Conventional wire scanners for TESLA

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I. Introduction

Conventional wire scanners with thin solid wires (conventional compared with new techniques using, for example, Lasers) are widely used for beam size measurements in particle accelerators. Their known limitations are: 1) The smallest measurable beam size is limited by the finite wire diameter of a few microns and 2) High beam intensities combined with small beam sizes will destroy the wire due to the high heat load. At some locations in TESLA both beam diameters are larger than a few microns and such a conventional wire scanner would survive for many scans. With a typical resolution of a micron, it could be used for calibration of other beam size devices, which would be used more frequently to determine the beam size. A second task of a conventional scanner might be the precise determination of the beam position with respect to an external alignment system. Such a system is realized in TTF with the wire scanners in the undulator section. The heat load of the wires is calculated in the following for the TESLA parameters. The heat load defines the wire scanner parameters, mainly the scanning speed, and other limitations at TESLA.

II. Parameters

1. Beam Parameters

The TESLA beam parameters used in this report are shown in the following table:

Parameter	Symbol	Unit	Value
Center of mass energy	E_{cm}	GeV	500
Repetition rate	f_{rep}	Hz	5
Bunches per pulse	n_b		2820
Pulse length	t_{pulse}	μs	950
Bunch spacing	t_{bunch} f_{bunch}	ns MHz	337 2.97
Bunch charge	n_{bunch}	1/e	$2 \cdot 10^{10}$
Beam width horizontal	σ_h	μm (cm)	100 (10^{-2})
Beam width vertical	σ_v	μm (cm)	10 (10^{-3})

Table 1: Parameters of TESLA

The beam width at a wire scanner should not be smaller than about 10 μm due to the typical wire diameter of 4-7 μm. The beam dimensions are about σ_h x σ_v = 100 x 10 μm^2 at the emittance measurement station in the beam delivery section of TESLA .

2. Wire Scanner

The following table shows the parameters used in the calculations. At some of the accelerators at DESY wire scanners are already in use. The wires are 7 µm Carbon filaments. Good experience exist with these kind of wires at DESY and elsewhere.

Parameter	Symbol	Unit	Value
wire diameter	d	µm (cm)	7 ($7 \cdot 10^{-4}$)
mean wire diameter	d ' = d/2 · √π	µm (cm)	5.5 ($5.5 \cdot 10^{-4}$)
wire material	C	Carbon	
specific heat capacity*	c_p	cal / g / ^{0}C	0.42
Energy loss of min. ion. part. (MIPs) in carbon*	dE/dx_M dE/dx	MeV cm^2 / g MeV/cm	2.3 4.03
density of Carbon*	ρ	g/cm^3	2.3
melting temp. of Carbon	T_m	^{0}C	ca. 3500
speed of scan	v	cm/s	up to 1000
Conversion factor	C	cal / MeV	$3.8 \cdot 10^{-14}$

Table 2: Parameters of a wire scanner. *Data from Ref. 1

III. Temperature calculations

Each beam particle which crosses the wire deposit energy inside the wire. The energy loss is defined by dE/dx (ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$T = C \cdot dE/dx \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^0C],$$

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction):

$$G = 2 \cdot s_{v,h} \cdot d'^2 \cdot r \quad [g].$$

The number of particles N hitting the wire during one scan depends on the speed of the scan (~1/v), the repetition rate of the bunches (~f_{bunch}), the wire diameter (~d') and the bunch charge (~n_{bunch}):

$$N = \frac{d' \cdot f_{bunch}}{v} \cdot n_{bunch}.$$

Fig. 1 shows the a graphical representation of the parameters. The quotient d/(v/f) is the ratio of the scanned beam area or, in other words, like a grid seen by one bunch, assuming that all bunches are equal. However, the ratio can exceed the value 1 (a foil) if the scanning distance between two bunches is smaller than the wire diameter.

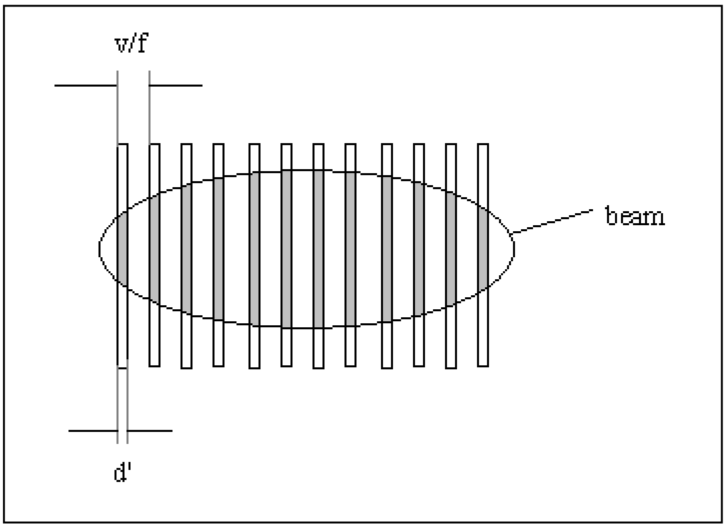

Fig. 1: Geometrical meaning of the parameters v/f and d'

Therefore, the temperature increase of the wire after one scan becomes:

$$T_{h,v} = C \cdot dE / dx_M \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_{v,h}} \cdot \alpha \quad [^0 C]$$

Where $_{h,v}$ denotes horizontal (h) or vertical (v) scanning direction. The cooling factor 'α' is described in the next section. Note that the temperature does not depend on the wire diameter and that it depends on the beam dimension perpendicular to the measuring direction. The temperature increase is inverse proportional to the scanning speed, therefore a faster scanner has a correspondingly smaller temperature increase.

a) Cooling mechanism

1) Secondaries: Some energy is lost from the wire by secondary particles. In the work in Ref. 2 about 70% is assumed. At HERA, the theoretical temperature of the wire (without secondaries) exceeds the melting temperature (T = 10 000 ^{0}C) after a scan. Considering the loss by secondaries of 70%, the temperature reaches nearly the melting point. In practice, the wire breaks about once in 6 months. The observation is that the wire becomes thinner at the beam center. This may indicate, that during a scan some material of the wire is emitted because of nuclear interactions or is vaporized because it is very close to the melting temperature. This supports the estimate of the 70% loss and one has to multiply the factor $\alpha = 0.3$ in the equation above.

2) Heat transport: The transport of heat along the wire does not contribute to short time cooling of the wire (Ref. 3). However, frequent use of the scanner heats up also the ends of the wire and its connection to the wire holders (fork).

3) Black body radiation: The temperature T_{bb} at which the radiated power is equal to the deposited energy in the wire during one scan P_{dep} [MeV/s] can be calculated from the Stefan-Bolzmann-law:

$$T_{bb} = \sqrt{\sqrt{\frac{P_{dep}}{s \cdot A}}}$$

where s = 35.4 MeV / (s^1 cm^2 $^0K^4$) is the Stefan-Bolzmann-constant and A is the area of radiating surface. The surface of the heated wire portion A is $2 \cdot \sigma_{v,h} \cdot d \cdot \pi$ [cm^2]. The power can be calculated by:

$$P_{dep\ h,v} = \alpha \cdot dE/dx \cdot d' \cdot n_{bunch} \cdot \frac{f_{bunch} \cdot d'}{v} \cdot \frac{1}{t_{scan}} \quad [MeV/s]$$

where $t_{scan} = 2 \cdot \sigma_{h,v} / v$ is the time for a scan (in the assumpion of 2 σ it is neglected that only about 70% of the power is concentrated within 2 σ). α is the expected loss from secondaries.

4) $c_p(T)$: The heat capacitance is a function of the temperature. Fig. 2 shows the increase of c_p for Carbon with T. The expected temperature after a scan is inversely proportional to c_p. Therefore one can expect a slightly smaller resulting temperature because of this dependence.

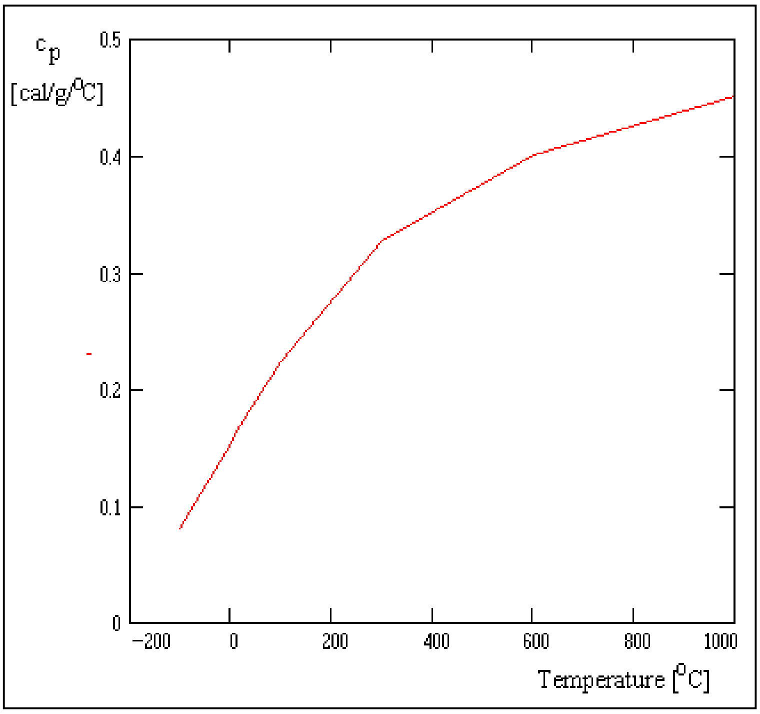

Fig. 2: The heat capacitance versus the temperature of Carbon.

IV. Results

In the following, a fast scan with a speed of 10 m/s was assumed. Such scanners are in use, see for example Ref. 4, 5. First tests with the scanner in Ref. 5 a resolution better than 10 microns was reached, without any big effort, even at that speed. One can expect to reach a resolution of around 1 micron. The following table shows the results of the temperature estimates from the formulas above and parameters in Table 1 and 2.

	horizontal scan σ = 100μm; v=10m/s	vertical scan σ =10 μm; v=1m/s
beam width σ_v	10 (10^{-3}) μm (cm)	
beam width σ_h		100 (10^{-2}) μm (cm)
wire temperature $T_{h,v}$	1400 °C	1400 °C
equilibrium temp. T_{bb} after t_{scan}	9690 °C	9690 °C
time for scanning 2σ: t_{scan}	$2 \cdot 10^{-5}$ s	$2 \cdot 10^{-5}$ s
signals in 2σ ($f_{bunch} \cdot t_{scan}$)	58	58

Table 3: Calculated temperatures and other parameters after a fast scan.

A horizontal scan with a speed of 10 m/s and a vertical scan with 1 m/s at the nominal current of TESLA will keep the wire temperature below its melting temperature. The number of signals within 2σ are satisfactory to observe even non gaussian beam shapes. Black body radiation will not contribute significantly to cooling during the scan. But after about 60s this mechanism decreases the wire temperature to about 200 °C, which defines approximately minimum time between scans.

At the start-up of TESLA, one might have a few bunches per pulse only. Nevertheless, the beam emittance is even at that stage of high importance to understand the behavior of the beam. Therefore the scanning speed has to be significant lower, e.g. a scanning speed of 1 μm/pulse vertically and 10 mm/pulse horizontally. The following temperatures were calculated assuming one bunch per pulse (f_{bunch} = 5 Hz) with the nominal charge.

	horizontal scan σ = 100μm; v=50μm/s	vertical scan σ =10 μm; v=5μm/s
beam width σ_v	10 (10^{-3}) μm (cm)	
beam width σ_h		100 (10^{-2}) μm (cm)
wire temperature $T_{h,v}$	483 °C	483 °C
equilibrium temp. T_{bb} after t_{scan}	350 °C	350 °C
time for scanning 2σ: t_{scan}	4 s	4 s
signals in 2σ ($f_{bunch} \cdot t_{scan}$)	20	20

Table 4: Calculated temperatures and other parameters after a slow scan.

In this mode, the scanning wire will survive more bunches/pulse, especially because black body radiation reduces the temperature between the bunches. For more details see Appendix 1.

Experience at SLAC (Ref. 6) shows that about $2 \cdot 10^9$ particles/μm^2 may destroy the wire. Following this value, the number of scans can be calculated before this value is reached:
1) fast horizontal scan: The affected area of the wire is $A = d' \cdot 2\sigma_v$ [μm^2]. The number of beam particles hitting the wire is $N = n_{bunch} \cdot d' \cdot f_{bunch} / v$ [particles/scan} and therefore:
$N/A = 2.9 \cdot 10^8$ particles / μm^2 / scan
2) slow horizontal scan: $N = n_{bunch} \cdot d' \cdot f_{pulse} / v$ and $N/A = 10^8$ particles / μm^2 / scan.
Therefore only about 10 scans at design current can be done.
3) The same calculation for HERAp (100 mA current) gives $N/A \approx 5.2 \cdot 10^8$ particles / μm^2 / scan. The HERA scanner was used about every second day for a few scans. It had survived for about 5 month, therefore more than 200 scans were done before it broke. From this experience, the number of Ref. 6 might be a little pessimistic. However, the conventional wire scanner should not be a device for frequent measurements, but for precise calibration purposes and for low current operations e.g. during start-up of the accelerator.. Other instruments like laser wire scanners should be used for regular measurements during operation.

Experiences from TTF, SLAC and other accelerators have shown, that the signal detection by scintillators and photomultipliers works very reliably. The secondary emission current from the wire is disturbed by thermal emission and can be used only at small currents.

V. Conclusions

A scanning speed of minimum 10 m/s and a position resolution of 1 µm will be sufficient for a fast wire scanner for TESLA. Depending of the beam size and beam aspect ratio, it should run with 1 or 10 m/s. This may be achieved with one type of scanner.
A slow scanner with a speed of 1 to 10 µm/pulse will be sufficient for the setup phase of TESLA, where one can expect a few bunches/pulse. The design of such a scanner will be significantly different to the fast scanner, therefore two different scanner types, a slow and a fast type, will be needed for TESLA.
The number of scans at nominal current is limited by the accumulated number of crossing particles. Experiences from SLAC and HERAp gave a limit between 10 to ≈200 scans, respectively.
All calculations where done for a beam dimension of 100 x 10 μm^2. Smaller sizes will result in a higher temperature of the wire. Positions in the LINAC with such beam sizes should be avoided.

VI. References

Ref. 1: L.R. Evans, R.E. Shafer; A Carbon Filament Beam Profile Monitor for high Energy Proton-Antiproton Storage Rings, Proceedings 1979 Workshop on beam current limitations in storage Rings (Ed. C. Pellegrini); Place: Upton: 16-27 Jul 1979

Ref. 2: J. Bosser et al.; The micron wire scanner at the SPS, CERN SPS/86-26 (MS) (1986)

Ref. 3: P. Lefevre; Measure tres peu destructive des distribution transversales dans le PS de 800 MeV a 26 GeV, CERN PS/DL/Note 78-8

Ref. 4: FV. Agoritsas et al.; The fast scanner of the CERN PS, CERN PS 95-06-BD-OP

Ref. 5: A.A.Loginov, E.A.Merker; Device for measuring beam profile in the accelerator, Proceeding of the Workshop on Advanced Beam Instrumentation, April, 1991, KEK, Tsukuba, Japan, V.1, P.121.

Ref 6: C. Fields et al; Wire breakage in SLC Wire Profile Monitors;

VII. Appendix 1

Assuming that the wire is always in the middle of the σ_h x σ_v = 100 x 10 μm beam and one bunch per pulse. The number of particles/pulse, which hit the wire, can be calculated by (horizontal scan):

$$N = n_{bunch} \cdot \int_{-\frac{d'}{2}}^{\frac{d'}{2}} \frac{1}{\sigma_h \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(\frac{-x^2}{2 \cdot \sigma_h{}^2} \right) dx$$

N = 4.95 · 10^8/pulse. The temperature increase caused by one bunch is then

$$\Delta T = C \cdot dE/dx_M \cdot d' \cdot n_{bunch} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v \cdot d'^2} \cdot \alpha$$

ΔT = 19.2 ^{0}C/pulse

Each bunch will add this temperature increase to the wire without any cooling (c_p(T) = constant). In the time between two pulses $1/f_{rep}$ cooling by black body radiation can take place:

$$T_{bb} = \sqrt{\sqrt{\frac{dE/dx \cdot d' \cdot N \cdot \alpha \cdot f_{rep}}{35.4 \cdot d' \cdot 2 \cdot \sigma_v}}}$$

Fig. 3 a, b show the temperature dependence from the number of pulses hitting the wire for 1 and 20 bunches per pulse, respectively. The temperature T_{bb} is valid just before the next pulse arrives at the wire, therefore the real temperature T_{real} just after the bunch crossing is of ΔT higher (solid line). With 20 successive bunches in one pulse T_{real} reaches the melting temperature of the wire (at about 300 pulses). Therefore the number of bunches for a slow scan will be about 20 bunches/pulse. There is still a safety margin, because only 58 pulses will hit the wire (2σ) during a slow scan and the wire is not always in the beam center.

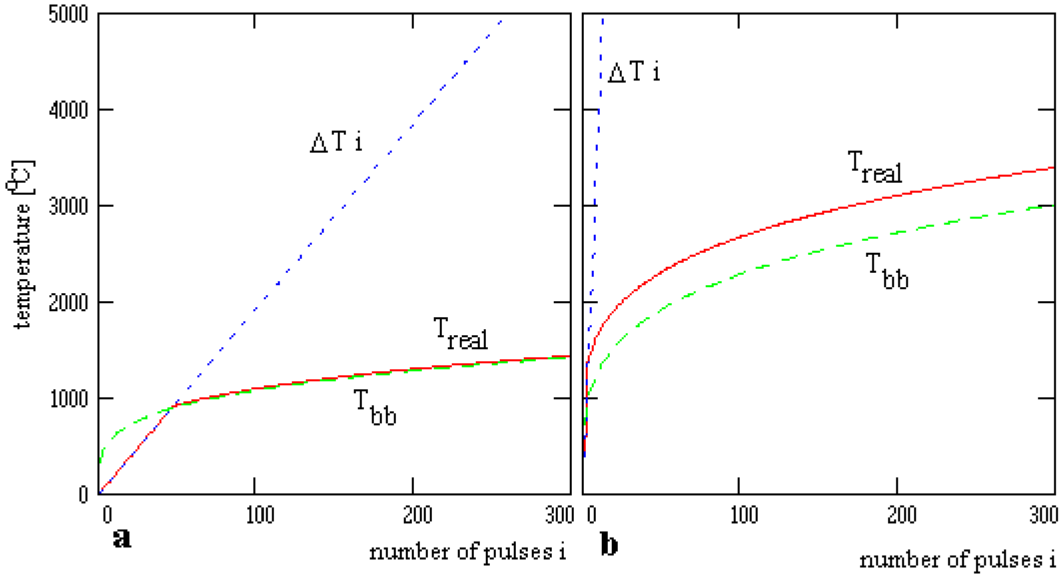

Fig. 3 a, b: Temperature increase of the wire for 1 and 20 bunches per pulse, respectively. $\Delta T \cdot i$ is the linear increase without any cooling due to black body radiation, T_{bb} is the equilibrium temperature just before the next bunch and T_{real} is the temperature just after the bunch.