Growth of Electric Field Enhancing Precursors for Vacuum High-Voltage Breakdown

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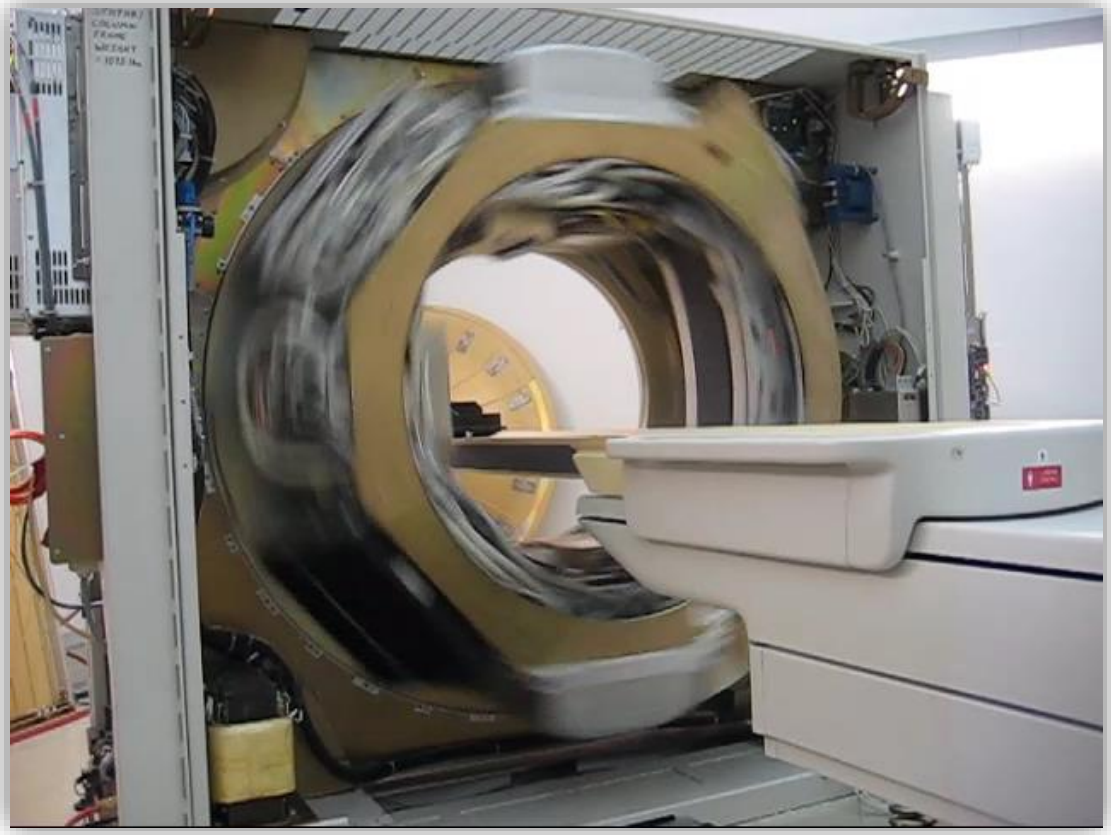
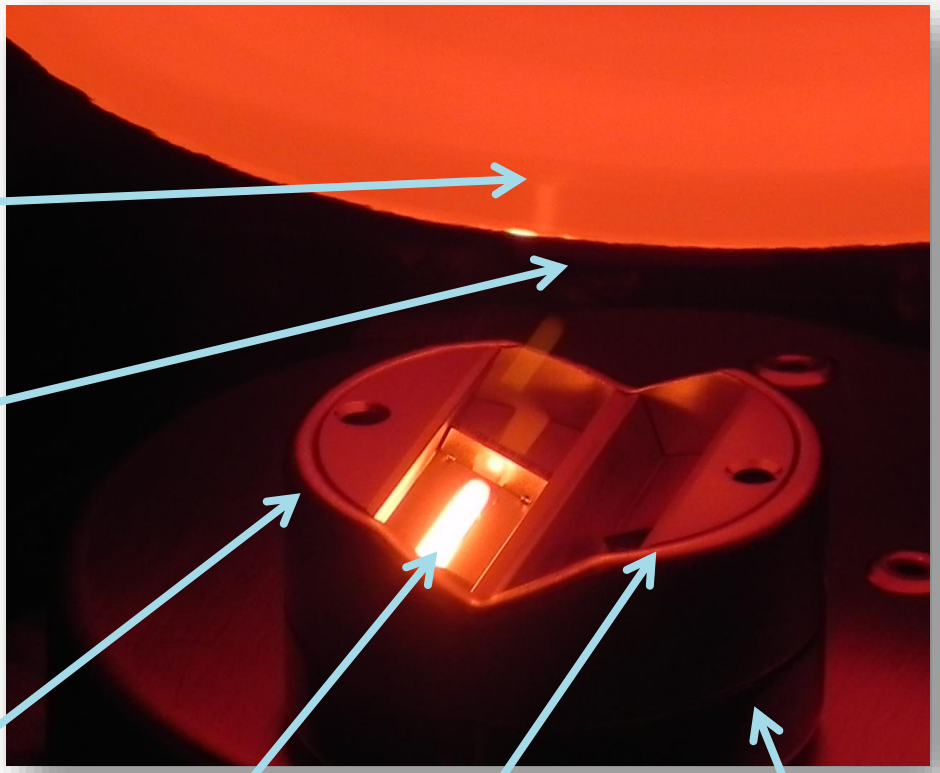
X-Ray Tubes in Computed Tomography

- “Arcing” is a primary cause of tube failure in CT
- 140 kV DC, 120 kW, 4 s
- 200 k exposure seconds per year
- Unwanted discharges every 1,000 to 20,000 scan seconds
- 90+ % remediated by high voltage electronics



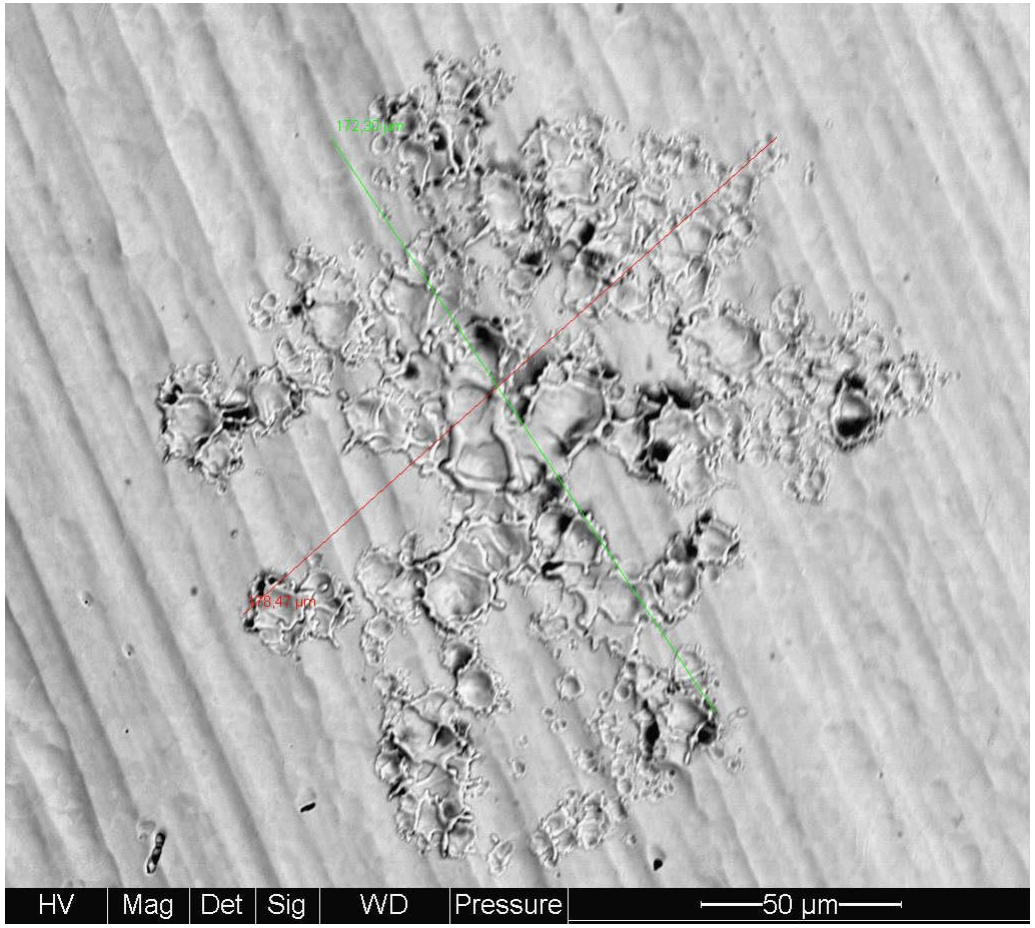
Sample X-Ray Tube

- Electron beam 10 mA up to 1,300 mA
- ~50 % electron backscatter from target
- No active vacuum pump (ions buried in negative electrodes)
- Up to 10^{-2} Pa CO, …



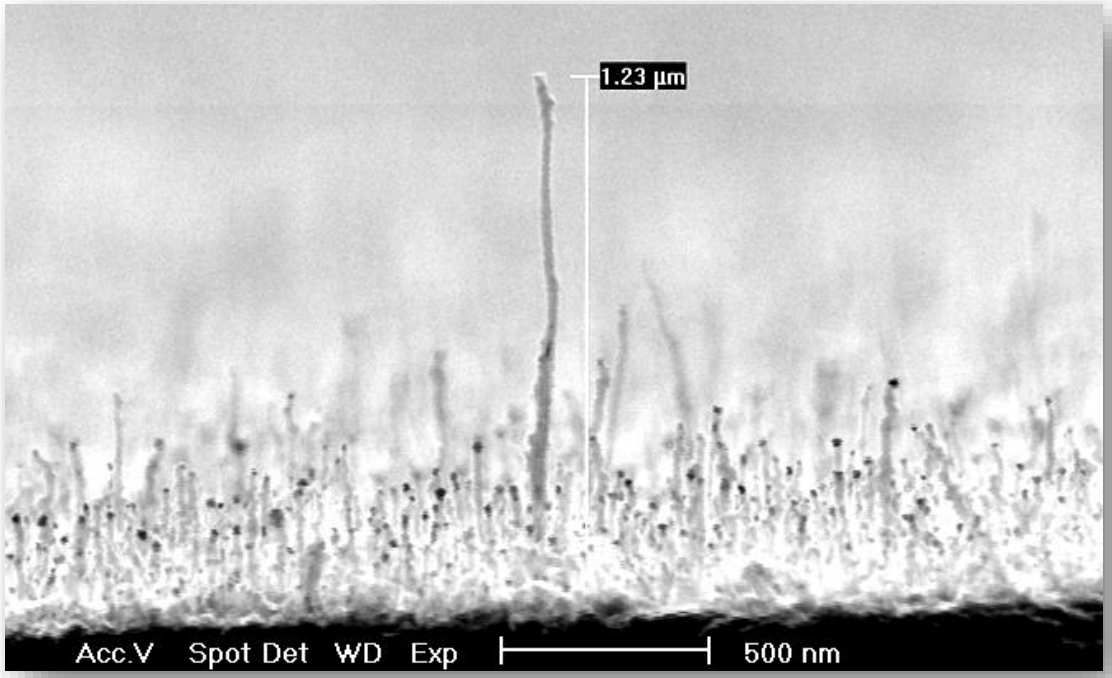
Characteristic Craters on Negative Electrodes

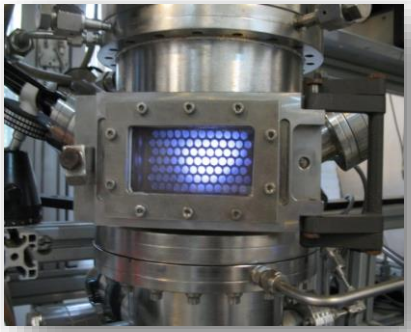
- Explosive Electron Emission (EEE) model
- Assemblies of craters
- Full or (sometimes) partial discharge of the high voltage cable

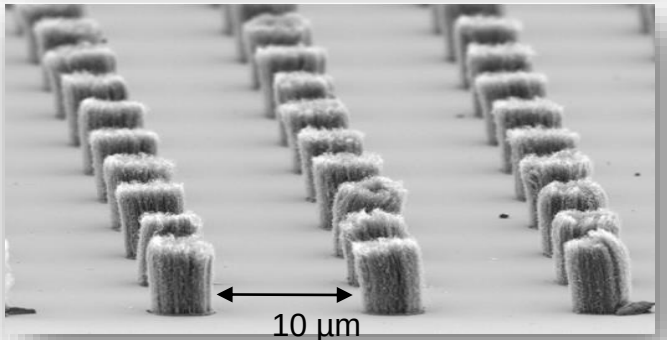


Carbon-Structure Growth of Discharge Precursors?

- CNT’s are grown in industrial PE-CVD processes
- Catalytic growth: Metallic nanoparticles convert hydrocarbons to CNT’s
- Metal nanoparticles in the apex of tip-grown MWCNT, SWCNT
- Nanoparticle distribution controls CNT growth

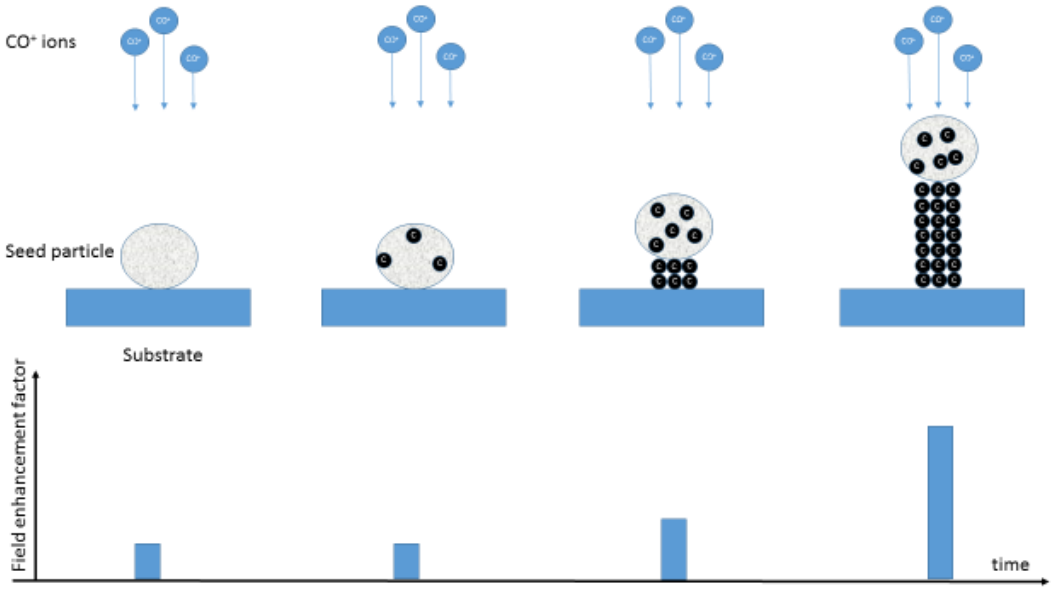






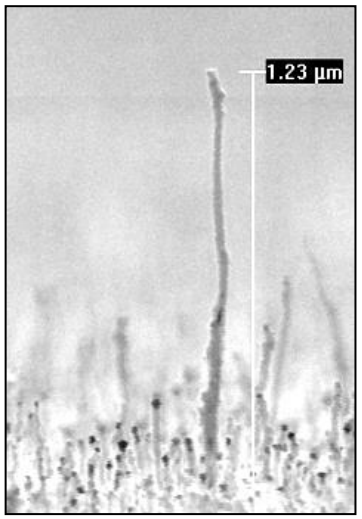
Can CNT's Tip-Grow in X-Ray Tubes?

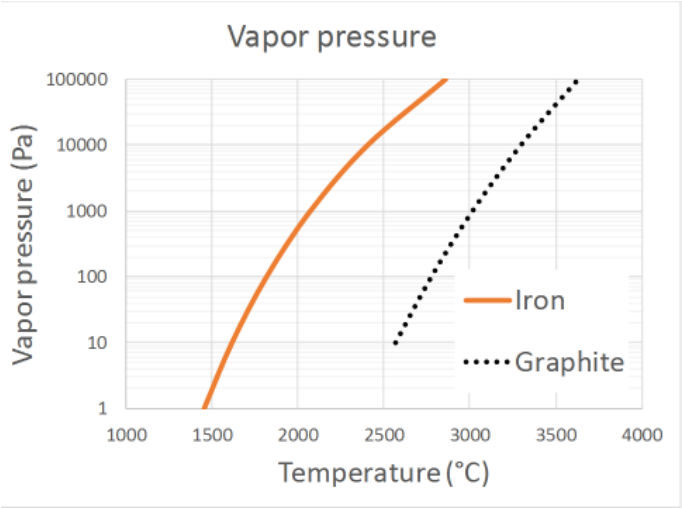
- Carbon source exists: CO form metal anode comprising carbonites and oxides
- Nanoparticles exist, 20+ nm
- Dissociation may happen $CO^+ \rightarrow C + O$
- Carbon would precipitate at "cold end" (CNT), while nanoparticle is lifted
- Field Enhancement Factor and Emission would rise
- Tip eventually explodes in EEE

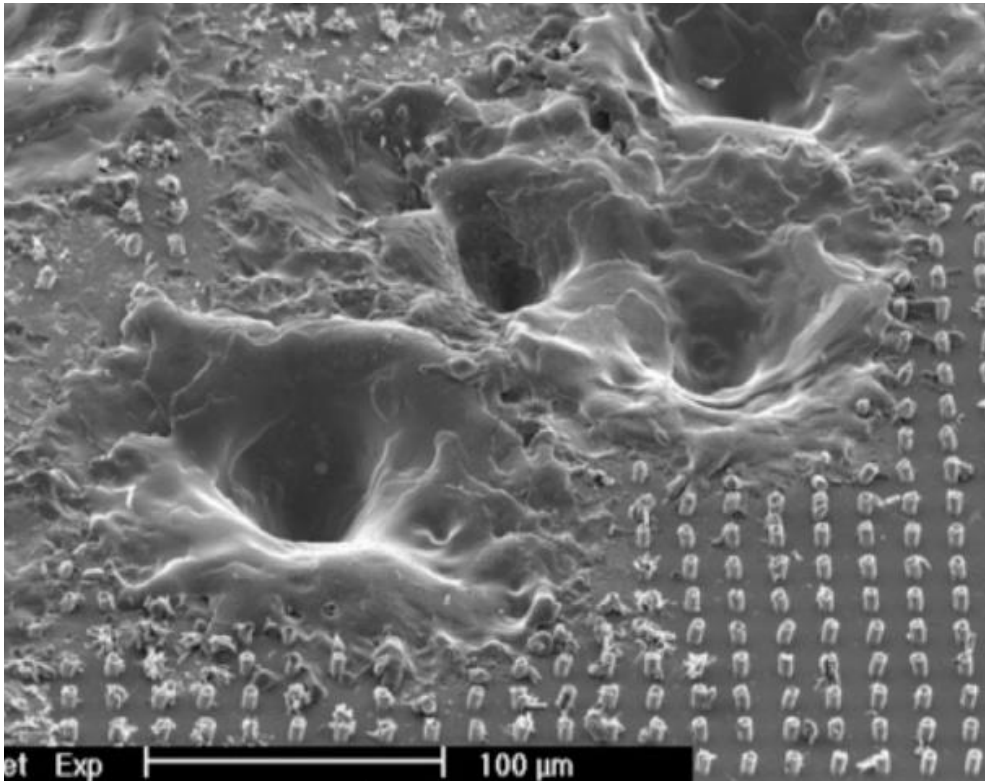


Attractive Model

- We know: Hydrocarbons impair h/v stability
- Nanoparticles always exist
- FN plots: work function carbon-like, high FEF
- Stochastic discharge events
- High metal vapor pressure would alleviate EEE

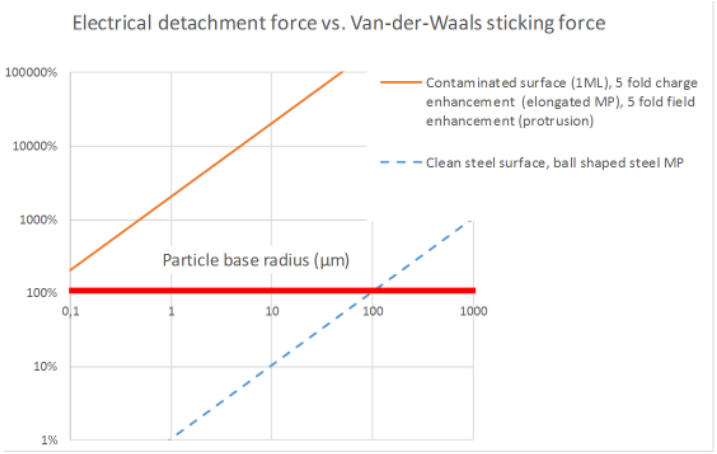


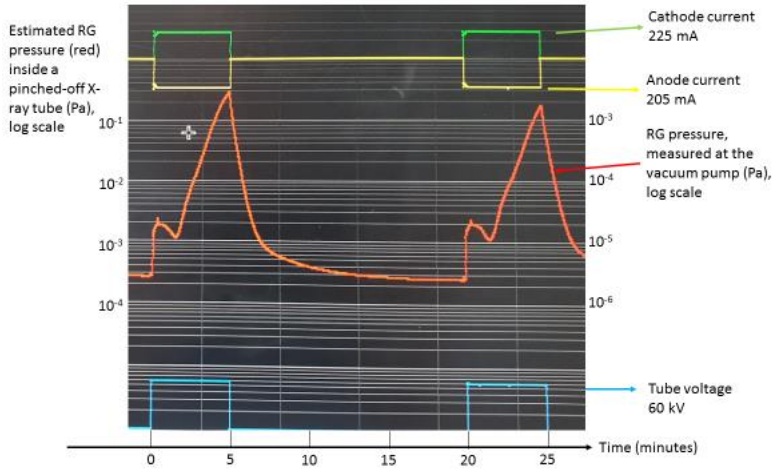




Is it Realisitc (1)?

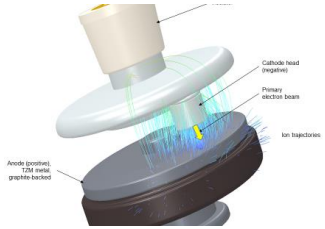
- CNT's will stick under electric field
- Carbon source exists (CO)

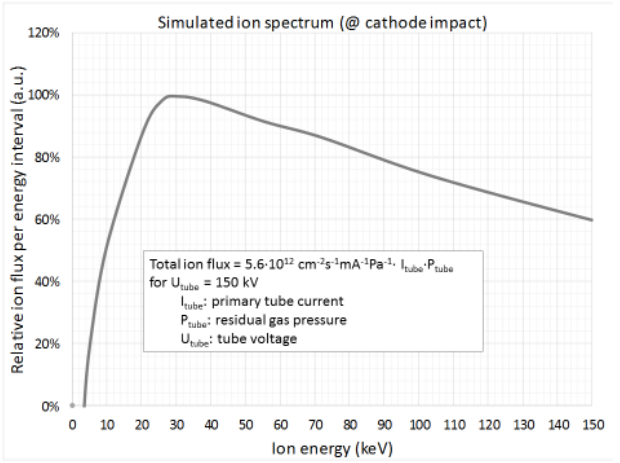


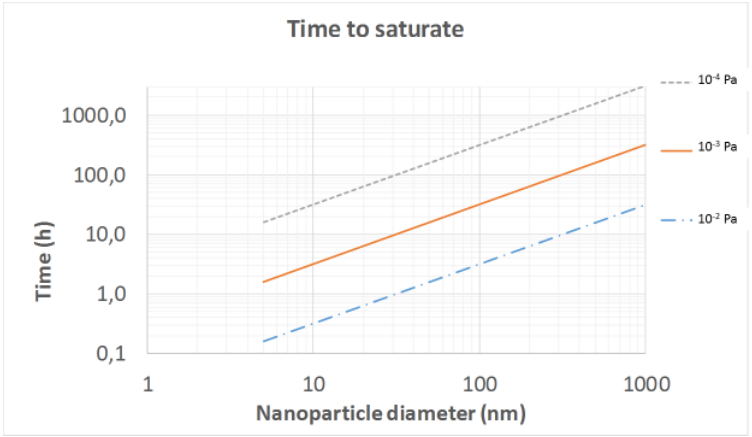


Is it Realistic (2) ?

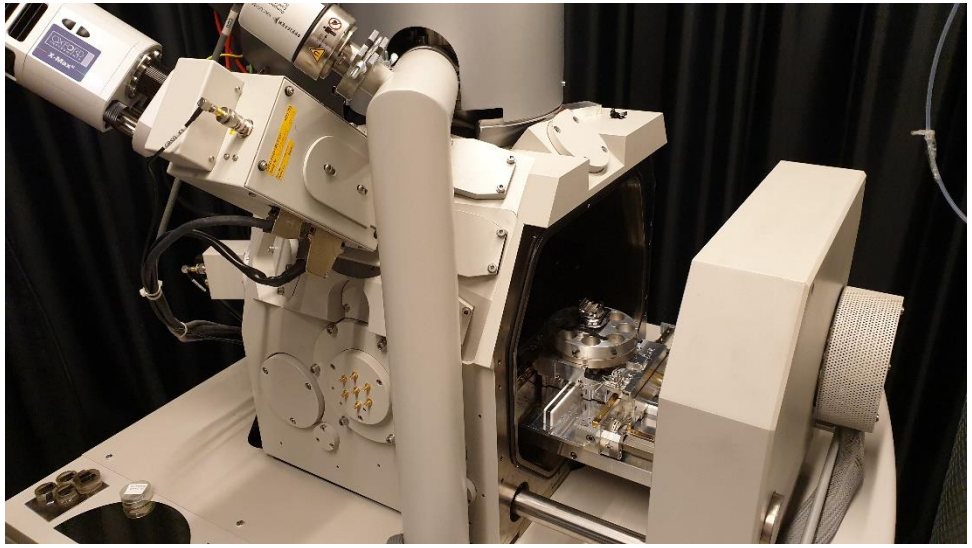
- Ion bombardment exists, 10…140 keV
- Iron nanoparticle (NP) penetration 5… 80 nm
- Time to saturate typical NP matches discharge frequency
- Minor growth efficiency would already be problematic (few FE sites would grow)





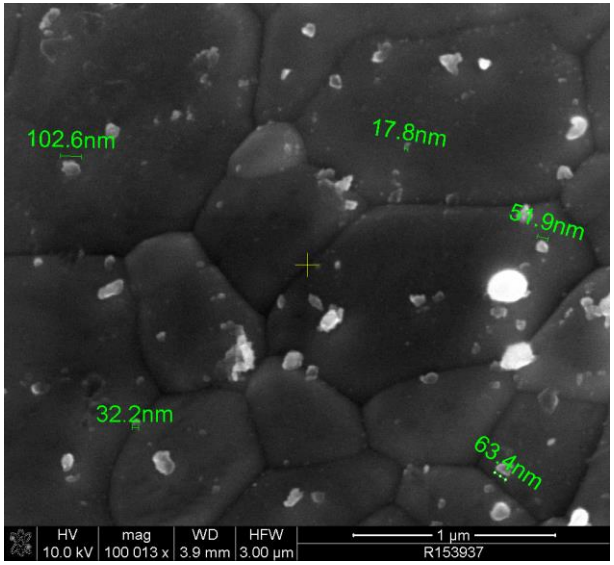


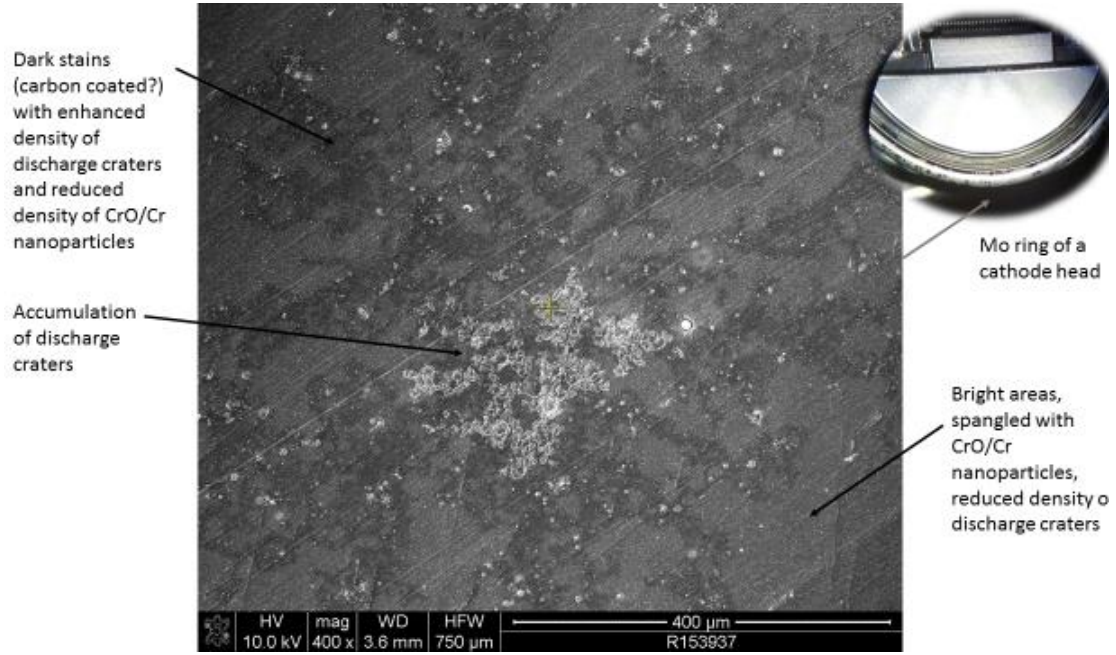
Evidence?



Model System

- Cr/CrO NP on Mo
  - 10-100 nm: $4 \cdot 10^8$ cm^{-2}
  - >100 nm: $1 \cdot 10^8$ cm^{-2}
- Literature: Cr used before for CNT growth *)
- Cathode temperature in operation 300…700°C
- Ion flux ~10^{17} cm^{-2}
- Patches of craters



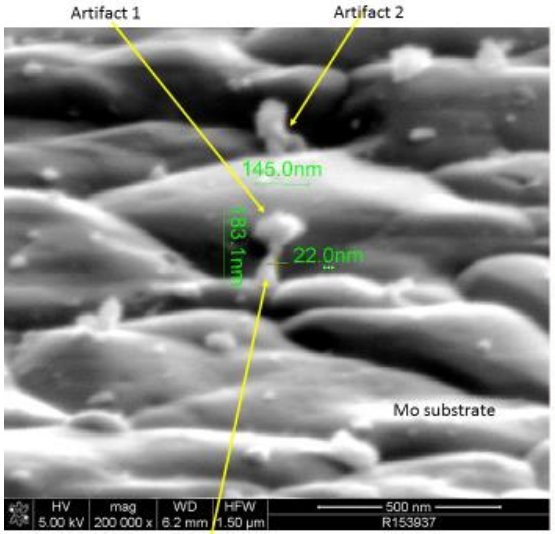


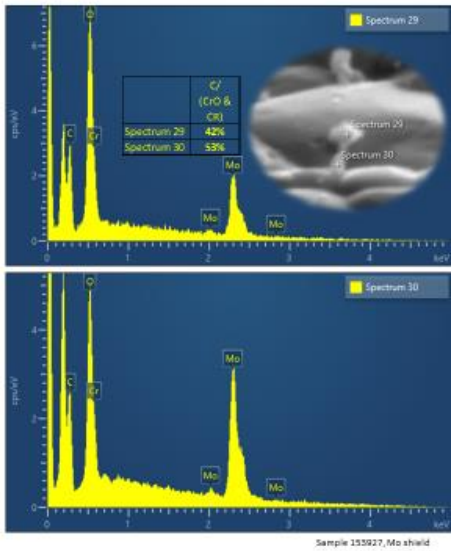
*) J. Balamurugan, R. Thangamuthu, A. Pandurangan, Effective synthesis of carbon nanotubes of high purity over Cr-Ni-SBA-15 and its application in high performance dye-sensitized solar cells, RSC Adv. 3 (2013) 4321–4331. doi:10.1039/c3ra23081c.

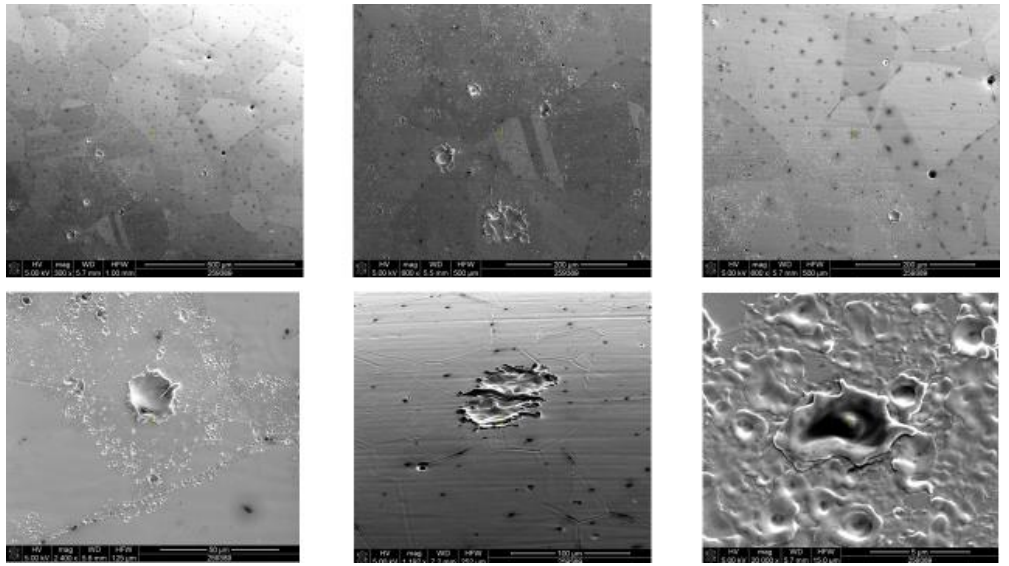
But: NO Unambiguous Sign of C Fiber Growth

- 2 x Mo substrates from operated metal frame X-ray tube had dense population of NP
- → Only one single fiber structure identified with weak C signal underneath Cr/CO NP

- 1 x Ni42 substrate from operated glass X-ray tube type had no NP contamination and no fiber growth. Observe: inclusions at grain boundaries



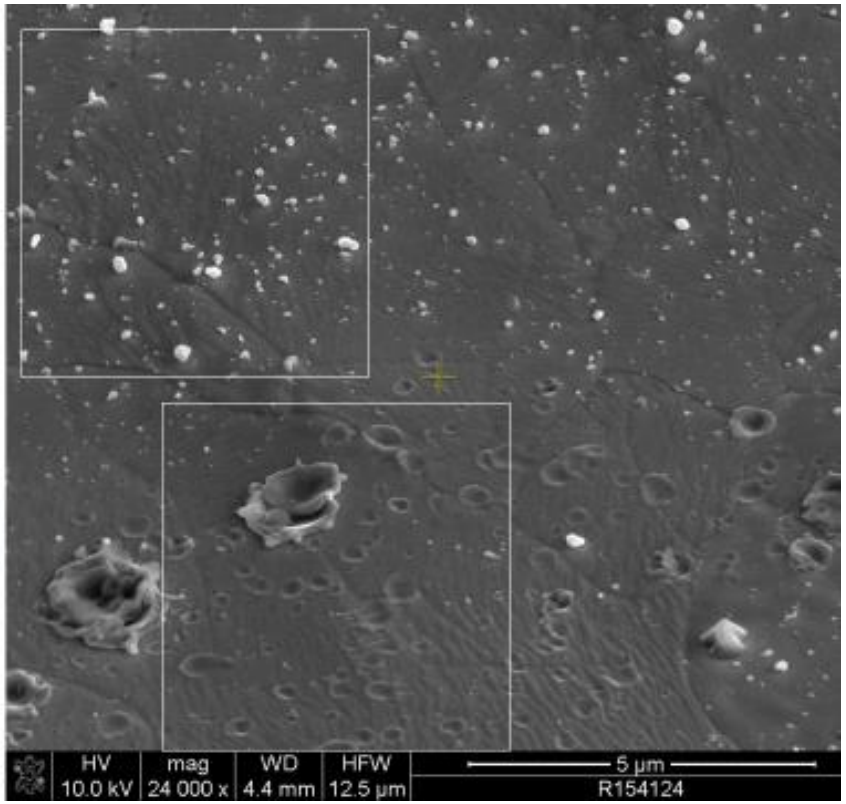




Correlation of Crater Density and NP Density

- Same order of magnitude of
  - ~0.5 µm craters and
  - <100 µm NP

- Patches of discharge craters cleared of NP



Conclusion

- **No** CNT growth identified for Mo cathodes of X-ray tubes, despite of extreme Cr/CrO NP density of $5 \cdot 10^8$ cm^{-2} and CO^+ dose ~10^{17} ions per cm^{-2}
- **Nanoparticles** seem relevant
- Destruction of NP by ion bombardment and subsequent EEE (anti-correlated densities)?