Status Update of PSI Experiment R-89.01.1

A PRECISE MEASUREMENT OF THE $\pi^+ \to \pi^0 e^+ \nu$ DECAY RATE

THE PIBETA COLLABORATION

25 January 2001

The PIBETA project at PSI is a program of measurements with the aim of making a precise determination of the pion beta decay rate, initially to $\sim 0.5\,\%$. This document presents a condensed update of the current status of the experiment and a beam time request for 2001.

1. Activities completed in 2000

While the major commissioning and development tasks were completed in 1999, during 2000 we have successfully continued taking data at the π^+ stopping rate of $\sim 9 \times 10^5\,\pi$/s.

We have also focused on accomplishing the following goals:

(i) We have fully automated the timing offset adjustment and detector gain matching procedures. This has enabled more reliable on-line data acquisition and monitoring, also partly reducing the off-line replay.

(ii) We have implemented the domino sampling chip (DSC) readout for all PMT signals, including all of the CsI and plastic veto counter detectors.

(iii) We have completed the implementation of near-100 % experiment automation, requiring that only a single experimenter be physically present and on call at the PSI site while running.

(iv) We have run a series of measurements aimed at mapping out details of our detector system response, particularly of the CsI calorimeter.

Further, we have focused on the analysis of the data as it came in. Our detector is taking high-statistics data on all of the rare pion and muon decay channels. We are analyzing all of these as they provide (a) an important check of self-consistency of our analysis and simulation, and (b) a high-statistics data sample that will result in new physics results. We summarize the current status of our analysis in the next section.

2. Current status of data analysis and simulation

Our efforts on data analysis have focused on three fronts, all of which are of vital importance to the final result. These are:

(a) replay of data pertaining to the individual pion and muon rare decay modes,

(b) replay of data pertaining to the extraction of critical detector and running parameters, such as: beam spot geometry, individual detector efficiencies, calorimeter response lineshape, etc., and

(c) high-statistics self-consistent simulation of both (a) and (b) in order to achieve the required level of systematic uncertainties.

Below we present some of the results illustrating the current status of our analysis. Results reported for the pion beta as well as the pion and muon radiative decays are based on an analysis of about 40 % of our 1999 and 2000 data sample.

2.1. The $\pi \to e\nu$ decay

This decay is used as the normalizing reaction in the evaluation of the pion beta decay branching ratio, as well as one of the benchmarks of the calorimeter response simulation. The quality of our data is illustrated in Fig. 1 which shows replay results for a small subset of data taken to date.

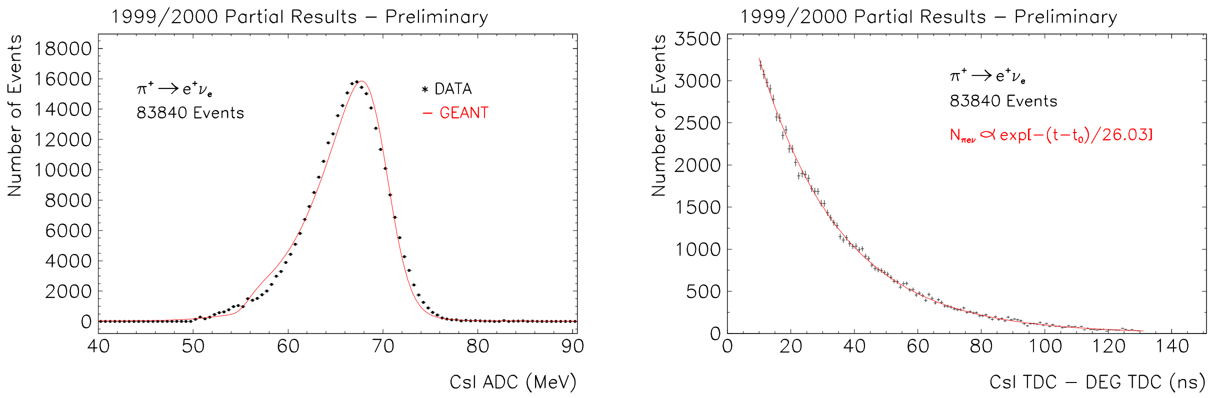

Figure 1: Energy (left panel) and timing distribution (right panel) of the measured $\pi \to e\nu$ events for a subset of acquired data. Solid curves: GEANT simulation. Preliminary.

The simulation result shown in the left panel was the "predicted" GEANT calculation that has not been adjusted with respect to the results of our calibration runs. In fact, the $\pi \to e\nu$ decay provides one of the critical standards for our GEANT simulation. We note that the starting point gives an energy spectrum very close to the measured one. The fine adjustment of GEANT detector parameters is currently under way.

2.2. The $\pi^+ \to \pi^0 e^+\nu$ decay

Having fully replayed some 40 % of the data acquired, we find that the quality and yield of the pion beta decay events are in good agreement with the original experiment design goals. The π^0 energy spectrum and the corresponding event time distribution are displayed in Fig. 2. The γ-γ opening angle and time difference distributions are plotted in Fig. 3.

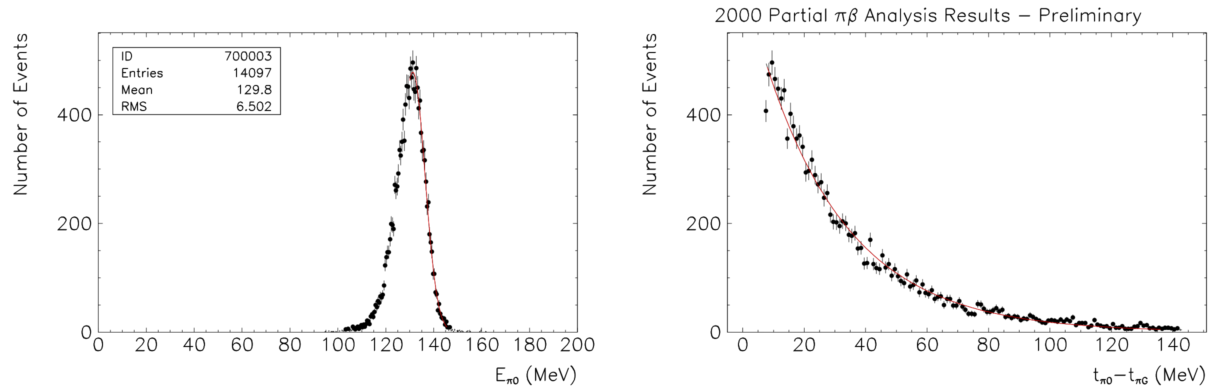

Figure 2: Left panel: energy distribution of the measured pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of acquired data; solid curve: GEANT simulation (preliminary). The low energy tail below about 110 MeV is cut off by the trigger threshold. Right panel: time distribution of pion beta decay events with respect to the beam pion stop time; curve: GEANT simulation (preliminary).

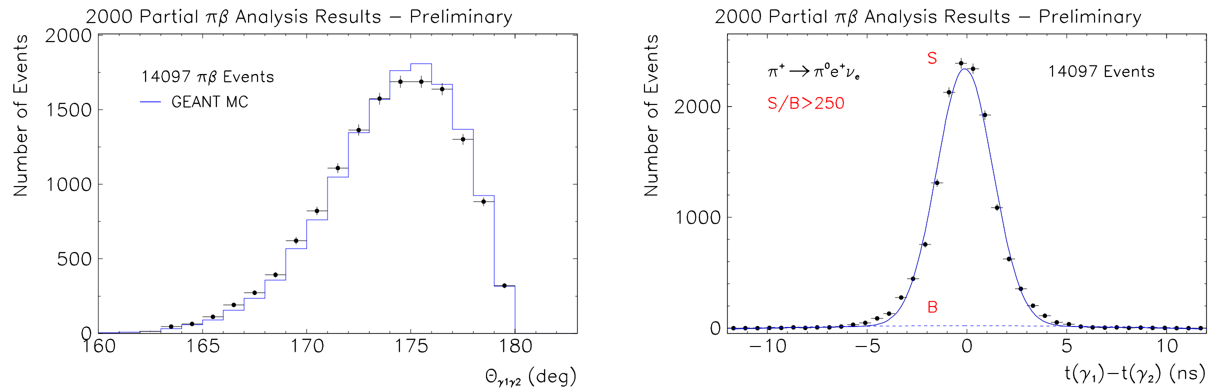

Figure 3: Left panel: distribution of γ-γ opening angles for the measured pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of acquired data; solid curve: GEANT simulation (preliminary). Right panel: γ-γ time difference for the same set of $\pi\beta$ data events (dots); curve: fit. Signal to background ratio exceeds 250. Preliminary.

As has already been indicated, the GEANT simulation results shown in the above figures are preliminary. Final simulation results will reflect further detector parameters which are currently being extracted from data. In any event, the data sample shown in Figs. 2 and 3 is evidently very clean. These data correspond to a set of rather stringent cuts. Relaxing these cuts results in about 20 % more events. The systematics of these cuts are currently under study.

2.3. Pion and muon radiative decays

We have already recorded about two orders of magnitude more data on the $\pi \rightarrow e\nu\gamma$ and $\mu \rightarrow e\nu\bar{\nu}\gamma$ decays than has been reported in all publications to date. As stated above, we are vigorously pursuing the analysis of these data not only for their intrinsic physics value, but also as a known background to our main decays, as well as a rigorous cross-check of our Monte Carlo simulation and systematics. At this point we present only some basic histograms showing the quality of our radiative decay data.

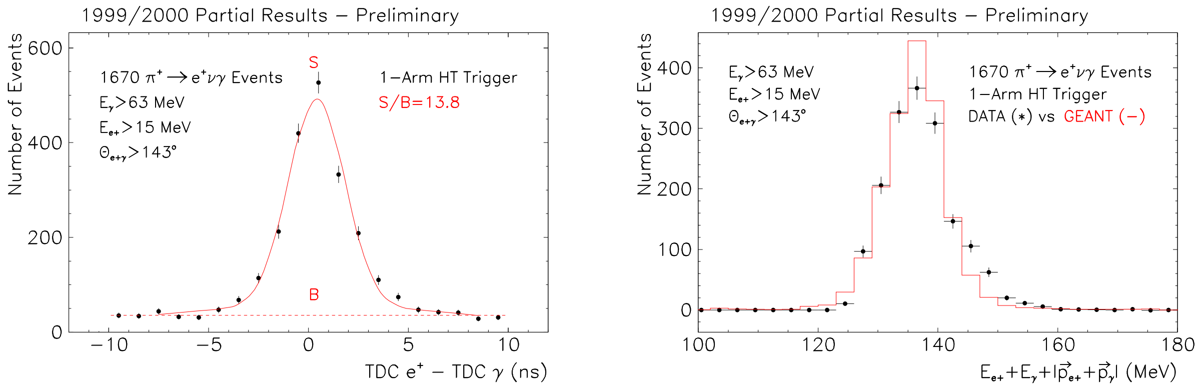

Figure 4: e-γ timing difference in a subset of the 1-arm trigger $\pi \rightarrow e\nu\gamma$ decay data (left panel). Two-arm data (not shown here) are virtually free of background, like the $\pi\beta$ events shown in Fig. 3. The right panel plots the "invariant π^+ mass" variable, reconstructed from the 1-arm subset of our radiative pion decay event data (dots) and simulation (histogram). Preliminary.

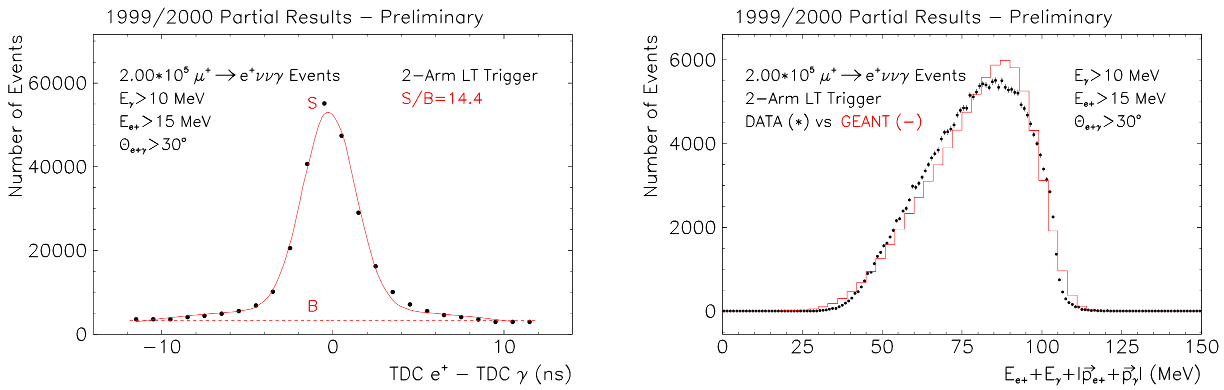

Figure 5: e-γ timing difference for the analyzed data subset of $\mu \rightarrow e\nu\bar{\nu}\gamma$ decays (left panel). The right panel plots the "invariant μ^+ mass" variable reconstructed from our muon radiative decay event data (dots) and simulation (histogram). Preliminary.

It is clear from the above figures that we have a very clean sample of radiative decay events with high signal to background ratios. We also note the sensitivity of these reactions to a good understanding of the detector acceptances and response.

A preliminary analysis of our $\pi \to e\nu\gamma$ data sample indicates that we should be able to improve significantly on the present accuracy of the pion form factor ratio F_A/F_V. This is a quantity of direct significance to the pion polarizability, and is one of the few observables cleanly predicted by effective QCD models such as the chiral perturbation theory[1]. In the same vein, we should be able to resolve the controversy regarding possible tensor coupling in pion radiative decay (if true, it would represent evidence of supersymmetric particles) that have been around for about a decade[2, 3, 4].

2.4. Experiment systematics: mapping the beam stopping distribution

As an example of some of the studies of the experimental parameters and detector response, we report below on an analysis of the PIBETA pion beam stopping distributions in x, y and z. Pion stopping spatial distribution needs to be determined accurately for a precise determination of the detector acceptance.

Pion stopping distributions were studied by two methods:

(a) adjusting theoretical stopping distributions parameters so that they reproduce the measured energy spectra in the active target detector elements for "pion stop trigger" events, and

(b) direct trace-back and tomography of $\pi \to e\nu$ and Michel decay events in the target.

The first method is in essence an iterative deconvolution of the measured pion stopping yields in the nine target elements. Results of the two methods are in remarkable agreement.

For illustration, we include in Fig. 6 the x and y beam stopping profiles reconstructed using the first method (we will report details of this procedure in a paper which is currently in preparation).

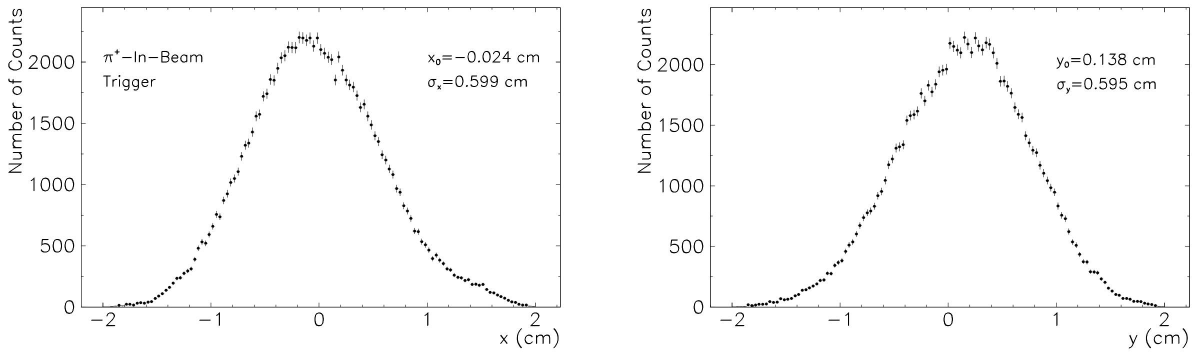

Figure 6: Reconstructed horizontal (x, left) and vertical (y, right) π^+ stopping profiles in the target, using method (a) based on the pion stopping yields in the target ADC's. Central positions of the distributions as well as the standard deviations of the fitted Gaussian forms are written on the graphs. Preliminary.

Subsequently, we selected a subset of our large sample of $\pi \to e\nu$ and Michel decays to get an independent check of this stopping distribution. The second method relies on tracing $\pi \to e\nu$ and Michel positron trajectories back to the target and incrementing each cubic cell of the target volume through which a ray passes. Statistically, the combined density of tracks maps out tomographically the spatial source distribution[5].

Before we could interpret the back-tracking tomography results, we needed to determine the tracking resolution of our wire chambers. This was accomplished using the copious cosmic muon data and the fact that a through-going muon leaves four hits in our two concentric chambers. Typical tracking resolution histograms are shown in Fig. 7.

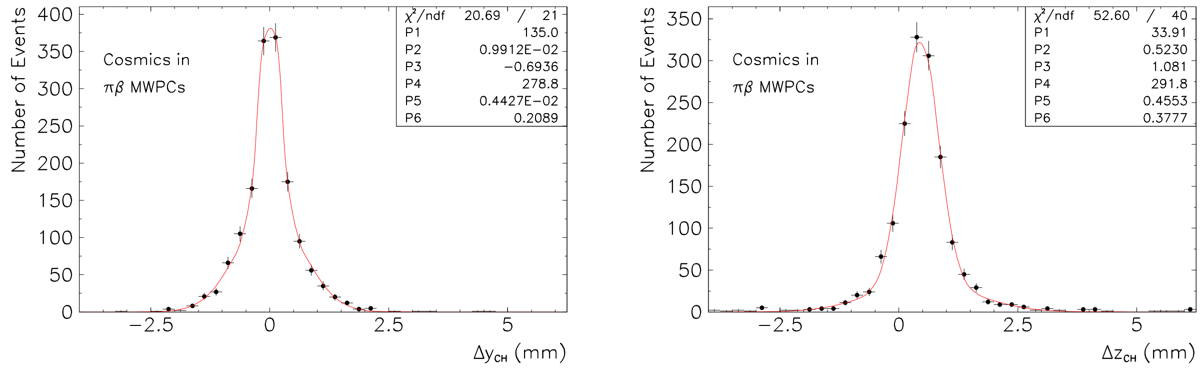

Figure 7: Reconstructed transverse (y, left panel) and longitudinal (z, right panel) tracking resolutions in Chamber 1. Preliminary.

Thus, we were able to compare the results of the tomographic analysis, shown as dots in Fig. 8, to the appropriately propagated spatial distributions of method (a), shown as curves in Fig. 8. (The flat background under the reconstructed distributions is inherent to the method and is to be disregarded.)

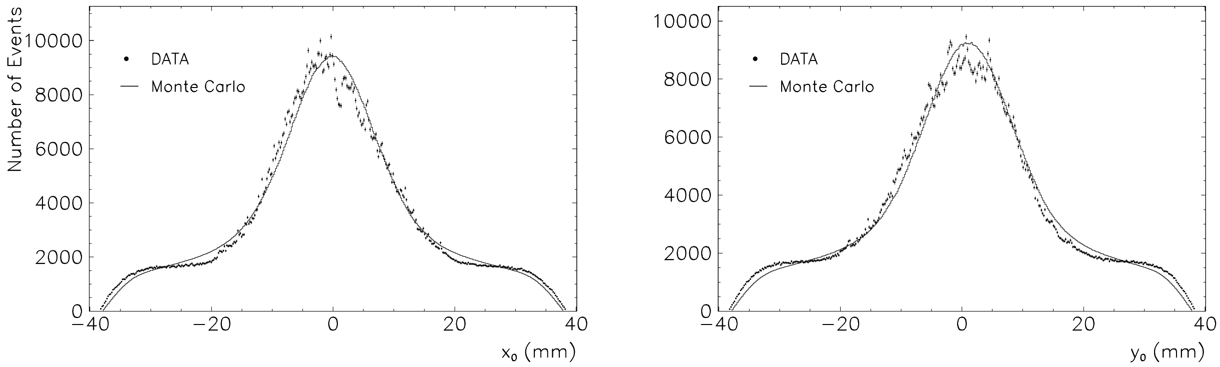

Figure 8: Tomography of trajectories of $\pi \to e\nu$ positrons. Dots represent the traced back horizontal (x, left) and vertical (y, right) profiles in the target. Curves show results of simulation based on the pion stopping profiles from Fig. 6, taken as input. Preliminary.

To summarize, the reconstructed two-dimensional transverse and one-dimensional longitudinal pion stopping distributions are shown in Figs. 9 and 10, respectively.

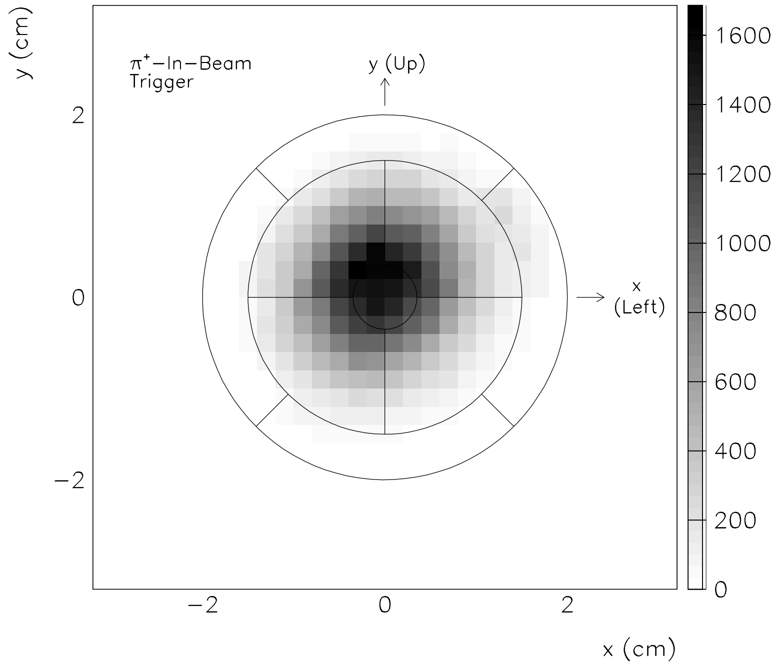

Figure 9: Reconstructed two-dimensional transverse pion stopping distribution for a series of 50 runs (60 hours of beam time), superimposed on a cross sectional outline of the active target. Preliminary.

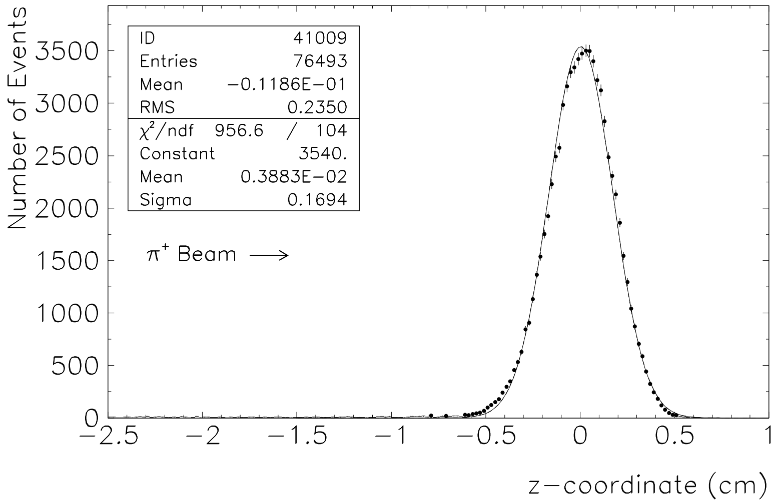

Figure 10: Reconstructed longitudinal pion stopping distribution for a series of 50 runs spanning 60 hours of beam time. The solid curve is a Gaussian fit. Preliminary.

We note that our method is accurate enough to discern the slight difference between the Michel and $\pi \to e\nu$ distributions, the former being spread out by the range of the muon in the intermediate decay $\pi \to \mu\nu$.

We stress that the above results represent only a first pass in the analysis. The precision of our initial result already yields the uncertainty of extracted $\sigma_{x,y}$ of the pion stopping distribution below 0.5 mm, which translates into $< 0.3\,\%$ uncertainty on the calculated acceptances. This analysis will be considerably refined and its precision improved.

The beam geometry reconstruction has revealed that the beam spot has been remarkably stable over the 1999/2000 run time. The reconstructed horizontal (x), vertical (y) and axial (z) centroids of the stopping distribution varied with $\mathrm{rms}_{x,y} \simeq 0.04\,\mathrm{mm}$ and $\mathrm{rms}_z \simeq 0.2\,\mathrm{mm}$, respectively, as shown in Fig. 11.

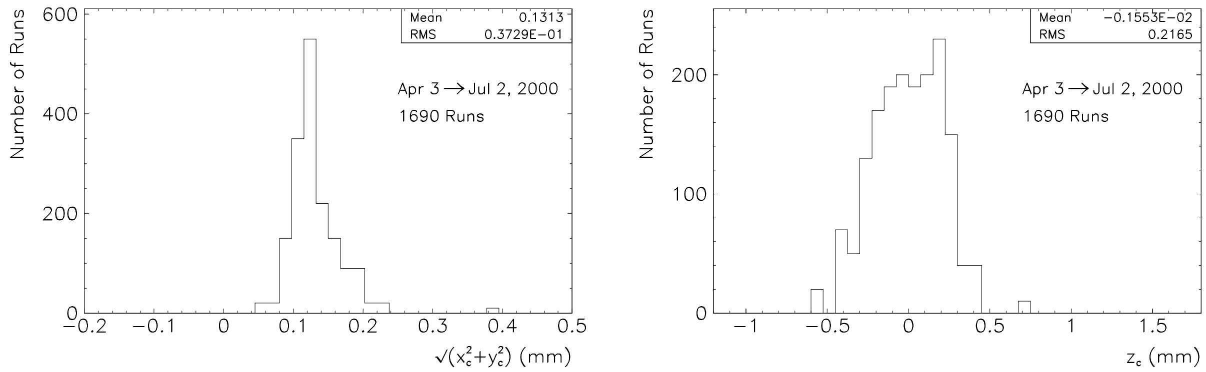

Figure 11: Spatial stability of the stopped π^+ beam spot center during a three month running period: histogram of lateral (left panel) and axial (right panel) coordinate values of the beam centroid, reconstructed using positron track tomography. The reconstruction uncertainty for a single run is $< 0.02\,\mathrm{mm}$. Preliminary.

Furthermore, there are additional stringent checks on the method outlined above. One important check has already been presented in Fig. 3. The γ-γ opening angle distribution depends critically on the exact position of the centroid of the beam stopping distribution, and is also sensitive to the spatial spread of the distribution. A more accurate reconstruction of the beam stopping distribution will further improve the agreement of the simulated and measured γ-γ opening angle distribution for the pion beta decay events.

Another consistency test involves taking the π^0 Dalitz decay subset of our large sample of prompt charge exchange events in the target. Subjecting these events to back-tracing vertex reconstruction will give us an independent measure of the pion beam profile.

Our publications to date reflect the important role that accurate detector description plays in minimizing the final systematic uncertainties, both in simulation and data analysis. In the last year we have published the following papers:

- *ADC common noise correction and zero suppression in the PIBETA detector*, accepted for publication in Nucl. Inst. Meth. **A**, e-print hep-ex/0009042.

- *Light Response of pure CsI calorimeter crystals painted with wavelength shifting lacquer*, Nucl. Inst. Meth. **A459** (2001) 426-439, e-print hep-ex/0006027.

- *OPTICS: general-purpose scintillator light response simulation code*, Comp. Phys. Commun. **134** (2001) 110-135, e-print hep-ex/0006033.

- *Cosmic muon tomography of pure cesium iodide calorimeter crystals*, Nucl. Inst. Meth. **A440** (2000) 57-85, e-print hep-ex/9905041.

As some of these techniques may prove useful to colleagues in the field, we have opted to publish them rather than writing internal reports only. We have several more reports/papers currently in preparation dealing with instrumentation, detector response, and controlling the systematic uncertainties.

3. Data rates

The primary goal of the current phase of the PIBETA experiment is to reach $\sim 0.5\,\%$ accuracy in the pion beta decay branching ratio. Extrapolating from the analyzed fraction of $\leq 40\,\%$ of our data, we have accumulated some 40,000 pion beta decay events to date. The corresponding data rate is about 3.4×10^{-9} $\pi\beta$ events per pion stopped in target. This is in good agreement with the data rate planned in the original experiment proposal of about 4×10^{-9} events per pion stopped, if we allow for the data acquisition live time fraction of about 0.87 which was not taken into account in the proposal.

Making use of all of the available running time in 2001 would approximately double the above event statistics and put us in the range required for a $\sim$ 0.5 % result.

4. Personnel

In August 2000 Stefan Ritt, a key member of our collaboration took on a new job at PSI with broad responsibilities for the new $\mu \to e\gamma$ project. While he remains a member of our collaboration, his departure means a substantial reduction of his effort on PIBETA. We have been unable to find a replacement for Stefan, but hope to be able to fill the position sometime in 2001, subject to available funding.

We have, however, taken on three new graduate students from UVa: Maxim Bychkov, Brent Vandevender and Ying Wang. As all three passed their PhD qualifying exam only in January 2001, their contributions to the experiment will grow significantly in the coming months. Additionally, we have had the help of two UVa undergraduate students whose contributions will become more substantial as the year proceeds.

With the existing collaboration team we feel that we should be able to adhere to our data acquisition and analysis timetable.

5. Future running and beam time request for 2001

Barring unforeseen circumstances, we expect that running during the entire 2001 PSI ring accelerator beam time would satisfy the requirements of the current phase of the PIBETA experiment.

Because this long running period should complete our data taking for the $\sim 0.5\,\%$ phase of the experiment, we ask to run without interruptions. While the modular self-sufficient design of our setup enables us to physically remove and re-install the detector rather quickly, the cost in time required to bring the detector system back into gain matched and stable operation is very considerable. As it now stands, we plan to accomplish detector stabilization in the beam area before the beam starts up in April/May 2001.

In view of the shortened beam schedule for the PSI ring accelerator in 2001, and given our past experience with beam or equipment outages, we consider our request well founded. If, however, the Program Committee finds it unavoidable to set aside some time in the πE1 channel for other experiments, we ask that this be scheduled at the end of the 2001 running period. We note that in the past we have always tried to be as flexible as possible in accommodating other beam requests, and have voluntarily given up some of our beam time in order to help our colleagues. However, as we are not planning to make a beam request in 2002, we no longer have the same flexibility as we did in the past.

Looking farther ahead, we note that with minor modifications the PIBETA detector system is ideally suited for a more precise remeasurement of the $\pi \to e\nu$ decay rate, now known with about 0.35 % uncertainties. This is of considerable theoretical interest with respect to constraints on possible extensions to the Standard Model[6].

In 2000 we took low rate calibration data needed for a precise mapping of the low energy tail in the the CsI calorimeter lineshape. These data will also provide us with an opportunity to evaluate carefully the prospects for a $\pi \to e\nu$ measurement to about 0.1 % accuracy, a strongly theoretically justified goal. In parallel we will also need to form a new collaboration and submit a new experiment proposal to the PSI Program Advisory Committee.

References

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