SELECTION OF WIRES FOR THE NEW GENERATION OF FAST WIRE SCANNERS AT CERN

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Abstract

A new generation of fast wire scanners is being produced as part of the LHC Injector Upgrade (LIU) project at CERN. The LIU beam parameters imply that these wire scanners will need to operate with significantly brighter beams. This requires wire scanner systems with micron level accuracy and wires with a considerably increased tolerance to beam damage. This paper presents the method of selection of such wires in terms of material choice and geometry. It also reports on studies with novel materials with a potential to further extend the reach of wire scanners for high brightness beams.

INTRODUCTION

Instrument Principle

Wire-scanners are devices used to measure the transverse beam density profile by moving a thin wire across the particle beam. The interaction between the beam and the wire creates secondary particle showers with an intensity proportional to the number of particles crossing the wire.

These secondary particles are intercepted by a scintillator, positioned downstream of the wire, coupled to a photomultiplier which amplifies the resulting signal. The acquisition of the wire position and the signal intensity are combined to reconstruct the transverse beam density profile.

The LHC Injector Upgrade (LIU) project at CERN [1] is increasing beam brightness across the LHC injector chain (Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS)), to produce smaller, higher intensity beams.

Due to this higher brightness, the principal wire failure mode is expected to be due to the fast increase of temperature leading to melting or surface sublimation. The loss of matter weakens the wire until failure occurs [2].

In order to minimise this issue, the new fast beam wire-scanner (BWS) developed at CERN for LIU (see Fig. 1) has increased the linear velocity of the wire to 20 $\mathrm{m.s^{-1}}$, such that the wire remains in the beam for much less time [3]. The downside to this, however, is that for very small beams a signal is only produced for a few points along the profile.

Wire Research Development

Wire-scanners were first used in 1964 in Oxford and Heidelberg [4], as robust and direct profile measurement instruments. They have since evolved along with accelerator technology, and remain one of the fundamental instruments for measuring the beam profile in most particle accelerators.

Different wire materials and geometries have been used throughout this time. Among the first were steel, tantalum and beryllium, followed later by carbon, quartz, tungsten and titanium, as well as copper-beryllium alloys and silicon carbide. The advantages and disadvantages of some of these materials will be investigated in this paper. In addition, the geometry of the wire has an important role to play. Existing wires used at CERN have diameters from 7 to 34 µm, and are either single or multi strand (see Table 1).

Table 1: Rotational Wire-scanner Configuration

Ring	PSB	PS	SPS
Wire configuration	12x 7	12x 7	1x 34
Equivalent diameter [µm]	24	24	34
Wire length [mm]	120	153	153
Forks length [mm]	150	183	183

The other important parameter in wire scanner design is the scan speed. This parameter defines the time needed by the wire to cross the beam and is directly related to the number of useful data points taken per scan. This combination of material, geometry and scanning speed must satisfy three main criteria:

- Maximal measurement resolution
- Sufficient interaction to generate a signal
- Maximal lifetime of the wire

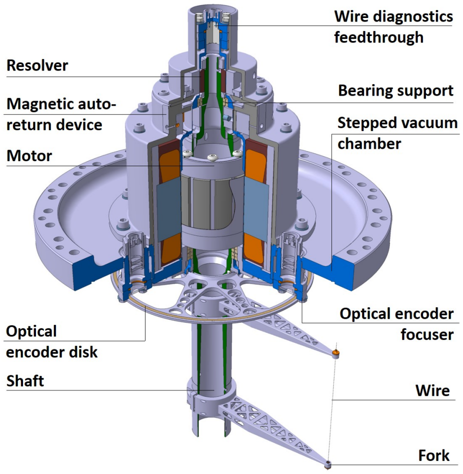

Figure 1: New Fast Beam Wire Scanner for LIU

MATERIAL SELECTION FOR MECHANICAL PROPERTIES

Wire Pre-Load

The pre-tension load is a key factor to determine the maximal wire deflection during movement of the scanner movement and hence the limiting resolution of the measurement. Table 2 compiles parameters, the ultimate tensile strength

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEPC19

(σ_{ult}) and the bulk density (ρ) for different candidate materials and gives the maximum pre-tension load (F_{pmax}) before failure. Clearly, larger cross sections of the same material allow for higher pre-tension loads.

Table 2: Maximum Preload Allowed for Minimal Deflection Calculation

	σ_{ult} **[MPa]**	ρ **[kg.m^{-3}]**	**F$_{pmax}$ [N] (24 µm)**	**F$_{pmax}$ [N] (34 µm)**
Be	550	1800	0.25	0.5
C	900	1800	0.41	0.81
Ti	460	4510	0.21	0.41
Fe	800	7840	0.36	0.73
Cu	220	8960	0.1	0.2
W	1920	19300	0.87	1.74

If the ultimate tensile strength (σ_{ult}) were the only parameter to evaluate, tungsten would be the best choice due to its high pre-tension load with carbon and steel over a factor two worse.

Deflection under Constant Angular Acceleration

Rotational wire-scanners accelerate to their nominal beam crossing velocity in ¼ of a turn. Hence the wire undergoes rapid angular acceleration. This can be modelled by a linear wave equation for a vibrating wire subjected to the centrifugal force produced by a rotation of angular velocity ω. Considering the attachment points of the wire ($x = 0$, $y = 0$) and ($x = L$, $y = 0$) are at a distance R (length of the forks) from the axis of rotation, the equation of motion in the rotating frame can be written as:

$$\frac{\partial^2 y(x,t)}{\partial t^2} = \frac{F_p}{\lambda}\frac{\partial^2 y(x,t)}{\partial x^2} + \omega^2 y(x,t) + \omega^2 R \tag{1}$$

where x is the position along the wire, y is the displacement of the wire from the nominal position (which depends on the x-position and the time t), F_p is the uniform pre-tension, λ the linear mass density of the wire material, L the length of the wire, and R the distance from the wire axis to the shaft axis (i.e. fork length).

Considering the case where ω is constant, the solution to equation Eq. (1) can be written explicitly as:

$$y(x,t) = y_{stat}(x) + \sum_{n=1}^{\infty} A_n \cos(\omega_n t)\sin\left(\frac{n\pi x}{L}\right) \tag{2}$$

where y_{stat} is the deformation function of the stationary state and An the Fourier coefficients of the vibrations around this stationary state.

In our case this stationary state describes the steady state shape of the wire without vibration. It is determined by the equation:

$$\frac{\partial^2 y(x)}{\partial x^2} + \frac{\lambda}{F_p}\omega^2 y(x) + \frac{\lambda}{F_p}\omega^2 R = 0 \tag{3}$$

Let us define a parameter $\alpha = f_m \times f_g$ where $f_m = \sqrt{\frac{\rho}{\sigma_{ult}}}$ and $f_g = \frac{v}{R}$ are material and geometrical functions respectively, with v defining the scan speed. We remark that α is independent of the wire diameter. This leads to

$$\frac{\partial^2 y(x)}{\partial x^2} + \alpha^2 y(x) + \alpha^2 R = 0 \tag{4}$$

The solution can be then expressed as

$$y_{stat}(x) = 2R\frac{\sin\left(\frac{\alpha x}{2}\right)\sin\left(\frac{\alpha(L-x)}{2}\right)}{cos\left(\frac{\alpha L}{2}\right)} \tag{5}$$

The maximal deflection, located in the middle of the wire, can be shown to be written as

$$y_{max} = 2R\frac{sin^2(\frac{\alpha L}{4})}{cos(\frac{\alpha L}{2})} \tag{6}$$

As shown in Fig. 2, the pre-tension is an important parameter, which determines the maximum deflection obtained for a given material.

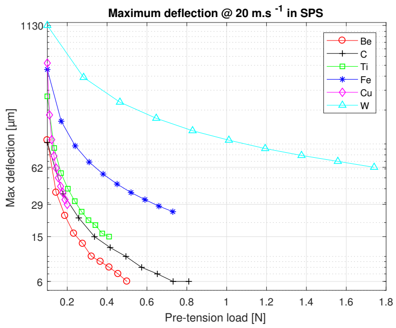

Figure 2: Maximum deflection for SPS @20 m.s^{-1}.

Hence materials with a high UTS and a low density will tend to have the lowest deflection during the scan.

Assuming the maximum pre-tension loads for each material, the maximum deflections obtained for the PS and SPS configurations are shown in Fig. 3. For the PSB complex the values decrease by about 30%.

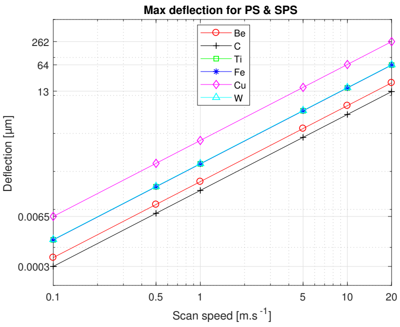

Figure 3: Deflection for PS & SPS at max pre-tension load.

Considering that beam sizes in the injectors range from a few hundred microns to several millimetres, the maximum

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEPC19

deflection of the wire during the scan must remain a fraction of this value. Copper is excluded as it has the highest deflection due to a poor combination of low UTS and high density. Despite its high UTS, tungsten also results in large deflections due to a high density, as does iron and titanium. We are therefore left with beryllium and carbon as the two best potential candidates.

Vibration of the Wire due to Acceleration

The harmonic frequencies of a vibrating string are defining by $f_{nstring} = \frac{n}{2L}\sqrt{\left(\frac{F_p}{\lambda}\right)}$. Considering the rotation of the wire around the axis with angular frequency ω, these wire vibration frequencies are modified because of the inertial load and can be expressed for the first mode as:

$$f_w = \frac{1}{2\pi}\sqrt{\left(\frac{F_p}{\lambda}\frac{n^2\pi^2}{L^2} - \omega^2\right)} \tag{7}$$

The resulting vibration frequencies are independent of R but dependent on the pre-load, the density of the wire, the length between the two forks and the angular rotation frequency. The first mode for each material is summarised in Table 3.

Table 3: First Harmonic Frequencies

	Harmonic frequencies [kHz]					
	Be	**C**	**Ti**	**Fe**	**Cu**	**W**
PSB	17.9	23.4	10.4	10.4	5.1	10.3
PS & SPS	14.7	19.2	8.6	8.6	4.2	8.5

The stationary state solution (Fig. 3) shows an amplitude of deflection in the range 3e-4 to 262 µm. In reality this value will be a combination of the steady state and the vibration, which depends on the speed profile, i.e. the acceleration function applied to the fork-wire system to bring it across the beam.

Two cases are considered: the 'nominal' profile with a slow constant acceleration up to 133 rad s^{-1} and the limiting case of a 'step function' increase in angular velocity of the shaft.

A slow, constant acceleration combined with a high pretension leads to smaller amplitude wire vibrations around the 'stationary state' deflection value. This is shown in Fig.4.

However, if the step function acceleration is applied (a situation which can be approached in case of control system failure), the wire amplitude can approach the stationary state value with a risk a breakage, as per Fig. 5.

Due to the deformation, the wire is subjected to an increase in internal stress, leading to a stretching of the wire. The new length can be written as

$$L_d = \int_0^L \sqrt{1 + \left(\frac{dy_{stat}(x)}{dx}\right)^2}\,dx \tag{8}$$

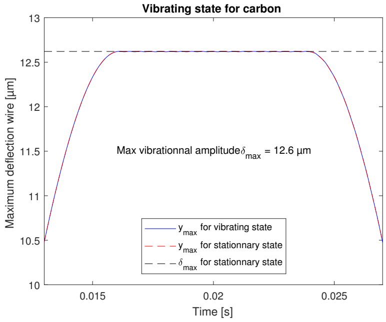

Figure 4: Carbon vibrating state for nominal speed profile.

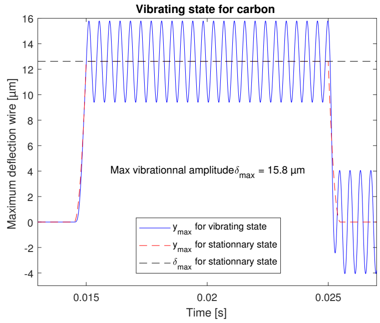

Figure 5: Carbon vibrating state for a sudden switch.

Considering the case with the maximal allowed pretension load, and a scan velocity of 20 ms^{-1}, the maximum deformation reached is 261 µm for copper in the SPS (Fig. 3). This value leads to an elongation of 0.8 µm (on 153 mm length) which is insignificant for an additional load. The stress inside the wire during the rotation is therefore the same as that in the initial state and only depends on the pre-load F_p.

Mechanical analysis shows that indeed, carbon and beryllium are the best candidates thanks to their low density and their high UTS. The main issue with beryllium is its lower melting temperature of 1560 K compared to 4095 K for the carbon fibre sublimation temperature. For carbon, there is a significant difference in mechanical properties for different strands, with the small 7 µm carbon fibres having a 70% higher UTS than the 34 µm. This is the reason why 7 µm carbon fibre bundles are used for PSB.

RESOLUTION OF A SCAN

The LIU-BWS has been designed for precision at high scanning speeds and to minimise damage to the wire material. However, in order to reconstruct profiles for a given bunch, at least three measurement points per beam sigma are required. As the beams are accelerated through the injector chain, the transverse beam size decreases and the circumference of the accelerator, and hence revolution time, increases. This is summarised in Table 4 [1].

For a given bunch (with a length assumed to be small compared to the revolution time) the number of points per

Table 4: Beam Parameters

	PSB	**PS**	**SPS**
Energy [GeV]	1.4	25	450
σ_x (horizontal) [µm]	1570	800	200
σ_y (vertical) [µm]	1200	500	300
t_{rev} [µs]	1.01	2.29	23.1

sigma is defined as

$$n_{pps} = \frac{\sigma_{x/y}}{v_{scan} t_{rev}} \tag{9}$$

Figure 6 summarises the transverse separation between measurement points for the different machines. Both the PSB and PS have large enough beams to resolve the profile with a good accuracy even at the highest speed with the acquisition never dropping below 10 points per sigma.

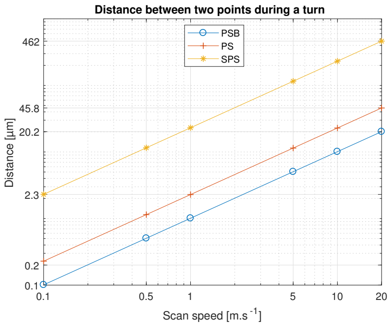

Figure 6: Wire movement per turn against scan speed.

However, to obtain at least three measurement points per sigma for the SPS at top energy, the scan speed has to be reduced to a maximum of 2.8 m.s^{-1} horizontally and 4.3 m.s^{-1} vertically. Such low speeds are currently obtained using precision linear scanners, but they can only be used with low intensity beams.

WIRE DAMAGE

It is well know that wires are destroyed by overheating, with recent examples during test in the SPS.

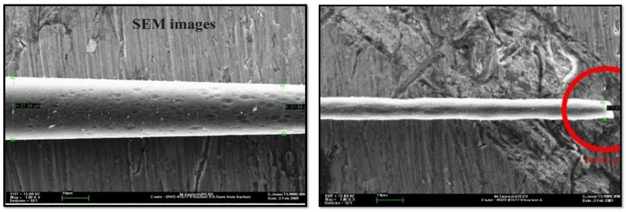

Figure 7: Impacted carbon wires.

Figure 7 shows micrographs of the visible impacts and sublimated damage for carbon in the SPS. The beam momentum was 400 GeV/c and intensity reached N_p = 2.4e13 protons with a longitudinal beam size of 570 µm and transverse beam size of 730 µm for a scan velocity of 0.5 m.s^{-1}. Only the core remains illustrating the limitation of the current materials [2]. A solution to this would be to use a material with similar mechanical and thermal properties to carbon filament, but will a lower mass density so that the wire absorbs less energy during a scan. Such materials, in the form of long strand carbon nano-tubes (CNT) (Fig. 8), are now becoming available on the market. The first picture shows the wire and the strips rolled onto themselves. The second picture details the inside of the strips, composed of CNT. Characterisation of physical and mechanical properties as well as performance with beam are currently underway at CERN.

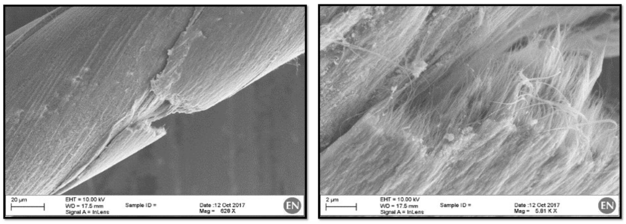

Figure 8: New CNT wire structure.

SUMMARY AND CONCLUSIONS

Wire-scanners for the high intensity circular accelerators at CERN use carbon wires due to their combination of low density, high ultimate tensile strength and very high sublimation temperature.

We have shown that these wires are also compatible when using high pre-loads with the high resolution needed for the new generation of LIU scanners in the PSB and PS in terms of mechanical deflection and vibration.

However, fundamental material limits are reached for such a wire in the SPS, preventing high-resolution scans of full intensity beams at top energy. Alternative wire materials are therefore actively being studied to push this limit to higher intensity.

ACKNOWLEDGEMENTS

Thanks to F. Roncarolo, J.Blasco, and A. Marin from CERN and M. Sapinski from GSI for their helpful discussions.

Thanks to M. Meyer from CERN for the CNT micrographs.

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