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OVERVIEW OF BEAM INTENSITY ISSUES AND MITIGATIONS IN THE CERN-SPS FAST WIRE SCANNERS

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Abstract

A new design of fast wire scanner was installed in the CERN injector complex as part of the upgrades linked to the High-Luminosity LHC Project. Initial operations with these instruments across the complex were good, but during the planned intensity ramp-up in early 2023, all four SPS scanners failed at the same time.

An urgent programme was put in place to understand and address this failure with experts from across the accelerator fields. Many measurements and simulations were performed, and solutions implemented.

This paper gives an overview to the issues seen, understanding and mitigations put in place to allow the instrument to perform at the maximum planned operational intensities.

INTRODUCTION

Fast Wire scanners (BWS) are used in the Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) at CERN as the principal measurement tools for transverse beam size and emittance.

During the recent LHC Injector Upgrade (LIU) programme, a completely new design of BWS was made with common design across all three rings [1]. A total of 17 instruments were installed and commissioned in 2022 [2].

The assembly consists of a cylindrical vacuum tank housing the instrument with a motor driving a protruding hollow shaft onto which are mounted two titanium forks which support a carbon fibre 'wire' of 34 µm diameter (see Fig. 1). The wire is rotated 270 degrees at high speed, crossing the beam at upto 20 ms^{-1}, scattering some particles which are detected downstream by a scintillator. A precise wire position measurement and particle loss flux are combined to produce a transverse beam intensity profile. The wires are electrically insulated from the forks and connected at each end to copper cables which exit the vacuum via a feedthrough. This allows additional wire properties such as resistance and current flow to be measured.

The instruments performed well in all machines, with more than 70'000 scans made in the first year [3]. However, early in 2023 operations an incident occurred with the SPS scanners. There are 4 wire scanners in the SPS ring, 2 mounted sequentially in the horizontal (H) plane (operational and 'hot spare' scanner) in the 'BA5' straight section and 2 sequentially in the vertical (V) plane, several hundred meters away in 'BA4'.

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DESCRIPTION OF THE INCIDENT AND INITIAL FINDINGS

On April 12, 2023, all 4 scanners were found with the wire open-circuit – normally a sign of wire breakage. At the time wire resistance was only logged during scans, so the precise time of the incident(s) was not known. However, this implied that the failures occurred with the wire in the 'parking' position (*i.e.* out of the beam) rather than during a scan. Previous scans and logs showed no anomalous signs.

In the first available access on 19 April, the two H scanners in BA4 were replaced with spares. Initial inspection showed that both carbon wires in the removed scanners were broken.

Operation resumed and the operational scanner in BA4 was successfully used on 21 April. However, shortly after on the same day, this scanner again was measured to be open circuit. Continuous logging of wire resistance was enabled for the 'hot spare' BA4 scanner and a failure of this wire was logged early on the morning of 22 April, with the scanner in parking position.

At this stage, a multi-disciplinary 'Task Force' was established to understand the causes of the failure and look for mitigations.

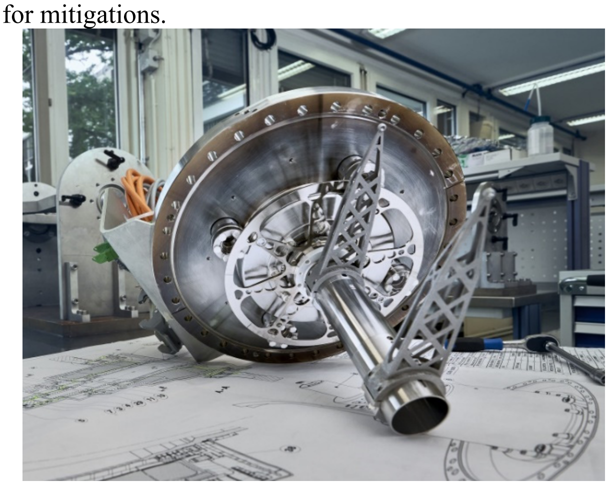

Figure 1: Fast wire scanner instrument showing shaft and forks.

ANALYSIS OF THE FAILURES

The scanners removed from BA4 were disassembled and the fork/wire assemblies inspected by optical microscope and SEM. Wires for these instruments are prepared by electro-plating the extremities with copper and the wire is soldered onto the fork to ensure reliable electrical and

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mechanical contact. SEM images revealed that wires had failed close to the copper/carbon transition and with two distinct failure aspects. Wire extremities on the 'motor' side (left hand fork in Fig.1) show a cleavage surface indicative of brittle fracture (see Fig. 2) – a typical failure mode for these carbon filaments under bending. However, extremities on the 'shaft' end (right-hand fork in Fig.1) showed a tapered wire with the end apparently fused into a ball (see Fig. 3). Carbon sublimates under vacuum at temperatures close to 4000 K [4]. This is a known failure mode for wire scanners and this tapered/necked shape has been observed in previous wire experiments in the SPS [5].

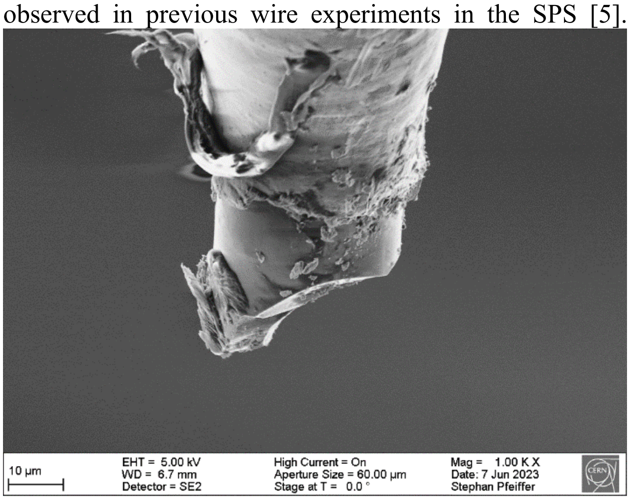

Figure 2: SEM image of carbon wire extremity after failure (motor side).

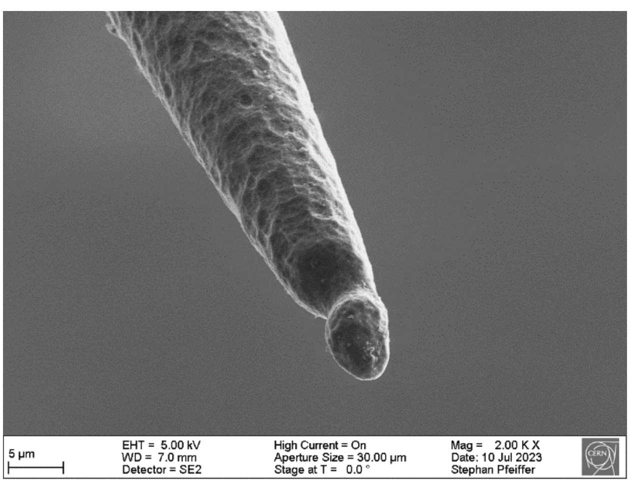

Figure 3: SEM image of carbon wire extremity after failure (shaft side).

These observations suggest that the wires were heated to a temperature close to 4000 K which caused either local or general sublimation leading to wire breakage. Any subsequent movement would result in the remaining part of the wire then snapping close to the copper transition, where the bending stresses are greatest. As at least one, if not all of the scanners failed in the parking position (the rest position between measurements), this could not have been caused by direct beam impact. It can therefore be assumed to be the result of inductive coupling with the electro-magnetic fields induced in the tank by the circulating beams.

Carbon Wire Resistance Measurements

The online resistivity and temperature estimation of the carbon wire was primarily aimed at identifying the beam conditions of the wire breakages. After the initial modification of the wire scanner tanks, the temperature estimation was also effectively used to assess the efficiency of two mitigation setups and select the most efficient.

Measurements involve injecting a constant current through the wire and measuring its voltage. The resistivity is evaluated using Ohm's law. The wire temperature is estimated by considering the resistance variation from the ambient value and using the thermal coefficient of carbon graphite with Equation 1. This basic model assumes a uniform electrical resistance within the wire volume. However, the energy is not evenly distributed along the wire, leading to potential underestimation of local temperatures.

$$T_{wire} = N_t + (W_r - W_{rn}) / (W_{rn} * T_c) \quad [1]$$

where, T_{wire} is the estimated temperature, N_t is the nominal temperature (in this case, 20°C), W_r is the wire's current resistance, W_{rn} is the wire's nominal resistance at 20°C, and T_c is the thermal coefficient of carbon graphite = -0.0005 [6].

After the first carbon wires broke, continuous wire measurements were implemented to observe the impact of beam parameters during injections, acceleration, and extraction. Initial observations showed a clear correlation between injection/extraction and a respective increase/decrease in the estimated temperature. During the acceleration phase, when the bunch length decreases, the estimated temperature seemed to remain stable until it decreases suddenly to zero. This rapid temperature decrease does not reflect the wire temperature but rather indicates another physical effect influencing the measurement, most likely thermionic emission counteracting the injected current. At the moment of beam extraction, the temperature suddenly peaked very high not perturbed anymore and then decreased exponentially, resembling a thermal cooling process.

Figure 4 shows the carbon wire temperature increase during an acceleration cycle in the SPS with 4 injections from the PS (intensity steps) for a tank without mitigation in green (2023) and with ferrites and coupler in purple (2024). It is observable that the maximum temperature is notably lower when mitigation techniques are used, even under the most severe beam conditions (higher beam intensity).

BREAKAGE SCENARIO SIMULATIONS

The wire heating measurements suggested that the failures occurred with a high intensity beam during a long flattop, used for scrubbing (electron cloud reduction [7]) of SPS components. Simulations were performed of the instrument and tank assembly [8] which revealed a coupling between the beam spectrum and an impedance peak coming from the geometry of the instrument in the tank at close to 800 MHz. This was confirmed by RF measurements using a spare instrument and tank [9].

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Beam-induced heating simulations were made for this coupled mode which predicted an average power dissipation in the wire of 20 W (with a range from 193 W to 7 W), which would be sufficient to heat the wire to sublimation temperature for less optimistic assumptions.

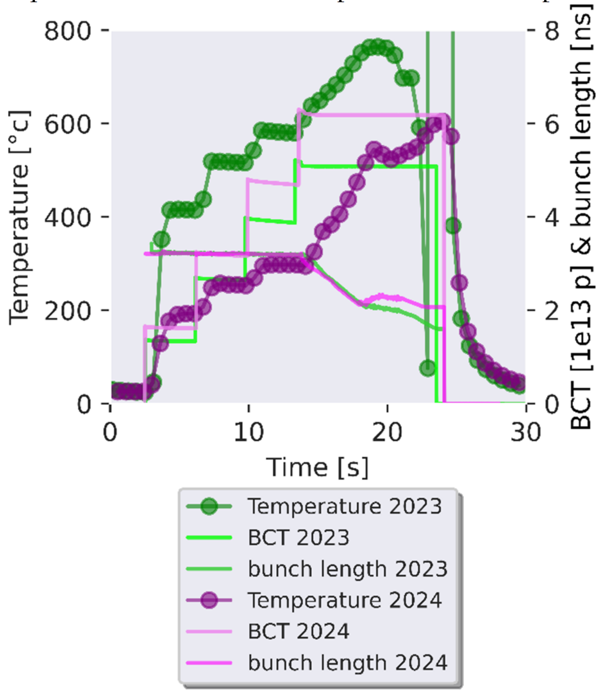

Figure 4: Temperature of the wire, derived from resistance, during operations before (2023) and after (2024) mitigations with corresponding bunch intensity (BCT signal) and bunch length.

STUDIES FOR MITIGATION OPTIONS

By design, the BWS had some options for impedance heating mitigation [10] which were not implemented in the baseline installation. Studies focussed on these options – specifically, addition of ferrites and a port for a mode coupler. Simulations detailed in [8] showed that the addition of 5 ferrite blocks of type Transtech TT2-111R would reduce the EM power deposited on the wire by concentrating the magnetic field in the ferrite material. This was simulated to reduce the power to the wire of 4 +/- 1 W. Thermal simulations were made of the heating of the ferrites. These showed that the temperature of the blocks should not exceed 46°C and the vacuum tank 26°C which are not problematic in terms of outgassing.

PRELIMINARY MITIGATION

A short machine access in June 2023 gave access to the two scanners in BA4 and allowed some preliminary mitigations to be made.

Both of the wire scanners were replaced with new devices and calibrated wires. One of the scanners was rotated 90° to allow both H and V operational capability to be retained. The V tank was fitted with 5x TT2-111R blocks (prepared for vacuum by air baking at 1000°C for 48h) and the H with 6 blocks as there was uncertainty on the optimal solution. The V scanner was also fitted with a probe/coupler (a capacitively coupled rod installed via a ceramic feedthrough and protruding into the shaft axis) connected by ~170m of CK50 cable to a spectrum analyser.

Pt100 temperature probes were also attached to the external tank surface at positions corresponding to the ferrites to log potential temperature rise.

Following this intervention, the operating intensity increased, but not to initial failure conditions due to limitations in other SPS devices. The carbon wires did not fail. The Pt100 probes showed a slow temperature rise on the tank of upto 4°C close to the ferrites and temperatures from the wire resistance showed a significantly lower energy deposition for the same beam parameters. Perhaps unexpectedly, the coupler gave indications of significant power (several W) absorbed at ~800 MHz.

FINAL MITIGATIONS

Following these successful results, including the utility of the coupler to mitigate heating, a full implementation was made (Fig. 5) in the year-end technical stop 2023-4.

All scanners were again replaced and all tanks fitted with 5 ferrites and a coupler. Logging was enabled for coupler and wire resistance.

Experience from 2024 operations to-date show intensity, bunch length and scrubbing run holds at levels exceeding those where wires failed in 2023. Figure 4 (purple points) show that wire temperatures are lower than 2023 values, even for beams with higher bunch intensity. These observations are consistent across the 4 modified tanks. The estimated temperature now stays below 700 °C and higher spikes in the range of 2000 °C observed in 2023 are absent.

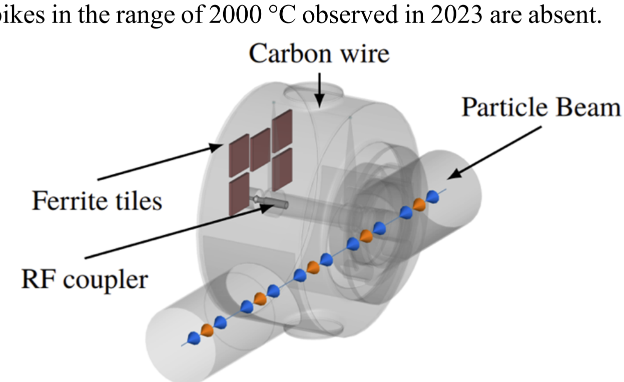

Figure 5: Final mitigation actions.

LESSONS LEARNED

Although this instrument was designed with impedance heating as a factor [10], the full impact of short bunch lengths at high intensity (shorter than nominal) and high intensity ‘scrubbing runs’ were not anticipated.

However, some margin had been allowed in the design for coupler and ferrites. Excellent simulations with recent tools allowed for rapid mitigations which seem to correspond well with results with beams.

Other possible mitigations, such as change in materials, fork lengths etc., were considered but shown to have less impact and require more fundamental design changes.

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