

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.

INTRODUCTION

In order to validate beam heating model [1], and determine the breakage mechanism of the $33 \mu\text{m}$ carbon fiber a damage test has been performed on the SPS beam at CERN in November 2008. The final goal of the test was to verify the predictions of the limits for the wire damage in LHC beam and conclude about the specifications of the future scanner.

EXPERIMENTAL CONDITIONS

A rotational Wire Scanner equipped with electronics which allow to measure wire resistivity and thermionic emission during the scan has been used in the experiment. The scanner contains two wires which scan the beam in horizontal and vertical directions. It can reach the scan speed of 6 m/s and performs two scans called IN and OUT. The speeds of both scans and interval between are set independently. This interval has been set to at least 1 second to allow cooling the wire. In this test the scan IN was always performed with maximum speed and the speed of scan OUT was gradually slowed down from scan to scan in the following sequence: 6, 3, 1.5, 1, 0.8, 0.7, 0.6, 0.5 m/s. Two other Wire Scanners have been used during the test to constrain additionally beam parameters.

A special beam cycle on CERN SPS accelerator has been prepared for this test. Beam intensity has been maximized and reached about $N_{\text{prot}} = 2.4 \cdot 10^{13}$ circulating protons. In order to diminish the effect from RF-coupling [2] the beam has been debunched. A 12-second long flat-top plateau has been kept providing enough time to perform measurements in stable beam conditions. Beam momentum has been 400 GeV/c.

WIRE BREAKAGE

The wires have been broken in conditions summarized in Table 1, where σ_l is the beam width along and σ_t perpendicular to the scan direction (beam is assumed to have Gaussian transverse profiles). The breakage occurred after a sequence of scans, therefore the wire has already been weakened by preceding scans. In addition the wires installed in the scanner have been used since at least a year and have performed unknown number of scans (typically a few thousand).

Table 1: Beam conditions at wire breakage.

scan speed	N_{prot}	σ_l [mm]	σ_t [mm]
0.5 m/s	$2.41 \cdot 10^{13}$	0.57	0.73
0.7 m/s	$2.18 \cdot 10^{13}$	0.73	0.57

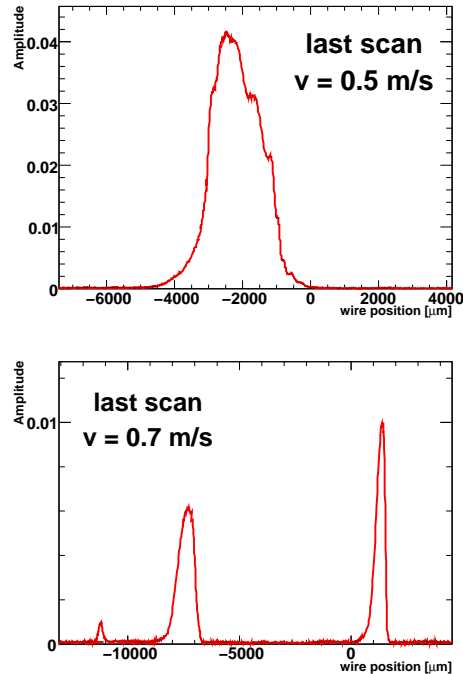


Figure 1: The last profiles after which the wire has been found broken. Upper plot shows breakage of vertical wire and bottom - the horizontal one.

In Fig. 1 the beam profiles registered during the last scans are shown. The deviations from Gaussian shape and multiple peaks are symptoms of the wire deterioration and

breakage. The measurement of the wire resistivity after these scans showed that the wire was broken.

POSTMORTEM ANALYSIS

After the experiment the wire scanner has been opened and both wires have been recovered. They have been photographed with scanning electron microscope. The images obtained with 1000 times magnification, taken in three positions: at the center of the beam impact, 0.5 mm away and 1 mm away are presented in Fig. 2. They clearly show that the main process deteriorating the wire is sublimation due to the high temperature. In the center of the beam-impact location the remaining wire diameter is only about $7.5 \mu\text{m}$, what is equal to the sublimation of 95% of the material. At 0.5 mm from the beam impact center the beam traces are still very visible and sublimation removed a fraction of the material. At 1 mm from the beam center the fiber is intact.

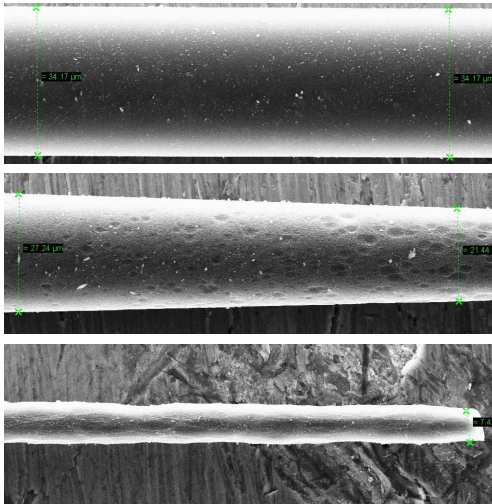


Figure 2: Fiber fracture at three distances from the beam impact location: 1 mm (upper plot), 0.5 mm (middle plot) and at beam center location (bottom plot).

In conclusion the wire breakage mechanism during these scans can be explained as a sublimation of the wire material until the moment when the mechanical properties of the wire does not allow to withstand forces which appear during the scan.

MODEL PREDICTIONS

The model described in [1] gives predictions of the temperature evolution of the wire during the scan. This temperature is a parameter of another model which describes the carbon sublimation.

Temperature evolution

The simulated evolution of the maximum temperature of the wire in the point where wire crosses the beam maximum is shown in Fig. 3 for scans with 0.5 and 0.7 m/s. At

the speed of 0.5 m/s a plateau of about 2 ms in temperature evolution due to the equilibrium between beam heating and cooling by thermionic emission is observed.

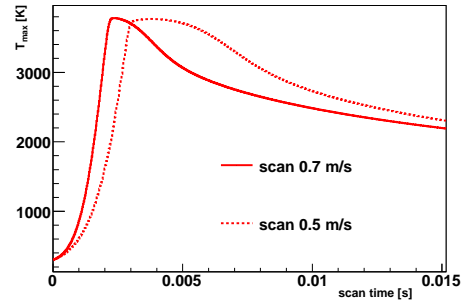


Figure 3: Simulated evolution of the maximum temperature of the wires during final scans.

Sublimation

The estimation of the sublimation rate is based on parametrization from [3]. In Fig. 4 the percentage of wire diameter expected to sublimate during scan as a function of the velocity is shown. Scans with speeds of 0.5-0.7 m/s lead to sublimation of 8-12% of the wire diameter. The whole scan sequence used in the damage test should leave about $12 - 14 \mu\text{m}$ of the wire. This expectation is almost two times higher than the wire diameter measured on post-mortem samples.

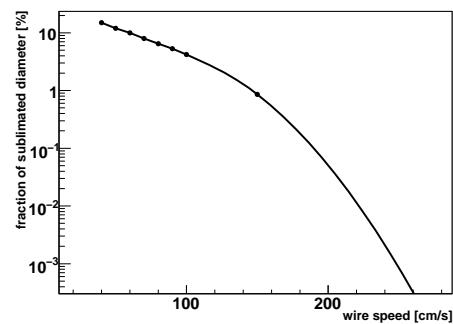


Figure 4: Simulated sublimation of the wire material in the wire center during scans with decreasing velocity.

From Figure 4 it is concluded that the sublimation process removes significant amount of material for all wire speeds slower than 2 m/s . This allows to determine the safety factor of 4, with respect to breakage conditions, as assuring a safe scanner operation. This factor can be obtained by decreasing the beam intensity or by increasing the wire velocity.

EXTRAPOLATION TO LHC CONDITIONS

From the model [1] it has been estimated that only a small part of about 5-7% of full LHC beam at collision (ie.

1.6–2.2·10¹³ protons) can be scanned with $v_{\text{wire}} = 1 \text{ m/s}$ before the wire breakage. These values correspond almost to the breakage limit ie. only a small safety factor is assumed.

In case of fast scans the cooling processes of the wire can be neglected in estimation of the maximum temperature reached by the wire. Therefore the T_{max} depends on the number of particles which pass the wire center during the scan. As the peripheral parts of the scan can be neglected, a good parameter is beam density in the center, as seen by a wire with diameter d_{wire} moving with a speed v_{wire} in accelerator with revolution time τ_{revol} . It is expressed by Equation 1¹.

$$\rho_{0,\text{tot}} = \frac{N_{\text{prot}} d_{\text{wire}}}{2\pi\sigma_x\sigma_y v_{\text{wire}}\tau_{\text{revol}}} \left[\frac{\text{protons}}{\text{mm}^2} \right] \quad (1)$$

In case of the two wire breakages described in this paper the $\rho_{0,\text{tot}}$ is $2.4 \cdot 10^{13}$ and $1.6 \cdot 10^{13}$ protons/mm². This value for the wire moving with 1 m/s through the LHC beam is $4.7 \cdot 10^{14}$ protons/mm², ie. about 30 times more. Therefore for full LHC beam at 7 TeV the safe scan conditions are below 3% of nominal intensity. This is about 2 times less then predicted by the model [1].

NEW WIRE SCANNER

A project has been started at CERN with a goal to manufacture a fast and accurate Wire Scanners which could safely scan LHC beams [4, 5]. A proper choice of the wire can boost scanner performance. The following remarks are results of bibliographical research.

- The model [1] shows a weak dependence of the wire maximum temperature from the wire diameter,
- Thinner wires produce less particles which could quench the downstream magnet; on LHC the quench limit has been estimated to be about 4.5% of the full beam intensity at 7 TeV,
- Because of internal wire structure [6] a thinner wire (for instance 7 μm) produced using a graphitization procedure in the last stage of preparation process has better mechanical properties then typical 30 μm wire,
- The wire breakage at Tevatron Main Injector [7] has shown that a wire with diameter of 4 μm broke at about $T_{\text{max}} = 3200 \text{ K}$, what might indicate that very thin wires have worse performance,
- Thin wires might have larger oscillation amplitude what might limit the scanner accuracy,
- The accuracy of the beam profile measurement is ultimately limited by the wire thickness.

¹Maximum temperature depends weakly on the wire diameter, in this Equation the beam density is averaged over d_{wire} .

A solution proposed for LHC are multiwires made of a few fibers twisted together. They should have enhanced strength as a bunch of thin fibers is stronger than a single thick wire. The vibration amplitude of multiwires should be smaller then in case of single wires. The method of optimal fabrication of such wires is being developed.

CONCLUSIONS

The wire damage test has been performed on high-intensity SPS beam. The test has shown that the wire damage mechanism is the sublimation and the following mechanical breakage. The results of the model [1] are probably too optimistic and the safe scanning of LHC beam with $v_{\text{wire}} = 1 \text{ m/s}$ at collision energy is possible up to intensity of about $4 \cdot 10^{12}$ protons. A new Wire Scanner project will provide with fast and precise devices. It is proposed to use multiwire in the new Scanner as it will provide better thermomechanical performance than a single wire.

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