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NUMBER OF TURN MEASUREMENTS ON THE HIPA CYCLOTRONS AT PSI

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Abstract

The number of turns is an important parameter for the tuning of a cyclotron, in particular for high intensity machines such as the 1.4 MW High Intensity Proton Accelerator (HIPA) facility. Up to recently, the number of turns for HIPA had to be measured using radial probes which can only be used during beam development shifts. The on-line estimate of the number of turns during normal operation is presently based on the acceleration voltage measurements, with the inherent limited precision of RF measurements.

A new scheme based on Time of Flight (ToF) measurements has been deployed on the two cyclotrons of HIPA, which removes the limitations of the previous techniques. It is based on the cross-correlation of fast sampled data from pickups located at the entrance and at the exit of the cyclotrons. For the first cyclotron, called Injector 2 (accelerating the beam from 870 keV to 72MeV), the beam had to be externally modulated whereas, for the Ring Cyclotron (72 MeV to 590 MeV), no external modulation was needed. This paper presents the details of both implementations on the HIPA cyclotrons.

INTRODUCTION

At the 1.4 MW high intensity proton accelerator facilities (HIPA) at PSI, the proton beam is accelerated from a Cockcroft-Walton source followed by two cyclotrons: the so-called Injector 2 cyclotron accelerating the beam from 870 keV to 72 MeV and the so-called Ring cyclotron accelerating it to 590 MeV.

For such high power machine, beam tuning is very important to minimize the losses. One of the crucial parameters to be set correctly is the number of turns in the cyclotrons; this parameter can change in particular after a long maintenance period.

Up to recently, the number of turns for HIPA had to be measured using radial probes. A handicap of such measurements is that they can be performed only during dedicated beam development time. An on-line estimate of the number of turns during normal operation is presently based on the acceleration voltage measurements, with the 1-2% inherent limited precision of RF measurements.

A new scheme based on the Time of Flight (ToF) measurements has been developed to remove the limitations of the previous techniques. The ToF is deduced by comparing the fast sampled signals from capacitive pickups at the entrance and exit of each cyclotron.

MEASUREMENT SETUP

Measurement Hardware

Capacitive pickups that are usually dedicated to the phase measurements in the cyclotrons have been used. The pickup signals have been recorded using a Teledyne-Lecroy HDO6104 1GHz scope with 12-bit resolution.

Machine Setup

A major difficulty into performing ToF measurements with a cyclotron accelerator is that the raw signals to be measured possess the periodicity of the RF for the proton beam acceleration. By adding an external modulation on the beam, it is possible to following the disturbance along the beam line. For the Inj.2 cyclotron a 500 Hz on/off modulation with a duty cycle of 1% was performed with a diverting magnet. In the case of the Ring machine, the proton bunches were enough different from each other to allow a time delay measurement without external modulation.

Signal Processing and Time Delay Measurements

Waveforms up to 2.5 10^6 points sampled at a frequency of 2.5GHz with 12 bit resolution were recorded with the scope. These waveforms were then analysed off-line using MATLAB for the preliminary analysis. LabVIEW was used for the on-line measurements (see next section).

The signal processing consists first of the envelope detection of each capacitive pickup signal before cross-correlating the envelopes. The delay corresponding to the cross-correlation maximum provides then an estimate of the ToF. Without the envelope pre-processing, the cross-correlation on the raw data would just deliver maxima at time differences corresponding to the repetition rate of the pulses (~50.6MHz).

Number of Turn Determination

The number of turns is the ratio between the effective time spent by a proton bunch in the cyclotron $T_{cyclotron}$ and T_{rev}, the time for a proton bunch to perform one revolution:

$$n_{turn} = \frac{T_{cyclotron}}{T_{rev}}$$

The revolution time T_{rev} is given by:

$$T_{rev} = \frac{h}{f_{RF}}$$

where h being the harmonic number, i.e. the number of bunches on a given turn. For the Ring, h is 6 and for the Inj.2 its value is 10, with respectively a time needed for one turn of 118.7 ns and 197.5 ns.

$T_{cyclotron}$ is obtained from the measured time delay with a correction ΔT_{cable} due to the length difference of the cables used for the measurements. An additional correction Δn_{pickup} is needed to compensate the position of the

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pickups which differ from the exact entrance and exit of the beam:

$$n_{turn} = \frac{\left(T_{measured\ delay} - \Delta T_{cable}\right).f_{RF}}{h} - \Delta n_{pickups}$$

Set-up for Online Implementation

Figure 1 shows the set-up for normal operation of the cyclotron, with the scope remotely controlled from a PC.

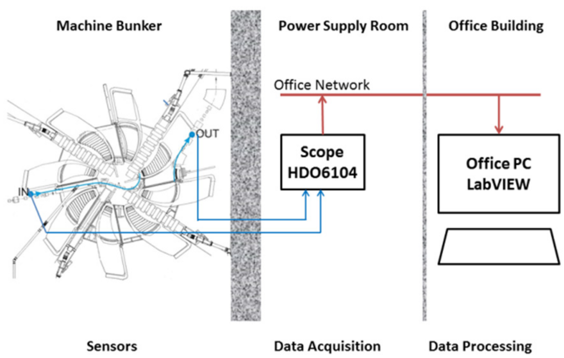

Figure 1: Set-up for online measurements.

OFF-LINE MEASUREMENTS

Ring Cyclotron Results

A simple maximum detection method was used for the envelope calculation in the case of the Ring cyclotron data. The cross-correlation results exhibit a single peak The maximum of cross-correlation between the Ring cyclotron entrance and exit capacitive pickup envelopes corresponds to a delay of 21.488µs (Fig. 2). No beam modulation was performed and yet the cross-correlation delivers an unambigous result, just one point rises from the cross-correlation envelope.

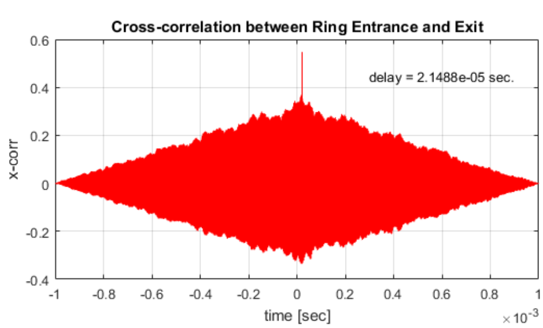

Figure 2: Ring cyclotron cross-correlation results.

With the corrections for the Ring setup configuration i.e. ΔT_{cable} = 44n and $\Delta n_{pickup} \cong 1$:

$$n_{turn} \cong \frac{\left(T_{delay} - 4.4\cdot10^{-8}\right)\cdot 50.6328\cdot10^{6}}{6} - 1 = 179.96 \cong 180$$

This result is consistent with the standard measurements using the radial probes.

Injector 2 Cyclotron Results

Cross-correlation of pickup signals for unmodulated beam conditions didn't give any meaningful result for the Injector 2 cyclotron. The pulses seemed to be too identical to allow a ToF measurement. For this reason a 500 Hz on-off modulation with a duty cycle of 1 % was applied on the proton beam using the AVKI diverting magnet (Fig. 3).

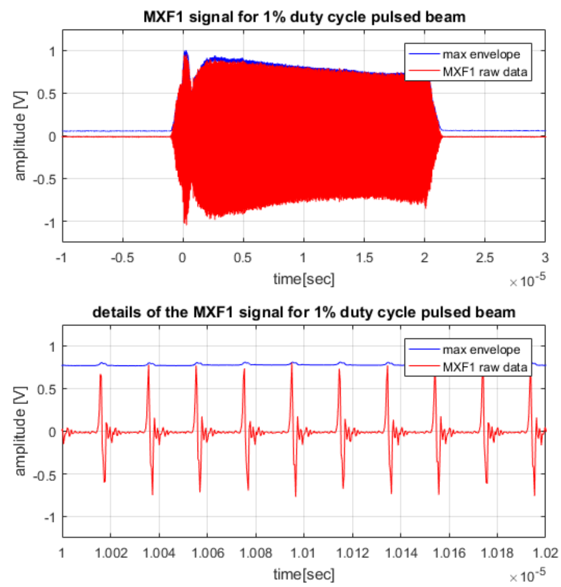

Figure 3: Time evolution of the MXF11exit pickup signal for 1% duty cycle beam operation. The upper plot shows the signal during one "on"- period. The lower plot shows the fine time structure within that period. The blue line is the envelope of the raw data (red line).

A Hilbert transform was applied for the envelope measurement of the Injector 2 cyclotron data. As expected, the cross-correlation with such periodic signals exhibits the same 500 Hz modulation periodicity (Fig. 4). However, there is no ambiguity about the peak selection since the 20 µs long proton bunch trains need about 16 µs to transit through the Injector 2 cyclotron, a time much shorter than the 2 ms modulation periodicity. Furthermore, the corresponding peak has the highest cross-correlation value.

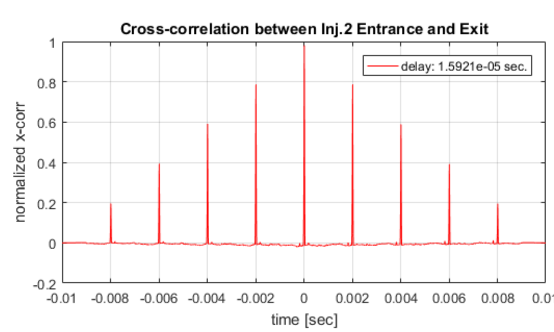

Figure 4: Injector 2 cyclotron cross-correlation results with beam modulation.

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The maximum peak width is however larger than the time corresponding to one delay, with a slight change of the slope at the times corresponding to ±1 turn (Fig. 5).

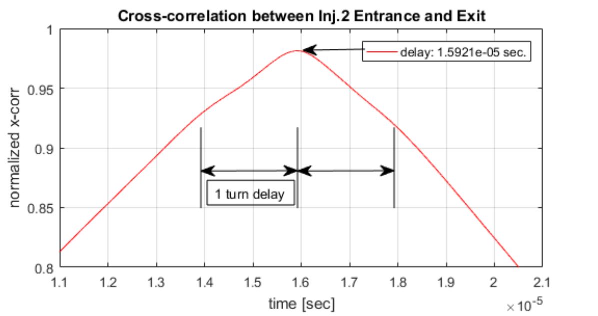

Figure 5: Details of the Inj.2 cross-correlation results around the peak maximum.

Note that the time delay determined with this technique can be checked by displaying the pickup signals as measured and with the timed delay compensation (Fig. 6).

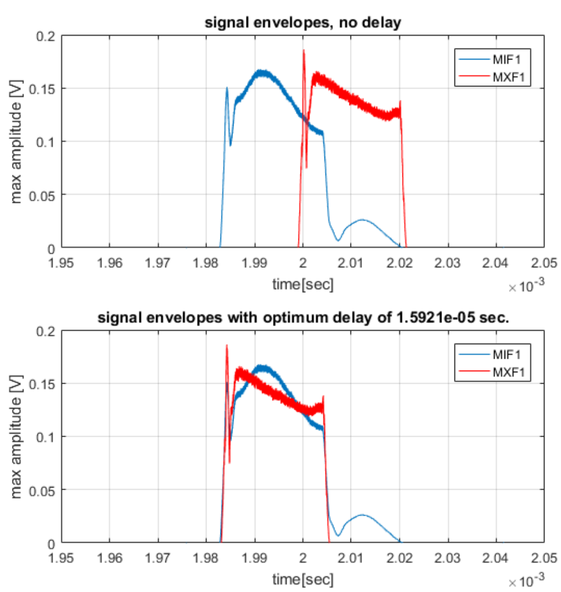

Figure 6: The upper plot shows envelopes of the same train as measured by the entrance (blue line) and exit (red line) pickups. The lower plot shows the same two envelopes, the one from the exit pickup being moved by the cross-correlation time delay.

With the corrections for the Inj.2 setup configuration i.e. $\Delta T_{cable} = 6.9$ ns and $\Delta n_{pickup} \cong 4\text{-}5$:

$$n_{turn} \cong \frac{\left(T_{delay} + 6.9 \cdot 10^{-9}\right) \cdot 50.6328 \cdot 10^{6}}{10} + 4 = 84.65$$

This number is not close to a integer. This may be attributed to the fact that the entrance pickup for the Injector 2 cyclotron is already located in the cyclotron and the measured signal cannot be attributed to a single turn, the pickup being actualy located between two circular trajectories (4th and 5th) of the proton beam. The measured entrance signal should then be a combination of the 4th and 5th turn signals. The contribution from proton bunches laying on different turns also explains the cross-correlation width. With this conjecture, the number of turns in the Injector 2 cyclotron that can be deduced from these measurements is between 83 to 85.

IMPLEMENTATION FOR NORMAL BEAM OPERATION

LabVIEW has been used for the remote control of the scope and the signal processing of the recorded data. The envelope detection before the cross-correlation has been performed with a specific LabVIEW virtual instrument (Fig. 7).

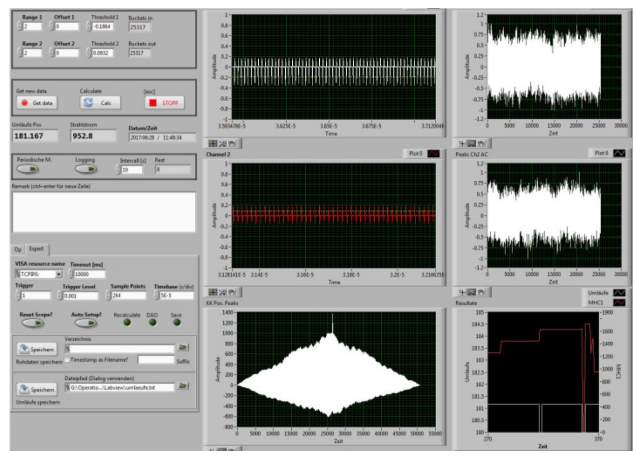

Figure7: LabVIEW GUI for the on-line measurements.

The cross-correlations obtained are similar as those obtained with MATLAB.

DISCUSSION

The maximum of cross-correlation between the Ring cyclotron entrance and exit capacitive pickup envelopes allows an unambigous measurement of the number of turns. This estimate is obtained without beam modulation and this allows a continous measurement during beam operation. For the Injector2cyclotron, the major difficulty was the position of the entrance pickup which is located within the cyclotron. Only a on-off beam modulation made the ToF measurement possible. The width of the cross-correlation maximum peak is rather large and makes the measurements less precise than for the Ring cyclotron. The installation of a capacitive pickup before the Injector 2 cyclotron may solve this problem. The possibility to superimpose a small amplitude modulation on the proton source will be investigated.

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