INSTALLATION AND TEST OF PRE-SERIES WIRE SCANNERS FOR THE LHC INJECTOR UPGRADE PROJECT AT CERN

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Abstract

A new generation of fast wire scanners is being developed for the LHC Injectors Upgrade (LIU) project at CERN. These will be essential tools for transverse profile measurement with the higher brightness LIU beams and are planned for installation in all three LHC injector rings in 2019.

An active period of development and test has resulted in prototype installations in the SPS and PSB rings. This paper will summarise the design and the results of tests to-date.

INTRODUCTION

The LHC injector rings, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), currently use fast rotary wire scanners with wire speeds up to 15 ms^{-1} for transverse profile measurements at high intensity. Slow (~1 ms^{-1}) linear scanners are also used for precision measurements at lower intensity in the SPS. The LIU project [1] will upgrade all these injectors, with the aim of producing higher brightness beams for the LHC from 2021.

This will require new scanners with precision equivalent to current linear scanners, but with scanning speeds of 20 ms^{-1} to prevent premature wire failure from beam heating. In addition, current operational scanners are obsolete, in terms of both mechanics and control electronics, with a number of recent operational issues affecting accelerator and instrument availability.

A fast wire scanner design project is in progress to produce a single device that can replace both fast and slow scanners in all LHC injectors. A first prototype was produced and installed in the SPS [2], with results of tests with beam presented here. However, this was not compatible with the tight physical constraints of the PSB. A new design, based on the same principles, along with new control and acquisition systems have therefore been developed to fit all machines.

ELECTRO-MECHANICAL DESIGN

The design concept of this new scanner has been discussed in detail in [2]. It consists of a permanently installed vacuum tank and removable 'kinematic unit'. The kinematic unit is a bellow-less, 'direct drive' design with two forks to hold the wire, the motor rotor, optical encoder and all other moving components built around a hollow, mass-optimised shaft (see Figure 1).

This direct drive design minimises relative mechanical movement between in-vacuum kinematic components. The rotor is separated from the air-side stator coils by an optimised 'stepped vacuum chamber' of 0.4 mm thickness, removing the need for vacuum bellows.

A number of changes have been made in order to integrate this device into the restricted space of the PSB. Bearings were moved to both sides of the rotor (the component with the highest inertia), with the shaft-fork assembly cantilevered into the vacuum tank. The internal geometry of the shaft was optimised to maintain stiffness with the design acceleration of 15'600 rad.s^{-2}.

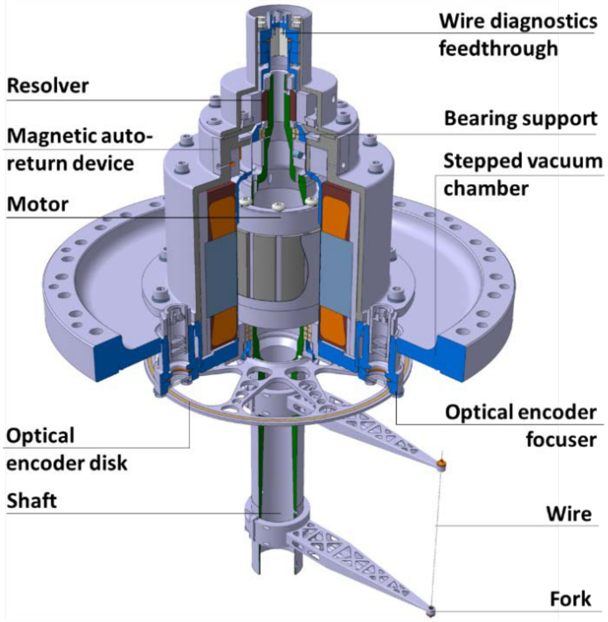

Figure 1: Part-section through PSB kinematic unit.

Angular position of the wire is determined using an optical encoder. It is composed of a mass-optimised, patterned, metallic disk rigidly fixed on the shaft, with the pattern read by two lasers. The optics and fibres delivering the laser light are located outside vacuum, allowing easy adjustment.

The motor was replaced with a commercial unit (ALXION 145STK2M023), with the rotor modified by the supplier for vacuum compatibility, using a stainless steel 'rotor band' rather than glue to retain the magnets.

Another feature of new scanner design is a passive magnetic auto-return device, to return the shaft to its home position in case of power loss. This is composed of a steel rotor is fixed on the shaft and permanent magnets on the air-side to provide two 'home' positions for the forks. During normal operation, the motor easily overcomes this additional magnetic force.

The vacuum tank was designed to provide easy integration within the PSB. There is a port for a vacuum pump, a viewport for visual inspection of the wire and a feedthrough for impedance measurement and possible mitigation.

CONTROL SYSTEM ELECTRONICS

The wire-scanner system is composed of four different parts (see Figure 2). The electro-mechanical scanner and secondary shower detector are in the accelerator tunnel, whilst the scanner control system and acquisition crate are in a surface building. The motivation for this was presented in [3], based on failure analysis of scanners used at CERN and the need to use modern electronics technology. Connections between surface and tunnel are via copper cables and fibre optics to ensure simple and robust design against radiation damage and single event upset to electronics. The drawback is that some 100 meters of cable runs are required, with associated cost, limits to system bandwidth and higher sensitivity to noise and perturbations.

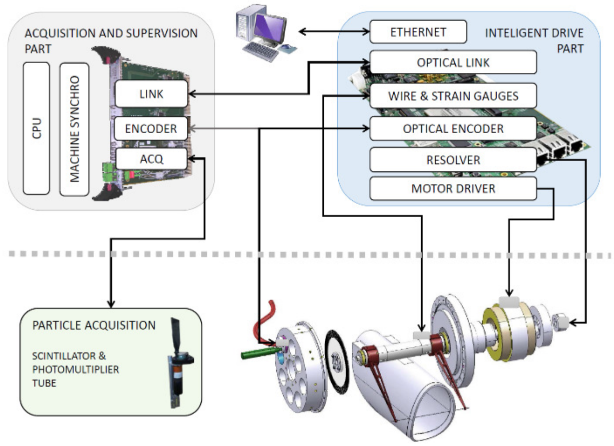

Figure 2: Wire-scanner architecture of the electronics for the control and acquisition.

The “intelligent drive” consists of a central logic platform and a drive and measurement interface. The interface provides information to the central logic to control and monitor the scanner including motor phase current and voltage, voltage adapters, motor control, resolver drive and position calculation, carbon wire measurements and optical encoder interface. A prototype interface board was developed to validate these functionalities before final integration, providing digitized values to the central logic and acting on the driver via Pulse-width modulation (PWM) techniques.

The motor phase currents, measured by Hall effect transducers located inside the drive, are conditioned and digitized in parallel and at higher speed and precision than necessary to facilitate digital signal processing on the controller with the aim of improving noise immunity.

A special resolver having no windings on its rotor is used to measure the absolute angular position of the shaft, with the position resolved by measuring the coupling ratio between a primary and two secondary coils.

The digital processing platform, where control and monitoring algorithms are implemented, is based on Field Programmable Gate Arrays (FPGA) technology and was tested in a prototype installed in the SPS [2].

The final system is being designed, based on a new VME VFC-HD digital platform developed at CERN [4].

OPTICAL POSITION SENSOR SYSTEM

An optical position sensor, based on fibre optic incremental encoders, is used to accurately determine the wire angular position [5] and avoid active components in irradiated areas. Surface electronics drive a 1310 nm laser diode and photodiode, connected to an optical circulator. The continuous optical signal is sent through a long (100-250m) radiation hard, single mode, optical fibre to the scanner. A system of aspheric lenses focuses the beam onto the encoder disk attached to the scanner shaft, through an optical viewport. The encoder disk contains a track with a pattern of alternating 10 µm reflective and non-reflective areas, with longer reflective areas acting as references. As the disk rotates, reflections are coupled back into the fibre and directed to the photodiode on the surface through the optical circulator. Two detectors physically separated by 180 degrees give on-line correction of systematic position errors coming from disk eccentricity.

The current PSB configuration provides angular position increments of 214 µrad ± 10.7 µRad rms. This translates to an incremental wire position projection of 26 µm ± 1.33 µm rms within the beam/wire interaction region. The systematic eccentricity correction shows a reproducibility of ~4 µRad rms, equating to 0.5 µm rms on the projected wire position. Other sources of error on the actual wire position include wire vibration and fork deformation.

SECONDARY SHOWER ACQUISITION

One drawback of the current scanner systems is the limited dynamic range of the acquisition system. These are based on scintillator-photomultiplier assemblies combined with filter wheels. The correct setting of light attenuation and photomultiplier high voltage is crucial for accurate beam-size determination. This makes the system difficult to set-up for the varied beams produced by the injectors. Diamond detectors combined with a high dynamic range read-out system were tested in the SPS to try to overcome this limitation, but the active detector area was found to be too small for all but the highest intensity and energy beams. For the PSB prototype two independent secondary shower acquisition systems have therefore been installed, one standard system dedicated for operational testing and a second as an evaluation platform for high dynamic range acquisition. Both systems are based on 30x30 mm organic cylindrical scintillators BC-408 (EJ-200) followed by a waveguide and wheel of selectable filters. The resulting photon flux is detected with metal package photomultiplier tubes (PMT).

CALIBRATION SYSTEM

An optical bench is used to determine the overall mechanical reproducibility of the system, and uses a 532 nm laser to emulate the proton beam. An optical assembly generates two parallel laser beams separated by a known, constant distance. On the other side of the scanner, another optical assembly combines the laser beams and directs the light onto a photodiode. Two micrometric stages displace the light beams across the scan axis. When the wire crosses each laser beam, the light arriving at the photodiode is reduced, producing two dips in transmission (see Figure 3). The angular interaction position is taken as the centre of the two peaks, with the reproducibility determined from multiple scans. Accuracy is determined by comparing the angular interaction point for different laser beam positions with the analytical angular-to-projected position transformation.

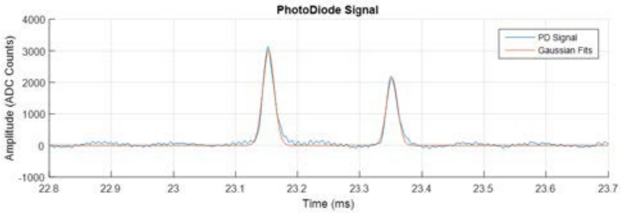

Figure 3: Light attenuation as detected by a photodiode during a calibration scan.

INTEGRATION INTO THE PS BOOSTER

A horizontal scanner prototype was recently installed in ring 3 of the 4 stacked rings of the PSB. This was chosen as the most challenging position for integration and installation and hence fully qualified the new design for these aspects. Detailed vacuum measurements were carried out on the sintered magnets and ceramic bearings, with vacuum outgassing simulations crosschecked with the results of measurements performed on the prototype wire scanner to validate the vacuum design.

RESULTS OF TEST WITH BEAM

Beam test measurements were made with the SPS scanner prototype at the end of the 2016 run using a fill with a single bunch of 1.1e11 protons at 400GeV. The SPS prototype performed nominal speed scans at 20 ms^{-1} with secondary particles shower detected by a pCVD diamond detector attached to a high bandwidth amplifier. Reliable beam profile measurements were obtained with diamond detectors under these beam conditions. An existing linear scanner (BWS.517.V scanning at 1 ms^{-1}) was used for performance comparison with scans performed on the same beam with a few milliseconds delay. Figure 4 shows a graphical summary of the results.

A significant improvement is observed when comparing the new scanner to the high precision linear operational scanners in terms of both beam position and beam size determination. Considering the measured beam sigma of ~500 μm, the linear (1 ms^{-1}) BWS.517 scanner provides a total of 25 points per sigma compared with just 1 for the prototype at 20 ms^{-1}. Even considering this significantly lower number of points for the Gaussian beam profile fitting, prototype scanner performs much better due to the reproducibility of the wire position determination.

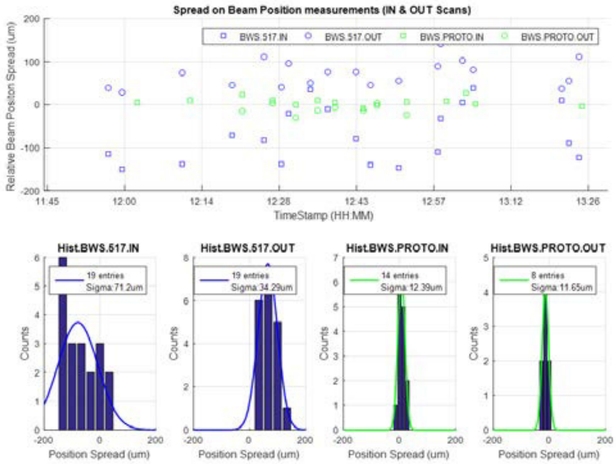

Figure 4: Beam centroids detected by linear scanner BWS.517 and BWS.SPS prototype during beam tests.

SUMMARY

An optimised prototype wire scanner has been designed, produced and installed in the very limited space available in the PSB during the 2016-17 shutdown. New control electronics for this scanner have also been developed. Tests with beam made with an initial prototype based on the same concept indicate a significant improvement in beam size determination using this new type of mechanics and control electronics. The project will now advance to series production, with 17 instruments planned for installation in the CERN PSB, PS and SPS during 2019 and 2020.

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