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ABOUT THE DAMAGE MECHANISMS OF THIN TARGETS EXPOSED TO HIGH-POWER PARTICLE BEAMS

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Abstract

Thin targets, in the forms of wires, stripes, or foils, are often used in accelerators to measure the properties of particle beams. Motivations for a small thickness, typically between several and hundred micrometers, are diverse. Minuscule diameter of a wire allow for precision measurement because it is probing a small fraction of the beam's transverse profile. In case of high-power beams, the important rationale is also a small energy which beam deposits in the target and a good cooling because of a large surface-to-volume ratio. In certain beam conditions, the temperature of the target is still very high and lead to wire damage. This paper presents detailed analysis of ductile breakage of a molybdenum wire and gives a short overview of other damage mechanisms for various materials.

INTRODUCTION

Thin wires, stripes or foils, are often used in accelerators to probe the particle beams or to strip ions to different charge state. They are also used in electrostatic septa magnets, to separate space with field from a field-free region. Here we focus on wires used in wire scanners and Secondary Electron Monitors (SEM grids), where they serve as thin targets to probe the transverse beam profile. Nevertheless, the presented findings can be also useful for other applications.

The small thickness of the target has the following consequences:

- thinner objects have larger surface-to-volume ratio; the main cooling processes are determined by the surface while heating depends on the volume, therefore a larger surface-to-volume ratio leads to lower temperature;
- the heating process is mainly due to particle interaction with target electrons; for thin targets some of the electrons are kicked-out effectively leading to the energy deposition significantly smaller than expected from the Bethe-Bloch model;
- thinner objects lead to smaller beam perturbations; wire scanners in high-energy proton machines are almost non-intercepting devices.

Limiting the temperature of the wire is crucial because of the damage but also because the thermionic electron emission at high temperatures can dominate the secondary electron emission process, which is the measured signal.

The lower limits to the thickness of the wires and foils are related to the way they are handled and mounted. For practical reasons it should be easy to manipulate them manually, without special equipment. In case of carbon fibers the manual handling becomes very difficult for wires thinner than 10 μm.

There are two ways of reading the signal from thin target detectors, either by above-mentioned secondary emission current or by measurement of the flux of the secondary particles shower generated in the wire.

MATERIALS

Tungsten, molybdenum and carbon fibers dominate material choice for thin targets in high-power beams. It is because of a very good combination of thermal (i.e. melting or sublimation temperatures), mechanical and electrical properties of those materials. Other materials are beryllium, silicon carbide, tantalum, quartz and titanium. There are ongoing researches on use of high-temperature resistant ceramic material or carbon nanotubes (CNT) [1]. Some of the critical parameters of the materials are shown in Table 1. Strength stands for an approximate ultimate tensile strength for wires of the relevant diameter. Heat capacity and ultimate tensile strength values are given at room temperature. Final choice is a compromise between various parameters of the material, beam, RF-environment and the scanner itself.

Table 1: Thin Target Material Properties. For carbon fibre (CF) melting temperature is replaced by sublimation temperature and for SiC by chemical decomposition temperature.

	Density [g/cm^3]	Strength [GPa]	Melting temp [K]	Heat cap [J/mol K]	Z
CF	1.8	3.1	3915	8.5	6
Be	1.8	0.8	1560	16.4	4
SiC	3.16	4.0	3100	1.1	12.6
Mo	10.3	2.1	2896	24.1	42
Ta	16.7	0.7	3290	25.6	73
W	19.3	3.4	3695	24.3	74
CNT	0.2	0.5	3915	7.2	6

HEATING AND COOLING

The main wire heating mechanisms are coupling to the RF fields generated by the beam or leaking from the cavities, and direct interaction with the beam particles. In the first case, the maximum temperature depends on RF field and is reached at various positions along the wire. In the second case, the heating pattern follows the beam profile. The Bethe-Bloch formula states that the heating is proportional to $Z \cdot \rho$, so low-Z and low-density materials make better tar-

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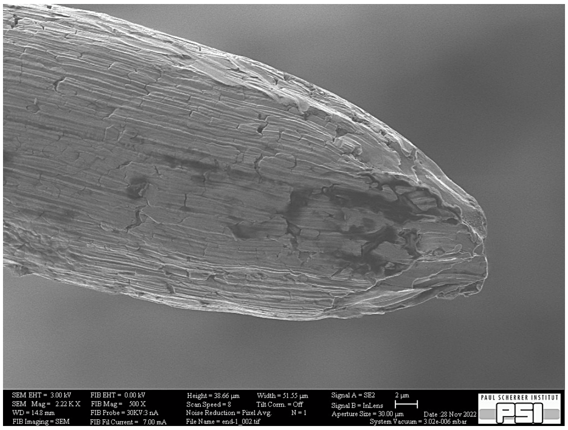

Figure 1: Electron microscope image of molybdenum wire broken in proton beam at PSI transfer line.

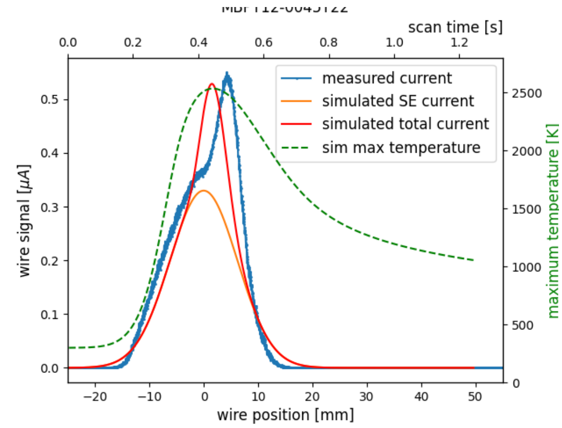

Figure 2: Observation of beam profile during a scan number 45, with the thermionic emission bump.

gets. Therefore, researchers hope for targets made of carbon nanotubes [2].

Other heating mechanisms are, for instance, ohmic heating due to currents flowing through the wire or electromagnetic discharge between the wire and the accelerator components.

Cooling

The two principal cooling mechanisms are radiative and thermionic emissions. The heat capacity of the wire plays an important role for the fast scan of high-brightness beams [3]. Due to small cross section of the wire, the conductive cooling is usually negligible.

DUCTILE DAMAGE

The scanner studied here [4] is located on the 590 MeV proton beam of Ultra Cold Neutron beamline at the PSI High Intensity Proton Accelerator facility . The beam is produced in 8 s long pulses with 1.8 mA current. The beam size in scanner position is 6.2 mm in the direction of scan (horizontal) and 1.3 mm in vertical. The scanner uses 25 μm molybdenum wire stretched on a C-shaped fork with a prestress of approximately 400 MPa. The scan speed is 6 cm/s.

The scanner was installed in 2022 and the wire broke in the during the commissioning at scan number 52. Figure 1 shows an electron microscope image of the broken end with signs of plastic deformation. The stress imposed on the wire exceeded its ultimate strength, causing necking at the weakest point. The thinned zone is about 10 μm long, much shorter than the beam size.

The beam profile observed during one of the scans is presented in Fig. 2. It shows a clear contribution of thermionic emission on top of the secondary electron current. A simulation of both currents, using pyTT code [5], is overlapped with data. The simulation slightly underestimates the secondary emission current, which could be partly due to the fact that it assumes a Gaussian beam, while in the observed profile the tails are cut. Another discrepancy is the 50 ms delay of the thermionic emission observed in the data and not in the simulation. The dotted line represents the simulated maximum temperature profile. The duration of the thermal pulse is about a second.

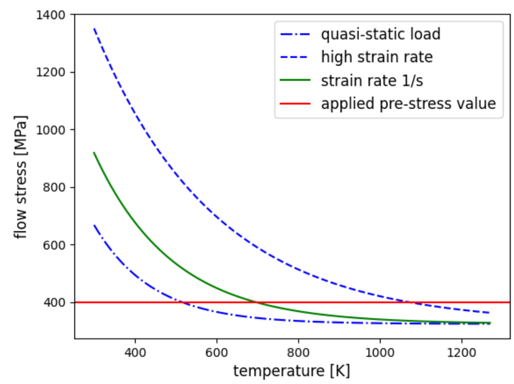

Figure 3: The flow stress as a function of temperature.

The ductile damage observed in Fig. 1 means that the wire was in conditions in which the prestress repeteadly exceeded the flow stress (Y_f), i.e. the value of stress necessary to keep the material flow. Zerilli-Armstrong model [6] is used to parameterise flow stress as a function of temperature, strain, and strain rate. The parameters of this model for molybdenum can be found in [7]. Figure 3 shows the evolution of flow stress as a function of temperature for various strain rates. The green curve corresponds to the approximate duration of the heat pulse during the scan. In all cases, the values of Y_f decrease very quickly with temperature, reaching an asymptotic value of approximately 350 MPa. It crosses the applied prestress value (red line) already at about 700 K. This explains the plastic deformation seen in Fig. 1. The repeated exposition to those conditions leads to continued deformation, exceeding the ultimate strength, necking, and breakage.

Figure 4 presents the evolution of the thermionic emission current during the series of scans with a beam intensity of 1.8 mA. Earlier scans can be neglected, because they were done without the beam. Despite constant beam conditions, the thermionic current increases from negligible at the be-

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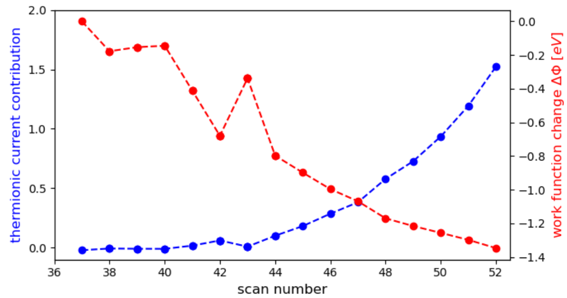

Figure 4: Thermionic current excess during series of scans performed on Aug. 2, 2022.

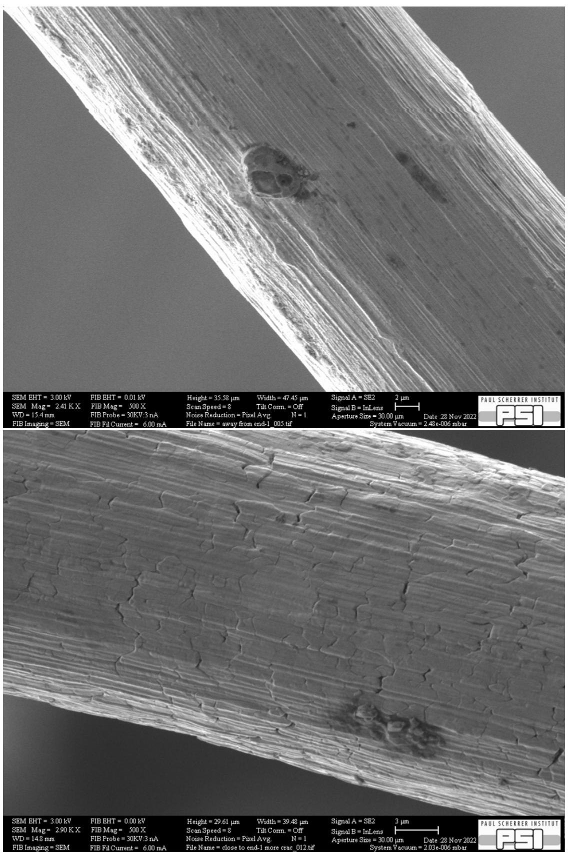

Figure 5: Electron microscope images of molybdenum wire away (upper picture), and close to the beam (bottom picture).

ginning to about 1.5 times the secondary current at the end. The reason for this must be structural changes to the wire as a result of thermal cycling and repeated exceeding of the flow stress.

Comparison of electron microscope images taken along the wire, seen in Fig. 5, reveal surface cracks created in the zone affected by the beam, but before the breakage point. These cracks can potentially affect two properties of the wire: emissivity and work function.

The impact of plastic deformation on work function was discussed, for example, in Ref. [8], where a decrease of approximately 0.2 eV was found in plastically deformed aluminum and copper, however, no literature on the behavior of work function under thermal stress was found. The red curve in Fig. 4 shows the decrease in the work function required to explain the observed thermionic emission, suggesting that a decrease of emissivity could also play a role.

Countermeasures

The remedies to wire breakage are: reduction of prestress, usage of different wire material (e.g. carbon fiber will withstand the beam intensity and the prestress), and the scan speed increase.

The solution currently applied is the installation of a thinner wire, which will lead to lower scan temperatures. A wire with a diameter of 13 µm was successfully used to scan the beam. However, the calculations show that it will suffer from the same breakage but after a higher number of scans.

OTHER DAMAGE MECHANISMS

Material melting was observed, for example, in the case of LEP beryllium wires [9], where the wires were heated due to coupling to the beam RF field. Electrical discharges between the tungsten wires and a support stud were found to be responsible for the damage observed on the SLAC scanners [10].

In vacuum, the vapor pressure of the materials is very low, leading to high sublimation rates. The case of carbon fiber was studied in a series of measurements at CERN [11]. Due to the stabilizing effect of the thermionic emission on temperature, it is possible to gradually sublimate the wire material. Extreme sublimation, down to 4 µm (more than 90% of wire material), has been reported [3]. The decrease in diameter leads to smaller heating and higher cooling mechanism performance, which makes carbon fiber a particularly good target. The sublimation process is relatively well understood and good agreement has been reported between predictions and measurements [12]. A new damage mechanism that leads to "blowing" of carbon nanotube wires was recently observed [2]. The reason was tracked to the presence of iron impurities in the wire structure.

CONCLUSIONS

The mechanism of wire breakage used in the instrumentation of high-power hadron accelerators is presented. A detailed analysis of the ductile breakage of the metallic wire shows how too high prestress affects its lifetime. Cracking in the wire surface due to plastic deformation is documented. An attempt to explain the sudden increase in thermionic emission by a decrease of the work function due to the plastic strain of the wire is plausable, but additional measurements are needed to prove it.

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