Flat Field Emitter Based on Ultrananocrystalline Diamond (UNCD) Film for SRF Technology*

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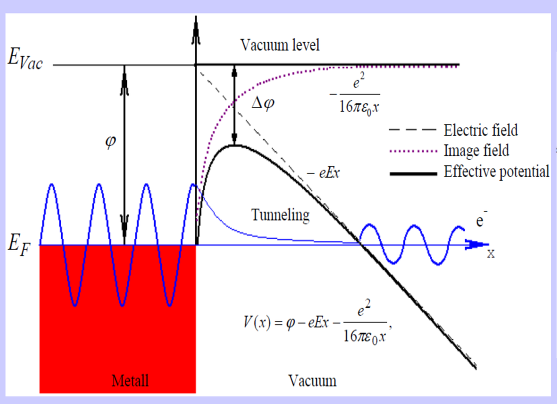
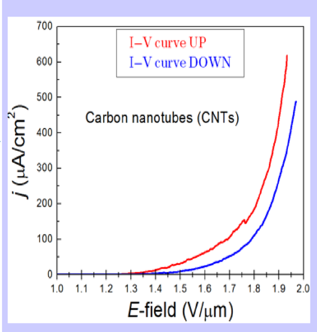
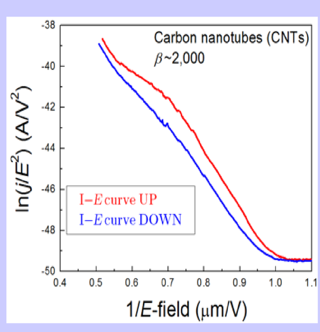
ABSTRACT

Euclid TechLabs LLC, in collaboration with BNL, present our recent results to complement and simplify SRF injectors by creating a simple, robust and scalable field emission cathode fabrication technology. To achieve this goal, our material of choice is ultrananocrystalline diamond (UNCD). UNCD has been proven to be a highly emissive material being stable under heavy electrical and heat loads. Thus, it is suitable for high rep-rate/CW applications. A case performance study of a planar nitrogen-incorporated UNCD, (N)UNCD, FEC was carried out in a 1.3 GHz RF electron gun. Electron emission from the (N)UNCD planar surface with excellent emittance, energy spread, and stability was confirmed. A peak current of ~100 mA was achieved. At high rep-rate/CW operation, this current serves as an average current estimate for SRF applications.

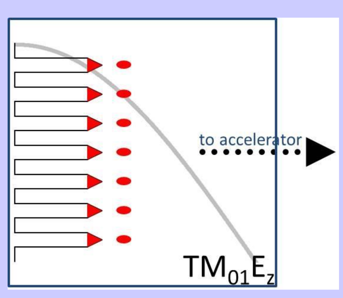
Field Emission: Basics and Accelerator Application







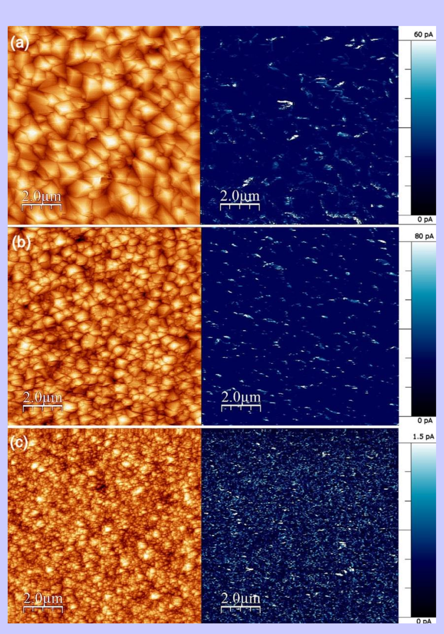
$$j_{FN}(E) = \frac{A(bE)^2}{f} \exp\left(-\frac{Bf^{3/2}}{bE}\right)$$



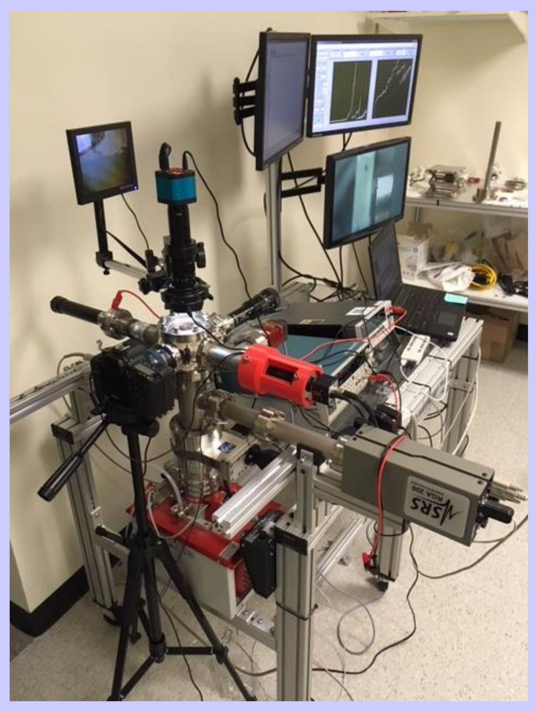
Field emission is described by Fowler-Nordheim theory; CNTs exhibit field enhancement factors β >1000. Typical behavior is a more stable IV curve ramping down vs ramping up, but with higher turn-on field after processing.

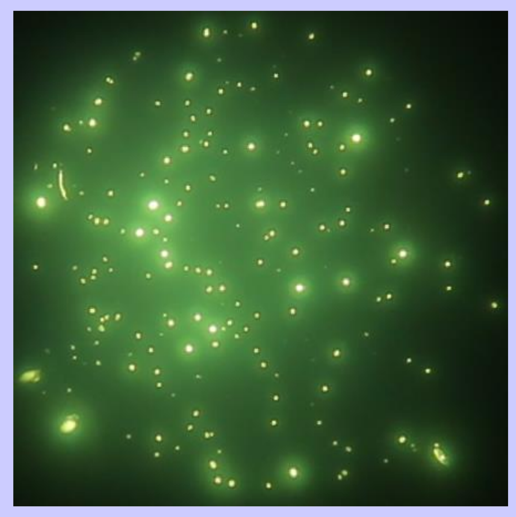
DC Field Emission: Grain Boundaries (GB) = Key

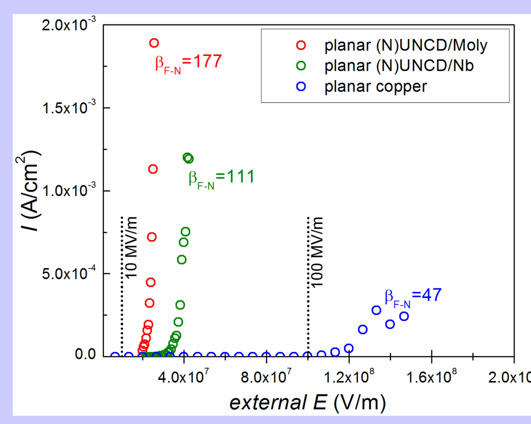
- Electrons preferentially emitted from GBs in (N)UNCD;
- The larger GB area, the higher current the field emitter may yield;
- (N)UNCD can have 10^{13} emitting GBs/cm² (compare to Spindt source with 10^8 emitting tips/cm².

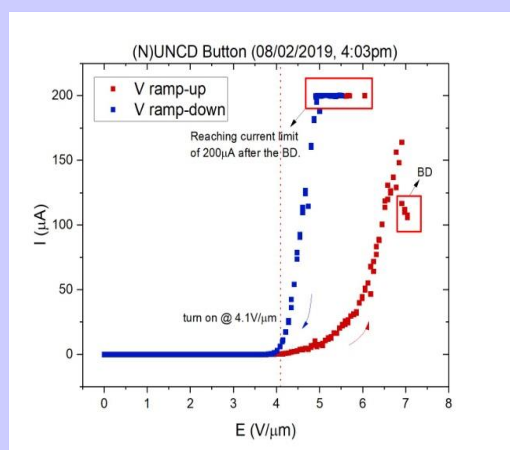


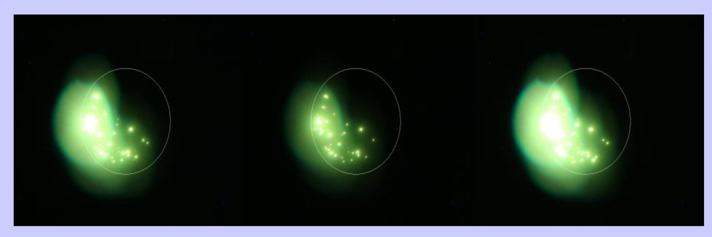
1.1 kV DC Field Emission (FE) Test Stand.







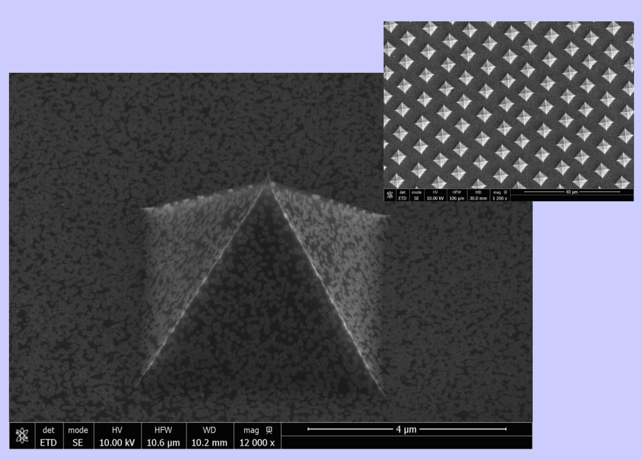


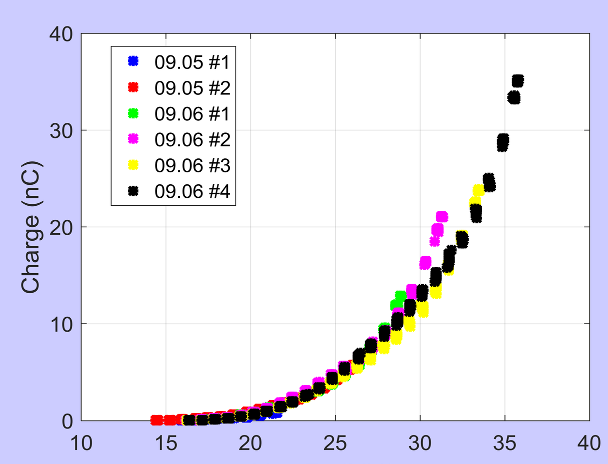


29.7 μA @ 5.5 V/μm 60.3 μA @ 5.9 V/μm 100 μA @ 6.1 V/μm

The (N)UNCD/Mo/SS field emitter (diameter of 3.8 mm) has been tested at the 1.1 kV DC field emission (FE) test stand. Four IV scans have been performed on the (N)UNCD button. The measured FE currents reached the current limit of the ammeter (Keithely 2410), **and the measured maximum current was found to be ~200 μA, or nearly 2 mA/cm² on average.**

AWA Tests: Diamond Array FE Cathode at 1.3 GHz RF Gun



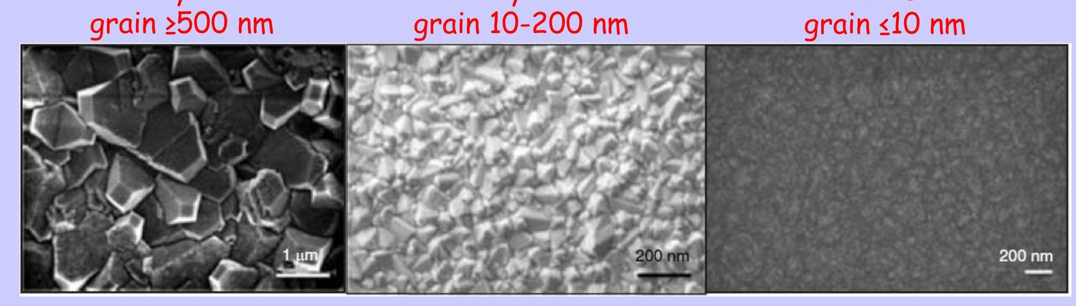


LANL provided a pyramidal NCD array on Mo. I-V curves were developed while conditioning the cathode to 36 MV/m, the highest achieve gradient. Breakdowns above this level reduced FE significantly.

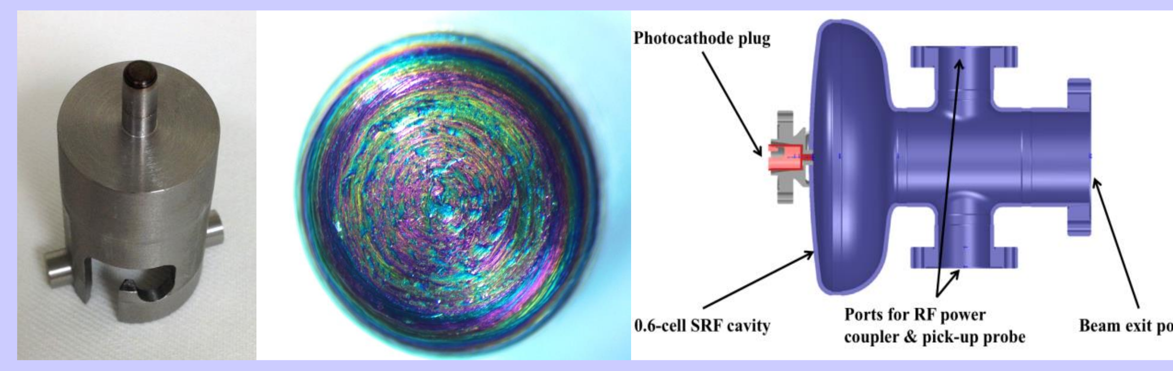
Max charge: **35 nC**
Max current: **35nC/2.2us = 16 mA**
Max current density (assuming uniform emission):
16mA/0.433 mm² = 3.7 A/cm²

Ultra-Nanocrystalline Diamond (UNCD) <10 nm

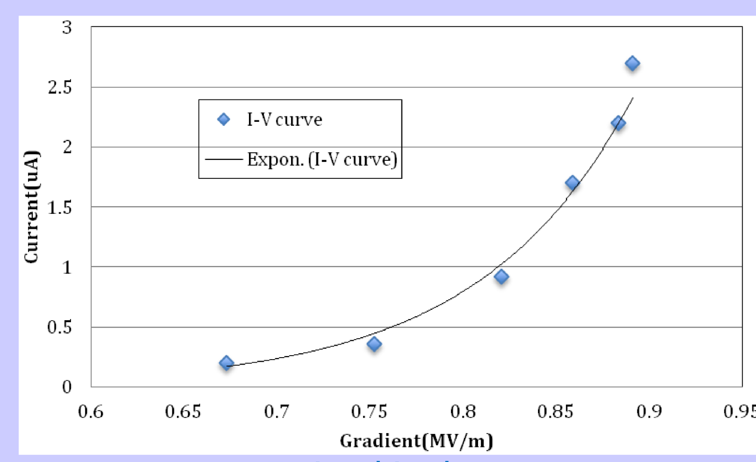
Microcrystalline: grain ≥500 nm | Nanocrystalline: grain 10-200 nm | UNCD: grain ≤10 nm



(N)UNCD emitter in TESLA 1.3 GHz gun; First-ever UNCD SRF Experimental Emission



3 μA→3mA/cm² @ ~1 MV/m and 2 Kelvin
Turn-On 0.7 MV/m



~ Emitted in the gun
~ Detected at P4, 1.5 m away from the gun after 90° bending magnet

SUMMARY

- **In summary, this project has fully explored and characterized UNCD FE cathode technology. Although the upper limit of emission was found to be at ~100 mA/cm2, its robustness and long lifetime make it well suited for many applications. In particular, we successfully performed the first-ever demonstration of strong emission of a UNCD FE cathode in an SRF gun (2K). We also have integrated the UNCD FE cathode in an industrial, compact, accelerator-based X-ray source. We have actively promoted the UNCD FE cathode technology, including exhibitions at NA-PAC2016, LINAC2016 and AAC2016, and oral and poster presentations at related conferences and workshops. In 2017, we completed two sales of (N)UNCD cathodes (customers: Duke University and BESSY of Germany) and the sale of a cathode imaging system (George Washington University). We also have another potential customer now in advanced discussions, Fermilab (industrial SRF accelerator currently under development at IARC in Fermilab). Overall, we strongly believe the outcome of this project is an important leap forward in UNCD FE technology and will lead to broad applications in the market.**