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Residual Radiation Hints for Aperture and Alignment Issues in the Main Injector

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Contents

Abstract

A radiation survey of Main Injector components was conducted in preparation for the 2004 Fermilab Facility Shutdown. This was part of effort to locate regions of the Main Injector which require attention to alignment in preparation for the high intensity operation required for NuMI and MINOS. Several regions have been identified which exhibit residual radiation of more than 500 mrem on contact. These locations raise concerns in that the Main Injector will likely operate with more than 5 times the injected intensity within a year. At least one pattern has been identified and explored in the regions showing high radiation. It involves the beampipe minitube at the upstream end of MI Defocusing Quadrupoles in Regular Cells. This note will introduce the issues and review some of the data which is now available.

1 Introduction

The Main Injector operates with low losses for most operational cycles. Nevertheless, a few locations in the tunnel exhibit radiation levels which require attention when planning upgrade or repair work on the accelerator. In order to assess the need for alignment work during the Summer 2004 Shutdown, aperture scans with beam and tunnel radiation surveys were initiated to understand the aperture available and to identify problems which may become significant as the intensity is raised.

It is known that there are high radiation regions near each of the Lambertson magnets used for beam transfer or abort. These will be addressed in the Summer 2005 Shutdown by constructing and installing quadrupoles which have larger apertures (see Proton Plan[1] p 17) to permit improved aperture for both circulating beams and adjacent areas for the beam being transferred through the bending region of the Lambertsons. This will permit reduced losses at these locations. In addition to other radiation survey work, we will initiate regular monitoring of these locations to attempt to document progress and limitations in these regions.Some other tunnel locations have required posting for radiation but much of the beam pipe shows very low levels of residual radiation.

Since no program for automatic aperture scans of Main Injector has been available, only a very limited set of scans have been carried out and no pattern for observed apertures has been established. With this limited knowledge base and limited resources, it was decided that the emphasis on aperture scans would be placed on locations identified by radiation survey. On June 10 and June 11, 2004 a radiation survey of the Main Injector beampipe was carried out. In addition to the known locations near Lambertson Magnets and several other new hot locations, it was observed that a pattern of residual radiation exists involving the minitube upstream of many of the defocusing quadrupoles in regular cells. Before summarizing other aspects of these studies, we will describe this newly identified problem.

2 Losses at Defocusing Quads

2.1 Initial Observations

During the survey of the tunnel on June 10, it was noticed that there were unusual patterns of losses which included residual radiation which peaked in bare beam pipe between two magnets. Such a pattern in the Main Ring was occasionally due to an 'obstacle' which was frequently a sliver of beam pipe which remained from a previous repair. However when a second and then a third of these patterns was observed and the location was consistently about 18 inches from the end of the upstream dipole steel, it was recognized that this was a new pattern which was surely not due to an obstacle loose in the

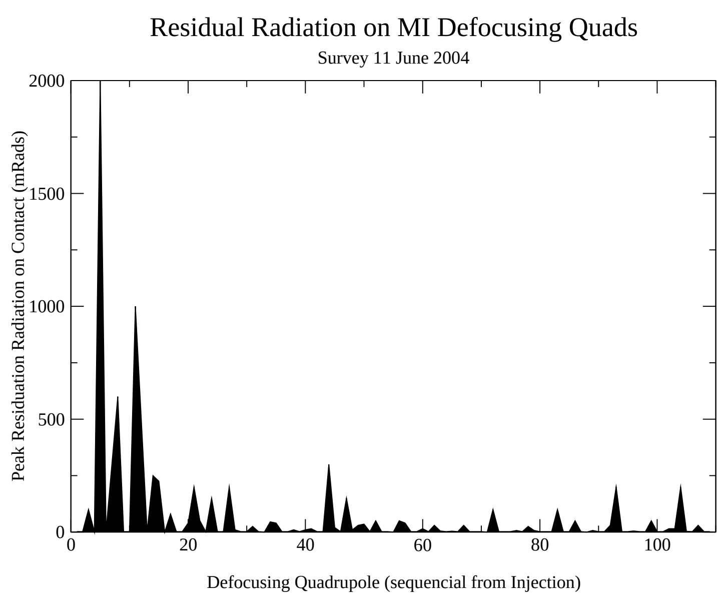
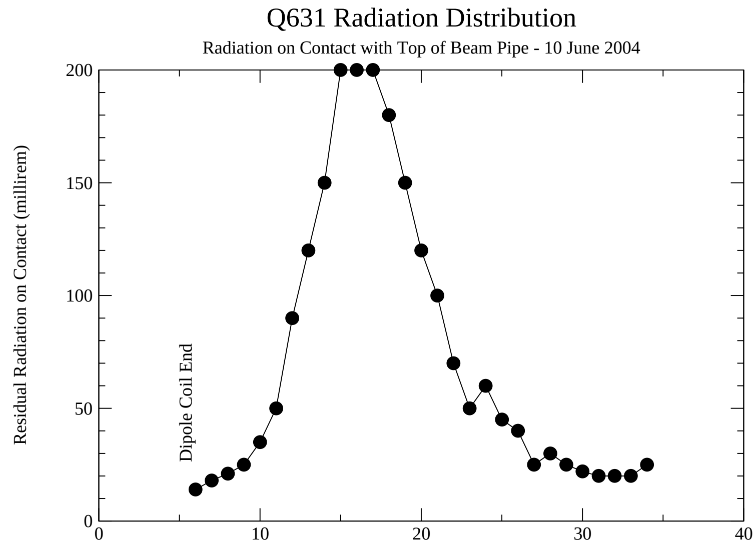


Figure 1: Residual Radiation on Contact at minitube on upstream of Main Injector Defocusing Quadrupoles after few hours cooldown.

beam pipe.



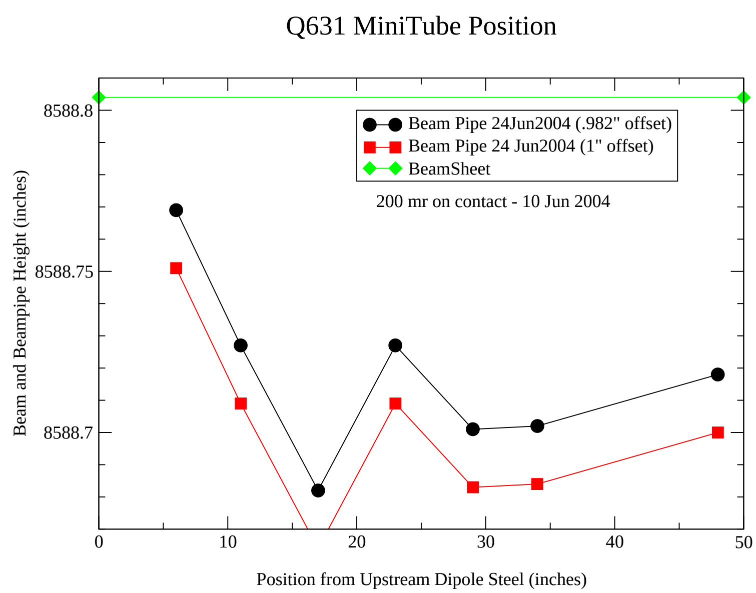


Figure 2: Upper Figure shows residual radiation pattern at Q631 as measured on contact with the top of the beam pipe. Lower Figure shows the elevations as surveyed at the top of the beam pipe but expressed as location of beam pipe center assuming a constant 1 inch or 0.982 inch offset from center to top of beampipe.

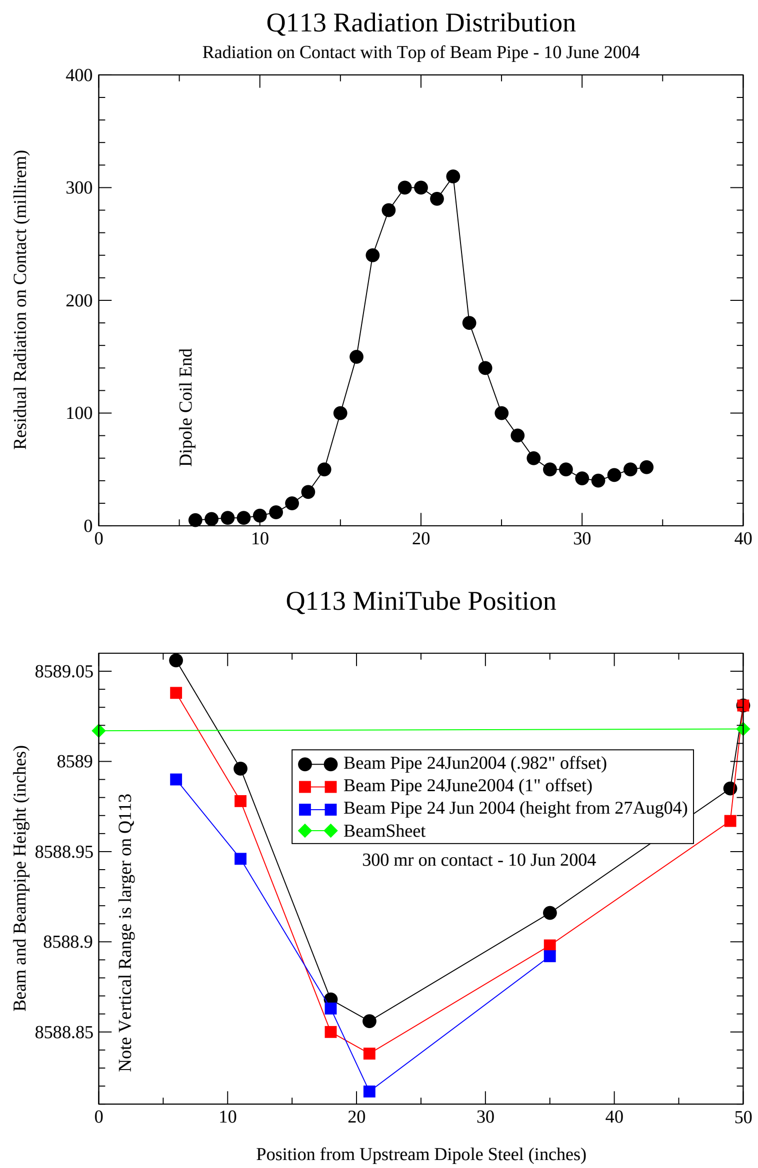


Figure 3: Upper Figure shows residual radiation pattern at Q113 as measured on contact with the top of the beam pipe. Lower Figure shows the elevations as surveyed at the top of the beam pipe but expressed as location of beam pipe center assuming a constant 1 inch (red squares), 0.982 inch offset (black circles) or as measured offset (blue squares) from center to top of beampipe.

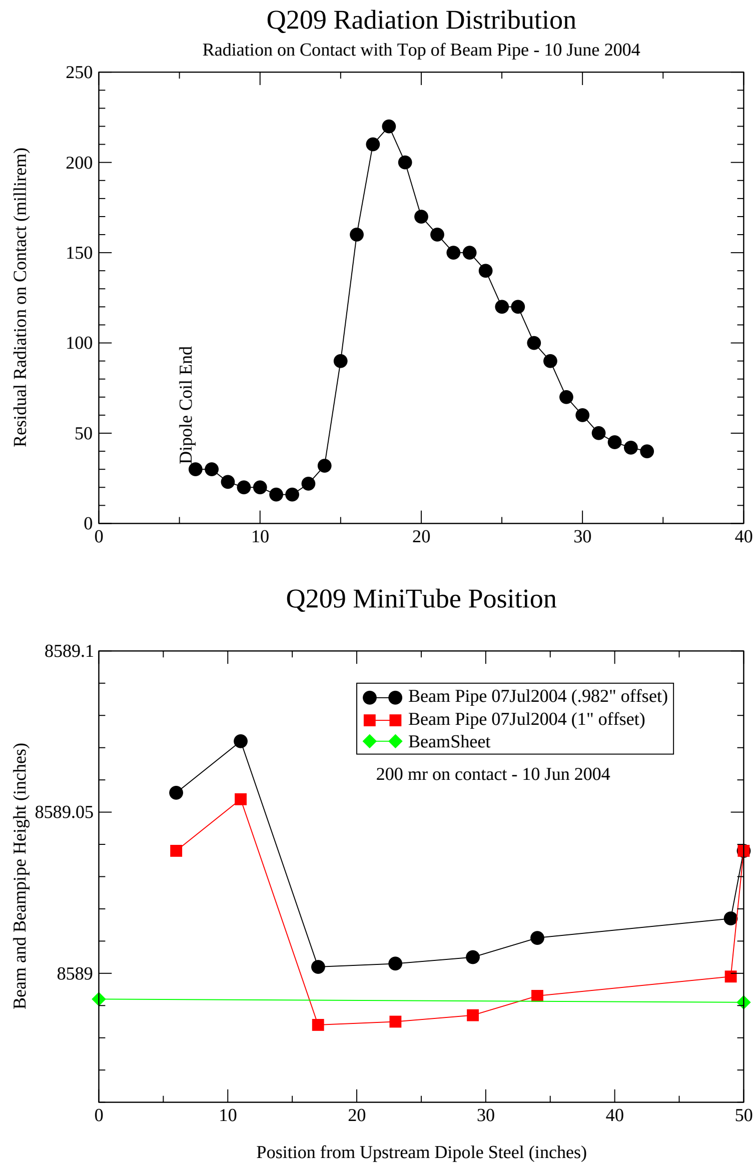


Figure 4: Upper Figure shows residual radiation pattern at Q209 as measured on contact with the top of the beam pipe. Lower Figure shows the elevations as surveyed at the top of the beam pipe but expressed as location of beam pipe center assuming a constant 1 inch or 0.982 inch offset from center to top of beampipe.

On June 11 the radiation survey was continued with an awareness of this pattern which appeared at D Quad (odd half cell) locations. The pattern was detailed at three locations by recording at one inch intervals the residual radiation measured on contact at the top of the beam pipe. This data is plotted in Figures 2, 3 and 4. It is sharply defined and local to the bare beam pipe.

This patterned of localized losses at vertically focusing locations repeats in many locations around the ring. The radiation survey on June 11 documented the residual radiation on contact at the top, bottom, aisle and wall side of the beam pipe in many locations. The results of this survey at odd (defocusing) cells is recorded in Tables 1,2 and 3 and the reading on the top of the beampipe is plotted in fig 1. This pattern was shown to be due to the residual radiation at the top of the beam pipe by comparing, at several locations, the radiation at the bottom of the pipe with that the same distance (2 inches) above the top of the pipe. These "Top+2in" readings are very similar to the "Bottom" readings (compare 6th and 7th columns in tables), confirming that the activation is at the top of the beam pipe. To document these localized radiation patterns, the 8th column in the tables shows the z position of the radiation peak. The pattern is apparent for both very high and some quite moderate radiation locations. Readings below about 10-20 mrad may not have been recorded.

Is is known that some of the magnets have apertures which make it difficult to insert an elliptical Main Injector Beam Pipe through the star-shaped tube which was the Main Ring Beam Pipe. For the main installation effort, a hydraulic device was used to complete the insertion process. For magnet replacement, some pipes have be inserted using the persuasive power of a fork truck. No record was kept of which installations were more difficult. This process must have resulted in a stress in the beam pipe as it was inserted from the downstream end. Perhaps it relieves that stress by bending? Perhaps some geometric design feature of the magnet or of the insertion process creates an up-down asymmetry for this stress relief such that the preponderance of the problems make the point of minimum aperture downstream of the bellows to be low. We considered this possibility. Another fact about Main Ring Quadrupoles is that some of the rebuilds were less satisfactory, including less beam pipe aperture. The column listing the magnet number was an attempt to search for a correlation between higher residual radiation and the suspect newer quadrupoles. If there is such a correlation, it is not a reliable indicator.

Table 1: Information recorded at Defocusing Quad Locations in Sectors MI100 and MI200 during Radiation Survey on June 11, 2004

		mrad	mrad	mrad	mrad	mrad	Peak
Location	Quad	Outside	Inside	Top	Bottom	Top+2in	Z(In.)
Q101	IQG333			2			
Q103	IQB176			2			
Q105	IQD051	100	100	100	100		
Q107	IQD031			2			
Q109	IQB183	300	300	2000	500		18
Q111	IQB173			3			
Q113	IQB308	40	50	300	40	50	
Q115	IQB049	150	100	600	150		
Q117	IQB208			2	2		
Q119	IQB103			2	2		
Q121	IQB174	250	300	1000	350		29
Q123	IQB186	80	90	500	100	100	18
Q125	IQB056			2	2		
Q127	IQB229	40	40	250	60	50	18
Q129	IQB298	60	60	225	70		28
Q201	IQB281	150	100	80	90		16
Q203	IQB262			2			
Q205	IQB269			2			
Q207	IQB129	6	6	40	6		17.75
Q209	IQB167	50	40	200	60	50	18.5
Q211	IQB180	7	7	50	9		17.25
Q213	IQB130			2			
Q215	IQB296			150	60		
Q217	IQD005			2			
Q219	IQD042			2			
Q221	IQB106	150	150	200	800		
Q223	IQC037			10			
Q225	IQD002			2			
Q227	IQD002			2			
Q229	IQC001			25	5		18
Q231	IQD001			2			

Table 2: Information recorded at Defocusing Quad Locations in Sectors MI300 and MI400 during Radiation Survey on June 11, 2004

		mrad	mrad	mrad	mrad	mrad	Peak
Location	Quad	Outside	Inside	Top	Bottom	Top+2in	Z(In.)
Q301 upstream	IQC008			45	20		
Q303 upstream	IQB082			40			
Q305 upstream	IQB055			2			
Q307 upstream	IQB216			2			
Q309 upstream	IQC004			10			
Q311 upstream	IQD011			2			
Q313 upstream	IQC005			10			
Q315 upstream	IQC007			15			18.5
Q317 upstream	IQD047			2			
Q319 upstream	IQC009			2			
Q321 upstream	IQB071	50	60	300	90		
Q323 upstream	IQD037			20			
Q325 upstream	IQD012			2			
Q327 upstream	IQB312	25	25	150	40		16.5
Q329 upstream	IQB219			10			
Q331 upstream	IQB267	5	5	30	7		17.5
Q333 upstream	IQB295			35			
Q335 upstream	IQB170			2			
Q337 upstream	IQB135			50			
Q339 upstream	IQD040			2			
Q341 upstream	IQD046			2			
Q401 upstream	IQB093			50	10		23
Q403 upstream	IQF278			40			
Q405 upstream	IQD004			2			
Q407 upstream	IQD033			2			
Q409 upstream	IQB202			15			
Q411 upstream	IQB107			2			
Q413 upstream	IQB114	4	5	30	7		17
Q415 upstream	IQB080			5			
Q417 upstream	IQB172			2			
Q419 upstream	IQB215			4			
Q421 upstream	IQB051			2			
Q423 upstream	IQB227			30	7		
Q425 upstream	IQB054			2			
Q427 upstream	IQB280			2			
Q429 upstream	IQB087			2			

Table 3: Information recorded at Defocusing Quad Locations in Sectors MI500 and MI600 during Radiation Survey on June 11, 2004

		mrad	mrad	mrad	mrad	mrad	Peak
Location	Quad	Outside	Inside	Top	Bottom	Top+2in	Z(In.)
Q501 upstream	IQB081	15	15	100	20		17
Q503 upstream	IQB094			2			
Q505 upstream	IQB274			2			
Q507 upstream	IQB349			2			
Q509 upstream	IQB263			7			
Q511 upstream	IQB264			2			
Q513 upstream	IQB282			25			
Q515 upstream	IQB053			7			
Q517 upstream	IQD050			2			
Q519 upstream	IQD035			2			
Q521 upstream	IQB177			2			
Q523 upstream	IQC006			100			
Q525 upstream	IQD048			2			
Q527 upstream	IQC010			2			
Q529 upstream	IQC016			50			
Q531 upstream	IQD003			2			
Q601 upstream	IQC020			7			
Q603 upstream	IQB067			2			
Q605 upstream	IQB323			2			
Q607 upstream	IQB162			30			
Q609 upstream	IQC013			200			
Q611 upstream	IQD039			2			
Q613 upstream	IQC032			2			
Q615 upstream	IQC011			5			
Q617 upstream	IQD052			2			
Q619 upstream	IQC014			2			
Q621 upstream	IQB124			50			
Q623 upstream	IQD034			2			
Q625 upstream	IQD044			2			
Q627 upstream	IQB109			15			
Q629 upstream	IQB112			15			
Q631 upstream	IQB310	35	40	200	50	50	16.5
Q633 upstream	IQB096			3			
Q635 upstream	IQB271			2			
Q637 upstream	IQB314	4	5	30	6		
Q639 upstream	IQD008			2			
Q641 upstream	IQD009			2			

2.2 Beam Pipe Alignment Measurements

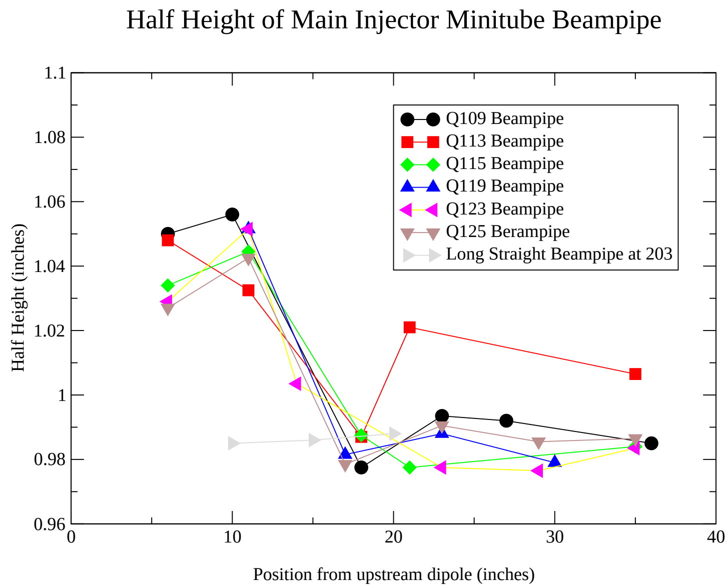


Figure 5: Minitube half heights (external) upstream of defocusing quadrupoles.

Review of the radiation patterns did not immediately suggest any pattern associated with the lattice other than the fact that these localized patterns occur in defocusing halfcells in a regular cell (not is dispersion suppressor nor straight sections). No pattern suggestive of a Beta wave or a dispersion wave was obvious. Since the peak was downstream of a bellows, we considered the possibility that the bellows beam shield had been disturbed. Examination of a failed bellows assembly made it clear that such a failure would be apparent in the tunnel. None of the locations showed the disruption which would have to occur for this to be the source of the problem. In addition, the number of localized radiation problems (more than 20) is inconsistent with bellows installation problems. See Beams-doc-1385[2] for pictures.

Alignment checks were the next obvious option. We organized to employ an alignment crew on June 24 and again on July 7. The alignment crew checked the location of the top of the beam pipe and the quadrupole upstream location for all except the first two locations measured. Results of these surveys are shown on Figures 2, 3 and 4 shown previously and in Figures 8 - 18 which follow. The alignment data were initially analyzed assuming a constant beampipe height but that assumption required a check.

On August 27th, a digital caliper was employed to record the beam tube height at a number of the locations of interest[1]. In Figure 5 the data are plotted. We see that the initial assumption that the pipe would exhibit the two inch dipole gap was to simple. The beam pipe is more than 2.1″ high in the region where the ion pump is attached (a port pointing to the aisle side) and maintains this height as it attaches to the bellows assembly which also has beam pipe about 2.1″ high. Lengths of pipe unsupported and under vacuum are about 0.986″ high (see right-pointing triangles in figure). The transition from the bellows support size to the size unsupported under vacuum occurs in about 6 inches and changes the beam pipe half height by about 0.05 - 0.07″ (1.5 mm). Plots showing the survey analysis with the measured beam pipe height are shown in Appendix A.

2.3 MARS Calculation for Localized Loss

In order to find what level of localized beam loss would result in the observed residual radiation levels, a MARS calculation was performed[2] The beam pipe vertical profile reported above (approximate) was applied to a 2″ diameter, 1.5 mm thick circular pipe. An 8 GeV beam was assumed to be pointlike (zero transverse size), impinging on the top of the pipe where the pipe was lowest. A geometry correction (reduction) factor of 3 for a 1.5-mm thick SS pipe which was determined in a previous calculation was applied. Results are shown in Figure 6. The dose longitudinal profile shows the same features reported above. The calculation predicted that for a rate of 3×10^7 protons/sec for thirty days of exposure and 1 day of cooldown, the residual radiation would measure 300 millirem on contact.

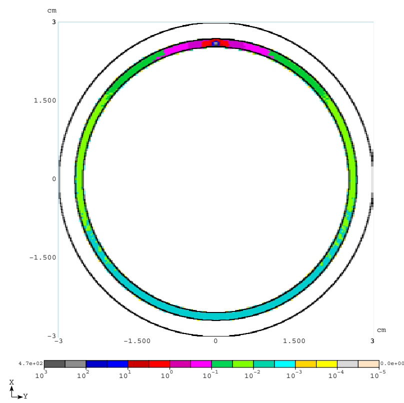
2.4 Main Injector Operation 2004

The Main Injector operated during most of 2004 in a mode where almost all of the protons injected from the Booster were on AntiProton Production (Stacking or $29) Cycles. Using the Programs B87 and the Beam Budget Monitor (BBM), the weekly proton total beam was recorded for the beam injected and the beam on the antiproton production target.[3] See Table 4. We find that about 6×10^{17} protons/week were passing into/through the

[1] Jim Klen used the calipers, Bruce Brown recorded the data

[2] The calculation and graphs were provided by Nicolai Mokhov, Beams Division, Fermilab.

[3] Thanks to Denton Morris, Main Injector Operations Specialist, for documenting these numbers.



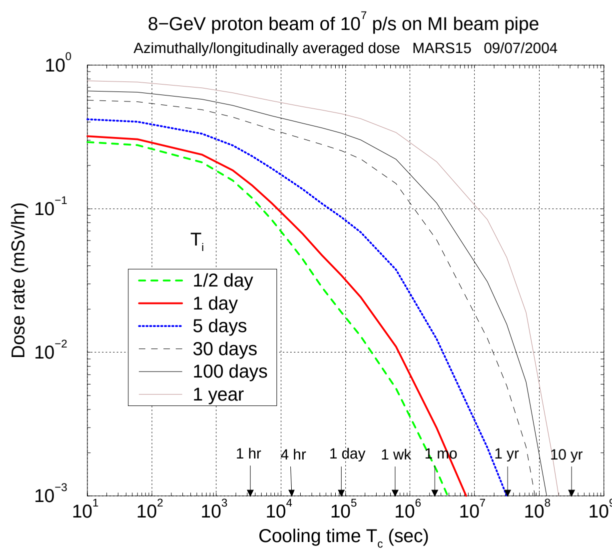


Figure 6: Upper Figure shows residual radiation pattern from MARS calculation of beam interacting at top of a beam pipe. Lower Figure shows the variation of residual radiation for various exposure and cooldown times

	B87 Data	BBM	
	Booster ($14)	AP0 target	
Week Starting	Total protons	M:TOR109	% to target
4-Jun-04	6.89E+17	6.76E+17	98.1
28-May-04	5.53E+17	5.40E+17	97.6
21-May-04	5.90E+17	5.80E+17	98.3
14-May-04	6.29E+17	6.15E+17	97.8
7-May-04	6.19E+17	6.12E+17	98.9
30-Apr-04	4.75E+17	4.70E+17	98.9
23-Apr-04	5.60E+17	5.46E+17	97.5
16-Apr-04	5.71E+17	5.58E+17	97.7
Average	5.86E+17	5.75E+17	
15-Aug-04	3.84E+17	3.31E+17	86.2
8-Aug-04	4.86E+17	4.51E+17	92.8
1-Aug-04	4.99E+17	4.46E+17	89.4
25-Jul-04	6.38E+17	5.98E+17	93.7
18-Jul-04	6.24E+17	5.88E+17	94.2
11-Jul-04	7.44E+17	7.10E+17	95.4
4-Jul-04	6.57E+17	6.39E+17	97.3
27-Jun-04	8.03E+17	7.74E+17	96.4
Average	6.04E+17	5.67E+17	

Table 4: Main Injector Beam in Spring and Summer 2004. The B87 Program recorded the beam accelerated in the Booster and directed to the Main Injector on Stacking ($14) cycles. The Beam Budget Monitor Program reports the beam which hit the AP0 antiproton production target as recorded by the M:TOR109 toroid. The calibration of these has not been carefully checked so the fraction transmitted may not be sufficiently accurate to permit a determination of the losses. This report will only normalize to the weekly averages.

Main Injector. Given 6×10^5 seconds/week, a loss rate of 3×10^7 protons/sec implies a loss of 1.8×10^{13} protons/week which is a fractional loss of 3×10^{-5}. A spreadsheet of these and related observations will be included in this Beams doc location.

2.5 Orbit and Beam Emittance Issues

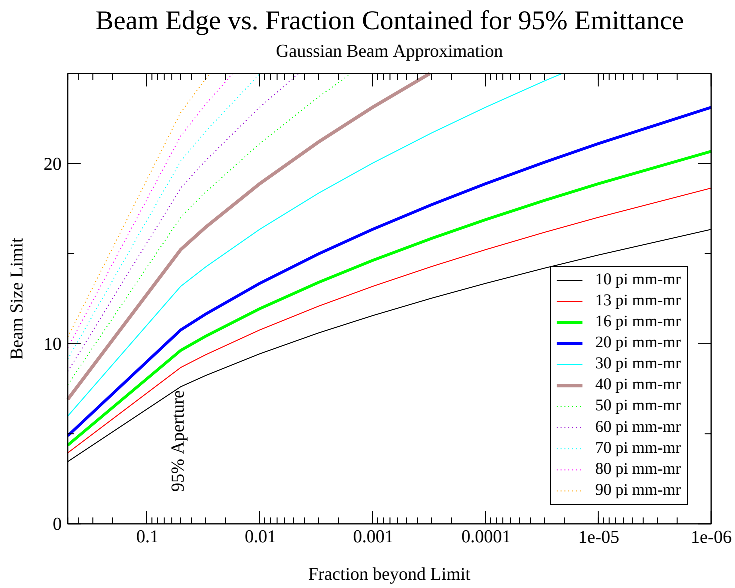


Figure 7: For specified emittance this plot shows the beam size (half height at $\beta_v = 55$ m) which will contain all but the fraction shown on the horizontal axis.

The emittance of the Main Injector beam is measured with flying wires as a part of the Tevatron Shot data. The operation for pbar stacking and other functions is less closely monitored but the size is only modestly different. The normalized beam emittance ϵ_N containing 95% of the beam is given by

$$\epsilon_N(95\%) = \beta\gamma \frac{6\pi\sigma^2(s)}{\beta(s)} \tag{1}$$

where β, γ are the relativistic factors, $\beta(s)$ is the Courant-Snyder envelope function and σ is the RMS beam size. For a Gaussian distribution of beam particles, the number at radius r of the center is given by

$$dN = \frac{N_0}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}}\ r\ dr d\theta \tag{2}$$

while the fraction inside radius a is

$$f = \frac{N}{N_0} = 1 - e^{-\frac{a^2}{2\sigma^2}} \tag{3}$$

We noted above that the MARS calculation predicted an activation of 300 mr for a fractional loss rate of 3×10^{-5}. For a Gaussian beam distribution and a vertical emittance of 16π mm-mr (95%) we would expect 3×10^{-5} of the beam to be at vertical positions larger than 18 mm. The beam pipe under vacuum shows an external height of 24.8 mm at the observed minimum point (see Figure 5). Wall thickness of 1.5 mm leaves 23.3 mm. Typical beampipe misalignments of 1.5 to 2.5 mm leave us with clearance of 20.8 to 21.8 mm. We observe that a combination of closed orbit errors plus injection errors of 3 to 4 mm is sufficient to create the conditions described by the MARS calculation.

Our present observations and understanding do not permit us to disentangle the several possible ways this activation can occur. It may be due largely to the average operating conditions for most pulses. Alternatively, it may be modest deviations (injected beam quality, injected beam steering or closed orbit errors) on an important fraction of the pulses (say 10%) or it might be due to much larger changes of conditions for a very small fraction of the pulses (say 1% or 0.1%). We know that in July/August 2004, only a couple of locations showed losses on the loss monitor for typical pulses which could not be tuned away. Further observation with the existing loss monitor electronics or use of the improved electronics which will be available in the future will allow more understanding of these possibilities.

3 Activation in Other MI Locations

The radiation surveys were inclusive. All of the Main Injector beam pipe was examined and residual radiation recorded at locations with more than 10 - 20 millirem on contact. (the lower level for recording was not precise. Some locations with lower radiation were recorded to examine patterns while some locations with levels between 10 and 20 mr were documented.) A spreadsheet is being kept which will document these and a series of future contact radiation surveys. A snapshot of this spreadsheet will be stored with this document. There are some patterns which we will discuss in this section.

3.1 Activation at F Quad Locations

The focusing quadrupoles exhibited many fewer activation issues. The issues which were noted were at the downstream end. Since (almost) all quadrupole have beam position monitors inserted into their downstream end and many have sextupole magnets immediately downstream, the LSM meters are too large to be able to reach the beam pipe at many quadrupole downstream locations. For this reason, the observations we can make are cruder than for the bare beam pipe issues. However, in the June survey, we did observe that there are a group of quadrupoles in the MI400 sector which are 30 to 150 millirem one contact or at the location where we could insert the probe. These typically show there highest residual radiation on the radial inside (aisle). Locations include Q404, Q408, Q410, Q416, Q418, and Q426. We also see the same sort of issues at Q626 and Q634, Q114 and Q302. In August we noted similar effects at Q504 and Q512.

In seeking an explanation for these activation issues, the list was examined by Bob Webber to look for correlations with BPM sensitivity as measured by the BPM calibration. It is assumed that if the BPM geometry is wrong by more than a millimeter or so, there would be a sufficient effect on the calibration (but we have not calculated our sensitivity). These BPM's do not show a substantially different calibrated response so we must look elsewhere for an explanation of the higher radiation in these locations.

3.2 Activation at Lambertson Locations

The aperture for beam transmission in the Main Injector is primarily limited at the beam transfer and extraction points because the transfer of beam requires beam through both the field-free and bending regions of the Lambertson while each beam must pass through the quadrupole. The distance required by the bend available from the Lambertsons is not available in free straight sections given the FODO design of the lattice (no long straight sections). As a result, the circulating beam as well as the transfered (or extracted) beam must be separated by the septum width, yet remain in the aperture of a quadrupole which is placed between adjacent ILA-style Lambertsons at each of the high field transfer location (MI400, MI520, MI602, MI620). The Lambertsons for the low field transfers must be adjacent to a quad but each is a single magnet so the quad is not included between two Lambertsons at MI101, MI221, MI321. These aperture restrictions result in activation at some of these Lambertson locations. Beginning in November 2003, December 2003 and March 2004, some of these locations were examined for residual radioactivity. The June and August surveys included monitoring which may become a basis for long term activation monitoring of the ILA-style Lambertsons. We will continue to develop long term monitoring for the other transfer locations.

The measurements at ILA Lambertsons includes measurements at the beam pipe or more typically at the bellows radius on top, bottom, aisle and wall. These are supplemented by measurements on the side of the magnet, adjacent to the upstream side of each ion pump. With 4 pump locations per Lambertson and 3 Lambertson magnets at each location, a detailed map of the activation is possible. Radiation levels are higher at both the upstream and downstream ends of the Lambertson string with lower levels observed at interior points. For the August 2004 survey, the highest of the measurements at MI520 was 800 millirem while at MI400 it was 200 millirem on contact at the upstream pump. Beginning with the August survey, a separate worksheet was added to record the Lambertson pump measurements.

3.3 Miscellaneous Activation Issues

Attempts to understand alignment issues from aperture scans have not yet revealed any results but the radiation survey found several additional alignment problems. These were addressed during the Fall 2004 Facility Shutdown.

The Beam Valve at 301 was misaligned. It had been attached to an angle bracket which should have provided 90^o but did not. As a result, the beam pipe was misaligned.

Residual Radiation	At Upstream Weld	At Downstream Weld
Top	200 mr	150 mr
Bottom	40 mr	500 mr

The valve was removed and a properly aligned valve inserted.

A 30 l/s vacuum pump was installed in an unsupported section of beam pipe downstream of Q521. It was too low and the top of the pipe was 200 mr in June and 1500 mr in August. It was realigned. Another 30 l/s vacuum pump just downstream of the NuMI Lambertson's at MI608 is just below the NuMI 'C' Magnet. It was greater than 2000 millirem on contact in August. It was also realigned.

4 Summary

Examination of the residual radiation patterns is the Main Injector found a few patterns:

- Expected loss points at Lambertsons were documented.
- A pattern of losses in the Minitube upstream of defocusing quadrupoles was documented. The activation was at a point where vacuum forces

have reduced the vertical acceptance. The points which were radioactive were found to have pipe which were not straight. They were low by typically 1.5 to 2.5 mm. Radiation levels suggest that the loss is from tails of the beam. Beam pipe alignment during the Fall 2004 Facility Shutdown is expected to change the pattern of these vertical tail losses.

- A few locations show activation of the downstream end of focusing quadrupoles. We do not have an understanding of these losses.

- Some locations with misaligned beam pipe were found and realigned.

5 Conclusions

The most significant conclusion we reach for the vertical aperture and alignment of the Main Injector is that the design, installation and alignment have met their goals of 40π mm-mr acceptance. For our locations with beta = 55 m, this demands a half-aperture of about 15 mm (95% beam size). We observe that the vertical loss points, while more common near injection (MI105, MI109...), extend all the way to MI631 and MI637 but with no extraordinary misalignment at these points we note that beam tails are circulating all the way around the Main Injector. The comparable statement about horizontal acceptance is not so cleanly supported with this study but is also not contradicted.

We find that for rather modest fractional losses (3×10^{-5}), radiation levels of 300 mr on contact can be created locally. Levels above 2000 mr on contact have been found despite operation at only 6×10^{17} protons/week. Operation at about 5 times this level is expected soon. We attribute much of this activation to losses from the tails of the beam.

Collimation to reduce the tails of beam sent from the Booster may be significant in avoiding activation of the Main Injector tunnel. The MI8 Transfer Line has space which is well suited for several steps of collimation. We expect to implement such a system. If this is not sufficient, collimation in the Main Injector may be required. Collimation in the vertical plane can probably be placed in the region near the RR transfer lines where beam transfer is radial. Radial collimation is more difficult to site. Efforts are underway to explore these options so that design efforts can proceed in case collimation in the MI8 line is not sufficient.

The radiation survey and beam acceleration history data have been entered into spreadsheets. These files will be included in the Beams Document database along with this report.

The first five years of MI operation have provided few challenges with regard to activation of the tunnel. This NuMI Era will be different. This document represents an initial step to begin monitoring the beam accelerated and beam lost as well as the associated activation. We will need to learn what issues are important. The minitube locations examined in this note may not be significant problems since the loss point is localized (radiation at 30 cm is not high yet) and the required occupancy is expected to be small (nothing to break). The Booster suffers from limited aperture in the RF cavities which are items which demand lots of work. The MI RF cavities have large apertures and they have remained at very low activation levels. What areas will remain as significant problems? The Lambertson locations are being addressed by the large aperture quad program but even without that, they should not require extensive maintenance. What locations should be most stringently monitored remains to be discovered.

A MiniTube Alignment Results

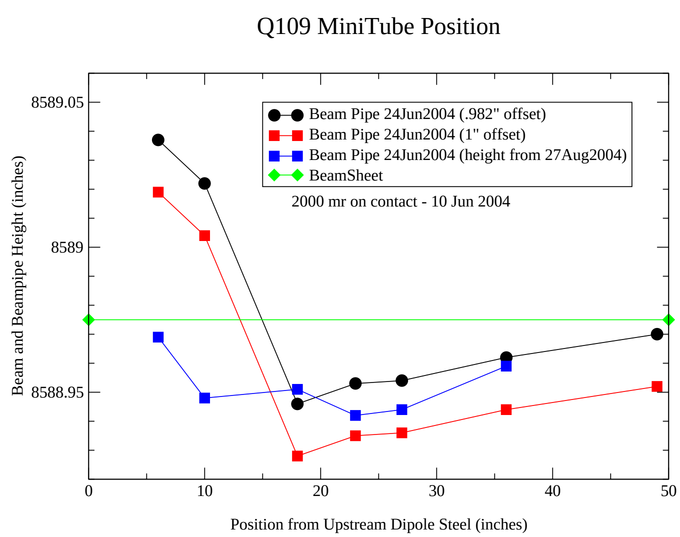


Figure 8: Alignment of Minitube upstream of Q109. Results assuming a constant pipe half height are shown in black and red. Results shown in blue use the measured beam tube half height. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

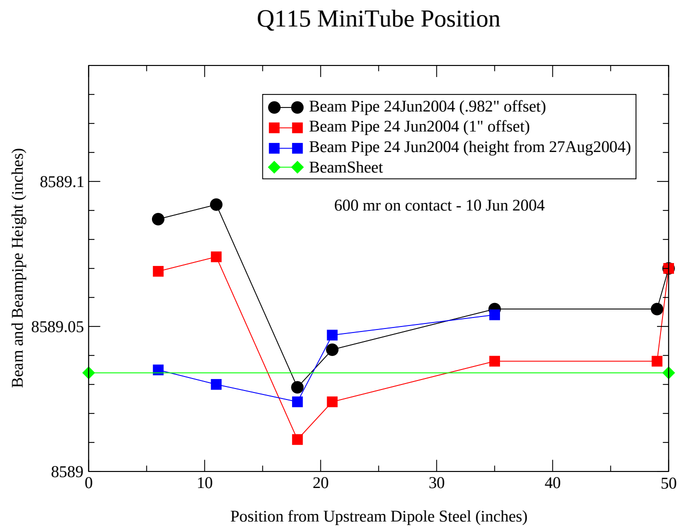


Figure 9: Alignment of Minitube upstream of Q115. Results assuming a constant pipe half height are shown in black and red. Results shown in blue use the measured beam tube half height. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

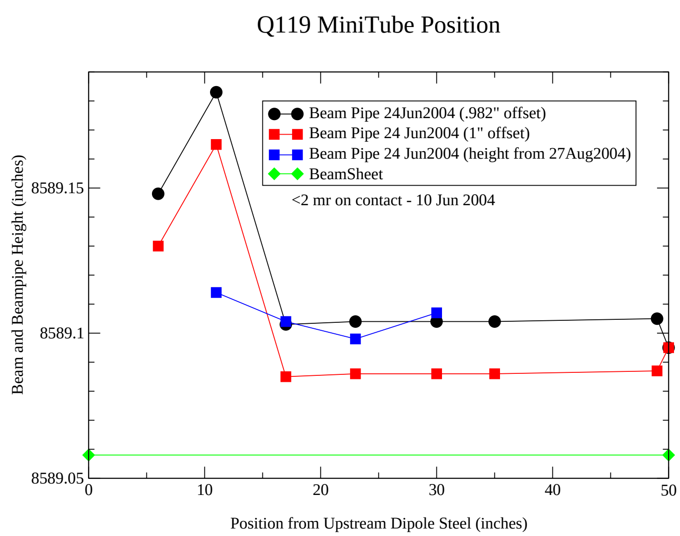


Figure 10: Alignment of Minitube upstream of Q119. Results assuming a constant pipe half height are shown in black and red. Results shown in blue use the measured beam tube half height. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

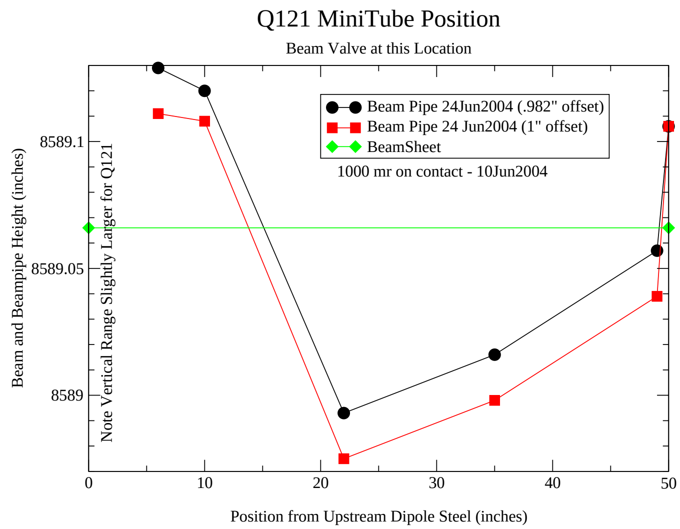


Figure 11: Alignment of Minitube upstream of Q121. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

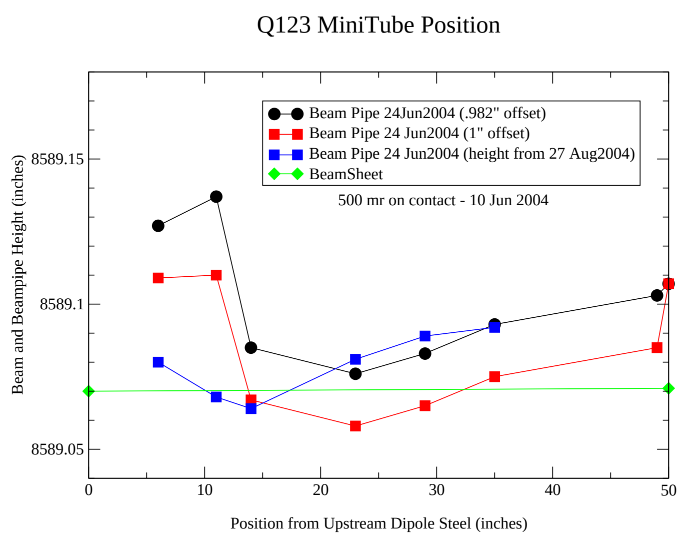


Figure 12: Alignment of Minitube upstream of Q123. Results assuming a constant pipe half height are shown in black and red. Results shown in blue use the measured beam tube half height. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

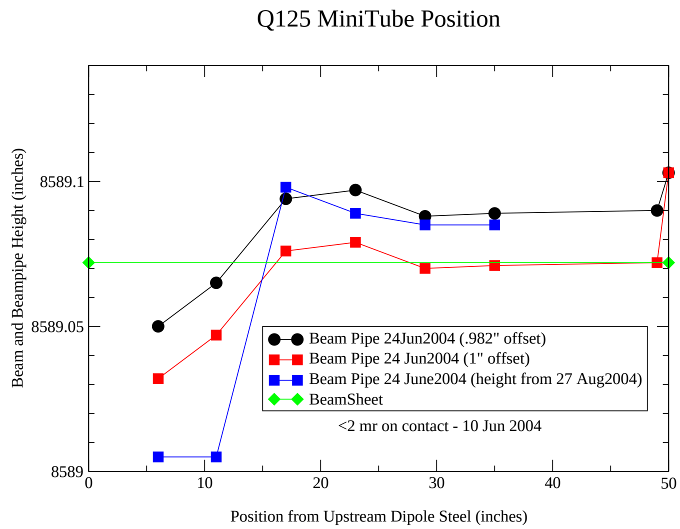


Figure 13: Alignment of Minitube upstream of Q125. Results assuming a constant pipe half height are shown in black and red. Results shown in blue use the measured beam tube half height. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

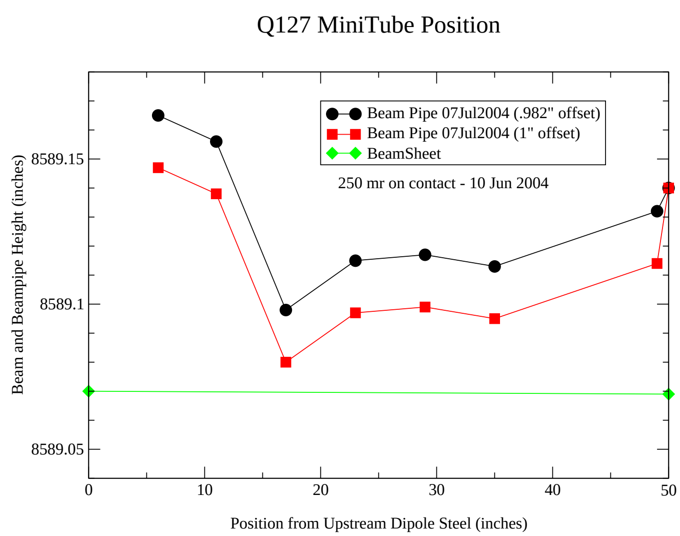


Figure 14: Alignment of Minitube upstream of Q127. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

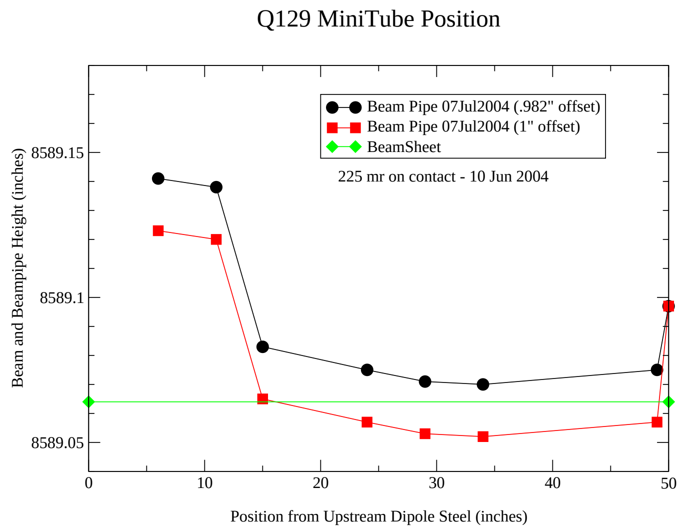


Figure 15: Alignment of Minitube upstream of Q129. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

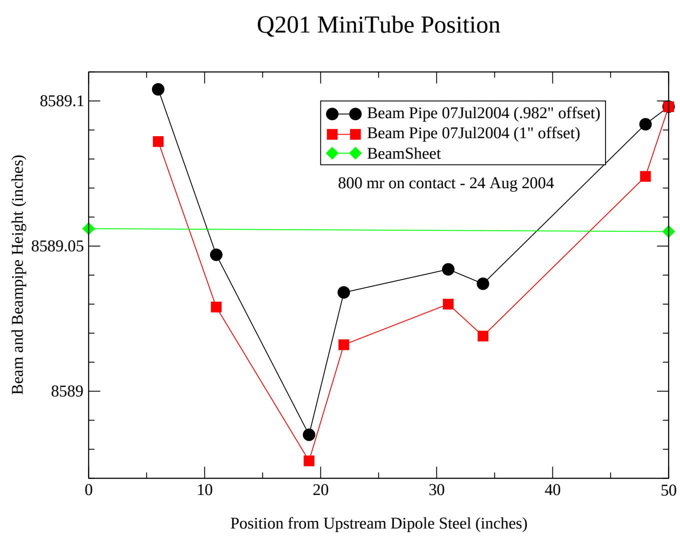


Figure 16: Alignment of Minitube upstream of Q201. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

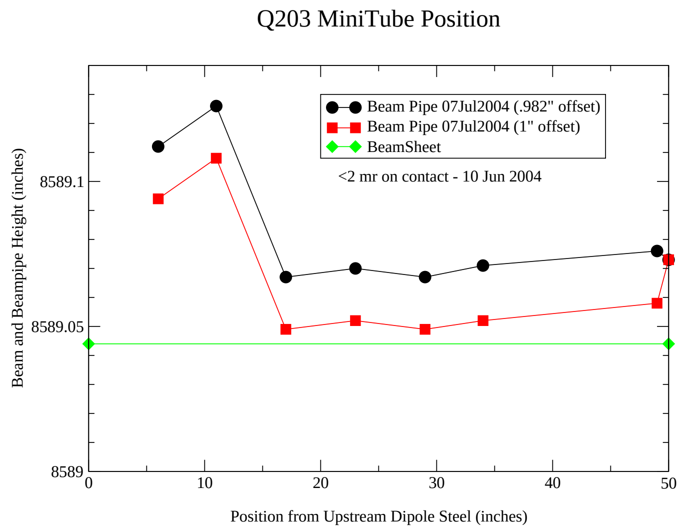


Figure 17: Alignment of Minitube upstream of Q203. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

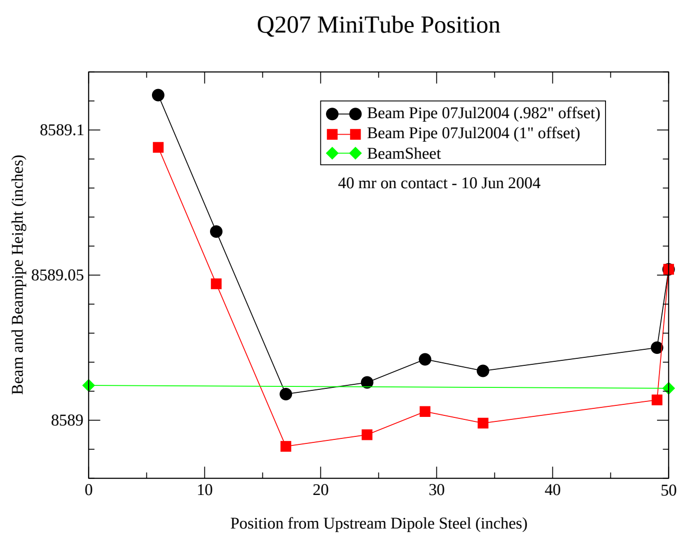


Figure 18: Alignment of Minitube upstream of Q207. Results assuming a constant pipe half height are shown in black and red. Expected Dipole and Quadrupole elevations from the Main Injector Beam Sheets are shown in green.

Alignment Crews checked the location of the beam pipe at the upstream minitube in eight Defocusing Quadrupole locations on June 24, 2004 and an additional six on July 7, 2004[4] The measurements were referenced to the tunnel wall elevation markers for the halfcell. Analysis used the current reference positions for these markers which were most recently updated based on surveys in 2001. The reference position for the dipoles and quadrupoles are documented in the Main Injector "BeamSheet" which shows the desired position for installation in the 1996 - 1998 era. In Figures 2 - 4 and 8 - 18 this alignment data is plotted. Locations with low residual radiation were included in the sample.

B Photographs of Radiation Damage

Figure 19: Image of upstream minitube at Q113 showing radiation damage to tape.

The MiniTubes provide a readily available open place for climbing in the tunnel. I believe it is an 'urban myth' that the Recycler Ring installation involved many occurrences of people stepping on the minitubes. I think that the likely explanation for the fact that the tubes are no longer straight is

[4] June 24 Crew: Glenda Adkins and Randy Wyatt with Bruce Brown accompanying; July 7 Crew: Gary Teafoe, Glenda Adkins and Randy Wyatt with Bruce Brown accompanying. Analysis by Babatunde Oshinowo.

Figure 20: Image of upstream minitube at Q129 showing radiation damage to tape.

Figure 21: Image of upstream minitube at Q321 showing radiation damage to tape.

Figure 22: Image of upstream minitube at Q401 showing radiation damage to tape.

due to the stress relieving after being shoved through a quad with less than fully adequate aperture. In any case, the tunnel installation includes a tag on each minitube which requests,

FRAGILE
NO STEP

and these tags provide a visual representation of the beam loss. The are usually discolored where the radiation is high, not discolored where it is low and the image reveals a band indicating the limited horizontal extent of the beam. At Q321, the offset due to the requirement that the beam reach the off-centered field free region of the Lambertson is quite apparent (in the tunnel if not in the picture). Figures 19,20, 21 and 22 were photos taken in Summer 2004.

References

[1] Eric Prebys et. al. Proton Plan. Beams Doc 1441, Fermilab, November 2004.

[2] Bruce C. Brown. Pictures of a Good and a Failed Main Injector Bellows. Beams Doc 1385, Fermilab, September 2004.