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UPDATES OF THE ARGONNE CATHODE TEST-STAND

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Abstract

The Argonne Cathode Test-stand (ACT) is a unique testbed to develop cathodes and to conduct fundamental surface study under ultra-high rf field (up to 700 MV/m with pin-shaped cathodes). The test-stand consists of an L-band 1.3 GHz single-cell photocathode rf gun and a field emission (FE) imaging system to locate emitters with a resolution of ~20 µm. In the recent upgrade, UV laser has been introduced to improve the imaging system and to significantly expand the ACT towards photoemission and laser-assisted field emission research. In addition, a load-lock system has been added to the beam line to expedite the cathode switching period. The paper will present details of the upgrade as well as experiments planned in the near future.

INTRODUCTION

Owing to its potential to deliver low transverse emittance and high current beam without an auxiliary laser or heating system, field emission electron source is a good candidate for rf gun based facilities such as free electron lasers, ultrafast electron diffraction/microscopes, and Compton scattering sources [1–3]. Recently, various advanced FE cathodes have been characterized in rf gun environment, including the diamond FE array (DFEA) [1], the planar ultrananocrystalline diamond (UNCD) [2,4], and the carbon nanotube (CNT) [3]. The common method to derive the field enhancement factor β, one decisive parameter of FE current, is to fit the emission current and the applied electric field according to the Fowler-Nordheim (F-N) equation with the assumption that FE current uniformly emits from the whole cathode. As pointed out by a recent dc study, however, the emitters could be well separated so the previous method may cause remarkable error in β and current density estimation [5]. What's more, the uniformity itself is also an essential requirement for high brightness electron sources. Therefore, in-situ high resolution observation of emitters is important for the FE cathode development.

On the other hand, field emission in accelerating structures is unfavored as it may trigger rf breakdown, which is one of the major limitations when attempting to achieve high gradient during stable operation [6]. Despite intense investigation with theories, simulations, and experiments, the nature of rf breakdown has not been fully revealed yet. There is an urgent need to locate FE emitters in-situ in order to understand the physics connection between field emission and rf breakdown.

The ACT at the Argonne Wakefield Accelerator (AWA) facility is a flexible, well-instrumented testbed for cathode R&D as well as for the fundamental study of field emission and rf breakdown [2,7,8]. The unique FE imaging system of ACT consists of solenoids and collimators for selecting FE electrons with certain energy and emitting phase in order to obtain in-situ emitter images with high resolution. In a previous experiment, a resolution of ~100 µm has been successfully demonstrated and separated emitters on a copper cathode have been identified [8].

RECENT UPGRADE OF ACT

FE electrons in rf structures can emit during half of the rf period when the applied electric field is positive, which then leads to a wide energy spread and a large beam size . In order to obtain a high resolution FE image, the ACT places a collimator with a small aperture after the solenoids which only allows electrons with the proper focusing position and emitting phase to pass through [8], as illustrated in Fig. 1.

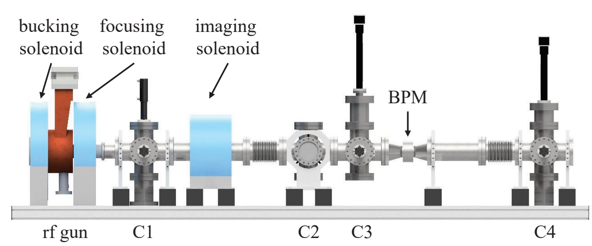

Figure 1: Layout of the upgraded ACT (the cathode load-lock system is not shown). C1: Faraday cup and YAG station; C2: In-vacuum laser mirrors; C3: Collimators, slits, and YAG station; C4: Faraday cup, USAF target, and YAG station.

With a ~2.1 MW input power for the single-cell rf gun, the electric field on the flat cathode designed for imaging experiments can reach ~110 MV/m. By adjusting the solenoids, electrons emitting from a certain phase can be selected by the collimator and the imaging properties by ASTRA simulation are illustrated in Fig. 2. When the selected phase is 90^o, the magnification is 10 and the radial resolution is ~20 µm.

The imaging properties depend on the selected phase which was indirectly obtained by dynamics simulation before the upgrade. After introducing UV laser (wavelength:

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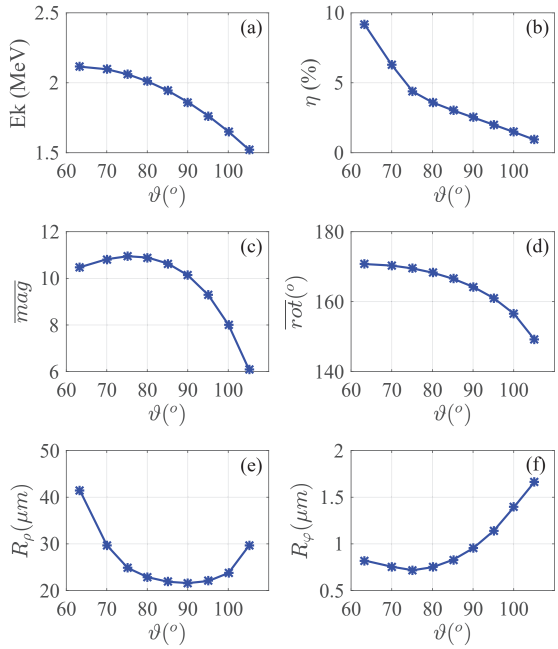

Figure 2: Imaging properties of the ACT for an zero-size emitter with 0.5 mm off-axis as a function of the selected emitting phase. The aperture size of the collimator is ϕ200 μm. (a) The average beam kinetic energy; (b) The transmission through the aperture; (c) The average magnification; (d) The average rotation; (e) The radial resolution; (f) The angular resolution.

248 nm; pulse length: 1.5 ps FWHM; maximum energy: ~10 mJ) to the test-stand, the selected phase can be directly determined as following. When the laser is on, the emitting phase of the photoelectrons is narrow and well controlled. The solenoids are adjusted to transmit the photoemission current through the collimator. When the laser is off, the same solenoid strength would also be proper to select FE electrons emitting from the same phase, eventually forming a high resolution FE imaging.

The new-introduced laser will expand the ACT capability to characterize photoemission and laser-assisted field emission. Slits to measure emittance and a beam position monitor to measure fast photocurrent signal have been added to the test-stand.

The detachable cathode of the rf gun makes ACT a flexible testbed for cathode study. When switching the cathode, however, the whole beam line had to be vented and pumped, which was time-consuming. In the upgrade, a cathode load-lock system comprising two gate valves, a transportation chamber, an intermediate chamber, and pump stations, has been attached to the rf gun to expedite the cathode switching time from 1-2 weeks to 1-2 days. The load-lock system would also enable vacuum-sensitive cathodes, such as semiconductor ones, to be tested at ACT.

PLANNED EXPERIMENTS

With the upgraded ACT, several experiments have been planned to be conducted soon.

Field Emission Evolution During RF Conditioning

rf conditioning in which the input power is gradually raised before reaching the designed value is a necessary procedure for a new-built accelerating structure. A recent statistical study in CERN suggests that during this period, the surface condition is being continuously modified by every rf pulse [9]. Understanding the nature of rf conditioning is critical for high gradient accelerating structure development in terms of shortening the condition period and achieving higher gradient. Since the FE current strongly depends on the surface condition, it could be a valuable indicator during rf conditioning.

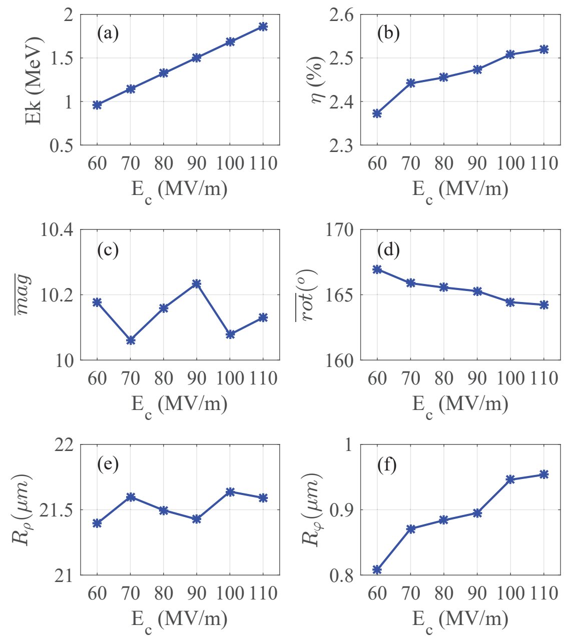

Figure 3: Imaging properties of the ACT for an zero-size emitter with 0.5 mm off-axis as a function of the cathode electric field. The selected phase is set to 90^o. The aperture size of the collimator is ϕ200 μm. (a) The average beam kinetic energy; (b) The transmission through the aperture; (c) The average magnification; (d) The average rotation; (e) The radial resolution; (f) The angular resolution.

Previous experimental research with rf structures in general could only measure FE current from a large surface or from the full structure. Since field emission is a localized phenomenon, such measurements could lead to inaccurate conclusions. ACT is a powerful tool to study the FE evolution during rf conditioning as emitters can be individually located with high resolution. Under various cathode electric field E_c, the solenoids can be adjusted to obtain almost the same transmission, as illustrated in Fig. 3(b). Therefore, the field enhancement factor can be derived by fitting the brightness of an emitter and the applied field according to

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the F-N equation. The imaging properties except the beam energy remains nearly unchanged, as illustrated in Fig. 3.

The copper cathode to be used in this experiment has a ϕ5 mm flat-top and a large rounding to suppress FE from the edge, as illustrated in Fig. 4(a). Five ~100 µm tall, ~ ϕ70 µm cylinder pins in ϕ400 µm wells have been created on the flat-top by fs-laser ablation as reference positions for imaging, as illustrated in Fig. 4(b-d). The geometry field enhancement of the pins is ~3 and the field could be even higher given the rough surface finishing of the tip.

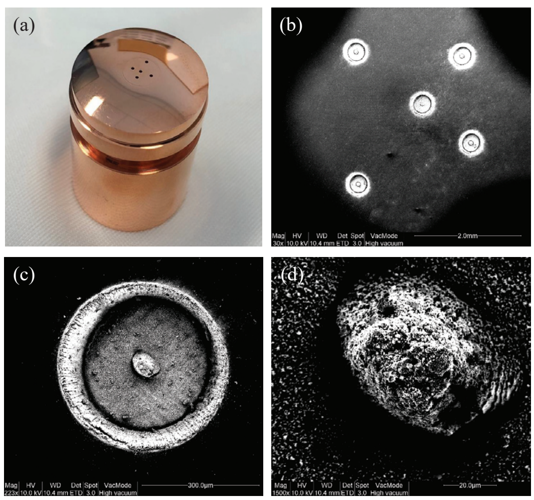

Figure 4: The flat cathode for FE evolution observation. (a) Cathode after single diamond turning at Tsinghua University and fs-laser ablation at Euclid Techlabs LLC; (b-d) SEM images of the pins in wells as the pre-defined emitters.

UNCD Cathode Characterization

The thin film UNCD is a material with high electron conductivity. No tips are needed in thin film UNCD because FE current is considered to emit from the high density grain boundaries [2, 4]. The synthesis is scalable while growth can be done on various metal substrates. Thus, the thin film UNCD is a promising candidate for FE cathode.

Up to date, UNCD cathodes have only been studied under low and moderate rf electric fields (20-70 MV/m) at 1-10 GHz in normal conducting rf electron guns [2,4], under low dc electric fields (1-20 MV/m) [5], and under low electric field (1 MV/m) at cryogenic temperatures of 2-4 K at 1 GHz in a superconducting rf gun. With the upgraded ACT, test of the thin film UNCD cathode with rf electric field up to 110 MV/m has been planned in order to fully characterize its performance with unprecedented details such as uniformity, current density, resistance to high field, and lifetime.

Laser Pulse Heating Effect

The blowout regime is a promising operation mode for generating high-brightness electron bunches because a uniformly filled ellipsoid distribution can be produced with longitudinal space charge expansion and there is no nonlinear space charge force inside the bunch. For low quantum efficiency cathodes like copper, producing high charge (>100 pC) electron bunches at the blowout regime requires laser beam with high fluence and short pulse length. Such a laser pulse with high energy density will pump the cathode to a nonequilibrium state, in which the electrons reach an equilibrium state with very high electron temperature (thousands of Kelvin), while the lattice temperature remains low (close to room temperature) [10, 11]. The thermal emittance and QE will increase under this laser pulse heating effect.

The improvement of QE due to the laser pulse heating effect is to be experimentally verified at ACT. With a UV laser pulse length of 1.5 ps FWHM and a cathode electric field of 200 MV/m, a 20% QE growth is expected to be observed from a 20 mJ/cm^2 laser fluence, as illustrated in Fig. 5.

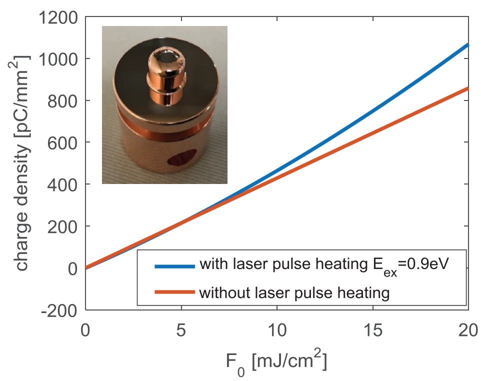

Figure 5: The simulated charge density of the electron bunch as a function of the laser fluence. Inset: A new-designed cathode with a 6 mm tall, ϕ6.6 mm cylinder on the top to achieve 200 MV/m E_c with 2 MW input power.

CONCLUSION

The Argonne Cathode Test-stand has been recently upgraded to improve its unique in-situ high resolution FE imaging system and to expand its capability for cathode development. Various experiments will be conducted soon, including FE during rf conditioning, benchmarking the thin film UNCD FE cathode, and study of the laser pulse heating effect. A single-cell deflecting cavity is under investigation to be attached to the beam line for photocathode response time measurements.

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