A feasibility study on the upgrade of the ISIS μSR spectrometers

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1. Introduction.

The muon spin research (μSR) instruments at ISIS[♣] would benefit from improvements to their detectors to improve their scientific output and maintain the international leading edge. μSR hosts a variety of techniques that are used to investigate the structure and dynamics of materials at the microscopic level. This is done by implanting well spin-polarised muons to a sample, where they thermalise and subsequently decay at rest to positrons and neutrinos with a characteristic lifetime of 2.2 μs . The detection of the positron emission intensity as a function of time is used to determine the evolution of the muon spin polarisation inside the sample. This allows the muons to act like miniature magnets that probe local microscopic domains with atomic precision. The positron detection is conventionally done by arrays of scintillators arranged around the sample in two concentric rings, as shown in Fig. 1, that detect the forward/backward emitted positrons.

The present μSR instruments at ISIS are equipped with the DIZITAL spectrometer or its variations. This consists of scintillator/PMT detectors with each unit read individually by the corresponding data acquisition electronics. The latter comprise of a discriminator and a Time-to-Digital Converter (TDC). The time resolution achieved is 16 ns and gives the present limit for time resolved measurements in the observation of dynamic phenomena.

The upgrade of the μSR experiments, taking into account present limitations and future requirements, as expressed by the ISIS experts, calls for:

- Average data rates in each detector of at least seven counts per ISIS frame, i.e. 20 msec.
- Time resolution of the order of 1 nsec and in any case below the present 16 nsec.
- Operation at high magnetic fields (~ 2 T).
- High positron detection efficiency (~100 %).
- High granularity with at least 512 channels.
- High spatial resolution preferentially at the sub-millilitre level.
- The ability to perform positron tracking by reconstructing the e^+ flight path.

In addition, the new detector system should incorporate a Windows-based DAQ to be compatible with the planned ISIS transition from VMS to Windows based data acquisitions systems.

[♣] For more info look at http://www.isis.rl.ac.uk/muons/ and references therein.

2. Work programme.

To address the above requirements and also to perform a feasibility study for the possible upgrade of the μSR experiments, a project was funded by the Centre for Instrumentation (CFI 2002/03 programme) with two objectives:

- Short Term: Identify ways to improve the DIZITAL spectrometer in order to increase the counting (data) rate by simultaneously reducing the time resolution to 1 nsec.
- Medium/Long Term: Provide with a "proof-of-principle" for positron tracking within the context of μSR experiments.

A staged approach was adopted to achieve the stated objectives with maximum efficiency at minimal risk, the detailed Gantt chart of which can be found in Appendix 2. A brief summary of the major tasks is given below:

1) A literature survey of the possible solutions was performed to consider the available detection technologies for positron tracking (Appendix 1).
2) This resulted in a novel re-design, see Fig. 4, of the basic detector module encountered in the typical muon spectrometers at the ISIS μSR stations, to allow for track reconstruction.
3) A team of specialised personnel based in the Instrumentation Department was assembled for the construction of the prototype detector in close collaboration with the corresponding detector experts in ISIS and under the continuing consultation of the ISIS μSR group.
4) The necessary equipment for the assembly of the scintillator detector and its associate electronic components, e.g. discriminators, power supply, PC and time to digital converter (TDC), were procured.
5) The scintillator/PMT detector was assembled (Fig. 2) and its electronic operation tested, as was for all other components in the read-out chain.
6) The successful operation of the scintillator as a radiation detector for charged particles was confirmed at the laboratory with the use of sealed sources, Fig. 3.
7) The dead time of the complete read-out chain of the scintillator detector, i.e. scintillator/PMT/CFD/TDC, was evaluated under realistic conditions for a μSR experiment by testing its performance in the DEVA station of ISIS (Section 3).
8) The timing performance of the new scintillator detector system was evaluated in a RF μSR experiment also in DEVA and its time resolution measured (Sec. 3).
9) The prototype demonstrator for the tracking of positrons was built by :
    a) Acquiring a suitable position sensitive detector (PSD) and read-out chip.
    b) Designing and fabricating a front-end hybrid card (PCB) to mount the PSD and its associated electronics (Fig. 6).
    c) Developing a suitable DAQ system for the PSD control and read-out (Fig. 13).
    d) Manufacturing in-house the necessary modules for the triggering of the PSD detector by the scintillator (Fig. 7).

10) The prototype demonstrator was assembled (Fig. 5).

11) The successful operation of the DAQ for the control and data acquisition of the PSD was tested in the laboratory with sealed sources (Sec. 3).

12) The performance of the combined scintillator/semiconductor detector system in a muon experiment was evaluated in DEVA and the spatial as well as temporal measurement of the positrons that follow the muon decays was demonstrated (Section 3).

13) The results of this work were disseminated to the user community following the project's completion in a meeting at ISIS and with the submission of a written report that also includes recommendations for the future (Sec. 4).

3. Experimental Work - Results.

The work in this project and its major achievements are summarised in the following:

- Dead time evaluation - Count rate improvement.

  The count rate capabilities of any detection system is monotonically depended of the system's dead time. The latter, in turn, equals the dead time of the slowest link in a read-out chain. In order to calculate the dead time of our system we followed the standard procedure adopted by the μSR experiments [1]. This assumes a non-paralysable dead time model, where the detection system is inactive for a fixed amount of time (t_d) after every count. In this case, the relation between the measured (m) to the expected (n) count rate is [1, 2]:

  $$m = \frac{n}{1 + nt_d}$$

  In the case of a muon decay experiment, the time evolution of the emission of the decay products (positrons) follows the characteristic law of radioactive decays, i.e. $n = n_o e^{\lambda t}$, with the muon lifetime 2.197 •μs. This is the expected counting rate which would have equalled the measured one had it not been for the dead time, in the absence of any background. Thus, the above equation can be re-arranged as:

  $$m e^{\lambda t} = -n_o t_d m + n_o$$

  By performing a linear regression fit to the above formula one is able to deduce the dead time of the system. This was done by measuring the muon decays in a silver (Ag) sample in the absence of any magnetic field, both with the DIZITAL spectrometer and this project's detector. Fig. 8, shows the fitting results for all the detectors comprising the DIZITAL spectrometer in the DEVA station where the average dead time is found to be **14 nsec.** This was independently verified by the station manager (J. Lord). The corresponding value for the dead time of our detector was found to be **8 nsec**, as shown in Fig. 9.

  By further investigation it was found that the main source of dead time in DIZITAL is due to the discriminator's (LeCroy 3412E) pulse width. This is set to 10 nsec to satisfy the requirements of the spectrometer's TDC's (either the DASH2 or LeCroy3377). As shown in Fig. 10, the DIZITAL detectors are capable of achieving higher counting rates when connected to this project's read-out chain. This is because our TDC (Fast ComTek 7886) can cope with the minimum pulse width of its associated discriminator (Canberra 454) of around 3 nsec.

- RF experiments - Time resolution improvement.

When performing μSR experiments in continuos muon sources as in PSI the maximum muon precession frequency that can be observed is restricted by the time resolution of the measuring system (detector and electronics) at the expense of limited data rates since only one muon is allowed to be counted at a time. On the contrary in a pulsed muon source the maximum observable frequency is limited by the width of the muon pulse. In ISIS this is 80 nsec which corresponds to a maximum usable frequency of around 6 MHz. Resonance techniques provide a solution by which this restriction can be removed allowing thus to take advantage of the higher data rates offered by ISIS [3].

The ability of our detector to perform RF-type μSR experiments was tested by implanting muons to a quartz sample and observe how the muonium atoms' polarisation develops after an initial excitation with a RF field. Muonium (μ^+e) is formed as a result of an electron capture by the muons while they thermalise in the sample. The RF field's direction is at 90^o to the constant magnetic field around which the muonium spins are precessing. For direct comparison purposes, both detection systems (DIZITAL, CFI) were used simultaneously in every data taking run. In the case of the DIZITAL spectrometer the LeCroy TDC was used since this is the high resolution TDC presently available to the μSR stations. This TDC is capable of 0.5 ns resolution as opposed to the 16 ns of the DASH2 that was used in the above experiments. The CFI TDC was also configured to a 0.5 ns resolution. In Fig. 11, a typical example of such a measurement taken with both systems is presented. The limitations encountered in high time resolution experiments by the DIZITAL spectrometer are clearly visible with the observation being limited to **4 μs**, which corresponds to less than two (2) muon lifetimes. By comparison, the CFI TDC shows no such limitations with the observation time extending to **24 μs**, i.e. around twelve (12) muon lifetimes…! This enhances the statistics provided by the available data, an important factor when dealing with weak signals or phenomena that require long observations, e.g. more than a couple muon lifetimes. It should be noted, that the limit of 24 μs in this measurement was chosen arbitrarily, as it provided with a long enough observation to make the point, and is was **not** a system limitation.

In RF experiments the time distribution of the counts is given by [4]:

$$N(t) = N_o * e^{-t/\tau_\mu}[1 + A * F(t)]$$

where τ_μ is the muon lifetime,• A is the asymmetry and F(t) gives the evolution of the muon spin polarisation, with $F(t) = \int F(\omega)\cos(\omega t - \phi)d\omega$. When the muon encounters a distribution of magnetic fields as inside a sample, F(ω) gives the distribution of precession frequencies, which map directly to the distribution of the internal magnetic fields through the gyromagnetic ratio. Thus, in order to extract F(ω) from the data one has to perform a Fourier Transform (FT) . This can be seen in Fig. 12, which shows the FT spectra for data taken at identical conditions with both the DIZITAL and CFI systems. The detector numbered 24 is the DIZITAL detector that corresponds to the location where the CFI detector was based, once again for direct comparison purposes. As can be seen in the figure, both systems can resolve a precession frequency close to 200 MHz, with the CFI system having a much **improved** “signal-to-noise ratio”. It should be noted that in order to avoid “data corruption” by direct coupling of the detectors with the RF system (“RF leakage”), the FT spectrum in both cases was taken for a time interval that corresponds after the end of the application of the RF pulse.

- Feasibility study for positron tracking.

To allow for positron tracking in future μSR experiments we propose to modify the detector design encountered at the conventional muon spectrometers, like DIZITAL. We envisage of including a Position Sensitive Detector (PSD), like a silicon microstrip linear array, to provide with the necessary spatial information for the detected positrons, in a similar fashion to experiments in Particle Physics. A drawing of our novel concept for the basic detection module in the future μSR spectrometer is presented in Fig. 4. The basic idea is of two detectors, a silicon PSD and a scintillator, working in tandem for the detection of the same particle. In this scheme the fast scintillator is connected to a single channel (anode) PMT to detect the incoming positrons, as is done in the present day spectrometers, and to provide with the temporal information. However, in addition it also provides with a trigger for the read-out of the silicon detector that is placed directly in front and which will measure the spatial co-ordinate of the detected positron. This of 'course requires the same geometrical acceptance by both detectors, in other words the same detection area, and that both detectors are 100% efficient for the detection of positrons with energies as those encountered in μSR experiments, i.e. from 10 to 50 MeV.

For the scope of this project and as a "proof of principle" of our concept, we developed a demonstrator of the proposed new detection module of the future μSR spectrometer. This is shown in Fig. 5, in accordance with the conceptual drawing that was presented in Fig. 4. A more detailed photo of the silicon PSD detector showing the detector and read-out chip is shown in Fig. 6. The silicon detector[1] is the rectangular “grey” coloured component on the right-hand side and in the middle of the PCB. It has 128 detecting elements (strips) with a pitch of 50 μm and overall dimensions of 1 x 5 cm^2 . The detector is wire-bonded to the read-out ASIC, which is CCLRC's APV chip designed at the MED group of ID, that can be seen immediately adjacent and on its left. The rest of the components in the picture are peripheral electronics necessary for the chips operation and data acquisition. In Fig. 7, a detail of the NIM modules is presented showing in particular, the "NIM-to-LVDS" and the "START/STOP" modules that were made in-house by ID’s DE group. Finally, it should be noticed for completeness that the data acquisition (DAQ) PCI board of the silicon detector was based on the GDAQ card and was developed by ID's ESD and RTS groups.

[1] Courtesy of Dr. M. Raymont, Imperial College London.

To prove the principle of using a silicon PSD in tandem with a scintillator-PMT detector in the context of a μSR experiment tests were carried out in DEVA in July 2003. There, an Ag sample was used as the target for the incoming muons with the Si microstrip and scintillator detectors being placed behind it and off the beam axis, in order to avoid triggers due to direct muon detection and due to positrons from in flight muon decays. The T0 signal that indicates the arrival of an ISIS pulse and that is provided by the ISIS upstream Cerenkov counter was used as the "start of frame" for our DAQ and to initialise the APV (see Fig. 4). Positrons emitted form the subsequent muon decays in the sample and passed through the geometrical acceptance of the scintillator triggered the APV to register the corresponding event. This was possible only for decays 330 ns after the T0 due to the chip's dead-time that follows every initialisation (RESET). Other further limitations coming from the chip's origins in HEP applications, as it has been designed for the CMS experiment at the LHC, were the maximum number of events (32) and the chip's latency of 4 μs (at 40 MHz).

Nonetheless, after extensive lab tests with a Sr^{90} β-emitter source in order to set-up the correct latency, we were able to successfully detect muon decays in DEVA with the APV working in Peak Mode and a clock of 30 MHz. A typical event is shown in Fig. 14, where the pulse height amplitudes of all 128 strips are recorded after a scintillator trigger. It should be noted that this represents "raw" data, i.e. data with minimal off-line processing that was restricted to pedestal subtraction only. The signal over noise was calculated around 17, a value which should be treated as a lower limit due to the common noise present, nonetheless in close proximity with what is reported in the literature. Taking only geometrical considerations into account, the position resolution provided by such an arrangement is:

$$\sigma_x = \frac{pitch}{\sqrt{12}} = \frac{50}{3.5} \approx 12\mu m$$

Once more this should be treated as an upper limit, since the chip provides the possibility for improved resolutions, due to its analogue output, if one uses charge interpolation methods [5]. In such cases the achievable spatial resolution is inversely proportional to the signal over noise, i.e. $\sigma_x \sim$ pitch/SNR, a fact routinely exploited in HEP experiments. Thus, in our case the resolution would have been better than 3 μm.

4. Conclusions - Future work

Having proven the case for a novel μSR spectrometer that provides with spatial as well as temporal information following a positron detection after each muon decay, the next step should be to design a positron "tracker". This is a detector that will be able to completely reconstruct the positron track, allowing one to trace it back to its point of origin within the sample, i.e. the "vertex" of the muon decay. It is well known from studies in particle physics experiments that the accuracy in the reconstruction of the decay vertex (σ_V) of a charged particle track in a magnetic field is given by:

$$\sigma_V \propto \sigma_x \oplus \frac{a}{p \sin^{3/2}\theta} \oplus c$$

where the first term (σ_x) is the intrinsic spatial resolution of the position sensitive detector, the second term is related to multiple scattering (MS) effects and the last represents all other effects, such as alignment errors. Whereas the detector's resolution is mainly related to its geometric characteristics, namely the strip pitch, and can be easily estimated as was shown in the above, to calculate the MS effects one needs to take into account the design of the whole tracker and the operating conditions. That is, one needs to have a detailed design of the PSD's indicating the number of layers, their position, their geometrical and material construction and also the presence of a magnetic field, as well as the field map. This is a far from trivial calculation and in anyway not one that can be done "back of the envelope". Luckily, this problem has been exhaustingly studied in particle physics and there exists nowadays a number of computer simulating tools, like the famous GEANT package [6], that allows for the complete track reconstruction of a charged particle in any arbitrary 3D geometry and also in the presence of a magnetic field. Therefore, the next step towards a novel μSR spectrometer should be the detailed detector simulations of the muon decays within the constraints imposed by the station's design. The outcome of the simulations should be the specifications for the optimum detector geometry, as for example the strip pitch, number of layers etc., that will allow for a positron track reconstruction and eventually the determination of muon decay vertex, within the set limits.

An alternative approach, not studied in this project, is the possibility of performing both spatial and temporal measurements of the positron detection with the same detector. Such possibility is highly desirable, as it will reduce the material present in the tracker by negating the use of the "bulky", i.e. of relatively high radiation length, scintillator/PMT detectors. This will minimise the error due to MS, which is the dominant one in the accuracy of the vertex determination given in the aforementioned formula. It will also avoid constraints imposed in the magnitude of the magnetic field due to the presence of the PMT. This, however, requires the use of a silicon microstrip detector with sufficient spatial, at the level of a few tens of micrometers and time resolution, at the order of a few nanoseconds. Although the latter is not possible at the moment with present day technology mainly due to the limitation in the read-out speed imposed by the front-end electronics, it maybe achievable in the future with the use of a new read-out chip currently under development at CERN [7]. This is an ASIC that employs current-mode amplifiers and is designed for the detection of minimum ionising particles with better than 3 ns accuracy. Preliminary results are already very promising with peaking times as low as 6 ns for a detector load of 25 pF. This, however, represents riskier challenge since this technology is not an in-house development and therefore may not be accessible to CCLRC. One could of' course envisage that our microelectronics designers will be capable of designing such an ASIC, but this means designing a new chip from "scratch" and not building on existing "know-how", therefore of considerable effort and cost.

5. "Spin-offs"

The work undertaken in this project was beneficial to other areas of research in ISIS. Following an initial enquiry by one of us (E.S.) users of the resonant neutron absorption technique that were in urgent need of a high time resolution and stability data acquisition system to improve their data quality, were provided with the TDC of this project. Two highly successful trials followed in the HiPr station of ISIS in May and July 2003 after the user's request (Dr. H. Stone, Earth Science Dept., Cambridge University♠). An exemplary plot of the results is presented in Fig. 15. This highlight the main problems encountered with the measurements taken with the ISIS DAE, where a regular pattern of spurious pulses appears at regular intervals in the Time-of-Flight spectrum, termed the "beating" effect. This effect was so far the limiting factor in the data analysis, as the user was not able to fit satisfactory the data with his theoretical models and thus was unable to extract the wanted parameters with the desired accuracy. However, such an effect was not observed in the T.O.F. data taken with our TDC as is evident in the figure. Furthermore, it should be noted that this project's TDC provided with a time resolution of 0.5 nsec, which is unprecedented in these kind of experiments, where data are commonly acquired at 250 ns time bins.

Acknowledgements

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Appendix

1. Detector Options

The energy spectrum of the electrons (positrons) that originate from the $\mu^{-/+}$ decay has a maximum at 50 MeV [8] and lies in general above 10 MeV, thus the task becomes the detection of minimum ionising particles (MIP). The detection of MIP is the "bread-and-butter" of the detectors designed for tracking in particle physics experiments. There are various choices for the detection of MIP, at least as many as the technologies used for the detection of charged particles, i.e. by using semiconductor, gas or scintillator detectors. In what follows the basic principles in the design of such detector will be considered and the possible limitations highlighted, wherever encountered.

1.1. Silicon PSD

At present the favourable technology for Position Sensitive Detectors (PSD) in HEP experiments is the use of silicon microstrip detectors. For example, both the forthcoming experiments at LHC in CERN will have all silicon trackers (e.g. ATLAS 10^8 channels, total area of coverage 10 m^2). They will be operating in magnetic fields of 5 T with a spatial resolution of a few micrometers. The latter is easily achievable with microstrip detectors and does not require a significant technological breakthrough; on the contrary it is rather "low" since spatial resolutions of 1.9 μm have been achieved as early as the early 1980's [9]. Therefore, all but one of the detector requirements that outlined in the above, namely the 1 nsec time resolution, can "easily" be accomplished by using such detectors. This is due to the limitations opposed from the collection time of the signal carriers in the traditional design of planar microstrip detectors (planar = electrodes are deposited on opposite surfaces of the silicon wafer).

In order to maximise the signal-over-noise ratio (s/n) the detector's active region should extend all the way trough the bulk of the Si wafer; this is termed "depletion". For an abrupt p-n junction, which is the model of a Si p-on-n microstrip where the electrodes are p-type strips on n-type bulk, the relation between applied voltage and depletion region width is [10]:

$$V = \frac{d^2}{2 \cdot \varepsilon \cdot \mu \cdot \rho} \qquad (1)$$

where d is the depletion region width, ε the permitivity of Silicon, μ the electron* mobility and ρ the resistivity. Substituting typical values used in HEP experiments, e.g. d = 300 μm, ρ = 10 kohm cm, we can calculate the depletion voltage to be $V_d \approx 30$ V.

The maximum electric field (E) for an abrupt junction is given by [3]:

* this assumes that the bulk is n-type

$$E_{max} = \frac{2 \cdot V_d}{d} \quad (2)$$

where d is the depletion region width, which equals the detector thickness in the case of fully depleted detectors. Hence, by substituting for the calculated V_d, the maximum E-field strength is $E_{max} \approx 2$ kV/cm .

Finally, the collection time of the signal carriers as they drift for collection at the corresponding electrodes (in the case of a reverse biased p–on-n microstrip this will be holes drifting to the strips) is given by [11]:

$$t = \frac{d}{u_h} = \frac{d}{\mu_h \cdot E} \quad (3)$$

where u_h is the drift velocity of holes, μ_h the hole mobility and E the electric field. Substituting from the above, the time for complete collection of the signal carriers (holes) that have been generated after the passage of a MIP through the silicon bulk, is found to be:

$$t_c = 30 \text{ nsec}$$

It is obvious, that this opposes a limit in the time resolution of such a detector. However, this is a “back of the envelope” calculation and by “fine tuning” the available parameters in the detector design one could possibly reduce the collection time. It should be noted that signal formation at the collecting electrodes begins immediately with the drift of the charge carriers. i.e. the e-h pairs, thus the above should be treated as an upper limit . The precise pulse formation in a multi-electrode structure, like a silicon microstrip detector, is described by the “weighting field” concept [12] and calls for detailed device simulations for optimisation purposes.

Indeed, there are many ways to improve the collection time, for example by reducing the detector thickness by a half, the collection time will be reduced by the same amount, as is evident form eg. 3. However, a decrease in the detector thickness has the detrimental effect of reducing the signal size, since the energy deposited by the passage of a MIP in a semiconductor detector follows the Bethe-Block formula, that scales linear with detector thickness [13]. Thus the amount of detector thinning is subject to satisfaction of the specified s/n for a successful operation, which in turn implies knowledge of the expected read-out electronics noise. Alternatively, the applied bias can exceed the one required for depletion, thus rendering the detector operating in the “over-depleted” mode. For example, the breakdown field in Si is [14] $3\ 10^5$ V/cm, so from eq.3 the collection time for a field of, say 10^5 V/ cm to allow for some degree of safe margin, will be 0.7 nsec**.** This is within the required specifications. However, detector operation in such high fields is far from trivial and is subject to careful design to avoid premature breakdown due to high fields. Once again, careful and detail device simulations of the detector are needed in order to verify the feasibility of operation at fields close to breakdown and even then, allowance should be made for effects of variations in the device fabrication.

Finally, one should bear in mind that the overall time response of a detector system combines the responses of the detector and read-out electronics, and is determined by the slowest component. At present, the fastest front-end electronics for the read-out of a microstrip work at 25 ns, e.g. CCLRC's APV chip, which is slower than the 16 nsec presently achieved at the μSR experiments in ISIS and in case can not provide with 1 nsec resolution.

1.2. Gaseous detectors – RPCs

Resistive Plate Chambers (RPC) are part of the muon detector system in the future particle physics experiments at LHC. Recent developments have seen the construction of MIP detectors with an area of 4x4 cm^2 , a pitch of 4 mm in both x and y, achieving a time resolution of 55 ps rms. However, the best spatial resolution was around 3 mm, which is worst than the required sub-millimetre one. The system also suffered from a 1 μs dead time and the detection efficiency was low, 75 %. Finally, for completeness it should be noticed that a large area detector covering 160x10 cm^2 was also built with this technology, and found to operate successfully at the aforementioned time resolution values (50 ps). However, the position information was limited to at best >1 cm, with a worst value (5 cm) for the other direction. In order to achieve detection efficiencies >90 % a multi-layer structure has to be used, increasing the total material thickness to an excess of 5 cm. This will have an adverse effect in the tracking precision due to an increase in multiple scattering. Moreover, of additional concern will be the gas system necessary for the continuos gas flow required for the successful operation of the chambers.

A final note concerns the (lack of) in-house expertise in this technology. Although there is considerable expertise in ID (and other departments) in the R&D and operation of gaseous detectors, there is limited knowledge in this particular type of detector. Furthermore, they are not a finished commercial product, guaranteed to achieve the required specifications on its data-sheet. They are the product of research at university lab's, which increases the risk of not achieving the required specifications, without going first trough a lengthy R&D program that will create in-house expertise in the design, fabrication and commissioning of RPCs and also create confidence in their operation.

1.3. Scintillating fibres

The use of scintillators in the detection of charged particles is another technique well known over the last 40 years. In particular plastic scintillators provide the fastest response and are therefore extensively used in applications with extreme (ns) time requirements [3]. These kind of detectors have been proposed and tested as MIP tracking detectors in HEP experiments [15] since the late 1980s. Towards that end, scintillating fibres are made from a plastic scintillator, like polystyrene, and subsequently coupled to a closed packed bundle to achieve position sensitivity. Thus by coupling the bundle to a suitable visible light detector like a photo-multiplier tube (PMT) or more recently hybrid photo diodes (HPDs) and avalanche photodiodes (APDs), one has created a positioning sensitive device.

1.3.1. PS-PMTs

Position sensitive PMT (PS-PMT) have become recently commercially available, see for example at www.hamamatsu.com. They comprise of patterned anodes in either a linear array or a pixelated format, thus providing either 1D or 2D position information respectively.

An example for such a position sensitive detector for MIPs tracking is given by Salomon et al. [16] It is made by 2 mm fibres grouped in a bundle of 5 cm in diameter and coupled to a commercial position sensitive PMT with 4mm anode spacing. It has achieved 800 μm spatial resolution with a response time of 4ns and an operating count rate of 10 MHz/anode (100 MHz total). Recent developments, however, show commercial available PS-PMTs with less than 1 ns rise time (Hamamatsu R5900U series). Other options are Hamamatsu's RS900U-L16 with a linear anode array of 1 mm pitch that show response times of 0.6 ns, or 2D segmented anodes, like the R3292 with 28x28 pixels at a pitch of 2.5 mm and 6 ns response or the H75546 array of 8x8 pixels with 1.5 ns response.

One potential drawback in using PMTs is their sensitivity to magnetic fields. For a successful operation in high magnetic fields, eg. close to 1 T, special tubes need to be developed. Otherwise fibres of sufficient length should be used that allow for the position of the PMTs outside the magnetic field. For the former, one example is the Hamamatsu R5505 series, which however is not position sensitive. Furthermore, there is no commercially available PS-PMTs capable at operating at 1T. The latter solution is comparable to what currently is done in the μSR experiments with the employment of lengthy wave-guides between scintillator and PMT. However, care should be taken due to the lower light yield of the fibres as opposed to a conventional scintillator crystal, coupled to the effect of light attenuation with increased propagation length, which limits the effective practical length of the fibres.

1.3.2. HPDs

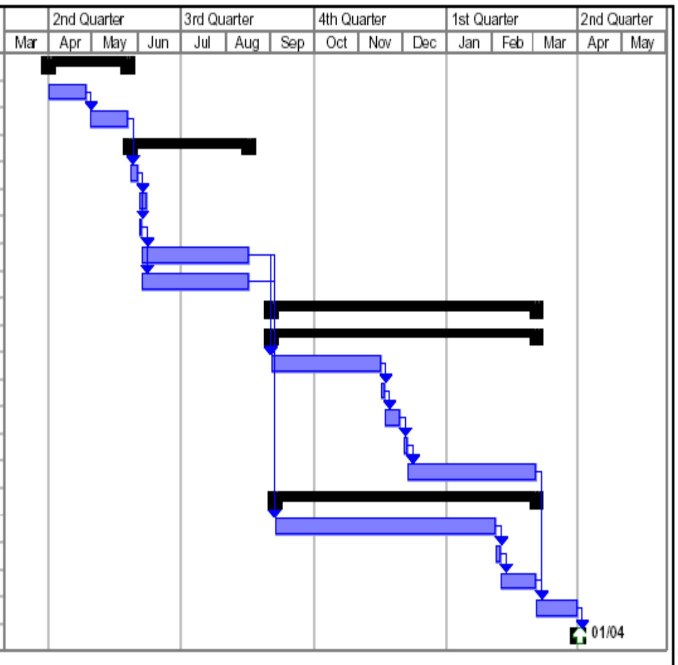
Hybrid photodiodes have been studied as an alternative way for the multi-channel read out of scintillating fibres [17]. HPD is a vacuum device that incorporates a photocathode in the entrance window, where electrons are emitted as a result of the incoming photons. By applying a substantial electric field (~2 kV/cm) the electrons are accelerated, in vacuum, towards the other end of the device where they impinge to a series of silicon diodes and are absorbed within a few microns. Reading out each diode individually provides the means for position sensitivity. Rise times of less than 1 nsec have been reported [18] together with the ability of detecting MIP's [10]. However, in order to utilise the position sensitivity of the device a suitable read-out system should be used. Towards that end, special ASIC's have been developed and successfully used [19]. The time response of the device is then dominated by the speed of the read-out electronics chip, which currently doen't exceed 25 nsec. Finally, HPD's are not immune to magnetic fields with strengths greater than 10 G.

1.3.3. APDs

Avalanche photodiodes serve both as photon detectors and as electron multipliers. They rely on impact ionisation in semiconductors for the multiplication of the charge carriers (e-h pairs) that have been liberated by the incoming light. By using heavily doped extrinsic silicon, one can achieve relatively high gains ($>10^3$) with only moderate noise. Subsequent pixelation of the surface adds position sensitivity to the device capabilities. They are found [20] to have superior temporal response, with rise times of around 1 ns, and also to be immune to high magnetic fields (2 T). However, they require cryogenic operation (6-7 K) to suppress noise, which complicates their installation and subsequent use.

2. Project Plan

ID	Task Name	Duration	Start	Finish
1	**Design Phase**	**40 days**	**Mon 01/04/02**	**Fri 24/05/02**
2	Literature survey	1 mon	Mon 01/04/02	Fri 26/04/02
3	Design	1 mon	Mon 29/04/02	Fri 24/05/02
4	**Constuction Phase**	**60 days**	**Mon 27/05/02**	**Fri 16/08/02**
5	Market search	1 wk	Mon 27/05/02	Fri 31/05/02
6	Equip. purchase	1 wk	Mon 03/06/02	Fri 07/06/02
7	Assemble team	2 days	Mon 03/06/02	Tue 04/06/02
8	Fabrication & assembly	2.65 mons	Wed 05/06/02	Fri 16/08/02
9	prgramme DAQ	2.65 mons	Wed 05/06/02	Fri 16/08/02
10	**Testing Phase**	**132 days**	**Mon 02/09/02**	**Mon 03/03/03**
11	**Dizital upgrade**	**132 days**	**Mon 02/09/02**	**Mon 03/03/03**
12	lab. tests	2.75 mons	Mon 02/09/02	Fri 15/11/02
13	DEVA tests - dead time	2 days	Sat 16/11/02	Mon 18/11/02
14	Data analysis	9 days	Tue 19/11/02	Fri 29/11/02
15	DEVA tests - time res.	3 days	Mon 02/12/02	Wed 04/12/02
16	Data Analysis	63 days	Thu 05/12/02	Mon 03/03/03
17	**Tracking prototype**	**130 days**	**Wed 04/09/02**	**Mon 03/03/03**
18	lab. tests	110 days	Wed 04/09/02	Mon 03/02/03
19	DEVA tests	3 days	Tue 04/02/03	Thu 06/02/03
20	Data Analysis	0.85 mons	Fri 07/02/03	Mon 03/03/03
21	Write report	1 mon	Tue 04/03/03	Mon 31/03/03
22	End of Project	1 day	Tue 01/04/03	Tue 01/04/03



6. Figures

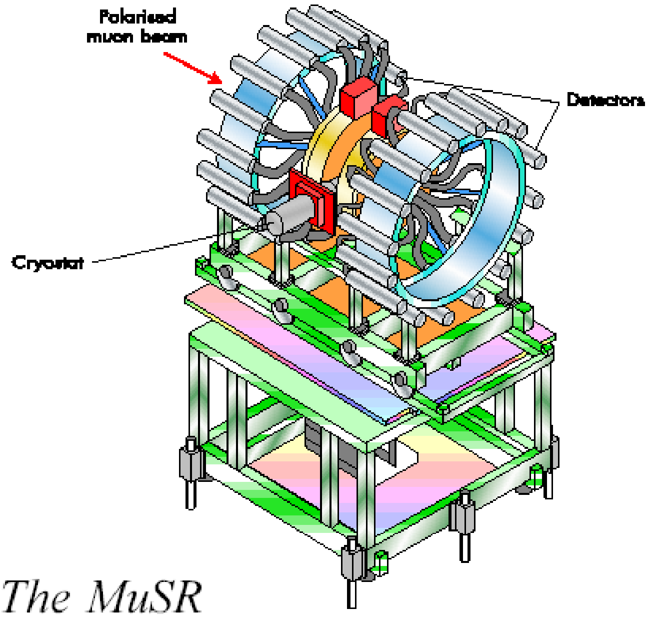


Figure 1. The μSR experiment in ISIS equipped with the DIZITAL spectrometer.

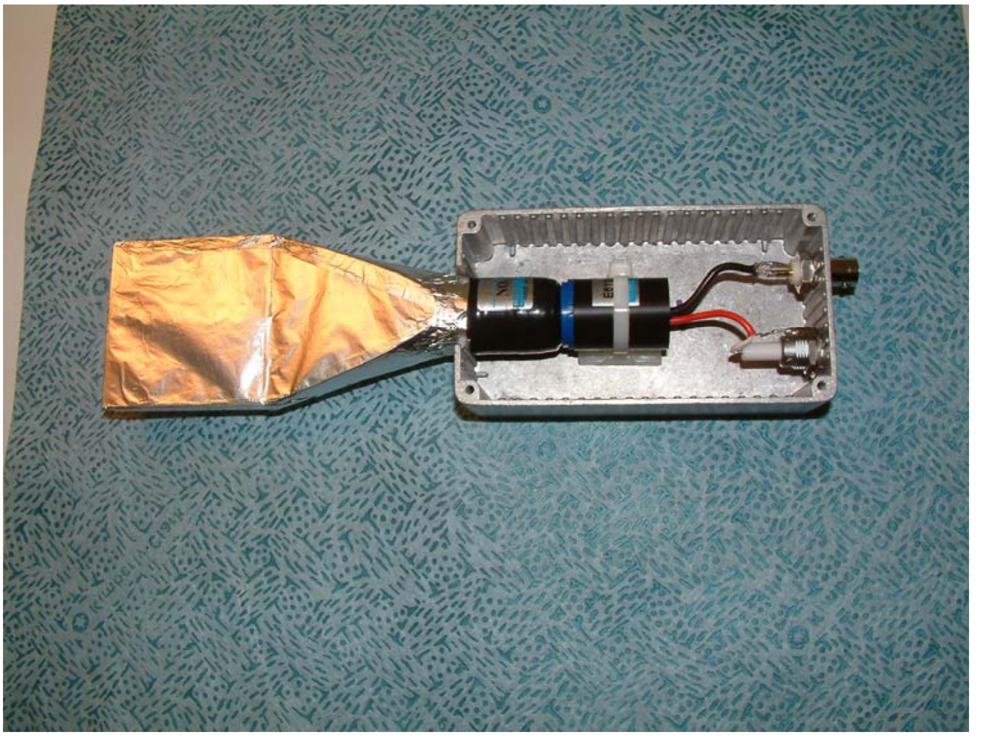


Figure 2. Photograph of the assembled scintillator detector. The scintillator and waveguide shown on the left of the picture are covered in aluminium foil and are connected optically to the PMT (HAMATSU R5505) inside the metal housing.

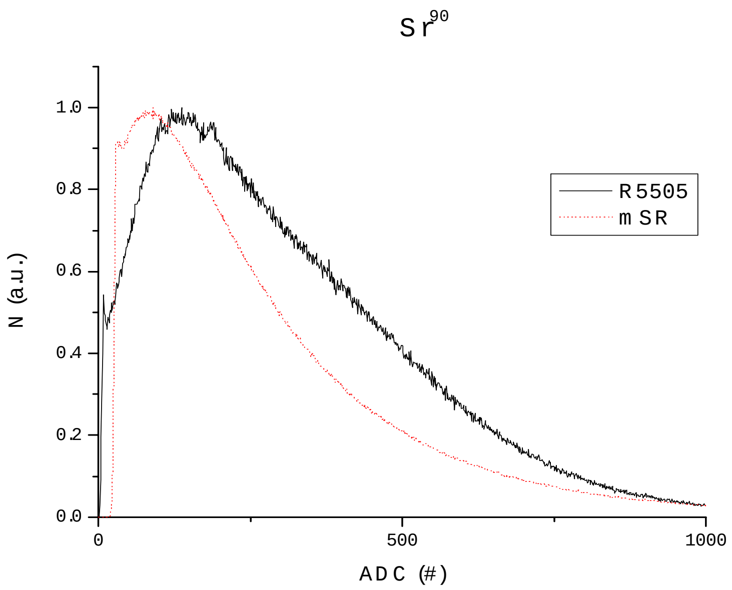


Figure 3. Sr^{90} spectrum taken with the CFI scintillator/PMT detector (solid black line) and a similar detector from the DIZITAL spectrometer (dotted red line).

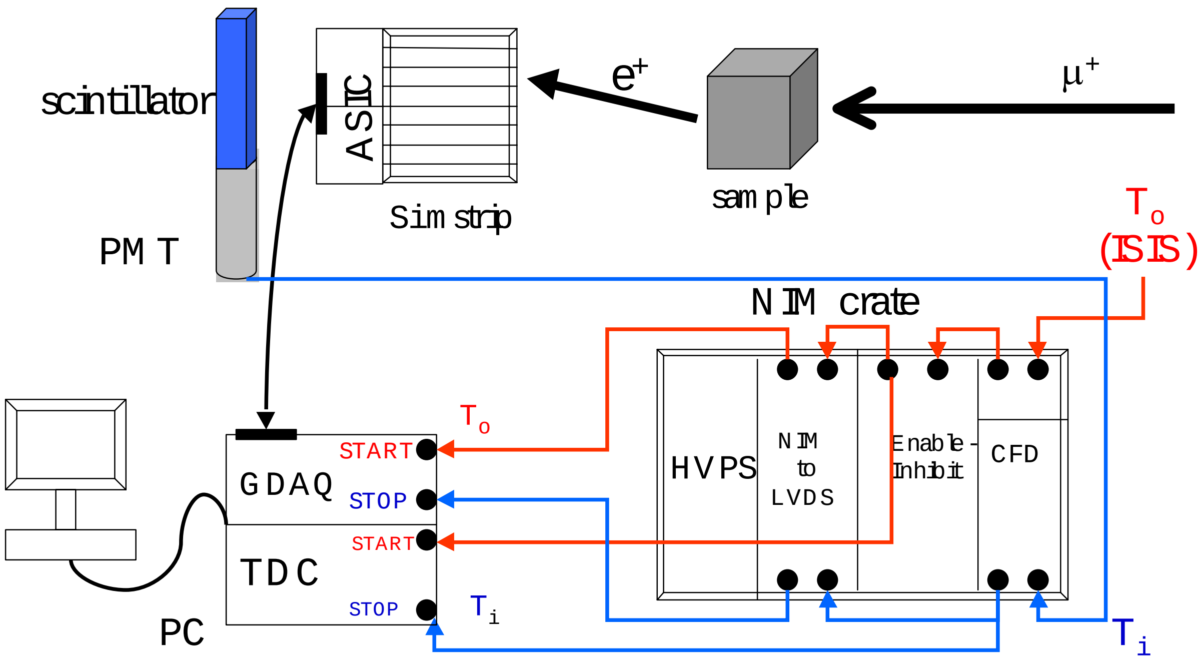


Figure 4. Conceptual drawing of the basic detector module to enable positron tracking in a future upgrade of the μSR spectrometers, as proposed in this project.

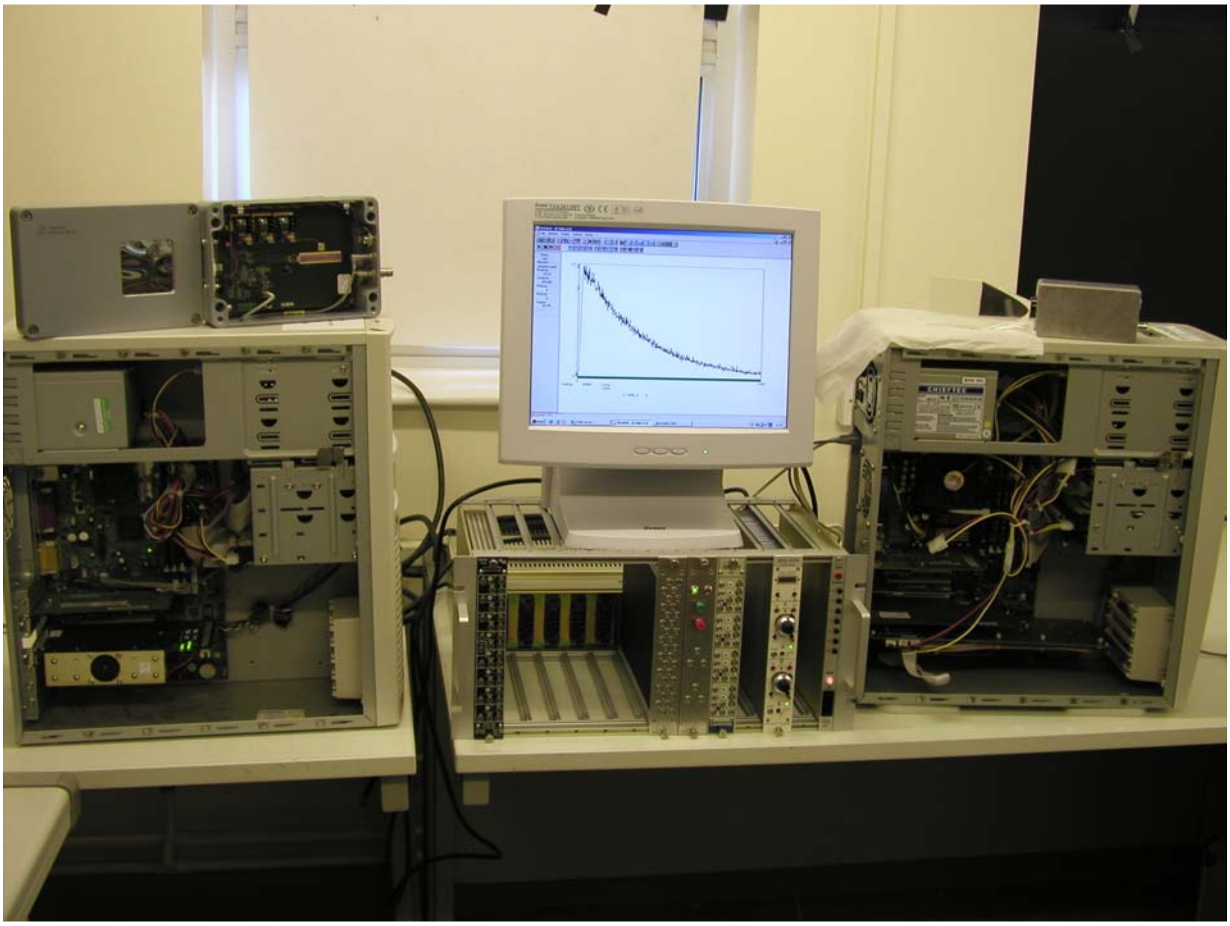


Figure 5. Photo of the completed demonstrator module that was presented diagrammatically in Fig. 4. The PSD detector is on top of the left-hand side PC with the GDAQ card visible in a PCI slot (green LED's), whereas the scintillator/PMT detector is on top of the right-hand side PC with the TDC as a PCI card.

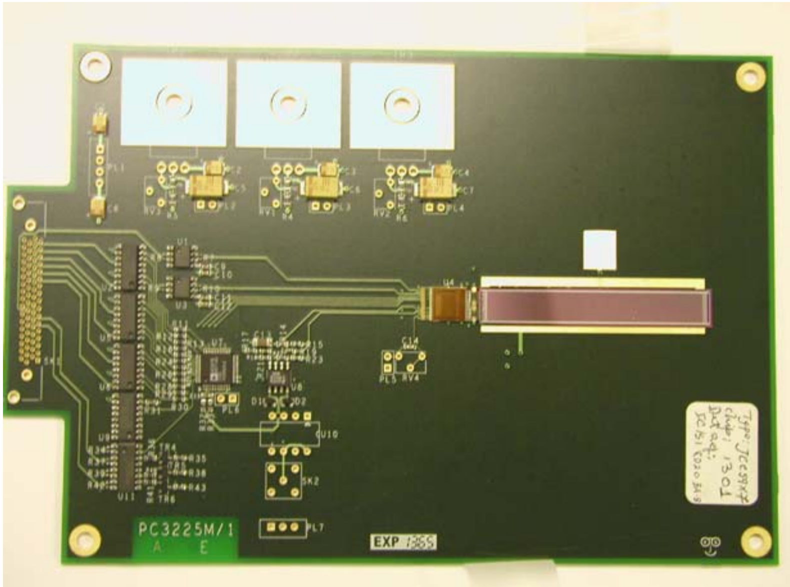


Figure 6. Silicon detector PCB board showing the detector connected to read-out ASIC (APV25) and the associated peripheral electronics (see text for more).

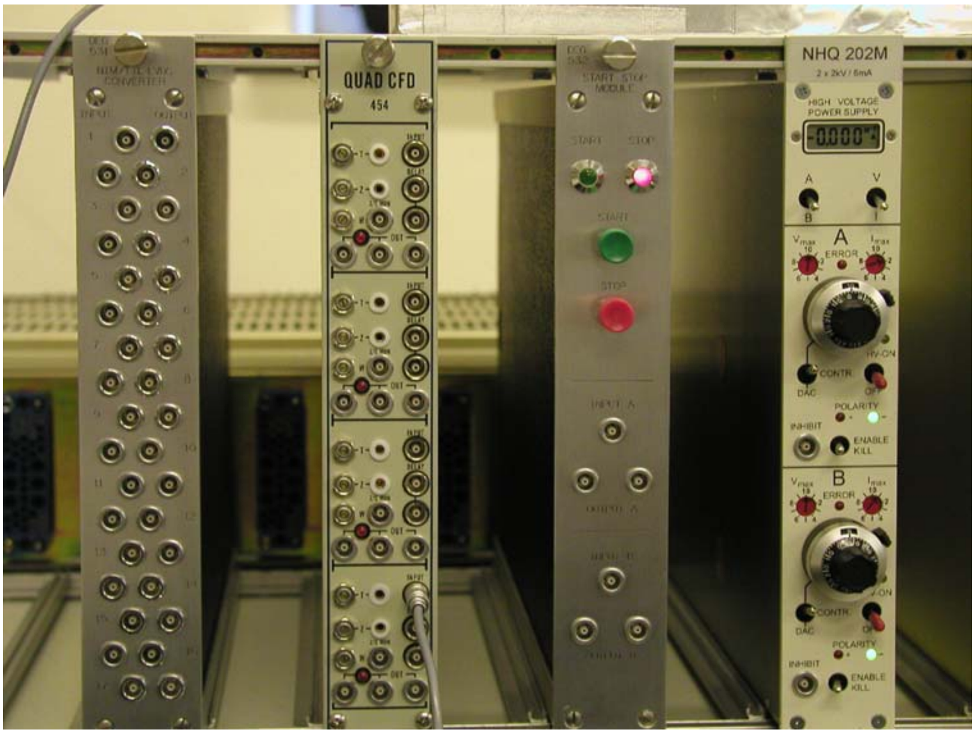


Figure 7. Detail of the completed demonstrator system showing only the NIM modules. From left to right: a) The NIM-to-LVDS conversion module, b) the Constant Fraction Discriminator, c) the "Start/Stop" unit and d) the HV Power Supply for the scintillator.

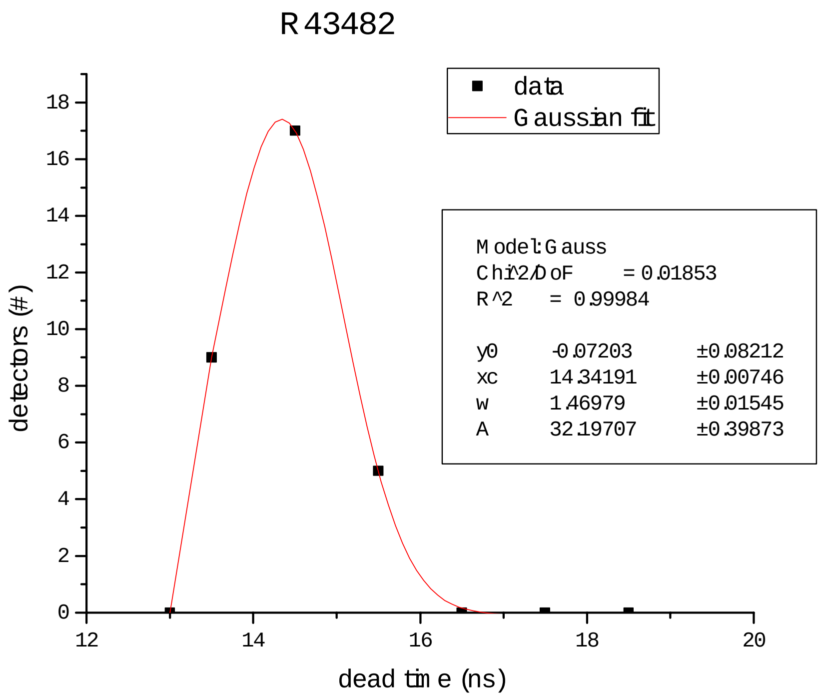


Figure 8. The dead times of the 32 detectors comprising the DIZITAL spectrometer of the DEVA station, measured with the standard configuration used in μSR experiments, i.e. a LeCroy 3412E discriminator and the DASH2 TDC.

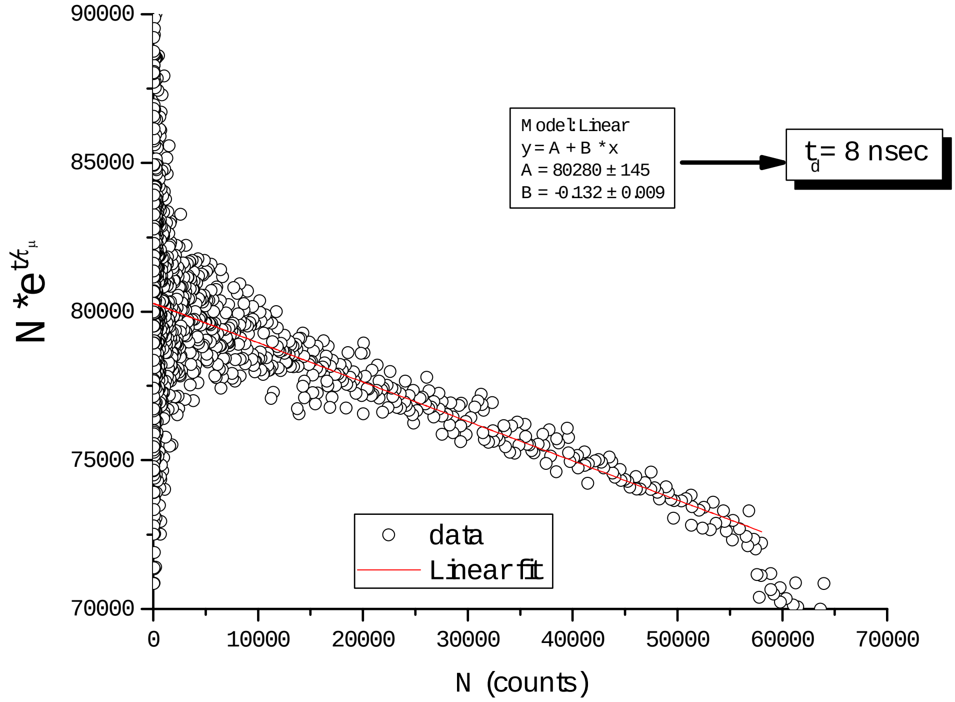


Figure 9. Dead time (t_d) calculation for the CFI detector system, for more explanation see text.

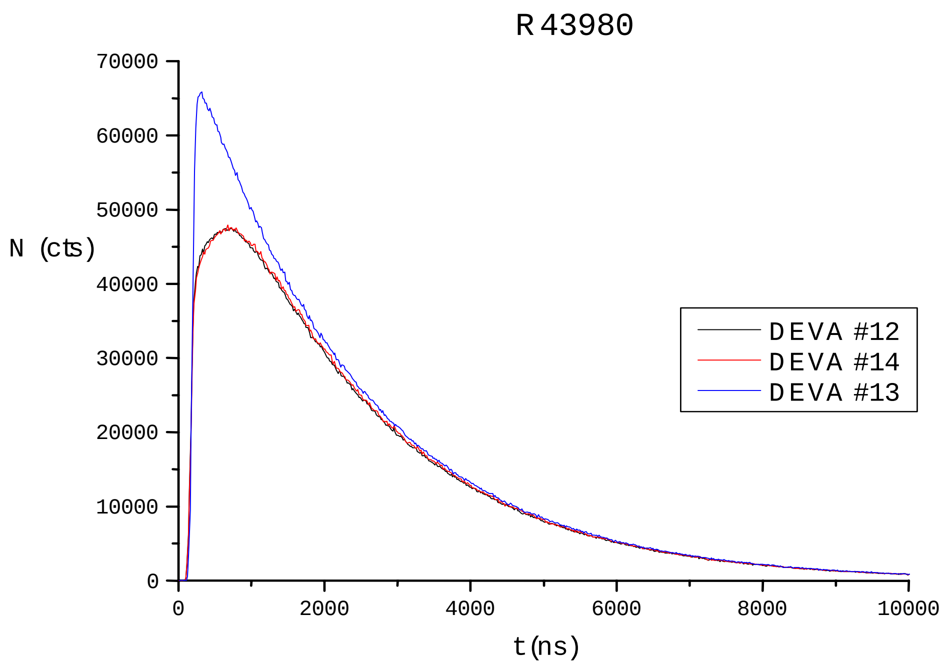


Figure 10. Muon decay measured with DIZITAL detectors. Detectors no. 12,14 were connected to the spectrometer's own read-out, whereas no. 13 to this project's CFD and TDC.

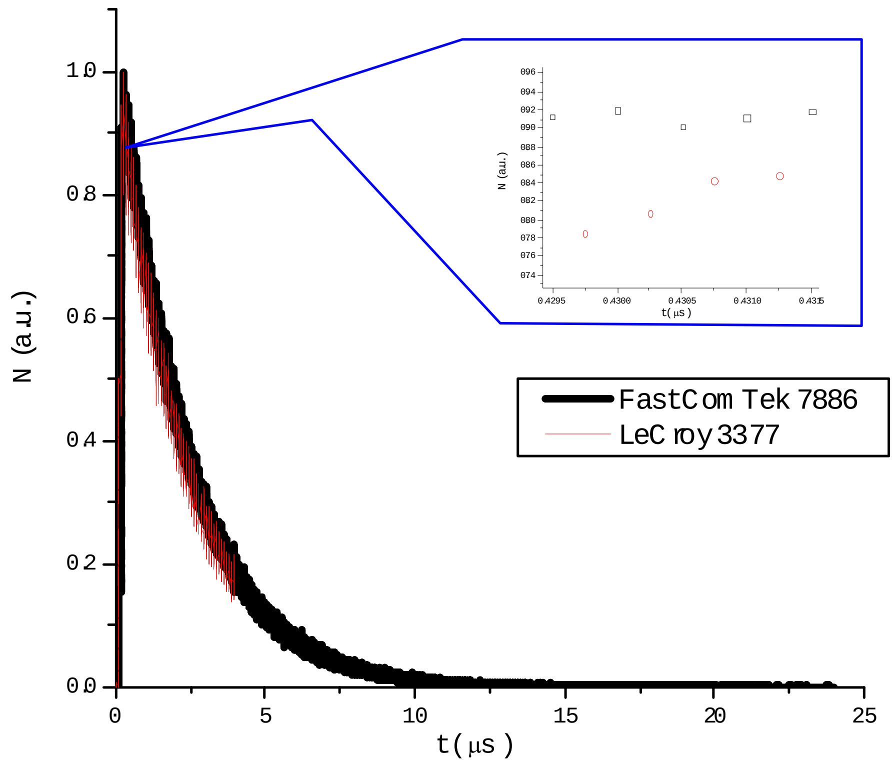


Figure 11. RF experiment at maximum TDC time resolution of 0.5 ns (see inset).

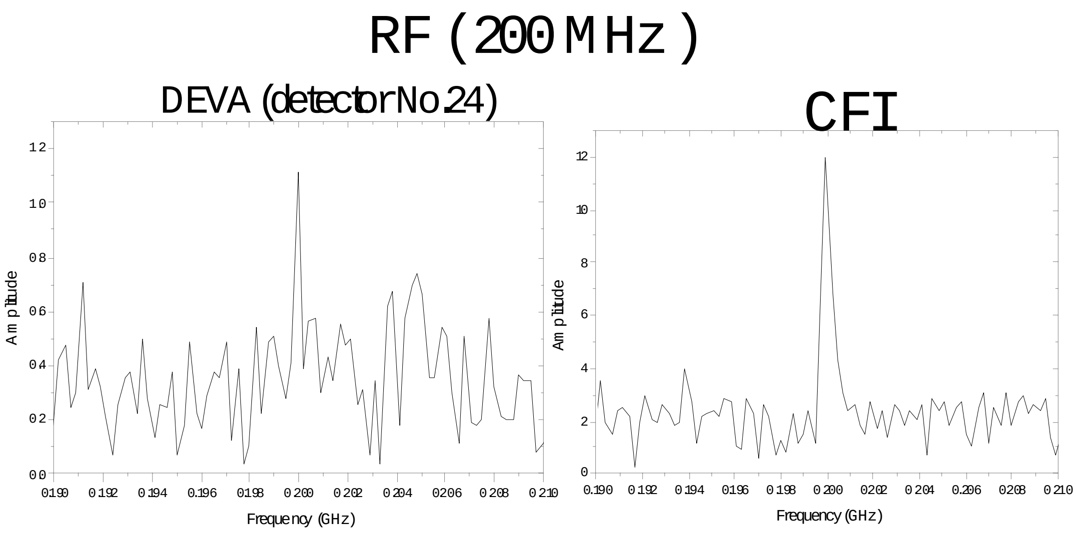


Figure 12. FFT spectrum of a RF type experiment at 200 MHz record with both the station (left figure) and this project (right figure) detectors.

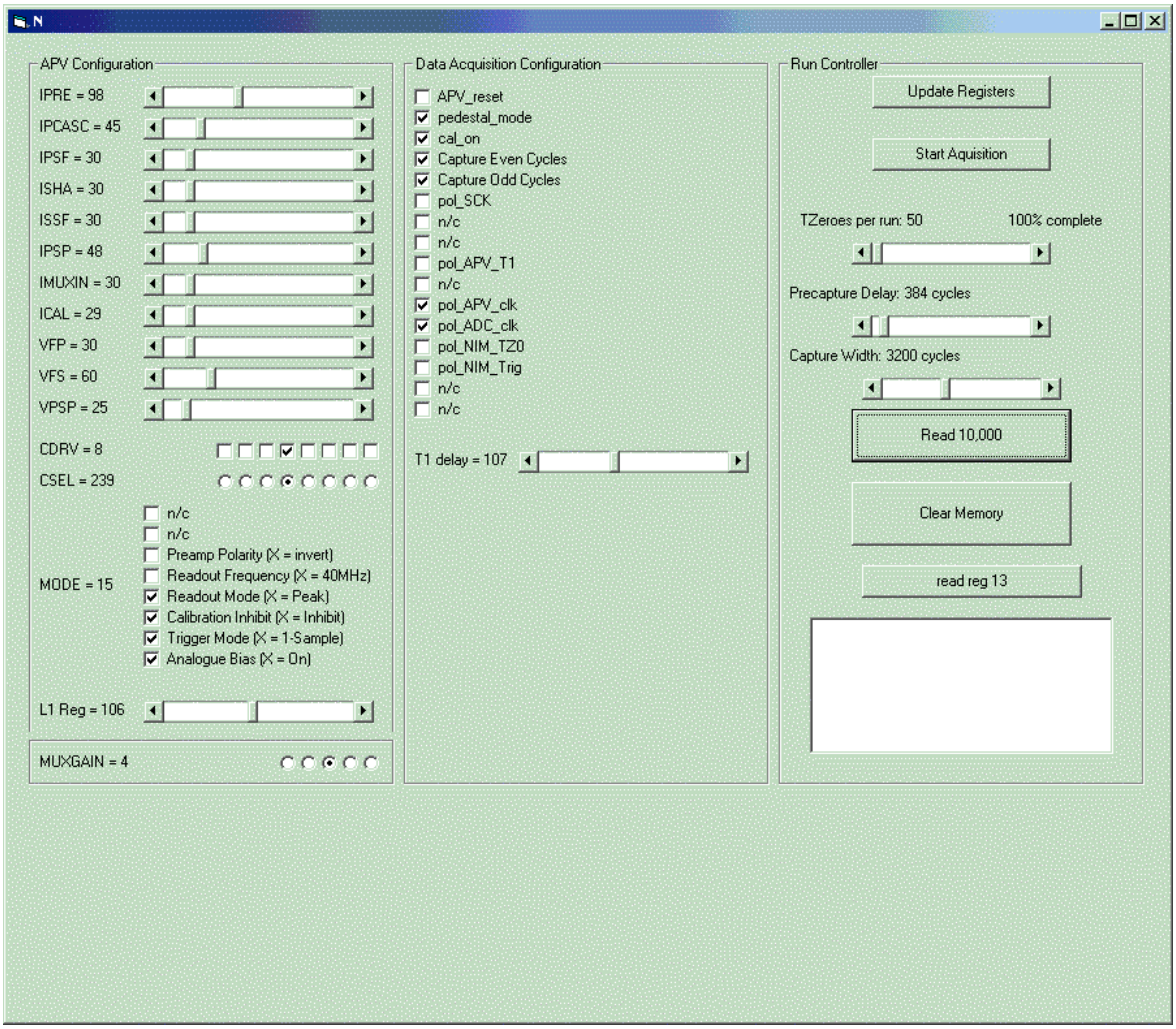


Figure 13. Display of the data acquisition software for the control and read-out of the APV; PC interface via GDAQ card.

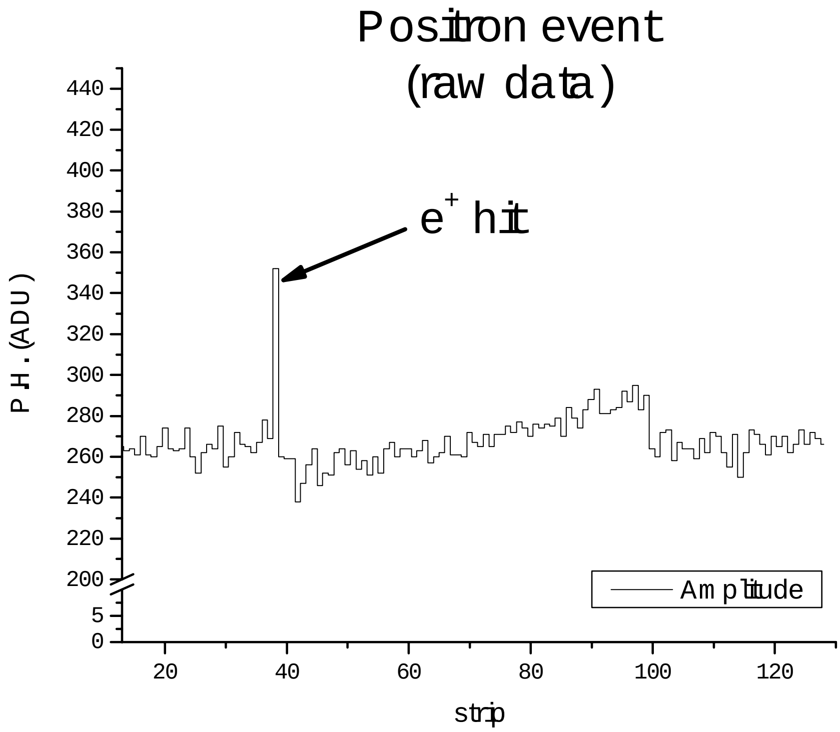


Figure 14. Positron detection by the project's silicon microstrip PSD in a μSR experiment in DEVA.

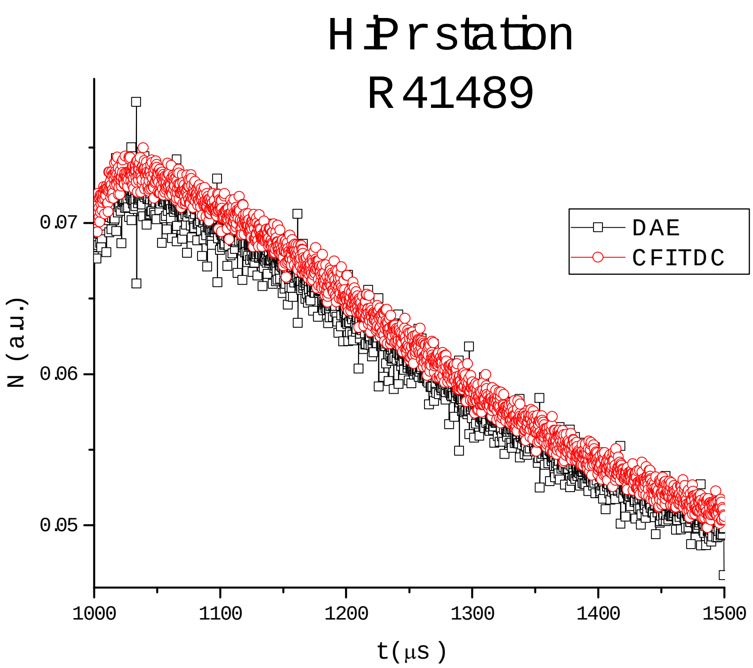


Figure 15. Comparison of a neutron absorption T.O.F. spectrum recorded in ISIS with the CFI (red line, open circles) and the ISIS DAE (black line, open squares) TDC's.

References

[1] S. Kilcoyne et al., RAL-94-080.

[2] G. Knoll, Radiation Detection and Measurement, Wiley pub.

[3] G. Eaton, RAL-TR-1998-019.

[4] B. D. Rainford, "Aspects of Data Treatment for Transverse μSR", lecture notes, μSR training course, RAL Janouary 2003.

[5] S. Manolopoulos, "A study of GaAs detectors for tracking in the ATLAS experiment", RAL-TH-97-006.

[6] Geant4 - A Simulation Toolkit, the Geant4 Collaboration, CERN-IT-2002-003; KEK-Preprint-2002-85; SLAC-PUB-9350.

[7] W. Bonivento et al., NIMA 491 (2002) 233-243.

[8] D.H. Perkins, Introduction to High Energy Physics, Wesley Pub.

[9] E. Belau et al., NIM 214 (1983) 99

[10] G. Knoll, Radiation Detection and Measurement, 4th ed, Wiley Pub.

[11] C. Damerell, Vertex Detectors: The State of the Art and Future Trends, RAL-P-95-008

[12] S.Manolopoulos, A study of GaAs detectors for tracking in the ATLAS experiment, RAL-TH-97-006, and references therein

[13] E. Heijne, Muon Flux Measurement with Silicon Detectors in the CERN Neutrino Beams, CERN 83-06

[14] Sze, Physics of Semiconductor Devices, 2nd ed., Wiley Pub.

[15] M. Atac, ICFA Summer School notes and reference therein, Lubljana (1995)

[16] M. Salomon et al., IEEE Trans. Nucl. Sci., v.34, No.1 (1987) 525

[17] C.P.Datema et al., IEEE Trans. Nucl. Sci., v.45, No.3 (1998) 338

[18] P. Benetti et al., NIM A409(1998) 434-438

[19] C.Datema et al., to be published in IEEE NSS

[20] M. Petroff, High energy particle tracking using scintillating fibres and solid state photomultipliers, IEEE Trans. Nucl. Sci., v.36, No 1, 1989