GEANT Simulation of the RF Separated K^+ beam for the CKM Experiment

R. Coleman, T. Kobilarcik, C. Milstene
June 6, 2000

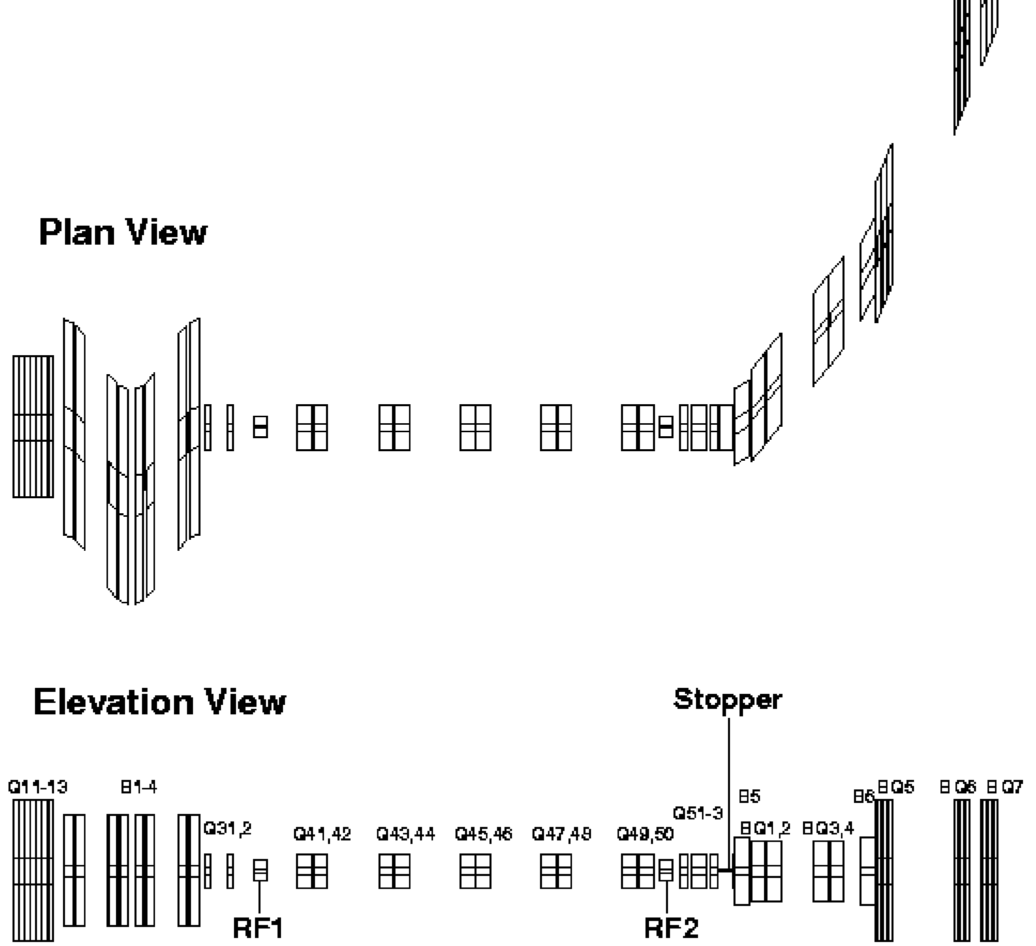
1. Introduction

A base beam design [1] exists for CKM which meets all the specifications[2]. This design is an optimization for CKM of earlier designs by Doornbos[3]. The earlier designs were complicated by the fact that originally two experiments were to be accommodated by a single beam design running at two different beam energies with different optics and intensity requirements.

The issues explored here are what beam purity of K^+ can be accomplished and what are the background rates at the experiment. Most if not all of this work has been presented at CKM bi-weekly meetings over the last few months. The GEANT [4] Monte Carlo program is described in detail in appendix I. The simulations are based on the optics design[1] made using the program TURTLE [5]. Though this base design satisfies the CKM requirements, we have realized that opening the horizontal production angle from +/- 4mrad to +/- 8 mrad gives a factor of 1.5x more production with no significant degradation of the final optics. Also we have increased the stopper width from 8mm to 12mm to maintain good purity. Appendix II describes the comparison between the GEANT model and the optics model TURTLE, which is good but differs at the mm level over 100 m of beam transport. The Malensek production parameterization is used for the absolute rates[6].

This beamline layout is shown in Fig. 1.1. The beamline consists of 3 stages: a collection stage (z=0-52m), rf separation stage (z=52-144m) and a transport stage to the experiment (z=144-210m). For this simulation, we assumed two RF stations (3.9 GHz) for separation with each station giving 15 MeV transverse kick. The length of the station is determined by the peak deflection gradient estimated to be 5 MeV/m; these parameters are described in detail elsewhere [7]. The beam energy is 22 GeV which is optimal for CKM [8] .

Fig. 1.1 Beam Layout



2. Beam Rates and Purity

GEANT was used to generate 200,000 initial particles of each type with a production angle of +/- 4 mrad vertically, +/- 8 mrad horizontally with a momentum of 22 GeV +/- 2%. The source size was 0.75 mm (σ) in each plane with a length of 10 cm. Table 2.1 gives the raw results. Table 2.2 gives the normalized results at the entrance to the experiment (210 m from the target). At the production target, a pion to kaon ratio of 9.86 to 1 and a proton to kaon ratio of 3.47 to 1 were used[1,6]. The beam size at the experiment in contained within a 8cm x 8 cm region.

Table 2.1. Raw GEANT results for beam contents (8cmx8cm) at entrance to experiment

type	#generated	photon	electron	Mu+	Pi+	Pi-	KL/n	K^+	Proton
K^+	200K	297	17	556	244	44	2	13,285	0
Pi^+	200K	0	0	196	156	0	0	0	0
P	200K	0	0	0	0	0	0	0	347

Table 2.2. Normalized GEANT rates (MHz) for beam

	K^+	pion+proton	muons	total charged	photons
Rate (MHz)	30	6.7	5.6	42	0.7
% hadronic	82	18	NA	100	
% total	71	16	13	100	

The hadronic purity of 71% just meets the CKM requirement of 67%. Turtle predicts a much better purity as discussed in the Appendix. We believe the discrepancies are due to the accuracy of tracking over a long distance in GEANT.

The required kaon rate for CKM is 30 MHz this is achievable with 3.75 E12 protons per pulse.

3. Rates at Detector entrance

Table 3.1. Raw GEANT results for detector rates; inside 1 m x 1m but outside beam area (8cmx8cm) at entrance to experiment

type	#generated	photon	electron	Mu+	Pi+	Pi-	KL/n	K^+	Proton
K^+	200K	107	13	1065	94	17	2	27	1
Pi^+	200K	0	0	88	9	0	0	0	0
P	200K	0	0	0	0	0	0	0	10

Table 3.2. GEANT rates (MHz) for detector normalized to 30 MHz of Kaons

	pion+proton	muons	total charged	photons
Rate (MHz)	0.5	4.4	4.9	0.24

So the rate of particles outside the beam but within the detector is about 5 MHz much less than the ~60 MHz predicted for the beam region. Momentum distributions and the effect of the final bends on these rates are discussed in the next section.

4. Effect of eliminating bends after beam stopper

To investigate the necessity for a clean-up bend after the beam stopper, we repeated the results of section 3 without these bends, B5 and B6 in Fig. 1.1. This straight beamline configuration is more compatible with some of the site selection options such as Meson MP.

Table 4.1. Raw GEANT results for beam contents (8cmx8cm) at entrance to experiment

type	#generated	photon	electron	Mu+	Pi+	Pi-	KL/n	K^+	Proton
K^+	200K	356	28	567	318	52	0	13,481	2
Pi^+	200K	0	0	1057	142	0	0	0	0
P	200K	0	0	0	0	0	0	0	312

Table 4.2. Normalized GEANT rates (MHz) for beam

	K^+	pion+proton	muons	total charged	photons
Rate (MHz)	30	6.2	24.5	61	0.8
% hadronic	83	17	NA	100	
% total	50	10	40	100	

Table 4.3. Raw GEANT results for detector rates; inside 1 m x 1m but outside beam area (8cmx8cm) at entrance to experiment

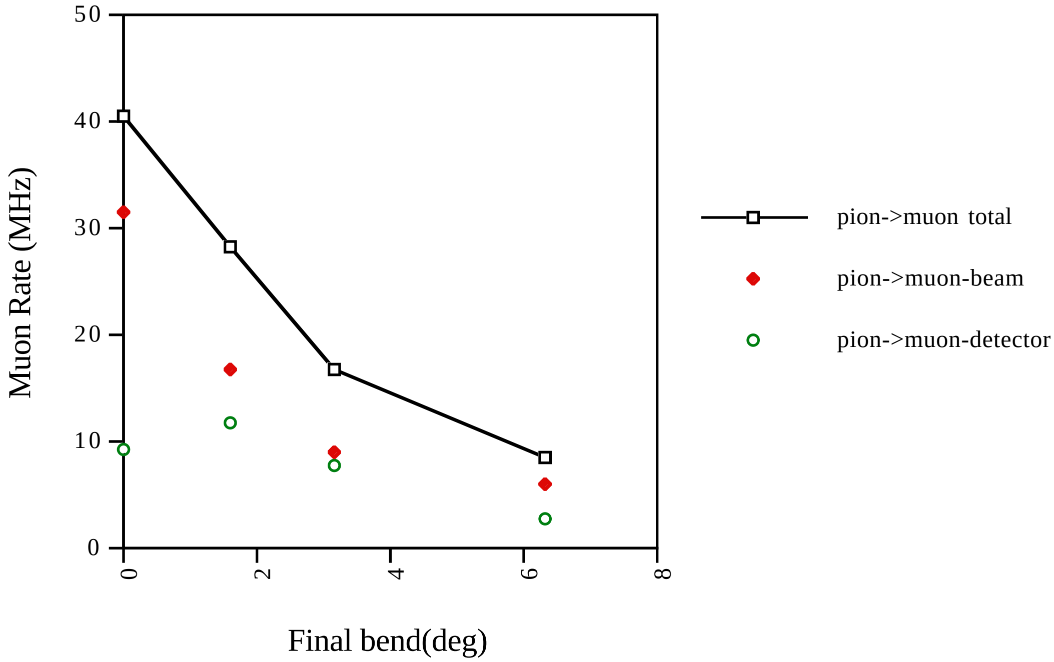
type	#generated	photon	electron	Mu+	Pi+	Pi-	KL/n	K^+	Proton
K^+	200K	147	13	900	133	17	3	17	1
Pi^+	200K	0	0	306	7	0	0	0	0
P	200K	0	0	0	0	0	0	0	4

Table 4.4. GEANT rates (MHz) for detector normalized to 30 MHz of Kaons

	pion+proton	muons	total charged	photons
Rate (MHz)	0.48	8.7	9.2	0.33

Muons:

Fig. 4.1 Muon rate vs Final Bend



The most significant change to the rates without the bends is the increase in muons both in detector and beam. To investigate muon rate vs clean-up bend, several runs were taken varying the value of the bends. (Two bends and quadrupoles between the bends are needed to make the beam achromatic.) The results of several runs with different values for the sum of the two clean-up bends is shown in Fig. 4.1. The number of muons striking the upstream detector plane increases by a factor of 4 in the comparison of no bend vs the standard 6.3 degrees.

Figures 4.2a-d compare the z origin of the beam muon reaching the detector with the standard bends after the stopper (B5/6). The pion decays dominate and are sensitive to the final bend. They also have a very interesting z origin distribution which we are currently investigating. The kaons are relatively insensitive to the choice of final bends, due to the larger opening angle of the muon from kaon decay.
Figures 4.3 a-c show the momentum distribution of the muons reaching the detector plane. Clearly the absence of downstream bends opens the momentum acceptance up, giving a broader peak in the beam muon case Fig. 4.3 b.
Figure 4.4 shows the interactive GEANT display of 29 events which have a muon from pion decay which enters the detector. All but 4 of the 29 remain inside the beam aperture as shown in more detail in Fig. 4.5. In Fig. 4.5 pions are shown as solid lines while muons are dashed lines. The muons are sufficiently close to the beam momentum that their trajectories resemble the nominal beam particles closely.

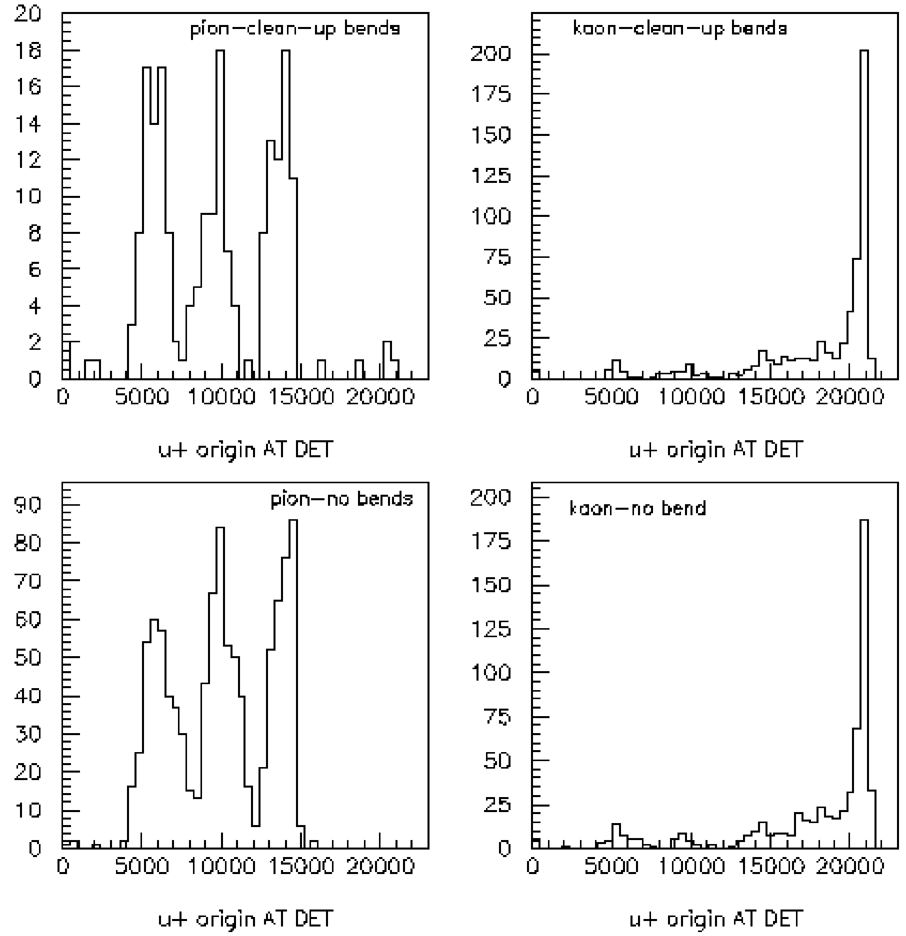


Fig4.2 Z(m) location along beam for decay to beam muons

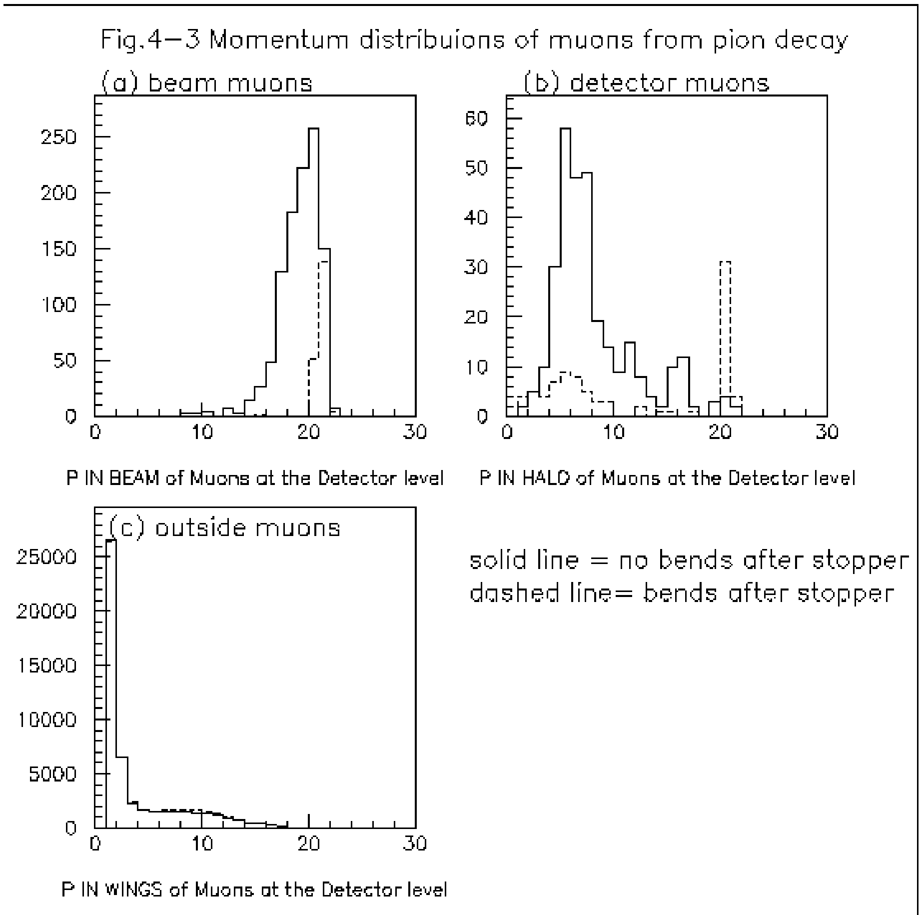
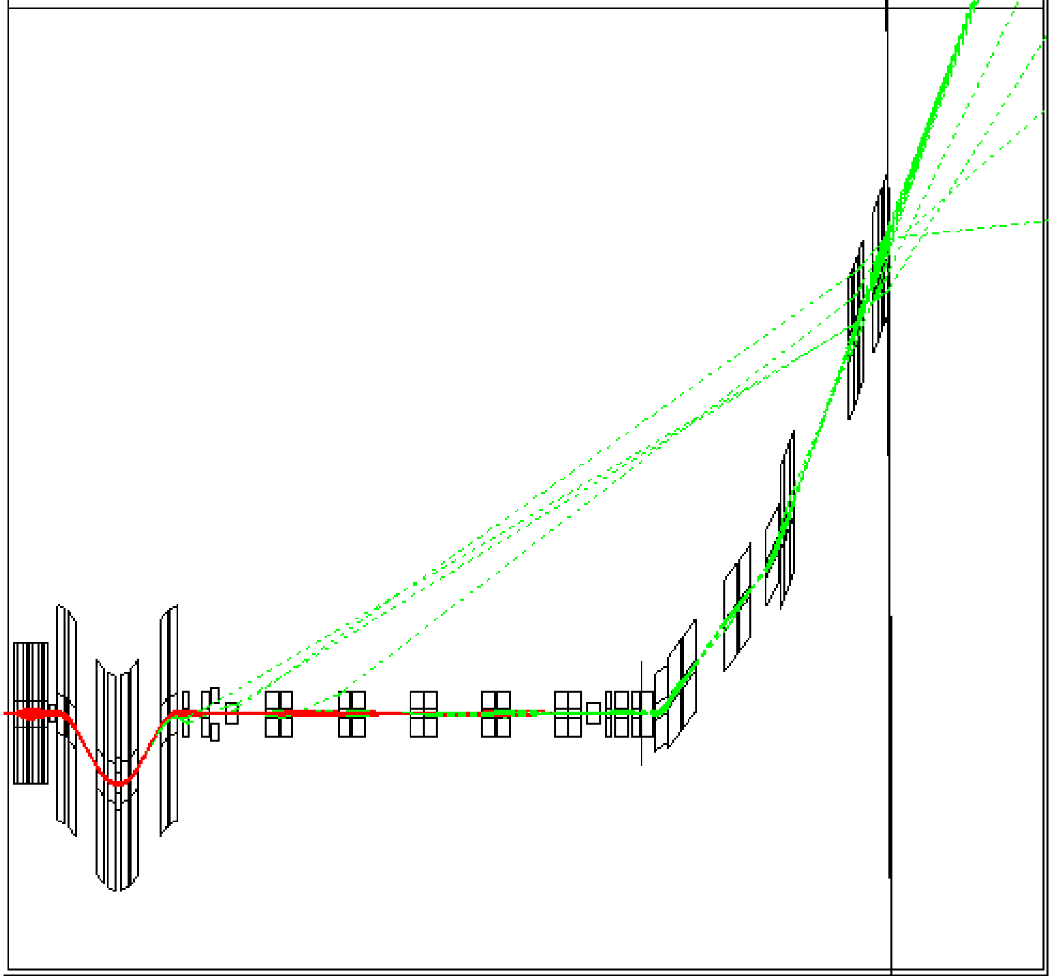


Figure 4.4 shows the interacitve GEANT display of 29 events which have a muon from pion decay which enters the detector. Most remain inside the beam aperture as shown in more detail in Fig. 4.5.

Fig.4.4 Pi-decay muons entering detector



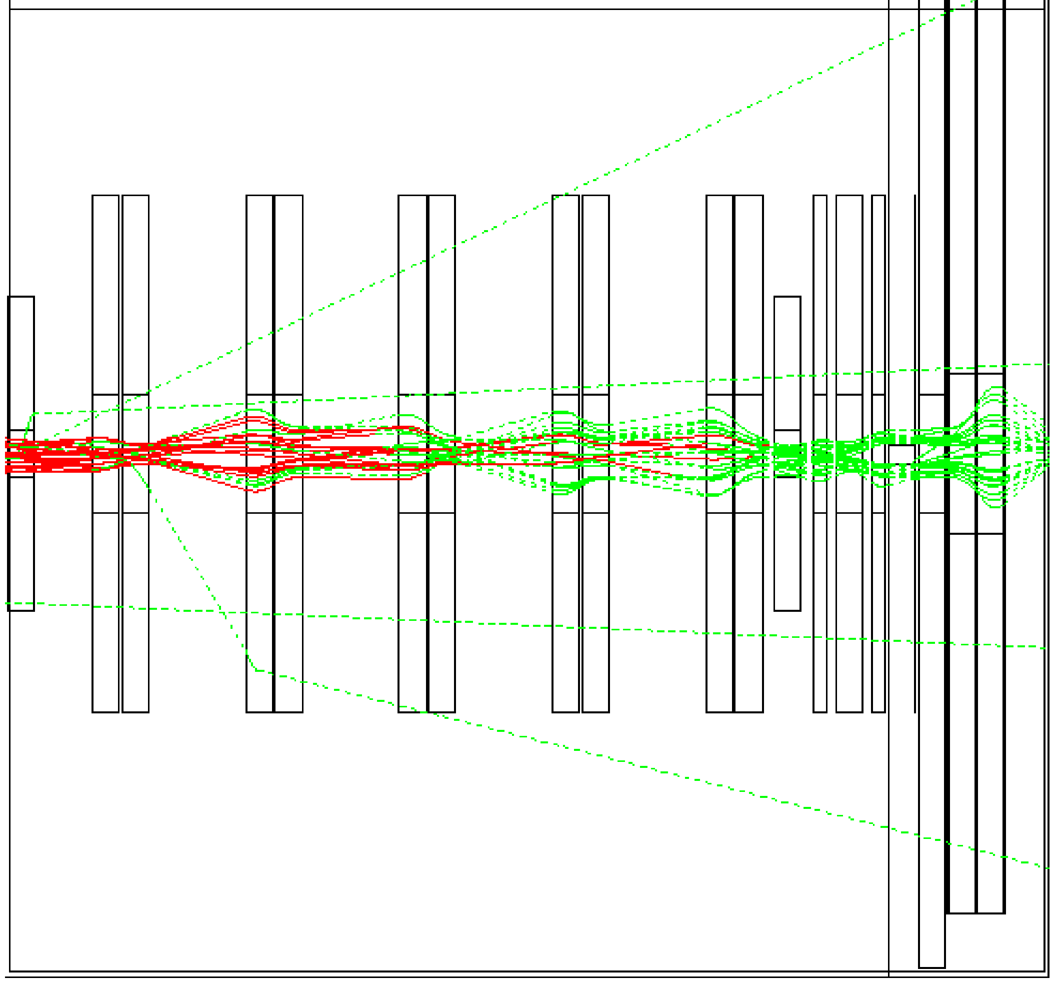


Fig.4.5 Pi-decay muons entering detector

Neutrals:
The dominant source of neutrals in the beam/detector come from kaon decays near the end of the beam, similar to the muons from kaon decay shown in Fig. 4.2. At the level of simulating 200K events, as we have done here, surprisingly only a handful of events come from the beam stopper. Table 4.5 summarizes the rates. Also only a handful of KL/neutron events are found.

Table 4.5 Neutral rates (MHz) in beam/detector with and without final bends

	<---Standard B5/B6 = 6.3 deg.--->		<B5/B6 OFF--------------------->	
	photons	KL/neutron	photons	KL/neutrons
beam	0.89	0.006	1.07	~0
detector	0.32	0.012	0.44	0.009
total	1.21	0.018+/-.009	1.51	0.009+/- 0.006

5. Muons exiting along the beamline- Radiation safety issues

To investigate the shielding along the beamline, the code used in an earlier CKM memo[9] was modified for the current design. A tube of concrete 2m thick with an inner radius of 1.5 m was placed along the beamline. An addition tube of concrete was placed around the stopper. The stopper shielding was 0.5 m thick with an inner radius of 0.3m and had a length of 2.88 m centered on the stopper. Fig 5.1 shows the layout along with a sample of 100 events generated by initial pions. Fig. 5.2 (5.3) shows the raw number of particles penetrating the shield for 200K kaons (pions) generated as discussed earlier in this memo. The conversion factor from particles to mrem/hr at the outside of the shield is ~0.01 (0.1) for kaons(pions). So with 2m of concrete the peak radiation levels are ~ 5 mrem/hr just outside the shield.
Increasing the concrete tube thickness from 2m to 3m, would reduce the peak dose from 5 mrem/hr to less than 2 mrem/hr.

The rate of muons reaching the detector entrance(1m square box cut after BQ7) is only slightly affected by the shielding (~10% fewer with shield). The rate of muons outside the detector (>1m box cut after BQ7) is very dependent on the tube shield. The results are given in Table 5.1 below. For the muons outside the detector the peak levels of radiation are order of 100 mrem/hr about 1 m off the beam axis. This is true for either 2m or 3m concrete tube thickness. Additional shielding at the end of the beamline could reduce this rate, but we have not investigated this further yet.

Table 5.1. Muon rates at Detector Entrance Plane –outside the detector area (+/- 0.5 m)

Particle type	No shield (MHz)	Shield- 2m concrete tube (MHz)	Shield- 3m concrete tube (MHz)
K+	186	8.9	2.9
Pi+	1520	63.4	18.2
proton	329	0.1	~0
total	2040	72.4	21.1

Fig.5.1 Pi-decay muons and 2m Concrete tube

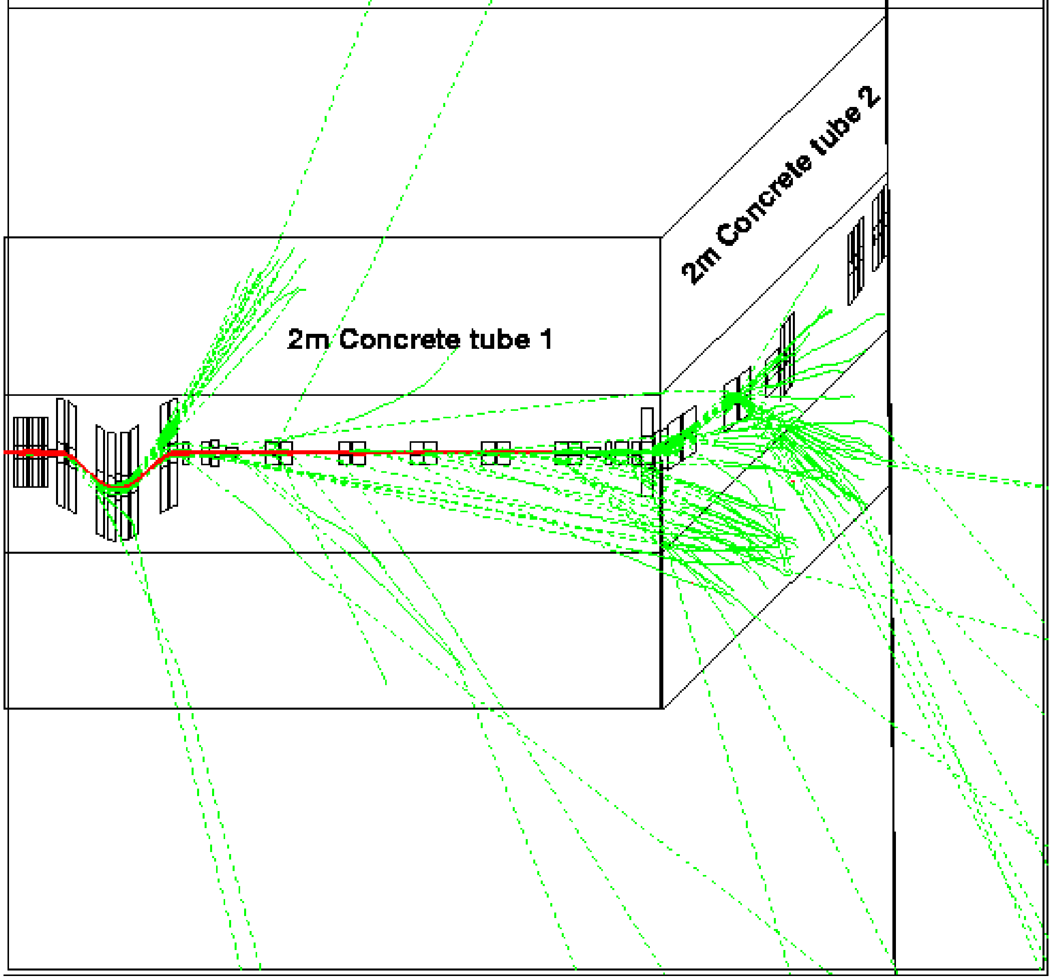


Fig.5.2 Muons from kaon decay leaving the concrete tube
phi(deg) vs z(m)

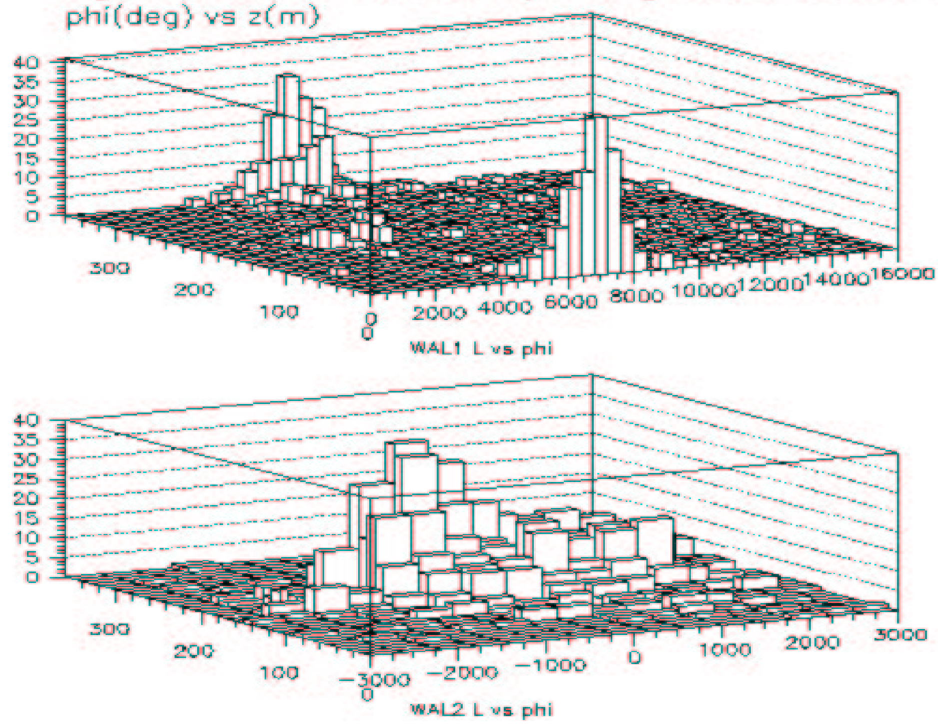
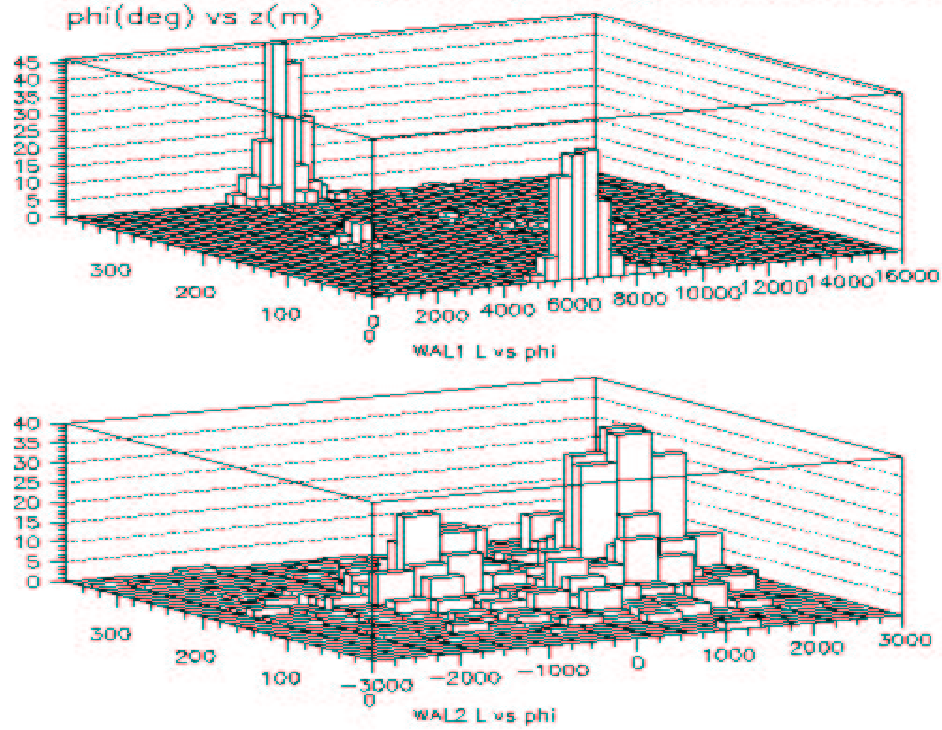


Fig.5.3 Muons from pion decay leaving the concrete tube
phi(deg) vs z(m)



Conclusions

A detailed GEANT simulation of the CKM beam has been done. The kaon yield of a previous study[1] has been verified. The beam purity just meets the CKM specification, but still is more pessimistic than the earlier TURTLE study. Rates of various particle types are predicted at the detector. The output of the beam GEANT are available to hand-off to the detector GEANT. The clean-up bends downstream of the beam stopper are important for reducing muon backgrounds. Other techniques may also work but have not been fully explored. A first look at shielding downstream of the target/dump has been completed and 2 to 3m of concrete equivalent seems in the right ball park.

The remaining simulation work on the beam includes:

- Understand the z distribution of muons from pion decay within the FODO channel of quads between the RF stations
- Estimate the flux of muons from the target/dump regions by generating primary proton interactions and secondary particles in the target/dump
- Site Location issues; including alternative bending schemes downstream of the stopper to reduce muons
- Study tolerances: RF phasing/amplitude errors, alignment errors
- Higher order effects? In both magnets and RF

References

[1] T. Kobilarcik, CKM Beamline Design, CKM internal note#26, March 2000.
[2] Charged Kaons at the Main Injector, R. Coleman et al, submitted April 15, 1998 to Fermilab PAC.
[3] Optics design of 25 GeV/c RF separated K^+ beam, December 3, 1997, Jaap Dornbos, TRIUMF.
[4] GEANT version 3.21, CERN.
[5] TURTLE, D.C.Carey, K.L.Brown, Ch. Iselin, September, 1999, Fermilab-Pub-99/232.
[6] A. Malensek, FN-341.
[7] An RF Separated Kaon Beam from the Main Injector: Superconducting Aspects, D. Edwards et al, TM2060, November 1998.
[8] J. Ritchie, Beam Energy consideration for CKM, CKM internal note#12,October,1998.
[9] R. Coleman, C. Milstene, Study of muon background, CKM internal note#13 November, 1998.

Appendix I: Description of model used in GEANT

GEANT Version 321 details:

1. Secondary products are generated from the target as a cone (+/- 8 (4)mrad in x(y)) with +/- 2% of central momentum of 22 GeV/c. The source size was taken as 3 mm x 3 mm and 10 cm long.
2. All optics is first order, i.e. quadrupole fields are taken as proportional to the displacement off axis with the appropriate gradient.
3. Magnets are modeled as boxes of iron with proper dimensions. The fields in the magnet steel are taken from POISSON. Then these are read into GEANT and normalized to the central fields appropriately.
4. RF cavities are made as a tube of iron with inner aperture of 3.0 cm and outer aperture of 20 cm. The cavity has 4 mil Mylar windows on each end.

   The transverse deflection of 5 MeV/m is modeled as a perfectly uniform horizontally oriented equivalent magnetic field of 0.1667 kg*SINWT (see below) within the 3.0 cm diameter. Details of the code added to the stepping routine GUSTEP and the B field routine GUFLD in GEANT listed below.

   The code for the first cavity in GEANT/GUSTEP is

```
WT = (1 – 2*RANF(0))*180.          here the phase is arbitrary.
SINWT = SIN(WT*PI/180.)
```

   Then the field in RF1 is calculated in GUFLD as

```
B(RF1) = .1894*SIN(WT*3.14159/180.)
```

   The code for the 2nd cavity is

TOF12 = TOF2 – TOF1 where TOF1(2) is the GEANT transit time between the production target and RF1(2) entrance, then

RF12= (TOF12-288452.3)(360/ 256.5979)

R12 = (TOF12- 372445.1) (360/256.41) where 256.5979= 1/freq of cavity and 288452.3 ps is the TOF from RF1 to RF2 for a pion with momentum of 22 GeV with the cavity spacing = 86.474 m.

5. Vacuum is assumed everywhere except where elements are inserted, i.e. beam pipes are not yet simulated explicitly.
6. Collimators are modeled after existing Fermilab collimators. These are two separate blocks (jaws) of 5”x5”x ~5 ft.
7. The cavities vertical deflection is simulated using a horizontal magnetic field in the standard way with GEANT. RF1 and RF2 were 3 m long with a total kick of 15 MeV each.
8. To facilitate reasonable running times a 1 GeV threshold was taken. Studies with a 10 Mev thresholds showed only the photon content of the beam was underestimated using a 1 GeV threshold (by ~ 2-3x). Approximately 4-8 hours of CPU per 200,000 generated events was needed depending on particle type.
9. The iron stopper vertical width was tuned from 8mm to 12 mm to get good beam purity.

Comparison of GEANT and TURTLE

For the comparison of GEANT and TURTLE, both individual rays and phase space distributions were compared. Due to the long length of the beamline it was required to convert GEANT to double precision to get good agreement. We used the methods of the MU-COOL group and are particularly indebted to Paul LeBrun for helping us with this conversion. The user routines have been rewritten and/or altered in order, for the phase-space, to be generated and carried in double precision all the way to the detector, stepping through different magnetic fields. The Poisson mapping of the magnet iron has been slightly altered as well. The goal being to keep the information on the phase space up to the 6th significant digit through a distance of 210 meter.

For speed and compatibility with Turtle: the positions and angles where generated using RANF, the momentum and all other the random variables generated afterward uses GEANT random generator grndm.

The initial conditions were : 120 GeV/c protons targetted at zero degrees on a 50 mm Beryllium target with a beam spot size with gaussian distribution of 0.75mm radius (1 sigma); 22 GeV/c secondary particles with +/- 2% momentum bite and angular momentum bite of +/- 4 mrad in both x and y. The pt kick for each of the two RF stations was 15 MeV and the stopper full width was 8 mm.

Figures A1-3 show a comparison between the phase space of Turtle vs GEANT at different element locations. In Fig. A1-3 the left column gives the Turtle results while the right column is the GEANT results. In each case first x vs x' and then y vs y' is compared. The agreement is qualitatively good.

Figures A4-6 show the vertical position at the entry to the stopper for kaons, pions and protons with Turtle and GEANT. In all cases, the GEANT distributions are broader than the Turtle distributions by a few mm. Using a 8 mm full width stopper leads to large discrepancies between GEANT and Turtle in the beam purity. For example, for 10,000 pions generated with the above initial conditions we find 37 (202) background pions in the beam as it enters the detector in Turtle (GEANT). We believe that the discrepancies are due to the large number of steps required in the GEANT version. We are not sure a viable solution (CPU time wise that is) is available using GEANT. For now, we have increase the stopper width to 12 mm to insure good purity. A future study will investigate the smearing of the unwanted particle spot size at the stopper position.

Finally, we can compare losses along the beamline. The Turtle program traces rays and records any losses at the entrance or exit of each element- if a particle is outside the aperture, it is lost. GEANT was coded to follow the same rules and we obtained the following comparison.

Table A1 Summary of particles lost by apertures in Turtle and GEANT per 10,000 kaons generated.

Element	Turtle	GEANT
Q31	2	3
RF1 entrance	634	797
RF1 exit	122	83
Q41	73	77
Q42	275	309
Q48	61	112
RF2 entrance	119	81
RF2 exit	91	56
Stopper	3442	3068
Total	4819	4586

Initially, we had more particles lost in GEANT in the Q41-42-48 elements(see Fig. 1.1). GEANT prediction was about 2.5 x more rays lost than Turtle in that region. We found by tuning the GEANT tracking parameter to a smaller value(TMAXFD=0.175 degree), the maximum turning angle in a step in a magnetic field, we were able to achieve the above. The phase space distribution shown were also sensitive to this parameter and TMAXFD=0.175 was used for those GEANT plots show above.

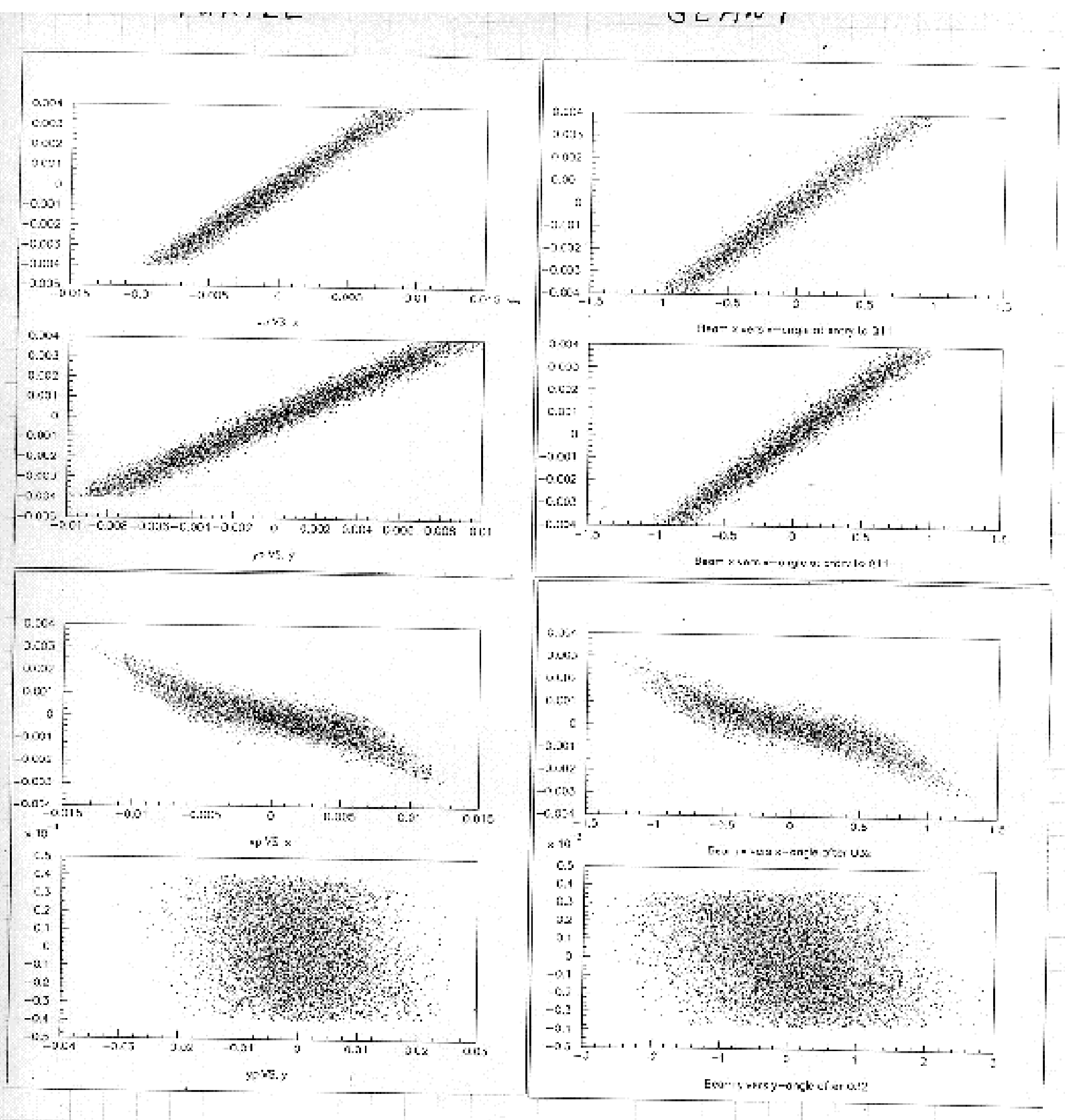


Fig. A1 Phase space comparison between TURTLE and GEANT at entry to Q11 and exit of Q32. Units are radians and meters (cm) respectively.

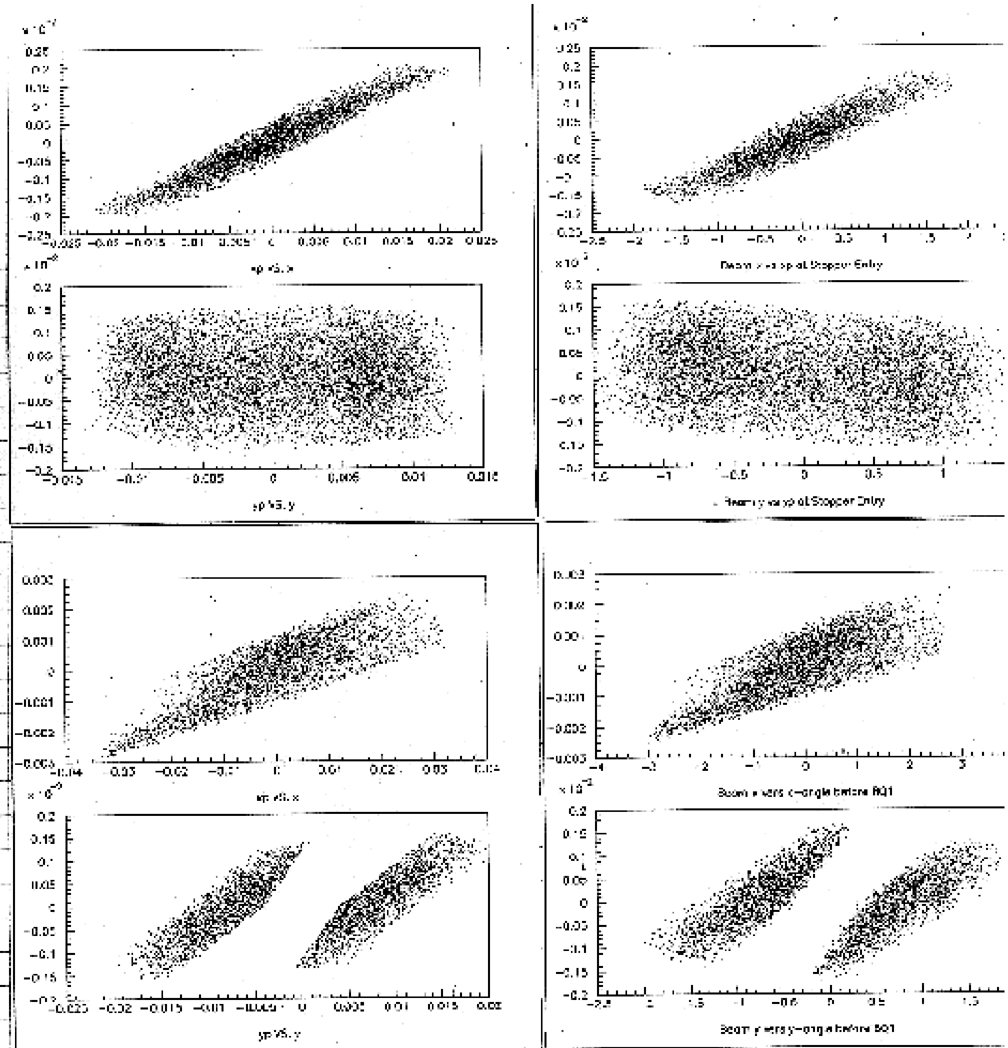


Fig. A2 Phase space comparison between TURTLE and GEANT at stopper entry and BQ1 entry.
Units are radians and meters (cm) respectively.

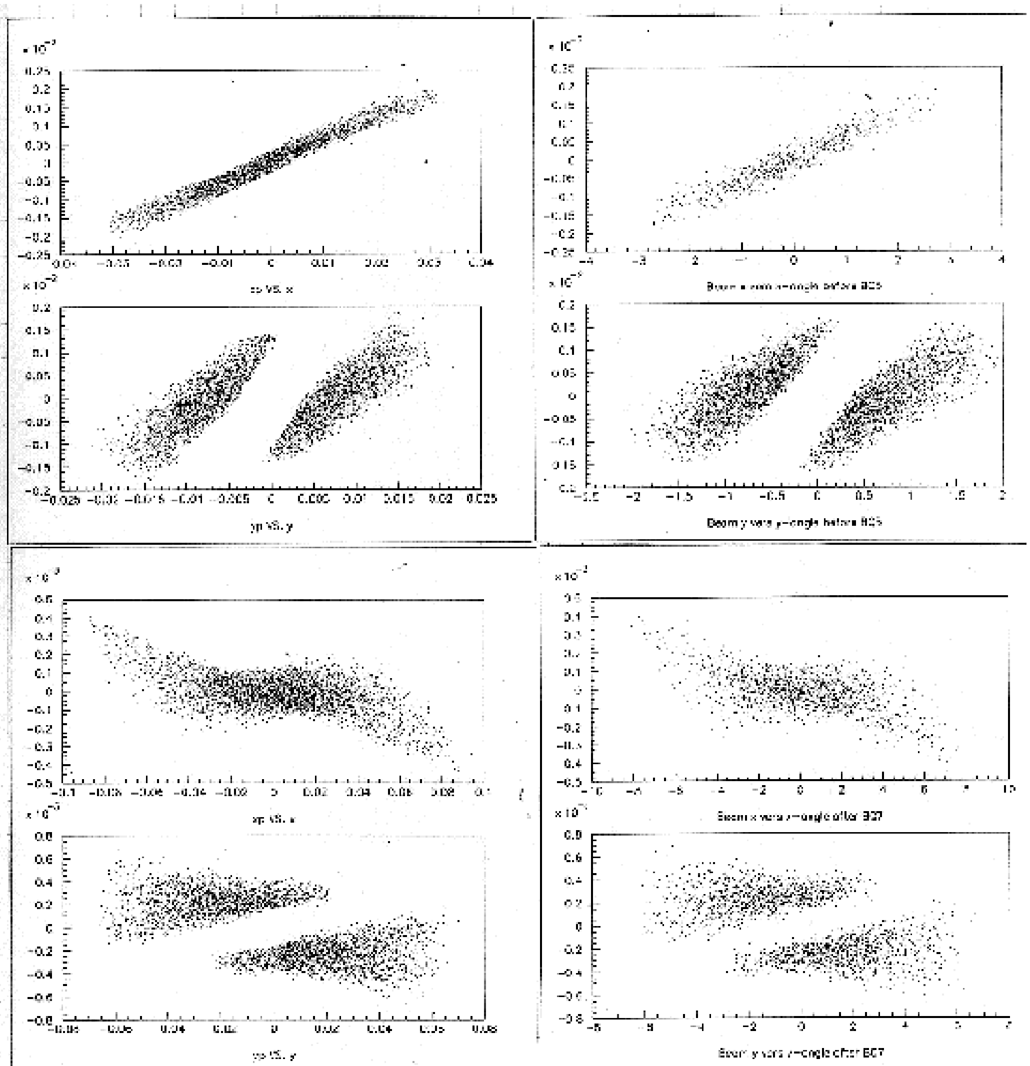


Fig. A3 Phase space comparison between TURTLE and GEANT at entry to BQ5 and exit of BQ7 (entry to detector). Units are radians and meters (cm) respectively.

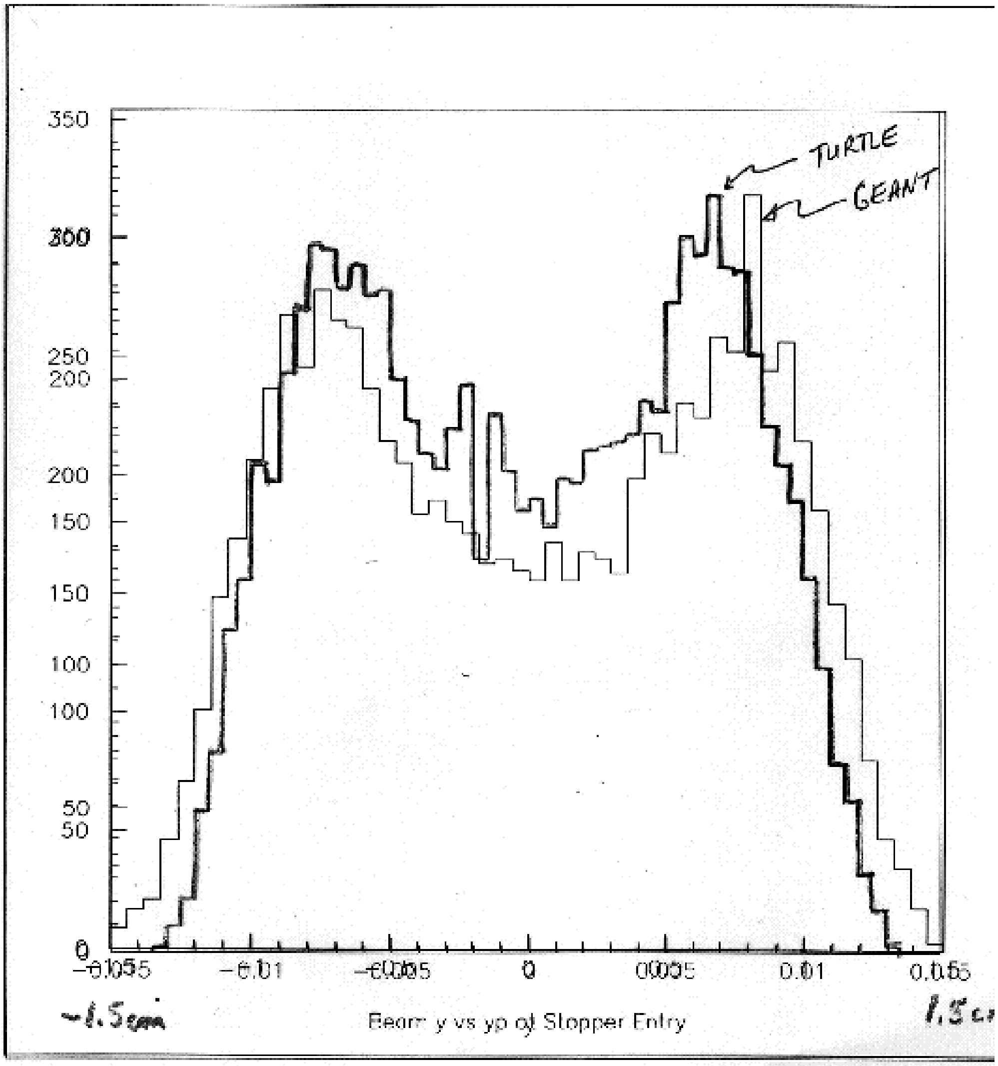


Fig. A4 Vertical position at Stopper - GEANT vs TURTLE f

Units are ±1.5 cm edge to edge.

Fig. A5 Vertical position at Stopper for π^+

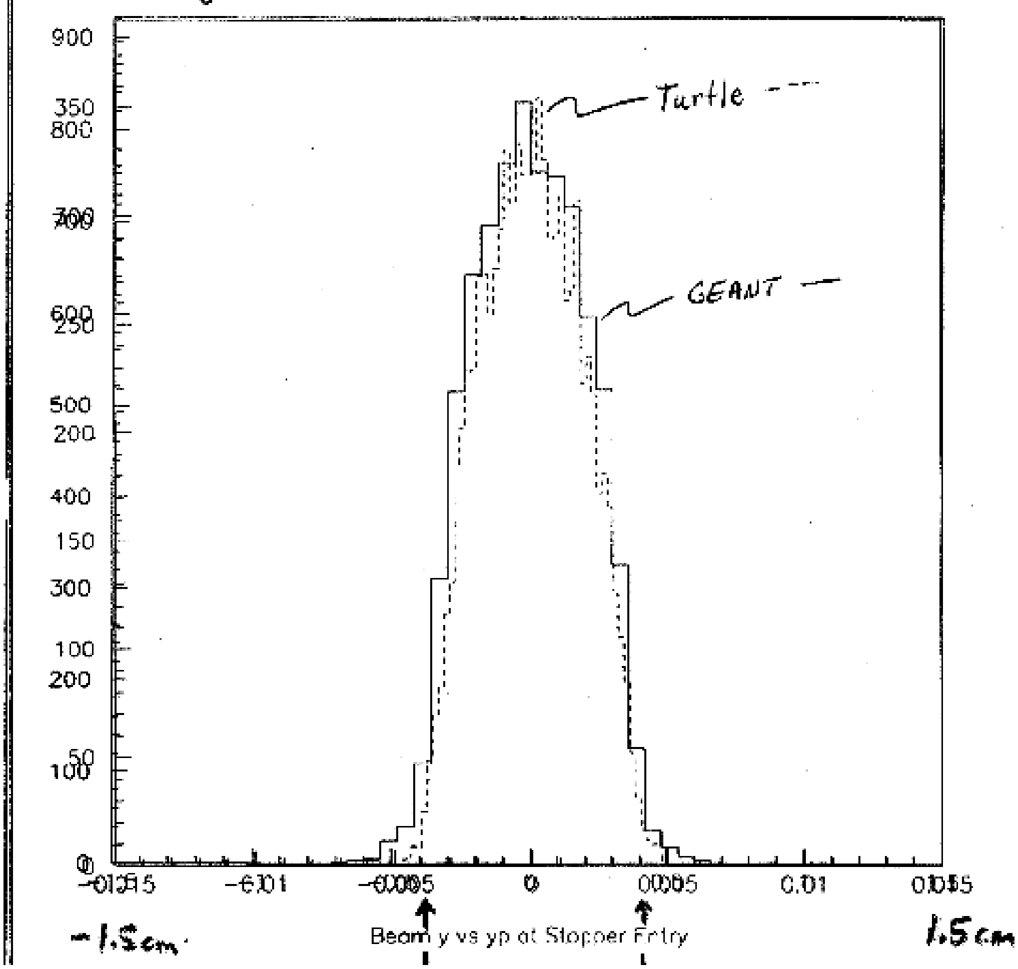


Fig. A6 Vertical position at Stopper for protons