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The main injector particle production experiment at Fermilab

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Abstract. We describe the physics capabilities and status of the MIPP experiment which concluded its physics data taking run in March 2006. We show some preliminary results from this run and describe plans to upgrade the spectrometer.

Keywords. Main injector particle production experiment; particle production.

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1. Introduction

The main injector particle production experiment (FNAL E-907, MIPP) [1] is situated in the Meson Center beamline at Fermilab. It received its approval [2] in November 2001 and has installed both the experiment and a newly designed secondary beamline in the interim. It received its first beams in March 2004, had an engineering run to commission the detector in 2004 and had its physics data-taking run in the period January 2005–March 2006. The experiment is currently busy analyzing its data.

MIPP is designed primarily as an experiment to measure and study in detail the dynamics associated with non-perturbative strong interactions. It has nearly 100% acceptance for charged particles and excellent momentum resolution. Using particle identification techniques that encompass $\mathrm{d}E/\mathrm{d}X$, time-of-flight [3], multi-cell Čerenkov [4] and ring imaging Čerenkov (RICH) detectors [5], MIPP is able to identify charged particles at the 3σ or better level in nearly all of its final-state phase-space. As currently envisaged, MIPP will provide events of unparalleled quality and statistics for beam momenta ranging from 5 to 90 GeV/c for six beam species ($\pi^{\pm}, K^{\pm}$ and $p^{\pm}$).

2. Physics motivation

The primary physics motivation behind MIPP is to restart the study of non-perturbative QCD interactions, which constitute over 99% of the strong interaction cross-section. The available data are of poor quality and old and are not in easily accessible form. The time projection chamber (TPC) [6] that is at the heart of the

MIPP experiment represents the electronic equivalent of the bubble chamber with vastly superior data acquisition rates. It also digitizes the charged tracks in three dimensions, obviating the need for track matching across stereo views. Coupled with the particle identification capability of MIPP, the data from MIPP would add significantly to our knowledge base of non-perturbative QCD.

One of the primary goals of the present run of MIPP is to verify a general scaling law [7] of inclusive particle production that states that the ratio of a semi-inclusive cross-section to an inclusive cross-section involving the same particles is a function only of the missing mass squared (M^2) of the system and not of the other two Mandelstam variables s and t, the center of mass energy squared and the momentum transfer squared, respectively.

Stated mathematically, the ratio

$$\frac{f_{\text{subset}}(a+b \to c+X)}{f(a+b \to c+X)} \equiv \frac{f_{\text{subset}}(M^2,s,t)}{f(M^2,s,t)} = \beta_{\text{subset}}(M^2),$$

i.e., a ratio of two functions of three variables is only a function of one of them. This scaling relation has been shown to hold very well in a limited number of reactions [7]. MIPP will test this scaling for 36 reactions as a function of both s and t with great accuracy.

In addition to this, MIPP will acquire high quality data in liquid hydrogen with excellent particle identification and statistics over a range of beam momenta, which should make possible a systematic study of exclusive reactions that is essential for testing any future theory of non-perturbative QCD. We can also make forays into searches for exotic resonances such as glueballs. The existence of beams of differing flavor and energies will be a great advantage in sorting out the flavor content of any new states seen. The other physics clients for MIPP data are nuclear and heavy ion physics groups who are interested in data from several nuclear targets. An important service measurement MIPP hopes to perform is the measurement of particle production off the NUMI [8] target in order to minimize the systematics in the near/far detector ratio in the MINOS [8] experiment. NUMI target measurements by MIPP will also benefit the Minerva [9] and the Nova [10] experiments planned in the NUMI beamline in the future. MIPP will also make measurements with proton beams off various nuclei for the needs of proton radiography [2].

Another measurement MIPP hopes to make in the upgraded mode is that of pion and proton cross-sections off liquid nitrogen targets for the better prediction of atmospheric neutrino fluxes. The data taken during the physics run is shown as a function of beam energy and nuclear target type in figure 1.

3. Experimental set-up

We designed a secondary beam [11] specific to our needs. The 120 GeV/c primary protons extracted by slow resonant extraction from the Fermilab Main Injector are transported down the Meson Center line at Fermilab. They impinge on a 20 cm long copper target producing secondary beam particles. This target is imaged onto

Data Summary 27 February 2006			Acquired Data by Target and Beam Energy Number of events, x 10^6									
Target			E									Total
Z	Element	Trigger Mix	5	20	35	40	55	60	65	85	120	
0	Empty[1]	Normal		0.10	0.14			0.52			0.25	1.01
	K Mass[2]	No Int.				5.48	0.50	7.39	0.96			14.33
	Empty LH[1]	Normal		0.30				0.61		0.31		7.08
1	LH	Normal	0.21	1.94				1.98		1.73		
4	Be	*p* only									1.08	1.75
		Normal			0.10			0.56				
6	C	Mixed						0.21				1.33
	C 2%	Mixed		0.39				0.26			0.47	
	NuMI	*p* only									1.78	1.78
13	Al	Normal			0.10							0.10
83	Bi	*p* only									1.05	2.83
		Normal			0.52			1.26				
92	U	Normal						1.18				1.18
Total			0.21	2.73	0.86	5.48	0.50	13.97	0.96	2.04	4.63	31.38

Figure 1. The data taken during the first MIPP run as a function of nucleus. The numbers are in millions of events.

an adjustable momentum selection collimator which controls the momentum spread of the beam. This collimator is re-imaged onto our interaction target placed next to the TPC. The beam is tracked using three beam chambers and identified using two differential Čerenkovs [12] filled with gas, the composition and the pressure of which can be varied within limits depending on the beam momentum and charge.

Figure 2 shows the lay-out of the apparatus. The TPC sits in a wide aperture magnet (the Jolly Green Giant) which has a peak field of 0.7 Tesla. Downstream of the TPC are a 96 mirror multi-cell Čerenkov detector filled with C_4F_{10} gas, and a time-of-flight system. This is followed by a large aperture magnet (Rosie) which runs in opposite polarity (at -0.6 Tesla) to the Jolly Green Giant to bend the particles back into the ring imaging Čerenkov counter. The RICH has CO_2 as the radiator and an array of phototubes of 32 rows and 89 columns [12a].

Downstream of the RICH we have an electromagnetic calorimeter [12b] and a hadron calorimeter [12c] to measure forward going photons and neutrons. The electromagnetic calorimeter will also serve as a device to measure the electron content of our beam at lower energies, which will be useful for measuring cross-sections.

MIPP uses $\mathrm{d}E/\mathrm{d}x$ in the TPC to separate pions, kaons and protons for momenta less than $\approx$1 GeV/c, the time-of-flight array of counters to do the particle identification for momenta less than 2 GeV/c, the multi-cell Čerenkov detector [4] contributes to particle identification in the momentum range 2.5–7.5 GeV/c and the RICH [5] for momenta higher than this. By combining information from all counters, we get the expected particle identification separation for K/p and π/K as shown in figure 3. It can be seen that excellent separation at the 3σ or higher level exists for both K/p and π/p over almost all of the phase-space. Tracking of the beam particles and secondary beam particles is accomplished by a set of drift chambers [13] and proportional chambers [14] each of which have four stereo layers.

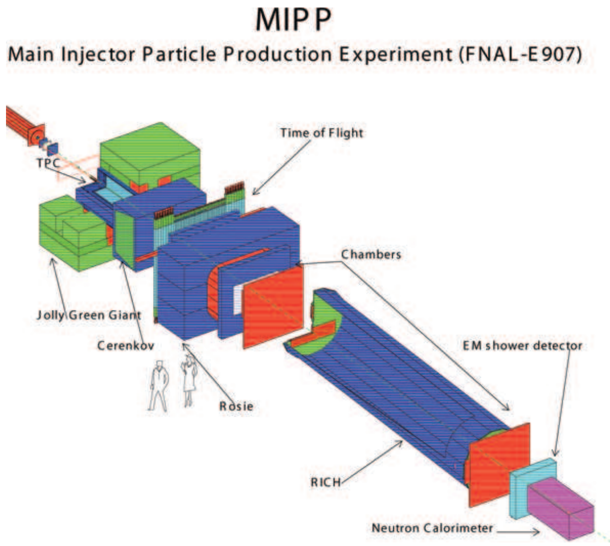

Figure 2. The experimental set-up. The picture is a rendition in Geant3, which is used to simulate the detector.

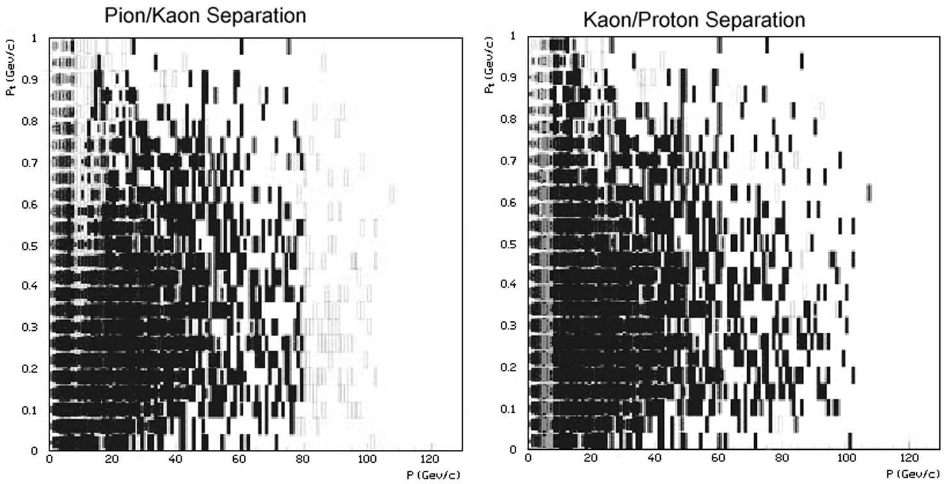

Figure 3. Particle identification plots for pion/kaon separation and for kaon/proton separation as a function of the longitudinal and transverse momentum of the outgoing final-state particle. Black indicates separation at the 3σ level or better and grey indicates separation at the $1-3\sigma$ level. The boxes at largest values of the longitudinal momenta suffer from lack of kaon statistics.

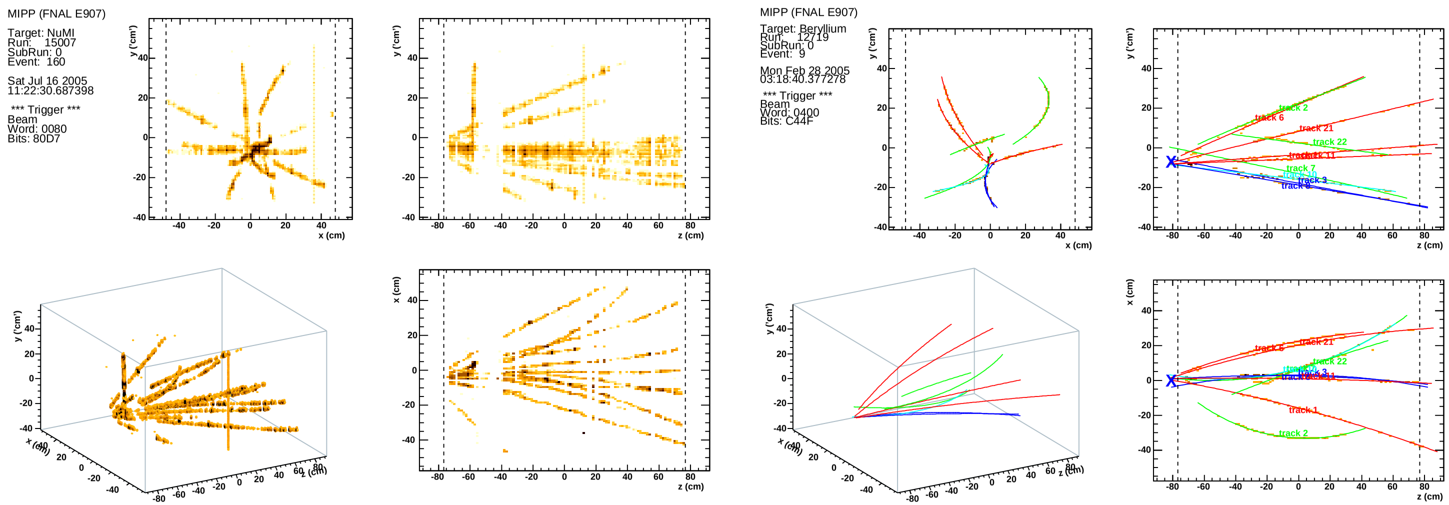

Figure 4. RAW and reconstructed TPC tracks from two different events.

4. Physics run results

Figure 4 shows the pictures of reconstructed tracks in the TPC obtained during the data-taking run. The tracks are digitized and fitted as helices in three dimensions. Extrapolating three-dimensional tracks to the other chambers makes the pattern recognition particularly easy.

Figure 5 shows the distribution of dE/dx of tracks measured in the TPC as a function of the track momentum in a preliminary analysis of p-carbon data. The TPC is capable of separating pions, protons and kaons in the momentum range below ≈1 GeV/c. Figure 6 shows events with rings in the RICH counter. Some are due to single beam tracks and others are due to tracks from interactions. Figure 7 shows the histogram of ring radii for a +40 GeV secondary beam. There is clean separation between pions and kaons and protons and their relative abundances [15] match expectations. Applying the particle identification trigger from the beam Čerenkovs enables us to separate the three particle species cleanly. The kaons which form 4% of the beam are cleanly picked out by the beam Čerenkov with very simple selection criteria. These can be made much more stringent with offline cuts to produce a very clean kaon beam. The ring radius of the particle contains information on the mass of the particle. The pion and proton masses are very well measured. The charged kaon mass has measurement uncertainties of the order of 60 keV. Improving the precision of both charged kaon masses will pay dividends in rare K-decay experiments involving charged kaons where the matrix elements depend on the kaon mass raised to large powers. A precision measurement of the kaon mass is thus possible with a high statistics MIPP run. Towards the end of our physics run, we switched off the TPC and acquired data at the rate of 300 Hz to investigate how well we can measure the charged kaon mass. These statistics are also indicated in figure 1.

MIPP took 1.75 million events using 120 GeV/c primary beam protons impinging on the NUMI (spare) target. These events will play a crucial role in the prediction of neutrino fluxes in the NUMI beamline and will enable the MINOS experiment to control the systematics in the near/far detector ratios as well as helping them

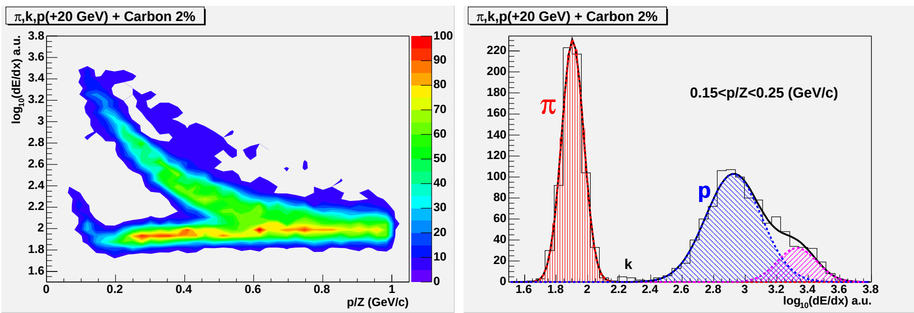

Figure 5. Preliminary dE/dx distributions in the TPC. The scatter plot shows the pion and proton peaks in the distribution as a function of the lab momentum. The second plot is the projection on the dE/dx axis for a momentum slice 150 MeV/c to 250 MeV/c for p-carbon data.

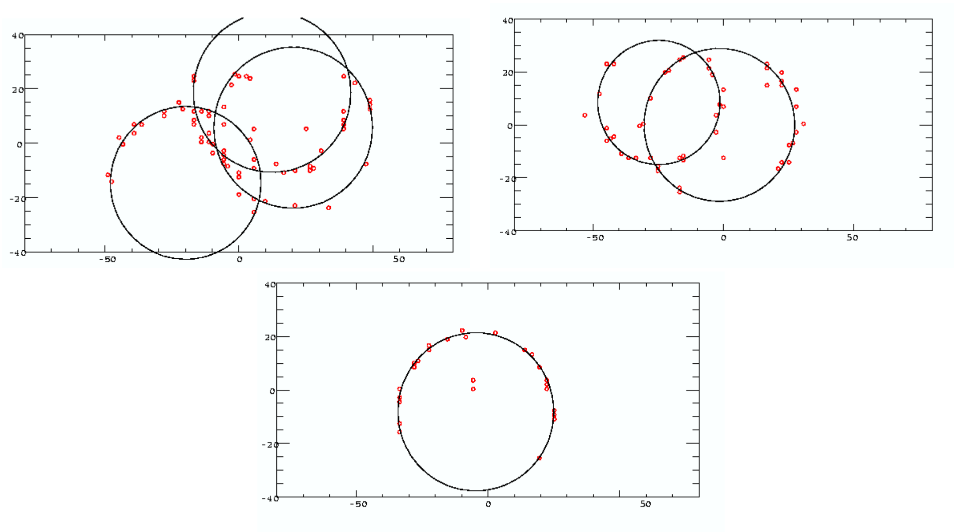

Figure 6. Examples of events with rings in the RICH counter for a 40 GeV/c beam.

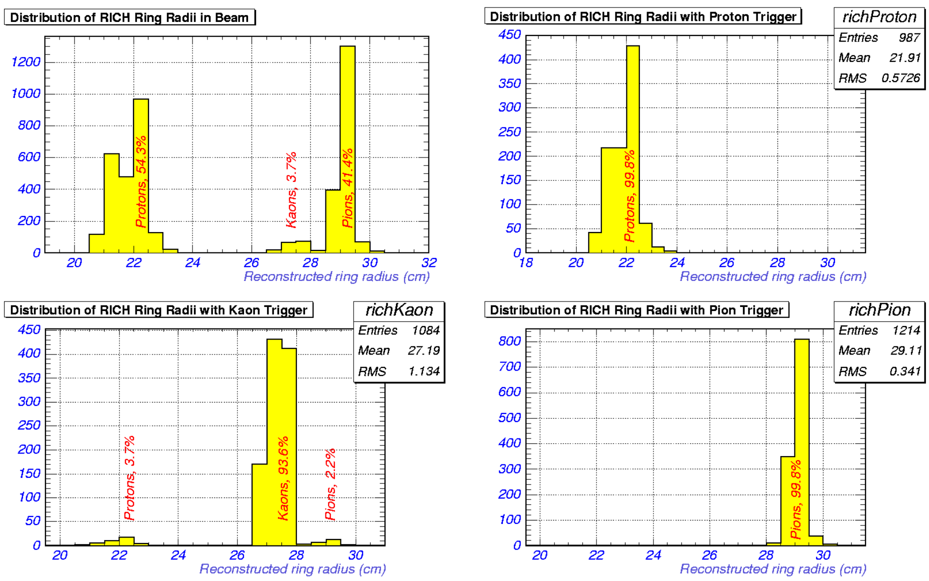

Figure 7. An example of a 40 GeV/c primary beam (non-interacting) trigger. The RICH identifies protons, kaons and pions by the ring radii. The beam Čerenkov detectors can be used to do the same. When the beam Čerenkov identification is used, one gets a very clean separation of pions, kaons and protons in the RICH.

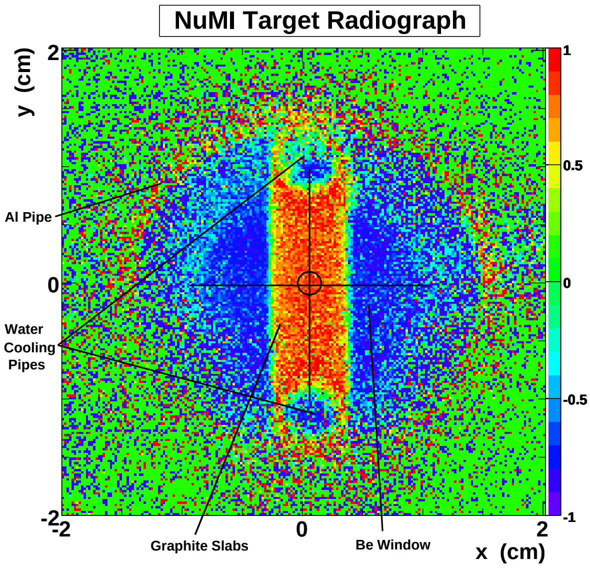

Figure 8. Radiograph of the MINOS target. The beam direction is perpendicular to the paper. The graphite slabs and cooling tubes can be seen.

understand the near detector performance. Figure 8 shows a radiograph of the MIPP measurements of the MINOS target.

5. Plans to upgrade MIPP

At present the data-taking rate in MIPP is limited by the 60 Hz rate imposed on us by the TPC electronics. These can be made considerably faster (by at least a factor of 100) [16] with more modern electronics. This will enable MIPP to expand its present scope and acquire data on a large number of nuclei (≈30) which will help improve hadronic shower simulation programs such as Geant4, Fluka and MARS dramatically. It will also produce tagged neutral beams [17] which can be of great use in understanding calorimeter response for particle flow algorithms proposed for the international linear collider.

Acknowledgments

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References

[1] The main MIPP web page is at http://ppd.fnal.gov/experiments/e907/. The MIPP collaboration list may be found using links here

[2] The MIPP proposal and Addendum to the proposal may be found at http://ppd.fnal.gov/experiments/e907/Proposal/E907_Proposal.html
[3] The time-of-flight detector was fabricated by MIPP and consists of an array of 10 cm × 10 cm scintillators and 5 cm × 5 cm scintillators. See http://ppd.fnal.gov/experiments/e907/TOF/TOF.html for a detailed description of the detector
[4] The multi-cell Čerenkov detector was initially built for Brookhaven Experiment E766 and later in Fermilab experiment E690 and then used in several other Brookhaven experiments. In MIPP, we fill the detector with the gas C_4F_{10} which has the appropriate refractive index at atmospheric pressure
[5] The details of the SELEX RICH construction and performance may be found at J Engelfried *et al, Nucl. Instrum. Methods* **A43**, 53 (1999). We have replaced the front end electronics, and done extensive work on the safety systems. MIPP uses CO_2 gas as the radiator for the RICH
[6] The TPC was built by the BEVALAC group at Berkeley in the 1990s and used effectively at several Brookhaven experiments (e.g. E910) and then donated to Fermilab by LBNL for use in MIPP. See, G Rai *et al, IEEE Trans. Nucl. Sci.* **37**, 56 (1990); LBL-28141
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R Raja and Y Fisyak, Proceedings of the DPF92 meeting, Fermilab
[8] NUMI stands for Neutrinos at the Main Injector and refers to the Fermilab Main Injector neutrino beam. MINOS is the first experiment to utilize this beam. MINOS proposal may be found at 'P-875: A long baseline neutrino oscillation experiment at Fermilab', E Ables *et al*, FERMILAB-PROPOSAL-P875 (1995). See also their website at http://www-numi.fnal.gov/
[9] The Minerva website is at http://www.pas.rochester.edu/ksmcf/minerva/
[10] The Nova experiment is currently still a proposal and the website is at http://www-nova.fnal.gov/
[11] C Johnstone *et al*, Beamline design for particle production experiment, E907 at FNAL, *Proceedings of the PAC03 Conference*
[12] For more details on the beam Čerenkov system, see http://ppd.fnal.gov/experiments/e907/Beam/BeamCerenkov/BeamCerenkov.html
[12a] During the engineering run in 2004, we lost 20% of the phototubes in the RICH due to a fire in one of the phototube bases. This does not impact adversely on our pattern recognition, since the Čerenkov angle is large and there is plenty of light over most of our momentum range
[12b] The electromagnetic calorimeter was fabricated by MIPP and uses lead as the radiator and an array of proportional tubes with 2.54 cm wire spacing as the readout. It has 10 radiation lengths and has 10 longitudinal segments
[12c] The hadron calorimeter is recycled from the HyperCP collaboration and uses scintillator fibers embedded in iron as readout. It has 9.7 interaction lengths and has four longitudinal segmentations each of which is segmented in two transversely
[13] We have reused beam and drift chambers from the E690 Collaboration. D C Christian *et al*, *Nucl. Instrum. Methods* **A345**, 62 (1994)
[14] The large proportional chambers straddling the RICH find their use again after having been used by numerous previous experiments. M De Palma *et al*, *Nucl. Instrum. Methods* **216**, 393 (1983)
[15] A Malensek, Fermilab Technical Memo FN-341, 1981 (unpublished)

[16] The TPC DAQ upgrade scheme may be found at
http://ppd.fnal.gov/experiments/e907/
notes/MIPPnotes/public/pdf/MIPP0068/MIPP0068.pdf
[17] The scheme to produced tagged neutron, anti-neutron and K_L^0 beams is detailed in
http://ppd.fnal.gov/experiments/e907/
notes/MIPPnotes/public/pdf/MIPP0130/MIPP0130.pdf