# FAST AND HIGH ACCURACY WIRE SCANNER

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*Abstract*

Scanning of a high intensity particle beam imposes challenging requirements on a Wire Scanner system. It is expected to reach a scanning speed of 20 m.s$^{-1}$ with a position accuracy of the order of 1 $\mu$m. In addition a timing accuracy better than 1 ms is needed. The adopted solution consists of a fork holding a wire rotating by a maximum of 200$^\circ$. Fork, rotor and angular position sensor are mounted on the same axis and located in a chamber connected to the beam vacuum. The requirements imply the design of a system with extremely low vibration, vacuum compatibility, radiation and temperature tolerance. The adopted solution consists of a rotary brushless synchronous motor with the permanent magnet rotor installed inside of the vacuum chamber and the stator installed outside. The accurate position sensor will be mounted on the rotary shaft inside of the vacuum chamber, has to resist a bake-out temperature of 200$^\circ$C and ionizing radiation up to a dozen of kGy/year. A digital feedback controller allows maximum flexibility for the loop parameters and feeds the 3 phases input for the linear power driver. The paper presents a detailed discussion of the selected concept and selected components.

## INTRODUCTION

Wire scanners are installed and operated on a daily basis on all circular accelerators of CERN. However, they present some drawbacks:

- For high intensity beams the energy deposited by the incident particles on the wire may be sufficient to break the wire [1].
- The wire can also be destroyed due to the energy transferred by the beam to the wire through its accompanying electromagnetic field [2].
- Inaccuracy of position measurement primarily due to vibrations of the mechanics and the wire.
- Vacuum leakage in the bellows due to wear.

To improve the optimization of the luminosity in the Large Hadron Collider (LHC), much higher measurement accuracies than those currently achievable are required. The new performance demands include a wire travelling speed of up to 20 m.s$^{-1}$ and a position measurement accuracy of the order of 1 $\mu$m, in addition to a timing accuracy better than 1 ms. This implies the design of a system with extremely little vibration and electro-magnetic interference. Other requirements related to interface and environment issues such as radiation, temperature, vacuum and interactions with the beam must also be accounted for.

The baseline solution (Fig. 1) consists of a small diameter rotary brushless synchronous motor with the rotor's magnetic field provided by permanent magnets, installed inside the vacuum chamber. This rotor is supported on a shaft by roller bearings with materials and solid lubricants to be selected for low outgassing and friction characteristics in vacuum environment. Attached to the same shaft is a fork on which the wire is stretched. In order to minimise the outgassing from the motor, the stator windings which excite the rotor are placed outside the vacuum chamber. The air-vacuum interface is made in the magnetic gap through a low magnetic permeability stainless steel wall. A position transducer to be mounted on the rotating shaft shall provide its absolute angular position for the feedback control loop of the motor and also a highly repeatable relative position during the scan.

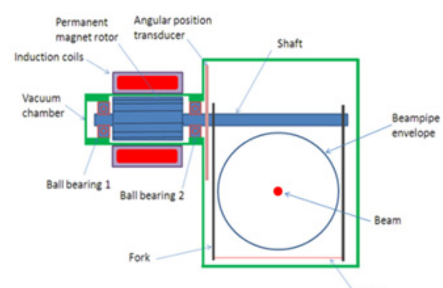


Figure 1: Simplified drawing of the future wire scanner. The green lines enclose the vacuum area.

In this paper, the motor requirements are defined first starting from the wire scanner specifications. Thus, the motor and its power supply are chosen with regard to the constraints obtained in terms of the needed torque, speed, and acceleration. After a brief description of the motor model some simulations achieved on the base of the physical parameters given by the manufacturer are included and commented based on the specifications.

## WIRE SCANNER SPECIFICATIONS AND MOTOR CHOICE

In this section, the different requirements to be met by the wire scanner device are listed and used to choose the motor ensuring the drive function. For the first prototype, a frameless brushless synchronous motor has been chosen taking into account the requirements in terms of dynamics and environmental constraints.

### Dynamic Requirements

The driver shaft will have a reciprocating movement of a stroke of $\theta_{max} = 180^\circ$, which will comprise an optimised curve of acceleration and deceleration which will allow reducing the vibration. In order to estimate the required acceleration, the following assumptions are made. The acceleration will be done over 90$^\circ$ up to a peak velocity of $\Omega_{max} = 200$ rad.s$^{-1}$(linear speed of $V = 20$ m.s$^{-1}$ with a fork length of 10 cm) and the deceleration to a stop over the remaining 90$^\circ$ stroke (Fig. 2).

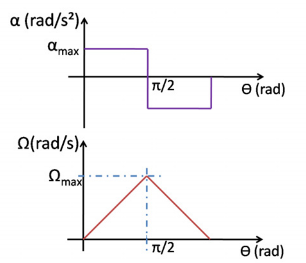


Figure 2: Theoretical angular acceleration (top) and angular speed (bottom) profile of the system.

To reach the peak velocity (200 rad.s$^{-1}$) in 90$^\circ$ the motor must provide an angular acceleration $\alpha$ of:

$$\alpha = \frac{1}{2}\frac{\Omega^2}{\theta} = 12755 \text{ rad.s}^{-1}$$

### Environmental Constraint Requirements

The rotor materials must have, after bake-out, a total outgassing not exceeding $10^{-9}$ Pa.m$^3$.s$^{-1}$. The permanent magnets on the rotor must have a thermal demagnetizing largely superior to bake-out temperature (200$^\circ$C). The whole motor must be resistive to a cumulated ionizing radiation dose of 20 kGy (roughly 1kGy/year).

### Geometrical Requirements

The motor air gap must be sufficiently thick to allow introducing a low magnetic permeability stainless steel wall.

### Motor Choice

The chosen motor for the prototype is a Parker K500-150-5Y frameless synchronous machine proposed in two independent parts: a three phase stator and a permanent magnet rotor with six pairs of poles.

The maximum torque provided at 200 rad.s$^{-1}$ ($T_{max@200rad/s}$) is determined from the datasheet of the manufacturer. The relationship between the maximum torque at 200 $rad.s^{-1}$ ($T_{max@200rad/s}$) and the acceleration provided by the motor ($\alpha_{max}$) is

$$\alpha_{max} = \frac{T_{max@200rad/s}}{J_r + J_s + J_f}$$

where $J_r$, $J_s$, $J_f$ are the inertia constants of the rotor, the sensor moving part and the fork, respectively. This motor can provide more than 2.5 times the acceleration needed for the wire scanner [3]. The rotor lamination is made of standard steel which will be made vacuum compatible. Samarium cobalt alloy has been chosen as adequate magnetic material for the rotor instead of neodymium which is less resistive to temperature. The foreseen glue based fixation of the magnets on the rotor will be replaced by a mechanical solution. The air gap between the rotor and the stator is comprised between 0.7 and 0.85 mm which is large enough to introduce the vacuum chamber barrier [4]. The chamber tightness and its eddy current effect will be tested with the first prototype.

### Linear Power Supply

As the wire scanners will be mounted in EMI sensitive environment, the power supplies working on the principle of high frequency switching (PWM) must be avoided. A three-phase linear power supply is currently under design. From simulation (Fig. 4), the maximum current needed by the motor ($I_{max}$) is 80 A.

The maximum needed voltage is the sum of the maximum back-EMF and the maximum voltage drop across the phase resistor and the synchronous inductor. From simulations, the maximum peak to peak voltage is 120 V.

Starting from the specifications above, the MOSFET power amplifier “PA52 by Apex” has been chosen. It can provide an output voltage of 200 V and a peak current of 80 A with a gain bandwidth product of 3 MHz.

### Angular Sensor

The transducer must provide information on the angular position of the shaft for two independent functions with different requirements: an absolute position readout for the motor control with an accuracy of 30 arc minutes (8.7 mrad) r.m.s and a relative position measurement for determination of the wire trajectory with an accuracy of about 5 arc seconds (25 $\mu$rad) r.m.s. The signal processing may be performed offline.

The use of an analog position sensor with capacitive coupling between its fixed and moving elements to measure the angular position with high accuracy, resolution and repeatability is under consideration.

As this sensor consists of two printed flat plates (free of electronic components), almost any material can be used for the supporting plate and the conductive traces. This advantage allows making the sensor vacuum compatible and resistive to radiation and temperature.

## SIMULATION STUDY

In order to test the validity of the chosen motor with regard to the wire scanner specifications, a simulation study has been achieved starting from the manufacturer characteristics. After the dynamic modelling of the motor, a servo control has been carried out under Matlab/Simulink software. The linear amplifier and angular sensor have been modelled through simple gains.

### *Dynamic Model of the Motor*

The three-phase windings are balanced. As a result, the voltage equations of the three-phase stator windings can be expressed as:

$$v_{an} = i_a r_s + L_s \frac{di_a}{dt} + \lambda'_m.p.\Omega_r.cos(p.\theta_r)$$
$$v_{bn} = i_b r_s + L_s \frac{di_b}{dt} + \lambda'_m.p.\Omega_r.cos(p.\theta_r - \frac{2\pi}{3})$$
$$v_{cn} = i_c r_s + L_s \frac{di_c}{dt} + \lambda'_m.p.\Omega_r.cos(p.\theta_r + \frac{2\pi}{3})$$

where $v_{an}$, $v_{bn}$, $v_{cn}$ and $i_a$, $i_b$, $i_c$ are respectively the three-phase voltages and currents of the stator windings, $r_s$ and $L_s$ are their resistance and inductance, $\lambda'_m$ is the maximum flux produced by each permanent magnet, $p$ is the number of pairs of poles and $\Omega_r$ and $\theta_r$ are the rotor speed and position, respectively.

$$T_e(\theta_r, t) = -K_T \Big[sin(p.\theta_r).i_1(t) + sin(p.\theta_r - \frac{2\pi}{3}).i_2(t) + sin(p.\theta_r + \frac{2\pi}{3}).i3(t)\Big]$$

where $K_T$ is the torque constant.

The motor speed can be expressed as

$$\frac{d\Omega_r}{dt} = \frac{1}{J_T}[T_e - B_m.\Omega_r]$$

where $\Omega_r$ is the rotor speed, $J_T$ the total inertia on the shaft and $B_m$ the viscous coefficient.

### *Simulation Results and Discussion*

The following simulation parameters were used: $R_s = 0.245\,\Omega$, $L_s = 1,365$ mH, $K_E = 0.2598$ V.rad.s$^{-1}$, $p = 6$, $J = 5.8 \cdot 10^{-4}$ kg.m$^2$. Assuming sinusoidal voltage waveforms in function of the electric angle and by using two specific functions for the initial phase and magnitude of the sine, the following waveforms of angular speed and position have been obtained (Fig. 3). In Fig. 4, the corresponding three-phase voltages and currents are shown. It can clearly be seen that the speed reaches a peak of $\Omega_r = 200$ rad.s$^{-1}$ in less than 90°, oscillates around this value and decelerates to a stop. This behaviour fulfils the specifications of the wire scanner in terms of maximum values of speed and acceleration. However, there are oscillations which must be minimised in the final test bench by an adequate control strategy. This control must adapt the magnitudes and phases of the three voltage sources in order to optimise the angular speed waveform.

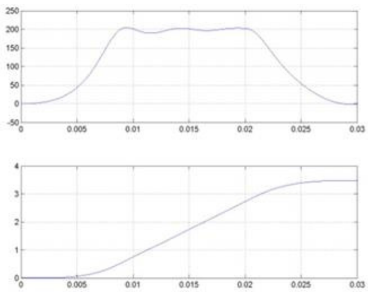

Figure 3: Simulated angular speed (top) and position (bottom) waveforms versus time in seconds.

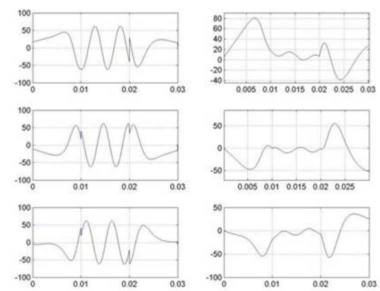

Figure 4: Simulated three phase voltage (left in volts) and current (right in amps) waveforms versus time in seconds.

## CONCLUSION

On the basis of simulations one concludes that the prototype of the fast wire scanner actuator is now ready to be built in order to optimize the control and to test the functionalities of the device. A dSPACE® Controller Board will be used as the real-time interface in the bench prototyping. Thereby, the control strategy will be optimized regarding the vibration phenomena and disparities of the physical parameters such as the circuit resistors.

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