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Title: g-2 tracker (calibration) tools

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Abstract:

This report describes the calibration tools that have been developed for the g-2 straw tracker. These comprise of three systems: a vacuum test-stand, a cosmic test-stand and a source test-stand. The data from these test-stands coupled with a GARFIELD simulation have been used to fully characterise the straw trackers that are presently taking their first data from stored muons in the g-2 storage ring at FNAL.

Introduction:

The g-2 straw trackers measure the muon beam profile and momentum and will be used to identify lost-muon and pileup events which can potentially bias the a_μ determination and are a source of systematic uncertainty. The beam profile measurement is convoluted with the field measurements to provide the weighted magnetic field traversed by the decaying muons. The momentum measurement, through an E/p determination, can be used as an in-situ monitor of the calorimeter gain which is another source of systematic uncertainty in the a_μ determination. A measurement of the vertical asymmetry of decay positrons in the trackers will also serve to increase the sensitivity to a possible muon electric dipole moment by two orders of magnitude compared to the BNL experiment. To achieve the required reduction in the a_μ systematic uncertainty, the trackers must measure tracks with high efficiency and resolutions of 1mm, 10mrad and 3% in impact parameter, momentum and vertical angle respectively and must do this without perturbing the magnetic field or significantly degrading the vacuum in the storage region. To achieve these efficiencies, resolutions and vacuum load, a suite of calibration tools has been developed at FNAL which are described below. They comprise of three test-stands: one measuring the leak rate (vacuum test-stand), one measuring the gain and wire positions (source test-stand) and one determining the time to distance calibration (cosmic test-stand). The results of these are used to calibrate the detectors and set their optimum operating conditions (high-voltage, gas mixture, threshold) and to optimise the simulation so that it reliably matches the observed data. This optimisation is critical to ensure that the performance of the trackers meets the design goals.

Vacuum Test-Stand

The g-2 muon beam is vertically focussed by 4 sets of quadrupoles that pulse for O(1ms) at 20-35kV. To avoid sparking they must operate in a vacuum of at least 1μTorr. The g-2 trackers flow Ar/Ethane through mylar straws in the vicinity of the quadrupoles and the capacity of the vacuum pumps requires a leak rate of less than 6μTorr l/s per tracker module to maintain the appropriate vacuum for operation of the quadrupoles. A vacuum/leak calibration test-stand has thus been established at FNAL. At the start of the module production prior to wiring and mounting the straws, straws are initially selected from the large batch available that have a leak rate at least a factor of two less than the specification. Once the module has been constructed and shipped to FNAL it then undergoes a rigourous leak/vacuum calibration in the test-stand at MTEST (see Fig. 1).

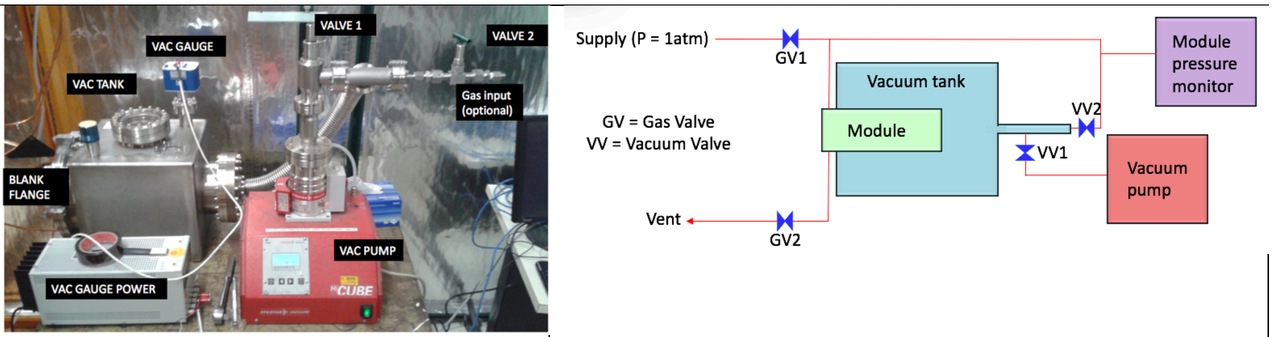


Fig-1: (LEFT) The vacuum/leak calibration test-stand in MTEST at FNAL. *(RIGHT): A schematic of the system.*

The leak rate of the straws is determined using the "rate-of-rise" (ROR): the module is inserted into the vacuum tank and pumped down until the pressure is low and stable, the vacuum pump is then turned off and the pressure ROR is measured which is then converted to a leak rate. The time it takes to attain a pressure of 30μT, the pressure attained after 24 hours of pumping and the ROR can all be used to determine whether the module has a leak rate that is sufficiently low for the module to be put into the g-2 storage ring. The results of this calibration for the modules presently in the storage ring are shown in Fig.2. The leak/vacuum calibration test-stand has also been used to compare the leak rates with different gasses: N_2, Ar/CO_2, Ar/Ethane and is presently being used to measure the dependence of the leak rate (primarily through permeation through the mylar straw wall) on temperature in order to establish whether chilling the input gas can help significantly reduce the leak rate.

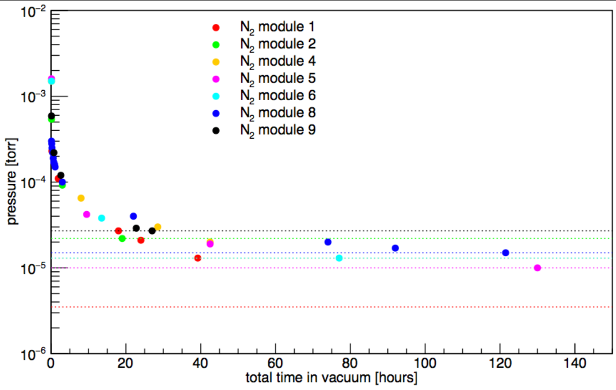
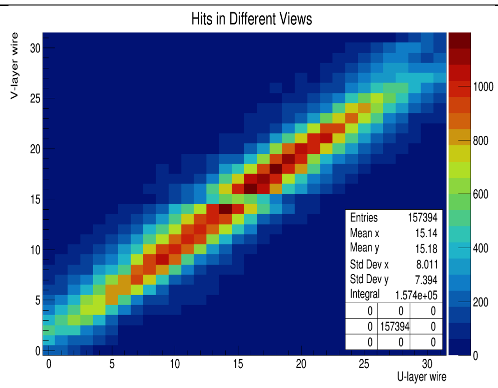


Fig-2: Pressure as a function of time recorded in the vacuum/leak calibration test-stand in FNAL MTEST. The dotted lines indicate the lowest pressure ultimately reached by a given module when flushed with N_2.

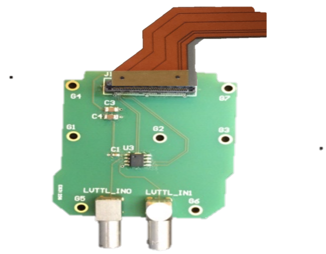
Cosmic Test-Stand

A test-stand (see Fig. 3) to calibrate the straw tracking modules using cosmic rays was established in Lab-3 at MTEST. The stand comprises of two scintillator paddles and aluminium plates one of which has been milled to be the same as the vacuum plates in the storage region such that the trackers can be placed with identical spacing and mounted in the same way but rotated by 90 degrees. A custom PCB was developed so that a TTL signal from the scintillators PMT NIM electronics could be readout by the same TDC used by the straw tracker, thus ensuring that the same readout/DAQ software could be utilised and that the clocks would be synchronous across the two detector systems. A dedicated MC simulation was also developed so that the results from the cosmic-stand could be used to improve the simulation, and hence calibration of the detectors.

Fig-3 (LEFT): The cosmic test-stand in FNAL Lab-3, showing 3 straw tracker modules mounted horizontally and the two (black) scintillator paddles.



(CENTER) Hits recorded by a tracker in the cosmic test-stand showing the uniform distribution of hits in both straw planes except at the edge where the scintillator acceptance drops off.



(RIGHT) Bespoke PCB developed to convert a TTL signal into the correct LVDS signal to be readout by the straw tracker TDCs.

The scintillator trigger allows a very clean sample of tracks to be selected and these have been used to refine the cross-talk model based on the pulse height of the recorded hits and to determine the efficiency with which a hit is recorded. Hits originating from cross-talk have been found to have a pulse width about a factor of two less than from a genuine hit and can thus be excluded from the data in a rather straightforward manner (see Fig-4).

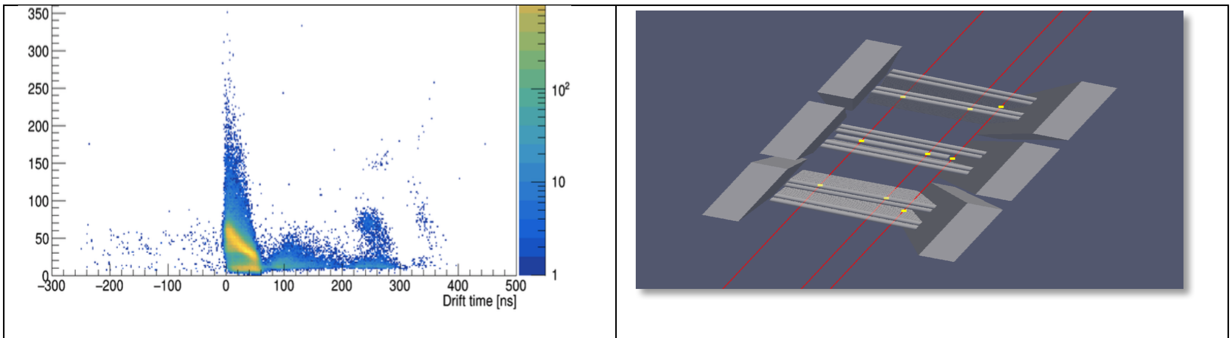


Fig-4: (LEFT) Pulse height (vertical axis) vs drift time of hits recorded from tracks in the cosmic test-stand.

(RIGHT): A display of the simulated tracks from the GEANT simulation of the cosmic test-stand.

Radioactive Source Test-Stand

The final test-stand established at FNAL was one using radioactive sources where each module was exposed to both a ^{90}Sr source: to measure the wire positions and determine the optimum HV setting and a ^{55}Fe source to measure the gain. The sources were mounted in a collimated holder and scanned across the straws in X-Y using a computer controlled motor stepping in 6 micron increments. The setup is shown in Fig.5. The trajectory of the ^{90}Sr electrons is determined by the source collimation and a scintillator/Si PMT detector that is readout using the same bespoke PCB developed for the cosmic test-stand.

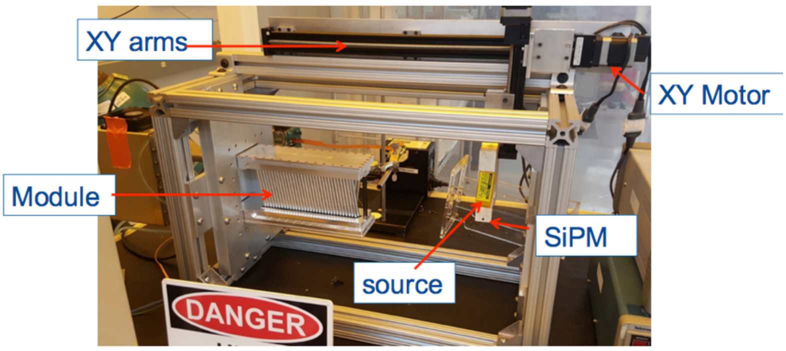


Fig-5: The radioactive source test-stand in Lab-3 at FNAL. This is used to calibrate the gain of the detector, determine the optimum operating voltage and to map the position of the straws.

The number of hits from a ^{90}Sr source is recorded as a function of HV to determine the so-called “plateau” region, where the gain does not vary significantly with HV and where the rate of “re-firing” is not significant. A plot of this for two different gases is show in Fig.6 and defined the operating voltages of 1625V (Ar/Ethane) and 1500V (Ar/CO_2) used in the June-2017 commissioning run.

A ^{55}Fe source deposits a known charge (at two energies) in the straws and can be used to calibrate the gain of the detectors. The hit rate is recorded as a function of threshold at thresholds above the range at which the ASDQ saturates. This rate is fitted two Gauss error functions and an exponentially falling noise distribution as a function of threshold to determine the gain at several HV values (see Fig. 7).

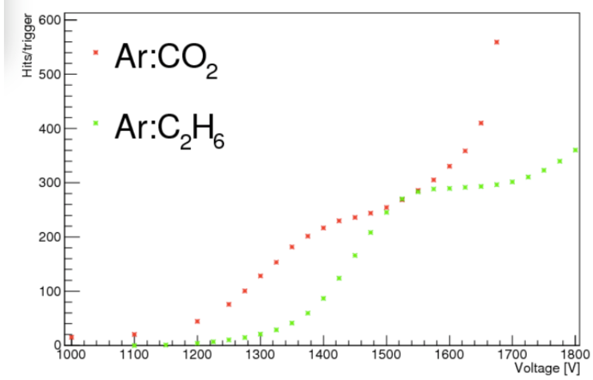
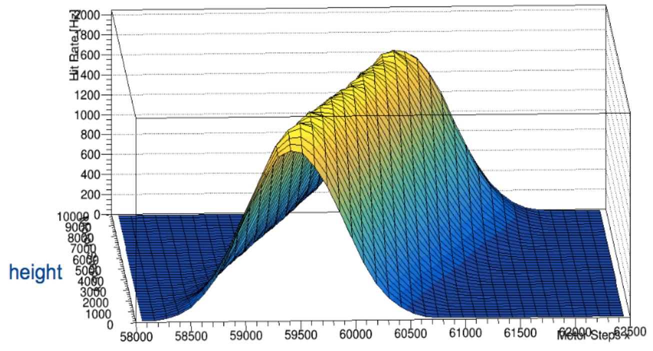


Fig-6 (LEFT): The number of hits from a single straw tracker module recorded in 10ms as a function of HV for two different gases: Ar/CO_2 and Ar/Ethane from a ^{90}Sr source.



(RIGHT) The hit rate (Hz) recorded from a ^{90}Sr source as it is moved across the detector. The peak can be used to accurately determine the straw (and wire) positions as a constraint in the final alignment procedure. The motor moves in 6μm steps.

The gain measurements are determined at different HV settings as a function of channel (HV board): see Fig-7. In this way, it can be ensured that all modules are running at the same gain and hence hit efficiency.

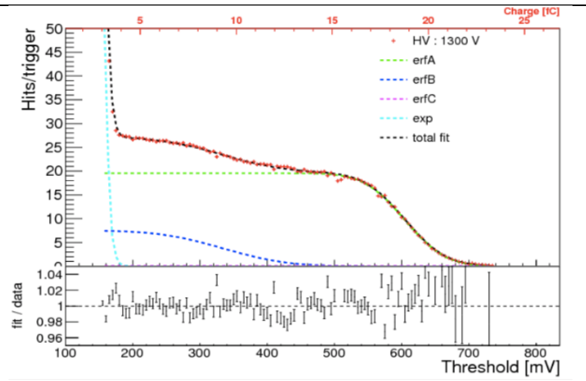
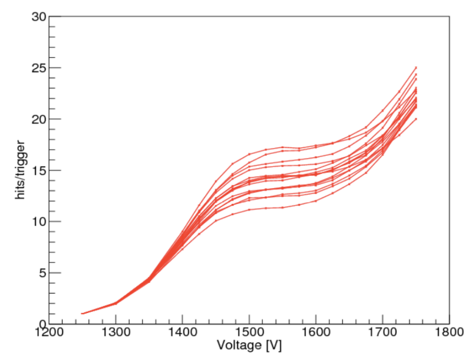


Fig-7 (LEFT). The fits as a function of threshold from ^{55}Fe scans that are used to determine the gain.



(RIGHT): The hit rate (gain) as a function of HV for different TDCs.

Garfield Model of the Tracker

The above systems calibrate the detectors in terms of gain (hit efficiency), initial alignment, resolution and the time-to-distance calibration. The final aspect of the calibration and the one critical to attaining the best possible performance is the implementation of these results in the Monte Carlo simulation: the detector measures hit times and these must be converted to a hit position which are then fitted to form tracks. The time-to-distance (so called "r-t") calibration is thus particularly important and the inverse of this must be implemented in the Monte-Carlo i.e. from GEANT hit positions, hit times are computed. The GARFIELD++ programme is used to simulate the generation of hits from the ionisations and avalanches created by charged particles passing through the gas of the straw trackers. A new C++ version of the programme was recently released and we have implemented several improvements to the code so that it now reproduces all the features of the well-established Fortran version of the code and matches well the data recorded in the test-stands at FNAL: see for example in Fig.8, a comparison of the gain measured in the Lab-3 test-stand with the GARFIELD++ prediction. In Fig.8, the hit time distribution is shown from the cosmic stand data, this along with the results from GARFIELD++ of the mean distance and RMS of the primary ionisation from the wire have been taken to produce functions mapping the drift distance to hit time. The hit time distribution for hits close and far from the wire are shown in Fig.8.

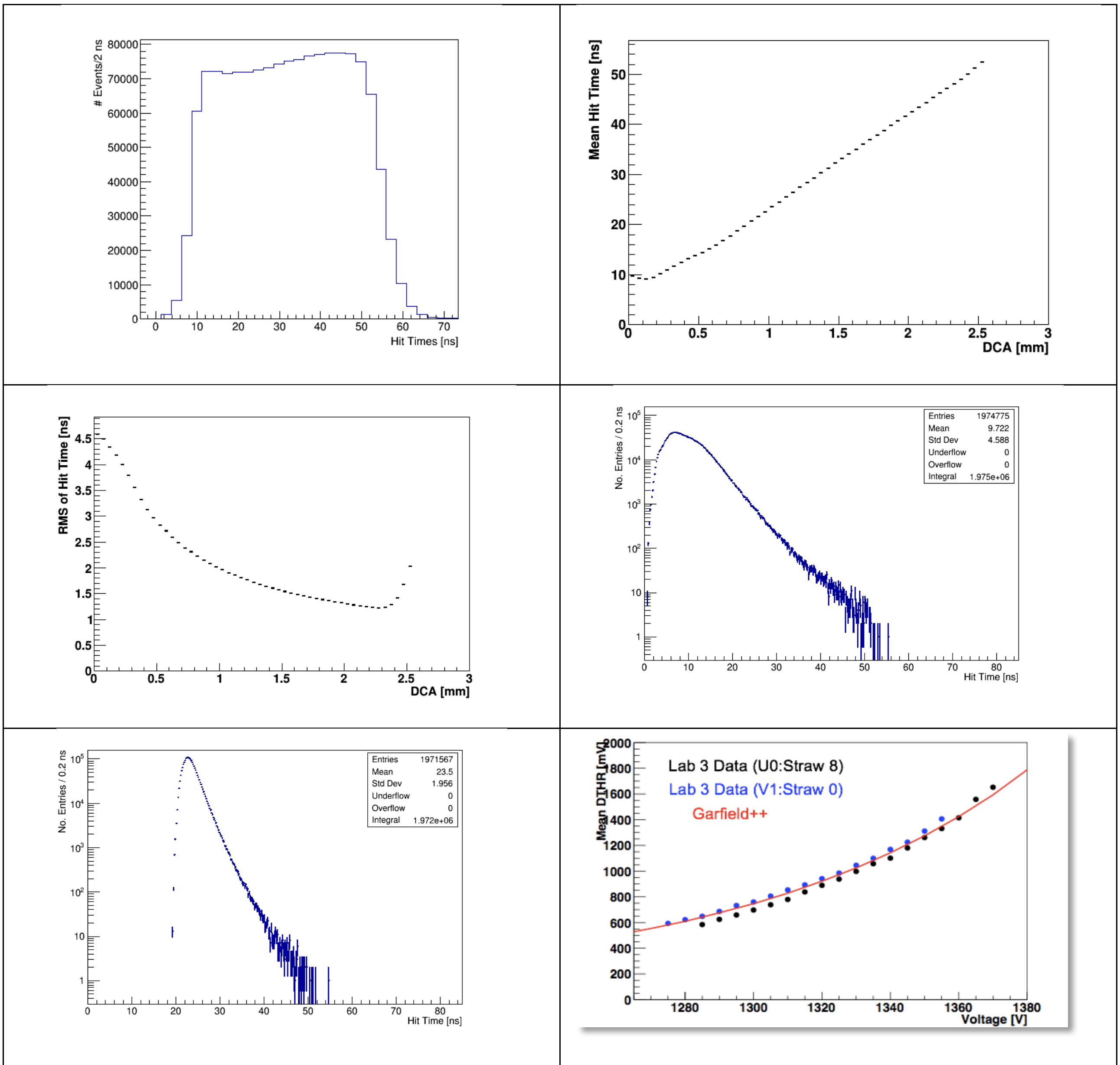


Fig-8 (TOP-LEFT): Hit time distribution recorded in the cosmic test stand. (MIDDLE-LEFT): the RMS of the hit time versus the distance of closest approach (DCA) of the ionising particle to the straw wire. (BOTTOM-LEFT): the hit time distribution for particles that are 1.025 mm from the straw wire. *(TOP-RIGHT): the mean of the hit time vs DCA. (MIDDLE-RIGHT): the hit time distribution for particles that are 0.025 mm from the straw wire. (BOTTOM-RIGHT): a comparison of the gain calculated in GARFIELD++ with that measured in the Lab-3 test-stand.*

Summary

All the infrastructure: both hardware and software, necessary to calibrate the g-2 straw trackers has been established. Three test-stands: vacuum, cosmic, radioactive-source have been used to characterise the performance of the modules and this has also been implemented in an improved Monte-Caro model based on GARFIELD++ simulations. These calibrations have been used in the first data taken with muon beams in June-2017. To date well over a million tracks have been recorded.