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Continued Development and Testing of Carbon Nanotube Cathodes

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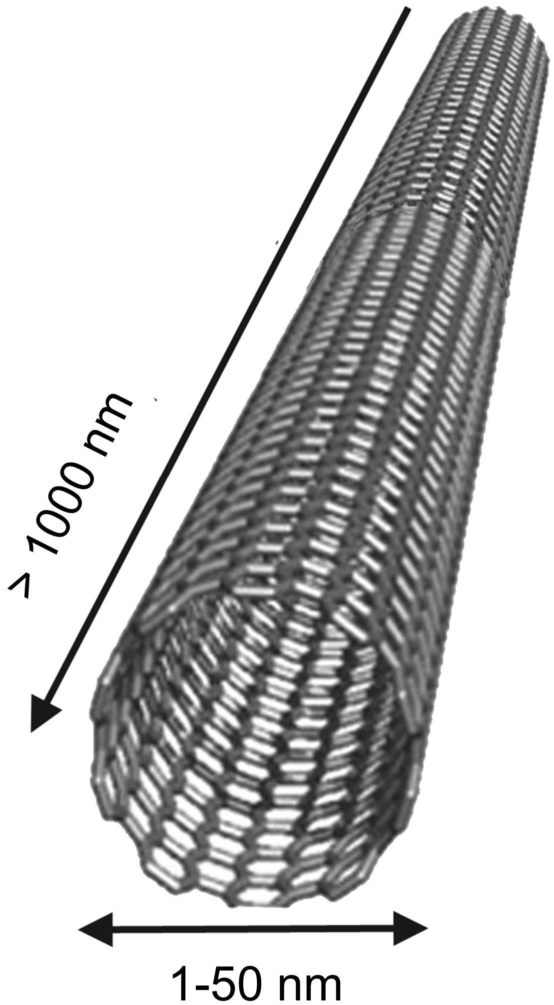
Overview

- Motivation
- Carbon nanotubes (CNTs) as field emitters
- RadiaBeam's production of CNT cathodes
- High voltage testing
- Plans for evaluation in RF environment

Motivation

- Field emission cathodes are attractive for their simple operation and low power requirements
  - Unlike thermionic cathodes, no additional heat load placed on system
  - Unlike photocathodes, no laser system needed
- Traditional field emitters can be expensive to fabricate and are often fragile
  - CNTs present economical approach
- Well suited for use in dual frequency gun
  - Novel approach to gating emission

CNT's as Field Emitters



Fowler-Nordheim Relationship:

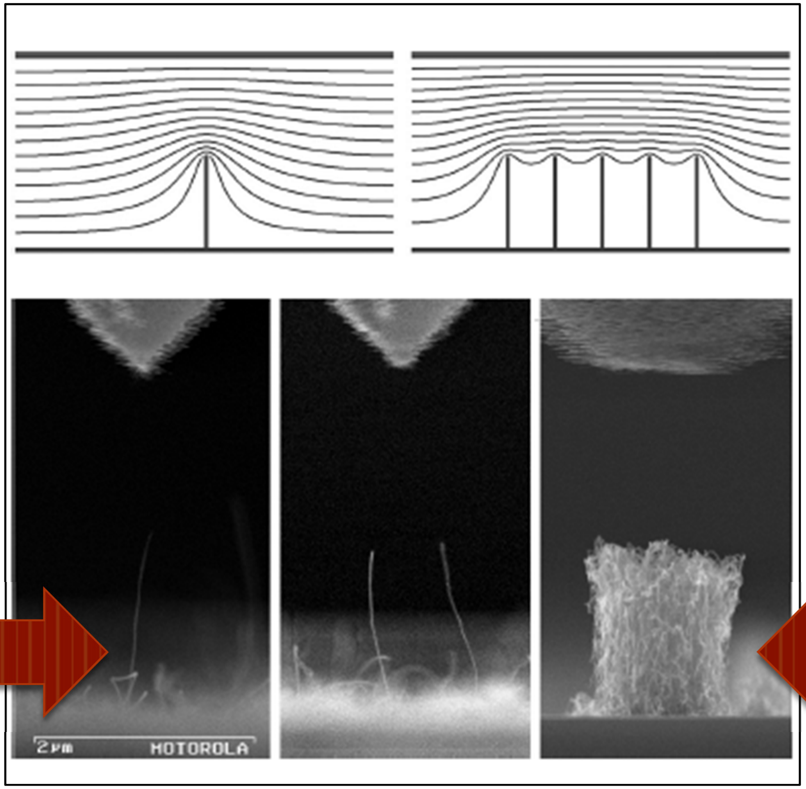
$$J \propto \frac{(\beta E)^2}{\Phi} e^{-\frac{\Phi^{3/2}}{\beta E}}$$

J: Current density
E: Electric field strength
β: Enhancement factor
Φ: Work function

- Extreme aspect ratios create large enhancement factors (β = 100-1000)
- Single CNT capable of emitting ~1μA, densities of 1e9 CNTs per cm^2

CNTs as Field Emitters

Single CNT maximizes electric field strength



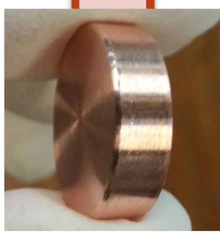
High density ray screens electric field

"Carbon nanotube electron sources and applications," Philips Research and the Institute for Nanostructure Physics

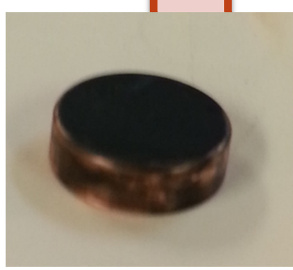
- Need to optimize CNT spacing to achieve best emission
- Chose to investigate electrophoretic and chemical vapor deposition

Production of CNT Cathode

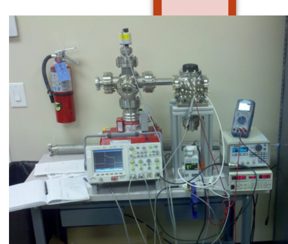
Substrate fabrication/ cleaning



Deposition and post-processing



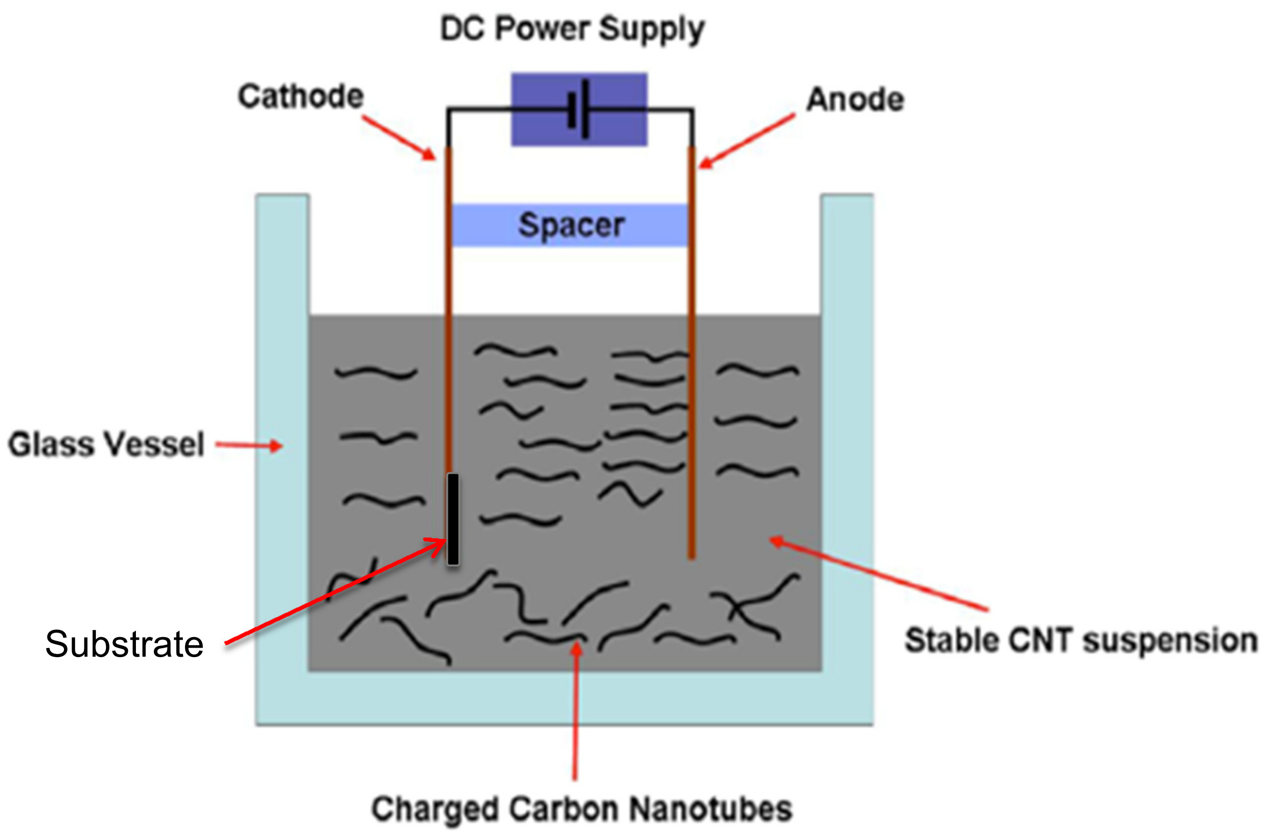
HV testing



RF testing

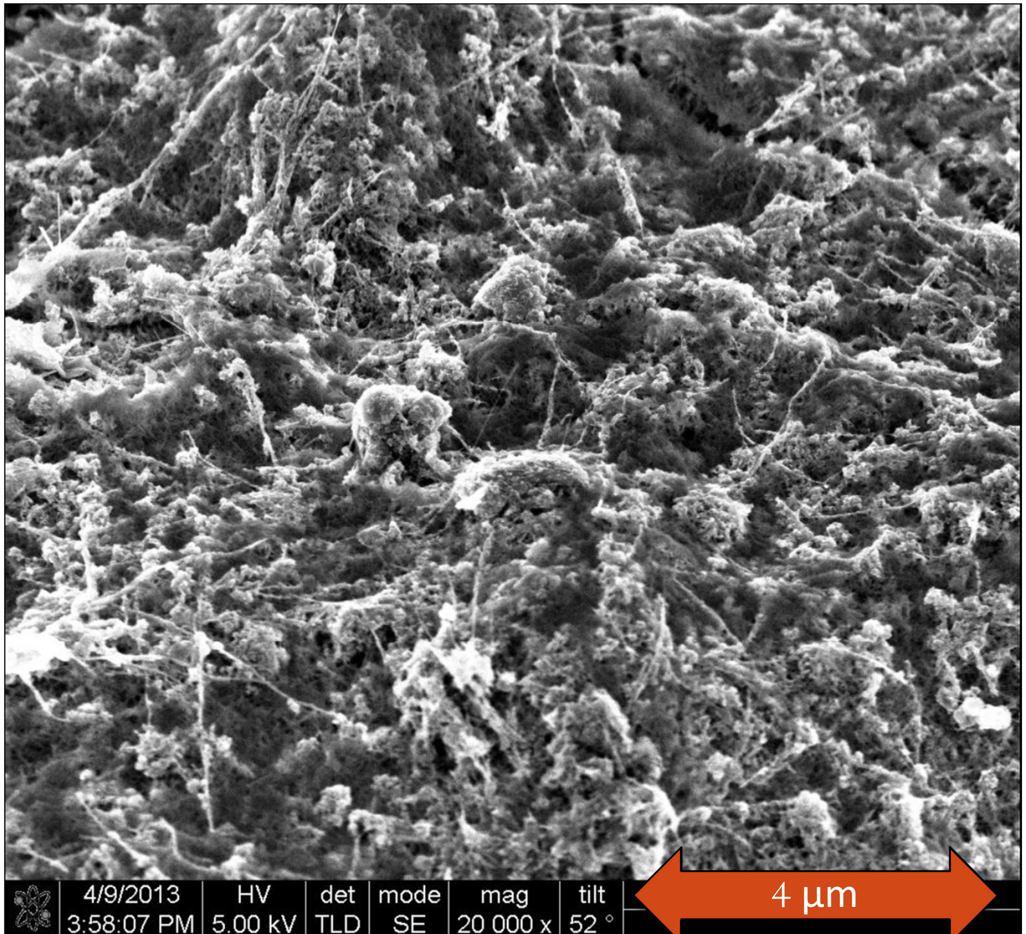
Electrophoretic Deposition

- Deposits pre-made CNTs from a methanol suspension
- Simple, economical process
- Less control over microscopic properties (density, diameter, etc)

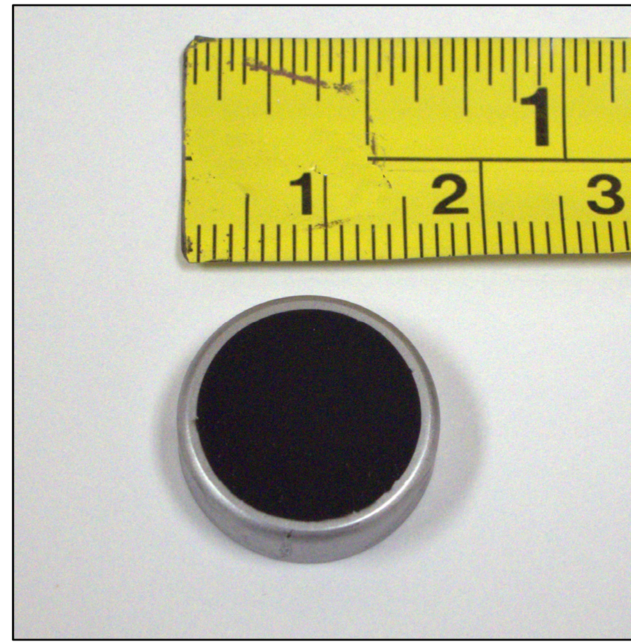


CNT Cathodes via EPD

- EPD produces "carbon wool," a layer formed of multiple carbon allotropes with many distinct CNT's protruding



SEM micrograph of carbon wool



High quality deposition on Mo substrate

Chemical Vapor Deposition

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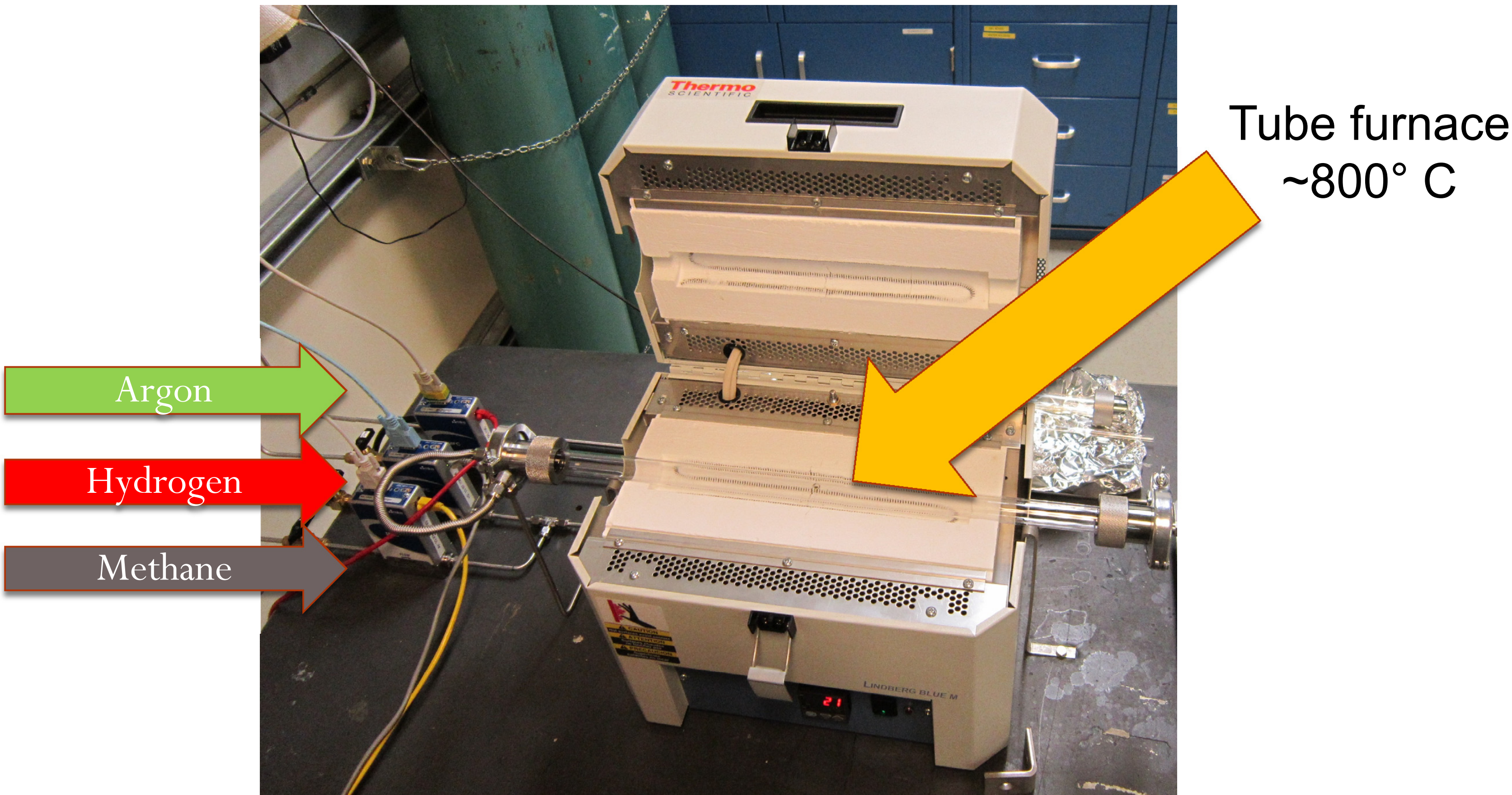
- Grows CNT’s in-situ on nanoparticle catalysts (Ni)
- Requires more complex equipment and processes
- Offers significantly more control over microscopic properties



CNT Cathodes via CVD

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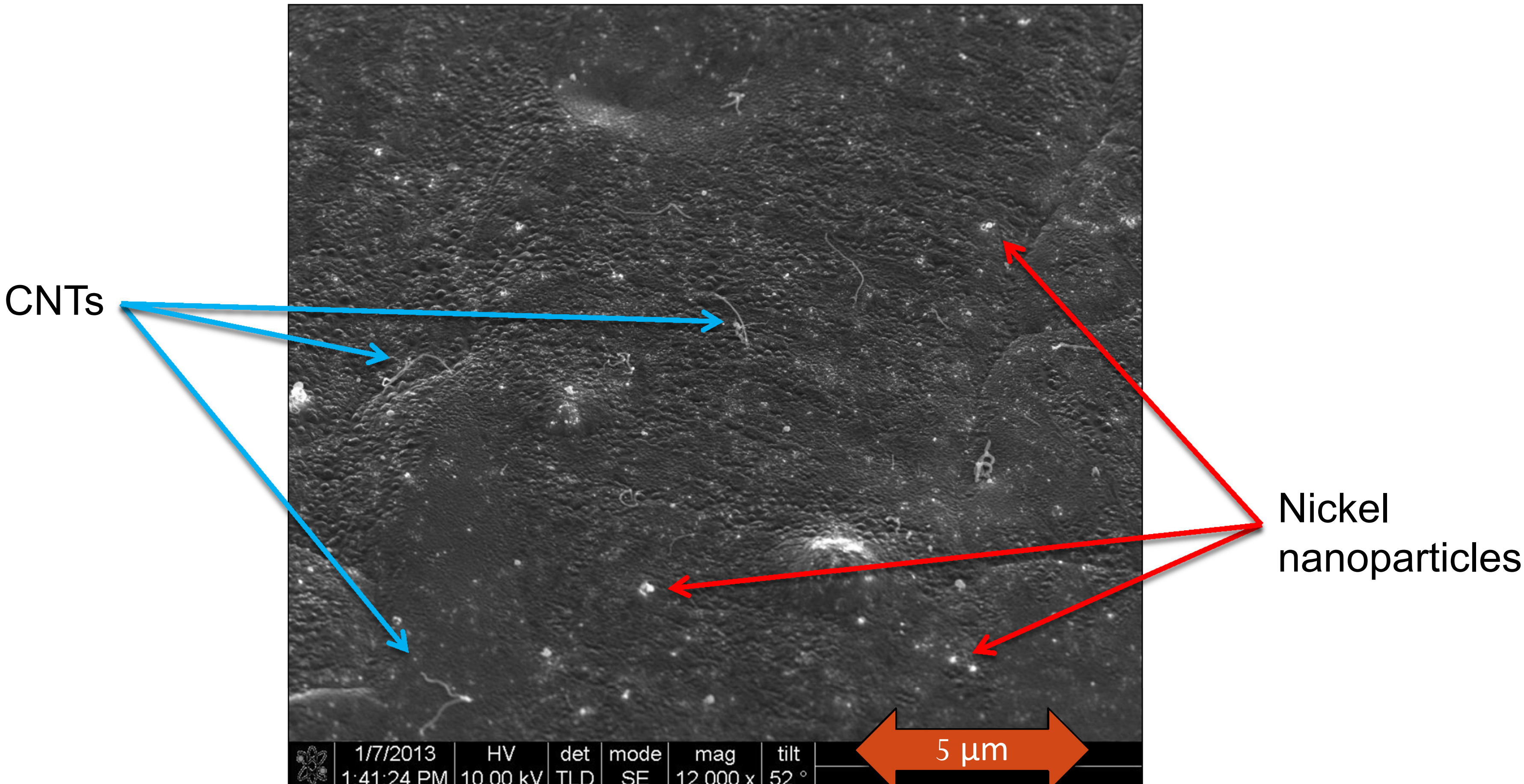
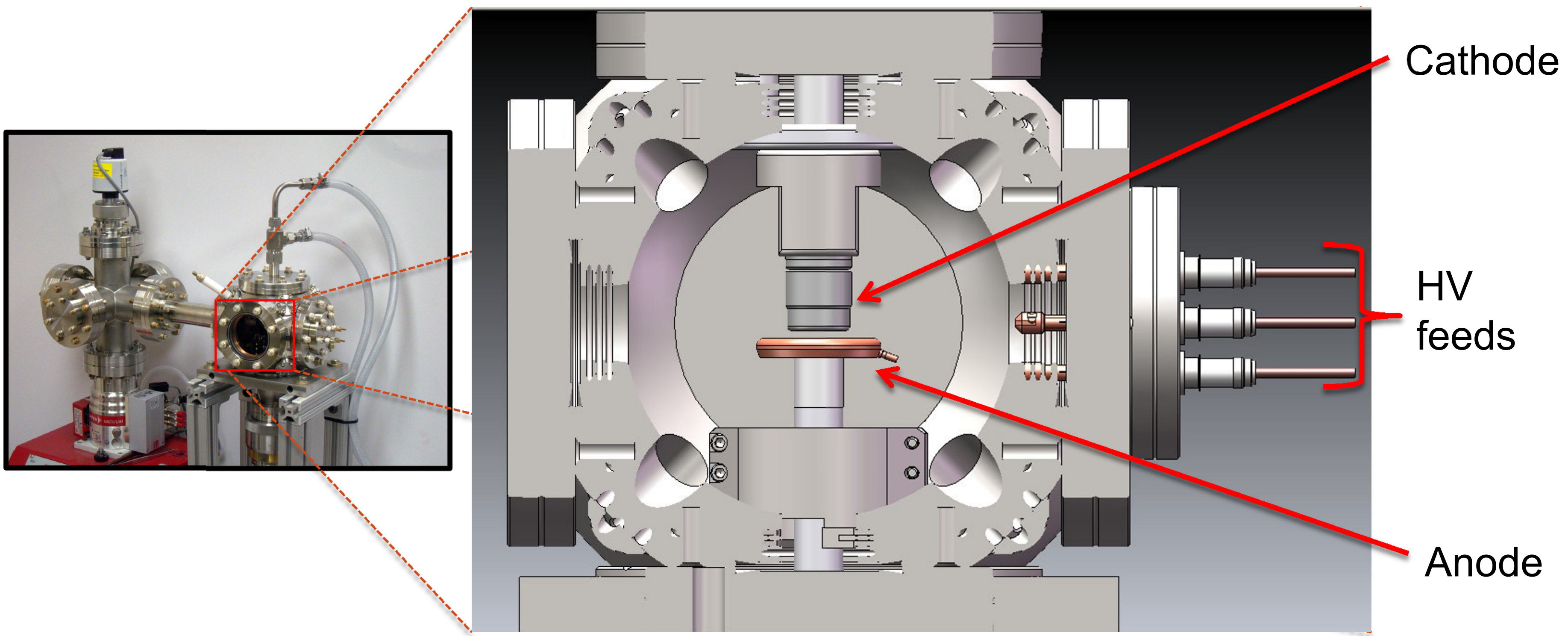
- Demonstrated growth on copper substrate (low density)
- Still need more work to refine CVD process

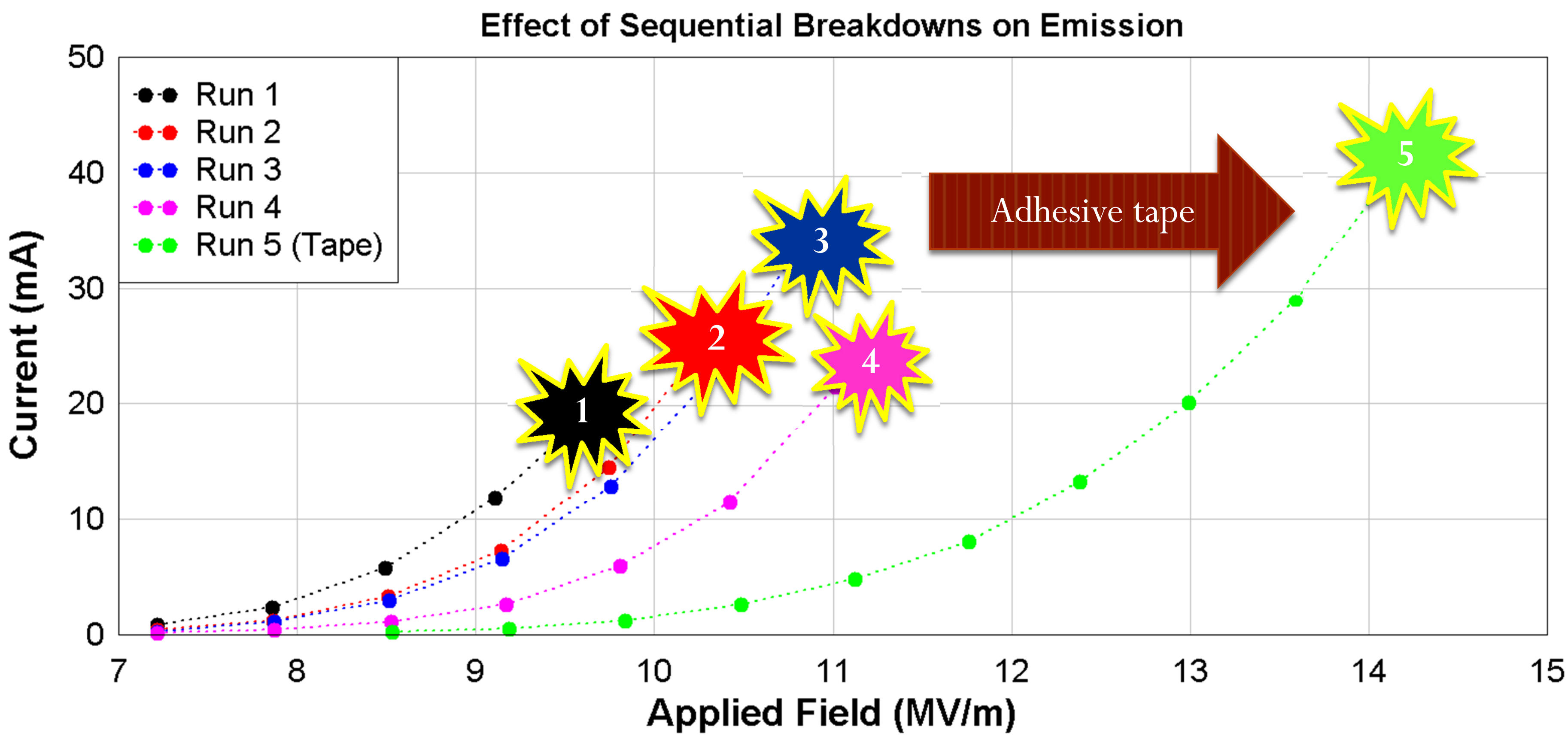


High Voltage Testing

- Base pressure <10^{-8} Torr
- Pulsed mode:
  - 0 – 2.5 kV, 0-500 mA
  - 10 μs pulse length
- Variable gap: 0 – 25 mm
- DC Mode:
  - 0 – 20 kV, 110 mA
  - Water-cooled anode



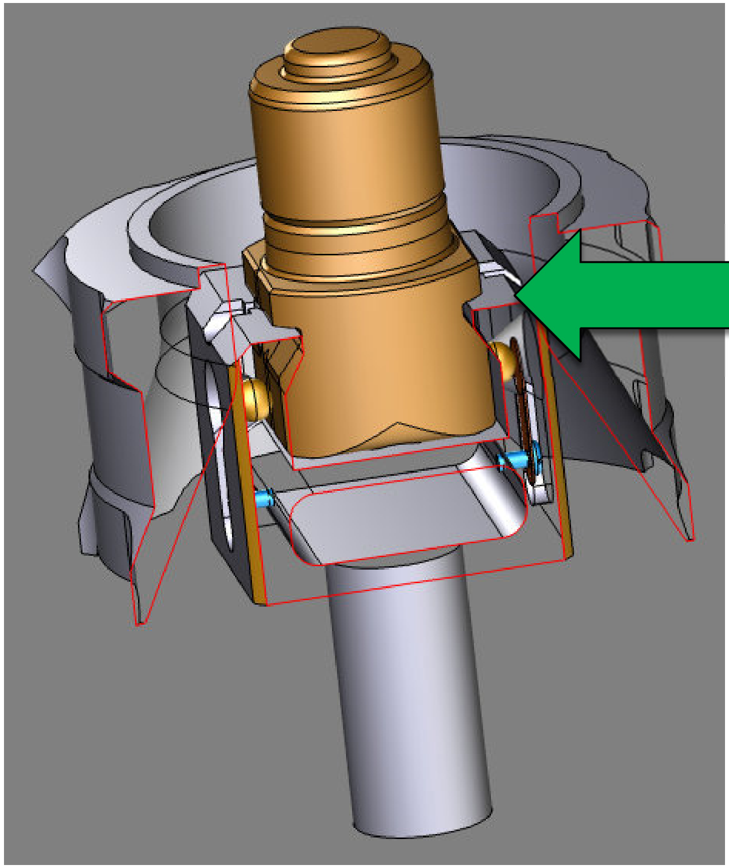
Electrical Breakdown

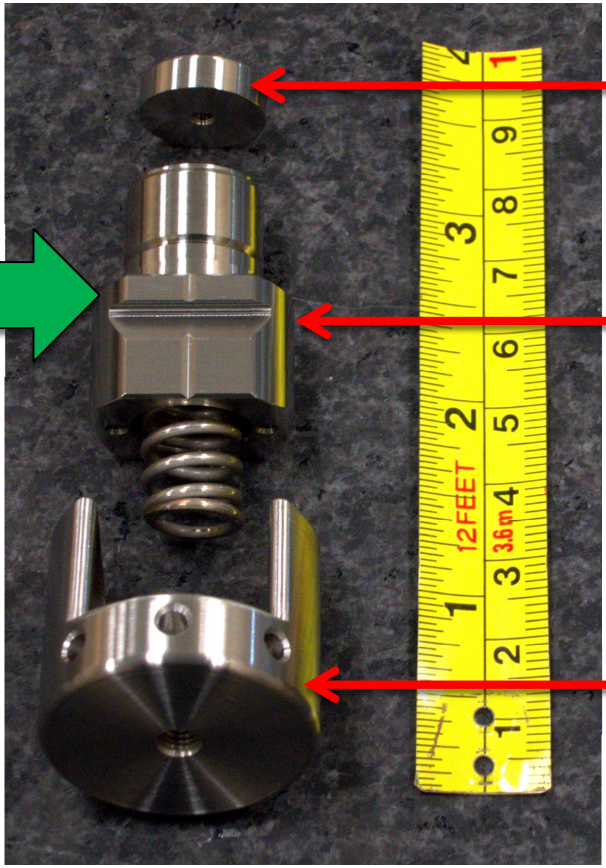


- Sequential breakdowns increase the maximum field a cathode can support, but reduce the emission for a given voltage
- Loose material pulled off of substrate initiating breakdown

First Experiment at Fermilab

- Our test-cathodes are designed to be compatible with Fermilab's A0 photo-injector system
- Less demanding initial experiment





Dual-frequency gating

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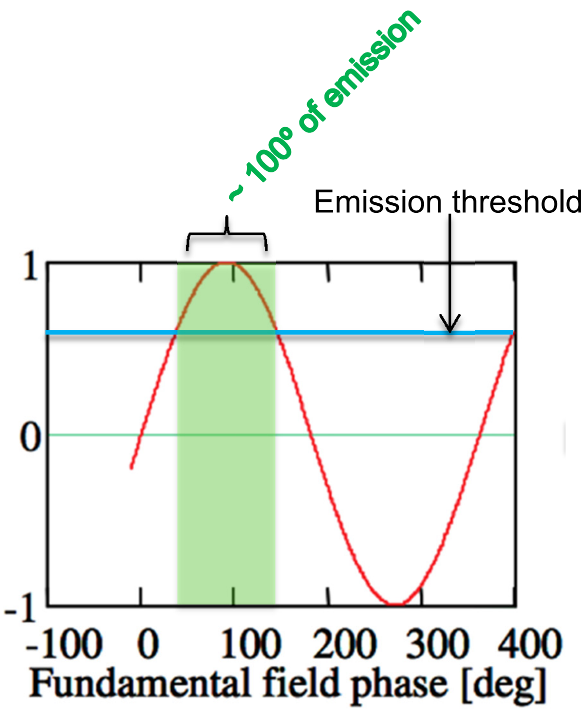
- Proposed by Lewellen and Noonan, Phys. Rev. ST Accel. Beams 8, 033502 (2005)
- Summed field generates emission over a shorter part of the cycle
- Field emission cathodes are optimal for dual frequency gating

Electric field at cathode surface

~ 50° of emission



Fundamental

Second Experiment at Fermilab

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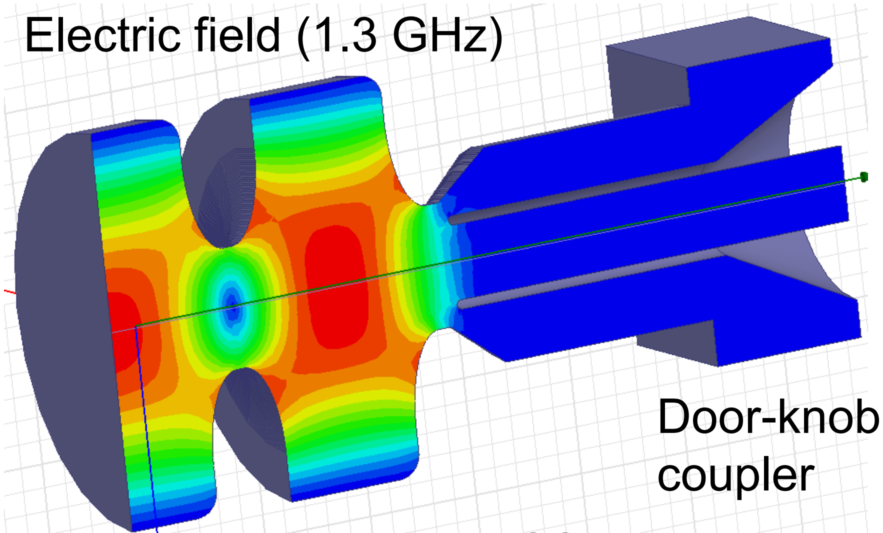
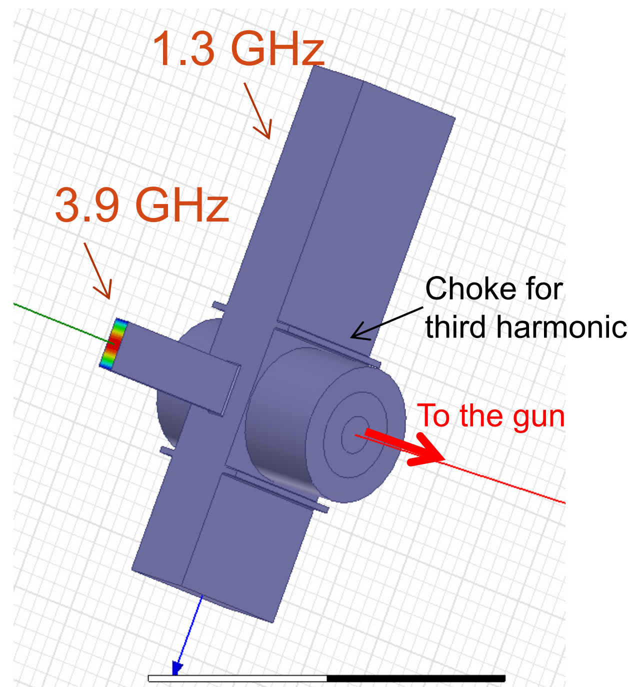


3D model, HFSS

- Fabrication and installation planned for 2014

Door-knob coupler



- Uses existing RF sources and diagnostics at Fermilab's A0 facility

Conclusion

- Fabricated CNT cathodes via two methods, EPD and CVD
  - EPD is economical, but harder to adjust microscopic properties
  - CVD takes more effort to optimize
- Evaluated cathodes with HV system
  - Rapidly evaluated emission and breakdown in pulsed mode
  - Lifetime measurements in DC mode
- Preparing for evaluation in an RF environment
  - Direct installation in photo-injector (laser turned off)
  - Evaluate timing, energy spread, and performance in dual-frequency gun

Acknowledgements

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  - Chris Regan
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