VACUUM ACTUATOR AND CONTROLLER DESIGN FOR A FAST WIRE SCANNER

B. Dehning, J. Emery, J. Herranz Alvarez, M. Koujili, J.L. Sirvent Blasco
CERN, Geneva, Switzerland

Abstract

To cope with increasing requirements in terms of accuracy and beam intensity limits a beam wire scanner (BWS) design is under development for the CERN accelerators complex. The main parameters have been determined; the wire speed should be 20 m·s^{-1} when interacting with the beam and a beam width determination accuracy of 2μm under the harsh radioactive environment should be reached. To meet this goal, the proposed solution locates all moveable parts of the actuator and the angular sensors in the beam vacuum pipe in order to reduce the friction and to allow a direct position measurement. One absolute positioning sensor will be used for the brushless motor feedback and one custom, high precision incremental design will target the beam size determination. The laboratory tests set up for the actuator and the incremental sensor will be presented along with the motor control feedback loops developed with the DSpace environment using Simulink and MatLab tools. Finally, the development of the digital feedback platform and the control and acquisition system design for the future operational system will be introduced.

PRINCIPLE OF THE WIRE SCANNER

The beam wire scanner belongs to the category of interceptive beam transversal profile measurement system. It uses electro-mechanical parts to move a thin wire of about 30μm through a beam. As shown on the figure 1, the losses generated by the interaction of the beam with the wire matter are escaping the beam pipe and are detected by a scintillator and photomultiplier. The generated current is proportional to the beam intensity at the position of the wire, which allows the reconstruction of the transversal beam intensity profile. This profile is processed to obtain the beam sigma and combined with other information to obtain the emittance of the beam.

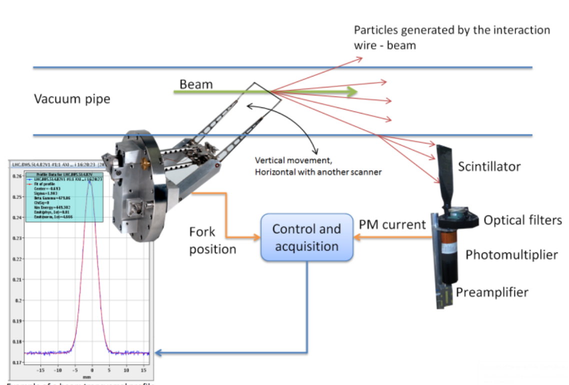

Figure 1: Principle of the beam wire scanner.

OPERATIONAL SYSTEMS AT CERN

The operational beam wire scanners at CERN are located along the injector's chain and in the Large Hadron Collider (LHC). They are used on a regular basis to measure the emittance of beams and to calibrate other beam transversal profile measurement systems such as the Beam Synchrotron Radiation Transversal and the Beam Gas Ionization. The table 1 details the different scanner types installed, their quantity and positions.

Table 1: Operational beam wire scanners at CERN

Accelerator	WS	type	speed
Proton Synchrotron Booster	8	Rotating Fast	20 m·s^{-1}
Proton Synchrotron	5	Rotating Fast	20 m·s^{-1}
Super Proton Synchrotron	6 4	Rotating Linear	6 m·s^{-1} 1 m·s^{-1}
Large Hadron Collider	8	Linear	1 m·s^{-1}

The Linear scanners are the most precise, because the fork position is directly measured by high precision linear potentiometers [1]. On the other side due to their low velocity the safely scanned beam intensity is limited to low values [2]. Rotating scanners are able to reach higher velocity due to the low mass of the rotating part. The fast wire scanners are using a complex mechanism [3] in order to reach the velocity of 20 m·s^{-1} resulting in a higher uncertainty of the wire width [4]. The Super Proton Synchrotron (SPS) rotating scanners are using a simpler mechanics and long forks of up to 200 mm compared to the proton synchrotron and its booster, which limits the velocity at 6 m·s^{-1} [2]. To communicate the movement from the motor located outside the vacuum pipe to the forks, all of them are using bellows. The control electronics for all this different types was unified adapting the LHC system, new features like the individual bunch transversal profiling was introduced in the SPS and an improved robustness and repeatability was reached.

MOTIVATION FOR A NEW DESIGN

The development of a new scanner type is motivated by the need of measuring smaller beam sizes and having higher intensities beams to scan. The basic concept is to combine the high velocity of the rotating scanners with an accurate and direct wire position determination as used in the linear scanners.

The velocity needed to profile the LHC beams at full intensities has been determined to be around 20 m·s^{-1} to avoid significant wire damage due to slow sublimation of

ISBN 978-3-95450-121-2

the wire material or thermal and mechanical fatigue [2]. Additionally to this effect, a shorter duration of the wire in the beam means lower induced losses and lower risk of quenching superconducting magnets. The expected smallest beam size is given with a sigma of 120µm, assuming 3 points per sigma and 5% accuracy; the wire determination accuracy is set at 2µm. To meet these specifications, many ways have been investigated taking into account the experience with the operational scanners, the environmental conditions and the state of the art in the fields of electromechanical systems.

Table 2: Main parameters of the vacuum scanner

Description	value
Minimum wire velocity during the wire – beam interaction	$20\ m{\cdot}s^{-1}$
Wire position determination, relative accuracy for the beam size measurement	2 µm
Inner pressure Ultra High Vacuum	10^{-8} Pa
Maximum outgassing	$10^{-9}\ Pa{\cdot}m^3{\cdot}s^{-1}$
Bake-out temperature, cycle of 24h	200 ℃
Cumulated ionizing radiation dose	20kGy

Environmental and Geometrical Constraints

The primary location of the vacuum scanner will be the LHC accelerator and all constraints linked to this location have to be met. The vacuum pressure, outgassing rate as well as the high temperature induced by the bake-out and the ionizing radiation level constraints the selection of the components to be compatible with the table 2. The use of active electronics in tunnel areas should be avoided and other ways to perform the required functions have to be found. Electronics should be located in the surface buildings and long cablings will connect it to the scanner location in the tunnel. The use of a rotor coupled with its stator though a vacuum barrel forces to select a motor with a large air gap to allow the introduction of a low magnetic permeability material.

Drive and Position Measurements Requirements

A scan cycle represents an angular movement of the rotating parts of π rad which includes a phase of acceleration, deceleration and constant speed when the wire interacts with the beam at a minimum of $20\ m{\cdot}s^{-1}$ i.e. an angular speed of $210\ m{\cdot}s^{-1}$ considering a reasonable fork length of 100 mm. The top angular speed has to be reached in less than 1/6 of turn i.e. a minimum angular acceleration of $20'000\ rad{\cdot}s^{-1}$.

The angular position of the scanner must be known for the motor control feedback with an absolute reference while the determination of the beam size can be incremental, but is much more demanding in term of acquisitions speed and accuracy. For these reasons the two functions have been separated into two distinct devices.

OVERVIEW OF THE SOLUTION

The selected solution uses a permanent magnet rotor placed in the vacuum chamber and coupled to the stator through a wall of low magnetic permeability material. By this way the use of bellows is avoided and the inherent constraints due to this type of construction such as heavy moving mass, vibrations and limited number of cycles can be avoided. The rotor is fitted on a shaft supported by roller bearings and solid lubricant vacuum compatible. Additionally to the rotor, the shaft holds all the other moving parts present in the vacuum, the absolute angular position sensor for the feedback control loop of the motor, the forks holding the thin wire and the disk of the optical incremental encoder for the beam size determination. The figure 2 shows a simplified drawing of the future scanner.

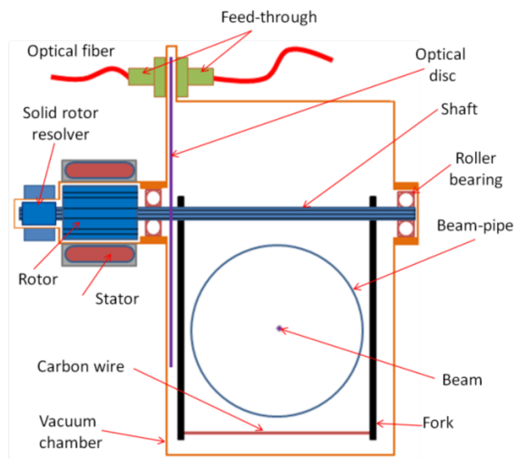

Figure 2: Simplified drawing of the future wire scanner.

Motor and Resolver

The Parker K500150 frameless permanent magnet motor has been selected with a peak and nominal torque greater by 50 % than the requirement [5].

The rotor core is made of standard steel which will be made vacuum compatible. Samarium cobalt alloy has been chosen as adequate magnetic material for the magnets instead of standard neodymium incompatible with the temperature levels. A mechanical fixation on the rotor has replaced the standard glue mounting to match the vacuum requirements. The air gap thickness between the rotor and the stator is large enough, 0.7 mm for the vacuum barrier integration.

For the absolute angular position measurement used for the motor position feedback, the Rotasyn® product with solid rotor has been selected for its intrinsic compatibility with vacuum. Unlike the traditional brushless resolver, it has both primary and secondary windings on the stator, thus no rotary transformer is needed.

Incremental Optical Angular Sensor

The principle selected for the high precision determination of the beam size is a glass disk with µm patterns of chrome photo-lithographed, placed inside the vacuum chamber and fixed on the scanner shaft. An optical fibre and feedthrough route a laser beam on a lens

ISBN 978-3-95450-121-2

which focuses it on the disc surface. Using the reflective property of the chrome pattern, the laser is coupled back into the same fibre. Using this technique, only one fibre and feedthrough is needed. The laser emitter, splitter and receiver will be located in the surface building and only one optical fibre will go down to the accelerator tunnel. The one fibre angular position sensor has been tested on the bench shown in figure 4. The laser beam is transmitted by a 65µm multimode fibre and focussed down to 30µm on a disc having 50µm slits and reflective pattern. The back reflected signal shown in figure 3 is obtained when the disc is rotating. Further investigation are ongoing to study the feasibility of the use of single mode fibres and feedthrough to decrease the beam spot size and disk patterns to about 5-10µm.

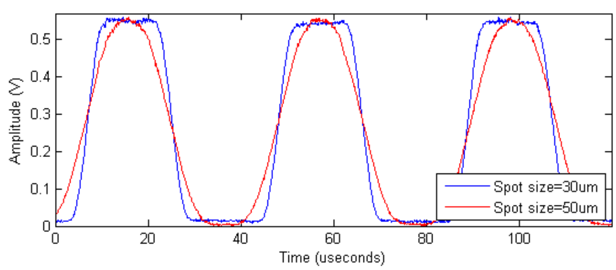

Figure 3: Resulting signal with 50µm width reflective patterns for different beam spotsizes.

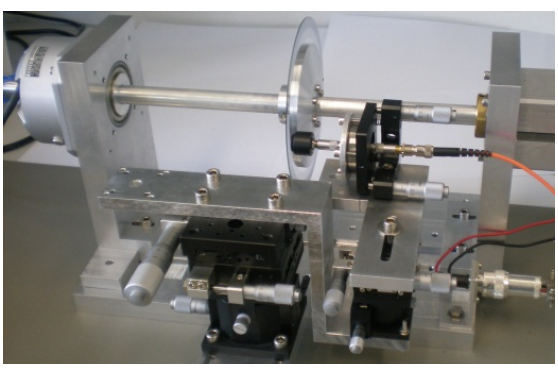

Figure 4: Laboratory setup of the incremental sensor.

Power Amplifier Stage

Two generations of scanners operating at CERN are using linear drivers to avoid the use of pulse width modulation, which can introduce high electromagnetic interferences on the measurement cables located close by.

Based on the needed torque, the motor torque constant and the expected velocity of the system, a linear amplifier has been selected and used on the laboratory test bench. Some operating modes have shown insufficient power dissipation margin in the amplifier. Investigations are now on-going to use state of the art switching power amplification to overcome these limitations without introducing significant perturbations.

Actuator Modelling and Control Feedback

In order to demonstrate the performance of the proposed design, a Simulink model of the actuator was developed using the Permanent Magnet Synchronous Motor Model (PMSM). In addition, perturbations coming from the inertia of the system and additional torque due to frictions and Eddy currents are taken into account. The control feedback is using the Park transform and Proportional Integral (PI) correctors for the current and speed feedback. The results of this model are consistent with the required performance and the laboratory test bench development has been done.

The DSpace environment for the optimisation of the feedback has been selected for its flexibility and for the software platform using MatLab/Simulink compatible with the developed models. Experimental results and performance assessment will soon be published [6].

TOWARD THE VACUUM SCANNER OPERATIONAL SYSTEM

The vacuum actuator and controller design presented in this contribution as well as the assessment of the performances on the laboratory tests benches is well advanced and is being completed with a study of the wire vibration.

Additionally, a study will be conducted to optimize the actual acquisition system and to cope with the high dynamic range required by the wild range of beam types.

The development of the control system based on the presented design will be integrated into Field Programmable Gate Array platforms to make use of its flexibility and the parallelization of the processing. It will contain the optimized feedback algorithms and the processing of the acquisition signals of the resolver and the incremental sensor. Emphasis will be made on the condition monitoring of multiples parts such as the motor, resolver, optical fibre signals and probably vibrations of the mechanism and the wire.

The construction of the first prototype will be started shortly and is planned to be installed during 2014.

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ISBN 978-3-95450-121-2