Carbon fiber damage in accelerator beam

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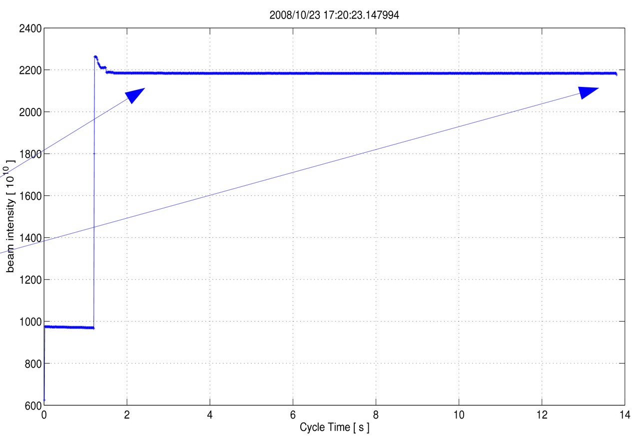
Abstract: *Carbon fibers are commonly used as moving targets in Beam Wire Scanners. Because of their thermomechanical properties they are very resistant to particle beams. Their strength deteriorates with time due to radiation damage and low-cycle thermal fatigue. In case of high intensity beams this process can accelerate and in extreme cases the fiber is damaged during a single scan. In this work a model describing the fiber temperature, thermionic emission and sublimation is discussed. Results are compared with fiber damage test performed on SPS beam in November 2008. In conclusions the limits of Wire Scanner operation high intensity beams are drawn.*

Experimental conditions

Special SPS cycle (SFTPRO.LONG1) :
- Debunched – minimization of RF-heating influence
- Long – about 12 seconds leaves time to perform even very slow scans

High intensity beam – up to 2.4 10^{13} protons



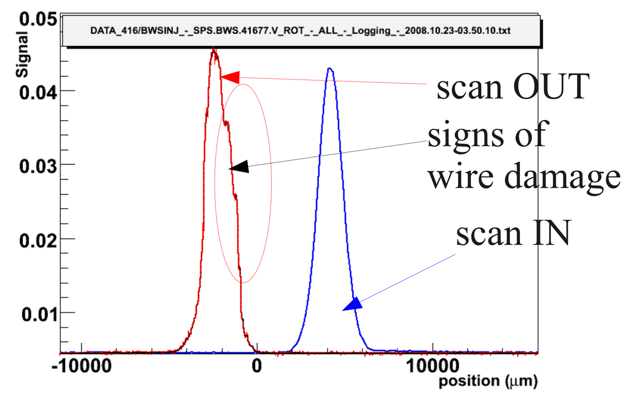
Scanner 416:
- Rotational up to 6 m/s
- Wire diameter 33 μm
- Speeds of scans IN and OUT set independently
- Time between scans about 1 sec (cooling)
- Measurement of thermionic current and wire resistivity

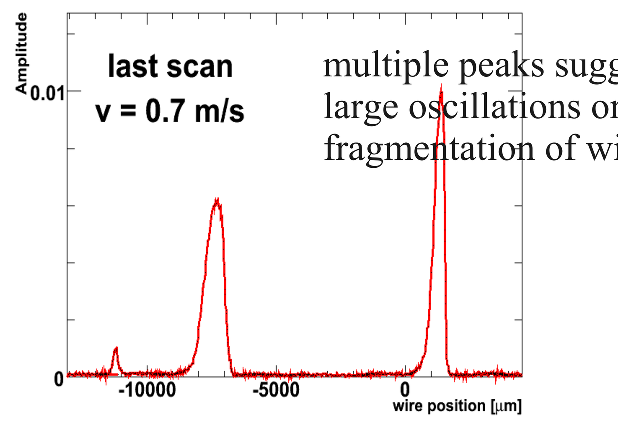
- MD date: November 23rd 2008
- Scan sequence: 6, 3, 1.5, 1, 0.8, 0.7, 0.6, 0.5 m/s
- Scanner has 2 mechanisms – scanning in horizontal and in vertical directions
- Other scanners involved (emittance check and other measurements)

BREAKAGE

- 2 wires broken:

scan direction:	vertical	horizontal
velocity at breakage [m/s]	0.5	0.7
N_{prot}	$2.41\cdot10^{13}$	$2.18\cdot10^{13}$
beam σ_{long} [mm]	0.57	0.73
beam σ_{tran} [mm]	0.73	0.57
$N_{0,tot}$ [prot/mm²]	$2.4\cdot10^{13}$	$1.6\cdot10^{13}$





- where beam density seen by the wire:

$$N_{0,tot} = \frac{N_{prot} d_{wire}}{2\pi\sigma_x\sigma_y v_{wire}\tau_{revol}}\left[\frac{protons}{mm^2}\right]$$

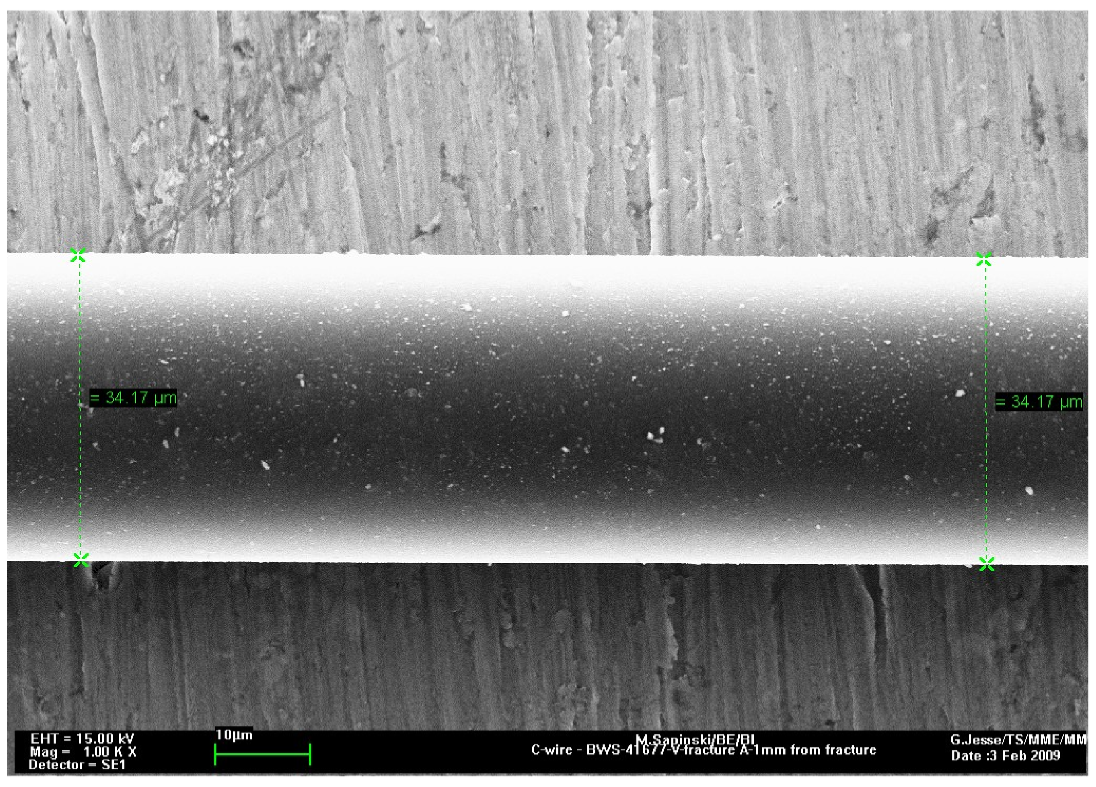
for LHC at 7 TeV it is 4.7 $\cdot10^{14}$ prot/mm²

→ 30 times more then for SPS experiment

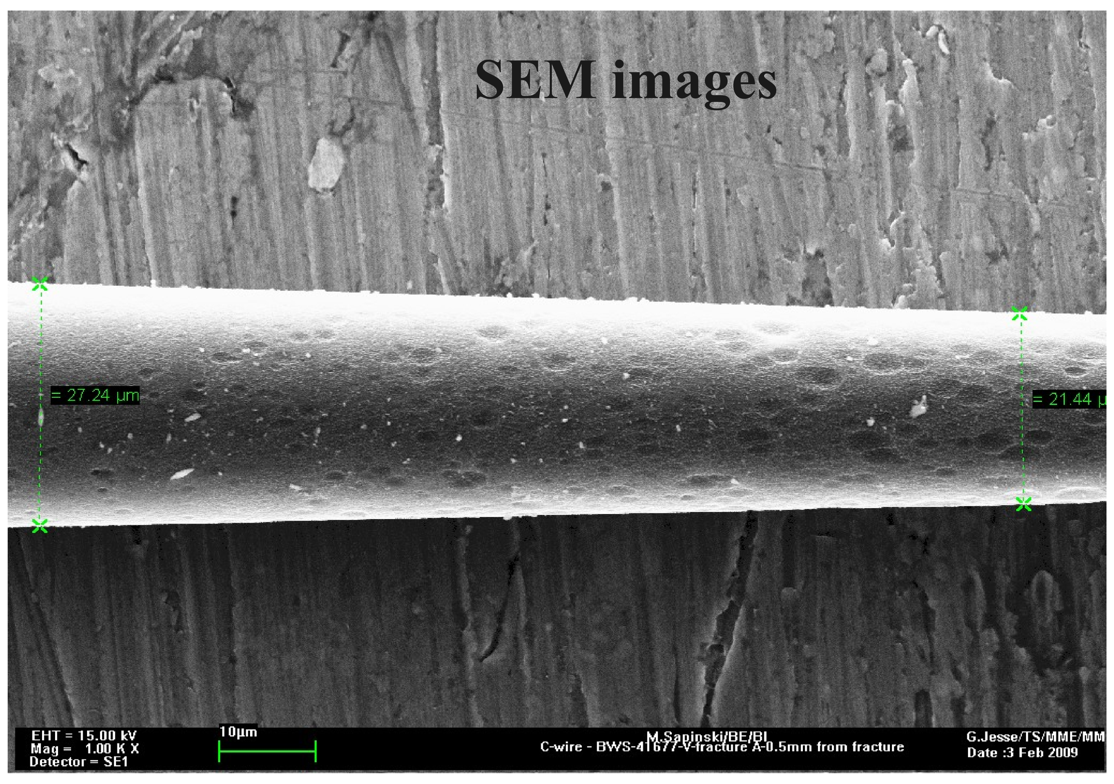
→ model-independent estimation of max scannable LHC intensity is 3% of nominal (no safety factor)

Post Mortem analysis

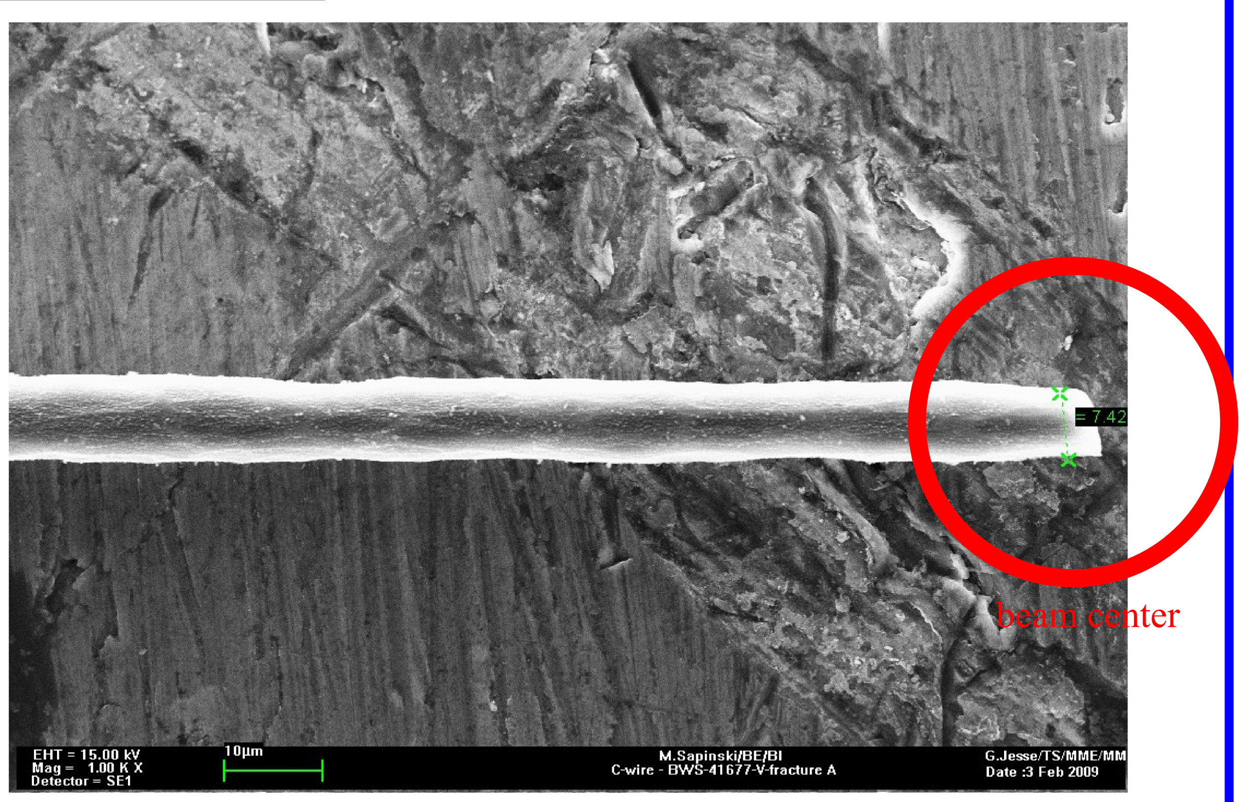
SEM images



intact wire surface, 1 mm from beam centre



visible sublimation effect, 0.5 mm from beam centre



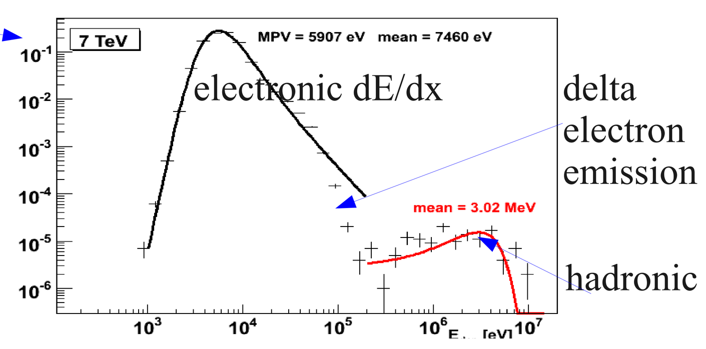
wire diameter 7.5 μm, 95% of wire mass sublimated in beam centre

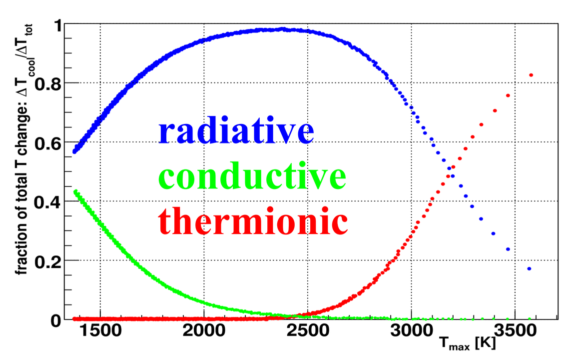
Heat transfer model

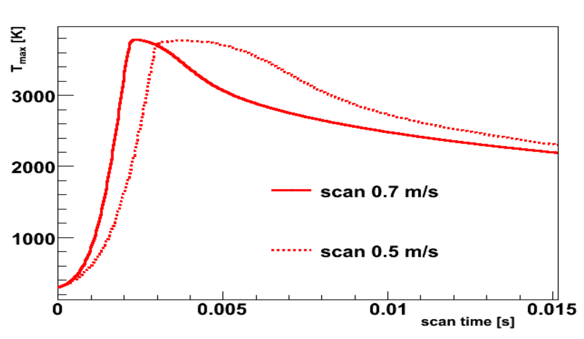
beam heating, heat capacity

$$E_{dep}\frac{\Delta N_{hits}}{\Delta t} = \rho_C V c_p(T)\frac{\Delta T}{\Delta t} - A_{rad}\epsilon\sigma(T^4 - T^4_{amb}) - \lambda(T)A_d\frac{\Delta T}{\Delta y} - A_{rad}\left(\phi + \frac{2k_BT}{q_e}\right)J_{th}(y) + C(y)\Delta RJ^2_{th-tot} - H_{sub}\frac{\Delta n}{\Delta t}$$

coolings





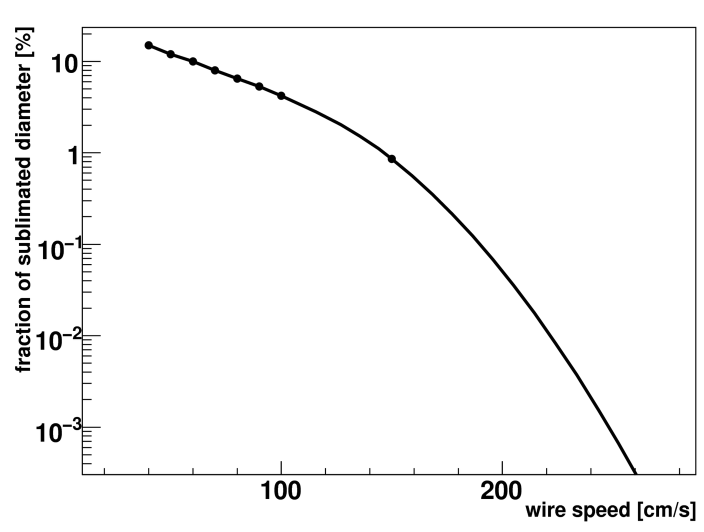


- For fast scans of intense beams cooling cooling weakly affects the maximum temperature profile
- Thermionic cooling dominates for T>3200 K
- In case of two critical scans model predicts reaching temperature of about 3800 K
- Model predicted possibility of scanning 5-7% of LHC beam at collision (v_{wire}=1 m/s)

Sublimation model

Based on phenomenological parametrization from "Scientific foundations of vacuum technique" by Saul Dushman

log W [g/cm²/s] = 12.04 – 0.5 log T – 4·10⁴/T



Sublimation model uses temperature evolution calculated by heat transfer model.

It predicts that after sequence of scans which lead to wire breaking the wire diameter should be 12.5 μm ie. 2X more then measured on the Scanning Electron Microscope images.

Considering the lack of informations about wire history the factor 2 difference is not large.

Safe scans (when small amount of material sublimates) are at speeds about 4 x higher then critical ones

→ safety factor = 4

Conclusions

The wire damage mechanism on high intensity SPS beam has been established to be sublimation followed by deterioration of mechanical properties of the wire. A similar mechanism is expected to limit use of LHC Wire Scanners.

For LHC the limits found by model are 5-7% of full intensity at 7 TeV. Using model-independent extrapolation of experimental results a value of 3% is obtained. The sublimation model suggests usage of safety factor 4.

On LHC additional limiting factor is quenching the downstream magnet. Geant4 simulations indicate that this quench could happened at 4±2% of nominal intensity.

In order to meet LHC demands for beam scanning an New Wire scanner project has been estabilished. (https://project-wire-scanner.web.cern.ch/project-wire-scanner)

The goal is to scan with velocity of 20 m/s and wire position micrometer accuracy

The proper choice of the wire will additionally boost the scanner performance:
- thinner wire produces less particles which can quench magnets
- wire maximum temperature does not depend on the wire thickness
- thin fibers have better mechanical properties

(look for poster: "Fast And High Accuracy Wire Scanner")

use of multiwires is probably optimal from mechanical point of view

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