NON-DESTRUCTIVE BEAM POSITION AND PROFILE MEASUREMENTS USING LIGHT EMITTED BY RESIDUAL GAS IN A CYCLOTRON BEAM LINE

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Abstract

A non-destructive beam diagnostic system, based on the measurement of light radiated by beam-excited rest-gas atoms, has been built for beam profile measurements, and tested in the transfer beam line between a K8 injector cyclotron and a K200 separated-sector cyclotron. The equipment, signal processing and results of measurements are discussed.

INTRODUCTION

At iThemba LABS [1] high-intensity proton beams are used for the production of radioisotopes and neutron therapy. A low-intensity beam is used for proton therapy, and for nuclear physics research beams of light and heavy ions, as well as polarized protons, with variable energy, are available. Non-destructive beam position monitors (BPMs) have been developed and installed [2] to monitor beam positions at intensities of up to 700 μA. A beam-induced fluorescence monitor, using a photomultiplier tube (PMT), has been built for non-destructive beam profile measurements and the first results have been reported previously [3]. Several modifications to the experimental setup have been made, new electronic measuring equipment has been built and new data processing methods developed to reduce the background level and to increase the sensitivity and positional resolution of the monitor. The equipment and results of measurements on 3.14 MeV and 8 MeV proton beams are described in the following.

THE EXPERIMENTAL SETUP

The section of the beam line in which the PMT has been installed is shown schematically in Fig. 1. The two BPMs, that are used for alignment of the beam from the light-ion injector cyclotron to an accuracy of about 1 mm, are 1.15 m apart. A profile grid with a wire spacing of 1 mm was installed for verifying measurements that were made with the PMT. A rotating-wire scanner was also installed since the profile grid can only be used up to a maximum beam current of 1 μA at the position at where it was installed. The PMT is a Hamamatsu model H7260 linear array with 32 photocathodes, spaced at 1 mm intervals, with a width of 0.8 mm each. The focal length of the lens is 100 mm. With the magnification factor of 0.4 the width of a photocathode corresponds to a transverse distance of 2.5 mm at the beam position.

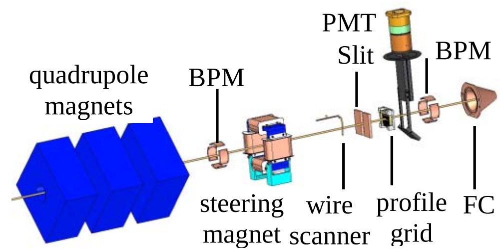

Figure 1: Schematic layout of the section of the beam line with the PMT.

Fig. 2 illustrates some of the measures that were taken to prevent light reflected from the inside of the diagnostic vacuum chamber and the tube and lens support, to reach the photocathodes. The inside of the chamber was blackened. A diaphragm, 10 mm long in the direction of the beam, and 60 mm wide perpendicular to the beam direction, was installed inside the chamber to allow only light from a cross-section of the beam to pass through the glass window. A blackened plate was installed at an angle below the beam to reflect light, which is not absorbed on its surface, away from the glass window. It was additionally found necessary to install another diaphragm, not shown in Fig. 2, on top of the glass window to further prevent light, not directly originating from the rest gas, from reaching the photocathodes.

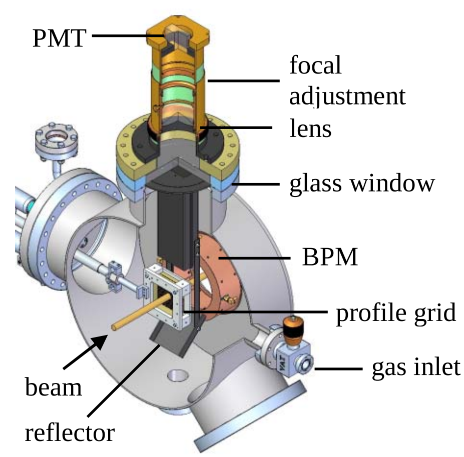

Figure 2: The main components in the diagnostic vacuum chamber on which the PMT is installed.

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Coaxial cables from the PMT and the profile grid were connected through a previously developed multiplexer to the current measurement electronics. The signal from the rotating-wire scanner was displayed on a digital oscilloscope.

ELECTRONIC EQUIPMENT

Fig. 3 shows a block diagram of the electronic equipment for current measurement. It consists of an integrating 48 channel module, that measures from 10 pA to 100 µA in 6 variable ranges, with a maximum conversion time 200 ms. The integrators convert the currents into voltage values. An accuracy of 1% of the full scale value and a resolution of 1 pA on the most sensitive range are obtained. The input voltage offset is ±0.5 mV and average drift is ±1 µV/°C. Input current zero-point adjustment is done with software. A gain adjustment is available for the ADC. The module measures current at virtual earth potential.

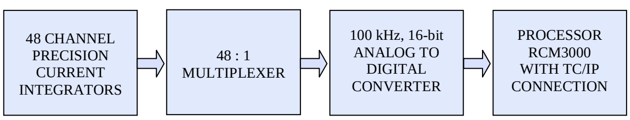

Figure 3: Functional diagram of the equipment for current measurement.

The equipment is designed around the ACF2101 integrated circuit from Burr Brown. The ACF2101 is a dual-switched integrator for precision applications. Each channel can convert an input current to an output voltage by integration, using either an internal or external capacitor. Included on the chip are precision 100 pF integration capacitors, hold and reset switches, and output multiplexers. The ranges are obtained by changing the integration times. Rejection of 50 Hz is obtained by using integration times equal to multiples of 20 ms. For shorter integration times two samples are taken 10 ms apart and averaged.

An external 48-channel multiplexer is used, since the on-chip switches are used for input switching. Integration is done in parallel whereafter the integrators are put in the hold mode. A 16-bit ADC digitizes the channels sequentially. The conversion time for 48 channels is about 1 millisecond. These values are stored and sent as a single packet at the end of the full conversion.

A Rabbit 3000-series processor is used onboard for control. The Rabbit is a low EMI processor that can be used when measuring low currents for beam diagnostics. This characteristic is due to the split power supply, the clock doubler, the clock spectrum spreader and good printed circuit board layout. The board is connected via a TCP/IP socket to a PC that is used to display the data.

CONTROL AND DATA PROCESSING

The Rabbit microprocessor communicates with the hardware using general purpose IO and SPI signals. From there the microprocessor communicates over the network using TCP/IP to send the data to the PC and to receive instructions from the PC. On the PC is a program written in C# DotNet. The user interface part of the program and the DotNet Library, called Srabbit, communicates with the Rabbit and processes the incoming data so that it can be displayed.

The Rabbit also calibrates the ADC upon start-up. This is done by reading a reference ground and 2.5 V values and also to read all the channels in their reset states. This way more accurate measurements can be made. After integration the Rabbit reads the voltages on all 48 integrators twice and sends the ADC values and also the integration time back to the PC using the TCP/IP connection.

The code on the Rabbit microprocessor is written in dynamic C and requires version 9.50 or later to execute properly. Large parts of the embedded code are written in embedded assembler. This is done to produce faster code. The assembler code also gives much better control over timing and exactly what happens in the microprocessor. The DotNet programming library communicates with the Rabbit using TCP/IP and processes all information obtained from the Rabbit. It also sends commands back to the Rabbit and tells the Rabbit to start and stop reading the currents.

When the data is received from the Rabbit microprocessor, it is still in the raw 16-bit ADC format. Combining the ADC value and the integration time while still remembering the calibration values and also, if available, the channel offset values, the current value is calculated in ampere, since the integration time is very accurate. The Rabbit microprocessor controls the integration of the currents and reads the ADC. All processing of information happens on the PC. From here the values can be displayed in text or graphic form.

There are 120 different ranges for current measurement. The ranges are very close to each other and overlap largely. This way an appropriate range can easily be selected for any operating condition. Apart from calibrating the ADC, using the reference GND and 2.5 V values, the program can also read the offsets on every channel and subsequently subtract them from the read values. In this case the Rabbit microprocessor continues as normal but the software library on the PC will store the read values as offset values. These values are subtracted from the read values. In a running system there are both voltage and current offsets that behave differently in the system. Current offsets stay the same regardless of the integration time while voltage offsets result in an offset in the displayed current that changes with the integration time.

The offsets are calculated at every 5th integration time intervals. This means about 20 ranges are read during the offset calibration step. The average value of the number of samples influences how the ranges are read and therefore the accuracy of the resulting offset calibration. Then at runtime, linear interpolation is used to find the correct offset to subtract from the value read. This is all done according to integration time and not according to the scale value.

RESULTS OF MEASUREMENTS

All the measurements were made at the maximum PMT operating voltage recommended by the manufacturer to obtain the greatest sensitivity. No noise or dark current from the PMT could be detected as the cathode voltage was increased from zero to the final value of 800 V. For a 3.14 MeV proton beam the gamma-ray background is negligible except when an appreciable fraction of the beam is intercepted on the slit directly in front of the PMT or when the beam is stopped on the Faraday cup 0.43 m downstream from it. At 8 MeV the PMT had to be shielded or the gamma-ray background removed with the software.

The lowest beam current at which the beam position could be measured, at the normal operating pressure of 10^{-5} mbar, is 0.5 μA. Fig. 4 shows that the sensitivity increases linearly with a factor of 44 for a pressure increase in the chamber from 10^{-5} mbar to $7.8 \cdot 10^{-5}$ mbar.

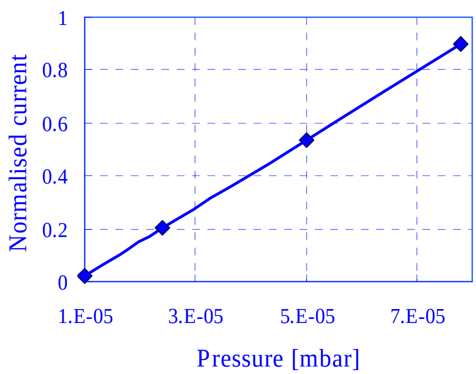

Figure 4: The peak current in the beam profile of a 3.14 MeV proton beam, measured with the PMT, as a function of the pressure in the vacuum chamber.

In Fig. 5 beam positions measured with the profile grid, the PMT and the BPM, all in the same diagnostic vacuum chamber with an overall length of 190 mm, are shown for different currents through the steering magnet.

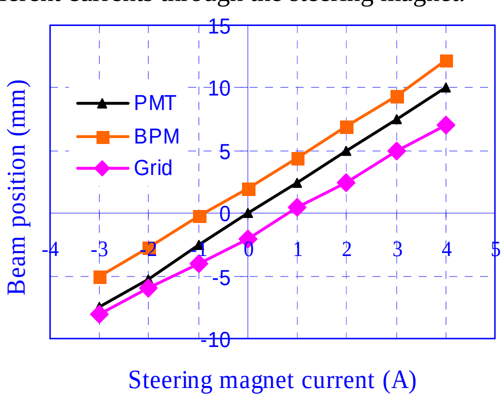

Figure 5: Beam position measurements with the profile grid, the PMT and the BPM deliberately displaced by 2 mm to show the tendency.

Fig. 6 shows the beam profiles measured at the PMT and slit positions, which are 257 mm apart, with the flat-topping system of the injector cyclotron switched off. A circular aperture of 8 mm in the diaphragm on top of the glass window was used for the PMT measurement with a fully open slit. The second profile was determined by measuring the current on the Faraday cup for different positions of the slit with a 1 mm gap. The width difference in the two profiles is mainly due to the fact that the beam diverges in the region where the profiles were measured. For a slit gap of 1 mm the PMT display shows a signal on only one of the 32 channels.

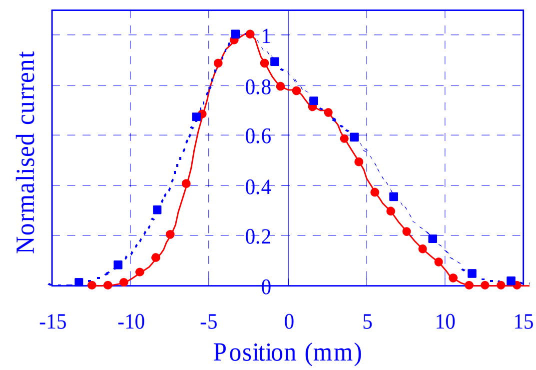

Figure 6: The profile of a 420 μA, 3.14 MeV proton beam measured at the slit position (solid line) and with the PMT.

CONCLUSIONS

The method works well for beam position and profile measurements. The accuracy of about 2 mm that can be achieved for beam position measurements is limited by the optical arrangement. A sensitivity of 0.5 μA could be achieved for a 3.14 MeV proton beam at the normal operating pressure of 10^{-5} mbar. The sensitivity can be increased by increasing the pressure in the chamber. This is not always practical since rebunchers in the beam line require an operating pressure of not more than 10^{-5} mbar. With an adjustable iris in the diaphragm above the glass window it would be possible to choose either position measurement accuracy or sensitivity. At high energies the PMT has to be shielded from gamma rays. Great care has to be taken to eliminate stray light that distorts the beam pattern and ionisation pressure gauges should be mounted at an angle on the vacuum chamber to prevent unwanted light from reaching the PMT.

REFERENCES

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