EP note 6

# Environmental Protection Note No. 6

# Calculation of Dose Equivalents due to Offsite Muons for Calendar Year 1991

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## Introduction

The determination of dose equivalents due to Fermilab operations at offsite locations has always been an important part of the environmental monitoring program of the Laboratory. This program includes the measurement of muon radiation patterns near the site boundary and the estimation of both individual and population doses resulting from operating the fixed target experimental program. The results obtained during previous years have been formally documented in the annual Site Environmental Reports and their predecessor document, the annual Environmental Monitoring Reports. Other publications describing the methods of measuring the muon radiation fields have also been generated.[1-12] The purpose of the present note is to present the results of the measurements of muon dose equivalent at the Fermilab site boundary during Calendar Year 1991 and describe in detail the method of estimating the population dose at more distant locations due to these muons. For purposes of this note, the entirety of the CY1991 fixed target run is included in the results. Approximately 5 % of fixed target beam operations, as measured by the integrated Tevatron beam intensity delivered to the experimental areas, occurred during the first few days of January, 1992. This small fraction of the delivered beam is included as part of the calculated dose equivalents for CY1991.

## Summary of Site Boundary Muon Measurements

As described in several of Refs. 1-11 (in detail in Refs. 4, 5, and 9), the muon fields near the Fermilab site boundary are conventionally measured by use of scintillation counters mounted in the Mobile Environmental Radiation Laboratory (MERL). The raw data consists of measurements of the normalized muon fluence (muons/cm$^2$ per 1 X $10^{12}$ protons) obtained during scans transverse to the muon trajectories. These data are based on average counts (background-corrected) in each of two plastic scintillation paddles; the ratio of coincidence to singles counting rates vary from 0.2 to 0.6 at site boundary locations. This ratio depends on the direction and divergence of the muons incident on the paddles. It will be unity for a broad beam parallel to the horizontal. The conversion factor for converting integrated fluence to dose equivalent has been determined by G. R. Stevenson to be independent of energy over a wide range;[13] its value is 1 mrem per 25,000 muons/$cm^2$.

The only significant muon radiation fields produced by Laboratory operations occur to the northeast of the site. These fields follow the extension of the fixed target primary beamlines since the production of energetic muons is kinematically restricted to forward angles relative to the direction of primary protons incident on a given production target[§]. Measurements conducted during the fixed target physics program, which operated from June, 1991 through the first few days of January, 1992 found significant muon fields (in terms of instantaneous flux density) at the site boundary originating from three beamlines: MW, MC, and NM. (The MP beamline, a significant source of muons during CY1990 was inactive as a recipient of primary protons from the accelerator during 1991). Three other beamlines produce barely detectable muons at the site boundary: PW, PE and PB. Operational conditions for most of these beamlines were much the same as those which existed during the 1987-1988, and 1990 fixed target run described in Ref. 8 and 12. For most of the data, the reproducibility of the major features of the results for the three running periods was quite good.

Figure 1 is a site map which shows the location and directions of these seven beamlines. Since vehicular accessibility is required to actually make the measurements, Roosevelt Road (Route 38, slightly outside the site boundary) is the most convenient place to perform site boundary scans. Fortuitously, it also provides opportunity to make scans of the muon radiation pattern transverse to their trajectories. Results were obtained at this location for all of the beams except for NM and these measurements form the basis of the offsite dose determinations. For the NM beam, measurements were made at the Power Line Road just inside the site boundary.

For the Meson Area beams and the NM beam, the most relevant fluence measurements obtained in the vicinity of the site boundary are shown in Figs. 2 and 3. The results for MW represented by the solid squares in Figure 2 are normalized net fluence based on the subtraction of MC data obtained on January 2, 1992 from measurements performed on November 8, 1991 when MW and MC beams were both in operation. On Fig.3, the 1991 results for NM are compared with those for 1990. Figure 4 shows the fluence associated with Proton Area beams. The measurements at Eola Road (well <u>within</u> the Fermilab site) indicate that both PE and PB contribute

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[§]Another possible source is the aborts at C0. In a measurement conducted in February of 1988 and documented in a memorandum from Alex Elwyn to Sam Baker dated March 18, 1988, it was reported that at the service road parallel with Butterfield Road, results at 400 GeV were consistent with zero muon flux density. At the same location, which is about 1.06 miles from the C0 abort, a value of $(2.0 \pm 0.8) \times 10^{-7}$ mrem per $10^{12}$ protons was found for 800 GeV protons. During 1991, $1.52 \times 10^{17}$ 800 GeV protons were aborted at C0 resulting in an insignificant offsite muon dose of 0.03 mrem.

to the fluence while the fluence for PW can only be measured as an upper limit and PC gives only a hint of a measurable muon fluence. Moreover, at the site boundary location, Route 38, there is only scant evidence of muons from PE and PB as well. Only an upper limit for the muon fluence at Route 38 due to PW was established.

Near the site boundary, the terrain is relatively flat. The muons are expected to have relatively high momenta (tens of GeV/c) so that attenuation due to multiple scattering in air and muon decay should be small. Therefore, muon flux density should obey an inverse square law dependence as a function of the distance from their "source". As was discussed in Ref. 12, the inverse square law dependence is reasonable at locations near the Fermilab site boundary for all but Proton Area beams, for which values of muon fluence fall faster with distance than $1/Z^2$, where Z is measured from the appropriate source locations for each beam line. In what follows, the inverse square dependence is used to extrapolate (or interpolate) to the actual site boundary from the location at which measurements were performed.

Table 1 lists, by beamline, the results of measurements in spreadsheet form (Microsoft Excel™) and tabulates conversion to muon dose equivalent at Route 38 and at the actual site boundary location. These data form the basis of the worst case dose scenarios and offsite population dose assessment. Data for PW is based on the upper limits obtained from the measurements made during the 1991 run. During 1991, MW operated in a number of different running modes. In one mode, the beam was configured to produce 530 GeV $\pi^+$'s for transport to the physics experiment by having the primary protons interact with a thin target (10 per cent of the protons interacting). In this mode an average peak fluence of 0.33 $\pm$ .015 muons/cm$^2$ per 1 X $10^{12}$ protons resulted at Route 38. At total of 3.9 X $10^{16}$ protons were delivered in this mode. In other modes, the beam was configured to produce either 530 GeV $\pi^-$'s or $\pi^+$'s from the collisions of the primary protons with a one-interaction length target. These particles were then transported to the experiment. Under such conditions a peak fluence of 0.70 $\pm$ .07 muons/cm$^2$ per 1 X $10^{12}$ protons resulted at Route 38. At total of 5.4 X $10^{16}$ protons were delivered under these circumstances. In a third mode, attenuated primary protons were delivered to the experiment. In this mode no detectable muon fluence resulted at Route 38. At total of 2.7 X $10^{16}$ protons were delivered in this mode. Thus the values for MW tabulated in Table 1 correspond to weighted averages over the two operating modes which produced muons. The columns in the spreadsheet are described as follows:

Column B is the Z-value of the location where the measurements nearest to the site boundary were done. For all but NM, this is Route 38. For NM this value is for the Power Line Road.

Column C is the measured peak value of the fluence in units of muons/$cm^2$ per $10^{12}$ incident protons as measured using the MERL.

Column D is the full width at half-maximum (FWHM) of each distribution at the measurement location.

Column E is the integrated proton beam intensity for each beam during 1991 as recorded by the Secondary Emission Monitors (SEMs) logged by the Research Division. (With the single exception noted above for MW.) The SEMS are calibrated in collaboration with the Environment, Safety, and Health Section using the facilities of the Activation Analysis Laboratory.

Column F is the Z-value at the site boundary for the given beamline.

Column G is the integrated dose equivalent during 1991 at the site boundary for each beam using the peak fluence, the integrated proton intensity, the dose conversion factor described above, and the $1/Z^2$ dependence to correct from the measured peak value to an estimate at the actual site boundary.

Column H is the standard deviation ($\sigma$) of each distribution at the site boundary, approximating the distribution with a Gaussian. It is obtained from the FWHM (i.e., $\sigma$ = FWHM/2.35) at the point of measurement, assuming a linear dependence with Z.

Column I is the Z-value at Route 38.

Column J is the integrated dose equivalent during 1991 at Route 38. Note that the value for NM is obtained from the measurement at the Power Line Road assuming the $1/Z^2$ dependence.

Column K is the standard deviation of the distribution at Route 38. Four times this value is the full width used to define the areas of population exposure due to the muons from these beamlines. This value is also useful in determining the degree of overlap from the various muon fields.

Column L is the location of the muon peaks measured from the intersection of Town Road with Route 38. (If Z is along the beam, then the X coordinate is essentially along Route 38).

Column M is the angle east of geographic North of the line determined by the peak value of the muon flux density at Route 38 and the source.

As observed in this Table, all beamlines produced peak off-site dose equivalents below the 10 mrem/year Fermilab guideline set by the Laboratory Director. The largest value at the site boundary value for any beamline (approximately 7.2 mrem found for NM) represents about 2.5 per cent of the natural background dose equivalent of 300 mrem (including the recently identified effects of indoor radon) to the average U. S. resident.[14] From this Table and Fig. 1 it is clear that the muon patterns do not have significant overlaps nor do they cross each other. There are no residences near the Fermilab site boundary. This reduces the probability that any one individual actually received even this much dose equivalent. Comparison with results obtained in previous years can be made. The worst case dose equivalent during 1987 was 13 mrem[15] while the same quantity in 1988 was 1.2 mrem[16]. In those years, the beamline producing the highest offsite muon fluence was NM. The lack of fixed target operations in 1989 resulted in no exposure during that year[17]. During 1990, the largest dose at the site boundary was due to MW and had a value of 16 mrem.[12] The worst case muon fluence averaged over the last 5 years is thus about 7.5 mrem at any offsite location. These locations vary and are dependent on the configuration of the physics research program. Clearly, the average peak offsite dose equivalent due to muons is less than 10 mrem/year. The year-to-year fluctuations are thus due to the changing requirements of the experimental physics program.

**Population Dose Equivalent Due to the Muon Radiation Fields**

The normal environmental monitoring program includes the assessment of effective dose equivalent to the population due to U. S. Department of Energy operations. The results of these assessments are published in the annual Site Environmental Reports. This has been done for muons produced during fixed-target operations at Fermilab. The muons of concern are those which leave the site parallel with the ground. Those which enter the earth are ranged out while those emitted upward at significant angles are likewise of no concern since there are no tall buildings or mountains in the immediate vicinity of Fermilab. The elevation above sea level at the NE corner of the Fermilab site is 745-750 feet. To the northeast of the site, in the general direction followed by the muons, the elevation gradually rises to approximately 800 feet above sea level at a distance of 5 miles from the center of the site. Within the first 20 miles, the elevations rise to no more than approximately 900 feet above sea level. Elevations beyond that distance are generally lower as Lake Michigan is approached. At a distance of 20 miles, muons which were traveling horizontally at the site boundary are found 270 feet above the typical surface elevation of 750 feet (and thus about 120 feet above the surface at the point of highest elevation of 900 feet) due to the curvature of the Earth. Thus they are not a feasible source of dose equivalent to people.

However, the Earth's curvature has not been included in the calculations done here; we, in effect, assume a flat Earth. The consequences of this assumption are insignificant compared with other errors in the assessment.

The calculation of population dose equivalent due to these muon fields consists of the determination of the intensity distribution and the direction and width of the muon cone at the site boundary. These values are listed in Table 1. For offsite locations, the muon distributions are taken to be Gaussians. As can be seen from the measured distributions (Figs. 2, 3, and 4), this is an approximation more accurate for some beams than for others. However, it is a conservative choice in all cases if the peak value is taken to be the peak of the Gaussian and the FWHM is measured by ignoring "spikes" such as are seen in the pattern due to some beams (e.g., MW). In other words, the FWHM is taken to include both of the MW spikes (see Fig. 2) which are found to be superimposed on an otherwise rather flat distribution. Thus, if the peaks are assumed to be Gaussians, the area within $\pm 2\sigma$ of the peak includes 95 % of the muons and is a good approximation to the total muon fluence.

In the calculation of population dose equivalent, we need the average muon intensity within a full width of $4\sigma$ at each longitudinal distance Z for points beyond the site boundary. To simplify this calculation, the assumed Gaussian distribution at Route 38 is replaced by a rectangular one of width $4\sigma$. The height of the rectangle, which represents the average muon fluence, is obtained by setting the area equal to the area of the Gaussian distribution taken from $-2\sigma$ to $+2\sigma$. This prescription gives a value of $[0.95 \text{ X } (2\pi)^{0.5}]/4 = 0.6$ times the Gaussian peak height for the average muon intensity. For other offsite locations, the width of the distribution relative to that at Route 38 is assumed to increase linearly with Z and the average intensity relative to that at Route 38 is assumed to scale as $1/Z^2$, where Z is measured from the source.

Figures 5 and 6 display the 1980 population distributions in the vicinity of the laboratory, binned in sectors originating from the center of the Tevatron. (These are shown as a guide, since corresponding figures which show 1990 U. S. Census data were not available at the time of the preparation of this report. In the tabulations which form the basis of the actual calculation, 1990 U. S. Census data as prepared by Oak Ridge National Laboratory are used.[18]) It is clear that the directional information of the muons and this population data can be used to determine the population dose equivalent due to the muons. Obviously, only the NE and NNE sectors are in the path of these muons.

Table 2 presents the calculation of the population dose in spreadsheet (Microsoft Excel™) form. At the bottom of page 1 of this Table are listed the inner and outer population bin boundaries (rmin and rmax), the computed area* of these bins in $mi^2$, the 1990 U. S. Census values for the population within them for the two sectors of concern, and the population densities (per $mi^2$) computed here. In the upper part of the table are displayed the population dose calculations. The contents of each column are described below:

Column B is the Z-value at Route 38.

Column C is the peak dose equivalent in mrem received at Route 38 as determined above.

Column D is the standard deviation of the muon distribution transverse to the muon trajectories at Route 38.

Column E is the mean dose equivalent delivered within the width ($\pm 2\sigma$) taken for purposes of this estimate at the Route 38 reference location.

For the remainder of the table, the different rows under each beamline correspond to values pertinent to the population zones being traversed by the muons starting with the first one encountered at the site boundary and extended out to a 50 mile radius from the Tevatron center.

Column F is the distance of the point where the trajectory enters a given population zone from the Route 38 for a given beamline.

Column G is the distance of the point where the trajectory leaves a given population zone from the Route 38 for a given beamline.

Column H is the path length of the muons within a given population zone.

Column J is the area of the given population zone exposed to the muons from the given beamline. It is computed by multiplying the width (4 standard deviations) at the center of the trajectory within the zone times the path length in the zone.

Column K is the average dose equivalent within the bin. Since the $1/Z^2$ dependence is being used here, the average within a population bin corresponds to that found at the geometric mean of the values listed in Columns F and G.

Column L is the population density of the appropriate bins from the other part of the chart. The MW, MC, and MP distributions are entirely contained within the NNE sector while the other four beamline muon distributions cross from the NNE sector to the NE one. This is taken into account in the chart.

*For the 2- 3 mile bin, approximately 1/6 of the area is within the Fermilab site and thus contains no residences. Hence, the tabulated areas for these bins is taken to be 1/6 of that bin.

Column M is the number of exposed people taken as the product of the population density and the exposed area.

Column N is the population dose determined as the product of the entries of columns K and M.

Column O is a summation of the population doses for each of the beamlines. The grand total of population exposure is listed at the bottom of this column.

Column P is a summation of the total number of people potentially exposed to muons from each beamline. The grand total of people potentially exposed people is listed at the bottom of this column along with average dose equivalent per exposed person.

Thus, the result of this assessment is that a total collective population dose equivalent of 6196 person-mrem was distributed over an estimated 467,695 persons. The average dose equivalent to exposed person was, then, 0.013 mrem. As mentioned above, natural background (including the newly-recognized significant contribution of indoor radon) results in an average dose equivalent of approximately 300 mrem to each person in the United States[14]. Thus the estimated 467,695 people potentially exposed to the muons would receive a dose of $1.4 \times 10^5$ person-rem from natural background. Hence, the Fermilab muons result in an insignificant increment in the total population dose equivalent of 0.0044 per cent. By comparison, in 1987, 1988, 1989, and 1990 the population effective dose equivalents were 2.0, 0.6, 0.0, and 4.9 person-rem, respectively.[15,16,17,12] A major portion of the increase from 1990 to 1991 may be attributed to the increase in population in this rapidly growing suburban area in the last decade as recorded by the detailed results of the 1990 U. S. Census. Much of this rapid growth has occurred in the vicinity of the Fermilab site. The distribution of the population exposure among the various beamlines may be of interest in the planning of future operations.

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Figure Captions:

Figure 1 Map of the vicinity of the Fermilab site showing the locations of the seven beamlines that have been identified to have measurable offsite muon fluences when they are operational. The 22.5 degree sectors used for determining population dose are also shown on this figure and are labeled according to compass direction (N, NNE, NE, etc). These sectors have their origin at the center of the Tevatron.

Figure 2 Muon fluence measurements for the Meson Area beams MW and MC measured at Route 38 during the 1991 fixed target run.

Figure 3 Muon fluence measurements for the NM beam measured at the Power Line Road during the 1991 fixed target run.

Figure 4 Muon fluence measurements for Proton Area beams PE and PB measured at Eola Rd and for PB measured at Route 38 during the 1991 fixed target run.

Figure 5 Residential population distribution in the vicinity of Fermilab based on the 1980 U. S. Census. The populations have been grouped in bins as indicated within 22.5° sectors originating from the center of the Tevatron. The numbers displaced on the plot are the residential population of a given bin. The labeled rays indicate the muon trajectories due to the corresponding Fermilab beamlines.

Figure 6. Residential population distribution within 50 miles of Fermilab based on the 1980 U. S. Census. The populations have been grouped in bins as indicated within 22.5° sectors originating from the center of the Tevatron. The numbers displayed on the plot are the residential population (in thousands) of a given bin. The labeled rays indicate the muon trajectories due to the corresponding beamlines.

3 miles

5 miles

**Table 1 Calculation of Muon Doses at the Site Boundary and Route 38 During CY1991**

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Beam | Z-measure | u/cm2 | FWHM | # protons | Z-Site. | mrem @ | sigma @ | Z-Rte.38 | mrem @ | sigma @ | X,West of | Angle |
| 2 | | (ft) | per 1E12 | (ft) | | Bnd. (ft) | site bnd. | site bnd (ft) | (ft) | Rte. 38 | Rte. 38 (ft) | Town Rd (ft) | (deg.) |
| 3 | | | | | | | | | | | | | |
| 4 | MW | 10196 | 0.54 | 460 | 9.300E+16 | 7305 | 3.913 | 140 | 10196 | 2.009 | 195 | 4557 | 27.5 |
| 5 | | | | | | | | | | | | | |
| 6 | MC | 10108 | 0.5 | 285 | 2.081E+17 | 7708 | 7.158 | 92 | 10108 | 4.162 | 121 | 4222 | 29.5 |
| 7 | | | | | | | | | | | | | |
| 8 | MP | 10076 | 0.17 | 225 | 0.000E+00 | 8440 | 0.000 | 80 | 10076 | 0.000 | 95 | 3657 | 31.5 |
| 9 | | | | | | | | | | | | | |
| 10 | NM | 5450 | 0.28 | 115 | 5.401E+17 | 6620 | 4.100 | 59 | 7056 | 3.609 | 63 | 1430 | 38.5 |
| 11 | | | | | | | | | | | | | |
| 12 | PW | 10280 | 0.014 | 300 | 1.452E+16 | 9844 | 0.009 | 122 | 10280 | 0.008 | 127 | 1000 | 40.0 |
| 13 | | | | | | | | | | | | | |
| 14 | PE | 10340 | 0.02 | 300 | 2.775E+17 | 9904 | 0.242 | 122 | 10340 | 0.222 | 127 | 400 | 43.5 |
| 15 | | | | | | | | | | | | | |
| 16 | PB | 10260 | 0.03 | 300 | 3.823E+17 | 9769 | 0.506 | 121 | 10260 | 0.459 | 127 | -200 | 45.5 |

**Table 2 CY1991 Population Dose Due to Muons**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | Beam | Z @ Rte. 38 | mrem @ | Sigma @ | Mean Dose | Z-Z(@Rte 38) | Z- Z(@Rte 38) | pathlength |
| 2 | | (ft) | Rte. 38 | Rte. 38 (ft) | in4-Sigma | at inner bnd. | at outer bnd. | in zone (mi) |
| 3 | | | | | (mrem) | (mi) | (mi) | |
| 4 | | | | | | | | |
| 5 | MW | 10196 | 2.009 | 195 | 1.205 | -0.55 | -0.2 | 0.35 |
| 6 | | 10196 | 2.009 | 195 | 1.205 | -0.2 | 0.85 | 1.05 |
| 7 | | 10196 | 2.009 | 195 | 1.205 | 0.85 | 1.85 | 1 |
| 8 | | 10196 | 2.009 | 195 | 1.205 | 1.85 | 6.85 | 5 |
| 9 | | 10196 | 2.009 | 195 | 1.205 | 6.85 | 16.85 | 10 |
| 10 | | 10196 | 2.009 | 195 | 1.205 | 16.85 | 26.85 | 10 |
| 11 | | 10196 | 2.009 | 195 | 1.205 | 26.85 | 36.85 | 10 |
| 12 | | 10196 | 2.009 | 195 | 1.205 | 36.85 | 46.85 | 10 |
| 13 | | | | | | | | |
| 14 | MC | 10108 | 4.162 | 121 | 2.497 | -0.5 | -0.17 | 0.33 |
| 15 | | 10108 | 4.162 | 121 | 2.497 | -0.17 | 0.85 | 1.02 |
| 16 | | 10108 | 4.162 | 121 | 2.497 | 0.85 | 1.85 | 1 |
| 17 | | 10108 | 4.162 | 121 | 2.497 | 1.85 | 6.85 | 5 |
| 18 | | 10108 | 4.162 | 121 | 2.497 | 6.85 | 16.85 | 10 |
| 19 | | 10108 | 4.162 | 121 | 2.497 | 16.85 | 26.85 | 10 |
| 20 | | 10108 | 4.162 | 121 | 2.497 | 26.85 | 36.85 | 10 |
| 21 | | 10108 | 4.162 | 121 | 2.497 | 36.85 | 46.85 | 10 |
| 22 | | | | | | | | |
| 23 | MP | 10076 | 0.000 | 95 | 0.000 | -0.3 | -0.15 | 0.15 |
| 24 | | 10076 | 0.000 | 95 | 0.000 | -0.15 | 0.87 | 1.02 |
| 25 | | 10076 | 0.000 | 95 | 0.000 | 0.87 | 1.92 | 1.05 |
| 26 | | 10076 | 0.000 | 95 | 0.000 | 1.92 | 6.92 | 5 |
| 27 | | 10076 | 0.000 | 95 | 0.000 | 6.92 | 16.92 | 10 |
| 28 | | 10076 | 0.000 | 95 | 0.000 | 16.92 | 26.92 | 10 |
| 29 | | 10076 | 0.000 | 95 | 0.000 | 26.92 | 36.92 | 10 |
| 30 | | 10076 | 0.000 | 95 | 0.000 | 36.92 | 46.92 | 10 |
| 31 | | | | | | | | |
| 32 | NM | 7056 | 3.609 | 63 | 2.165 | -0.13 | 0.9 | 1.03 |
| 33 | | 7056 | 3.609 | 63 | 2.165 | 0.9 | 1.9 | 1 |
| 34 | | 7056 | 3.609 | 63 | 2.165 | 1.9 | 6.9 | 5 |
| 35 | | 7056 | 3.609 | 63 | 2.165 | 6.9 | 16.9 | 10 |
| 36 | | 7056 | 3.609 | 63 | 2.165 | 16.9 | 26.9 | 10 |
| 37 | | 7056 | 3.609 | 63 | 2.165 | 26.9 | 36.9 | 10 |
| 38 | | | | | | | | |
| 39 | PW | 10280 | 0.008 | 127 | 0.005 | -0.12 | 0.9 | 1.02 |
| 40 | | 10280 | 0.008 | 127 | 0.005 | 0.9 | 1.92 | 1.02 |
| 41 | | 10280 | 0.008 | 127 | 0.005 | 1.92 | 6.92 | 5 |
| 42 | | 10280 | 0.008 | 127 | 0.005 | 6.92 | 16.92 | 10 |
| 43 | | 10280 | 0.008 | 127 | 0.005 | 16.92 | 26.92 | 10 |
| 44 | | 10280 | 0.008 | 127 | 0.005 | 26.92 | 36.92 | 10 |
| 45 | | | | | | | | |
| 46 | PE | 10340 | 0.222 | 127 | 0.133 | -0.1 | 0.93 | 1.03 |
| 47 | | 10340 | 0.222 | 127 | 0.133 | 0.93 | 1.93 | 1 |
| 48 | | 10340 | 0.222 | 127 | 0.133 | 1.93 | 6.93 | 5 |
| 49 | | 10340 | 0.222 | 127 | 0.133 | 6.93 | 16.93 | 10 |
| 50 | | 10340 | 0.222 | 127 | 0.133 | 16.93 | 26.93 | 10 |
| 51 | | 10340 | 0.222 | 127 | 0.133 | 26.93 | 36.93 | 10 |
| 52 | | | | | | | | |
| 53 | PB | 10260 | 0.459 | 127 | 0.275 | -0.1 | 0.95 | 1.05 |
| 54 | | 10260 | 0.459 | 127 | 0.275 | 0.95 | 1.95 | 1 |
| 55 | | 10260 | 0.459 | 127 | 0.275 | 1.95 | 6.95 | 5 |
| 56 | | 10260 | 0.459 | 127 | 0.275 | 6.95 | 16.95 | 10 |
| 57 | | 10260 | 0.459 | 127 | 0.275 | 16.95 | 26.95 | 10 |
| 58 | | 10260 | 0.459 | 127 | 0.275 | 26.95 | 36.95 | 10 |
| 59 | | | | | | | | |
| 60 | Population Bin Boundaries: | | | | | | | |
| 61 | rmin | rmax | Area (mi**2) | NNE Pop. | NE Pop. | NNE Pop. | NE Pop. | |
| 62 | (mi) | (mi) | | in 1990 | in 1990 | per mi**2 | per mi**2 | |
| 63 | 2 | 3 | 0.160 | 76 | 296 | 475.0 | 1850.0 | |
| 64 | 3 | 4 | 1.374 | 1924 | 5002 | 1400.5 | 3641.1 | |
| 65 | 4 | 5 | 1.766 | 1433 | 5321 | 811.3 | 3012.6 | |
| 66 | 5 | 10 | 14.719 | 18484 | 33126 | 1255.8 | 2250.6 | |
| 67 | 10 | 20 | 58.875 | 166874 | 113168 | 2834.4 | 1922.2 | |
| 68 | 20 | 30 | 98.125 | 160005 | 357243 | 1630.6 | 3640.7 | |
| 69 | 30 | 40 | 137.375 | 150130 | 107609 | 1092.8 | 783.3 | |
| 70 | 40 | 50 | 176.625 | 154133 | 0 | 872.7 | 0.0 | |

## Table 2 CY1991 Population Dose Due to Muons

| | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|
| 1 | Beam | exposed | Ave Dose @ | Pop. density | No. exposed | Pop. dose | Summed | Summed |
| 2 | | area (mi**2) | in bin | (per mi**2) | people | (pers.-mrem) | pop. dose | exp. pop. |
| 3 | | | (mrem) | | | | (pers.-mrem) | |
| 4 | | | | | | | | |
| 5 | MW | 0.04 | 1.88E+00 | 475.0 | 20 | 37.2 | | |
| 6 | | 0.18 | 9.34E-01 | 1400.5 | 254 | 237.0 | | |
| 7 | | 0.25 | 4.27E-01 | 811.3 | 204 | 87.0 | | |
| 8 | | 2.40 | 1.35E-01 | 1255.8 | 3017 | 408.5 | | |
| 9 | | 10.54 | 2.73E-02 | 2834.4 | 29882 | 814.5 | | |
| 10 | | 18.19 | 8.32E-03 | 1630.6 | 29665 | 246.7 | | |
| 11 | | 25.84 | 4.03E-03 | 1092.8 | 28241 | 113.7 | | |
| 12 | | 33.49 | 2.38E-03 | 872.7 | 29229 | 69.4 | 2014 | 120511 |
| 13 | | | | | | | | |
| 14 | MC | 0.02 | 3.71E+00 | 475.0 | 12 | 44.0 | | |
| 15 | | 0.11 | 1.90E+00 | 1400.5 | 154 | 292.7 | | |
| 16 | | 0.16 | 8.79E-01 | 811.3 | 127 | 111.5 | | |
| 17 | | 1.50 | 2.77E-01 | 1255.8 | 1883 | 522.5 | | |
| 18 | | 6.59 | 5.56E-02 | 2834.4 | 18681 | 1039.6 | | |
| 19 | | 11.38 | 1.70E-02 | 1630.6 | 18555 | 314.6 | | |
| 20 | | 16.17 | 8.21E-03 | 1092.8 | 17668 | 145.0 | | |
| 21 | | 20.96 | 4.84E-03 | 872.7 | 18288 | 88.5 | 2558 | 75368 |
| 22 | | | | | | | | |
| 23 | MP | 0.01 | 0.00E+00 | 475.0 | 5 | 0.0 | | |
| 24 | | 0.09 | 0.00E+00 | 1400.5 | 122 | 0.0 | | |
| 25 | | 0.13 | 0.00E+00 | 811.3 | 106 | 0.0 | | |
| 26 | | 1.19 | 0.00E+00 | 1255.8 | 1499 | 0.0 | | |
| 27 | | 5.22 | 0.00E+00 | 2834.4 | 14782 | 0.0 | | |
| 28 | | 8.99 | 0.00E+00 | 1630.6 | 14653 | 0.0 | | |
| 29 | | 12.76 | 0.00E+00 | 1092.8 | 13942 | 0.0 | | |
| 30 | | 16.53 | 0.00E+00 | 872.7 | 14425 | 0.0 | 0 | 0 |
| 31 | | | | | | | | |
| 32 | NM | 0.06 | 1.43E+00 | 1400.5 | 89 | 127.1 | | |
| 33 | | 0.10 | 5.34E-01 | 811.3 | 79 | 42.4 | | |
| 34 | | 1.02 | 1.45E-01 | 2250.6 | 2305 | 334.5 | | |
| 35 | | 4.73 | 2.57E-02 | 1922.2 | 9087 | 233.9 | | |
| 36 | | 8.30 | 7.51E-03 | 3640.7 | 30213 | 226.9 | | |
| 37 | | 11.87 | 3.58E-03 | 783.3 | 9298 | 33.3 | 998 | 51071 |
| 38 | | | | | | | | |
| 39 | PW | 0.12 | 3.50E-03 | 1400.5 | 165 | 0.6 | | |
| 40 | | 0.17 | 1.65E-03 | 3012.6 | 510 | 0.8 | | |
| 41 | | 1.57 | 5.31E-04 | 2250.6 | 3541 | 1.9 | | |
| 42 | | 6.85 | 1.09E-04 | 1922.2 | 13172 | 1.4 | | |
| 43 | | 11.79 | 3.34E-05 | 3640.7 | 42939 | 1.4 | | |
| 44 | | 16.74 | 1.62E-05 | 783.3 | 13109 | 0.2 | 6 | 73436 |
| 45 | | | | | | | | |
| 46 | PE | 0.12 | 9.52E-02 | 3641.1 | 437 | 41.6 | | |
| 47 | | 0.17 | 4.55E-02 | 3012.6 | 501 | 22.8 | | |
| 48 | | 1.57 | 1.48E-02 | 2250.6 | 3532 | 52.2 | | |
| 49 | | 6.82 | 3.04E-03 | 1922.2 | 13116 | 39.9 | | |
| 50 | | 11.74 | 9.36E-04 | 3640.7 | 42728 | 40.0 | | |
| 51 | | 16.65 | 4.55E-04 | 783.3 | 13041 | 5.9 | 202 | 73356 |
| 52 | | | | | | | | |
| 53 | PB | 0.12 | 1.95E-01 | 3641.1 | 448 | 87.4 | | |
| 54 | | 0.17 | 9.23E-02 | 3012.6 | 506 | 46.7 | | |
| 55 | | 1.58 | 3.00E-02 | 2250.6 | 3562 | 107.0 | | |
| 56 | | 6.88 | 6.19E-03 | 1922.2 | 13223 | 81.8 | | |
| 57 | | 11.83 | 1.90E-03 | 3640.7 | 43070 | 82.0 | | |
| 58 | | 16.78 | 9.25E-04 | 783.3 | 13145 | 12.2 | 417 | 73954 |
| 59 | | | | | | | | |
| 60 | | | | | | Grand Total | 6196 | 467695 |
| 61 | | | | | | | | |
| 62 | | | | | | | Ave Dose per | |
| 63 | | | | | | | exp. person: | 0.013 |
| 64 | | | | | | | (mrem) | |
| 65 | | | | | | | | |
| 66 | | | | | | | | |
| 67 | | | | | | | | |
| 68 | | | | | | | | |
| 69 | | | | | | | | |
| 70 | | | | | | | | |

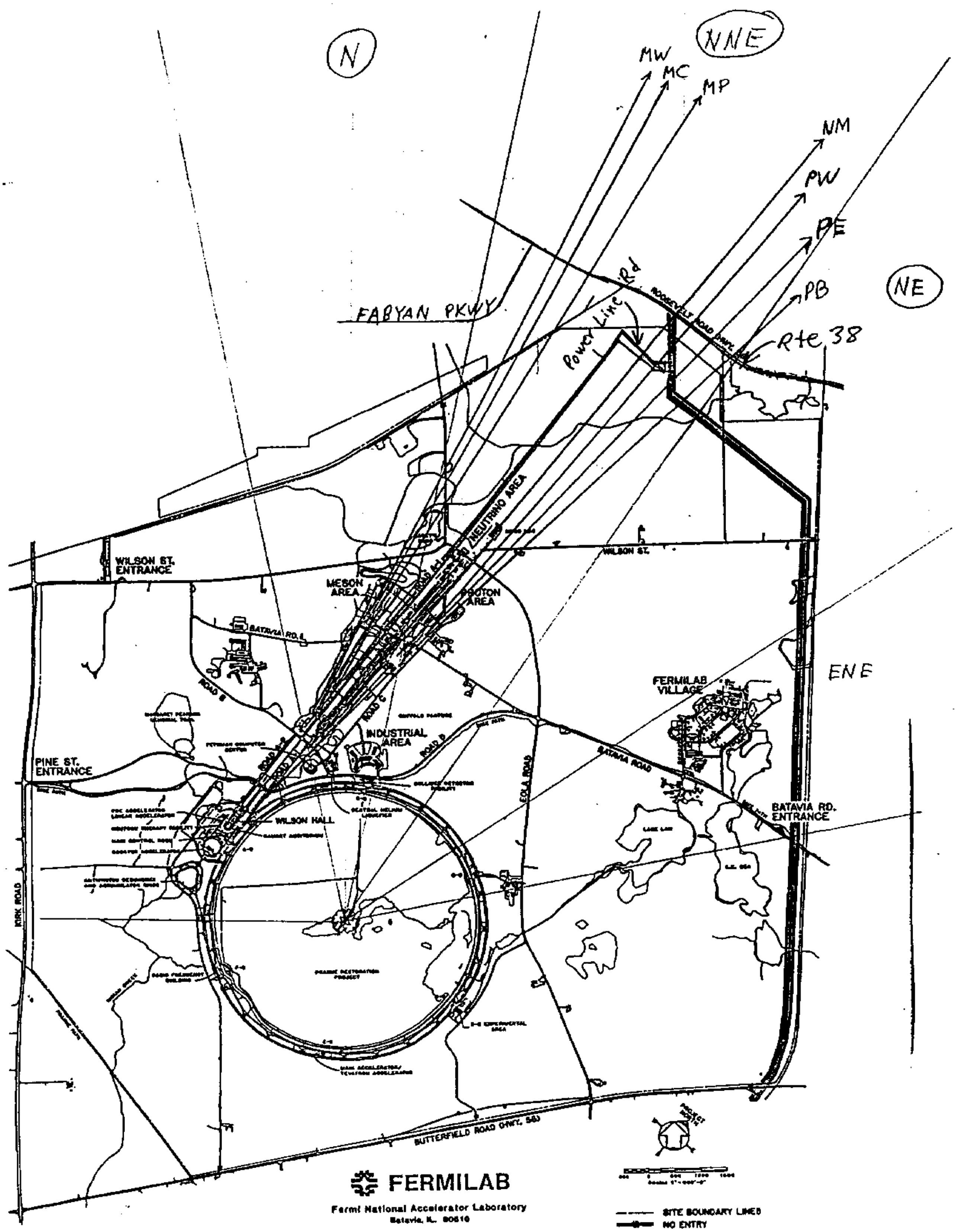
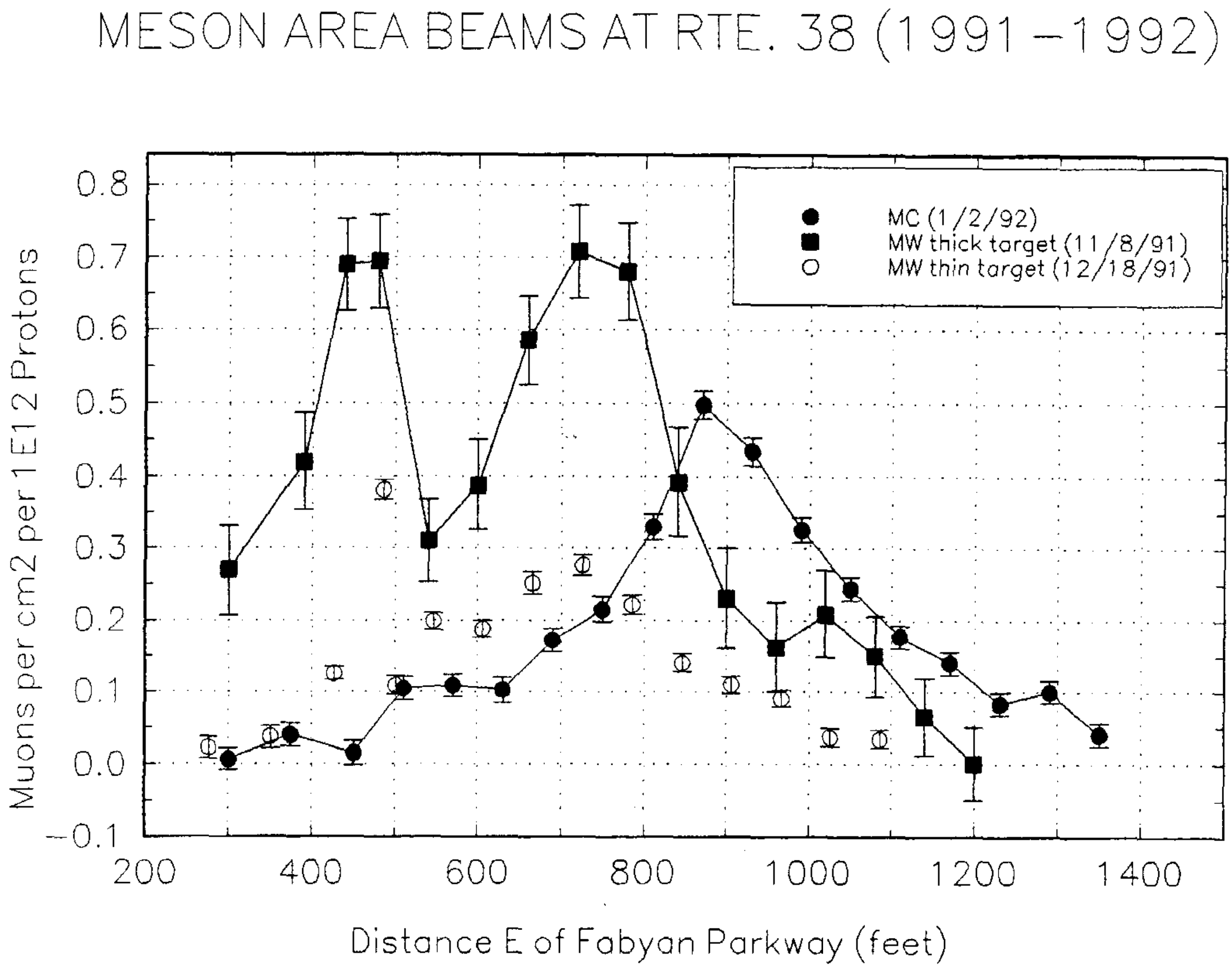



Figure 1 Map of the vicinity of the Fermilab site showing the locations of the seven beamlines that have been identified to have measurable offsite muon fluences when they are operational. The 22.5 degree sectors used for determining population dose are also shown on this figure and are labeled according to compass direction (N, NNE, NE, etc). These sectors have their origin at the center of the Tevatron.

**Figure 2** Muon fluence measurements for the Meson Area beams MW and MC measured at Route 38 during the 1991 fixed target run.

Axum Mar. 25, 1992 4:28:56 PM



# NM BEAM AT POWERLINE ROAD

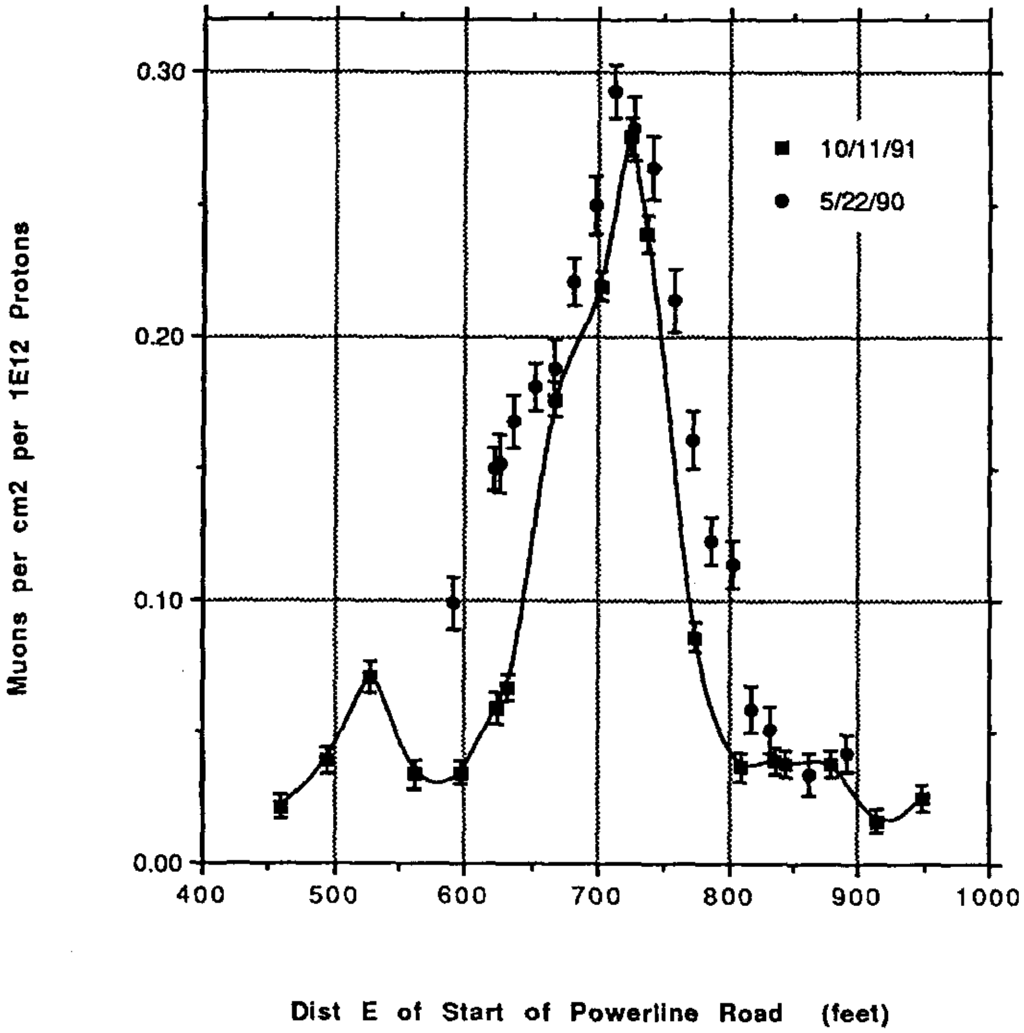
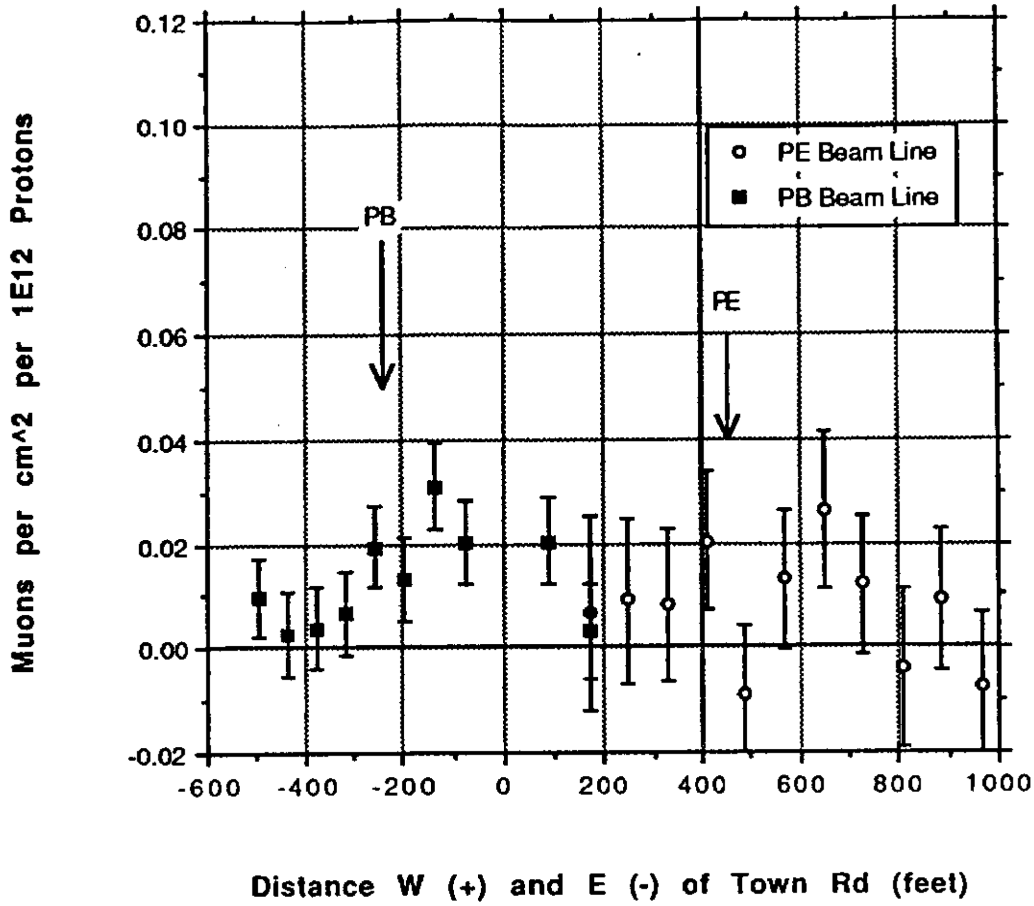



Figure 3 Muon fluence measurements for the NM beam measured at the Power Line Road during the 1991 fixed target run.

## PROTON AREA BEAMS AT RTE. 38 (1991)




## PROTON AREA BEAMS AT EOLA ROAD - 1991

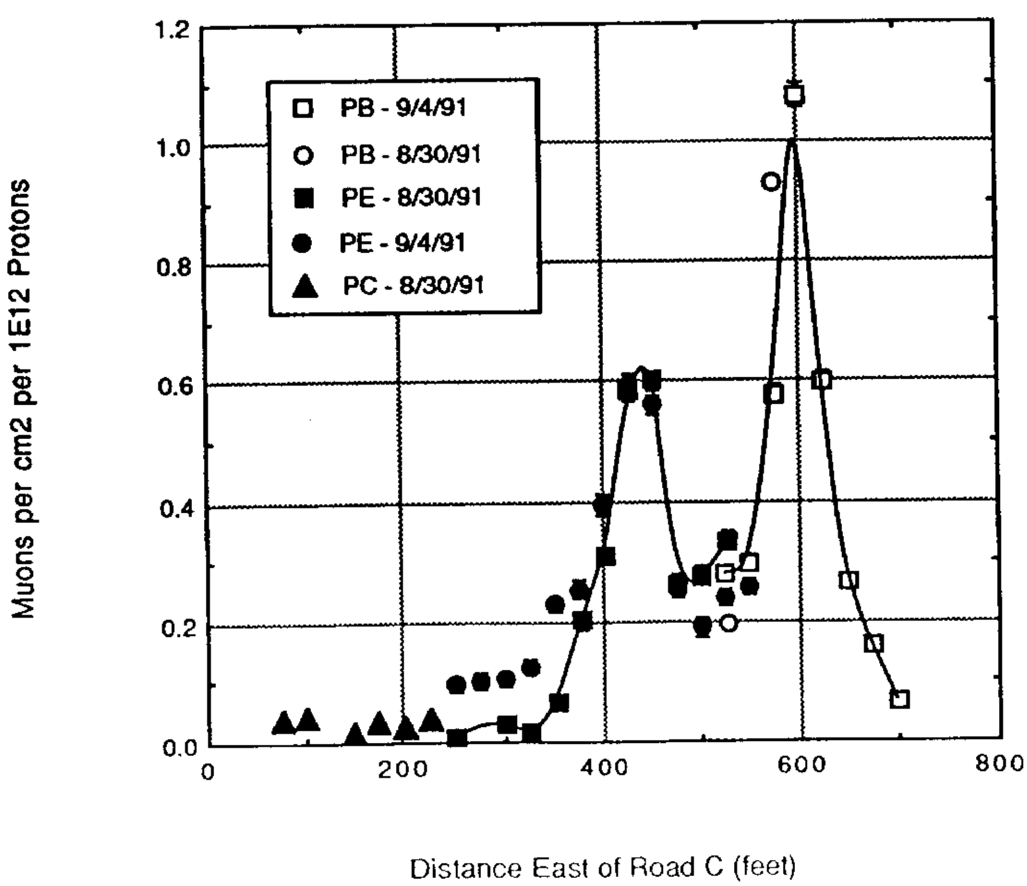



Figure 4 Muon fluence measurements for Proton Area beams PE and PB measured at Eola Rd and for PB measured at Route 38 during the 1991 fixed target run.

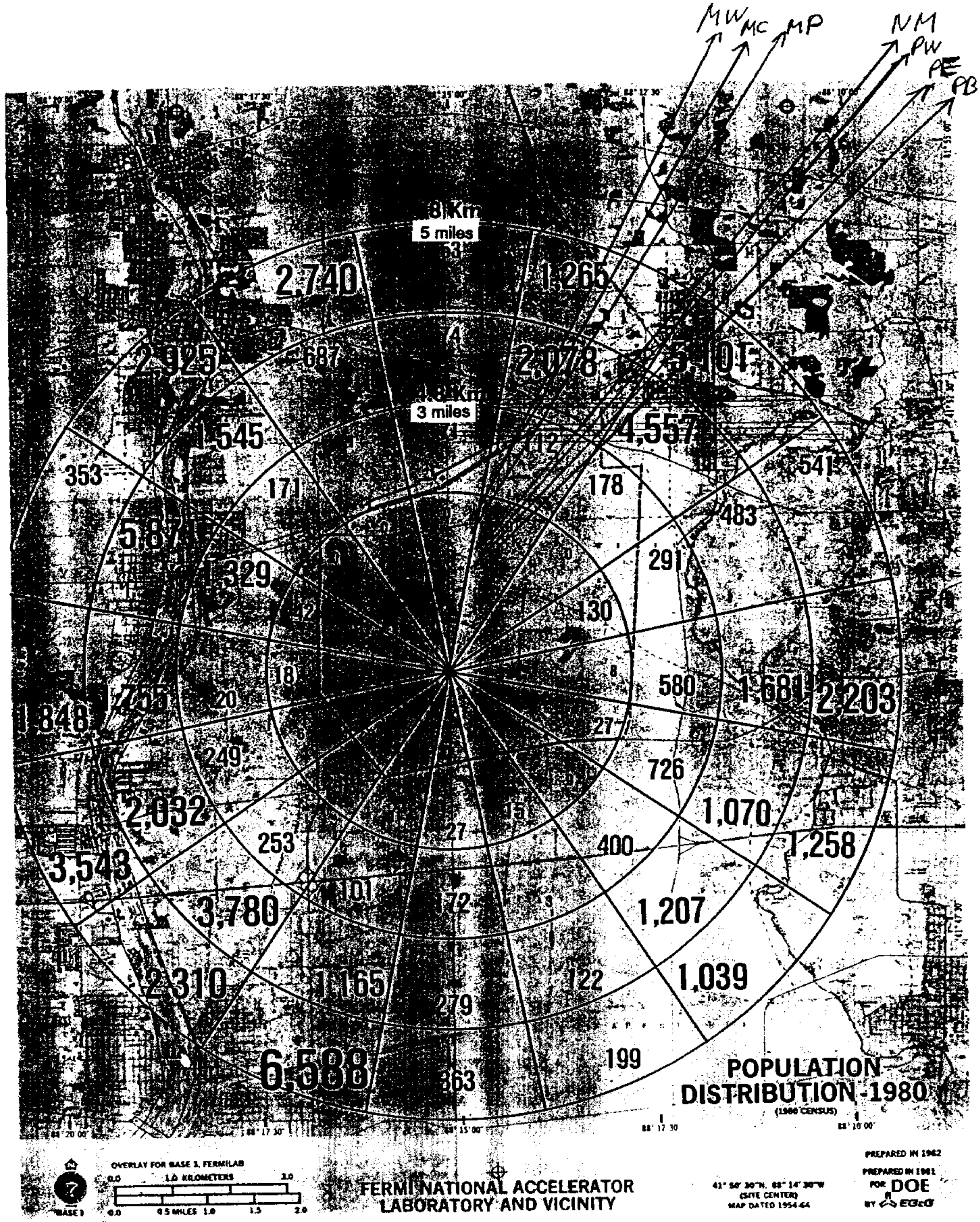



Figure 5 Residential population distribution in the vicinity of Fermilab based on the 1980 U. S. Census. The populations have been grouped in bins as indicated within 22.5° sectors originating from the center of the Tevatron. The numbers displaced on the plot are the residential population of a given bin. The labeled rays indicate the muon trajectories due to the corresponding Fermilab beamlines.

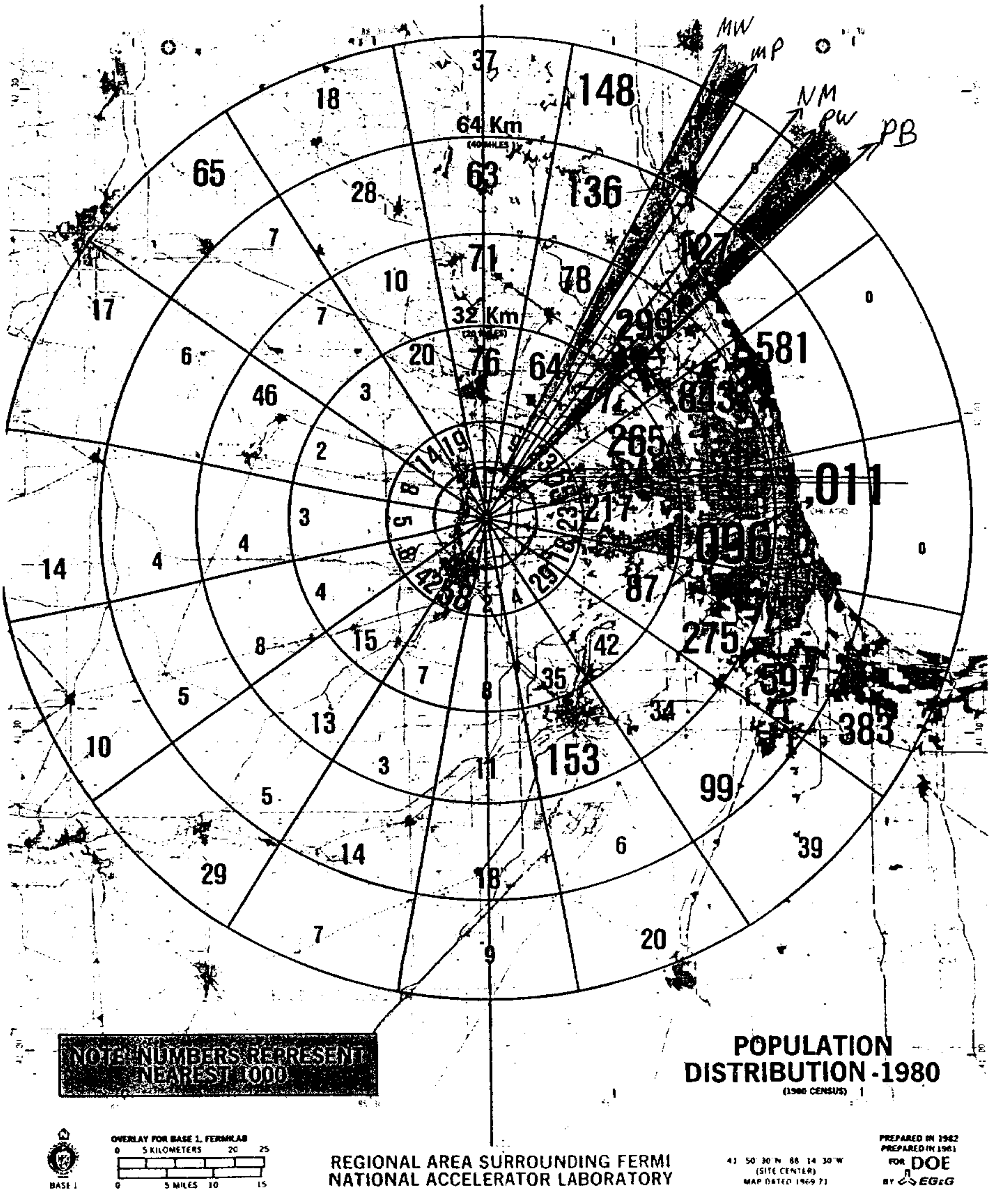



Figure 6. Residential population distribution within 50 miles of Fermilab based on the 1980 U. S. Census. The populations have been grouped in bins as indicated within 22.5° sectors originating from the center of the Tevatron. The numbers displayed on the plot are the residential population (in thousands) of a given bin. The labeled rays indicate the muon trajectories due to the corresponding beamlines.