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

SBIR Phase II (May 2016~August 2018) Contract # DE-SC0013145

Dr. Eric Montgomery, Euclid Techlabs LLC

Team:

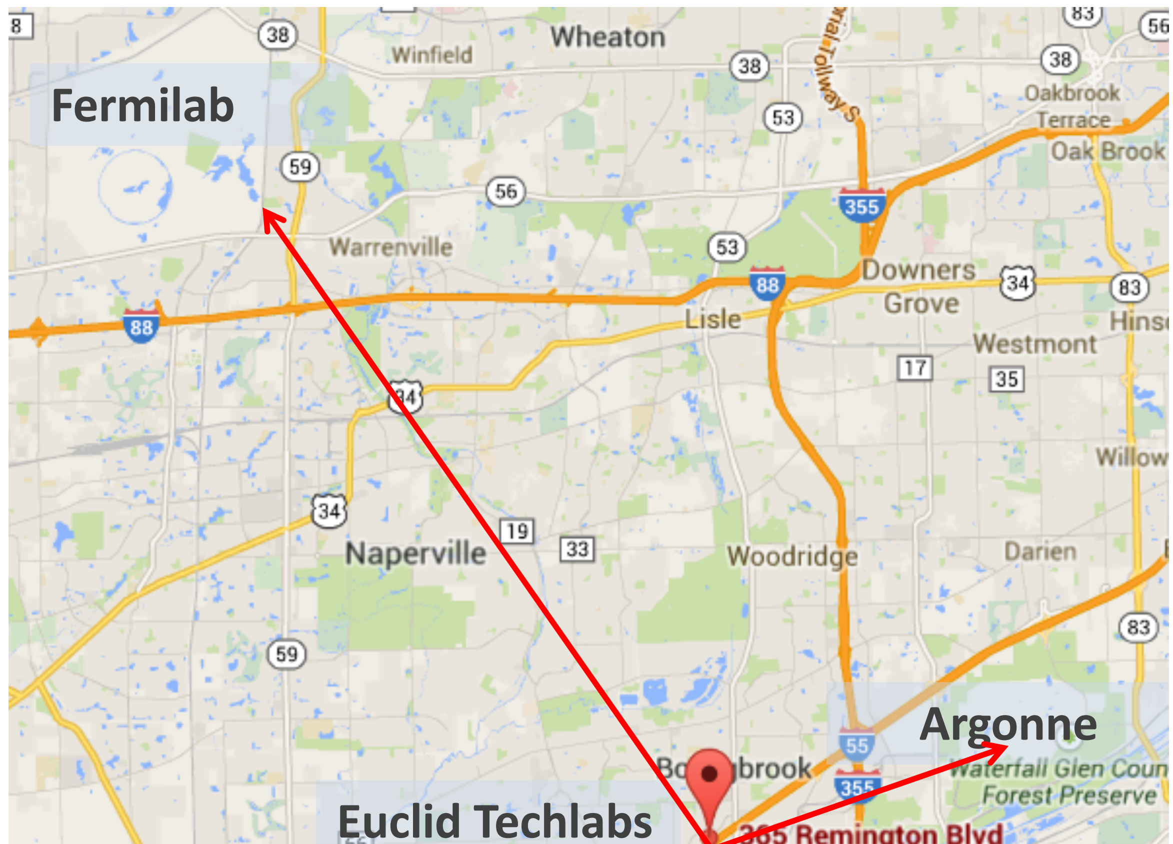
1. Dr. Alexei Kanareykin, PI
2. Dr. Chunguang Jing
3. Dr. Eric Montgomery
4. Dr. Kiran Kumar Kovi

DOE-NP SBIR/STTR Exchange Meeting, Aug. 7-8, 2018

Euclid Techlabs LLC

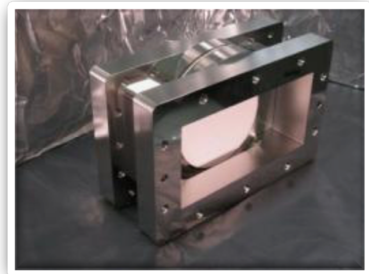
Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced electrons-structure interaction apparatuses for various applications. Areas of expertise include electron accelerators, high power rf components, photoinjectors, dielectric accelerators, diamond based electron sources and other applications, etc.

- 2018: 16 person research staff and 3 administrative,
- 2 offices: Bolingbrook, IL (lab) and Washington DC (administrative).
- Tight collaborations with National Labs and Institutes: Fermilab, ANL, BNL, LBL, LANL, Jlab, NIST, NIU, IIT, etc.



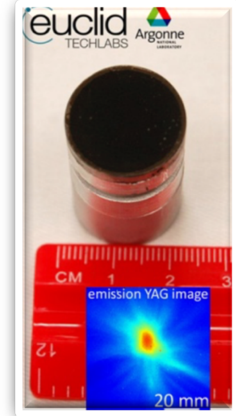
Selected Products

L-band high peak current LINAC

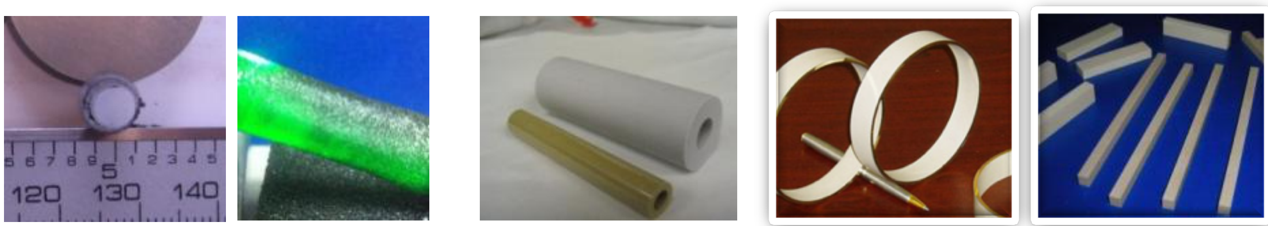


UHV L-band RF window

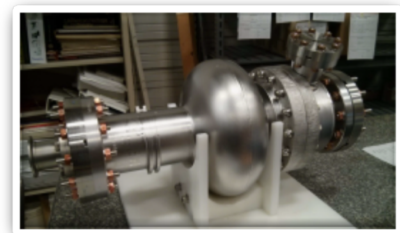
BPM compact readout



UNCD FE cathode

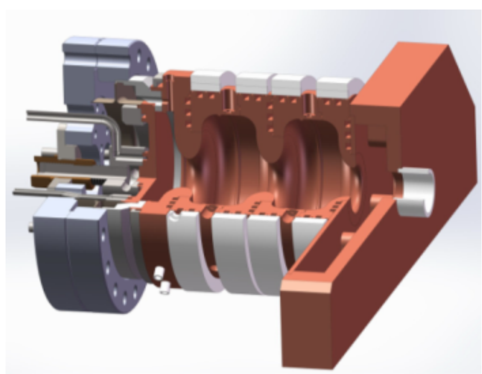


Linear and non-linear ceramics low loss; various form factors



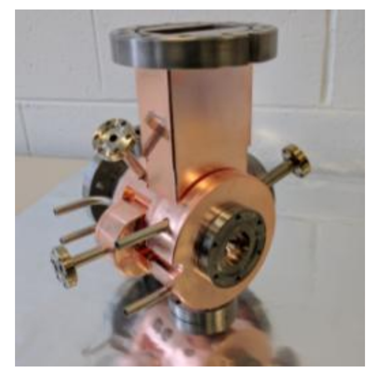
Detachable SRF coupler

L-band 100nC Photogun



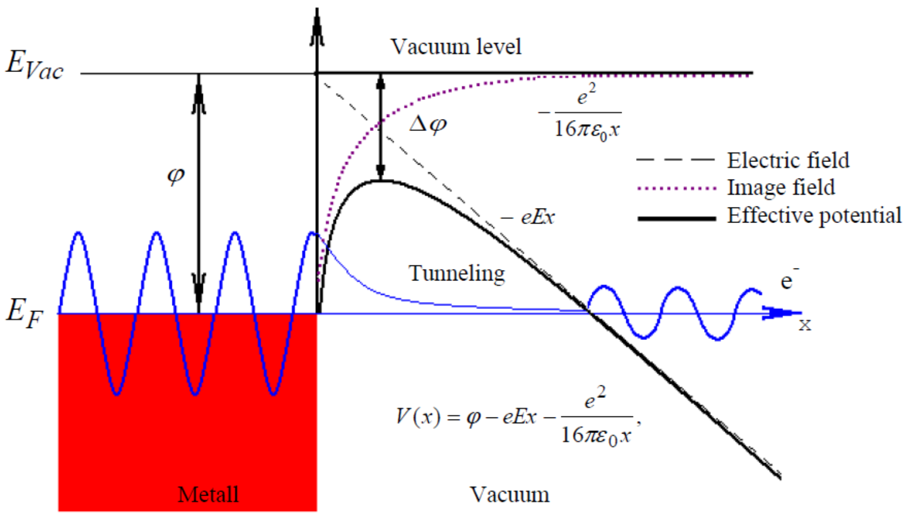
S-band 1000 pps Photogun

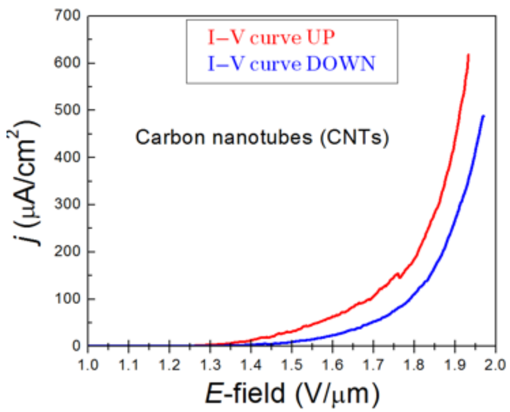
S-band 100MV/m Photogun

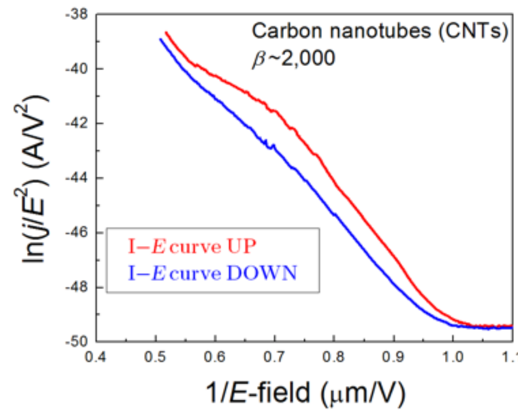


S-band Thermionic RF gun

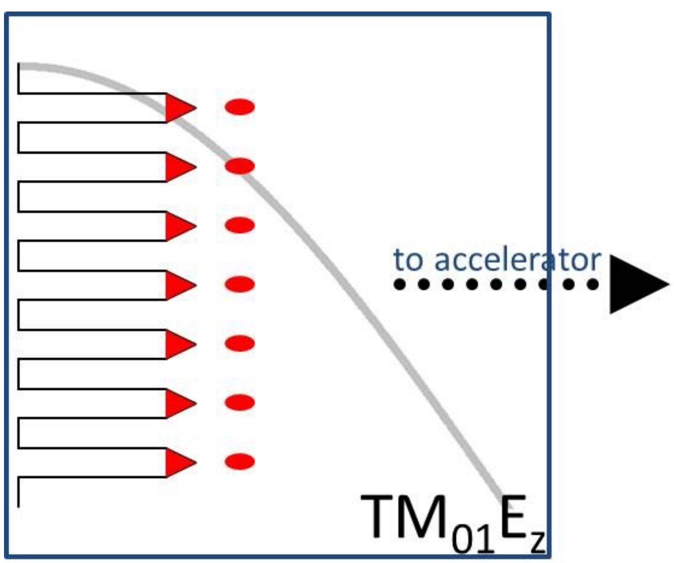
Field Emission: Basics and Accelerator Application







$$j_{FN}(E) = \frac{A(\beta E)^2}{\phi}\exp\left(-\frac{B\phi^{3/2}}{\beta E}\right)$$



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

Ref: Fowler and Nordheim, Proc. Royal Society A **119**, 173 (1928)

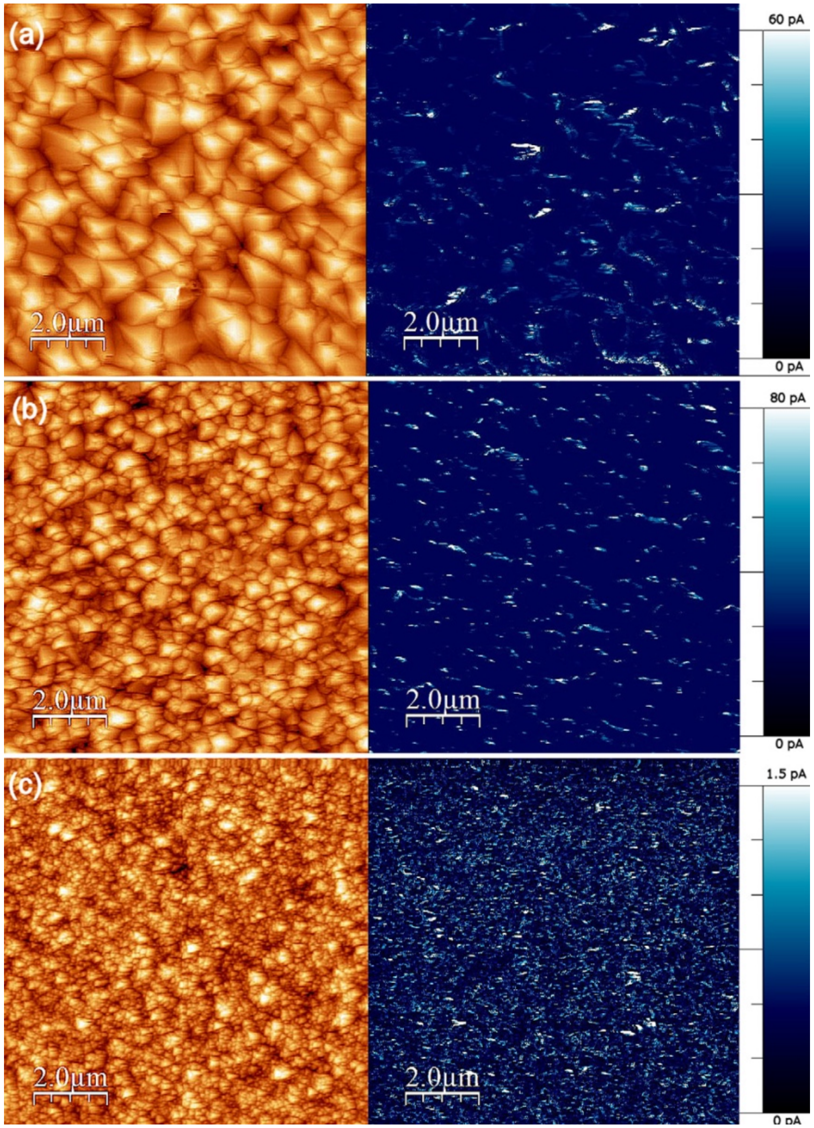
DC Field Emission: Grain Boundaries (GB) = Key

Electrons preferentially emitted from GBs in (N)UNCD

The larger GB area the higher current field emitter may yield

(N)UNCD can have 10^{13} emitting GBs/cm^2

(compare to Spindt source with 10^{8} emitting tips/cm^2)



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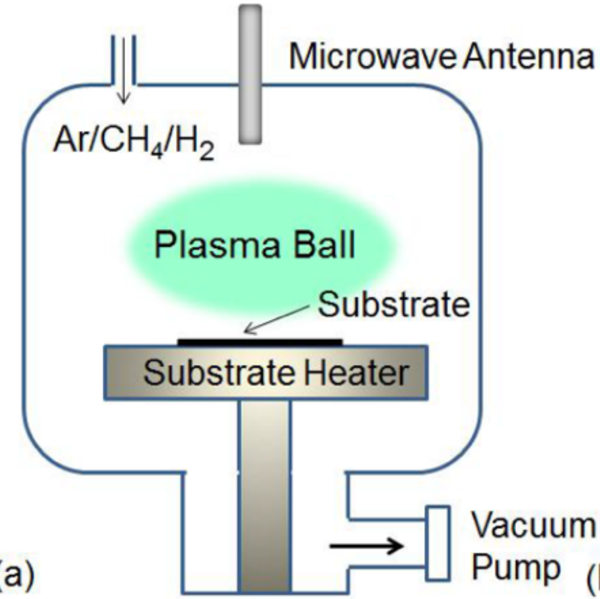
Refs: Chatterjee *et al*, APL **104**, 171907 (2014); Harniman *et al*, Carbon **94**, 386 (2015)

How We Grow/Characterize (N)UNCD

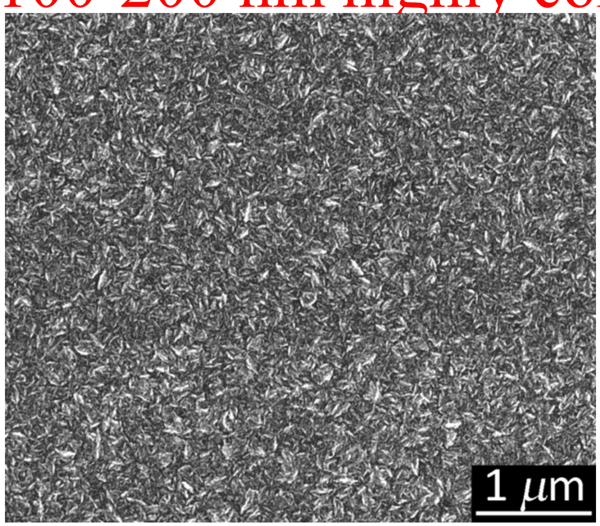
(a)

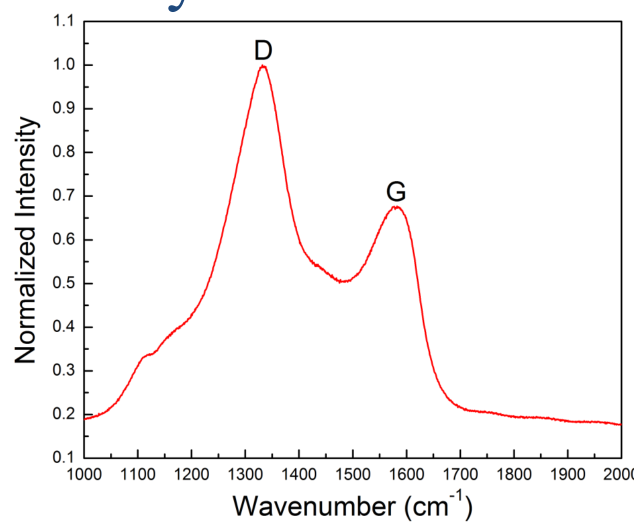


(b)

915 MHz microwave-assisted plasma chemical vapor deposition

100-200 nm highly conductive (N)UNCD by SEM and Raman





Ref: Sumant *et al*, MRS Bulletin **35**, 281 (2010)

Overview of NCRF, SRF, and DC Tests

New for 2018

Test Platform	Description	Main Results
NC RF	• Flat cathode @ 1.3GHz RF gun , AWA facility (Prior to Phase 2) • Grooved cathode@ 1.3GHz RF gun of AWA facility (Phase 1) • Flat cathode @ 9GHz compact RF gun developed at Euclid (Phase 2)	➢ operating up to 65 MV/m, 6us pulse width, peak currents of 80 mA (equivalent to 25 mA/cm^2), core beam emittance of 1.5 mm×mrad/mm-rms ➢compact X-band electron source, operating at 45MV/m, 1um pulse width for 2 weeks.
SRF	• Nb base cathode @ 1.3GHz SRF gun of BNL (Phase 2)	➢ the first FE SRF cathode ➢ 3mA/cm2 @ ~1 MV/m under 2 Kelvin
DC	• Flat cathodes @DC emission and imaging test stand developed at Euclid • Pyramidal cathodes with LANL • (P)UNCD with Hasselt U, Belgium • Photolithographic patterning	➢ automatic I/V and imaging characterization ➢ life time emission test ➢ emitter area control and diamond pyramid arrays, phosphorus UNCD

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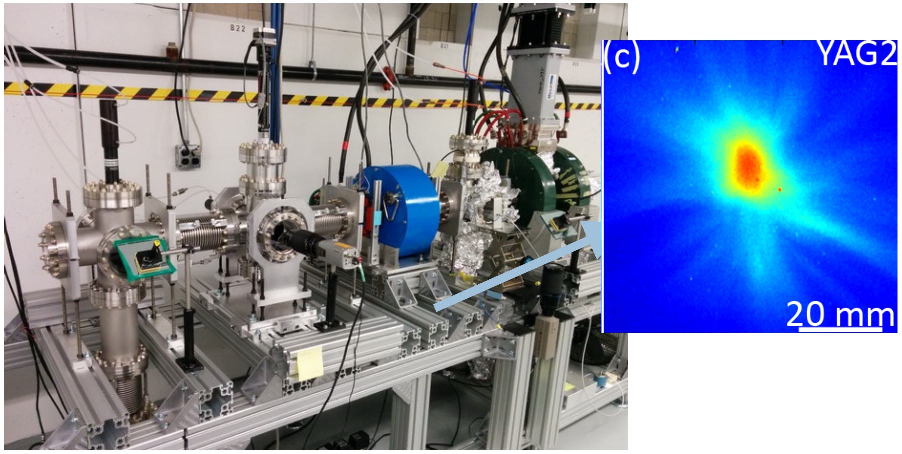
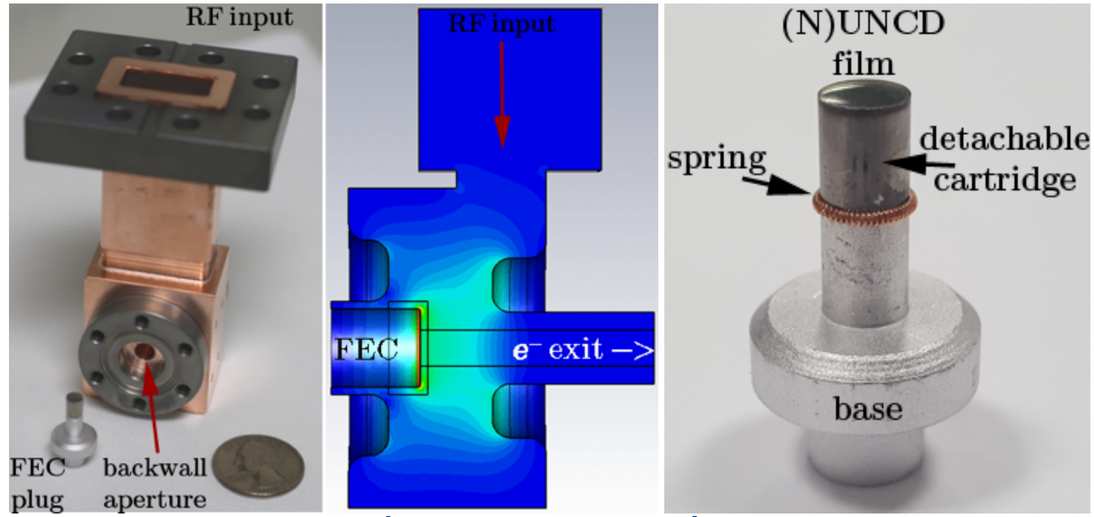
AWA Tests: Flat UNCD



Time(s)/RF pulses/GHz oscillations	Peak current (mA) at 65 MV/m
0 s/0/0	79.37 ± 3.97
3600 s/36 $\times 10^3$/288 $\times 10^6$	79.26 ± 3.96

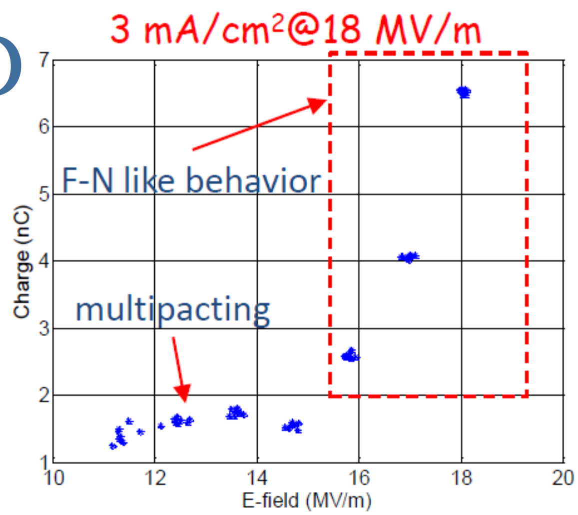
Euclid Tests: X-band 9 GHz



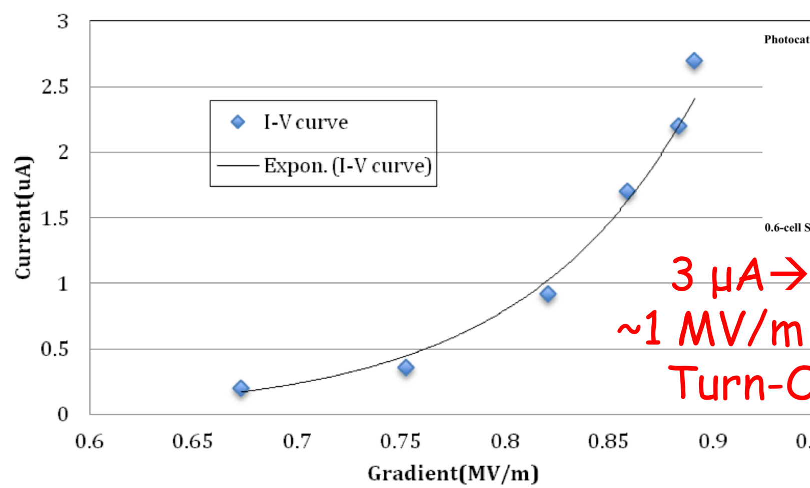
Faraday cup signal:

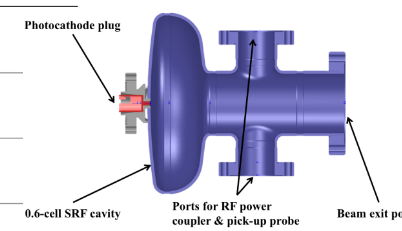
2 mA/cm²@28 MV/m

AWA Tests: Grooved UNCD



BNL: First-ever UNCD SRF



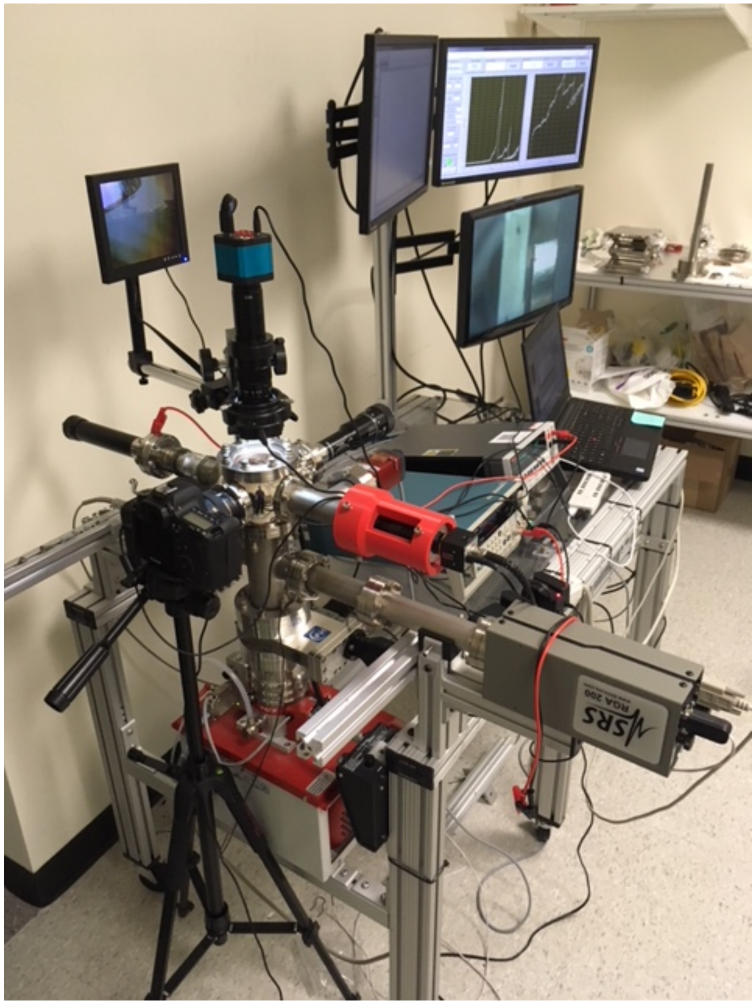


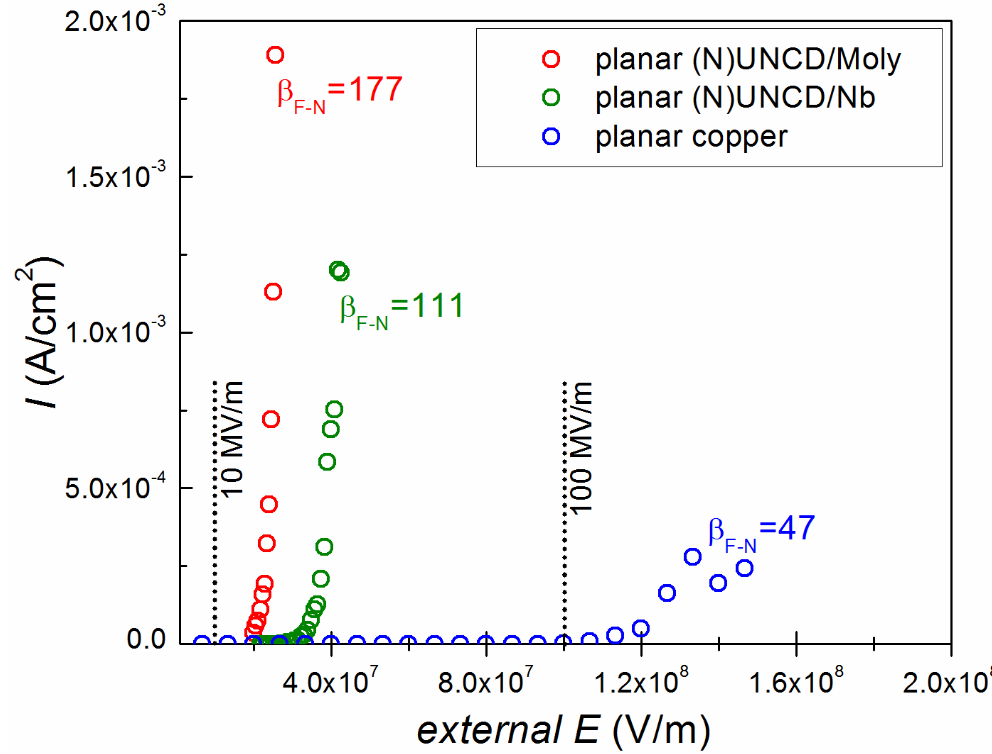
3 µA→3mA/cm² @ ~1 MV/m under 2 Kelvin

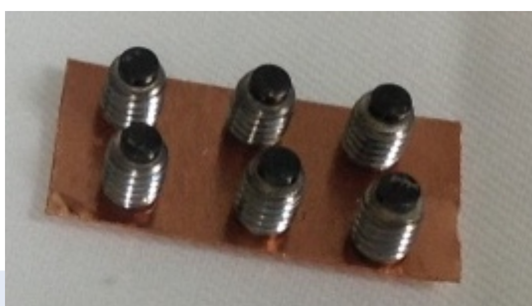
Turn-On 0.7 MV/m

Ref: Baryshev *et al*, APL **105**, 203505 (2014)

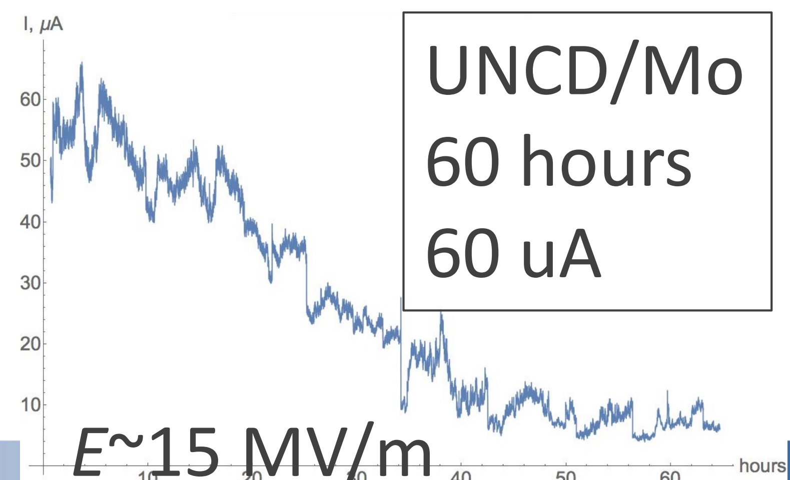
(N)UNCD at Euclid DC Test Stand: I/V curve







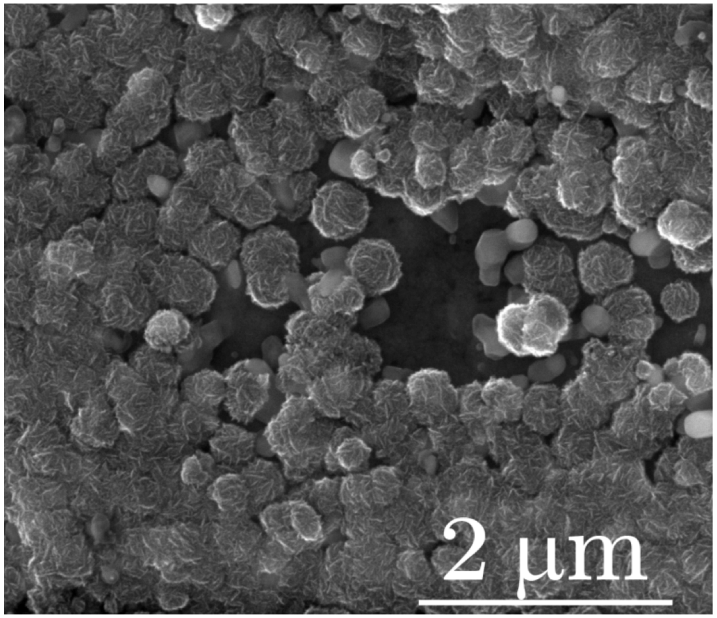
Lifetime test

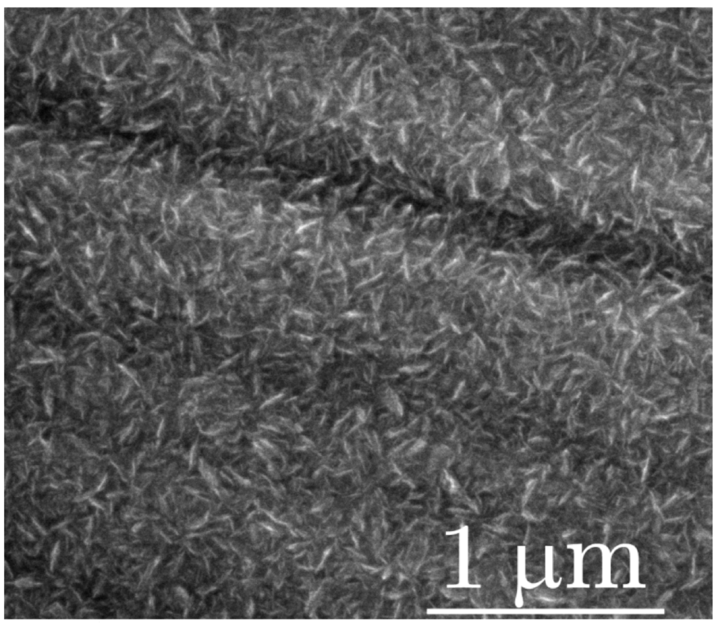


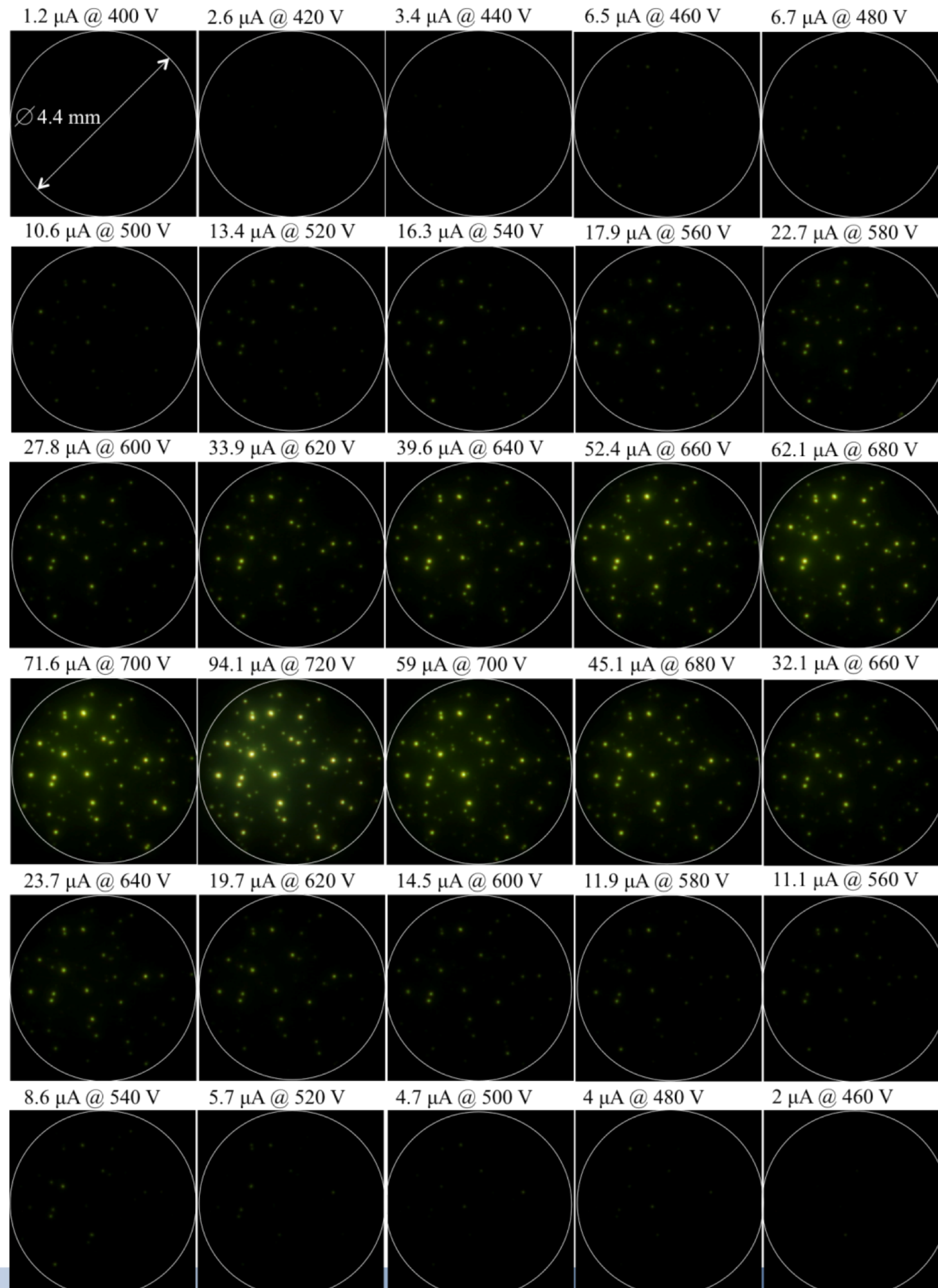
UNCD/Mo
60 hours
60 uA

E~15 MV/m

Example of a dataset: (N)UNCD/Ni/Mo/SS







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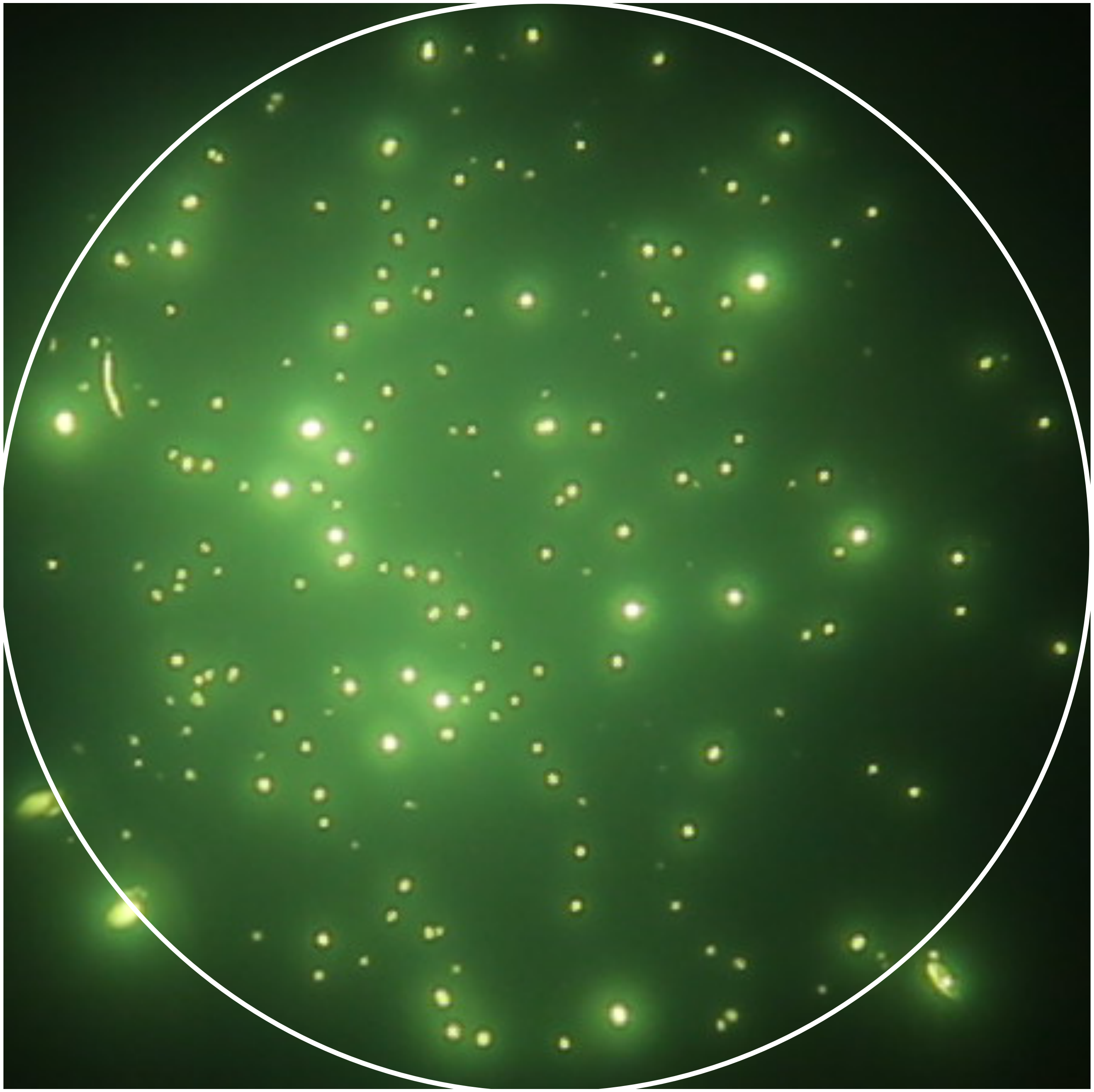
"The Emitter Galaxy"



Field of view is 4.4 mm

What Makes Good Emitters?

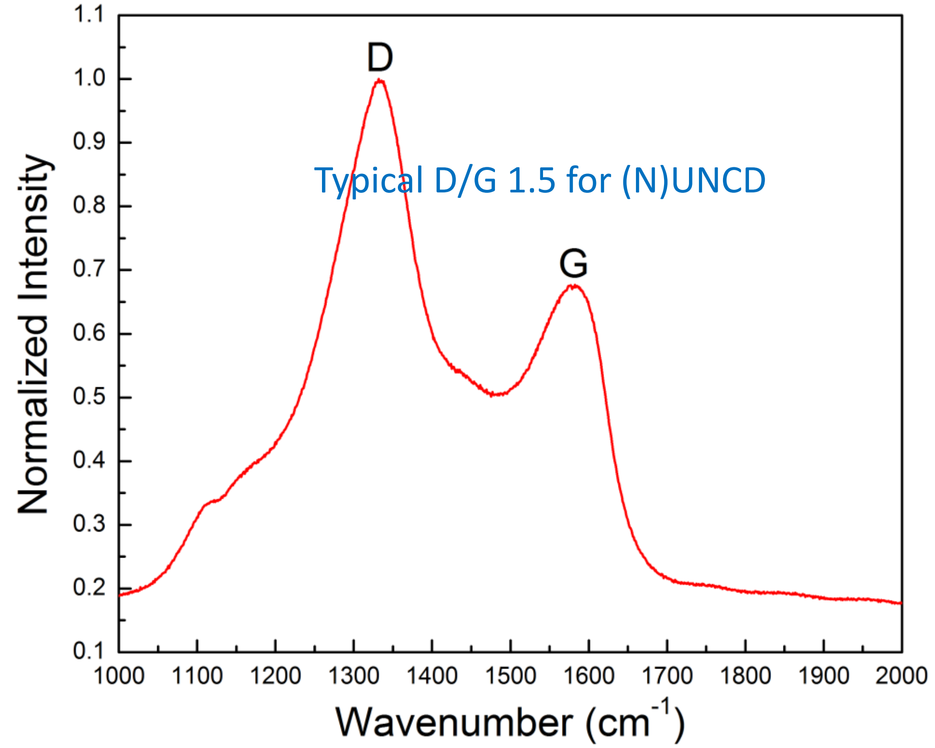
- Nanoscale composition debated
- Fowler-Nordheim beta >1000 can't be explained by sharp tip geometry
- Non-diamond (likely graphitic) carbon at GBs >>

- Turn-on voltage lowered by diamond adjacent to GB [1]
- UNCD: superior thermal conductivity
- Synergy of high-beta carbon GB and robust diamond thermal conductivity

- Question: Can we perform a simple experiment to indicate whether emitters are carbon or diamond?

Key Point: Raman spectroscopy D/G Ratio reveals GB carbon

D/G > 1.5 is "good" UNCD, but would lower D/G improve emission?



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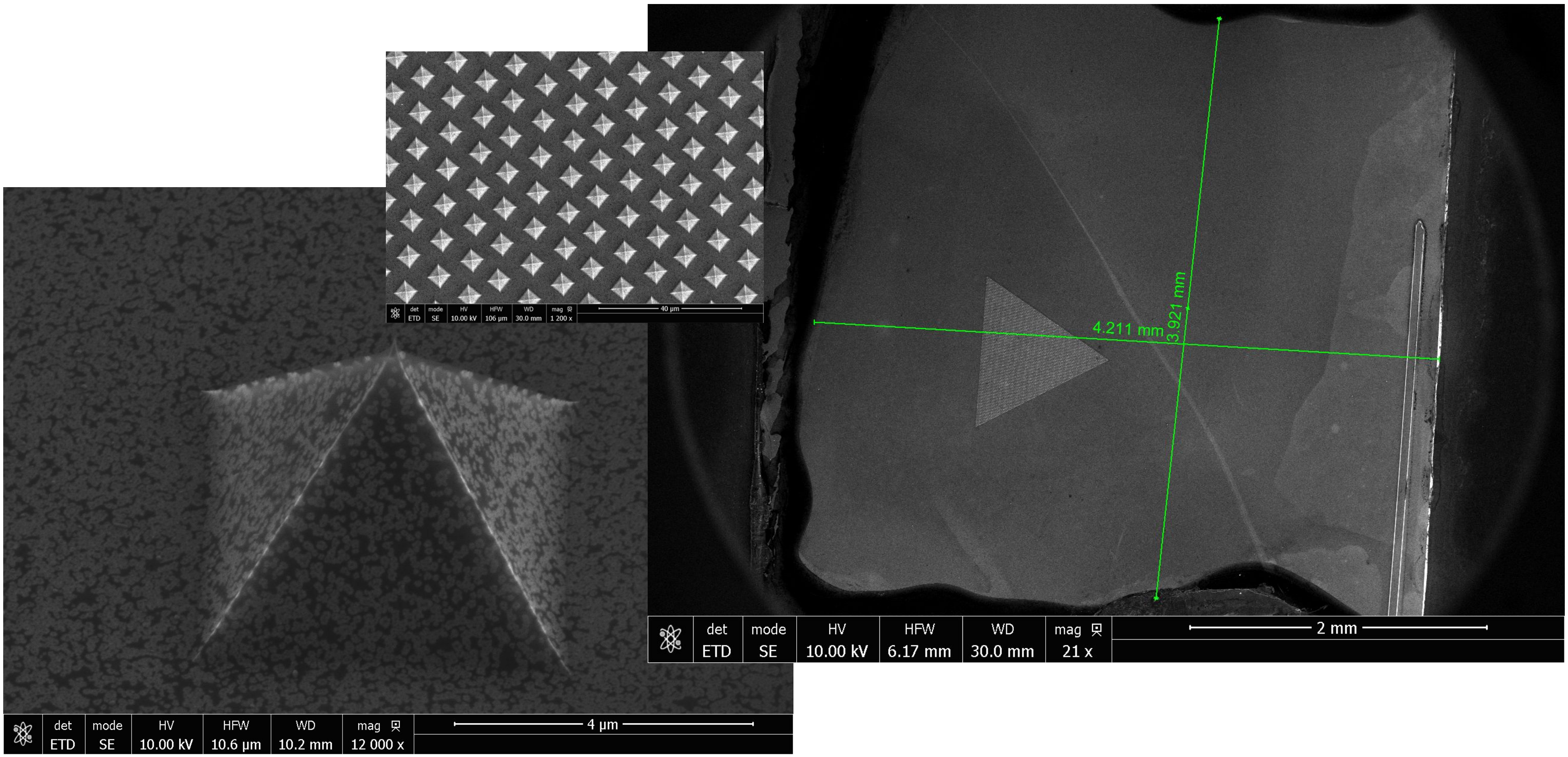
1. "Direct observation of electron emission from grain boundaries in CVD diamond by PeakForce-controlled tunnelling atomic force microscopy", R. Harniman et al, Carbon 94, 386 (2015).

Intentionally Induced Local D/G variation

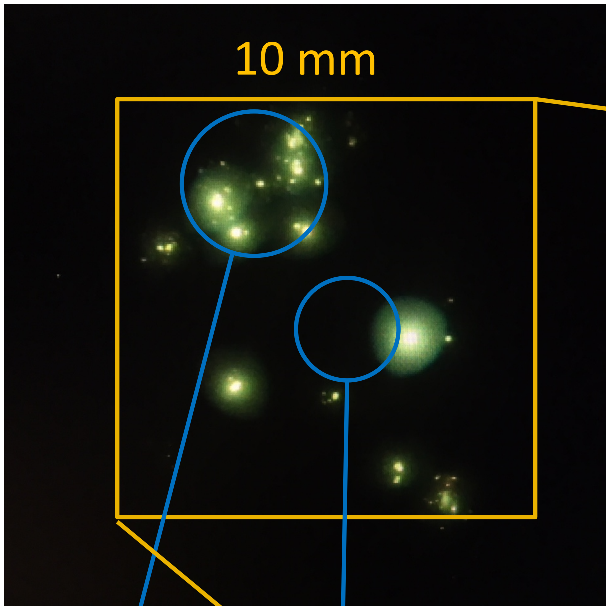
July 2018: LANL provided pyramidal NCD array on Mo.
Experiment: Omit nanodiamond seeding, grow otherwise as normal in Argonne CNM reactor
UNCD diamond is self-seeded on array and carbon should preferentially grow on unseeded Mo elsewhere.

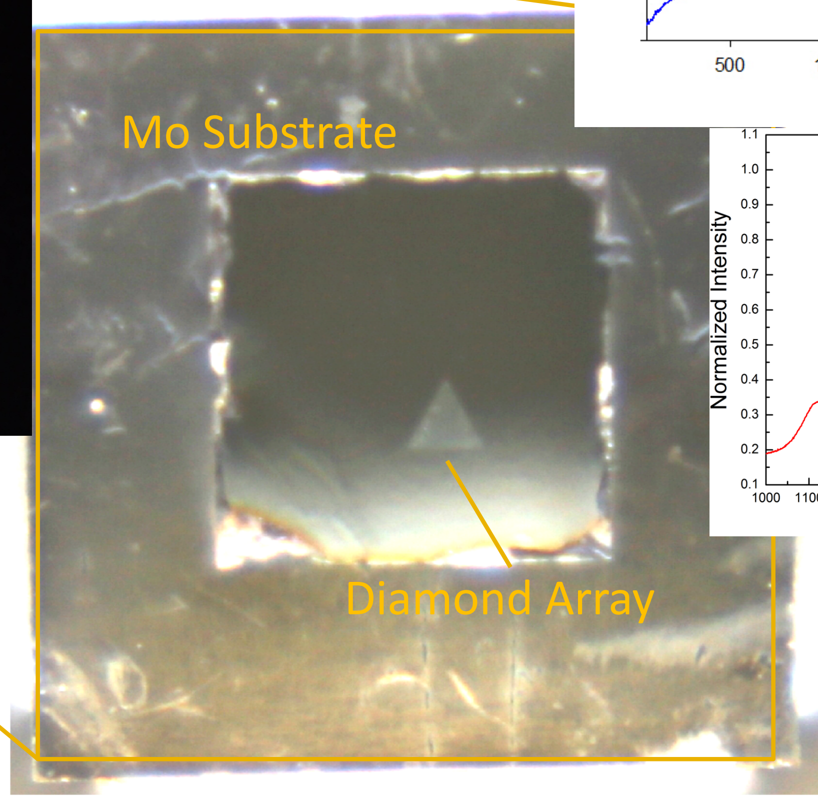


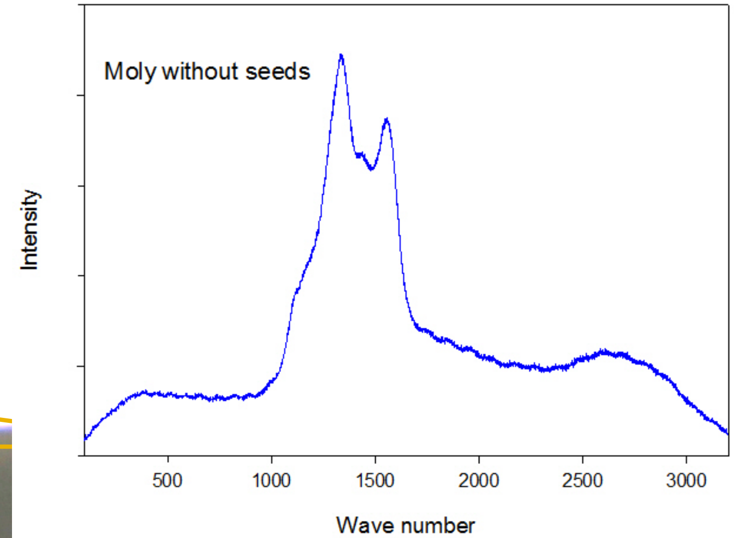
Pyramid from 7-12-18 LANL cathode

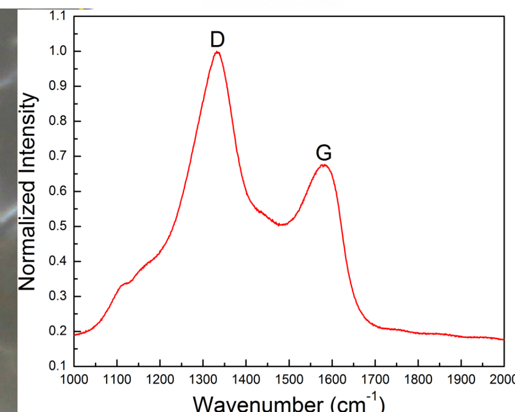
Emitters Denser where D/G is Low

Unseeded, otherwise standard (N)UNCD growth on Mo substrate and self-seeded diamond array. Carbon emitter sites dominate, bounded by diamond nanocrystals.









D/G = ~1.2

D/G = ~1.5

Turn-on Field:
<1.8 MV/m
100 uA ~6.1 MV/m

Towards Emitter Density Control

Emitters very common in regions NOT pre-seeded before M-CVD reactor growth

More GB material is non-diamond, indicated by Raman spectroscopy D/G ratio 1.2, less than typical 1.5 for (N)UNCD.

Grain boundary graphitic or CNT carbon emitters as emission sites suggested

FUTURE: intentional seeding of grain boundaries with CNT catalysts to maximize current density while gaining diamond's excellent thermal conductivity, with the promise of extended lifetime compared to bare carbon emitters

Phosphorus-Doped UNCD

Expected high emission current expected [1]
Entire grains emit, not just grain boundaries [2]
Initial results show doping density matters!

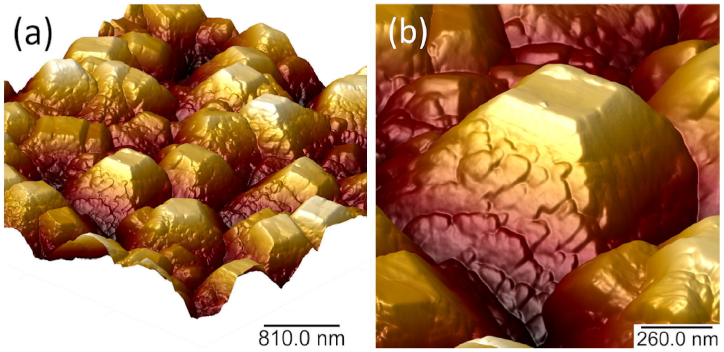


Image credit: Hasselt University, Belgium [2]

1. W. Janssen et al., "Substitutional phosphorus incorporation in nanocrystalline CVD diamond thin films", Phys. Status Solidi Rapid Res. Lett. 8 (8), 705 (2014).
2. "Direct observation of electron emission from grain boundaries in CVD diamond by PeakForce-controlled tunnelling atomic force microscopy", R. Harniman et al, Carbon 94, 386 (2015).

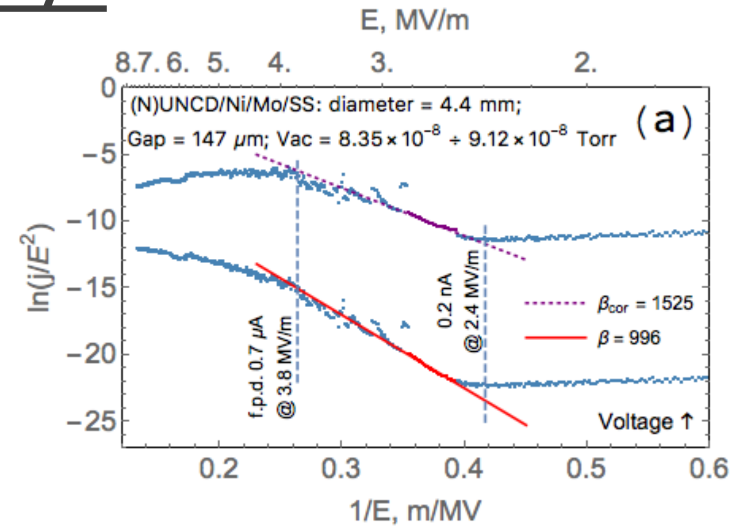
Phase II Takeaways

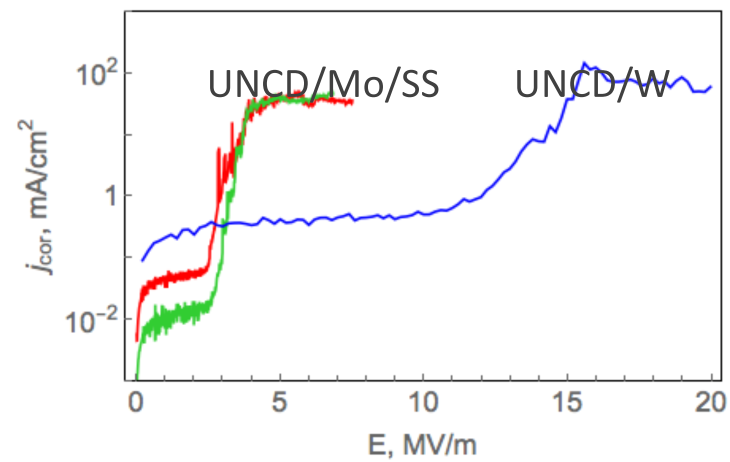
1. Semi-metallic (N)UNCD saturates similarly to semiconductors: thus (N)UNCD contains *non-FN non-metallic field emitters*

2. Uniform (N)UNCD exhibits nonuniform emission from E-field-dependent area.

3. (N)UNCD saturates at local j ~100 mA/cm^2, any substrate, but substrate chemistry optimizes density and type of emitters, hence total achievable j

4. D/G control shows good emitters occur more frequently on unseeded Mo, a known CNT catalyst. New idea: use two nanoparticles to simultaneously seed both emitters and UNCD. Potential for robust source with high current density.





- Four papers in two years.
- Exhibitions in the NA-PAC 2016, LINAC2016 and AAC2016, and oral and poster presentations at a number of conferences and workshops including IVNC2017

Utility patent US 9418814:
Planar field emitters and high efficiency photocathodes based on UNCD

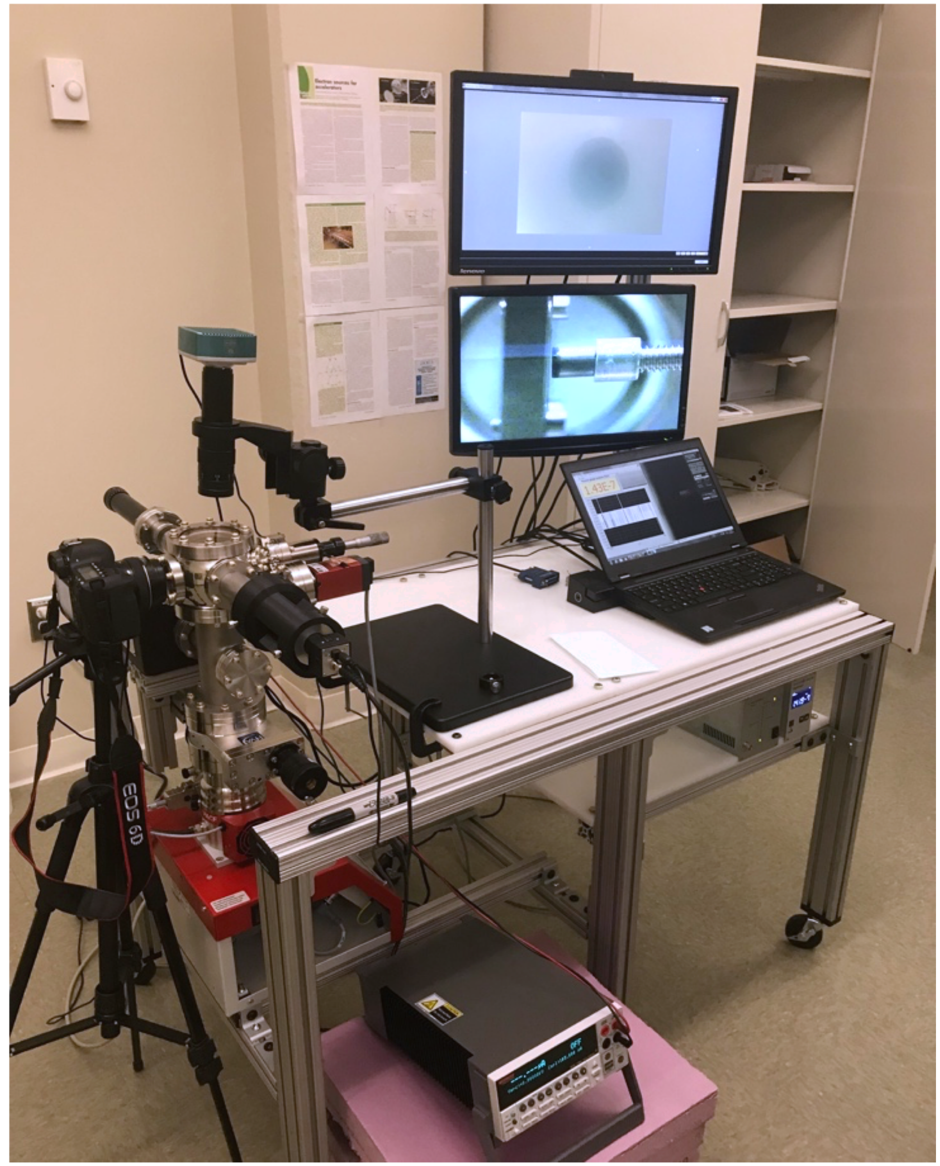
Commercial Product: FE Imaging Test Stand

2018 Sales to Date

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

YAG Screen + Camera: 10 micron resolution
IV characterization: ~30 MV/m, 21 mA DC

Fully automated IV curve acquisition
10^-9 Torr vacuum
Two-axis piezo tilt control
1 micron anode-cathode gap precision
Multiple collectors/screens available



Courtesy Prof. Andrei Afanasev, George Washington U.

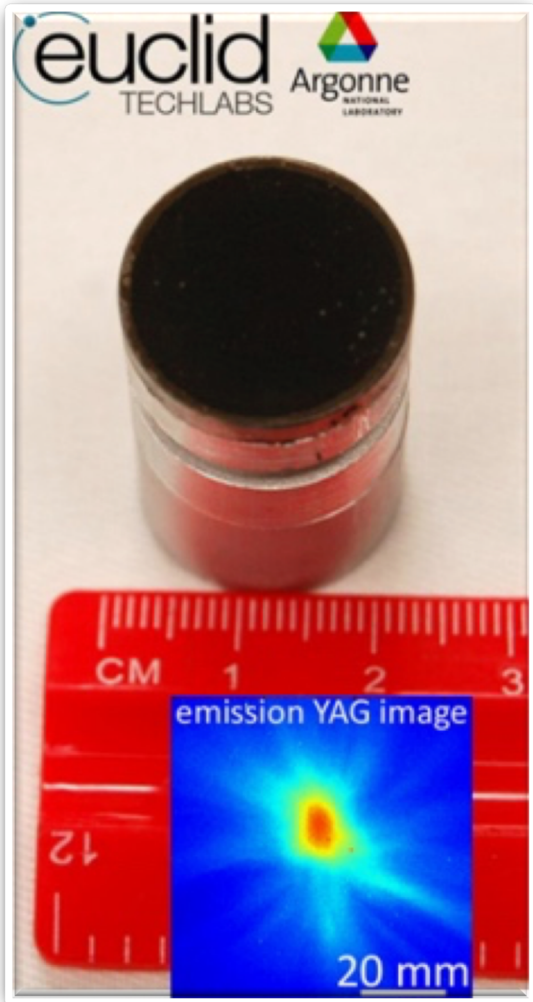
Commercial Product: (N)UNCD Cathodes

Highly robust field emission cathodes

Gun-tested

Many substrates available including single crystal Mo, Mo-coated stainless, highly doped Si, Mo-coated Si, and photolithographically patterned on Si.

Multiple sales 2018 with future sales in ongoing discussions



2018 Sales to Date

Duke UNIVERSITY

HZB Helmholtz Zentrum Berlin

Future Sales Now In Discussions

Fermilab

ADCAP VACUUM TECHNOLOGY CO,LTD.

Utility patent US 9418814:
Planar field emitters and high efficiency photocathodes based on UNCD

Joint Award for (N)UNCD Cathode Work

Dr. Ani Sumant, Argonne National Laboratory

Presented on May 14, 2018, at TechConnect's annual World Innovation Conference and Expo, the award recognizes Dr. Ani Sumant's work on nitrogen-incorporated ultrananocrystalline diamonds [(N)UNCDs] for application as a portable electron source in field emission cathodes.

The technology was developed in partnership with Euclid Techlabs under the DOE Technology Commercialization project to create a superior field emission electron source for use in linear accelerators, or linacs, outpacing photoemission and thermionic emission technologies. Euclid, an R&D company specializing in conventional, dielectric and superconducting RF accelerators, has a long history of successful collaboration with Argonne.

Conclusions

- *n*-type (N)UNCD is a promising field emitter that is already available for RF injectors and other applications (the first sales have been delivered to Duke, BESSY)
- (N)UNCD is a remarkable platform to keep finding and understanding fundamental processes in field emitters

Next

- Possible path to higher current density and long lifetime: dual seeding of emitters & (N)UNCD grains
- Further efforts needed to compare (N)UNCD vs (P)UNCD, especially varying P doping density
- New collaborations: LANL, Hasselt University

Acknowledgements

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Use of the Center for Nanoscale Materials, an Office of Science user facility, was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences and Office of High Energy Physics under Contract #DE-AC02-06CH11357.