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Residual Radiation Monitoring in the Main Injector with the ROTEM RAM DA3-2000 Radiation Survey Meter

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Abstract

Systematic monitoring of residual radiation levels in the Main Injector tunnel have been carried out since Fall 2005 using a dual-range Geiger counter dosimeter with bar-code reading capability. Bar coded locations have been monitored periodically during operations and cool-down measurements during facility shutdown periods have been carried out. We will describe the bar-code tagging, meter operation, data storage and some results.

Overview

The Main Injector was planned for supporting high intensity operation for PBar and neutrino production. From commissioning, which started in September 1998, the operation with a single Booster batch resulted in very low losses. When multi-batch operation for the Tevatron fixed target program was replaced with operation for the Tevatron Collider in single batch mode again, the tunnel radiation was at very low levels. In response to a Booster intensity limit at about 5E12 protons per cycle, the Main Injector slip stacking injection was developed. This could be used to slip two Booster batches together, increasing the intensity for PBar production at the expense of some loss. By Spring 2004, it was apparent that much higher intensities would be used in normal operation of the Main Injector to support the NuMI neutrino program. We anticipated that losses would rise faster than linearly with intensity. In preparation for the 2004 Facility Shutdown, a survey for high radiation areas was conducted in the Main Injector using a regular Fermilab LSM (Log Survey Meter). This monitoring effort was continued as access permitted [1]. By Fall 2005, we had procured a new meter, identified points at which regular surveys would be carried out, and placed bar-coded tags to assist in providing accurate data recording. This document will describe the components of this residual radiation monitoring system, provide guidance on the procedures and identify where data is available.

Residual Radiation Meter with Bar Code Reader

We need to record measurements at more than 100 places around the Main Injector on a long term basis. This suggested the need to have a system which automatically associated the readings with the location and provided electronic storage to minimize clerical errors. Some locations of interest were reading more than the 2 R/hr range of the standard LSM so a range up to about 5 R/hr was appropriate. A bar coded label was selected to identify the points which were to be monitored. A meter with memory to store radiation and bar code readings was selected to minimize operator and clerical errors.

The meter we selected is

RAM DA3-2000
ROTEM Industries
Rotem Industrial Park
Mishor Yamin, D.N Arava 86800, ISRAEL

The vendor through which we made the purchase was

Bioscan, Inc.
4590 MacArthur Bld., NW
Washington, DC 20007
Tel: 1-800-255-7226

Two meters were purchased, one for the Main Injector Group and one for the Proton Source Group for use in the Booster.

ROTEM Meter Features

<table>
<tr><td>Model</td><td>RAM DA3-2000</td></tr>
<tr><td>Detectors</td><td>Two Energy Compensated GM tubes</td></tr>
<tr><td>Range</td><td>50 microRoentgen to 100 Roentgen/hr, dual range, autoranging</td></tr>
<tr><td>Control</td><td>Microprocessor</td></tr>
<tr><td>Memory</td><td>347 readings
(ordered but did not get extended memory for 1415 readings)</td></tr>
<tr><td>Display</td><td>Multi-field LCD, illuminated, includes bar graph rate display</td></tr>
<tr><td>Readout</td><td>RS-232 communication port</td></tr>
<tr><td>Software</td><td>RMV (ROTEM Meter View) which outputs .csv files</td></tr>
<tr><td>Bar Code</td><td>Laser Scanner Bar Code Reader -- Class II laser, maximum power 1.0 mW</td></tr>
<tr><td>Power</td><td>three 1.5 V C-type cells (rechargeable possible but do not keep charge long enough to be a good solution for our intermittent monitoring schedule -- alkaline have long life)</td></tr>
<tr><td>Response Time</td><td><table>
<tr><td>Background to 0.5 mR/hr</td><td>50 sec</td></tr>
<tr><td>0.5 mR/hr to 2 mR/hr</td><td>30 sec</td></tr>
<tr><td>2 mR/hr to 5 mR/hr</td><td>5 sec</td></tr>
<tr><td>5 mR/hr to 20 mR/hr</td><td>3 sec</td></tr>
<tr><td>20 mR/hr to 100 R/hr</td><td>2 sec</td></tr>
</table></td></tr>
<tr><td>Accuracy</td><td>15% of reading</td></tr>
<tr><td>Features</td><td>Auto ranging
Freeze Mode to record the highest dose rate
Clock/Calendar
Memory stores ID#,date,time,reading,measuring unit and detector type</td></tr>
</table>

This meter is available with either Sievert or Roentgen measuring units. Both units (Main Injector and Booster) were purchased with Roentgen units. We have a manual for this meter which should be consulted for further details.

Meter Selection Counter Examples

The ROTEM meter was an easy choice, once one accepted the >$4000 price. The most significant limitation of other systems which associated a bar code reading with a residual radiation reading was the need to operate with two or perhaps three separate devices. One might need to carry into the tunnel

- A meter with electronics and memory
- A GM probe
- A bar code reading device

One would have to manage all three at the same time. In contrast, the ROTEM can be operated with one hand in most locations. If one required the wide dynamic range available with the ROTEM, one might need two probes. Other options included meters based on ion chamber readout.

Label Selection and Bar Code Printing

Label materials were selected per a suggestion from Butch Hartman.

Brady Catalog # LAT-24-747-1
A Matte White Permanent Polyester label
with Transparent Overlaminate (PermaShield B-747/B-966)
1.75" x 1" with 3 labels per row, 21 labels per sheet.

We probably would not think that polyester would be the best place to start for radiation resistance, but these labels have this nice overlaminate on the same sheet so we hoped that we would get good results for most of our locations. The labels come on a sheet with the clear overlaminate portion on the bottom and the white label on top. One prints the bar-code and text on the sheets of labels. In the tunnel, one removes the white label with the printed material from the stacked labels and installs it at the monitor location. One then removes the clear overlaminate tag from the same location on the sheet and covers the printed tag to protect it. Results have been very satisfactory. There has been no noticeable degradation from radiation.

For each label we print the bar code information in the middle of the tag. Above it we print "MIRadMon" so these tags will not be mistaken for other bar codes in the tunnel (At several locations, tags without this identifier were installed and not replaced. A list of locations is employed by the radiation survey team so these locations should not provide significant confusion.) Below the bar code, the labeling information encoded by the bar code is printed in text, such as "V103" or "LAM61A1". Similar tags were printed for use at the monitor locations in the Booster.

We have had the Overlaminate material turn dark in Lambertson magnet locations where the magnet, including the bar-coded tags, were under a blanket and heated as part of the vacuum system bake-out. Some overlaminate tags have darkened from the heat to the point that one can no longer read them visually. The red light employed by the bar code reader and its sensor are more capable and many of these tags are still quite usable. At present, the tags at the LAM40, LAM60-61 and LAM62 regions are still in use. Those at LAM52 have had duplicate tags installed below the darkened tags during the 2009 Fermilab Facility Shutdown. The new tags have been used for bar code reading while using the old tags to identify the preferred location for residual radiation monitoring. One of the original tags at MI52 fell off so the new tag replaced it.

The bar code printing was carried out in the TD Quality And Materials Department, Process Engineering Group by Jan Szal. Bob Jensen was the principal contact. For software to format the labels they employed Microsoft

Office Access Database.

Readout of Stored Data

The data stored in the ROTEM memory is accessed by connecting to a PC with an RS232 cable and exercising the RMV program provided with the meter. See further discussion below

Selection of Monitor Locations

The choice of locations to monitor for residual radiation is a compromise between completeness and resources. The possibility of creating a robotic system to provide a complete residual radiation map of the ring was considered and rejected due to the urgency of providing timely guidance and the perceived challenges of making an adequate, reliable system. In like spirit, the need to monitor enough places had to be balanced against the time and radiation exposure of the personnel who will make the radiation survey. The monitoring from June 2004 onward (See Beams-doc-2834-v1 [1]) was done with the intent to identify all locations with radiation above some not-quite-fixed threshold on the range of 10 - 20 mR/hr. This provided an excellent starting point. We choose to make on contact measurements to minimize the time required at each location. Locations at the top of magnets was preferred in hopes that the would be more like the readings at 1 foot from the beam pipe hot spots than would contact measurements at the loss points.

Most of the monitoring points are on the top of trim dipoles, main quadrupole or sextupoles. The ILA Lambertson magnets at the major transfer points and the RR Lambertson magnets where the beam transfers to/from the Recycler were the most serious loss points so residual radiation measurements at these points were emphasized. Monitoring points on the ILA Lambertsons were labeled beside each ion pump (upstream of the first three and downstream of the fourth ion pump). We also measured at the top of the quadrupole in the middle of the string of Lambertson magnets. This provided twelve plus one monitor points at MI40, MI52, MI60 and MI62 (52 total). In addition to the trim dipole and sextupoles where we had observed significant residual radiation, we selected a few additional ones spread through the ring so that we could know if there was some general increase beyond identified loss locations. When the large aperture quad project (2007) replaced the IQB quadrupoles with WQB quadrupoles, we replaced the lost bar-coded tags with new ones on the upstream top of the new quadrupoles at Q402, Q522, Q608, and Q620. The initial list was supplemented with new monitor points during the MI300 collimation installation in 2007. Three points in the ECOOL region were added in 2009. Currently there are 142 monitoring locations. Measuring at all of these locations on an access during normal operations had resulted in an exposure of between less than 20 to more than 60 mR for various occasions. It requires about 1.5 hrs to complete the survey. Since acquiring access keys and traveling to the MI requires additional time, we have rejected up to now the temptation to reduce the measurements since the overall gain would not change our ability to carry out measurements during typical operational shutdown opportunities.

Special Cases

- Beam Valves -- At 301 and 404, we had points of interest which were better served by placing the tag on the body of a beam valve, in order to be in the desired longitudinal location.
- Monitor Points at low loss points -- Some of the locations were originally quite low but we wanted to see that they did not get higher losses. A case in point is V619 where the fear that the aperture restrictions near LAM62 would eventually create significant loss. It has not yet occured.and readings there in Fall 2009 have been in the range of 0.1 to 0.2 mR/hr. Some other monitor points also now have very low residual radiation.
- Measurements for low radiation levels -- Since the meter has sensitivity which is adequate for measurements to 0.05 mR/hr, we have used it to document that extended regions of the aisle in the MI tunnel have radiation levels well below 1 mR/hr. Since other locations have much higher levels, we can use this meter to identify areas where personnel can wait in the tunnel while other work is carried out nearby.

Calibration

The calibration of the ROTEM meters has been carried out by the Instrumentation Team of the Environment, Safety & Health Section. Butch Hartman has been the usual contact person. They have developed and documented a procedure for this meter and apply it annually as requested. As part of the routine calibration, they have confirmed not only the high range but also the low range of the ROTEM meter.

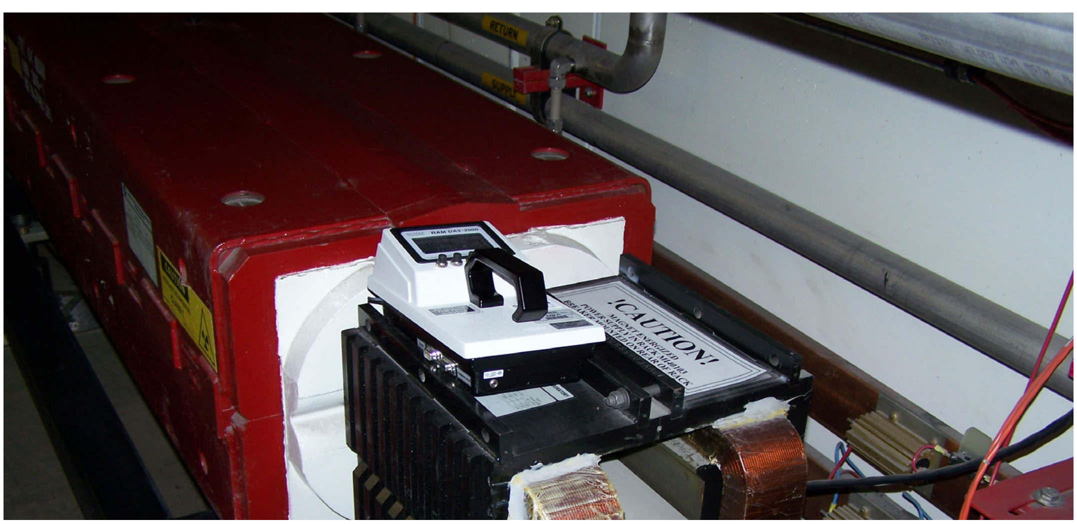
Measurement Procedure

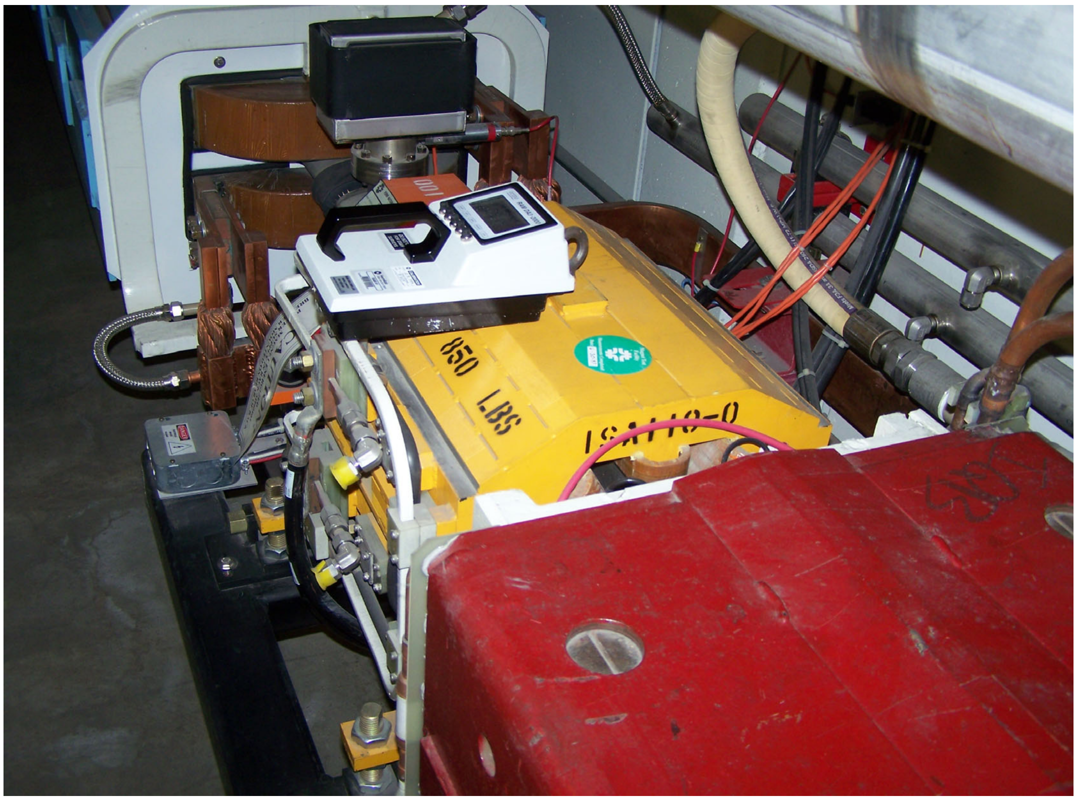
To achieve repeatable measurements, a systematic procedure has been developed for use of the ROTEM meter for Main Injector radiation monitoring. We read radiation levels in milliRoentgen per hour (mR/hr) with a mode which holds the highest reading (FREEZE). We scan the bar-coded tag for that location, then record the data into memory. Except for a few locations noted below, the reading is made by placing the meter on the bar-coded tag. The two internal Geiger tubes are near the bottom of the meter below the readout display so that portion is placed on the tag. The five buttons have multiple uses so the label will not correspond to the function described below.

Measurement Steps

1. Turn on the ROTEM by pressing the 'ON/OFF' button (left).
2. Set to or confirm that mode is mR/hr ('UNITS' button).
3. Locate a bar-coded tag location.
4. Set to FREEZE mode ('COUNT' button). The display will show FREEZE just above the 'COUNT' button that was used to achieve this setting.
5. Place meter on tag and wait about 7 seconds to achieve a stable reading.
6. Read the bar code. Activate the scanner by pressing the 'SPEAKER' button. The display will show 'bAr'. Point it to the bar-coded label. It will issue a sound (4 short and one longer beep)and display 'Go.' when it has read a bar-code. See further discussion below.
7. To store the radiation reading and bar code reading, press the 'LIGHT' button. **Do not hold down this button since holding it for 5 seconds will erase the contents of memory !!!**
8. Press 'COUNT' button to release (reset) FREEZE mode.
9. Go to Item 3 for next location and continue

ROTEM Meter in Use

Picture	Comments
	ROTEM placed to measure at Vertical Trim Dipole. This is typical of position for both horizontal and vertical trim dipoles.

	Measurements on Quadrupole monitor points is quite similar.
	ROTEM placed to measure at MI Sextupole. This location on the aisle side at the top provides a very regular place for measuring at this location. Note that it may or may not be placed on the bar-coded tag.
	ROTEM placed to measure at Lambertson. Note that meter is 'upside down'. These locations, adjacent to the ion pumps are awkward so attempting to hold it 'right-side up' places the arm near the buttons. **On one occasion the**

	'LIGHT' button was pushed and memory was erased -- sigh!

Special Locations

The following situations deserve some comment:

- For the ILA Lambertson magnets, we choose to make measurements just upstream of the first three ion pumps and downstream of the fourth ion pump. Such detail seemed appropriate when these were places had the highest residual radiation in the ring. The bar-coded tags have been very resilient elsewhere but when they have been exposed to the heat involved in a vacuum bake out, the cover turns dark. At MI52, we have added new bar codes to supplement the old ones. We have not yet (Fall 2009) installed the additional tags at MI40. If both tags are present we will read at the location of the old tags. The bar-coded tag for LAM40A1 could not be placed in the point where earlier monitoring had been done since it could not be read (the protective barrier is in the way). From 2005 thru 2009, this reading was taken at the location of the bar-code tag which is a few inches above the location beside the upstream ion pump. Beginning in Fall 2009, we MAY take the reading back down adjacent to the ion pump. If we forget and take the measurement at the tag, one can tell by comparing the readings at LAM40A1 and LAM40A2 since the ratio is quite stable.
- After the bar-coded tags were in place, it was realized that it would be sensible to measure all the sextupoles on the aisle side on the top as indicated in the picture above. This implies that the reading will not be at the tag location.
- At 301 and 404 locations, we chose to place the bar code on the body of the vacuum valve box. This is a bit further from the beam line that is typical of other locations but it provided a good place for a reliable reading.
- The bar code on V619 and H404 could not be placed on the top due to devices immediately above the trim dipoles. These are a bit more awkward for placing the meter for the radiation reading (usually we hold it 'upright' against the tag) but otherwise it is simple enough.
- The marble shielding on the collimators is a success. It is such a success that monitoring the location on the aisle side of the collimator requires a special procedure. This is due to the fact that the 'FREEZE' reading increases as one moves away from the bar coded location on the marble surface. [In essentially all other locations, one can move the meter back toward the aisle to read the bar code and without finding a higher reading.] This is the recommended procedure for C301, C303, C307, and C308 bar-coded tags:
    1. Read the bar code.
    2. Position the meter against the tag (meter upside down).
    3. Cycle the 'FREEZE' mode ('COUNT' button) to reset to minimum reading
    4. Press the 'LIGHT' button to store the reading and bar code.

Thoughts and Comments

- The bar code reader gives best results when not directed directly at the bar code but so that the red light beam is at an angle of from 30 to 60 degrees from the perpendicular. The meter can be from a few inches to a few feet from the tag and still get a reading. If the tone and the 'GO.' signal do not appear, then one presses the 'SPEAKER' button again and activates the reader again. Success has been had after 4 or 5 failures. However, if one cannot get a reading, either use a paper copy of the bar code (which you could be carrying with you) or remember the event and appropriately edit the data before loading to the database. Essentially all data sets have required editing of one or more bar code readings.
- To speed measurement, the reading is done on contact rather than at at one foot (a more typical reading to report). When accessing the tunnel immediately after high intensity operation, a person taking a radiation

survey may experience significant doses.
- It is helpful to carry a list of monitor locations so as to find and monitor all of the desired locations. A list is maintained on the windows file server at (e.g.) \\beamssrv1 \minjectr.bd\console\MIAperNLoss\RadMonLoc2009.csv on 'beamssrv1.fnal.gov'
- A Xerox copy of all bar codes is available (well, almost all). It was expected that some would be hard to read and one could use the paper copy when that was useful. A good plan has not yet been implemented.

Data Readout, Editing, and Storage

Readout

The data stored in the ROTEM memory is accessed by connecting to a PC with an RS232 cable and exercising the RMV program provided with the meter. There are 'interesting' quirks associated with this process. When one is setup to read out the data, it is erased upon readout so one must exercise care to be sure the data is stored to disk (we also e-mail immediately to another user as further assurance). The output file is in csv format with a header and a line of data for each reading. On many occasions, the RMV program has stalled while reading out the meter. By storing the data which has been read and re-initializing the program, additional data can be read out. In this way, two and even three or four separate files have been created from one set of measurements. These results are then combined when editing the results into the output file for that day.

Editing

The data for Main Injector monitoring is moved to a windows server, edited and stored with a standard name. The RMV program allows some control of the header information but we generally check and/or modify that information as we edit. The data as obtained from the meter readout has two sorts of problems which we correct during the editing step:

- The bar code reader (or perhaps the bar code tags) is 'less-perfect' than might be expected. When we monitor 140 or so locations in the tunnel, we usually find several bar code values in the data which do not correspond to the tags in the tunnel. Usually this is due to dropping one of the ACSII symbols such as "LM61A1" for "LAM61A1". Since we proceed around the tunnel in an orderly fashion, we can almost always correctly identify these location. We modify them in the output file and keep a log of the values changed. [See \\beamssrv1\minjectr.bd\console\MIAperNLoss\RAD_transferNotes.txt]
- After a half-dozen or more tunnel tours for radiation monitoring, the operator (BCB) has reduced his 'operator-error' level to a few per monitoring session. When he is alert, he may notice that the attempt to place the meter in FREEZE mode has failed, for example. If the data has already been stored, he usually chooses to repeat the measurement and edit out the extraneous data from the data file.

We put the file from the ROTEM meter into (e.g.)
\\beamssrv1\minjectr.bd\console\MIAperNLoss\MI_RadDataTransfer\RmvData 51.csv
Edited data is stored into the file
\\beamssrv1\minjectr.bd\console\MIAperNLoss\MI_RadData\MIRADyyyymmdd.csv where yyyymmdd corresponds to the date of the measurements.
A typical header is as follows where the (ROTEM-supplied) Signature line is edited to provide the time when beam was turned off in the Main Injector.

```
Department: MI
Date: 10/14/2009
Instrument Type: RAM DA3-2000
Survey location: MI Tunnel
Surveyor: BCBrown
Signture: 10/14/2009 06:59:49
```

Typical lines of data may be as follows:

H104 ,10/14/2009 9:08:00 AM,33.90,fmR/h,OK,Internal
whereas data from higher residual radiation locations might have
V105 ,10/14/2009 9:09:00 AM,731.00,fmR/h,OvrThrRate,Internal

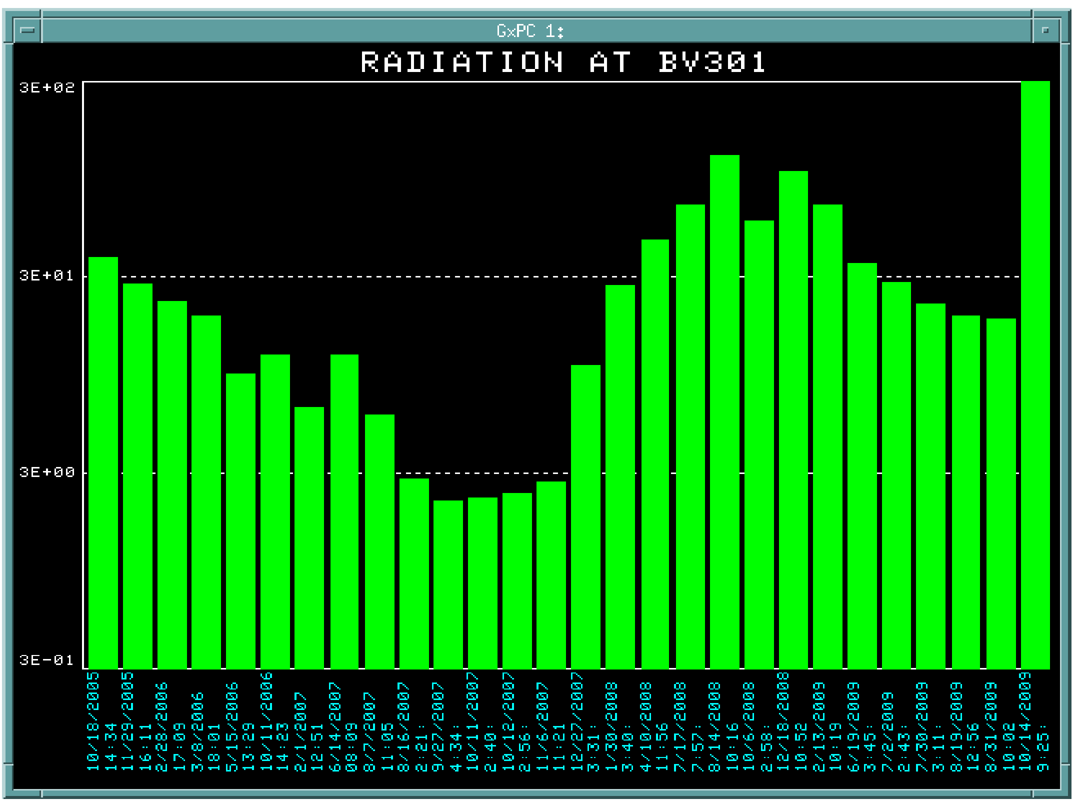
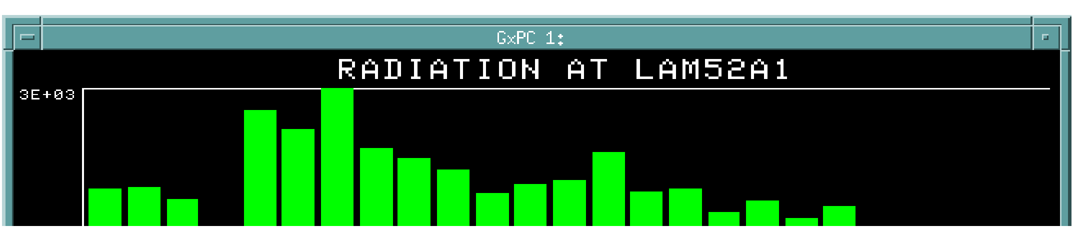
The indication fmR signifies that the meter was in FREEZE mode with milliRoentgen units.

Storage and Display

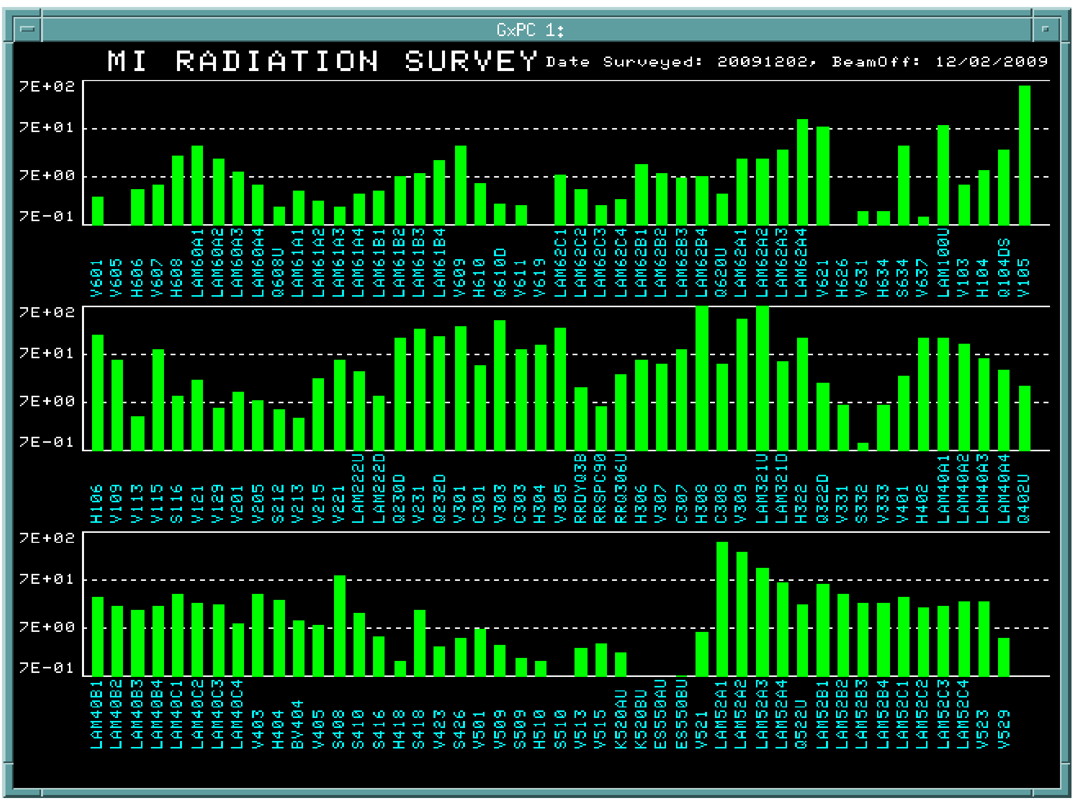
Console Program I128 (pa4078) was developed by Guan Wu to store and display the residual radiation measurements. Suitable SYBASE database tables have been designed. I128 loads data from the edited data files into the database and provides a check for unexpected label names. Each bar-coded location has its label and a descriptor in the database along with a position around the Main Injector (approximate) with an origin at the MI10 injection point.

Plots of the data are provided. File based plots provide a graph of the measurements from a single tunnel tour. A text view of the readings at each location are available from this part of the menu. Location list based plots provide a time ordered view of the data from one location. An autoplot feature allows one to sequentially view the time history at each bar-coded location.

Displays from I128 - MI RADIATION SURVEY

Picture	Comments
	Plot of Residual Radiation Measurements at BV301
	

Plot of Residual Radiation Measurements at LAM52A1



Residual Radiation Survey on 2 Dec 2009

Some Results

Many results are available from the data collected with this monitoring system. Some exceptional loss situations have been identified and the overall decrease in residual radiation around the ring due to better tuning due in part to the improved loss monitor readout system can be inferred. In the table below we compare the radiation levels in the 11-Batch slip stacking era from two measurements before the use of the collimator system (20071227 and 20080130) divided by two measurements with collimation (20090213 and 20090406). These are 'raw' results whereas the change in loss is more concentrated. Long lived isotopes are still important in these results.

Residual Radiation Ratios -- After/Before Collimation

MI113 - MI221	Col	LAM40	MI405 - MI521	LAM52	LAM60/61	LAM62
0.26	5.06	0.55	0.30	0.68	0.65	0.70

Conclusions

The system described here for monitoring the residual radiation in the Main Injector has been a success. The most important loss locations have been monitored for residual radiation and trends readily identified. The ROTEM meter has some quirks. On occasion one does not get the expected result when the button is pushed (or the operator thought it was pushed) but with experience this is not a big problem. The danger of holding the 'store' button too long (>5 sec) has been identified and is also not so very serious. The tag materials selected for printing the bar codes have adhered very well and show no problem with radiation damage. The overlaminate portion of the tag is discolored if exposed to the temperature used to vacuum bake our Lambertson magnets but this has been a manageable problem.

The ROTEM meter has not yet been employed in the Fermilab Booster. We hope that the detailed Measurement Procedure above may encourage that use.

References

[1] Bruce C. Brown, Main Injector Residual Radiation Data 2004 - 2007 Beams-doc-2834-v1