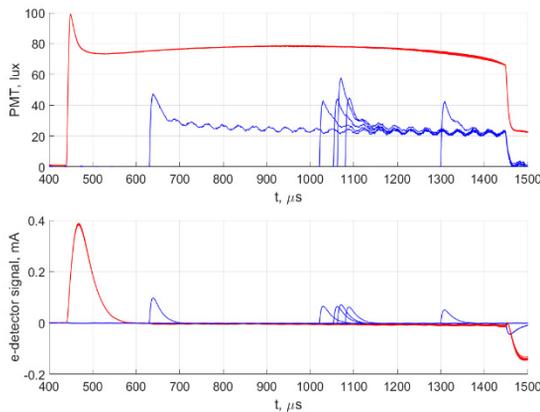

Figure 4: IL signals from 1 ms pulses. Top plot – WG1 VWV PMT (red), WG2 VWV PMT (blue). Bottom plot – electron detector signals: WG1 (red), WG2 (blue).

Mini-breakdown Events

After more than 200 days of conditioning, the Gun5.1's RF performance is limited by so-called mini-breakdowns within RF pulses detected by the gun's 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), after which the amplitude is reset to the nominal amplitude within the characteristic cavity filling time [3]. The mini-breakdown rate (the ratio of the number of "broken" pulses to the total pulse count, BDR) was measured to be ~0.05...0.2% at various RF pulse lengths and peak power levels (Fig. 5). It starts to be detectable at an RF pulse length of ~350...400 µs and increases with increasing peak power. All mBD events are always accompanied by a small vacuum pressure spike (from ~$2\cdot10^{-9}$ mbar to $5...8\cdot10^{-9}$ 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 dependence on repetition rate was measured for the peak power of ~7.8 MW at 800-µs pulses. Two sets of measurements - 1 Hz and 10 Hz - are also shown in Fig. 5.
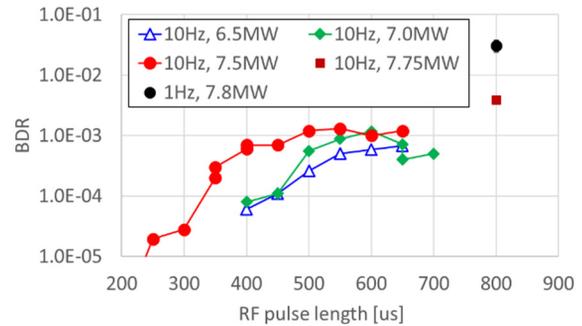

Figure 5: The mini-breakdown rate as a function of the RF pulse length for various peak power in the gun and two repetition rates.

CONCLUSION

RF conditioning of 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 performed at PITZ. The goal of a high average RF power up to 65 kW was achieved. Currently the gun performance is limited by occasional, short RF pulse interruptions within first 30 µs of the pulse, called mini-breakdown events. The breakdown rate was measured as a function of pulse length, peak power in the cavity, and pulse repetition rate. The reason of these events is still unclear and to be investigated in detail.

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