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

SBIR Phase II (May2016~April2018) Contract # DE-SC0013145

Chunguang Jing, Euclid Techlabs LLC

Team:

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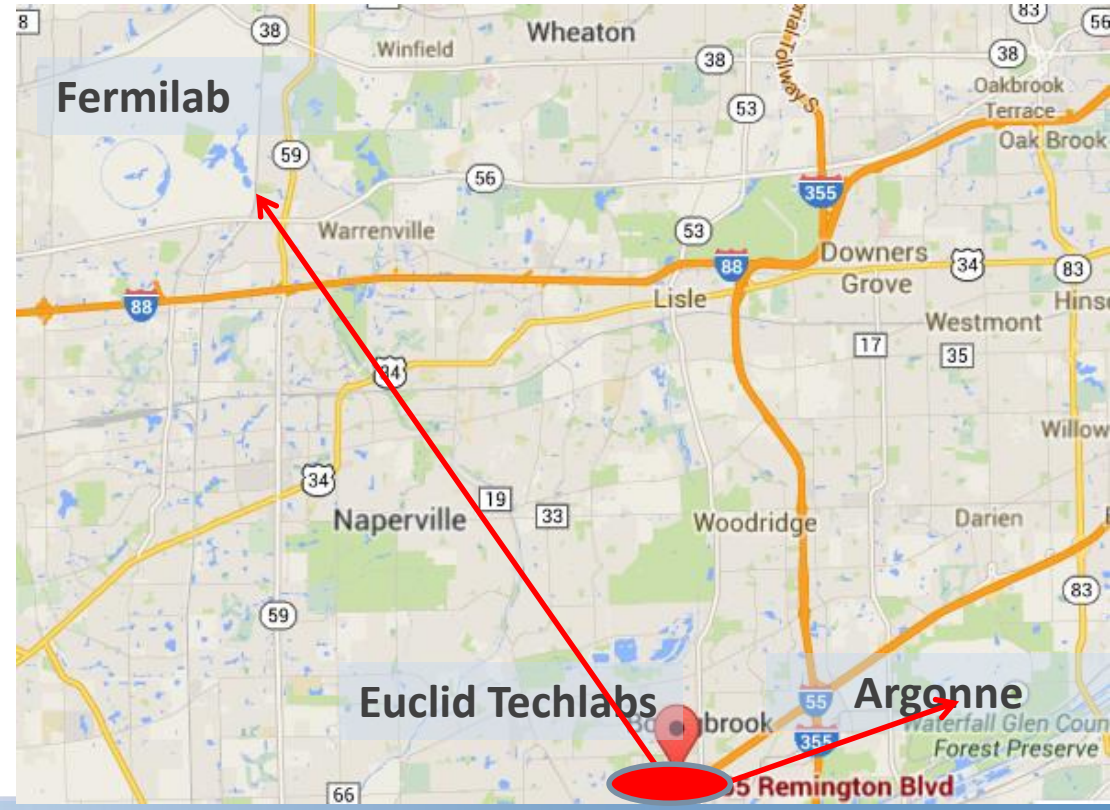
2. CNM, ANL (lead by Dr. Anirudha Sumant)
3. AWA, ANL (lead by Dr. Jianghang Shao)
4. TESLA, BNL (lead by Dr. Erdong Wang)

Euclid Techlabs LLC

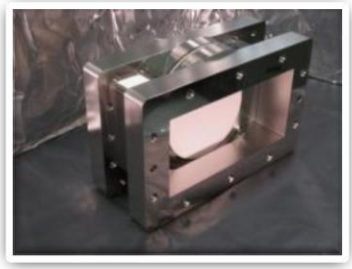
Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced electrons-structure interaction apparatuses for various applications. Areas of expertise include electron accelerators, high power rf components, Photoinjectors, dielectric accelerators, diamond based electron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

- 2016: 12 people 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.



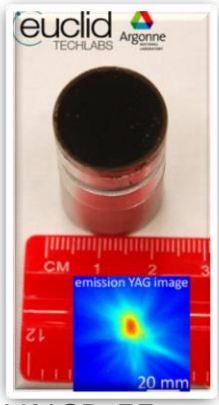
Selected Products

L-band high peak current LINAC

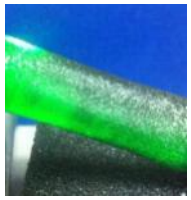


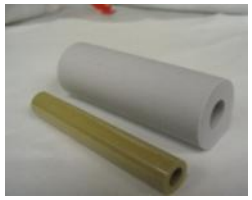
UHV L-band RF window

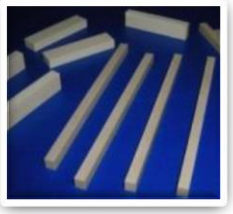
BPM compact readout



UNCD FE cathode



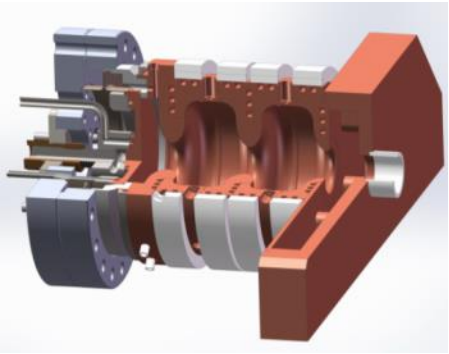




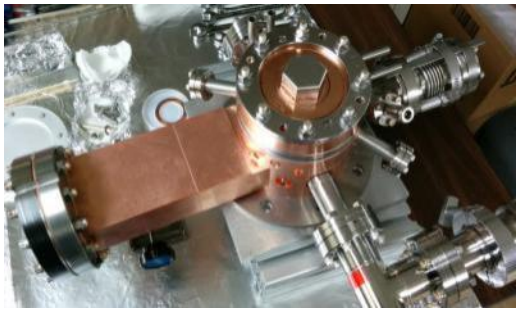
Linear and non-linear ceramics low loss; various form factors

Detachable SRF coupler

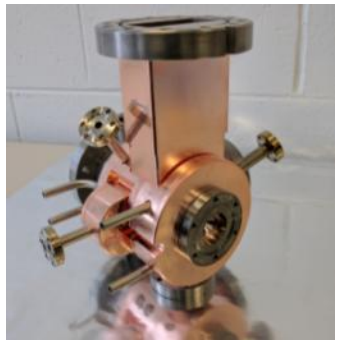
L-band 100nC Photogun



S-band 1000 pps Photogun



S-band 100MV/m Photogun



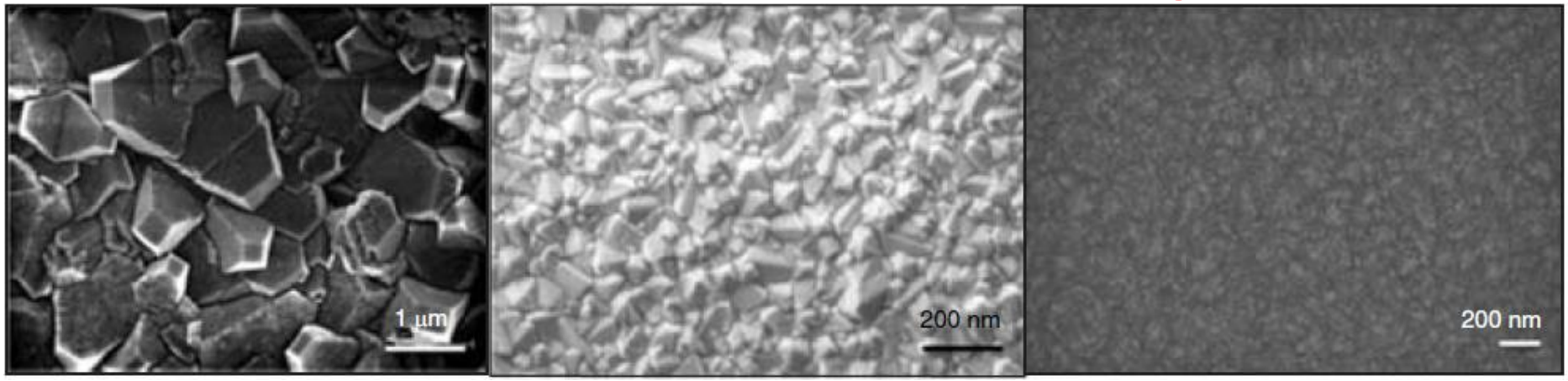
S-band Thermionic RF gun

Ultra-Nano-Crystalline Diamond (UNCD):

Microcrystalline:
grain ≥500 nm

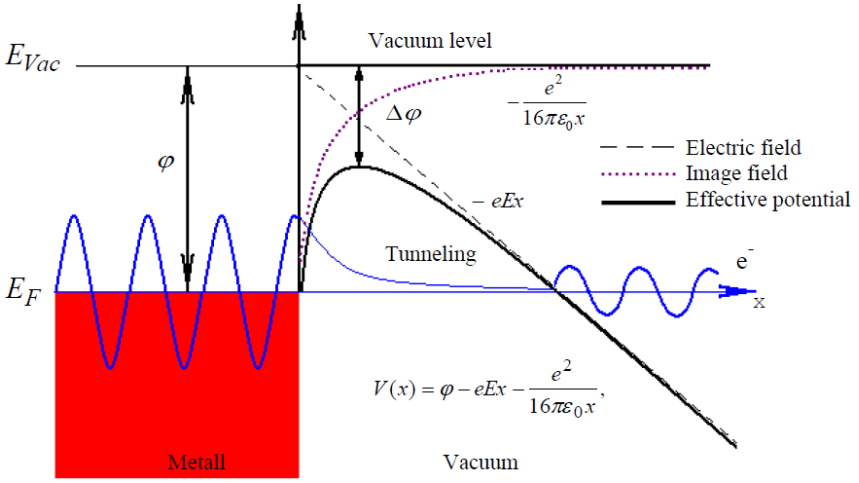
Nanocrystalline:
grain 10-200 nm

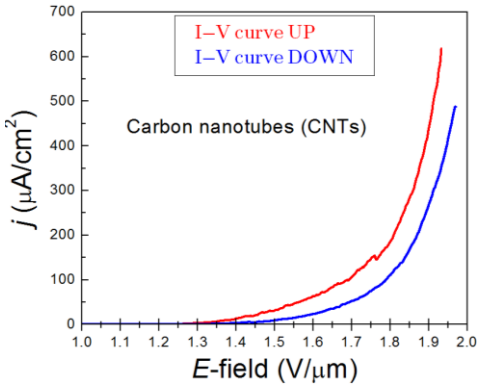
UNCD:
grain ≤10 nm

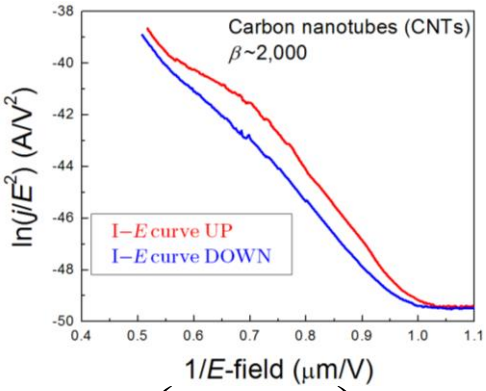


Ref: Sumant *et al*, MRS Bulletin **35**, 281 (2010)

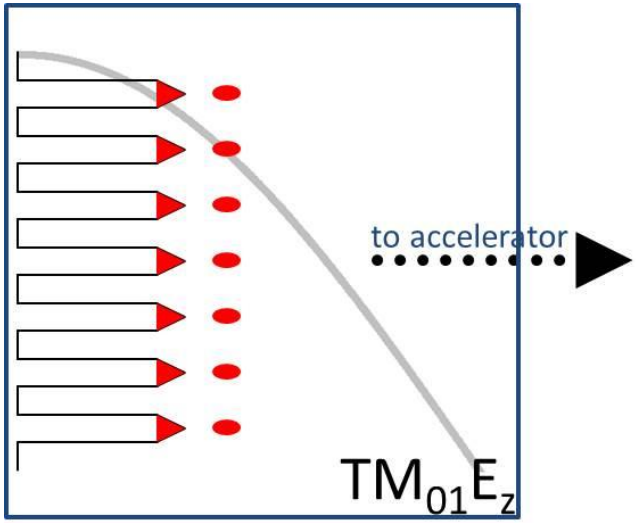
Field Emission: Basics and Accelerator Application







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

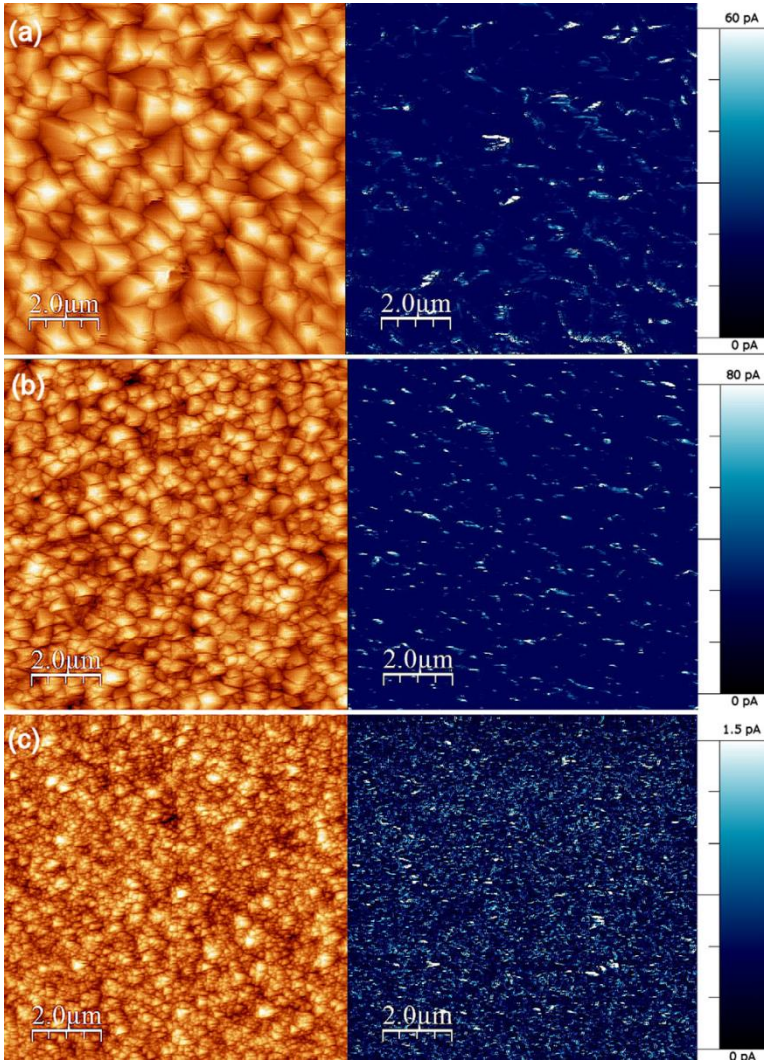


Ref: Fowler and Nordheim, Proc. Royal Society A **119**, 173 (1928)

DC Field Emission: Grain Boundary (GB) is a Key

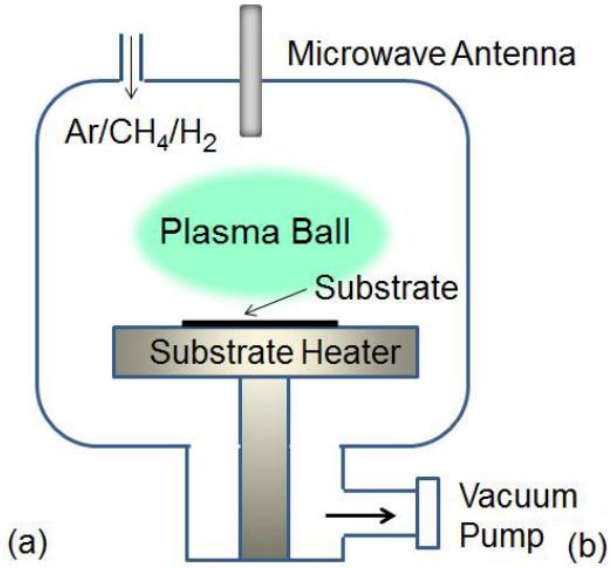
The larger GBs area the higher current field emitter may yield

UNCD has
10^{13} emitting GBs/cm^2
(compare to Spindt source with
10^8 emitting tips/cm^2)



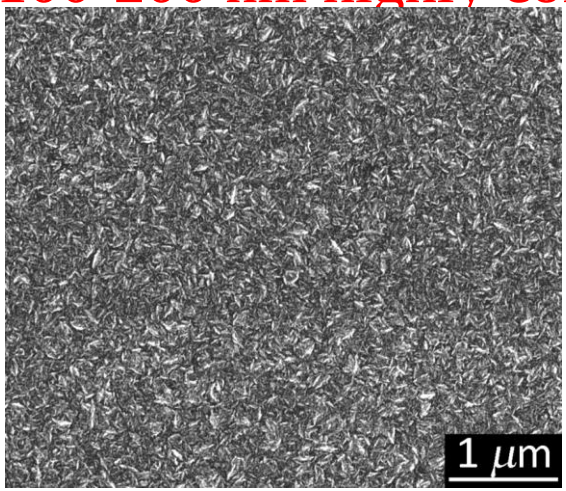
Refs: Chatterjee *et al*, APL **104**, 171907 (2014); Harniman *et al*, Carbon **94**, 386 (2015)

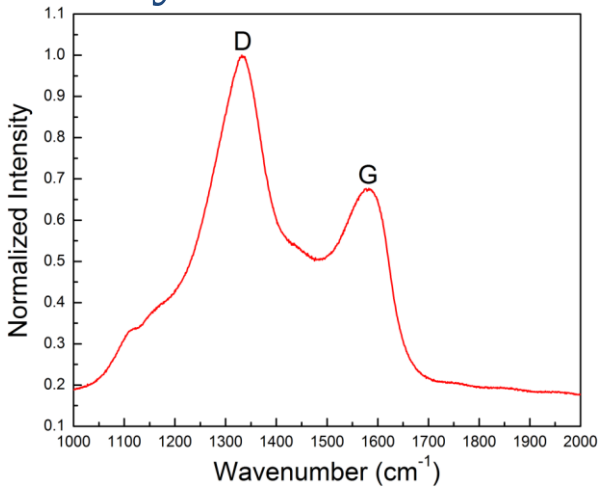
Nitrogen Doped UNCD. Basic Characterization



915 MHz microwave-assisted plasma chemical vapor deposition

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

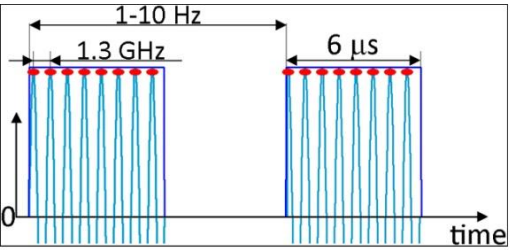


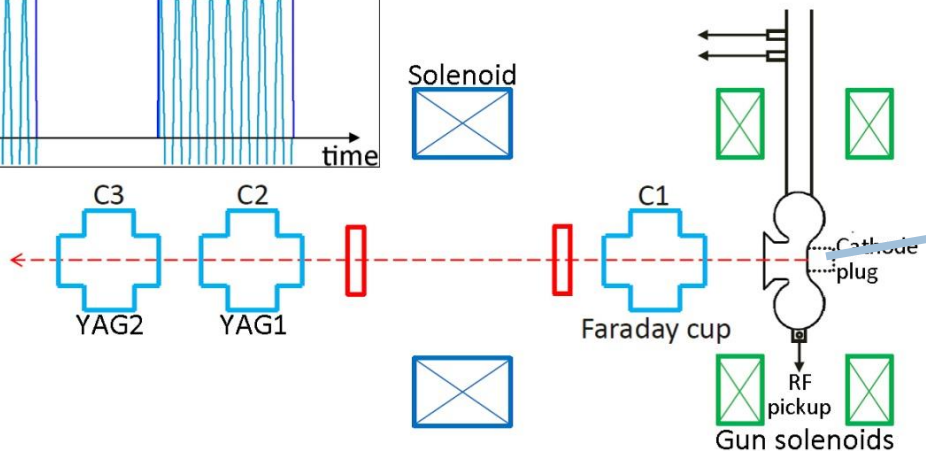


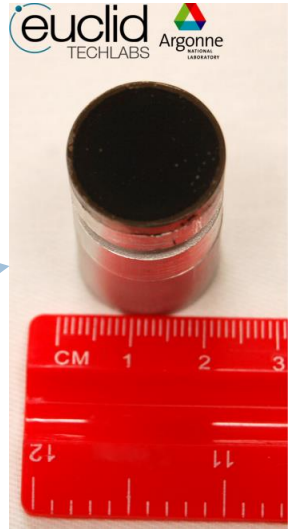
Survey of UNCD FE Cathode Tests to Date

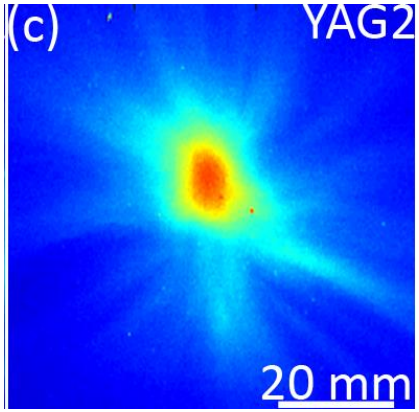
Test Platform	Description	Main Results
NC RF	• flat cathode @ 1.3GHz RF gun , AWA facility (Prior to Phase 2) • grooved cahtode@ 1.3GHz RF gun of AWA facility (Phase 1) • flat cathode @ 9GHz compact RF gun developed at Euclid (Phase2)	➢ operating up to 65 MV/m, 6us pulse width, peak currents of 80 mA (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 teststand developed at Euclid (Phase 2) • flat cathodes @ DC emission imaging system devleoped at Euclid (Phase 2)	➢ automatic I/V characterization ➢ life time emission test ➢ with help of the in situ emission imaging system, the UNCD emission features were first time revealed.

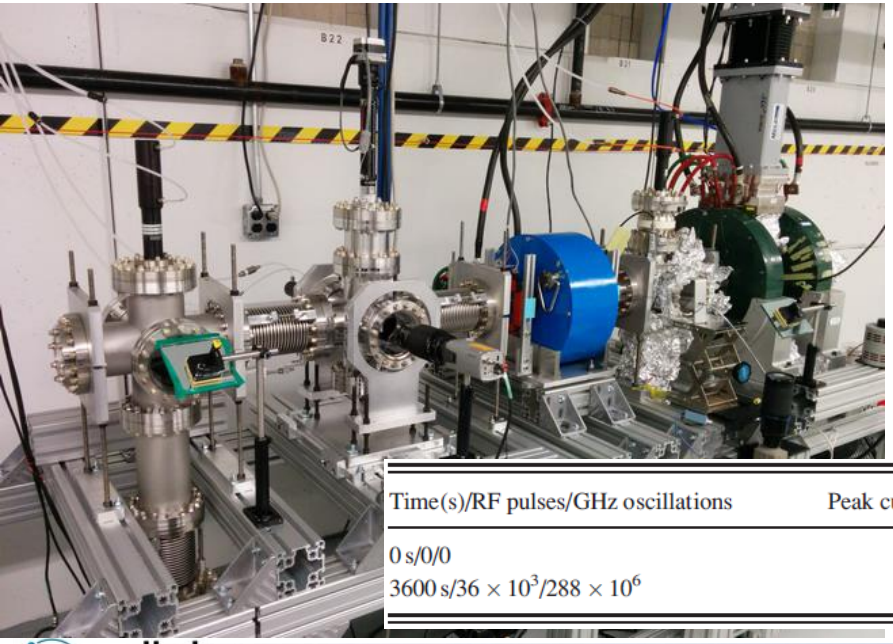
Flat UNCD FE Cathode tested at AWA

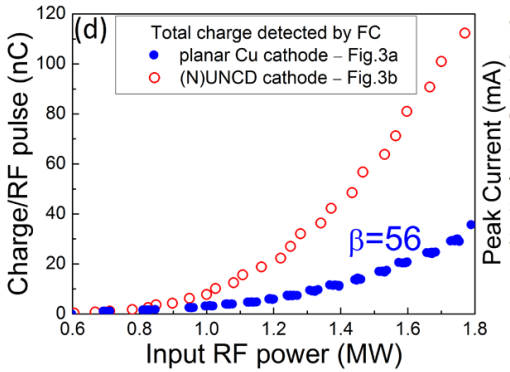


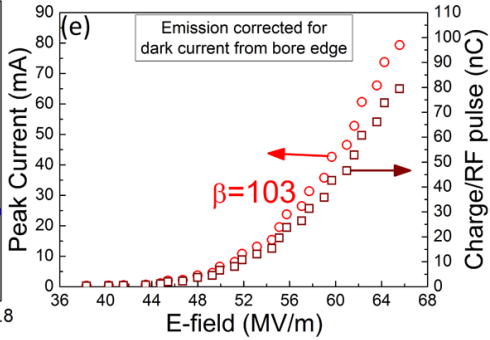








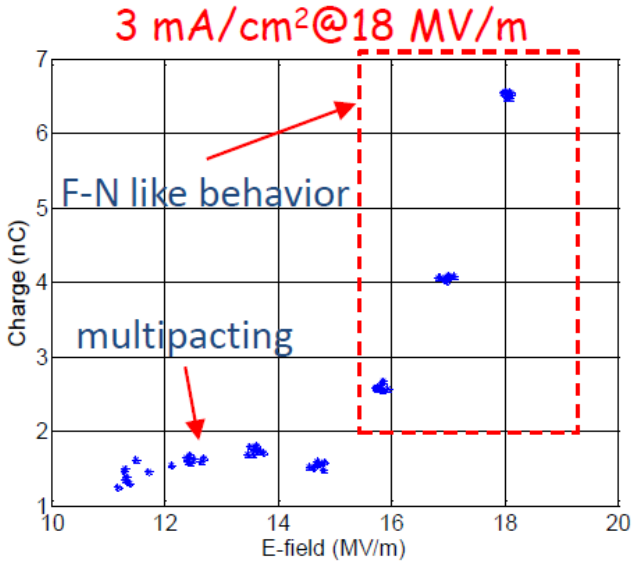


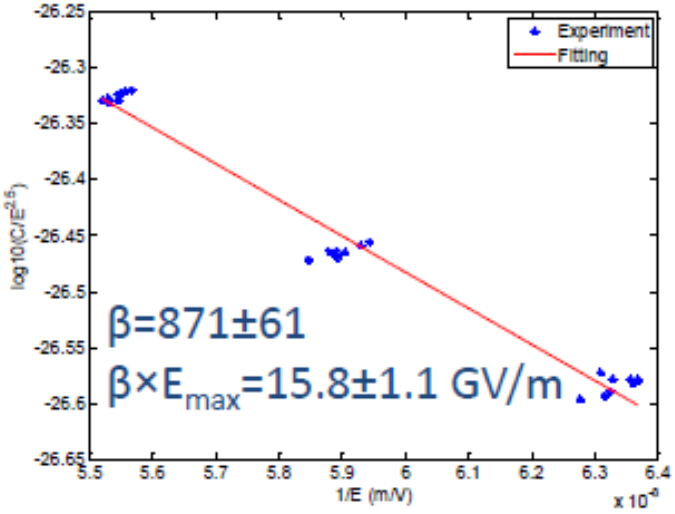


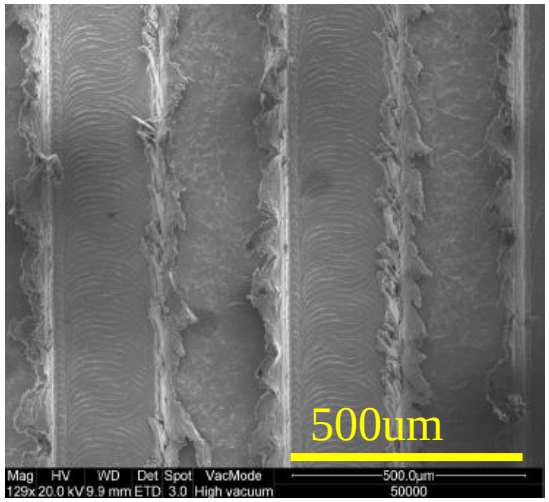
Time(s)/RF pulses/GHz oscillations	Peak current (mA) at 45 MV/m	Peak current (mA) at 55 MV/m	Peak current (mA) at 65 MV/m
0 s/0/0	1.56 ± 0.08	19.54 ± 0.98	79.37 ± 3.97
3600 s/36 × 10^3/288 × 10^6	1.47 ± 0.07	19.24 ± 0.96	79.26 ± 3.96

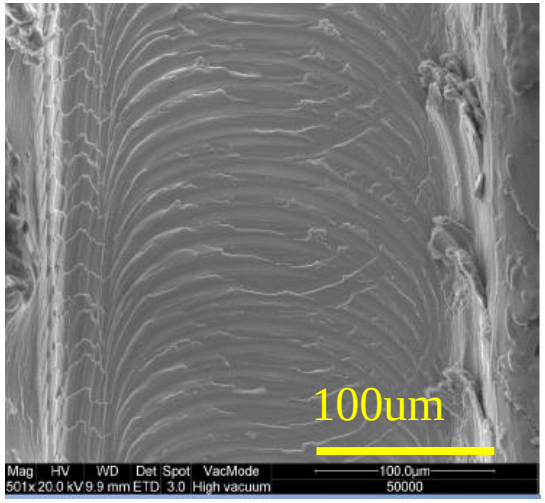
Ref: Baryshev *et al*, APL **105**, 203505 (2014)

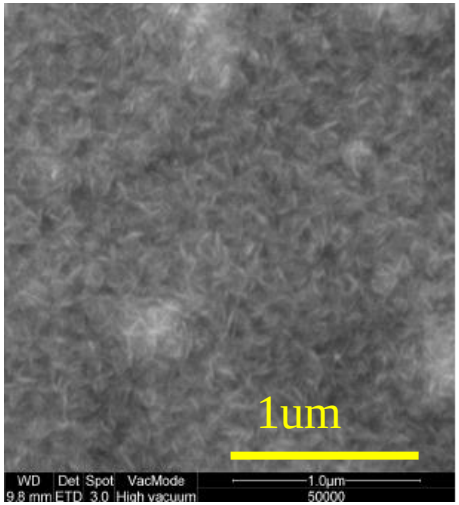
Grooved UNCD FE Cathode tested at AWA



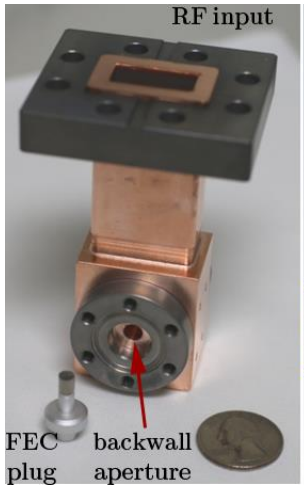


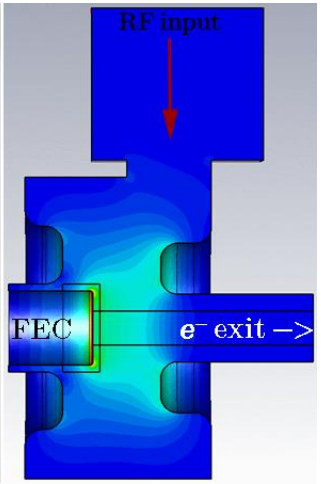


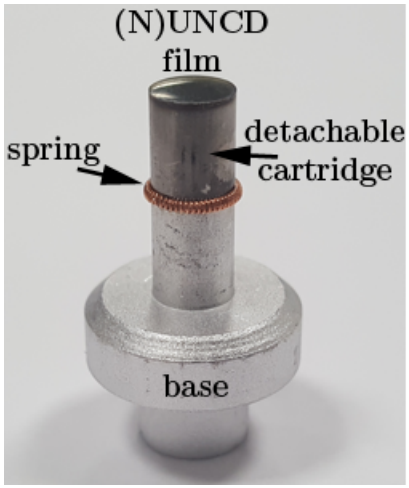


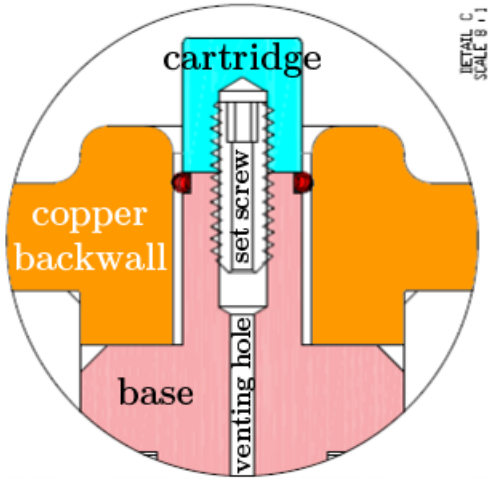


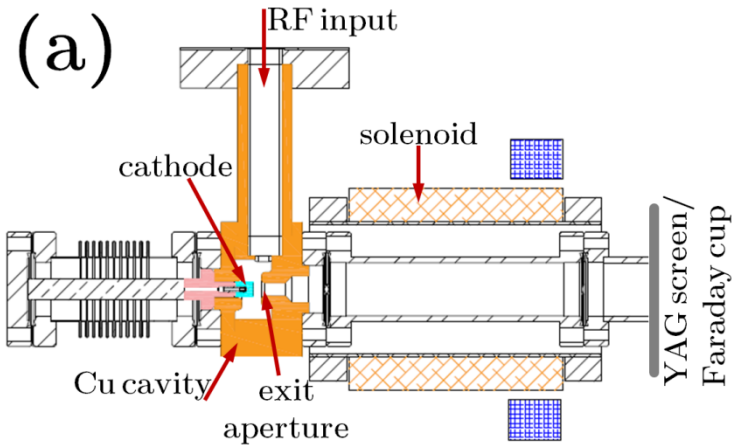
(N)UNCD Cathode in X-band 9 GHz Gun

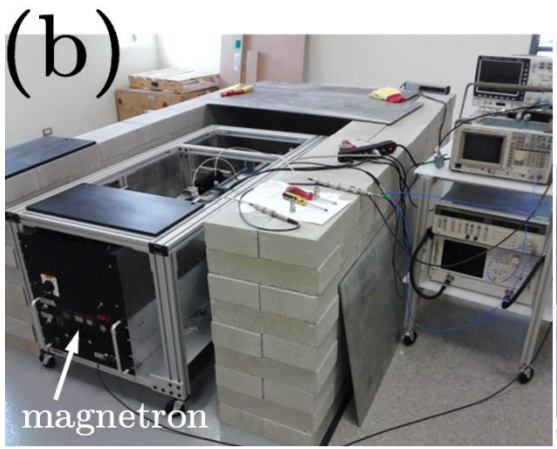


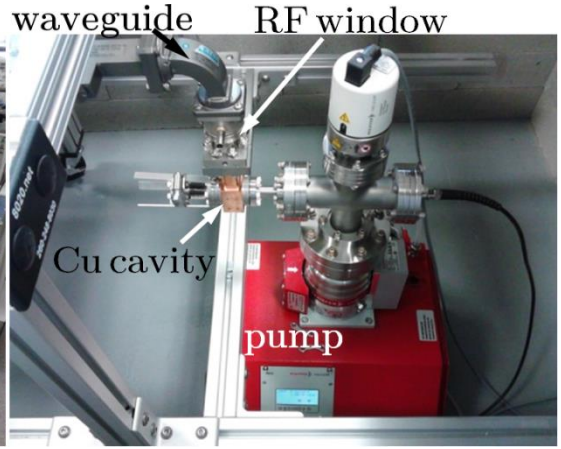






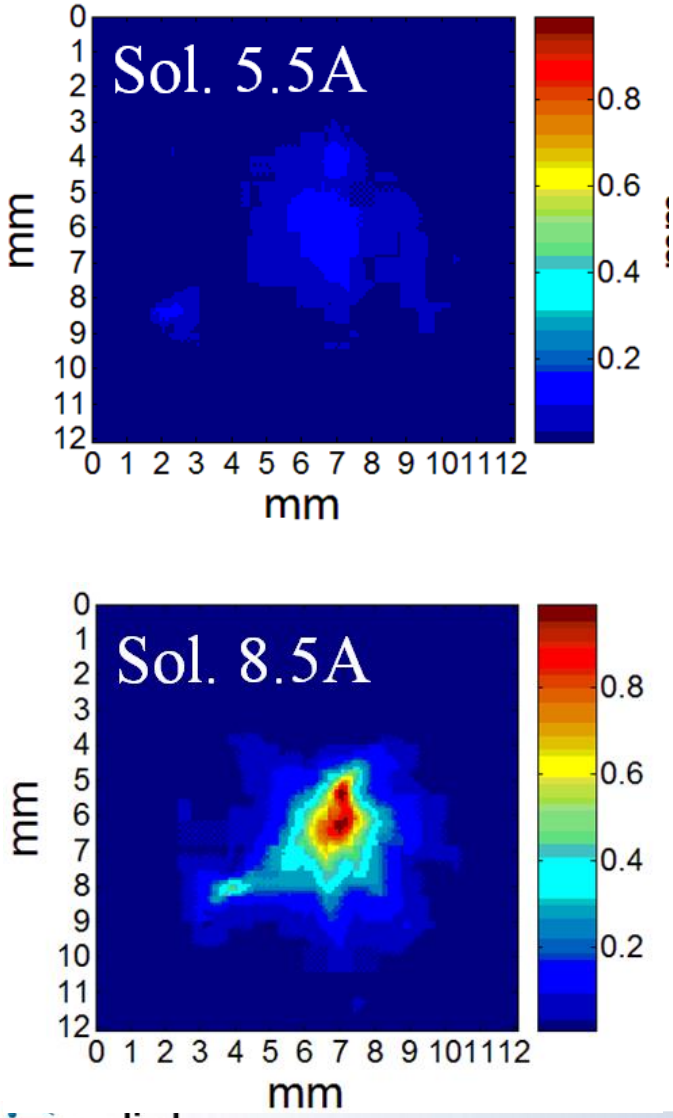






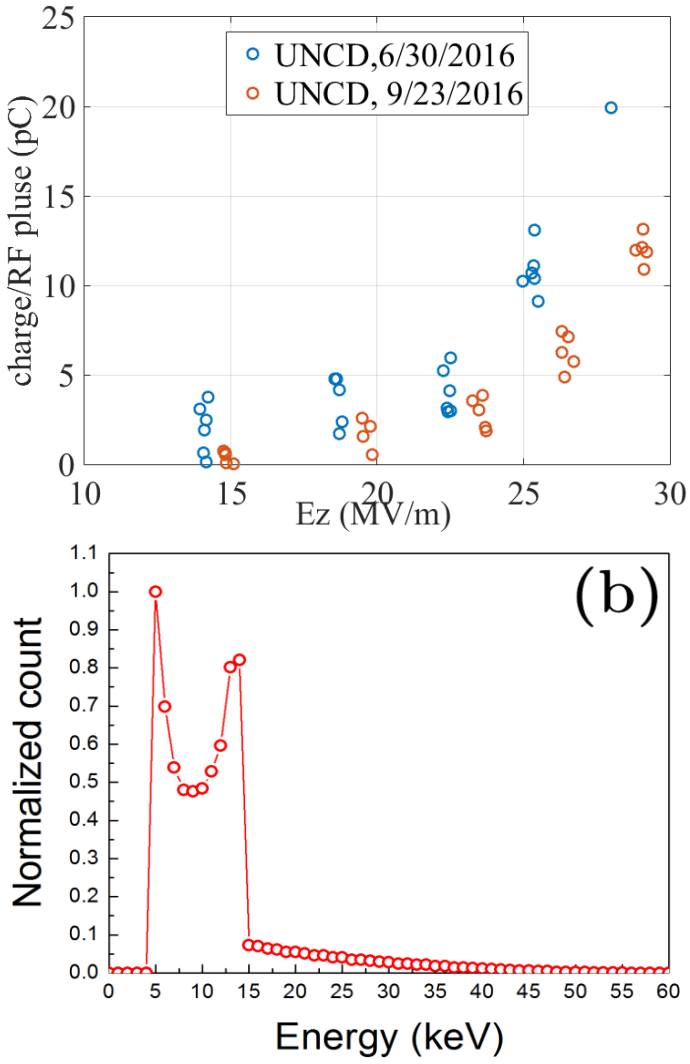
(N)UNCD in X-band 9 GHz Gun Results

YAG image

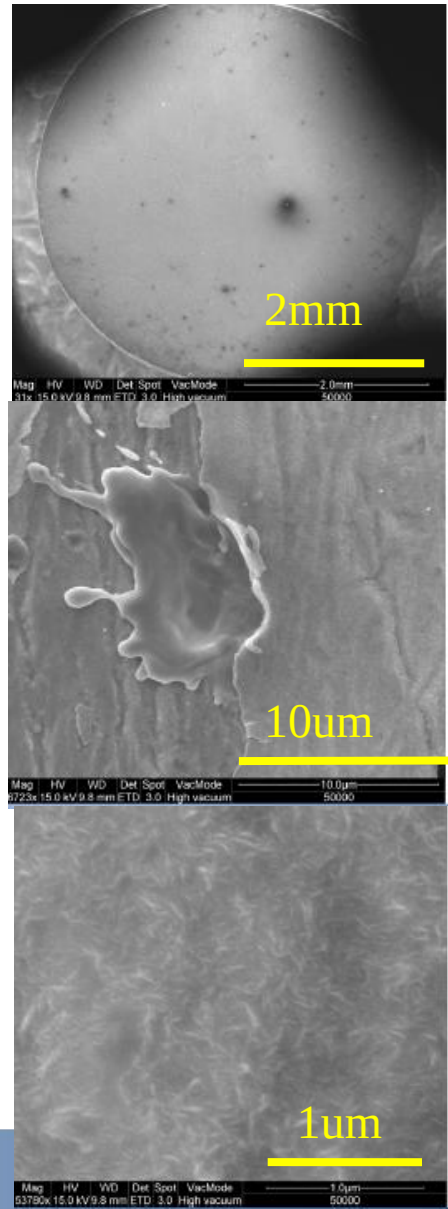


Faraday cup signal:

2 mA/cm^2@28 MV/m

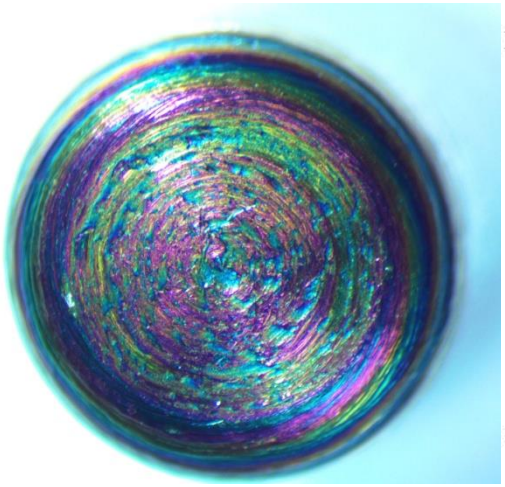


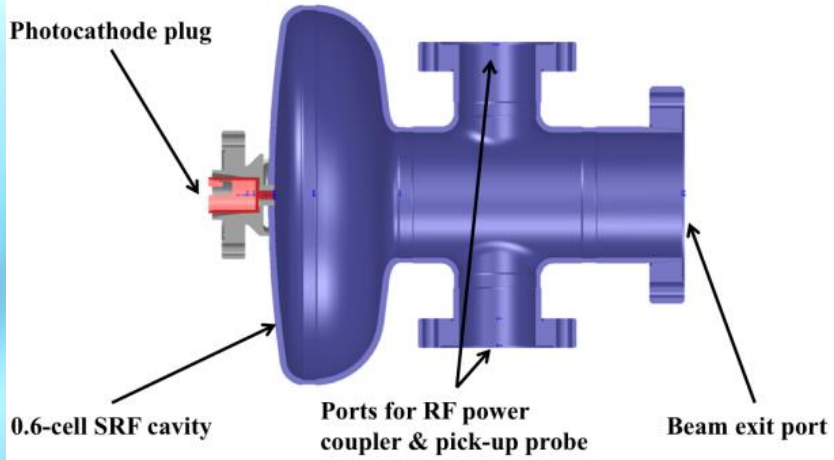
Post test SEM



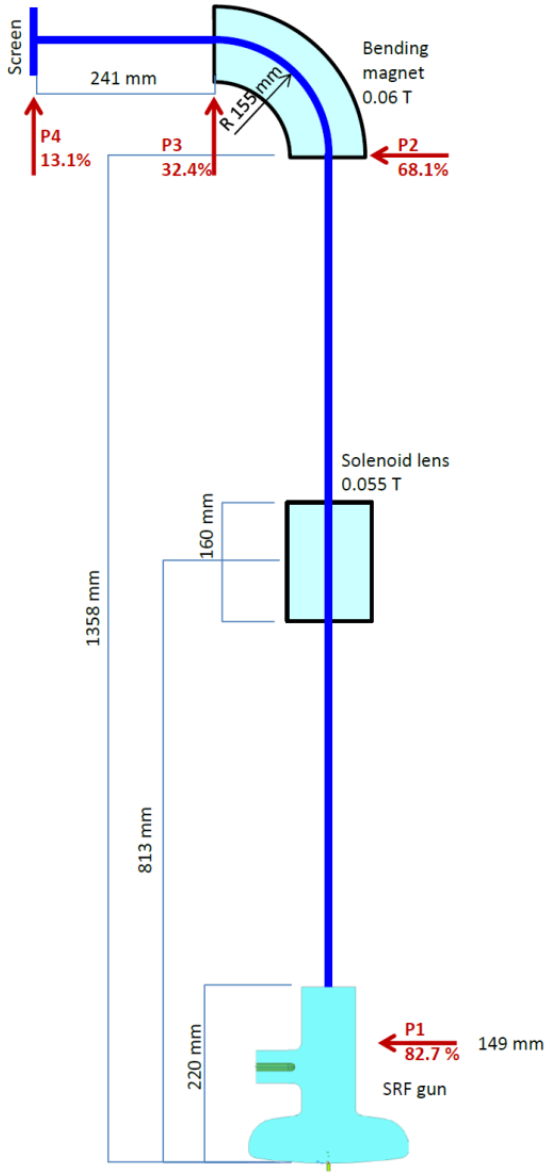
euclid TECHLABS

(N)UNCD emitter in TESLA 1.3 GHz gun:

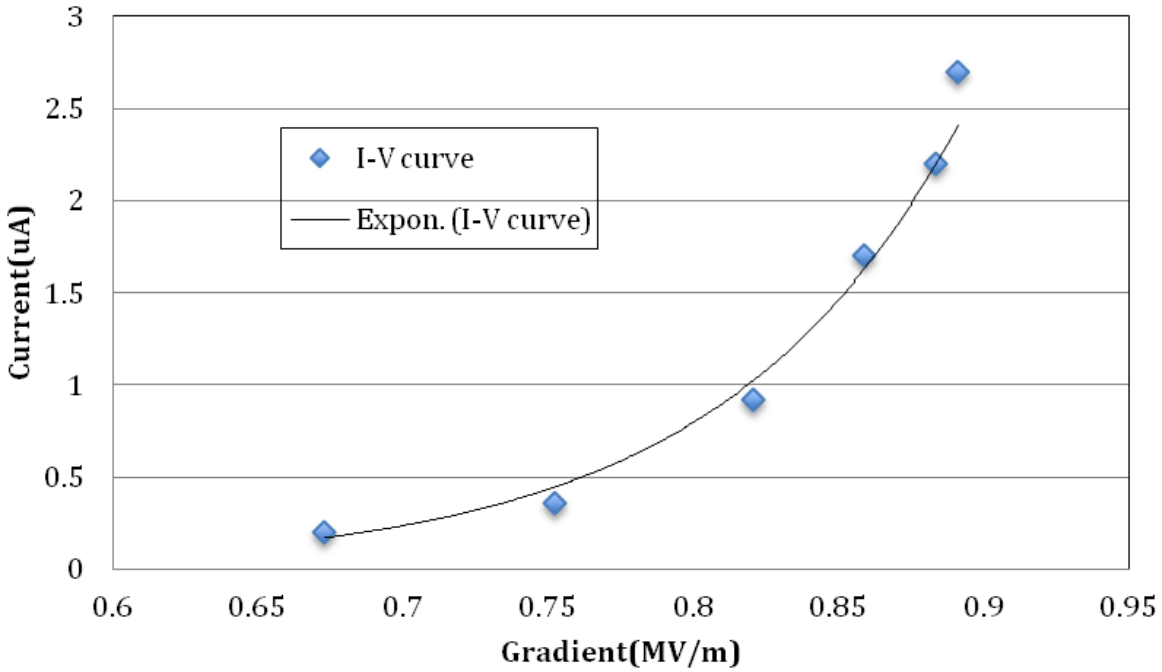




First to Date Experimental Emission Data



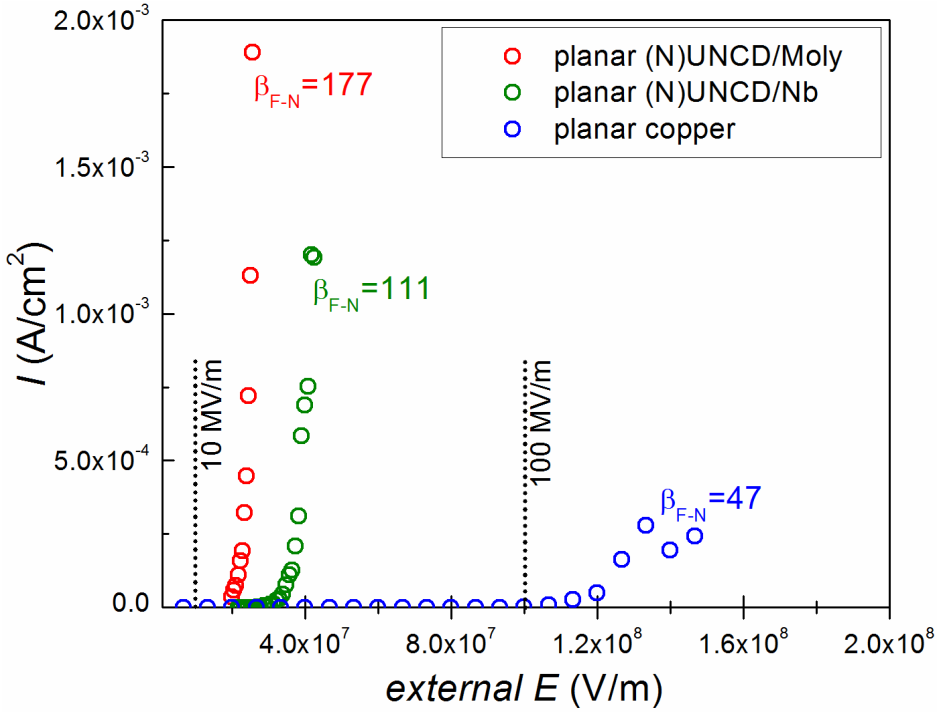
3 μA→3mA/cm² @
~1 MV/m under 2 Kelvin



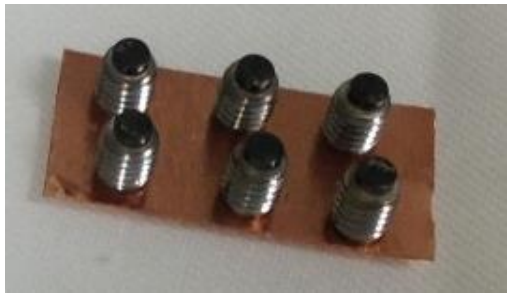
~ Emitted in the gun

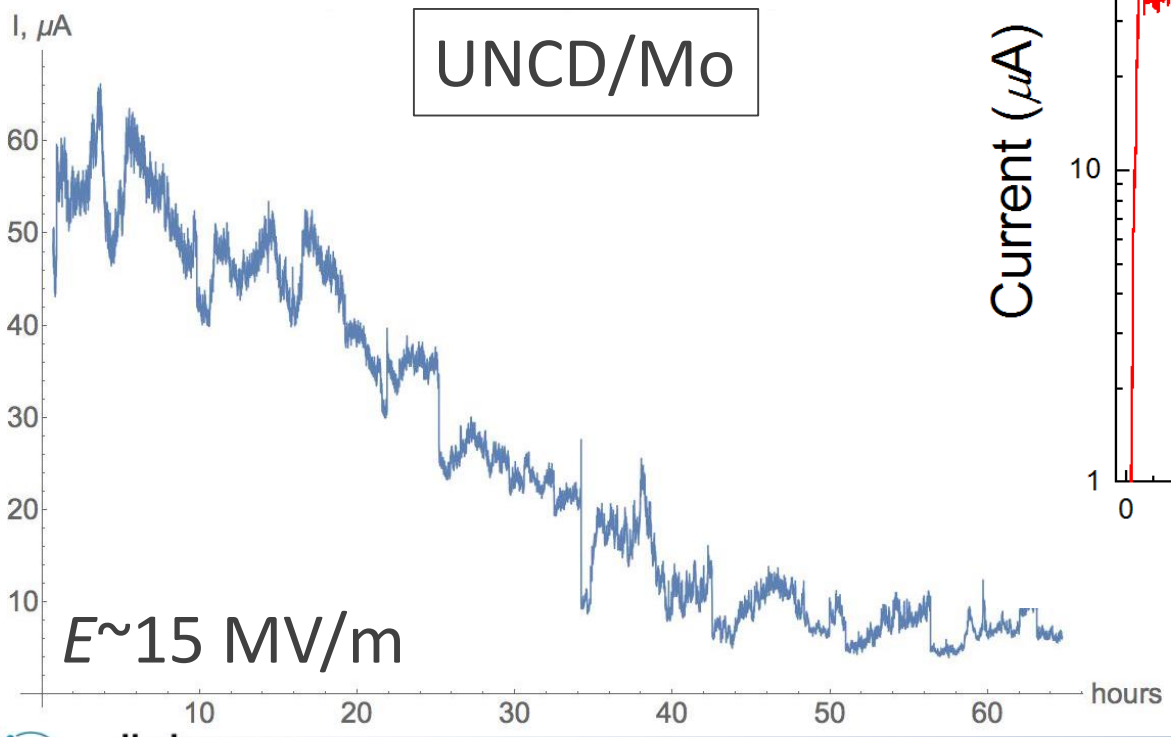
~ Detected at P4, 1.5 m away from the gun after 90° bending magnet

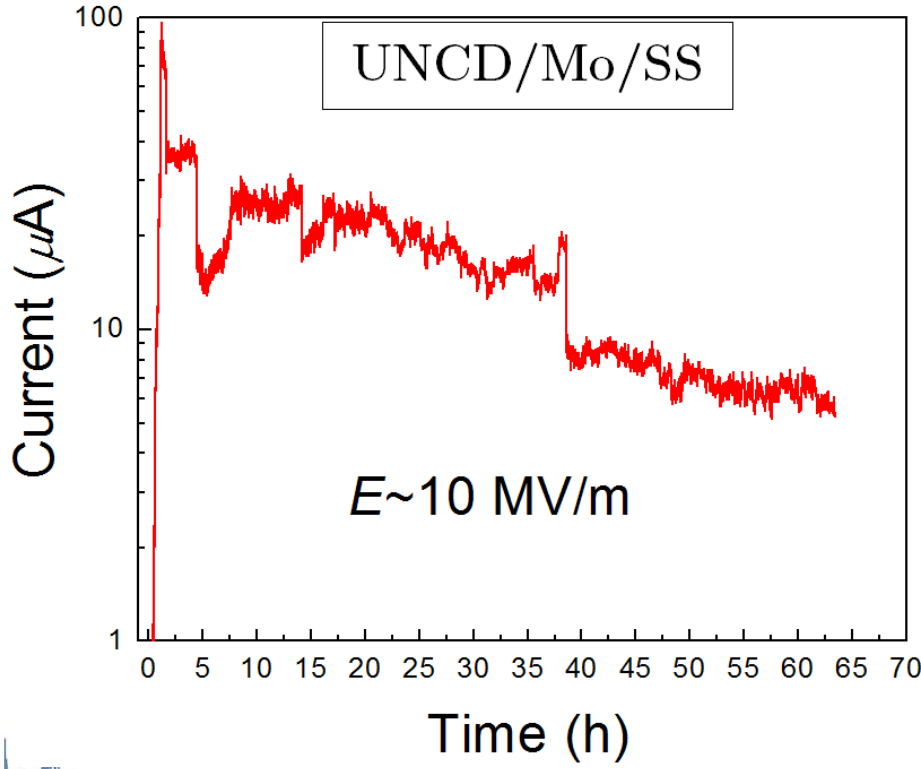
(N)UNCD at DC Test Stand: I/V curve



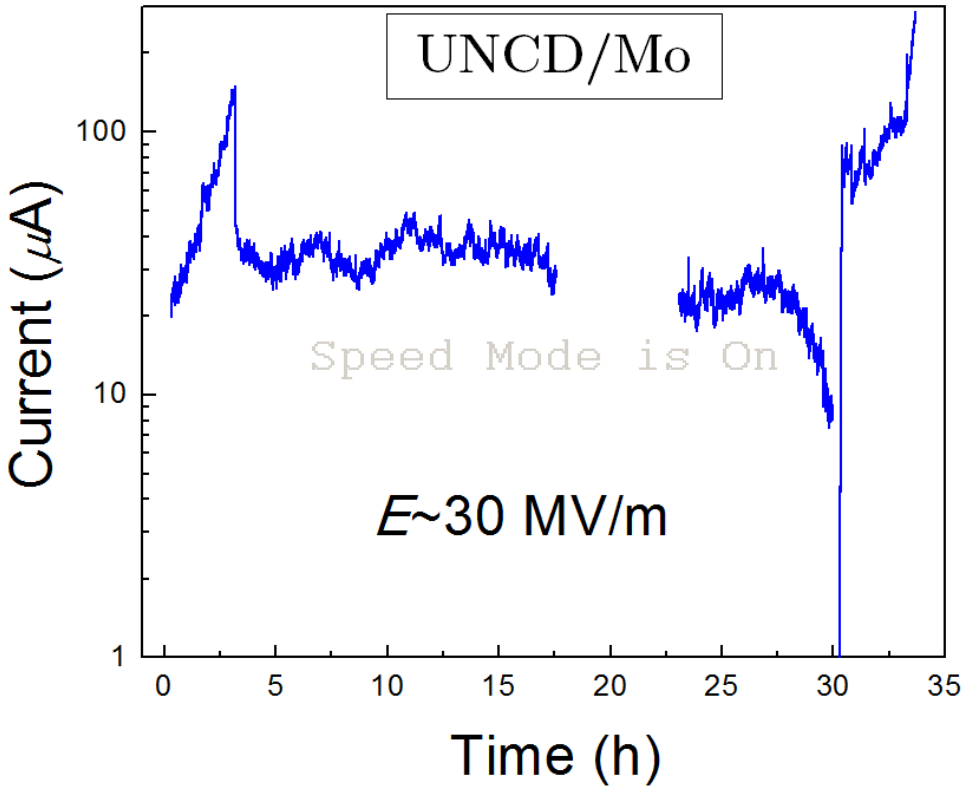
(N)UNCD at DC Test Stand: lifetime test

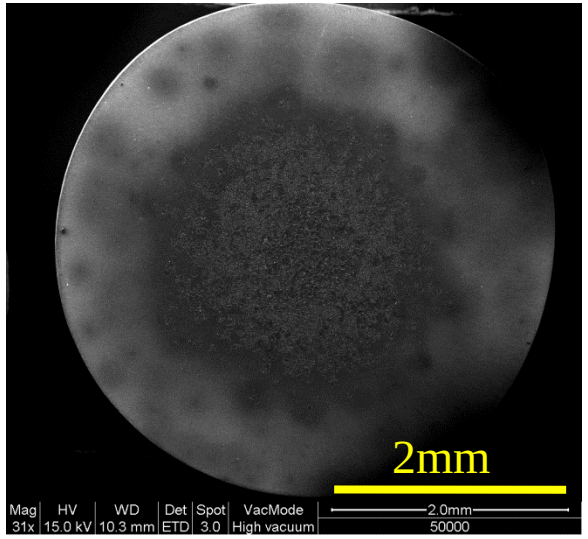


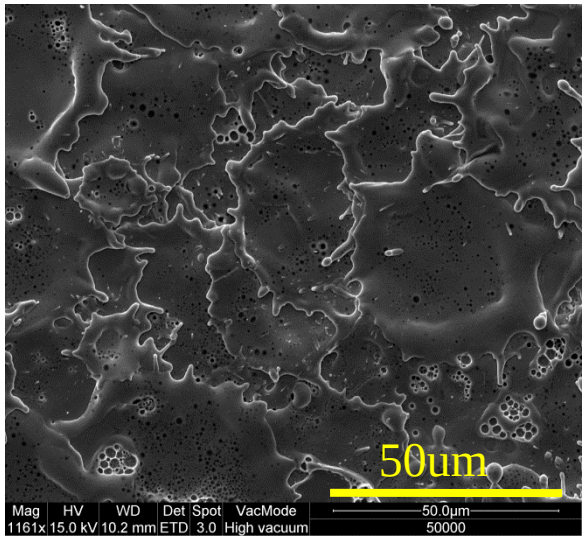




(N)UNCD at DC Test Stand: degradation and breakdown

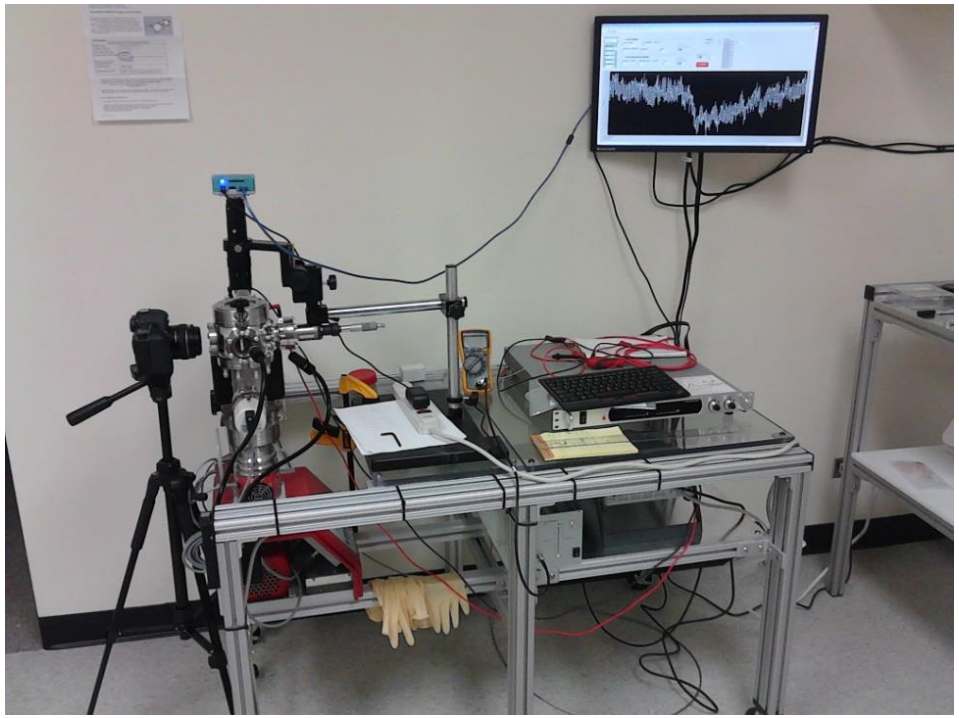


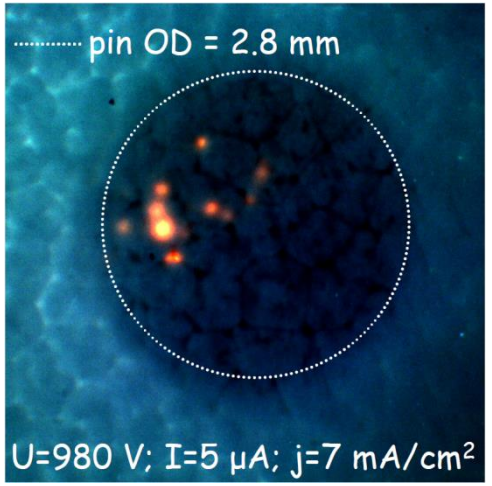


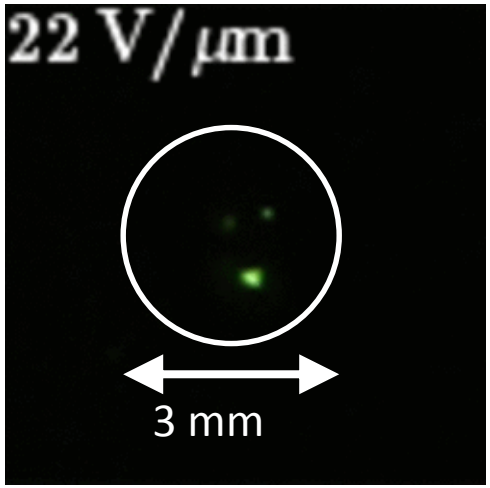


(N)UNCD at DC Imaging Test Stand

UNCD/Mo/SS: ~5/1000 of total area is emitting







What's going on inside?

Field of view is 4.4 mm

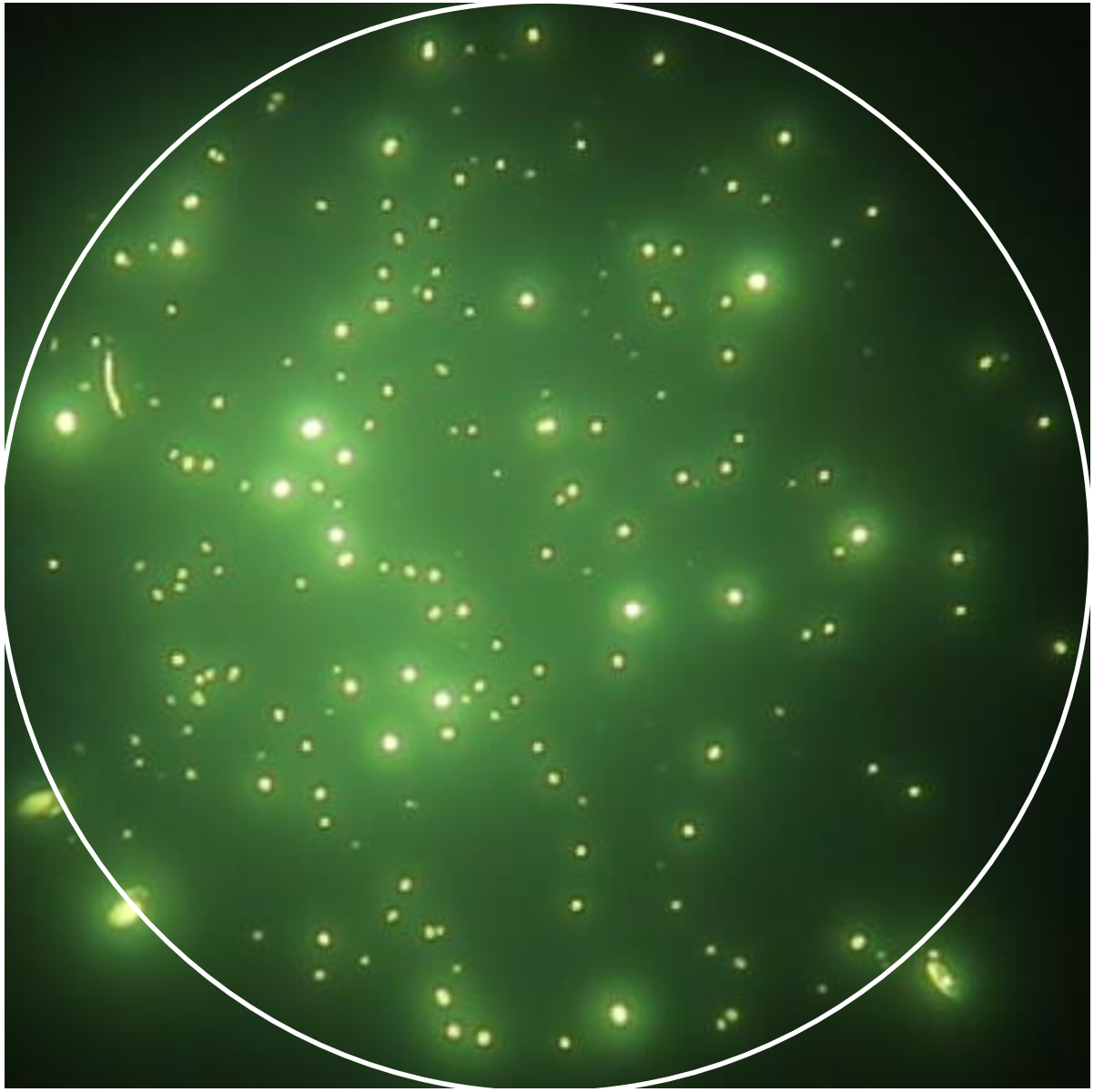
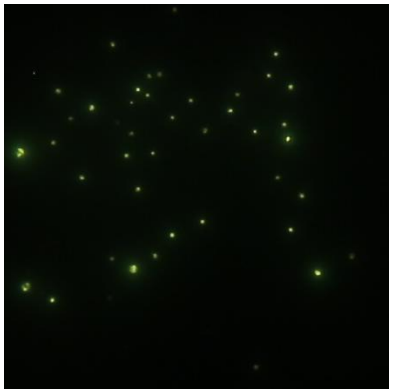
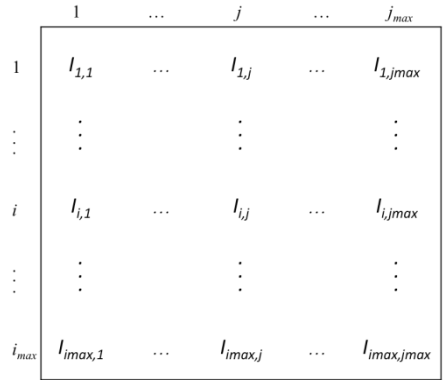
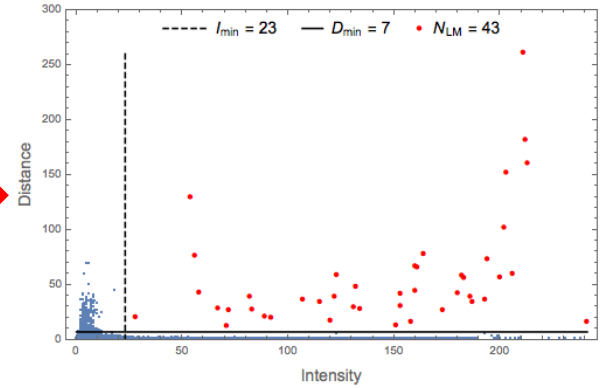
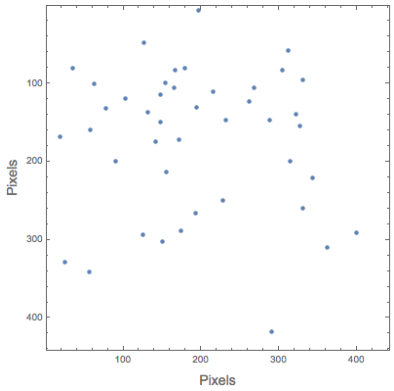


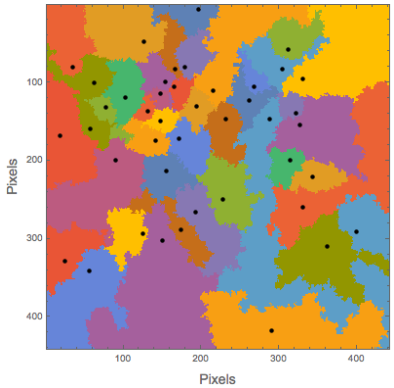
Image processing algorithm

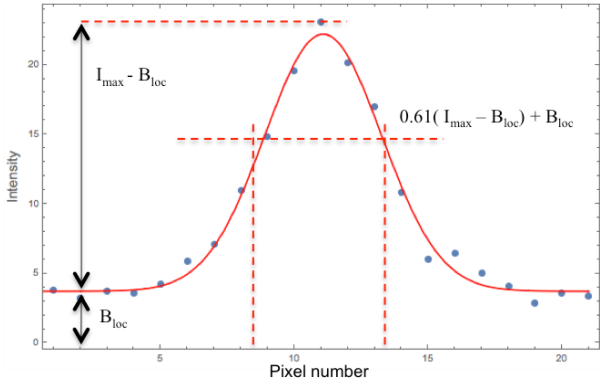


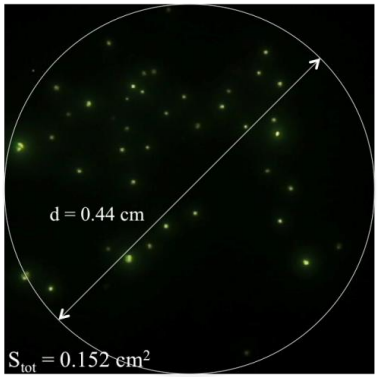


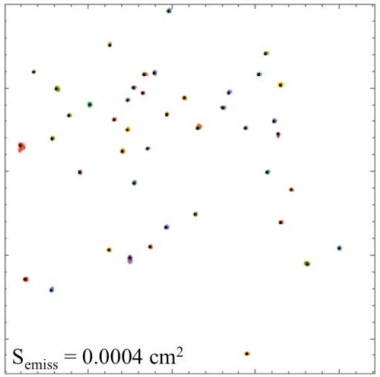






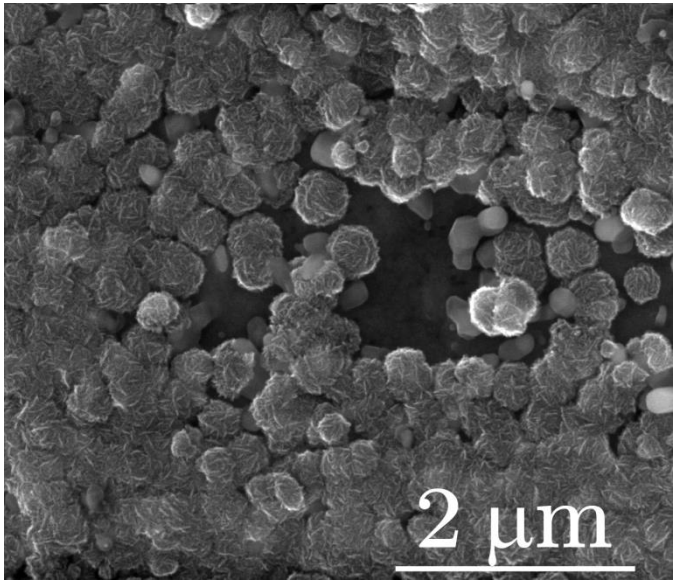


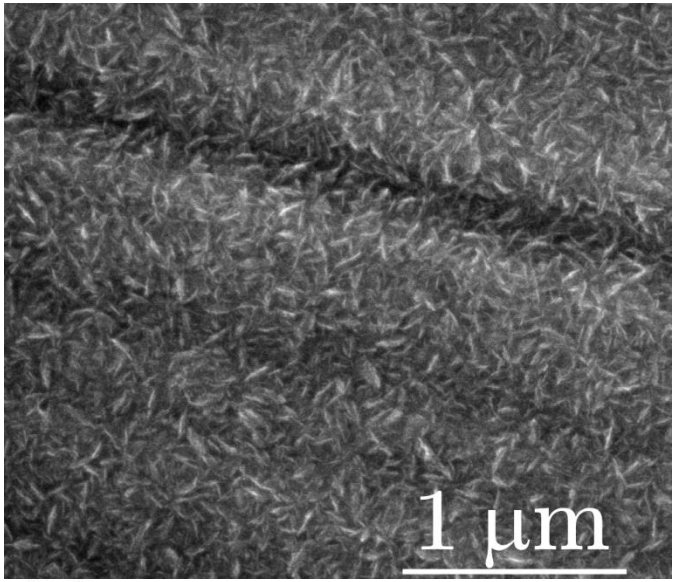


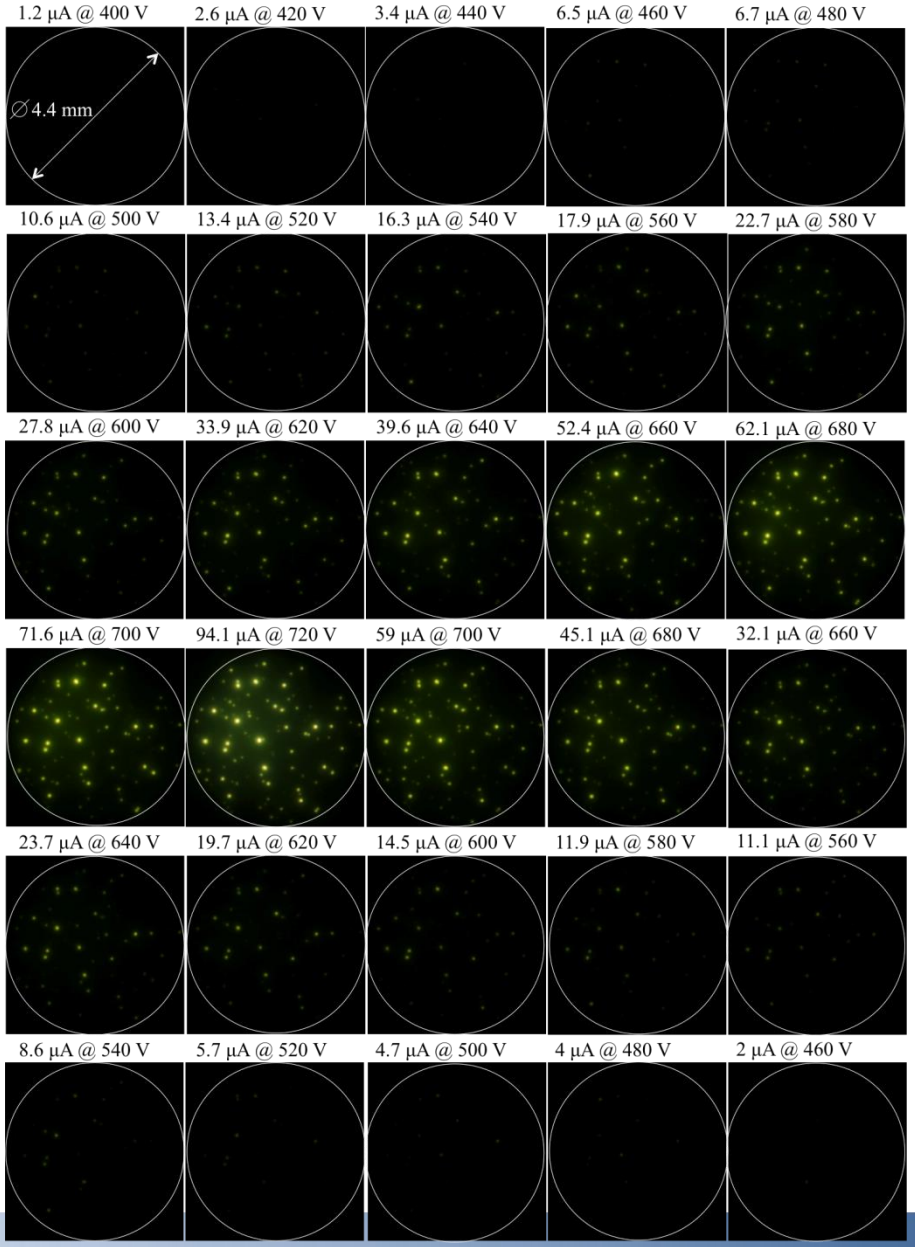


Refs:
Gavriil *et al*, Astrophysical J. **607**, 959 (2004);
Zepka *et al*, Astrophysical J. **427**, 438 (1994);
Rodriguez and Laio, Science **344**, 1492 (2014)

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







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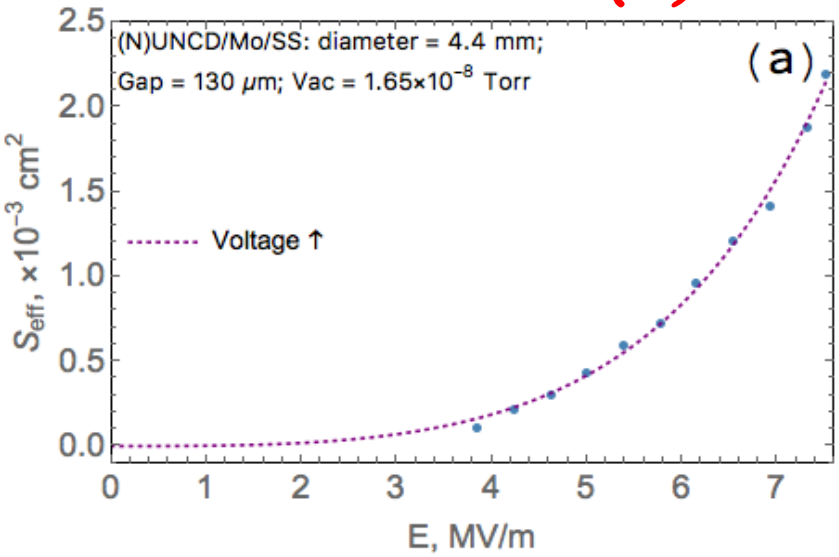
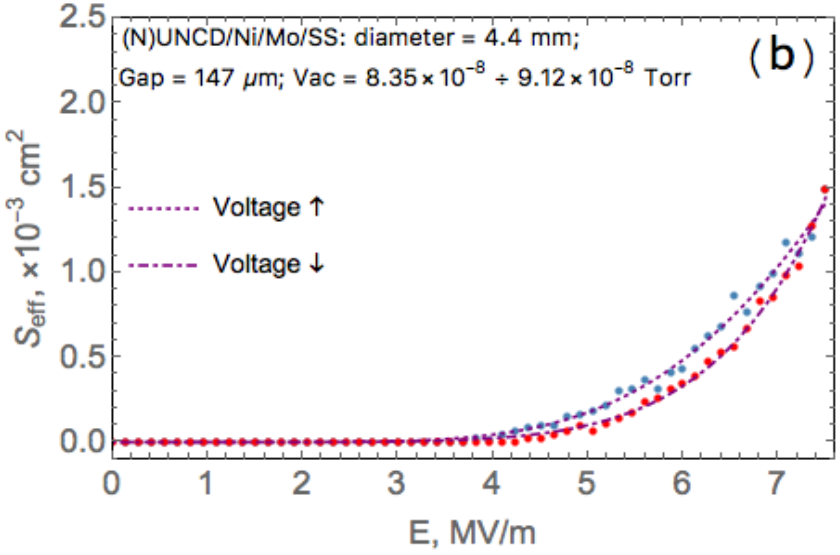
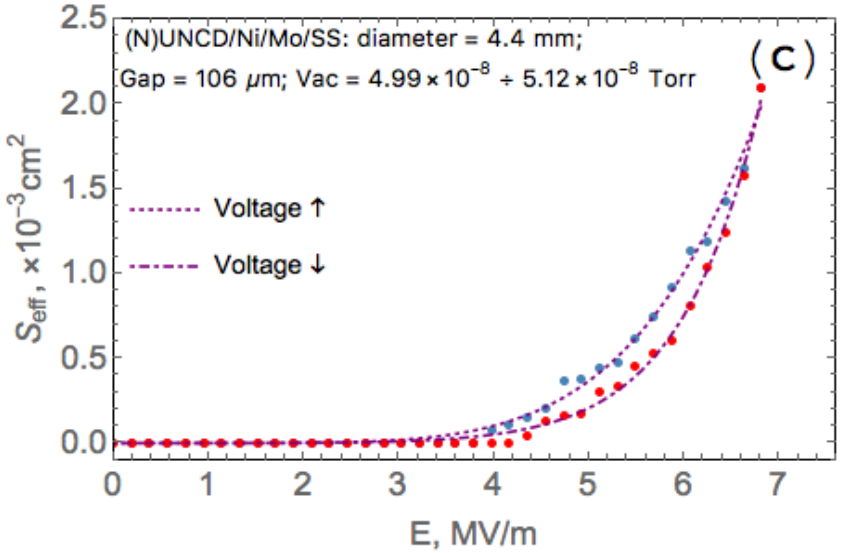
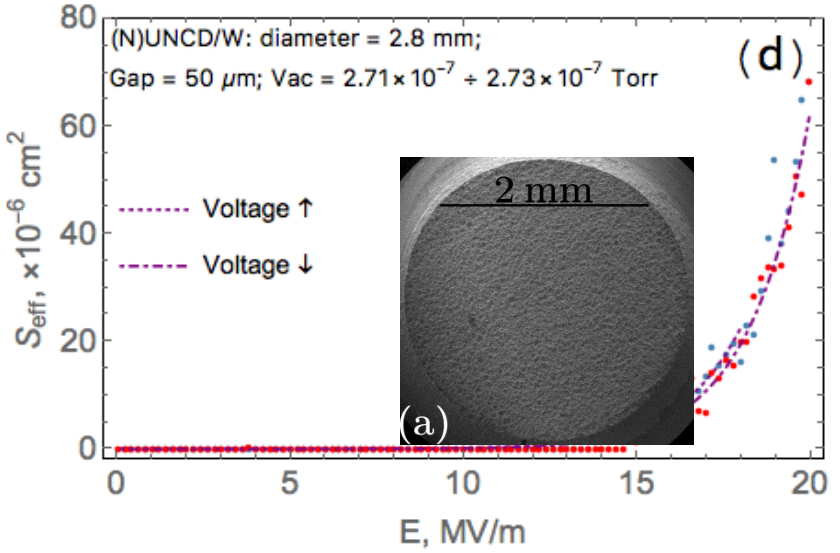
More samples: *S* depends on *E*

S(E) is not a *const*



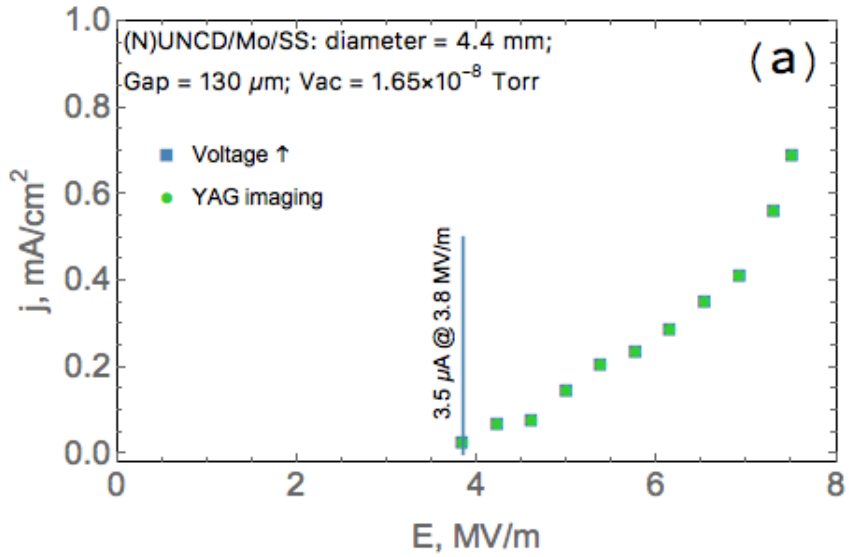


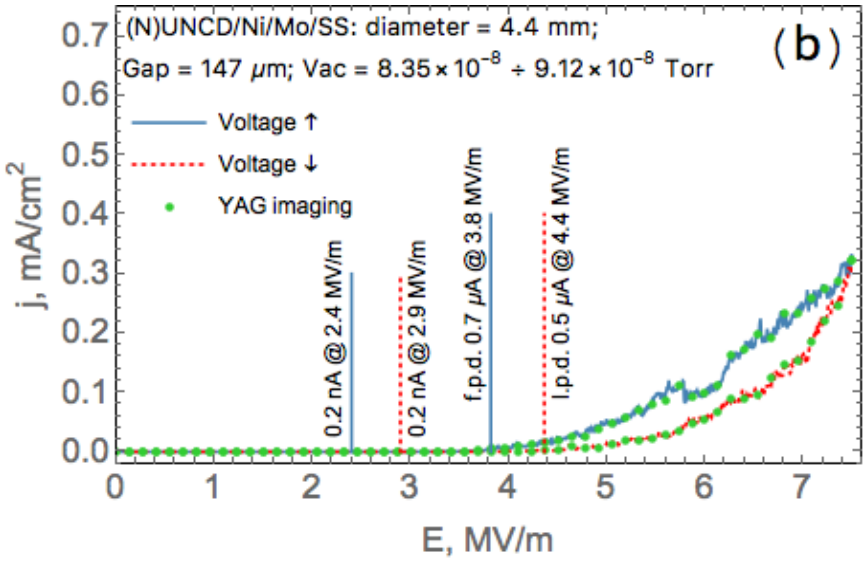


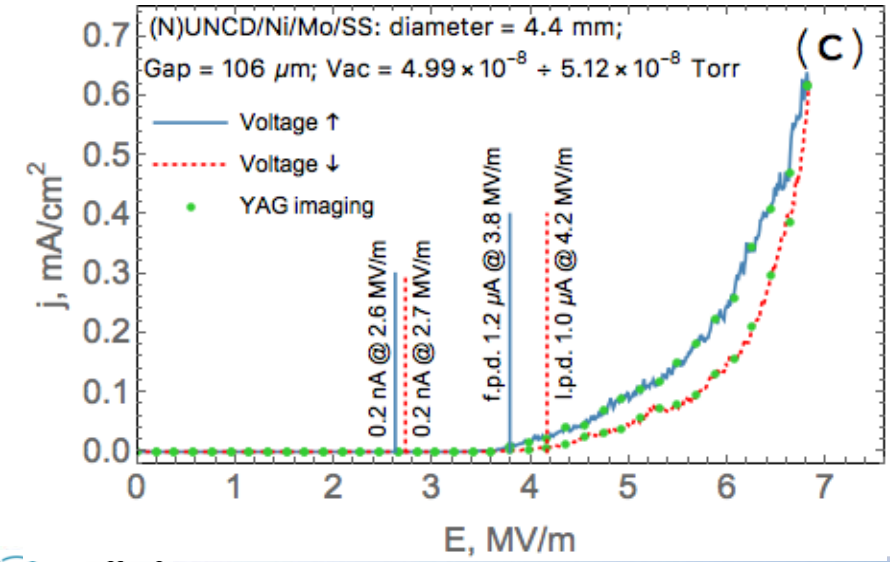


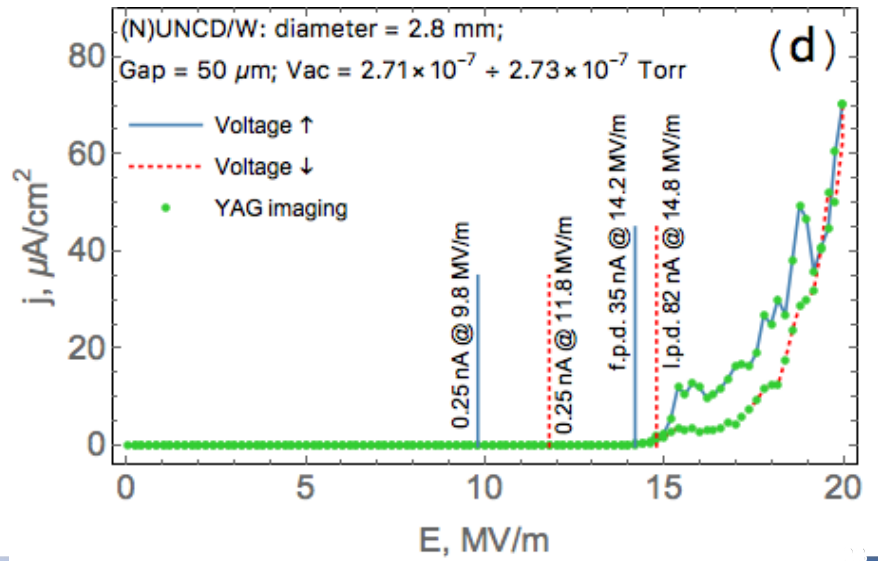
More samples: as measured *I-E* curves

By convention, $I \rightarrow j$ assuming $S(E) = S_{cathode} = const$



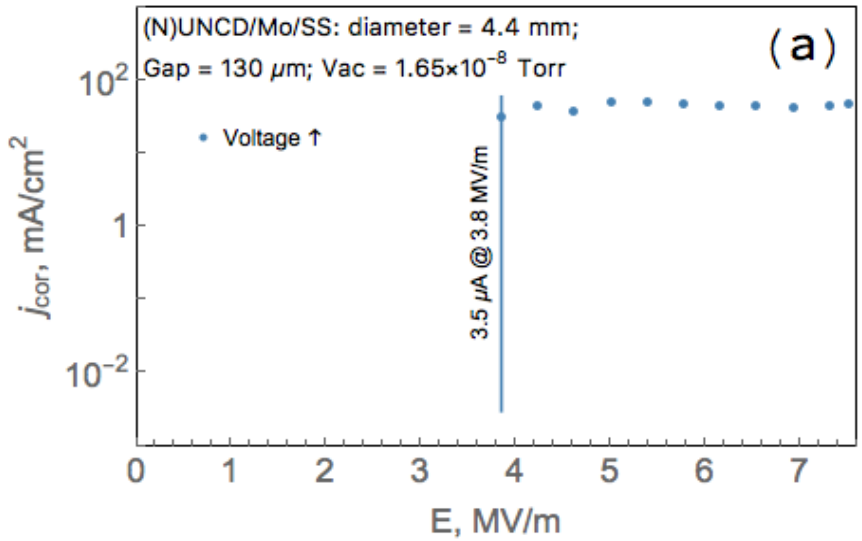


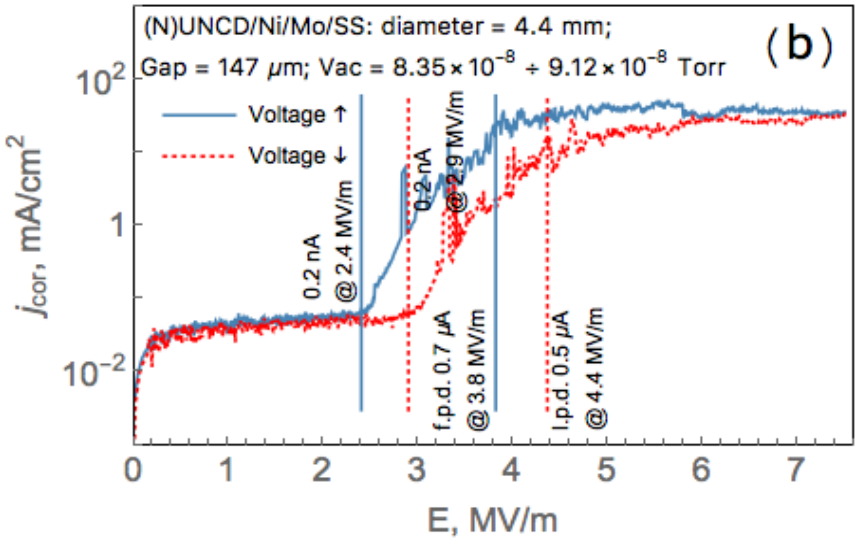


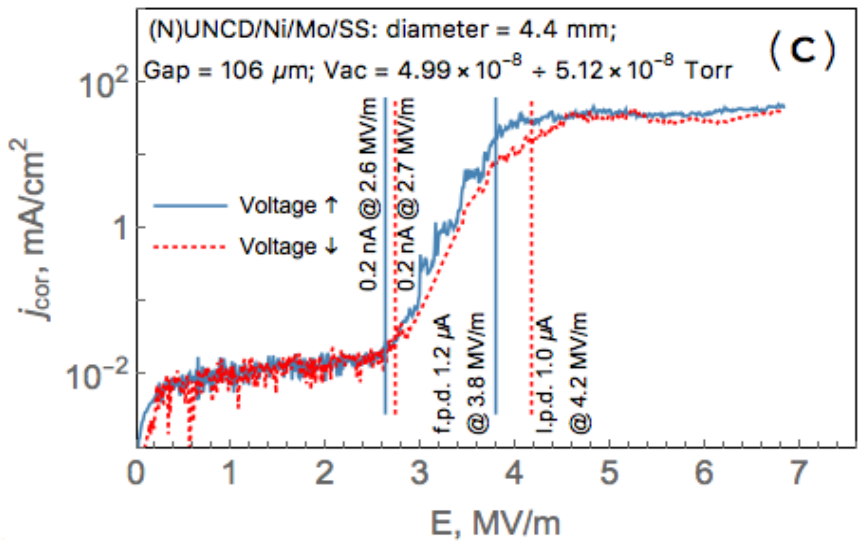


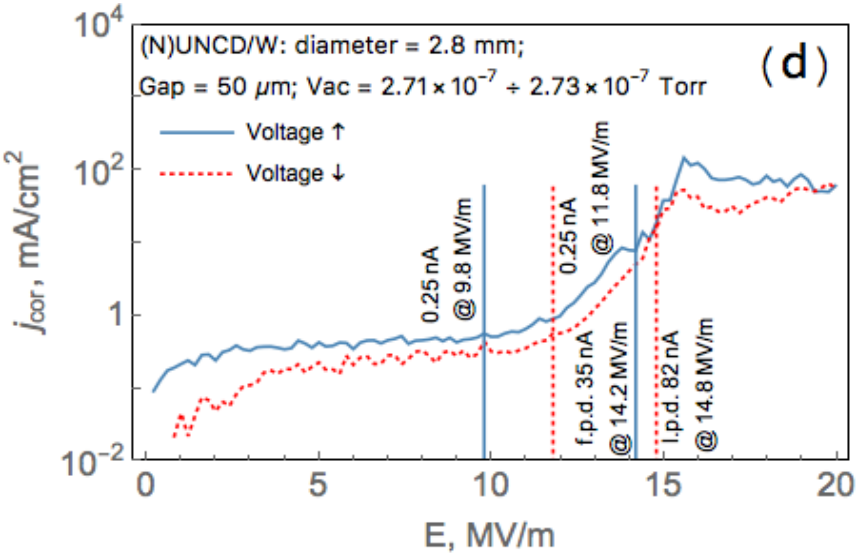
More samples: *S*-corrected *j-E*

$j_{cor}=I/S(E)$









5 Takeout Notes (Discoveries)

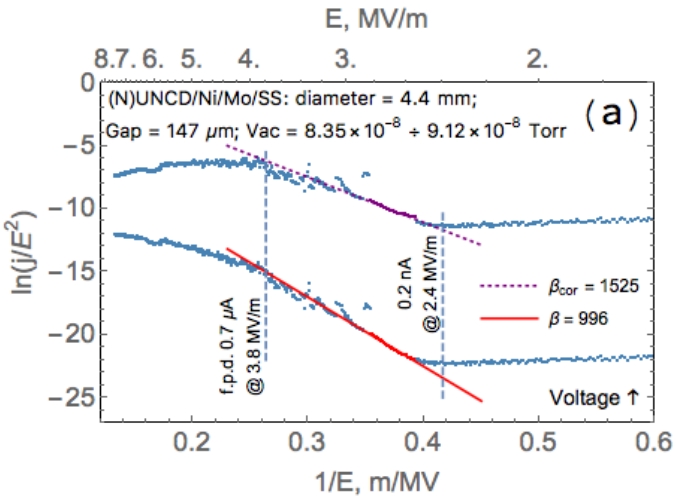
1. Semi-metallic (N)UNCD saturates similarly to semiconductors: **non-FN non-metallic field emitters**

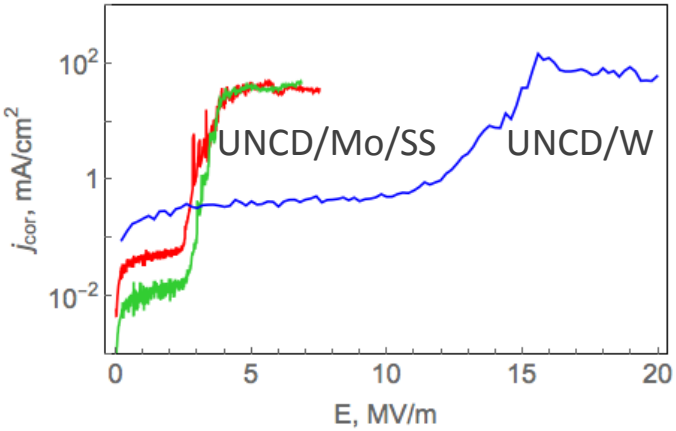
2. In planar uniform (N)UNCD, field emission is not uniform

3. Emission area depends on electric field

4. Saturation is ~100 mA/cm^2 is specific to (N)UNCD, regardless of substrate

5. Roughness and topography are not prerequisites for good FE properties. Chemistry of the substrate is a key





Conclusions

- *n*-type (N)UNCD is a promising field emitter that is already available for RF injectors and other applications (the 1st sale is under contract)
- (N)UNCD is a remarkable platform to keep finding and understanding fundamental processes in field emitters

Next

- More tests are schedules at ACT (AWA Cathode Teststand) to in-situ image the UNCD emission under high gradient RF.
- Expand DC imaging system capable of measuring MTE of UNCD emitter

Acknowledgments

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