CARBON FIBER DAMAGE IN PARTICLE BEAM

M. Sapinski*, B. Dehning, A. Guerrero, M. Meyer, T. Kroyer
CERN, Geneva, Switzerland

Abstract

Carbon fibers are commonly used as moving targets in beam wire scanners. The heating of the fiber due to energy loss of the particles travelling through is simulated with Geant4. The heating induced by the beam electromagnetic field is estimated with ANSYS. The heat transfer and sublimation processes are modelled. Due to the model non-linearity, a numerical approach based on discretization of the wire movement is used to solve it for particular beams. Radiation damage to the fiber is estimated with SRIM. The model is tested with available SPS and LEP data and a dedicated damage test on the SPS beam is performed followed by a post-mortem analysis of the wire remnants. Predictions for the LHC beams are made.

INTRODUCTION

A thermodynamic model of a carbon fiber scanning a particle beam has been developed [1]. To validate this model and determine the breakage mechanism of the fiber, a damage test has been performed on the SPS beam at CERN in November 2008. The main purpose of the test was to verify the predictions of the limits for the wire damage in LHC proton and ion beams and to conclude about the specifications of the future wire scanner. In addition, recommendations about a type of carbon fiber to be used are given.

In frame of this study a radiation damage to a fiber is also investigated, as a possible long-term damage mechanism.

DAMAGE MECHANISMS

The carbon fibers are known to break after a few thousand scans. The possible mechanisms responsible for this breakage are radiation damage, low-cycle thermal and mechanical fatigue or a slow sublimation of the wire material. The LHC wire scanners are equipped with an acquisition system which allows the estimation of the total dose absorbed by the wire as well as the thermal cycle history.

The wire can also break during a single scan of high intensity beam. In this case the possible breakage mechanisms are thermal stress or a sublimation of the wire material. The estimation of the maximum beam intensities which can still be scanned without damaging the wire are particularly important for the intense LHC beams.

* mariusz.sapinski@cern.ch

RADIATION DAMAGE

The estimation of the radiation damage has been made using SRIM code [2] using a PS beam as an example because of their high intensity and heavy use. It has been found that a single scan of a proton beam will introduce about $3.5 \cdot 10^{-7}$ displacements per atom (dpa) and for the ion beam the results are similar [3]. The measurable effects of radiation damage on mechanical properties of the fiber start to present themselves at about 1 dpa level. One can therefore conclude that the wire properties are not affected by radiation during a few thousand scans. The mechanism of the wire breakage is therefore a slow sublimation of the wire material or thermal and mechanical fatigue.

WIRE BREAKAGE EXPERIMENT

An experiment at the CERN SPS accelerator has been performed to validate the thermodynamic model of carbon fiber in the accelerator beam and to determine LHC beam intensity limits for the wire scanner.

Experimental Conditions

A rotational wire scanner equipped with electronics which allows the measurement of 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. The maximum scan speed is 6 m/s and each time two scans called IN and OUT are performed. The speed of each scan and the interval between them is set independently. This interval has been set to at least 1 second to allow the wire to cool down. In this test the scan IN has always been performed with maximum speed and the speed of scan OUT has gradually slowed 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 measure independently the beam sizes.

A special beam cycle on the SPS has been prepared for this test. Beam intensity has been maximized and reached about $2.4 \cdot 10^{13}$ circulating protons. In order to diminish the effect from RF-coupling [4] the beam has been debunched. It has been estimated, using Ansoft HFSS code, that RF-coupling of the debunched beam has negligible effect on the results of the experiment. A 12-second long flat-top plateau has been kept, providing enough time to perform measurements in stable beam conditions. The beam momentum has been 400 GeV/c and the beam transverse profiles have been close to Gaussian in both directions.

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. The breakage occurred after a sequence of scans with decreasing speed indicating that the wire had been gradually weakened. Therefore, the preceding scans must be take into account in analysis of the data. Additional uncertainty results from the installed wires in the scanner having been used for at least a year prior to the experiment having performed an 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

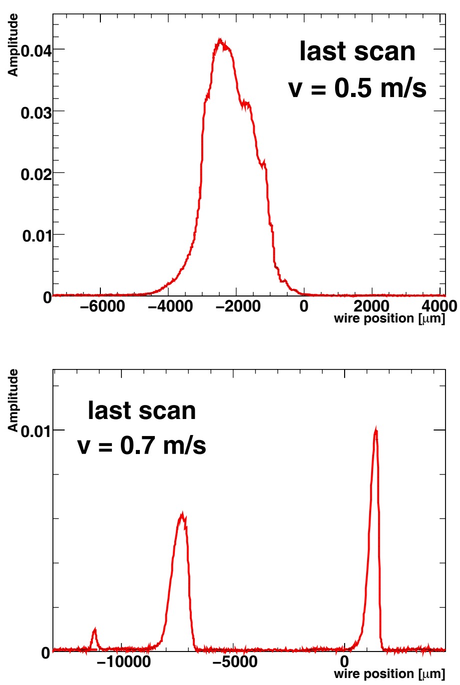

Figure 1: The last profiles before the wires broke. The upper plot shows breakage of vertical wire: deviation of the registered profile from Gaussian shape is visible. The bottom plot shows breakage of the horizontal wire: multiple peaks suggest that the wire was already fragmented.

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 shows that the wire has been broken.

Postmortem Analysis

After the experiment the wire scanner was opened and both wires removed. 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 location of the fracture the remaining wire diameter is only about 7.5 µm, which corresponds to the sublimation of 95% of the material. At 0.5 mm from the fracture the beam traces are visible and sublimation removed about a half of the material. At 1 mm from the beam center the fiber is intact.

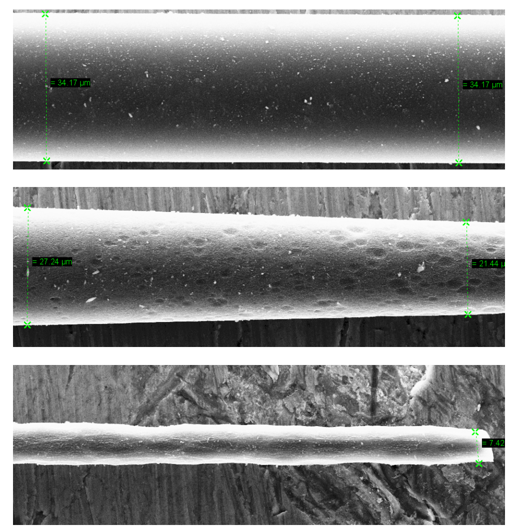

Figure 2: Fiber fracture at three distances from the beam impact location: 1 mm (upper plot), 0.5 mm (middle plot) and at beam center location (bottom plot). The presented wire has been installed in the vertical scanner.

In conclusion, the wire breakage mechanism during these scans can be explained as a sublimation of the wire material until the point at which 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.

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 at 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.

The estimation of the sublimation rate is based on parametrization from [5]. In Fig. 4 the percentage of

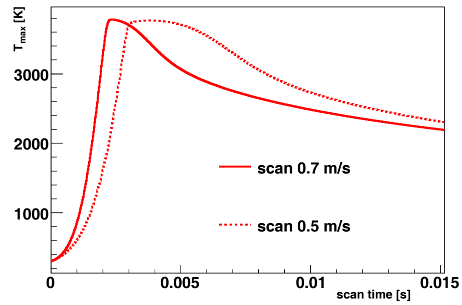

Figure 3: Simulated evolution of the maximum temperature of the wires during final scans.

the 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 $12-14\,\mu$m of the wire. This expectation is almost two times higher than the wire diameter measured on post-mortem samples.

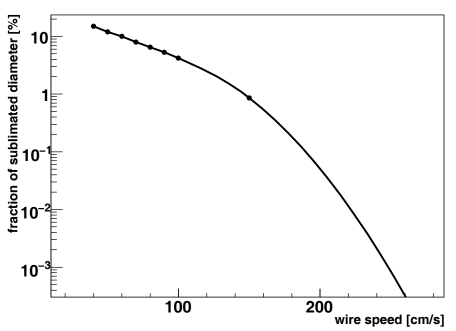

Figure 4: Simulated sublimation of the wire material in the wire center during scans with decreasing velocity.

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 determines a safety factor of 4, with respect to breakage conditions to assure safe scanner operation. This factor can be obtained by decreasing the beam intensity or by increasing the wire velocity.

EXTRAPOLATION TO LHC CONDITIONS

In case of fast scans, the cooling processes can be neglected for an estimation of the maximum temperature reached by the wire. Therefore the temperature depends on the number of particles which pass the wire center during the scan and energy they leave in the wire. 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} and with number of particles in the beam N_{part}. This density must be scaled by energy deposition in the wire per impacting particle E_{dep}. Such a parameter is expressed by Equation 1[1].

$$\mathcal{E} = \frac{N_{part} d_{wire} E_{dep}}{\sqrt{2\pi}\sigma_t v_{wire} \tau_{revol}} [\frac{MeV}{mm}] \qquad (1)$$

Using Geant 4.9.3 for protons used in wire breakage experiment, ie. with momentum 400 GeV/c the E_{dep} has been found to be about 7.6 keV. Similar estimations for ions with energy 0.177 TeV/nucleon and 1.38 TeV/nucleon give a result of 21.6 MeV (almost independent on energy).

In case of the two wire breakages described in this paper the $\mathcal{E}$ is $2.7 \cdot 10^{11}$ and $2.3 \cdot 10^{11}$ MeV/mm. The safety factor 4 has been deduced from Figure 4 and therefore the critical $\mathcal{E}$ is about $5 \cdot 10^{10}$ MeV/mm which corresponds to 8 mJ/mm.

Table 2 shows the use of these values for LHC beams. The wire breakage is not expected to occur up to about 255 nominal proton bunches for a 3.5 TeV beam or at about 134 nominal ion bunches at an energy of 1.38 TeV/nucleon.

Table 2: LHC Beam Parameters and a Maximum Beam Intensity Safe to Scan with Existing Wire Scanners

parameter	values	
particles	p	Pb^{82+}
E_k	3.5 TeV	287 TeV
E_{dep}	7.2 keV	21.6 MeV
σ_t [mm]	0.6	0.6
σ_l [mm]	0.8	0.8
N_{part}	$2.8 \cdot 10^{13}$	$9.4 \cdot 10^{9}$

The predictions of the thermodynamic model [1] in the case of a 7 TeV proton beam was that a safe beam intensity is about $1.6 \cdot 10^{13}$ protons. Here a the scan-safe beam intensity value is two times higher, although a direct comparison of these two results might be misleading because of different assumptions about the beam size and the safety factor. Concerning the ion beam, it has been scanned in the SPS safely, with intensity of $5 \cdot 10^{8}$ [6]. This corresponds to $\mathcal{E} = 1.2 \cdot 10^{10}$ MeV/mm, which is safe according to the above calculations.

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 [7, 8]. A proper choice of the wire can boost the Scanner performance. The following remarks are results of bibliographical research, modelling and experiments.

- The model [1] shows a weak dependence of the wire maximum temperature from the wire diameter.

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

- 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 [9] a thinner wire (for instance 7 μm) produced using a graphitization procedure in the last stage of preparation process has better mechanical properties than a typical 30 μm wire.

- The wire breakage at Tevatron Main Injector [10] has shown that a wire with diameter of 4 μm broke at about T_{max} = 3200 K, which might indicate that very thin wires have worse performance.

- Thin wires might have larger oscillation amplitude which might limit the scanner accuracy.

- The accuracy of the beam profile measurement is ultimately limited by the wire thickness.

A solution proposed for LHC are multiwires made of a few fibers twisted together. A multiwire is expected to present strength significantly larger than a single wire with the same thickness. Also the vibration amplitude of multiwires is expected to be smaller than in the 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. A conclusion of this test and of Geant4 simulation of energy deposit in the wire is the maximum safe-scan beam intensity being $2.8 \cdot 10^{13}$ of 3.5 TeV protons and $9.4 \cdot 10^{9}$ lead ions Pb^{82+}. It has also been found that the radiation damage of the wire material is not high enough to explain wire breakage during the normal operation. A new, fast and precise, wire scanner is being produced at CERN to fulfill the requirements of scanning high intensity beams. It is proposed to use multiwire in the new Scanner as it will provide better thermomechanical performance than a single wire.

ACKNOWLEDGEMENTS

The authors wish to thank: Barbara Holzer for help during the damage experiment, Jesse Gudrun for taking post-mortem images of the wire with scanning electron microscope, Michel Sillanoli for taking a good care of the wire while removing it from the scanners after the test, which allowed to perform post-mortem analysis. Finally authors were happy to participate in a few fruitful discussions with Serge Rebouillat, an expert in physics and chemistry of the carbon fibers.

REFERENCES

[1] M. Sapinski, "Model of carbon wire heating in accelerator beam," CERN-AB-2008-030.

[2] J. Ziegler, J. Biersack, and U. Littmark, "The Stopping and Range of Ions in Solids", Pergamon Press, New York (1985).

[3] M. Meyer, M. Sapinski, "Estimation of radiation damage to Wire Scanner carbon fiber on PS beam", CERN-EDMS 1028351.

[4] M. Sapinski, T. Kroyer, "Operational Limits of Wire Scanners on LHC Beams", proceedings of Beam Instrumentation Workshop, May 2008.

[5] S. Dushman, "Scientific foundations of vacuum technique," Wiley Inc., New York 1966.

[6] G. Arduini, private communication, 2010.

[7] `https://project-wire-scanner.web.cern.ch/project-wire-scanner`.

[8] M. Koujili et al., "Fast And High Accuracy Wire Scanner," proceedings of DIPAC 2009.

[9] J-B. Donnet, S. Rebouillat, T.K. Wang, J. Peng, "Carbon Fibers", Taylor & Francis Inc, 1998.

[10] Martin Hu, private communication, 2008.