The construction of the MICE TOF2 detector

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This note reports the construction and laboratory tests done at INFN Milano Bicocca for the MICE TOF2 detector at RAL. In addition the studies done for the local magnetic shielding of conventional Hamamatsu R4998 PMTs and the preliminary detector performances obtained in beam at RAL are summarized.

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1 Introduction

In the MICE experiment, precision timing measurements are required to correlate 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) have been built and installed at RAL in 2008 and 2009 [1], [2], [3]. 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.

The two most downstream detectors (TOF1,TOF2) must allow a 99% rejection of the pion contamination in the muon beam. For this purpose, a TOF measurement resolution better than $\sim 100$ ps is enough. All TOF detectors are also used to determine the time coordinate ($t$) in the emittance measurement.

Due to the low residual magnetic field produced by the last quadrupole of the beam channel in the proximity of the TOF0 detector ($\leq 50$ Gauss), conventional PMTs with elongated $\mu-$metal shielding (extending 30 mm beyond the photocathode surface) may be used. The other two TOF stations (TOF1/TOF2) will work instead in the stray fields of the measuring solenoids, that are only partially shielded by a 100 mm iron annular plate (“the Virostek plate”). As residual magnetic fields are up to 0.13 T (with a component along the PMTs axis up to 0.04 T), a local or global magnetic shielding for TOF1 and TOF2 detectors had to be envisaged. All detectors have to sustain an high incoming particle rate: from more than 1 MHz at TOF0 to about 0.5 MHz at TOF2.

2 The design of the TOF2 detector

The design of TOF2 is quite similar to the one of TOF0 and TOF1, except for the heavy local shielding for magnetic fields (see figures 4 to 6 for details). Two planes of fast 1” thick scintillator counters along X/Y directions (to increase measurement redundancy) are read out at both edges by R4998 Hamamatsu fast photomultipliers (PMTs) $^1$. In the downstream section, the TOF2 planes cover a $60 \times 60$ cm$^2$ active area, with a 6 cm counter width. Time calibration of individual counters has been done with impinging beam particles by using the detector X/Y redundancy.

$^1$ one-inch linear focused PMTs, typical gain $G \sim 5.7 \times 10^6$ at -2250 V, risetime 0.7 ns, transit time spread (TTS) $\sim 160$ ps
2.1 Construction of TOF2 counters

The TOF2 scintillator counters have been assembled in-house starting from DTF (diamond tool finished) BC404 scintillator bars from Bicron\(^2\), to which UVA PMMA light-guides have been glued with BC-600 optical cement. A simple design with flat fish-tail 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 to allow an easy mechanical assembly. Wrapping and assembly has been realized with total tolerances around 1 mm for individual counters of each TOF2 plane. The final choice of wrapping is aluminized mylar + black PVC covering (GOBLEX). The light-tightness of the GOBLEX covering has been tested measuring the transparency of a small sample inside a spectrophotometer. In each TOF2 counter, the PMT assembly case is pressed from the back against the beginning of the trapezoidal PMMA lightguide to ensure light tightness. The optical contact between the end of the lightguide collar and the PMT photocathode is assured by silicone elastomers, such as Bicron BC-634. At the center of each counter, a total reflection prism will convey, after a 1 m long multimode fiber, the light of the foreseen laser diode calibration system.

2.2 Resume of tests on R4998 PMTs and magnetic shielding for TOF2

R4998 PMTs have been delivered by Hamamatsu in assemblies (H6533MOD) that include the PMT tube, the active voltage divider chain and a 1 mm \(\mu\)-metal shielding, extending 30 mm beyond the photocathode surface. With this shielding only longitudinal fields up to \(\sim 150\) Gauss and orthogonal fields up to \(\sim 60\) Gauss may be tolerated. TOF2 will work inside the high residual magnetic field, either side of the measuring solenoids, not fully shielded by the 100 mm iron shield (“the Virostek plate”). Figure 1 shows the longitudinal \(B_L\) and orthogonal \(B_B\) components of the magnetic field at the position of TOF2 [4], computed with a 2D COMSOL [5] or Tosca [6] calculation\(^3\).

Orthogonal components (up to 0.1 T) and longitudinal components (up to 0.025 T) of the fringe magnetic fields have to be shielded. For TOF2 a local shielding was adopted as the detector must be as near as possible to the KL calorimeter for acceptance reasons.

Magnetic shielding materials are chosen for their characteristics respect to permeability and saturation. As permeability increase in magnetic shielding materials, their saturation level decrease. Therefore, the highest permeability alloys (such as \(\mu\)-metal) have the lowest saturation values. Table 1 reports some commercially available materials with their permeabilities. Up to fields \(\sim 50 - 100\) Gauss \(\mu\)-metal shieldings are adequate. For higher field values, such a shield saturate and becomes

\(^2\) \(\lambda_{\text{emission}}\sim 408\) nm, \(\lambda_{\text{bulk}}\sim 160\) cm, 1.8 ns decay constant, 0.7 ns risetime

\(^3\) 3D Tosca calculations were redone in reference [7] and results were found compatible
ineffective. It must be surrounded by an additional shield, usually of soft iron. The usual choice is a low carbon content iron (less than 0.01%, such as ARMCO), that has relatively high permeability (compared to other steel) and excellent saturation characteristics.

As shielding is a mass effect, box-shaped soft iron shieldings are more effective than cylindrical ones. This idea pioneered in the D0 experiment [8] has been tested in the case of MICE using different geometrical configuration for the iron shielding boxes and different iron materials: Fe360, ARMCO, ... The problem is usually the longitudinal component $B_L$ of the magnetic field, while the orthogonal component $B_\perp$ may be more easily shielded.

<table>
<thead>
<tr>
<th>material</th>
<th>% of C</th>
<th>$\mu_{r}^{\text{max}}$</th>
<th>saturation (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe360 iron</td>
<td>0.25%</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>ARMCO iron</td>
<td>$\leq$ 0.01%</td>
<td>180000</td>
<td>21500</td>
</tr>
<tr>
<td>Super-permalloy</td>
<td></td>
<td>800000</td>
<td>8000</td>
</tr>
<tr>
<td>$\mu$-metal (80 % Nickel)</td>
<td></td>
<td>100000</td>
<td>6500</td>
</tr>
</tbody>
</table>

Table 1
Properties of some commercially available shielding materials.

Systematic studies have been done, using a built on purpose solenoid of 23 cm inner diameter, 40 cm length \(^4\) shown in figure 2 and are fully reported in reference [9]. Results are shown versus $B$ (the magnetic field is along the PMT axis ) in figure 3 for a composite shielding that includes the 1 mm $\mu$-metal shielding with an additional $5 \times 5$ or $6 \times 6$ cm\(^2\) iron box. As a general conclusion, we see that:

- very low carbon content iron (ARMCO) is more effective than standard Fe360, even if this is quite good up to 500 Gauss longitudinal fields

\(^4\) built by TBM srl, Uboldo (VA), Italy
2.3 Detector layout

As expected conventional 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 may be more marked. The local shielding with $6 \times 6 \text{ cm}^2$ ARMCO iron in addition to the 1-mm $\mu$–metal case seems more than adequate for TOF2 PMTs \footnote{as explained in \cite{9}, the proposed shielding is adequate also for perpendicular magnetic fields $B \perp$ up to 1000 Gauss}. In addition the PMTs individual shields will be magnetically linked between them and to the “Virostek” plate, giving extra mass effect and so more effective shielding. In this way, our tests on single local PMTs represents a situation worse than the real one. Figures 4, 5 and 6 shows how the local shielding has been implemented in TOF2, using different sheets of ARMCO to make a “single bar structure” for all the PMTs of one side, instead of single boxes for individual PMTs. The effective shielding amounts to $\sim 6.6 \text{ cm}$ of ARMCO thickness, with extra shieldings effect due to the fact that all bars shielding the TOF2 PMTs are magnetically linked between them and to both the KL shielding and the “Virostek” plate making a single magnetic loop.

3 Laboratory acceptance tests on TOF2 counters

The delivered Hamamatsu H6533MOD assemblies showed an unusually high breakdown rate ($\sim 15\%$) and a very noisy behaviour. To minimize the problem an additional kapton insulation between the PMT photocathode and the $\mu$–metal case and a diode protection for the active divider were introduced by Hamamatsu, after a long series of tests, see \cite{3} for details.
Fig. 3. Signal ratio at field $B$ and $B=0$ G and FWHM ratio at field $B$ and $B=0$ G for the timing difference, measured as $\Delta t = t_{\text{START}} - t_{\text{STOP}}$ with different iron box shieldings in addition to the the mu-metal one. The $B$ field is along the PMTs axis. The plots show the average and rms for a sample of ten R4998 PMTs.

Figure 7 shows the distribution of the nominal gain and the dark current noise for the R4998 PMTs used in TOF2. It can be noticed that the gain is on average smaller than for TOF0/TOF1 PMTs (a factor $\sim 2$) and the dark current noise is much smaller (a factor $\sim 7$).

All the built TOF2 counters had to pass a laboratory acceptance test in Milano Bicocca based on several steps:

- At first, PMTs were pre-tested for dark current with a several days long test and then pulse-height and fall time were tested with a YAP pulser source as outlined in [3], after a burning time of few hours at $-2250$ V.
- With the YAP pulser  a pre-calibration duty cycle was done for each PMT.

6 The YAP pulser consists in a $^{241}$Am $\alpha$ source embedded in a 4 mm diameter YAP:Ce scintillator from SCIONIX Ltd. The pulser generates about 5500 photoelectrons on a bialkali photocathode. With a nominal rate of $\sim 20$ Hz, a calibration run of a few $10^3$ events was done in about 10-20 minutes instead of the many days needed in the cosmic rays testbench.
Fig. 4. Exploded view of the full TOF2 detector with magnetic shieldings stripped out.

Fig. 5. Exploded view of the TOF2 detector PMTs magnetic shielding for one row of PMTs. In dark the ARMCO sheets making the PMTs “box shielding” are shown.

changing the H.V. in the range from -1800 to -2300 V (see later for details).

- After a matching for similar gains (L/R PMTs of the same counter) PMTs were mounted on the TOF counters. A further test for counter light-tightness was done
by measuring the anode dark current with a picoammeter.\(^7\)
- The response of a single counter was tested first with cosmic rays and then with laser pulses simulating a one-two MIPs signals at frequencies from 100 KHz to 500 KHz, changing the H.V. in the range from -1800 V to -2300 V.

The tests were foreseen as a standard acceptance test to select PMTs and determine counter plateau’s and HV working points for them.

4 PMTs and scintillation counter pre-calibration

To equalize the amplitude response of TOF2 scintillation counters\(^8\) the different PMT’s gain and optical coupling\(^9\) must be accounted for. Neglecting this last factor, equalization has been done by looking only to the PMT’s gains.

By using a YAP pulser P.H. spectra were recorded with a VME CAEN V792 QADC, readout by a CAEN V2718 VME-PCI interface. Data were recorded at nominal H.V. set on a CAEN N470 module at values from about -1800 V to -2300 V, in 50V steps. The amplitude (in ADC counts) has been plotted as a function of the H.V. (in kV) and fitted with a functional form \(\beta \times \kappa \times V^\alpha\), with \(\kappa, \alpha\) free parameters for each

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\(^7\) Keithley model 616 programmable pico-ammeter
\(^8\) This is useful in order to have similar time-walk corrections for the two (L/R) PMTs of the same scintillator bar
\(^9\) both between the scintillator bar and the lightguides and the lightguide collars and the PMTs
Fig. 7. Distribution of nominal gain and dark current noise for the PMTs used in the TOF2 detector.

PMT. Figure 8 shows the fit for two typical PMTs. Figure 9 shows the distribution of the $K = \beta \times \kappa$ and $\alpha$ parameters for the sets of PMTs used in TOF2 and their correlation, where $\beta$ is the conversion factor to go from ADC counts to a P.H. value in mV.

The $K$ and $\alpha$ values of each PMT and the functional form $K \times V^\alpha$ were subsequently used in the detector equalization for amplitudes at variance with the TOF0/TOF1 situation, the variation of the $K$ parameter in TOF2 is quite small (it was up to a factor of ten).

- choose the L/R PMTs for a single counter with similar gains
- choose the PMTs of the horizontal/vertical planes such as to have the most similar gains

All this was done to avoid very different time slew corrections for the timing measurements. At this point each H or V plane of TOF2 had the PMTs H.V. set to a
Fig. 8. Dependence of average P.H. from H.V. settings, for two typical PMTs of TOF2.

value to equalize their pulse heights to a common value $V_{i}^{\text{ref}}$ for $i=1,2$. The values $V_{i}^{\text{ref}}$ (around 1 V) were chosen to assure:

- a good signal after the 50% – 50% splitter
- to keep most PMTs H.V. settings as low as possible, to minimize noise problems, spike noise and try to avoid as much as possible divider breakdown.\textsuperscript{11}

5 Assembly of TOF2 in MIB mechanics workshop and installation/preliminary tests at RAL

The TOF2 counters, after a long acceptance test, have been assembled in the INFN Milano Bicocca mechanics workshop. This included the local magnetic shielding. Figure 10 shows some steps in the assembly.

Positioned outside the closed DSA area, on the final RM3 downstream platform, TOF2 was installed at RAL in the MICE Hall in November 2009 and since then tested with a few dedicated runs. Figure 11 shows a rendering of the downstream RM3 platform with installed TOF2, KL and EMR, while figure 12 shows the present installation of TOF2 at RAL with TOF1 in front of it on a temporary trolley.

\textsuperscript{11} as respect to a nominal HV of -2250 V, this means a deterioration of timing resolution of $\leq 2\%$ taking for granted $\sigma_t \approx \frac{1}{\sqrt{H.V.}}$
The channel naming for the TOF2 detector in the MICE hall is shown in figure 13 ("PMT number" refers to the physical channels on the detector 80 to 119).

Signal cables have delays $\sim 169.7 \text{ ns}$ on average, as in TOF0 and TOF1, and included 20 refurbished RG213 $\sim 41.5 \text{ m}$ long cables \(^{12}\) (channels 80-99) and 20 new RG213 cables \(^{13}\) (channels 100-119). To allow easy positioning of the TOF2 detector in all foreseen MICE steps, the HV cables are $\sim 31\text{ m}$ long.

Some data have been taken starting in December 2009 with pion and electron/positron beams to calibrate the TOF detectors. After time-walk corrections and the calibration procedure (see reference [10] for details), figure 14 shows the time difference $\Delta t_{XY}$ between the vertical and horizontal slabs of TOF2. The ob-

\(^{12}\) CERN type C-50-6-1, with rated delay 4.08 ns/m

\(^{13}\) cable type 213HRS284 from NOVACAVI srl. Milano, with rated delay 5.03 ns/m. To have the same delays as the old one, these cables have been cut 33.8 m long.
Fig. 10. Assembly of TOF2 at INFN MIB mechanics workshop. Top to bottom: from the bare magnetic shieldings to the installed counters of a TOF2 plane.

Fig. 11. Rendering of the downstream RM3 platform with installed TOF2, KL and EMR from front to back. Detectors may be moved along the z-axis to allow easy repair and operations.

The obtained resolution $\sigma_{XY}^{(2)}$ for the difference is $\sim 100$ ps, that translates to $\sigma_T^{(2)} \sim 52$ ps for the full TOF2 detector with crossed horizontal and vertical slabs. Resolutions are compatible in the TOF0 detector (4 cm wide slabs) and the TOF2 detector (6 cm wide slabs).
cm wide slabs), showing that path lengths fluctuations effects are negligible. The distribution of the time-of-flight between TOF1 and TOF2 for the pion and electron beam is shown in figure 15. The first peak is considered as the *time of flight* of the positrons and is used to determine the absolute value of the time in TOF2. A natural interpretation of the other two peaks is that they are due to forward flying muons from pion decay and pions themselves.

### 6 Conclusions

The construction and laboratory tests to assemble the MICE TOF2 detector have been described. TOF2 has been working since December 2009 at RAL in the MICE Hall without major problems and its preliminary performances in beam are described.
Fig. 14. Time difference $\Delta t_{XY}$ between vertical and horizontal slabs in TOF0 (left panel) and TOF2 (right panel). Trigger is on TOF1.

Fig. 15. Time of flight between TOF0 and TOF2 (left panel) and TOF1 and TOF2 (right panel) for the pion beam. The baseline between TOF1 and TOF2 is presently only 2.42 m, giving a poor separation between forward flying muons and pions.

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References


[6] [http://www.vectorfields.com]


[8] R. Stephens et al., internal note D0 2706, 1996
