Abstract

The time-structure monitor at the last turn of the 72 MeV Injector-2 cyclotron has been improved in order to meet the stringent time-resolution requirement imposed by the short bunch length. Protons scattered by a thin carbon-fibre target pass through a first scintillator-photomultiplier detector and are stopped in a second one. The longitudinal bunch shape is given by the distribution of arrival times measured with respect to the 50 MHz reference signal from the acceleration cavities. From a coincidence measurement, the time resolution of the detectors has been determined to be 51 ps and 31 ps fwhm. Longitudinal and horizontal bunch shapes have been measured at beam currents from 25 µA to 1700 µA. Approximately circular bunches were observed with diameter increasing with current. The shortest observed proton bunch length was 38 ps fwhm.

1 INTRODUCTION

Time-structure measurement has been used at PSI since 1974 and has delivered valuable information during the commissioning of Injector 2 and at the introduction of the buncher in the injection line to Injector 2 [1 - 6]. Due to the buncher, the bunch length inside the cyclotron was reduced from ~15° fwhm of RF period to below 5° and it was not clear if the resolution of the time-structure monitor was still sufficient to resolve the bunch shape. In the end of 2000 a new double detector set-up based on NE111 scintillators and Hamamatsu R7400 metal package PMTs with custom divider circuits was tested, which allowed for the determination of the time resolution.

2 EXPERIMENTAL SET-UP

The monitor is located half a turn in front of the beam extraction in the space between two sector magnets. A carbon fibre of 30 µm diameter is moved transversally through the beam by a motorised feedthrough (Fig. 1). The detectors are located above, behind a 0.5 mm stainless steel window and a stainless steel aperture of 4.5 mm diameter. Scintillator A (a 8x8x16 mm³ piece of NE111) is separated from scintillator B (8x8x40 mm³ from the same piece of raw material) by a 12 µm aluminium foil which also covers the surface opposite to PMT A in order to enhance light collection. Both PMTs are coupled to the scintillators by silicon grease.

An overview of the electronic set-up and modes of operation is given in Fig. 2. The output signals from the PMTs are transmitted through approximately 80 m of 50 Ω Cellflex LCF ½" cable to the control room. After passing an ohmic divider, one part of the signal is fed to an Elscint STD-N-1 snap-off timing discriminator (SOD) [7] and the other part is used for pulse height discrimination. Besides the elastically scattered protons, there are protons with lower energy from inelastic scattering at the carbon fibre and from scattering at the aperture, which arrive later. Hence, only the highest pulses at PMT B correspond to the correct timing information, and pulse height discrimination is necessary. This is provided by a SIN-FDD100 leading edge discriminator (LED). For a time-structure measurement with PMT B, the fast timing signal of SOD B is allowed to proceed as the start signal to a Canberra 2043 time-to-amplitude converter (TAC) if the pulse height of PMT B surpasses a defined high level. Gating is provided by a SIN-FC107B logic module. The stop signal is derived from the 50 MHz RF-reference signal by a SIN ZCD100A zero-crossing detector and gated in the same way. If the probe is positioned at the centre of a 1600 µA beam, the rate of accepted pulses is of the order of 250 cps.

If the time structure is measured with PMT A, pulse height discrimination is done also with the PMT B signal.
3 RESULTS AND DISCUSSION

3.1 Non-linearity of pulse height and charge

The height and shape of the highest PMT output pulses, corresponding to elastically scattered protons, were measured with a fast oscilloscope. The dependency of pulse height and pulse charge $Q_{\text{pulse}}$ on the PMT supply voltage $U_{\text{PMT}}$ is given in Fig. 3. The non-linear behaviour at higher supply voltages can probably be attributed to space-charge forces resulting from the high pulse current density at the last dynodes. No dependency of pulse height on pulse rate was observed.

3.2 Estimation of the number of photoelectrons

The gain of the individual PMT is determined from the ratio of anode and cathode luminous sensitivities provided by the manufacturer. The quantities of photoelectrons generated at the photocathodes of the individual PMTs 1 and 2 at positions A and B in response to elastically scattered protons were determined according to Fig. 3. This was repeated after interchanging the PMTs (Table 1). The higher numbers with PMT 2 reflect its higher quantum efficiency.

Table 1: Quantities of generated photoelectrons.

<table>
<thead>
<tr>
<th></th>
<th>PMT 1</th>
<th>PMT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>serial number</td>
<td>AD7126</td>
<td>AD7266</td>
</tr>
<tr>
<td>cathode</td>
<td>anode luminous sens.* [µA/Im] [9]</td>
<td>56.9</td>
</tr>
<tr>
<td>individual gain*</td>
<td>33.3</td>
<td>21.2</td>
</tr>
<tr>
<td>$N_{\text{PE}}$ at position A</td>
<td>585000</td>
<td>323000</td>
</tr>
<tr>
<td>$N_{\text{PE}}$ at position B</td>
<td>1927</td>
<td>2173</td>
</tr>
<tr>
<td>4900</td>
<td>5500</td>
<td></td>
</tr>
</tbody>
</table>

* at $U_{\text{PMT}} = -800$ V

3.3 Estimation of time resolution

The time resolution of detectors A and B can be deduced from the width $t_{\text{AvsB}} = 60$ ps of the coincidence spectrum measured according to Fig. 2, mode III. From the separation

$$t_{\text{AvsB}}^2 = t_{\text{loc,A}}^2 + t_{\text{det,A}}^2 + t_{\text{det,B}}^2 + t_{\text{elo}}^2$$

$N_{\text{PE}} = Q_{\text{pulse}} / (e * \text{gain})$ with $e$ the electron charge.

$N_{\text{PE}}$ follows with $N_{\text{PE,A}}, N_{\text{PE,B}}$ from Table 1 (PMT 1 at position A, PMT 2 at position B).
The resolution of the time-structure measurement with detector A or B can be calculated according to
\[ t_{\text{resol,B}} = \sqrt{t_{\text{det,B}}^2 + t_{\text{elo}}^2 + t_{\text{ref}}^2} = 35 \text{ ps} \]  
(5)
\[ t_{\text{resol,A}} = \sqrt{t_{\text{det,A}}^2 + t_{\text{elo}}^2 + t_{\text{ref}}^2} = 53 \text{ ps} \]  
with \( t_{\text{ref}} \), the jitter of the RF-reference signal, assumed to be negligible.

Similarly, the width \( t_{\text{TS}} \) of a time spectrum measured according to Fig. 2, mode I or II is separable as
\[ t^2_{\text{TS}} = t^2_{\text{bunch}} + t^2_{\text{resol}} \]  
(6a)
The bunch length \( t_{\text{bunch}} \) can be derived by Eq. (6a) from the measured \( t_{\text{TS}} \) and known \( t_{\text{resol}} \) (6b). Alternatively, \( t_{\text{resol}} \) can be deduced from the measured \( t_{\text{TS}} \) and the known \( t_{\text{bunch}} \) (6c).

Short bunch lengths measured according to Eq. (6b) with detectors A and B agree well, thereby corroborating the above derived values of time resolution.

Fig. 4 compares the derived time resolution, according to Eq. (4), to that of other experiments. Also the performance of the former set-ups of the time-structure monitor at Injector 2 is estimated from Eq. (6c) using \( t_{\text{bunch}} \) determined with the present set-up. The inferior time resolution is probably mainly due to the electronic components used at that time.

Fig. 5: Bunch length (accord. to Eq. (6b)), and width at the last turn of the Injector-2 cyclotron. (PMT 2 at position B was used. \( U_{\text{PMT}} \) in the range -700 V … -850 V.)

4 CONCLUSION

The time resolution of the time-structure monitor has been determined by a coincidence measurement. It has been improved significantly by using a set-up with enhanced light-collection efficiency, an advanced PMT (and divider circuit) and improved electronics. The detector is compact and the PMT offers an enhanced immunity to magnetic fields. Hence, a moving detector covering nearly all turns of Injector 2 seems feasible.

REFERENCES

[14] T. Mashimo, International Center for Elementary Particle Physics, Univ. of Tokyo, private communication