BEAM-LINE DIAGNOSTICS AT THE FRONT END TEST STAND (FETS), RUTHERFORD APPLETON LABORATORY, OXFORDSHIRE, UK

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Abstract

The H^- ion source and beam-line at FETS will require the beam current and beam position to be continually monitored. Current transformer toroids will measure the beam current and beam position monitors (BPMs) will determine the beam position. The ion source delivers pulses at a rate of 50 Hz with a current up to 60 mA, each pulse is 2 ms long, and a 324 MHz micro-bunch structure imposed by the radio frequency quadrupole (RFQ) accelerating structure. The toroid outputs will be acquired on a fast oscilloscope. Two BPM designs are under consideration (shorted strip-line or button type) but the processing for both types is similar and has been designed, with simulated measurements made. Each BPM uses four pickups, at a frequency of 324 MHz, which are mixed using RF electronics to an intermediate frequency of 10.125 MHz. The resulting signals are then digitized at 40.500 MHz and processed in an FPGA to produce the position and phase of the beam at each BPM location, with a precision of better than 100 µm and 0.05 rad. The measurements from the toroids and BPMs will be available via EPICS servers at every pulse.

FETS BEAM-LINE

The ion source delivers pulses up to 2 ms in length with energy of a few tens of keV. After the ion source and post acceleration is the beam-line as shown in Fig. 1. The beam-line consists of a low energy beam transport (LEBT), diagnostics vessel, radio-frequency quadrupole (RFQ) and medium energy beam transport (MEBT). The MEBT contains focussing quadrupoles, re-bunching cavities, fast and slow beam choppers, BPMs and a laserwire emittance scanner [1, 2]. A number of toroids are located along the length of the beam-line. The LEBT has been built and has run successfully [3]. The RFQ and MEBT, along with the relevant diagnostics, will start to be installed in summer 2014. The 2 ms bunch is accelerated in the RFQ to 3 MeV with a 324 MHz bunch rate.

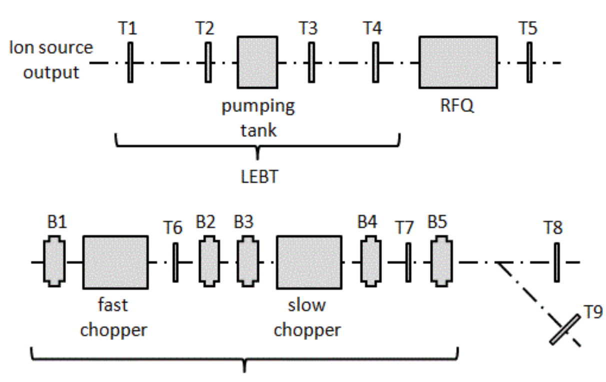

Figure 1: FETS Beam-line schematic.

TOROIDS

A suite of nine conventional AC current transformer toroids, eight of which have been designed, constructed and tested in-house, will be used to measure the beam current at various locations along the beam-line. The toroids have varying response times according to the pulse parameters at its location as described in Table 1. The toroid immediately after the ion source is a Bergoz ACCT with a very fast response. Fig. 2 shows one of the toroids built in-house for use in the MEBT.

Table 1: Toroid Locations and Parameters

Toroid	Location	t_r	Droop	ID
T1	Ion source Output	0.35µs	<2 %/ms	82 mm
T2	LEBT pumping vessel input	10 µs	1 %/ms	94 mm
T3	LEBT pumping vessel output	10 µs	1 %/ms	94 mm
T4	RFQ input	5 µs	1 %/ms	82 mm
T5	RFQ output	5 µs	1 %/ms	82 mm
T6	Slow chopper beam dump	5 µs	1.2 %/ms	46 mm
T7	Fast chopper beam dump	5 µs	1.2 %/ms	46 mm
T8	Straight-through beam dump	5 µs	1.2 %/ms	46 mm
T9	After-dipole beam dump	5 µs	1.2 %/ms	46 mm

Figure 2: In-house designed and built toroid.

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Toroid Functions

The outputs from toroids T1-T3, T8 and T9 will be displayed on oscilloscopes. The signals from toroids T4-T7 will be digitized using a National Instruments PXI-5152 two-channel 1 GS/s digitizer and the digitized waveforms served via an EPICS IOC. The beam current as measured by toroids T2 and T3 should be identical and any difference will indicate any H^- stripping losses. The current difference between toroids T4 and T5 will indicate the transmission of the RFQ. Toroids T6 and T7 should show notches in the 2 ms macropulse due to the chopping action, although the toroids aren't fast enough to show individual chopped bunches. The final two toroids, T8 and T9, indicate transmission through the dipole and how much power is absorbed by the beam-dumps.

Toroid Evaluation

Two of the toroids built in-house have been tested to determine the rise-time and droop. The results are shown in Fig. 3 and 4. As can be seen both toroids meet the specification for rise time, but one has a droop of about 3 %/ms, possibly due to a lower than expected core permeability.

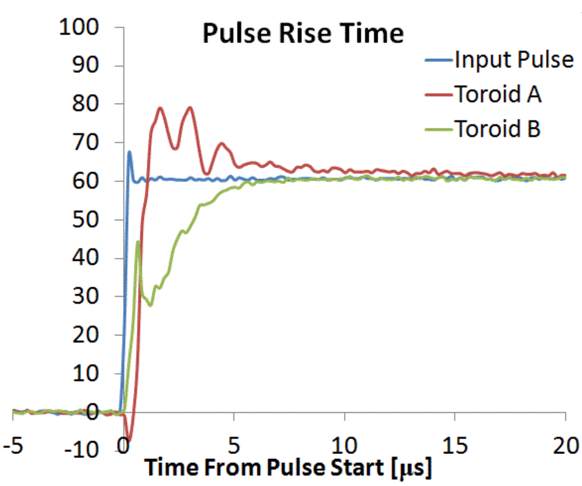

Figure 3: Toroid rise time.

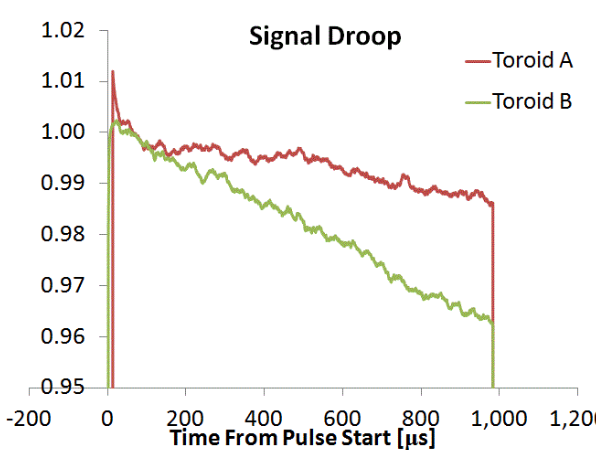

Figure 4: Toroid droop.

Toroids T1-T3 are already installed in the LEBT and have been running for over a year with no problems. More testing of the toroids T4-T9 will take place in the lab before being installed in the beam-line in 2014. In the future it is envisaged to have all toroid outputs digitized and the data served via EPICS IOCs.

BEAM POSITION MONITORS

Each BPM will produce a position of the beam centroid a number of times during the duration of the macro-pulse of 2 ms. Between three and six BPMs are envisaged when the beam-line is completed, depending on the final design of the MEBT. The BPM signals are mixed in analogue front-end electronics before being digitized for processing by a commercial FPGA card running custom software.

BPM Specification

Each BPM is identical, as is its signal processing chain. Each has four electrodes, spaced at 90° apart. The BPM type is still to be decided (button or strip-line) since there are merits to both types. The button-type requires less longitudinal space, but the output signal is lower than a strip-line type. As part of the development of LINAC4, prototypes of several BPM designs have been simulated and tested, an example strip-line BPM is shown in Fig. 5. Since the BPM requirements for FETS and LINAC4 are almost identical the FETS BPMS will be modelled on the LINAC4 design.

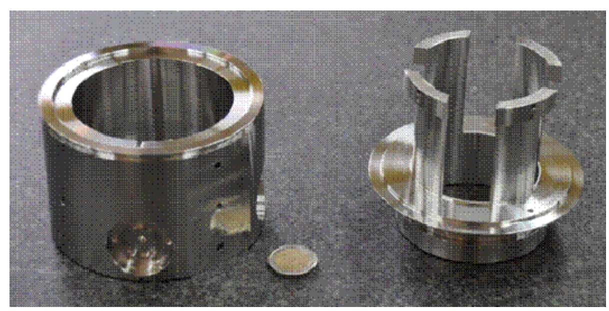

Figure 5: LINAC4 strip-line BPM.

Front-End Electronics

The signal from each BPM electrode is taken to the front-end electronics where it is first amplified and then mixed with a local oscillator (LO) signal of 334.125 MHz to produce an intermediate frequency (IF) signal of 10.125 MHz. The electronics was developed at CERN for use with the LINAC4 BPM system [4]. The LINAC4 RF is 352 MHz and the IF is 22 MHz, whereas the FETS RF of 324 MHz and IF of 10.125 MHz, necessitating some simple changes to the filtering components on the electronics card.

IQ Sampling

A periodic waveform can be sampled at intervals of $\pi/2$ radians (exactly four times its frequency) to produce samples that equate to the in-phase and quadrature components I, Q, -I and –Q, as shown in Fig. 6. The magnitude (V_{peak}) of the signal is given by Eq. 1and Eq. 2.

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$$V_{peak} = \sqrt{I^2 + Q^2} \quad (1)$$

$$V_{peak} = \sqrt{-I^2 + -Q^2} \quad (2)$$

The phase of the signal is given by Eq. and 3 Eq. 4.

$$\phi = tan^{-1}\left({}^{Q}/_{I}\right) \quad (3)$$

$$\phi = tan^{-1}\left({}^{-Q}/_{-I}\right) \quad (4)$$

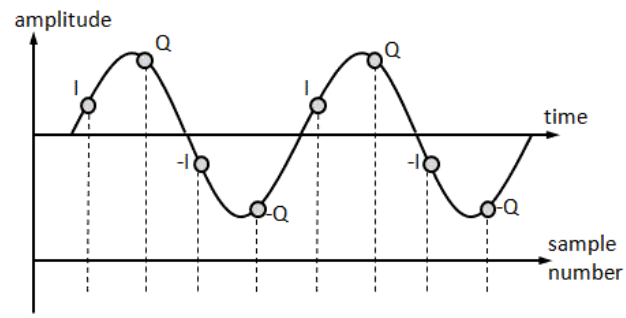

Figure 6: IQ Sampling of waveform.

Processing Hardware

The digitizing and processing of the BPM IF signals is performed by a National Instruments PXI-7954R FPGA card and NI-5752 modular Digitizer card. After evaluating options for processing the BPM signals, this was deemed the most cost effective option whilst retaining the position and phase precision required. The PXI-7954R contains a Xilinx Virtex5 FPGA and can host a variety of front-end modules, including the NI-5752 32 channel 50 MS/s simultaneously sampling digitizer module. The FPGA code is programmed using National Instruments LabVIEW with the FPGA module.

BPM Position Calculation

The position of the beam centroid within the BPM is given by Eq. 5 and Eq. 6.

$$Position_x = k_x * \frac{V_{right} - V_{left}}{V_{right} + V_{left}} \quad (5)$$

$$Position_y = k_y * \frac{V_{up} - V_{down}}{V_{up} + V_{down}} \quad (6)$$

where k_x and k_y are constants and V_{left} etc are the peak –to-peak magnitudes of the respective BPM electrodes. The phase difference between successive BPMs can be used to calculate time-of-flight.

FPGA Algorithm

For each BPM channel (up to 24 in total) the FPGA acquires data from the Digitizer channels at a rate of 40.5 MHz which is then buffered in a FIFO. The FIFO is read at 40.0 MHz and the data passed sequentially into four adder units, representing the I, Q, -I and –Q samples. Each adder output is then divided (right-shifted) by the number of cycles added. The resulting means are passed to a processing block in the FPGA, where the magnitude and phase are calculated. Finally the position for each BPM is calculated. The BPM positions are passed along the PXI bus to the PXI host processor where the data is served via EPICS IOCs. The BPM electrode processing algorithm is shown schematically in Fig. 7. The time to calculate the beam position for each BPM is 3.1 µs when the FPGA is running at 40 MHz. The beam position processing time can be reduced by further pipelining of the stages of calculation, with a target time of below 1 µs.

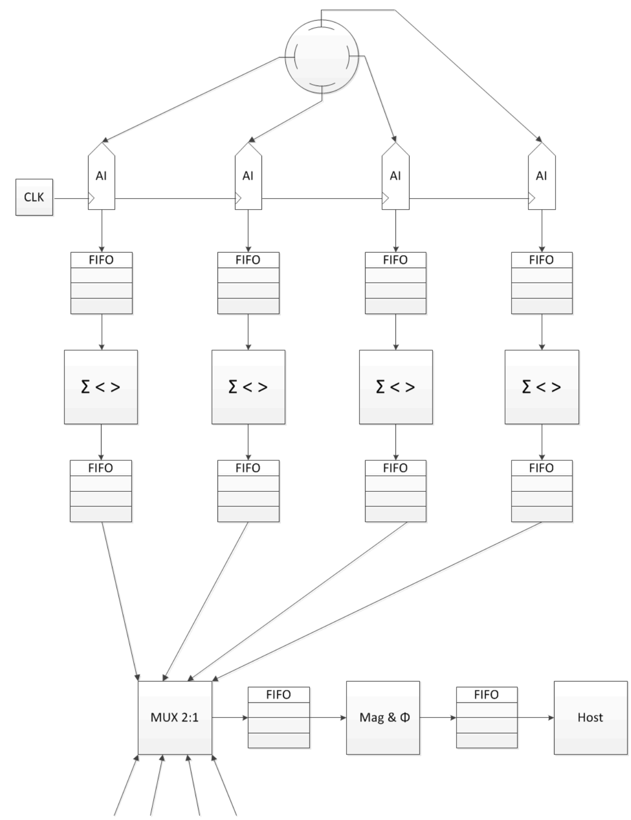

Figure 7: BPM electrode processing in FPGA.

OTHER DIAGNOSTICS

The other main diagnostic on the beam-line is a laserwire emittance scanner [5]. A pulsed laser is focussed and scanned across the H^- bunches to strip electrons, with the resulting neutrals passing into a scintillator, which is viewed by a camera. A small fraction of the laser power is directed to a photodiode and the signal monitored via a digitizer channel on a card in the PXI chassis, in order to determine the laser power hitting each bunch. A slit-slit emittance scanner has been used in the commissioning of the LEBT but will not be part of the final beam-line. Various parameters such as temperatures, voltages etc will also be monitored and the data available via EPICS.

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PXI SYSTEM & EPICS IOCS

The toroid and laserwire emittance scanner data acquisition cards and the BPM FPGA/Digitizer card are housed in an eight-slot PXI chassis. The chassis has a PXI-8106 controller running Windows XP and the LabVIEW development environment. A clock and trigger card for distributing triggers and a 10 MHz reference clock, as well as an eight-channel counter card and also installed. The controller is networked with a 100 Mbit Ethernet connection.

EPICS IOCs

All of the data from the toroid signal acquisition and the BPM position data will be available on for EPICS clients to read. The toroids and BPMs will have their own IOC running on the PXI controller, and a watchdog configured to ensure each IOC automatically starts upon system power-up.

FUTURE WORK

The FETS beam-line will have the RFQ and MEBT installed starting summer 2014. The FPGA code for the BPM processing has been developed and testing has already started using simulated IF signals. When completed, the front-end electronics will be added to the test set-up using BPM-like RF signals. The BPMs will be investigated in a test-jig at CERN, along with the electronics and digital processing, starting late 2013, to determine the constants for the BPM position calculation.

ACKNOWLEDGMENT

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REFERENCES

[1] S. Gibson *et al.*, "Overview of Laserwire Beam Profile and Emittance Measurements for High Power Proton Accelerators", IBIC2013, Oxford, UK
[2] A.Bosco *et al.*, "Description of Laser Transport and Delivery System for the FETS Laserwire Emittance Scanner", IBIC2013, Oxford, UK
[3] J. Back *et al*, "Comssioning of the Low Energy Beam Transport at the Front End Test Stand", IPAC'10, Kyoto, Japan, (2010)
[4] J. Tan *et al.*, "Development of BPMs for the Linac4", Linac4 Instrumentation Review, (2011)
[5] C. Gabor *et al*, "Design of a Photo-detachment Emittance Instrument for FETS", HB2012, Beijing

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