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How high-power accelerators damage thin wires?

Low Density Materials for Beam Instrumentation, **CERN, June 20th, 2023**

Remarks and Outlook

Presentation:

- Focuses on experience from CERN and PSI/HIPA wire scanners (not exhaustive)
- Signals some open questions
- Is not about carbon nanotubes

Outlook:

1. Breakage tests at CERN SPS – carbon fiber sublimation, ion beam mystery
2. Quench test at LHC – precise sublimation of carbon fiber, impact on profile reconstruction
3. Long history of RF-damages (carbon) – mystery of skin effect
4. Ductile damage of Molybdenum wire – importance of surface quality

Other cases (not discussed):

- Gold layer melting in LINAC4 SEM grids
- Tungsten wire corrosion due to electric discharges
- Carbon fiber breakage by possible thermal shock (SLAC)

see: C. Field et al., “Wire Breakage in SLC Wire Profile Monitors”, BIW98

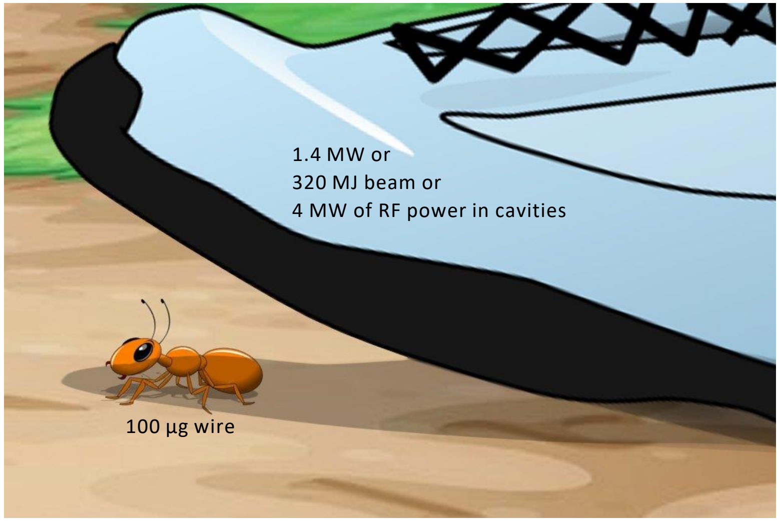
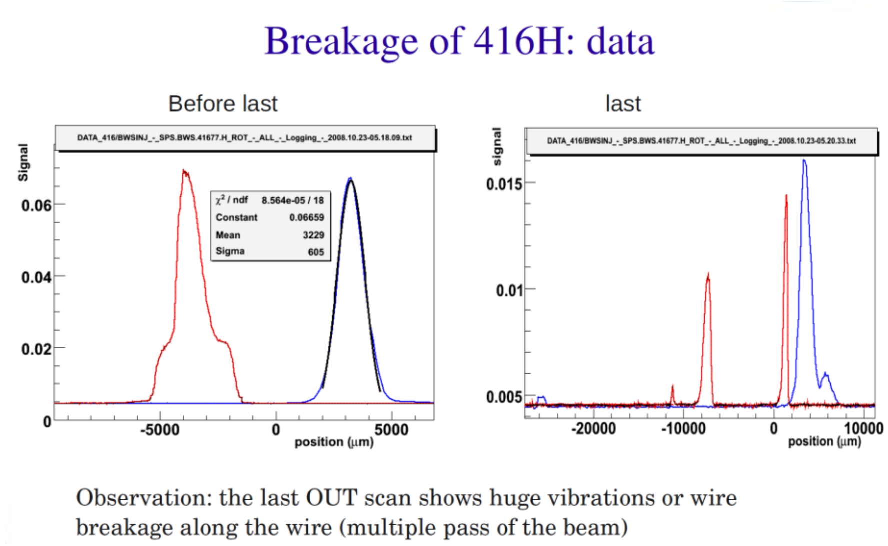


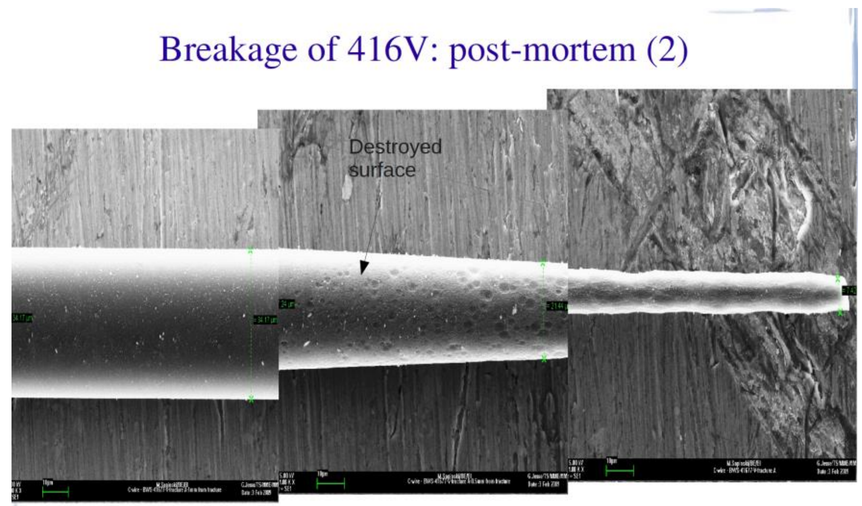
image from sacompassion.net

SPS experiment, 2008

- Scanners used: 416V, 416H
- 450 GeV proton beam, coasting (reduce RF)
- Breakage at 50-70 cm/s (nominal 6 m/s)
- Scans before breakage suggest strong wire deformation and/or vibrations
- Electron microscope analysis shows significant sublimation, from 34 µm diameter down to about 6 µm
- Model predicts temperature ~3500 K
- 95% of material sublimated before the wire breakage,

  carbon fiber is truly a strong material
- Sublimation increases surface-to-volume ratio, leading to better thermal behaviour
- As a result of these experiments the limits for LHC scanners were established





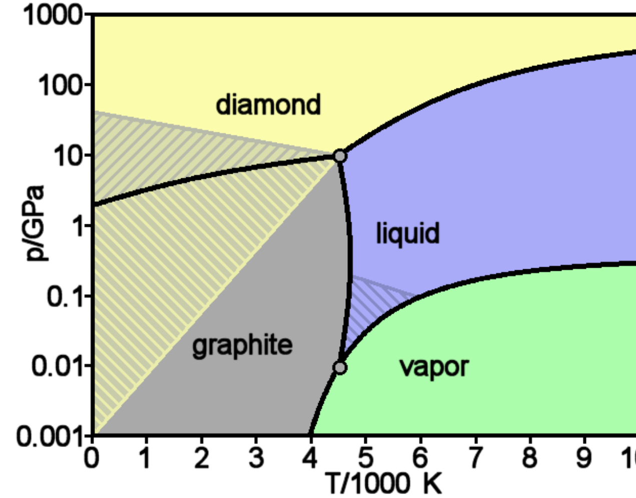
see: "Carbon Fiber Damage in Accelerator Beam", proceedings of DIPAC 2009, CERN-BE-2009-028

Sublimation calculation

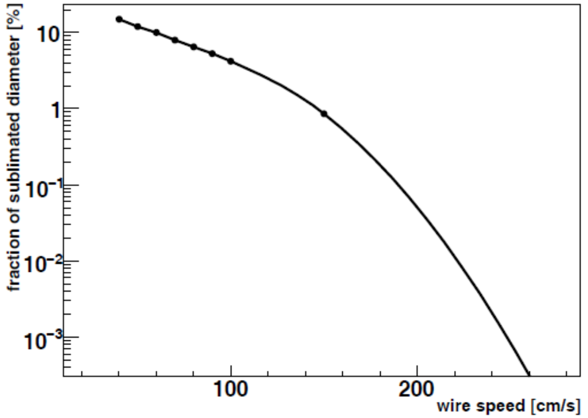
- In vacuum graphite does not melt, it sublimates
- Sublimation rate can be calculated using simplified model assuming steady-state conditions:

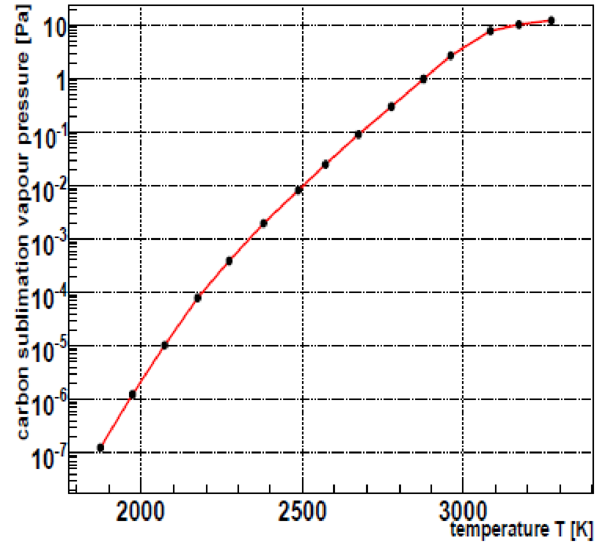
  $dD/dt = ½\, v_{vap}(T)\, \frac{\rho_{vap}}{\rho_C}$,

- vapour density computed from vapour pressure
- Measurements: 2 times more material sublimated than foreseen by the model, what is large error but not completely crazy result



Simplified carbon phase diagram





see: *"Carbon Fiber Damage in Particle Beam"*, 46th ICFA Advanced Beam Dynamics Workshop on High- Intensity and High-Brightness Hadron Beams, Morschach, MOPD61

SPS experiment with Pb^{82+}, 2011

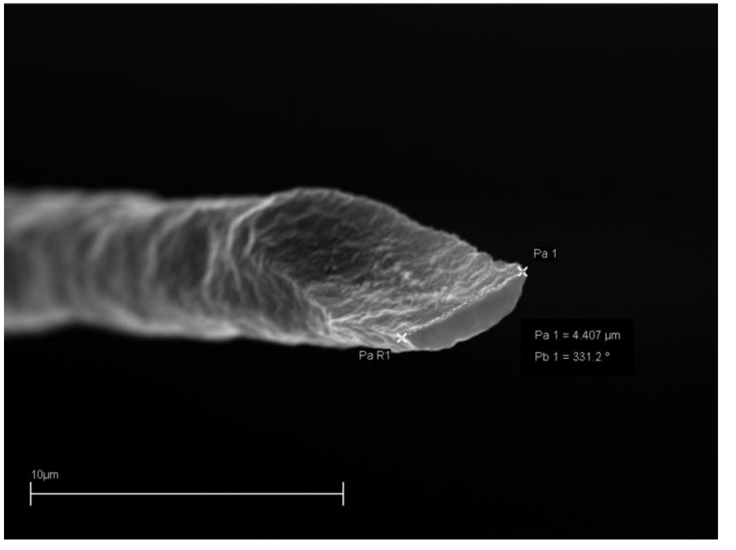
- Goal: test wires with ion beam
- Ion energy deposition Z^2 higher than protons
  (this is why GSI do not have wire scanners)
- SPS scanner used: linear horizontal
- 450 ZGeV Pb^{82+} beam
- Wire never broke with the beam, even at the smallest registered velocity of 2 cm/s
- It broke during the process of removal
- Electron microscope shows sublimation down to 7.7 µm
- Reason why wire did not break remains a mystery
  - z^2 law does not apply to thin targets?
  - δ-electron cooling is much stronger than for protons?
- If confirmed, this could open the possibility to use wire scanners in heavy ion machines…

$$-\frac{1}{\rho}\frac{dE}{dx} = 4\pi N_A \frac{q_e^4}{(4\pi\varepsilon_0)^2 m_e} \cdot \frac{Z_1^2}{v^2} \cdot \frac{Z}{A} \cdot \ln\left(\frac{2m_e v^2}{I}\right)$$

Where:

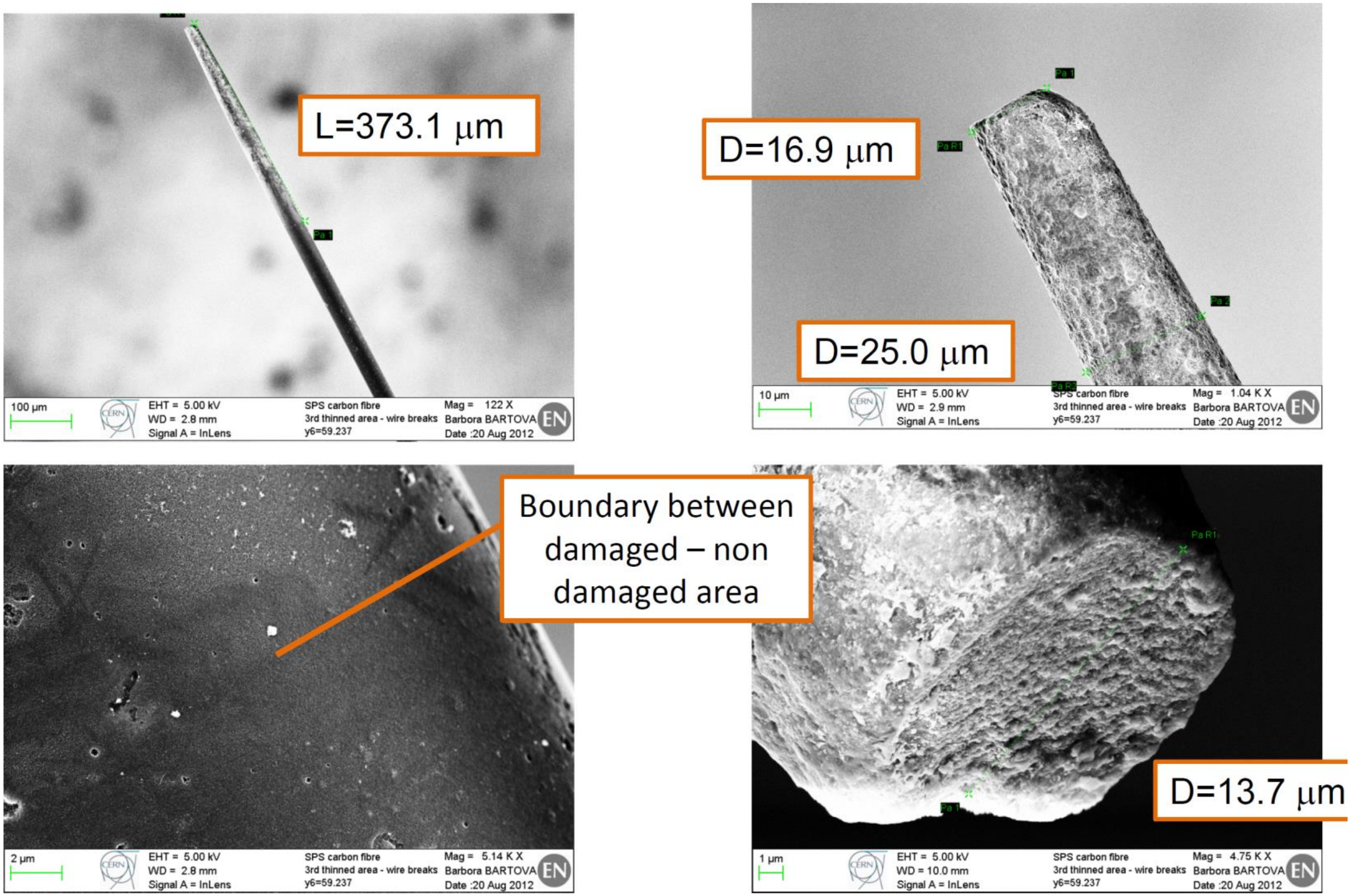
q_e, m_e are the charge and mass of the electron

Z_1, v are the charge number and velocity of the heavy charged particle



SPS breakages (protons, 2012)

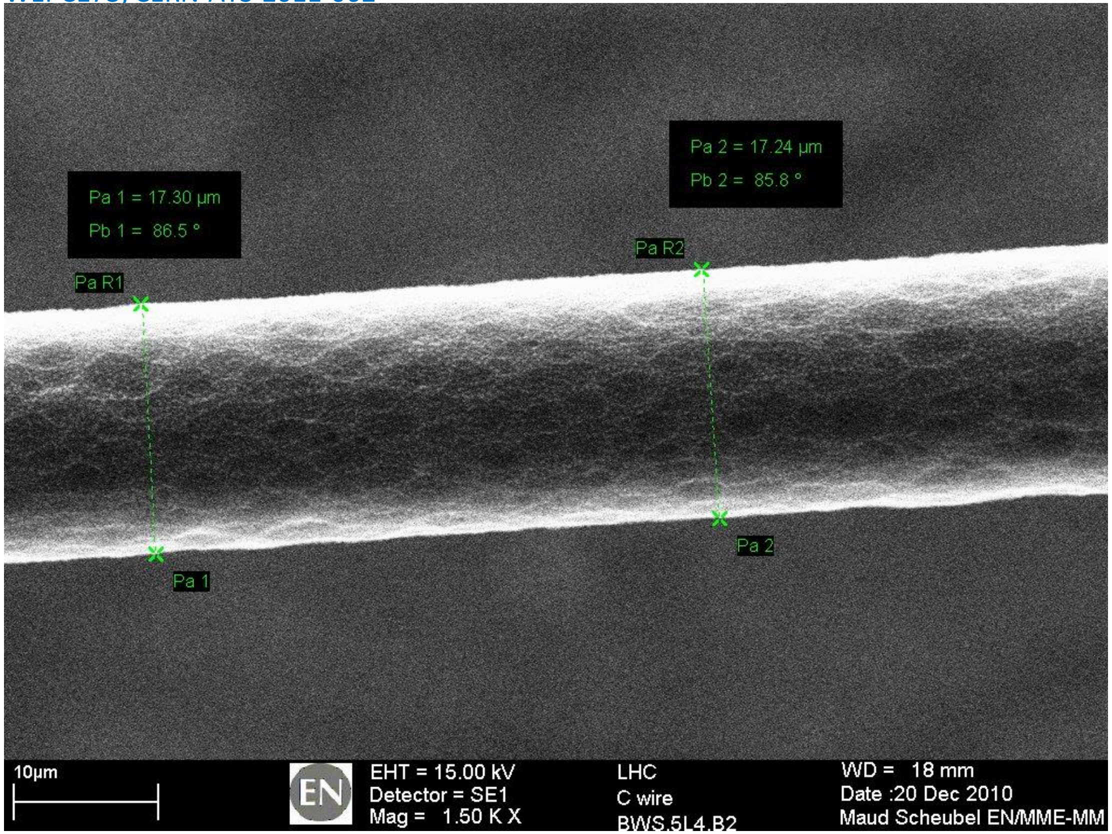
- Experiment in which wire was irradiated in 3 places with increasing intensities
- Surface damage already at relatively low intensities, sublimation damage consistent with previous observations

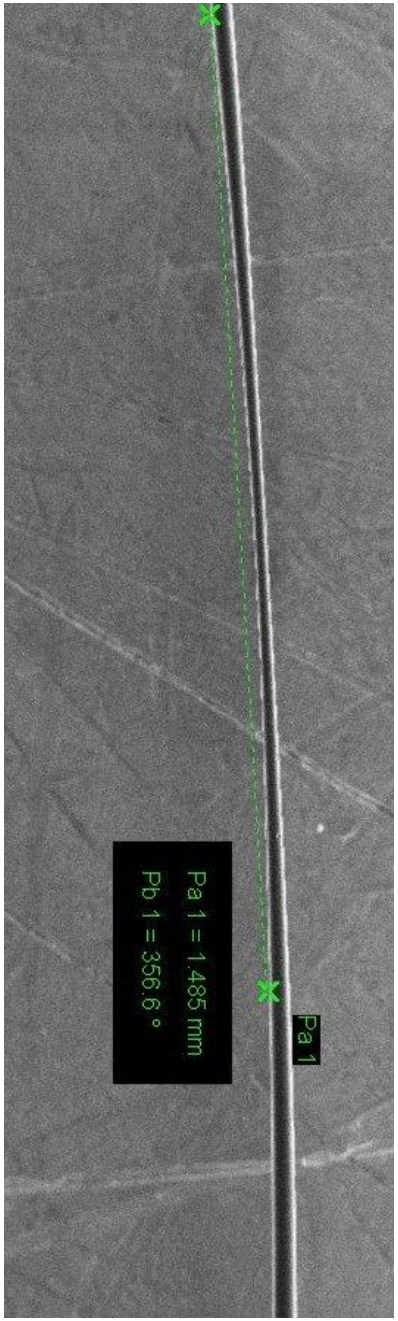


LHC quench test (protons, 2010)

- 3.5 TeV proton beam
- Goal: to quench the superconducting magnet NOT to damage the wire
- Wire recovered in one piece
- Analysis with electron microscope: familiar sublimation images

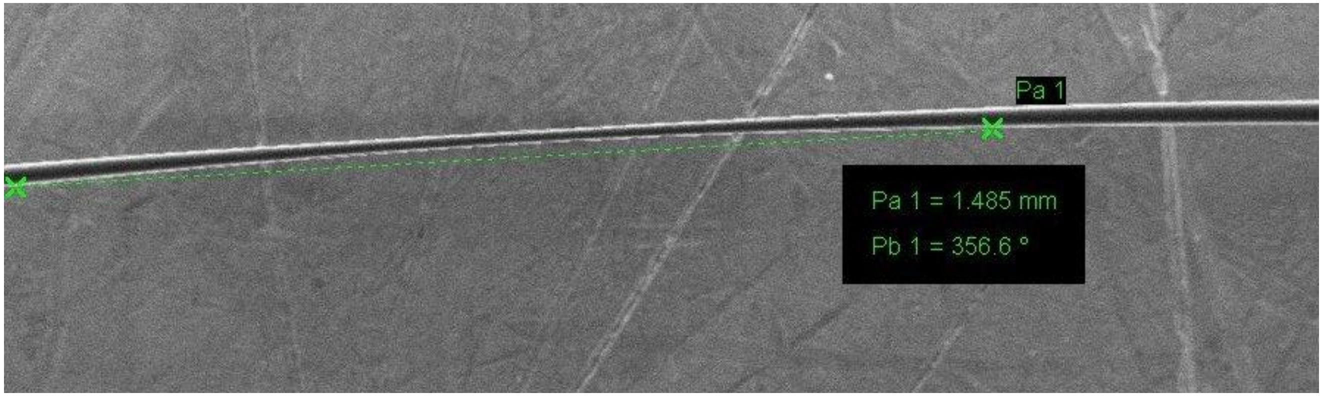
see: "LHC magnet quench test with beam loss generated by wire scan" , in Proceedings of IPAC11, WEPC173, CERN-ATS-2011-062



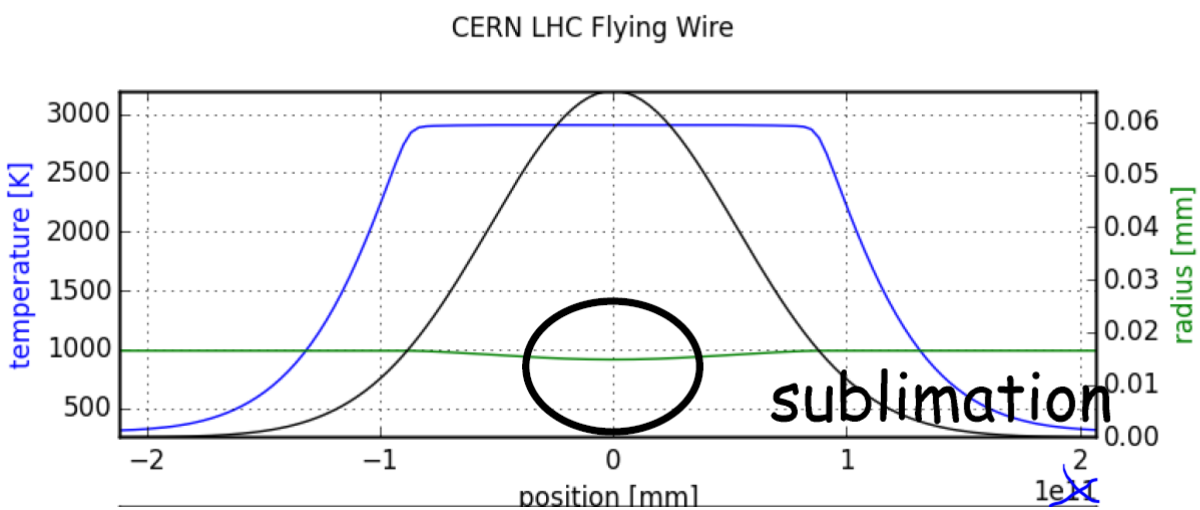


Pitfalls of sublimation

- One may think that controlled sublimation is a legitimate wire scanner operational mode but:



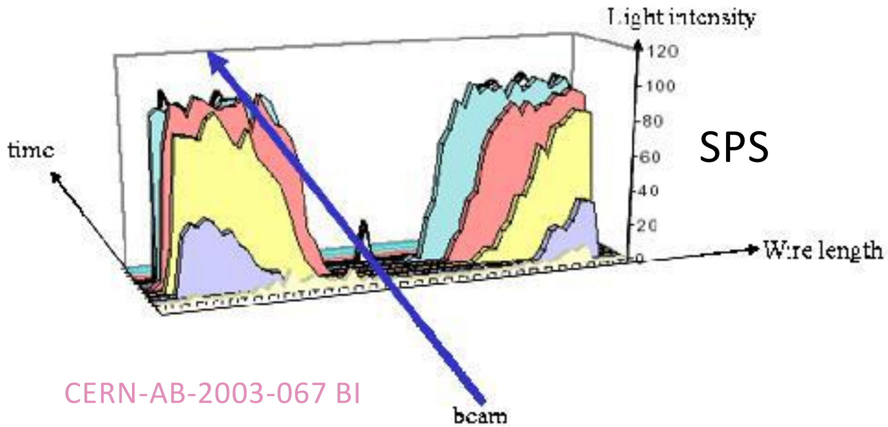
- Thinner wire = less signal from the beam center → potential measured profile deformation
- Fortunately, because of "stabilizing effect" of thermionic emission on temperature, effect is not as strong as one could think, but still "controlled sublimation" operation is not recommended



It could be a nice subject for a summer student

RF damage

- RF can be generated by beam or can leak from RF cavities
- Metal or semimetal (graphite) wire is a good antenna, therefore there is a rich record of wire damage due to coupling to RF
- RF can break wire without the beam (in parking position)



SPS

CERN-AB-2003-067 BI

- RF heating is typically at the ends of the wire (no overlap with beam)
- In CERN case the ends are copper-plated; different thermal expansion coefficients
- In PSI case the breakage occurs at the glue surface

- Countermeasures:
  - Damping RF using ferrites
  - Changing tank geometry
  - RF shields

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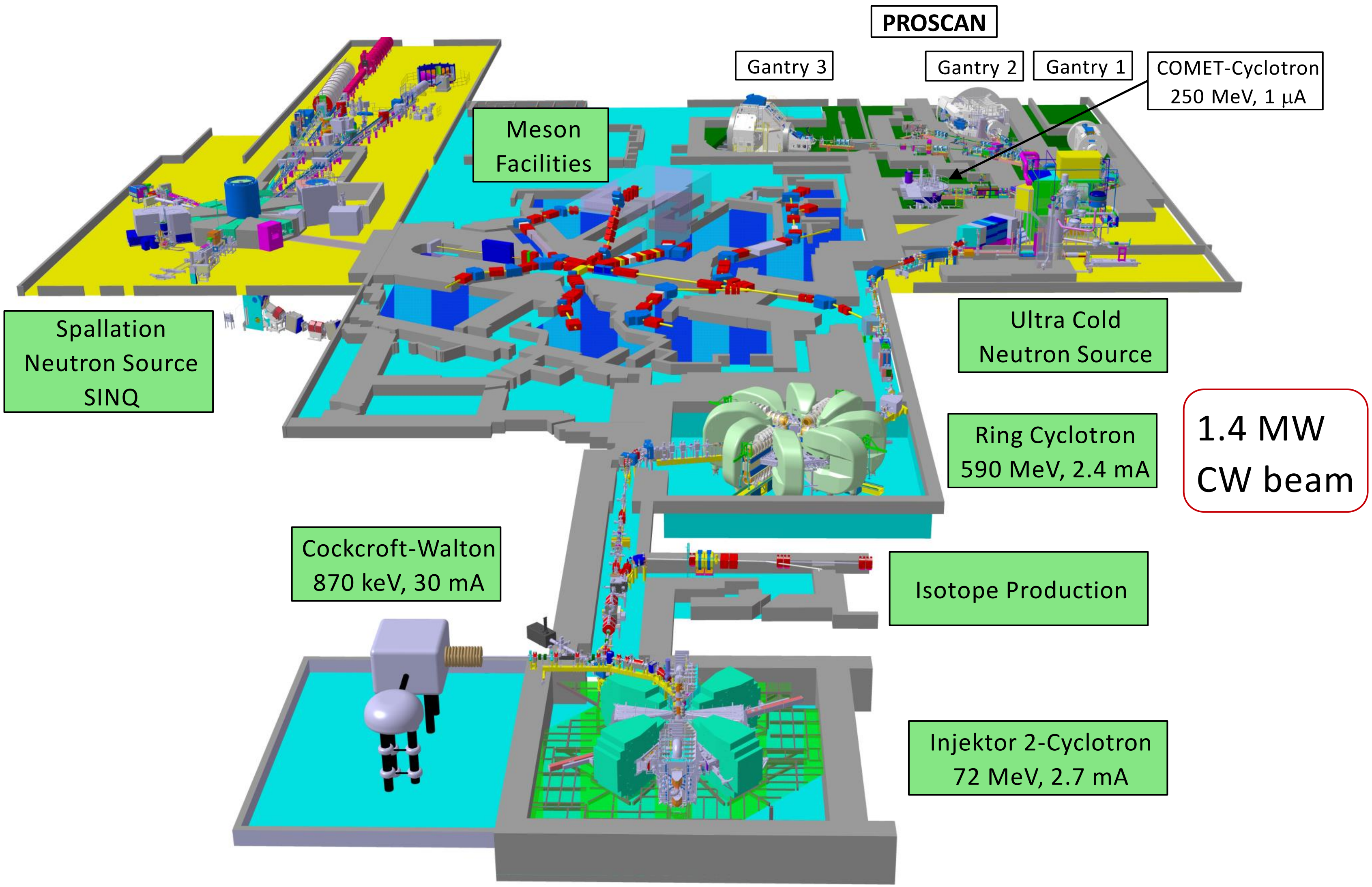
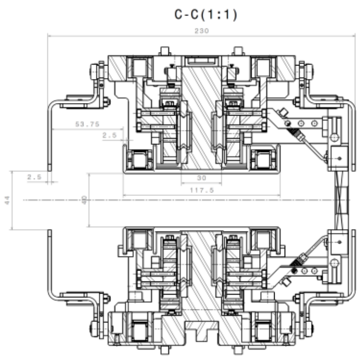
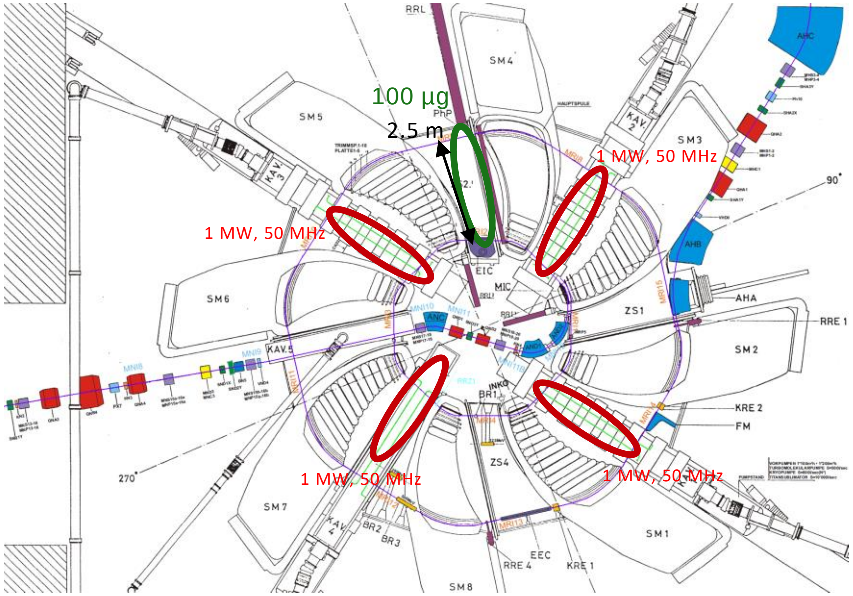
High Intensity Proton Accelerator Facility

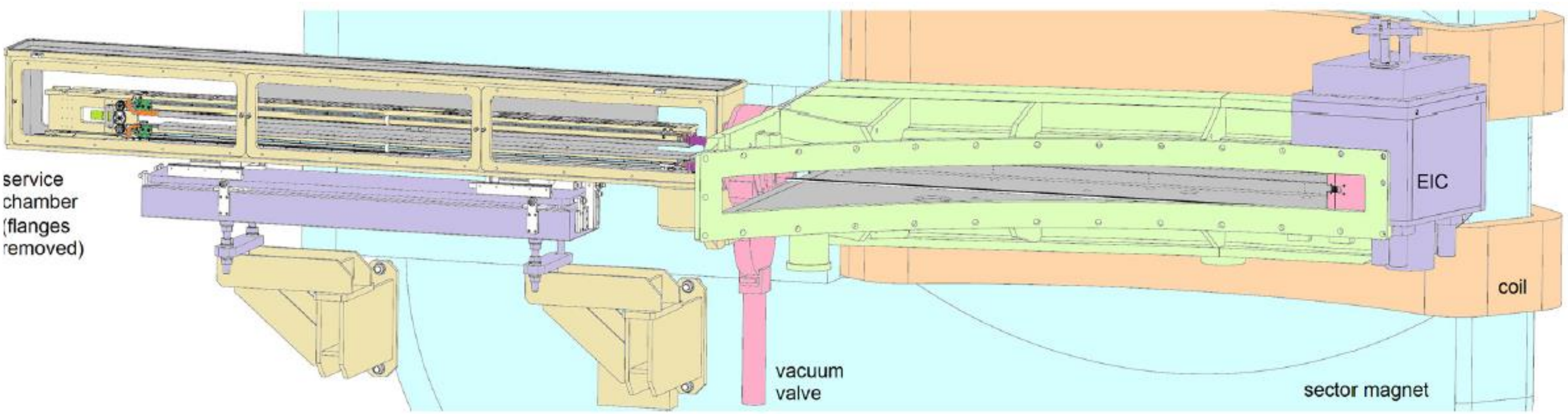


RF damage in cyclotron

- Sector cyclotrons are filled with cavities
- Long radial probe is a special, very long (2.5 m) wire scanner designed to scan all turns (180) of a cyclotron
- RF shields in anticipation of problems

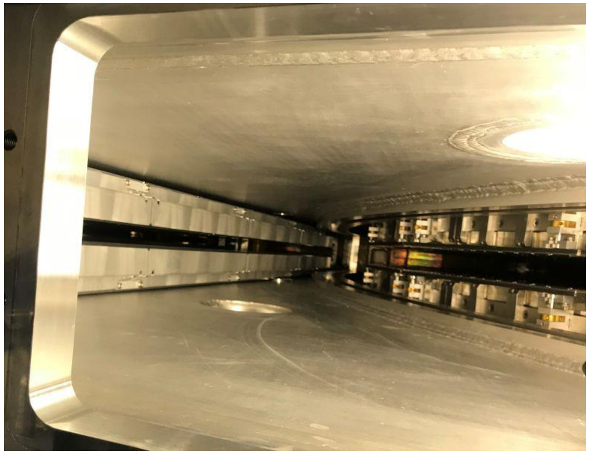


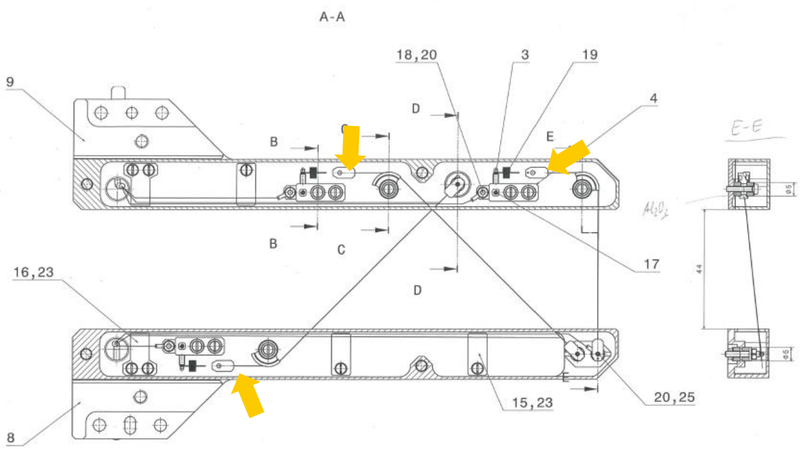


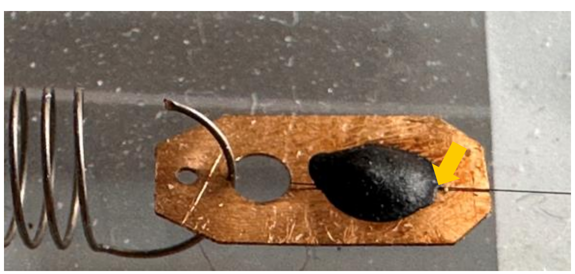


RF damage in cyclotron - observations

- Wire getting hotter towards the center of the cyclotron
- Breakage usually at wire bending or wire-glue interface
- Breakage when neighboring cavities are powered asymmetrically (eg. one on and one off)







RF damage in cyclotron - observations

- RF imbalance leads to imminent breakage
- Skin effect? Let's check:

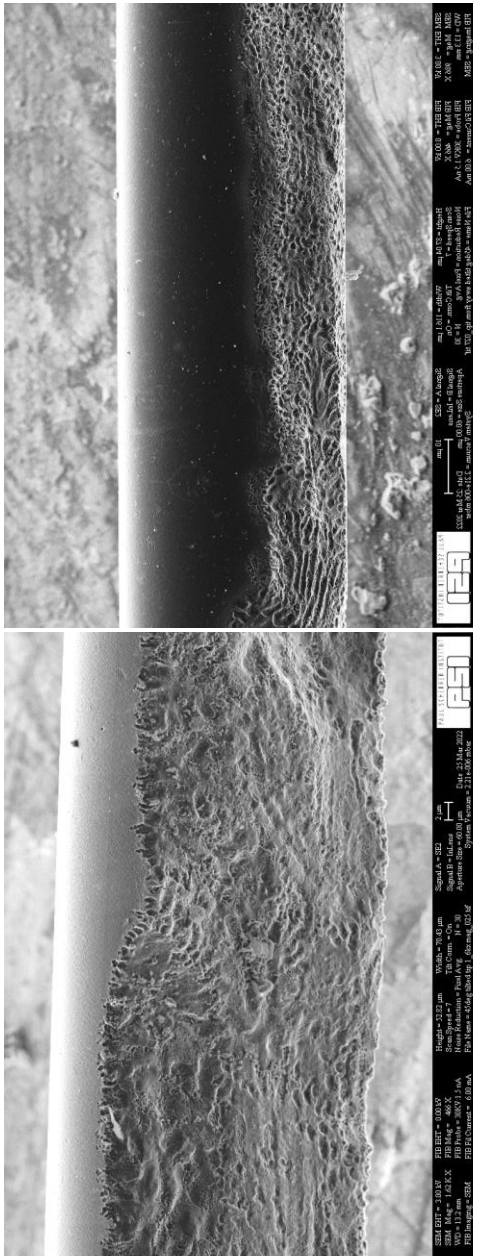
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \; .$$

- $\rho = 8 \cdot 10^{-6}$ [Ωm] – at room temperature

  $\mu = 1.26 \cdot 10^{-4}$ [H/m]

  $\omega = 2\,\pi\,50$ [rad*MHz]

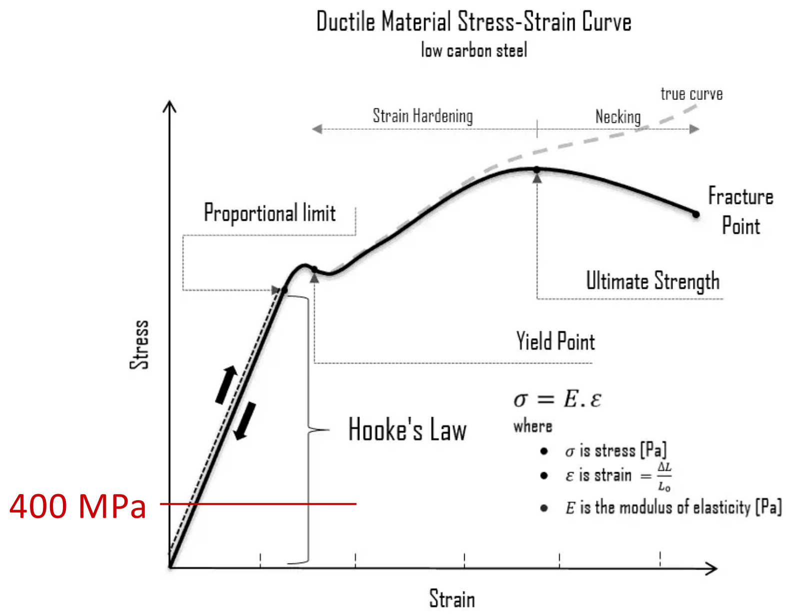
  → δ = 19 µm – close enough!
- It is possible that RF leaking from opposite cavities undergo destructive interference in the location of the wire saving it from damage



Metal wires

- Metal wires are easier to mount and less fragile to transverse bending forces
- We use 24-µm Molybdenum wires in less critical areas
- Wires must be tensioned (pre-stressed) to keep their shape
- The pre-stress is much below the proportional limit at room temperature

	Density $[g/cm^3]$	Strength [MPa]	Melting temp [K]	Heat cap [J/mol K]	Z
CF	1.8	900	3915	8.5	6
Be	1.8	550	1560	16.4	4
SiC	3.16	290	3100	1.1	12.6
Mo	10.3	965	2896	24.1	42
Ta	16.7	450	3290	25.6	73
W	19.3	1920	3695	24.3	74
CNT	0.2	540	3915	7.2	6



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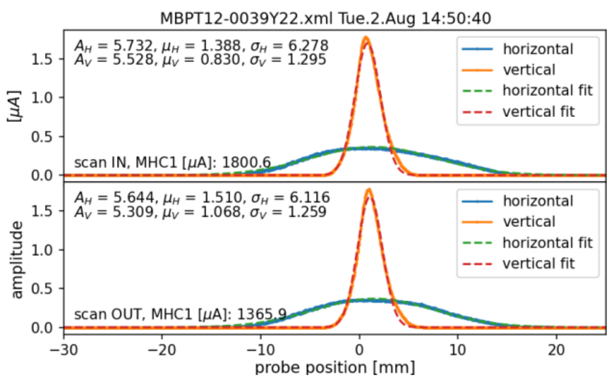
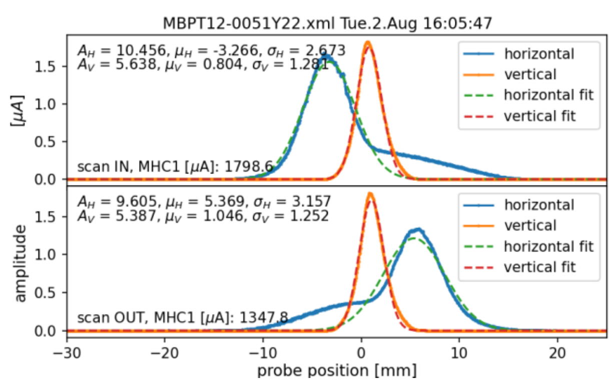
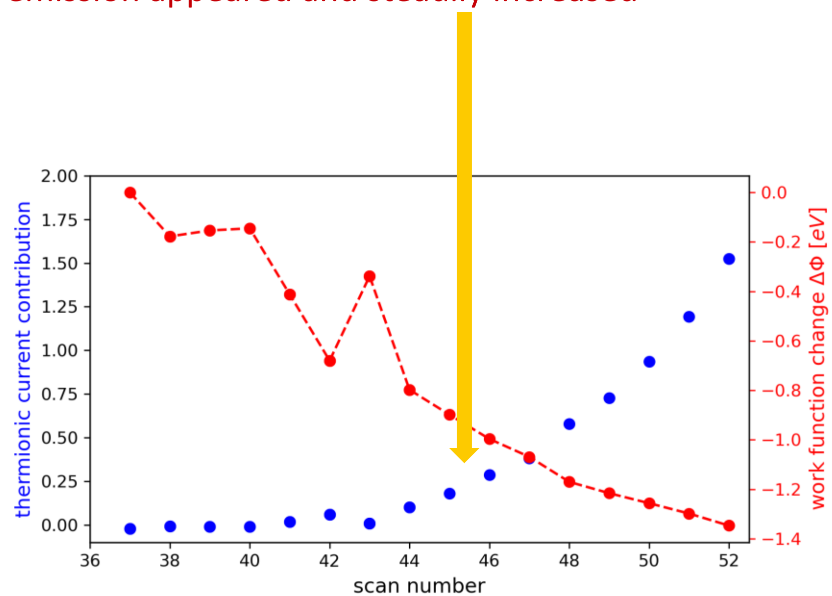
Damage event

- In 2022 a brand new wire in a wire scanner on Ultra Cold Neutron beamline broke after ~20 scans
- For each scan the beam conditions were always the same:
  - Beam current 1.8 mA
  - Beam energy 590 MeV
  - Beam size: σ_H = 6.2 mm, σ_v = 1.3 mm (very asymmetric)
  - Wire speed 60 mm/s
- During the consecutive scans thermionic emission appeared and steadily increased







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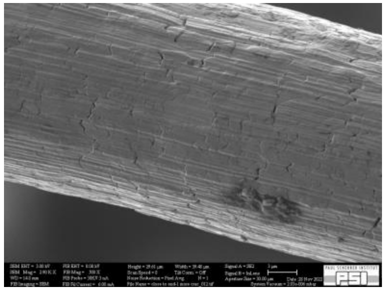
Ductile damage

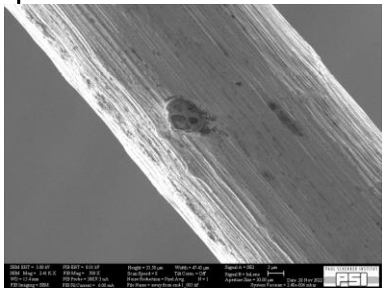
- Electron microscope analysis revealed characteristics of ductile damage

necking

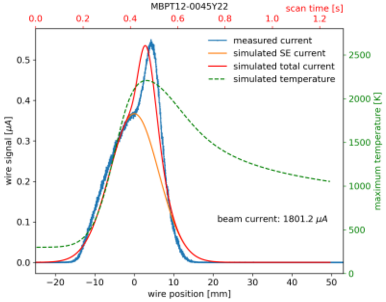
surface cracks

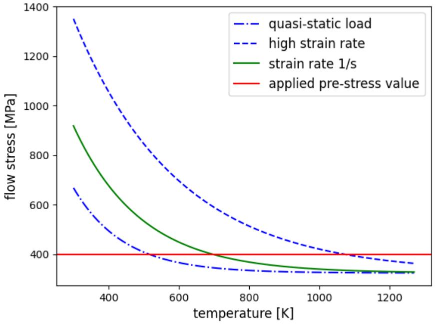


pristine



- Thermal simulation show temperatures far from melting, but easily exceeding the flow stress value at higher temperatures





IPAC23 THPL151

- The increase of the thermionic emission could be due the cracking of the wire surface which lead to decrease of work function
- Some prior observations of similar effects exist

Sumary and conclusions

- Sublimation is the main damage mechanism for carbon fibers in high-power beams
- Sublimating material is a “negative feedback” phenomena:

  increased Surface-to-Volume ratio leads to lower temperatures
- But wire with varying diameter affects beam profile measurement (is it negligible?)
- RF coupling is a major issue at PSI and CERN, but for very different reasons
- In case of metal wires the damage could be due to decrease of proportionality limit with increasing temperature
- Open points:
  - Unexpected resistance to ion beam
  - Impact of wire nonuniformity on measured profile
  - Is RF skin effect really visible on carbon fiber?
  - Can surface cracks explain increase of thermionic emission?

Superman (Clark Kent), 1978