STRIPPING FOIL DISPLACEMENT UNIT CONTROL FOR H^- INJECTION IN PSB AT CERN

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Abstract

For CERN's Linac4 (L4) Proton Synchrotron Booster (PSB) injection scheme, slices of the 160 MeV H^- beam will be distributed to the 4 superposed synchrotron rings of the PSB. The beam will then be injected horizontally into the PSB by means of an H^- charge-exchange injection system using a graphite stripping foil to strip the electrons from the H^- ions. The foil and its positioning mechanism will be housed under vacuum inside a stripping foil unit, containing a set of six foils that can be mechanically rotated into the beam aperture. The band with mounted foils is controlled by a stepping motor while a resolver, micro-switches and a membrane potentiometer provide foil position feedback. The vicinity of the ionizing beam and vacuum requirements have constrained the selection of the above mentioned control system parts. The positioning and interlocking logic is implemented in an industrial Programmable Logic Controller (PLC). This paper describes the design of the stripping foil unit electronics and controls and presents the first results obtained from a test bench unit which will be installed in the Linac4 transfer line by the end of the 2015 for foil tests with beam.

INTRODUCTION

As part of the LHC Injectors Upgrade (LIU), CERN has planned the replacement of the current Linac2 by the Linac4 as injector to the PSB. This new linear accelerator (linac) is expected to increase the beam brightness of the PSB by a factor of 2, making a Large Hadron Collider (LHC) injectors' upgrade possible for higher intensity and eventually a luminosity increase [1]. A combination of bending, kicker and septum magnets will distribute the 160 MeV H^- ions to the four superposed PSB synchrotron rings. The beam will subsequently be injected horizontally into the PSB using the stripping foil. The orbit of the circulating beam is displaced by ~81 mm, using two independent closed orbit bump systems, to meet the incoming beam [2]. The first injection bump uses four pulsed dipole magnets (BSW) magnets while a series of 4 horizontal kicker magnets (KSW), located in the PSB circulating orbit, will produce an additional closed orbit dump with varying amplitude to accomplish transverse phase space painting to the required emittance. This is illustrated in Fig. 1 [3]. The injected beam will be stripped by a H^- charge exchange injection system (i.e. stripping foil) where the ions will be converted to protons. Partially stripped H^- and ~1% H^- missing the foil will be directed to an internal dump.

In order to reduce machine downtime it will be possible to remotely interchange the carbon foil (~1 μm thick) when deemed necessary, e.g. in case of rupture or decreased performance. For that reason a foil interchange mechanism (FIM) has been designed, incorporating a rotating band with six interchangeable foils. This paper discusses the electronic actuators, sensors and control system that make a foil exchange possible.

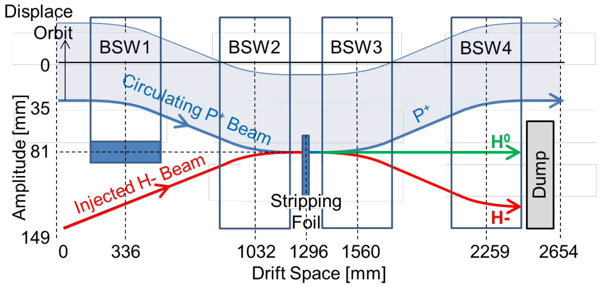

Figure 1: PSB injection region.

SENSORS & ACTUATORS

The FIM consists of a band, inside a vacuum chamber, that rotates over two pulleys so to displace a foil into the beam aperture. This will allow for a perpetual rotation so that each of the six foils can be reselected. Each foil is attached to a frame that has two important positions: *foil in* and *foil out*. Each of these positions allow for a 4 mm fine-tuning in order to find an optimum position for operation.

A retractable beam observation TV monitor (BTV) screen for beam position measurements on the selected foil is installed at the other side of the vacuum chamber, as shown in Fig. 2. When inserted it will be parallel next to *foil in* frame. To prevent BTV screen and FIM frame collisions, no FIM movement will be allowed when the BTV screen is in and at the same time any BTV movement is interlocked when the frame is not in the above mentioned positions. It is important to emphasise that a collision would result in major downtime because machine access and vacuum breakage will be required to replace the FIM. It is thus vital to know at all times the absolute position of the frame close to the beam aperture.

The choice of sensors is driven by obtaining that exact frame position and furthermore deal with the stringent vacuum pressure and radiation dose constraints. Furthermore the requested positioning reproducibility of 200 μm from the specification has to be taken into account.

Component Selection

The below electrical components are used to displace the band of ~50 cm so that one of the six foil frames is positioned into the injected beam aperture. The motor is the

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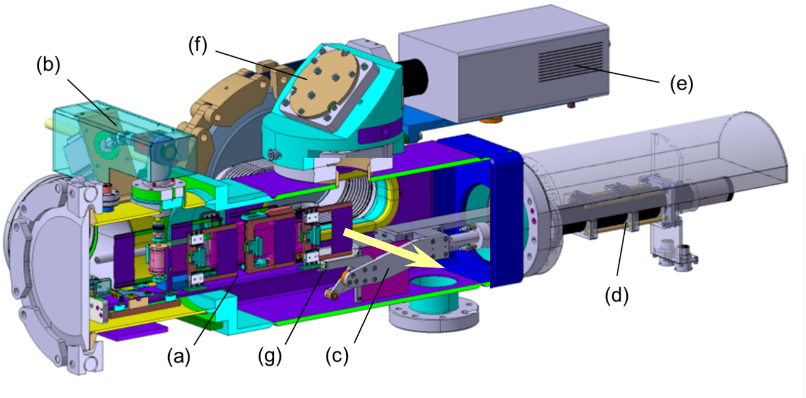

Figure 2: Cross section of the full design with (a) the FIM, (b) stepping motor, gearbox and vacuum feed-through, (c) BTV screen in retracted position, (d) the BTV motorisation, (e) BTV radiation hard camera, (f) mirror and optical filters unit and (g) the mirror positioned below the beam. The arrow indicates the beam direction.

sole actioning component, the other components are used for position readout.

Motor and Resolver The band pulley with a radius of 12 mm has its shaft connected to a mechanical vacuum feed-through. Outside of the vacuum chamber the feed-through is connected to a stepping motor through a 10:1 worm and wheel gearbox. Although some commercial off-the-shelf (COTS) stepping motors are made for operation inside the vacuum, placing the motor inside the chamber would endanger vacuum acceptance tests and complicate signal integrity and motor replacement.

The 1.8°stepping motor is microstepping driven which yields a higher positioning resolution and smoother frame movement. A microstepping factor of 8 steps per full-step has been chosen taking into account the microstepping disadvantages of torque variation and resulting loss of positioning accuracy. Taken all numbers into account the step resolution yields:

$$R = \frac{2\times12\times10^3\mu m\times\pi}{200\text{ steps}\times8\text{ microstepping}\times10\text{ gearbox}} = 4.7\mu\text{m/step} \quad (1)$$

This is well below the required 200µm positioning accuracy and hence allows for several missed motor steps before the frame will be considered mispositioned. Although a stepping motor can function without feedback, i.e. open-loop control, a resolver has been added to provide command feedback. When the control system detects a difference between the motor command (i.e. the requested amount of steps) and the actual movement seen by the resolver, one can consider missed steps (steps loss). In this application the main cause of steps loss is mechanical friction that cannot be overcome by the motor's torque. Detecting this is crucial because it will result in mispositioning. Furthermore the small step resolution versus required accuracy is important because the asynchronous behaviour of the motor drive and resolver readout module means that several missed steps during positioning should be allowed, as it will be explained later.

For this application a resolver was chosen over an encoder because the elevated radiation doses don't allow for the electronics that are implemented in all but mechanical encoders. Mechanical encoders don't provide the required resolution for this application. Although a final motor has not been chosen yet, several suppliers offer motor-resolver combinations that are radiation hardened.

Microswitch The use of microswitches has several advantages because of their simple construction and operation. Several COTS switches, mainly for use in space, are made to minimize vacuum outgassing and resist radiation. Furthermore the open/close contacts accept a wide range of voltages and can be interpreted by any control system. From a mechanical point of view it is more challenging to implement these switches in the limited space of the vacuum chamber and route the cables through an electrical vacuum feed-through. The production of dedicated frame and microswitch supports has allowed us to detect the *foil in* and *foil out* positions over the 4 mm range. A microswitch is also used for calibration as explained later. After lengthy research, the Honeywell 17HM6 has been selected and successfully tested for outgassing. For each position two switches have been installed for redundancy. Figure 3 shows the two switches that indicate the *foil in* position.

Potentiometer While the closed-loop stepping motor and microswitches are able to provide frame position information, it was seen necessary to include an additional position measurement for reasons of reliability. Furthermore the stepping motor needs to be calibrated and while the calibration can be done using a microswitch, that method doesn't allow for actual position verification. Also microswitch degradation, caused by radiation, could displace its triggering point, hence altering the calibration point. Several sensors such as inductive and capacitive position sensors were evaluated but either they were not vacuum compatible

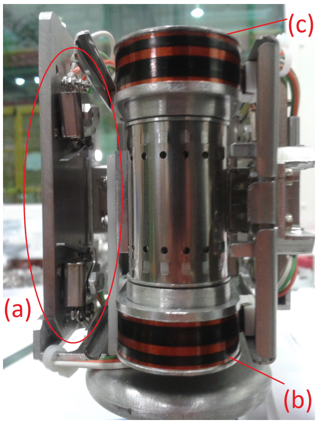

Figure 3: Front view with (a) microswitches and (b) (c) membrane potentiometers.

or they could not be physically fitted in the limited vacuum chamber space.

Because of the particular band movement it is clear that any linear position measurement won't cover the full range. However with a potentiometer that measures a single frame, preferably the one closest to the beam aperture, and with frame counter mechanism (see further in **Calibration**) an absolute position can be deducted. One has to take into account the limited chamber space and the fact that the frame closest to the beam aperture makes a rotational movement. These considerations have led to the choice of a membrane potentiometer. If the potentiometer consists of Kapton®, a polyimide film, and conductive ink it will experience limited outgassing and furthermore it can be bent around the pulley to follow the frame's movement. Germany-based Hoffmann+Krippner has produced a membrane potentiometer to our design. Figure 3 shows two of these potentiometers on the first test stand unit. The thicker line is the 20kΩ resistance while the smaller line makes up the conductor. Each frame has small wipers that short a certain part of the resistance with the conductor line. The measured resistance can then be translated to an absolute foil position.

Radiation Levels

The vicinity of the beam dump, mentioned in the introduction, is the main source of elevated levels or radiation. FLUKA [4] calculations show that some components can accumulate doses up to 10MGy which is why the microswitches and potentiometers will be sent to Fraunhofer INT for radiation tests. It is important to understand the degrading of the components as this might negatively impact the calibration which relies on for instance the potentiometer's linearity. The test results will also allow us to implement preventive replacement of the components when required. The foils themselves will become activated [5] so any unnecessary or unplanned intervention is to be avoided. The stepping motor and resolver are further away from the dump and can be commercially purchased to be radiation hardened so they will not undergo additional radiation testing.

Vacuum Cabling

For vacuum chamber cabling, no plastic-insulated cables will be used because the outgassing property of polymers cannot be accepted in the PSB vacuum. PEEK and Kapton® are to be avoided so all the cabling will be done by pure, uninsulated copper wire. The amount of microswitches and potentiometers result in a high number of cables that need to be insulated from each other. For this purpose COTS ceramic beads and tubes are used. All electrical contacts are passed through an electrical 26 pin High Density (HD) D-Sub vacuum feed-through.

CONTROL SYSTEM

The discussed components are all wired to the control system that is responsible for positioning the foils by actioning the stepping motor and reading the microswitches, potentiometer and resolver. There is no need for fast control so a PLC was chosen as main controller. PLCs, in general, provide out of the box axis control for positioning but due to the specific nature of the stripping foil this could not be used, as described below.

Hardware

The functional logic is implemented in a Siemens 1515F CPU with decentralised Inputs/Outputs (I/O) over PROFINET. For the final PSB installation there will be one master crate with the CPU and local touchscreen while each PSB ring will have a dedicated control crate with the I/Os. A safety PLC was chosen taking into account the machine downtime that a collision between a BTV screen and stripping foil could cause and not because of risk of human life which is normally the main reason. The implemented safety functions are surveilling the non-equivalent microswitch contacts and will open a contactor to open the motor phases in case of a detected discrepancy. Dedicated modules, for the resolver readout and stepping motor control & drive, have been integrated in the control chassis.

Positioning Algorithm

Calibration Positioning of the foil frames with a 200 µm precision relies mainly on the calibration of the band. Calibrating means finding a point on the band, the zero-point, which is considered to have the absolute position of 0 µm and from where all other positions are referenced. In case of a full turn the absolute position will set to zero again at that point. We know from Eq. 1 that the step resolution is small enough for accurate positioning, as long as the zero-point is found with an accuracy of better than 200 µm. The zero-point calibration error is however added to the existing calibration error with each full turn. Tests have shown that this accumulative error will result in exceeding the required precision after a few band turns. For reasons of consistency it was chosen to recalibrate with each full turn which only takes an additional few seconds. This is acceptable because of the band's slow motion, chosen so not to damage the fragile carbon foils.

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Calibration Methods Three different calibration methods have been selected for evaluation, the most accurate two will be kept for reasons of redundancy. All three methods rely on detecting the zero-point at nominal speed, returning a small distance and moving forward with reduced speed for a more precise zero-point calibration.

The first method uses an additional microswitch that can only be triggered by one of the six frames, called the zero-frame, because of a special support on that frame. The second method uses the same microswitch for indicating the zero-frame but it will then use one of the two potentiometers to calibrate the system at a fixed resistance value. Finally the third method uses a linear actuator to mechanically block the band and relies on the resolver to detect missed steps. This method is the least favourite because it requires the motor's torque to be high enough to make the band turn, but low enough so that a blocked band is detected as quick as possible to have an accurate zero-point calibration. A stepping motor's torque can easily be controlled by limiting the current through the stator phases but this is a trial-and-error method and because of slight mechanical construction and friction differences this is expected to be different for every unit constructed.

Absolute Reference Axis A PLC or stepper driver has a certain functionality to allow for automated positioning and axis control. In order to use that functionality however the system assumes certain basic configurations and a band that allows full band turns and recalibration is not one of them. That's why for this project the motor driver is used in relative positioning mode and an algorithm to allow for absolute positioning has been developed for the PLC. A well-known methodology called *finite state machine* has been used to have precise control over the (re)calibration and positioning methods and asynchronous commands to the motor driver. The algorithm also deals with the asynchronous command and readout of the motor drive and resolver modules, as these operations are not synchronous with the PLC program cycle. This asynchronous behaviour imposes that during movement a certain discrepancy between the motor command and resolver position needs to be allowed. The small step resolution ensures that even in this situation the required positioning accuracy is within specification.

Test Results

The implemented positioning algorithm and the positioning accuracy, based on the zero-point recalibration, needs statistical validation so a test-run functionality has been implemented in the PLC. A laser distance sensor with a resolution of 20 µm and linearity of 100 µm has been purchased for position measurement and verification of the potentiometer's linearity in the test bench.

During a test-run the system will position itself to a configurable amount of positions on which all sensor's data is written to an comma-separated values (csv) file. That file can be read in by spreadsheet software for statistical analysis and graphical representation. A test-run that requested 500 successive 100 µm positions has been used to evaluate the potentiometer's linearity, as can bee seen in Fig. 4. At the moment of writing several test runs are being made to evaluate the three calibration methods and currently a standard deviation of 250 µm has been compiled from the data. The reason for that high positioning error has been found due to the mechanical axis feed-through, which allows for a small amount of slack, which is amplified by the pulley's diameter connecting the axis to the band. Work is ongoing to reduce this mechanical slack.

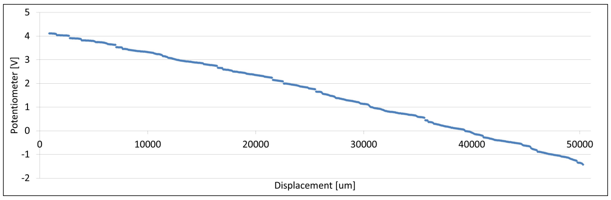

Figure 4: Potentiometer linearity test result, displacement (x) versus voltage (y).

STATUS AND FUTURE

The first unit will be installed at the end of the Linac4 Tunnel (L4T) for stripping foil performance tests. Currently that unit is being prepared for commissioning by the end of 2015 and is actually used as a test bench for the final validation of the mechanical and electrical system. As part of the Linac4 injection scheme for the PSB, the stripping foil exchange units need to be ready by the end of 2016 for an installation during LS2 (Long Shutdown 2) at the latest. The installation of two units, a definite one in the (L4T) and a temporary one as part of the half-sector test [6] scheduled in 2016, will provide us with useful experience that might require some improvements.

REFERENCES

[1] Gerigk F, Vretenar M et al, Linac4 technical design report, CERN-AB-2006-084.

[2] W. Weterings, B. Balhan et al, Status of the 160 MeV H$^-$ Injection into the CERN PSB, CERN-ATS-2012-212.

[3] W. Weterings, C. Bracco et al, The stripping foil test stand in the Linac4 transfer line, J Radioanal Nucl Chem (2015).

[4] A. Ferrari, P.R. Sala, A. Fasso, and J. Ranft, FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[5] R. Froeschl, Activation of the stripping foils of the future H$^-$ charge exchange injection into the PS Booster, CERN–RP–2015–048–REPORTS–TN.

[6] Chamonix 2014 Workshop on LHC Performance, Chamonix, France, 22-25 September 1014, CERN-2015-002.