

Performance of the MICE diagnostic systems

5

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Abstract

This paper will describe:

- The detectors as we have it installed in the MICE Hall at November 2017
- The performances of the detectors and the PID
- The absorbers model(s) and their validation
- The track matching
- The detector alignment

10

Reference to the published papers. Target: JINST volume.

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1 Introduction

- 55 To include:
- Motivation
 - Outline of the experiment

2 Time-of-Flight Detectors

List of figures

- 60 • PMT charge correlation PMT0 vs PMT1 - maybe, if relevant
- TW calibration of one channel
 - Slab DT before TW correction and after - single pixel.
 - Residual TW
 - T0 correction for 1 channel - electron peak fit
 - Slab DT mean and sigma for all pixels after calibration
 - Overall slab DT
 - Space-point creation efficiency per pixel/slab
 - Particle detection efficiency - don't know how to extract from the data, ideally pixel map for each TOF
- 65

2.1 Introduction

- 70 Three time-of-flight detectors (TOF0, TOF1, TOF2) have been built and installed at RAL in 2008 and 2009 to measure the position and the time of crossing particles. TOF0 and TOF1 [1], [2], [3] are placed upstream of the cooling channel, and TOF2 [4] is downstream of the channel, mounted in front of the KL, as shown in Fig. ???. The time of flight between two TOF stations provides particle identification information and can

also be used for momentum measurement. TOF1 served most of the time also as an experimental trigger. They
75 have smoothly operated during the so-called Step I and Step IV [5], [6] running periods of the MICE experiment and were essential for all the measurements done.

The good performances of the TOF detectors, over an extended period of time, has enabled the MICE experiment to characterize fully its muon beams during Step I data-taking, by measuring their emittance [7] and assessing their pion contamination [8].

80 Each TOF station is made of two planes of fast 1" thick scintillator counters along X/Y directions (to increase measurement redundancy) read out at both edges by R4998 Hamamatsu fast photomultiplier tubes¹. R4998 PMTs have been delivered by Hamamatsu in assemblies (H6533MOD) that include the PMT tube, the voltage divider chain and a 1 mm thick μ -metal shield, extending 30 mm beyond the photocathode surface.
85 **TheTo** increase the count rate stability active dividers were used, instead of conventional resistive ones. A simple design with flat fish-tail PMMA light guides, as **respectopposed** to tilted ones (to reduce the influence of magnetic field) or Winston cones, has been chosen to optimize the timing detector resolution (favouring the collection of straight light) and to allow an easy mechanical assembly. **any picture or reference here?** TOF0, TOF1, and TOF2 have active areas of $40 \times 40 \text{ cm}^2$, $42 \times 42 \text{ cm}^2$, and $60 \times 60 \text{ cm}^2$ respectively. The slabs in TOF0 are 4 cm wide, while the slabs of TOF1 and TOF2 are 6 cm wide respectively. The PMTs signal, after
90 ~ 34 m long RG213 cable and a 50% – 50% passive splitter, arrive to a leading-edge CAMAC Lecroy 4115 discriminator followed by a CAEN V1290 TDC for time measurements and to a CAEN V1724 FADC for pulse-height measurements, to correct time-walk. As reported in reference [2], RG213 cables² have a better temperature stability than conventional RG58 cables. Their delay have been individually measured in laboratory, before installation in the experimental hall. Time calibration of individual counters has been done with
95 impinging beam particles by using the detector X/Y redundancy [9]. **This is too vague. Calibration will be covered later. What does counter refer to here?**

Due to the low residual magnetic field produced by the last quadrupole of the beam line in the proximity of the TOF0 detector (≤ 50 G), the used conventional PMTs had to use elongated μ -metal shielding. The other two TOF stations (TOF1/TOF2) had to work instead in the stray fields of the cooling channel solenoids, that
100 are only partially shielded by a 100 mm thick annular iron plates. 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. The local shielding option was chosen, at the end, for convenience and easiness of implementation. As magnetic shielding is a mass effect, box-shaped soft iron shielding are more effective than cylindrical ones. This idea pioneered in the D0 experiment has been tested in the case of MICE
105 using different geometrical configuration for the iron shielding boxes and different iron materials (e.g. Fe360, ARMCO³, etc). The problem is usually the longitudinal component of the magnetic field, while the orthogonal component may be more easily shielded. Systematic studies have been done, using a built on purpose solenoid of 23 cm inner diameter, 40 cm length⁴ and are fully reported in reference [10]. A composite structure based on the 1 mm μ -metal shielding of the H6533Mod assemblies and an external additional $6 \times 6 \text{ cm}^2$ ($5.6 \times 5.6 \text{ cm}^2$)
110 ARMCO box, 15 cm long, with an internal hole of 3.2 cm diameter has been adopted for the PMT's magnetic shielding of TOF2 (TOF1) [11]. Fig. 1 show 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 ~ 6.6 cm of ARMCO thickness, with extra shielding effect due to the fact that all bars shielding the TOF2 PMTs are magnetically linked between them
115 and to both the KL shielding and the shielding plate making a single magnetic loop. Fig. 2 shows some steps

¹one-inch linear focused PMTs with 10 stages, typical gain $G \sim 5.7 \times 10^6$ at -2250 V and B=0 T, rise time 0.7 ns, transit time spread (TTS) ~ 160 ps

²CERN type C-50-6-1, with rated delay 4.08 ns/m

³ARMCO steel from AkSteel is a pure iron with a maximal carbon content of 0.025% and very high magnetic saturation

⁴built by TBM srl, Ubondo (VA), Italy

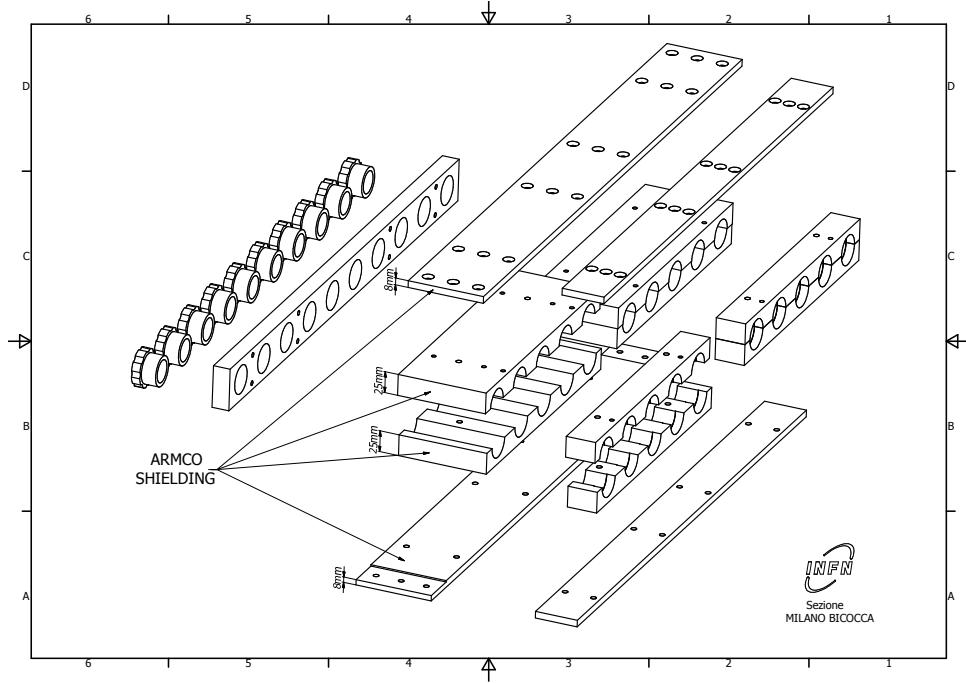


Figure 1: Exploded view of the TOF2 detector magnetic shielding for one row of PMTs.



Figure 2: Assembly of TOF2 at INFN MIB mechanics workshop. Left to right: from the bare magnetic shielding to the installed counters of a plane.

of the assembly procedure for the TOF2 detector at INFN MIB mechanics workshop.

The paragraph above is rather detailed, with many things that could be explained incorrectly. Should be made brief, unless full technical design description is required.

The following paragraph is summarising the performance. It states overly optimistic performance.

For what attains performances, TOF0, TOF1, and TOF2 had timing resolutions around 50-60 ps respectively (*currently observed ~ 110 ps*), over the 8 years running period, consistent with design requirements, with the spatial resolution around 1 cm. *We don't use any special reconstruction method. Resolution kept at 4 cm or 6 cm for TOF0 or TOF1 and TOF2 respectively. Do we say resolution = 1/2 of strip width or $1/\sqrt{12}$?* Fig. 3 shows distributions of the time of flight between TOF0 and TOF1 where electrons, muons and pions fall into three well defined peaks.

What is currently the main purpose of TOFs? This determines the requirements on the performance. Will need to tell that current T-o-F measurement has sufficient resolution, which appears to be $\sim 100\text{-}120$ ps

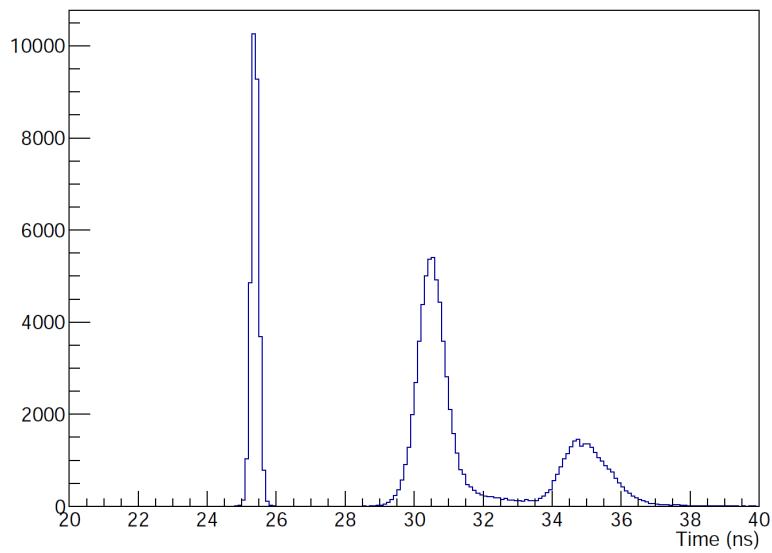


Figure 3: Time of flight between TOF0 and TOF1 for a “pion” beam. From the left: the well separated electron, muon and pion peaks.

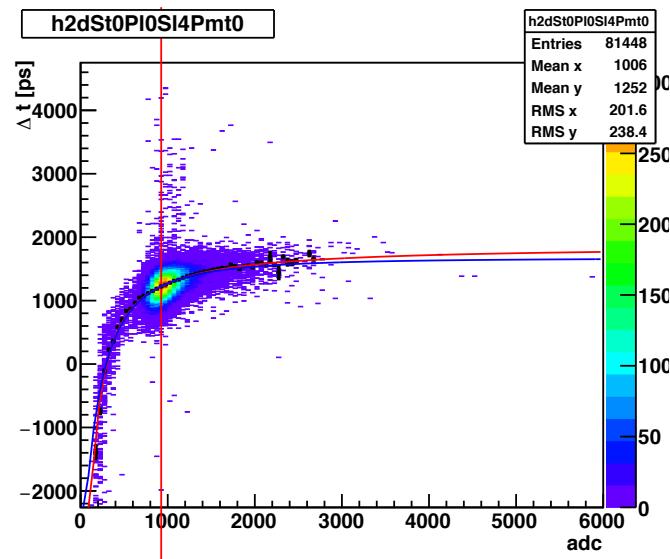


Figure 4:

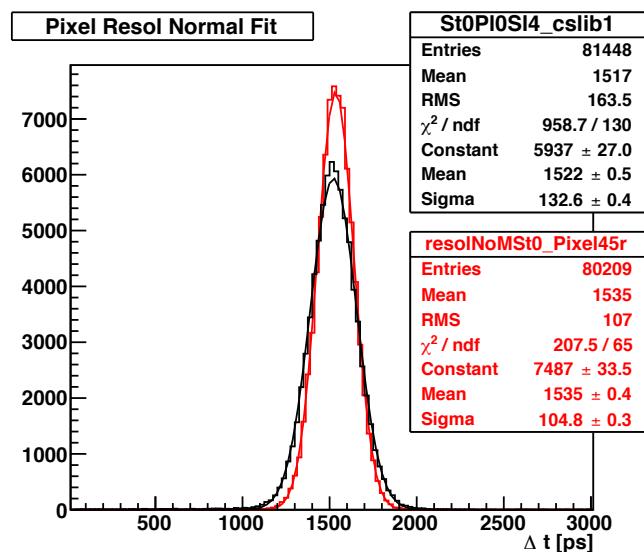


Figure 5:

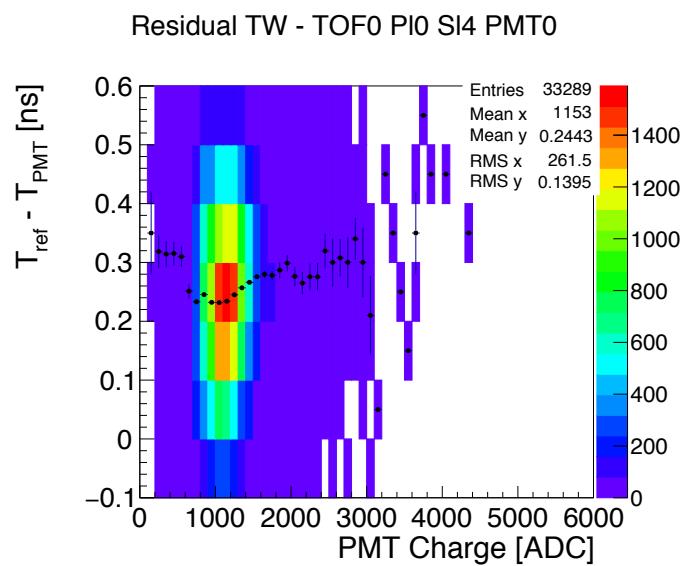


Figure 6:

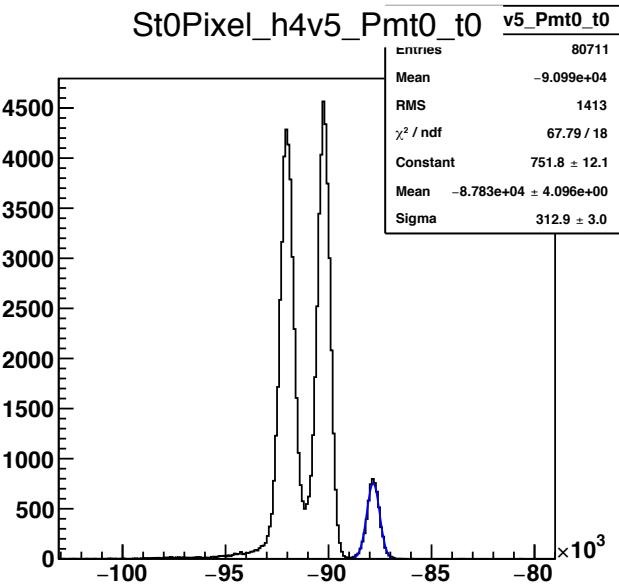


Figure 7:

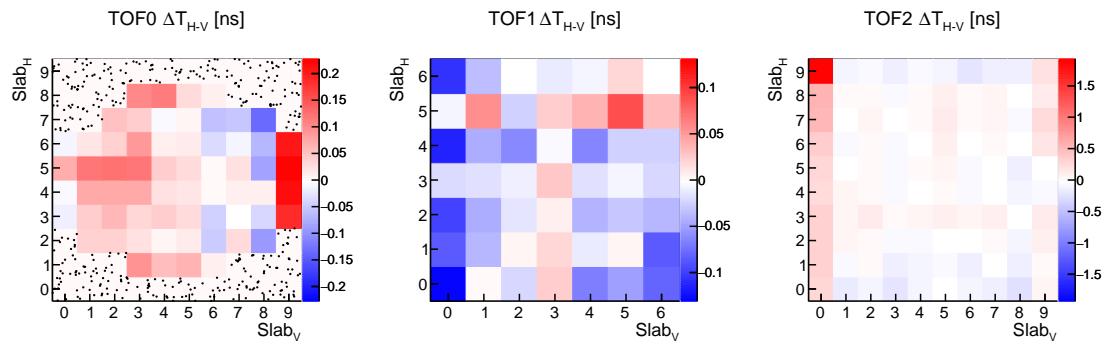


Figure 8:

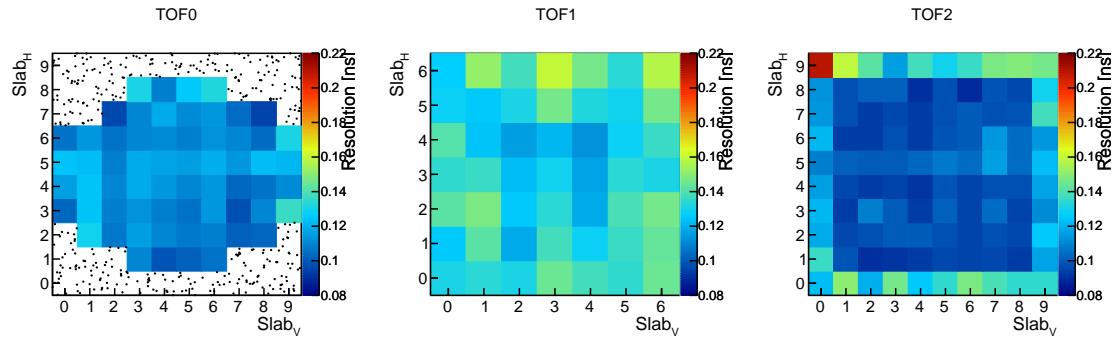


Figure 9:

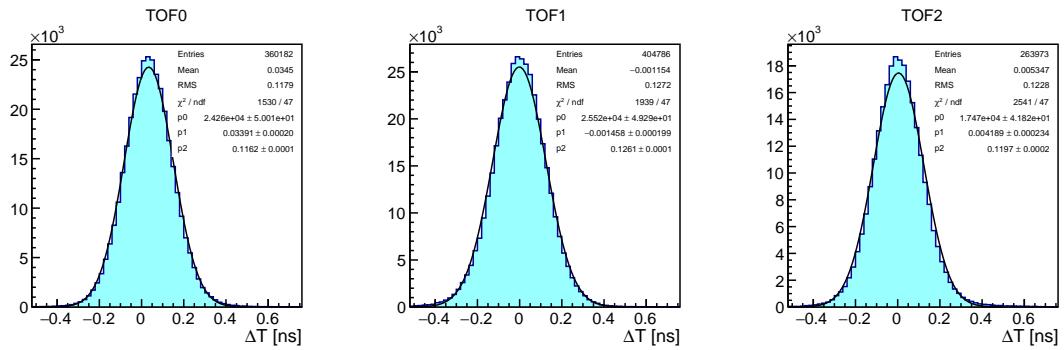


Figure 10:

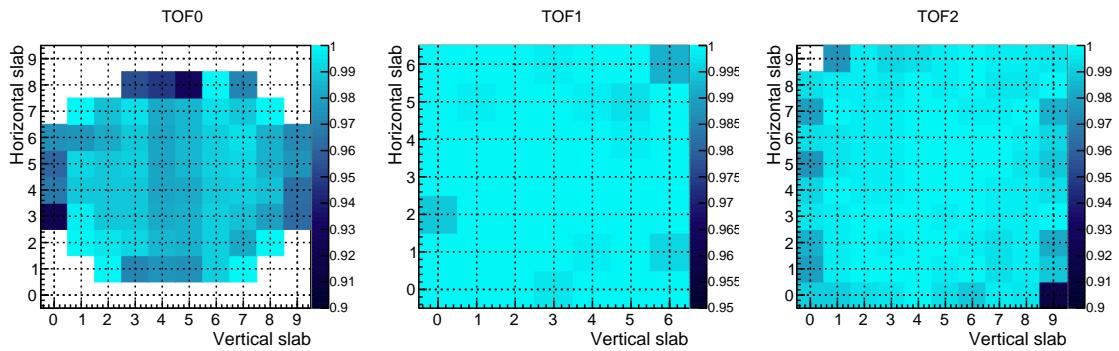


Figure 11:

2.2 TEMPORARY - Plots

2.3 Calibration Method

130 Describe the method. Based on MICE note 251.

TOF NIMA paper says that measured time resolution of the CAEN TDC was 22 ps/count, as opposed to declared 25 ps!

Some description of the calibration method is also described in the paper.

2.3.1 Time Walk Correction

135 *Fig of a selected PMT TW 2D hist. + Profile + Fit Fig of residual TW. Fig of Slab DT before TW correction and after.*

Time walk was considered to be constant property of each channel. The same correction was used for all runs.

2.3.2 Trigger Delay Correction

140 2.3.3 T0 Correction

2.4 Reconstruction

2.5 Performance

Several figures are already in the TOF NIMA paper.

Figures to show up here:

- 145
- Slab DT - selected slabs/counters + overall TOFs
 - ToF10 - + detail of electron peak
 - Space-point reconstruction efficiency - shows that slab hits are within the required cut, inefficiency from only single slabs hit by different particles in the given spill/bunch
 - particle detection efficiency - how to show?

150 2.5.1 Low-level Characterisation

- PMT charge correlation PMT0 vs PMT1 - maybe, if relevant
- Residual TW - this should go to the calibration section
- Slab DT

2.5.2 Time-of-Flight Resolution and Efficiency

- 155
- Resolution
 - Slab DT for all TOFs, show similar performance, although they have different construction.
 - Efficiency

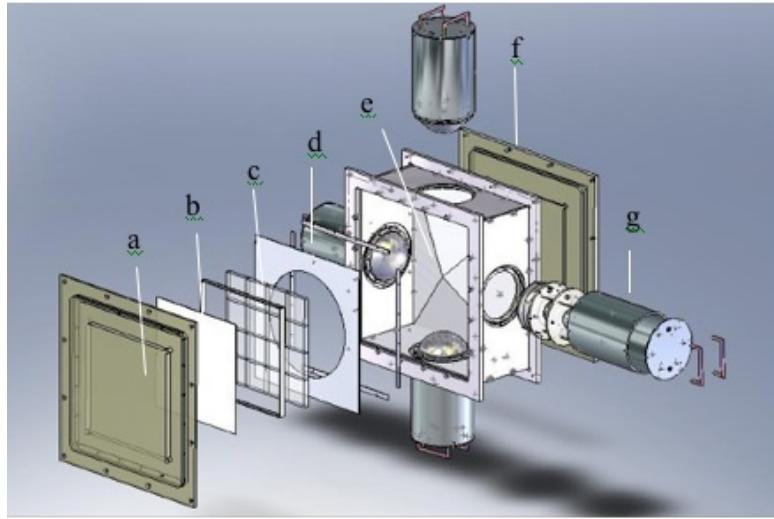


Figure 12: MICE aerogel Cherenkov counter blowup: a) entrance window, b) mirror, c) aerogel mosaic, d) acetate window, e) GORE reflector panel, f) exit window and g) 8 inch PMT in iron shield.

3 Cherenkov Detectors

3.1 Introduction

¹⁶⁰ The Cherenkov detectors are primarily designed to provide π - μ separation in the higher momentum ranges, where TOF separation is not sufficient for conclusive particle identification.

In order to provide separation over a large range of momenta, two high density silica aerogel Cherenkov detectors (CkovA and CkovB) with refractive indices $n=1.07$ and $n=1.12$ are used. They are each read out by four 200 mm photomultiplier tubes and placed directly one after another in the beamline, located just after the ¹⁶⁵ first TOF counter. In Fig. 12 an exploded view of one detector is shown.

Their respective thresholds provide different responses in four distinct momentum ranges, i.e. in the 200 MeV/c beams, pions are below the threshold which would fire the detector for both CkovA and CkovB whereas muons are above only for CkovB, while for the 240 MeV/c beams, pions are above the threshold for CkovB while muons are above for both CkovA and CkovB. Using this information algorithms can be written that ¹⁷⁰ produce likelihood distributions of particle type. Below the CkovB muon threshold of about 217.9 MeV/c, where there is no separation, the TOFs provide good separation, whereas the momentum range above the CkovA pion threshold (367.9) MeV/c is outside of the MICE running parameters [12].

3.2 Performance

4 KLOE-Light Calorimeter

4.1 Introduction

The KLOE-Light (KL) pre-shower sampling calorimeter is composed of extruded lead foils in which scintillating fibres are placed in volume ratio scintillator:lead $\sim 2:1$, “lighter” than the one of the KLOE experiment calorimeter (1:1).

The fibres are 1 mm diameter BICRON BCF-12, scintillating in the blue, 1.35 mm distant from each other

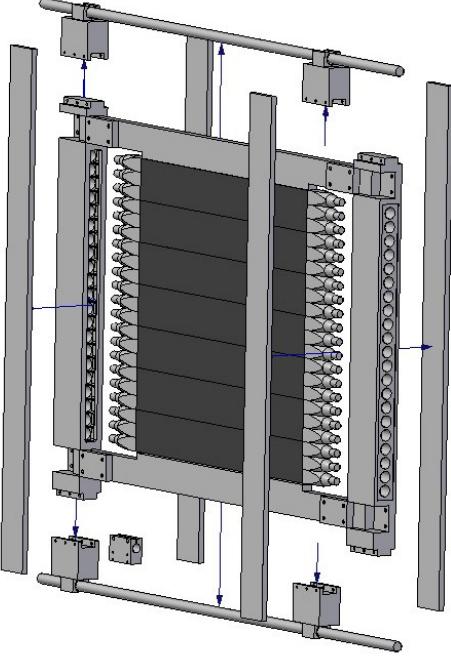


Figure 13: Magnetic shielding of KLOE-Light PMTs.

180 within a layer. The distance between two layers is 0.98 mm, one layer being shifted by half the fibre pitch with
 respect to the next. Scintillation light is guided from each slab into a total of six PMTs (three on each side).
 Iron shields are fitted to each photomultiplier to mitigate against large stray magnetic fields from the cooling
 channel (see Fig. 13). The signal from each PMT is sent to a shaping amplifier (SA) module, which shapes and
 stretches the signal in time in order to match the sampling rate of the flash ADCs (Fig. 14 shows the design of
 185 a single slab). A total of 7 slabs forms the whole detector, which has an active volume of 93 cm×93 cm×4 cm.

With its 2.5 radiation lengths the KL is used to distinguish muons from decay electrons providing energy deposition and timing information and to act as pre-shower in front of the EMR. The detector has been used to estimate the level of pion contamination within the MICE muon beams to be around 1% [8].

4.2 Performance

190 The study of KL response to different particle types at different momenta is based on particle identification obtained by time-of-flight detector, as shown in the example of Fig. 3, by applying proper cuts on the time-of-flight spectrum. The performance is presented for 140, 170, 200, 240 and 300 MeV/c momenta at the absorber position, and depending of species population for muons, pions and electrons. The results presented below are obtained from the straight tracks data (i.e. without magnetic fields in the trackers or focus coil) taken mainly
 195 in 2017. The KL response to muons, pions and electrons for all available momenta is presented in Fig. 15. It is clear in the cases of muons and pions that they are below mip momenta since energy deposition decreases with momentum increasing⁵.

⁵Actually the energy deposition is defined as the sum of ADC products from all cells in KL above a given threshold. The ADC product on the other hand is the product of left and right side of one slab divided by the sum of left and right side: $ADC_{prod} = 2 \times ADC_{left} \times ADC_{right} / (ADC_{left} + ADC_{right})$. The factor 2 is present for normalization. The product of two sides compensates the effect of attenuation.

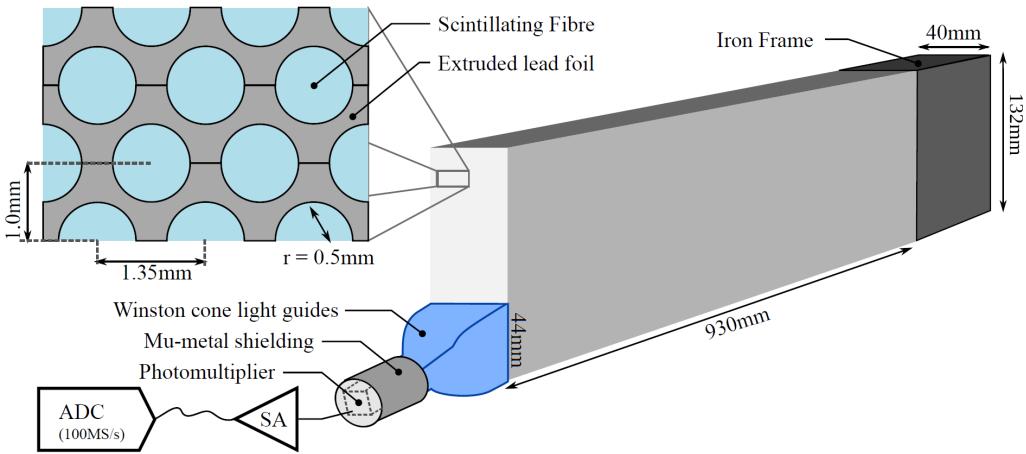


Figure 14: Single slab design of MICE KLOE-Light Calorimeter.

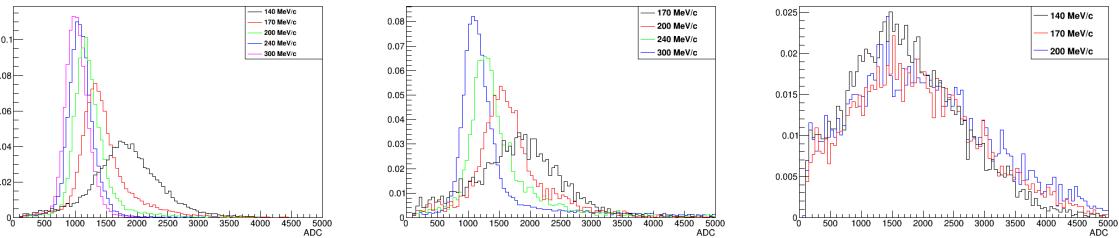


Figure 15: KL response to muons (left), pions (centre) and electrons (right) for several momenta. It is shown charge deposited by particles in KL in arbitrary units. All histograms are normalized to unity.

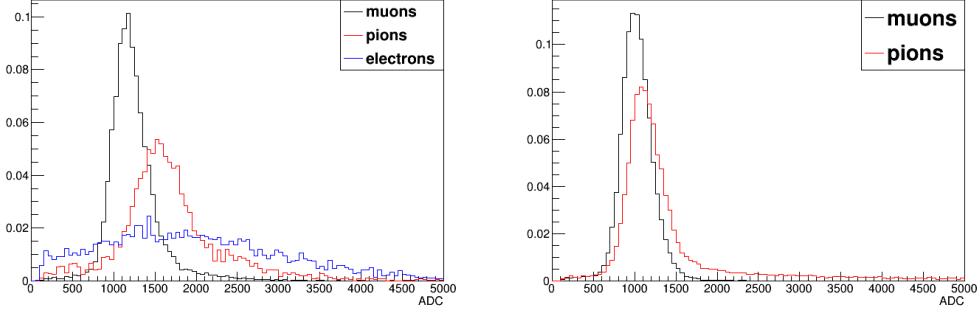


Figure 16: Comparison of energy deposition of muons, pions and electrons at 200 MeV/c (left) and of muons to pions at 300 MeV/c (right).

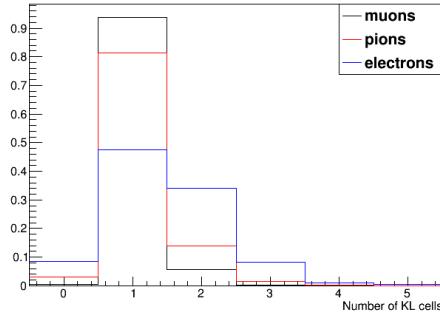


Figure 17: Particle multiplicity for 240 MeV/c, i.e. number of KL cells fired.

For comparison of energy deposition of muon, pions and electrons for fixed momentum Fig. 16 is presented. In the case of 300 MeV/c (Fig. 16, right), where muons and pions have almost the same maximum of distribution, the tail of pions is fatter than muon one. This is due to the fact that pions experience strong interaction as well. This pion behaviour has been used to estimate its contamination in muon sample.

The number of fired KL cells by a single muon, electron or pion is given in Fig. 17 for 240 MeV/c beam. For muons we expect one, in some cases two and almost never more fired cells depending on track inclination. Pions and electrons create avalanches in KL and electron ones is much wider than the pion ones as visible of number of KL cell hits. The same figure shows number of events when if there is a reconstructed TOF track, but no signal in KL above the threshold. This can be used to calculate efficiency of KL for the three species as a function of momentum. The results are presented in Table 1 and shows that efficiency for muon registration is close to 99%.

species	140 MeV/c	170 MeV/c	200 MeV/c	240 MeV/c	300 MeV/c
electrons	0.95 ± 0.02	0.95 ± 0.01	0.94 ± 0.03	n/a	n/a
muons	0.97 ± 0.02	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
pions	n/a	0.89 ± 0.03	0.95 ± 0.03	0.97 ± 0.03	0.98 ± 0.01

Table 1: Efficiency of KL for electrons, muons and pions as a function of particle momentum. The conditions required are existing of a TOF track and signal in KL above the threshold. The uncertainties are statistical.

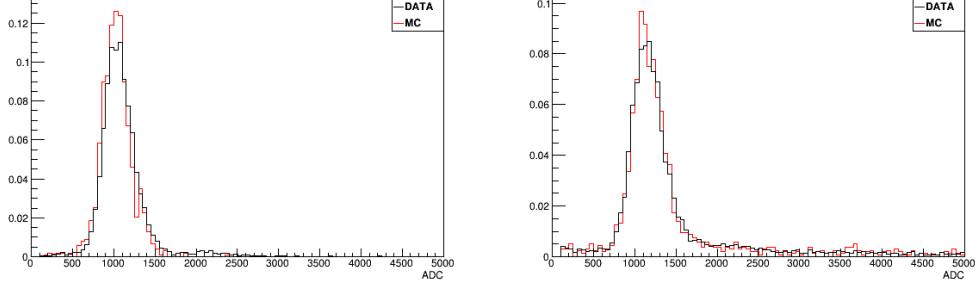


Figure 18: Comparison between data and Monte Carlo simulation of KL response to muons (left) and pions (right) at 300 MeV/c.

In Fig. 18 is shown simulation of KL response to 300 MeV/c muons and pions and the distributions are compared with data. The agreement between data and simulation is very good. The simulation is done via following steps:

- Smearing of produced photons in scintillator fibres. They obtain Poisson statistic so such is applied. In principle one can replace it with Gaussian because the number of photons created is large enough for such an approximation.
- Photoelectrons created on photomultiplier photocathode also have Poisson statistics. It cannot be replaced here with normal distribution because the number of photoelectrons is small enough so such an approximation is illegal.
- Photomultiplier gain obtains also statistical properties but it is neither Poisson nor gauss. Nevertheless it turns out that for simplicity one can use Gaussian distribution with mean value equals to PMT gain and sigma of distribution equals to half of the gain. KL photomultipliers have gain $\sim 2 \times 10^6$, so their sigma is simply 10^6 .

5 Electron Muon Ranger

5.1 Introduction

The Electron-Muon Ranger (EMR) is a fully-active scintillator detector [13]. It can be classified as a tracking-calorimeter as its granularity allows for track reconstruction. The EMR consists of extruded triangular scintillator bars arranged in planes. One plane contains 59 bars and covers an area of 1.27 m^2 . Each even bar is rotated by 180 degrees with respect to the odd one. A cross-section of bars and their arrangement in a plane is shown in Fig. 19. This configuration does not leave dead area in the detector for particles crossing a plane with angles that do not exceed 45 degrees with respect to the beam axis. Each plane is rotated through 90 degrees with respect to the previous one, such that a pair of planes defines a horizontal and vertical (x, y) interaction coordinate. The light, produced when a particle crosses a bar, is collected by a wave-length shifting (WLS) fibre glued inside the bar. At both ends, the WLS fibre is coupled to clear fibres that transport the light to a photomultiplier tube (PMT). Signals produced in a plane are read out collectively on one end by a single-anode PMT for an integrated charge measurement and separately on the other by a multi-anode PMTs for individual bar hit reconstruction. The full detector is composed of 24 X-Y modules for a total active volume of $\sim 1 \text{ m}^3$.

An array of analyses were conducted to characterize the hardware of the EMR and determine whether the detector performs to specifications [14]. The clear fibres coming from the bars were shown to transmit the

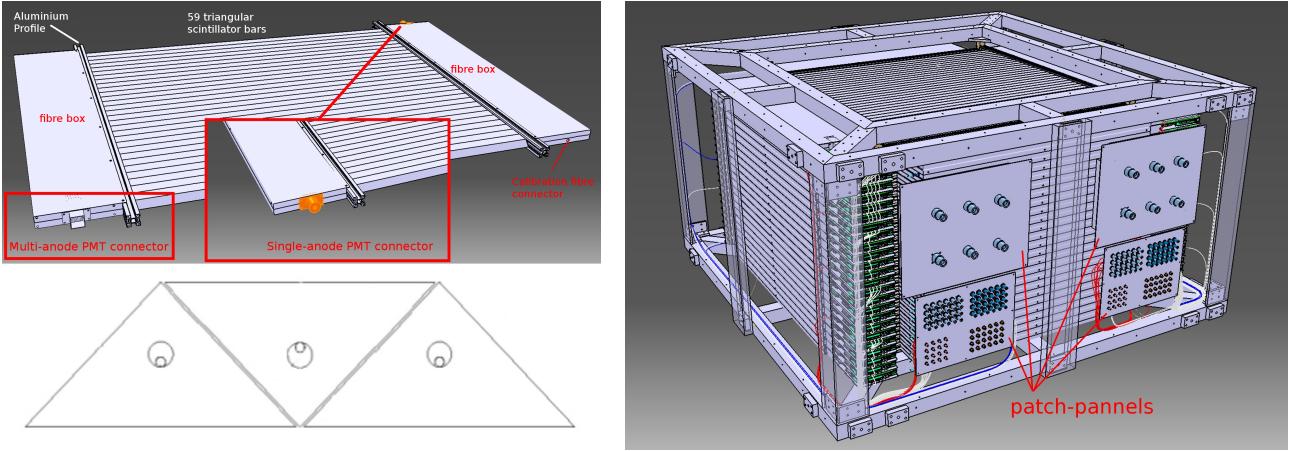


Figure 19: Drawing of one EMR plane (top left), cross section of 3 bars and their wavelength shifting fibres (bottom left) and drawing of the full detector (right).

desired amount of light, and only four dead channels were identified in the electronics. Two channels had indubitably been mismatched during assembly and the DAQ channel map was subsequently corrected. The level of crosstalk is within acceptable values for the type of multi-anode photomultiplier used with an average of $0.20 \pm 0.03\%$ probability of occurrence in adjacent channels and a mean amplitude equivalent to $4.5 \pm 0.1\%$ of the primary signal intensity. The efficiency of the signal acquisition, defined as the probability of recording a signal in a plane when a particle goes through it in beam conditions, reached $99.73 \pm 0.02\%$.

The primary purpose of the EMR is to distinguish between muons and their decay products, identifying muons that have crossed the entire cooling channel. Muons and electrons exhibit distinct behaviours in the detector. A muon follows a single straight track before either stopping or exiting the scintillating volume, while electrons shower in the lead of the KL and create a broad cascade of secondary particles. Two main geometric variables, the plane density and the shower spread, are used to differentiate them. The detector is capable of identifying electrons with an efficiency of 98.6 %, providing a purity for the MICE beam that exceeds 99.8 %. The EMR also proved to be a powerful tool for the reconstruction of muon momenta in the range 100–280 MeV/c [15].

5.2 Performance

6 The Trackers

6.1 Introduction

MICE is equipped with two identical, high precision scintillating-fibre ("sciFi") trackers, described in [1]. Each tracker is placed in a superconducting solenoid designed to provide a uniform field over the tracking volume. One tracker, TKU, is upstream of the cooling cell, the other, TKD, downstream. Each tracker consists of five detector stations, labelled 1 to 5, with the stations placed varying distances apart to help resolve ambiguities. The trackers are placed symmetrically about the cooling cell, with station 1 the nearest to the cooling cell for both. Each station is formed of three planes of $350\mu m$ scintillating-fibres, orientated at 120 degrees to one another. Each plane consists of two layers. The fibres in each plane butt up to each other and the two layers are offset with respect to each other by a fibre radius. A charge particle will then deposit energy in at least $350\mu m$ of scintillator, providing uniform response over the whole station face. The doublet layers are glued

to a sheet of mylar and the fibres are adjacent groups of seven fibres form one read-out channel. The three views are referred to as U, V and W, with the order being identical for each station and the U fibres running vertically. The light from the seven scintillating fibres passes into a single clear fibre, which takes it to a visible light photon counter (VLPC) which operate at 9k. The signal from the VLPCs is digitised using electronics developed by the D0 collaboration[2].

6.2 Tracker Performance and Reconstruction

6.2.1 Low Level Analysis

Low level analysis including digits, to spacepoints, 2 pages, Melissa U.

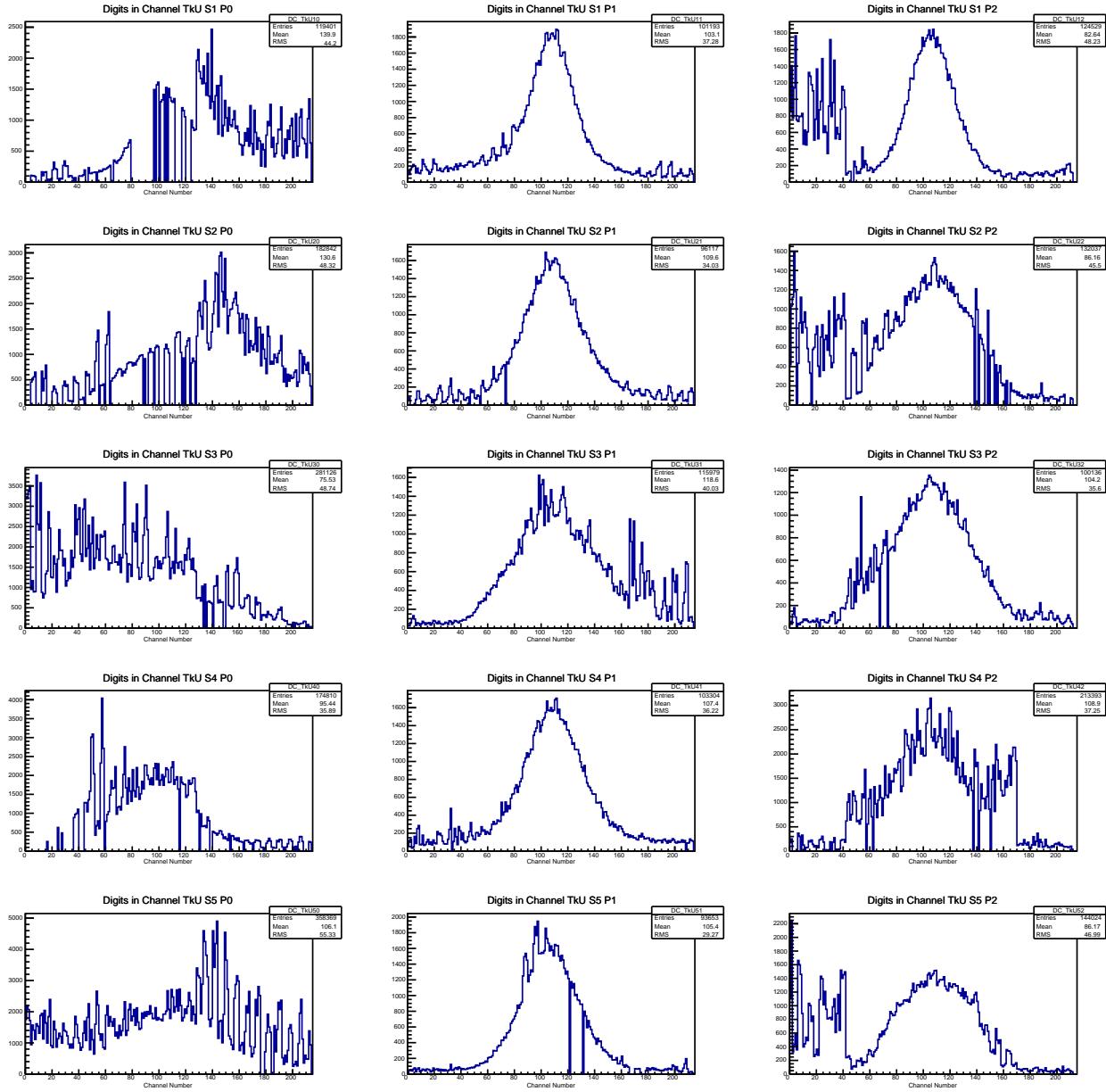


Figure 20:

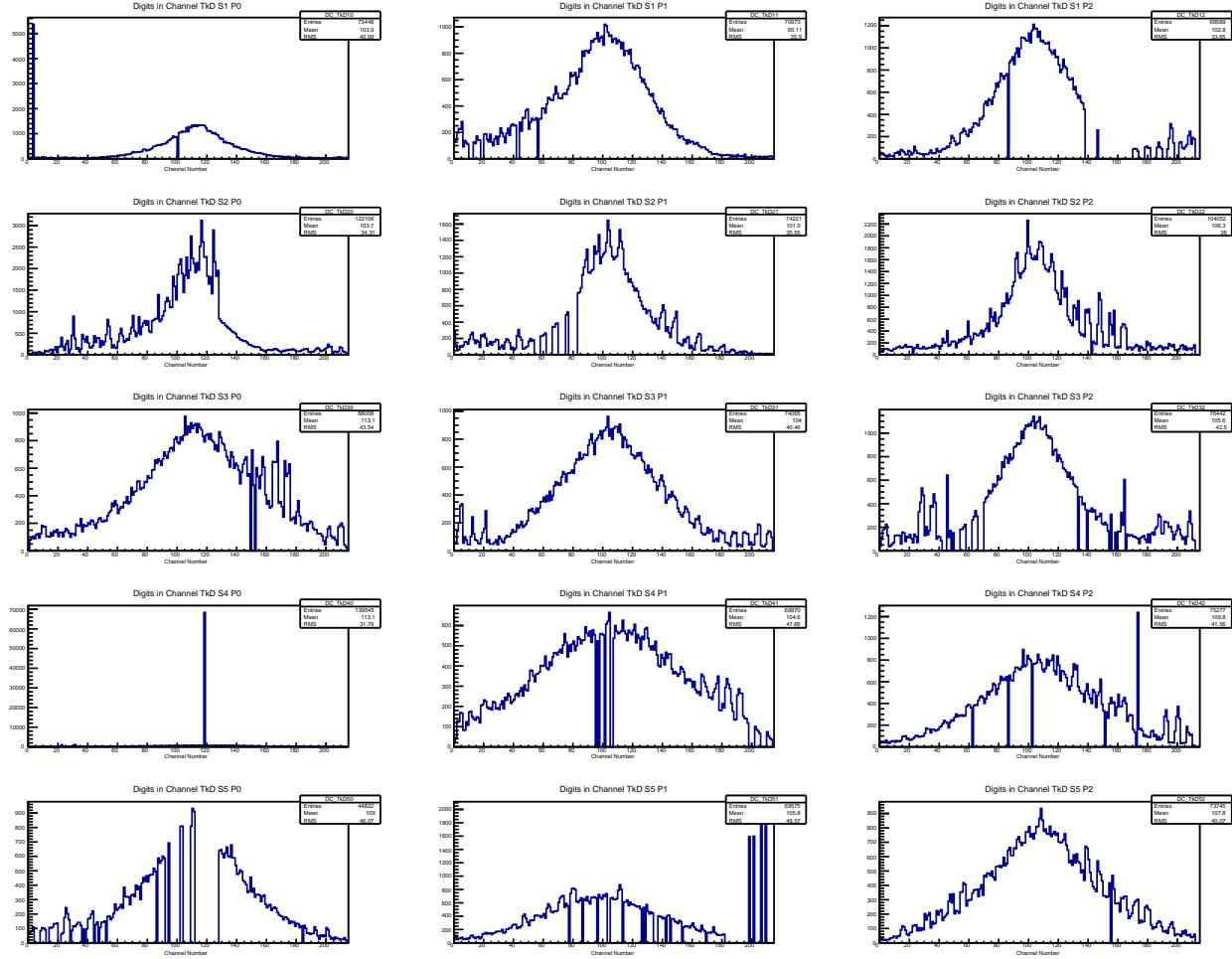


Figure 21:

6.2.2 Noise

Noise at electronics level discussion, 1/2 page, Chris H and Noise from data, 1/2 page, Chris H

6.2.3 Track Finding Efficiency

Track selection/Kalman, efficiency (from all data runs plotted by pt and if all equal just 10mm can be shown)

275 resolution (from MC), reference MAUS and Tracker SW paper, 1 page, Chris H.

6.2.4 Track Fit Predicted Performance

Monte Carlo simulation used with realistic field and beam conditions in order to estimate the reconstruction performance. Run number 09964 was used, representing a typical data set used for the study of emittance evolution.

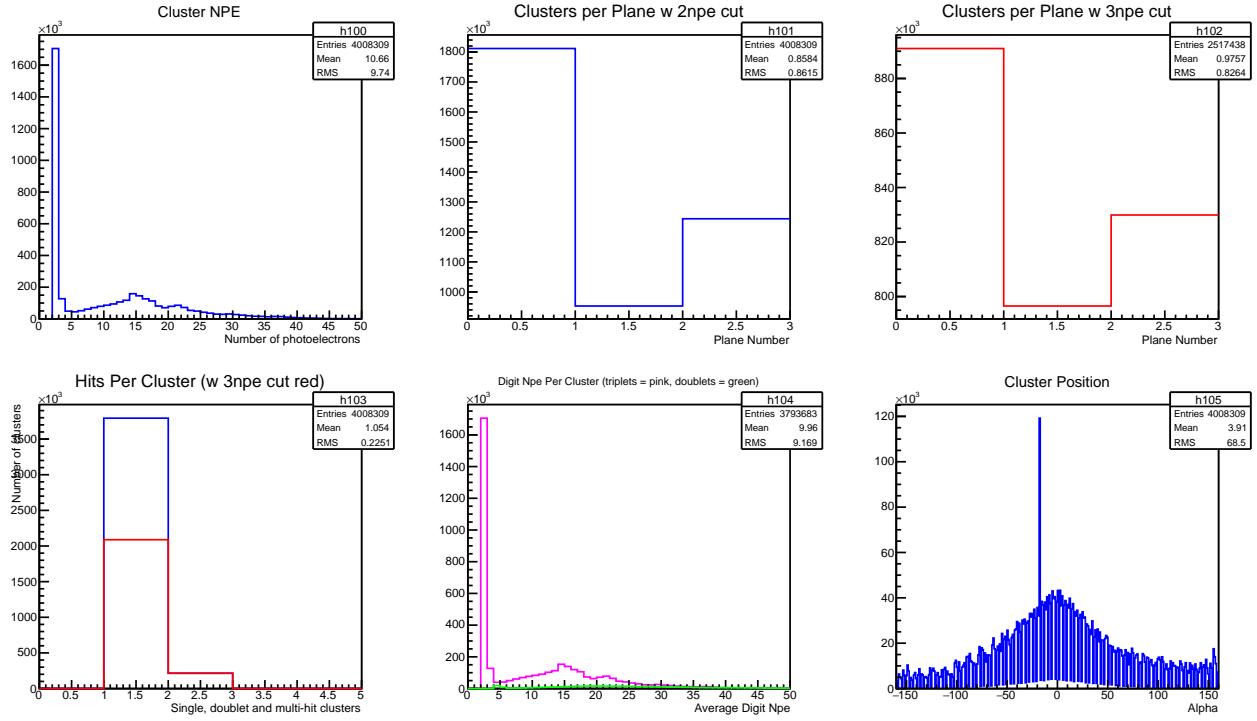


Figure 22:

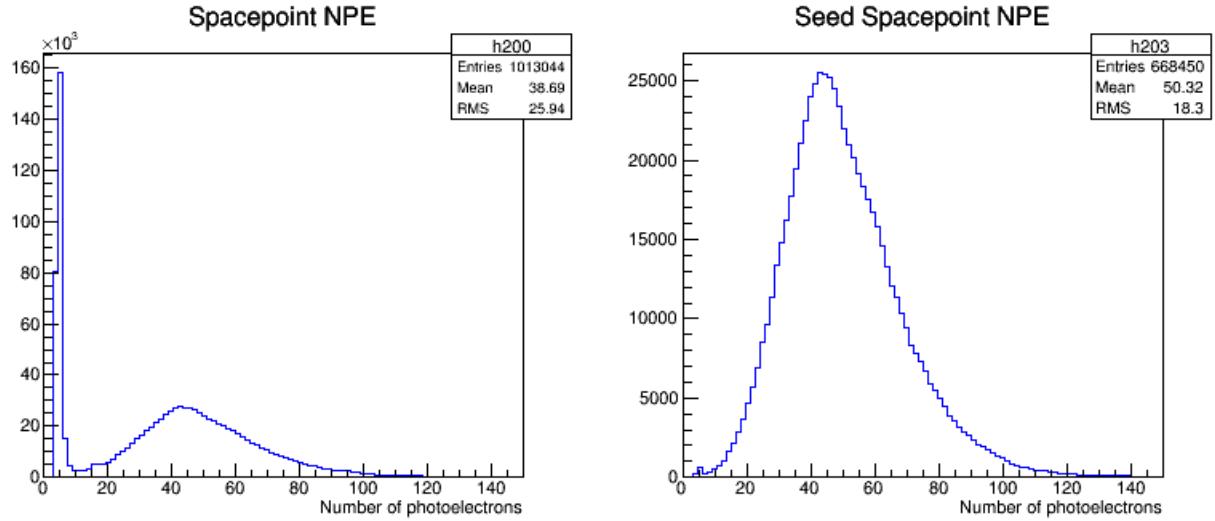


Figure 23: [left] The NPE of each spacepoint in the US and DS trackers combined. [Right] only the NPE of those spacepoints which go on to make tracks in the US and DS trackers combined are shown.

280 6.3 Tracker Efficiency Evolution

Tracker efficiency with time (maybe 1 runs every 3 months since start shown?), 1/2 page, Paul K.

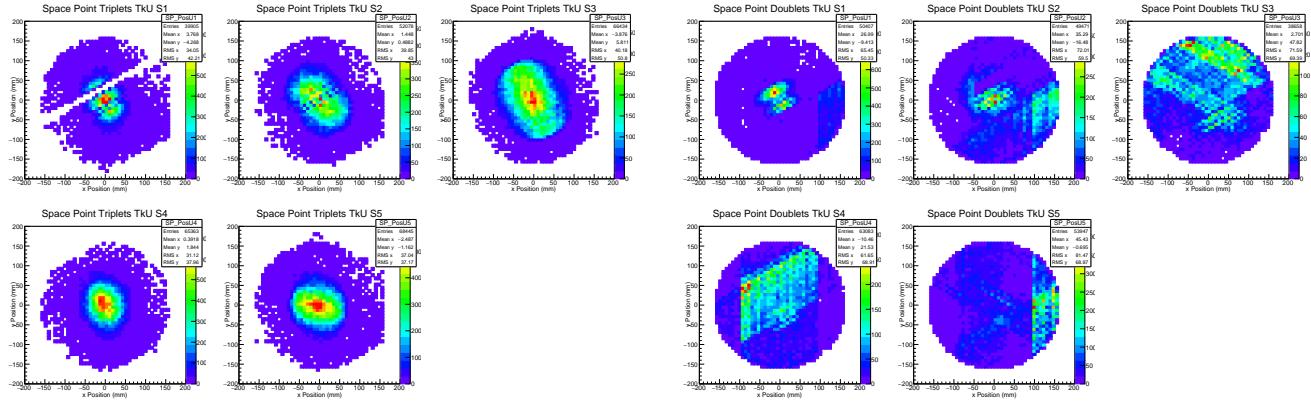


Figure 24:

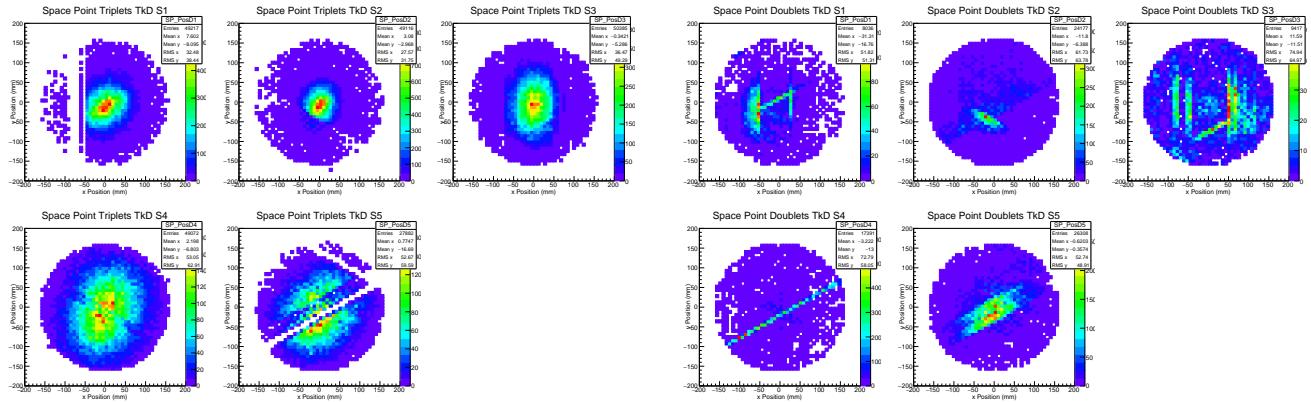


Figure 25:

7 PID

7.1 Introduction

7.2 Performance of the PID

285 8 Track Matching

8.1 Global reconstruction

The overall detector performance can be validated by extrapolating tracks from one detector to another and comparing the reconstructed coordinates with the extrapolated values. Tracks measured in the upstream tracker are extrapolated upstream to ToF1 and ToF0, and downstream to TKD and ToF2. Where there are materials in the beamline, the energy change on passing through the material is estimated using the most probable energy loss. Material thicknesses are approximated by the on-axis thickness.

290 Asymmetric effects can be introduced due to scattering from the walls of the cooling channel as the beam is not symmetric in the channel. In order to minimise the effects of such scattering, only events whose projected trajectory is significantly distant from the apertures are considered in this analysis. The following sample selection is considered:

- Downstream sample: Events must be included in the downstream sample to be considered in this analysis

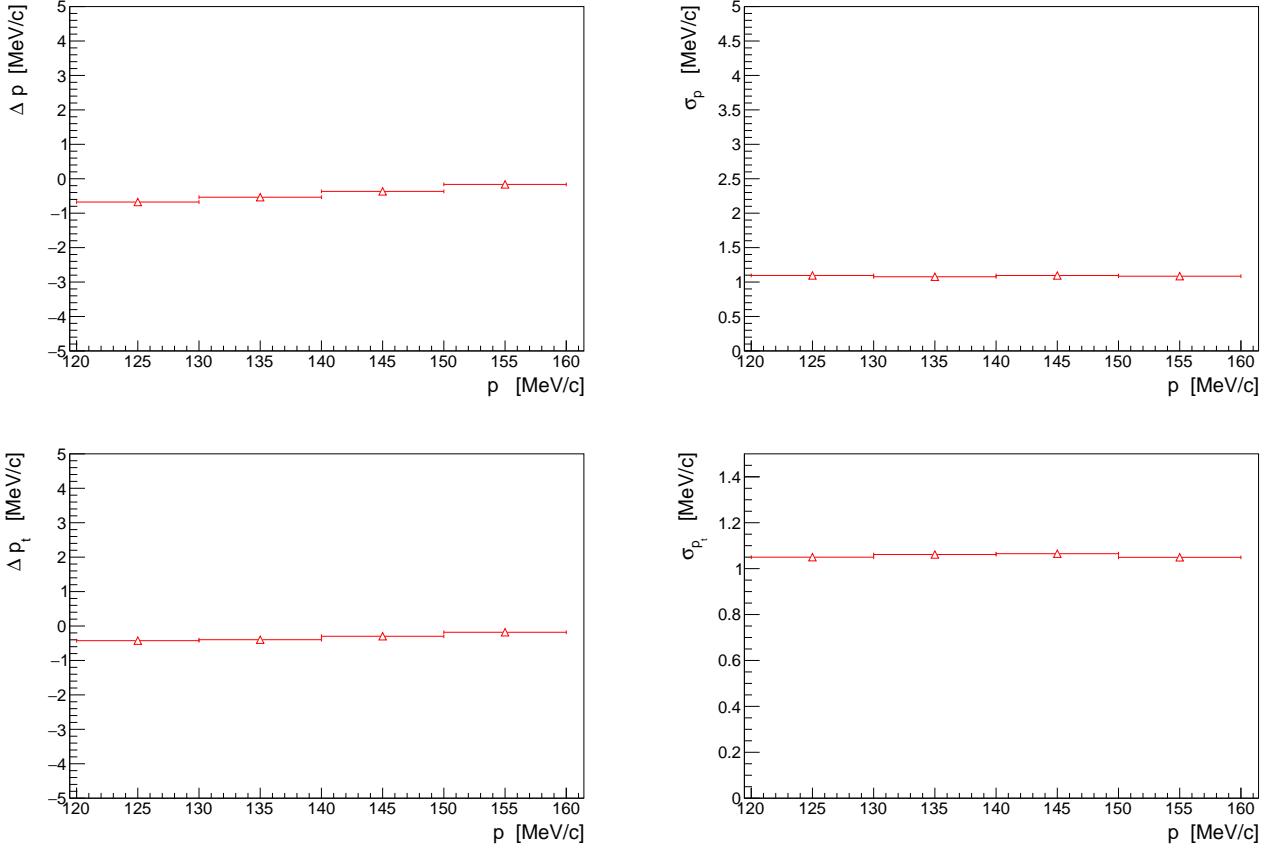


Figure 26: Predicted momentum reconstruction bias (left) and resolution (right) for the longitudinal (top) and transverse (bottom) momentum components in the upstream tracker.

- Aperture cut: The projected upstream track must be within 100 mm radius from the beam axis at the following apertures: the upstream absorber safety window; the upstream absorber window; the absorber centre; the downstream absorber window; the downstream absorber safety window; the upstream edge of SSD; the Helium window in SSD; the downstream edge of the downstream PRY aperture. This is performed even when the LH2 absorber was not installed, for the sake of consistency and because in some instances mounting flanges can limit the aperture and consistency.
- 1 space point in ToF2: The event must have exactly one space point in ToF2.
- Successful track extrapolation to ToF2: The projected upstream track must have been successfully extrapolated to ToF2

The sample sizes are shown for data in table 2 and 3. The equivalent MC sample sizes are listed in 4 and 5.

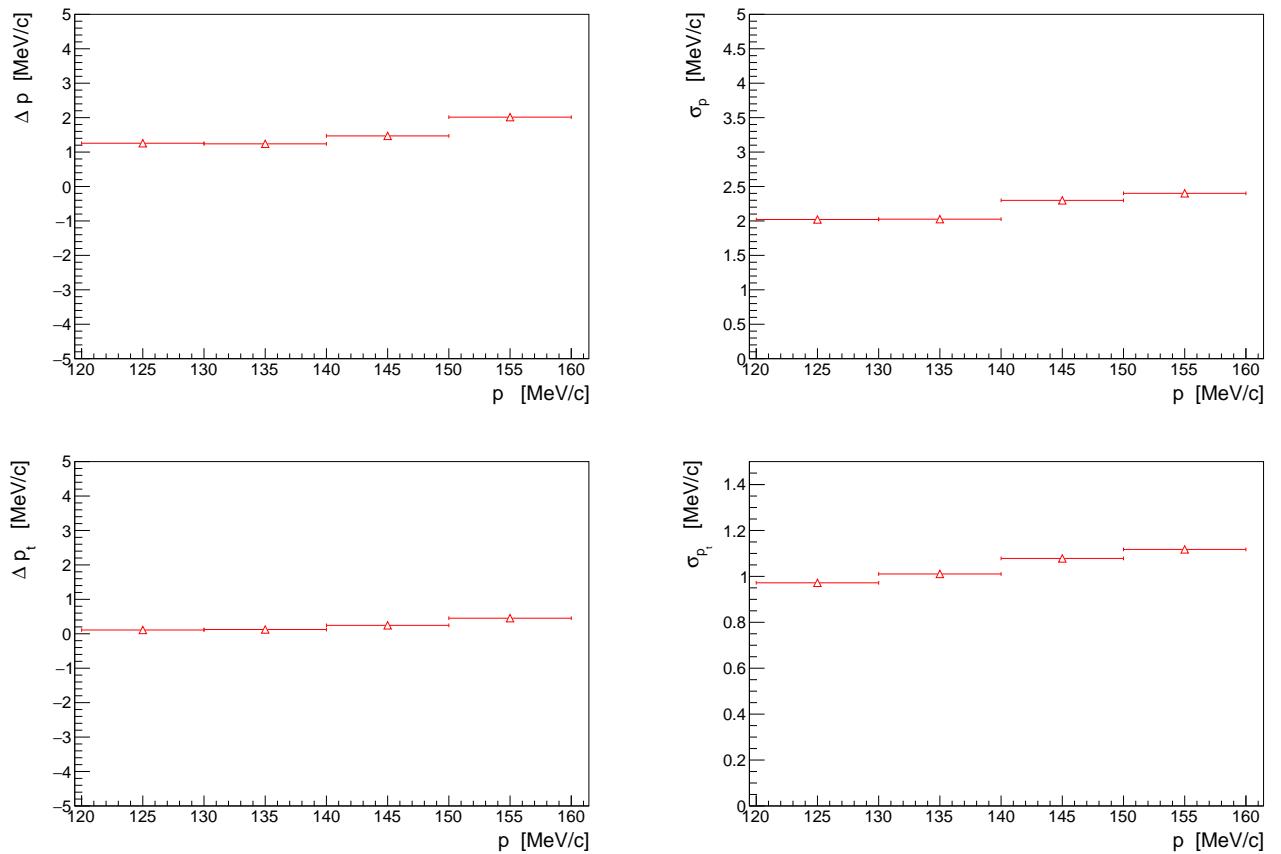


Figure 27: Predicted momentum reconstruction bias (left) and resolution (right) for the longitudinal (top) and transverse (bottom) momentum components in the downstream tracker.

Table 2: The extrapolated reconstructed data sample is listed. Samples are listed for 3-140 and 4-140 datasets.

	2017-2.7 3-140 None	2017-2.7 3-140 IH2 empty	2017-2.7 3-140 IH2 full	2017-2.7 3-140 LiH	2017-2.7 4-140 None	2017-2.7 4-140 IH2 empty	2017-2.7 4-140 IH2 full	2017-2.7 4-140 LiH
Downstream Sample	13019	8688	9058	11918	29712	23726	8407	24024
Cooling channel aperture cut	7203	4721	5166	6836	17731	14571	4935	14293
One space point in ToF2	6935	4506	4885	6477	16800	13817	4596	13362
Successful extrapolation to TKD	6935	4506	4885	6477	16800	13817	4596	13362
Successful extrapolation to ToF2	6935	4506	4885	6477	16800	13817	4596	13362
Extrapolation Sample	6935	4506	4885	6477	16800	13817	4596	13362

Table 3: The extrapolated reconstructed data sample is listed. Samples are listed for 6-140 and 10-140 datasets.

	2017-2.7 6-140 None	2017-2.7 6-140 IH2 empty	2017-2.7 6-140 IH2 full	2017-2.7 6-140 LiH	2017-2.7 10-140 None	2017-2.7 10-140 IH2 empty	2017-2.7 10-140 IH2 full	2017-2.7 10-140 LiH
Downstream Sample	27025	17783	29577	31257	14847	7278	14784	17138
Cooling channel aperture cut	15238	10129	16045	17122	5633	2837	5057	6075
One space point in ToF2	14432	9479	14826	15774	5276	2614	4471	5372
Successful extrapolation to TKD	14432	9479	14826	15774	5276	2614	4471	5372
Successful extrapolation to ToF2	14432	9479	14826	15774	5276	2614	4471	5372
Extrapolation Sample	14432	9479	14826	15774	5276	2614	4471	5372

Table 4: The extrapolated reconstructed simulated sample is listed. Samples are listed for 3-140 and 4-140 datasets.

	Simulated 2017-2.7 3-140 None	Simulated 2017-2.7 3-140 IH2 empty	Simulated 2017-2.7 3-140 IH2 full	Simulated 2017-2.7 3-140 LiH	Simulated 2017-2.7 4-140 None	Simulated 2017-2.7 4-140 IH2 empty	Simulated 2017-2.7 4-140 IH2 full	Simulated 2017-2.7 4-140 LiH
Downstream Sample	8585	8567	8511	8624	18247	18247	18455	18553
Cooling channel aperture cut	5112	4715	5032	5378	10884	10997	10758	10404
One space point in ToF2	4540	4184	4499	4820	9544	9747	9467	9117
Successful extrapolation to TKD	4540	4184	4499	4820	9544	9747	9467	9117
Successful extrapolation to ToF2	4540	4184	4499	4820	9544	9747	9467	9117
Extrapolation Sample	4540	4184	4499	4820	9544	9747	9467	9117

Table 5: The extrapolated reconstructed simulated sample is listed. Samples are listed for 6-140 and 10-140 datasets.

	Simulated 2017-2.7 6-140 None	Simulated 2017-2.7 6-140 IH2 empty	Simulated 2017-2.7 6-140 IH2 full	Simulated 2017-2.7 6-140 LiH	Simulated 2017-2.7 10-140 None	Simulated 2017-2.7 10-140 IH2 empty	Simulated 2017-2.7 10-140 IH2 full	Simulated 2017-2.7 10-140 LiH
Downstream Sample	17810	18031	18188	18259	8843	9029	9155	9294
Cooling channel aperture cut	10289	10071	9449	9906	3424	3393	3227	3337
One space point in ToF2	9014	8766	8219	8577	2941	2926	2772	2861
Successful extrapolation to TKD	9014	8766	8219	8577	2941	2926	2772	2861
Successful extrapolation to ToF2	9014	8766	8219	8577	2941	2926	2772	2861
Extrapolation Sample	9014	8766	8219	8577	2941	2926	2772	2861

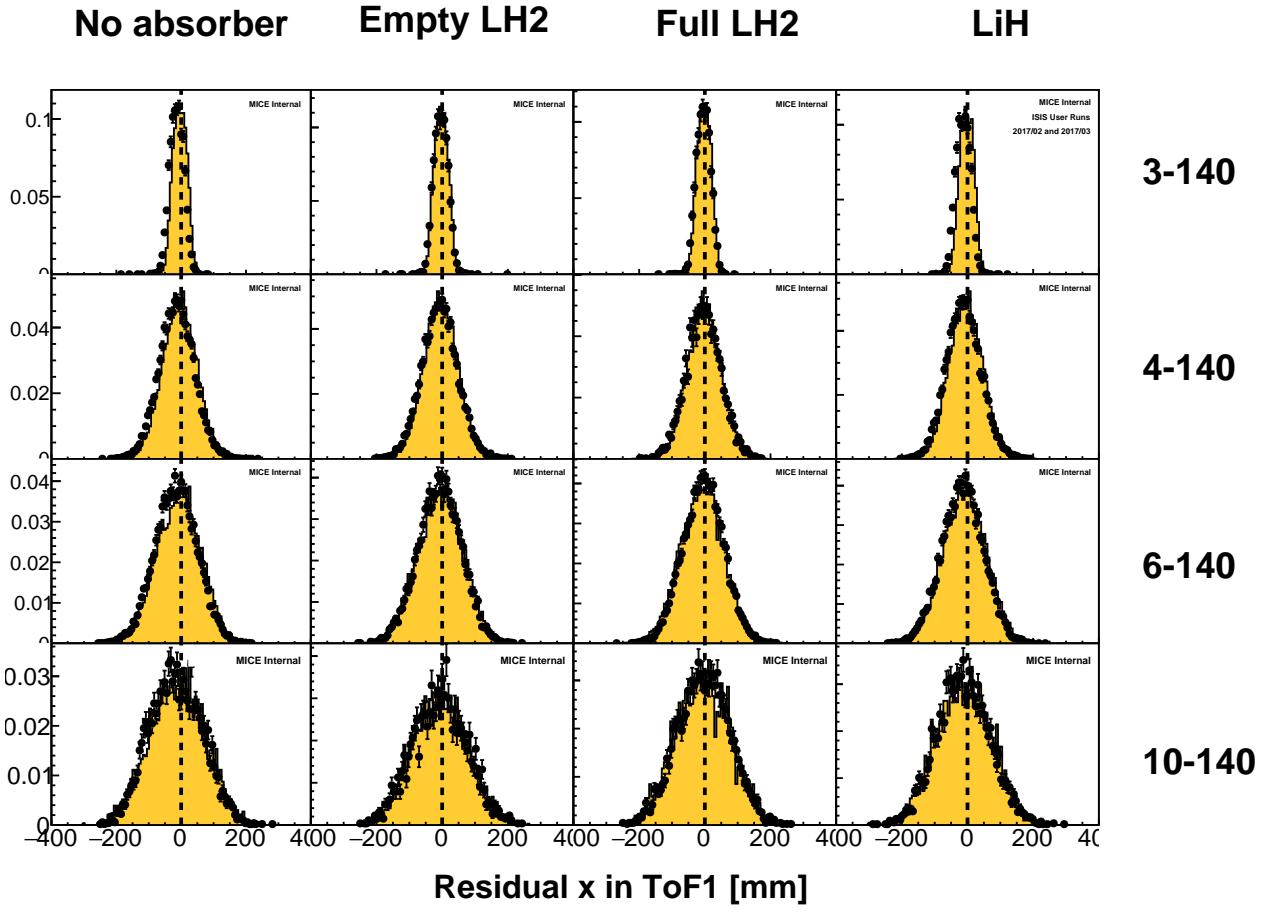


Figure 28: Residual horizontal (x) position in ToF1 of tracker tracks following extrapolation from TKU.

The extrapolated position following extrapolation to ToF1 is shown in fig. 28 and 29. In general the width of the distributions are comparable between MC and data. Where the diffuser is in place for higher emittance beams, the extrapolation goes through the diffuser material so the residuals are wider, owing to the increased
310 scattering from the diffuser.

The time-of-flight residual in data shows a systematic offset from 0 and relative to the MC. The offset from 0 gets worse for higher emittance beams. It is thought to be an intrinsic property of the beam; muons that are scattered in materials between the tracker and the TOF have systematically shorter path lengths than the
315 extrapolated trajectories, resulting in systematically longer extrapolated time of flight. The MC reconstruction is known to have issues, as evidenced by the discrepancy in slab dt for ToF0 and ToF1.

Plot momentum vs dt for ToF01 and ToF12

Small misalignments between TKU extrapolated tracks and TKD are observed, indicated by the offset of transverse variables from 0, shown in fig. 31 and 32. There are known, uncorrected misalignments in the detector system and there are expected to be additional misalignments in the magnets which could lead to these
320 offsets.

The total momentum shows discrepancy between TKU and TKD of about 1 MeV/c. This is consistent with the systematic offset in the tracker momentum resolution shown in fig. ?? and ???. It is interesting to note that the level of agreement between MC and data varies on a setting-by-setting basis in a statistically significant manner. Agreement is better for the settings where the liquid hydrogen windows were installed.

325 Further small misalignments are observed in the position residuals between TOF2 and tracks extrapolated

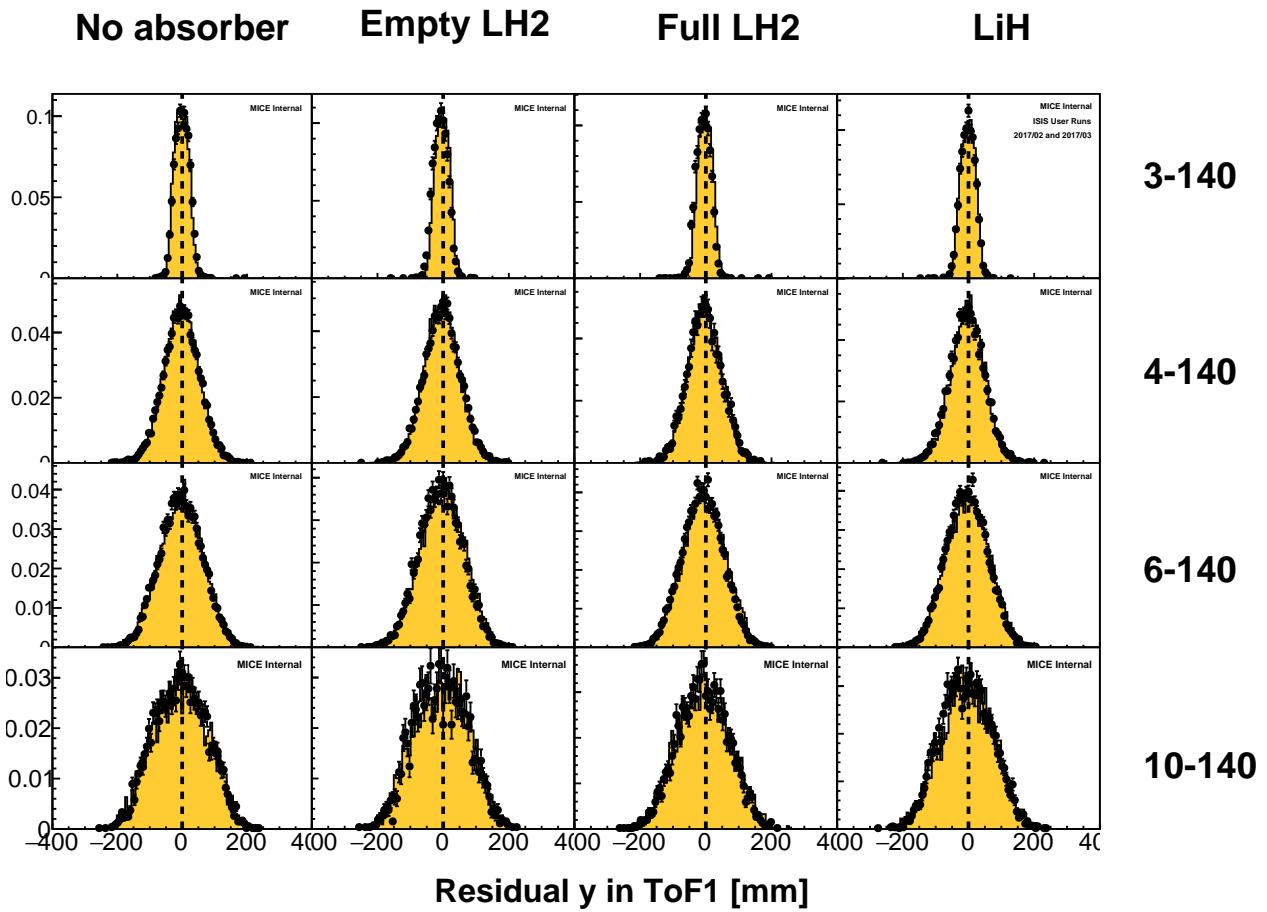


Figure 29: Residual vertical (y) position in ToF1 of tracker tracks following extrapolation from TKU.

from TKD. This is attributed to alignment issues.

TOF2 exhibits a significant offset from the extrapolated track.

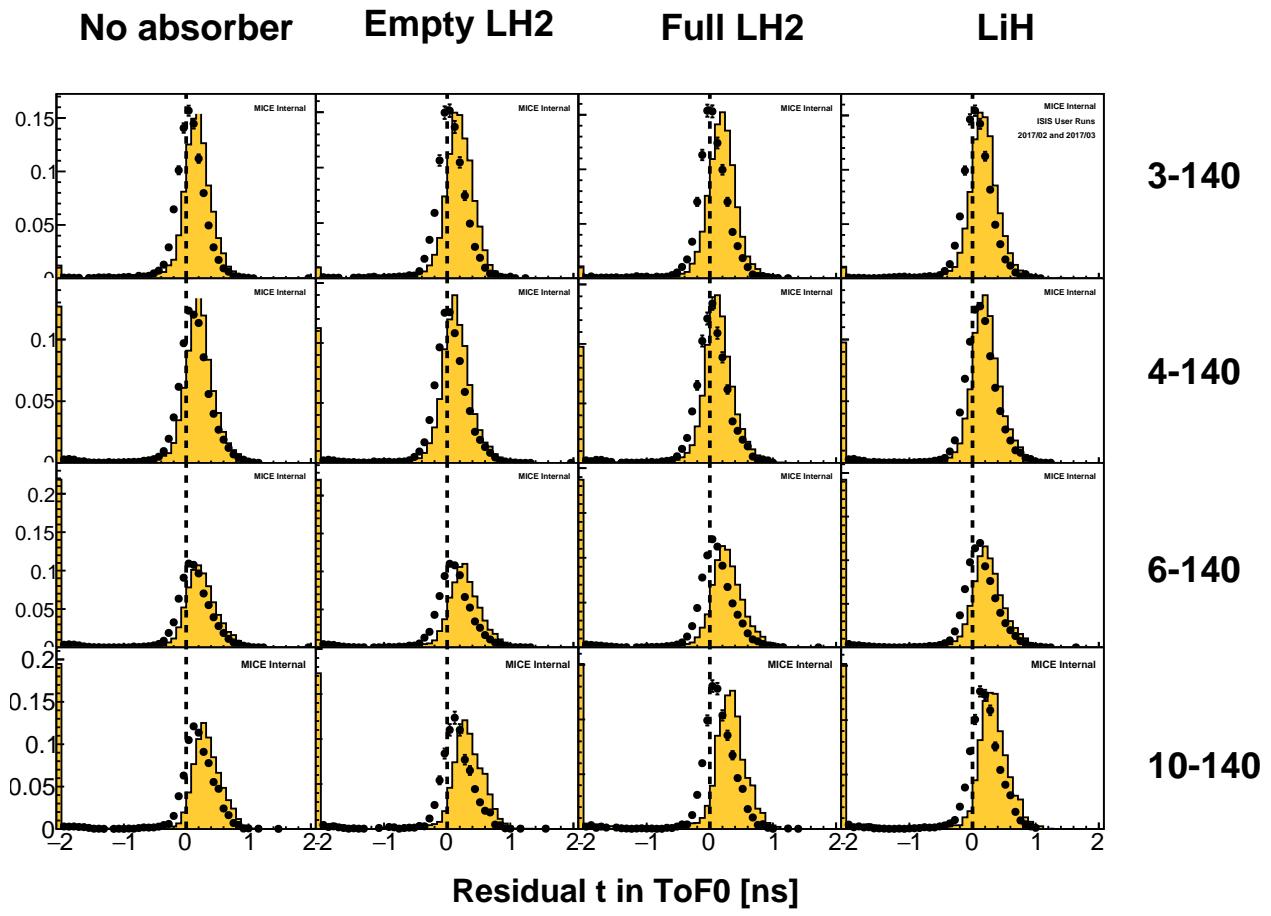


Figure 30: Residual ToF0 time of the extrapolated track. Track trajectories were drawn from TKU, while the track times were drawn from ToF1 with appropriate offsets for time-of-flight from TKU to ToF1 considered.

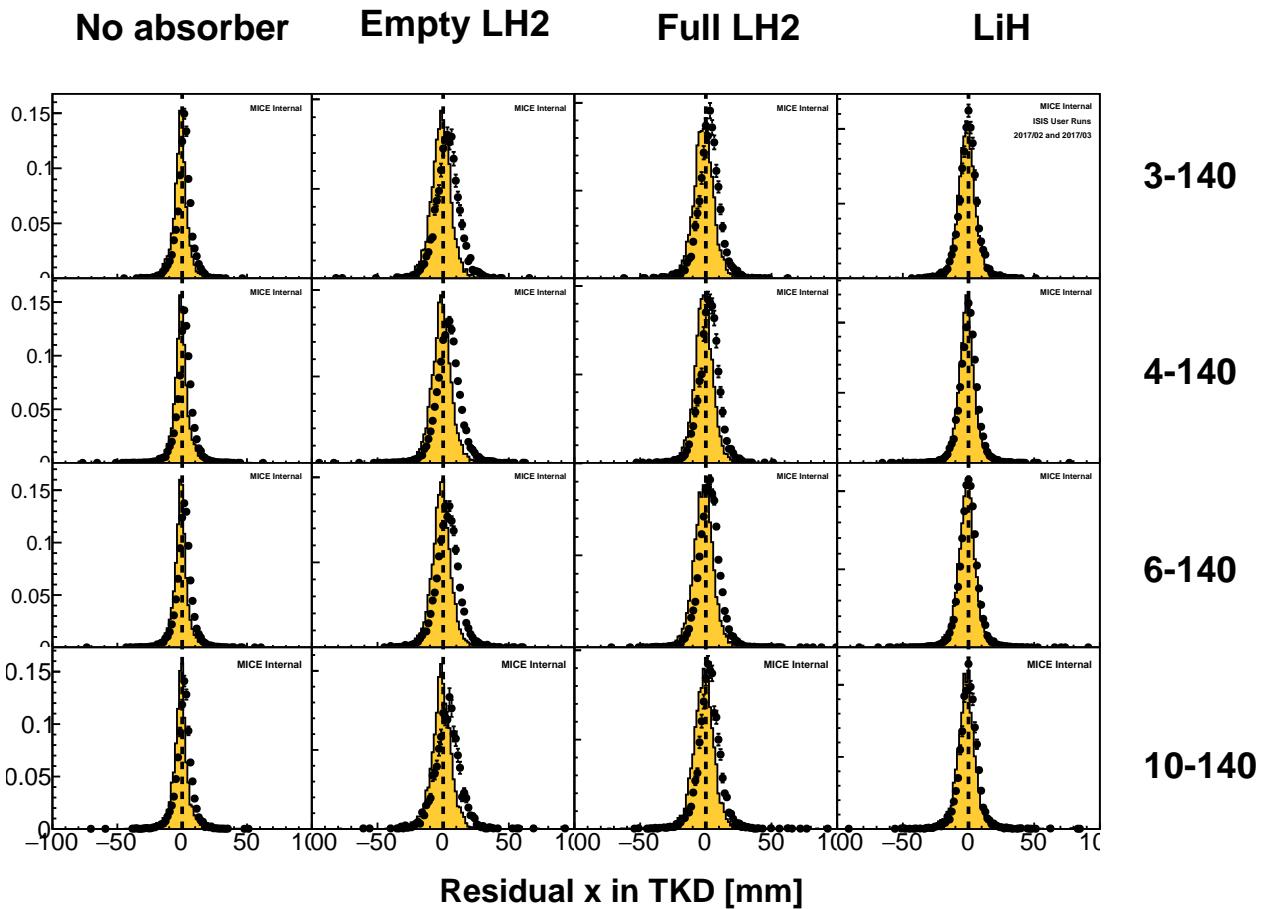


Figure 31: Residual x position of TKU tracks extrapolated to TKD, as compared to the tracks in TKD.

8.2 Beam based magnet alignment

9 Detector alignment

330 9.1 Introduction

9.2 Beam based detector alignment

10 Magnets and Beam Optics

10.1 Introduction

10.2 Beam based magnet alignment

335 10.3 Beam line optics

11 Absorber

As a muon beam passes through material, some of the kinetic energy of the muons is lost through ionization of the material. This process results in a reduction of the normalised transverse emittance and the beam is said to

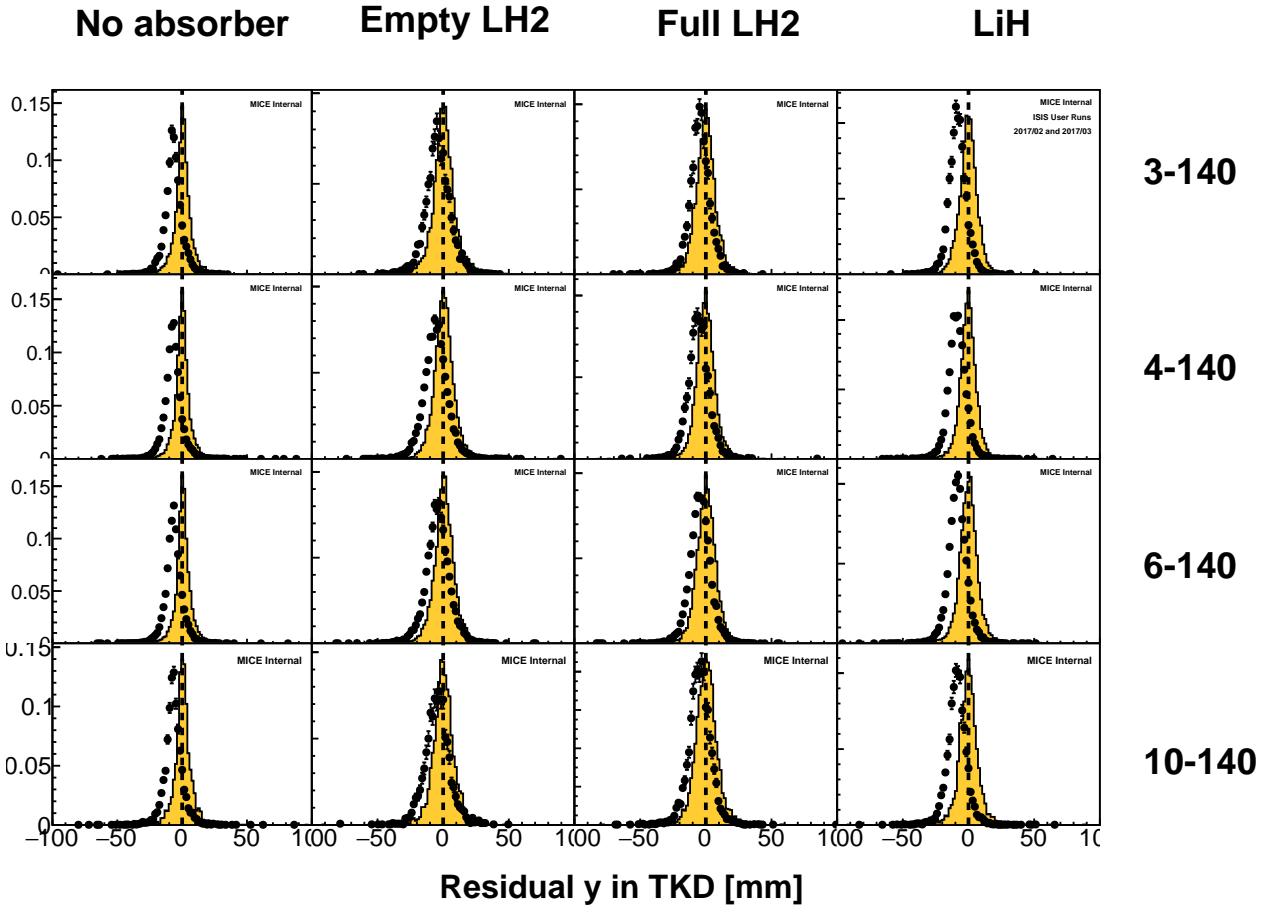


Figure 32: Residual y position of TKU tracks extrapolated to TKD, as compared to the tracks in TKD.

be cooled. Muons will also undergo multiple Coulomb scattering which increases the divergence of the beam,
340 thereby increasing the normalised transverse emittance and heating the beam.

Ionization-energy loss is characterised by $\frac{dE}{dx}$, where E is the muon energy and x is the distance travelled
within the absorber. Multiple Coulomb scattering is characterised by the radiation length, X_0 . For liquid
hydrogen, $\frac{dE}{dx} \sim 0.03 \text{ MeV/mm}$ and $X_0 \sim 8905 \text{ mm}$ [?]. The absorber vessel was manufactured using
aluminium for which $\frac{dE}{dx} \sim 0.4 \text{ MeV/mm}$ and $X_0 \sim 90 \text{ mm}$ [?]. To maximise the cooling effect from energy
345 loss in liquid hydrogen, while minimising the heating effect from multiple Coulomb scattering in the aluminium
windows, these windows were required to be as thin as possible.

Figure ?? shows the drawings of the absorber focus coil (AFC) module and the installed absorber vessel.
The absorber vessel was set at the centre of the FC magnet coils. Safety considerations required a secondary
350 containment system. Therefore, the absorber vessel was situated in an evacuated space within two more thin
aluminium safety windows, so the muon beam had to traverse four windows, as shown in the left panel in
Figure ??.

geometry definition and validation.

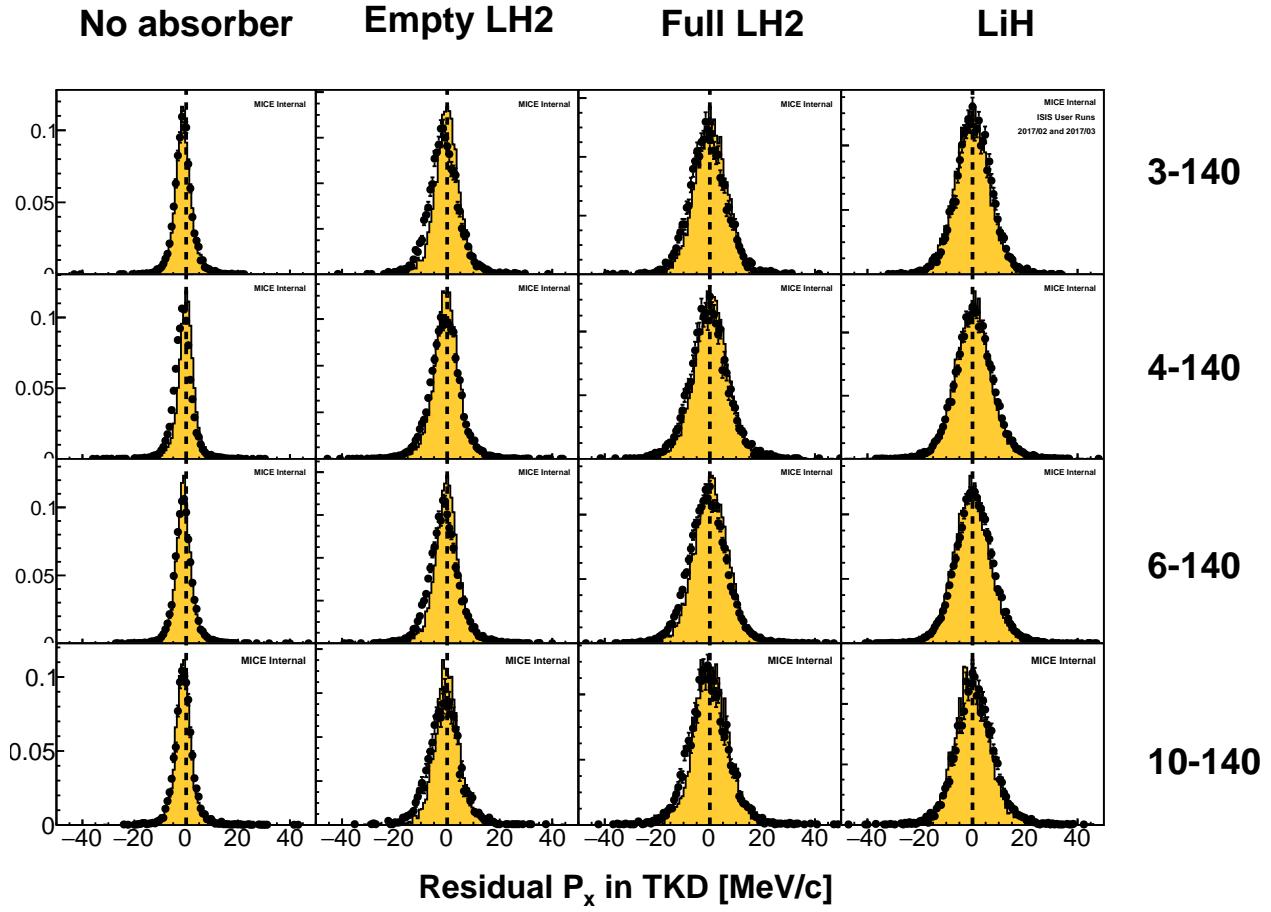


Figure 33: Residual p_x of TKU tracks extrapolated to TKD, as compared to the tracks in TKD.

11.1 Absorber vessel body

The absorber vessel comprised a cylindrical aluminium body sealed with two thin aluminium end windows, as shown in the right panel of figure ???. The absorber vessel was specified to contain 22 l of liquid, so the body had an inner diameter of 300 mm and a length between its end flanges of 230 mm. The length along the central axis between the two domes of the thin aluminium end windows was 350 mm. The body contained an annular cooling channel within its walls that could act as a heat exchanger. This channel was designed to allow the possibility of cooling the vessel body directly using liquid nitrogen, or even liquid helium. However, it was found that this cooling was not necessary because the absorber vessel cooled sufficiently quickly with cold gas from the condenser, as described in section ???. Small indium-sealed flanges connected the aluminium pipes from the absorber vessel to the stainless-steel pipes from the condenser.

Figure 39 shows a photograph of the inside of the absorber vessel body. The two flanged windows were sealed to the end flanges of this body using indium contained in grooves. The heat exchanger fins and five pairs of thermometers (LakeShore Cernox 1050-SD) are visible in this photograph. These five thermometer pairs were inside the vessel at locations spaced by 45° around the circumference and were monitored with a LakeShore 218S. Each pair monitored the presence of liquid hydrogen at that position; one of these Cernox sensors was operated with a small current as a thermometer, and the other was occasionally heated by a pulse of larger current. The difference between the two measured temperatures was small when these sensors were in liquid

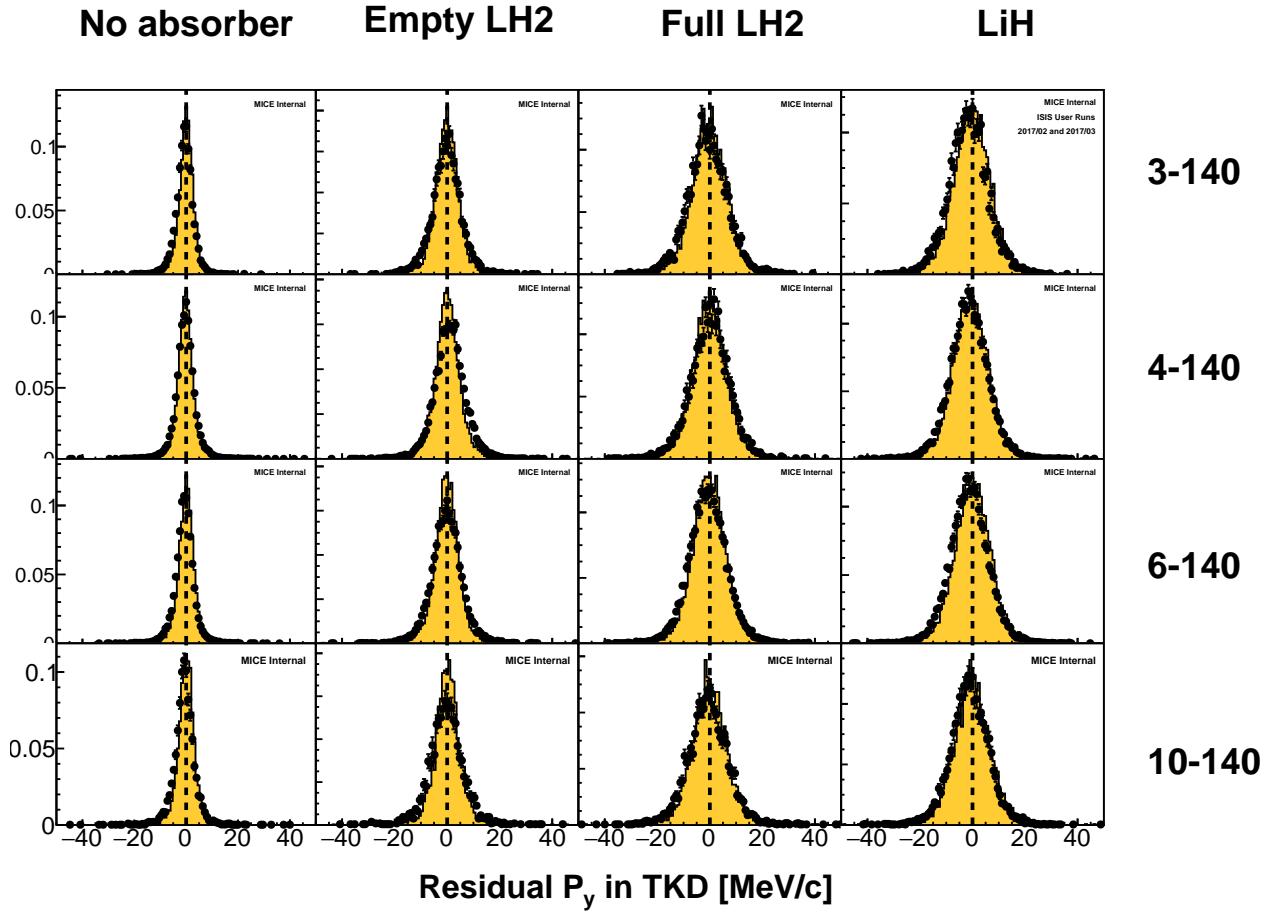


Figure 34: Residual p_y of TKU tracks extrapolated to TKD, as compared to the tracks in TKD.

370 due to good cooling efficiency, but the difference was larger when these sensors were in gas since heat transport
 through the gas is worse than in the liquid. The sensor wires were extracted to vacuum part-way along the
 liquid-hydrogen inlet pipe at a 30-pin hermetic feed-through, as shown in figure ???. Signals from each sensor
 were carried on two wires inside the absorber vessel, between the sensor and the feed-through, and by four
 wires in the vacuum outside the vessel. Two Cernox thermometers and two heaters (LakeShore HR-25-100)
 375 were mounted externally on each end flange. Two additional Cernox thermometers were mounted externally
 on the hydrogen inlet and outlet lines. These thermometers were exposed to vacuum and thermal radiation so
 the thermometry here was less accurate than that inside the absorber vessel, but gave indications of the flow
 of cooling gas in the circuit. To minimise heat input from contact with the magnet bore, the absorber vessel
 was mounted on glass-epoxy (G10) supports of low thermal conductivity. To minimise radiative heat input,
 380 multilayer insulation (MLI) was wrapped around the absorber vessel and all the low-temperature pipework.
 The number of layers of MLI over the end windows was first entered into a Monte Carlo program to check that
 the scattering of muons by the MLI was insignificant compared to that of the windows, before the vessel was
 integrated into the system and cooled.

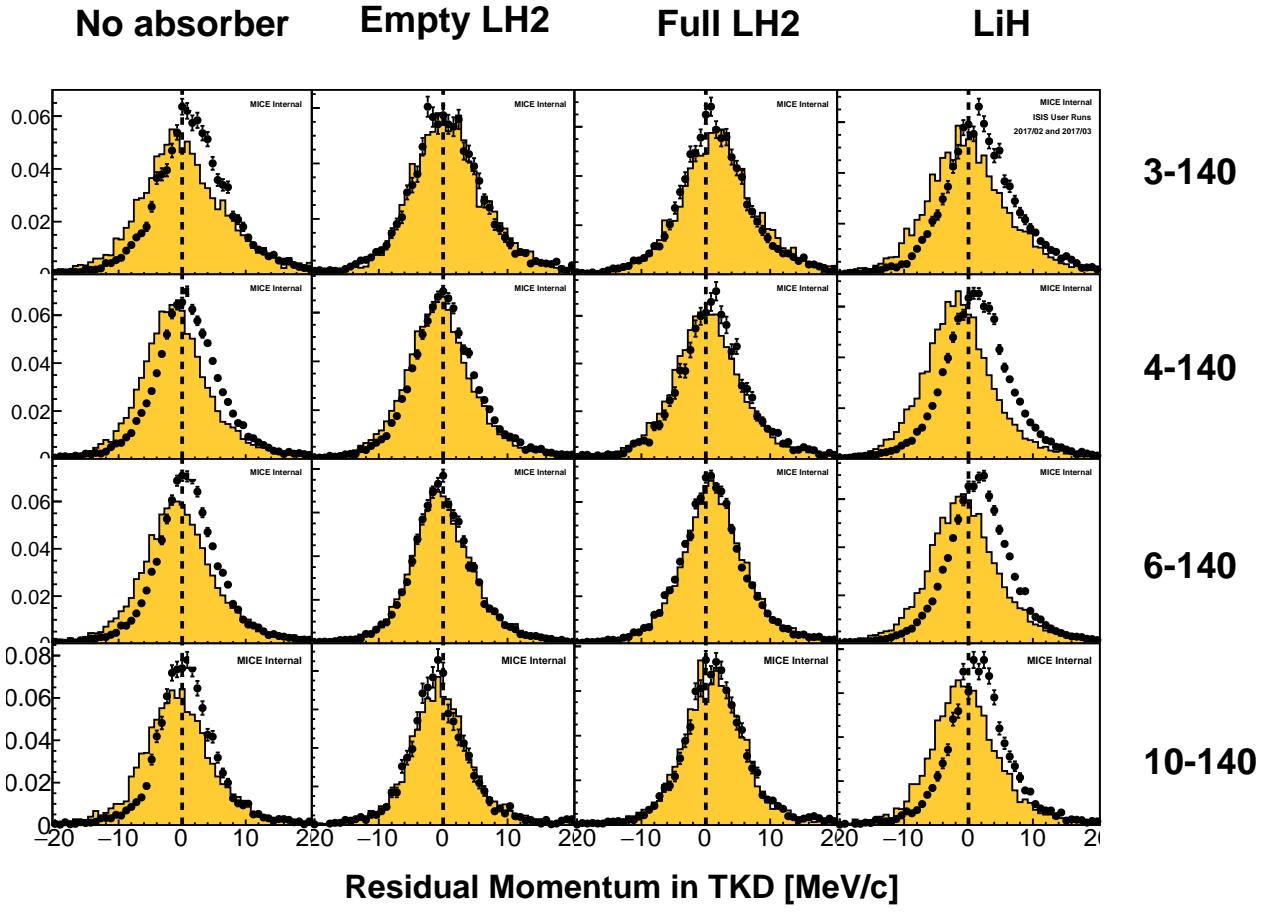


Figure 35: Residual p_{tot} of TKU tracks extrapolated to TKD, as compared to the tracks in TKD.

11.2 Windows

385 The liquid hydrogen was contained between two aluminium windows, each having a thickness of $180\ \mu\text{m}$ at the centre and increasing to $360\ \mu\text{m}$ near the outer flange. Aluminium safety windows, each with a central thickness of $210\ \mu\text{m}$, enclosed the absorber vessel in the magnet bore. Thin aluminium was chosen to minimise multiple scattering. Thinner windows lead to less scattering and more muon-beam cooling. Although a MICE window with a central thickness of $125\ \mu\text{m}$ had successfully been machined using alloy 6061-T651, it
 390 would not withstand enough pressure. The pressure in the absorber vessel reached 1500 mbar during typical operations. The aluminium alloy we chose to use (6061-T651) was assayed to contain 0.61% silicon, 0.26% iron, 0.25% copper, 0.02% manganese, 1.02% magnesium, 0.20% chromium, 0.01% zinc, 0.05% titanium, 0.01% zirconium, 0.15% maximum other material, and at least 97.42% aluminium (all measured by weight).
 395 The yield strength was measured at room temperature to be $39,900 \pm 700$ psi (275 ± 5 MPa), although this would be greater at 20 K. A drawing of a MICE absorber vessel window is shown in figure 40. The double-bend geometry increases the burst strength.

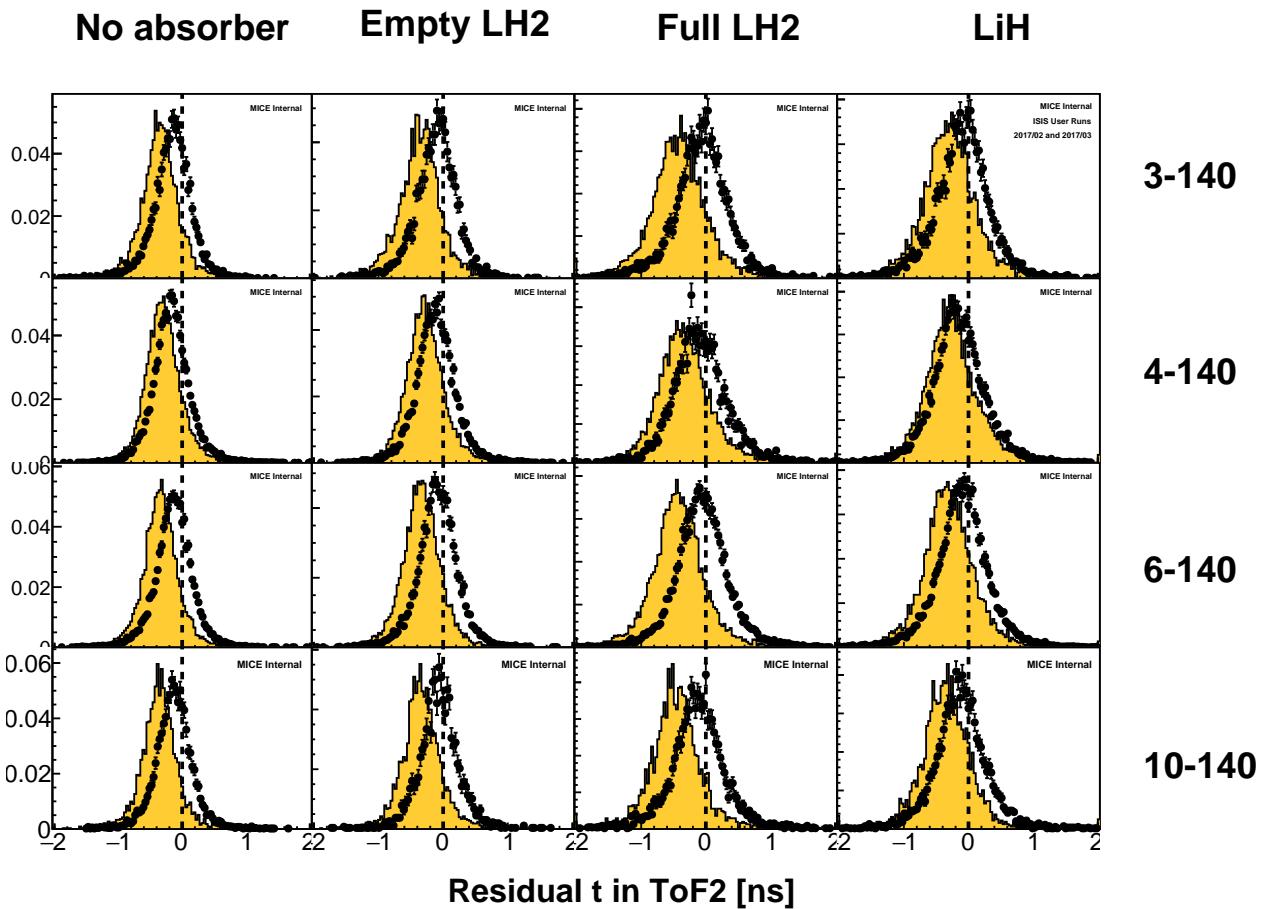


Figure 36: Residual time of TKU tracks extrapolated to ToF2, as compared to the time measured in ToF2. The track times were drawn from ToF1 with appropriate offsets for time-of-flight from TKU to ToF1 considered.

11.2.1 Window manufacture

A CNC Fadal 5020A vertical machining centre and a CNC Romi lathe with a 27 inch swing were used to machine the windows from a solid block of aluminium alloy. Precision backing plates supported the windows during this process. Each window was machined to a $2000 \mu\text{m}$ central thickness, and then measured with the micrometer jig shown in figure 43. The window was then returned to the lathe for final machining while the lathe still had the positions stored in its memory. Clear plastic cases were fabricated to protect the windows from damage in transit, while still allowing visual inspection. Finished windows can be seen in figures 41 and 44.

11.2.2 Window thickness measurement

The thicknesses of three different types of finished windows (one absorber and two safety) were measured with the View Precis 3000 Optical Co-ordinates Measurement Machine (CMM) shown in figure 41. The complete surface profile of a window was measured with the laser on one side, and then the window was turned over to measure the other side. The difference between the surface profiles of both sides of the window gave the thickness. Three tuning balls were glued to the window to establish the reference coordinate system; key

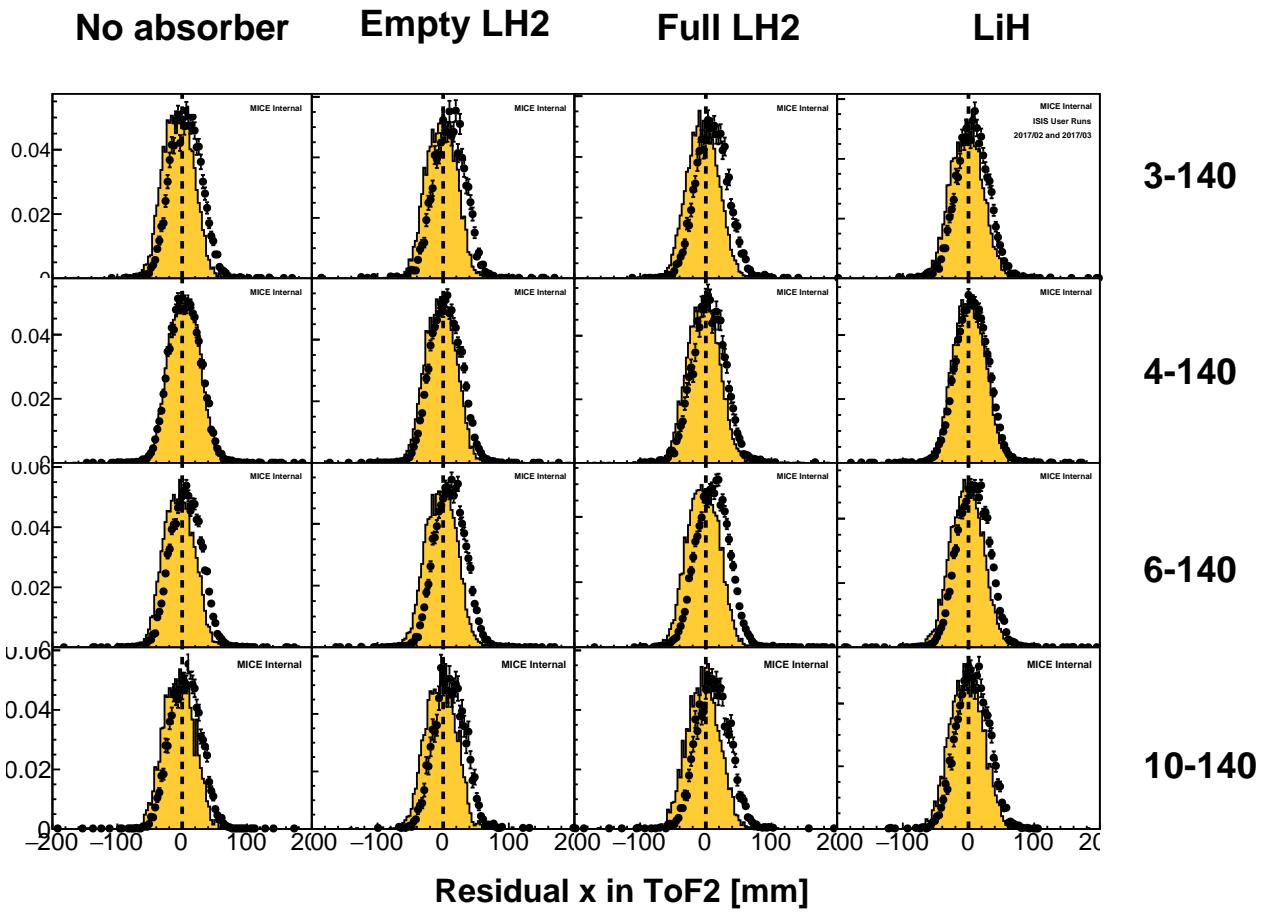


Figure 37: Residual x position of TKD tracks extrapolated to TOF2, as compared to the position measured in TOF2.

to getting a good measurement was to establish the same reference coordinate system for both sides of each window. Some results of the measurements are shown in table 6 and figure 42. For some of the windows, the thickness measurement was checked by scanning only the small area around the window centre with a very dense meshing. This gave a more accurate measurement of the thickness at the window centre.

Low energy electrons are strongly attenuated by modest thicknesses of aluminium. Two different beta sources, ^{90}Sr and ^{204}Tl , were used to measure the thickness of a MICE window. The source and detector (Geiger tube) were on opposite sides of the window so there was no need to move the window during this process, as was required with the laser CMM. The attenuation of electrons in a thin sheet of material of thickness x was described using the equation:

$$R = A e^{\alpha x} + B e^{\beta x} + C. \quad (1)$$

415 The apparatus was optimised to measure the central window thickness by choosing beta sources with electron energies that have a half-range of about $180\ \mu\text{m}$ in aluminium. Due to electron scattering, the result can be sensitive to apparatus geometry so a careful calibration was performed using aluminium sheets of known thickness with counts being accumulated for 10 minutes per sheet. The central thickness of the absorber window in figure 44 was measured to be 178 ± 6 (stat) ± 4 (fit) μm .

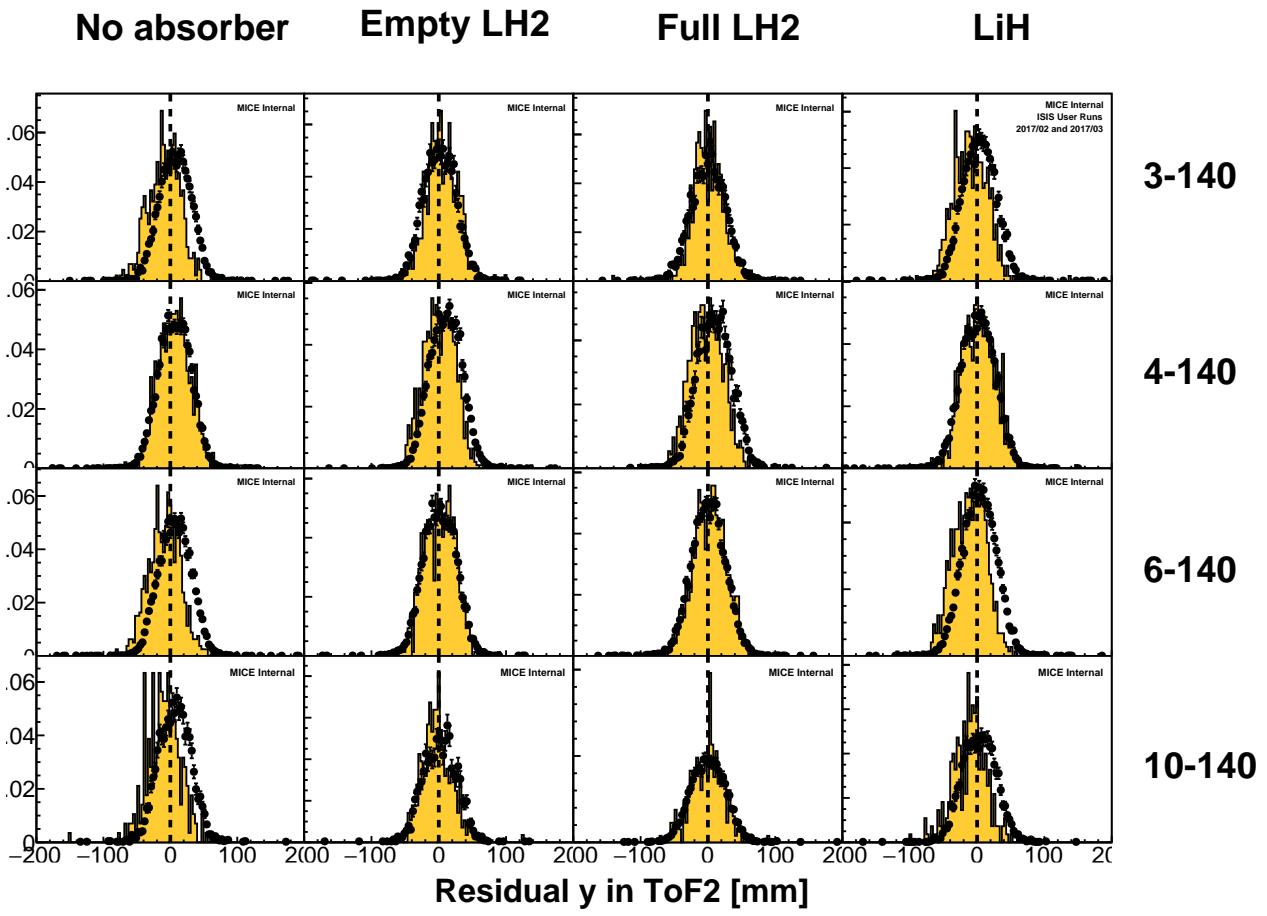


Figure 38: Residual y position of TKD tracks extrapolated to TOF2, as compared to the position measured in TOF2.

420 11.3 Validation of the absorber model in MAUS

11.4 refs

12 Conclusions

To be written at last.

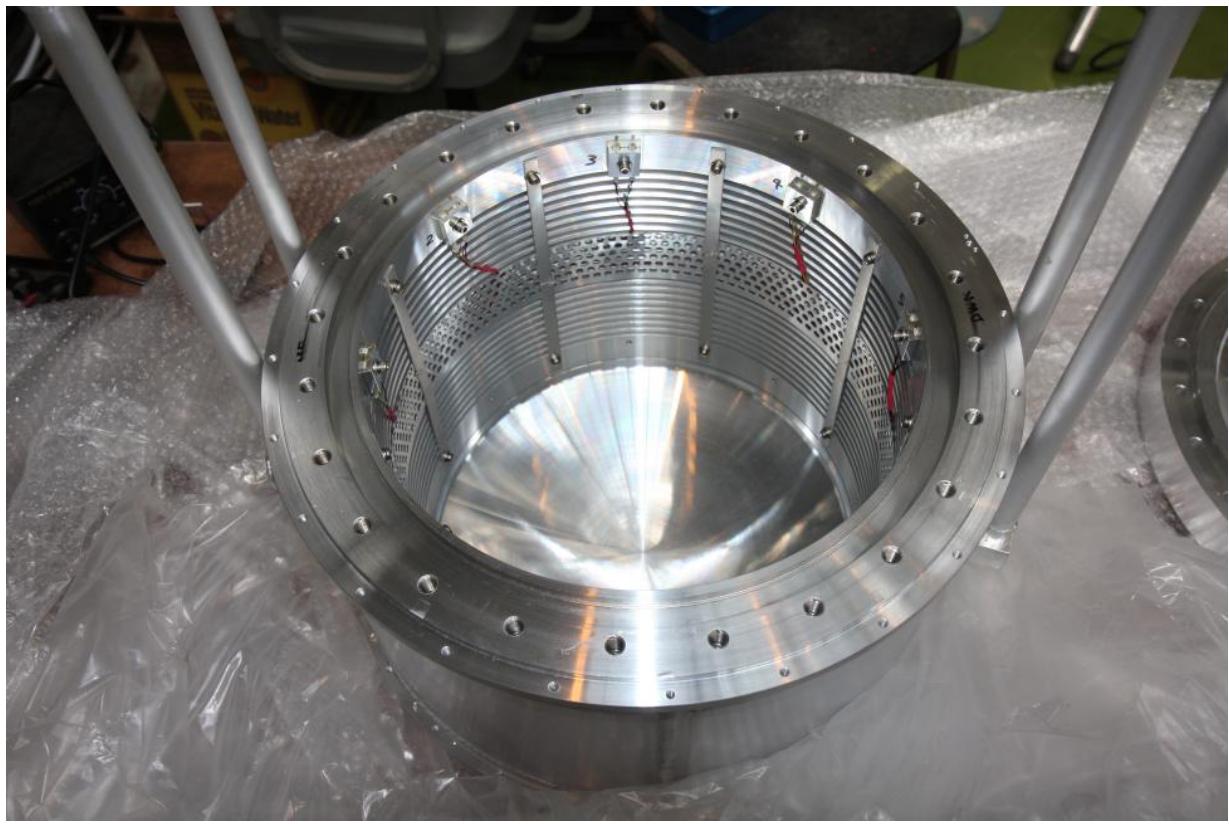


Figure 39: Photograph of the absorber vessel body.

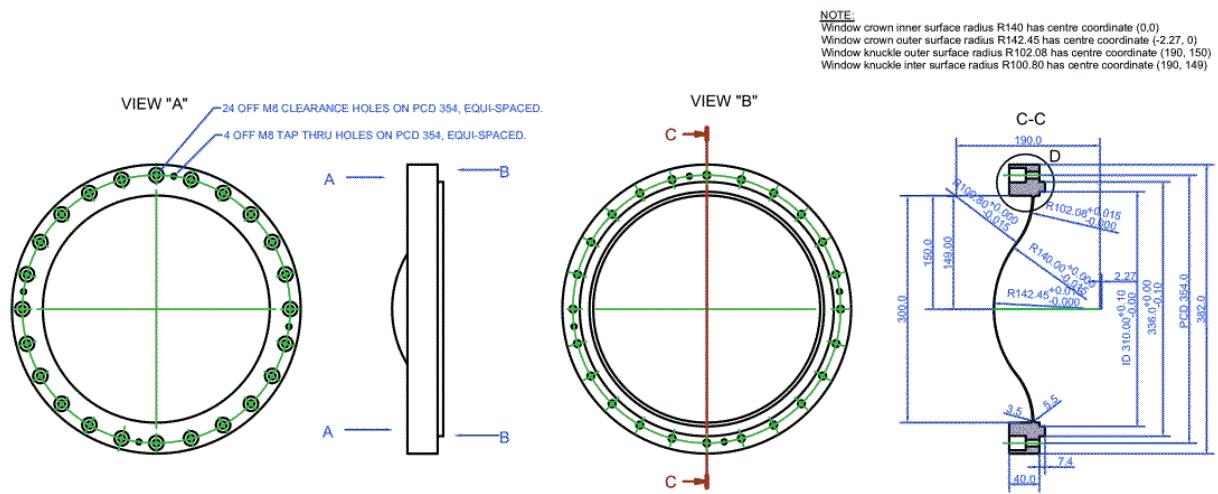


Figure 40: Aluminium absorber vessel window with a central thickness of $180 \mu\text{m}$ for the containment of liquid hydrogen. Both types of safety windows were similar to the vessel window, but had a central design thickness of $210 \mu\text{m}$.

Table 6: Results of measuring the central thickness of the three types of windows with the View Precis 3000 Optical CMM shown in figure 41. The windows actually used in MICE were numbers 002, 003, 009, and 014.

Window #	Window Type	Central Thickness Measured (μm)	Central Thickness Design (μm)	Note
001	Absorber		180	
002	Absorber	174 ± 5	180	
003	Absorber	184 ± 2	180	
004	Absorber		180	
005	Absorber	176 ± 6	180	
006	Safety I	222 ± 6	210	flaw at centre
007	Safety I		210	flaw at centre
008	Safety II	233 ± 5	210	
009	Safety II	230 ± 9	210	
010	Absorber		180	
011	Absorber		180	
012	Safety I	197 ± 7	210	
013	Safety I		210	
014	Safety I	197 ± 8	210	



Figure 41: The View Precis 3000 Optical CMM measured the surface profile of each window, one side at a time.



Figure 42: Result of the CMM measurement of one side of one window. All the axes are labelled in units of millimetres.



Figure 43: Jig for measuring window thickness at the centre and at 15° from the peak of the dome with a pair of Starrett T465 micrometers accurate to 3 microns.



Figure 44: ^{90}Sr and ^{204}Tl beta sources and a Geiger tube were used to check the central thicknesses of windows.



Figure 45: This absorber vessel window burst when pressurised with water.



Figure 46: This Type I safety window (number 012 in Table 6) burst when slowly pressurised with nitrogen gas.

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