OPERATIONAL EXPERIENCE WITH BEAM LOSS, SHIELDING AND RESIDUAL RADIATION IN THE FERMILAB PROTON SOURCE

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Abstract

A report on beam loss, radiation shielding, and residual radiation experiences and status in the Fermilab Linac and Booster is presented. Historically, the Linac/Booster system has served only as an injector for the relatively low repetition rate Main Ring synchrotron. With the construction of an 8 GeV target station for the 5 Hz MiniBooNE neutrino beam and rapid multi-batch injection into the Main Injector for the NUMI experiment, the demand for Booster protons will increase dramatically over the next few years. Booster beam loss reduction and control are key to the entire future Fermilab high energy physics program.

1 THE LINAC

The original Fermilab Linac was designed and built as a 200 MeV proton accelerator in about 1969. It consisted of nine 200 MHz Alvarez style drift tube accelerating tanks. In 1977-78 the Booster was modified for multi-turn charge exchange injection and Linac was converted to accelerate H^- beam. Except for the ion source and preaccelerator, this was a minor change for Linac. It meant longer beam pulse lengths and lower pulse currents, typically 30 microseconds at 35 mA. In 1992-93, motivated by a desire to reduce space charge effects in the Booster, the four high energy drift tube tanks were replaced by 800 MHz side-coupled structures to increase the final Linac beam energy to 400 MeV. In addition to serving as an injector for the Booster, the Linac supplies 66 MeV H^- beam to the Fermilab Neutron Therapy Facility (NTF) for clinical cancer treatment. A ramped bending magnet between Tanks 4 and 5 steers beam to that facility between high energy physics (HEP) pulses.

The Linac RF power systems pulse continuously at 15 Hz; however, except for NTF operation, beam is not accelerated every 15 Hz cycle. Both the beam rate and pulse length are programmable for HEP needs. Typical operation is now 45 mA for 10-30 usec at an average rate of 0.5 Hz. This corresponds to an average beam current of 0.5 uA and 200 watts of beam power. The present capability of the 400 MeV Linac system is easily 20 uA or 8 kW (45 mA @15 Hz @30 microseconds). Acceleration efficiency from 10 to 400 MeV is >95% (see Figure 1). In early 1999, the Linac was outfitted with a proton source as a test to assess the ultimate beam current capability of the new high energy system. 400 MeV beam currents >90mA were accelerated before beam loading in the RF systems and beam losses became significant. It was determined that the existing cavities and RF power systems should not limit operations up to 80 mA for pulse lengths approaching 100 usec.

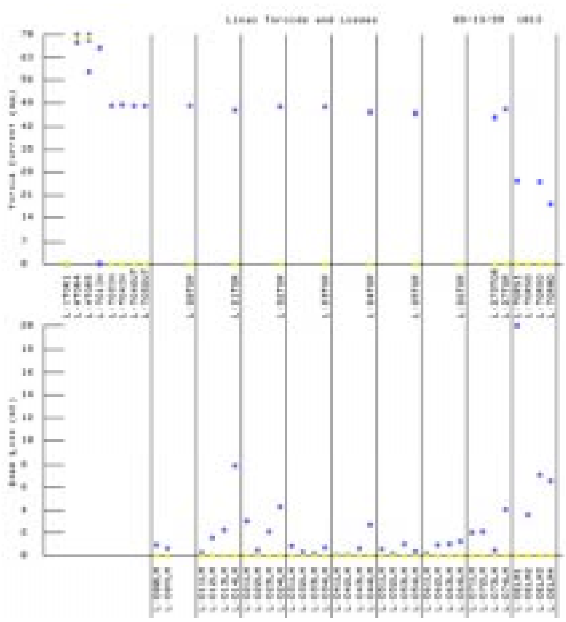

Fig. 1. Typical Fermilab Linac Beam Current (top) and Beam Loss Monitor (bottom) Display

Linac radiation shielding considerations [1] currently constrain operation to within a safety envelope of 3.5E17 400 MeV particles per hour. There are several interlocked radiation detectors monitoring sensitive locations to limit radiation under possible accident conditions. Given present operating conditions, detector trips are rare. Linac shielding limitations and detector trips may become an operational concern as the average HEP beam pulse rate increases, although Booster will be the tighter bottleneck.

Residual radiation levels of Linac beamline components have not been a significant problem for equipment maintenance. The highest radiation area in the Linac enclosure is the 400 MeV switchyard where a fast beam chopper sweeps beam across a Lambertson magnet to control the length of the beam pulse transported to the Booster. Figure 2 shows residual radiation readings taken along the Linac (excluding the 400 MeV switchyard

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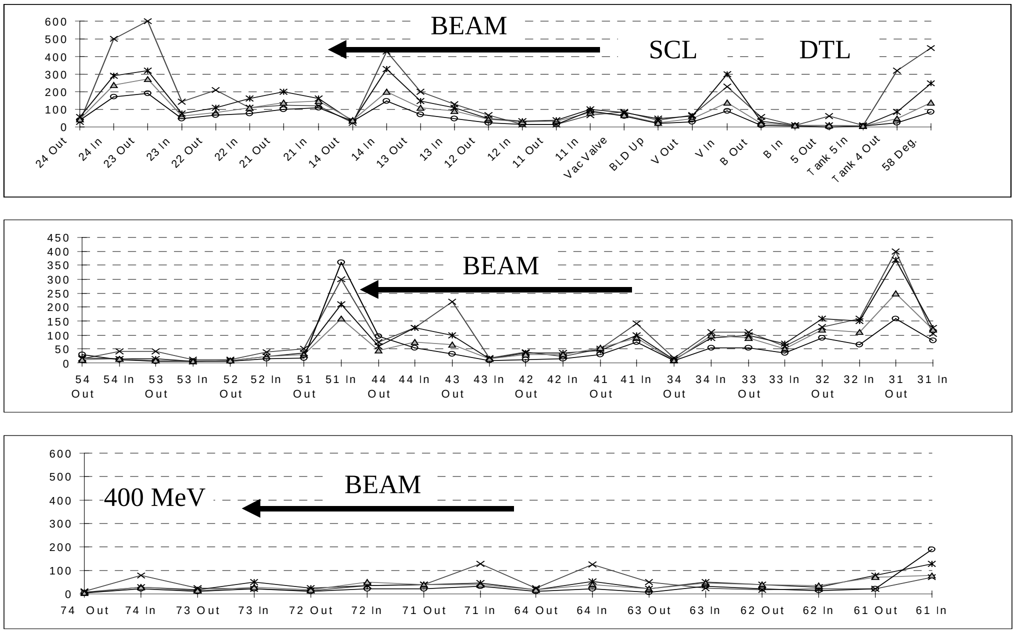


Fig. 2. Linac Residual Radiation Levels
Readings in mRem/hr "On Contact" after Several Hours Cooldown

region) on four different dates during the November 1994 to March 1996 period. Linac was regularly running around 1.3E16 particles per hour for Fermilab Collider Run I antiproton production during this time. Readings were taken "on contact" several hours after beam was turned off. In general, the high peak readings represent only very small regions of the beamline.

2 THE BOOSTER

The Fermilab Booster is a rapid cycling 8 GeV proton synchrotron built in 1970 [2]. Fundamental characteristics of the machine include a 15Hz sinusoidal magnetic cycle, a mean radius of 75 meters, adiabatic rf capture of the injected beam into harmonic 84 buckets, and a gamma transition of 5.4. Booster was originally built for 200 MeV single turn proton injection with various possibilities for multi-turn proton injection schemes. It was modified for multi-turn H^- charge exchange injection in 1977 and then upgraded for the 400 MeV injection energy in 1992.

2.1 Performance and Demands for 8 GeV Protons

Beam intensities exceeding 5.5E12 protons per pulse (ppp) to 8 GeV have been achieved in the Booster. Typical operation is at >4E12 ppp with 8-10 injected turns (2.2 usec per turn at injection). Figure 3 shows the typical Booster beam charge signal through the cycle for operation at two different intensities. The efficiency of beam extracted to beam injected is >80% at 1E12 and falls to around 60% for >4E12. As seen in Figure 3 most of the loss occurs in the first 5 msec. Beam loss occurs at various uncontrolled locations around the ring.

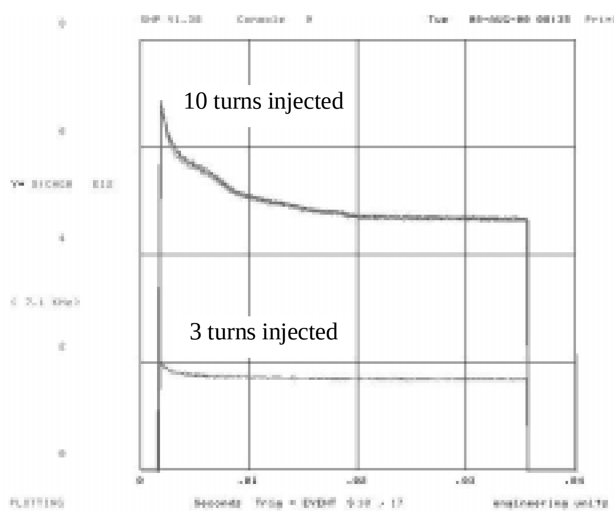


Fig. 3. Typical Booster Beam Intensity Through Cycle

Historically, Booster has run as high as 3E12 ppp at 2.5 Hz (2.7E16 protons per hour (pph)) for extended periods during Main Ring fixed target operations in the 1970's. Since that time construction of office buildings over the Booster tunnel, more restrictive radiation exposure regulations, and relocation of the Booster primary extraction point as Main Injector replaced the Main Ring have conspired to shrink the envelope for safe operations. Fermilab Collider Run II starting in March 2001 calls for Booster to provide 5E12 ppp at 0.7 Hz (1.26E16 pph). By 2003, with both MiniBooNE and NUMI experiments operational the demand rises to 5E12 ppp at 8 Hz, i.e. 1.44E17 pph. (Note for scaling purposes that 1E16/hr = 0.44 uA = 3.5 kW at 8 GeV.)

Within the coming year, the entire Fermilab program will be proton limited by allowed radiation around the Booster. Physical realities and the desire to maintain present building utilization severely limit options for additional shielding. Meeting these demands for 8 GeV protons within the radiation safety guidelines and controlling residual radiation levels to allow efficient maintenance of beamline components are key to the future of the entire Fermilab HEP program.

2.2 Booster 1998 Radiation Shielding Assessment

A complete reassessment of the Booster radiation shielding situation was undertaken in 1998 [3]. This effort was necessitated by several factors:

- the existing assessment was inadequate for anticipated proton requirements
- the primary extraction point was relocated for the Main Injector
- the existing assessment relied on a particular loss signature at a few locations to protect the entire ring which limited machine development flexibility, e.g. magnet moves and high energy orbit changes

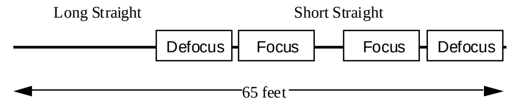
The new assessment was extensive:

- the complete shielding geometry for the entire ring was reviewed
- the utilization of all buildings and grounds in the Booster vicinity was reviewed
- many measurements and simulations were done to understand radiation patterns and levels for "normal" and for "accident" conditions
- numerous soil borings were taken for soil activation measurements

It was immediately obvious that the passive shielding around most of the Booster is woefully inadequate for the desired operating beam intensity. Efforts concentrated on establishing an array of interlocked radiation detectors to ensure a safety envelope for personnel in buildings and grounds around the Booster.

The Booster lattice is a regular DOFOFODO pattern comprised of gradient magnets. It was expected that radiation patterns due to beam loss should reflect the lattice periodicity. Figure 4 depicts the typical Booster lattice period with a chart of physical apertures and apertures normalized to beam size. Quite naturally, limiting apertures are associated with specific locations in the lattice. Measurements and simulations were performed for all conceivable beam loss scenarios to verify radiation patterns and to establish suitable locations for interlocked detectors with assurance of complete coverage.

Figure 5 shows measured surface radiation through thirteen feet of earth shielding directly above Period 9 in the Booster while using corrector dipoles to dump all the injected 400MeV beam in that period on the first turn. The family of curves corresponds to different corrector settings in attempts to lose beam at all possible locations in that lattice period. Clearly the radiation patterns bear a strong relationship to the lattice elements. For all possible



Location	Physical Aperture (inches)		**R** Value ($cm^{1/2}$)	
	Horizontal	Vertical	Horizontal	Vertical
Short-straight (BPM)	4.5	4.5	**0.197**	0.501
F-magnet (short-straight end)	4.5	1.64	**0.197**	0.181
F-magnet (D-magnet end)	8.0	1.64	0.457	**0.126**
D-magnet (F-magnet end)	8.0	2.24	0.467	0.164
D-magnet (long-straight end)	3.25	2.24	0.294	**0.126**
Long-straight (Beam pipe)	3.25	3.25	0.334	0.185
Long-straight (RF or Kicker)	2.24	2.24	0.231	0.128
Long-straight (Dog Legs)	2.31	3.25	0.237	0.185
Long-straight (Injection)	2.56	2.56	0.264	0.146

$$R = physical\_aperture / \sqrt{\beta}$$

Fig. 4. Booster Lattice Period and Apertures
Limiting Apertures in Bold Numbers

beam losses within the period, the radiation is strongly peaked at one of two locations associated with either the long or short straight section apertures. The Booster lattice consists of 24 periods, so there are 48 regular potential radiation peaks around the ring.

In an effort to assess the energy sensitivity of this characteristic pattern, beam was lost at different energies by gating off the accelerating RF at various times during the acceleration cycle. Correction dipoles were adjusted so as to cause the losses to preferentially occur as much as possible at one place in the ring, in this case Periods 6 and 7. The resulting surface radiation measurements (scaled to 1.35E17 pph) are shown in Figure 6. The location of the radiation peaks is seen to be energy independent and in agreement with the pattern for radiation due to mis-steered 400 MeV beam. At the higher energies (>6 GeV), the measured radiation is actually less than at lower energy. This simply illustrates the fact that it is physically not possible to lose the entire beam at one point in the ring at high energy. The largest dose occurs at the point of intended loss, but many particles are actually lost elsewhere around the ring. Peak dose rates through the thirteen feet of shielding scale to >2R/hour at 1.3E17 pph, highlighting the inadequacy of Booster's passive shielding.

Drawings like Figure 7 were produced for each different tunnel/surface building cross section to identify the thinnest shielding at each location and to establish the critical areas to be protected by interlocked detectors. Given this geometry information, the radiation measurement data, and supporting MARS calculations, the locations for >50 interlocked radiation detectors were established to protect the areas around the Booster. Note that single pulse accidents are not an issue and the interlocked detectors are fast enough to provide the required level of protection. Figure 8 shows the resulting final detector array deployment overlaid on a building utilization map.

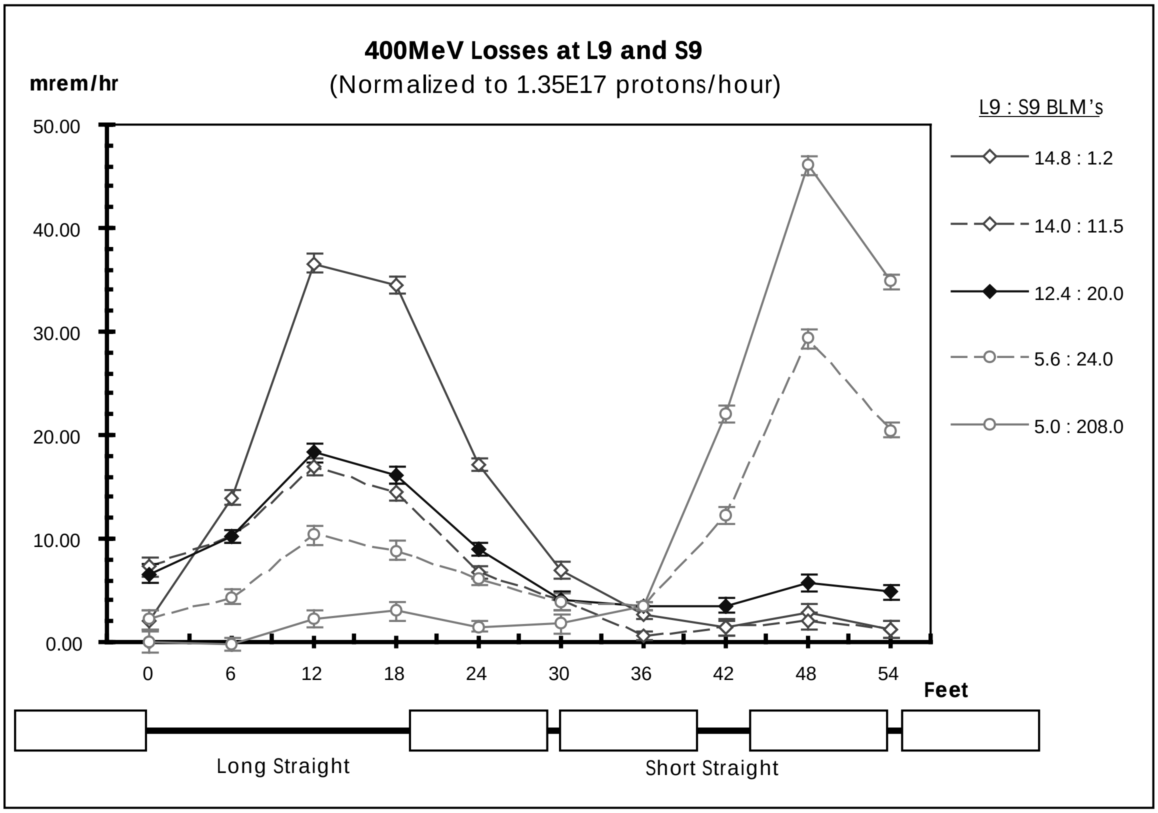


Fig. 5. Measured Surface Radiation Levels Through Thirteen Feet of Earth Shielding Attempting to Dump All Injected 400 MeV Beam in One Period (scaled to 1.35E17 pph)

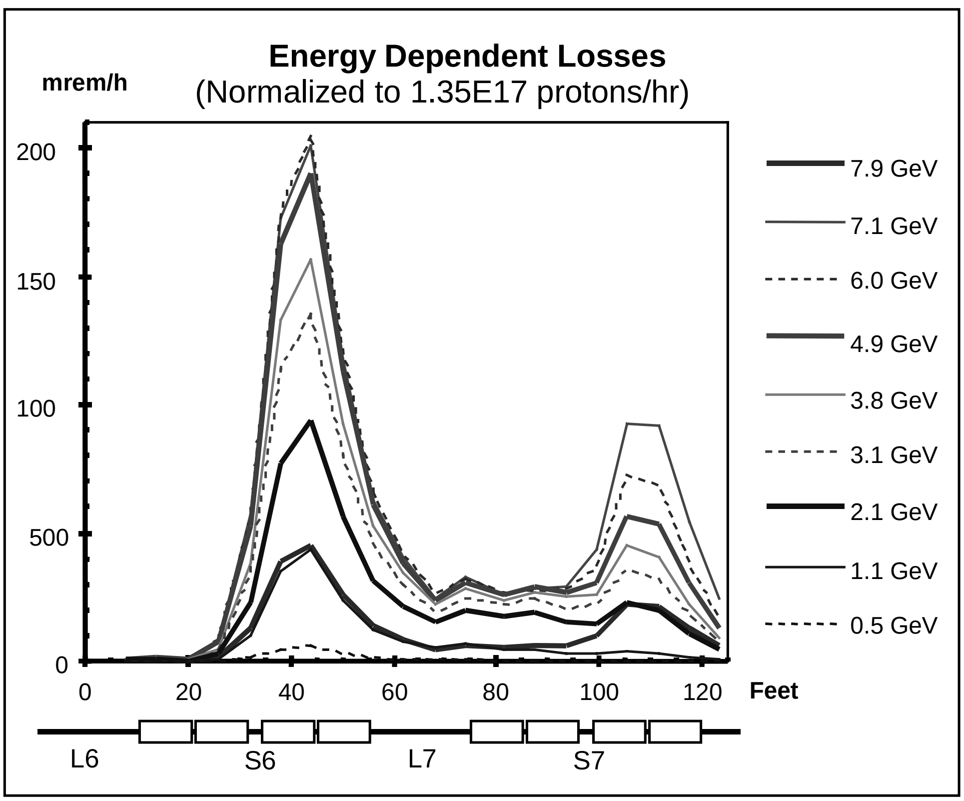


Fig. 6. Energy Dependence Measurements of Surface Radiation

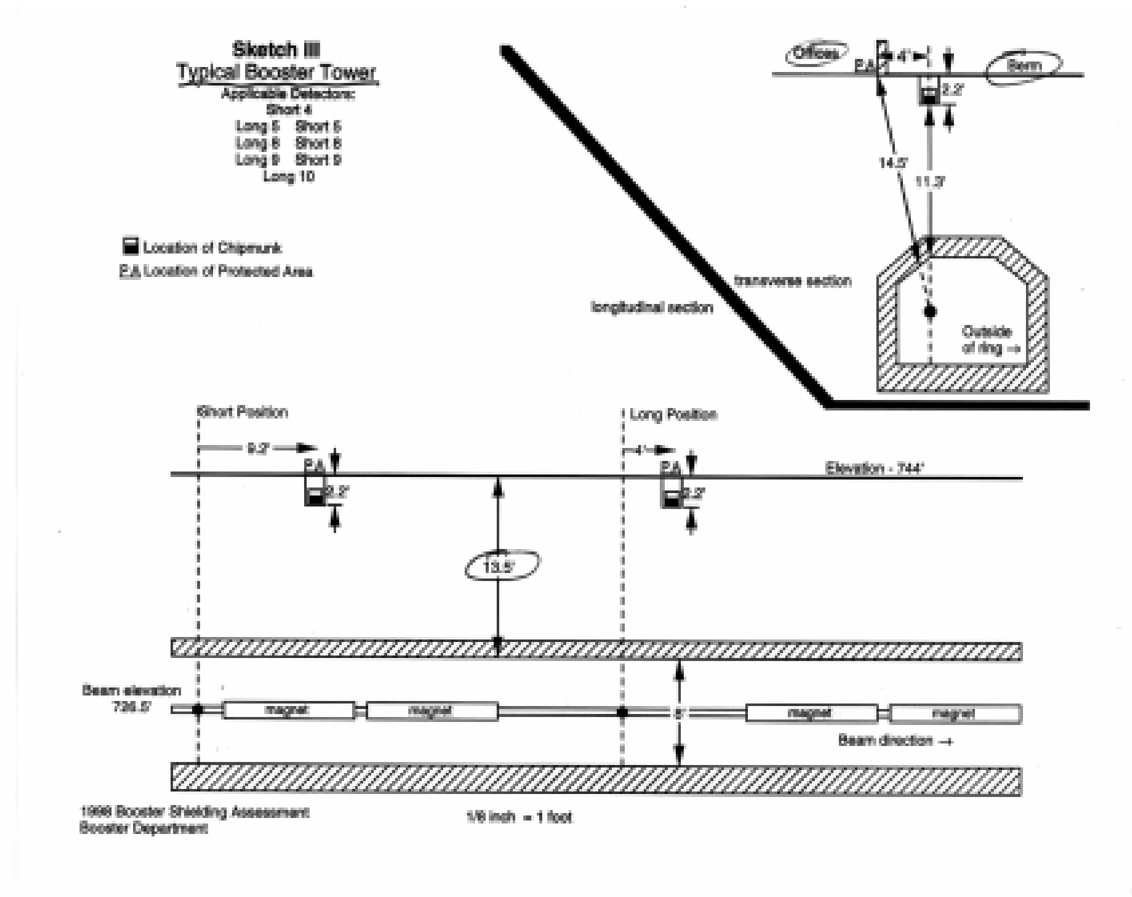


Fig. 7. Typical Shielding Drawing Produced as Part of Booster Assessment

2.3 Booster Residual Radiation

Hands-on maintenance of beamline equipment has not been greatly impacted to date by component irradiation issues. The best reference period for quantizing residual rates is during Collider Run I when Booster operated for extended periods at 8E15 pph. Figure 9 is a typical radiation survey data sheet from that time period showing rates >2 R/hr at one foot on the extraction septum, the hottest spot in the Booster. Rates at the injection girder during Run I would have been around 500 mR/hr at one foot. Short straight section hot spots correspondingly ranged from 10-100 mR/hr and long straight apertures like rf cavities and kicker magnets were from 50-200 mR/hr.

Monitoring and controlling residual radiation will be crucial to maintaining Booster's historically high reliability and low downtime for Run II and beyond.

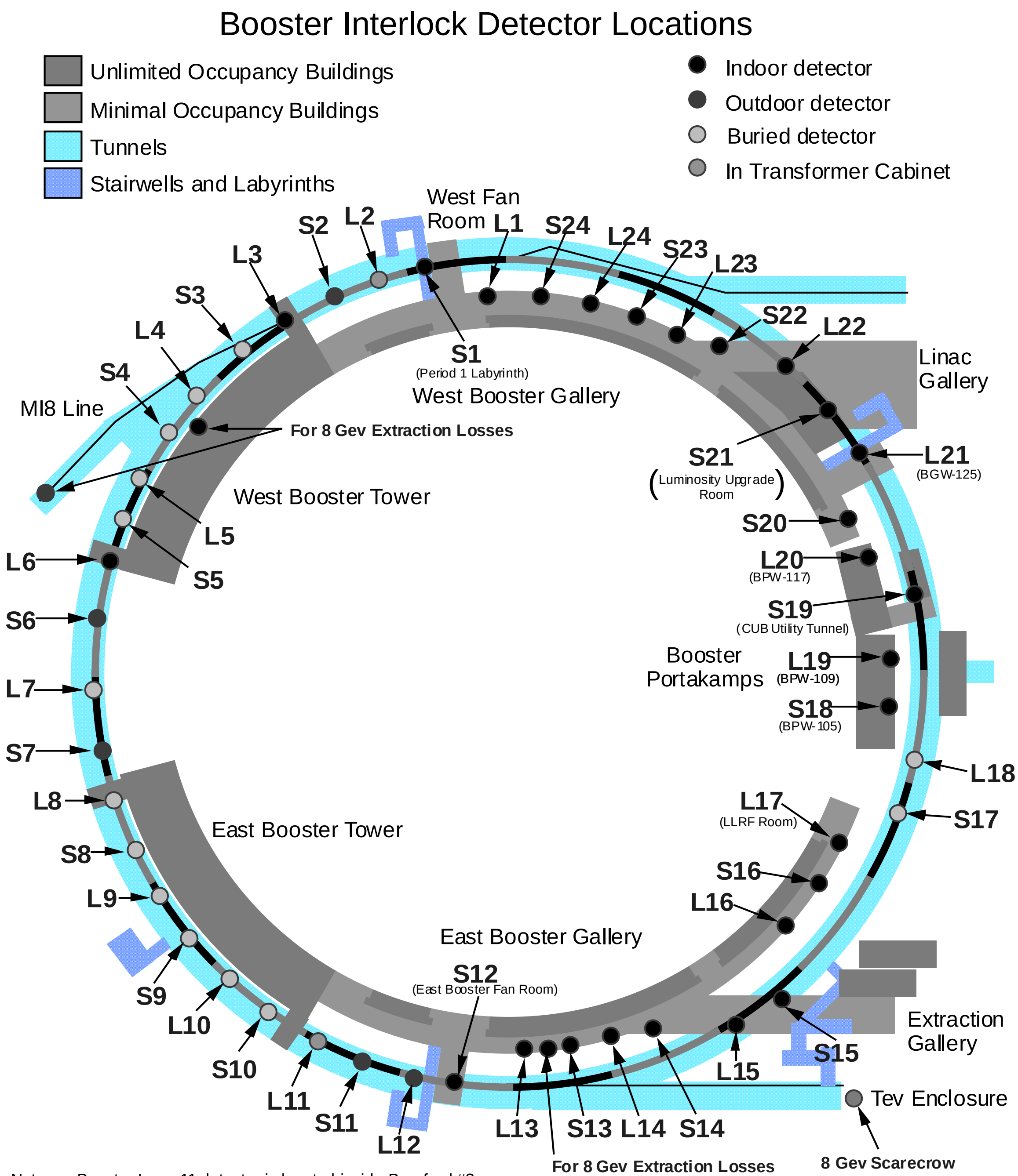
2.4 Towards Loss Reduction and Control

Booster beam loss is the result of numerous causes, some well understood and some not.

Beam from Linac is injected with 200 Mhz bunch structure. The revolution frequency in Booster during the multi-turn injection is not controlled to be a subharmonic of that frequency. The 200 Mhz bunch structures of successive turns interlace randomly and the remaining structure is allowed to de-bunch within a few turns. This beam is then semi-adiabatically captured by the Booster rf in 38 Mhz buckets. Some beam is lost as a result of this process. Efforts continue to understand and improve the efficiency of this process.

Space charge effects have long been associated with Booster beam loss; this was the motivation for increasing the injection energy from 200 to 400 MeV. Machine performance has improved, but debate continues as to whether the predicted improvement has been in fact quantitatively realized and to what extent space charge remains a significant problem.

Alignment and apertures have long been an issue in the Booster and continue to be addressed. There is an ongoing program of magnet moves to correct misalignments, open apertures, and adjust the high field closed orbit. DC corrector magnets are used to set the injection orbit, but as acceleration proceeds the effect of these elements diminishes and poor orbit control results. This, coupled with the small dynamic aperture of the Booster gradient magnets, makes for a touch-and-go situation to control transverse tunes and chromaticity even with existing ramped trim quads and sextupoles. The rf cavities, occupying eight of the twenty-four long straight sections, present themselves as limiting apertures.



Note: Booster Long 11 detector is located inside Brenford #3.
Booster Short 19 is located in the CUB Utility Tunnel on the West side of the LCW Piping.
Booster Short 12, located in the East Booster Fan Room, requires an AC-33 key.
Booster Long 21, located in BGW-125, requires an AC-2 key.
Booster Short 21, located in the Luminosity Upgrade Room, requires an AC-2 key.
Booster Long 7 located in a manhole in the road between the Booster Towers.
Booster Long 2 detector is located in the YBW1 transformer cabinet.
The 8 Gev Line Sarecrow is located in the Tev enclosure.

Fig. 8. Booster Area Utilization Map and Interlocked Radiation Detector Deployment Map

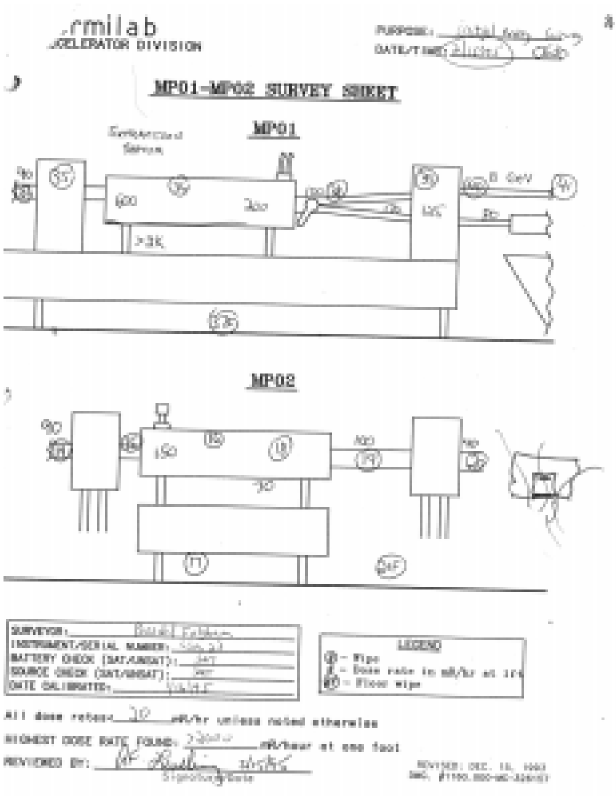


Fig. 9. Radiation Survey at Extraction Septum During Collider Run II (mR/hr at 1 ft. 24 hrs. after beam off)

R&D activity is underway to produce a modified cavity with increased drift tube aperture and satisfactory rf performance as a proof-of-principle.

At intensities above 3.5E12 ppp, coupled bunch longitudinal instabilities will cause beam loss after transition time in the cycle. Four single mode longitudinal dampers are used to control these instabilities.

Historically, Booster has operated with beam in all buckets. This results in extraction losses when the finite risetime of the extraction kicker wipes out two of the eighty-four bunches on the extraction septum magnet. This systematic 2% loss at 8 GeV is significant, especially since the extraction point happens to be located below offices at a region with the most stringent radiation controls. An additional four feet of steel shielding was installed under the offices in 1998. Recently a fast short-pulse kicker has been implemented to create a short gap in the Booster beam shortly after injection. Synchronizing this gap with the extraction kicker provides an important reduction in 8 GeV losses at the sensitive extraction location for the price of dumping some 400 MeV beam into a Booster magnet at a less sensitive location. This method of gap creation is far from ideal, but currently provides significant relief from the most pressing problem.

Further plans include

- improved longitudinal dampers to control coupled bunch instabilities at higher intensities
- design and installation of a scraper/collimator system to force unavoidable losses to occur at a controlled location which may be well shielded
- a cleaner method of creating a beam gap for the extraction kicker
- an improved beam loss monitor data acquisition system to better track machine performance trends

3 CONCLUSIONS

Beam loss and radiation issues will remain a chronic and increasingly important problem for the Fermilab Booster. A large array of interlocked radiation detectors has been deployed to ensure adherence to Fermilab Radiological Control Manual standards despite insufficient passive shielding. Learning to operate the Booster within this tightly constrained envelope at the required proton throughput rates is key to planned Fermilab high energy physics programs.

4 ACKNOWLEDGEMENTS

Larry Allen provided the Linac residual radiation measurements. Peter Kasper wrote the 1998 Booster Shielding Assessment, Figures 4-8 are taken from that document. Jim Lackey, Tony Leveling, and Ray Tomlin worked many hours performing the radiation measurements and poring over shielding drawings for that assessment. This author gratefully acknowledges their efforts.

REFERENCES

[1] Fermilab Linac Shielding Assessment, Fermilab.
[2] 'Booster Synchrotron', edited by E.L. Hubbard, Fermilab, TM-0405, 1973.
[3] 1998 Booster Shielding Assessment, Fermilab, 1998.