OPERATIONAL LIMITS OF WIRE SCANNER ON LHC BEAM

M. Sapinski*, Tom Kroyer, CERN, Geneva, Switzerland

Abstract

A heat flow equation with beam-induced heating and various cooling processes for a carbon wire passing through a particle beam is solved. Due to the equation nonlinearity a numerical approach based on discretization of the wire movement is used. An estimation of the wire sublimation rate is made. Heating of the wire due to the beam-induced electromagnetic field is taken into account. The model is tested on SPS data. Results are discussed and conclusions about limits of Wire Scanner operation on LHC beams are drawn.

INTRODUCTION

Wire Scanners [1] are devices widely used in accelerators to measure the beam profile. They provide direct and accurate measurement with resolution down to 1 μm and they are considered as a reference for calibration of other instruments.

During the scan, the wire is moved through the beam. It is heated by the RF-coupling to the beam. When it enters into the beam it is irradiated, heated up and cooled down by heat transport along the wire, by thermal radiation and by thermionic emission. In high temperatures it sublimates and it might melt if the pression due to thermal stress is high.

The wire breakage has been observed many times with different beams. The cross-section of the broken wire has been photographed and analysed [2, 3]. These photographs indicate different breakage mechanism depending on beam conditions.

The mechanisms leading to the wire damage during the scan can be: brittle failure, plastic failure, sublimation, melting and thermal fatigue. In case of normal operation, when the wire breaks after thousands of scans, a combination of the above factors is relevant. For instance, as seen in some photographs in [2], the wire has significantly sublimated before breaking. The sublimation removes the external part of the wire which contributes the most to its total strength, as it contains crystals which are more oriented then the ones in the core [5]. In case of LHC beams the heating is slower than the sound speed therefore the thermal shock does not develop.

The LHC beam poses very demanding conditions for the wire. If scanning of the full beam would be possible the total energy deposited by the direct beam interaction during a scan would be about 0.1 J in a time of 900 μs, in 1μg of fiber. No material can withstand such conditions.

* mariusz.sapinski@cern.ch

In this paper the modeling of the wire temperature during the scan is presented. Separate models describe RF-heating and beam heating as they apply to different length scales along the wire. Conclusions about operational limits of Wire Scanners on LHC beams are drawn.

INDUCTIVE HEATING FROM BEAM

The wire heating due to RF-coupling to the beam field has been observed even when the scanner was in the parking position [6], with the wire hidden in a cavity. After this experience RF-absorbing ferrites have been fixed in the parking cavity what cured the wire breaking problem. In this paper the wire heating during the scan is calculated.

Ansoft HFSS was used for the simulation of the beam power loss on the wire [4]. The model parameters are summarized in the Table 1.

Table 1: Parameters used in the simulation.

parameter	unit	value
beam pipe side length	mm	60
structure length	mm	40
RMS beam size	mm	1
wire radius	μm	15
wire conductivity	S/m	$4 \cdot 10^4$
relative permittivity		1

The losses on the wire scale with the square of the beam current density. They increase with the distance from the beam pipe center and with frequency as shown in Figure 1. Due to symmetry no current is generated in the wire center therefore there are no losses in the place which later is heated by direct interaction with the beam.

For a given beam the power deposited in the wire can be calculated by weighting the relative losses from Figure 1 with the beam spectrum. The field power in the 40 MHz harmonics of the nominal LHC beam at top energy is depicted in Figure 2.

The power deposition has been used in the wire model which contains thermal conductivity. Other cooling processes are not adequate for the temperatures reached by the wire. The thermal conductivity gives relatively small effect due to weak thermal conductivity of the wire. In Figure 3 the temperature evolution along the wire during the scan is presented. The characteristic pattern with large losses on the sides of the wire and almost no heating in the wire center, observed in LEP wire scanners [7], is confirmed.

The temperature of the wire center, in case of scan of 25% of LHC injection beam, increases only by a few de-

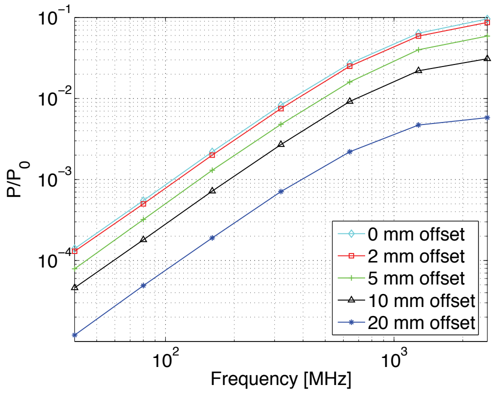

Figure 1: Total relative loss on the carbon wire as a function of frequency. Different curves are for different distances of the wire from the beam.

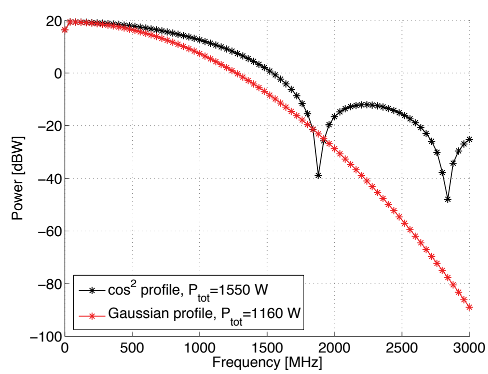

Figure 2: The power in the harmonics of nominal LHC beam at top energy, 4σ bunch length 1.06 ns. From experience with the SPS a Gaussian profile is believed to be more realistic.

grees. It can be concluded that in case of LHC wire scanners the RF-heating during the scan is small.

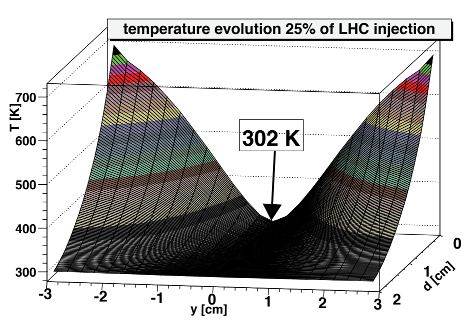

Figure 3: The wire temperature evolution due to RF-heating. A 25% of LHC injection beam is assumed.

WIRE HEATING MODEL

The temperature evolution of a wire placed in a particle beam is described by Equation 1. The left side of the Equation represents heating of the wire by the beam and the right side represents the wire heat capacity and four cooling processes: radiation, heat transport along the wire, thermionic emission. and sublimation. The description of variables used in the Equation 1 is presented in Table 2.

$$\begin{aligned} \mathrm{E_{dep}}\frac{\mathrm{dN_{hits}}}{\mathrm{dt}} &= \rho_{\mathrm{C}}\mathrm{V}\mathrm{c_p}(\mathrm{T})\frac{\mathrm{dT}}{\mathrm{dt}} \\ &- \mathrm{A_{rad}}\epsilon\sigma(\mathrm{T}^4 - \mathrm{T}^4_{\mathrm{amb}}) - \lambda(\mathrm{T})\mathrm{A_d}\frac{\mathrm{dT}}{\mathrm{dy}} \\ &- \mathrm{A_{rad}}(\phi + \frac{2\mathrm{k_B}\mathrm{T}}{\mathrm{q_e}})\mathrm{J_{th}} + \mathrm{C(y)}\mathrm{J_{th}} \\ &- \Delta\mathrm{H_{sub}}\frac{\mathrm{dn}}{\mathrm{dt}} \end{aligned} \quad (1)$$

Table 2: Variables of the wire model.

variable	description
$\mathrm{E_{dep}}$	energy deposited by a proton
ρ_{C}	graphite density
$\mathrm{c_p(T)}$	graphite specific heat
$\mathrm{A_{rad}}$	the surface of the wire which radiates heat
ϵ	the emissivity
σ	Stefan-Boltzmann constant
$\mathrm{T_{amb}}$	temperature of environment
$\lambda(\mathrm{T})$	is the graphite thermal conductivity
$\mathrm{A_d}$	wire cross-section $\pi \mathrm{d}^2/4$
$\mathrm{k_B}$	Boltzmann constant
ϕ	carbon work function
$\mathrm{J_{th}}$	thermionic current
$\mathrm{q_e}$	elementary charge
$\mathrm{C(y)}$	current compensating the thermionic current
ΔH_{sub}	is the entalphy of sublimation
dn	amount of material sublimated

The wire is divided into bins with volume V, along the wire length (y-axis), in which the temperature is uniform. The bin size, Δy, is chosen as a fraction of the beam width σ_y. The total wire length considered in the calculation is $6\sigma_y$. The scanning process is divided into steps where, during the time Δt the wire moves by distance Δx. For every step a contribution from all processes is calculated. The initial temperature is set according to results of the RF-heating model.

BEAM ENERGY DEPOSITION

A Geant4 (in version 4.9.0.p01) simulation has been carried out in order to estimate the beam energy deposition in a thin target, where the Bethe-Bloch approach does not apply directly due to significant energy removal by escaping electrons. The distribution of energy deposited in the wire is presented in Figure 4. The low energy part of the distribution has been fitted with a Landau curve which is a good approximation for thin targets [8]. The discrepancy between the fit and the simulation for energies above 70 keV is interpreted as an effect of energy transfer to electrons which are knocked-off from the material [9]. The spectrum of particles emited from the wire is dominated by those electrons.

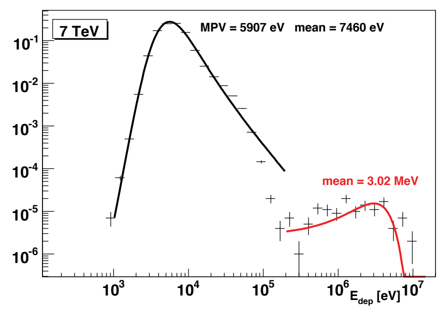

Figure 4: The energy depositions in the wire by a 7 TeV proton beam (Geant4 simulation).

The nuclear interactions with the wire material give tail of high energy depositions (red curve) but the contribution to the total deposited energy is below 1%.

In the following calculations the value of energy deposited per proton has been taken as the mean value of the distribution in Figure 4. To correct for the cylindrical shape of the wire, the total energy deposited is multiplied by a factor $\pi/4$. The error in the estimation of the mean value of energy deposition in Geant4 simulation is below 10%.

COOLING PROCESSES

Because of a very small cross section of the wire the heat transfer plays negligible role in heat distribution during the scan. Nevertheless its relative contribution is important for temperatures below 1300 K.

In the temperature range between 1300 K and 3200 K the main cooling process is the radiative cooling. It is proportional to the wire surface, fourth power of the wire temperature and to emissivity which quantifies deviation from ideal black-body radiation. The last parameter is poorly known and can have values between 0.4 and 0.8.

The thermionic emission is a dominant cooling process for temperatures above 3200 K. It determines the wire temperature for scans of the high intensity beams like the LHC or SPS ones. The electric current emited by the hot body is described by Richardson-Dushman Equation:

$$\mathrm{J_{th}} = \mathrm{A_R} \cdot \mathrm{T}^2 \cdot \exp(-\frac{\phi}{\mathrm{k_B T}}) \qquad (2)$$

where $\mathrm{A_R}$ is Richardson constant. The power dissipated by the thermionic current is proportional to the surface of the wire and depends exponentially on the temperature.

The thermionic emission removes electrons which are replaced by a current flowing from the fork supporting the wire. This current, described in Equation 1 as $\mathrm{C(y)J_{th}}$, is taken into account as an additional source of heating, but it has a negligible contribution.

The thermionic emission may lead to a phenomena observed in Figure 7, where the temperature is stabilized at about 3600 K due to equilibrium between beam heating and thermionic cooling. For very narrow LHC beams this equilibrium is not observed because the heating is faster than characteristic time of cooling processes. In this case the maximum temperature is determined mainly by the heat capacity of the wire.

The relative contribution of different cooling processes is illustrated in Figure 5.

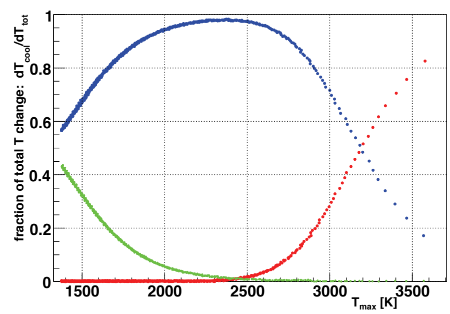

Figure 5: Relative contribution of cooling processes to the total temperature change as a function of temperature. Blue points are for radiative cooling, red for thermionic emission and green are for the heat transfer.

ESTIMATION OF WIRE SUBLIMATION RATE

The wire sublimation rate has been estimated from a simple model [10] which assumes that in a thin layer around the wire the carbon vapour pressure is in equilibrium with the wire material. The second assumption is that the carbon vapour is an ideal gas, therefore it does not have internal degrees of freedom. Both assumptions are conservative therefore the amount of sublimated material is overestimated.

The vapour pressure data have been obtained from [11]. The error on this data is significant and it is the main source of uncertainty of the model.

The depth of the layer sublimated in the time Δt can be expressed by:

$$\mathrm{d_{sub}} = \frac{1}{2}\mathrm{v_{vap}}\rho_{\mathrm{vap}}\Delta \mathrm{t}/\rho_{\mathrm{C}} \qquad (3)$$

where:

$$\rho_{vap} = \frac{m_{mol}}{V_{mol}}\frac{T_{std}}{p_{atm}}\frac{p_{vap}(T_{vap})}{T_{vap}},$$

$$\mathrm{v_{vap}} = \frac{1}{2}\sqrt{\frac{8kT_{vap}}{m\pi}}$$

The total amount of sublimated material depends on the maximum temperature reached during the scan and the time the temperature remains high. The removal of the material from the wire leads to decrease of the wire heat capacity and cools down the wire because of sublimation entalphy. The contribution of this cooling to the total cooling at high temperatures is only about 1.5%.

In Figure 6 the maximum temperature of the wire during the scan is confronted to the decrease of wire radius. The sublimation process starts sharply at temperature of about 3300 K for vapour pressure of a few Pa.

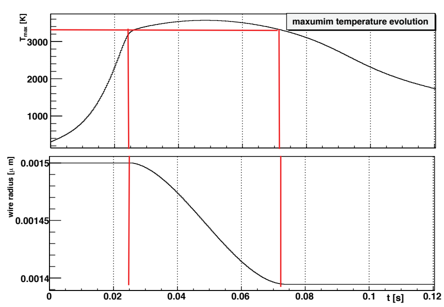

Figure 6: Illustration of the temperature evolution and corresponding decrease of the wire diameter in the sublimation model. The scan conditions correspond to SPS experiment with wire velocity of 10 cm/s.

RESULTS

The different sets of beam parameters, presented in Table 3, have been used to test the calculation against the known experimental results and to predict the wire scanner operational limits for LHC.

Table 3: Values used in the calculations for different beams.

parameter	unit	SPS	LHC	
			inject.	coll.
beam σ_x	cm	0.163	0.053	0.016
beam σ_y	cm	0.065	0.080	0.023
No of protons in beam $(\cdot 10^{13})$		2	32	32
protons energy	TeV	0.45	0.45	7
wire velocity	cm/s	10	100	100

SPS experiment

The model has been tested on the results of an experiment made in 1988 on SPS beam. During this experiment the consecutive scans were performed with decreasing wire velocity. The wire has been broken at velocity of $10\ \mathrm{cm/s}$ [12] in beam conditions described in Table 3. At velocity of $20\ \mathrm{cm/s}$ the wire was still not broken, although probably it was significantly weakened. At 1 m/s the scans of this beam were safe for the wire.

The evolution of the maximal temperature during the scans with different velocities is visualized in Figure 7. The arrows show the moment when the wire passes the beam center.

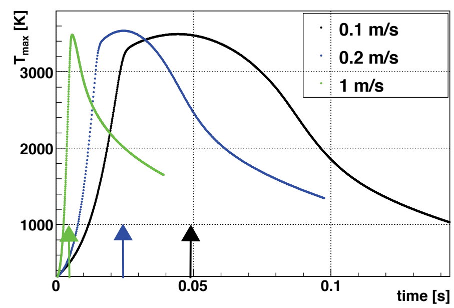

Figure 7: temperature of the central bin of the wire for 3 scan velocities: 10 cm/s (black curve), 20 cm/s (blue curve) and 100 cm/s (green curve).

For all velocities the maximum temperature is about 3550 K. The fastest scan passes the center of the beam 4.9 ms after the beginning of the scan and the wire continues to absorb beam energy without a visible influence from cooling processes until it reaches the maximal temperature at 6.2 ms. The period of high temperature lasts relatively short leading to sublimation of a 0.3% of the wire material in the central bin.

For the scan with $10\ \mathrm{cm/s}$, after 30 ms from the beginning, when the temperature of the wire reaches about 3300 K, the thermionic cooling slows down the wire heating substantially. The maximum temperature is reached when the wire crosses the beam center at 49 ms from the beginning of the scan, but temperature increase between 30 ms and 49 ms is small. The total material sublimated is about 7% of the wire diameter.

The thermionic cooling is the main cooling mechanism therefore the poor knowledge of the carbon work function is an important source of uncertainty. The work function variation by 20% results in the maximal temperature change between 3100 K and 3800 K.

LHC injection beam

The LHC beam is much more dense than the SPS one. It contains 16 times more protons and the beam dimensions are smaller. From the other hand the revolution time is almost 4 times longer.

At 1 m/s wire speed the heating from the beam would destroy the wire. A fraction of the nominal beam intensity which reproduces the safe scans on SPS is found to be between 22% and 25%. The maximum temperature is about 3600 K for 22% and 3700 K for 25% of nominal intensity.

The total material sublimated is between 0.02% and 0.5% of the wire diameter. In Figure 8 the evolution of the beam temperature along the wire is presented for scan of 25% of the nominal beam intensity.

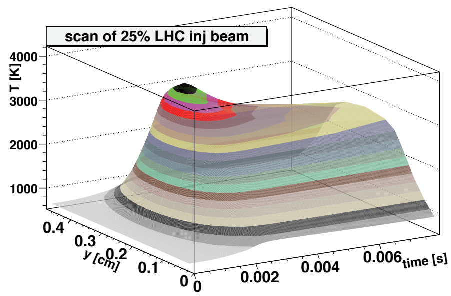

Figure 8: Distribution of wire temperature during a scan of LHC injection beam with 25% of the nominal intensity.

LHC colliding beam

During the acceleration the LHC beam not only gains energy but also is squeezed by a factor of almost 4.

Using the same criteria for safe operation as for injection it is found that between 6% and 7% of the nominal beam intensity can be safely scanned. In Figure 9 the temperature evolution during the scan of 6.5% of the LHC beam is presented. The beam center is reached after 0.48 ms and the maximum temperature of about 3670 K is reached 0.67 ms after the beginning of the scan. The total material sublimated according to calibrated model is about 0.16% of the wire diameter. The comparison of the temperature evolution of different-diameter wires is also shown.

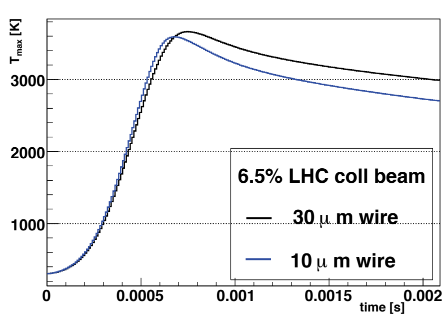

Figure 9: Distribution of wire temperature during a scan of LHC collision beam with 6.5% of the nominal intensity.

CONCLUSIONS

A model of the heating and cooling of the carbon wire has been obtained, tested on SPS data and solved for LHC beams. The main conclusion is that the maximum intensity which can be safely scanned is between 22% and 25% for injection beam and between 6% and 7% for collision beam.

The other outcomes of this research are the following:

- thermionic current plays crucial role as a cooling process in temperatures above 3200 K,
- the main factor affecting the maximum temperature is the wire heat capacity,
- RF-heating does not affect significantly the maximum wire temperature in case of LHC beam,
- sublimation rate becomes significant above 3300 K, but for fast scans of narrow beams the total amount of material sublimated is small,
- the model critical parameters: the carbon work function and vapour pressure are poorly known.

The LHC wire scanners work in critical conditions. The most valuable development would be to assure fast and automatic exchange of the broken wire, operate at higher speeds and use a thin carbon fiber with optimized mechanical properties.

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