https://www.egr.msu.edu/mam/

Light and Electron Emission as Breakdown Probes in X-band rf microscope

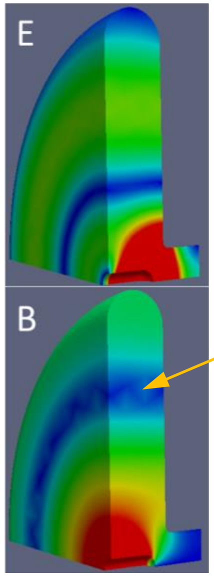
Taha Posos, Mitchell Schneider, Emily Jevarjian and Sergey V Baryshev
Electrical Engineering, Michigan State University

Zenghai Li and Sami Tantawi
Stanford Linear Accelerator Center

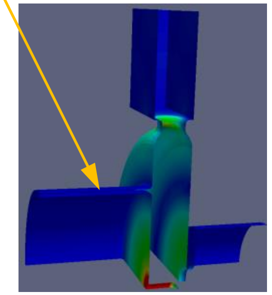
9th MevArc, March 12, 2021

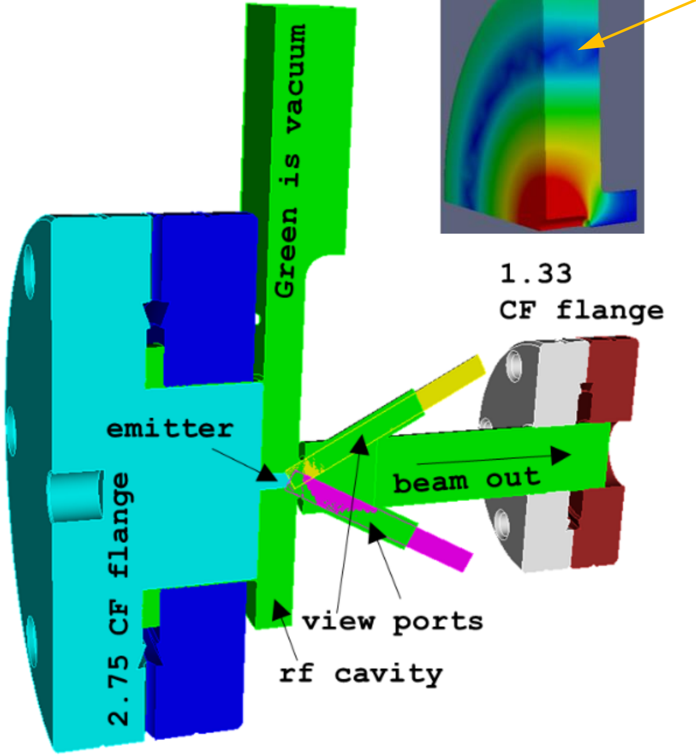
What and how are we building?

rf design



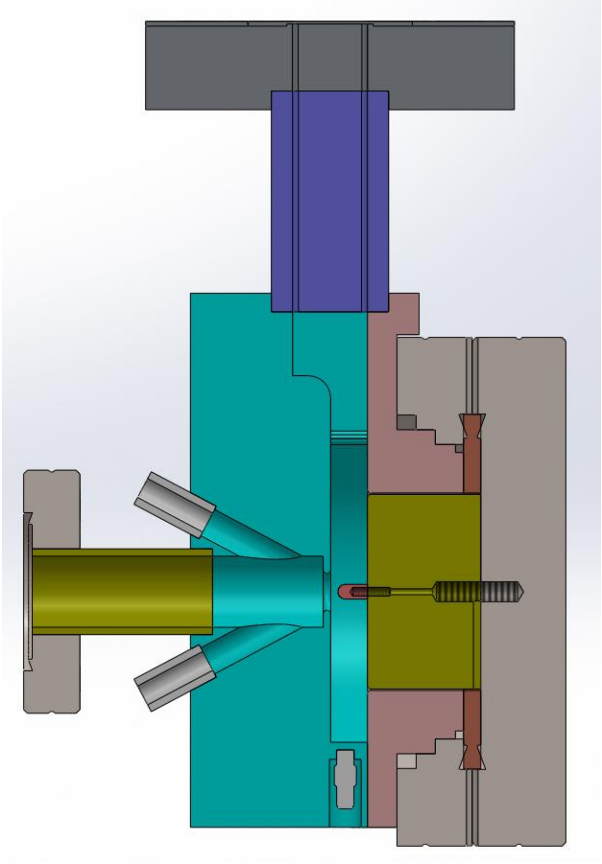
sample port designed around the zero B contour



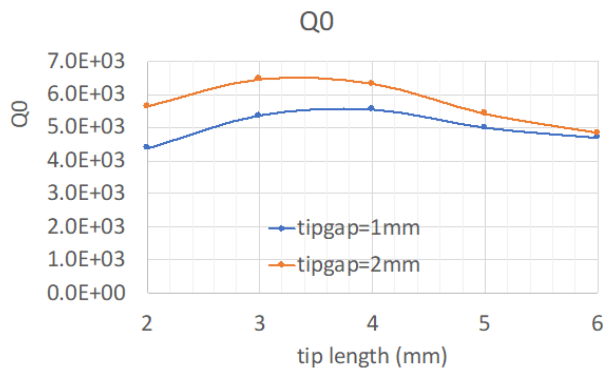


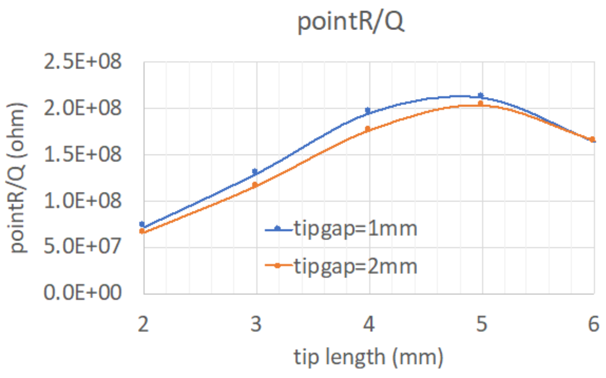
TM02 11.4 GHz gun

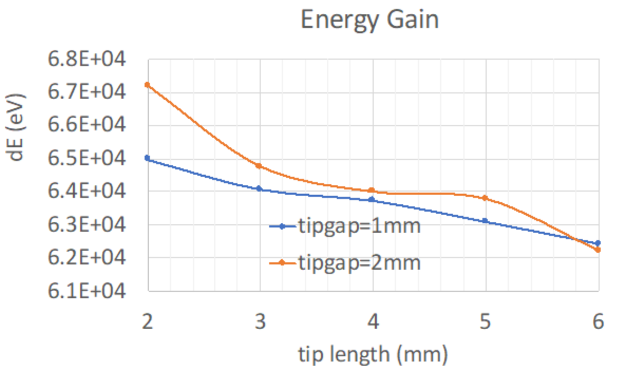
mechanical design

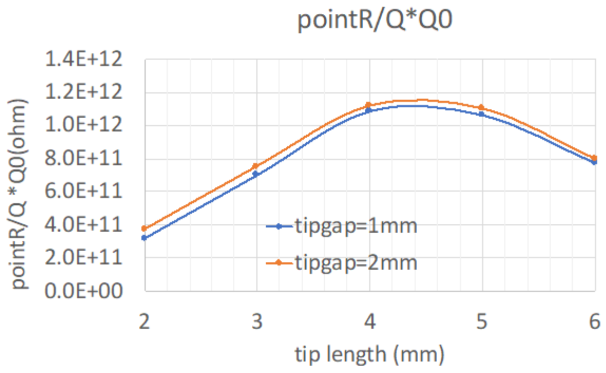


More details on design

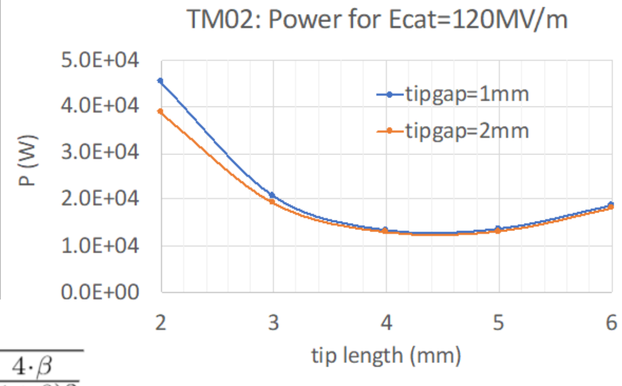








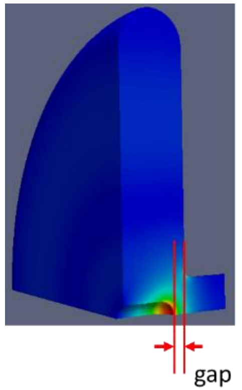
$$\frac{pointR}{Q} = \frac{E^2_{cathode}}{\omega \cdot U}$$

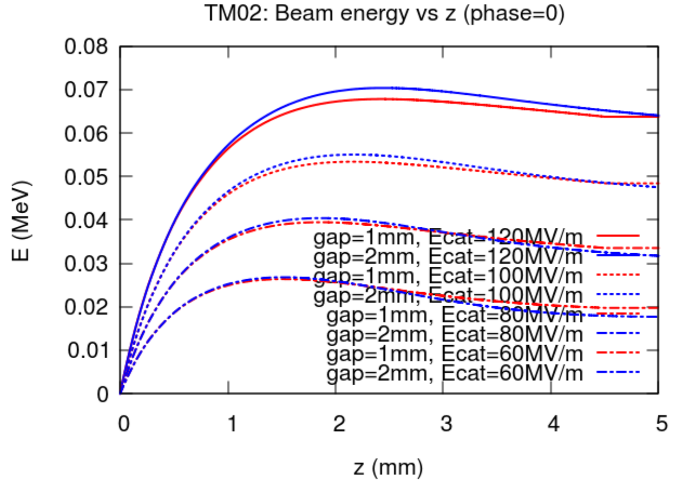


$$Power = \frac{E^2_{cathode}}{\frac{pointR}{Q} \cdot Q_0 \cdot \frac{4 \cdot \beta}{(1+\beta)^2}}$$

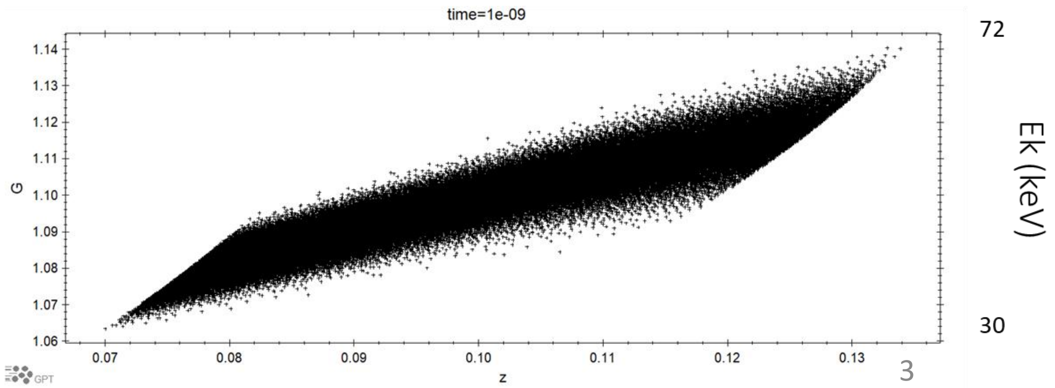
15 kW to achieve a field close to 120 MV/m

Impact-T

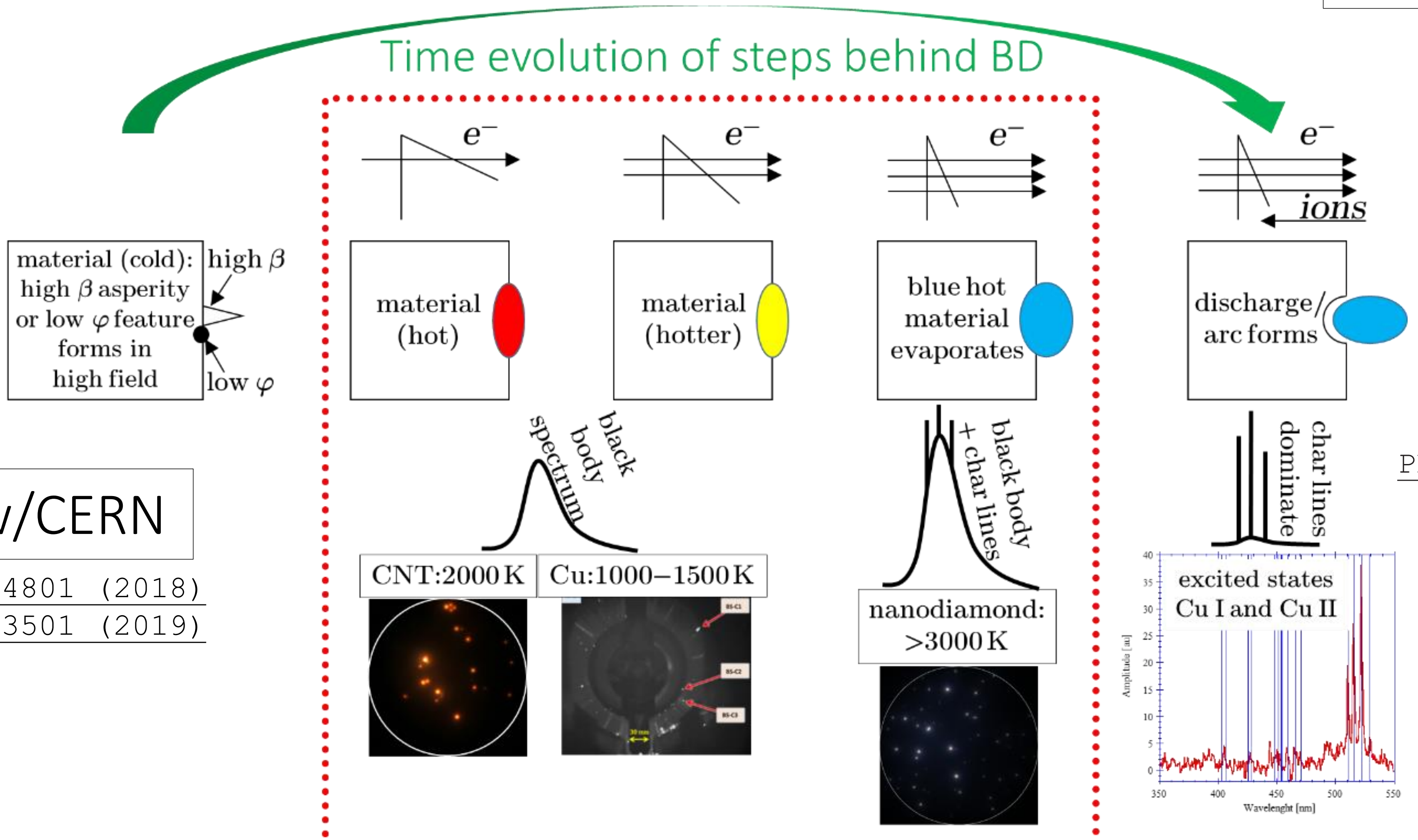




FEgen+GPT



Evolution of steps leading to BD and discharge

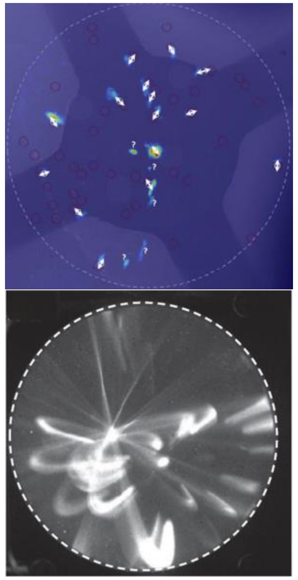


Hebrew/CERN

PRL 120, 124801 (2018)

PRAB 22, 083501 (2019)

AWA



PRL 117, 084801 (2016)

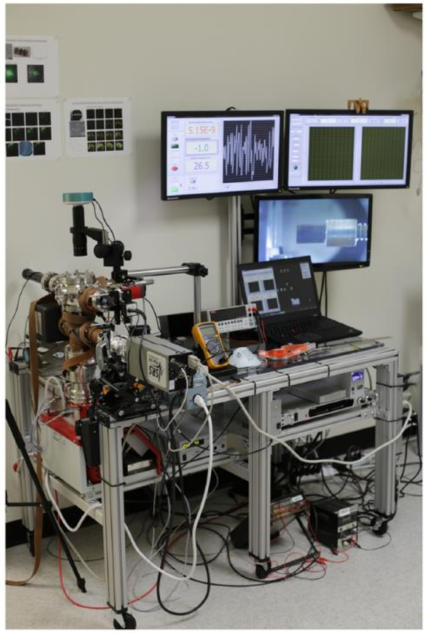
electron current ~7 kA

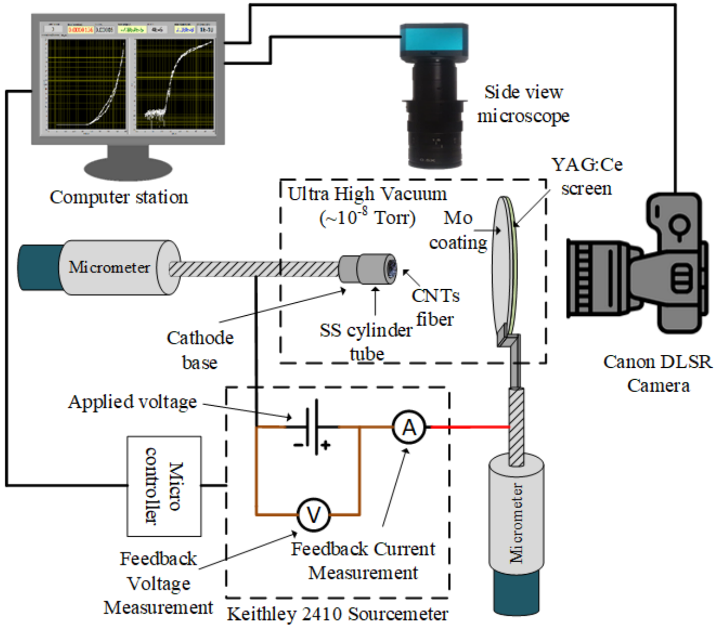
ion current ~30 A

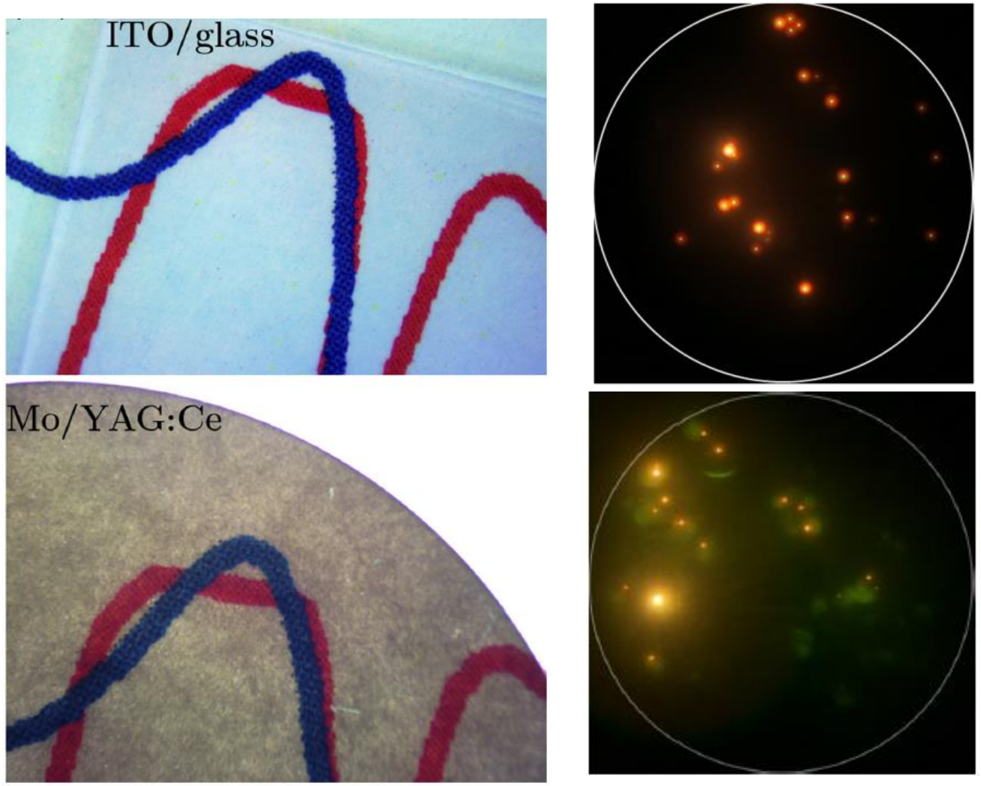
SLAC

SLAC-PUB-10355

Red light from CNT



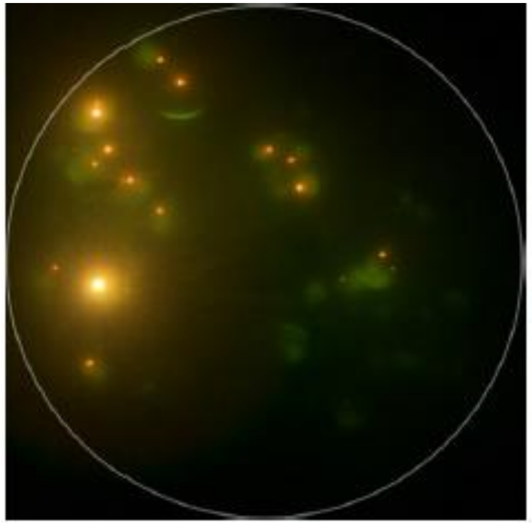




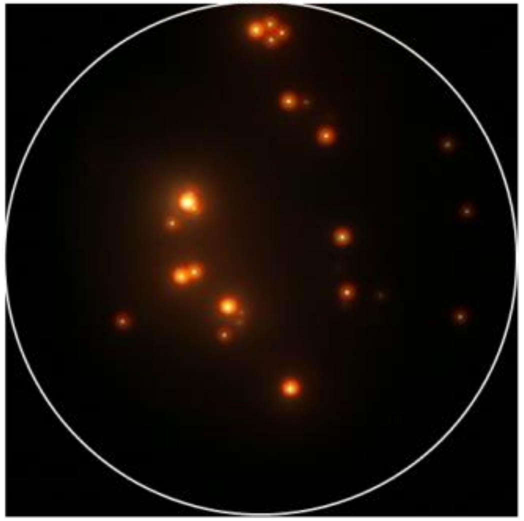
RSI **88**, 033701 (2017); JVSTB **38**, 024006 (2020)

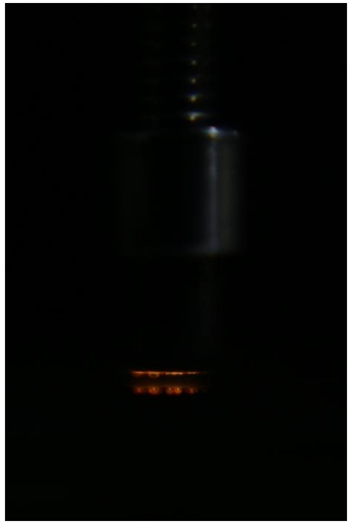
Red light is a common effect for CNT

YAG screen



ITO screen





VOLUME 88, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 2002

Hot Nanotubes: Stable Heating of Individual Multiwall Carbon Nanotubes to 2000 K Induced by the Field-Emission Current

S. T. Purcell,* P. Vincent, C. Journet, and Vu Thien Binh

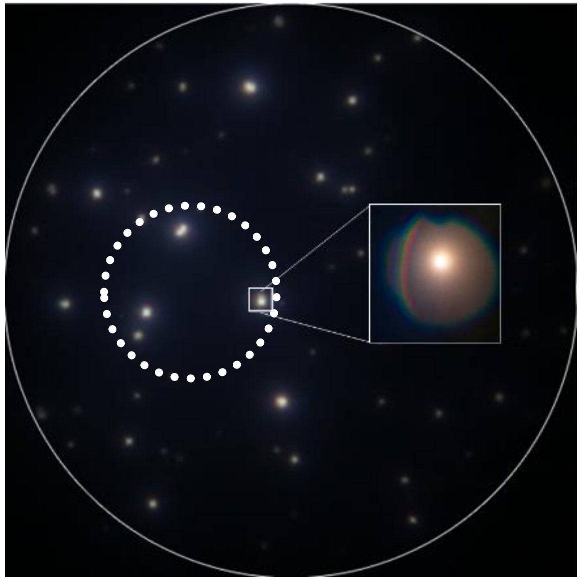
Laboratoire d'Émission Électronique, DPM UMR CNRS 5586, Université Lyon-1, Villeurbanne 69622, France

(Received 27 October 2001; published 20 February 2002)

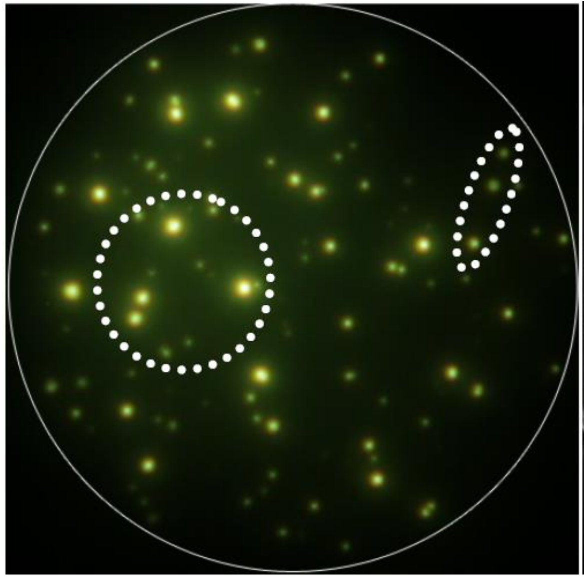
Field emission (FE) electron spectroscopy from an individual multiwalled carbon nanotube (MWNT) is used to measure quantitatively stable temperatures at the apex, T_A, of up to 2000 K induced by FE currents ≈1 μA. The high T_A is due to Joule heating along the length of the MWNT. These measurements also give directly the resistance of the individual MWNT which is shown to decrease with temperature, and explain the phenomenon of FE-induced light emission which was observed simultaneously. The heating permits thermal desorption of the MWNT and, hence, excellent current stability.

Blue light from *n*-type nanodiamond

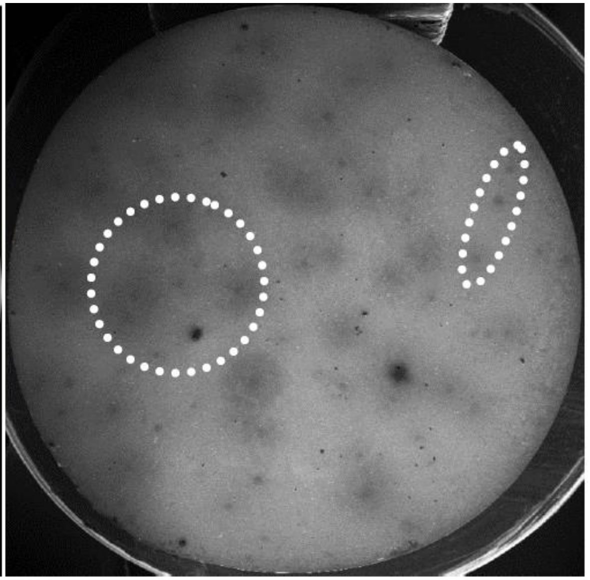
ITO



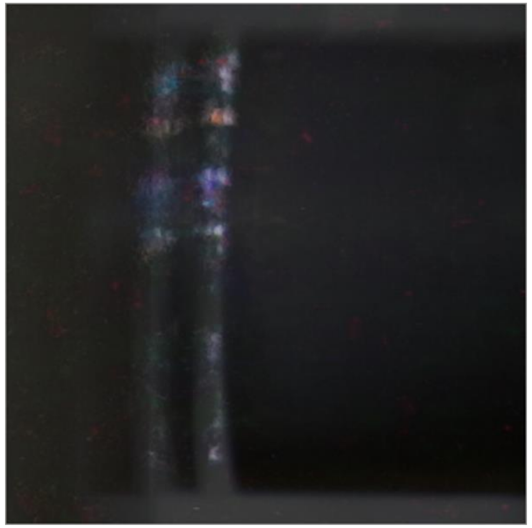
YAG



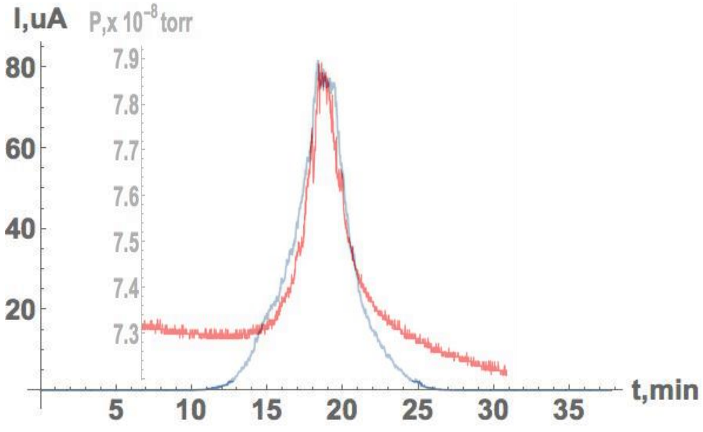
SEM



Side-view into the gap



Current/pressure vs. time



Nottingham or Joule heating

VOLUME 13, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1964

NOTTINGHAM EFFECT IN FIELD AND *T*-*F* EMISSION: HEATING AND COOLING DOMAINS, AND INVERSION TEMPERATURE

F. M. Charbonnier, R. W. Strayer, L. W. Swanson, and E. E. Martin
Field Emission Corporation, McMinnville, Oregon

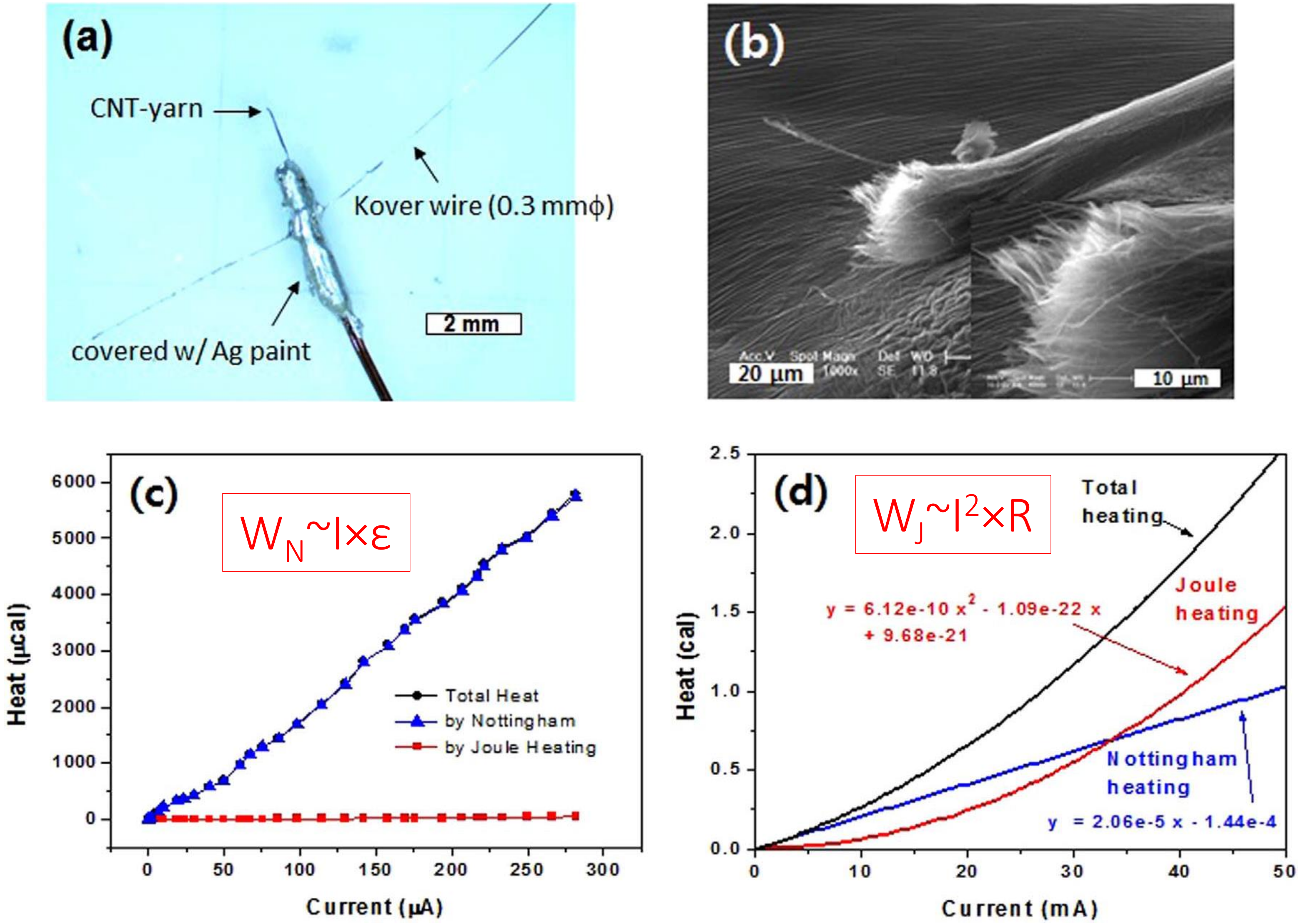
$$T_i = \frac{d}{2k} = \frac{he}{4k(2m)^{1/2}} \frac{F}{\varphi^{1/2} t(y)} \cong 5.32 \times 10^{-5} \frac{F}{\varphi^{1/2}},$$

material is tungsten

Table I. Inversion temperatures at various currents.

Emitted current (μA)	Cathode field (10^7 V/cm)	Inversion temperature (°K) Calculated by Eq. (3) with $\varphi \cong 4.5$ eV	Derived from $H_N(T)$ data
50	4.79	1200	1092
100	5.02	1260	1160
200	5.30	1326	1250
300	5.42	1360	1360

Or both?!

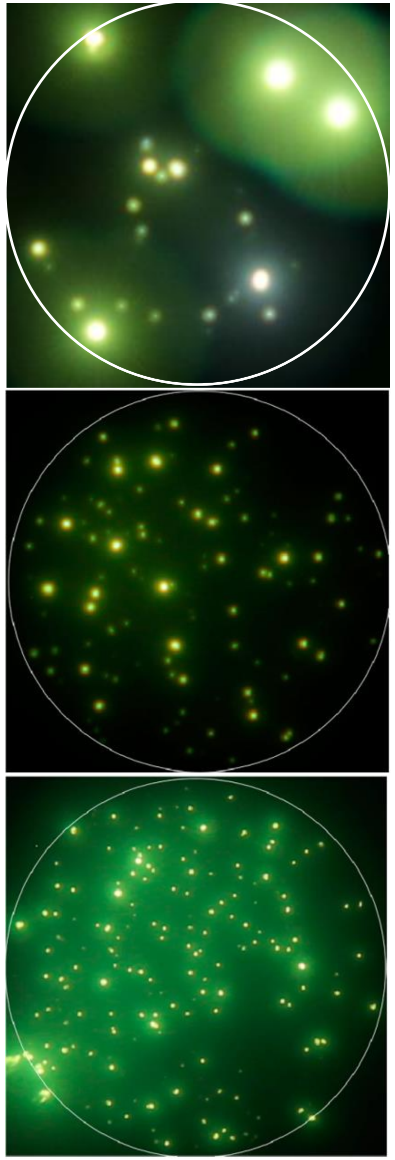


Physica E **86**, 52 (2017)

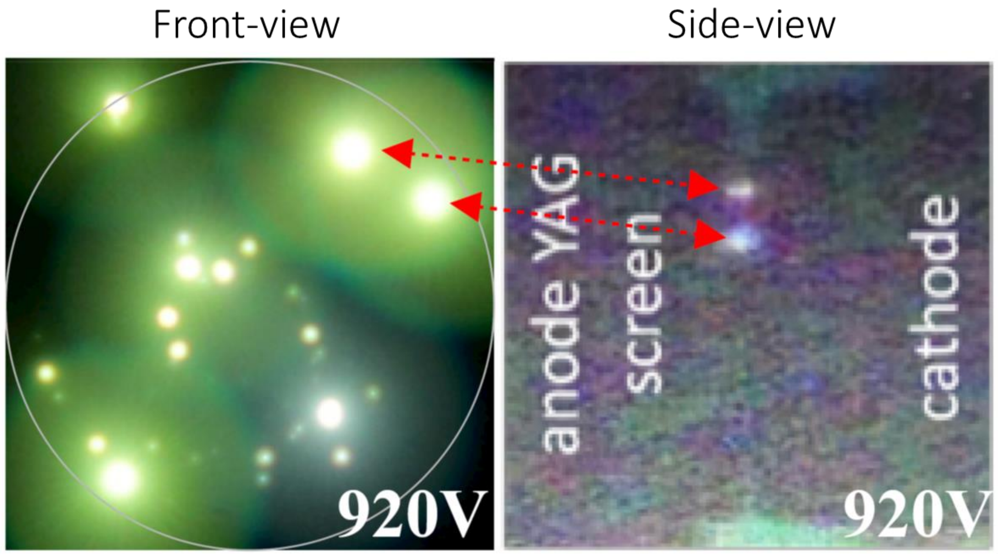
Designer cathodes attesting thermal scenario

All samples

~100 μA@1 kV

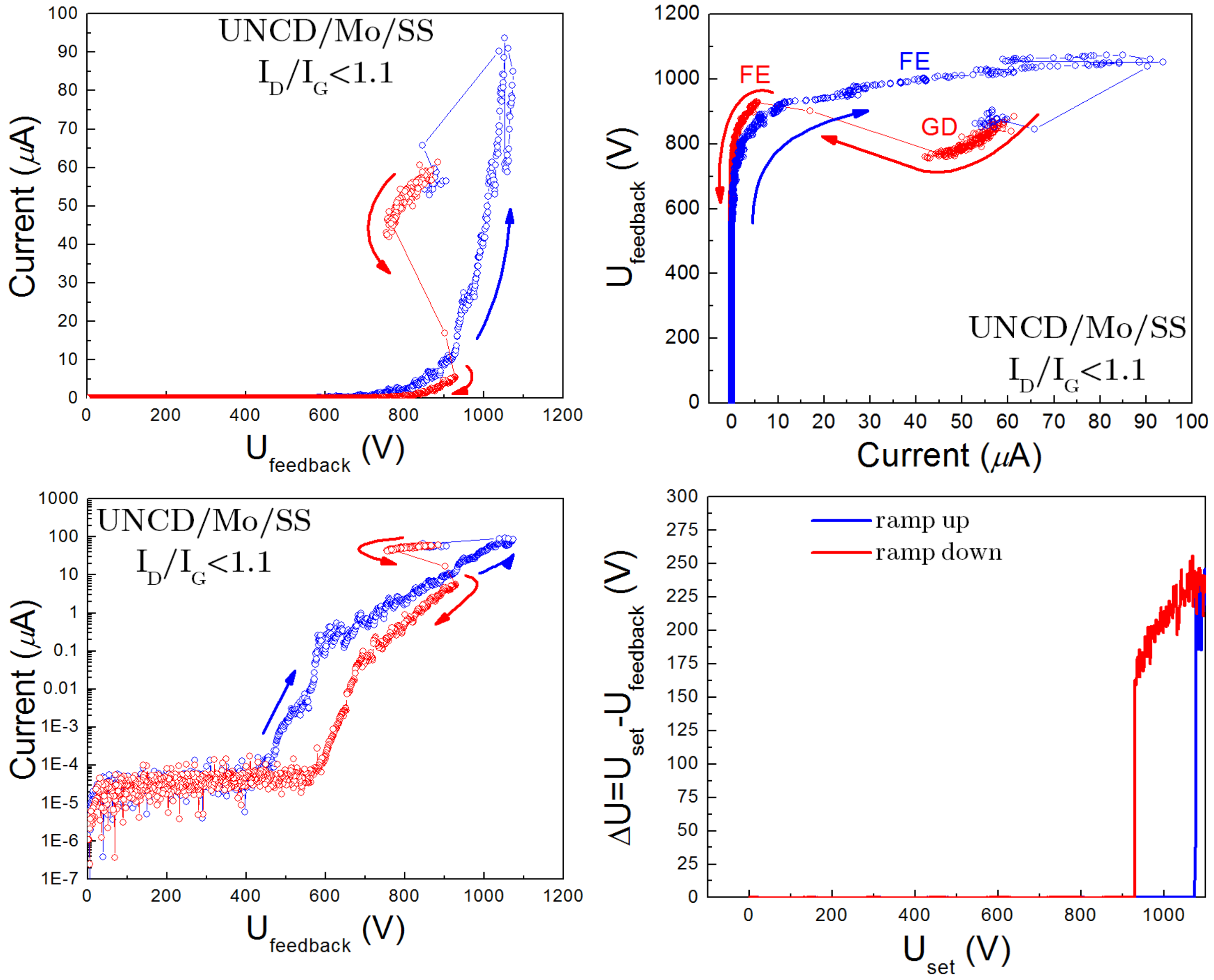


Vacuum ~10^{-9} Torr



J. Phys. D: Appl. Phys. **52,** 325301 (2019)

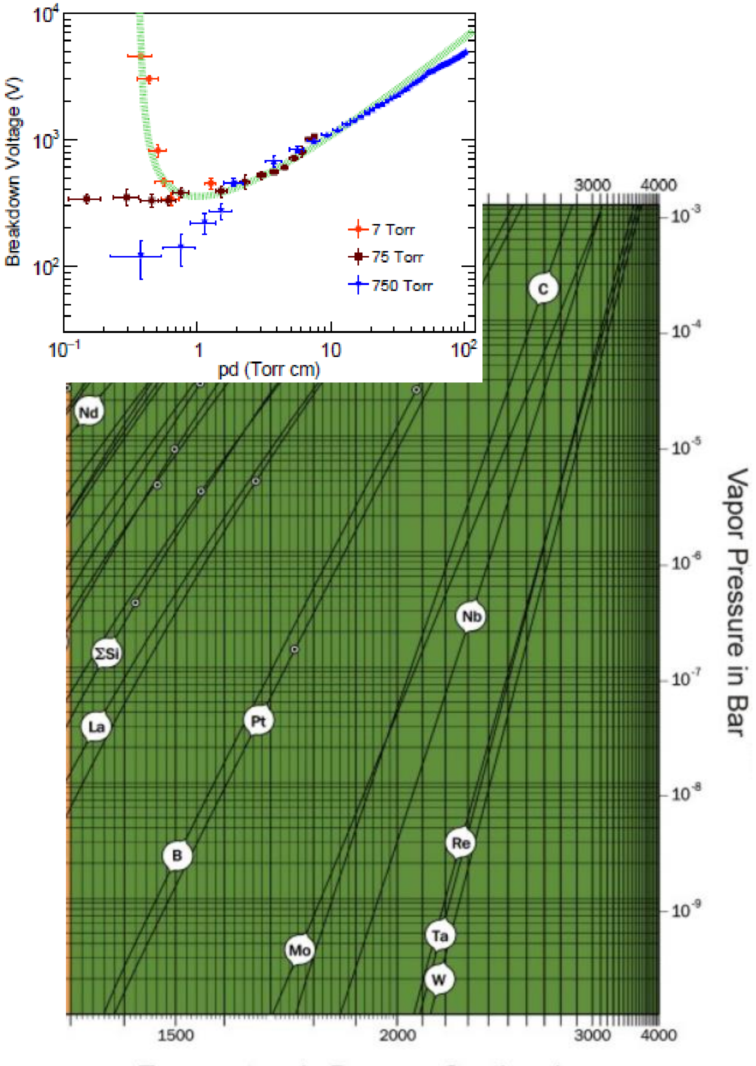
Self-induced, self-stabilized glow discharge



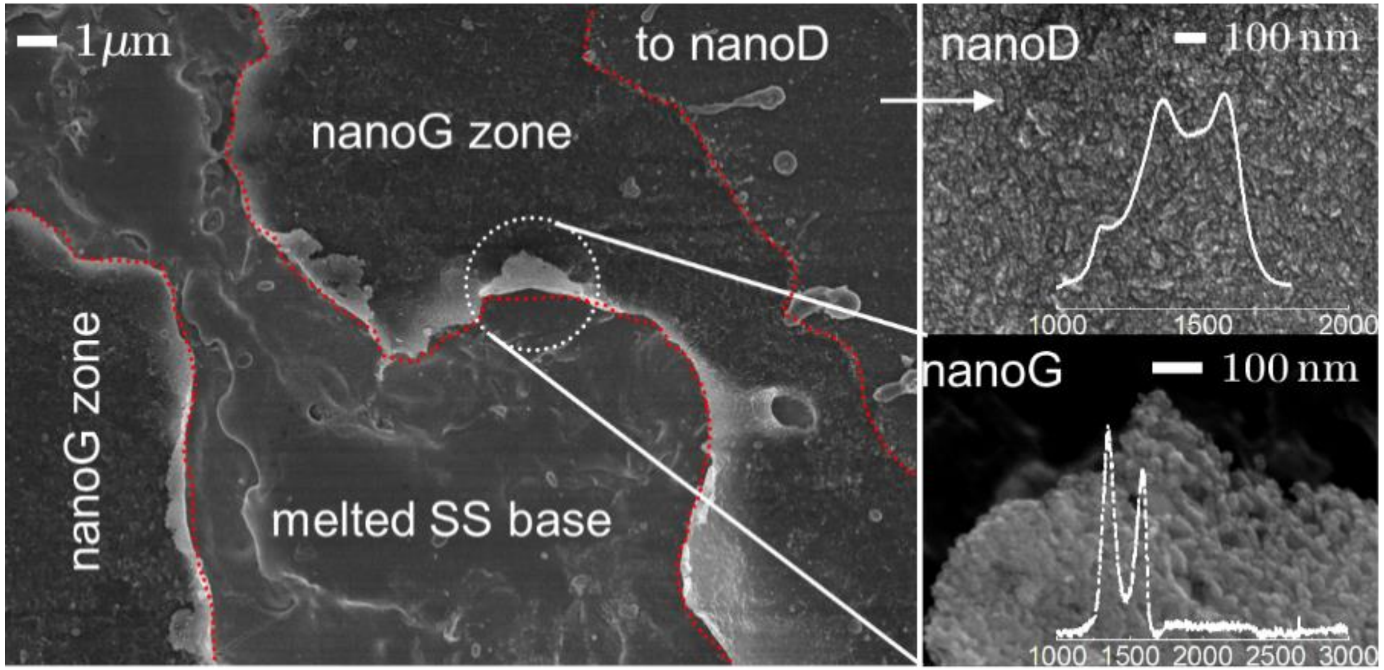
J. Phys. D: Appl. Phys. **52**, 325301 (2019)

Two estimations on temperature

Phase diagram
(T>~3,500 K)



Diamond-to-graphite
(T>~2,000 K)



J. Phys. D: Appl. Phys. **52,** 325301 (2019)

Third temperature estimation

VOLUME 13, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1964

NOTTINGHAM EFFECT IN FIELD AND T-F EMISSION: HEATING AND COOLING DOMAINS, AND INVERSION TEMPERATURE

F. M. Charbonnier, R. W. Strayer, L. W. Swanson, and E. E. Martin
Field Emission Corporation, McMinnville, Oregon

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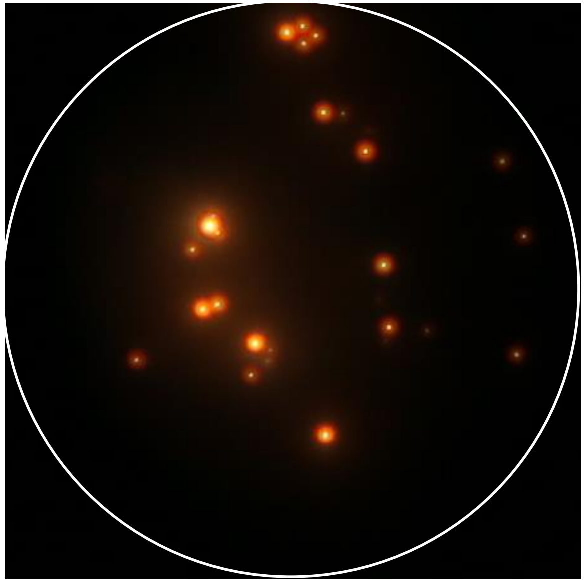
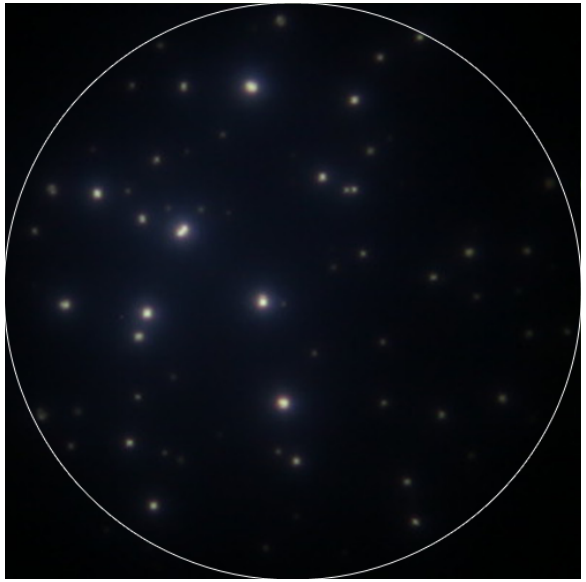


stable 2,000 K
(m_{eff}~$1/2m_0$)

$R \sim \exp(-\Delta H/kT)$

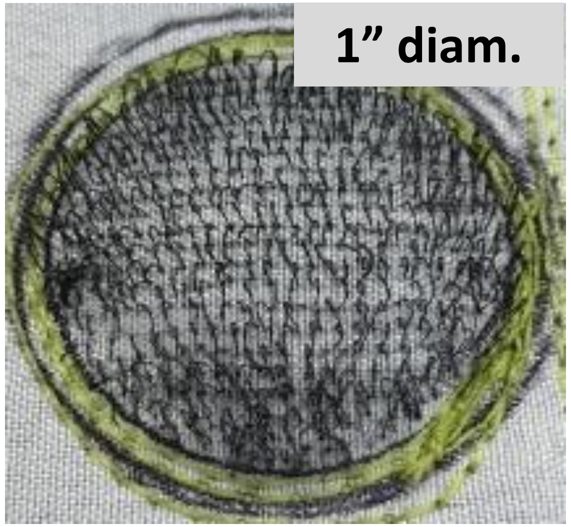
$\Delta H \approx 7 eV$

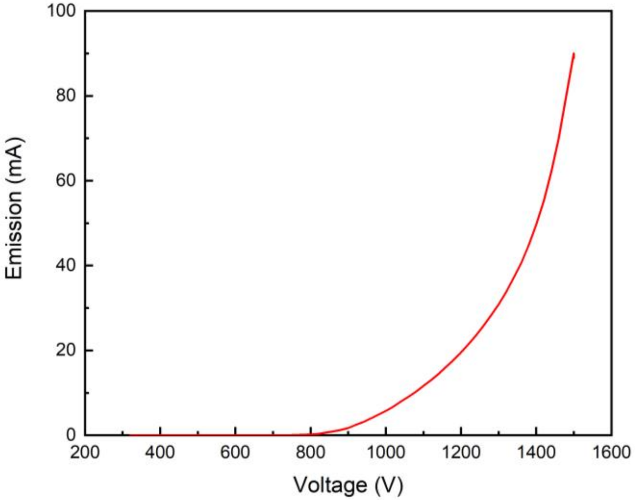


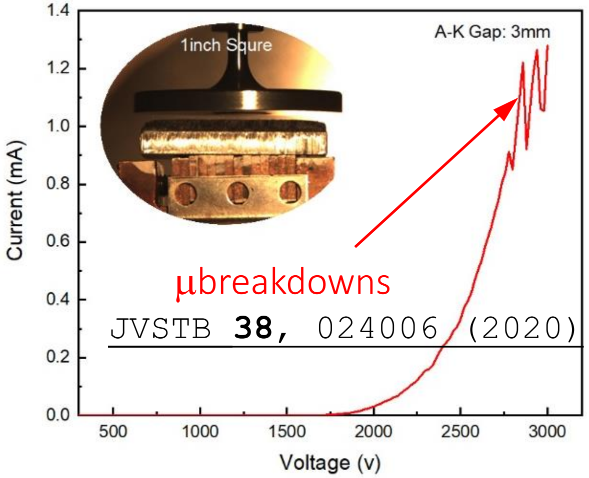
runaway 4,500 K
(m_{eff}~$1/18m_0$)

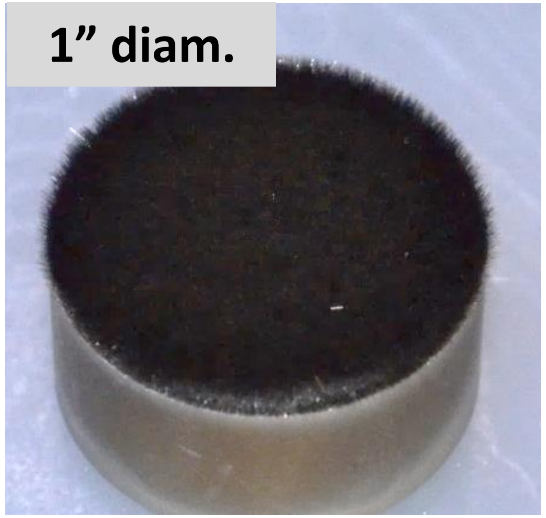
Implications: Cathode R&D at AFRL

(images courtesy of Steve Fairchild and Jeongho Park)

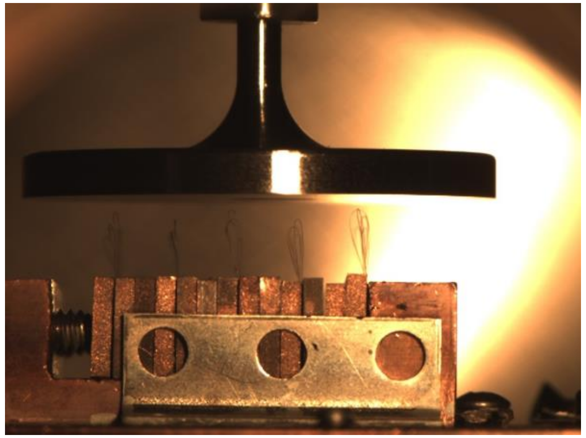




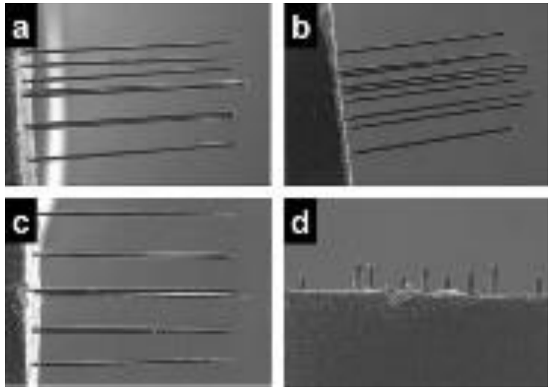




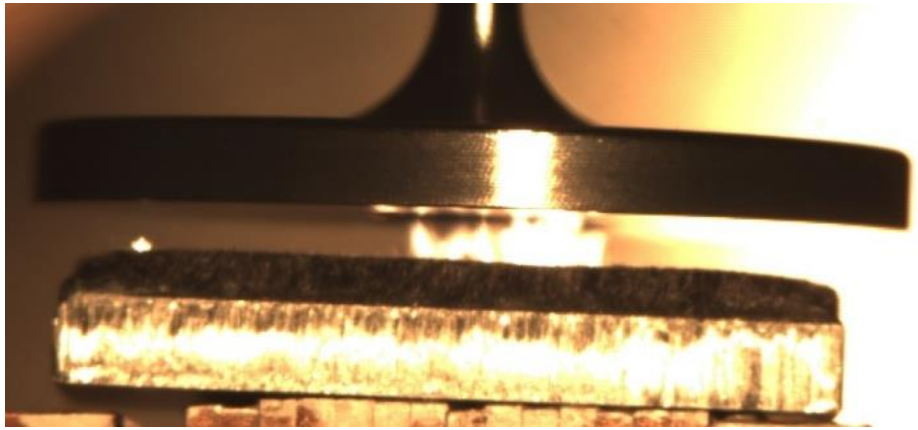
CNT-fiber



C-fiber



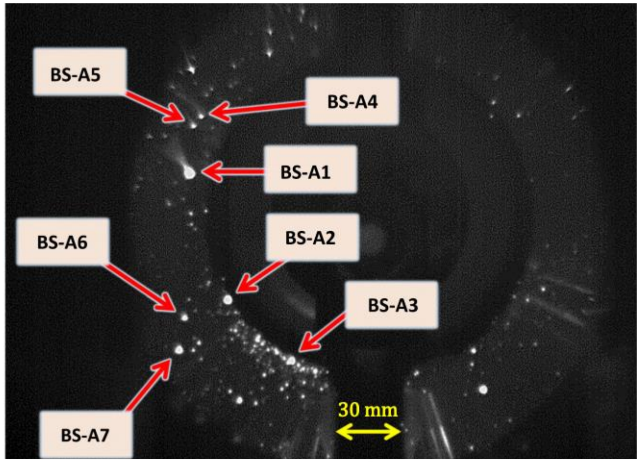
JAP **121**, 203303 (2017)

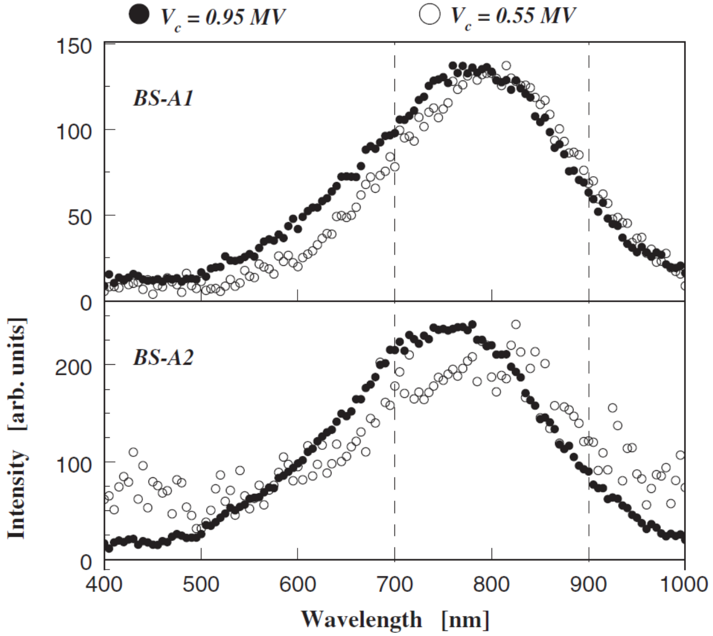


Implications: breakdown/arc/discharge

All temperatures at breakdown locations are >1,300 K

KEK

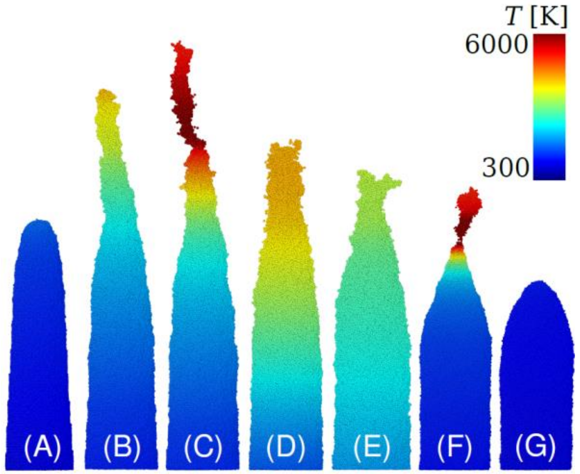


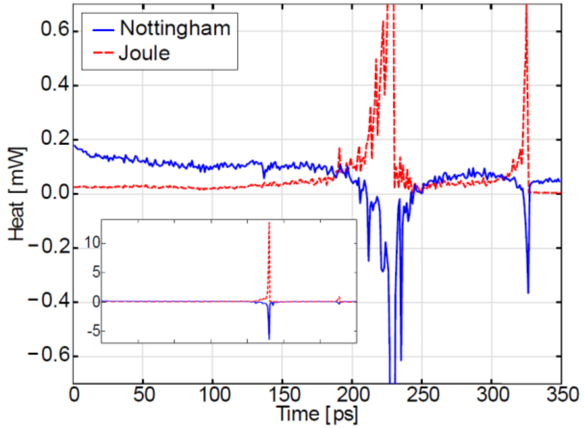


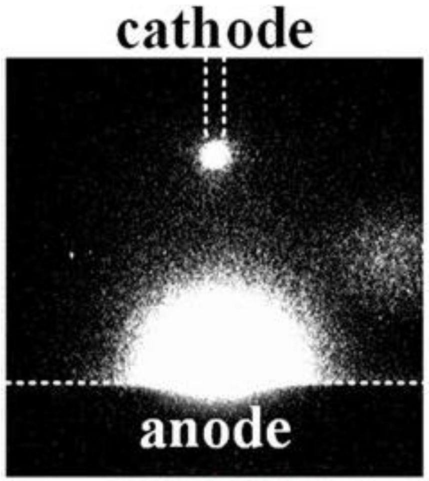
Phys. Rev. Accel. Beams **21**, 122002(2018)

Thermally driven cathodic plasma forms discharge/arc

Helsinki/CERN







J. Phys. D: Appl. Phys. **51**, 225203 (2018);
Sci. Rep. **9**, 7814 (2019)

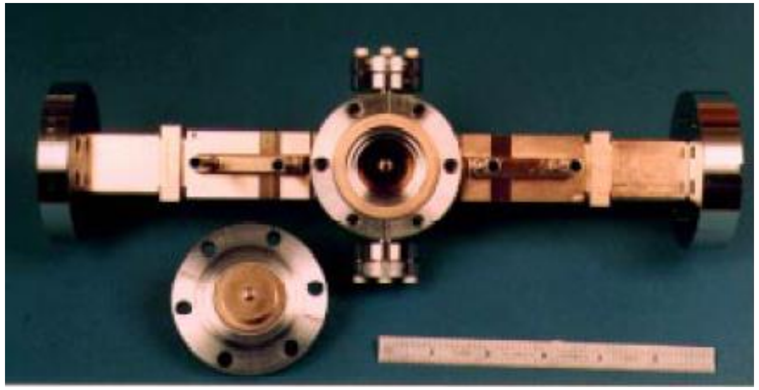
Pulsed rf breakdown studies

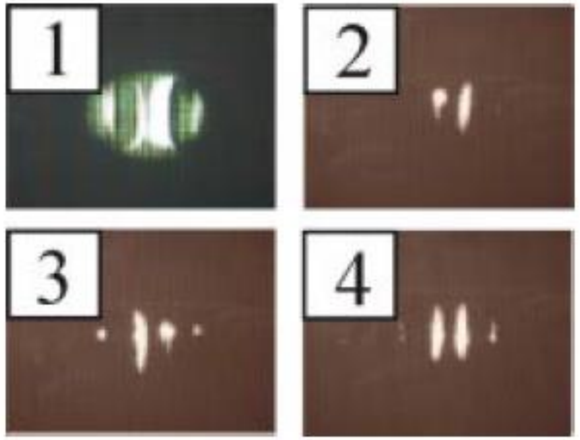
L. Laurent[a,b], G. Caryotakis[a], G. Scheitrum[a], D. Sprehn[a], N.C. Luhmann, Jr.[b]

[a]Stanford Linear Accelerator Center, Menlo Park, CA 94025

[b]University of California Davis, Davis, CA 95616

TM020





This study has also investigated the pulse length (τ^{-n}) dependence of breakdown fields for pulse durations ranging from 80n to 1500ns. Between 800ns to 1500ns, the breakdown fields were observed to follow a $\tau^{-1/2}$ time behavior. This might be expected when considering average power for pulse lengths less than the energy threshold where the field time behavior approaches CW. At shorter pulse durations (< 800ns), a transition in the breakdown field time behavior is evident, shifting from $\tau^{-1/2}$ to $\tau^{-1/3}$. This transition occurs above the space charge limited region where the field emission current continues to rise but at a much slower rate. The breakdown field at shorter pulse lengths occurs at field levels where there appears to be significant surface heating. The physical mechanism that reduces the breakdown field may be due, at least in part, to thermal mechanisms, although the source remains unclear.

SLAC-PUB-8409

Conclusions and outlook

1. Vast evidence exists on thermal runaway as a leading terminal breakdown/arc formation in dc diodes and rf cavities

2. Field emission, commonly called cold emission, is a very complex phenomenon that can cause severe thermal load via Nottingham and/or Joule heating

3. Testing hot cathodic scenario in relevant rf environment is underway using X-band rf microscope

4. Materials of choice to largely probe the parameter space of Nottingham/Joule processes are metals (copper vs refractory metals), nanodiamond and CNT

Acknowledgments

Work at MSU was supported by DOE under Award No. DE-SC0020429 and under Cooperative Agreement Award No. DE-SC0018362

Work at SLAC was supported by DOE under contract No. DE-AC02-76SF00515

We would like to thank Dr. Eric Colby (DOE) for his continuous support

and

Yevgeny Raitses (PPPL) for his useful comments regarding carbon arc