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EXPERIMENTAL RESULTS OF CARBON NANOTUBE CATHODES INSIDE RF ENVIRONMENT

Luigi Faillace

RadiaBeam Technologies, Santa Monica, CA

Fermilab

NIU
Northern Illinois University

C N S I
California NanoSystems Institute

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Overview

- Motivation
- Carbon nanotubes (CNTs) as field emitters
- Production of CNT cathodes
- High voltage DC testing at RadiaBeam
- High-power RF testing at the High Brightness Electron Source Laboratory (HBESL at FermiLab)
- Conclusions and Applications

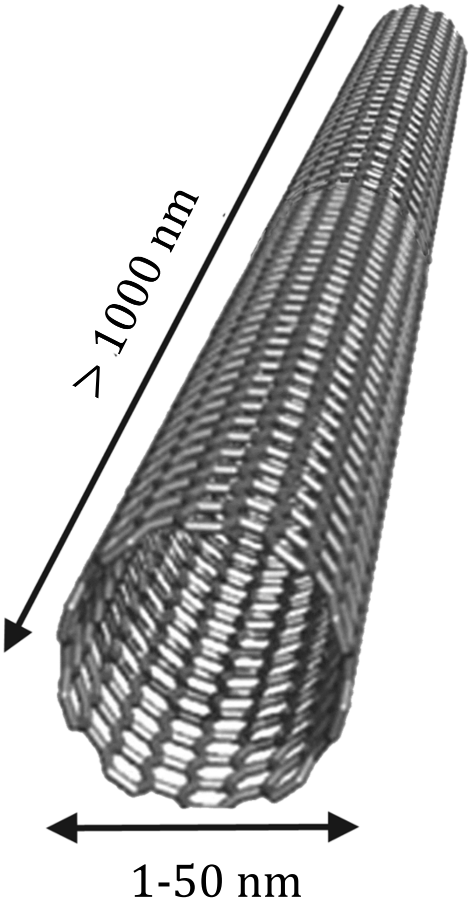
Motivation

- Field emission cathodes are attractive for their simple operation and relatively low power requirements
  - Unlike thermionic cathodes, no additional heat load placed on system
  - Unlike photocathodes, no expensive laser system needed

- CNTs
  - Extraordinary Electrical properties, current density $4x10^9$ A/cm^2 (1000x Copper)
  - High mechanical strength, tensile strength>100GPa (100x Stainless-steel)
  - Thermal Stability, up to 2.800 °C in vacuum (750 °C in air)
  - Robust, transportation in air is OK
  - Cheap and easy to process

- Well suited for use in dual frequency gun
  - Novel approach to gating emission

CNT’s as Field Emitters

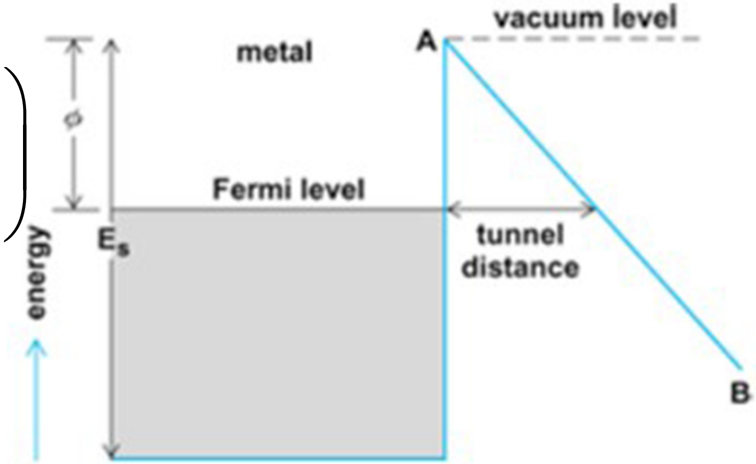


CNTs were discovered in 1991 [S. Iijima, Nature, 354 56 (1991)]

Field Emission: electron escape from a bound state to vacuum level through *quantum tunneling* in the presence of an external electric field.

$$j = aE^2\exp\left(-\frac{b}{E}\right)$$

Fowler-Nordheim
Relationship (1928):



j: Current density
E: Electric field strength: $\beta E_{applied}$
β: Enhancement factor
Φ: Work function, 4.9 eV
a: $1.42\times10^{-6}/\Phi\exp(10.4/\Phi^{1/2})^*$
b: $-6.56\times10^{9}\ \Phi^{3/2}$

[*] E. Minoux et al., Nano Lett., 5 (11), 2135 (2005). doi: 10.1021/nl051397d

- Extreme aspect ratios create large enhancement factors (β ~ 100-1000)
- $E_{applied} \approx 1\div100$ MV/m (Macroscopic Field)

Production of CNT Cathode

Substrate fabrication/ cleaning

Deposition and post-processing

CNSI

Xintek Nanotechnology Innovations

Electrophoretic Deposition (EPD)

Chemical Vapor Deposition (CVD)

HV testing

RF testing

Production of CNT Cathode

Substrate fabrication/ cleaning

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C (N) S I

Xintek
Nanotechnology Innovations

Electrophoretic Deposition (EPD)

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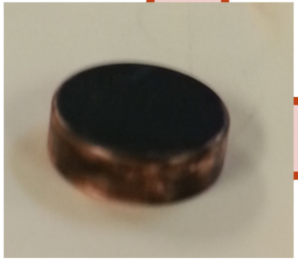
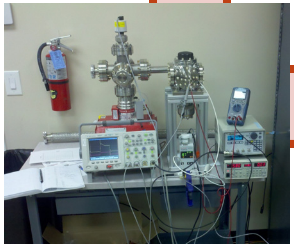


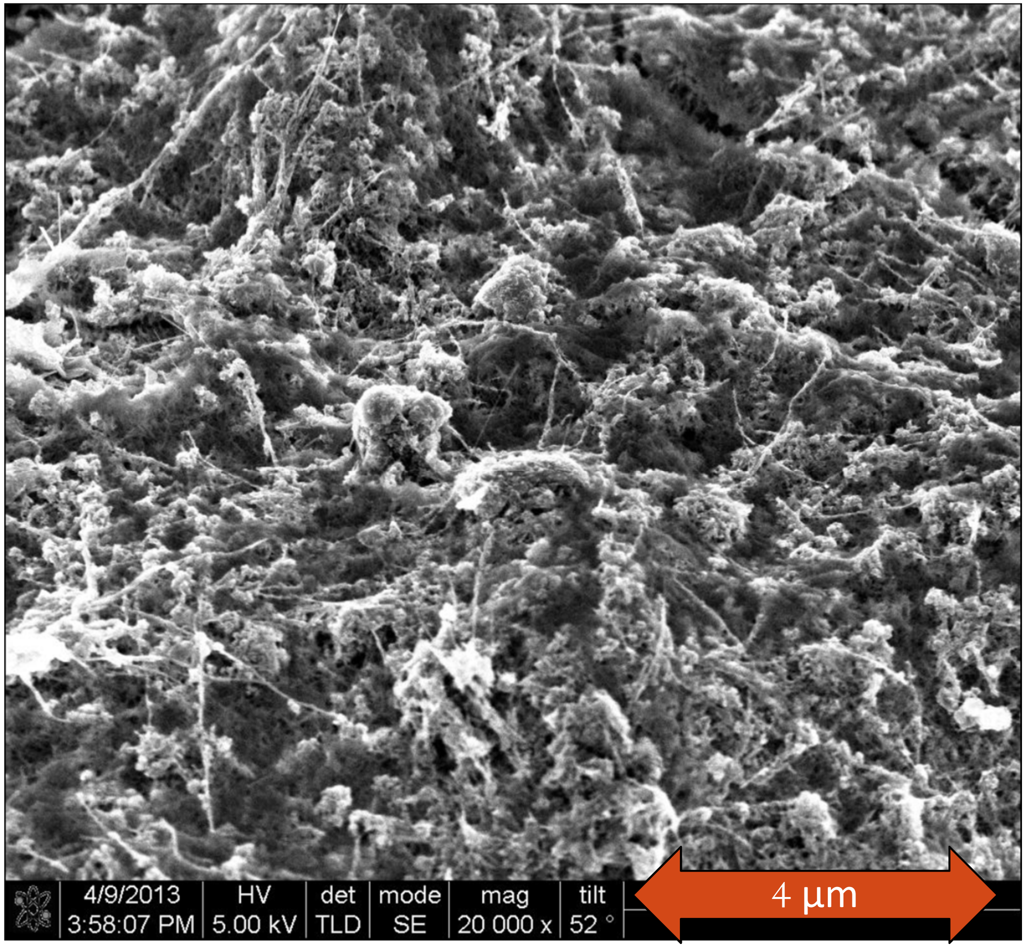
HV testing



RF testing

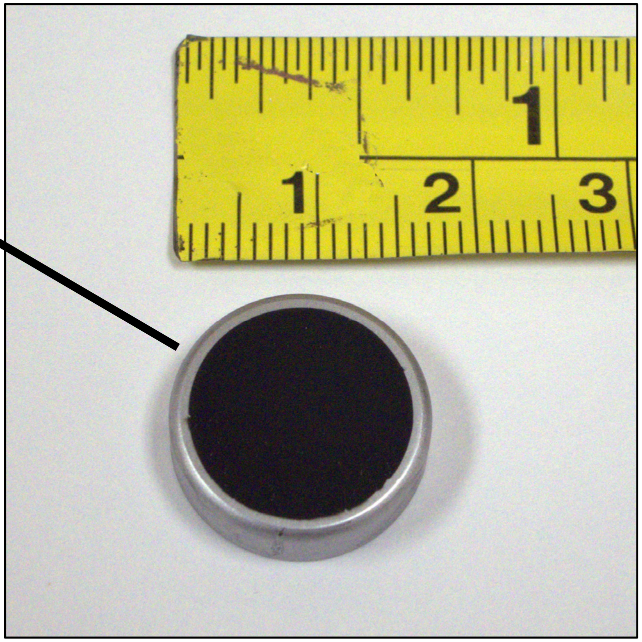
CNT Cathodes via EPD

- Pre-made CNTs, floating inside a methanol suspension, are deposited on substrate (cathode) through applied DC voltage.



SEM micrograph of carbon wool

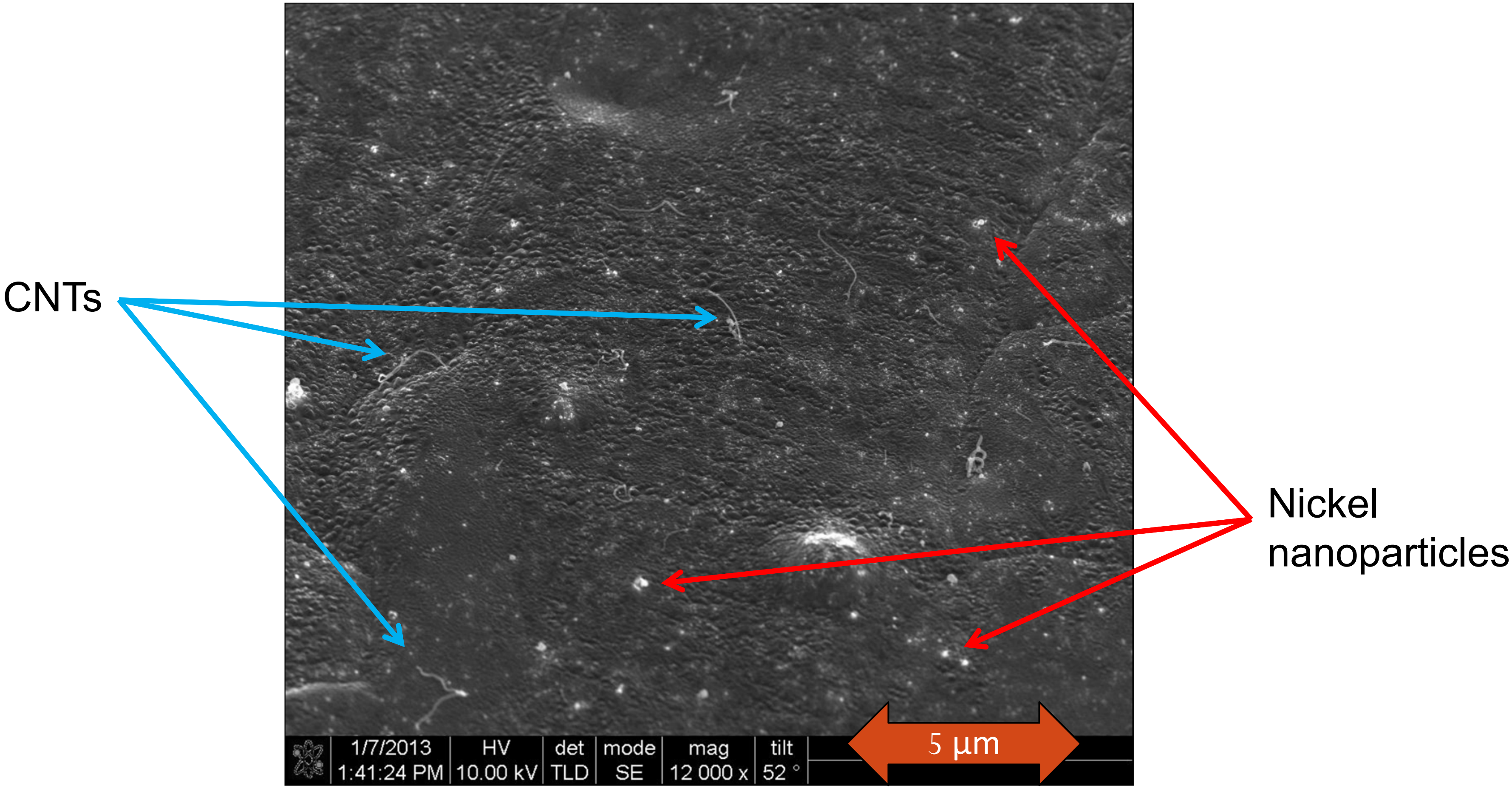
- EPD produces “carbon wool,” a layer formed of multiple carbon allotropes and adsorbents with many distinct CNT’s protruding.



High quality deposition on Mo substrate

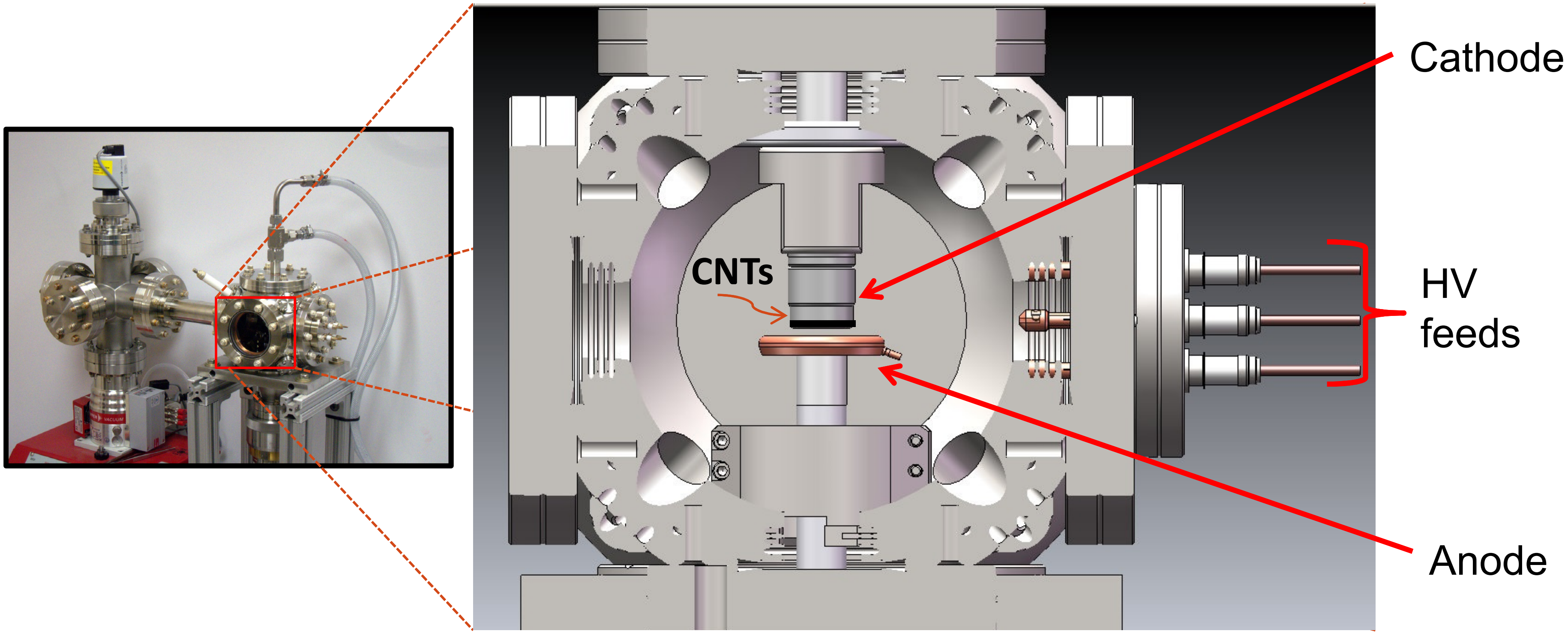
CNT Cathodes via CVD

- CNT’s are grown in-situ on nanoparticle catalysts (Ni): hydrocarbon vapor is decomposed by high-temperature catalysts.
- 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

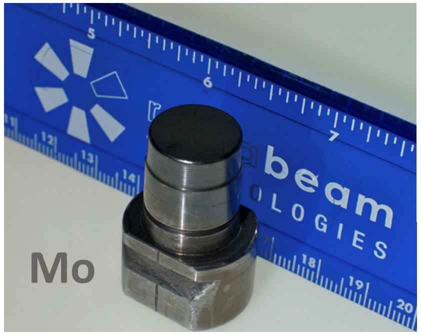


Cathode samples

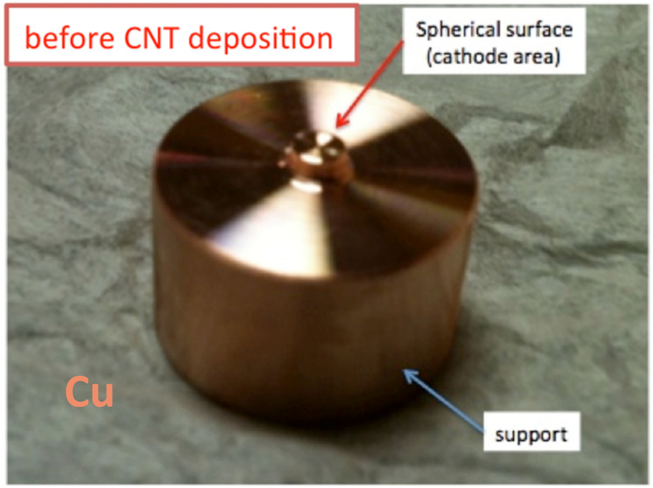
Materials

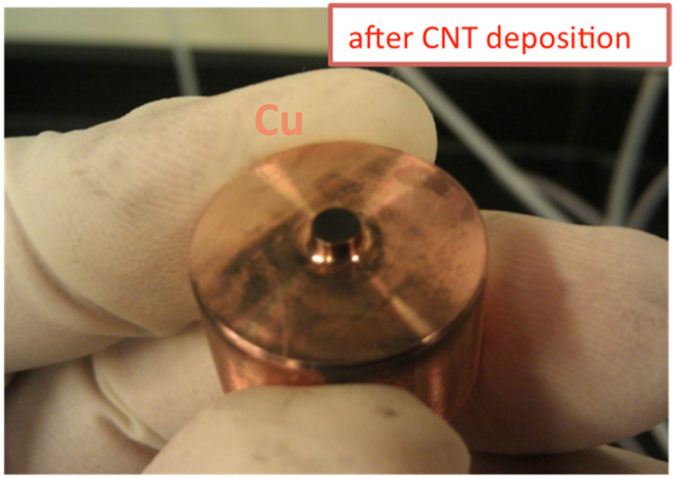
- Stainless-Steel (**SS**): more robust for the insertion in a load-lock system
- Copper (**Cu**): easier to machine
- Molybdenum (**Mo**): preferred for its better response to CNT deposition processes

"Large" samples
Discs: 1.5 cm diameter
½ cm thickness

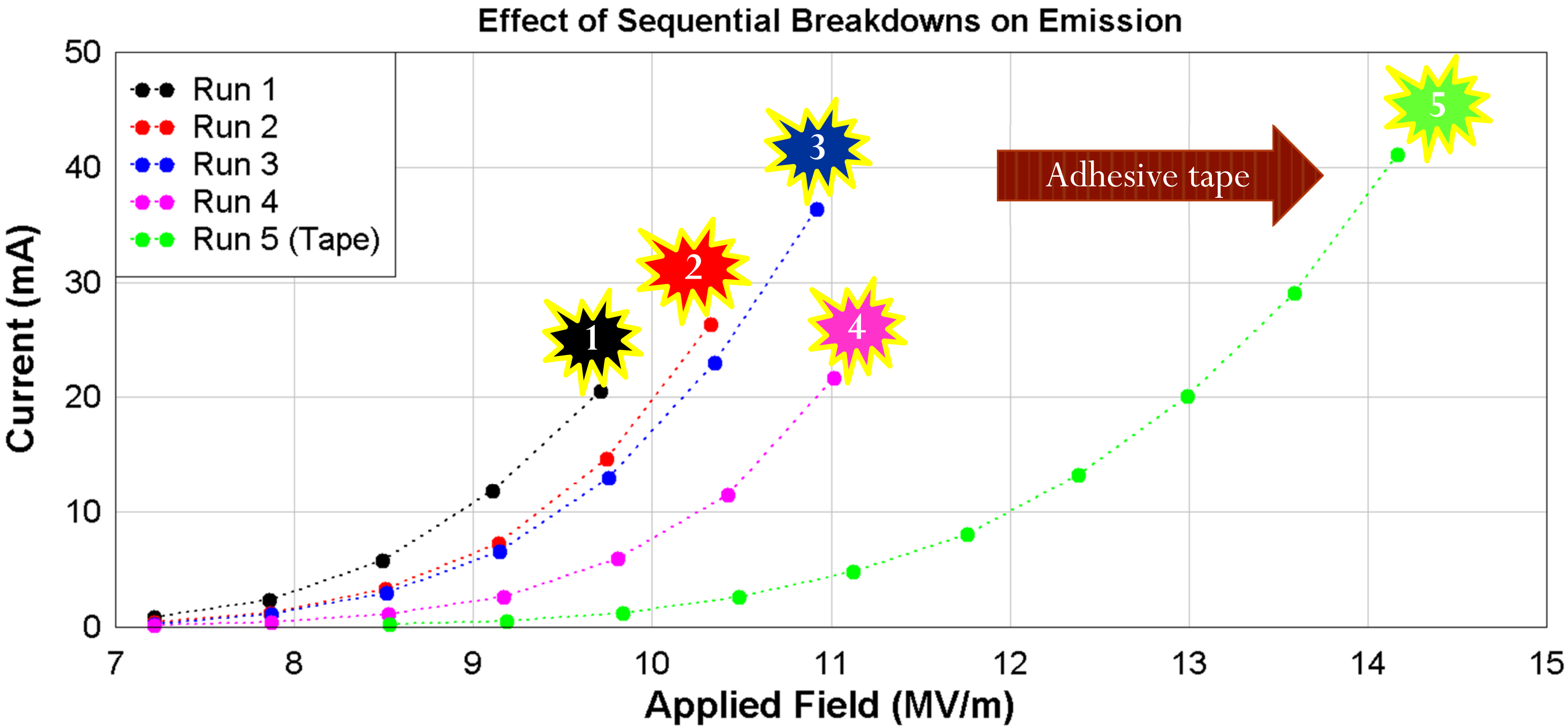


"Small" samples
Nipples protruding from a ½ cm thick support: deposition area ~ 1.5mm diameter





DC testing results and Electrical Breakdowns

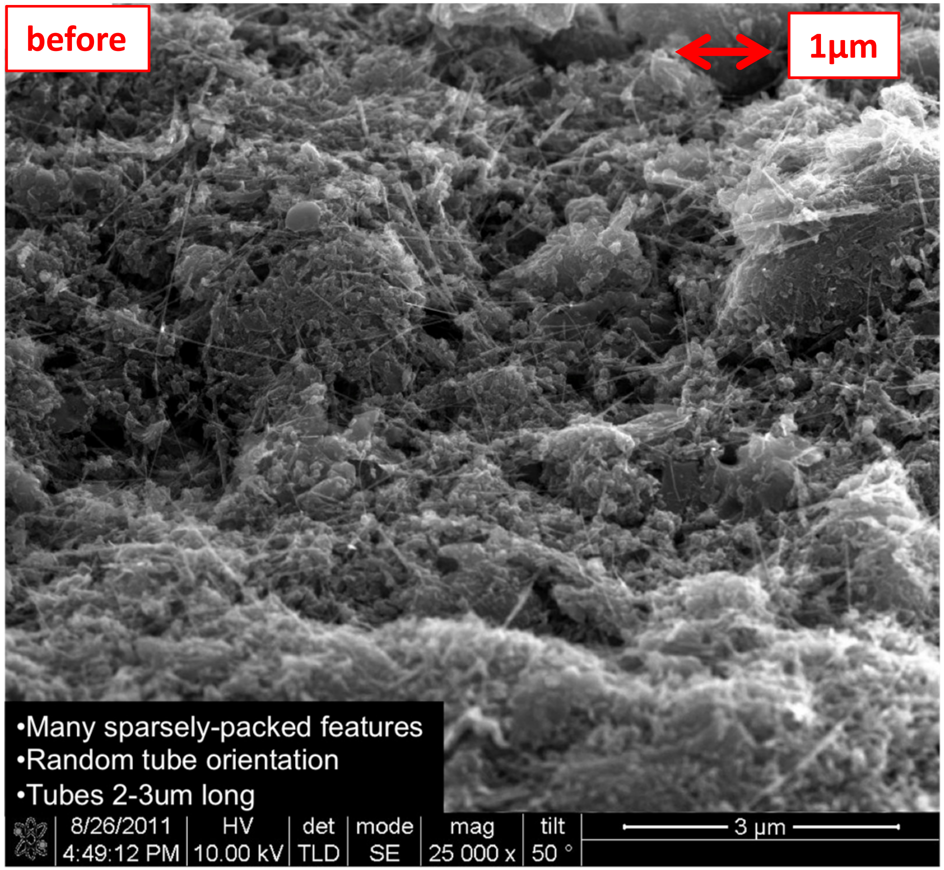


- Emission curves from a “large” cathode sample.
- Sequential breakdowns increase the maximum field a cathode can support, but reduce the emission current for a given voltage.
- Loose material pulled off of substrate initiating breakdown.

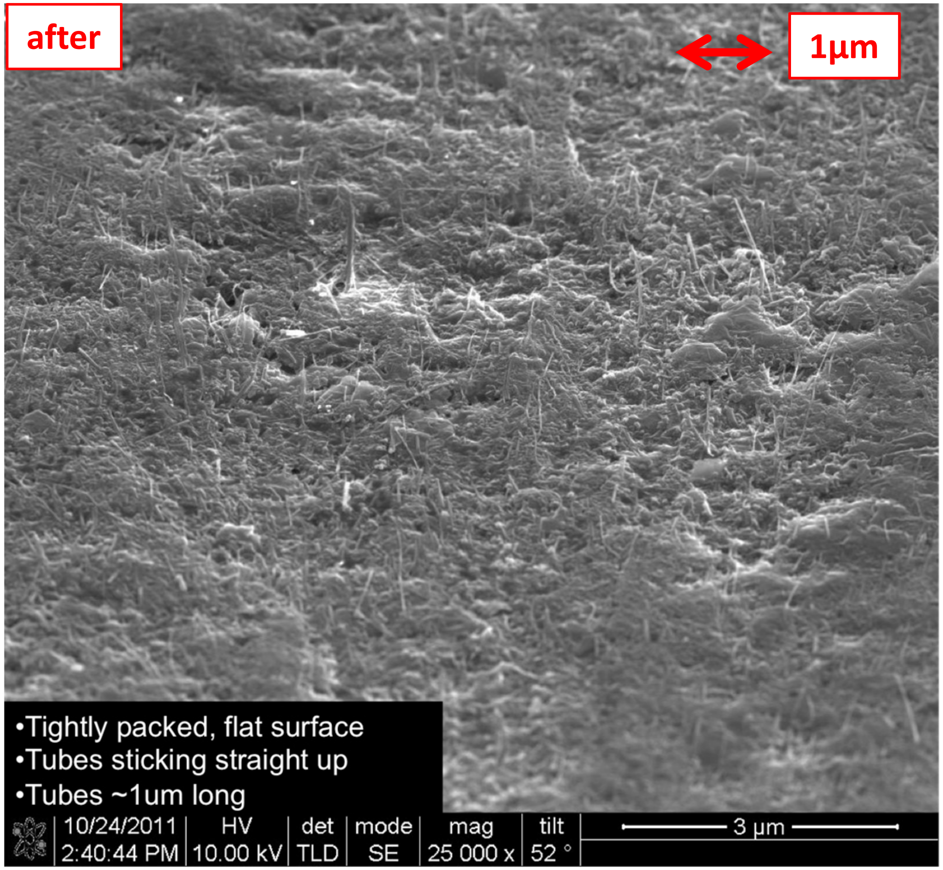
Pre-Post DC testing SEM pics

- Pictures of the emission area with a Scanning Electron Microscope (SEM)

- Cleaner substrate: reduction of adsorbents showing a very smooth the surface.
- Alignment of CNTs: tubes parallel to each other, improved tube spacing and height uniformity (each tube is trimmed by about a factor of 2, from 2-3µm to 1µm length).

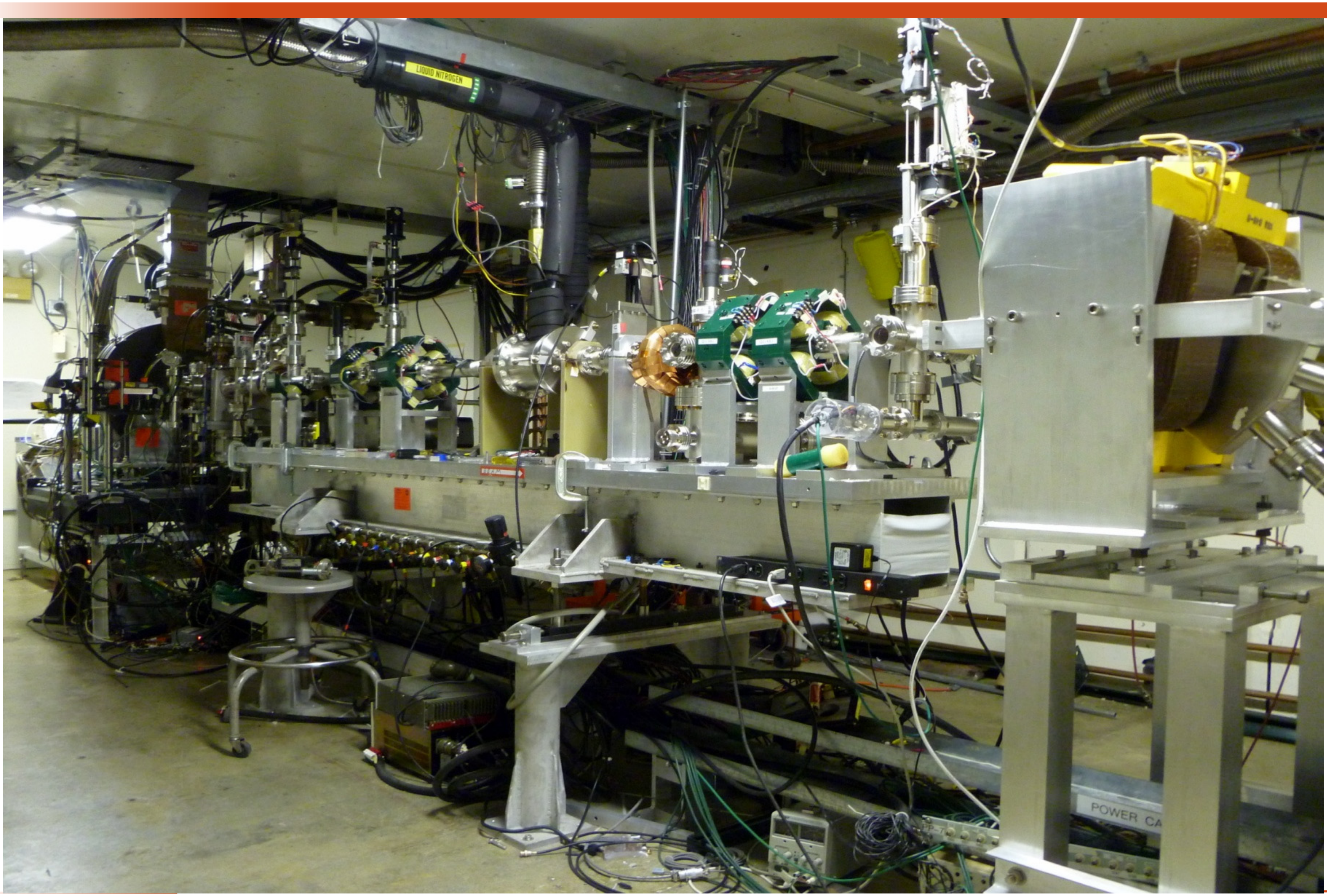


- Many sparsely-packed features
- Random tube orientation
- Tubes 2-3um long

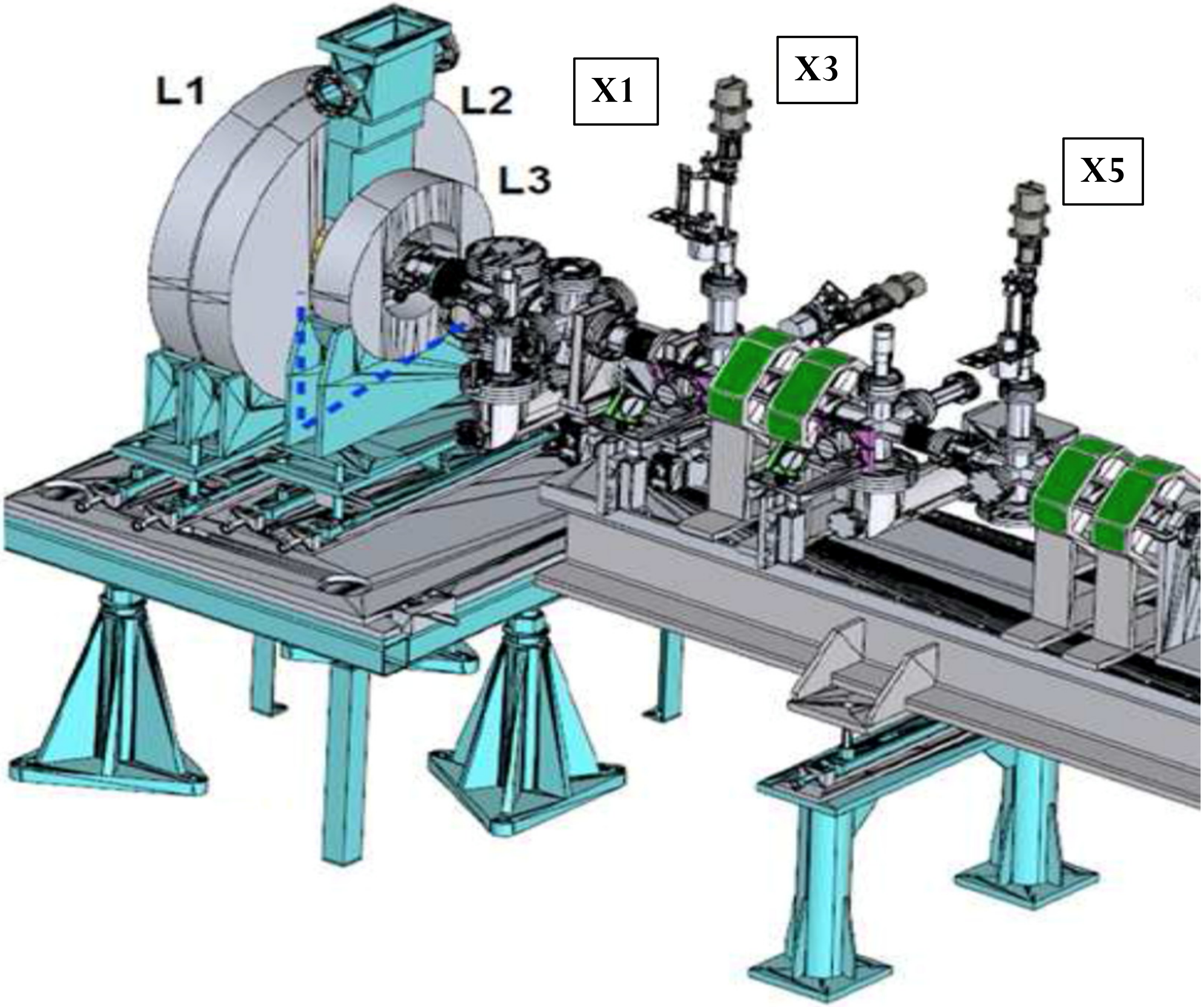


- Tightly packed, flat surface
- Tubes sticking straight up
- Tubes ~1um long

HBESL Facility at FermiLab



HBESL Facility at FermiLab



- **Emitted Beam Current**

Faraday Cup @X1

- **Transverse Beam Profile**

YAG screens

@X1, X3, X5

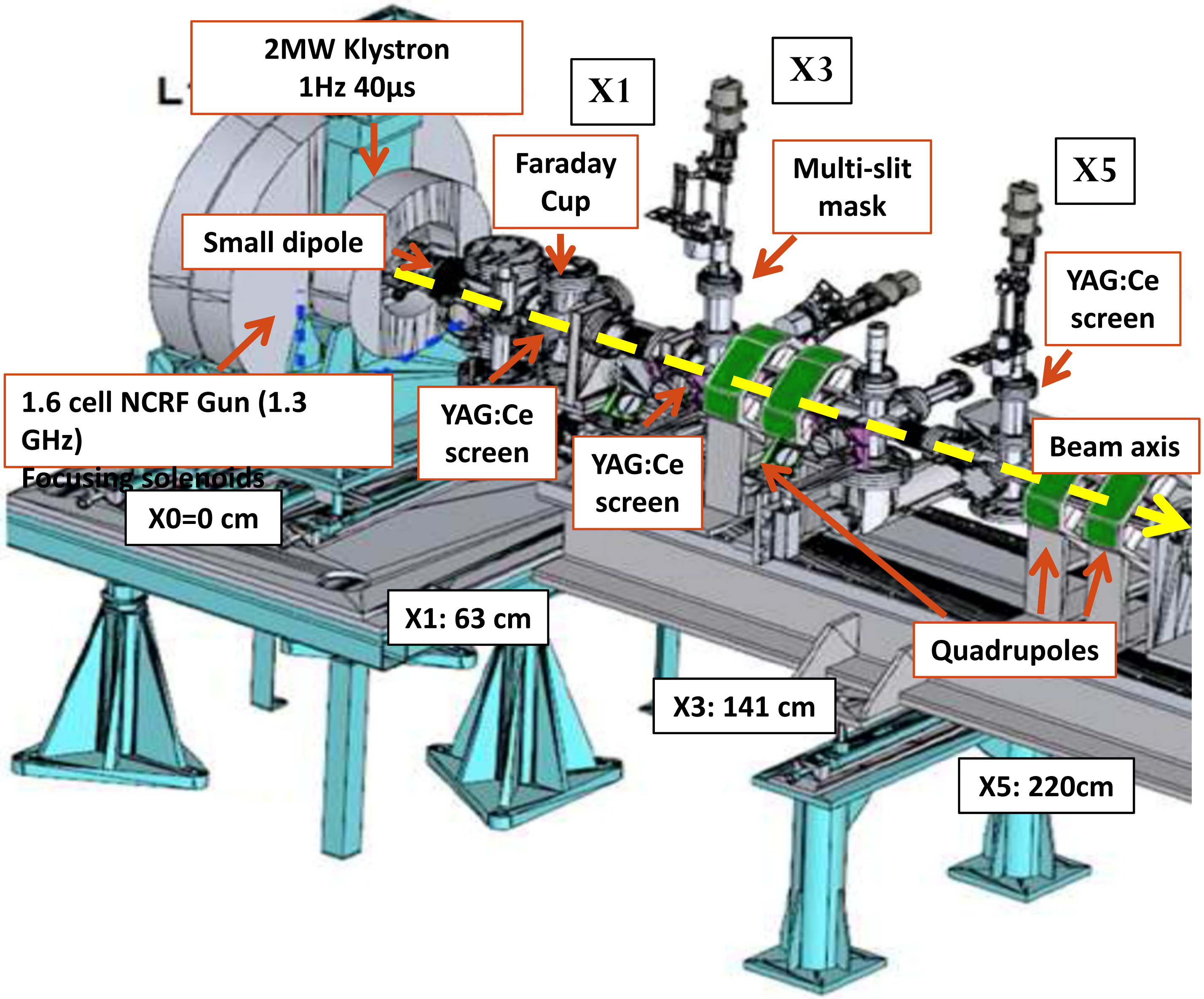
- **Beam momentum**

Small dipole upstream of X1

- **Emittance**

Multi-slit mask@X3

HBESL Facility at FermiLab



- **Emitted Beam Current**

Faraday Cup @X1

- **Transverse Beam Profile**

YAG screens @X1, X3, X5

- **Beam momentum**

Small dipole upstream of X1

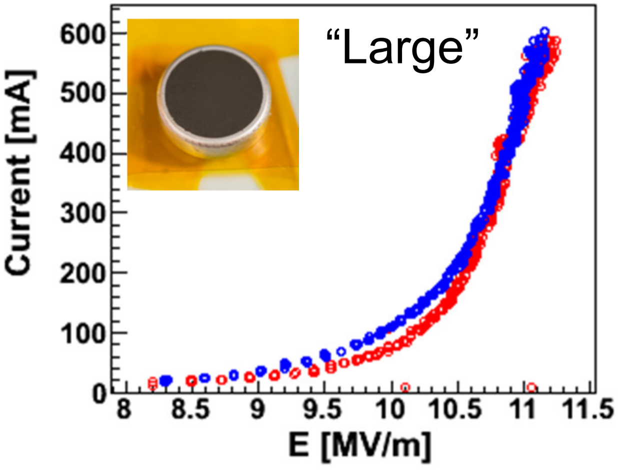
- **Emittance**

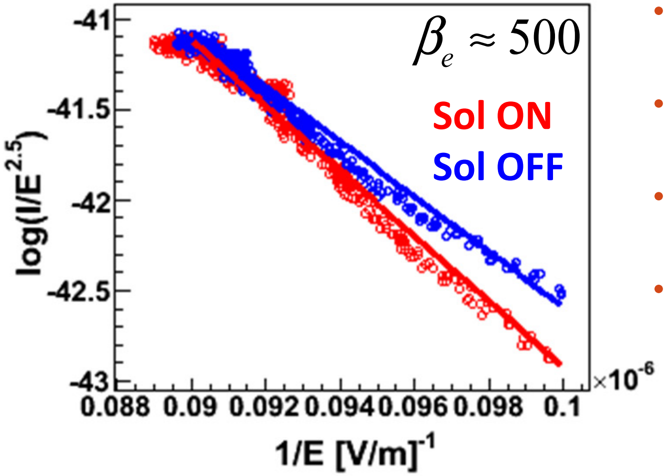
Multi-slit mask@X3

Emitted Beam Current

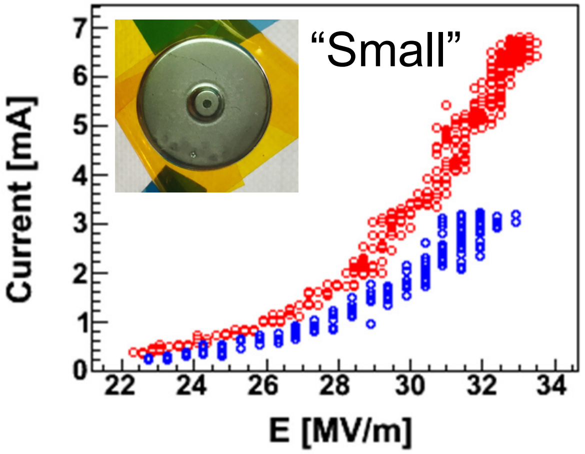
- "Large" cathode: diameter ~1.5 cm, Molybdenum substrate, EPD process
- "Small" cathode: diameter ~1.5 mm, Stainless Steel substrate, EPD process

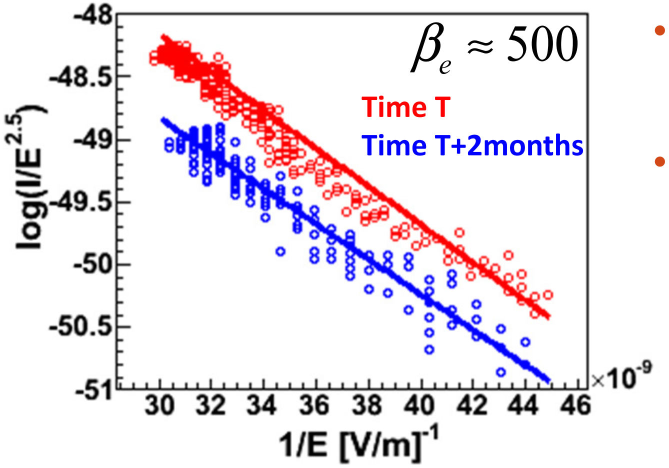
$$\bar{I} = \frac{1}{\sqrt{2\pi}} Aa(\beta_e E)^{5/2} e^{\left(-\frac{b}{\beta_e E}\right)}$$





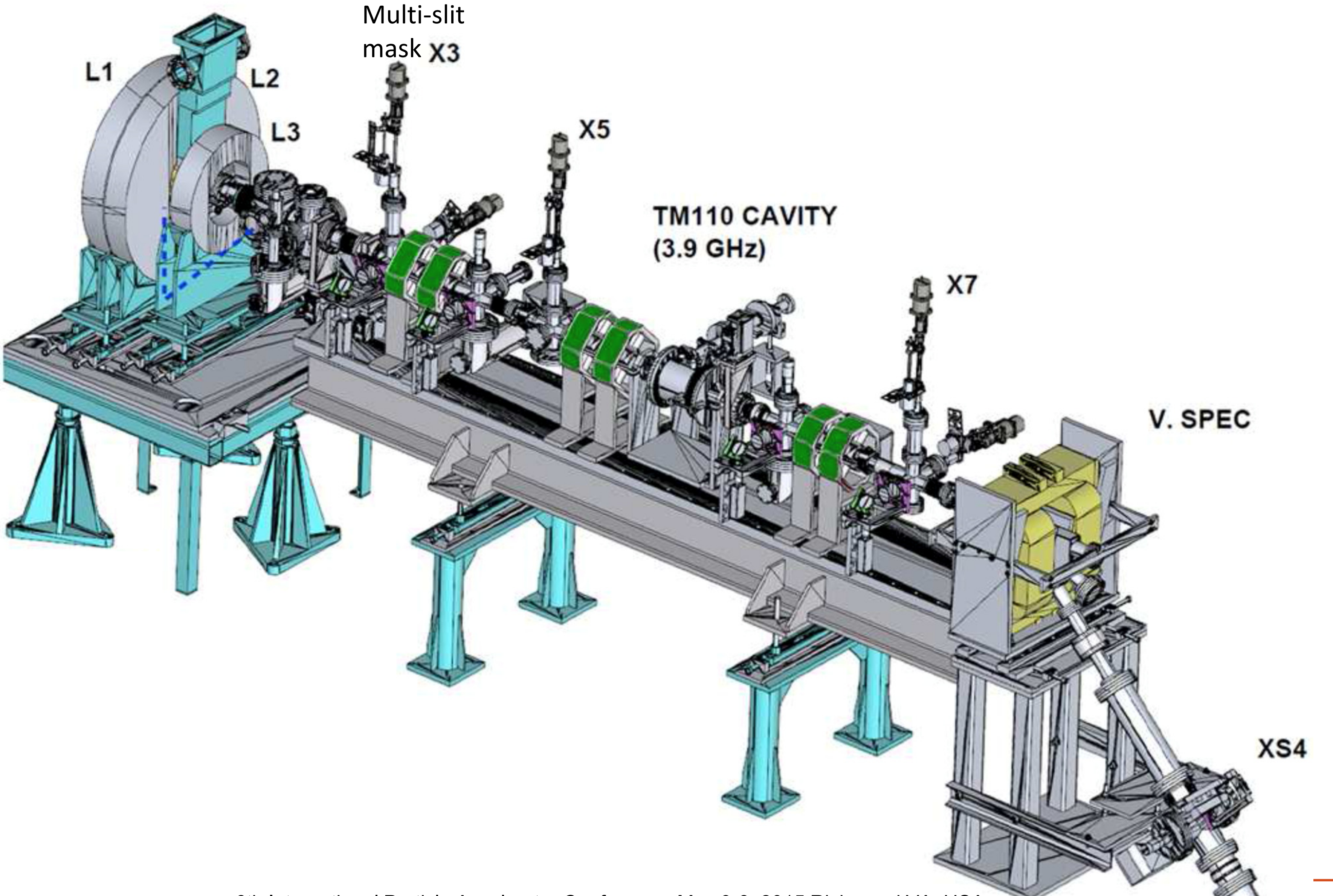
- 4 weeks between subsequent tests
- Cathode exposed to atmosphere
- No current degradation observed
- Currents close to 1A measured → RF Gun off resonance (heavy Beam-Loading)



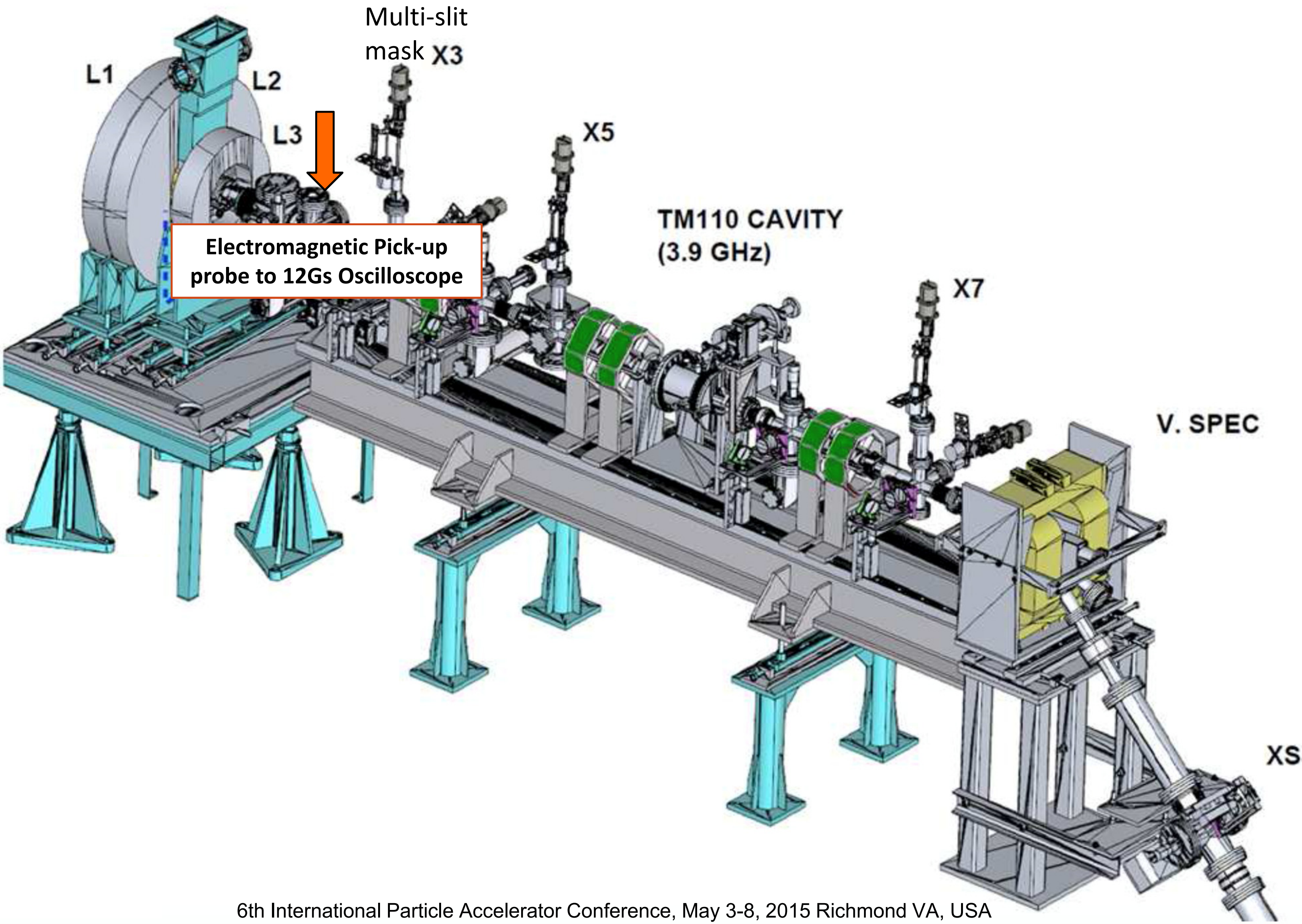


- Current degradation observed
- Dark spots observed on the SS substrate, likely caused by multipacting due to favorable emission yield

Bunch Length and Emittance

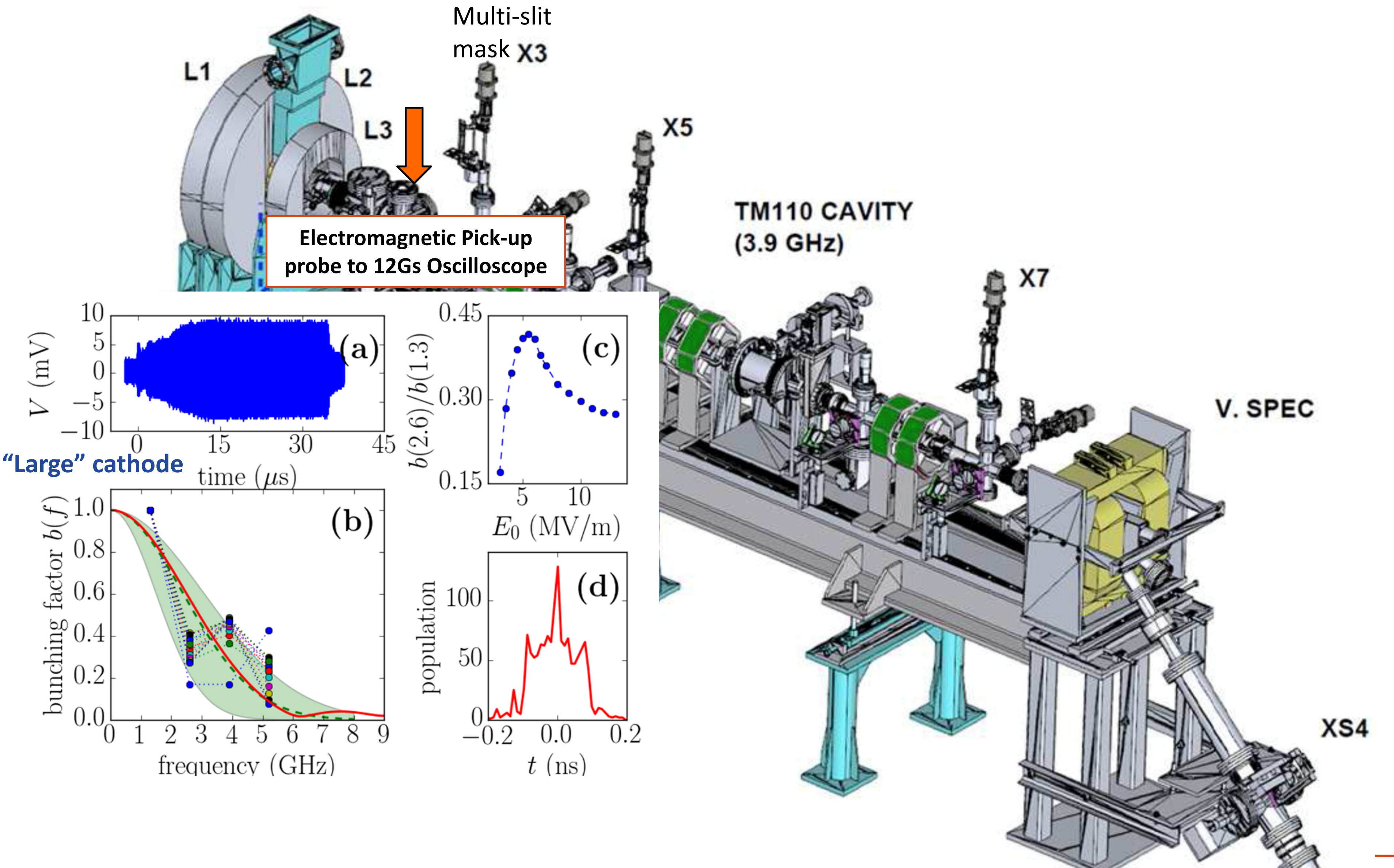


Bunch Length and Emittance



Electromagnetic Pick-up probe to 12Gs Oscilloscope

Bunch Length and Emittance

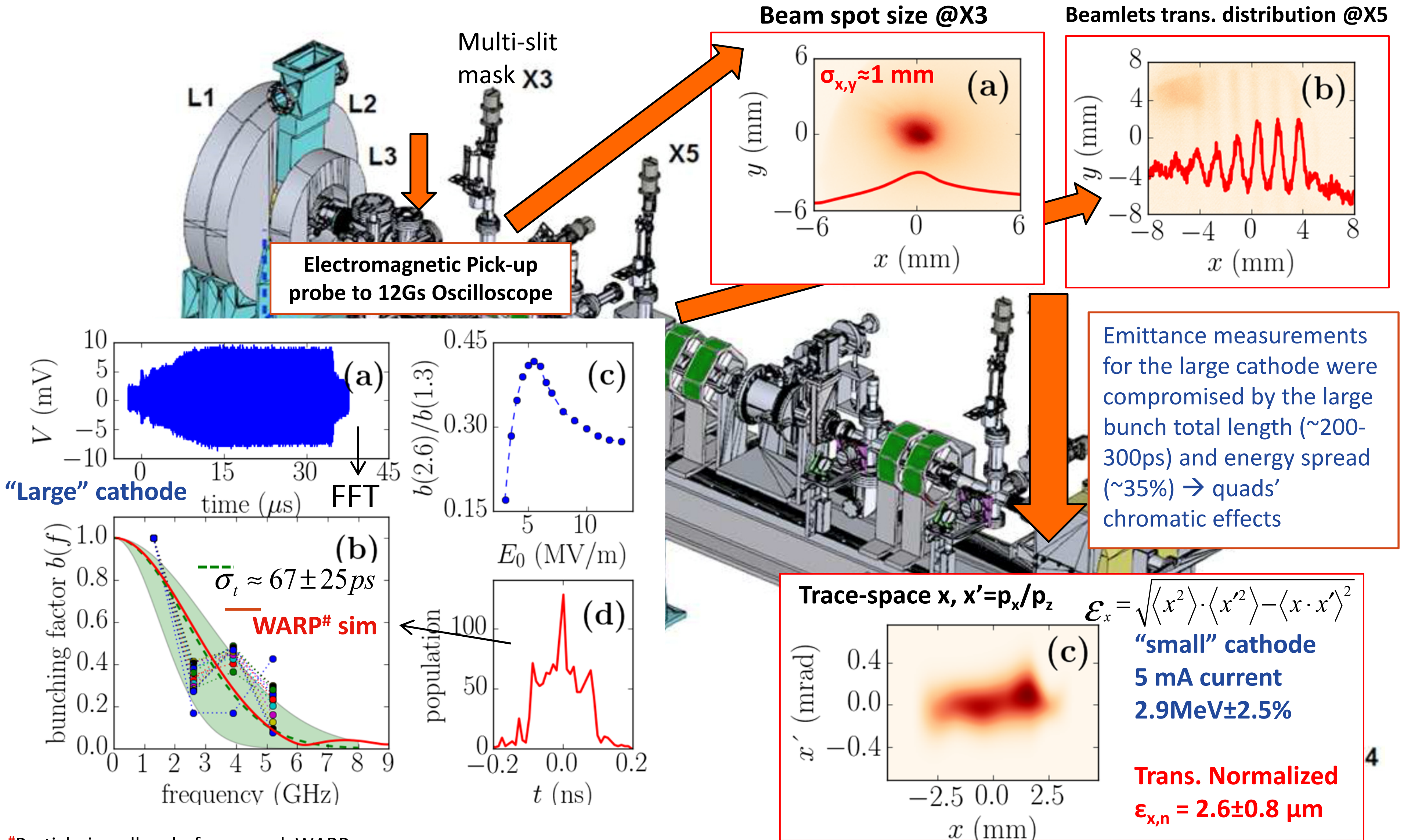


Multi-slit mask

Electromagnetic Pick-up probe to 12Gs Oscilloscope

“Large” cathode

Bunch Length and Emittance



Beam spot size @X3

Beamlets trans. distribution @X5

Electromagnetic Pick-up probe to 12Gs Oscilloscope

“Large” cathode

Emittance measurements for the large cathode were compromised by the large bunch total length (~200-300ps) and energy spread (~35%) → quads’ chromatic effects

Trace-space x, x’=p_x/p_z

$$\varepsilon_x = \sqrt{\langle x^2\rangle \cdot \langle x'^2\rangle - \langle x \cdot x'\rangle^2}$$

“small” cathode
5 mA current
2.9MeV±2.5%

Trans. Normalized
$\varepsilon_{x,n}$ = 2.6±0.8 μm

#Particle-in-cell code-framework WARP
J. L. Vay, D. P. Grote, R. H. Cohen, and A. Friedman, Comput. Sci. Disc. 5 014019 (2012).

Beam Current, Life-time study

- Very low jitter
- Relative rms fluctuation

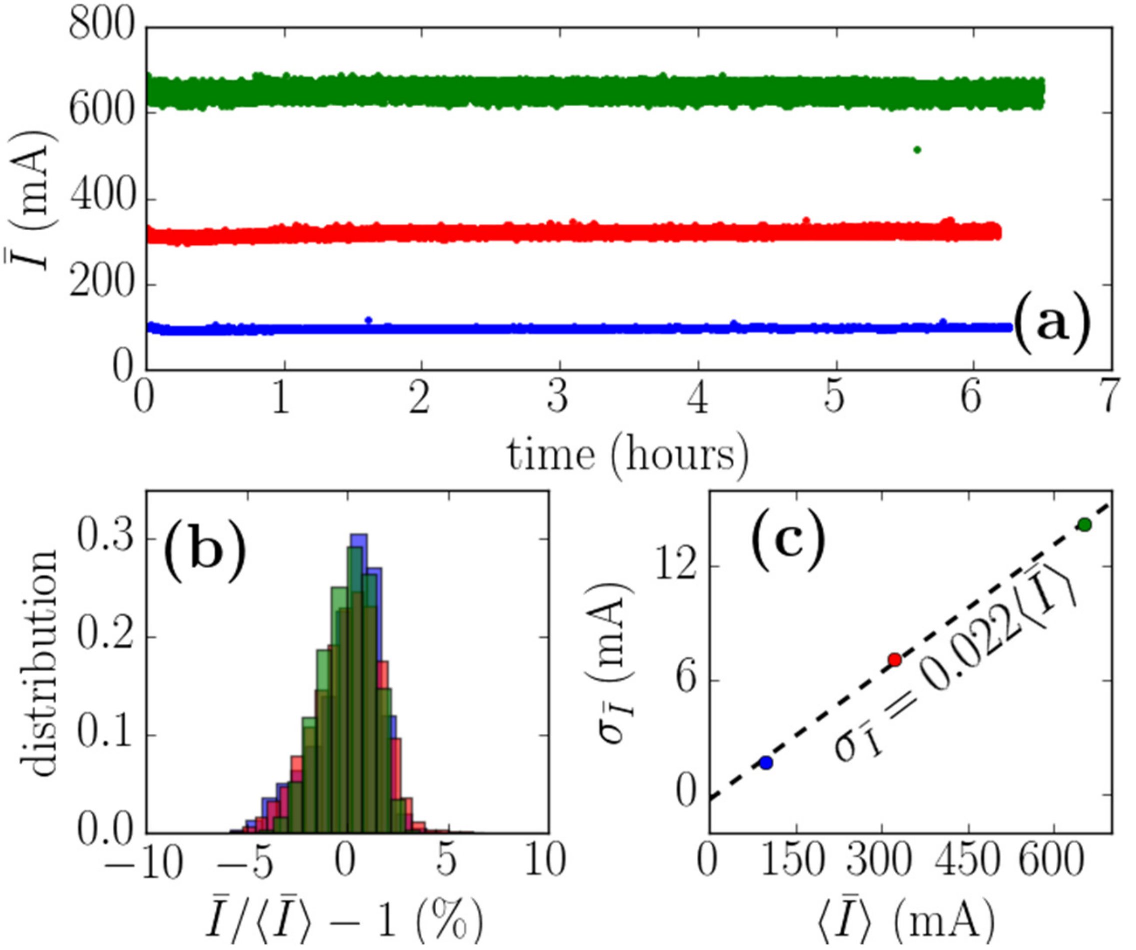
$$\sigma_{\bar{I}} = \sqrt{\langle \bar{I}^2 \rangle} \Big/ \langle \bar{I} \rangle \approx 2\%$$

- Stable emission at 100mA, 300mA and 650mA
- Charge per bunch and length

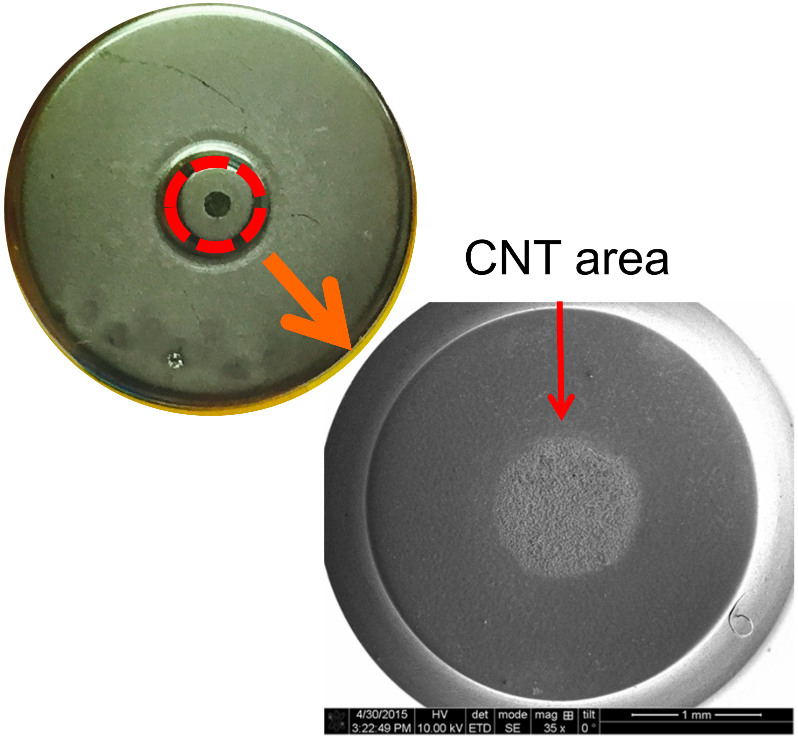
$$Q \approx \bar{I} / f_0 \approx 0.5nC \qquad \sigma_t \approx 70ps$$

- Single-bunch peak current

$$\hat{I} = Q \Big/ \sqrt{2\pi}\sigma_t \approx 3A$$

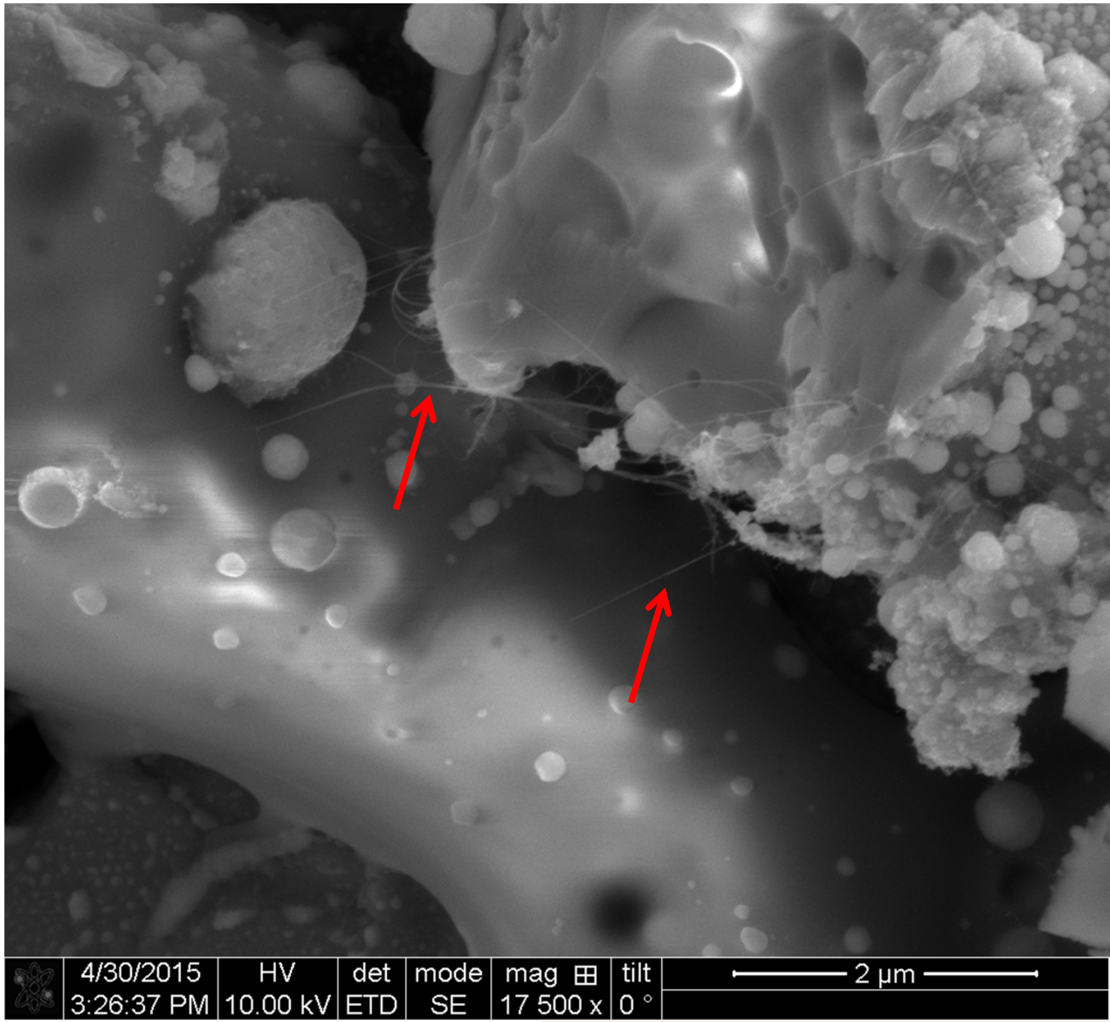


Post-test small cathode-SEM pics



CNT area

SEM



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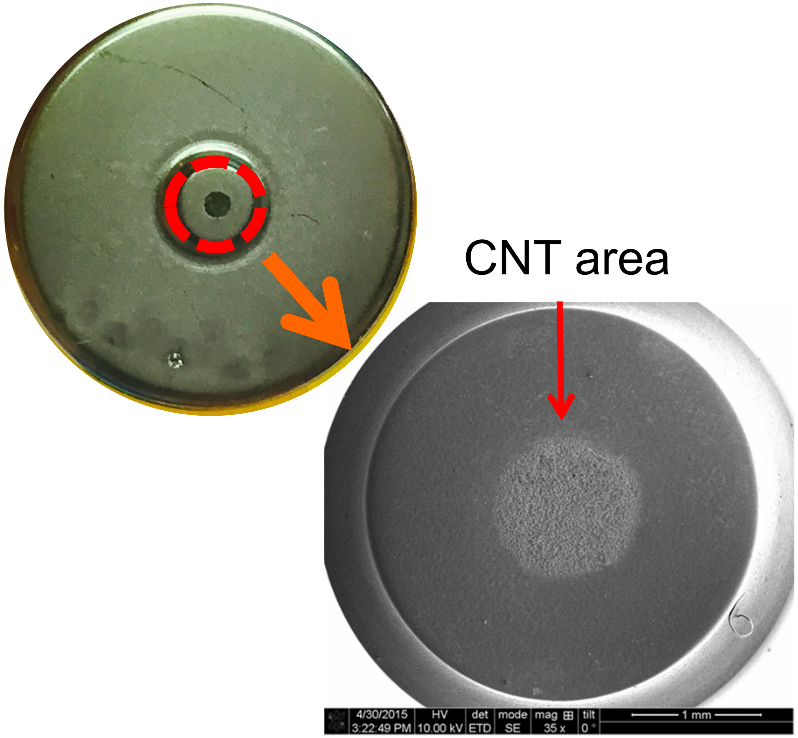
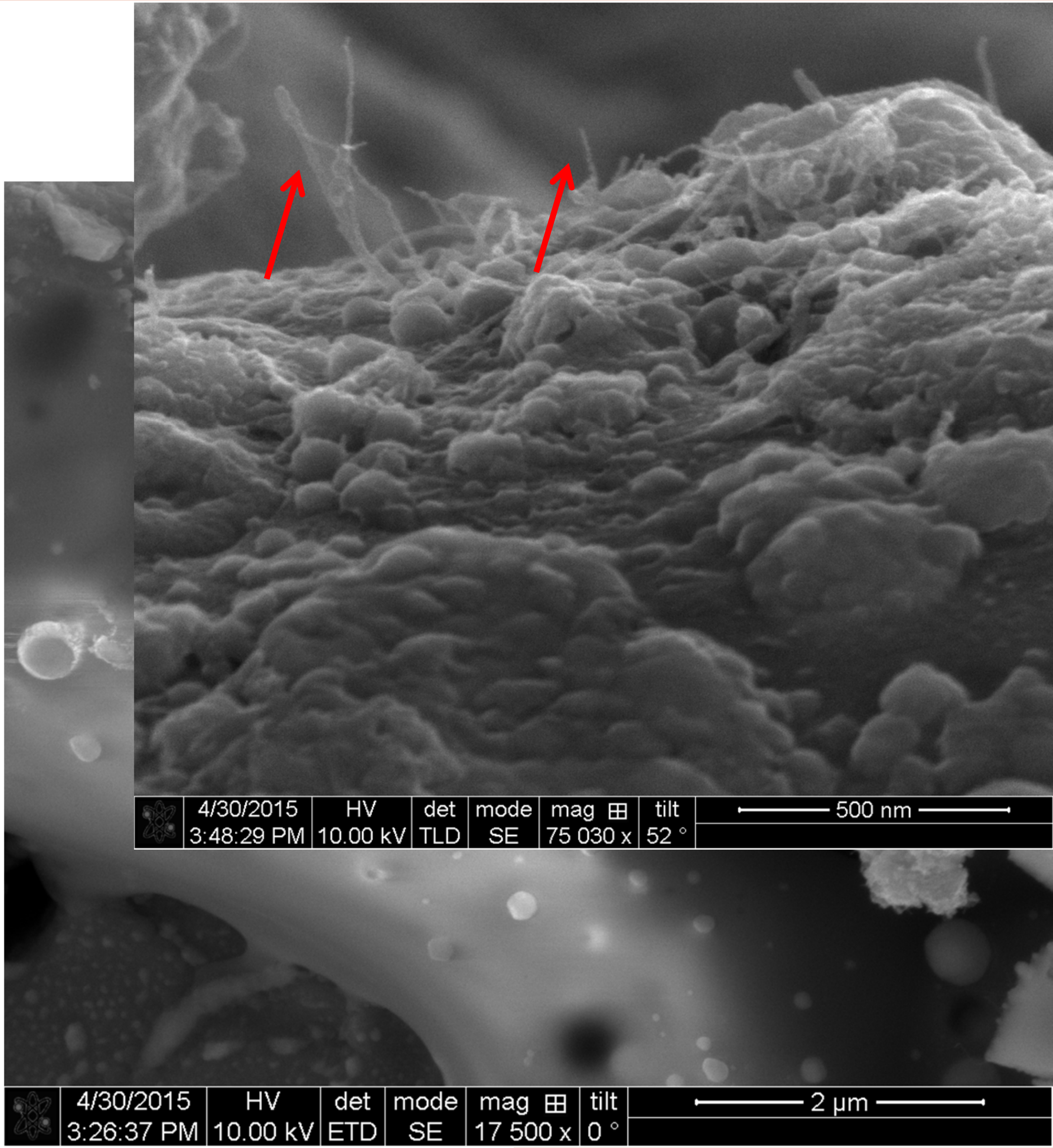


SEM



- **No morphological changes compared to similar samples soon after EPD process!**
- **Unlike High-Voltage DC tests, RF environment showed to be less aggressive on CNTs.**
- **Much higher currents observed with RF than in DC, for same cathode geometry and applied E field.**

Conclusions and Applications

- Field emitted current from CNTs deposited on cathode (1.5cm diameter) inside RF gun close to $\bar{I}$~1A, charge per bunch $Q \sim \bar{I}/f_0 = 0.5nC$ and length $\sigma_t \sim 70ps$ when exposed to RF fields with relatively low value (~12 MV/m).
- Beam dynamics simulations performed with the time-dependent PIC code WARP show good agreement with measurements.
- Cold-cathode and cheap technology: no heat-load needed, no expensive laser system
- Applications for high-average current, quasi-continuous-wave electron sources.
- Main challenge: temporal control of the emission process. Electrons field-emitted at unfavorable times are most likely to hit the cavity walls. Such resulting in secondary electron emissions and possible multipacting (as observed in some of our experiments).
- Possible solution: development of gating schemes aimed at shortening the electron-bunch durations and preventing the back-propagation of electrons.
  - A dual-frequency gun* supporting a fundamental and harmonic frequencies could effectively gate the emission of the CNT cathode to the proper phase of the accelerating RF wave.
  - It should be possible to reach ~10-ps bunch durations.

*J. W. Lewellen and J. Noonan, Phys. Rev. ST Accel. Beams, 8, 033502 (2005).

Acknowledgements

- RadiaBeam Technologies, DC tests
  - Josiah Hartzell

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  - William Hubbard

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  - Daniel Mihalcea
  - Harsha Panuganti
  - Charles Thangaraj

- D. Mihalcea, L. Faillace et al., ***Ampère-Class Pulsed Field Emission from Carbon-Nanotube Cathodes in a Radiofrequency Resonator***, report FERMILAB-PUB-14-527-APC (2015), waiting for publication on APL.

- [**WEPJE019**] D. Mihalcea, L. Faillace et al., ***Simulations of field emission electron beams from CNT cathodes in RF Photoinjectors,*** these proceedings.