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Booster Fault Study (No. 13) for Generic Areas on the Berm Not Monitored by Chipmunks

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Study Period:	March 10, 2000
Participants:	L. A. Ahrens, K. J. Boland, C. J. Gardner, J. W. Glenn, C.V. Karns
Reported by:	C. J. Gardner
Machine:	Booster
Beam:	Protons
Tools:	See Text
Aim:	(Fault Study)

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Following is a report on the Booster Fault Study carried out March 10, 2000. The original Fault Study Plan is reproduced here followed by the actual study, conclusions, and recommendations.

1 Study Plan

1.1 Goal

During the fault study conducted on 9 December 1999 [1], radiation dose rates as high as 10 mr/hour were measured on the berm in the BAF penetration region of the Booster. This was under a fault condition of 1.07×10^{12} protons lost per second at 1.74 GeV on the inside aperture of the D6 Dump. The location of the 10 mr/hour measurement was approximately above the point where the BAF beamline pierces the Booster tunnel wall. The depth of the soil cover here, according to drawings, is 13 to 17 feet. (Directly above the Dump the depth is 17 feet; elsewhere on the berm the nominal depth is 15 feet.) Extrapolation to an extreme fault condition with a maximum possible loss of 72×10^{12} protons lost per second at 1.74 GeV on the Dump, would give a dose rate of 673 mr/hour at this location—well above the limit of 100 mr/hour allowed by the current posting of the Booster berm as a Radiation Area. The BAF penetration region is in fact monitored by two chipmunks (NM066 and NM067) which, for the loss geometry of the study, keep the dose rate below 27 mr/hour at the measurement locations.

The 9-December-1999 study has raised the concern that not only under extreme fault conditions, but also in more typical chronic-loss situations, there may be areas on the berm not monitored by chipmunks where dose rates would be higher than those allowed by the current posting of the berm. Suppose, for example, that 6×10^{12} protons are lost per second at 1.74 GeV in some localized area of the ring. This is the maximum loss allowed at high energy with the current administrative ALARA constraints [2] in place. Extrapolating from the 10 mr/hour measurement of the study and assuming the same loss geometry, we then would expect a dose rate of 56 mr/hour on the berm above the localized loss area. Allowing for some uncertainty in the specific geometry of the situation, there could easily be an error of a factor of two in this estimate; this would put the dose rate above the 100 mr/hour limit.

The **goal** of this study, then, is to produce a primary beam loss fault in a generic area of the Booster ring not monitored by chipmunks, and to measure the resulting prompt radiation on the top and sides of the berm. The study is to be conducted in accordance with AGS OPM 9.1.9.

1.2 Original (non-fault) Beam Conditions

1. Establish clean injection and acceleration to full energy (1.94 GeV) in Booster. Intensity at full energy should be 1–5 TP per Booster cycle.
2. Record beam current transformer trace for complete magnetic cycle.
3. Record output (both tabular and graghical) from Ring Loss Monitor program at desired "fault time". Record output from Booster Chipmunks.

1.3 Method

1. Reduce intensity to 1 TP at full energy. (Intensity may have to be increased to achieve observable fault levels.)
2. Use the RF Radial Control to position the beam close to the inside or outside aperture at the desired fault time. (The desired fault time is close to, but before, extraction time.)
3. Put in a local distortion (a bump) of the equilibrium orbit centered on desired fault time and position. This can be done with the orbit-correction dipoles or with a bump produced by pole-tip windings on the main dipoles. The desired fault location in the ring

is the B4 or B6 Quadrupole. (These quadrupoles are at dispersion and horizontal beta maximums. The corresponding area on the berm is easily accessible.)

4. Observe loss on beam current transformer and ring loss monitors. Adjust the bump to localize the loss at the desired fault time and position.

5. Record loss on beam current transformer and ring loss monitors. Record output from Booster Chipmunks. Record Radius and Bump parameters.

6. Measure levels on and around berm (see Survey Locations below).

1.4 Survey Locations

Superperiod B is an easily accessible generic area of the Booster ring with no special shielding other than the berm. According to drawings, the depth of the soil cover here is 15 feet. We will use the orbit-correction dipoles to produce a localized loss at the B4 or B6 Quadrupole. Under this fault condition, a radiation survey will be done on the top and sides of the berm from B2 to B8. The survey should also include the air vent at B3.

Another area where radiation might be detected under the fault condition is the downstream end of the Linac building (930). A survey should be done here too.

All surveys will be done using the HP1010 meter unless otherwise noted.

1.5 Radiation Estimates

To obtain an estimate of the radiation levels on the Booster berm, we apply the following formula given by Tesch [3] for a point loss:

$$H = \frac{1}{r^2}(1.6 \times 10^{-6}) L e^{-d/117}. \tag{1}$$

Here H is the dose rate (mr/hour) on the berm directly above the loss point in the Booster ring, L is the loss rate (GeV/s), d is the mass-density thickness (g/cm^2) of the berm shielding, and r is the distance (meters) from the loss point. Assuming the depth of the soil on the berm is 460 cm (15 feet), and taking the density of the soil to be 1.8 g/cm^3, we have

$d = 460 \times 1.8 = 828$ g/cm^2. The distance from the loss point is 5.8 meters (19 feet). For a point loss of 10^{12} protons per second at 2 GeV kinetic energy, the dose rate on the berm would then be 80 mr/hour. (For the maximum allowed loss of 6×10^{12} protons per second at this energy, this would imply a dose rate of 480 mr/hour on the berm.)

J.W. Glenn has done a similar calculation which includes 1 foot of iron shielding from Booster magnets and assumes that the dose rate is measured 4 feet above the berm. His calculation gives a dose rate of 9 mr/hour on the berm for a point loss of 10^{12} protons per second at 2 GeV kinetic energy. (This is nearly one order of magnitude lower than the 80 mr/hour obtained above.)

2 Actual Study

2.1 Conditions

The Repetition Period was $164/60 = 2.7333$ seconds.

Under fault conditions, beam intensities shortly after injection and shortly before extraction were respectively 1.35×10^{12} and 1.06×10^{12} protons per Booster cycle.

Extraction normally occured at the peak of the magnetic cycle approximately 82 ms from BT0. Here the magnetic field is nominally 6.51 kG, which, assuming a magnetic radius of curvature $\rho = 13.8656$ m, implies a proton kinetic energy $W = 1.926$ GeV at extraction. The actual loss under fault conditions occured 80 ms from BT0 where the magnetic field is nominally 6.476 kG; the corresponding proton kinetic energy is 1.91 GeV.

The RLMs (Ring Loss Monitors) registered the following counts BEFORE the fault was introduced:

1. In the window from 75 to 80 ms (from BT0) all monitors registered less than 10 counts except: C4 = 12, C5 = 10, C6 = C7 = 17; D5 = 48, D6 = 15, D8 =32; F6 = 70, F7 = 105, F8 = 24.

2. In the window from 75 to 90 ms (which includes extraction) all monitors registered less than 400 counts except: A1 = 1420, A2 = 1281, A4 = 1365; B4 = 950, B5 = 403; C4 = 546, C6 = 426; D6 = 1221, D7 = 1768, D8 = 920; F5 = 419, F6 = 29062, F7 = 33792, F8 = 7068.

2.2 Loss Setup

Producing a localized loss of high-energy protons in Booster is tricky business. The correction dipoles do not have enough strength at high energy to produce the required local orbit distortion at just one location. One must instead move the tune close to 5 and use the correction dipoles to produce a 5th harmonic orbit distortion. One then fiddles with the harmonic amplitude and phase until beam loss occurs at the desired location. Getting the loss to occur only at this location can be difficult.

To produce the desired loss, the control point for the correction dipoles was set to 80 ms (from Bt0) and the horizontal tune at 83 ms was moved from 4.79 to 4.85. **Two slightly different loss setups were studied.** For the first, we found that changing the horizontal 5th harmonic COS and SIN components by 5.14 and −13.52 Amps, respectively, produced a fairly localized loss between B6 and B8. The second setup was the same except the COS component was changed by 4.14 Amps. This produced a fairly localized loss between A4 and A5. The Loss Monitor profiles for the two setups are given below.

In order to keep beam from hitting the F6 extraction septum, the extraction bump magnets (TDHF2, TDHF4, TDHF7, TDHA1) had to be disabled, or timed so that excitation occured after the fault time. We also had to move the radius to the inside (away from the septum) starting 70 ms from BT0. (The radial function was programmed to go from −0.2 cm at 70 ms to −0.8 cm at 80 ms from BT0.) Since "Synchro" normally takes control of the radius some 20 ms before extraction we had to disable it by turning OFF BRF.SYNCH-STRT.GT on Spreadsheet.

2.3 Loss Measurements

Using the Booster RLM system for this study was complicated by the fact that the loss monitors in the region of interest have relatively high gains. Under the fault conditions these monitors were saturated. (Each monitor has a relative gain factor associated with it. These are "hard-wired" and can not be changed easily. For monitors C6 and C7 the factor is 2; for D5, D8 and F8 it is 10; for D6 it is 4.9; for F6 and F7 it is 22; and for all others it is 1. A factor of N implies that the gain is **attenuated** by this factor.) In order to determine the relative loss in the region of interest, we had to reduce the intensity until most (if not all) of the monitors there came out of saturation.

2.3.1 First Setup

For the first loss setup, the Loss Monitor profile at low intensity was as follows. (The window of observation was from 75 to 90 ms from BT0.)

1. B6, B7 and A4 registered 2050 counts. (These monitors are still saturated here.)
2. All other monitors registered less than 200 counts except A5 = 1079, B2 = 410, B4 = 423, B8 = 1041, C1 = 451, C4 = 617, C6 = 684, C7 = 306, F6 = 220.

Although B6, B7, and A4 are still saturated at low intensity, the loss profile for the entire ring indicates (conservatively) that at least 50% of the beam is lost between B6 and B8. We expect that going to the high-intensity fault situation does not significantly alter the distribution of loss around the ring. At high intensity, the total beam lost in the ring (as measured by the Circulating Beam Monitor) was 1.06×10^{12} protons per Booster cycle. **We therefore expect a loss rate of 0.2×10^{12} to 0.4×10^{12} protons per second between B6 and B8 under the fault condition at high intensity.**

2.3.2 Second Setup

Similarly, for the second setup, the Loss Monitor profile at low intensity was as follows:

1. A4 and A5 registered 2050 counts; B2 and B4 registered 1000 counts.
2. All other monitors registered less then 200 counts except A6 = 500, B3 = 300, B6 = 500, B7 = 800.

Here we see a rather local loss at A4 and A5. The loss profile for the entire ring indicates (conservatively) that at least 50% of the beam is lost at A4 and A5. At high intensity, the total beam lost in the ring was 1.06×10^{12} protons per Booster cycle. **This again implies a loss rate of 0.2×10^{12} to 0.4×10^{12} protons per second between A4 and A5 under the fault condition at high intensity.**

2.4 Radiation Measurements

Figure 1 is a topographical map of the Booster Ring showing the survey region and radiation measurements. (The contour lines are labeled in feet.) The point labeled "vent" in the figure is located above the B3 straight section and served as a point of reference for the survey. The measured radiation dose rates are indicated in mr/hour. The circled numbers are the levels associated with the second fault condition. All measurements were made with the HP1010 meter placed on the ground.

2.4.1 First Setup (local loss from B6 to B8)

Under the first fault condition, the highest radiation dose rate measured on top of the berm (i.e. on the 95 foot contour) was 2.0 mr/hour over what was estimated to be the B5 region of the ring. Along the 87 foot contour on the inside slope of the berm a local "hot spot" was found. Here rates of 3.8, 9.0, and 5.5 mr/hour were measured over what was estimated to be the B3 to B7 region of the ring. Further down the inside slope, below the point where 9.0 mr/hour was measured, the measured rate was 4.8 mr/hour. Further down still, at the 75 foot contour, no pulsed radiation (less than 0.2 mr/hour) was detected.

No pulsed radiation was detected near the vent over B3.

No pulsed radiation was detected at the downstream end of the Linac Building (930).

2.4.2 Second Setup (local loss from A4 to A5)

Under the second fault condition, the measured rates were highest along the 87 foot contour on the inside slope of the berm. Rates of 1.1, 1.7, and 0.4 mr/hour were measured over what was estimated to be the A8 to B3 region of the ring.

2.4.3 Chipmunks

Chipmunks NM058 and NM059 (BTA Roof), NM066 and NM067 (BAF Tunnel), and NM060 (Bldg. 914 Plug Door) registered **no change** during the fault study.

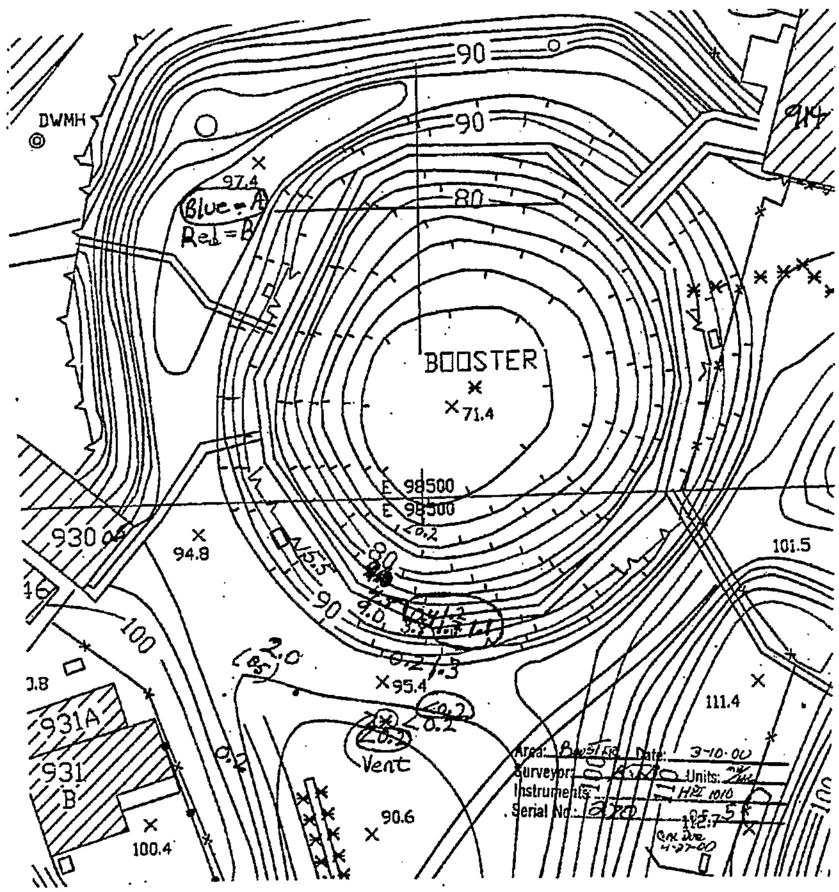

Figure 1: Map of survey region showing radiation measurements.

3 Conclusions

With a local loss in the Booster ring determined to be between 0.2×10^{12} and 0.4×10^{12} protons per second, at 1.91 GeV kinetic energy, the highest radiation dose rate measured on the Booster berm was 9 mr/hour. The location of the measurement was on the inside slope of the berm at or near the 87 foot contour and approximately over the B4 region of the ring.

By extrapolation, a local loss of 6.0×10^{12} protons per second—the maximum allowed at high energy under normal operating conditions with the current administrative ALARA constraints [2] in place—could give a dose rate on the berm of 270 to 135 mr/hour. This is well above the limit of 100 mr/hour allowed by the current posting as a Radiation Area.

An extreme fault condition—one in which all beam is lost at high energy in one particular location—could produce a dose rate of several Rem/hour on the berm. Consider, for example, the acceleration of protons for the muon g-2 experiment. Here, an upper limit on the number of protons accelerated in Booster per second is given by 6 Booster cycles per 2 second AGS period with 24×10^{12} protons at high energy per Booster cycle. In this case, an extreme fault condition could result in a local loss of as many as 72×10^{12} protons per second at high energy. By extrapolation, this could give a dose rate of 3.2 to 1.6 Rem/hour on the berm. For the case in which the Booster is cycling continuously at 7.5 Hz with 24×10^{12} protons at high energy per cycle, an extreme fault condition could result in a local loss of as many as 180×10^{12} protons per second at high energy. This could give a dose rate of 8.1 to 4.0 Rem/hour on the berm.

4 Recommendations

During high-intensity proton operations, the Booster berm should be posted as a Radiation Area **with the constraint that while people are in the area, injection of proton beam into Booster must be disabled with appropriate LOTO**. Entry requirements would be listed on the postings and enforced by MCR personnel who would hold the key to the area.

A further study should be carried out with TLDs (Thermolucent Detectors) deployed on the Booster berm. These would be deployed prior to the next high-intensity proton run and retrieved afterwards for analysis.

The TLD data would establish "routine" levels on the berm, allowing for a decision as to whether or not the posting needs to be upgraded to a High Radiation Area. (Note that upgrading the area to a High Radiation Area would require additional fencing to create a "buffer area" between the high-radiation and outside areas.)

References

[1] C.J. Gardner, L.A. Ahrens, J.W. Glenn, J.A. Kozak, J.F. Ryan, "Booster Fault Study for the BAF Penetration Site", AGS Studies Report No. 375, January 13, 2000.

[2] AGS OPM 6.1.10, "ALARA Strategies for Tuning During Proton Operations". The allowed loss at Booster extraction is 21×10^{12} protons every 3.6 second repetiton period.

[3] K. Tesch, Health Physics, Vol. 44, No. 1, pp. 79–82, January, 1983.