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EUROPEAN FEL Design Study

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Abstract

Two new L-band guns have been conditioned and characterized at the Photo Injector Test facility in Zeuthen (PITZ) in the last two years. These guns were of a similar design, the third prototype gun design put into operation at PITZ, for this reason they have been designated gun 3.1 and 3.2. Gun 3.1 was prepared as a spare gun for the Free-electron Laser in Hamburg (FLASH), therefore it was conditioned up to the full FLASH specifications: 3.5 MW peak power, 900 µs RF pulse length, and 10 Hz RF pulse frequency [1]. The second gun was conditioned up to about 6.5 MW peak power with 100 µs RF pulses at 10 Hz. Higher gun power, and therefore higher electric fields at the cathode surface, is required to meet the goals for the planned European X-ray Free Electron Laser (XFEL) project. The characterization of the two new guns has been performed, including electron beam emittance measurements. The detailed results represent encouraging progress toward the emittance goal for the XFEL, as will be discussed.

Introduction

Operation of a short wavelength free electron laser in the self-amplified spontaneous emission regime requires a high-quality electron beam. In this context, high quality refers to a high density of particles in the 6 dimensional phase space of the beam, that is, high electron current in short pulses with low energy spread and low transverse emittance. The goal of the PITZ facility is to test and optimize electron sources capable of providing such beams. The two gun cavities described in this report were designed as beam sources suitable for the TESLA Test Facility VUV free electron laser, now FLASH.

Both RF guns consist of a 1.5-cell copper standing wave cavity operated on the π-mode at 1.3 GHz. The cathode handling system allows the insertion of molybdenum plugs for gun conditioning, and cesium telluride coated cathodes for injection of photoelectrons. The gun cavity is surrounded by the main and bucking solenoids for beam focusing and for compensating space-charge-induced growth of the projected emittance. The design requirements included operation at peak power of 4.5 MW and average heat load of 50 kW, corresponding to a maximum peak electric field of 50 MV/m at the cathode surface [2]. Before 2007, these guns were only operated (at PITZ and FLASH) up to 3.5 MW and 42-45 MV/m cathode surface field. An electric field at the cathode of 60 MV/m is required for the XFEL [3], so the second of these guns was tested at a higher gun power, and future PITZ guns are being designed and built to handle this extra head load. More details on the PITZ facility and its future can be found in [4] and [5].

Gun Tuning and Conditioning

The tuning and conditioning of gun 3.1 has been described in [1]. This gun was built in 2003 with corrected dimensions to better match the resonance frequency to the chosen RF frequency, thus limiting the required tuning. The gun was also built with special tuning knobs, but it was discovered after the first measurements in 2004 that the range offered by these knobs was not sufficient to correct the resonance frequency of the gun. For this reason, new tuning tools were developed, a specialized tuning stamp for pushing on the cathode wall at the plane of the cathode, and a tuning clamp for adjusting the position of the wall in the full cell facing the coupler. Colleagues at BESSY built a small tapered coupler for frequency measurements, and a bead pull setup was mounted at DESY for field profile and frequency measurements.

By adjusting the cavity walls in 10-μm steps using these tools, the proper resonance frequency was achieved at an operating temperature of 54 ºC. The field balance was measured to be 1.06, meaning the electric field at the cathode is 6% higher than in the full cell. This field balance was determined to be a proper balance between the requirements on average accelerating gradient and high field at the cathode surface. The mode separation between the 0-mode and the π-mode was measured to be 5.0 MHz.

In previous gun tests in autumn 2005, peak powers of 6.8 MW in short RF pulses (up to 100 μs) were achieved, but vacuum problems in the gun appeared when the pulse length was increased. The conditioning of gun 3.1 (pictured in Figure 1) was then performed only up to the operating requirements of FLASH, in order to lower the risk of such damage to this needed spare cavity for that facility. The FLASH requirements, 3.5 MW peak power with 900-μs RF pulses at 10 Hz, correspond to an average power in the gun of 31.6 kW, the highest reached at PITZ at that time [4]. The forward and reflected power during a single RF pulse is shown in Figure 2, where the change in reflected power during the pulse shows that the cavity is operated in resonance.

Figure 1. Gun 3.1.

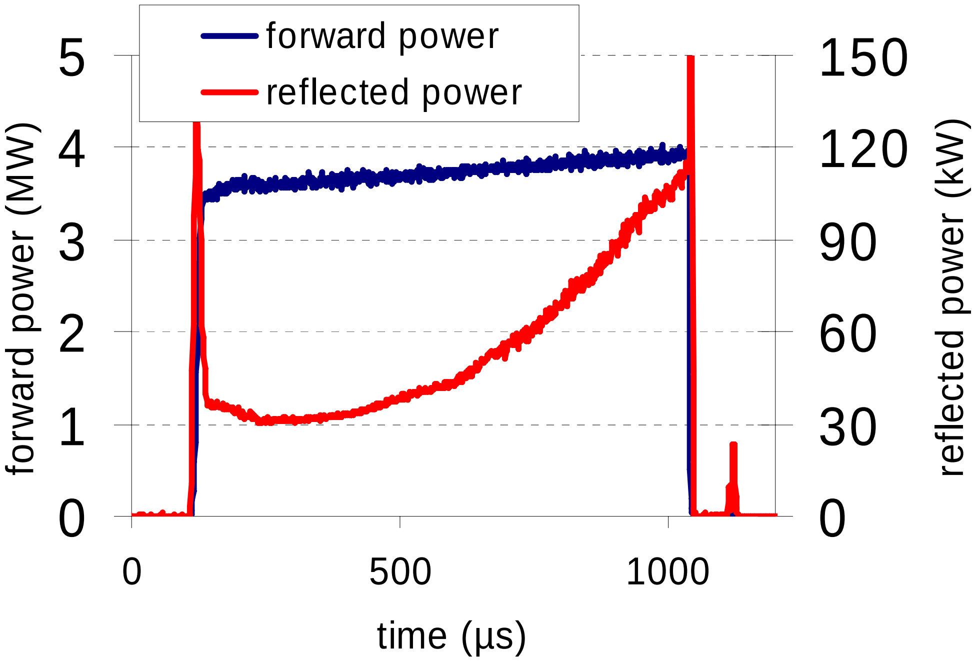

Figure 2. Forward and reflected power in gun 3.1 at resonance.

Gun 3.2 was tuned following the same procedure as gun 3.1, with the tuning tools already developed. The operating temperature during tuning was 64 ºC. The field balance was measured to be 1.03, and the mode spacing between the 0- and π-mode was again 5.0 MHz.

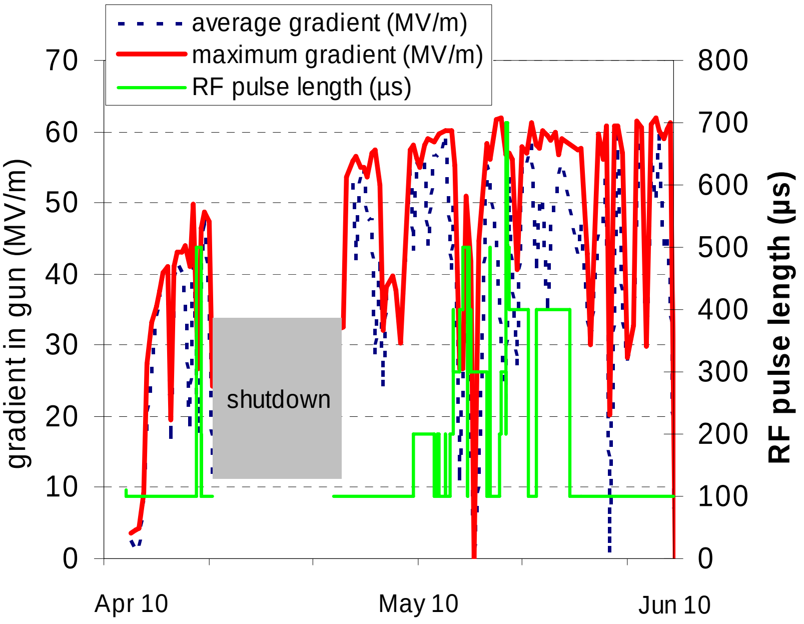

Figure 3. Conditioning results from gun 3.2.

The conditioning history of gun 3.2 in the summer of 2007 is shown in Figure 3. The red and blue dotted lines show the maximum gradient and the average during 1-hour measurement windows. The green line shows the RF pulse length. The gun was conditioned rapidly up to ~45 MV/m, at which point the facility was shut down to make necessary changes in the RF phase shifter [6]. Progress from 45 MV/m to the final gun gradient of 60 MV/m was much slower. As can also be seen in the figure, gun 3.2 was conditioned for only short periods with RF pulse lengths longer than 100 µs. During the gun characterization, the gun was operated using RF pulses of 140 µs.

Dark Current Studies

Dark current, electrons emitted when there is high field in the gun cavity but no laser light on the cathode, limits the maximum usable gradient in RF photoinjectors. The extra current interferes with beam measurements, and the radiation produced by dark current striking the walls of the vacuum chamber leads to failures in diagnostics and controls in the accelerator tunnel. Extensive dark current studies have been undertaken with both of the new PITZ RF guns to measure the level of dark current for different cathodes, different field gradients and magnetic focusing conditions, and also to examine the spatial and momentum distribution of the dark current.

The maximum total dark current measured from gun 3.1 was up to ~350 µA for the operating gradient of 43 MV/m at the cathode. The collected dark current varies with the magnetic focusing conditions, which change the effective aperture of the beam pipe. This variation is shown in Figure 4 [1]. The momentum distribution of the dark current has also been measured using a dispersive arm and screen [4].

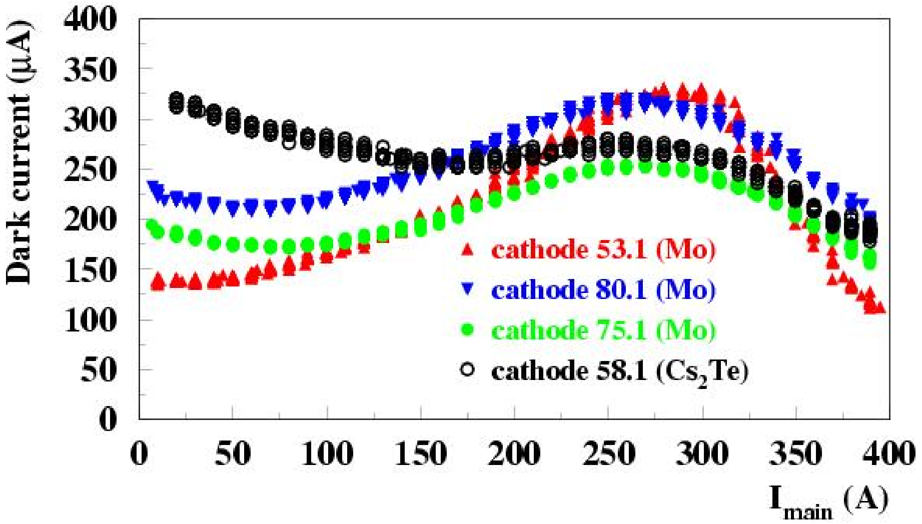

Figure 4. Variation of collected dark current from gun 3.1 with main solenoid current (operating gradient of 43 MV/m).

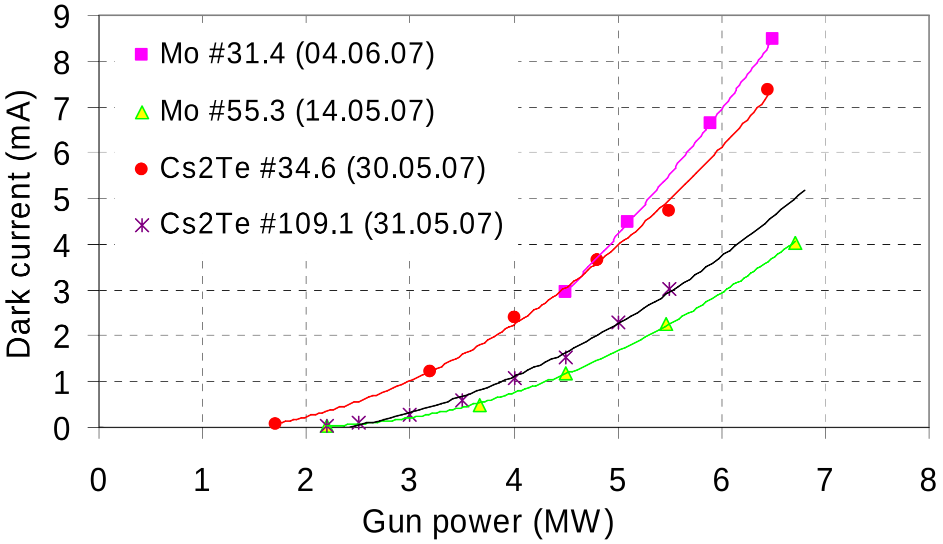

Figure 5. Dark current measurements with gun 3.2 (each point represents the maximum current from the solenoid scan).

Dark current studies were also performed with gun 3.2. With this gun the variation in dark current between different cathodes was greater than with gun 3.1, even at 3.5 MW, and the total dark current was initially found to be significantly higher, as shown in Figure 5. The figure shows the maximum collected dark current during solenoid scans at different gun power levels. The dark current increases rapidly with electric field on the cathode, approximately according to the Fowler-Nordheim law for field emission. With continued conditioning, the level of collected dark current decreases, except when cathodes become damaged. The dark current for a gradient of 60 MV/m was up to 6 mA. This level of dark current is a serious problem, as the radiation levels in the beam tunnel led to a large failure rate of cameras and other diagnostics. The high level of dark current is possibly due to a fabrication error in the gun cavity near the cathode which was thought to have been successfully repaired. This error and repair during the fabrication happened only for gun 3.2, but dark current studies on future guns will be necessary to show that this problem was the source of the anomalously high dark current measured. Also, an electropolished molybdenum plug used for dark current measurements showed promising results, with dark current significantly reduced. Future cathodes will be produced using this electropolishing procedure.

Emittance measurements

After the conditioning was completed, measurements of transverse emittance for electron beams generated using both gun 3.1 and gun 3.2 were performed [7]. These measurements use the PITZ facility's three emittance measuring stations (EMSYs), which measure the projected transverse emittance of the electron beam using the single slit scan technique [8]. The slit scan process has now been mostly automated, greatly increasing the measurement throughput.

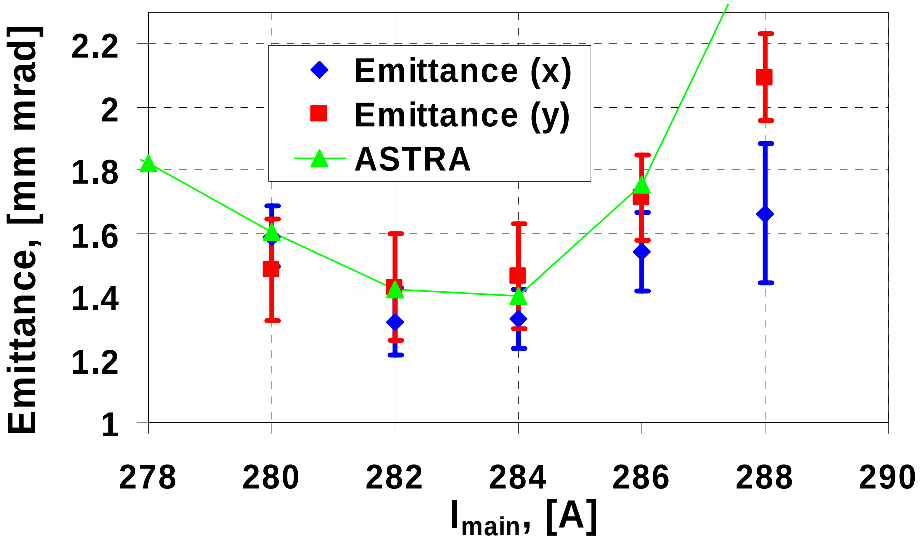

Figure 6. Emittance results from gun 3.1.

A number of parameters can be varied for emittance optimization, including the laser spot size on the cathode, the cathode electric field, the RF phase at emission, and the current in the main focusing solenoid. Additionally, the PITZ facility operates with a booster cavity, and the RF phase is varied relative to the gun RF phase. All measurements are taken with 1 nC bunch charge.

A solenoid scan showing the best results for emittance from gun 3.1 is shown in Figure 6. These measurements were taken at the first EMSY station, located 4.3 m downstream from the gun. The calculated electric field at the cathode during these measurements was 43 MV/m. The lowest measured emittance was 1.43 ± 0.17 π-mm-rad in the y-plane, and 1.32 ± 0.11 π-mm-rad in the x-plane. As the figure shows, this minimum emittance is essentially in agreement with predictions from the space-charge tracking simulation ASTRA [9].

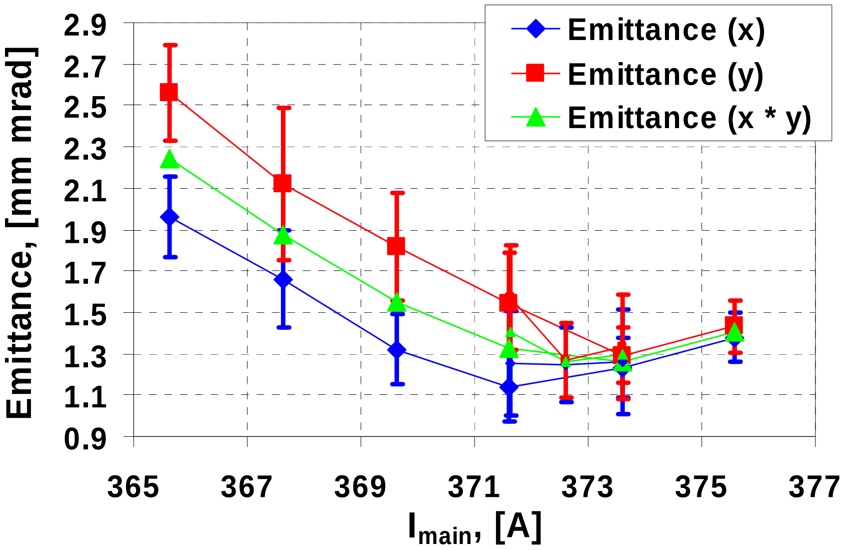

Figure 7. Emittance results from gun 3.2.

The best emittance results from the 2007 running period using gun 3.2 are shown in Figure 7. These data were taken with 60 MV/m surface electric field on the cathode. The lowest measured emittance was 1.27 ± 0.18 π-mm-rad in the *y*-plane, and 1.25 ± 0.19 π-mm-rad in the *x*-plane.

The standard slit scan at PITZ involves sampling the beam with the slit at 11 different positions along the projected beam distribution, but for the optimized operating point a detailed scan with 40 beamlets was taken. On the resulting detailed phase space reconstruction, a purposeful cut was placed on data points below 5% of the peak phase space density. This cut removes only 6.5% of the charge but reduces the emittance of the beam by 37% (the emittance reduction of 37% is confirmed by ASTRA simulation). If this cut is applied to the optimized operating point from the gun 3.2 data, the resulting emittance is ~0.8 π-mm-rad. This analysis illustrates the significance of the tails of the phase space distribution to the rms emittance, and is an encouraging step toward the beam quality goals for the European XFEL.

The next generation of L-band guns for PITZ have already been designed and constructed. These guns are designed for higher average power operation and the water cooling of the guns has been significantly improved. Conditioning of the first of two such guns will begin at PITZ in December 2007.

References

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