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Status report of the HARP experiment

1 Introduction

In a previous status report (CERN-SPSC/2002-013) the hardware performance of the HARP sub-detectors and the performance of the software were summarized. In addition, an estimate of the data-set obtained in 2001 and a number of plots showing the ability to reach the physics goals were given. We refer to this recent report ("March-report") for this information and a description of the apparatus.

Due to a lack of time between the data taking and the March-report some results could not be fully checked, and the collaboration preferred not to show them. Instead, a quite detailed account of all problems encountered in the analysis of the data had been given.

In the present report we concentrate on the solutions to the problems raised in the March-report and in particular on the assessment of the quality of the data taken in 2001. In addition, it will be shown that the experiment will be able to achieve its objectives in the 2002 run, although with a tight schedule.

2 Hardware: status and performance

A number of problems were described in the March-report. Here we will analyse the impact on the data already taken in 2001 and on the data to be taken in 2002. In the following section we will repeat briefly the description of the problems and describe the present status.

In summary, the longer TPC readout time and the reduced trigger selectivity influence in no way the quality of the events recorded; these events are therefore fully available for the final analysis. The cross-talk in the TPC has an impact on the momentum resolution and on particle identification by dE/dx. It was not considered realistic to solve the problem at the hardware level, therefore the data taken in 2001 and 2002 will remain homogeneous and can be analysed together. The effects will be treated by the reconstruction software, and the status of the activities will be described below. Owing to the large redundancy in the number of TPC channels, the impact of the dead channels is small. Effects introduced by the imperfections in the down-scale factor for normalization events are fully understood and only reduce the statistical significance of the normalization sample.

2.1 TPC performance

> *Some 5% of the* ~ 4000 *TPC pad-channels had problems; some pads were missing because 6 out of 200 'micro-flex' cables were not functional; some other pads were noisy because of interference effects in the voltage supplies for the preamplifier chips; this noise was the main cause of a large TPC data volume per event which limited the number of events per spill to* ≤ 200*, although the DAQ had the capacity to cope with 1000 events per spill.*

The repair campaign during the winter shutdown has virtually eliminated these electronics problems. The remaining noise is perfectly acceptable and does not increase the data volume significantly. As already mentioned before, the TPC data volume is larger than strictly necessary due to the presence of header information for each TPC channel. The average TPC readout time will be about 750 μs per event which limits the data taking capability to ~ 500 events per spill of 400 ms. The impact of this limitation will be analysed in section 5.

The option of skipping the TPC readout in case of absence of an ITC trigger is still open as a further means to increase the number of recorded events per spill.

> *The TPC readout electronics had considerable cross-talk within the multi-layer mother board for about half of the ~ 4000 TPC channels. This cross-talk alters the charge-sharing between neighbour pads and hence the $r \times \phi$ resolution deteriorates.*

During the shutdown a calibration effort to map the cross-talk pattern was undertaken. This will permit an *a posteriori* software correction which should largely eliminate the effects of the cross-talk. It is too early now to show results of the cross-talk *correction*. However, the *knowledge* of the effects of the cross-talk has been introduced in the momentum fit. This allows a better use of the *uncorrected* measurements. The results of these studies indicate that sufficient performance will be reached to achieve the physics goals of the experiment. Evidence, supporting this conclusion, will be shown below.

2.2 Trigger performance

> *A large background of triggers from non-interacting beam particles; these effects were fully understood only during the winter shutdown and are largely traced to electrons and photons in the MeV range, which originate from the passage of the beam particles through all sorts of material in their way, and cause FTP and ITC physics triggers. Typically, for one 'good' physics event (i.e. an event with an interaction of a beam particle in the target), one to two such background events were recorded.*

A set of targets has been prepared with a thickness of 5% of an interaction length. This will enhance the number of 'good' triggers relative to the background triggers. A trigger purity better than 50% is expected with these targets. The systematic errors introduced by the use of a thicker target are still negligible.

Some of the unwanted triggers were introduced by beam particles interacting in the material surrounding the target. A new target arm has been prepared using a design largely reducing the material. In addition, a new set of collimators was introduced in the beam line to improve the beam profile near the HARP target.

In order to further enhance the trigger selectivity a set of small scintillation counters has been prepared. A coincidence of these counters located downstream in the forward spectrometer will veto non-interacting beam particles. It is planned to test the impact of this additional veto during the first weeks of the 2002 running period. The effect of the veto will be recorded without applying it already in the trigger. An analysis of the flagged events will be used to show if the bias introduced in the trigger is acceptable. In the estimates of the statistics which can be obtained in the 2002 run (Section 5) the rejection by this veto will not be taken into account and the estimate will therefore be conservative.

The data taken with thick targets used a "beam-trigger", i.e. unbiased with respect to any interaction requirement in the target. The interaction rate in these targets is high enough to ensure a sufficient number of physics events without trigger requirement.

The down-scale factor for unbiased 'beam-events' which had been applied in order to provide the absolute flux normalization when using thin targets, was unstable during data taking.

The mechanisms changing the down-scale factor have been fully understood, and are not a result of any hardware malfunctioning. The effective factor can be reproduced by a simple simulation. Since the effective down-scale factor was also independently measured, no systematic error was introduced in the normalization. The statistical uncertainty introduced by this effect is at the 1 – 2% level in the 2001 data.

A different implementation of the down-scale factor has been simulated and has been implemented. The simulations confirm that the effective factor will be identical to the nominal one by construction. In addition, a smaller factor will be chosen for the 2002 data taking, enhancing the statistics of the normalization triggers and optimizing the statistical significance of the physics analysis.

Such a large sample of fully unbiased events eliminates the need for additional down-scaled triggers which were used in the 2001 run to evaluate the efficiencies of the trigger counters.

3 Software

The first software release coincided with the start of the technical run in October 2000. Both the simulation and analysis skeletons were made available. Since then, new versions have been regularly produced which add in a coherent way more and more functionality.

In HARP, modern software-engineering procedures were adopted and commercial software products supported by CERN were exploited:

- *User requirements were defined and then transformed into a set of software requirements;*
- *the architectural Object-Oriented design was worked out;*
- *the detailed software design and code production in C++ language were implemented;*
- *unit testing, system testing and release procedures were defined and implemented.*

The HARP software components described in Fig. 1 have been developed and are in use for detector performance studies, trigger and background studies, beam particle identification, online applications, data quality, and the first productions for data analysis (3 GeV/c protons on Tantalum thick and thin targets).

- HarpEvent is the component implementing the HARP transient event model, including a structured description of settings, reconstruction objects, MC information, etc.. It is based on Gaudi.
- HarpDD is the component implementing the HARP detector geometry and materials data in a neutral-representation format. It also contains the alignment and calibration data description.

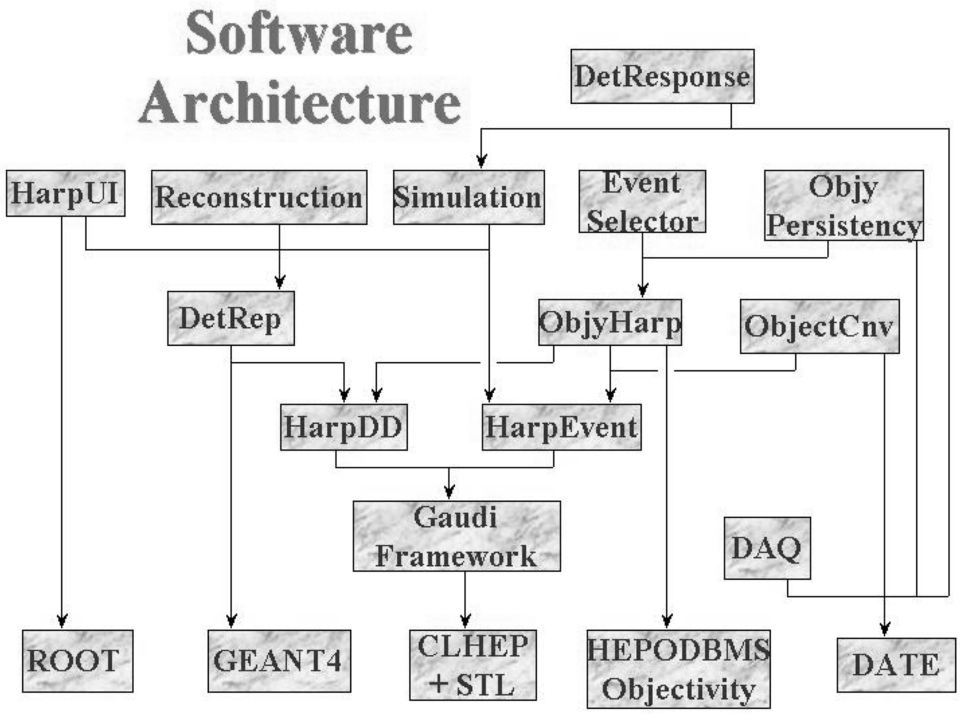

Figure 1: The Harp software model.

- DetRep is the component creating the various geometrical representations of the detector objects most suitable for use by the physics applications. It is based on the GEANT4 solid modelling.
- ObjyHarp is the component implementing the HARP persistent event model. It is based on Objectivity database, and mirrors the transient event model.
- ObjectCnv is the component implementing the unpacking of the raw data and the construction of the transient C++ objects used by the physics applications. It can use transparently both online data and stored offline data.
- ObjyPersistency is the component implementing the adapter to use the Objectivity database, while allowing the physics applications not to depend at compile time from the I/O solution.
- EventSelector is the component implementing the event selection and data navigation functionality.
- Simulation is the component implementing the HARP MonteCarlo. It is based on GEANT4. It has also been used for the T9 beam simulation, and for understanding and resolving the FTP and ITC fake-trigger problem.
- Reconstruction is the component implementing the computation of reconstructed objects at various levels: for example it produces the clusters, tracks, and particles for the TPC+RPC detectors, and it produces the triplets, segments, tracks, and particles for the NDC and forward detectors. These full reconstruction chains exist and are already functional.

- HarpUI is the component implementing the event display. It is used also online. It is based on ROOT.
- DetResponse is the component implementing the digitization of the main detectors. It has been used for specific productions for the TPC and the NDC.

Current plans include:

- the improvement of the spatial resolution of the points in the TPC (down to 1 mm), expected from the solution of the cross-talk problem and other effects, which should lead to the aimed momentum resolution;
- the finalization of the calibration and alignment of the NDC (down to 0.5 mm in x and 5 mm in y), which should lead to the aimed efficiency and momentum resolution of the spectrometer.

4 Performance

The key elements of the reconstruction software for off-line analysis are the track reconstruction in the TPC, and the track reconstruction in the drift-chambers of the forward spectrometer. We will concentrate here on the results using the tracking in the TPC.

4.1 Large-angle tracks

With a view to concentrating the available resources for the development of reconstruction software and data analysis, we selected for the analysis of 'large-angle' tracks protons at 3 GeV/c momentum with Ta target runs (thin and thick), plus 'no-target' runs.

The analysis of large-angle tracks is clearly focused on the reconstruction of tracks in the TPC. The extrapolation of reconstructed tracks to small radii into the ITC, and to large radii into the barrel RPC chambers, permitted the determination of the efficiency of these devices. The efficiency of the ITC trigger was confirmed to be higher than 99%, the efficiency of the RPCs is at least 95%.

The reconstruction of tracks in the TPC shows a high pattern recognition and momentum fitting efficiency. The efficiency for finding tracks was estimated to be $(98 \pm 0.5)\%$, for tracks with at least 10 points using simulated data. For a helix fit of good quality already with the present version of the software, an acceptance level of 90% was found. Of course, this number can be further improved.

To select events occurring in the target and to remove overlay events, tracks are extrapolated to the nominal beam axis and are required to originate from the target position. In addition, the tracks are required to point to an RPC hit inside the trigger time window. The combination of these criteria reduces the background to below the 1% level. The two criteria select largely overlapping samples, allowing the determination of their efficiency.

The resolution in p_T with the present status of the software can be obtained from an analysis of cosmic-ray data. Cosmic-ray tracks were selected by a trigger based on the RPC signals, selecting only events with hits in diametrically opposed pads. The software selected tracks passing through the target region. This selection enhances high energy particles.

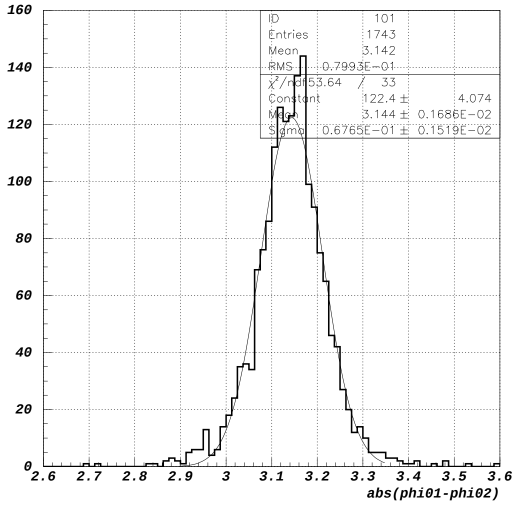

Figure 2: The distribution of $\Delta\phi$ for cosmic-ray tracks. The scale is in radians.

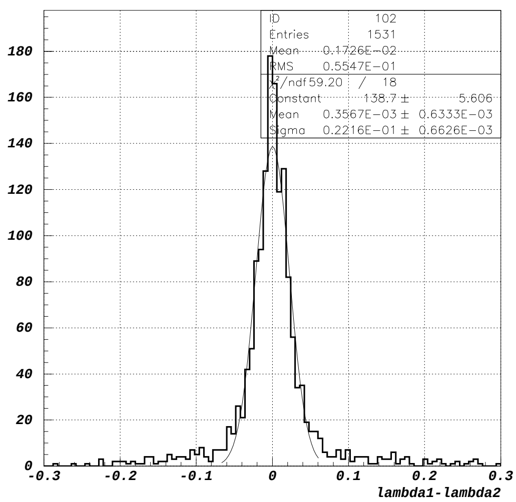

Figure 3: The distribution of $\Delta\lambda$ for cosmic-ray tracks. The scale is in radians.

The parts of the track on either side of the target region are found by the pattern recognition software as two separate tracks. This is still a rough selection. No attempt was made to reject tracks which did not belong to the same cosmic-ray particle. The comparison of the fit parameters of both halves can in principle be used to measure the angular and momentum resolution. The difference of the angle projected in a plane perpendicular to the nominal beam axis (ϕ) measured at the point of closest approach with the nominal axis on both parts of the tracks separately is shown in Fig. 2. The distribution is centred around 3.144 rad, with a width of 0.068 rad. Similarly, the angle λ is defined as the angle with respect to the beam axis in a plane given by the beam axis and the particle trajectory. The $\Delta\lambda$-distribution is shown in Fig. 3.

An estimate of $\Delta p/p \simeq 0.3$ was obtained from the study of these cosmic-ray tracks, at a momentum of 0.5 GeV/c. A thorough analysis of the resolution function will allow in the future an unfolding of the momentum distributions.

The two-dimensional distribution of the quantities p_T and p_L is shown in Figure 4 for a thin Ta target. In the same figure, the corresponding distribution for tracks with negative charge is shown. The geometrical acceptance of the track selection removes tracks with small angles with the beam axis in the backward and forward direction. A cut of 2 GeV/c was applied on the momentum to remove measurements outside the present sensitivity range (only about 10^{-3} of the tracks were removed).

The two projections of this distribution are shown in Figure 5, this time for the thick target data. The positively and negatively charged particles are shown separately together with the sum of both. The p_T spectrum of the negative particles reveals a two-component structure which hints at a component of electrons as well as pions. The distribution in p_L shows the ability of the HARP experiment to measure particles produced in the backward direction.

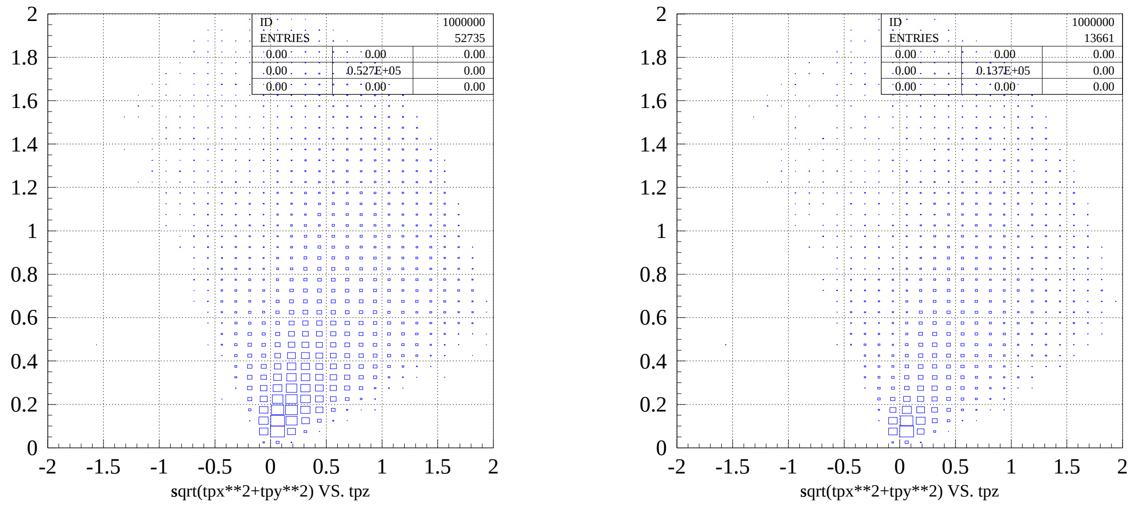

Figure 4: The two-dimensional distribution of the quantities p_T and p_L for a thin Ta target exposed to a 3 GeV/c beam, with protons selected by the TOF system in the beam. The distribution on the left contains tracks irrespective of their charge, on the right only tracks with negative charge. The scales are in GeV/c.

4.2 Small-angle tracks

The analysis of small-angle tracks depends heavily on the reconstruction of tracks in the drift-chambers which has been discussed in the March report. The precise alignment of the chambers and all individual wires is needed before an efficient track reconstruction can be achieved. A programme of alignment corrections is being undertaken.

5 Summary of data taken in 2001

We recall that the data taking strategy in 2001 was motivated by the desire to obtain a good understanding of the data taking and data analysis conditions for the planned wide range of beam momenta and targets, with a view to identifying and solving problems as early as possible.

Table 1 is an updated version giving the number of candidate physics events recorded in 2001, in various settings of beam momentum and target, separately for positive and negative beam momenta. With respect to the table presented in the March-report a number of corrections have been included. The momentum settings are chosen to sample the available range of the beam line. The 10 GeV/c setting, present in the previous version, will only be used for a small number of targets.

In the table, a candidate physics event is understood as an event with at least one reconstructable track in the forward spectrometer which is not due to a non-interacting beam particle. The numbers represent an estimate obtained from the number of such events found in a first pass on a subsample of runs, scaled up to all runs of the same setting using the same proportion to the total number of events. Of course further quality criteria will have to be applied in the final analysis.

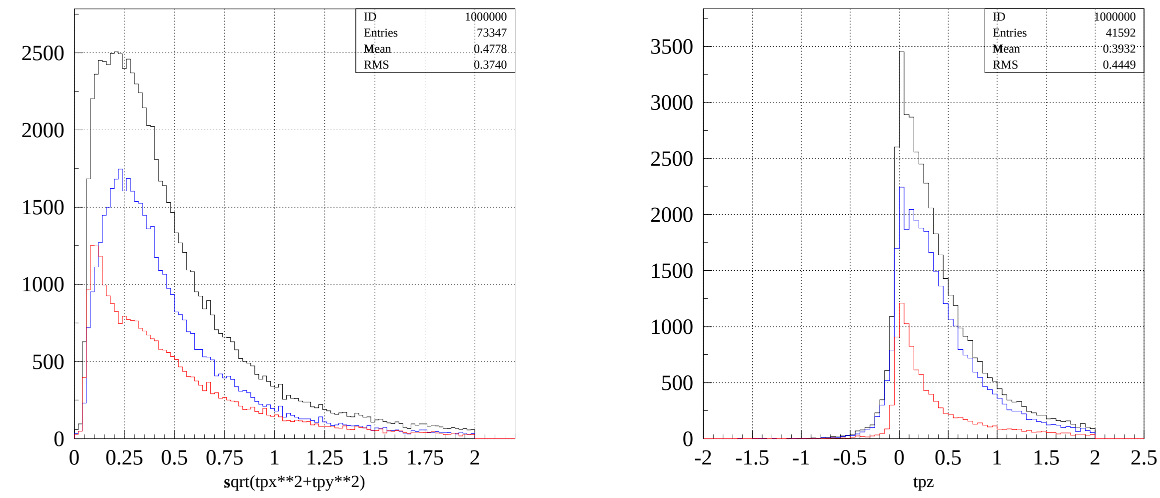

Figure 5: The distribution of p_T (left) and p_L (right) for a thick Ta target exposed to a 3 GeV/c beam, with protons selected by the TOF system in the beam. Each figure contains three histograms: the lowest histogram is for negatively charged particles; the middle histogram for positive charges; the top histogram is the sum of the two. The scales are in GeV/c.

6 Data taking in 2002

During the winter shutdown, small improvements were implemented in the T9 beam. An additional vertical collimator was installed to reduce the beam halo. A new diagnostics tool has been provided by PS Division to optimize the beam envelope and divergence. Both measures will help to reduce 'overlay' tracks in the TPC. The analysis of the data from the detection equipment in the beam confirmed that an excellent definition of the interacting beam particles used in the final analysis can be achieved.

HARP is approved for 140 days of running in 2002, which will permit the experiment to achieve its physics objectives. Data taking in the T9 beam starts on May 6th and ends on September 30th.

The list of HARP targets has been given in he March-report. The operation of the cryogenic targets is scheduled to start on July 8th until August 9th when HARP will return to operation with solid targets.

The chosen beam momenta are the same as in 2001: 3, 5, 8, 12 and 15 GeV/c, with 10 GeV/c as optional additional momentum. Thin and thick targets will be used with positively charged beam particles, while in the negative beam only the thin targets will be exposed. Taking into account the already accumulated statistics, as displayed in Table 1, it will be attempted to obtain sufficient statistics for all elements in the matrix. About 14 days will be needed for measurements with special targets (SPL, K2K and MiniBooNE). The 'empty-target' runs will be interspersed with the normal data taking, and require about 10% of the running time.

Subtracting from the 140 days of running time 28 days for cryogenic target operation, and 14 days for dedicated measurements and cross-checks, with about 7 days needed for setting-up and calibration, 91 days remain, to be used for the settings with standard targets.

Table 1: Summary of the number of candidate physics (forward) events recorded in 2001. The raw numbers of recorded events are give in "()". A "?" is used to indicate that no analysis of the forward candidate events has been done for that setting. Units are Million events.

Target	+3 GeV/c	+5 GeV/c	+8 GeV/c	+12 GeV/c	+15 GeV/c
Be 2%	? (2.2)	? (2.3)	—	1.9 (5.9)	0.84 (1.8)
C 2%	0.85 (2.4)	—	—	—	1.2(2.7)
C thick	—	—	—	—	—
Al 2%	? (2.4)	? (2.1)	—	2.0 (3.8)	0.94 (2.3)
Cu 2%	? (3.6)	0.75 (1.5)	—	? (2.0)	1.3 (3.0)
Cu thick	—	—	—	—	—
Sn 2%	0.5 (1.3)	—	—	—	0.87 (2.2)
Ta 2%	2.8 (4.9)	0.83 (1.5)	—	0.69 (1.6)	1.1 (2.6)
Ta thick	? (1.1)	—	—	—	—
Pb 2%	2.1 (4.4)	? (1.5)	—	1.4 (2.5)	1.0 (2.3)
Pb thick	? (1.0)	—	—	—	—
empty	(1.0)	(1.2)	—	(1.4)	(0.1)
Target	-3 GeV/c	-5 GeV/c	-8 GeV/c	-12 GeV/c	-15 GeV/c
Be 2%	0.07 (0.2)	0.33 (0.76)	—	0.47 (1.2)	0.44 (1.3)
C 2%	—	—	—	0.31 (0.86)	0.36 (1.1)
Al 2%	0.09 (0.27)	0.37 (0.79)	—	? (0.88)	0.31 (0.90)
Cu 2%	—	—	—	0.40 (1.11)	0.24 (0.7)
Sn 2%	—	—	—	—	0.41 (1.2)
Ta 2%	0.31 (0.82)	0.50 (0.80)	—	? (0.6)	0.71 (2.1)
Pb 2%	0.35 (0.94)	0.21 (0.34)	—	? (0.7)	0.49 (1.4)
empty	—	(0.86)	—	—	(0.06)
Special Targets					
K2K at 12.9GeV /c	thin: ? (1.5M),		medium: ? (2.2M),		thick: ? (1.4M)
MiniBoone Be at 8 GeV /c	1.3M (3.2M)				
Cu "button" at 12 GeV /c	? (1.45M)				

As explained in section 6, it is estimated that the maximum number of recorded events will be 500 per spill. The number of spills is estimated to be about 5000 per day. Depending on the beam conditions, during part of the spill a veto will be operational to avoid taking events with an overlay interaction in the TPC. This veto-time is estimated to be 25% for low momentum beams and as small as 5% for high momenta. Thus the total number of triggers recorded will be between 1.5×10^6 and 2.0×10^6 for low and high momentum settings, respectively. The fraction of triggers needed for normalization, analysis of beam properties, and trigger efficiency measurement is adjusted to about 25%. Taking into account the proton abundance in the beam (about 15% at low momenta and larger than 5% at high momenta), the selectivity of the trigger (pessimistically 50%), the total number of physics events is then about 50×10^3 for low momentum settings and 300×10^3 for high momentum settings. Acceptance and physics selections will be applied on these events. These rates will allow cross-section measurements at the 1 to 2% level.

Taking these numbers, complete statistics for a beam setting with positive charge for a thin target needs an exposure of two days on average; the same beam with a thick target one day.

Table 2: Summary of running time needed for HARP in 2002.

setting type	settings	days/setting	days	total days
Cryogenics targets				28
dedicated targets				14
setting-up				7
new, thin targets, positive beam	12	2	24	
additional, thin targets, positive beam	3	1	3	
new, thick targets, positive beam	18	1	18	
additional, thick targets, positive beam	1	0.5	0.5	
new, thin targets, negative beam	14	1	14	
additional, thin targets, negative beam	19	0.5	9.5	
total standard targets				75
empty target runs				8
total				132

The statistics in negative-charge beam settings can be obtained in one day, since only pion data has to be taken. The time needed to obtain the full HARP statistics is summarized in Table 2.

The DAQ of the experiment is configured such that several PS spills during a super-cycle can be profitably used if made available. Technical problems in the Easthall limit, however, the operation to no more than one spill per cycle. Therefore, efficient operation of both the detector and the accelerator complex will be needed during the full running period.