Update of NuMI Absorber Conceptual Design

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Introduction

This report[1] presents the results of work done on the Conceptual Design of the NuMI Hadron Absorber in the period between the 11/98 Lehman DOE Baseline Review and 10/99 (date scheduled for a Beams Division NuMI Shielding Review[2]). The main features of this work were the change in lateral size of the water-cooled core of the Absorber, a study (with MARS[3]) of energy deposition in the core materials, the use of MARS runs to calculate star densities (with the effects on groundwater irradiation in mind), and an evaluation of how well MARS predicts residual radioactivity[4].

Design Goals

The design goal for the Absorber is to safely dissipate the energy of the beam particles that remain in the beam at the end of the Decay Region. These particles no longer serve the purpose of generating neutrinos. The only particles of interest at this point besides the neutrinos are the muons, which can be used by the monitoring chambers downstream of the Absorber to gauge the quality of the focusing system in the Target Hall. Of interest are those muons resulting from pions which were subjected to the effects of the focusing magnetic fields in the Horn focusing system. For the Low Energy configuration of the focusing Horns either enough of these muons for monitoring purposes should exit the rear of the Absorber, or a monitoring chamber should be inserted at the downstream end of the Absorber at a point where enough of these muons are still present.

The central core of the Absorber should be able to withstand the energy density that results if the proton beam doesn't interact in the target and moves to the side to the limit provided by the Horn Baffle system. The shielding surrounding the core should provide sufficient attenuation that groundwater in the rock walls of the Absorber Cavern

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[1] An earlier report on the subject is NuMI note B-493, "Absorber Conceptual Design for the 11/98 DOE Baseline Review", dated 4/30/99.

[2] The timing is set so as to have the Shielding Review precede the groundbreaking for the first phase of underground construction.

[3] N.V. Mokhov, "The Mars Code System User's Guide", Fermilab-FN-628 (1995). N.V. Mokhov, S.I. Striganov, A. Van Ginneken, S.G. Mashnik, A.J. Sierk and J. Ranft "MARS Code Developments", Fermilab-Conf-98/379 (1998); LANL Report LA-UR-98-5716 (1998); nucl-th/9812038 v2 16 Dec 1998. O.E. Krivosheev and N.V. Mokhov, "A New MARS and its Applications", Fermilab-Conf-98/43 (1998).

[4] Measurements of residual radioactivity were made at the tops of steel modules in the AP0 shielding geometry, at the end of the 3rd quarter 1999 beam test of the NuMI prototype graphite target This geometry has been simulated with MARS.

does not get activated above acceptable limits. The draft TM "Refinement of Groundwater Protection for the NuMI Project" indicates a limit of 1.6 10^{-11} stars cm^{-3} p^{-1} for the Hadron Absorber, when the stars per proton are averaged over a volume of rock that starts at the inside walls and goes out two meters[5].

Additional considerations for shielding thickness and composition are residual radioactivity and prompt radiation. The bulk shielding for the Absorber is taken to be low cost steel, surrounded by a 3' (90 cm) wrap of concrete in order to attenuate the fast neutrons exiting the steel[6]. The energy spectrum produced by the concrete wrap is beneficial for the minimization of prompt dose at the personnel access control gate beyond the labyrinth in the Absorber Cavern Access passageway. The residual radioactivity level goal is governed by how much maintenance work is anticipated to take place in the Absorber Cavern, and by the use of the Absorber Cavern as a possible emergency exit passageway from the downstream tunnel areas. A value of residual radioactivity of 30 mRem/hr (0.3 mSv/hr) was used in NuMI-B-493, based upon an average beam intensity of 4 10^{13} per 1.9 second spill. Uncertainties in the composition of the concrete wrap and in the calculational method could mean that the value of 30 mRem/hr used for calculational purposes is low by a factor of three, and that the actual residual activity is 100 mRem/hr (1 mSv/hr). A somewhat conservative choice for the calculational limit would also allow for a higher beam intensity, should that prove possible[7].

<u>Core Parameters</u>

The water-cooled core of the NuMI Absorber is chosen as a low Z material, so that the energy deposition where the beam strikes it is minimized. Aluminum has been selected as a suitable low-Z material[8]. A suitable geometry might be plates of aluminum suspended in a bath of flowing water[9]. A detailed design of this core is the next step after the radiation/energy deposition conceptual design is completed.

For simplicity, the lateral dimensions of this core have been chosen to be large enough to contain all possible motion of the beam that are allowed by the baffle system that will physically protect the NuMI focusing horn inner conductors from being struck

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[5] A star is a nuclear interaction as recorded by a Monte Carlo shielding program such as MARS, using a kinetic energy threshold of 50 MeV. In the direction transverse to the beam the star density drops by roughly three orders of magnitude over a two meter distance. In the longitudinal direction the fall-off of star density is not as steep.

[6] This subject is discussed on page 3-41 of Fermilab TM-1834, "Radiation Physics for Personnel and Environmental Protection, J.D. Cossairt, February, 1999.

[7] Jorge Morfin would like to have residual activity no higher than 30 mRem/hr at the downstream end of the Absorber Cavern, where a muon monitoring chamber will be located. Thus, the current goal would be to design for 30 mRem/hr elsewhere and 10 mRem/hr in that region, assuming that the uncertainty in these design goals is a factor of three.

[8] The CERN neutrino beam design for the Gran Sasso long baseline experiment uses graphite in its core; a graphite core has not been studied for the NuMI Absorber.

[9] A plate geometry was used for the 60 kW tune-up beam dump at SLAC. This is described on pages 728 and 729 of the book, "The Stanford two-mile accelerator", R. B. Neal, general editor, W. A. Benjamin, New York, 1968. The containing chapter describes various beam power absorption devices.

directly by the proton beam. If the beam misses the target, in this scenario, it deposits all of its energy in the Absorber core, and is at minimum size because it hasn't undergone multiple scattering in the target material. This is the worst case for energy deposition.

Based upon these considerations the horizontal size of the core is 42 inches. In the vertical dimension this is increased to 48 inches, in order to allow for the Absorber to be level, yet accommodate a beam which has a change of elevation of 7 inches every ten feet[10].

The length of the aluminum section of the core is set at eight feet (244 cm). Beyond that is a similarly shaped core of steel, which is 8.6 feet long (263 cm). The energy density study conducted to date indicates that eight feet is an appropriate transition point from aluminum to steel (see next section).

MARS Runs

MARS runs made prior to Summer, 1999 emphasized the layout of the Target Hall and the Decay Pipe Region. Rather simple models of an Absorber were included in those run geometries. More recently, specialized MARS runs emphasizing the Absorber have been made[11]. Initial runs were done with energy deposition in mind, since that topic requires less running time to get reliable results (than does running to get star densities in the water-bearing rock that makes up the walls, floor, and ceiling of the Absorber underground cavern). The best available information[12] about the characteristics of the NuMI proton beam and target was included in the energy density runs. The energy deposition runs indicated that a choice of aluminum core eight feet long followed by a steel core seemed reasonable[13].

Later runs were designed to calculate star densities throughout the Absorber region. Simplifying assumptions for the Target Hall & Decay Region were made--with

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[10] The pitch angle of the beam is -3.33576 degrees (-58.2 mr).

[11] The MARS runs emphasizing the Absorber have all been done with the Medium Energy configuration of the focusing horns for the neutrino beam.

[12] Appendix I exhibits an e-mail with some of the basic information. Knowledge of the beam is not static, however, nor its design or method of production. There were later indications that the beam's transverse sizes might be a factor of two larger. If so, the energy density where the undissipated beam strikes the Absorber core would decrease; there would be a negligible effect on the core dimensions. In addition, there is serious consideration being given to using single-turn extraction to get the beam out of the Main Injector cleanly. Resonant extraction is quite likely to present problems with residual activation of the extraction elements and their surroundings. A beam extracted via single turn extraction would have horizontal and vertical emittance and phase space more similar to each other than does the resonant extracted beam, which has its horizontal emittance affected by the resonance induced emittance growth and stripping process used in extraction. No undue effects on the energy deposition in the Absorber core are expected.

[13] The peak energy deposition was $0.57\ 10^{-3}$ GeV g^{-1} p^{-1}, at a depth of 100 cm. This converts to 3.6 joules g^{-1} p^{-1} for $4\ 10^{13}$ protons per 1.9 sec spill and is a 4°K rise in temperature per beam pulse, in aluminum. The energy density dropped to $0.1\ 10^{-3}$ GeV g^{-1} p^{-1} at the start of the steel core. Thermal conductivity of iron is 1/4 that of aluminum, so the aluminum length seems to be appropriate. A more detailed study is planned.

the goal of minimizing running time. These simplifying assumptions included the following:

Cylindrical geometry

Don't follow interactions in the Target Hall Shielding. Simply impose an aperture with radius 69 cm.

Don't follow interactions in the materials for the first 200 meters of decay pipe (i.e. the steel of the pipe and the surrounding shielding concrete).

The last 475 meters of Decay Pipe was assumed to have steel pipe with wall thickness 2 cm, surrounded by 4.5 feet (137 cm) of concrete shielding (density 130 lbs/cu. ft.)[14].

Absorber Geometry

The MARS model for the Absorber has a cylindrical core of radius 53 cm, surrounded by steel thicknesses that correspond to the 52" x 52" x 26" steel blocks that are recycled low-radioactivity steel[15]. The 52" x 52" face on these blocks is oriented parallel to the beam. A 90 cm thick concrete wrap is used outside of the steel. A schematic of the MARS model is shown in Figure 1.

MARS Results

Figure 2 shows the region from z=72700 cm to 74418 cm. This includes the end of the decay pipe, a decay pipe window modeled as 1.27 cm of iron, and a six foot (183 cm) region ahead of the absorber core. The decay pipe window ends at 72900 cm. Transverse concrete shielding 4.5' thick (135.7 cm) was present between the end of the decay pipe and the beginning of the Absorber. Figure 3 shows superimposed the Absorber geometry and the star density color plot[16]. Figures 4-8 are various slices from Figure 3, with the star densities properly averaged. There are three transverse slices (ahead of the Absorber core, at the Absorber core, and along the inside face of the downstream rock) and two longitudinal slices (one along the center of the Absorber core and the other along the inside edge of the rock at the side of the Absorber Cavern).

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[14] The actual thickness of this shielding in the simulation shouldn't matter much. As of 9/22/99 the minimum transvers dimension of the shielding specification for this region was reduced from 56 inches to 44 inches (a favorable outcome of the continued study of the effects of groundwater movement); this change came too late to be incorporated into the MARS run.

[15] Fermilab has two hundred of these blocks. Of these, it is planned that 170 go into the Target Hall shield. More of these blocks can be ordered, at a cost that is lower than that of the Continuous Cast Salvage Steel that had been the candidate for steel shielding prior to learning about the blocks made from low radioactivity steel (~1 mr/hr). Dave Pushka is the source of information about these blocks. The good quality faces on these blocks are those with the 26" dimension (i.e. the 52" x 52" face is the one that has the poorest surface quality).

[16] MARS provides a star density histogram with 120 bins in r and 200 bins in z, when requested to do so. The limits in r and z for this histogram can be specified to be anywhere in the geometry.

In the geometry setup for the MARS run, the rock was between r=396 and 696 cm, for z between 72900 and 74118 cm. The downstream rock went from z=74118 to z=74418 cm, r = 0 to r=696 cm, The binning for star density in the rock was as shown on Figures 2 and 3. If one properly averages the star density over a volume that goes 2.1 meters from the inside edges (i.e. 7 bins in r at sides, 7 bins in z at DS end), the result is the first three rows in the following table:

	Star Density (stars cm^{-3} p^{-1})	Error	Volume (cm^3)
Sides	$7.8\ 10^{-12}$	$1.6\ 10^{-13}$	$8.1\ 10^{8}$
DS End	$2.4\ 10^{-13}$	$3.9\ 10^{-14}$	$3.2\ 10^{8}$
Sides + DS End	$5.7\ 10^{-12}$	$1.2\ 10^{-13}$	$1.1\ 10^{9}$
	Stars (stars p^{-1})	Error	
	$6.4\ 10^{-3}$	$1.3\ 10^{-4}$	

If the volumes used are not limited to 2.1 meters transverse, but instead use all of the bins (10, going 300 cm from the inside edge out), then the table becomes[17]:

	Star Density (stars cm^{-3} p^{-1})	Error	Volume (cm^3)
Sides	$5.1\ 10^{-12}$	$1.0\ 10^{-13}$	$1.3\ 10^{9}$
DS End	$1.8\ 10^{-13}$	$2.9\ 10^{-14}$	$4.6\ 10^{8}$
Sides + DS End	$3.8\ 10^{-12}$	$7.8\ 10^{-14}$	$1.7\ 10^{9}$
	Stars (stars p^{-1})	Error	
	$6.4\ 10^{-3}$	$1.3\ 10^{-4}$	

<u>Residual Radioactivity</u>

Section 2 of NuMI-B-493 gives the basis for using 4×10^{-11} stars cm^{-3} p^{-1} as corresponding to 30 mRem/hr dose rate at the outer surface of 3 feet (~90 cm) concrete surrounding steel in a shielding geometry[18]. Figures 4, 5, & 7 indicate that to achieve a residual radioactivity dose rate of 30 mRem/hr we would need to increase the transverse

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[17] At the risk of sowing confusion, this second table is shown because it gives an indication of what would happen if one averaged over a larger volume in the longitudinal direction. The fall-off in star density is slower in the longitudinal direction than it is in the transverse direction. If one choosed the averaging volume in the longitudinal direction based upon reaching a star density 0.1% of its value at the cavern downstream wall, then the longitudinal distance to use would be ~4 meters, rather than 2 meters. One can see that the total number of stars doesn't change, so an average over a larger volume than that used for the second table can be easily done--if desired.

[18] The comparison of MARS predictions with residual dose measurements at AP0 (after the initial NuMI graphite target beam exposure) has not matured to the point where it provides any new information on this subject.

shielding somewhat[19] (e.g. 9" of steel), but that longitudinally it seems that we have more than enough shielding[20]. As in NuMI-B-493 it should be possible to have an asymmetry present in the amount of transverse shielding, since not all sides of the Absorber will be equally accessible[21].

Groundwater Protection

As indicated earlier 1.6 10^{-11} stars cm^{-3} p^{-1} is the limit of average star density for the rock in the vicinity of the Absorber. This was based upon radionuclide activity generated in a region 6.5' (2 meters) from the walls of the cavern, and the average time spent by the activated water moving this distance and entering the cavern. The value given in the both of the star density tables is well under this limit. Thus, groundwater standards are easily met by this design[22].

Summary

The dimensions of the Absorber model described in this paper seem quite adequate to provide groundwater protection. Transversely they are undersized by ~ 9 inches of steel, if 30 mRem/hr contact dose residual radioactivity is desired (for the nominal design beam intensity of 4 10^{13} protons per 1.9 sec spill). Longitudinally the dimensions are sufficient to produce residual radioactivity dose (in downstream concrete-like materials) well under 30 mRem/hr[23].

A water-cooled Al core of size 42" x 48" x 96" seems capable of withstanding the energy density deposited by full beam intensity under any conceivable accident condition. The prompt rate at the entrance to the access labyrinth seems acceptable[24].

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[19] NuMI-B-493 had 30.5 cm of aluminum, 163 cm of steel, and 90 cm of concrete in the transverse direction--as dictated by residual radiation. In the MARS geometry presented here we have 53 cm of aluminum, 132 cm of steel, and 90 cm of concrete. Thus, it shouldn't be a surprise that more transverse shielding seems necessary.

[20] The trade-off between length of the Absorber and residual rate downstream hasn't been fully explored. There is still some flexibility left for this trade-off--assuming that it is desirable to avoid embedding a muon monitoring chamber inside the Absorber (for the LE configuration of the neutrino beam).

[21] There is indication that if the "Hadron Hose" option for MINOS (a focusing wire down the center of the Decay Pipe) is adopted at the MINOS mid-October, 1999 collaboration meeting, and is accepted by NuMI Management, then access to both sides of the Absorber would be necessary.

[22] Upon seeing a draft of this paper Jorge Morfin concluded that it is worth exploring removing one foot of steel from the length of the Absorber. The reason for wanting to do this has already been mentioned--namely the desire to avoid embedding a muon-monitoring chamber in the Absorber shielding. Based upon Table 3 in NuMI Note B-493 this would raise the "DS End" number in the first star density table from 2.4 10^{-13} to 8.9 10^{-13}. This increases the total star count from 6.4 10^{-3} to 6.6 10^{-3}, if one considers the change to only affect the "DS End". In actuality the "Sides" number would increase also, but the expectation is that the limit of 1.6 10^{-11} would not be breached. This will be studied further in the very near future.

[23] As already discussed the uncertainty in these design numbers for residual radiation could be a factor of three.

[24] This prompt rate, together with the attenuation in the labyrinth in the accessway, results in a prompt rate at a personnel gate, placed in any reasonable position after the labyrinth, that is lower than the applicable guidelines would indicate is necessary for unrestricted access.

Next Steps

The next steps in the design of the Absorber are:

A more detailed study of heat removal in the core.

Further discussion of the energy loss of muons in the Absorber for the Low Energy configuration of the neutrino beam, and a determination of the necessity of putting a muon chamber inside of the Absorber materials. Such a determination can be affected by the level of residual radioactivity deemed acceptable for work on the muon chamber at the downstream end of the Absorber Cavern.

A more practical shielding design, using actual block sizes, and taking into account the possibility of having to remove the water cooled core for serviceability. A re-estimate of the cost would be appropriate, upon completion of a more practical design.

A MARS study of the more practical design.

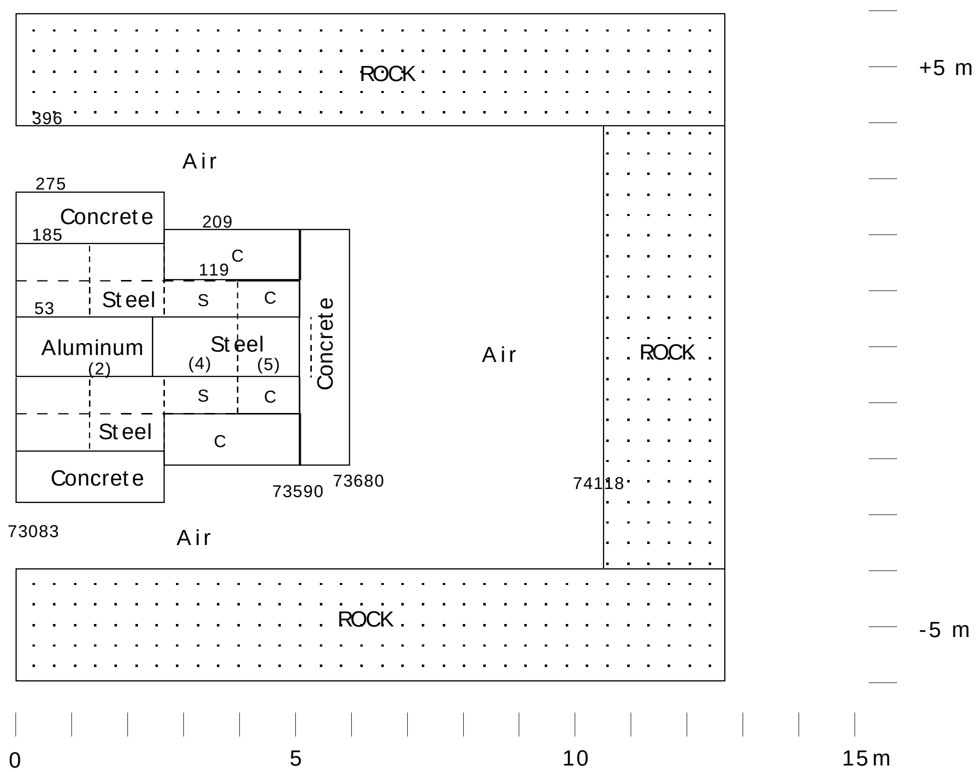

Figure 1

This is a Claris Cad drawing of the model of the Absorber. The dimensions are accurate except for the rock, which was made thicker (a total of 300 cm in both dimensions). Not shown is the region between the Decay Pipe downstream window and the start of the Absorber.

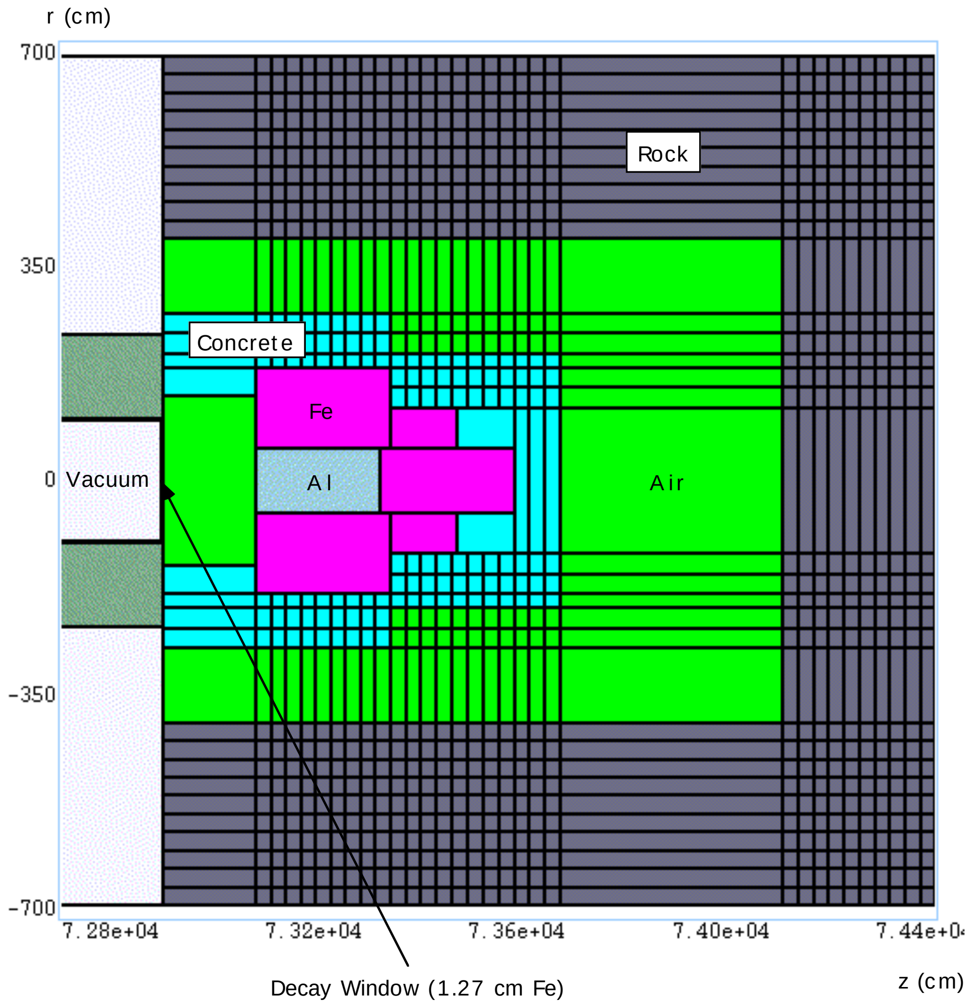

Figure 2

This figure shows the geometry of the Absorber model and its materials. It begins at z=72700 cm, which is 200 cm ahead of the end of the decay pipe. The absorber core starts at z=73083 cm. This figure is best viewed in color.

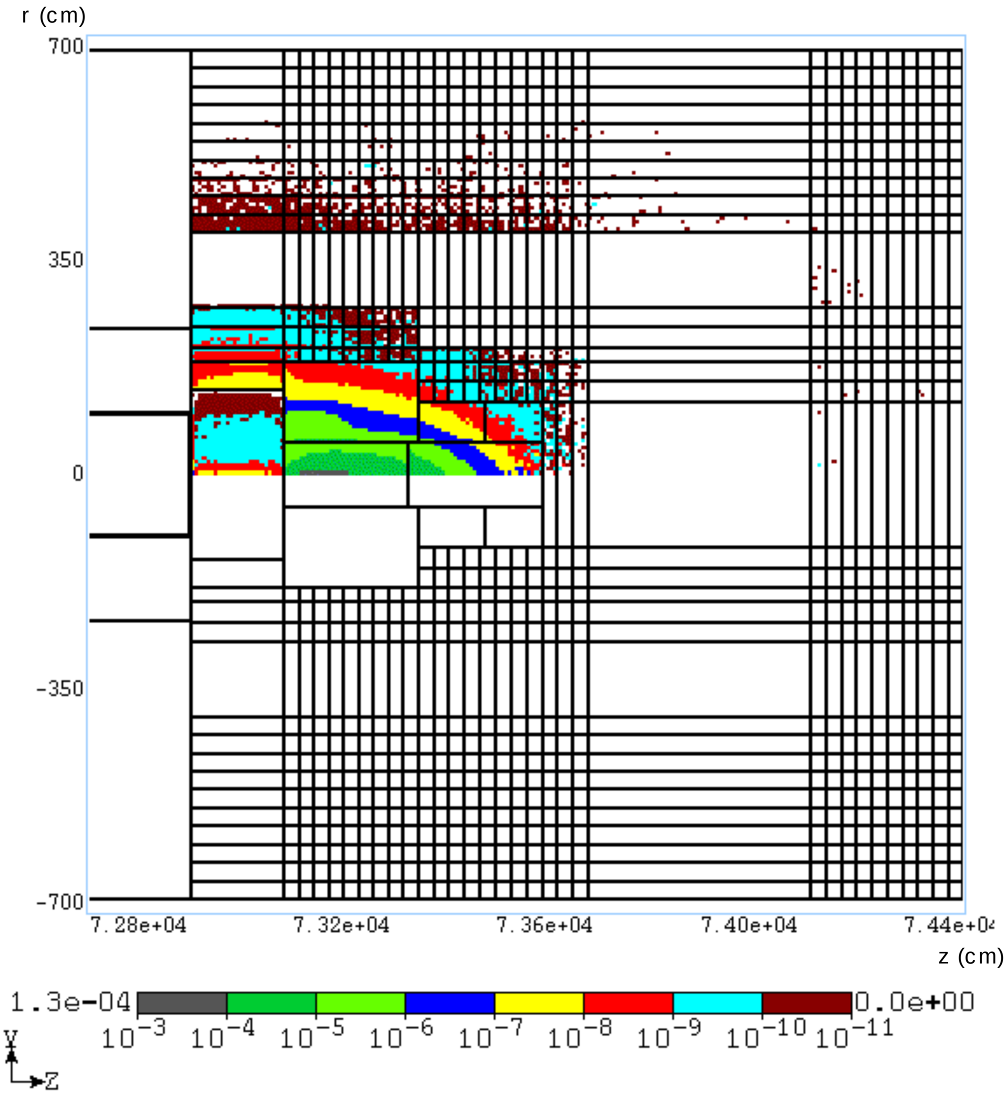

Figure 3

This figure is a superimposition of a star density plot and an Absorber Geometry plot. It starts at 72700 cm, which is 200 cm ahead of the end of the decay pipe. The star density units are stars cm^-3 p^-1; the star densities are best viewed in color. The absorber core begins at z=73083 cm.

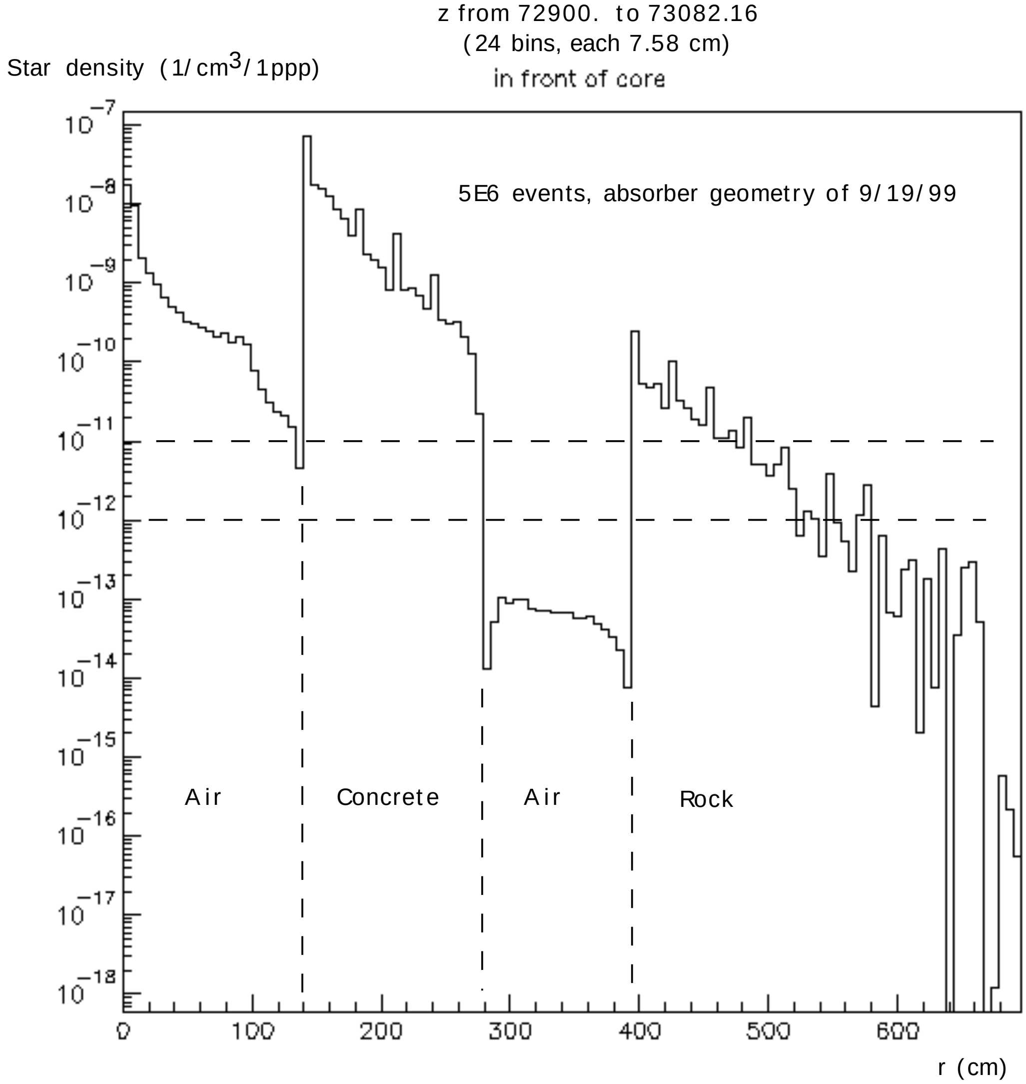

Figure 4

This figure shows star density vs radius for a slice in z ahead of the Absorber core. The lines shown are visual guides.

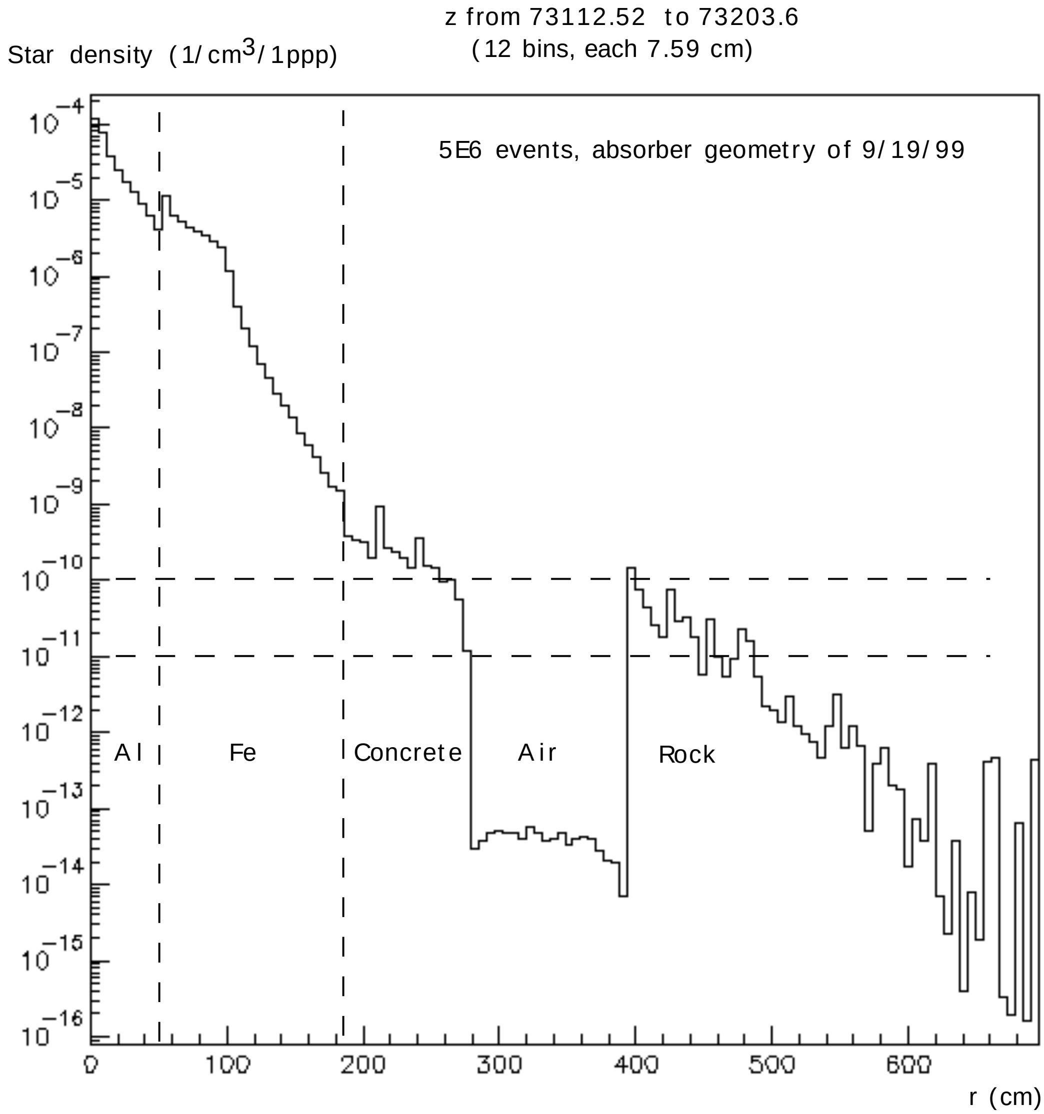

Figure 5

This figure shows star density vs radius for a slice in z at the upstream end of the Absorber core. The lines shown are visual guides.

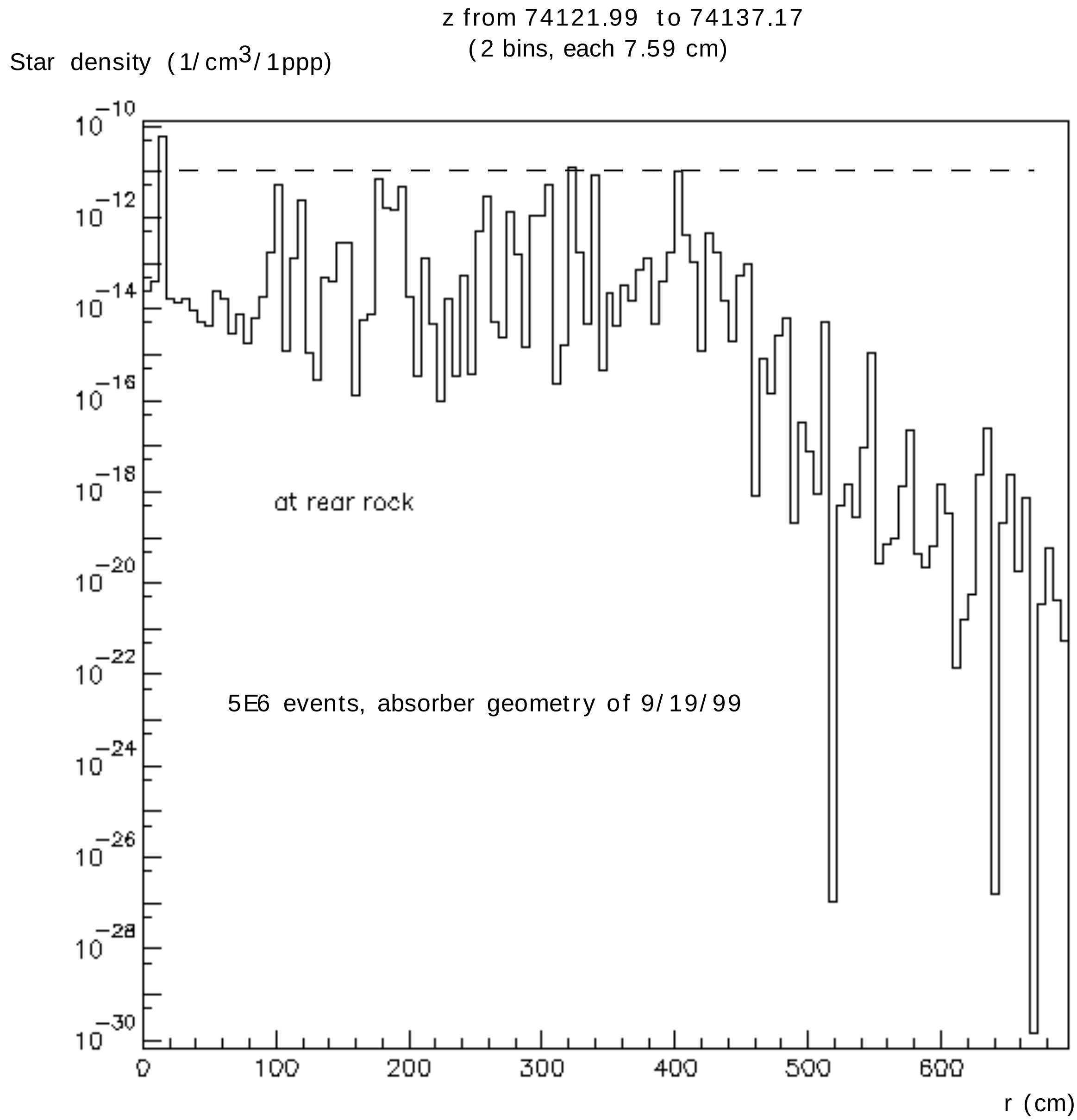

Figure 6

This figure shows star density vs radius for a slice in z at the upstream face of the rock at the downstrem end of the Absorber Cavern. The line shown is a visual guide.

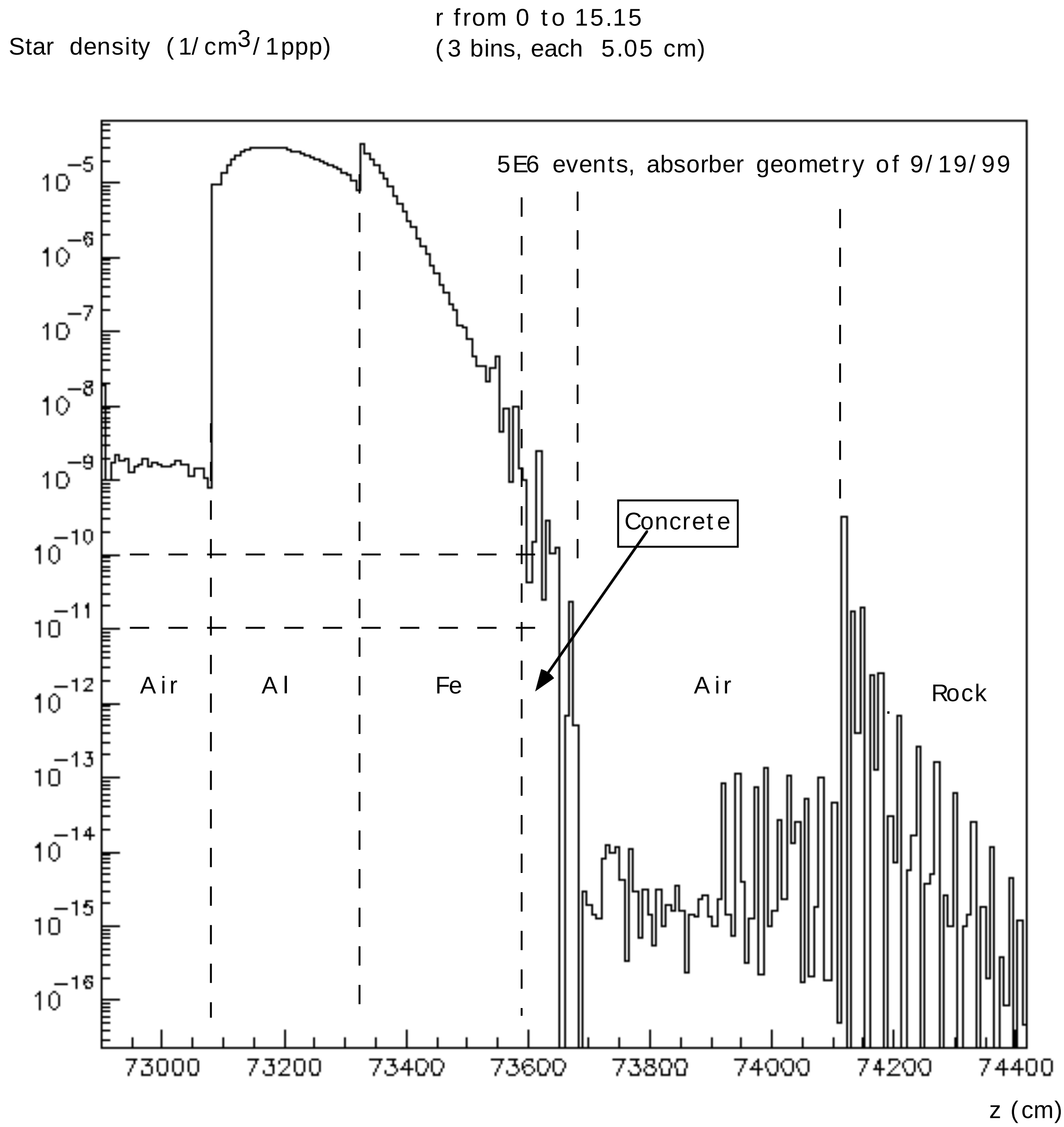

Figure 7

This figure shows star density vs z for a slice in r along the path of the beam. The lines shown are visual guides.

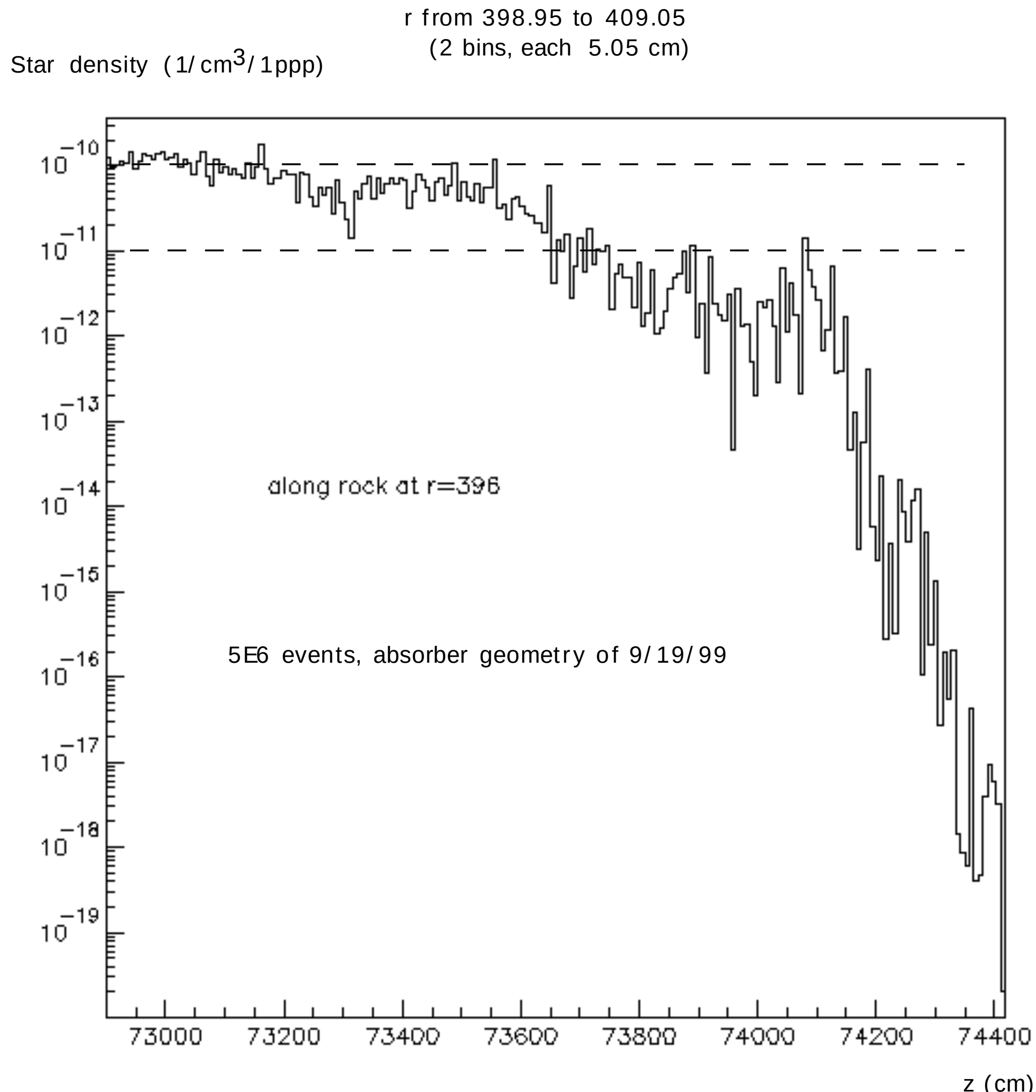

Figure 8

This figure shows star density vs z for a slice in r along the inside edge of the rock along the side walls of the Absorber cavern. The lines shown are visual guides.

Appendix

Date: Fri, 18 Jun 1999 12:03:49 -0500
From: "Peter W. Lucas" <lucas@fnal.gov>
Subject: Beam size at absorber
To: Sam Childress <childress@fnal.gov>, Alan Wehmann <wehmann@fnal.gov>,
Dave Pushka <pushka@fnal.gov>
Cc: Jim Hylen <jzh@fnal.gov>

Friends,

Here are the beam parameters at the absorber face. These results come from tracking a sample of 1000 rays through the beamline with focus conditions as established in recent weeks.

The horizontal position distribution is approximately flat with full width of 21cm. The standard deviation of the distribution is 5.6cm. The horizontal angular standard deviation is 76 microradians - there is a nearly 100% positive correlation between positions and angles.

The vertical position distribution is gaussian with sigma of 5.0cm. The vertical angular sigma is 67 microradians, again with nearly 100% correlation with the positions.

<Peter>

P.S. (added by me, after a conversation with Peter) at target vertical sigma is 1.4 mm, horizontal sigma is 0.7 mm (flat distribution with sharp edges)