The design of MICE TOF0 detector

M. Bonesini

Sezione INFN, Milano, Italy
Dipartimento di Fisica G. Occhialini, Piazza Scienza 3, Milano, Italy

on behalf of the MICE TOF group

In this note the design of the TOF0 time-of-flight station is outlined, as endorsed by the MICE TP Board. Both the mechanics layout, the tests done for the detector components (PMTs, scintillators, lightguides, ...) and the preliminary design of the front-end electronics are described in detail. A detector calibration scheme based on impinging beam muons and a fast laser monitoring scheme is shown. A complete description of testbeam results on detector prototypes at the Frascati BTF will be the subject of a separate report.
Contents

1 Introduction 1
  1.1 Working environment for TOF stations. 1
  1.2 The physics requirements for TOF stations. 2
2 Global design of TOF0 detector 3
  2.1 Single scintillator counter layout 3
  2.2 General layout for TOF0 5
3 Tests on TOF0 elements 6
  3.1 Tests on lightguides 7
  3.2 Tests on Hamamatsu R4998 PMTs 8
  3.3 Tests on single scintillator counters with an MCA at the BTF 18
4 Readout electronics. 19
5 Calibration issues 21
  5.1 Calibration with impinging beam muons 21
  5.2 The laser calibration system 21
6 Conclusions 23

References 24
1 Introduction

In the MICE experiment, precision timing measurements are required to relate the time of the incoming beam muons to the phase of the accelerating field in each RF cavity and simultaneously for particle identification (PID) by a time-of-flight (TOF) method. Three time-of-flight detectors (TOF0, TOF1, TOF2) are foreseen. The last two (TOF1/TOF2) are at the entrance and the exit of the MICE cooling channel; the first one (TOF0) instead is placed \(\sim 10\) m upstream of its entrance. Figure 1 shows a layout of the full cooling channel with the foreseen positions of the TOF detectors. This note will review the current status of the TOF0 design.

Fig. 1. Layout of the full MICE cooling channel, with the TOF detectors positions.

1.1 Working environment for TOF stations.

The first TOF0 station will work in the fringe field of the Q6 quadrupole magnet. Estimations of the \(\mathbf{B}\) field from [1] give a value well below 50 Gauss. The estimates of the incoming particle rate are shown instead in tables 1 and 2. The other two TOF stations (TOF1/TOF2) will work in the stray fields of the measuring solenoids with
a magnetic field up to 0.1-0.15 T, depending on the design of the global shieldings \(^1\)

The incoming particle rate is still reported in table 1. Therefore the TOF0 detector must work in a small residual magnetic field with a high incoming particle rate.

<table>
<thead>
<tr>
<th></th>
<th>LAHET</th>
<th>GEANT4</th>
<th>MARS</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF0</td>
<td>1722</td>
<td>1762</td>
<td>1508</td>
<td>1664</td>
</tr>
<tr>
<td>TOFI</td>
<td>813</td>
<td>832</td>
<td>712</td>
<td>786</td>
</tr>
<tr>
<td>TOFI</td>
<td>627</td>
<td>641</td>
<td>549</td>
<td>606</td>
</tr>
<tr>
<td>Good (\mu^+/s)</td>
<td>621</td>
<td>635</td>
<td>544</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 1
Rates (singles per ms) with a reduced target insertion to get 600 good \(\mu^+/s\) (AUG05 beamline simulation), from [2].

<table>
<thead>
<tr>
<th></th>
<th>1(\pi \text{ beam})</th>
<th>6(\pi \text{ beam})</th>
<th>10(\pi \text{ beam})</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF0 rate (MHz)</td>
<td>1.8</td>
<td>2.1</td>
<td>1.54</td>
</tr>
<tr>
<td>TOF0 (r_{ms_x}) (cm)</td>
<td>3.29</td>
<td>3.5</td>
<td>3.8</td>
</tr>
<tr>
<td>TOF0 (r_{ms_y}) (cm)</td>
<td>6.1</td>
<td>6.0</td>
<td>7.7</td>
</tr>
<tr>
<td>TOFI rate (MHz)</td>
<td>0.55</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>TOFI (r_{ms_x}) (cm)</td>
<td>1.2</td>
<td>3.25</td>
<td>3.4</td>
</tr>
<tr>
<td>TOFI (r_{ms_y}) (cm)</td>
<td>0.6</td>
<td>5.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 2
Preliminary estimation of rates and widths for different emittance beams at \(\sim 200 \text{ MeV/c}\). The design aims at widths \(\sim 4.2 \text{ cm}\) for 10\(\pi \) beams, from [3].

1.2 The physics requirements for TOF stations.

To determine the RF phase to a precision of 5\(^0\) and allow a 99% rejection of pions in the incoming muon beam, a TOF station time resolution \(\sigma_{TOFI} \sim 70 \text{ ps}\) will be required [5]. The resolution in the time-of-flight (TOF) measurement is expressed as:

\[
\sigma_{TOF} = \sqrt{\sigma^2_{TOFI} + \sigma^2_{START} + \sigma^2_{calibr}}
\]

where \(\sigma_{TOFI}(\sigma_{START})\) is the TOF station \(i\) (START) signal time resolution and \(\sigma_{calibr}\) is the resolution of the calibration system. Having two independent measurements from each TOF stations (due to the X/Y redundancy) \(\sigma_{TOFI}\) is given by \(\sigma_i/\sqrt{2}\), with \(\sigma_i\) single counter timing resolution.

\(^1\) With a single 10 cm iron global shielding the B field has a sizable component along the PMTs axis (B/ \(\sim 200 \text{ Gauss}\)), that is reduced to a manageable value (\(\sim 50 \text{ Gauss}\)) with an additional 1 cm thick iron global shield [4].
In the Harp experiment, the calibration of the large forward time-of-flight detector (TOFW) attained a resolution of $\sim 70$ ps over all the data-taking period, see [6] for more details. This included an initial calibration of delays with cosmic rays ($\sigma \sim 60$ ps) and their time monitoring with a fast laser-based system ($\sigma \sim 40$ ps) [7].

In TOF detectors based on scintillators, a simple parametrization of the timing resolution $\sigma_t$ for a single counter is given by [8]:

$$
\sigma_t = \sqrt{\frac{\sigma_{sci}^2 + \sigma_{pmt}^2 + \sigma_{p}^2}{N_{pe}}} + \sigma_{elec}^2
$$

(2)

where: $\sigma_{sci}$ accounts for the scintillator response, $\sigma_{pmt}$ for the photomultiplier’s (PMT’s) jitter, $\sigma_{pl}$ for the path length fluctuations and $\sigma_{elec}$ for the jitter of the electronic readout system. $N_{pe}$ is the average number of photoelectrons (p.e.). The dominating factors for $\sigma_t$ are $N_{pe}$ and the counter dimensions (mainly its length $L$). Below 100 ps, contributions such as $\sigma_{pmt}$ become increasingly important. Additional problems may be given by the operation inside high magnetic fields or with high incoming particle rates.

Taking all this into account, a conservative request for single counters timing resolution is $\sigma_t \sim 60 - 70$ ps. In addition, to avoid any deterioration of the TOF measurements, the calibration procedure over all data-taking period must attain a resolution of $\sigma_{calib} \sim 50 - 60$ ps or better: a not easy task.

## 2 Global design of TOF0 detector

In the present baseline design, TOF0 has a $40 \times 40 \text{ cm}^2$ active area and is based on two planes of 1” orthogonal scintillator slabs along X,Y directions. Slabs have dimensions $40 \times 4 \times 2.5$ cm$^3$. A 1” thickness (t) per scintillator plane has been considered a good compromise between intrinsic detector resolution, that goes as $1/\sqrt{(t)}$ and the presence of scattering material along the beamline (see figure 2 for typical scintillator performances, as obtained by the MEG experiment at the LNF BTF testbeam[9] with 100 cm long scintillators and the BESS experiment [10] with 95 cm long scintillators). The active area and the segmentation of the TOF0 detector have been defined taking into account the beamline simulation from references [2] and [3], as reported in tables 1 and 2.

### 2.1 Single scintillator counter layout

Each scintillator slab, after a straight PMMA lightguide, is read at the two edges by a fast PMT. Figure 3 shows an exploded view of a scintillator counter, with the PMT holder (that is the PMT’s μ-metal shielding with 2 M3 holes) and the fish-tail PMMA lightguides. Scintillator counters will be assembled in-house starting from
Fig. 2. Typical performances of ~ 100 cm long scintillators with PMT readout at both ends (as obtained by the MEG experiment at BTF or the BESS experiment).

DTF (diamond tool finished) scintillator bars from Bicron, to which PMMA light-guides (see figure 4 for details) will be glued with BC-600 or EPOTEK-301 optical cement. A simple design with flat PMMA lightguides, as respect to tilted ones (to reduce the influence of magnetic field) or Winston cones, has been chosen to optimize the timing detector resolution (favoring the collection of straight light) and allow an easy mechanical assembly. Wrapping and assembly can be easily realized with tolerances less than 1-2 mm for individual elements of each TOF0 plane. The final choice of wrapping: mylar + black PVC covering or white diffusing paper + black PVC covering is still under study, to allow optimization of performances.
Fig. 4. Mechanical layout of the fish-tail lightguides and the black pvc adapter to the PMT housing.

The PMT case is fixed to the PMMA lightguide collar (φ = 20 mm) through a black PVC cylindrical adapter (inner diameter 20 mm, outer diameter 29 mm) to ensure light tightness for the whole assembly and allow compensation for mechanical mounting tolerances.

The optical contact between the end of the lightguide collar and the PMT photocathode will be assured by Silicone optical grease, such as Bicron BC-630. For the scintillator material, different options have been considered (see table 3 for more details). BC-420 has been retained as a choice. Figure 5 shows the emission spectra of the Bicron BC420 scintillator, to be matched to the lightguide material transparency window. In spite of some small additional problems for the choice of lightguide material (high quality UVT plexiglas, instead of commercial plexiglas, as the scintillation emission peak is around 390 nm), BC-420 was expected to give better timing performances.

2.2 General layout for TOF0

The mechanical structure of the TOF0 assembly for X/Y planes is shown in figure 6 (top), while the detector support structure is shown in figure 6 (down). The CAD design of a single TOF0 plane is instead shown in figure 7: (bottom) front view,
Fig. 5. Bicron BC-420 emission spectrum.

<table>
<thead>
<tr>
<th></th>
<th>BC-408</th>
<th>BC-404</th>
<th>BC-420</th>
<th>EJ-204</th>
<th>EJ-230</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_{\text{emission}}) (nm)</td>
<td>425</td>
<td>408</td>
<td>391</td>
<td>408</td>
<td>391</td>
</tr>
<tr>
<td>(\lambda_{\text{bulk}}) (cm)</td>
<td>380</td>
<td>160</td>
<td>110</td>
<td>-</td>
<td>(\sim 100)</td>
</tr>
<tr>
<td>Light output % Anthr.</td>
<td>64</td>
<td>68</td>
<td>64</td>
<td>68</td>
<td>64</td>
</tr>
<tr>
<td>decay const. (ns)</td>
<td>2.1</td>
<td>1.8</td>
<td>1.5</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>risetime (ns)</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>pulse width (FWHM ns)</td>
<td></td>
<td></td>
<td></td>
<td>2.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 3

Main properties of considered scintillator from Bicron and Eijlen Technologies. BC-420 and EJ-230 (BC-404 and EJ-204) have similar composition.

(top) top view. All quotes are in mm.

As the space is limited along the beamline direction \((z)\), a very compact support structure has been designed for TOF0. The structure is based on commercially available anticorrodial X-shaped bars to form a rigid structure.

3 Tests on TOF0 elements

The tests to optimize the choice of the TOF0 elements and materials will be outlined in the following section.
3.1 *Tests on lightguides*

Commercial transparent PMMA has usually a strong absorption in the UV region of interest for Bicron BC-404 and BC-420 scintillators (UVA), as shown in figure 8 for the transmittance T of a 20 mm sample, made of commercial Lucite Perspex, as measured by a spectrophotometer.\(^2\) At 390 nm (BC-420 emission peak) only 64% of the incoming light is transmitted. This points to the use of special UVT PMMA (UV transparent), such as ALTUGLAS V920 UVT, Bicron BC-800 or REPSOL Glass. Figure 8 shows the transmission curve for a 20 mm REPSOL Glass sample, that is the chosen material.

All lightguides, see figure 4 for their design, will be tested with a spectrophotometer to assure a constant production quality, as regards their light transmission T.

\(^2\) Jasco Model V-530 UV/VIS model, with double beam, single monochromator with a spectral bandwidth of 2 nm in the wavelength range 190-1100 nm
Fig. 7. CAD design of a TOF0 plane (top): top view, (bottom) front view.

Fig. 8. Measured transmittance T for a 20 mm Lucite Perspex sample (left) and a 20 mm REPSOL Glass sample (right).

3.2 Tests on Hamamatsu R4998 PMTs

Due to the low residual magnetic field, in the fringe field of the Q6 quadrupole \(^3\), where the TOF0 detector will be placed, conventional PMTs with an elongated mu-

\(^3\) well below 50 Gauss, as from [1]
metal shielding (extending 30 mm beyond the photocathode surface) can be used. To obtain a good timing resolution, PMTs with a small TTS must be used. An additional requirement is a good rate capability, up to 0.5 MHz for single counter. This has led, as a natural choice, to 1” R4998 PMTs from Hamamatsu Photonics \(^4\), see table 4 for their main characteristics.

<table>
<thead>
<tr>
<th>Structure</th>
<th>R4998</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube diameter</td>
<td>1”</td>
</tr>
<tr>
<td>Active area diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>No. stages</td>
<td>10</td>
</tr>
<tr>
<td>Q.E. at peak</td>
<td>.20</td>
</tr>
<tr>
<td>Gain (B=0 T) typ.</td>
<td>(5.7 \times 10^6)</td>
</tr>
<tr>
<td>Risetime (ns)</td>
<td>0.7</td>
</tr>
<tr>
<td>Transit time (ns)</td>
<td>10</td>
</tr>
<tr>
<td>TTS (ns)</td>
<td>0.16</td>
</tr>
<tr>
<td>(\langle I_a \rangle ) (mA)</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 4
Main properties of Hamamatsu R4998 PMTs.

R4998 PMTs have been delivered by Hamamatsu in assemblies (H6533MOD) that include the PMT tube, the voltage divider chain and a 1 mm \(\mu\)-metal shielding (see figure 9 for details). To increase the countrate stability of PMTs, instead of a conventional resistive divider type, active dividers or a booster on the last dynodes were requested. In this way the theoretical rate capability is increased by a factor \(\sim 8\) (from \(\sim 260\) KHz to \(\geq 1\) MHz). After some tests, the performances of PMTs equipped with a booster or an active divider were found equivalent and thus the active divider option was chosen for its easiness of use.

3.2.1 PMTs test setup

Systematic studies have been done, using both a iron yoke resistive dipole magnet at LASA (INFN Milano), with magnetic fields up to 1.2 T and an open gap of 12 cm (used mainly for tests in high magnetic fields of the fine-mesh PMTs, foreseen for TOFI and TOF2, see figure 10 for details) \(^5\) and a home-made solenoid with magnetic fields up to 50 Gauss and an open bore of 20 cm diameter. The layout of the test setup for PMTs is shown in figure 11. A fast light pulse \(^6\) was sent to

\(^4\) A lower cost alternative based on 1” PET PMTs (R9800 from Hamamatsu), with a TTS \(\sim 250\) ps, a risetime \(\sim 1\) ns and a nominal gain \(G \sim 1 \times 10^6\), is also under study

\(^5\) for the measurement of conventional PMTs the magnet was used at very low fields (up to 200 G) with a DF1731SB DC power supply unit. Magnetic field values were measured with an Hall probe

9
Fig. 9. H6533MOD assemblies as delivered by Hamamatsu. (Top) assembly with booster divider; (bottom) assembly with active type divider.

due to the PMT’s photocathode via a multimode CERAM OPTEC UV 100/125 optical fiber (with a measured dispersion of \(\leq 15\ \text{ps/m}\), see [7]). At the end of the fiber a small Plexiglas prism, inserted in a black plastic cover in front of the PMT window, allowed illumination at the center of the photocathode. The laser spot was focused into the optical fiber (aligned by a micrometric x-y-z flexure system) by a 10x Newport microscope objective, after removable absorptive neutral density filters, to give light signals of different intensities. The laser beam was splitted by a broadband beamsplitter (BS) to give 50% of light on the fiber injection system and 50% on a monitoring detector. A fast Thorlabs DET210 photodiode (risetime \(\sim 1\ \text{ns}\)) was

\(^6\) in part of the measurements a PLP-10 Hamamatsu laser on loan (\(\sim 405\text{nm, 60 ps FWHM pulse width, max repetition rate 100 MHz}\) was used; in the others a home-made system based on a Nichia NDHV310APC violet laser diode and an AvtechPulse fast pulser (type AVO-9A-C laser diode driver, with \(\sim 200\ \text{ps risetime and AVX-S1 output module}\) was used. This last system gave laser pulses at \(\sim 409\text{nm, with a FWHM between \(\sim 120\ \text{ps and \(\sim 3\ \text{ns (as measured with a 6 GHz 6604B Tek scope and a max repetition rate of 1 MHz}\)}}\) was
Fig. 10. The used resistive dipole test magnet at LASA, INFN Milano. A PMT under test is shown inside.
used in most measurements, to monitor the laser intensity. Tests were done usually with a signal corresponding to about 150-300 photoelectrons: a typical value for a minimum ionizing particle (MIP) crossing a scintillator 1”-2” thick. The optical power was periodically monitored with an OPHIR PD-2A or an OPHIR NOVA laser powermeter. The number of photoelectrons ($N_{pe}$) was estimated via absolute gain measurement. This number was cross-checked with the powermeter measurements.

For gain measurements the PMT signal was acquired in average mode by a Tektronix TDS 3032 digital scope (300 MHz bandwidth, 2.5 Gs/s sampling rate) triggered by the laser output sync., that had a maximum jitter of 15 ps as respect to the delivered light pulse. In addition, in some measurements the signal was sent after a passive T divider to an EG-G Ortec 570 shaper (shaping time ~ 1$\mu s$, gain ~ 200) followed by an Ortec TRUMP-8k Multichannel Analyzer installed on a PC. For timing measurements, in part of the measures the same MCA chain was used with an ORTEC 566 TAC and a CF 8000 Ortec discriminator, while in the others the PMT signal was split 50% to an ADC line and 50% to a TDC line (see figure 11 for details). On the TDC line the signal, after being discriminated by a CAEN V895 module, was sent to give the TDC STOP to a CAEN V480 TDC module (25 ps/ch). The laser sync out signal was fanned out by a Phillips Research 711 discriminator to give both the START of the TDC and the gate for the used QADC (CAEN V465, 0.1 pC/ch). The jitter in the readout electronics was expected to be less than 30 ps. Acquisition, in VME standard, was made by a VXI-MXI 2 National Instrument controller.

3.2.2 Tests results for Hamamatsu R4998 PMTs.

Absolute gain measurements.

The absolute gain $G$ and PMT linearity as a function of HV supply was measured
Fig. 11. Layout of the test setup for PMTs measurements. In some measurements the readout section (splitter+QADC+TDC) was replaced by a TEK TDS 3032 scope or an ORTEC MCA.

Fig. 12. Layout of the test setup for absolute Gain measurement.

for the R4998 PMTs, by using the test setup outlined in figure 12. A continuous train of pulses was delivered by a Lecroy 9210 pulser, through an attenuator, to the test input of a Canberra 2005 preamplifier. The signal was shaped to $2\mu s$ by an Ortec 570 shaping unit and then fed into a Silena MCA. In this way the MCA scale was calibrated in pC/channel. Then the preamp was connected to the PMT output, with an illumination corresponding to a SER peak condition. From the MCA peak position, it was thus possible to determine the output charge $Q$ in pC as a function of HV and thus the absolute gain $G$. Figure 13 shows such a plot for a typical R4998 PMT with an active divider. The distribution of gains at $B=0$ Gauss at a nominal -2250 V H.V., as deduced from Hamamatsu datasheets, is shown instead in figure 14 for the sample of R4998 PMTs to be used on TOF0. In the same figure the distribution of the anode dark current (in nA) is also shown. Variation in gain up to a factor 10 are evident. This points to an accurate matching of PMTs for the left-right side of each TOF0 scintillator bar. It is planned to measure the absolute gain
Fig. 13. Absolute gain $G$ for a typical R4998 PMT, with active divider. $G$ as a function of voltage $V$ (assuming a power law $G = \beta KV^\alpha$) before installation for all PMTs, to allow an accurate equalization.

**Behavior in magnetic field**

The PMTs were inserted in the central region of the test magnets, where the field had a uniformity better than $\sim 1\%$, using supports to incline them up to $60^\circ$ ($90^\circ$) as respect to the field lines in the dipole (solenoid) magnet. Environment light was accurately masked, to reduce noise. Measures were done to see gain reduction, timing resolution and rate capability as a function of the magnetic field ($B$) and the relative orientation angle ($\theta$), between the PMT axis and the magnetic field $B$. Due to the effect of the magnetic field on the accelerated electrons inside the PMTs we can expect a reduction of gain as $B$ increases and also a marked dependence of the relative gain as a function of $\theta$. Results for the relative gain as a function of the magnetic field $B$ are shown in figure 15.

As expected PMTs behave well for orientation of the $B$ field orthogonal to the PMT axis ($90^\circ$), where the shielding effect is maximal, while along the PMT axis ($0^\circ$) the gain reduction is more marked. No differences are seen for booster vs active divider options. The same behavior appears also in timing measurements (see figure 16 for details).

As a conclusion, no problem is envisaged for longitudinal fields up to 50 Gauss ($\Theta = 0^\circ$) and orthogonal fields up to 100-120 Gauss ($\Theta = 90^\circ$).

**Rate capability**

Figure 17 shows the PMT response (P.H. in mV) as a function of the laser shot repetition rate $R$ (simulating an increasing particle rate), in different conditions of
Fig. 14. Absolute gain G distribution at -2250 V (top) and anode dark current (bottom) for the sample of R4998 PMTs, to be used in the experiment.

the external magnetic field, both with a conventional resistive divider and a booster. These results can be easily understood, remembering that the rate capability of fine-mesh PMT is limited by the maximum allowable anode current $I_a$.

In addition, the pulsed cycle of an accelerator was simulated giving laser shots in a 1 ms window (with a repetition rate up to 1.5 MHz) followed by a 20 ms interspill. As expected, no difference was found as respect to the operation mode with a continuous laser pulsing at the same frequency (see figure 18 for details).

Timing characteristics of R4998 PMTs show no deterioration going from 1KHz up to 1 MHz, for sensible number of photoelectrons as shown in figure 19 at $B=0$ Gauss.

**Photocathode uniformity**

R4998 PMTs have a diameter of 1" (25.4 mm) and a minimum active area diameter of ~ 20 mm. Studies were done to study the photocathode uniformity at the edges. Figure 20 shows for a typical R4998 PMT the relative P.H. response: $P.H.(r)/P.H.(r=0$ mm) as a function of the magnetic field $B$ for various impact position $r$ in mm. At each radial position $r$ the laser light was collimated to a spot of ~ 2.5 mm of diameter in front of the PMT’s photocathode. There no clear evidence
Fig. 15. Behavior of PMT gain in magnetic field B for typical R4998 PMT at various inclinations $\theta$ (right), with booster or active divider. In ordinate the gain ratio at B and B=0 T is reported.

Fig. 16. Timing properties of R4998 PMTs in magnetic field B, at two typical inclinations $\theta$. (Top) transit time, (bottom) TTS.

of any reduction of the photocathode active area in presence of B fields up to $\sim 50$ Gauss in the direction along the PMT axis. The PMT response is marginal (a factor 10 lower) for extreme radial impact point positions: $r \geq 10$ mm. This points to the use of lightguide collars of diameter not bigger than 20 mm.

PMTs stability

The PMT stability, under a continuous laser illumination, was studied to appreciate
Fig. 17. Rate capability of typical R4998 PMT, as a function of rate R at field $B=0$ G (measured P.H. in mV versus rate in KHz). The light signal corresponds to $\sim 300$ p.e.

Fig. 18. Rate capability of typical R4998 PMT, as a function of rate R at field $B=0$ G (measured P.H. in mV versus rate in KHz), comparing a continuous train of laser shots and a cycle simulating the ISIS one (1 ms light, 20 ms dark). The light signal corresponds to $\sim 170$ p.e.

fatigue effects. Figure 21 shows the PMT response for a typical PMT as a function of time. The system delivered laser pulses of $\sim 1$ ns width, with a repetition rate of 1 MHz and an amplitude corresponding to about 170 photoelectrons per laser shot. The laser stability was monitored with the Thorlabs DET210 photodiode and the plotted results are corrected for its readings. Runs up to 24 hours of duration were done. This corresponds, taking into account the ISIS accelerator cycle, to the fatigue effect.
Fig. 19. Timing resolution $\sigma_{TDWC}$ in ps units as a function of rate R (at B=0 T) for a typical R4998 PMT.

Fig. 20. Photocathode uniformity: P.H.(r)/P.H.(r=0 mm) vs position r (in mm) for various magnetic fields B.

effects that can be accumulated in a continuos running of more than 20 days. After some conditioning (the known burning up effect of PMTs) the PMT seems to show some fatigue effect, that is fully recovered after a period of darkness (see figure 21). This implies that the PMTs gains must be monitored during the running time, as for example with the laser system described later.
Fig. 21. The corrected PMT response as function of time, under continuous illumination (laser shots at 1 MHz rate).

3.3 Tests on single scintillator counters with an MCA at the BTF

A preliminary estimate of scintillation counter time resolution was obtained at the BTF[11], using an Ortec Trump-8K Multichannel Analyzer, with an Ortec 566 TAC and a PLS 711 L.E. discriminator, with a threshold set to $\sim -10$ mV. Triggering on two finger counters of transverse area $5 \times 20 \ mm^2$, one PMT of the scintillator bar under test was used as START while the other as STOP of the TAC unit. The counter intrinsic resolution is given by:

$$\sigma_C = \frac{1}{2} \sqrt{\sigma_{t_L}^2 + \sigma_{t_R}^2}$$

and is expected to be equivalent to the one calculated directly from $\frac{1}{2}(\Delta t_L - \Delta t_R)$, with $\Delta t_{L/R}$ time difference as measured by the Left/Right PMT of the same scintillator counter.

The BTF electron beam was tuned to have a majority of single electrons in the incoming spills. With a beam impinging at the counter center, a resolution of $\sim 50$ ps was obtained for 1” 40 $\times$ 4 cm$^2$ BC420 counters equipped with BC800 or REPSOL glass lightguides and R4998 PMTs; the baseline choice for TOF0. This result includes contributions from the finite size of the finger counters, misalignment of PMTs, discriminator effects and beam instabilities and compares well with requirements. Similar results were obtained using fine-mesh 1” Hamamatsu R5505 PMTs in place of the R4998 PMTs$^7$.

$^7$ R5505 PMTs have a TTS $\sim 350$ ps and a nominal gain of $\sim 5 \times 10^5$ at $+2000$ V
The MICE running conditions will require electronic modules with a better than 1 μs conversion time and a ~ 1000 events buffer, to handle the high incoming particle rate (up to 0.5 MHz on single counters), during the 1 ms long ISIS burst train and allow the writing out in the following ~ 20 ms dark period. The analog PMTs signal can be fed, after an RG213 cable \(^8\), to the digitization stage. A simple solution can be based on a discriminator (leading edge (LE) or constant fraction (CF)) followed by a TDC (baseline solution). The main characteristics of some discriminators under considerations are shown in table 5. In case of problems more complicate solutions will be considered, such as:

- to split the PMT signal by a splitter that divides the signal to a TDC and an additional QADC line for time-walk corrections (solution no. 2)
- to use an ALICE-like solution based on the NINO chip [12], before the TDC module, for time over threshold (TOT) correction (solution no. 3)

In all solutions the CAEN V1290 has been considered as a baseline TDC. This Multi-hit/Multi-Event TDC can detect hits raising/falling edges and work in continuous storage mode with a 32k × 32 bits deep output buffer. A 25 ps LSB couples to a 5 ns double hit resolution.

For solution no. 2, active splitters recuperated from the HARP experiment may be used to divide the signal to the QADC and TDC lines, see figure 22.

In the Harp experiment, the input impedance of the active splitters was modified to match the impedance of the RG-213 cable, thus reducing signal reflections between the photomultiplier and the front-end electronics (see figure 23). This has to be revised for the MICE experiment.

\(^8\) RG213 cables minimize skin effects and dielectric losses. Moreover, they show a better stability as a function of temperature, as respect to conventional RG58 cables. A single-channel time variation of ~ 30 ppm/°C, due to thermal drift, was measured: a factor 3 better than conventional RG58 cables (see [6] for details)

<table>
<thead>
<tr>
<th>Discriminator</th>
<th>no. of channels</th>
<th>walk (ps)</th>
<th>max rate (MHz)</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLS 711</td>
<td>6</td>
<td></td>
<td>150</td>
<td>LE</td>
</tr>
<tr>
<td>PLS 707</td>
<td>16</td>
<td>±400</td>
<td>100</td>
<td>LE</td>
</tr>
<tr>
<td>CAEN V812B</td>
<td>16</td>
<td>±250</td>
<td>65</td>
<td>CF</td>
</tr>
<tr>
<td>ORTEC CF8000</td>
<td>8</td>
<td>≤ ±250</td>
<td>20</td>
<td>CF</td>
</tr>
<tr>
<td>PLS 715</td>
<td>5</td>
<td>±75</td>
<td>100</td>
<td>CF</td>
</tr>
<tr>
<td>ORTEC CF935</td>
<td>4</td>
<td>≤ ±50</td>
<td>200</td>
<td>CF</td>
</tr>
</tbody>
</table>
Fig. 22. Block diagram showing a conventional scheme for the processing and conversion of PMT signals.

In solution no. 2, the time-of-flight measurement is achieved by combining time measurements (from the TDC) with pulse-height informations for time-walk corrections (from the QADC). This conventional approach requires an update to the existing CAEN QADCs that have conversion time $\sim 2.8\mu s$ and a limited 32 events buffer memory.

In all solutions, a relevant problem in the readout electronics is the channel-to-channel cross-talk, due to the fact that more channels are grouped in a single chip. This problem may affect both discriminators and TDCs. As an example, in the V775 Caen TDCs, where channels were grouped four by four, nearby channels may have cross-talk effects up to $\sim 50$ ps, as shown in [6].

In solution no. 3, as done in the TOF detector for the ALICE experiment at LHC [13], using a TDC to measure both the leading and trailing edge of the pulse, a time-over-threshold (TOT) correction can be used in place of the QADC amplitude measurement. This imply the introduction of a high bandwidth preamplifier with an integrator before the discrimination stage (as implemented in the NINO Chip). The ALICE collaboration, quotes a resolution of $\sim 51$ ps instead $\sim 46$ ps using a TOT correction, in place of a conventional QADC one, demonstrating the validity of the method. The main problem foreseen for the use of the NINO chip is the small signal range: 100fC - 2 pC, to be compared with MIP signals in the 50-100 pC range and the dedicated prototyping work needed.

9 With a simple analyzable model for deadtime, this gives a conversion time $\sim 200$ ns to be able to collect 600$\mu$/spill as required by the experiment.
The used calibration method must have a time resolution $\sigma_{\text{calibr}} \sim 50 - 60 \, \text{ps}$ or better, to avoid any deterioration of the TOF measurement resolution $\sigma_{\text{TOF}}$, see equation 1. The TOF measurement is based on single timing measurements from the individual counters $i$ of the TOF stations, given by:

$$\Delta t_{ij} = t_0 + \frac{L/2 \pm x}{v_{eff}} - t_s + \delta_{ij} \quad j = 1, 2$$

where the delays $\delta_{ij}$ include cable delays, PMT transit times, ... and must be measured at a time $T_0$ at the start of data-taking. Their time evolution $\delta_{ij}(T)$ must be followed by a monitoring scheme. $\delta_{ij}(T_0)$ can be measured with a cosmic ray setup as in the Harp experiment. The time evolution $\delta_{ij}(T)$ can be then evaluated with impinging beam muons and a fast laser calibration scheme.

5.1 Calibration with impinging beam muons

Due to the redundant X/Y structure of TOF0, the two independent timing measurements can be used to inter-calibrate the detector (time alignment of single X or Y counters). While in principle a very high precision can be reached, limits can be introduced by systematic effects and the limited statics available on the outer counters.

5.2 The laser calibration system

A fast laser system, similar to the one used in the HARP experiment, is foreseen (see figure 24 for details). The laser beam is split to a fast photodiode $^{10}$, that gives the START of the TDC system, and is injected into a bundle of fibers that transmit the pulse to the different scintillator counters.

Studies are under way to provide an economic and stable fast laser source, based on a Q-switched IR diode pumped laser at $\lambda \sim 532\,\text{nm}$ and optimize the choice of the fibers of the bundle, that will be quite long: $\sim 15 - 20 \, \text{m}$. Standard multimode fibers have typical dispersion $\sim 30 \, \text{ps/m}$ and are clearly out of question for transmission along sizable distances. Monomode fibers, on the other hand, have small dispersion (typically $\leq 1 \, \text{ps/m}$), but give problems for the laser light injection. An optional "launch" condition for the laser beam is essential to control the effective bandwidth of the used optical fibers. As respect to multimode fiber cores of $\sim 50 - 200\,\mu\text{m}$ diameter, green monomode fibers have core diameters of $\sim 2 - 3\,\mu\text{m}$ and IR monomode fibers have core diameters of $\sim 10\,\mu\text{m}$, to be compared to laser spot sizes of some

$^{10}$Hamamatsu G4176, with 30 ps risetime and falltime using a 5550B Picosecond Pulse Lab bias tee

21
mm. To reduce launch problems, IR monomode fibers will be used, that for green light behave as a “limited” number of modes fiber. As a first choice Corning SMF-28 IR monomode fibers (with a measured dispersion of 3.6 ps/m at 532 nm) will be used for the bundle. At the free end of each fiber the laser signal will be injected into a short (1 m long) multimode fiber\(^{11}\) ending in a small prism glued to the center of each scintillator slab. High numerical aperture multimode fiber with a small core diameter, to allow injection of laser light at large angles with a limited modal dispersion, have been searched. The high NA will increase the fraction of the injected laser light that will reach the PMTs photocathode with a small number of reflections at the scintillator boundaries, thus better simulating the situation with an incoming MIP.

The dispersion introduced by the 1 m used multimode fiber has been checked using a 7 ps FWHM home-engineered laser \(^{12}\), emitting at 532 nm, and a fast Hamamatsu G4176 photodiode connected to a high bandwidth scope \(^{13}\). The measurements results are reported in table 5, using a 8m long multimode fiber patch. Apparently there is a minimal deterioration of the 10 – 90% pulse trailing edge, that will give no major problem for a 1 m long injection fiber. The FT-110-LMT fiber has been chosen mainly for the easier mechanical mounting through standard SMA 905 connectors.

<table>
<thead>
<tr>
<th>Laser Configuration</th>
<th>10 – 90% risetime (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser only (no fiber)</td>
<td>48 ± 2</td>
</tr>
<tr>
<td>laser + 8m TECS FT-110-LMT fiber</td>
<td>59 ± 4</td>
</tr>
<tr>
<td>laser + 8m 3M HCS 125/140 fiber</td>
<td>49 ± 4</td>
</tr>
</tbody>
</table>

Table 6
Results on the fiber dispersion test

In addition the system may be used to monitor the gain stability of the used PMTs, that due to fatigue effects may show a drift in time.

\(^{11}\) type TECS FMT-110-LMT with a NA 0.37
\(^{12}\) developed at Dipartimento di Ingegneria Elettronica Pavia, by G. Reali and A. Agnesi
\(^{13}\) Tektronix 6604B with a 6 GHz bandwidth
Conclusions

The TOF0 MICE project has been described in detail, including the foreseen front-end electronics and calibration issues. Full estimates of the counter performances (mainly $\sigma_t$) as obtained at the BTF testbeam are under study: only preliminary results are reported here. No major bottlenecks are foreseen.

Acknowledgments

The essential help of Mr. R. Mazza and R. Bertoni of INFN Milano and of Ing. M. Rossella of INFN Pavia is acknowledged for the preparation of this report. We are indebted also to Dr. L. Confalonieri, Hamamatsu Italia, for help and many enlightening discussions.
References


